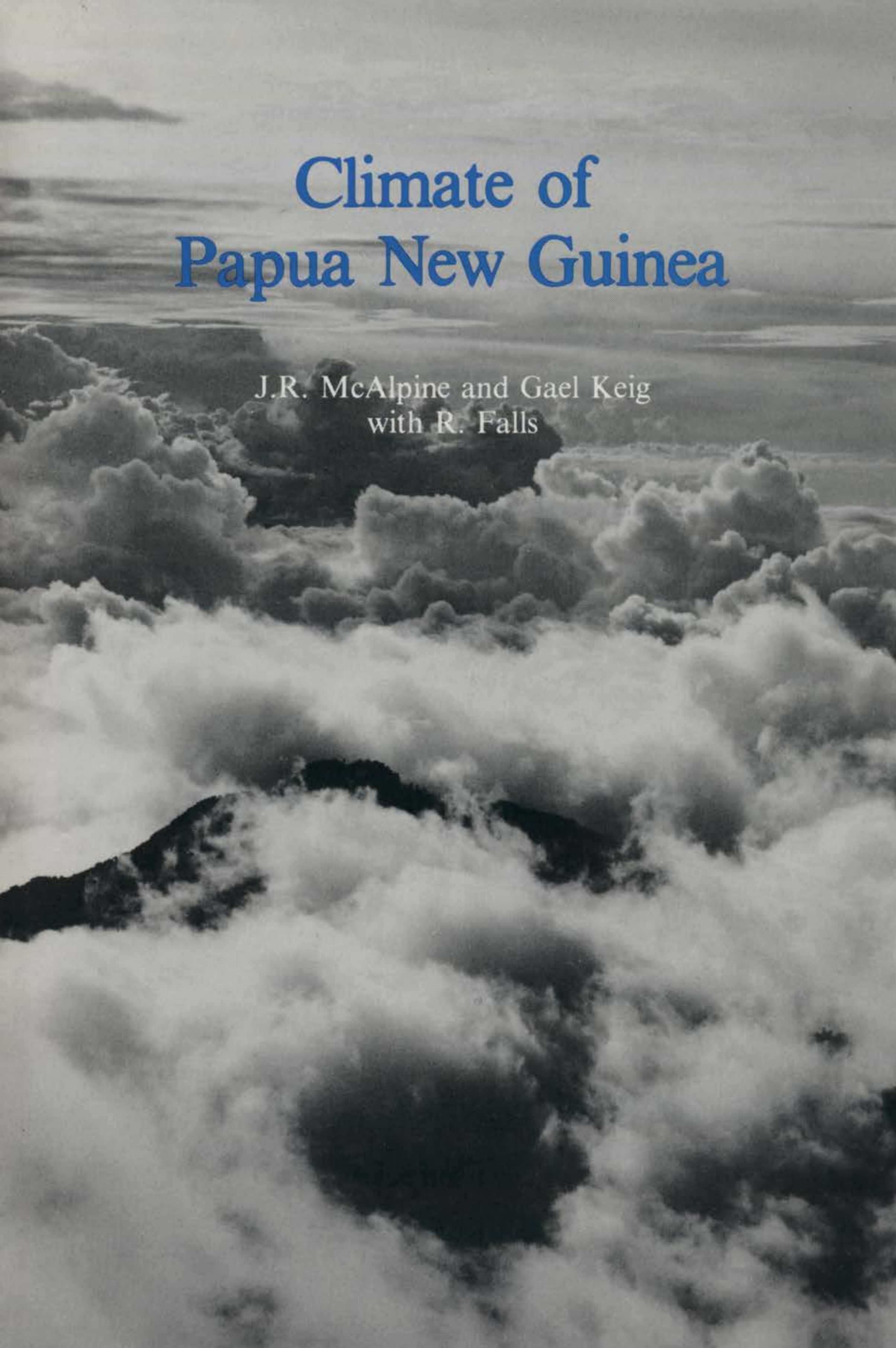
Climate of Papua New Guinea

J.R. McAlpine and Gael Keig
with R. Falls



This book presents the first comprehensive study of the climate of Papua New Guinea. It is based on an exhaustive analysis and interpretation of the basic meteorological data from the country's extensive recording station network, a network which resulted from the need for accurate weather information for the operation of widespread airstrips in an otherwise inaccessible interior. The data collected made it possible to undertake a climatic survey and analysis for Papua New Guinea which is perhaps unique in its spatial extent and time span for a less developed country.

The analysis has revealed the inadequacy of currently held theories of the major climatic controls operating in the region for explaining the various climatic patterns found there. The first chapters present a treatment of regional climatic controls which is in part entirely new. This explanation is then used as the basis for the succeeding chapters on specific climatic elements, the water balance and climatic classification.

Papua New Guinea is a land of many and varied cultures, each with its own traditional agricultural practices which have often evolved in response to climatic factors. Climate is also of major importance in planning and implementing many resource development projects such as the construction of roads and of hydro-electric power stations. For these reasons this book is directed to agriculturalists, engineers, planners and students as well as to professional meteorologists.

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Jacket photograph shows cloud formation around Mt Suckling. (CSIRO photograph).

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Preface

Within Papua New Guinea traditional knowledge of local climate has accumulated from the experience of past and present generations. Thus it is comprehensive both geographically and historically. While it might be possible (and would certainly be fascinating) to derive an overview of the climate of the country based on such knowledge, a more conventional approach for attaining the same objective is to proceed by collection and analysis of quantitative meteorological data. This latter approach requires the development of a meteorological reporting network which must cover a large area and be maintained for a considerable period of time, as it is not possible to produce a definitive and comparative climatology of a country in a few years. The process of developing an understanding of the climatology of a large and complex region usually involves a series of studies in which each study successively refines and extends the approximations developed in the previous one by using the new data that have become available from the extension of the reporting station network in both space and time.

Before 1970 a number of detailed studies, particularly of rainfall distribution and variability, and general but short accounts of the climate of the country as a whole had been produced. Subsequently, in the early 1970s, an assessment of the extent of the data available from the reporting network indicated that it would be possible to prepare a more comprehensive treatment of all the major climatic elements than had been attempted previously. As a result, the Papua New Guinea Government arranged for the preparation of a comprehensive set of climatic tables and for the publication of this book, which is based largely on the meteorological data presented in the tables.

The aim of the book is to describe the major climatic elements and their temporal and spatial variation across the country, and from this description to derive a regional climatic classification. Climatology has an important applied science component, and the present treatment is directed not towards the specialist climatologist but to an audience which has a wider range of interests, including natural resource scientists, engineers, social and medical scientists, planners and students. For this reason, considerable emphasis has been placed on presentation of information by means of diagrams, maps and figures, with brief descriptive text rather than detailed commentary. In addition, an even treatment of information for each of the major climatic elements over the whole country has been maintained, rather than a sole reliance on discussion of those aspects and areas for which there are more substantial sets of data. This attempt to say something about the climate of every region of the country has meant that extrapolation, particularly as portrayed in the maps, has been taken in places to the subjective limit and the reader should be aware of this constantly. Harold Brookfield, an earlier and noted contributor to knowledge of the climate of Papua New Guinea, stated in his work on rainfall that it was produced 'with no little imagination'. That tradition has been maintained in the present work.

In accord with the nature of the available data and the aim of the book, sophisticated techniques of analysis have been deliberately avoided. Such approaches have been considered more suitable for publication in appropriate learned journals. For instance, the complete absence of any studies of evaporation throughout the country required a separate specific investigation to be undertaken, the major results of which are reported in this book, while the technical details are published elsewhere. Similarly the climatic classification in the final chapter has been derived from a quasi-objective study of the data, rather than use of the techniques of numerical taxonomy. Thus the classification was designed to reflect the commonly perceived range of climates that occurs in Papua New Guinea. Nevertheless, standard and accepted methods of climatic analysis have been followed throughout. For example, standard time periods have been used for interstation rainfall comparison; interpolation using linear regression has only been used for normally distributed parameters, and distributions other than normal have been described by use of non-parametric statistics.

A note concerning authorship: work on the book was commenced by McAlpine and Keig, who intended initially to rely on the then current and widely accepted explanation of the meteorological controls affecting the climate of Papua New Guinea. Briefly, these explained the climate in terms of a seasonal alternation of south-east trade winds and north-west monsoon air masses, with local effects being attributed to orography. However, it rapidly became clear that this explanation was insufficient and consequently Rex Falls of the Australian Bureau of Meteorology was asked to prepare a more definitive account of the major meteorological controls. Chapters 2 and 3 are a condensation of his work, while the other two authors are responsible for the remaining seven chapters of the book.

The authors are grateful for the co-operation received from a large number of people and organisations. These include both the Papua New Guinea National Weather Service and the Australian Bureau of Meteorology. In particular, Dan Lee and Carol Skinner of the Australian Bureau of Meteorology have responded always most efficiently and courteously to what must have seemed endless requests for raw data and summaries. Arthur Douglas, also of the Australian Bureau of Meteorology, provided considerable background information from his extensive experience in Papua New Guinea. The assistance of the Snowy Mountains Engineering Corporation, and especially John Brown, in providing access to a number of detailed reports dealing with rainfall and runoff assessment is also most appreciated.

Eugene Fitzpatrick read the entire manuscript and the authors are indebted to him for constructive comments and valuable criticism. Jenny Bellamy provided excellent editorial assistance and also compiled many of the diagrams. The diagrams were drawn by Reg Munyard, Ninon Geier and Judy Sleep. The draughting effort involved will be obvious from even a cursory glance at the succeeding pages. The second part of the book consists of selected climatic tables which were prepared with the assistance of Karen Ewens as computer programmer.

Climatology, particularly at meso-scale as in this application, is unlike many other sciences in that the data requirements are very large. Moreover, the data are collected and recorded not by particular investigators but by a large body of observers drawn from a wide section of the community. The book attempts to integrate the information which these people in isolated locations have provided

on a daily basis, and frequently at odd hours, over many years—at some inconvenience and for little or no financial reward. This extensive, if not intensive, treatment of the climate of Papua New Guinea is dedicated to all the meteorological observers who have contributed their services to the Papua New Guinea meteorological reporting network. Without their efforts the book could not have been written.

Canberra, 1981

J. R. McAlpine
Gael Keig

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1 Introduction

The island of New Guinea, of which Papua New Guinea occupies the eastern half, is situated at the junction of the equatorial Indo-Malayan and South West Pacific regions (Fig. 1.1a). To the west of this predominantly oceanic area lies the large and relatively dense mass of islands that make up the Indonesian archipelago. To the east are the small scattered islands and atolls of the Pacific. The whole region has been referred to distinctively as a 'maritime continent' (Ramage 1951). It acts as an important global heat engine, driving not only its own internal atmospheric circulation but extensive regional circulations to the north and south as well. Thus an understanding of the meteorology of the area is basic to any explanation of the climate of subtropical Australasia and to the equivalent northern hemisphere areas of mainland south-east Asia and adjoining sea and islands.

New Guinea is the largest, highest and most massive island in this maritime continent. Its size is sufficient to result in significant local modifications to its climate, which would otherwise be equable equatorial, tropical and oceanic in nature. Principal locational features within Papua New Guinea are shown in Fig. 1.1b. No location is more than 300 km from the sea and most of the island, except for the main central range, is much closer. The highest point is more than 4500 m above sea level and approximately half the island is above 1000 m. Its height above sea level and the alignment of the island's physiography in relation to the main weather systems are the major factors which account for the climatic differences found within the island. This explanatory theme of altitude and alignment will be referred to on many occasions throughout this book. It

Fig. 1.1
Location maps of Papua New Guinea

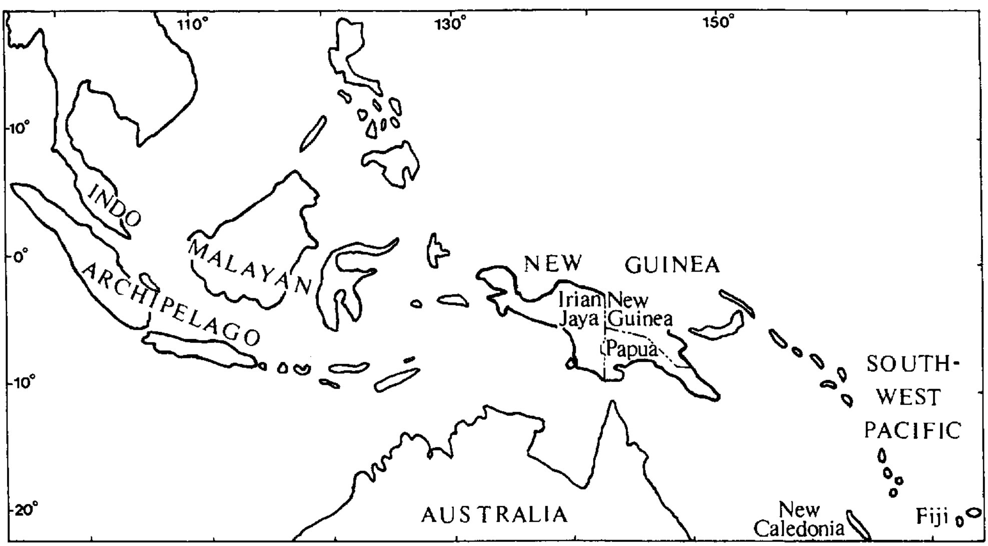


Fig. 1.1a
Papua New Guinea in the Indo-Malayan and south-west Pacific Regions

accounts, as stated, for much of the gross climatic variation within Papua New Guinea. Unfortunately, at a more detailed level of explanation, the same complexity of physiography makes extrapolation of point data from a climate recording station to surrounding areas an uncertain task.

The description and analysis of climate in Papua New Guinea fulfils many different requirements. At a theoretical level, it helps in understanding the origins, nature and distribution of those natural resources, such as soil and vegetation, whose formation is partly climate dependent. At a more applied level, the assessment of the capability of land to support different types of crop production must take into account not only factors such as soil and landform, but also the limitations imposed by climate on crop growth. More directly, climatic information is an essential part of a whole range of applied and engineering studies, such as the assessment of water resource potential for hydro-electric production, for urban water supply, for flood control design and for soil erosion control. Even more directly, knowledge of meteorological conditions is essential information in the aviation industry.

The climate in brief

Before proceeding further, it will be useful to readers unacquainted with the climate of Papua New Guinea to give a brief overview of its main climatic patterns.

The larger part of the country experiences relatively high annual rainfall of 2500-3500 mm. A few lowland areas of limited extent are drier, but annual falls of less than 1000 mm are unknown except in the national capital, Port Moresby. In contrast large areas of uplands to the north and south of the main central range

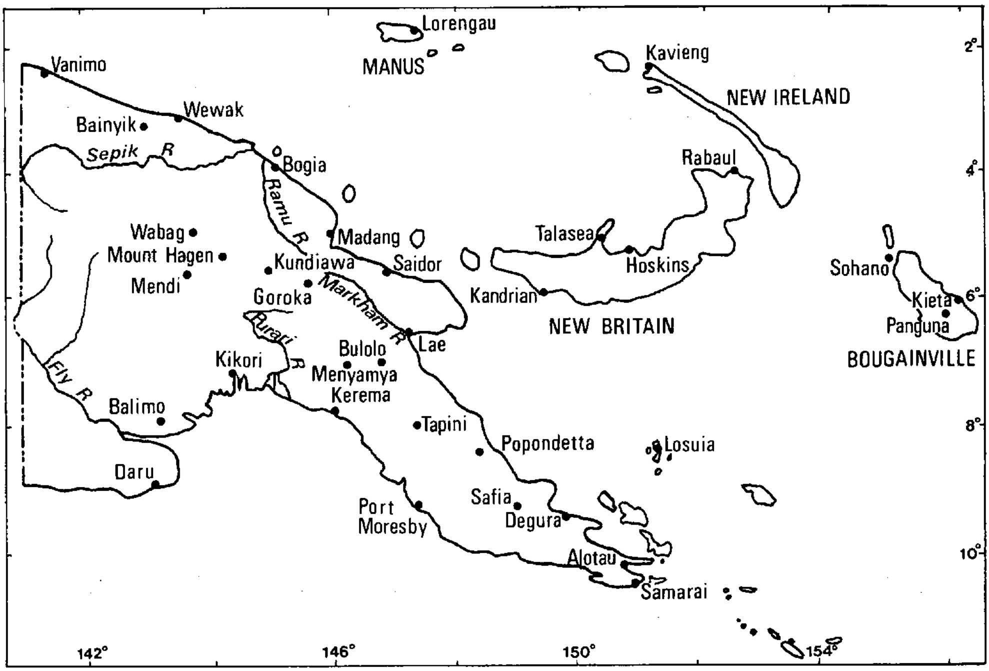


Fig. 1.1b
Principal locational features within PNG

have average annual rainfalls in excess of 4000 mm and in some locations these can rise to over 10 000 mm per year. Rainfall varies seasonally in most areas, but the degree of seasonality is not great. This seasonality is most evident in the drier areas, but even here there is no reliable period of nil or near nil monthly rainfall, as found in true 'monsoon' climates. The seasonal variation of rainfall over most of Papua New Guinea can be described best as a change from 'fairly wet' to 'very wet'. Nevertheless, minor droughts can occur from time to time even in moderately wet regions.

Temperature regimes are equable, showing little seasonal variation. Daily mean maximum temperatures on the coast are around 30-32°C, with minima around 23°C. The most marked characteristic of temperature is the drop associated with increasing altitude. A large proportion of the population lives in highland valleys and mountains at altitudes between 1500 m and 2000 m, where mean daily maxima are around 22-25°C and night minima are 11-15°C. Above 2200 m, frosts can occur and snow may fall and settle above 4000 m.

The combination of relatively high rainfall and temperature is associated with high humidity and cloudiness and moderate rates of evaporation, which range on the coast from 1500 mm to 2000 mm per annum (from a US Class A pan). Although wind patterns are reliable and consistent, and wind speeds can be strong, they are only very rarely destructive.

It is the purpose of this book to expand this brief description to the extent that the data will permit. In comparison with other developing countries, the problem is not so much lack of data as Papua New Guinea has a most adequate recording station network. As mentioned above the difficulty lies in extrapolating these data beyond the points to which they relate, in a region of complex physiography.

Sources of climatic information

There are two main sources of information relating to the climate of Papua New Guinea. These are, first, the long established knowledge of weather patterns held by the traditional society and, second, the recent collection of quantitative climatic data from a network of specifically established recording stations.

The depth of understanding of macro- and meso-scale climate in traditional society is most evident in the adaptation of agricultural activity to seasonal weather patterns, and to regional deficiencies and excesses of rainfall, which require the adoption of either irrigation or drainage practices. This understanding is also demonstrated by the timing and execution of traditional sea voyages in sailing canoes which relied on seasonal and diurnal shifts in wind, and of sea currents controlled by wind, tide and temperature gradients. Traditional knowledge of climate and its reliability is equally well developed at micro-scale. The use of composted mounds of earth for horticulture at high altitudes is an effective microclimatic adaptation to offset low temperatures, to decrease damage from frost and to improve soil drainage in a perhumid climate (Waddell 1972).

This local knowledge of climate includes an observational understanding of local atmospheric circulations and an approximate predictive capability based on observation. The occurrence of droughts as predictors of frosts at high altitudes is recognised, as are the signs of onset of line squalls at sea. The diurnal pattern of land-sea breezes on the coast and lowlands, and of valley-mountain winds inland is understood and, in the latter case, the relation to the timing of rainfall and the occurrence and usual paths of convectional storms is well established. While the knowledge of local observed climate is comprehensive, the meteorological and physical processes responsible for the climate were explained traditionally in terms of fable, or ascribed to magic. However, Prince (1969), in reporting on concepts of science in Pacific cultures, has shown that the magical beliefs explaining meteorological phenomena are not strongly held.

It is interesting to compare traditional climatic knowledge in Papua New Guinea with western climatological science. For traditional society, observational knowledge of the macro-scale processes at work in a region is limited to the major seasonal shifts of wind and changes in rainfall amounts. A deeper scientific understanding of macro-scale processes is fairly recent. At the meso- or local scale, traditional knowledge was adequate to the point of developing skills and practices to adapt livelihood to the climate, and to provide some degree of short term prediction. It is accepted that the science of meso-scale climatology is one of the less well understood branches of meteorology, and in fact the level of comprehension is not greatly in advance of traditional knowledge. As for micro-scale climate, it is fair comment to state that, of the few investigations that have been made, most have been prompted by observation of traditional micro-scale adaptive practices.

Thus the body of traditional climatic knowledge is considerable, but it is largely local in extent, qualitative rather than quantitative and applied in nature. It would provide a powerful and complementary source of information to the material included in this book, but unfortunately it has not yet been either researched or recorded. Traditional knowledge would be useful especially in the extrapolation of quantitative point data, upon which western scientific climatology is based.

The second main source of climatic information is that derived from a network of meteorological stations that record climatic data quantitatively, systematically, and over periods of time measured in years. These data are the basis for the climatic analyses presented in this book.

Development of the meteorological station network

The colonial domination of the south-west Pacific in the nineteenth century coincided in Europe with an explosion of knowledge and curiosity in the field of natural history, of which climate was seen as an integral part. Indeed, the geographic distribution and behaviour of many biological phenomena, including man, were explained at the time in terms of simple climatic determinism. Consequently, many of the early European exploratory expeditions and settlers measured climatic elements with the aim of commencing the evaluation of climatic types in the regions to which they travelled. In this regard, Papua New Guinea was no exception, and interest in its climate, which would have been perceived as most unusual by the British-Australian and German visitors and settlers, dates from the earliest explorations. Weather records are known to have been collected at Port Moresby, then part of British New Guinea, from 1875 to 1883. Similarly, in the German colony of New Guinea to the north, records were collected at Melamu (Konstantinhafen) and at Finschhafen in 1885.

Instrumented recording on a continuous basis, for which records are still available, dates from 1891 for Port Moresby (Brooks 1918). By 1910 a rainfall recording network of thirteen stations had been established in the Australian controlled Territory of Papua in the southern part of what is now Papua New Guinea. A network of similar size was developed in the north, in the then German administered colony of New Guinea. Following the conclusion of World War I, control of the German colony passed to Australia and, although it was administered separately from Papua, the climate recording network was centralised in the Department of Lands in Port Moresby. By 1920 this network had expanded to 52 stations and by the outbreak of World War II to 112. The growth in numbers of stations is shown in Fig. 1.2, which has been adapted from material presented by Brookfield (1966), and further extended. While this expansion of the network is important in terms of accumulation of climatological knowledge, the most significant feature in the development of meteorology in this period was the advent of air transport in the 1930s.

Gold was discovered in the rugged and inaccessible interior of New Guinea, and aircraft were the only means of transport to the mining areas. Some idea of the extent of the use of aircraft can be gauged from the fact that for a period during the 1930s the then Territory of New Guinea was among the world leaders in commercial air cargo movement. Aircraft of relatively low power were used for the purpose, but they were flown under full load. Consequently, most flights were made at low operational altitudes in conditions of low cloud cover and rain. This was important to the development of meteorology in the country in that a total change and upgrading of weather services was required—from provision of monthly reports in manuscript form to the establishment of a radio based system of real time reporting and analysis. Aviation also required an understanding of local meteorological situations as the basis for effective forecasting. In 1937 the Australian Bureau of Meteorology took over responsibility for this task and for the first time a professional meteorologist was appointed to the country.

World War II had a devastating effect on the country and with one or two exceptions the meteorological station network ceased to exist. It is known that the Japanese forces maintained climate data records for some main centres but

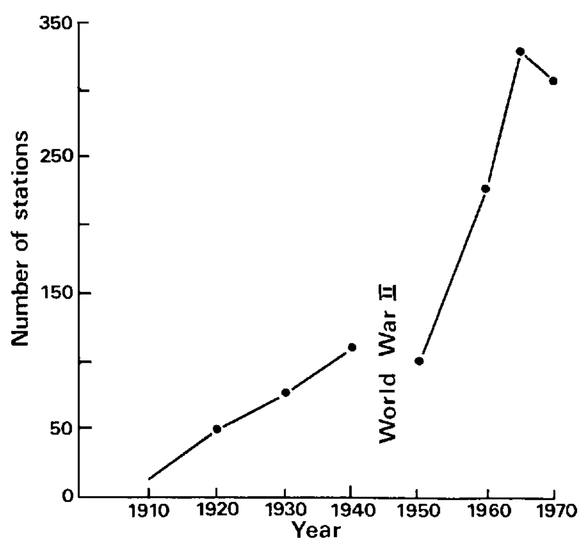
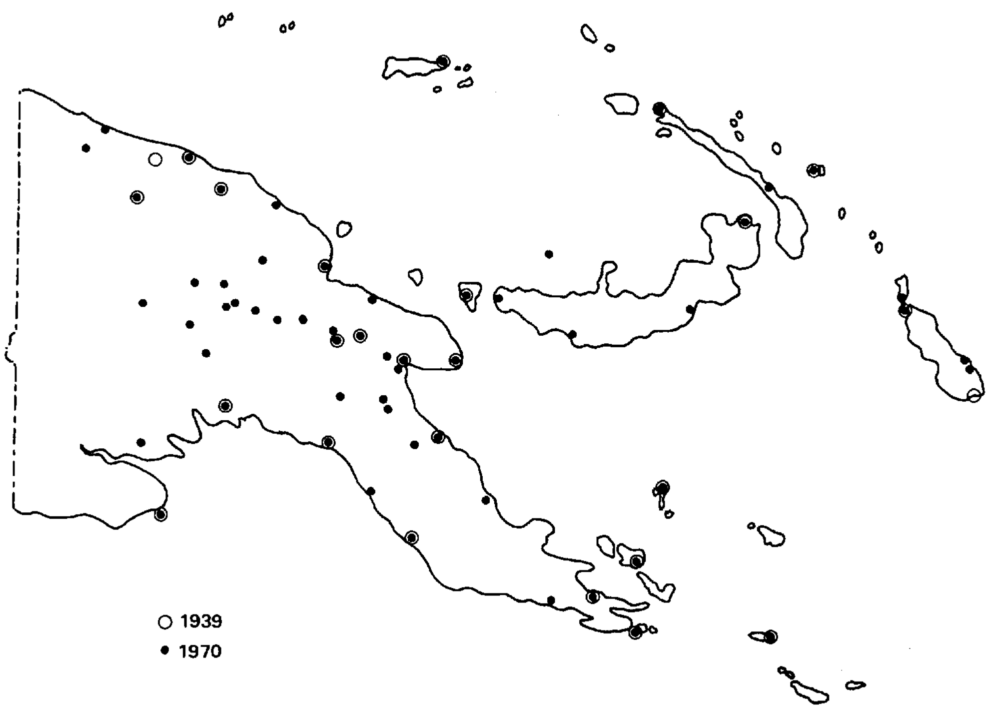


Fig. 1.2
Growth of meteorological network in Papua New Guinea between 1910 and 1970

these have not been located subsequently. Thus there is an important gap in the long term station records for virtually the whole of the network. On the other hand, the huge increase in aircraft and other military activity during the war meant that meteorological intelligence became a matter of considerable strategic importance. Consequently forecasting services were greatly expanded, as were investigations into basic meteorological processes operating in the area. For the first time existing climatic information was brought together in a substantial way by the Bureau of Meteorology (1940) and also in the form of a series of regional intelligence reports. While it is becoming increasingly difficult both to locate and to obtain access to these reports, their importance lies mainly in the fact that they provided a medium for passing on an awareness of regional weather conditions and processes which was not in existence prior to the onset of hostilities.

In the period up to 1940, the meteorological station network was largely restricted to the coast and nearby hinterland, and necessarily coincided with the area then under government influence. In the immediate post-war period the network was re-established and by 1950 it was back to its pre-war level. The pace of economic development was increased, and by the 1960s government influence had spread across the whole of the country. Again, aviation was crucial in the inland highland areas and, as a consequence, a new rainfall recording station was opened as each airstrip was built—and in the initial absence of roads there were many. The end result was that 330 stations were operating by 1970, and over the entire period 1910 to 1970 some 650 stations had contributed information. The number of stations that were opened and subsequently closed during this

Fig. 1.3
The distribution of stations recording a range of climatic data in addition to rainfall at 1939 and 1970



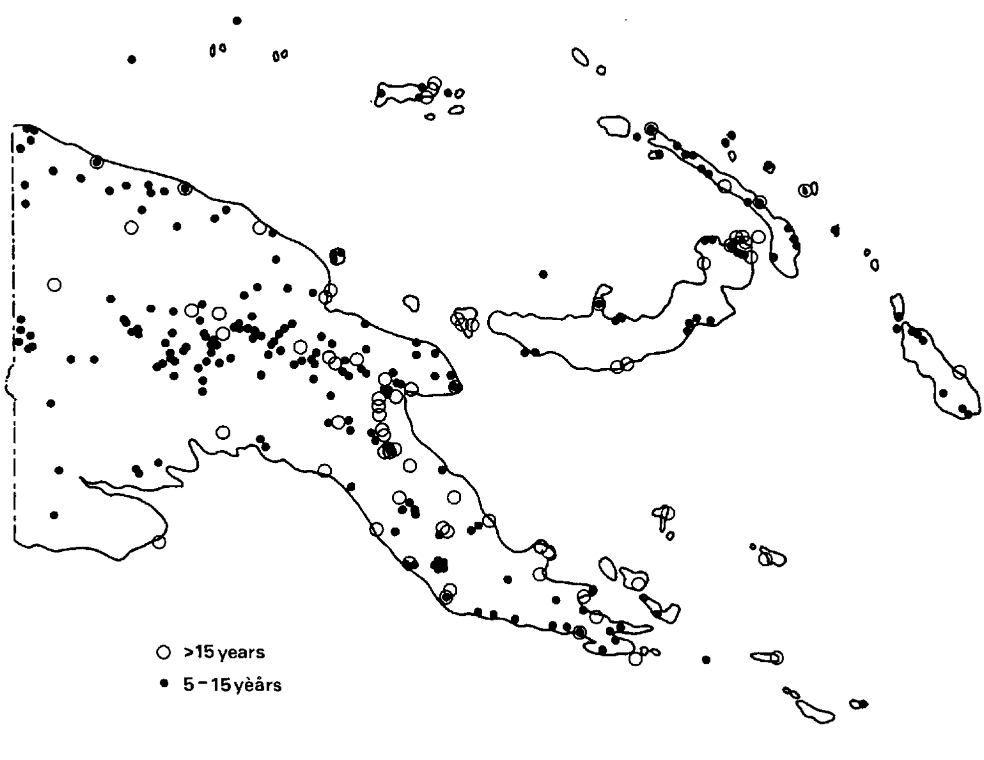
period—some after a very short time and others after many years—was a result of both the war and the short term settlement patterns typical of a colonial phase of development.

The stations which contributed usable lengths of record were of two types; first, climate stations at which a number of elements in addition to rainfall were recorded and, second, stations which recorded daily rainfall only. Observations at the former type of station were made at least twice daily, at 0800/0900 hours and 1500 hours local time. At those climate stations located at major airports, observations were made at three-hourly intervals. The distribution of climate stations in 1939 and 1970 is shown in Fig. 1.3. The distribution of rainfall recording stations with usable lengths of record is shown in Fig. 1.4. Rainfall observations were made once a day, usually at 0800 hours.

Distribution, length of record and reliability of meteorological data

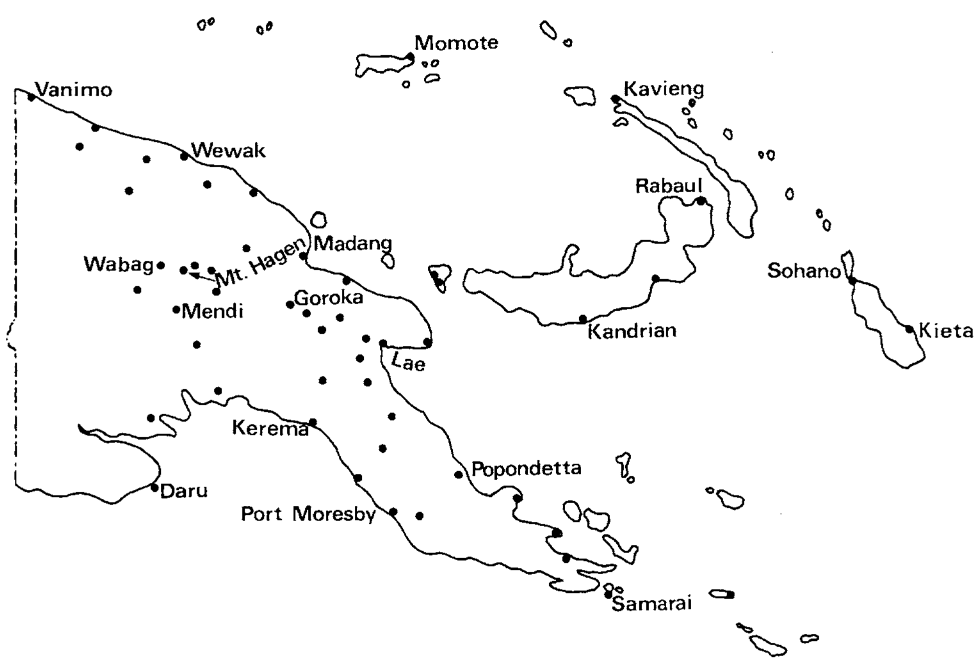
In most meteorological networks, the stations are distributed roughly in proportion to population density. This holds good for Papua New Guinea with regard to the extent of the network in 1970. Given the nature of population distribution, the result is an over representation of central highland areas between 1200 m and 2200 m, and an almost total lack of data for areas over 2200 m. Data are also scarce or totally lacking for the main coastal and island ranges and for the very heavy rainfall areas on the southern and northern slopes of the main central range.

Fig. 1.4
The distribution of rainfall stations for which there are lengths of record greater than 15 years and of between 5 and 15 years



The number of years for which data have been recorded at each station is highly variable. Of the 650 rainfall stations that had operated for any length of time between 1910 and 1970, 85 had records for over 15 years, 250 for between 5 and 15 years, and 325 for less than 5 years. Of this last group, 170 had records for only one year or less. The distribution of the first two groups of rainfall stations is shown in Fig. 1.4. As rainfall statistics should only be compared between stations using the same time period, it is necessary to establish a standard time period for analysis. The problem is that the time period selected to cover the whole of Papua New Guinea must be relatively short, as data recording only commenced post World War II in the highland areas. Thus the selected standard period must be limited to that restricted time interval, despite the fact that longer records are available for a number of stations on the coast. After a review of the rainfall data which were available, a sample of 52 stations was selected, which covered the period 1956-70 for a relatively wide geographic distribution and range of rainfall regimes. The locations of the sample stations are shown in Fig. 1.5, and it will be seen that the deficiencies in areal spread are similar to those for the network as a whole. The restriction to a 15-year period was less of a limitation than might be thought at first. Stations with long periods of records were analysed to find the shortest time period which, if randomly selected, would still reflect the greater part of the daily, monthly and annual rainfall variability. Fortunately, for the whole of the country, rainfall variability, encompassing either 50 per cent or 90 per cent of variation, can be expected to be revealed in as short a period as ten years and in some instances five years are sufficient. For parameters other than rainfall, variability is even less and the records from climate stations for elements

Fig. 1.5
The distribution of rainfall stations for which a standard period of record length of 15 years (1956-1970) is available and which have been used for comparative analysis of rainfall statistics in this book



such as temperature, humidity, etc., are of more than sufficient length for comparative analysis.

Data from the climate stations and the standard period rainfall were checked for reliability by comparison with likely extreme values, by examination of internal consistency, and by comparison with other stations where this was feasible. Two problems were found to be, first, short periods of missing data and, second, the 'Monday effect', where for some stations a whole weekend's rainfall would be recorded as being a single fall on a Monday. The selection procedure for standard period rainfall stations caused these occurrences to be rare. Where they were identified, substitute data from a nearby station were inserted or, if this was inappropriate, mean data from the station itself were used. This type of substitution was only employed where a continuous record was essential, as in the case of analyses of sequences of events. Otherwise, short periods of missing data were adjusted on a simple statistical frequency basis.

The data and analyses used in this book were presented in extended summary and tabular form elsewhere (McAlpine, Keig and Short 1975; McAlpine and Short 1974). As these publications are not readily available for reference, and as this book is intended to be complete in itself, the most important summary data are included as an Appendix.

2 Meteorological Controls on Climate and Weather

In tropical regions the net radiation balance of the earth-atmosphere system is positive, but it becomes increasingly negative at higher latitudes. In order to counter this radiative imbalance, sensible and latent heat are transported from lower to higher latitudes both by the motions of the general atmospheric circulation and by synoptic scale disturbances, such as cyclones and anti-cyclones.

The agency for release and vertical transport of heat energy in the tropics is thought to be the giant thunderstorms which originate in the approximately zonal (E-W) belt of high cloudiness and rainfall known as the 'intertropical convergence zone' (ITCZ) (Riehl and Malkus 1958). In the New Guinea region two factors contribute to an increased frequency of such storms relative to the tropical oceanic regions. First, the massive topography of the area extending from Malaysia through Indonesia to New Guinea provides a powerful aid to convection in moist equatorial air streams. Ramage (1968) has termed this area the 'maritime continent'. Second, there is a broad region of sea surface temperature maximum in the equatorial western Pacific (Reid 1969; Webster and Streten 1972), which would tend to be associated with lower surface pressures and higher air temperatures, and so act also as a stimulus to convection. The 'maritime continent' is thought to be the most energetic large-scale heat source in the global circulation.

The meridional (N-S) transport of the heat energy from the tropics towards higher latitudes is mainly accomplished by two particular large-scale circulation processes: (a) a direct, thermally-driven mean meridional circulation, known as the Hadley cell and (b) low pressure troughs of great meridional extent known as polar, or extended troughs. In addition, a large-scale zonal (E-W) circulation operating over the equatorial Pacific and known as the 'Walker circulation' is of particular relevance to the western Melanesian region.

The relation of these three major circulation systems to the ITCZ in the New Guinea region and the strong influence of the 'maritime continent' effect are considered in the following sections.

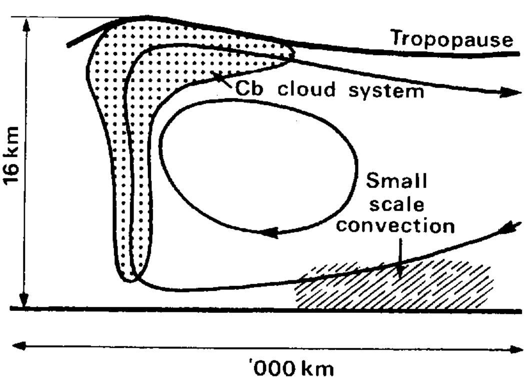


Fig. 2.1
Schematic representation of broad-scale flow in deep tropospheric cumulonimbus (Cb) convection applicable to Hadley cell and Walker circulations (adapted from Green *et al.* 1966)

The Hadley cell

A general model of tropical large-scale circulation systems such as the Hadley cell, which is the major means by which equatorial heat energy is transported polewards in the tropical belt, is shown in Fig. 2.1. In lower latitudes, vast amounts of moisture are evaporated from the tropical oceans and mixed by convection through the lower trade winds, which extend from the subtropical high pressure belts to the low pressure zone of the equatorial trough at the thermal equator. The latent heat energy so gained by the trades is released by thunderstorm activity and associated deep convection at the ITCZ, where the trades converge in the vicinity of the equatorial trough. The supply of heat energy thus made available in the high troposphere of the equatorial trough zone is transported to high latitudes by poleward components of the restlessly changing upper winds. As the air moves polewards it cools and begins to subside, returning to the lower troposphere in the vicinity of the subtropical high pressure belt. In the lower tropospheric trade winds there is a return flow towards the equatorial trough, so completing the Hadley cell circulation.

Not only does the Hadley cell vary in strength in different parts of the globe, but it is also stronger, and so transports more heat energy, in the winter hemisphere where the radiation deficit is greater. Ramage (1968) has described the very strong Hadley cell circulation during the northern winter over south-east Asia and the western Pacific, one component of which is the north-west monsoon over the 'maritime continent'. It appears that a pronounced Hadley cell circulation adjoining the 'maritime continent' also exists in the south-west Pacific during the southern winter.

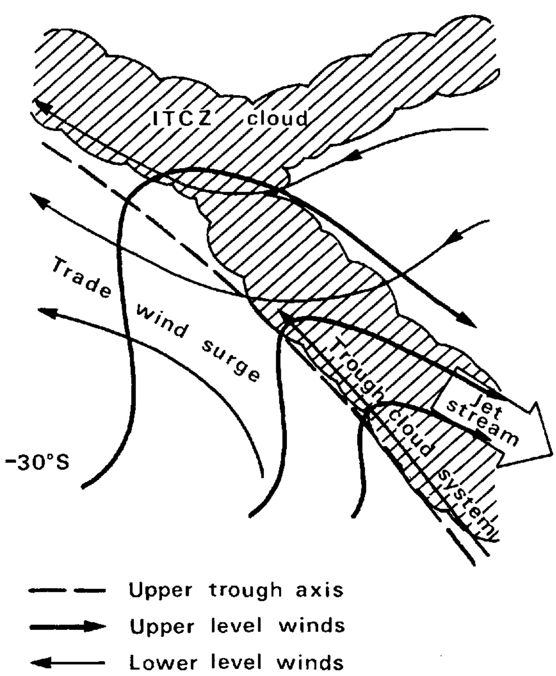


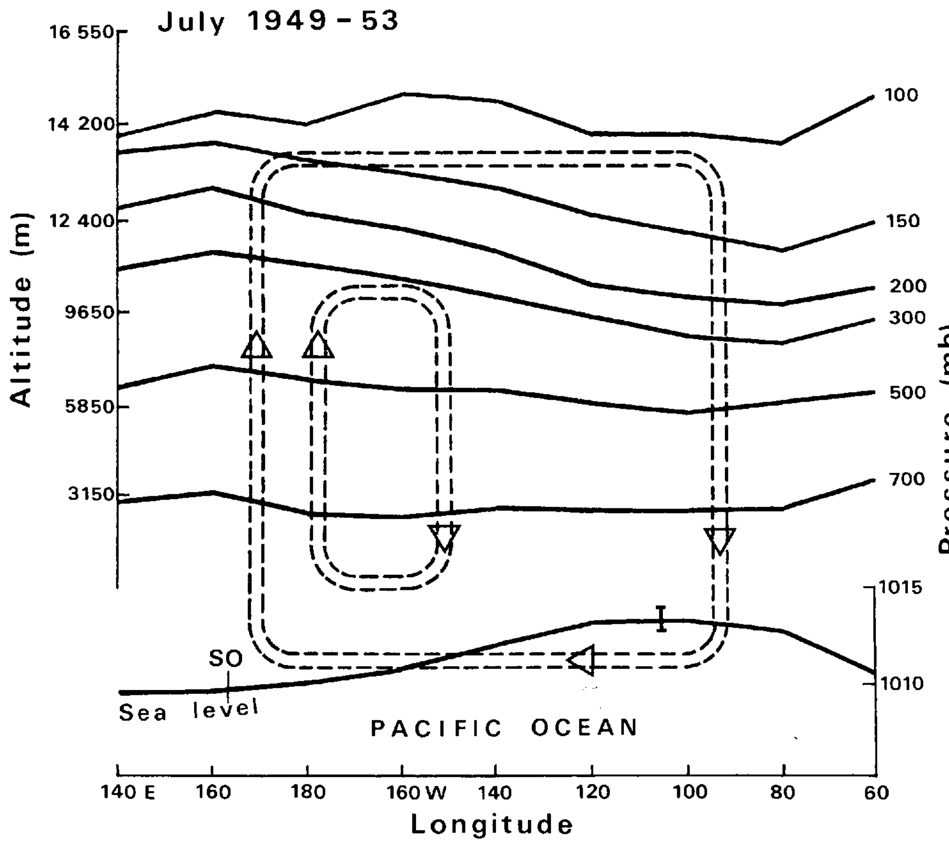
Fig. 2.2
Model of an extended trough in low latitudes, showing typical lower and upper level wind circulations, and associated cloud areas

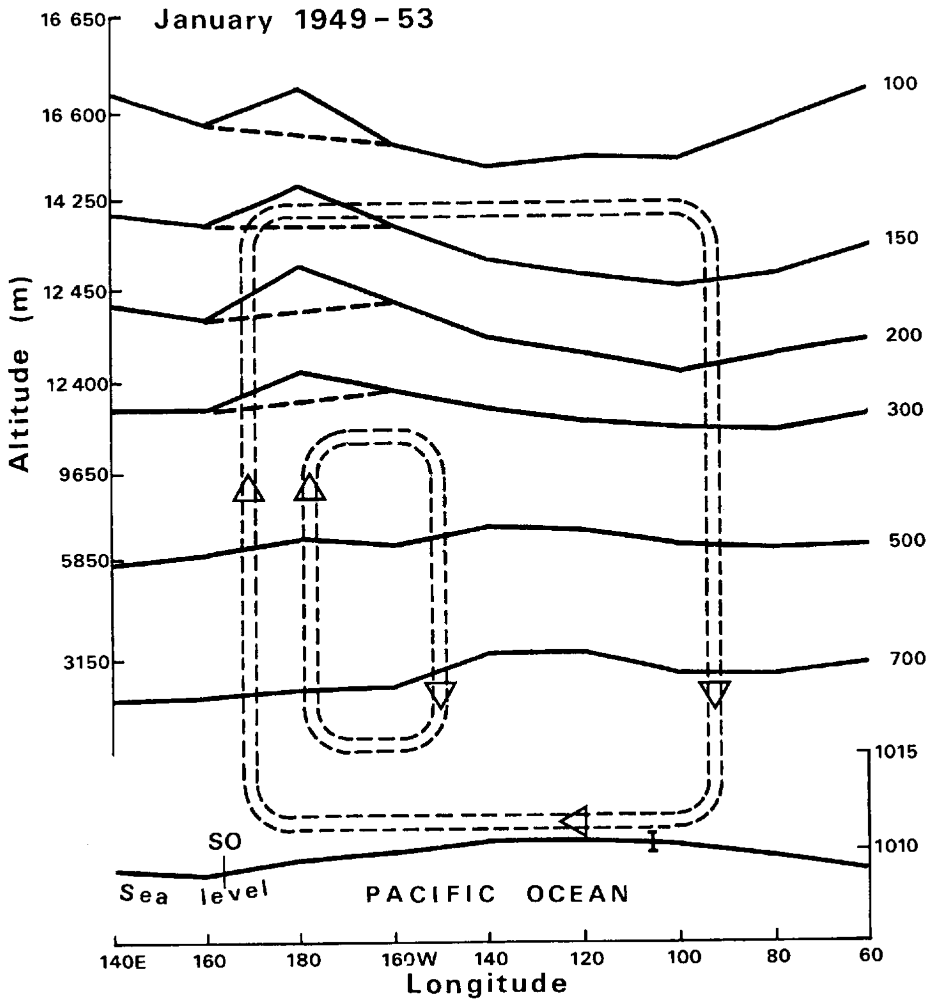
Meridional troughs

Low-pressure troughs of great meridional extent, sometimes extending almost from equator to pole (Fig. 2.2), are another means whereby heat energy is transported to higher latitudes (Riehl 1950, 1969). These extended, or polar, troughs are often accompanied on their western sides by surges of the lower trades, thus enhancing evaporation from the tropical oceans and causing increased convection in the ITCZ. In the high troposphere, energy released by convection in the ITCZ is drained away to higher latitudes by poleward wind components on the eastern side of the trough. Such transports regionally enhance the Hadley cell circulation. In the lower and middle troposphere, poleward wind components also occur, providing an effective avenue for poleward transport of moisture and latent heat energy.

Middle latitude troughs in the southern hemisphere often amplify and extend into very low latitudes in the region of Indonesia and Melanesia, linking a vigorous meridional circulation with the heat source of the 'maritime continent'.

Fig. 2.3
Dynamic model of Walker circulation over the Pacific (after Bjerknes 1969). Profile of altitude (dynamic metre) of standard isobaric surfaces along the equator in January and July, illustrating reversal of horizontal pressure gradient from low to high troposphere across the Pacific. Walker circulation entered as suggested by Bjerknes. SO denotes the Southern Oscillation and I the Indonesian low as referred to in the text.





The Walker circulation

Hitherto aspects of the general circulation relating to heat and mass transports in the meridional plane have been discussed. However, a zonal thermally-driven circulation operating across the equatorial Pacific, the 'Walker circulation' (Bjerknes 1969), is also of particular relevance to the climate of Papua New Guinea. Bjerknes postulated that when the cold water belt of the equatorial eastern Pacific is well established, the air above it would be too cold and dense to join the ascending motion of the Hadley circulations. Instead, the equatorial air would flow westward in the low level branch of the Walker circulation to the vicinity of the 'maritime continent'. There, after having been heated and supplied with moisture from the warm waters, the air could take part in large-scale ascent, with associated deep convection and latent heat release to maintain the circulation (Kreuger and Gray 1969).

Physical processes in the Walker circulation are similar to those occurring in the Hadley cell (Fig. 2.1) and Fig. 2.3 shows a model of the Walker circulation as postulated by Bjerknes. It appears that such east-west circulations may be of comparable strength to the Hadley cell (Krishnamurti 1971; Krishnamurti *et al.* 1973).

Bjerknes relates the Walker circulation in the Pacific to the Southern Oscillation, a large-scale fluctuation of the tropical atmospheric and hydrospheric circulation whereby there is an inverse pressure relationship implying an exchange of air between the south-eastern Pacific subtropical high-pressure region and the Indonesian low. Rainfall varies in the opposite direction to pressure. These fluctuations have a period varying between 1 and 5 years, with an average of 30 months (Berlage 1966). Evidence has been presented by Newell *et al.* (1974) that in years when the cold water in the equatorial east Pacific is well developed, the Walker circulation is relatively strong and the Hadley cell relatively weak: vice versa when the equatorial water is relatively warm.

Variations in the position and/or strength of the Walker circulation are associated with variations in rainfall in the east and central equatorial Pacific, and probably also with secular variations in rainfall as far west as Papua New Guinea and Indonesia. Preliminary evidence of this has been presented by Kyle *et al.* (1970) and Rowntree (1972), who reveal a tendency for low rainfall in the western equatorial Pacific to occur during periods of high central Pacific rainfall. Nicholls (1973) found that the 1972 Papua New Guinea drought occurred during a period of marked weakening of the Walker circulation, which brought about an increase in central equatorial Pacific rainfall.

Evidence has also been advanced of a Walker circulation operating over the equatorial Indian Ocean, with its ascending branch near Indonesia. It is possible that this circulation also affects Papua New Guinea from time to time.

The intertropical convergence zone (ITCZ)

The term intertropical convergence zone (ITCZ) has several definitions. Until recently the ITCZ was only considered as containing ascending components of the Hadley cell circulations, and as such constituted, ideally, a meteorological barrier between the tropical wind systems of either hemisphere. However, in regions such as western Melanesia, where ascending components of strong zonal circulations are also present, it is not possible, in practice, to separate convection associated with ascent in the meridional circulations from that associated with the zonal circulations.

Here the term ITCZ will be used in a very general sense to indicate an organised zone of high cloudiness and rainfall containing deep convective (cumulonimbus) clouds, and playing an appropriate role in the ascending branches of the large-scale meridional (Hadley cell) and/or zonal (Walker) circulations.

Study of the monthly variation in mean cloudiness over the Melanesian region derived from charts (Atkinson and Sadler 1970) and from satellite photographs (Fig. 2.4) shows that a zone of maximum relative cloudiness affects Melanesia throughout the year, although the zone is weaker around April and September. This observation is further supported by mean radiosonde data for Lae and Honiara (see Appendix), which suggests that deep convection can occur in the region in all seasons, including the southern winter. Mean monthly rainfall figures for atolls and small islands in the region, where seasonal variations in rainfall due to local effects should be considerably less than on the mainland and larger islands, are presented in Table 2.1. Inspection of these data suggests the generalisation that in the absence of important local effects, considering the region as a whole, there is no pronounced 'wet' or 'dry' season, rainfall being more or less evenly distributed throughout the year. However, weak rainfall maxima are evident around March and August.

All the above evidence leads to the conclusion that *a branch of the ITCZ affects western Melanesia throughout the year,* although the associated wind circulation patterns and the nature of disturbances in it vary greatly and the low

Fig. 2.4
Mean cloud cover (oktas) derived from satellite photographs, 1400 hr local time (from Miller and Feddes 1971)

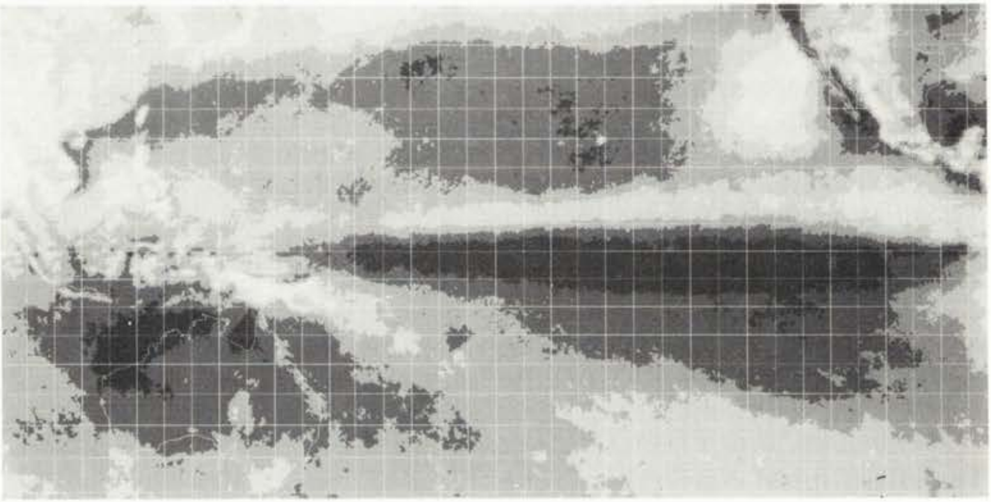


Fig. 2.4a—July

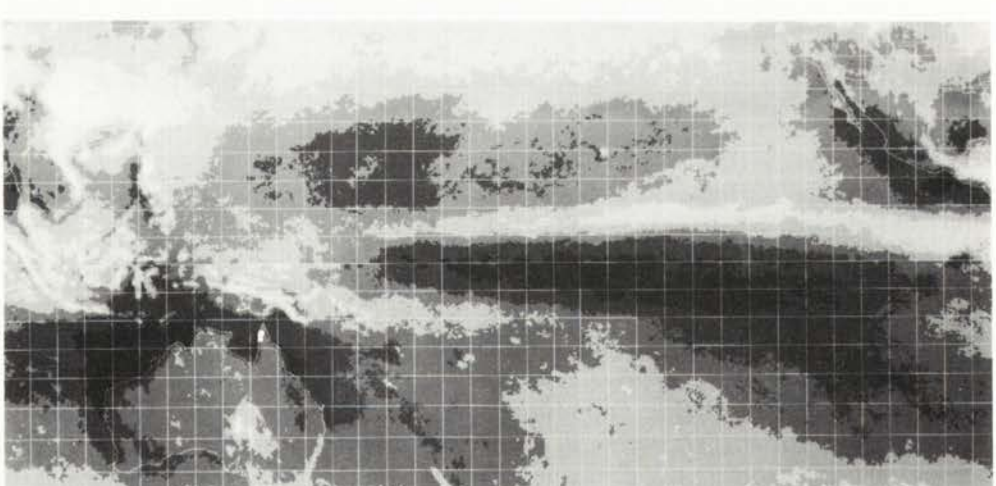


Fig. 2.4b—November

pressure belt of the equatorial trough migrates over a considerable range of latitude between seasons.

Figure 2.5 shows a tentative model of the configuration of the ITCZ in the vicinity of Melanesia in relation to the particular broad-scale circulations bearing on its development. The position and shape of the ITCZ shown in Fig. 2.5 is an annual average, based on an annual mean chart of satellite observed relative cloud cover given by Miller and Feddes (1971). Figure 2.4 indicates that a similar configuration is evident during individual seasons, although variations in the position, width and intensity of the various branches are evident.

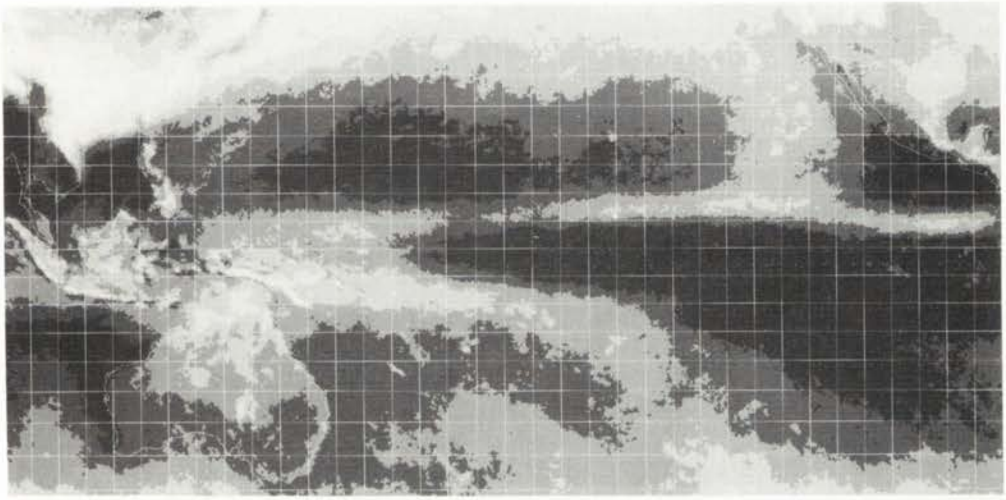


Fig. 2.4c—February

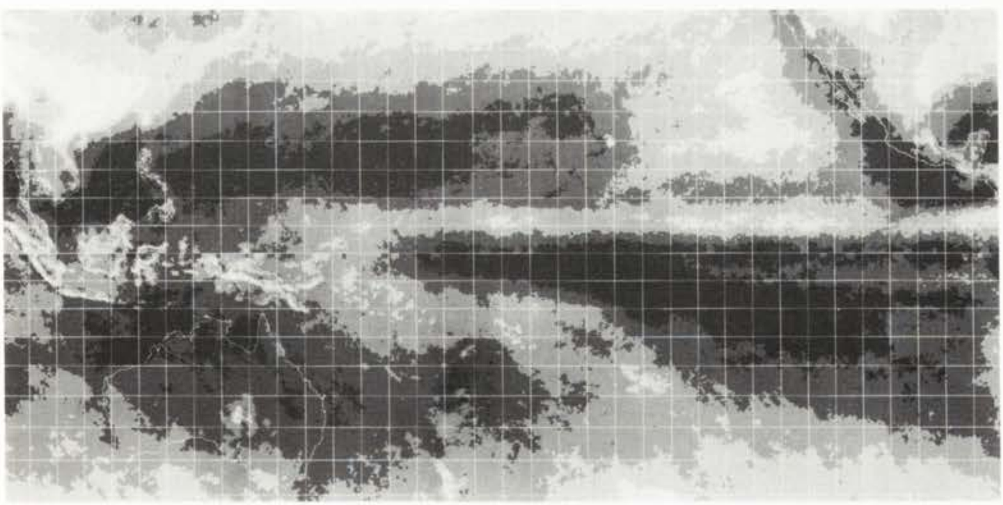


Fig. 2.4d—April

Table 2.1

Mean monthly and annual rainfall on small islands and atolls (mm)

Station	Record length (years)	Position Lat.° S	Long.° (E)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Fead Island	4	03:15	154.45	273	317	360	284	244	298	464	381	245	346	232	263	4169
Losuia	37	08:32	151:04	425	431	388	337	332	306	306	270	271	257	239	268	3942
Panasesa	10	10:45	151:44	188	160	174	177	161	121	99	130	120	157	147	83	1717
Pelleluhu	9	01:05	144:20	271	204	271	288	290	296	311	380	358	234	264	307	3178
Put Nonu	16	03:30	153:17	272	284	341	318	334	324	403	432	350	330	227	319	4033
Vanikoro	19	11:49	166:47	484	452	505	443	515	486	465	560	608	476	413	389	5717
Maron	3	01:32	145:02	231	200	336	304	208	353	497	582	330	387	429	296	4680
Agita	15	01:43	142:50	292	304	347	313	327	317	416	389	293	254	303	326	3866
Mortlock	3	04:50	157:00	417	344	333	309	247	245	344	413	233	243	328	290	3620
Nuguria	3	03:19	154:40	282	316	292	289	196	169	326	341	394	233	252	398	3487
Mean of all above stations				314	301	334	306	285	292	363	388	310	292	283	294	3841

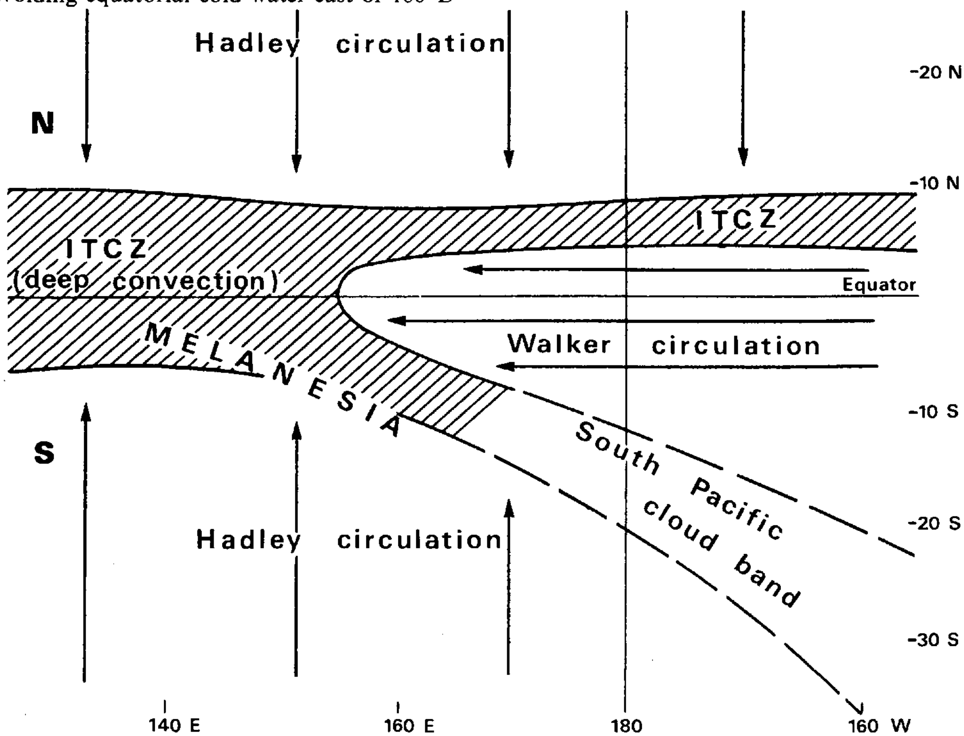
West of about 160°E, the ITCZ is broad and vigorous, containing major ascending components of the Hadley circulations of either hemisphere and the Walker circulation, in a region where deep convection associated with the massive topography of the 'maritime continent' plays a significant role. East of about 160°E the ITCZ branches, avoiding the equatorial cold water of the eastern and central Pacific. The northern branch is narrow and well organised, lying mainly between latitudes 5°N and 10°N, with small seasonal variation.

The southern branch extends east-south-eastward through Melanesia to join a recurring cloud band extending south-eastward across the central south Pacific into higher latitudes. The southern limit of ITCZ characteristics, or deep convection in this branch, will vary with seasons, being furthest south and east during the southern summer. The south Pacific cloud band has been shown to coincide with a zone of maximum rainfall (Streten 1970).

Broad-scale wind systems

Because of the earth's rotation, the east-west (zonal) components of the main tropical wind systems tend to be considerably stronger than their north-south (meridional) components. In this context, three main zonal tropical wind systems may be readily identified: (i) tropical easterlies, which include the trade

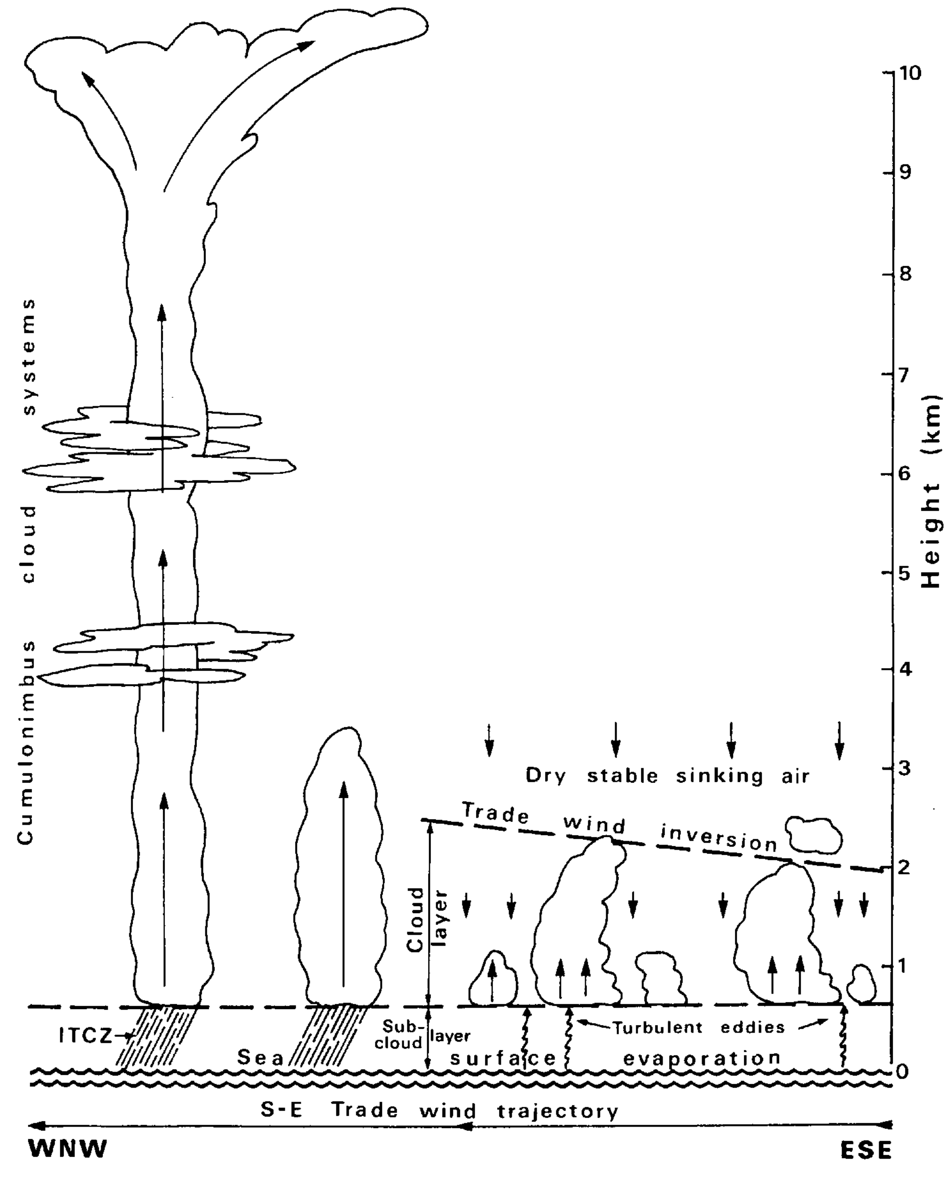
Fig. 2.5
Schematic representation of the ITCZ near Melanesia, suggesting how the field of convergence associated with low level meridional wind components of the Hadley circulations and low level zonal wind components of the Walker circulation over the Pacific could account for the broad and vigorous ITCZ over the 'maritime continent' west of 160°E, and the branching of the ITCZ avoiding equatorial cold water east of 160°E



winds, the latter being overlain by (ii) the upper-level westerlies or 'anti-trades'; (iii) the equatorial or monsoonal westerlies associated with tropically-situated land masses.

The most extensive of these wind systems is the deep belt of tropical easterlies found over vast areas between the subtropical ridge axes (that is, the high pressure zones in each hemisphere in which the tropical easterlies abut the subtropical westerlies). The lower boundaries of the system encompass the well-known oceanic trade winds. The trades are the steadiest surface wind system

Fig. 2.6
Schematic vertical cross section along the path of a south-east trade wind trajectory, oriented ESE to WNW. Adapted for southern hemisphere from Malkus (1958) and extended to the ITCZ. Clouds drawn much larger than scale.



on earth, blowing from a north-easterly direction in the northern hemisphere and a south-easterly direction in the southern hemisphere. Climatologically and dynamically they are of critical importance in that they provide one of the chief mechanisms for the conversion and transport of water vapour and stored latent heat energy to drive the global circulation.

Some distance from the equatorial trough the trades are stable and have a vertical structure (see Fig. 2.6) consisting of a lower moist, marginally stable, convective layer, topped by a dry layer extending upwards to the tropopause. Between these two layers is a very stable transition layer, a few hundred metres in thickness, known as the trade wind inversion. The lower moist layer may be subdivided into the sub-cloud layer, where heat and moisture are derived by evaporation and conduction from the sea surface and mixed upwards by small-scale turbulence, and the cloud layer, in which the trade wind cumulus clouds grow, carrying heat and moisture further upwards by convection. The trade wind inversion and dry upper troposphere act as a brake to convection, limiting the vertical development of the trade wind cumulus clouds.

As the trade air moves towards lower latitudes, the trade wind inversion rises and weakens and ultimately disappears near the ITCZ where deep convection breaks out in precipitating cumulonimbus cloud systems.

Overlying much of the trade wind belt is the system of restless upper level westerlies sometimes known as 'anti-trades', which provide upper level poleward energy transports from the equatorial trough zone. These upper level tropical westerlies are seen to be a low latitude extension of the deep tropospheric westerlies of middle latitudes.

In tropical oceanic areas unaffected by the presence of land masses the undiverted trades from both hemispheres converge at the equatorial trough, which remains within about 10° latitude of the equator. Where land masses intrude, as they do over about 180° of longitude from Africa, across the Indian Ocean to the western Pacific, the surface trade winds of winter alternate in lower latitudes during summer with winds containing predominantly westerly components and known as the equatorial or monsoon westerlies. The monsoons are developed mainly as a result of large seasonal shifts of the temperature and pressure belts caused by thermal effects of the large tropical land masses of Africa, Asia and Australia. The equatorial trough may be displaced up to 20° to 30° of latitude away from the equator in the summer hemisphere, and generally contains much lower pressures than in the undisturbed oceanic trade wind longitudes. The significant pressure gradient between the equator and the equatorial trough thus produces westerly monsoon wind systems. The main summer monsoon systems are the Asian south-west monsoon during the northern summer and the Indo-Australian north-west monsoon during the southern summer.

In broad circulation, the trades from the winter hemisphere in the monsoon region turn at the near-equatorial monsoon shear line to become the monsoon westerlies of the summer hemisphere which extend latitudinally to the more convectively active and energetic monsoon shear line at the equatorial trough. This 'active' monsoon shear line, also called the monsoon trough, is a major source of tropical cyclonic vortices (Sadler 1967). Beyond, the weaker trade winds of the summer hemisphere are found. Thus the monsoon westerlies may be regarded as deflected trade winds from the winter hemisphere, and are a component of the winter hemisphere Hadley circulation which in the monsoon region extends well across the equator in to the summer hemisphere; however zonal or Walker circulation systems also bear significantly on their development.

The New Guinea region

A cohesive view of the relationship to the local New Guinea region of the general circulation models and broad-scale wind systems discussed in previous sections can be gained from selected monthly vector mean wind charts (Figs. 2.7, 2.9, 2.11, 2.13) and from vertical cross sections of zonal wind patterns (Figs. 2.8, 2.10, 2.12, 2.14). Wind charts for two levels are presented; first, at gradient level (about 900 m), which lies approximately at the upper limit of major surface frictional influence over sea and low terrain and, second, at the 700 mb pressure level (about 3100 m). In the tropics, the gradient level charts are of particular interest in that much of the daily and seasonal changes in weather can be explained by them. The higher altitude charts are included because a large part of the New Guinea terrain lies above gradient level and hence these charts will be of interest in regard to weather at elevated localities. The upper wind data which were used in constructing the New Guinea portion of these charts and cross sections are presented elsewhere (McAlpine *et al.* 1975). The following discussion refers to these figures and traces out from them the annual cycle of seasonal weather patterns affecting the region.

Fig. 2.7
Analyses of vector mean winds at gradient and 700 mb pressure levels for July. As shown, solid lines denote direction, and lighter dashed lines denote speed (m/sec) of vector mean wind. A denotes centre of anticyclonic circulation and C denotes centre of cyclonic circulation. Also shown on Fig. 2.7a is the monthly mean sea level pressure (mb) for July as heavy dashed lines.

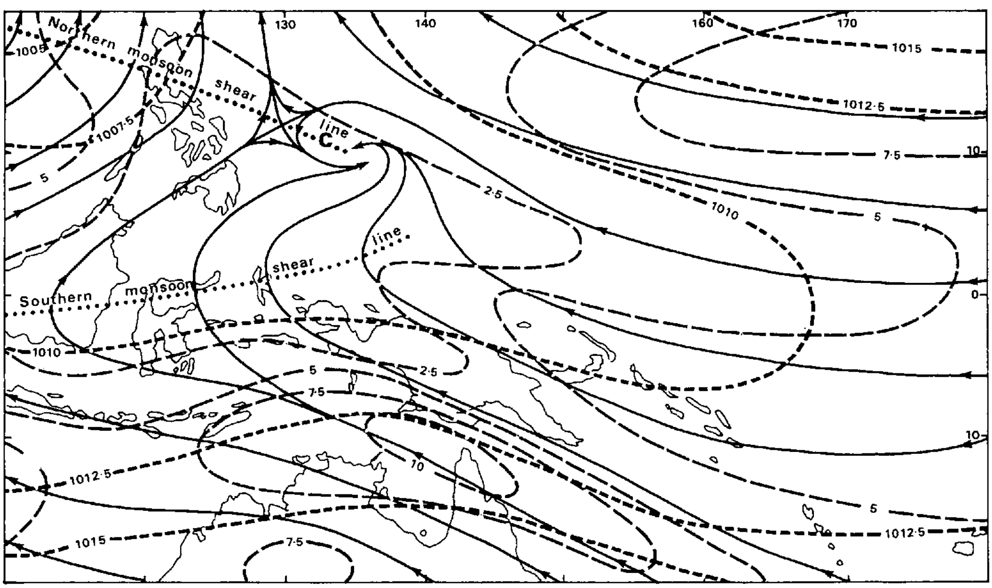


Fig. 2.7a—Gradient and MSL pressure

The July situation (Fig. 2.7, 2.8) is representative of the 'south-east season' lasting from May to October. The subtropical ridge axis in the southern hemisphere is oriented east-west near latitudes 25° to 30° S through a high over southern Australia. South-east trades emanate from the subtropical ridge and extend towards the equator in a diverging stream. Maximum speeds in the mean trade wind flow exceed 10m/sec (20 kt) at gradient level over northern Cape York and Torres Strait. The trades extend over New Guinea just northward of the trade wind maximum. North of the equator and west of longitude 140° E are equatorial westerlies bounded on their northern and southern sides by monsoon shear lines. The northern monsoon shear line lies close to the low pressure belt of the equatorial trough in the mean pressure field. East of 140° E the equatorial trough lies in an easterly trade wind regime.

Looking at the vertical structure of the July circulation in meridional section along longitude 140° E (Fig. 2.8), we see that New Guinea lies within the tropical easterly current at all levels. The most significant feature is the strong maximum in the lower trades flanking the land mass at 10° S. In the southern hemisphere, the subtropical ridge axis slopes sharply equatorward between the surface and 700 mb, and is nearly vertical above 700 mb. The vigorous trade wind circulation is thus overlain by westerly 'anti-trades' south of about latitude 10°S. The strongest westerlies are found in the subtropical jet stream which is strongly developed near latitude 30° S at about 200 mb. In the northern (summer) hemisphere the zonal components of the trades and polar westerlies are much weaker.

The 'south-east season' is followed by a transitional period of which November (Figs. 2.9, 2.10) is typical. Following the apparent southward progression of the sun, the equatorial trough in the southern hemisphere starts to develop and move southward. The associated monsoon shear line lies near latitude 5° S over New Guinea, bringing mainly light variable surface winds, or 'doldrums'. Centres of cyclonic inflow begin to appear in the shear line. In the northern hemisphere the

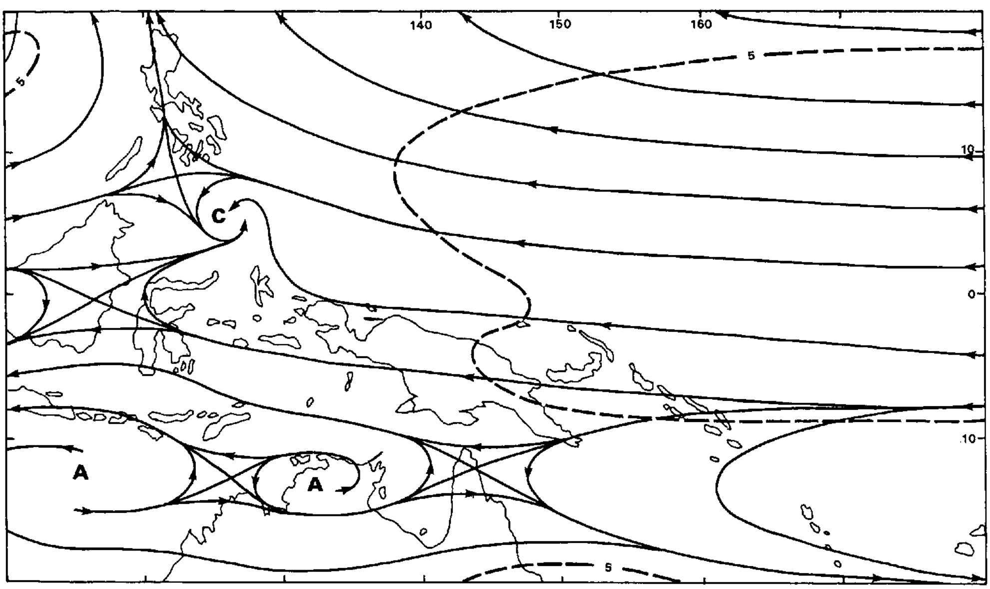


Fig. 2.7b—700 mb pressure level

equatorial trough weakens and the associated monsoon shear line moves to within a few degrees of the equator. The belt of equatorial westerlies contained by the monsoon shear lines extends southward and eastward of its July position, now affecting northern parts of Melanesia. The trades of the southern hemisphere weaken, but still affect Papua. The trades north of the equator strengthen. In the upper troposphere, the tropical easterlies weaken a little. The subtropical jet in the southern hemisphere weakens, while its northern hemisphere counterpart strengthens north of latitude 30° N.

This transition is followed by the 'north-west season' lasting from December to March, February (Figs, 2.11, 2.12) being typical. The equatorial westerlies further extend in depth and breadth near 140° E to cover New Guinea, reaching an average maximum height of about 6500 m at this longitude, while their eastern limit extends across the Pacific almost to the date line. The southern monsoon shear line, associated with the equatorial trough at the height of its development in the southern hemisphere, dips to about latitude 18° S at gradient level into a heat low over north-western Australia, crosses northern Cape York and extends eastward into the Pacific towards the date line. The northern monsoon shear line again moves a little closer to the equator, and although less active may still contain cyclonic vortices, including the occasional typhoon, in the northern winter. In the southern hemisphere, the trades weaken and recede further southward, no longer affecting New Guinea, while in the northern hemisphere a marked north-east trade wind maximum develops near 11° N, and a strong subtropical jet stream lies over southern Japan near 35° N.

Fig. 2.8
Vertical cross section (latitude against pressure (mb) or height (km)) of the mean zonal wind component at longitude 140° E in July. E denotes easterly wind components and W westerly wind components.

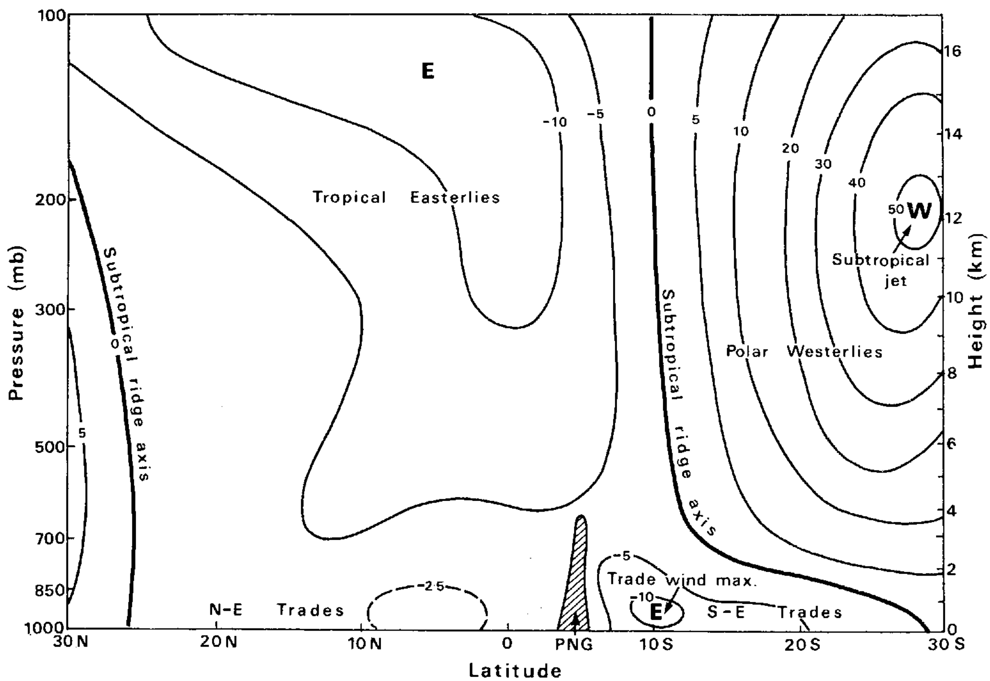


Fig. 2.9
Analyses of vector mean winds at gradient and 700 mb pressure levels, and monthly mean sea level pressure, for November, Notation and units as for Fig. 2.7.

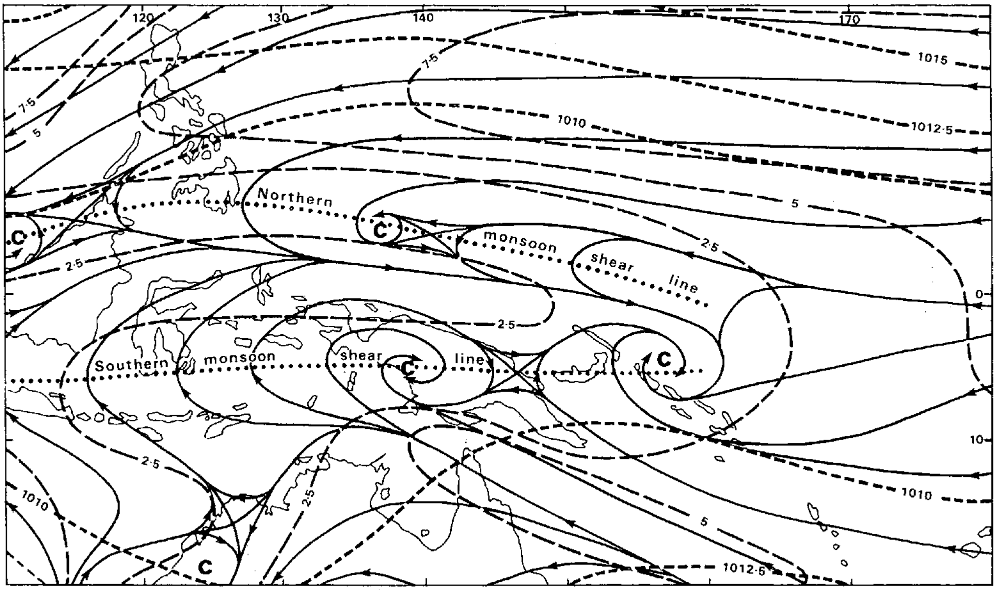


Fig. 2.9a—Gradient and MSL pressure

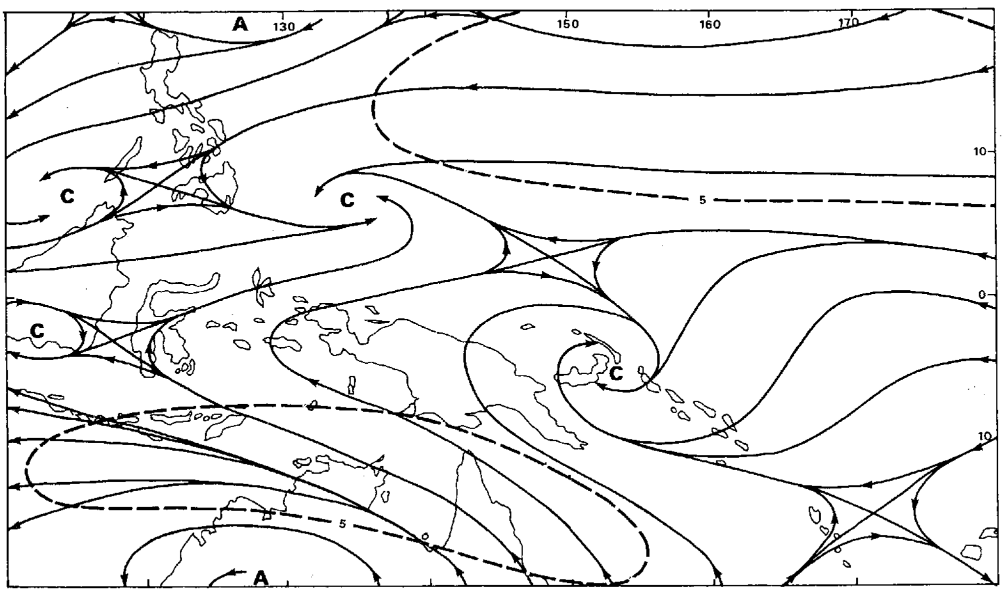


Fig. 2.9b—700 mb pressure level

Fig. 2.10
Vertical cross section of the mean zonal wind component at longitude 140° E in November. Notations and units as for Fig. 2.8.

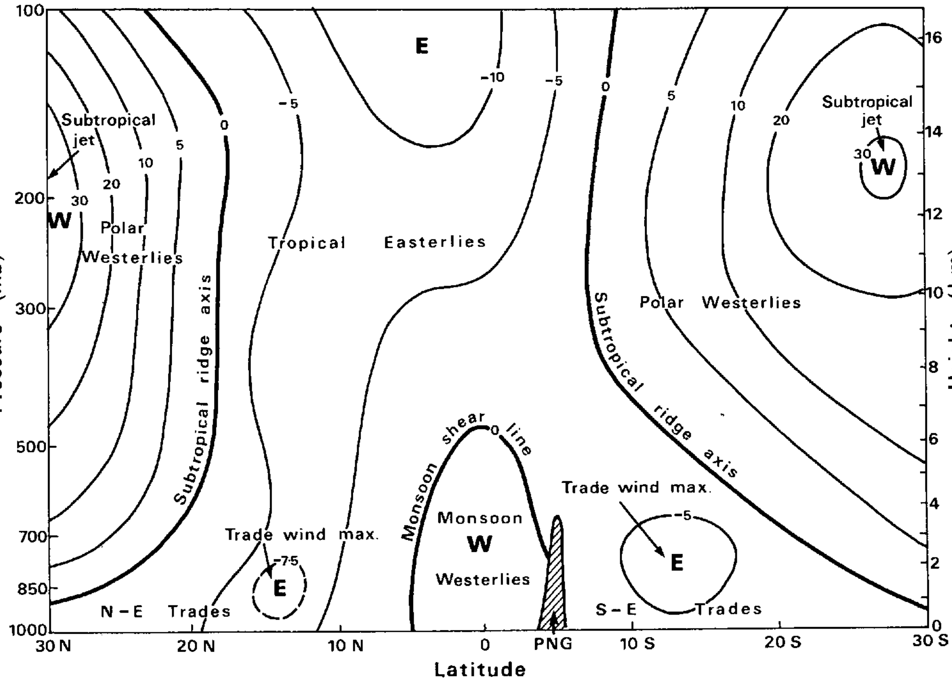


Fig. 2.11
Analyses of vector mean winds at gradient and 700 mb pressure levels and monthly mean sea level pressure, for February. Notations and units as for Fig. 2.7.

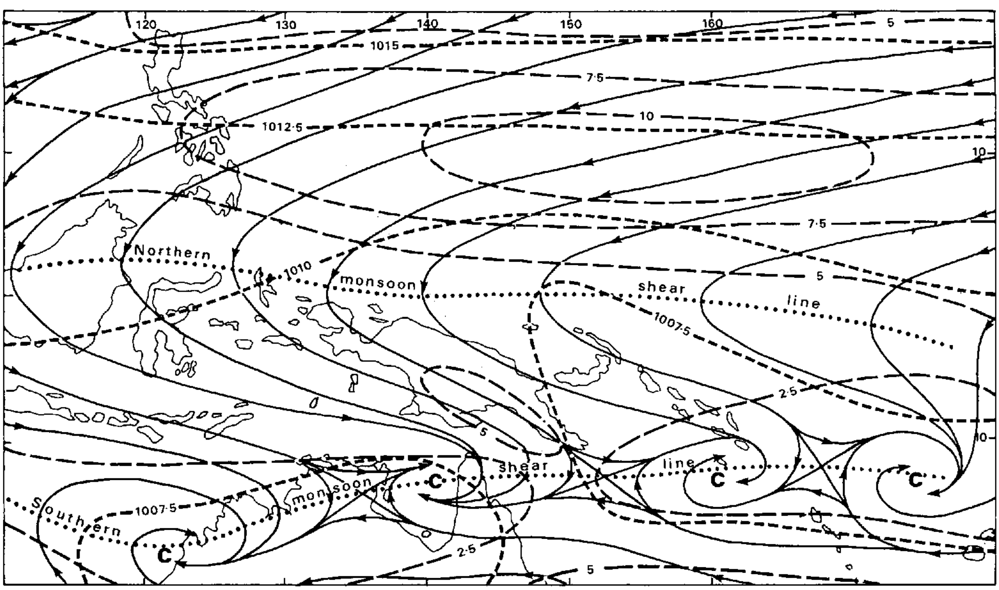


Fig. 2.11a—Gradient and MSL pressure

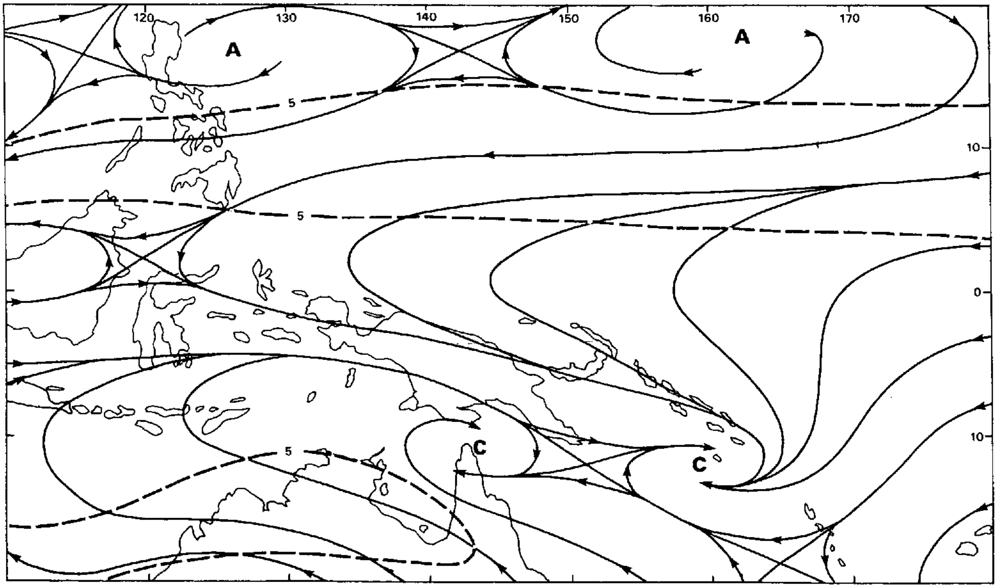


Fig. 2.11b—700 mb pressure level

Fig. 2.12
Vertical cross section of the mean zonal wind component at longitude 140° E in February. Notations and units as for Fig. 2.8.

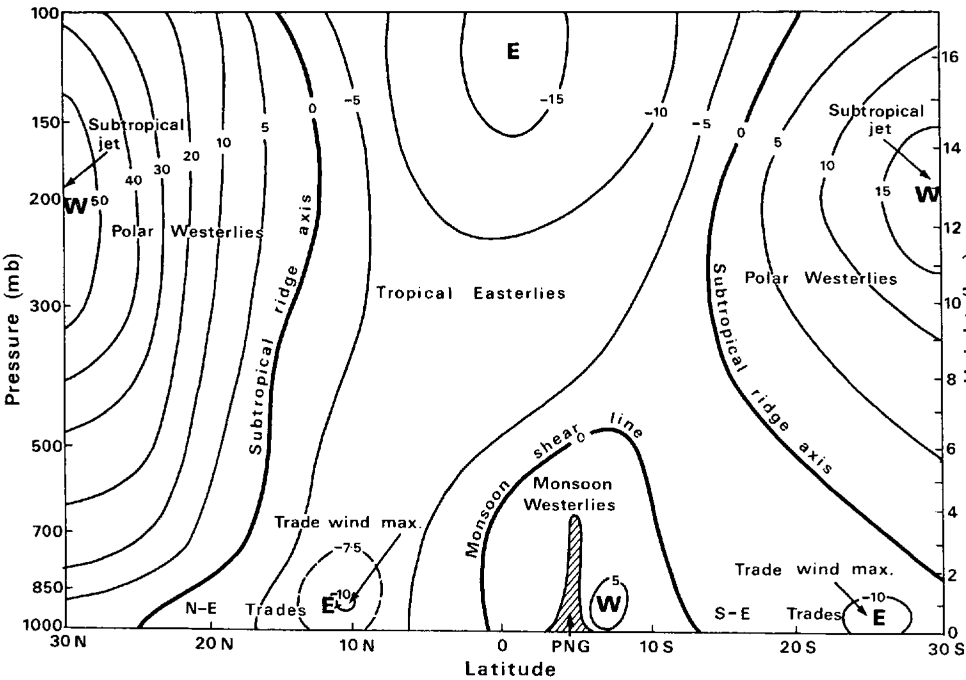


Fig. 2.13
Analyses of vector mean winds at gradient and 700 mb pressure levels, and monthly mean sea level pressure, for April. Notations and units as for Fig. 2.7.

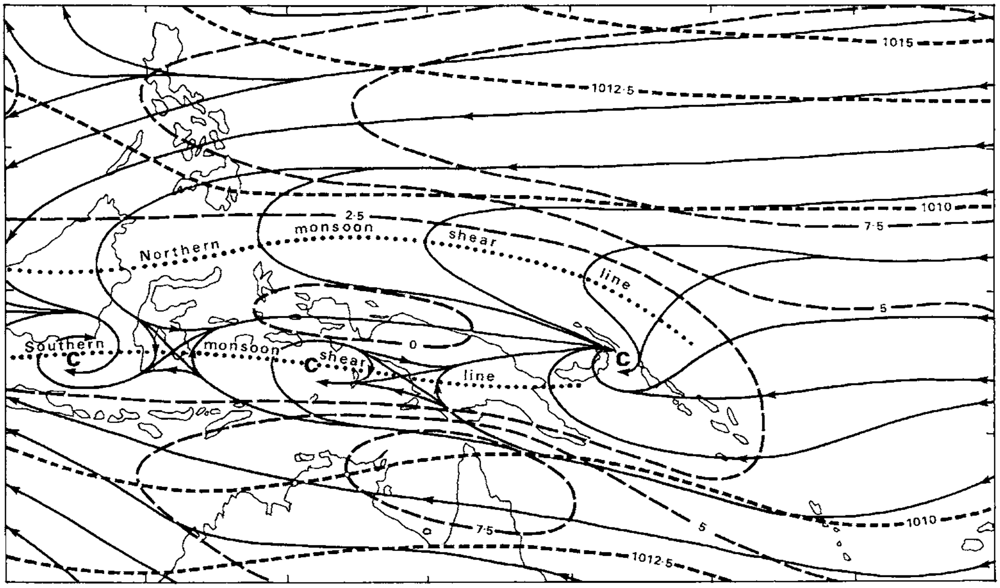


Fig. 2.13a—Gradient and MSL pressure

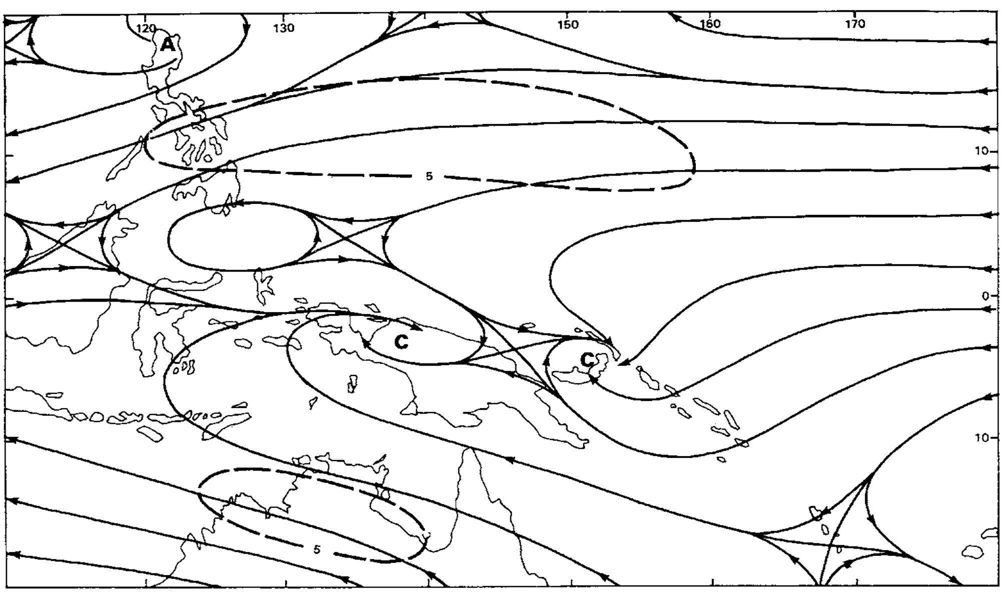


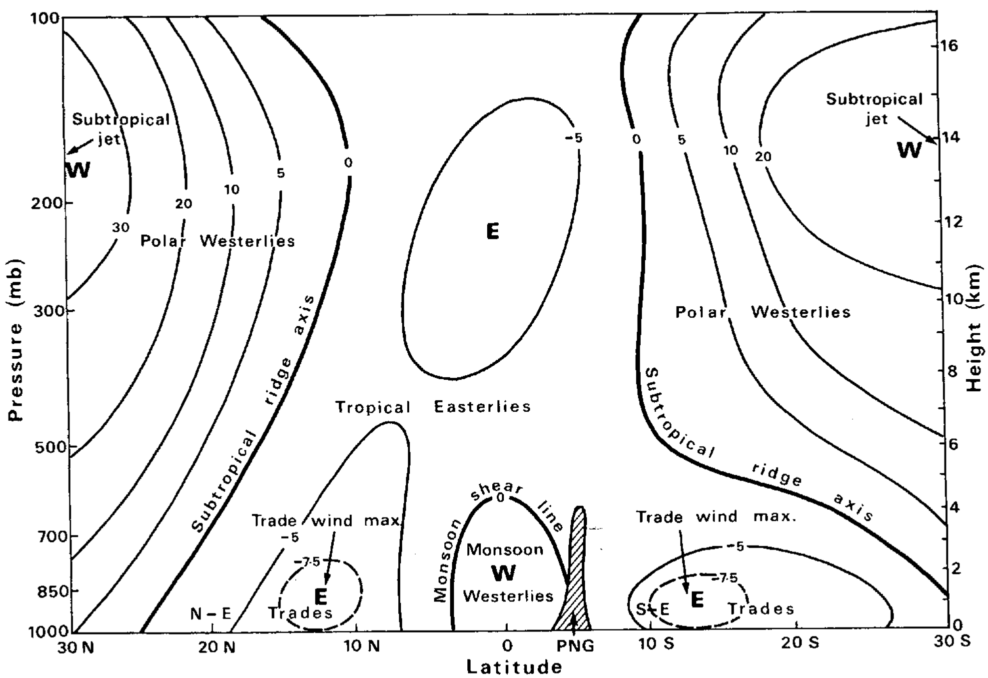
Fig. 2.13b—700 mb pressure level

The 'north-west season' is again followed by a brief transition, as illustrated by the April (Figs. 2.13, 2.14) situation. With the apparent northward movement of the sun, the eastern limit of the equatorial westerlies recedes to the Solomons, while at 140° E the westerly tongue narrows considerably and decreases in depth. The southern monsoon shear line moves northward close to its November position over New Guinea, bringing a return of 'doldrum' conditions, and south-east trades begin to affect Papua as the trade wind maximum becomes prominent over Cape York. The northern monsoon shear line is only slightly north of its February position, but the north-east trades begin to weaken. In the upper troposphere the subtropical jet in the northern hemisphere starts to weaken, while that in the southern hemisphere starts to strengthen. Further development of the trends evident in April takes us full cycle to the July situation described earlier.

Disturbances

The above discussion has outlined the broad-scale meteorological controls operating in the New Guinea region. Superimposed on this overall picture are the day to day variations in weather elements that result from small-scale disturbances arising in the broad-scale circulation patterns. Such 'synoptic-scale' and 'meso-scale' weather systems control the major variations in weather elements, particularly wind, cloudiness and precipitation, over the oceans and smaller islands and

Fig. 2.14
Vertical cross section of the mean zonal wind component at longitude 140° E in April. Notations and units as for Fig. 2.8.



atolls, for periods of the order of a few hours to a week or more, and over areas extending from a few hundred to a few thousand kilometres. Although every disturbance is different in detail, certain recurring 'types' can be recognised. Some examples of particular disturbances, illustrated by satellite photographs, are described below to provide an indication of their nature and effects.

The massive physiography of the New Guinea mainland and larger islands, however, distorts the wind and precipitation patterns associated with disturbances and exercises a strong control over local weather. These local controls are discussed in Chapter 3.

Convective line disturbances of the trades

Satellite pictures reveal convective cloud lines, which can be thousands of kilometres in length, and oriented approximately east-west. These cloud lines

Fig. 2.15

Mosaics of ESSA 8 satellite photographs taken during the mornings of the dates indicated. Inserts show upper air temperature (T) and dew point (Td) sounding at approximately 0900 hr. Vertical scale is pressure (mb). Height in km is also shown. Temperature scale is shown on diagonal lines.

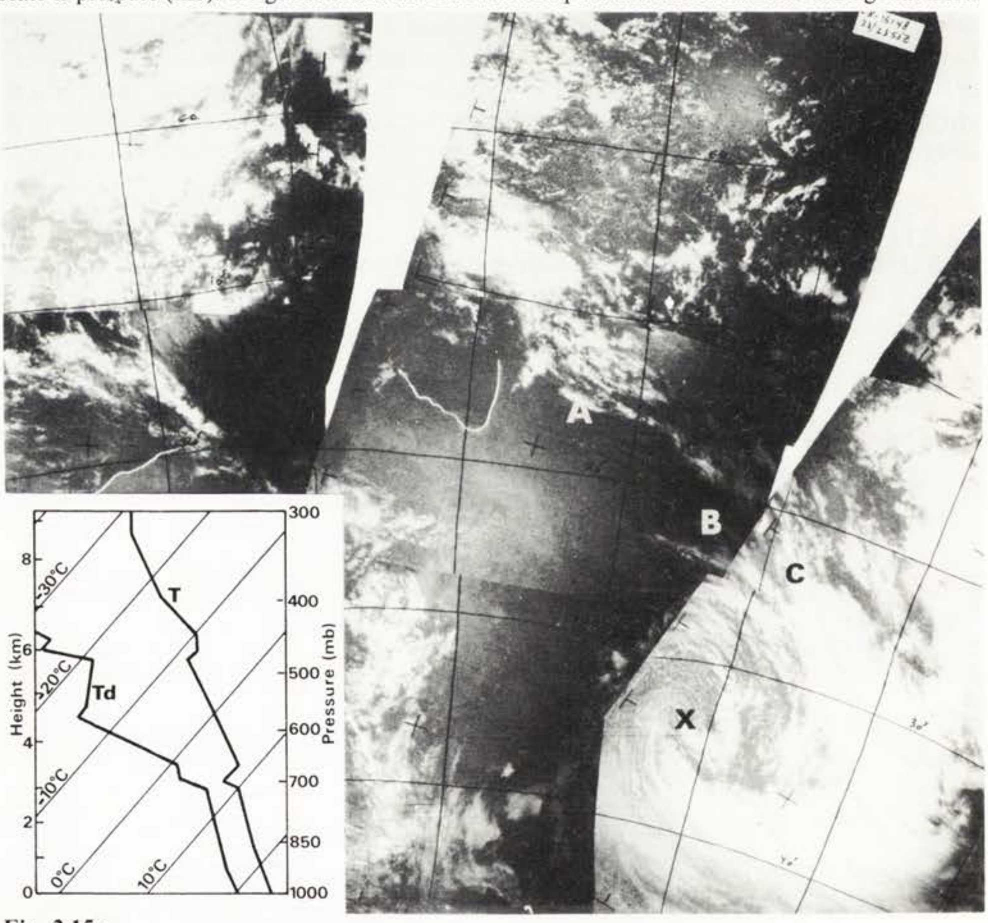


Fig. 2.15a

24 June 1972. ABC is a northward moving convective cloud line associated with extra-tropical low centred at X.

usually curve towards higher latitudes in their eastern flanks which move equatorward in the trade wind zone of the south-western Pacific. Together with the southern branch of the ITCZ, these convective cloud lines are the most common type of disturbance during the south-east season in Melanesia.

Some of the convective line disturbances, particularly the more vigorous ones, appear to be associated with wind shear lines generated by vigorous cold fronts as they approach tropical regions east of Australia, usually with the parent extratropical low pressure system initially located in the Tasman Sea. The sequence of satellite photographs in Fig. 2.15 illustrates such a case. The convective cloud line ABC generating from the Tasman Sea cyclone X (Fig. 2.15a) moved slowly northward to join the ITCZ cloudiness east of New Guinea (Fig. 2.15b). The cloud line became broader and more active as it moved into lower latitudes approaching the ITCZ.

The greater proportion of east-west convective cloud lines develop in apparently featureless trade flow, having no connection with cold fronts (Lajoie 1965). Equatorward movement of the line may be rapid if it lies beneath a jet stream, but in lower latitudes this is usually not the case, and movement is much slower.

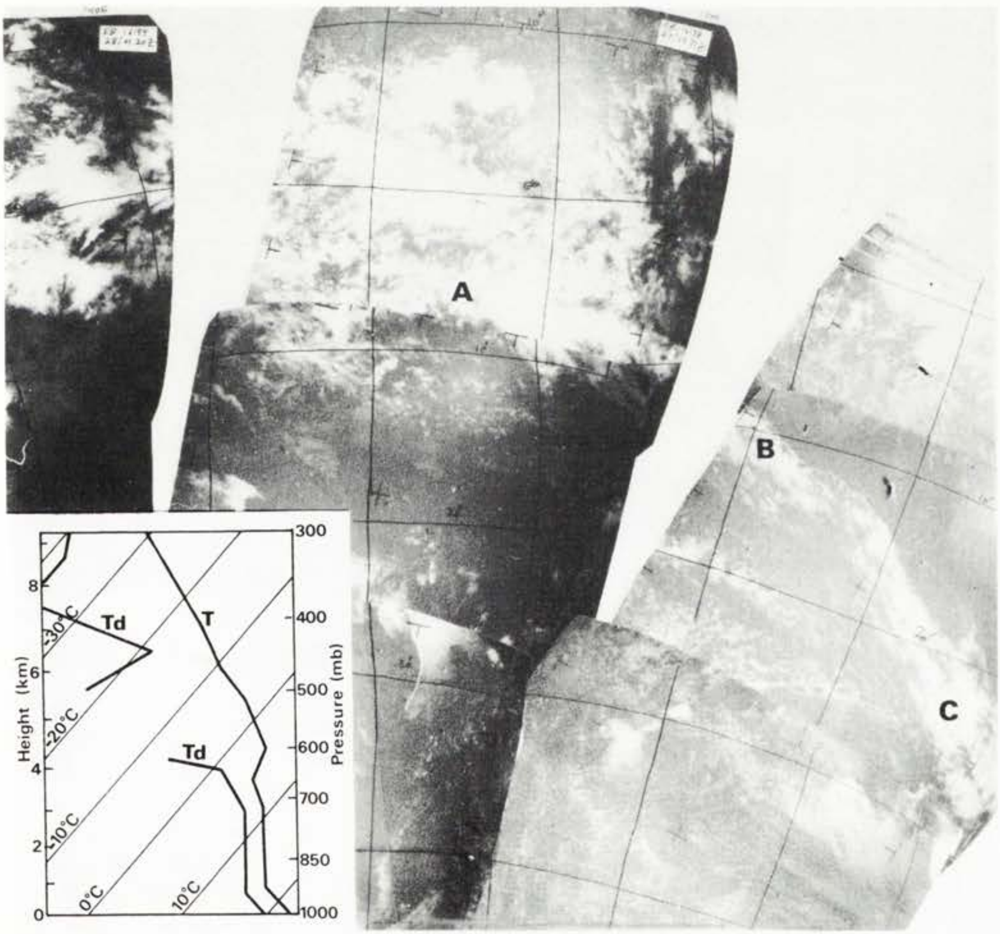


Fig. 2.15b
28 June 1972. Convective cloud line ABC has become broader and merged with the ITCZ.

From Fig. 2.15 the average northward speed of translation of the cloud line from 24 June 1972, until it joined the ITCZ on 28 June, was approximately 2.5 m/sec (5 kt) at longitude 150° E.

The variations which can occur in the stability and moisture content of trade air reaching the New Guinea region are also illustrated in Fig. 2.15. On many occasions, the air is conditionally unstable, with high moisture content extending to the mid troposphere and higher, as seen on insert to Figs. 2.15a and 2.15d, reflecting deep convection in the Huon Gulf and often the presence of a branch of the ITCZ through the region. Sometimes, however, marked trade wind inversions are observed as far north as Lae (see, for example, insert to Fig. 2.15c), associated with suppressed convection and fine conditions over much of the New Guinea mainland.

The degree of organisation of the winter ITCZ may also vary considerably, as shown in Fig. 2.15. The winter ITCZ typically becomes better organised and more active as a major east-west cloud line moves northward to join and reinforce it (Fig. 2.15a and 2.15b). Partial dissolution of the ITCZ south of the equator occurred when dry, stable trade air was advected to very low latitudes in

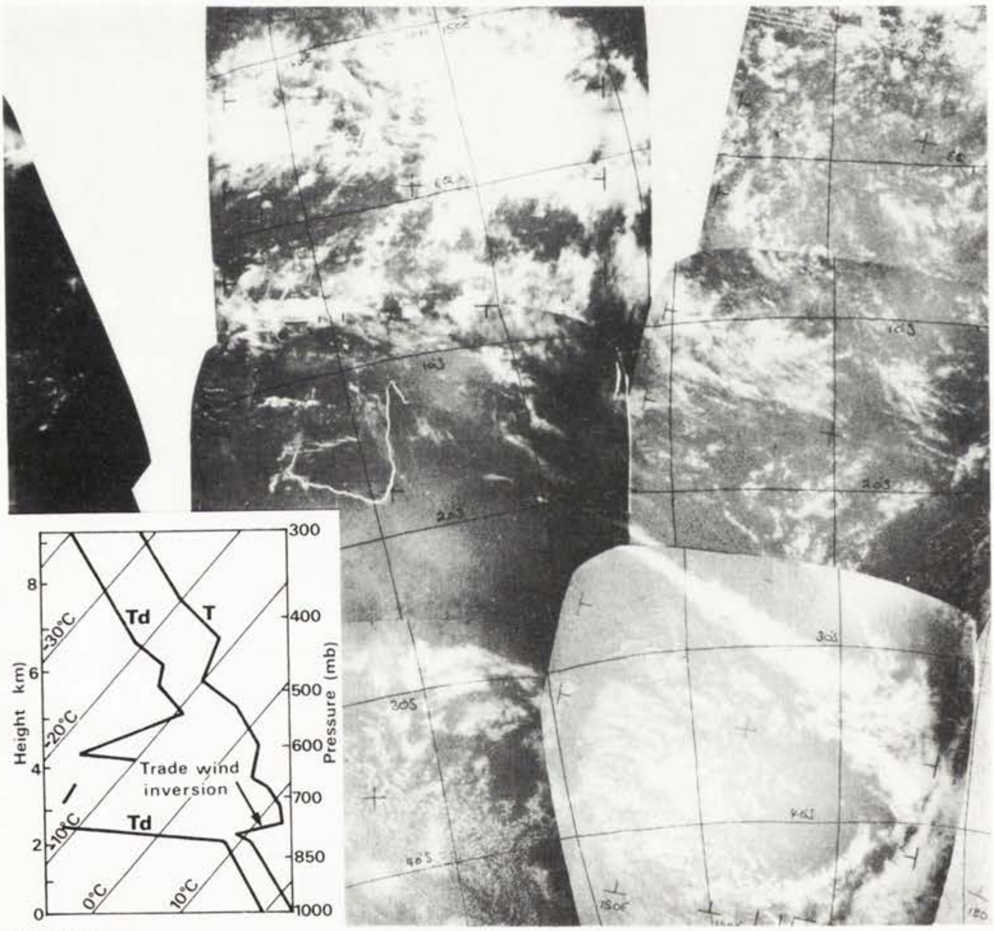


Fig. 2.15c
1 July 1972. ITCZ near 10° S has partly dissipated.

the wake of the cloud line (Fig. 2.15c), but a vigorous and well organised ITCZ reappeared along latitude 10° S east of New Guinea a few days later (Fig. 2.15d).

Extended, or polar troughs

As discussed earlier in this chapter, middle latitude troughs in the middle and upper troposphere often amplify in the Melanesian region. The resultant extended troughs are usually associated with increased cumulonimbus activity in the ITCZ, apparently triggered by strengthened trades, and with extensive raining stratiform cloud sheets over the tropical south-western Pacific.

Figure 2.16 illustrates the development of an extended trough in the longitude sector of Melanesia. On 16 June 1970, a middle latitude trough had started to amplify near eastern Australia, as illustrated by the 0000 GMT (1000 hr PNG time) 200 mb wind analysis (Fig. 2.16a). The infrared satellite photographs for 1200 GMT (2200 hr PNG time) 16 June indicated middle level cloud sheets, streaming south-eastward over Cape York and the Coral Sea from the convective area of the ITCZ north of latitude 10° S. By 18 June, the upper trough had shifted

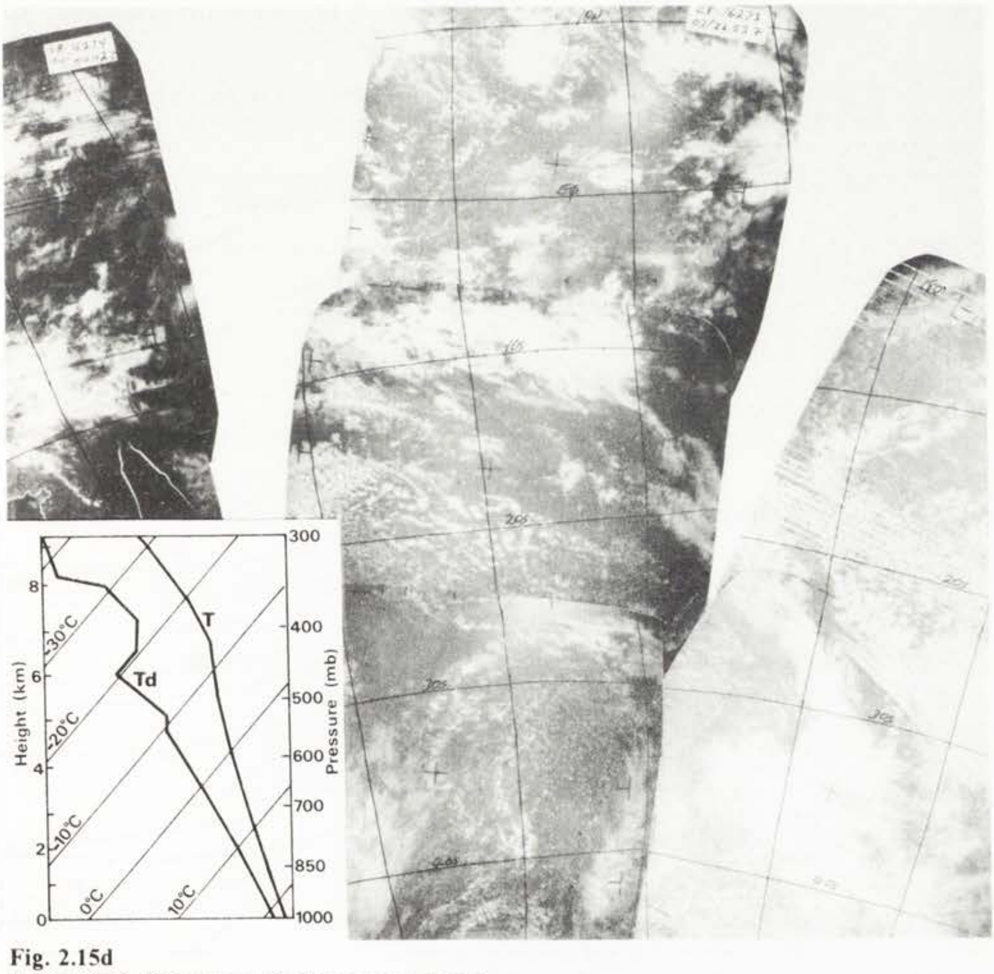


Fig. 2.15d
4 July 1972. ITCZ near 10° S has redeveloped.

eastward to near 155° E (Fig. 2.16b), and on the corresponding satellite photographs extensive stratiform cloud sheets extended from the vicinity of bright cumulonimbus cloud clusters in the ITCZ near the Solomons, south-eastward over the tropical south-western Pacific into middle latitudes.

Tropical depressions and cyclones

The majority of low pressure disturbances in the tropical south-western Pacific appear to develop in the monsoon shear line, which in summer coincides with the equatorial trough. These disturbances in their weaker form are known as tropical or 'monsoon' depressions. They most commonly develop in western Melanesia during transition months, around November and April, when the southern monsoon shear line lies close to New Guinea. They are characterised by multilayered cloud with rain, usually with embedded cumulonimbus clouds which produce squally conditions. Typical cloud swirls associated with monsoon depressions observed on satellite photographs are 300-600 km in diameter, but often merge with extensive cloud areas in the monsoon current to the north.

A small proportion of tropical depressions intensify into tropical cyclones, with sustained surface winds of 17 m/sec (34 kt) or greater in the areas affected.

Fig. 2.16
200 mb (12 400 m) wind analysis for 0000 GMT (1000 hr in PNG) on 16 and 18 June, 1970. Solid lines are streamlines indicating the wind direction and broken lines indicate wind speed in m/sec. H denotes centre of high pressure system.

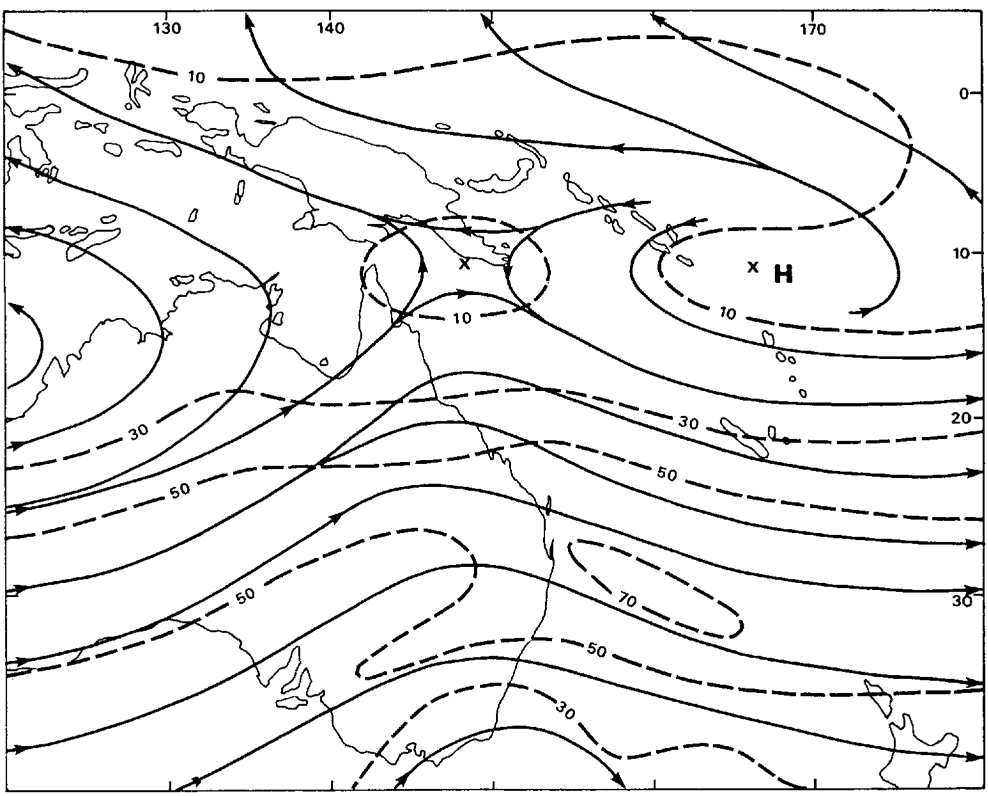


Fig. 2.16a—0000 GMT (1000 hr PNG time) 16 June 1970

In the tropical south-western Pacific an annual average of seven tropical cyclones develops, comprising eleven per cent of the global total (Gray 1968). In the low latitudes of western Melanesia, however, tropical cyclones are infrequent. Brunt (1969) cites an average frequency of approximately one cyclone per calendar year north of latitude 13° S and one cyclone per three calendar years north of latitude 10° S in this region.

The tracks of some low-latitude cyclones that have originated north of latitude 13° S are shown in Fig. 2.17. It would appear from this figure that, while cyclones are fairly well known around the Solomon Islands, their occurrence in low latitudes decreases westward towards the New Guinea mainland. In Papua New Guinea the region around the south-eastern tip, including Milne Bay and surrounding islands, is the most susceptible area. Brunt (1969) suggests that rare tropical cyclones which may be up to hurricane intensity (sustained surface winds 32 m/sec [64 kt] or greater) can affect any of the Papua New Guinea mainland coastline except, probably, the section bordering the Bismarck Sea, where there is no evidence of cyclones having occurred.

In November 1967 a small but intense cyclone, 'Annie', which originated east of the Solomons, moved through the Louisiade Archipelago before recurving south-eastwards towards New Caledonia. Heavy damage occurred in both the Solomon Islands and Louisiade Archipelago and a number of lives and vessels were lost in the Milne Bay/Louisiade Archipelago area. Cyclone 'Hannah' (May 1972), which caused considerable damage at Tufi, is the only well documented

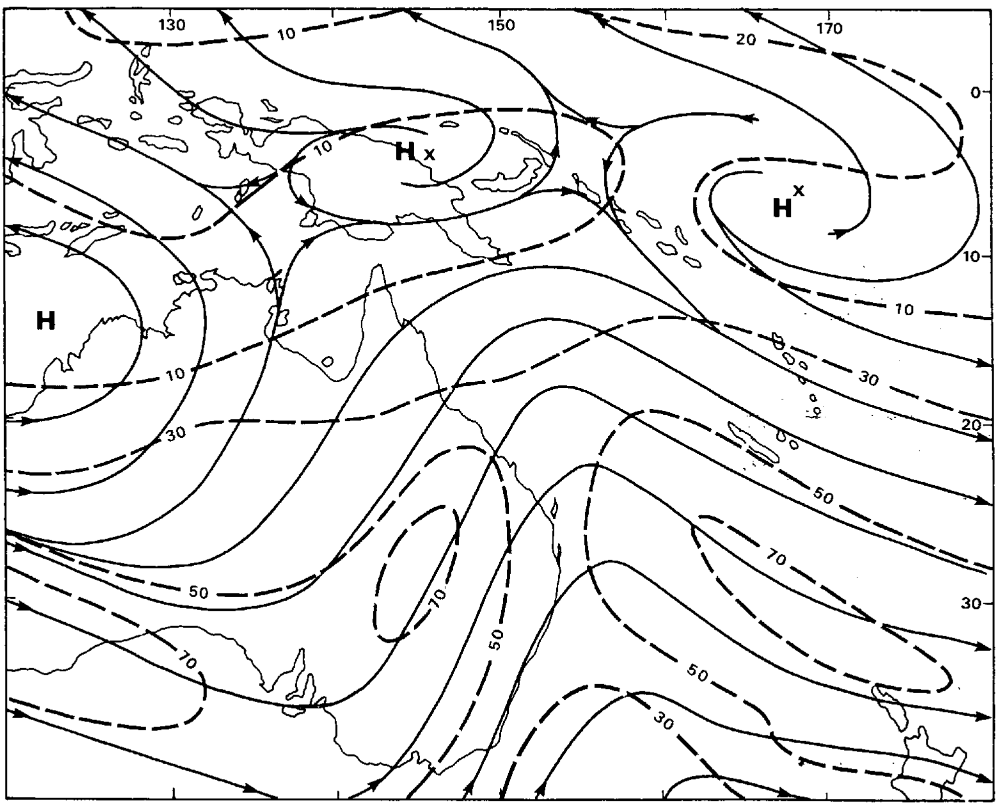


Fig. 2.16b—0000 GMT (1000 hr PNG time) 18 June 1970

cyclone to have seriously affected the Papua New Guinea mainland (Bureau of Meteorology 1972a). A satellite photograph of 'Hannah' showing a well defined eye, indicating its development to hurricane intensity, is shown in Fig. 2.18 and 'Hannah's' track is shown in Fig. 2.17.

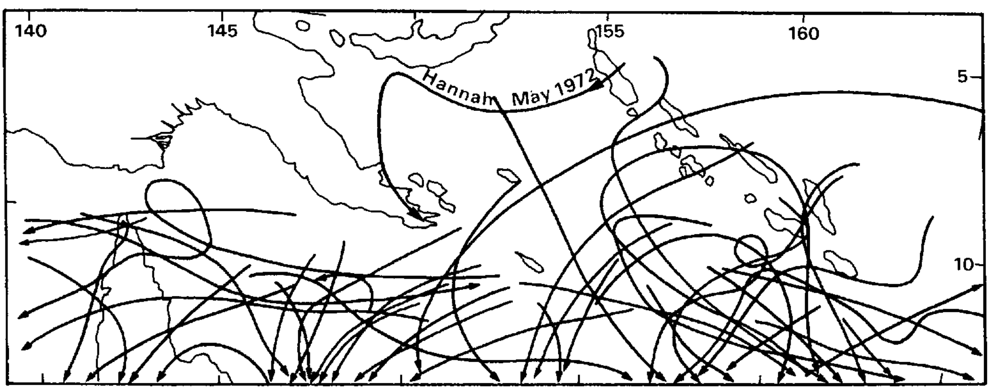
Very strong to gale force winds can be experienced in the vicinity of squally convective outer 'feeder bands' which typically develop and persist over the Bismarck Archipelago-Solomon Islands area when a mature tropical cyclone exists over the north-east Coral Sea, south of the Solomons.

Disturbances of the monsoon westerlies

As discussed previously, the north-west monsoon over Indonesia and New Guinea is an extension of the intense northern hemisphere Hadley circulation over the north-western Pacific and South China Sea. The equatorial westerly stream is nearly always very moist in the lower troposphere and conditionally unstable, facilitating the development of cumulonimbus cloud systems. Observations show that the monsoon westerlies contain heavier cloud cover when they are stronger. Under these conditions, extensive middle and high cloud layers associated with the cumulonimbus clusters are spread over wide areas by the action of strong vertical wind shear. Such 'monsoon surges' with widespread precipitating cumulonimbus cloud systems have on occasions been observed to develop over western Melanesia concurrently with strong trade wind surges over the north-western Pacific, and development of depressions in the equatorial trough to the south, indicating a general strengthening of the Hadley cell.

An illustration of these conditions is provided by Fig. 2.19. On 8 March 1971, satellite photographs showed a broad cloud band extending north-eastward from near 15°N 140°E associated with a cold outbreak over Japan and the north-western Pacific. The surface analysis (Fig. 2.19) indicated a strong trade wind surge developing east of the Philippines. ITCZ cloudiness extended in a belt from Cape York to near 10°S 170°E. At this time the north-west monsoon flow around New Guinea was not very strong and general cloudiness around the island comparatively low. By 11 March, east to north-east winds of 10-15 m/sec (20-30 kt) covered most of the trade wind belt north of latitude 10°N between the

Fig. 2.17
Tracks of some low latitude cyclones in the north-eastern Australian region originating north of latitude 13°S between 1920 and 1969 (after Brunt 1969). The track of cyclone 'Hannah' has been added.



Philippines and the date line (Fig. 2.19b). The north-west monsoon over western Melanesia had strengthened with gradient winds of 15-20 m/sec (30-40 kt) at Madang, Lae and Port Moresby, and tropical lows were deepening in the equatorial trough near 14°S 150°E and 16°S 165°E. Extensive cloud cover comprising several merging cumulonimbus cloud systems had developed in the strong monsoon belt between the equator and about 12°S, west of longitude 165°E. The tropical low near 14°S 150°E later developed into a tropical cyclone. The monsoon surge weakened and cloudiness around New Guinea decreased markedly when this cyclone moved southward towards middle latitudes, disrupting the equatorial trough.

Fig. 2.18
Satellite photograph of cyclone 'Hannah' taken at 0123 GMT (1123 hr in PNG). The arrow indicates the location of the eye of the cyclone, very close to Tufi. Broken lines indicate the position of the Papua New Guinea coastline.

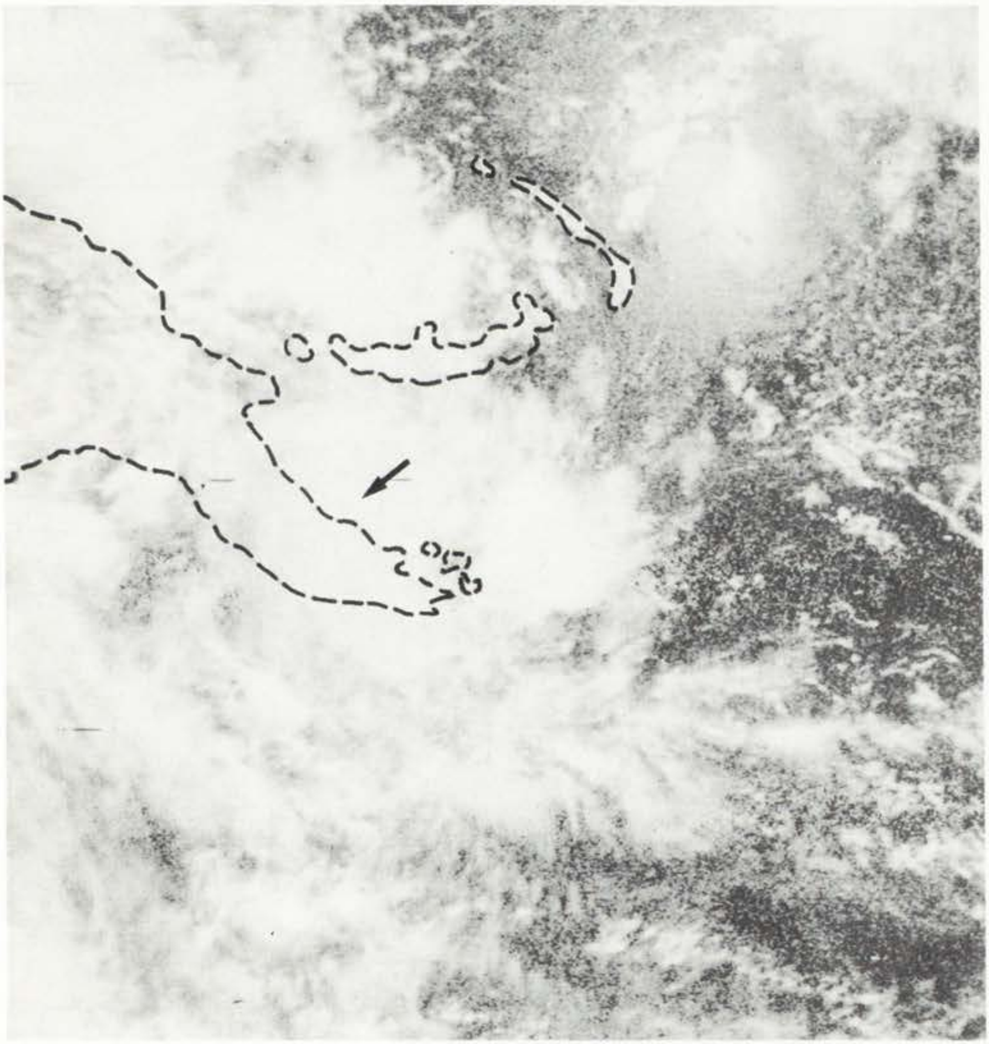


Fig. 2.19
Gradient (900 m) wind analysis for 0000 GMT (1000 hr in PNG) on 8 and 11 March 1971. Solid lines are streamlines indicating the wind direction and broken lines are isotachs indicating the wind speed in m/sec. The central pressure (millibars) of low pressure systems (L) is shown in brackets.

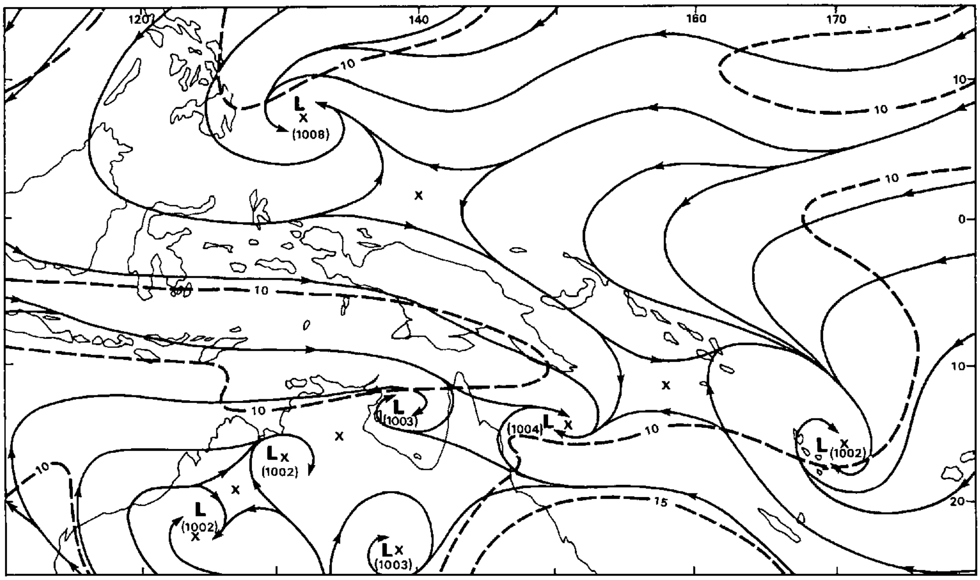


Fig. 2.19a—8 March 1971

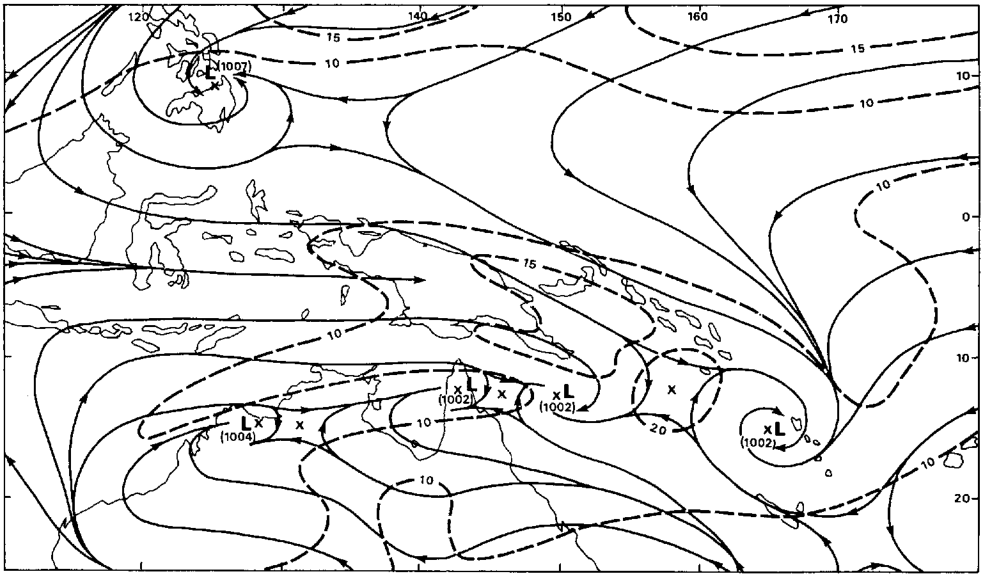
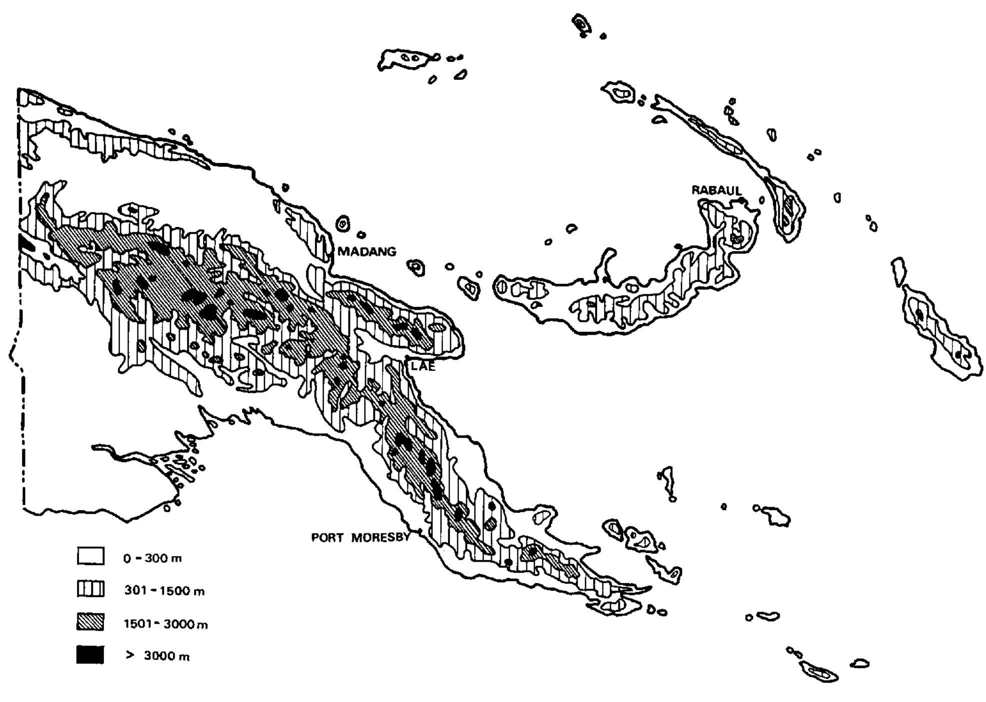


Fig. 2.19b—11 March 1971

3 Local Controls and Surface Winds

The preceding chapter has dealt with the broad-scale meteorological controls of climate in the PNG region, their role in determining seasonal conditions, and synoptic disturbances of smaller time and space scales which provide intra-seasonal weather variations. These provide the framework and set the limits to the types of climatic pattern that can occur in PNG. Local climatic patterns result from the modifications imposed on these larger-scale controls by the presence of the PNG land mass. Meso-scale 'local effects', resulting from the interplay of physiography with airstreams of the synoptic and broad-scale flow, cause locally forced patterns of wind and rainfall to be superimposed on the broad climatic patterns produced by the larger-scale circulation systems. Because of the rugged nature of the physiography and the relatively weak atmospheric pressure and temperature gradients, these local effects are of major importance in determining the weather and climate of PNG, and the following discussion will deal further with them. It should be emphasised, however, that there are insufficient detailed meteorological observations in PNG to allow more than a general treatment of the subject based on commonly accepted models of local circulation sytems.

Fig. 3.1
Physiography of PNG (from Löffler 1977). The height and alignment of the major mountain chains are important determinants of local weather patterns in that they modify the effects of the broadscale circulations.

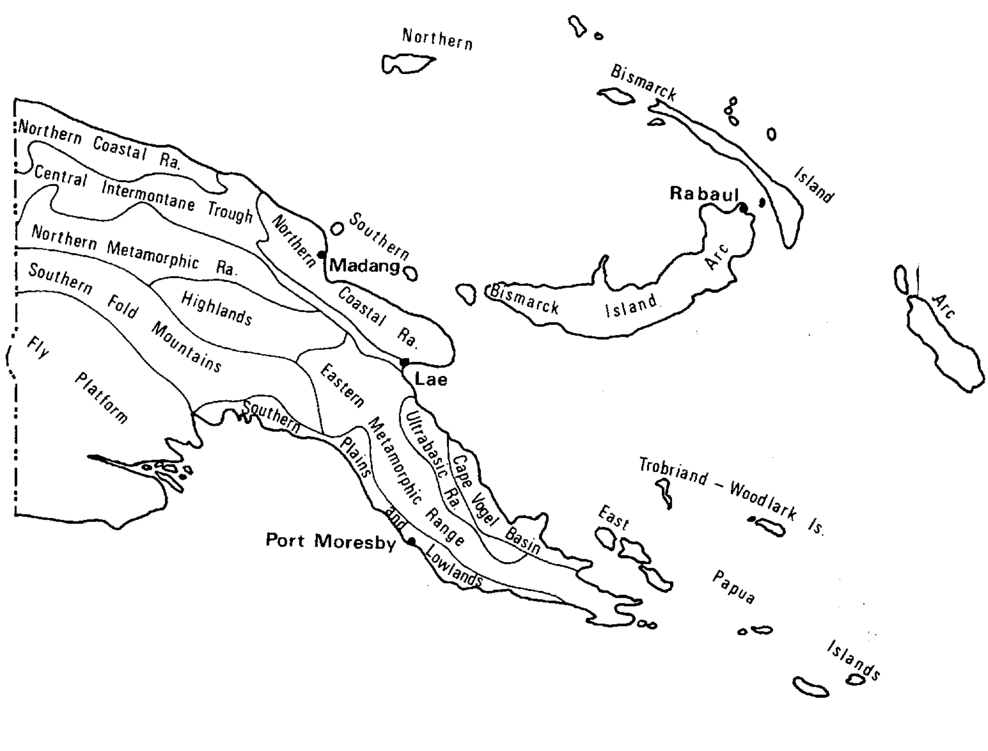


Influence of physiography

The rugged and mountainous nature of the physiography of PNG is evident from Figs. 3.1 and 3.2 and its influence on local climatic patterns will be a constantly recurring theme throughout this book. A full description of the landforms and geomorphology of PNG has been given by Löffler (1974, 1977), and includes the effects of climate on landform. Such effects will not be dealt with in the present volume, where the discussion will concentrate on the effects of landform (physiography) on climate. These are fourfold:

(1) The land mass presents mechanical barriers to the larger-scale winds, forcing areas of ascent, descent, turbulence and consequent thermodynamic modification of the air streams.
(2) The direction of the larger-scale flow over the sea is altered once the land mass is encountered because of the greater frictional resistance to the flow.
(3) Local land/sea breeze cells arise from the different thermal properties of the land and sea surfaces.
(4) Variations in the structure of the landform create anabatic/katabatic and mountain/valley wind circulations and other topoclimatic effects. These exert an additional influence on local weather patterns over the land and on the sea fringe.

Fig. 3.2
Major landforms of PNG (from Löffler 1977). The width of the central highlands and the presence of an intermontane trough between them and the northern coastal ranges are major factors in determining local climatic patterns.



Two major aspects of physiography—height and alignment — determine its effects on local climate. Generally, the summit level of the major mountain chains in PNG lies around 2500-3000 m with individual peaks rising as high as 4500 m. In terms of climatic patterns there are two types of mountain system. The ranges of the islands and northern coast are approximately triangular in section, while the central highlands are more complex, with large intramontane valleys and basins and other internal mountain systems lying within the fringing ranges of the highlands. In extent these mountains occupy more than 30 per cent of the country above 1500 m and large portions of the land mass are above the 700 mb pressure level. Thus the massive mechanical barriers imposed by these ranges can be expected to substantially modify air streams in their vicinity.

This effect is strongly reinforced by the alignment of the mountain ranges in relation to the dominant south-east/north-west wind regimes. Inspection of Figs. 3.1 and 3.2 shows that the mountains are aligned either nearly parallel to or transversely across the wind stream lines indicated in Chapter 2 and that there is an important intermontane trough between the central highlands and the northern coastal ranges.

Important influences of landform on climate result from differential surface frictional effects on the low level winds over rough terrain and the sea. The simple model shown in Fig. 3.3 allows 10° veering of the surface wind over sea and 30°

Fig. 3.3
Idealised model of large-scale surface wind pattern during north-west and south-east seasons. Wind vectors are reduced from gradient-level flow by allowing for greater Ekman type frictional veering and retardation of winds in the lowest layers over land compared with over the sea. Frictional effects of the New Guinea land mass generate zones of wind convergence and divergence at coast lines and areas of upslope and downslope flow over the main physical barriers.

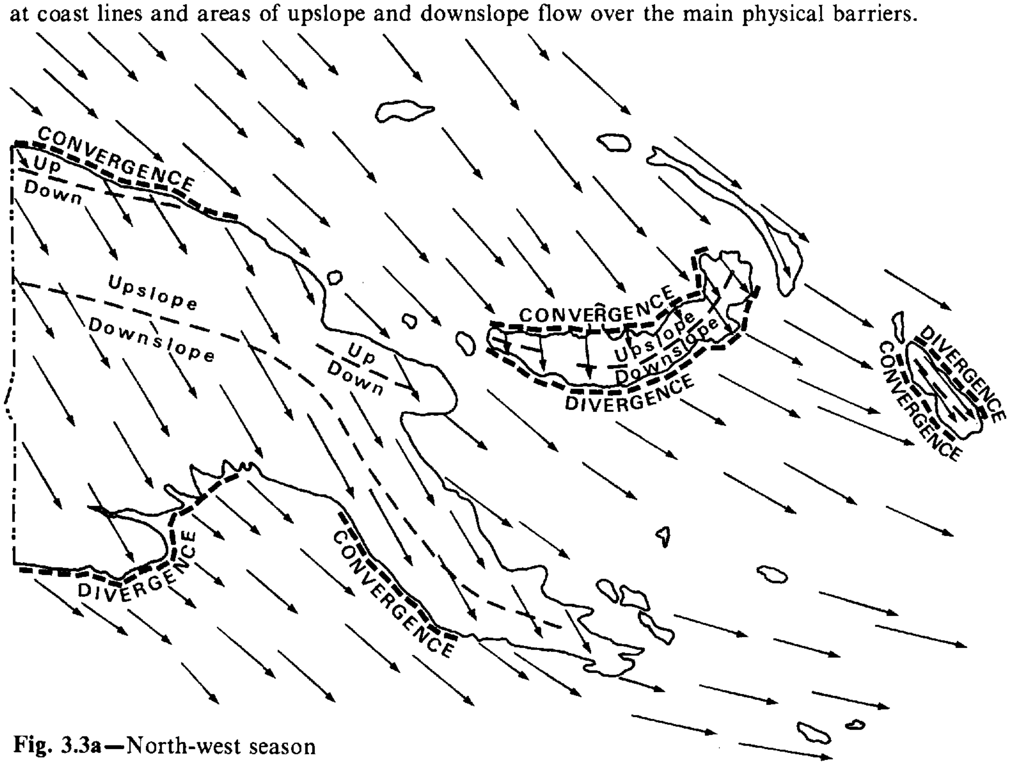


Fig. 3.3a—North-west season

over land, relative to the 'frictionless' broad-scale wind field at gradient level (about 1 km above the surface), and a wind speed over land which is 60 per cent of the value over water. It generates zones of convergence and divergence at the coast, and areas of upslope and downslope winds in relation to the main orographic barriers, which contribute to the explanation of the major seasonal differences in rainfall found in PNG. In areas of convergence and of upslope winds, rainfall should be enhanced, while in areas of divergence and of downslope winds, it should be suppressed. This model neglects of course the important local wind systems which exert local diurnally varying controls.

Land and sea breezes

Land and sea breezes play a significant part in controlling rainfall in coastal districts of PNG and at some places may completely dominate the seasonal controls. They are thermally driven local diurnal winds caused by the differential heating or cooling of the land relative to the adjacent sea. The resulting sea and land breeze circulation is shown schematically in Fig. 3.4. After its initial development the sea breeze cell is located near the shoreline in the mid or late morning but expands both landward and seaward as the day progresses. The inland expansion may vary from a few kilometres on steep mountainous coastlines to 150 km or more on flat unobstructed coastlines. The sea breeze usually dies out at the coast shortly after sunset but may continue longer inland.

The land breeze, the reverse of the sea breeze, usually sets in about midnight (or earlier in mountainous coastal regions) and may continue until two or three hours after sunrise. It is usually a much weaker circulation than the sea breeze

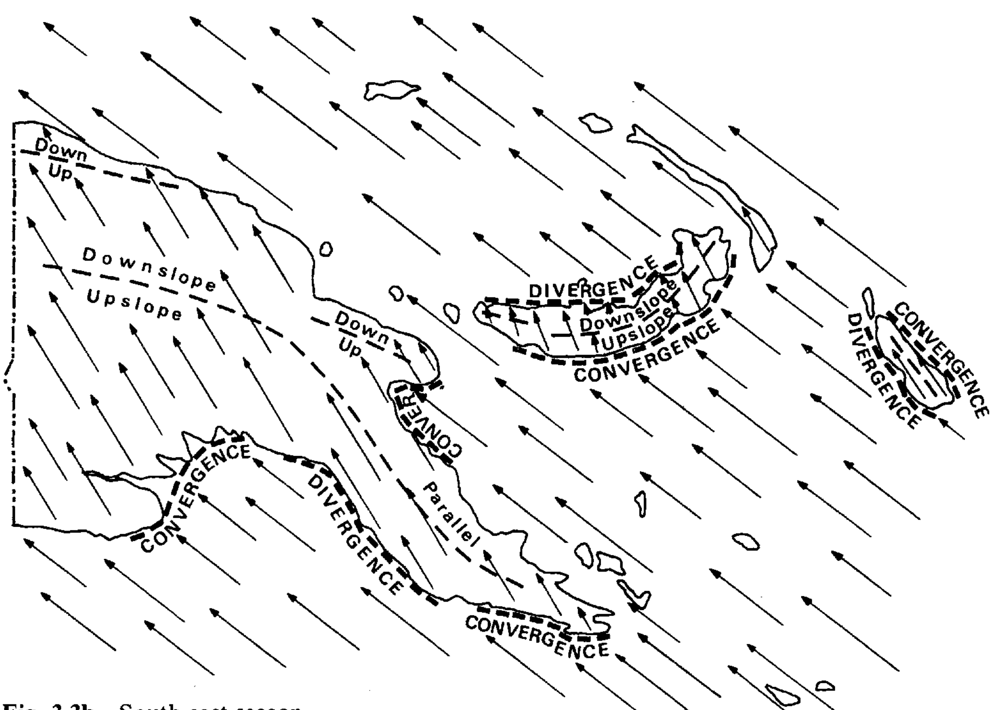


Fig. 3.3b—South-east season

because in the tropics the land-sea temperature difference due to daytime heating is much greater than that due to night-time cooling. However, in some locations the land breeze can reach considerable strengths when reinforced by katabatic winds (see below) and/or the larger-scale flow.

At any particular location the land and sea breezes are influenced by physiography, the larger-scale wind pattern, friction, stability of the air mass and the temperature difference between the land and sea. Hence, although land and sea breezes occur in all coastal areas of PNG, each locality may experience a different effect. In the case of a peninsula or island, sea breeze circulations can develop along opposite shores and this can lead to increased diurnal cloudiness and precipitation in the central region of the island or peninsula due to increased convergence there. Variations in coastline curvature can also affect the direction of the sea breeze (Fig. 3.5). A fuller treatment of land and sea breezes is provided by Anderson *et al.* (1969).

One of the most striking features of the sea breeze is the frontlike zone that forms under certain conditions at its leading edge. This particular phenomenon — the 'sea breeze front' — occurs in the Port Moresby region under conditions of light north to north-east larger-scale flow in the low levels. It may be accompanied by showers, a temperature decrease, humidity and wind change as it crosses the coast and moves inland. Conditions along its leading edge vary considerably. As the system moves further inland the convective clouds may develop rapidly along its leading edge and reach the thunderstorm stage by the time it reaches the ranges.

Fig. 3.4
Land and sea breeze cells (from Bureau of Meteorology 1975). Land and sea breezes are thermally-driven local diurnal winds caused by differential heating or cooling of the land relative to the adjacent sea.

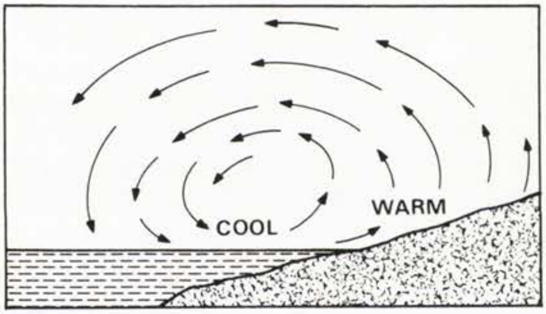


Fig. 3.4a—Model of a sea breeze cell

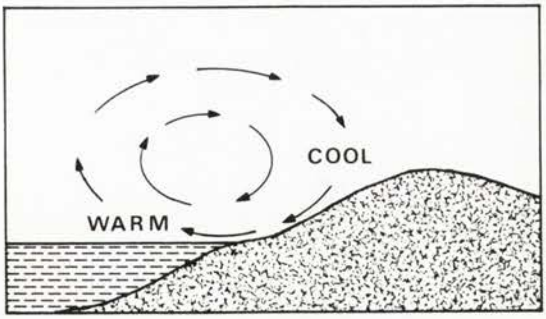


Fig. 3.4b—Model of a land breeze cell

Katabatic and anabatic winds

At night on high mountain slopes, the air cools rapidly by radiation and thus becomes denser. Under gravity, it flows downhill into the valleys, gaining momentum (katabatic wind). In the daytime, the slopes are warmed by insolation and the breeze begins to flow upslope (anabatic wind), usually beginning about half an hour after sunrise and continuing until half an hour before sunset. These wind systems are illustrated diagramatically in Fig. 3.6. The anabatic wind can reach 10 kt (19 km/h) up sunny slopes and the air flow can exceed 150 m in depth, increasing uphill. The katabatic wind is usually stronger and has its maximum effect on calm clear nights when the air is relatively dry. Because of the extremely mountainous nature of the terrain, katabatic winds are a regular occurrence over much of PNG.

Mountain and valley winds

Thermal and gravitational effects similarly cause night-time drainage of air along the axis of large mountain valleys into the adjacent plains (mountain wind). The reverse process during the day causes air to flow from the plains towards and up the valley (valley wind). The mountain wind is the stronger and, where especially favoured by physiography (such as narrowing of the valley), it can develop into a very strong wind. It may bring slightly cooler and usually drier air to the plains. In contrast the daytime valley wind carries upslope hot and humid air from the lower plains, but cooling processes are involved in the flow upslope. The change from the mountain wind (down valley) to the valley wind (up valley) can take place about 0900 hr and the opposite change soon after sunset. A full discussion of mountain-valley wind systems is given by Defant (1951) and Fig. 3.7 shows a general model of the processes involved.

A good example of mountain and valley winds can be seen at Mendi, which is situated in a valley, protected from both the north-west and south-east seasonal winds by high mountain ranges. Upslope, the valley is oriented northwards but downvalley from Mendi it lies towards the south-south-east. Thus the mountain and valley winds cause the early morning wind direction to be northerly and the

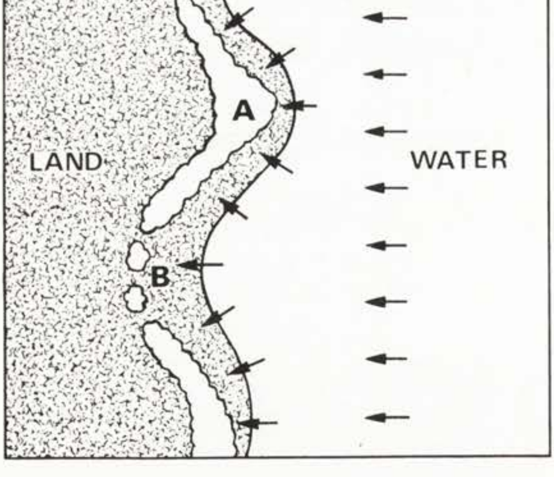


Fig. 3.5
Plan profile of sea breeze front (after Anderson *et al.* 1969). Variations in coastline curvature cause differences in frictional drag which result in convergence at A and divergence at B. These effects in turn strengthen or weaken the cloud pattern associated with the sea breeze front.

afternoon wind to be from the south-south-east. These directions are highly constant throughout the year. Mountain and valley winds are also prominent at Mt Hagen where south-west winds up 25 kt (46 km/h) develop in the valley in the afternoon (see Figs. 3.11, 3.12).

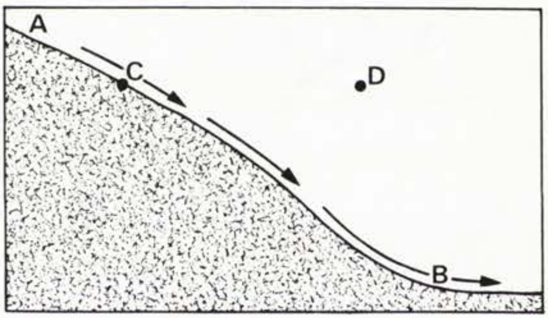
Foehn winds

Foehn winds are warm dry winds characteristic of nearly all mountain areas and are produced when the larger-scale flow is sufficiently strong and deep to force air completely across a major mountain range in a short period of time (see Fig. 3.8). On the windward side of the mountains the air cools and its relative humidity increases as it is forced to rise until it eventually becomes saturated, resulting in the formation of cloud, and usually precipitation, which continues as long as the air rises. On the lee side of the mountains the air descends rapidly and warms at the rate of about 10° C per km of vertical descent, the rate of warming during descent being much more rapid than the rate of cooling during ascent. The resulting wind, known as the foehn, is consequently a warm dry leeward wind and is associated with fine weather.

In PNG, conditions conducive to the development of foehn winds occur periodically in both the south-east and north-west seasons, particularly in areas

Fig. 3.6
Katabatic and anabatic winds (from Bureau of Meteorology 1975). The differential cooling and heating of air by radiation during day and night results in downslope (katabatic) and upslope (anabatic) winds.

Fig. 3.6a
Model of katabatic wind. AB is the slope of a hill on which point C is located. D is a point in free air at the same altitude as C. Radiational cooling on a clear night lowers the ground surface temperature at C and the air in contact with the land is then cooled by conduction. As a result, the air near C becomes denser than the free air near D and there is a gravitational flow of air down the slope.



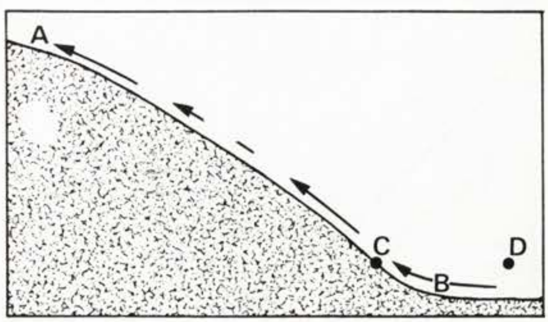
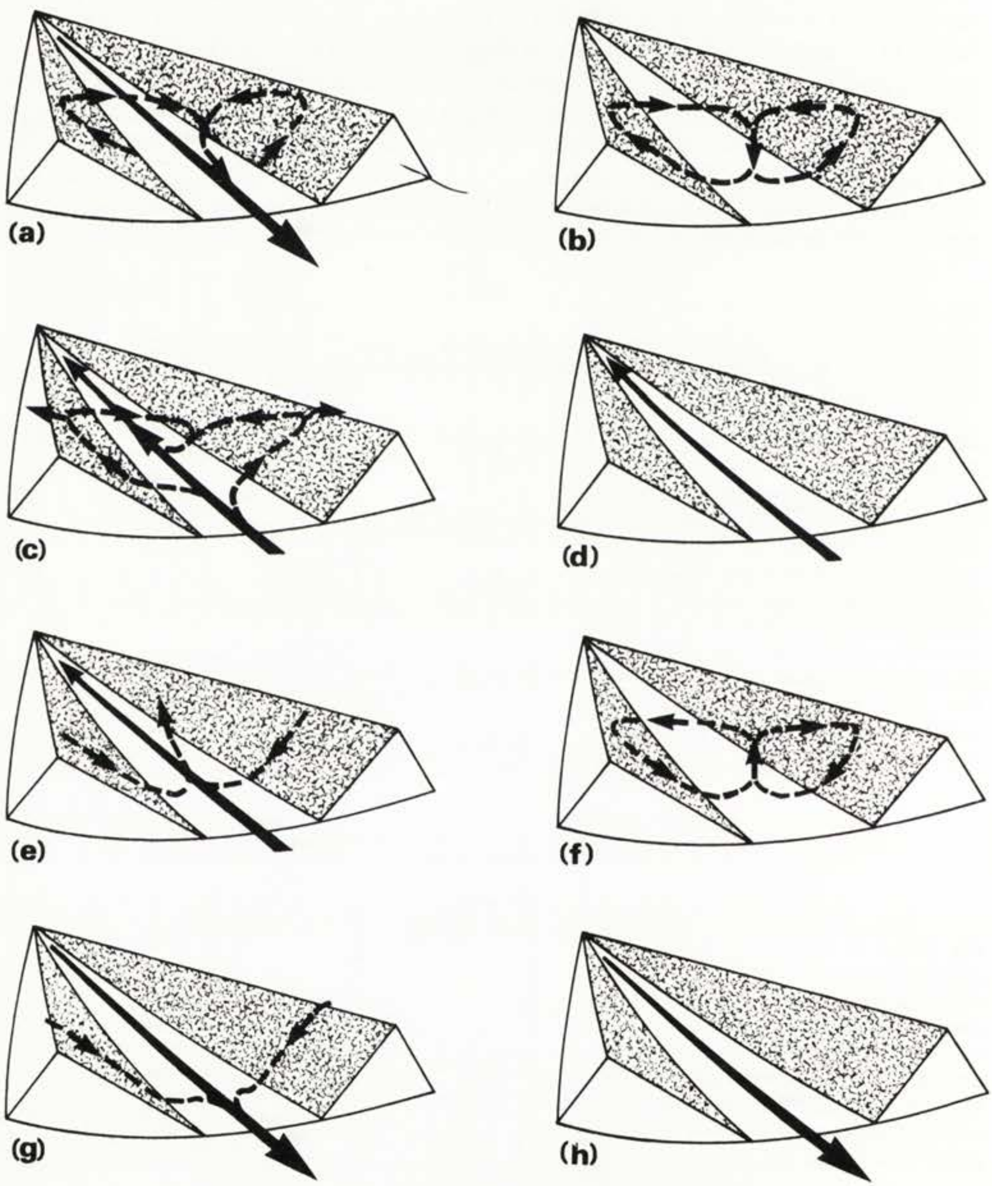


Fig. 3.6b
Model of anabatic wind. On a warm cloudless day, solar radiation causes the ground surface temperature at C to rise, and air in contact with the land becomes warmer than the free air near D. This warmer air tends to become unstable and rises up the slope AB as a gentle upward flow.

Fig. 3.7
Mountain and valley winds (from Defant 1951). Radiational cooling and heating of the air in large mountain valleys causes down-valley (mountain) winds at night and up-valley (valley) winds during the day. **a.** Sunrise; onset of upslope winds (dashed arrows), continuation of mountain wind (solid arrows). Valley cold, plains warm. **b.** Forenoon (about 0900); strong slope winds, transition from mountain wind to valley wind. Valley temperature same as plains. **c.** Noon and early afternoon diminishing slope winds, fully developed valley wind. Valley warmer than plains. **d.** Late afternoon; slope winds have ceased, valley wind continues. Valley continues warmer than plains. **e.** Evening; onset of downslope winds, diminishing valley wind. Valley only slightly warmer than plains. **f.** Early night; well-developed downslope winds, transition from valley wind to mountain wind. Valley and plains at same temperature. **g.** Middle of night; downslope winds continue, mountain wind fully developed. Valley colder than plains. **h.** Late night to morning, downslope winds have ceased, mountain wind fills valley. Valley colder than plains.



where the main mountain chain is aligned almost at right angles to the flow such as in New Britain. In such regions these winds will cause precipitation to be higher on the windward slope and lower on the lee side. However, the exact local nature of the foehn may vary considerably and depends on such things as local physiography, the strength of the wind stream, the amount of moisture lost through precipitation on the windward side, and on local conditions prior to its onset.

Resultant surface winds

There are several meso-scale phenomena which modify the effects of the larger-scale meteorological circulations affecting the PNG region and a few of these major local controls have been discussed in the preceding sections. The resultant weather patterns are created by interaction of the larger-scale flow with these meso-scale processes, which need to be considered collectively at individual localities.

An example of interaction between the meso-scale and larger-scale circulations is provided by off-shore convective zones which occur in some areas as the result of convergence of the katabatic and land breezes of the early morning with

Fig. 3.8
Foehn winds (from Bureau of Meteorology 1975). Foehn winds occur when an air mass is forced completely over a mountain barrier in a short period of time. The temperature gradients to which the air mass is subjected cause cooling and saturation on the upslope and rapid warming again on the downslope. As a result, windward slopes of the mountain range will experience higher rainfall than leeward slopes.

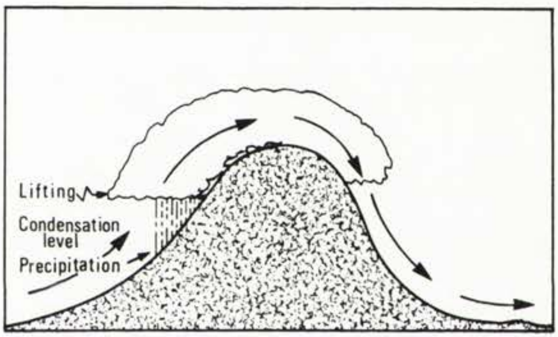


Fig. 3.8a—Model of a foehn wind

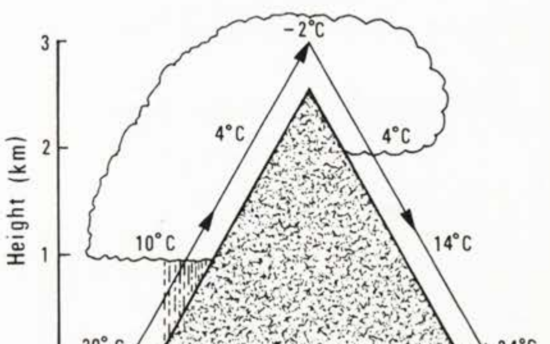


Fig. 3.8b—Temperature changes during foehn wind development

the directionally-opposed broad-scale seasonal flow. Some recognised convective zones in the PNG region produced by such effects are shown in Fig. 3.9 (A. W. Douglas pers. comm.).

As a first step in describing local weather patterns, locally observed surface winds will be examined in the following sections in terms of the resultant effects of interaction between local circulations and broad-scale seasonal flow patterns. For example, the diagram in Fig. 3.10 shows a gradient wind of different direction from the sea breeze cell. The resultant wind flow is angled at about 45° to the coastline. The complexity of processes producing resultant winds is illustrated by the situation at Lae. During the north-west season, the strong wind that flows down the Markham River valley is the resultant of the seasonal north-west monsoon wind producing, on occasions, foehn effects, which are reinforced in the early morning by the katabatic/mountain wind and land breezes. The resultant surface wind frequently attains quite considerable speed, clearing the valley of cloud. In the afternoon, the sea breeze and anabatic/mountain wind reverse the wind direction to south-east, and except on rare occasions completely mask the broad-scale north-west flow.

It will be seen that, although there is a general conformity in the pattern of surface winds with the broad-scale circulation, at least in coastal areas, the massive physiography of PNG is often a far more significant factor in determining surface wind flow, and in highland areas is entirely dominant.

Fig. 3.9
Convective zones. Off-shore convective zones result from the convergence of katabatic and land breezes of the early morning with the directionally-opposed broad-scale seasonal flow. Location of convective zones from personal communication, A. W. Douglas.

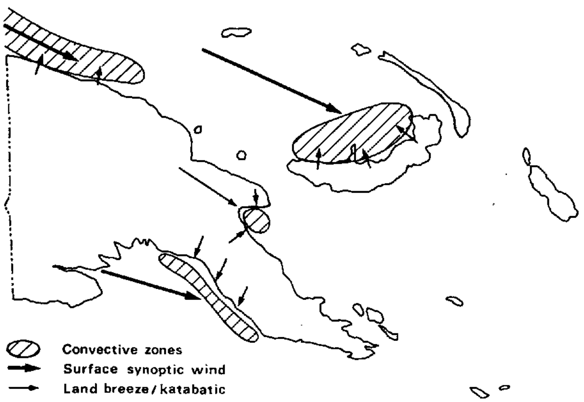


Fig. 3.9a—North-west season

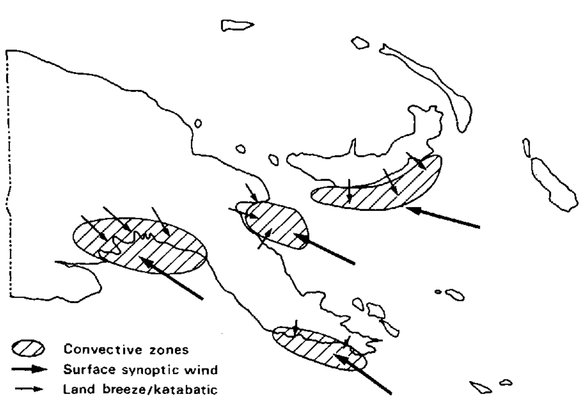


Fig. 3.9b—South-east season

Seasonal and diurnal variation in surface winds at selected stations

Figures 3.11 and 3.12 show wind roses for eight coastal and two highland locations in PNG derived from observations at 0900 and 1500 hr local time during selected months of the year. The seasonal changes in wind direction associated with changes in broad-scale circulation patterns are seen most clearly at island locations such as Momote, Kavieng and Rabaul, where physiographic barriers only minimally impede the broad-scale flow. Here winds are north-westerly in January and strengthen during the course of the day. The north-westerly components are less well-developed in the transition period around April, and are entirely replaced by moderate to fresh south-easterly winds in July, these being of relatively similar strength in the morning and afternoon. By October the south-easterly flow is weakening and the cycle is completed by the strengthening of the north-westerly component and return to the January situation.

The central highlands present a formidable barrier to the passage of the major broad-scale wind systems across mainland PNG. Thus, at places such as Wewak on the north coast and Port Moresby on the south coast the prevailing broad-scale flow is clearly evident only during the season when it is not intercepted by the central highlands, that is, during the north-west season at Wewak and the south-east season at Port Moresby. Hence local sea breezes are the dominant effect at Wewak in July. At Port Moresby the situation is complicated by the fact that the recording station lies in a north-west south-east aligned valley. This local configuration magnifies winds in these two directions through its funnelling effect. It also tends to modify other wind directions to conform with its own alignment. Thus the strong north-westerly component seen at 0900 hr in January at Port Moresby is probably less a result of broad-scale flow than of re-alignment of north and north-east land breezes.

Where the coast is closely flanked by an inland mountain range, broad-scale flow patterns are also modified. Thus at Finschhafen, which is located at the south-east corner of the Huon peninsula, the north-westerly winds of January are intercepted by the Saruwaged Ranges and no directional bias is seen at Finschhafen during the north-west season. With the approach of the south-east season the southerly wind components show marked development. Physiographic deflection causes the south-east trade flow to reach Finschhafen from the south to south-west, and moderate winds from these directions are recorded at both 0900 and 1500 hr in July.

On other parts of the coast the larger-scale flow can be almost entirely masked by overriding local effects. At Madang, well developed land and sea breeze cells

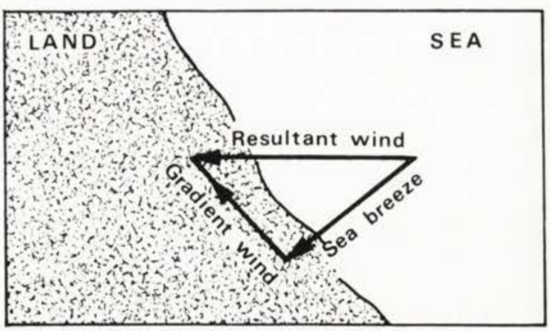


Fig. 3.10
Resultant winds (from Bureau of Meteorology 1975). The actual surface wind direction and strength is the result of the broad-scale (gradient) wind and local wind effects (e.g. sea breeze).

Fig. 3.11
Resultant surface wind patterns—0900 hr local time. Resultant surface wind directions and speeds vary with physiographic location and exposure to broad-scale circulations, as well as seasonally and diurnally.

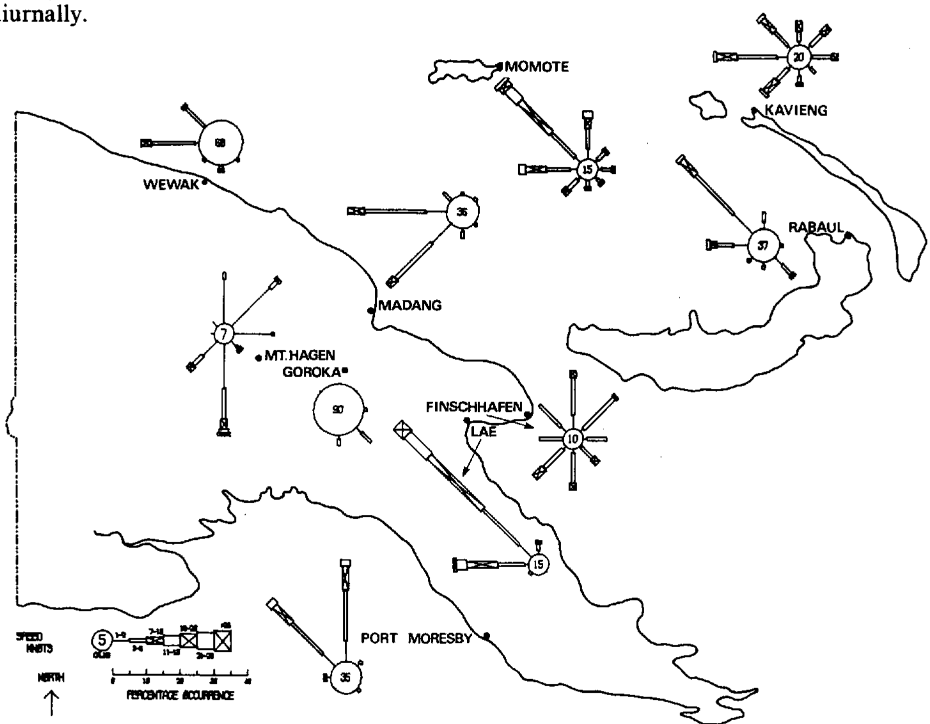


Fig. 3.11a—January

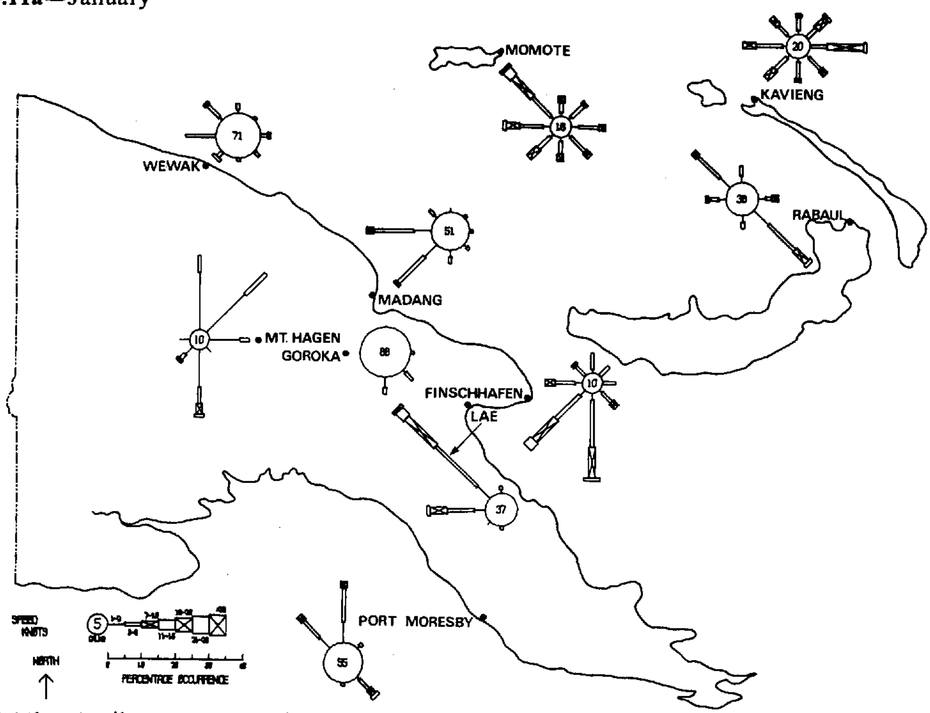


Fig. 3.11b—April

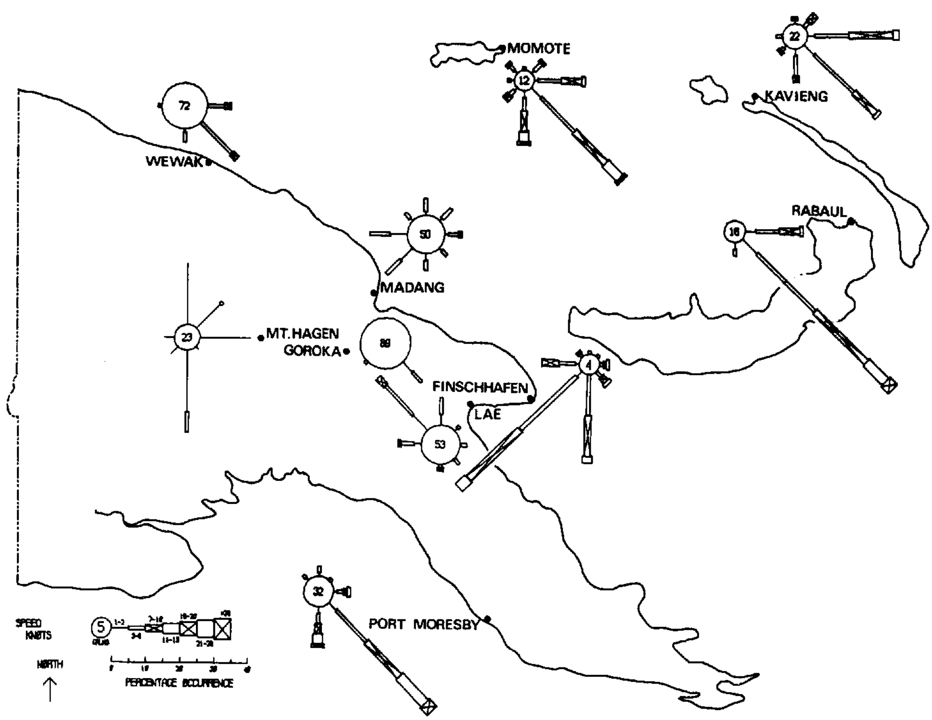


Fig. 3.11c—July

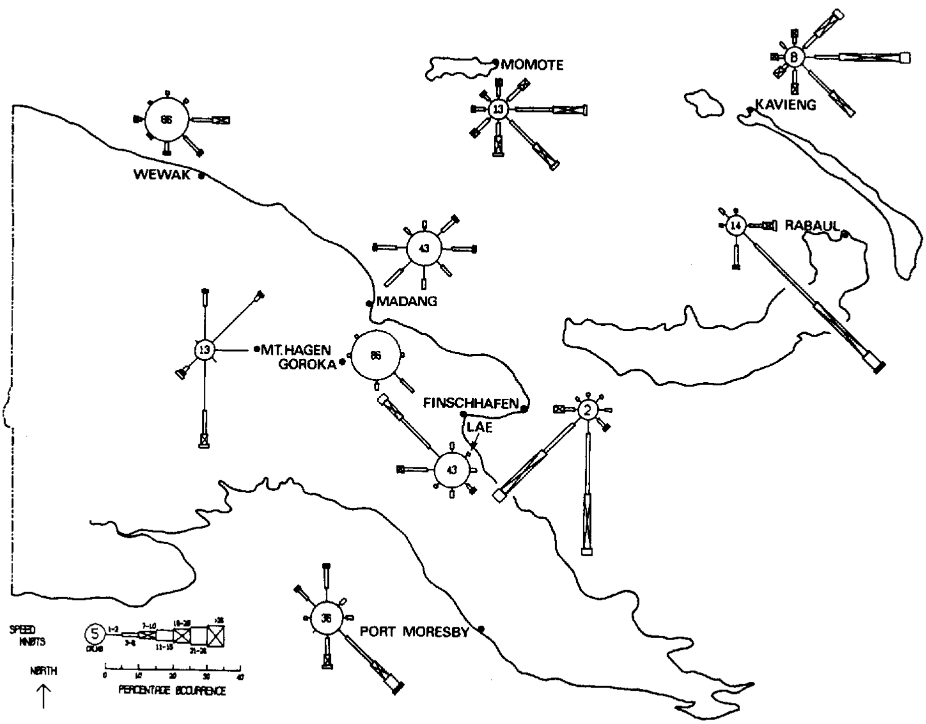


Fig. 3.11d—October

Fig. 3.12
Resultant surface wind patterns—1500 hr local time

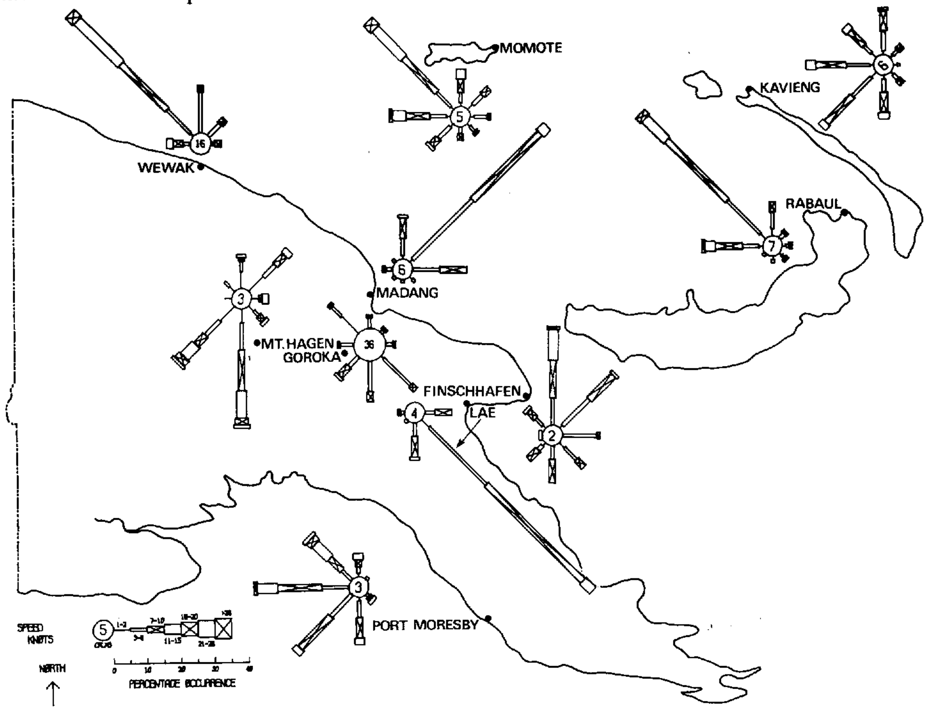


Fig. 3.12a—January

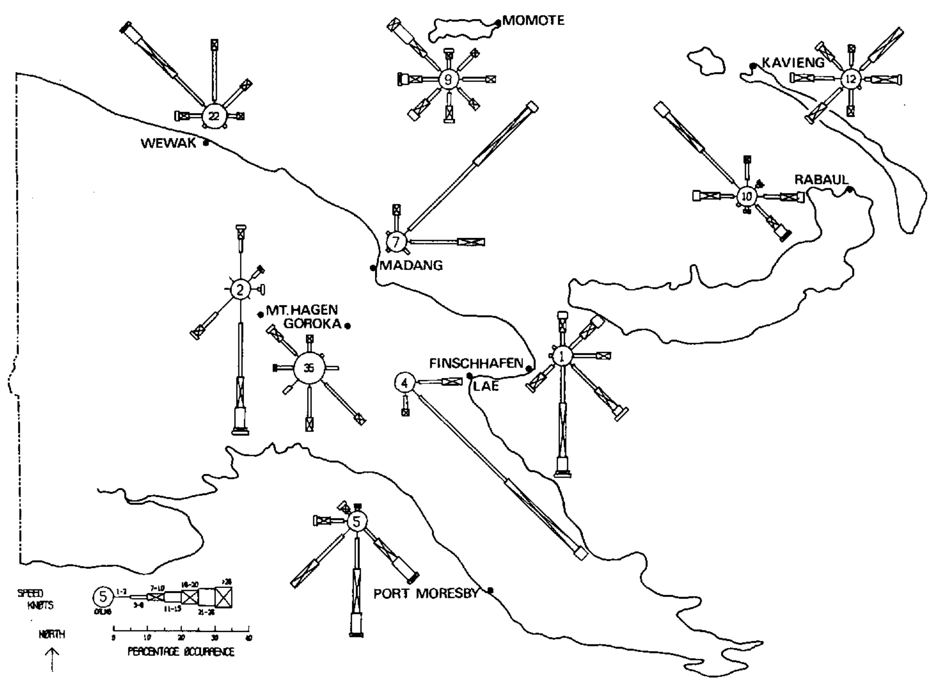


Fig. 3.12b—April

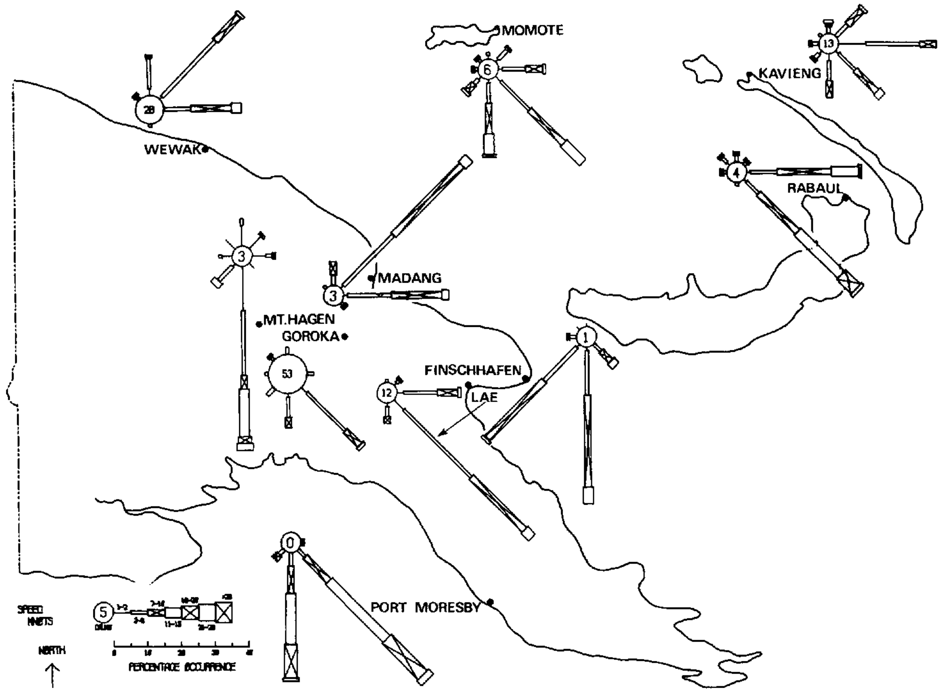


Fig. 3.12c—July

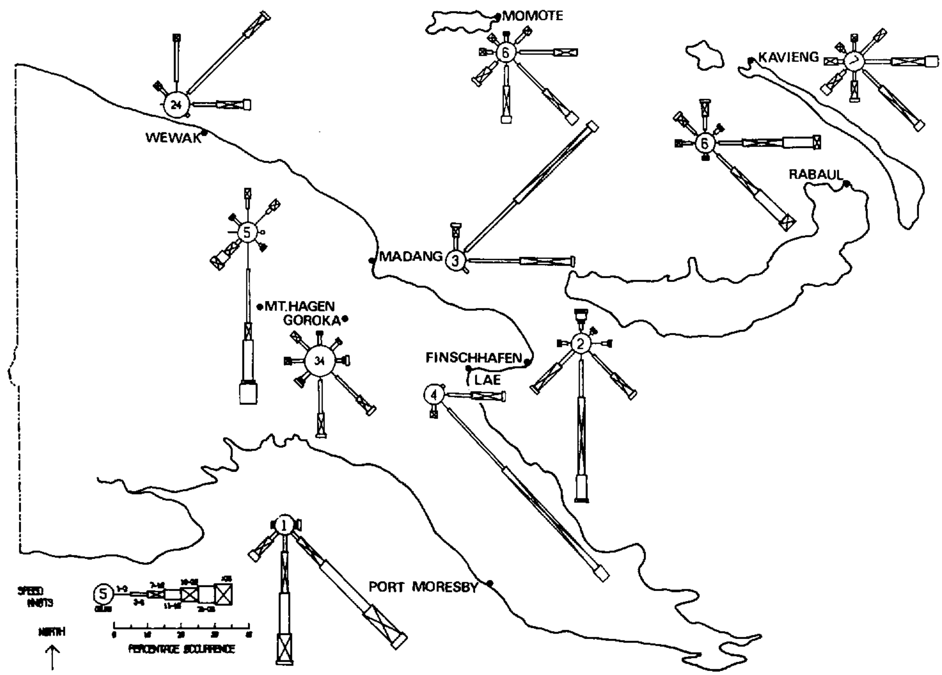


Fig. 3.12d—October

are dominant throughout the year. The morning land breeze is replaced by an afternoon sea breeze, the north-westerly component of the land breeze being reinforced during the north-west season. Well-developed local circulation systems are also evident throughout the year at Lae, owing to its location at the mouth of the NW-SE oriented Markham Valley. A combination of morning katabatic, land and mountain winds from the north-west gives way later in the day to combined anabatic, sea and valley winds from the south-east. These local effects are reinforced by the seasonal broad-scale flow, which considerably strengthens the morning north-west winds of January.

In the central highlands, mountain and valley wind systems create the observed surface flow patterns. These are generally unique to any particular location, so that the examples discussed here cannot be taken as representative of other parts of the highlands. At Goroka, surface winds are light in the morning throughout the year and only strengthen slightly during the day, the only marked directional bias being a strengthening of the south-easterly component in the afternoons during the height of the south-east season. At Mt Hagen, valley and anabatic winds flowing from the south and increasing in strength during the day dominate the situation throughout the year.

Variation in surface wind speed

Surface wind speeds vary almost continuously, both in period and in amplitude, and for this reason *mean wind speed* is recorded as the average surface wind speed over a ten-minute period. Momentary increases in mean wind speed due to turbulence in the surface flow are termed *gusts*. These should be distinguished from *squalls*, which are strong winds, lasting from some minutes, that commence and cease suddenly. Gale-force winds with sustained speeds of greater than 34 kt (62 km/h) are associated with *cyclones*.

The following sections will deal with the mean wind speeds that are recorded in PNG and the different types of variation in surface wind speed that can occur in this region.

Mean wind speed. Mean wind speeds recorded at the ten instrumented stations in PNG (see Figs. 3.11, 3.12) are generally less than 10 kt (20 km/h) at both 0900 and 1500 hr. At the eight coastal locations they range from 1-3 kt (2-6 km/h) at 0900 hr in January, strengthening to an average of 3-4 kt (6-7 km/h) by 1500 hr. Mean wind speeds at those stations where the north-westerly flow is most significant (i.e. Kavieng, Momote and Rabaul) are similar to those at locations where local circulations have a more dominant role. However, maximum mean wind speeds can reach 26 kt (49 km/h) at Wewak and the three island stations, but only 20 kt (38 km/h) at Lae and Finschhafen, while at Madang the maximum mean wind speed does not exceed 15 kt (28 km/h) at 1500 hr. North-westerly wind squalls in the Port Moresby region in January can cause maximum mean wind speeds at 1500 hr of over 27 kt (50 km/h).

At the height of the south-east season in July, mean wind speeds at 0900 hr range from 1-3 kt (2-6 km/h) at coastal stations. By 1500 hr wind speeds reach an average of 2-5 kt (4-9 km/h) on the coast, with the exception of Port Moresby and the Papuan coastal region where the strong south-east trade flow raises the mean wind speed to 7 kt (12 km/h). Maximum mean wind speeds are generally less than in January, not reaching more than 20 kt (38 km/h) at 1500 hr on the coast except at Rabaul and Port Moresby, where the flow can exceed 27 kt (50 km/h).

In the highlands, instrumented data are available for only two stations, Goroka and Mt Hagen. At Goroka winds are light throughout the year, increasing from about 0.2 kt (0.4 km/h) in the morning to an average of around 2 kt (4 km/h) in the afternoon. However, maximum mean wind speeds can reach 26 kt (49 km/h) at Goroka on July afternoons. The mountain/valley winds at Mt Hagen increase from about 1 kt (2 km/h) at 0900 hr to an average of 3 kt (6 km/h) at 1500 hr throughout the year, although under certain conditions maximum mean wind speeds can exceed 27 kt (50 km/h) in the afternoon.

Squalls. The rapid and irregular fluctuations, or gustiness, of surface winds in the PNG region cannot be described quantitatively by means of the available climatic data. However, the records do provide an indication of the frequency and intensity of squalls in PNG. These winds of considerable intensity, which begin and cease quickly and are sometimes accompanied by thunder, lightning and precipitation, are a common feature of equatorial weather. Many squalls are associated with synoptic disturbances or individual thunderstorms but others are more local in origin. The squall effects are produced by descending cold air. Thus they may arise from land breezes and mountain winds rather than from sea breezes or valley winds. They are also generated locally by intense convective cells. Where land breezes or mountain winds are reinforced by the seasonal (broad-scale) wind or where they can reinforce each other (such as where the contour rises steeply from the coast), the force of these squalls can be rendered unusually strong.

Localised squalls due to combinations of katabatic, physiographic or temperature effects and the seasonal (broad-scale) wind occur throughout PNG and often become so well known in a particular locality as to earn a distinctive title. An example is the 'Guba', a type of squall which occurs in the Papuan Gulf area, from the vicinity of Kikori/Kerema to Hood Point, usually in the north-west season with isolated cases during the transition periods of the year if the wind circulation is from the north-west. Gubas mostly occur between about midnight and dawn but are sometimes observed during the day. They are preceded by a calm which is broken suddenly by a squall from the west or north-west, sometimes reaching 50-70 kt (90-130 km/h), with strong winds lasting for about 30 minutes. One extreme gust recorded on an oil search rig off Kerema reached 93 kt (172 km/h). A rapidly moving roll or arch of cloud accompanies the initial squall and the sky then soon becomes overcast with thick cloud. Heavy rain frequently, but not always, accompanies the squall. Gubas occur about five times a year at Port Moresby.

Cyclones. The frequency of tropical cyclones, with sustained surface winds of greater than 34 kt (62 km/h), is very low in the PNG region. The reader is referred to Chapter 2 for a more detailed discussion of this subject.

Annual variation in mean surface wind run

Total wind run per day has been recorded at only five locations in PNG, for periods of between two and five years in length, and Fig. 3.13 presents plots of mean monthly wind run per day at these five stations. The figure clearly illustrates the greater force of the winds at Lae compared with those at the other coastal and highland stations. From November to March mean wind run at Lae exceeds 200 km/day—the result of enhancement by the seasonal flow of the katabatic, land and mountain winds flowing from the north-west in the mornings (see Fig. 3.11a). At the other three coastal stations, daily wind run reaches a peak of around 150 km in July-September, and falls to its lowest level of about 75 km in April-June. Well-developed local land/sea breeze cells at Madang probably cause the annual cycle of mean wind run to show less seasonal variation than at Rabaul and Port Moresby. The highland station, Kuk (1630 m, near Mt Hagen), shows little or no seasonal variation in wind run, as local effects are dominant throughout the year. However, the winds are less strong than on the coast, ranging from only 55 to 87 km/day during the course of the year.

Daily cycle of surface winds

Three-hourly observations of wind speed and direction are available only for the six major airfields in PNG. Two examples will be taken to illustrate the differences that are observed in the daily cycle of surface winds at locations where the broadscale flow is (i) unobstructed, and (ii) almost entirely masked by local effects.

The situation at Rabaul (Fig. 3.14) is typical of a location where there is only a slight physiographic barrier to either the north-west or south-east seasonal flows. At the height of the north-west season in January, there is little wind in the very early morning (0300-0600 hr), with light to moderate north-westerlies of up to 15 kt (28 km/h) being recorded on only 10 per cent of days. After sunrise (about 0550 hr) the north-west wind strengthens markedly, and shows a continued increase in velocity from 0900 to 1500 hr when light to fresh west to north-west winds of up to 20 kt (38 km/h) occur on 70 per cent of days. Thereafter velocities decrease slightly by 1800 hr. Following sunset at approximately 1810 hr there is a

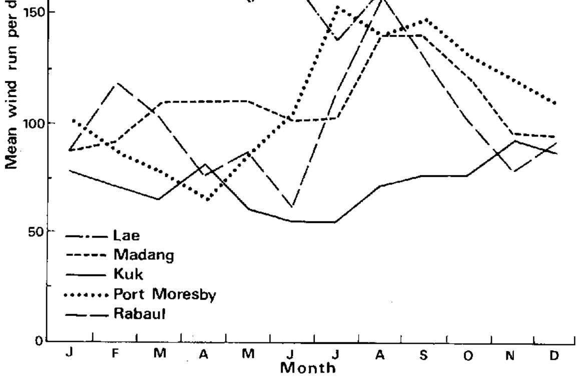


Fig. 3.13
Mean monthly wind run per day. A comparison of mean monthly wind run per day at five locations indicates the average coastal situation (Madang, Port Moresby, Rabaul), the lower highland values (Kuk) and the values attained at particular stations subject to strong local effects (Lae).

Fig. 3.14
Seasonal variation in daily cycle of surface wind flow—Rabaul. Mean three-hourly observations of wind speed and direction for January, April, July and October at a location where the broad-scale flow is relatively unimpeded show the strengthening of the seasonal winds during daylight hours.

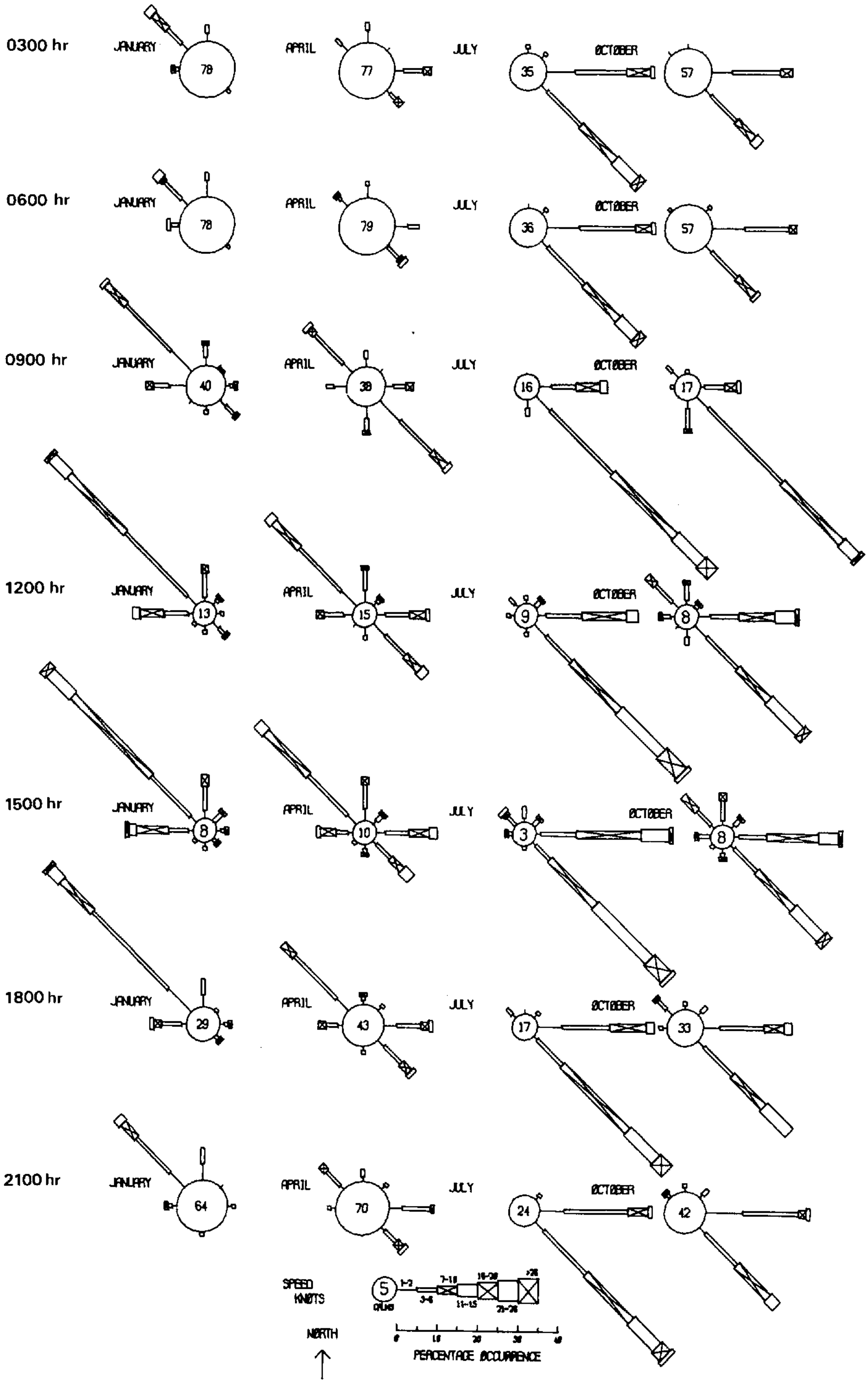
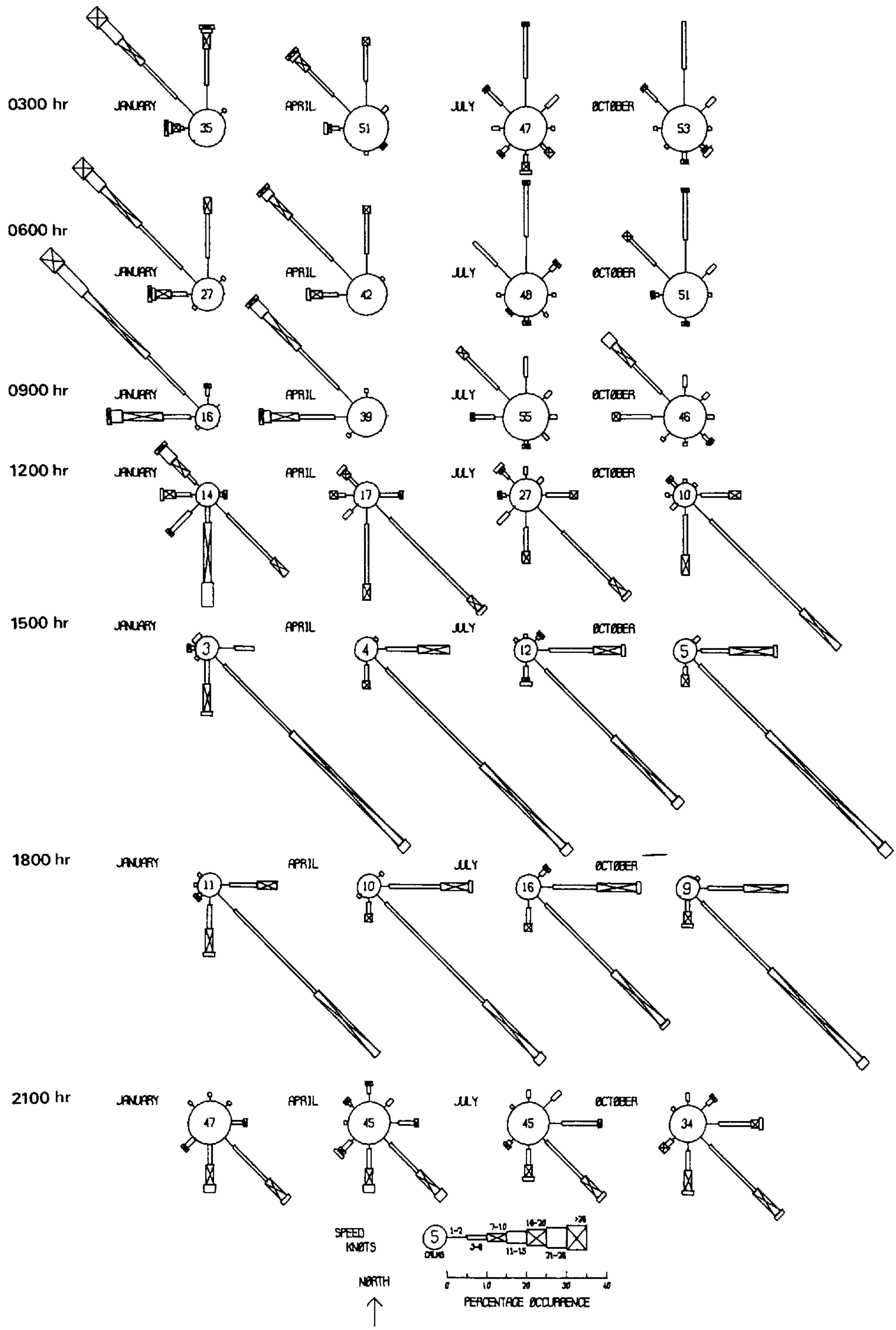


Fig. 3.15
Seasonal variation in daily cycle of surface wind flow—Lae. Mean three-hourly observations of wind speed and direction for January, April, July and October at a location where local effects largely mask the broad-scale flow show pronounced diurnal but little seasonal variation.



considerable drop in wind velocity (2100 hr) which continues throughout the night. During the transition month of April the north-westerly component is not as pronounced as in January and a slight easterly to south-easterly component becomes apparent. This is greatest at 0900 hr when light to fresh east to south-east winds of up to 16 kt (28 km/h) are recorded on 30 per cent of days. At the height of the south-east season in July, light to fresh east to south-east surface winds are observed at all times between 0300 and 2100 hr, the velocity increasing to a maximum of up to 20 kt (38 km/h) during the daylight hours (approximately 0600-1800 hr). A similar situation is evident in October, although the south-east trade flow is slightly weaker than in July.

Figure 3.15 shows the daily cycle of surface winds at Lae, where local effects to a large extent overshadow the broad-scale flow patterns. Light to fresh north-west winds of up to 20 kt (38 km/h) occur on 35 per cent of mornings in January (0300-0900 hr). These winds are probably caused largely by katabatic, land and mountain breeze effects, as there is a considerable diminution in their velocity and frequency between 0900 and 1500 hr when only 1 per cent of winds are north-westerlies and 78 per cent are east to south-easterlies of up to 15kt (28 km/h). The daily cycle at Lae remains virtually constant throughout the year, except that it is noticeably modified by the broad-scale circulation in the early morning hours (0300-0900 hr) during January and April, when the north-westerly components are stronger than during July and October.

While no three-hourly wind data are available for the highland regions, a comparison made by Budd (pers. comm.) of hourly mean wind speeds at Kaul (Karkar Island) and Lufa (2040 m, near Goroka) indicates that winds at the highland location are lower in speed than those on Karkar Island throughout the daylight hours.

4 Rainfall

Papua New Guinea is one of the wettest regions of the earth. Over most of its surface mean annual rainfall lies between 2000 and 4000 mm and is most reliable. No rainfall station record has a mean of less than 950 mm and areas having annual falls lower than 1500 mm are quite small and isolated. The national capital, Port Moresby, lies in the driest part of the country. In contrast, significant areas have mean annual falls above 4000 mm, and the highest mean annual point precipitation reaches nearly 10 000 mm. Most rainfall regimes exhibit some seasonality in their monthly distributions, although the variation is not so much between dry and wet as between wet and very wet.

Such consistently high rainfall patterns directly or indirectly control much of Papua New Guinea's physical form, its biological resources and human activities. Heavy rainfall regimes are reflected physiographically in the dense stream and river network that dissects much of the country and in the occurrence of many large seasonally flooded plains such as those that abut the Sepik, Fly and Ramu rivers. In terms of human activities such physical features and rainfall patterns determine, at subsistence level, the type of land use that can be adopted in an area and, at the cash economy level, may on the one hand cause difficulties and high costs in transport development while on the other provide a source of considerable hydro-electric potential.

The development and characteristics of the rain gauge network used to measure the amount and distribution of precipitation in PNG have been referred to in Chapter 1. The basic tables which have been produced to summarise these data have been published elsewhere (McAlpine *et al.* 1975) The analyses contained within these tables are based on all available years of record and, as well, on a 15-year (1956-70) standard period for a selection of stations. These latter tables were used as the basic data set for inter-station comparison and map construction in the present chapter. The period 1956-70 was the longest available span of years with the widest geographical coverage.

Previous rainfall studies

Because of the importance of rainfall as a determinant of so many other physical, biological and human distributions, processes and activities, it is the climatic element which has received most attention in the limited literature dealing with the climatology of PNG. References extend back to the early German and British colonial periods, such as those found in *Mitteilungen aus den deutschen Schutzgebieten* 1888-1932 (Vols. 1-30), and in the *Annual Reports of the Territory of Papua.*

Before World War II, references to rainfall were restricted to tabulations or broad descriptions and even broader comment on the associations of climate with other phenomena.

The Australian Bureau of Meteorology presented data and commentary relating to the pre-war rain gauge network (Challis 1939; Bureau of Meteorology 1940) and in 1940 published an annual isohyetal map (see Fig. 4.1). The network at this time did not cover the highlands and only very little of the inland lowlands.

These data were used extensively during the war in the Pacific in various wartime operational intelligence publications (for example, Royal Australian Air Force 1943). Following the conclusion of hostilities, the first general climatic summary of PNG was presented in a publication on the resources of the Territory of Papua and New Guinea prepared by the Department of National Development, Canberra (Hounam 1951). The map included in that publication was still based largely on pre-war data.

The war itself resulted in a collapse of the rainfall recording network and it was not until 1964 that a sufficient body of new data, particularly relating to the inland and highlands areas, had accumulated to allow Brookfield and Hart (1966) of the Australian National University (ANU) and Fitzpatrick *et al.* (1966) to publish the first spatially comprehensive analysis of rainfall in the south-west Pacific, including PNG. These 1966 publications were particularly important in two respects: they provided the first classification and regionalisation of rainfall regimes in PNG and also presented the first useful discussion of the interaction of physiography and local circulations in determining rainfall patterns. Subsequently Chang (1968) reviewed this earlier work and provided further discussion of the relation between rainfall and circulation patterns.

Concurrently with the ANU work and continuing after it, the Commonwealth Scientific and Industrial Research Organization (CSIRO) conducted a number of regional resource inventories, each covering about 4000 square miles, which included rainfall studies of successively greater detail as more data became

Fig. 4.1
Annual rainfall isohyets for PNG as published by Bureau of Meteorology (1940)

available (for example, Slatyer 1964; Fitzpatrick 1965; McAlpine 1970, 1973; Short 1976).

Both the ANU and CSIRO work were interlinked and were concerned with the establishment of a climatological framework for other studies. A limited number of other workers have studied rainfall at an applied level, for instance in relation to crop yields (for example, Bridgland 1953; Sumbak 1970a,b) and in relation to water quality and nutrient cycling in rainforest (Turvey 1975). However, by far the greatest recent effort in rainfall analysis has resulted from engineering investigations, particularly in relation to the provision of flood frequency information for civil works and land reclamation and to hydro-electric potential and design. Most of this work has been carried out by consultants, especially the Snowy Mountains Engineering Corporation (SMEC), and is only rarely formally published (for example, Aitken *et al.* 1972; Shaw 1972). While they are not confidential, the reports covering these investigations have been produced only in small numbers and hence are not readily available. A useful summary and set of references covering these reports are provided by the Bureau of Water Resources (1974). The results of the two main studies are in SMEC reports dated 1970 and 1973.

The discussion of rainfall which follows is based on a new analysis of the available data, and in some places varies in quantitative material and in conclusions from those given in the consultants' reports. This results partly from the differing data sets which have been used, but primarily because the requirements for general purpose climatic analyses differ from those for the more restricted engineering applications.

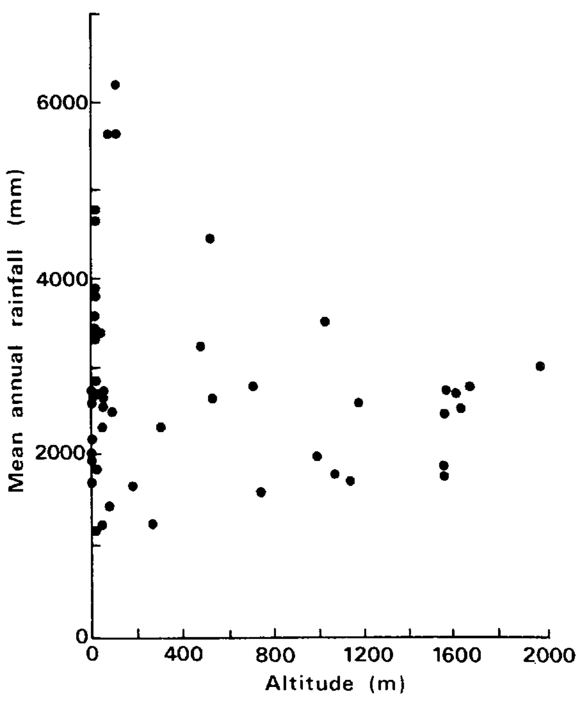


Fig. 4.2
Relationship of mean annual rainfall to altitude in PNG. Taken on a countrywide basis, there is no apparent relationship between annual rainfall and altitude.

Rainfall distribution

The interplay of general and local circulations and synoptic disturbances with the altitude and alignment of physiography combines to produce a large number of possible rainfall regimes. These are evidenced in the recorded rainfall data. It is clear that, while the major rainfall-producing controls can be discussed individually, explanations of how they interact to produce each particular regime cannot be assessed, given the present stage of climatological knowledge in PNG, except by way of exemplary material for some locations and regions. The problem of assessing the role of any particular control over the whole of the country can best be illustrated by example. The relationship of mean annual rainfall to altitude is shown in Fig. 4.2, from which it is apparent that, apart from the range of values in the coastal and lowland regions being greater than in the highlands, there is little relationship with elevation over the country as a whole. However, Fig. 4.3 illustrates that in particular areas a clear altitudinal relationship can exist, as in the case of the strong rainfall gradient running from Port Moresby into the nearby mountains.

Barry (1978a) indicates that, in the mountainous upper Chimbu Valley, the relation between rainfall and altitude is seasonal, with an increase in precipitation with altitude during the wet season but no apparent relation during the dry season. McAlpine (1970) contends that the relation of rainfall to altitude in highland areas is a direct consequence of the relative physiographic situation. Stations toward the centre of the major basins and valleys tend to receive less rain than those on the surrounding hills, partly as a result of the diurnal circulation of wind and cloud which was described in the previous chapter.

The following discussion concentrates on establishing the broad spatial distribution and statistical description of rainfall. Where possible, explanations for the patterns so described are offered but for the most part, given the lack of a close network of data, these must remain tentative, especially at the local level.

Annual rainfall and seasonality

The distribution of mean annual rainfall over PNG is shown in Fig. 4.4. This map has been constructed using all available data, but heavily weighting the 15-year standard period data. In contrast to previously published maps, it has also been

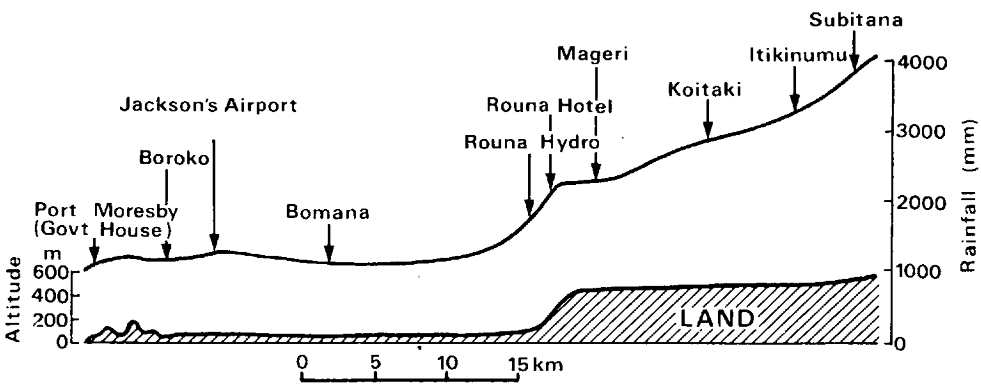


Fig. 4.3
Relationship of mean annual rainfall to altitude in the Port Moresby region. At local scale and within the same local circulation framework clear relationships exist between rainfall amount and altitude.

possible to extrapolate the isohyets in ungauged regions, especially in drier areas, by reference to Paijmans' (1975) vegetation map of PNG. Drier regions are associated with unique vegetation types which can be clearly distinguished and mapped using air photographs. For this reason it is likely that all larger occurrences of low rainfall areas have been identified. Conversely, very high rainfall areas (that is having greater than 4000 mm per annum) are not normally distinguishable in terms of vegetation from those with falls ranging from 2000 to 4000 mm annually and, in addition, being lightly populated, they are likely to have few if any rain gauges. As a result the occurrence and full extent of very high rainfall areas may not yet be fully indicated.

The seasonal distribution of rainfall is shown in Fig. 4.5, which updates Brookfield and Hart's (1966) earlier maps by weighting for the 15-year standard period, and by the use of more recently available data especially in those areas where rainfall gauges have been installed since 1964 (the date at which Brookfield and Hart's data terminate), and again by reference to Paijmans' map. The mean monthly distribution for a selection of stations is given in Fig. 4.6 and the associated statistic of number of rainy days per month is given in Fig. 4.7.

As can be seen from the maps, most of PNG lies between the 2000 and 3500 mm annual rainfall isohyets and by far the greater part of the country has a seasonal rainfall pattern with the maximum occurring during January to April, commonly referred to as the 'north-west' season, and with the minimum during May to August, the 'south-east' season. Mean monthly rainfall lies between 250 and 300 mm in January, falling to around 100-150 mm in July.

The wetter parts of the country with mean annual rainfalls above 3500 mm tend to be associated with those areas which experience a reversed seasonality,

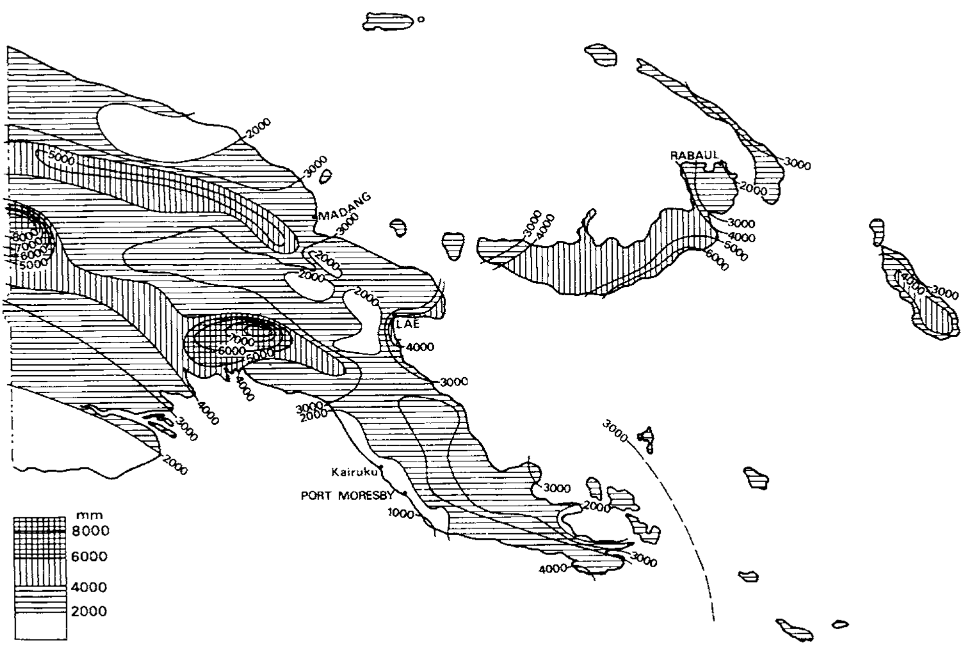


Fig. 4.4
Mean annual rainfall over PNG. The bulk of the country lies in the 2000-4000mm rainfall zone, with the wettest areas being associated with major topographic barriers to surface flow.

with rainfall maxima occurring between May and August. These are areas which have backing mountain ranges aligned directly north-east/south-west (that is, across the prevailing south-east trade winds), as found on the south-eastern coast of New Britain, around the Huon Gulf and the eastern tip of Papua and Bougainville (see Fig. 4.8). A further occurrence of 'reversed' seasonality occurs near Kerema-Kikori, possibly caused by surface wind veering to produce a similar effect to that of a cross-wind alignment of physiography. In these areas having south-east season rainfall maxima, mean annual falls range up to 6000 mm in New Britain and rise further to 9000 mm inland from Kikori. For the most part these regions experience mean monthly falls in January of around 250 mm, a figure comparable with that for the 'wetter' part of the year elsewhere. In July, however, falls rise on average to approximately 500 mm with mean falls at some stations rising to 1200 mm per month.

The only known occurrence of similarly high rainfall in areas subject to north-west season maxima is in the narrow belt lying along the northern fall of the central range from Aiome, and possibly running as far as or beyond the border with Irian Jaya. The cause here is again probably orographic alignment and height in relation to the direction of north-west season air masses. Mean monthly falls in this area range from 650 mm in January to 300 mm in July.

Fig. 4.5
Seasonal rainfall patterns. The alternation of areas having rainfall maxima at different stages of the year (January and July mean monthly rainfall) is clearly shown, as are the areas where seasonal variation is minimal.

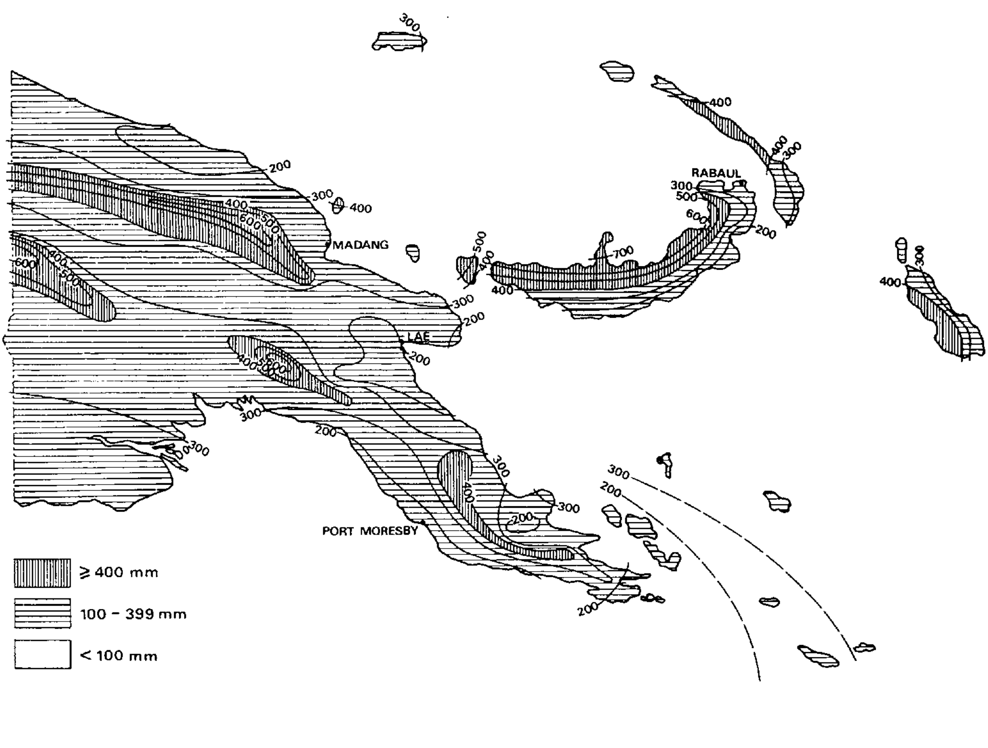


Fig. 4.5a—January

In contrast with these significantly large wetter areas, the drier regions of PNG are of considerably less extent and occur in relatively restricted and localised pockets. They consist of a narrow coastal strip in the central Papuan region approximately centred around Port Moresby and a small section of the Markham valley where annual precipitation rates drop to 1000 mm and 1200 mm respectively. Other relatively drier pockets of lower rainfall occur in the Wau-Bulolo-Menyamya area (1500-1700 mm), around Safia on the Musa River (1600 mm) and at Dogura in eastern Papua (1500 mm). Mean monthly falls average

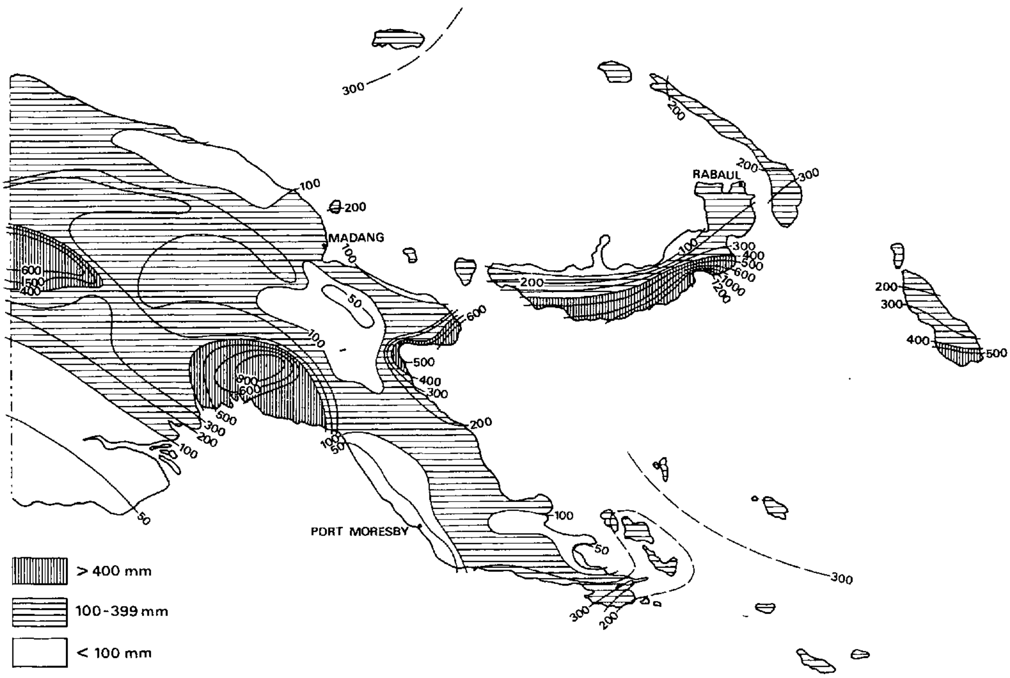


Fig. 4.5b—July

approximately 200 mm in January, falling to 80 mm or less in July in these areas. In total the drier regions occupy less than 1 per cent of the land surface and are generally explicable in terms of orographic barriers and/or deflected surface flows giving rise to rain shadow type effects.

Four other areas have somewhat lower annual rainfall, although they could not be described as dry. These are the Goroka-Kainantu area of the Eastern Highlands Province (1800-1900 mm), the northern tip of New Britain around Rabaul (2000 mm), the Maprik-Angoram area of the western Sepik (1700-1900 mm) and the south-west coast of Papua between Daru and the Morehead River (1900-2000 mm). Each of these areas is drier as a result of lower than average dry season rainfall in absolute terms. In the wet season they receive similar amounts of precipitation to other areas having north-west season maxima. It is probably significant that, with the exception of the Daru-Morehead region where the soils are poor, each of these areas is associated with much higher than average population densities.

Finally, as indicated in Figs. 4.4 and 4.5, there occur a number of isolated areas with annual rainfalls lying in the 2000-4000 mm class but which show little or no seasonality, having rainfall more or less evenly distributed throughout the year. These are also shown in Fig. 4.8 and, except for the area around Wewak, tend to have somewhat higher than average precipitation rates of around 3000 mm annually.

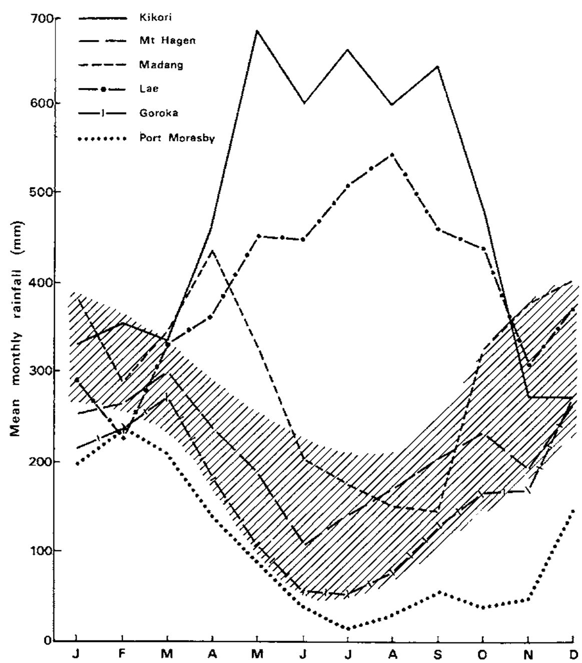


Fig. 4.6
Mean monthly distribution of rainfall for selected stations for standard period (1956-1970). The graphs show the driest and wettest regimes and the hachured area indicates the regime range which occurs most commonly for stations having north-west season rainfall maxima.

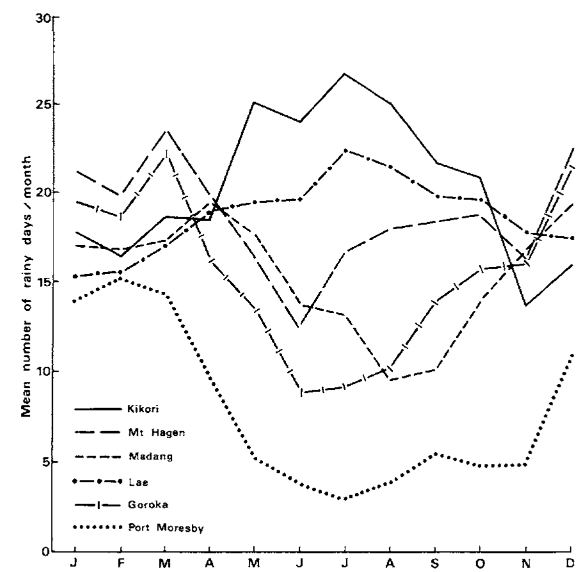


Fig. 4.7
Mean number of rainy days (>1mm) per month for selected stations for standard period (1956-1970). This graph extends the information provided in Fig. 4.6 and illustrates the rainy nature of the major portion of PNG.

The maps in Figs. 4.4 and 4.5 reveal that the sharpest rainfall gradients are those around 2000 mm and 3500 mm and these are closely associated with physiographic barriers. Conversely, however, not all sharp physiographic gradients result in sharp rainfall gradients. Additionally, the isohyetal patterns presented probably disguise a degree of local variability. Thus, in the Woitape-Tapini area north of Port Moresby, data from a relatively dense network of rain gauges in mountainous country which might be considered fairly uniform in physiography reveal variations from 2000 to 3000 mm over quite short distances (see Fig. 4.9).

An impression of the seasonal variation in rainfall can be gained from the various maps so far presented, but the degree of seasonality is actually a reflection of the difference between the wettest and driest periods of the year. There are many methods of indicating seasonal variation. For the purpose of this discussion, the difference between the highest and lowest mean monthly rainfall has been calculated for each station and this has been standardised by dividing by the mean annual rainfall. The resulting 'seasonality index' has been mapped in Fig. 4.10, with more weight being placed on the standard period stations than on the remainder. Another analysis in which the sum of the mean monthly rainfalls for the three consecutive wettest months was divided by the sum for the three consecutive driest months for each station was also carried out, and the resulting pattern was similar to that shown in Fig. 4.10. The map indicates that generally the greatest rainfall seasonality tends to be associated with drier areas, or those with south-east season rainfall maxima, although there are significant exceptions. In the southern portion of the central highlands a large block of country

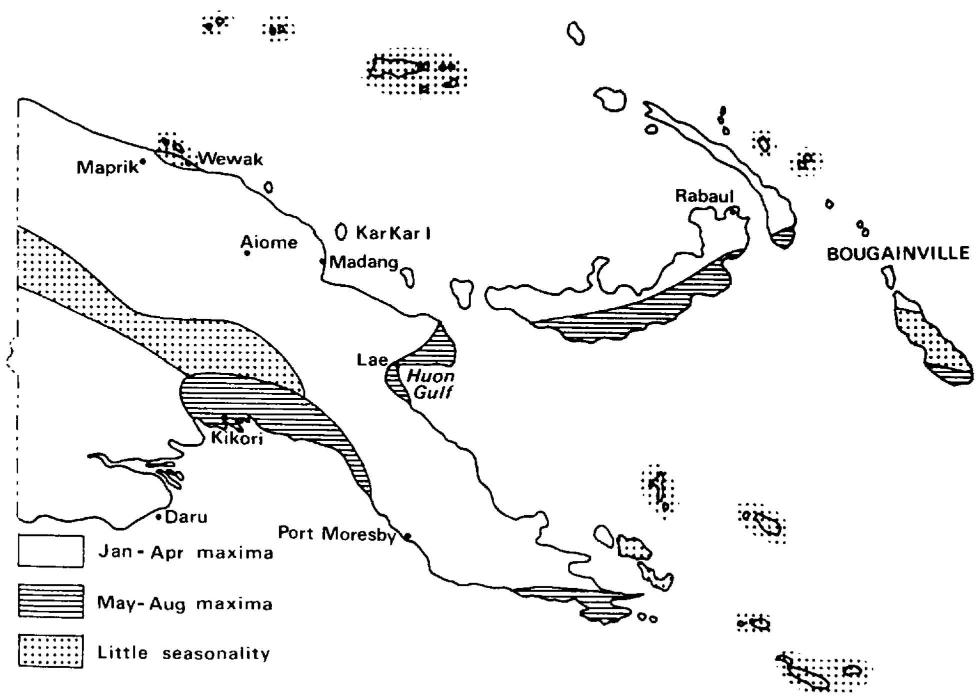


Fig. 4.8
Time of occurrence of maximum monthly rainfall.

has high rainfall but low seasonality and on the north-west coast of New Britain high seasonality occurs in an area having north-west season rainfall maxima.

Fitzpatrick *et al.* (1966) investigated rainfall seasonality in the PNG region using harmonic analysis and constructed maps of the time of occurrence of highest and lowest mean weekly rainfall and of the amounts involved. They arrived at a classification of rainfall regime types derived on the basis of seasonal

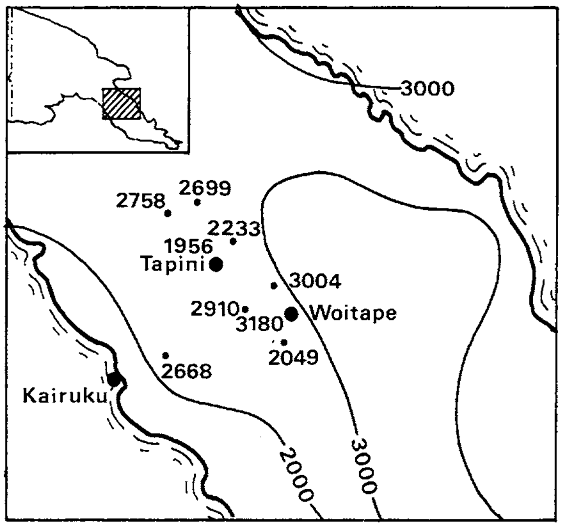


Fig. 4.9
Annual rainfall in the Woitape-Tapini area. As a result of the mountainous terrain, it is quite possible for stations in close proximity to experience significant differences in annual rainfall. Thus Figs. 4.4 and 4.5 should be read with some caution. Isohyets as in Fig. 4.4.

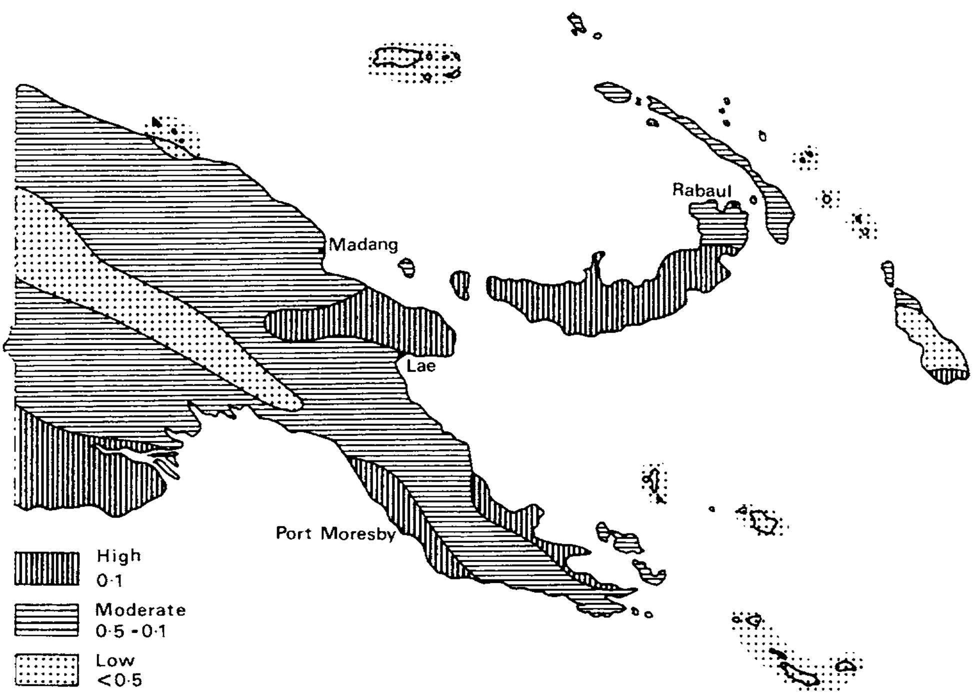


Fig. 4.10
Distribution of the index of seasonality. The seasonality index (the lowest mean monthly rainfall subtracted from the highest and divided by the annual) is generally highest in drier areas and those subject to south-east season rainfall maxima.

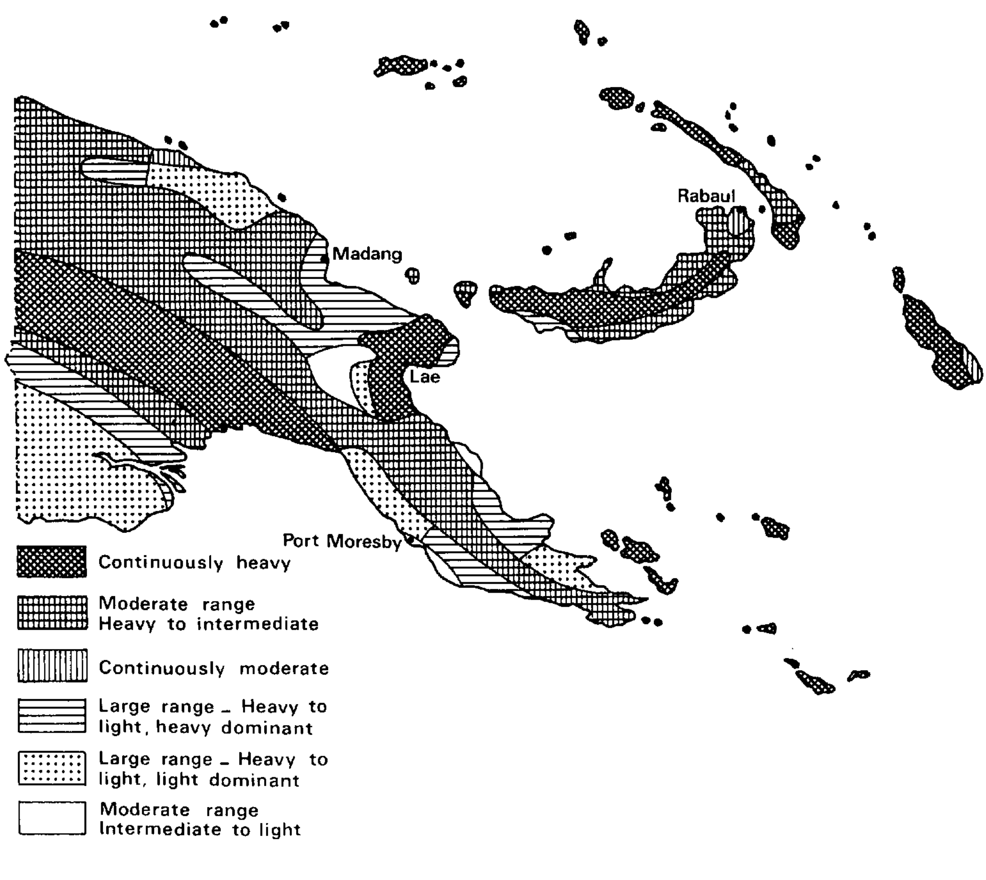
Rainfall variability

A totally reliable assessment of year to year rainfall variability in PNG, given the short lengths of record available for inter-station comparison, is impossible at the present time. Fortunately, however, an analysis of data from those few stations with long record lengths indicates that variability in PNG appears to be low, and hence it is possible to indicate broadly the likely picture of temporal variation using relatively short record lengths.

Overall it appears that PNG possesses a remarkably reliable rainfall. One measure of this can be illustrated by mapping the coefficient of variation of annual rainfall for the 15-year standard period (see Fig. 4.12). This coefficient expresses the standard deviation of annual rainfall as a percentage of the mean. The map shows that virtually the whole of the country has coefficients of less than 20 per cent and that there is a clear regional pattern in their distribution. The central highlands and Sepik plains have very low variability of less than 15 per cent, while most other island, coastal and lowland areas do not exceed 20 per cent. The only exceptions are the somewhat higher values experienced in south-east New Britain and around Daru, Samarai and the eastern Papuan islands.

Variation in annual rainfall for a selection of stations is expressed as percentile ranges in Fig. 4.13. It can be seen for each station that in 50 per cent of years (the

Fig. 4.11
Geographical distribution of six distinctive rainfall regime types (from Fitzpatrick *et al.* 1966)



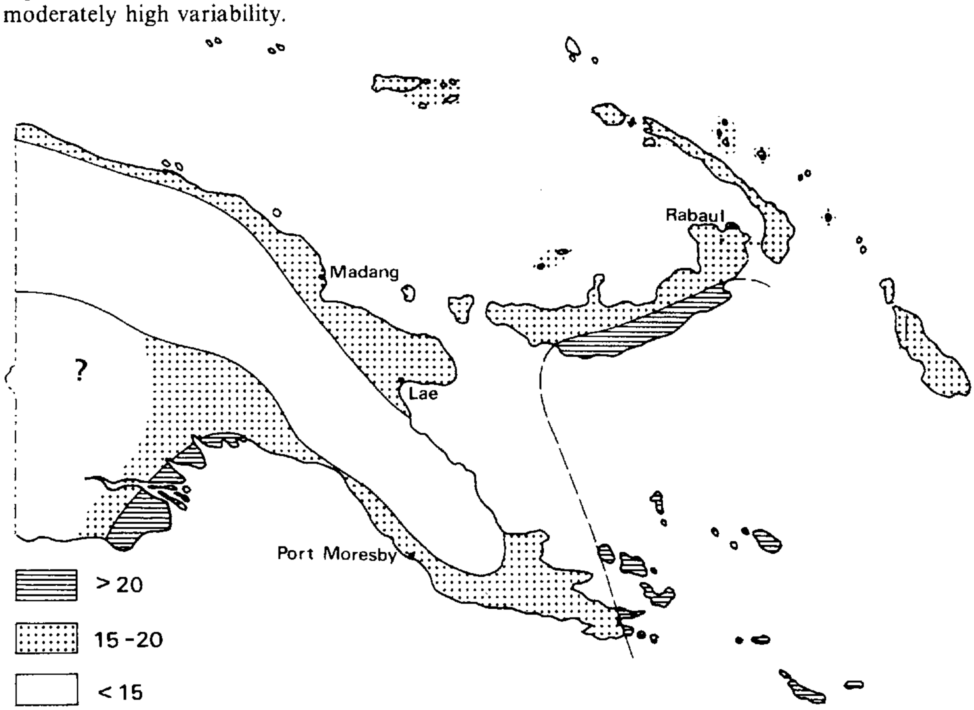
range and persistence. Although their maps do not indicate seasonal differences directly, they are in broad accord with Figs. 4.8 and 4.10. The map by Fitzpatrick *et al.* of distinctive rainfall regime types is re-presented in Fig. 4.11.
inter-quartile range) the variability is small and it is only somewhat larger in 90 per cent of years.

Monthly distributions are skewed and hence are best compared on an actual value basis. Consequently the inter-quartile range of monthly distributions has been calculated for all stations covering the 15-year standard period and these have been compared. A representative selection of inter-quartile ranges has been plotted in Fig. 4.14.

A number of broad generalisations can be made from this comparison. First, monthly falls in the wet season show less variation than those in the dry season irrespective of location; second, the contrast between seasons in rainfall variability tends to be less for stations with south-east season rainfall maxima than for those with north-west season maxima; third, drier stations (for example Port Moresby) tend to have more variable monthly rainfall in both wet and dry seasons than do wetter stations; and, fourth, in the central highlands monthly rainfall variability is greater in the dry season in the east than in the west. However, these generalisations are based on only a short standard period and the number of stations considered is small, with considerable interstation variation.

Records are too short to permit analysis of long-term rainfall fluctuations and trends, especially for the country as a whole. Magari (1980) has analysed the trend at Port Moresby from 1945 to 1976 and concludes that precipitation during the wet season could be increasing.

Fig. 4.12
Coefficient of variation of annual rainfall. The variability of annual rainfall is lowest in the highlands and only slightly higher in most lowland and coastal regions. Only small areas have moderately high variability.



The degree to which closely adjacent and more distant stations experience similar rainfall patterns through time has also been investigated. Actual monthly and annual rainfalls for similar spans of years were correlated for six stations in the Aiyura-Goroka area, three stations at Madang and Saidor, four stations in the Port Moresby-Sogeri area, and for three locations at Wau. Monthly and annual values for six stations spanning the country were also correlated to test variability at the national scale. The correlations were calculated using untransformed rainfall values, and also using the logarithms and square roots of the values, as these transformations were expected to provide more nearly normal distributions. Results were similar in all three cases. Correlations based on the logarithmic transformations are presented in Figs. 4.15 and 4.16, from which it can be seen that there were significant correlations in only one of the test areas, that around Aiyura-Goroka, where the correlations of monthly values were more significant in January, during the north-west season when monthly rainfalls are highest, than in July (Fig. 4.16).

Fig. 4.13
Percentile ranges of annual rainfall for a selection of stations

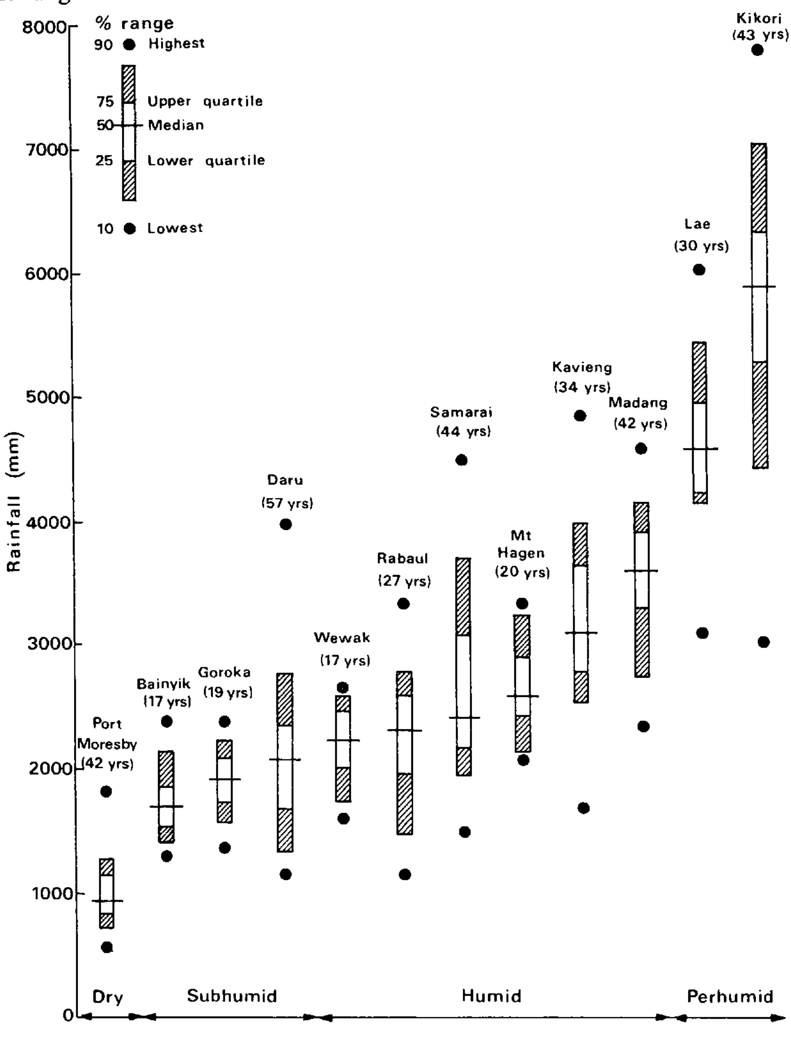
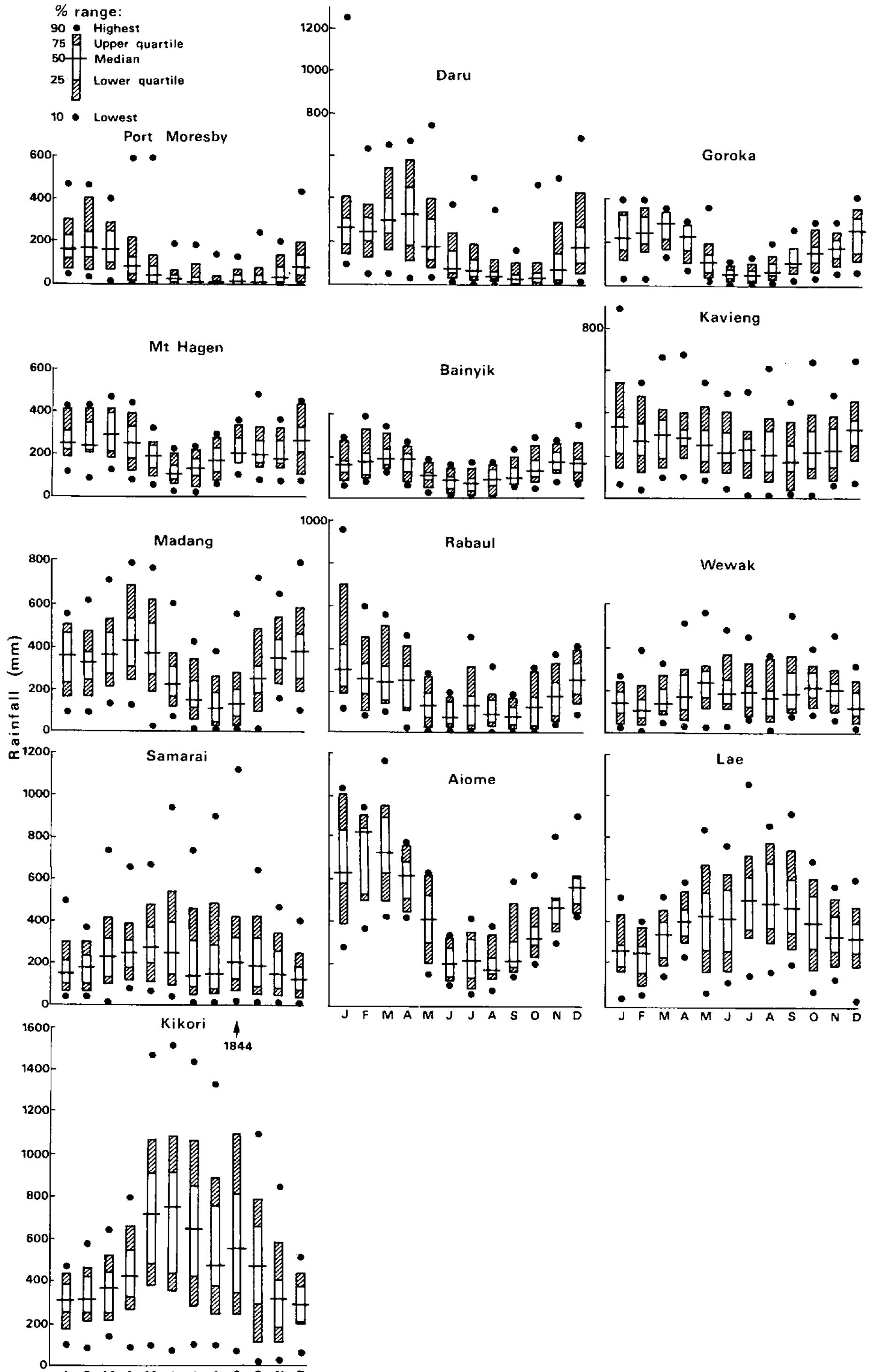


Fig. 4.14
Monthly rainfall variability expressed as percentile ranges for a selection of stations



Generally, the greater the distance between stations, the lower was the correlation between them, except where a group of stations were all subject to the same local circulation patterns, as in the case of the Port Moresby-Sogeri region (Fig. 4.16a). At the national scale little or no correlation was found between either the monthly or the annual rainfalls for the six stations (Fig. 4.15).

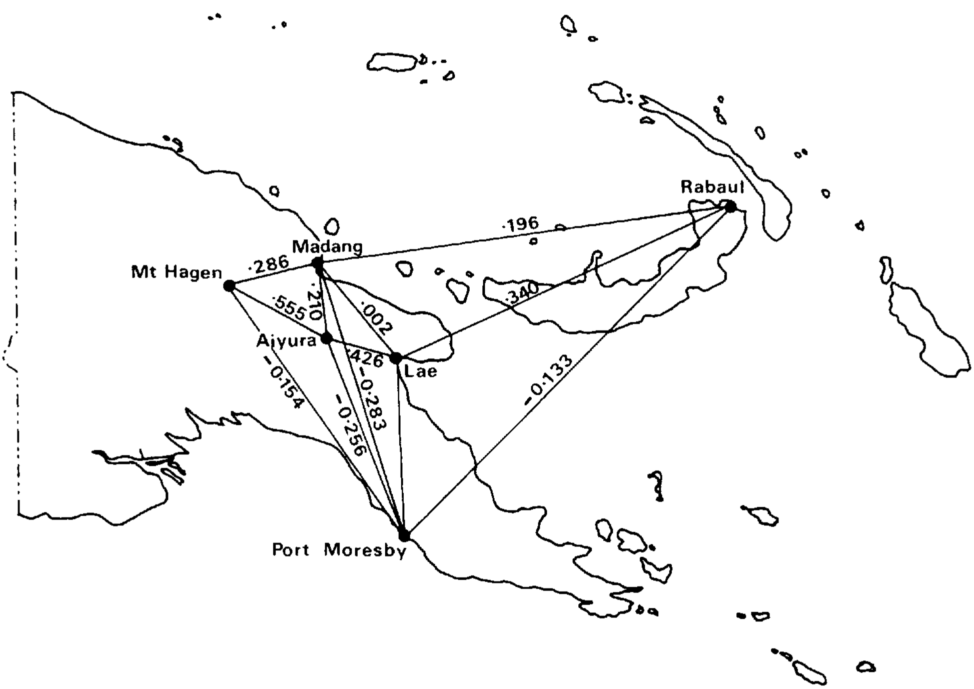
Rainfall intensity

Rainfall intensity usually refers to a rate of rainfall per unit time and it is of vital importance in flood frequency and erosion studies. Measures of intensity based on annual or monthly falls are meaningful at a global scale but in general merely distinguish between high and low rainfall areas at a national scale.

To determine rainfall intensity patterns and rates, an analysis of daily rain gauge and pluviometer data is necessary. Such a study was carried out (SMEC 1973) in the context of an investigation into flood estimation procedures. Although the results of the study are more directly relevant to engineering practice than climatic analysis, appropriate parts have been used to supplement the present treatment.

As a first step, a daily rainfall frequency analysis has been made for the stations in the rain gauge network covering the 15-year standard period and this, supplemented by a similar analysis for a number of other stations, is presented elsewhere (McAlpine *et al.* 1975). From these analyses the probabilities of daily rainfalls exceeding 50 mm per day are presented for typical stations in Fig. 4.17.

Fig. 4.15
Inter-station correlations of logarithms of annual rainfall values for selected groups of stations for a standard period (1951-1970). Little or no correlation is evident at the national scale. In general, the further apart the stations, the lower is the correlation between them except in those areas where all stations are subject to the same local circulation system.



To illustrate the occurrence of intense daily falls, two maps (Fig. 4.18a and b) have been prepared showing the frequency per annum of daily falls exceeding 100 mm and 150 mm.

The following general statements on daily rainfall intensity can be made from these maps. First, falls of over 100 mm per day do not occur in the main body of the central ranges but can rarely occur on the coastal and island ranges. This lack of heavy daily falls in the highland areas results from the fact that the diurnal cycle of convectional storms is the chief source of rain in these areas. Such storms can be intense, as will be seen below, but they are not sufficiently persistent to produce high 24-hour totals. Second, the heaviest daily falls of over 150 mm have occurred at nearly all lowland stations, but they are considerably less frequent in drier areas and on the islands nearer the equator. Except in these latter areas, such falls can be expected on average once in every 1 to 3 years. Third, the most frequent heavy falls occur in the wettest areas of PNG, particularly in those areas subject to south-east season rainfall maxima. Here such falls occur at least once a year and generally more frequently.

To provide an indication of the heaviest daily falls on record, these values have been plotted for a number of stations in Fig. 4.19 (from SMEC 1973). It is not possible, except at a gross level, to make inter-station comparisons from this map as the record lengths from which the values have been taken vary considerably.

Fig. 4.16
Inter-station correlations of logarithms of January, July and annual rainfall values for a range of locations. Rainfall between locations is more highly correlated in the north-west season (January) at the time of highest monthly rainfalls, than in the south-east season (July).

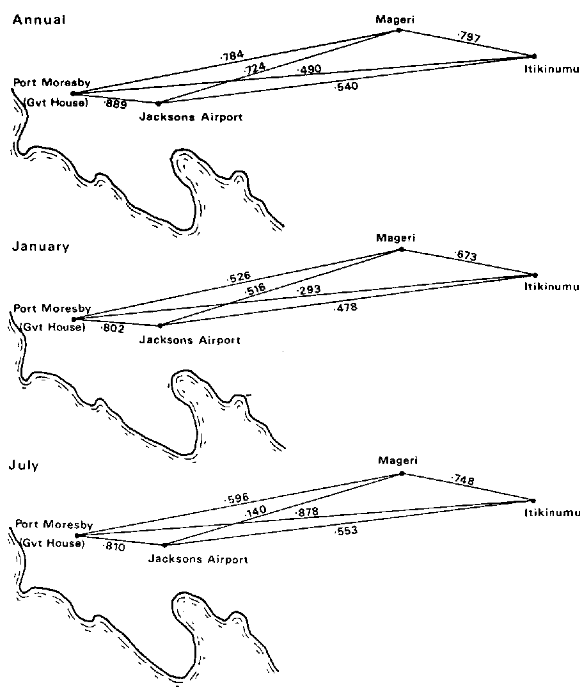


Fig. 4.16a—Port Moresby-Sogeri area

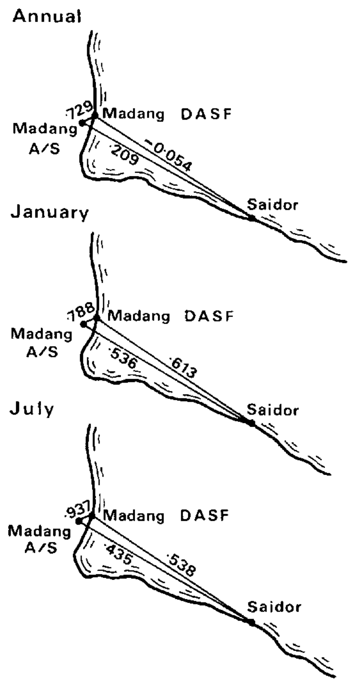


Fig. 4.16b—Madang-Saidor area

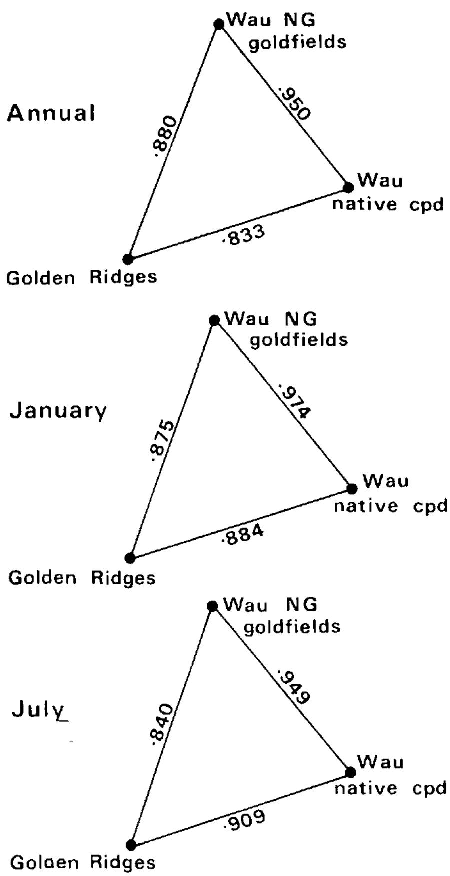


Fig. 4.16c—Wau area

An additional map of the highest daily rainfalls that can be expected on average every two years has also been produced by SMEC (1973) (Fig. 4.20). Although the statistical basis on which this map has been prepared differs from that used in Fig. 4.18, the three maps are generally in good agreement.

The above discussion concerns rainfall intensity as indicated by the rain gauge network, from which observations are recorded once daily. A network of pluviometers has also been established in PNG to gather data concerning the nature of short duration rainfall (that is, of less than one day). The network is sparse and the records are of variable length and consistency, and so discussion of spatial variation in short duration rainfall must remain speculative.

Graphs of the frequency of rainfall intensities derived from pluviometer data are presented in Fig. 4.21. The same data are plotted in Fig. 4.22 for a single return period, to provide a direct inter-station comparison. From a consideration of these diagrams, some speculative generalisations can be made, particularly as Fig. 4.22 suggests that the grouping of rainfall patterns as wet or dry, highland or lowland, or by north-west or south-east season rainfall maxima also holds for pluviometer data.

If Port Moresby is taken as typical of drier areas, then these have falls of shorter duration and lower intensity than elsewhere. For Port Moresby, short duration falls at the rate of 100 mm/hr in 6 minutes can be expected every two

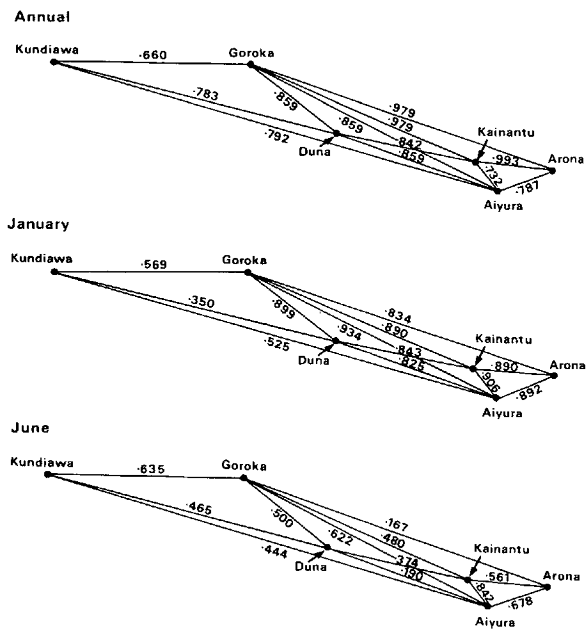


Fig. 4.16d—Aiyura-Goroka area

years, while falls at the rate of 150 mm/hr in 6 minutes can be expected every ten years. At the level of one hour's duration, the rates fall respectively to 50 mm once every 2 years and 65 mm once every 10 years.

In the highlands, short-term intensities of less than one hour are somewhat higher than in drier lowland areas, but the rate of decline in intensities of over one hour is considerably greater. Cumulatively, this results in the previous observation of lower 24-hour totals in the central highlands than in the lowlands.

In the coastal lowlands with north-west season rainfall maxima (for example, Madang and Rabaul), short-term intensities of less than 6 minutes occur at the rate of 140 mm/hr every 2 years, rising to 180 mm/hr for a 10-year return period. At the level of one hour's duration, the rate falls to 75 mm. Taking Lae as representative of stations having south-east season rainfall maxima, the 6 minute short-term intensities occur at the rate of 170 mm/hr for the 2-year return period and 200 mm/hr every 10 years. The decline in intensities to the one hour duration level is less than at all other stations.

Confirmation that this seasonal grouping of wet lowland regimes is meaningful in terms of intensity is seen from the Momote data, where seasonality is slight

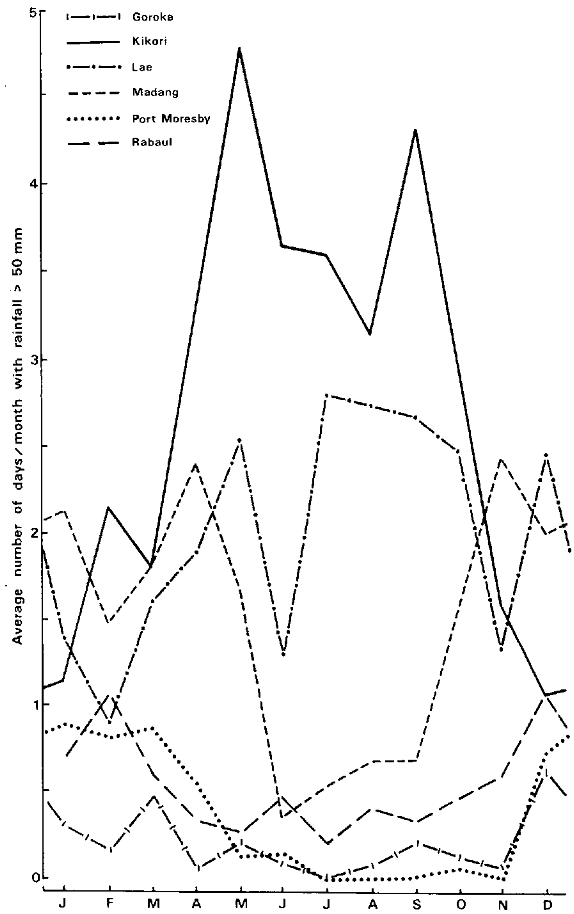


Fig. 4.17
Frequencies with which daily rainfalls exceed 50 mm for selected stations

and where the curves are intermediate between those of Lae and Madang/Rabaul.

The possible explanation of these differences in intensities is indicated in Chapters 2 and 3. Dry areas such as Port Moresby may normally be outside the centres of main storm foci and receive a significant proportion of their rain from the periphery of storms in surrounding hills and mountains. This would also partly account for the quite local occurrence of dry areas. Similarly in the central

Fig. 4.18
Average number of days per year with rainfall exceeding specified amounts. The greatest frequency of high daily falls of rain occurs generally in those areas with south-east season rainfall maxima. In the highlands falls of over 100 mm do not occur.

Fig. 4.18a
Average number of days per year with rainfall exceeding 100 mm.

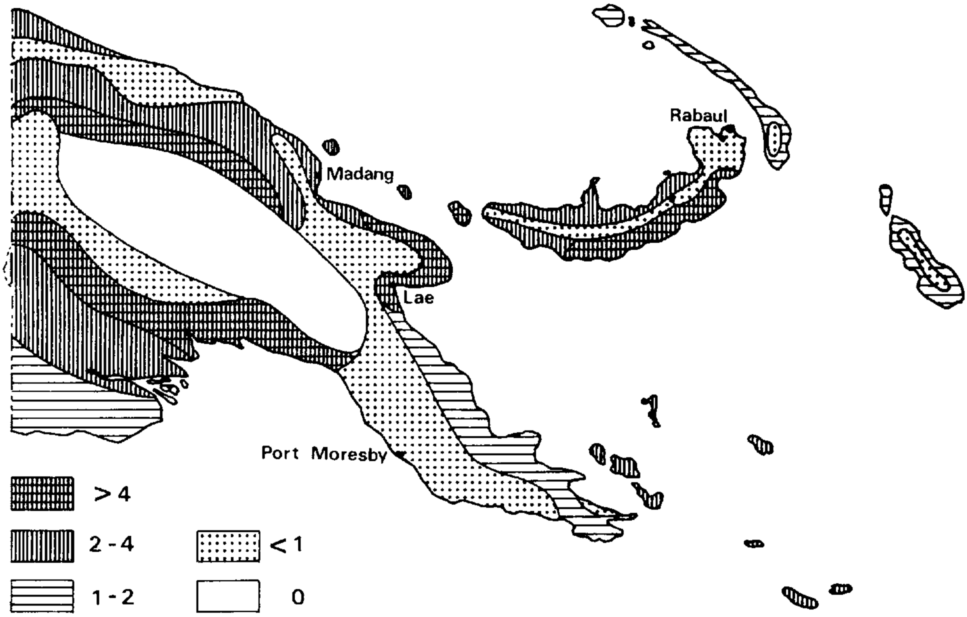
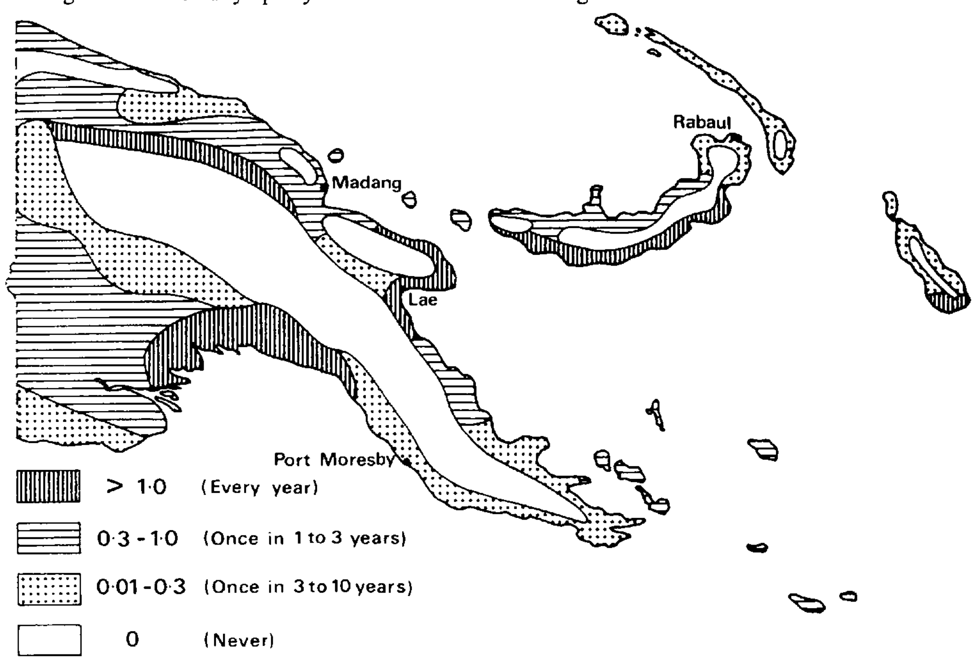


Fig. 4.18b
Average number of days per year with rainfall exceeding 150 mm.

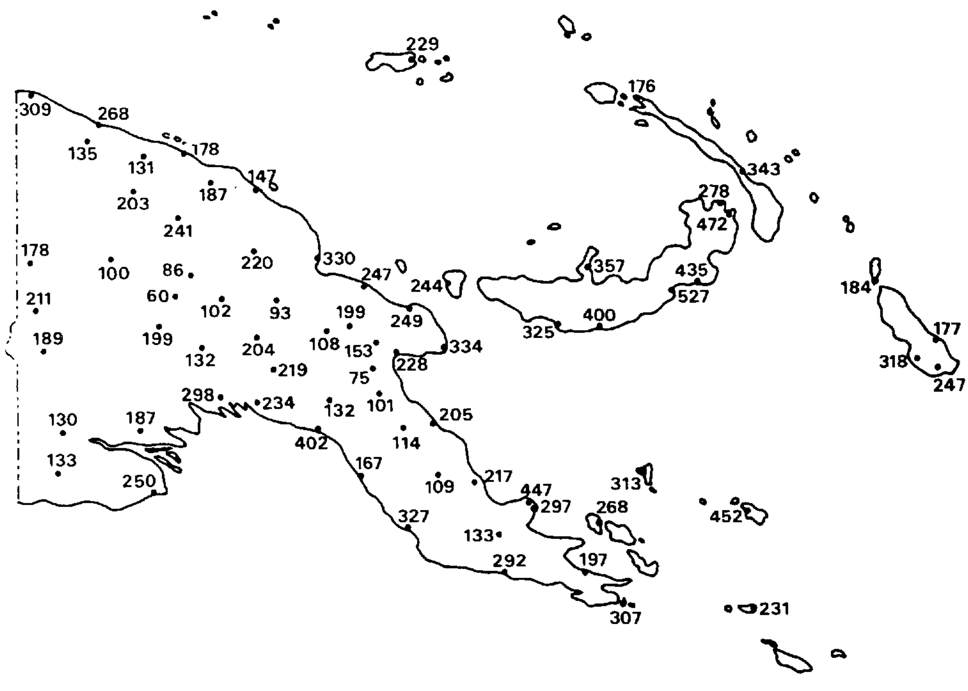


highlands the main rainfall-producing mechanism lies in the diurnal cycle of convectional storms which cause heavy falls but of short duration. As the highlands are largely protected from the major weather systems operating in the lowlands, they do not experience the longer duration rainfalls associated with such systems and this is illustrated by the sharp decline in duration and intensity of falls of over one hour in this region compared with elsewhere. Rainfall intensities are probably fairly similar throughout the wet lowlands, except in those areas where physiography induces greater total rainfall and particularly in regions experiencing south-east season rainfall maxima such as at Lae.

Diurnal cycle of rainfall

The pluviometer data used to analyse rainfall intensity can also be used to determine the diurnal cycle of rainfall. Fig. 4.23 presents graphs of these distributions for eight locations in January and July and for two levels of intensity.

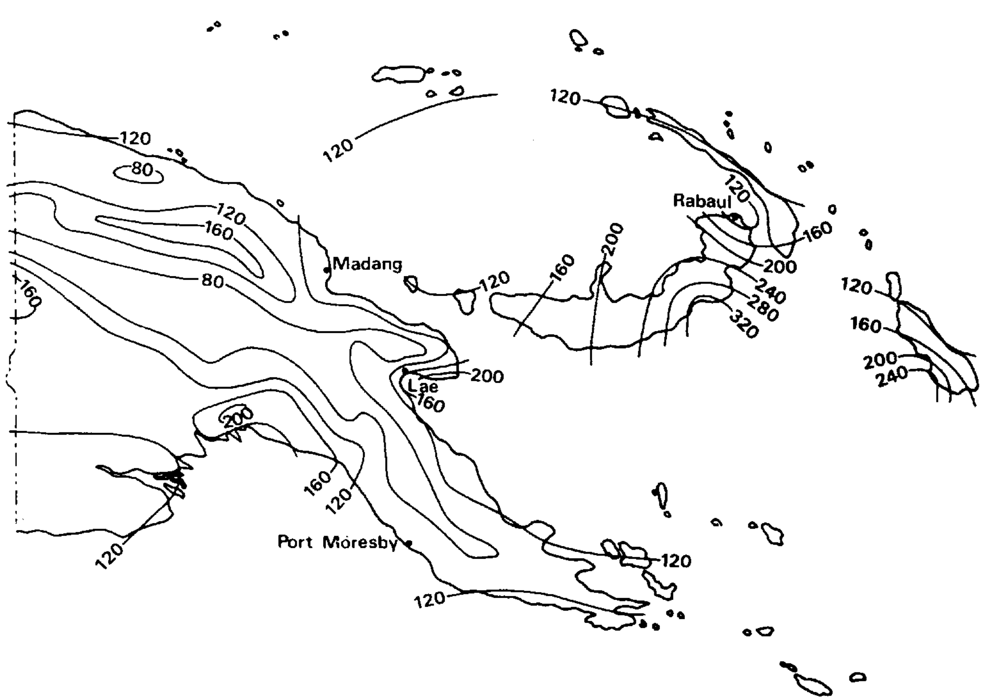
Fig. 4.19
Maximum recorded daily rainfalls (mm) (adapted from SMEC 1973).



Taking the island stations Rabaul, Momote and Kupei as a group, the first two are located on the coast while the last is situated inland on the central Bougainville ranges. It can be seen that there is little variation in the incidence of rain throughout the day or between seasons or intensities at either Rabaul or Momote, although the latter shows a slight peak around 1500 hr. By contrast, Kupei shows a marked peak in the frequency of rainfall at 1500 hr. This pattern is an excellent example of the effect of the diurnal cycle of cloud movement found on small mountainous islands lying in humid tropical wind systems. Malkus (1955) describes such islands as 'heat engines' and traces the offshore build-up of morning cloud which moves towards land in the afternoon. This movement results from daytime heat convection over the mountains and causes mid to late afternoon precipitation as the clouds are forced upwards and cooled by orographic convection.

Madang could be typical of many mainland coastal locations that experience north-west season rainfall maxima. The incidence of rain is highest at night during January, and while this pattern persists in July it is considerably less

Fig. 4.20
Maximum daily rainfalls (mm) likely to occur every 2 years (adapted from SMEC 1973).



marked. Lae, a station with a south-east season rainfall maximum, has a similar night-time incidence of rain in January as has Madang but during July, the wetter period at Lae, the preponderance of rain falls during the night and mid-morning. The graph for Port Moresby, a dry coastal station, is also shown, but whether it relates to other dry areas is not known.

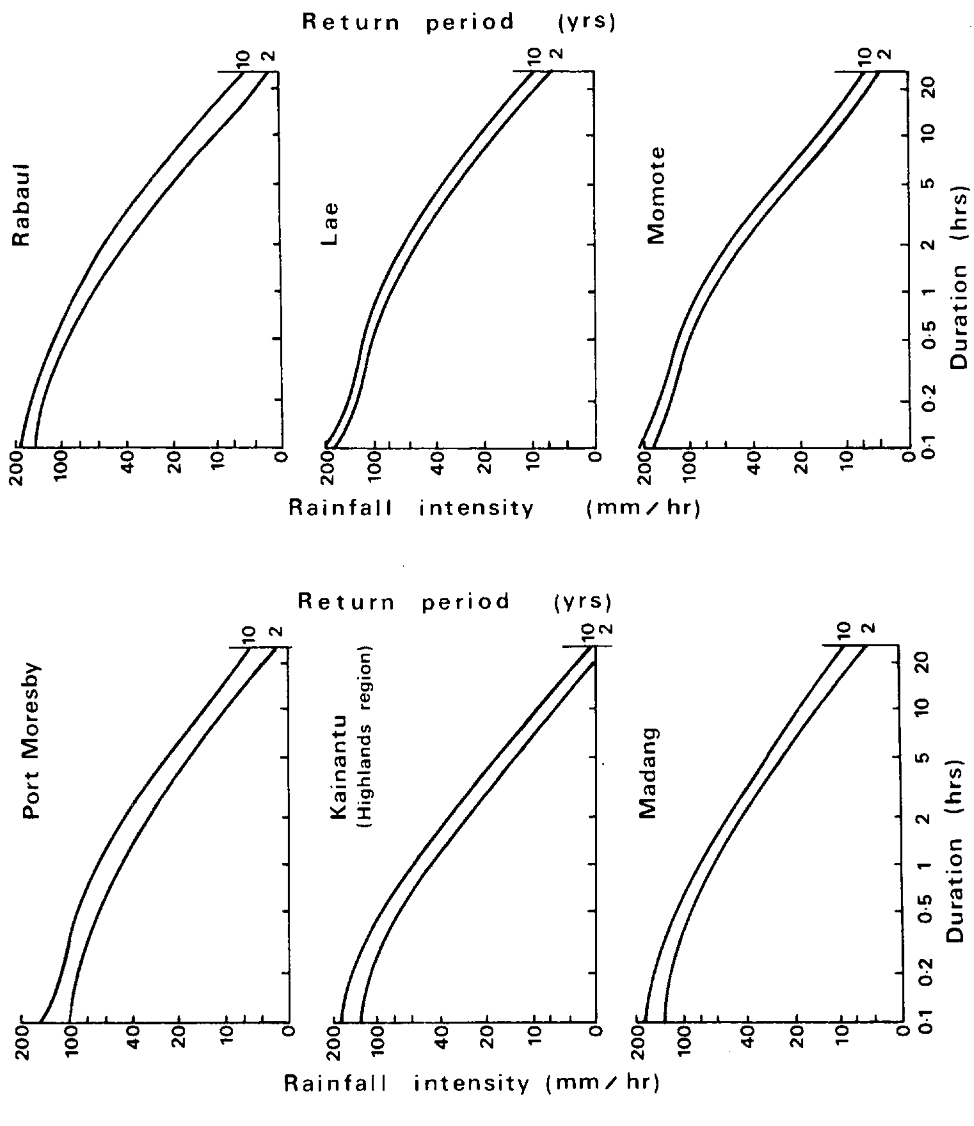
Two stations are used to represent the situation in the central highlands—Kainantu and Kum River, near Mt Hagen. While they differ in absolute frequency, the maximum incidence of rain in January occurs in the mid-afternoon, dropping to a minimum in the morning around 0800 hr. This pattern too is explicable in terms of the diurnal movement of cloud in highland valleys and basins, which has been discussed in Chapters 2 and 3. In July the total rainfall incidence is low, and the diurnal pattern disappears at Kainantu.

In general it can be seen that the pattern of heavier falls in terms of frequency and time of occurrence is similar at all locations.

Wet and dry spells

An analysis of wet and dry spells of weather has been made for the stations covering the 15-year standard period, with a rainy day being defined as one on which 1 mm or more of rain was recorded. The detailed results of the analysis are published by McAlpine *et al.* (1975).

Fig. 4.21
Rainfall intensity-duration-frequency diagrams for selected stations.



From the sequential data thus derived, the mean lengths of wet and dry spells for the four seasons have been calculated and the graphs for a selection of stations are shown in Fig. 4.24. These indicate the full range of values encountered.

The majority of stations with north-west season rainfall maxima follow the pattern illustrated by Madang, while the graph for Wabag is typical of stations in the west of the central highlands, and Goroka of those in the east. Lae and Kikori show the pattern and range in values that can occur at stations with south-east season rainfall maxima, while Port Moresby is probably typical of the situation in drier areas.

These graphs demonstrate the consistent wetness found over virtually the whole of PNG, especially as evidenced by the generally short mean lengths of rainless periods.

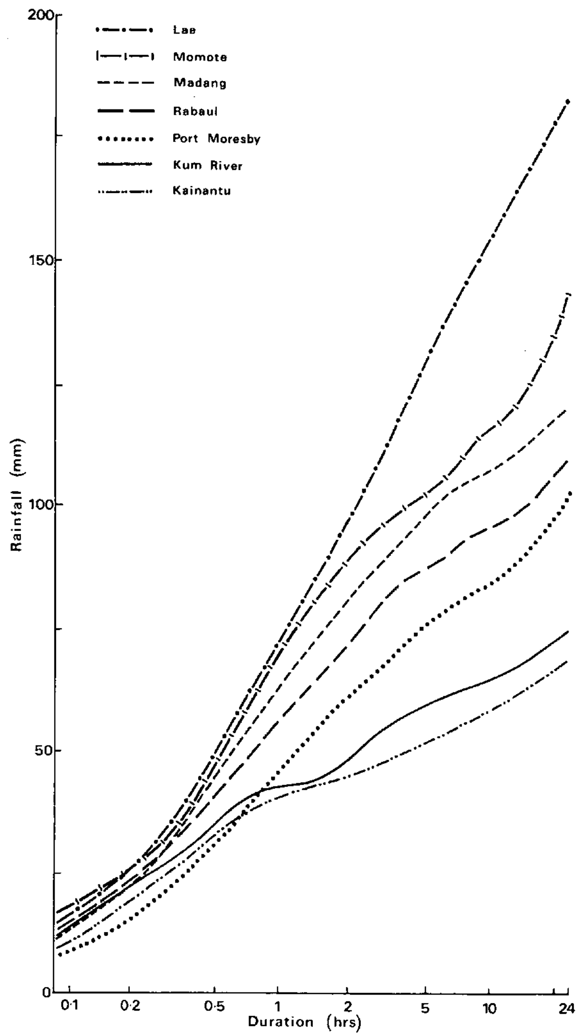


Fig. 4.22
Rainfall intensities of short duration that can be expected every 2 years. While all stations have relatively similar intense falls at durations of less than 12 minutes, considerable differences in intensity regimes can be seen beyond that interval. The highlands have lower intensities, as does the drier station Port Moresby. The greatest intensities occur at Lae, which has its heaviest rainfall in the south-east season.

The actual distribution of rainless periods for the standard period is shown in Fig. 4.25 for a selection of stations. In studying these graphs, it should be noted that the plotted lines showing the number of periods of greater than 10 days in length cover durations of either 11-15 days or 11-20 days in different graphs. For Port Moresby, the driest station, an additional line shows the number of rainless

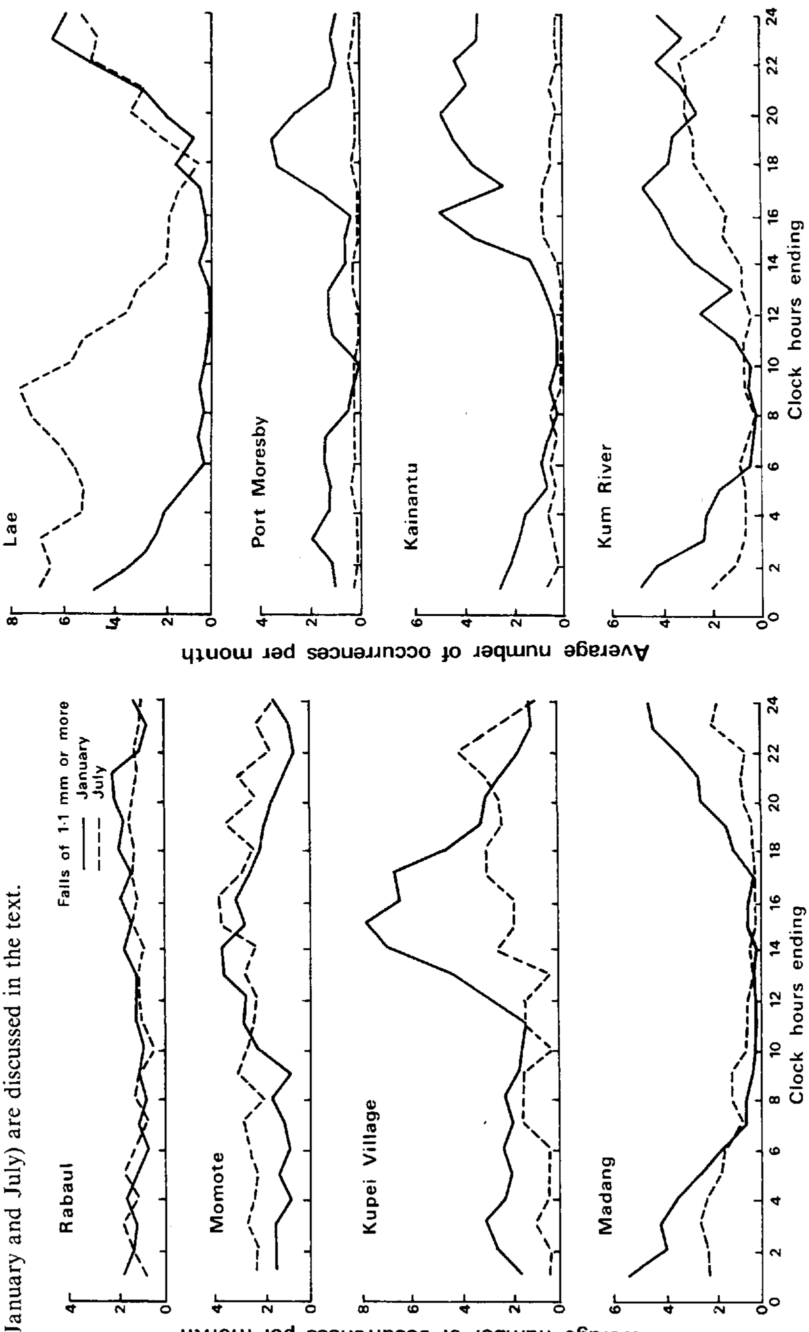


Fig. 4.23
Diurnal cycle of rainfall. The plots indicate the variations in the daily pattern of rainfall incidence. The plots represent the average number of daily occurrences per month when rainfall exceeded 1.1 mm on an hourly basis throughout an average day. Generally lowland areas on the mainland receive most rain at night and in the highlands rain falls mostly in the mid-afternoon and night. In the islands, at coastal locations, there is little diurnal variation in the incidence of rainfall, but in the island ranges most falls occur in the mid-afternoon. The differences between wet and dry season (January and July) are discussed in the text.

periods of between 21 and 40 days duration. The lengths of rainless periods at Port Moresby are greatest during the south-east season, when there were eight occasions during the standard period when rainless periods exceeded 40 days in length. Of the two other coastal lowland stations which experience north-west season rainfall maxima, Madang also has its longest rainless periods during the south-east season, when durations between 11 and 20 days can occur, while Rabaul shows less variation in the lengths of rainless periods between different times of the year, with slightly longer durations which can reach 11-20 days during the south-east season. At Lae, which receives its heaviest rainfall in the south-east season, rainless periods are generally of short duration (1-4 days) throughout the year.

At the drier highland station, Goroka, rainless periods have longer durations than at Mt Hagen, with lengths of 5-10 days and even up to 20 days occurring mainly during the south-east season. At Mt Hagen, most sequences are of short duration (1-4 days), while sequences of 11-15 days duration are rare, even during the south-east season.

In summary, it is clear that frequencies of rainless periods of greater than 4 days duration are low throughout PNG, except in the driest areas.

Fig. 4.24
Mean lengths of rainy and rainless periods for selected stations by season. The rainy nature of the climate is clearly revealed in these diagrams where, with the exception of Port Moresby, mean lengths of rainless periods are mostly less than 3 days.

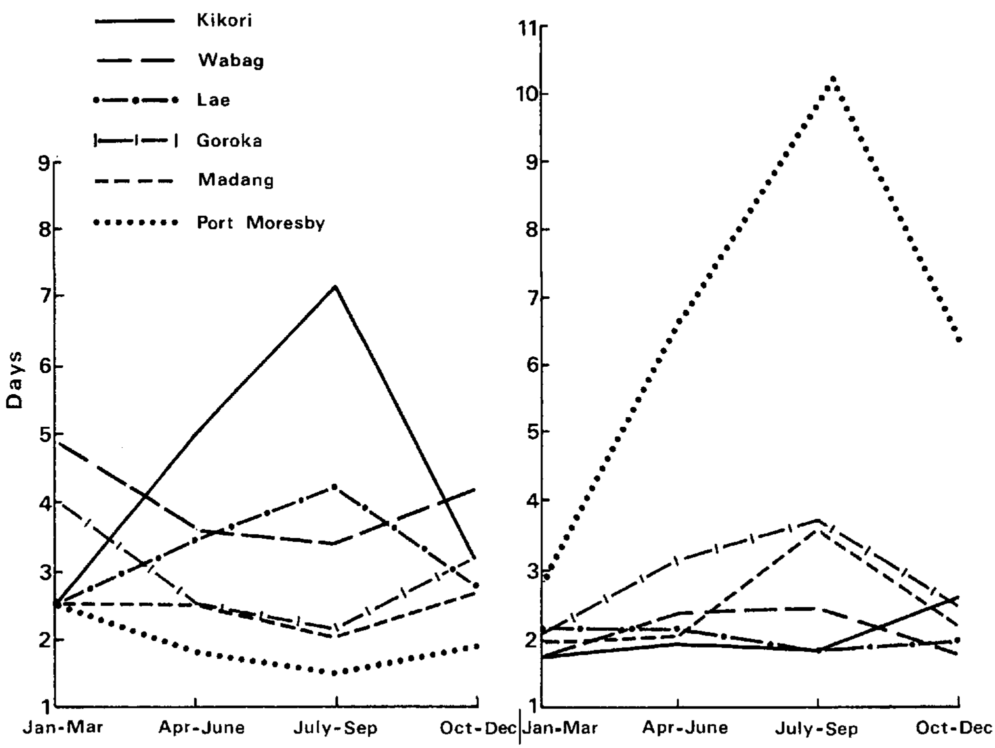


Fig. 4.24a—Rainy periods **Fig. 4.24b**—Rainless periods

Other forms of precipitation—snow

The occurrence of snow in PNG is confined to a few high mountain peaks, and even there it is a rarity. Although no data are available on the frequency of snowfalls, McVean's (1968) observations and reports by aircraft pilots suggest that falls of snow, sleet and soft hail occur on the summit of Mt Wilhelm (4509 m) at all times of the year, with possibly higher frequencies during the south-east season. The snow, however, does not accumulate for long periods. Aircraft in flight also occasionally encounter snow but it almost always melts before reaching the ground. More extensive snow fields exist in the Star Mountains of Irian Jaya, and there are even a number of glaciers in this region, perhaps the best known of which is Caarstenz.

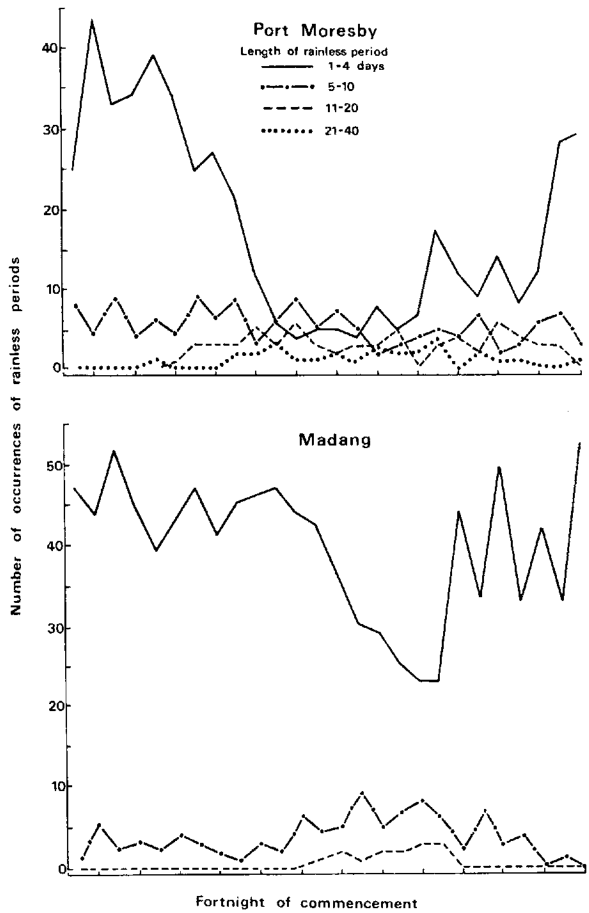
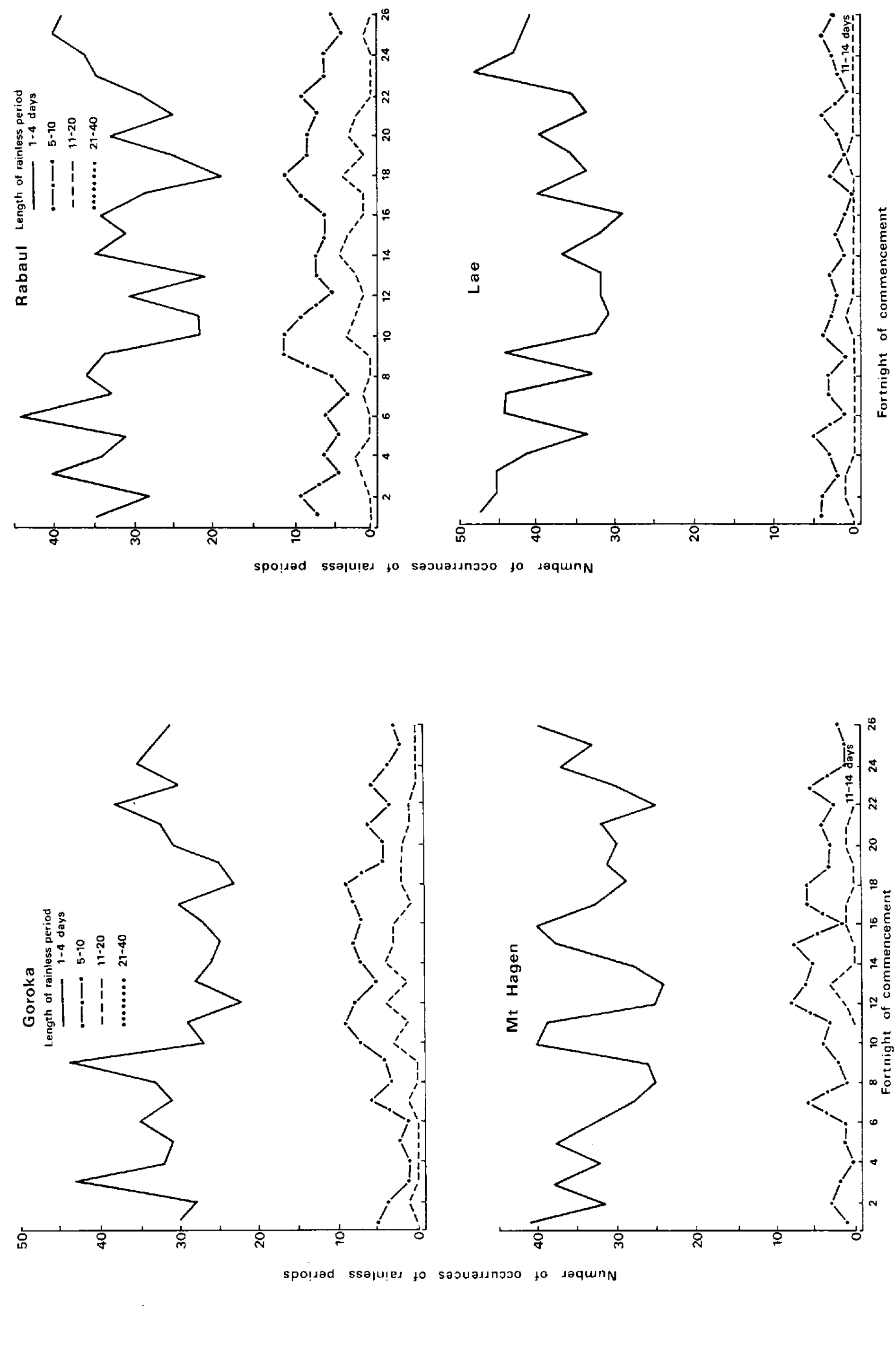


Fig. 4.25
Frequency distribution of rainless periods for selected stations during a 5-year standard period (1956-1970). Each plot is for a period of different specified length and the plots are non-cumulative. The data are presented by the fortnight in which the rainless period commences.


Rabaul
Lae
Goroka
Mt Hagen
Length of rainless period
1-4 days
5-10
11-20
21-40
11-14 days
Number of occurrences of rainless periods
Fortnight of commencement

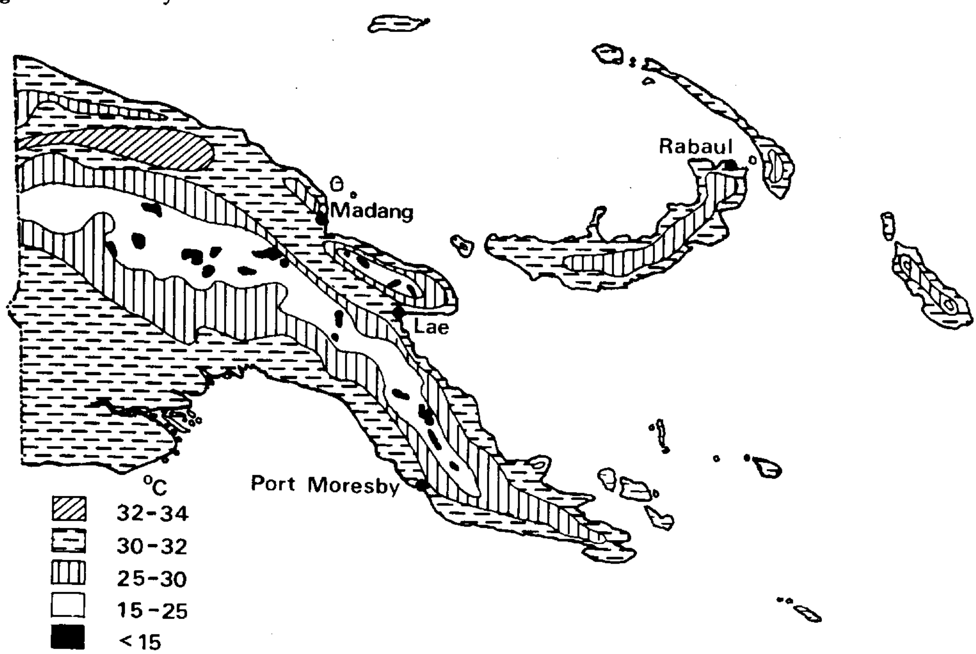
5 Temperature

The equable temperature patterns found in PNG result from its humid equatorial and oceanic location. They are marked by moderately high temperatures at sea level and exhibit little seasonal variation. The most notable temporal variation is that associated with the daily cycle of temperature from day to night, and the main component of spatial variation is the difference which occurs with change of altitude. So regular and consistent are the main temperature patterns and their relation to height that it is possible to construct maps of their distribution directly from contour intervals. Such a series of maps for mean maximum and minimum temperatures during January and July are shown in Figs. 5.1 and 5.2. (Unless otherwise indicated, the temperature data discussed in this chapter are those recorded in a standard Stevenson screen.) The maps clearly indicate the minor degree of seasonal variation over the whole country and, when considered in relation to physiography (see Fig. 3.1), the degree to which change in temperature regime is dependent on height above sea level.

The broad overall temperature patterns shown in the maps are extended in Fig. 5.3 where, for a selection of typical locations, diagrams indicating the daily and seasonal cycles of temperature are presented, together with extreme values

Fig. 5.1
Mean maximum temperature. The main component of spatial variation in temperature is the difference which occurs with change of altitude.

Fig. 5.1a—January



so far recorded. The effects of altitudinal variation are also evident in these diagrams.

From the information presented in these figures, the temperature regimes occurring in PNG can be broadly described. In the lowlands, mean maxima (day) temperatures range around 28-32° C, dropping to 20-24° C at night, with coastal locations having slightly lower mean maxima and higher mean minima than the interior lowlands. With increasing altitude, maximum temperatures fall approximately 6.7° C per 1000 m increase in altitude and minima decrease at a rate of 5.4° C per 1000 m. Thus in the main populated highland areas around 1500-2000 m mean maximum temperatures range from 24 to 26° C and minima from 13 to 15° C. The mean daily variation in temperature ranges from 7-10° C in the lowlands to 11-13° C in the populated highland areas. Seasonal variation in mean temperature varies from virtually nil at locations nearest the equator to 2-3° C over the year at latitudes around 9-10° S.

The low variability and absence of extremes in temperature at any station can be seen from Fig. 5.3. For the stations shown, the maximum temperature on record lies mostly within the range of 3-6° C above the mean maximum and never exceeds 10° C. Generally the highest temperatures occur at dry lowland or inland stations, although abnormally high temperatures also occur under particular meteorological conditions such as at Lae during the north-west season.

The range of extreme minima below the mean minima is larger than that for extreme maxima, varying from 5-10° C, with 15° C being the greatest single variation, and inland and highland locations having lower extreme temperatures than those on the coast.

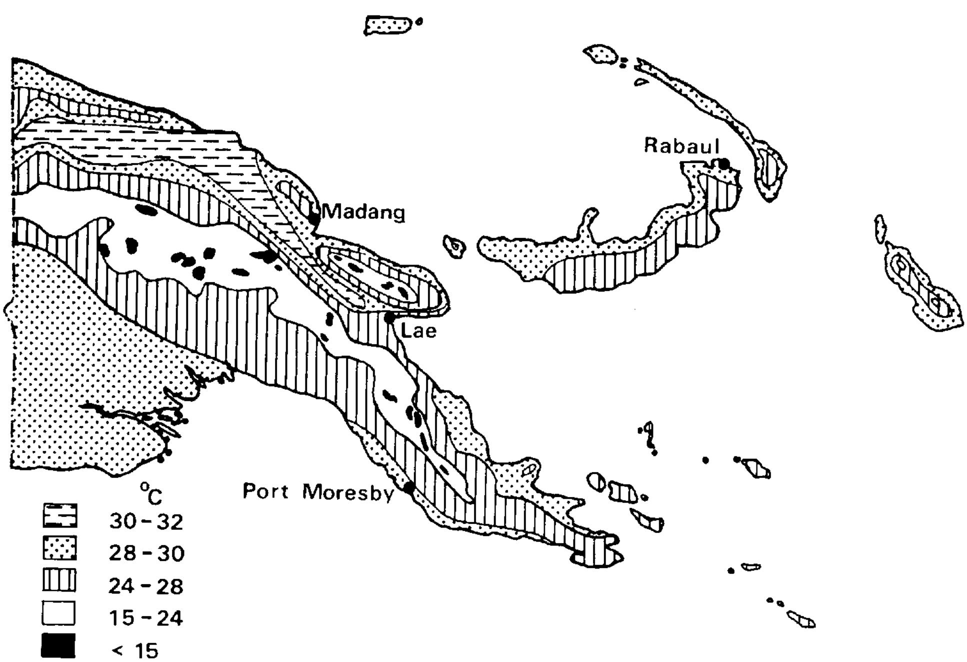


Fig. 5.1b—July

To understand the reasons for these broad patterns and the variations within them, it is necessary to discuss the determinants of temperature in PNG selectively and in more detail.

Factors determining temperature regimes

The major factors determining temperature regimes are the equatorial location of PNG and its insular and maritime position. In conjunction these result in a situation whereby PNG receives relatively high radiation throughout the year and is at the same time surrounded by seas with high and constant temperatures. These latter vary in January from 28.5° C in the south to 29° C in the north, falling respectively to 25.5° C and 28.0° C in July (Reid 1969; Webster and Streten 1972). The higher figure of 29°C is virtually the practical upper limit to the surface temperature of oceans (Priestley 1966). These locational factors in combination result in the moderately high lowland temperatures and the seasonal and diurnal temperature conditions discussed previously.

The main variations in temperature patterns that do occur within and between regions result from physiographic factors arising from differences in altitude, relative position within the PNG landmass and latitude.

Altitude

The greatest differences in temperature regimes are those associated with altitudinal variation. The spatial importance of this can be recognised from an inspection of the physiographic map of PNG (see Fig. 3.1). The terrain is rugged and

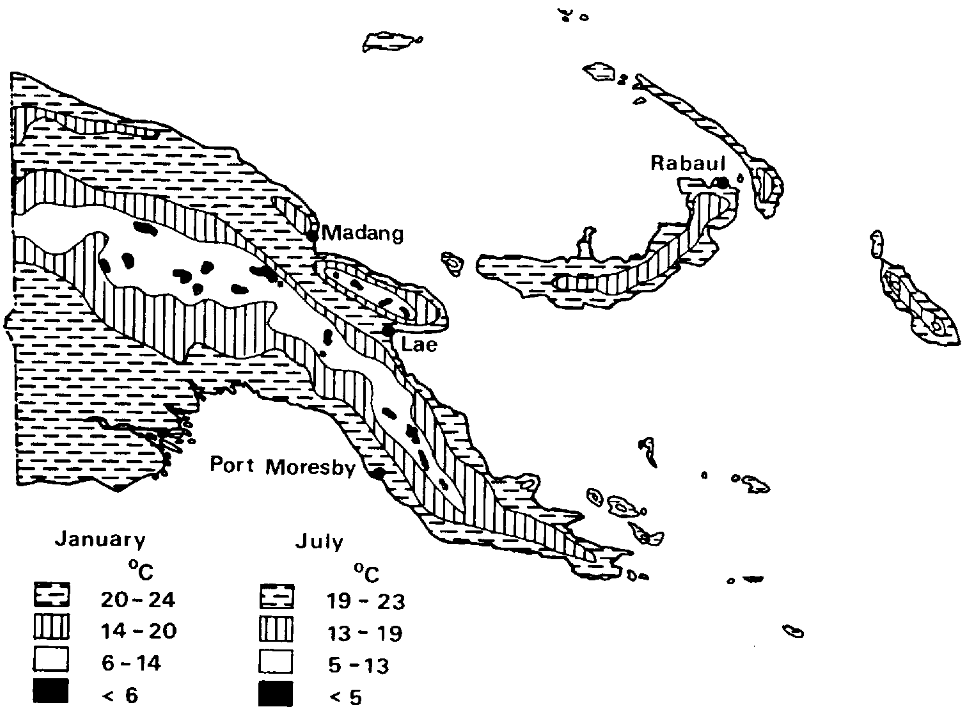


Fig. 5.2
Mean minimum temperature for January and July

mountainous, and over 30 per cent of the landmass lies over 1500 m, with the highest peak Mt Wilhelm rising to 4509 m.

The broad relationship between temperature and altitude is shown in Fig. 5.4, where mean annual maximum and minimum temperatures for all climate stations have been plotted against altitude. It is clear from these plots that there is a regular rate of decline in temperature with altitude (termed lapse rate) above 500 m. Below 500 m factors other than altitude are of greater importance in influencing the level and distribution of temperature. It can be seen that extension of the lapse rates to sea level would result in overestimation of maximum temperature and could not account for the wide spread of either maximum or minimum temperatures around the extended lapse rate lines in the lowlands.

Fig. 5.3
Monthly temperature characteristics (°C) for typical stations. The ranges of mean monthly maximum and minimum temperatures are shown by black bars, at the mid-points of which lie the mean monthly temperatures. Extreme maximum and minimum temperatures lie beyond the ranges of the black bars.

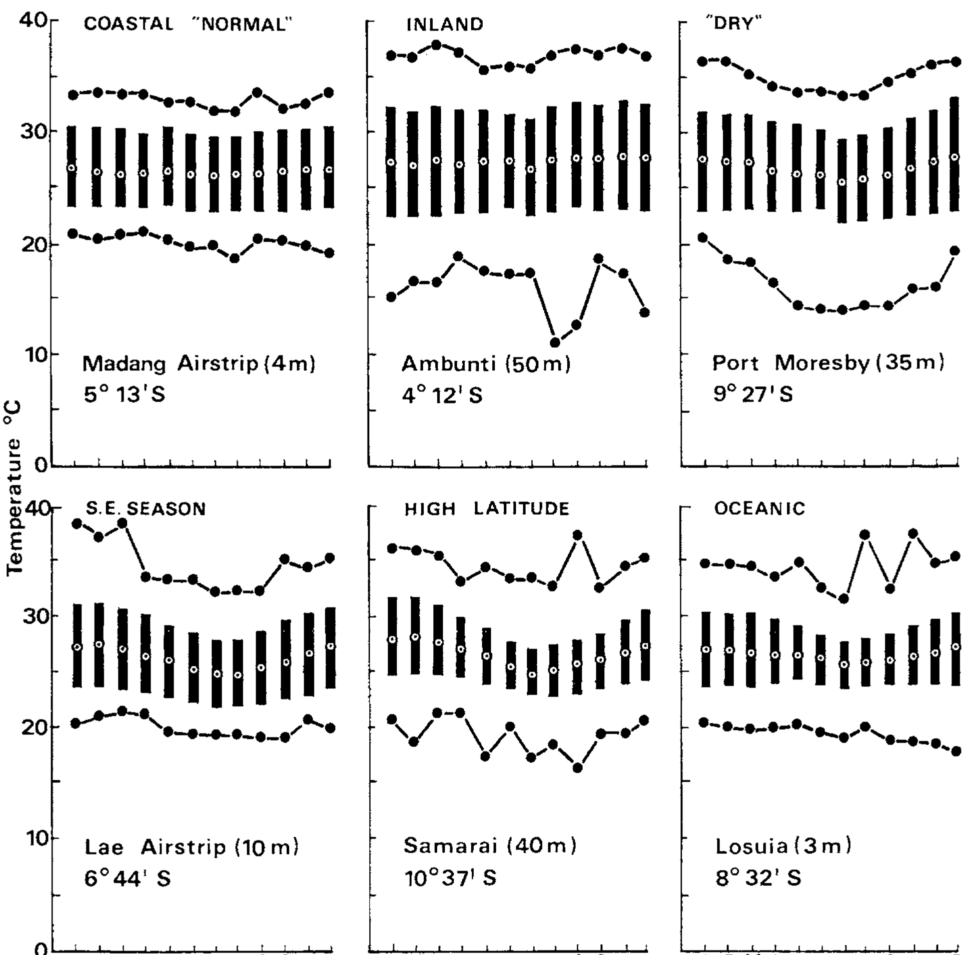


Fig. 5.3a—Locational differences

To asses the actual relationship between altitude and temperature above 500 m, lapse rates for annual and monthly maximum and minimum temperatures have been calculated from the data for the 21 stations lying between 500 m and 3480 m as a set of regression equations. The data for the highest point (3480 m) were obtained from McVean (1968) and Smith (1975, 1977). The regression lines for annual maximum and minimum temperature so obtained have been plotted on Fig. 5.4, and they indicate that above 500 m mean annual minimum temperature decreases with altitude at a rate of 0.54°C per 100 m and mean annual maximum temperature falls at 0.67°C per 100 m.

The lapse rates above 500 m for January and July are plotted in Fig. 5.5, which also shows the lapse rate line for 0900 hr free air radiosonde data from Lae for comparative purposes. The regression equations used to derive the lapse rates are given in Table 5.1 and it can be seen that the percentage of variance accounted for by the lapse rate equation is high. To indicate the rates of change in terms of actual temperature values at specific altitudes the data in Table 5.1 have been transformed to a temperature/altitude matrix in Table 5.2. The maximum and

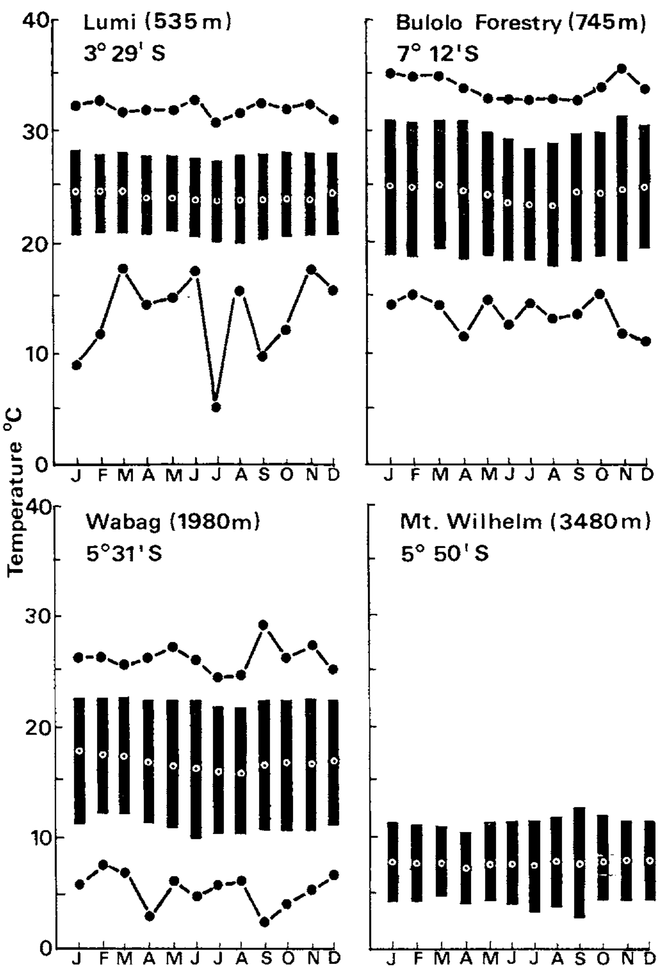


Fig. 5.3b—Altitudinal differences

minimum estimates for each altitude are derived from surface observations. The radiosonde data at Lae provide a comparison with the free air situation at 0900 hours local time. Differences between the maximum and minimum lapse rates may be used to calculate mean diurnal temperature variation at any given altitude. Thus at 1500 m the mean daily range of temperature is 11.0°C and 10.3°C in January and July respectively.

An inspection of the actual distribution of points around the regression lines reveals that, while variation is low, Lumi—the only station above 500 m lying outside the central highlands and situated on the coastal Torricelli Mountains—is anomalous in regard to maximum temperature lapse rate. Lumi lies at an altitude of 535 m, but has mean maximum temperatures which in the central highlands would be found at approximately 1150 m. Limited data, not included in the regression calculations, for Panguna (655 m) on an island range in Bougainville provide further confirmation that this depression in maximum temperatures (but not in minima) in isolated coastal and island ranges is real. A similar situation has been reported elsewhere in the montane tropics (Hastenrath 1968) and the data confirm Robbins' (1968) and Heyligers' (1972) observations that vegetation boundaries associated with altitude occur at lower heights on the coastal ranges than in the main ranges of the central highlands. Unfortunately there are insufficient climatic data from the coastal ranges to establish reliable separate lapse rates for these localities.

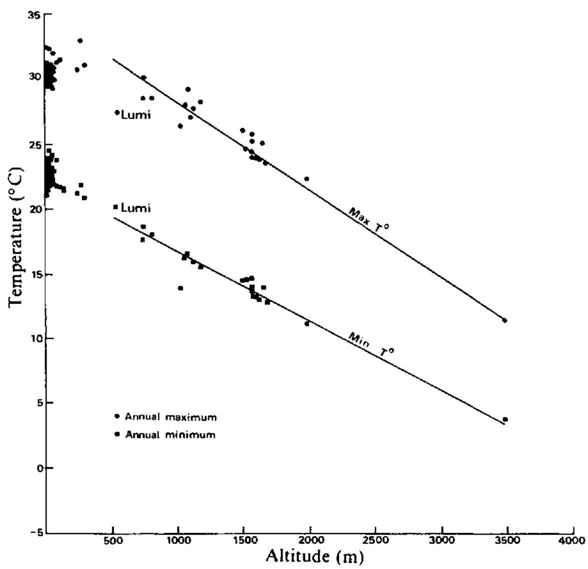


Fig. 5.4
Mean annual maximum and minimum temperatures (°C) for all climate stations by altitude. Straight lines represent lapse rates above 500 m

Table 5.1

Lapse rate statistics calculated from temperature data for stations 500-3500 metres excluding Lumi

Month	Statistic	Maximum temperature	Minimum temperature
January	Rate	-0.710° C/100 m	-0.532° C/100 m
	Regression	Max. temp = -0.00710 × alt. + 35.9	Min. temp = -0.00532 × alt. + 22.3
	r	-0.98	-0.97
	% variance accounted for	97	94
July	Rate	-0.611° C/100 m	-0.535° C/100 m
	Regression	Max. temp = -0.00611 × alt. + 32.9	Min. temp = -0.00535 × alt. + 21.4
	r	-0.95	-0.97
	% variance accounted for	90	94
Annual	Rate	-0.672° C/100 m	-0.535° C/100 m
	Regression	Max. temp = -0.00672 × alt. + 35.0	Min. temp = -0.00535 × alt. + 22.0
	r	-0.97	-0.97
	% variance accounted for	95	94

Table 5.2

Temperature/altitude relations 500-3500 metres

Altitude (metres)	Maximum temp. °C January	July	Annual	Minimum temp °C January	July	Annual	Radiosonde temp °C January	July	Annual
500	32.4	29.8	31.6	19.6	18.7	19.3	24.5	21.3	23.1
1000	28.8	26.8	28.3	17.0	16.1	16.7	21.5	18.6	20.2
1500	25.3	23.7	24.9	14.3	13.4	14.0	18.5	15.9	17.3
2000	21.7	20.7	21.6	11.7	10.7	11.3	15.5	13.2	14.5
2500	18.2	17.6	18.2	9.0	8.0	8.6	12.5	10.5	11.6
3000	14.6	14.6	14.8	6.3	5.4	6.0	9.4	7.7	8.7
3500	11.1	11.5	11.5	3.7	2.7	3.3	6.4	5.0	5.8
4000	7.5	8.5	8.1	1.0	0.0	0.6	3.4	2.3	2.9

Latitude, location and seasonality

Below 500 m differences in temperature regime are mainly related to locational differences in physiography and latitude. As these two factors are interconnected and as the former is not readily quantifiable, it is not possible to determine the effects of each separately but, as will be seen below, even in combination their effect on temperature over the whole range of latitude and lowland location in PNG is quite minor compared with the effect of altitude. Generally they account for only a 1-2°C difference in temperature regime, extending in specific and limited areas to 4°C.

The political boundaries of PNG extend from the equator to 12°S, while geographically the mainland and island areas lie between 3 and 10°S. Any effects of latitude on temperature theoretically could be expected to be seen most clearly in day rather than night temperatures. However, after testing for correlations between latitude and a number of temperature characteristics, the only statistically significant relationship between temperature and latitude was found to be that involving the mean seasonal range of maximum temperature ($r=0.67$, $p<0.01$). Even in this case the relatively slight effect of latitude is revealed by the fact that while more northerly lowland stations may have seasonal ranges of maximum temperature of 0.5-1.5°C, rising to 2-3°C in the south, the highest ranges (3-5°C) are possessed by stations with a south-east season rainfall maximum irrespective of latitude.

The relationships between physiographic position and temperature in the lowlands cannot be expressed in simple numeric terms. A broad indication of these effects can be gained by reference to the graphs of temperature regimes presented for selected stations in Fig. 5.3. Taking Madang as an arbitrary reference point for a 'normal' coastal station, it can be seen that inland stations such as Ambunti have higher maxima, lower minima and a greater range of extreme temperatures than is the case for coastal locations. The effects of physiography on rainfall have been discussed in an earlier chapter. They are of consequence here in that drier rainfall regimes tend to be associated with slightly higher temperature regimes and, in areas where physiography induces rainfall

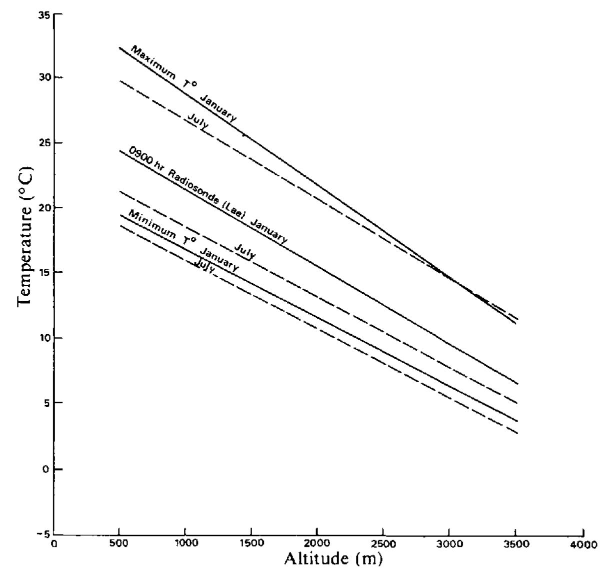


Fig. 5.5
Generalised lapse rates for maximum and minimum temperature (°C) for January (solid line), and July (dashed line) and radiosonde data for Lae

maxima between May and September (south-east season), temperatures tend to be lower and of greater seasonal range irrespective of latitude, as stated above. Port Moresby is an example of a drier rainfall regime with slightly higher temperatures, especially if the seasonal/latitude effect is discounted. Lae provides an example of lower temperatures and greater seasonal range associated with a south-east season rainfall maximum. Finally the effects of an oceanic location with no mountain barriers can be seen in the graph for Losuia in the Trobriand Islands. In this case all sign of seasonality in minimum temperature disappears and the range of maxima for the year is only 2° C.

In combination the effects of physiographic location and latitude may be cumulative and reinforcing. For instance, where a station is situated inland and has a low rainfall such as Erap, mean maximum temperatures reach the highest levels in PNG. Likewise where a coastal station having a south-east season rainfall maximum is located at a higher latitude, as in the case of Samarai, July maximum temperatures are the lowest and seasonal temperature range the highest in the lowlands of PNG. Yet even these extremes indicate that variation in lowland temperature is not great and that the effects of physiographic location and latitude are only minimal compared with those of altitude. For instance, the highest mean monthly maximum temperature in PNG occurs during March at Erap and reaches 34° C, while the lowest occurs at Samarai during July, falling to 27° C, a difference of 7° C. These represent the extremes—elsewhere the majority of lowland stations vary by less than 3° C as a result of locational variation.

Diurnal cycle

Only a few stations in PNG record temperature at three-hourly intervals between 0300/0600 and 1800/2100 hr local time. An indication of the diurnal cycle of temperature is obtained from the three-hourly data for January and July presented for a selection of stations in Fig. 5.6. The three-hourly data are supplemented by maximum and minimum temperature data, for which times of

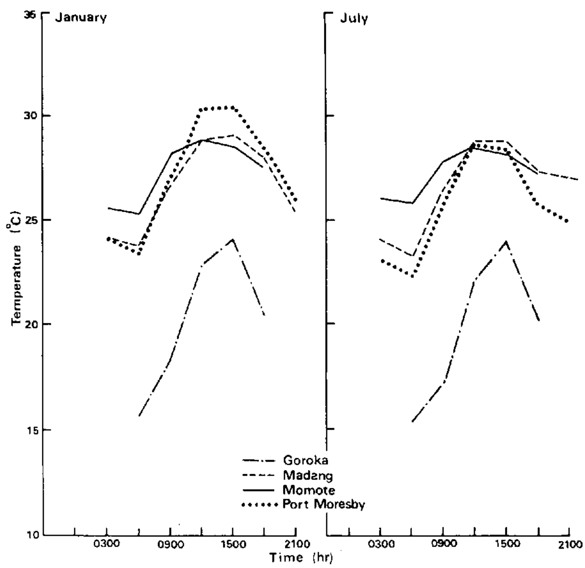


Fig. 5.6
Diurnal temperature cycles for selected stations. Differences between daily maximum and minimum temperatures are generally least at wetter coastal stations, and increase inland and with altitude.

occurrence are not available. Limited thermograph data collected by Budd (pers. comm.) and Ballantyne (pers. comm.) at 146-147°E longitude indicate that maxima occur between 1300 and 1400 hr in the highlands and from 1200 to 1300 hr in the lowlands, while minima occur between 0600 and 0700 hr in both locations. The graphs for Port Moresby and Momote probably encompass the range of daily cycles of temperature found in the great majority of coastal stations. The plot for Goroka, with its somewhat greater amplitude in diurnal cycle, would also be typical of the highlands pattern. Three-hourly observations are not available for inland stations in the lowlands but the daily cycle for such stations would be intermediate between that of the coastal and highland stations illustrated.

The diurnal range of temperature, that is the difference between daily maximum and minimum temperatures, has been referred to earlier. Generally the range is least on the coast, averaging 7-9°C in January, increasing inland and with elevation to 10-12°C in the populated highland areas and falling again to 7°C on Mt Wilhelm at 3480 m. The diurnal range of temperature tends to be 1-2°C less in most locations in July than in January.

High screen and radiant temperatures

Very high air temperatures and heatwaves are largely absent from PNG. The reason for this lies in the constraints placed on the upper limit to which the temperature of the air will rise over well watered terrain. These constraints arise from general considerations of the energy balance and are discussed in a paper by Priestley (1966) dealing with the limitation of temperature by evaporation in hot climates. He shows that mean monthly screen maxima of around 30°C have a very high frequency in wet tropical environments and that such values will not rise above 34°C. These limitations apply in PNG, where even absolute extreme daily values on record at the hottest stations in the drier areas lie mostly in the range 35-37°C. Another indication of the absence of very high temperatures in PNG is given by the maximum temperature probability curves for selected stations shown in Fig. 5.7.

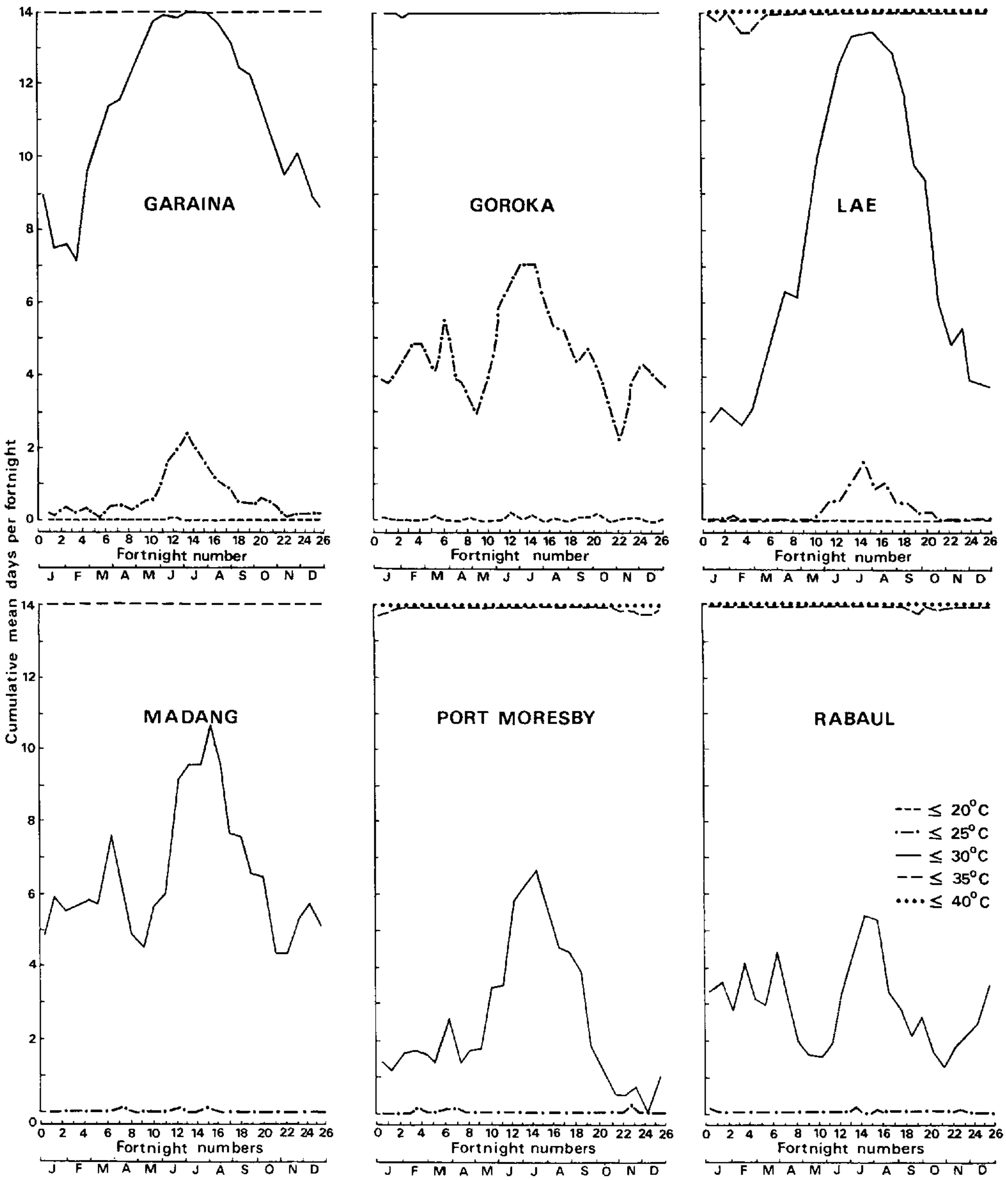
In contrast, radiant temperatures measured with a standard black globe thermometer can reach much higher levels than 34°C in direct sunlight and lightly shaded areas. It is this relative difference between screen temperatures and radiant temperatures which accounts for the perceived coolness of the interior of the rain forest as against the heat of the open grasslands or gardens. Some indication of these differences is provided by Budd *et al.* (1974) who, during a research program in human biology, measured radiant temperatures throughout the day in the vicinity of Lufa (2042 m) in the highlands and at Kaul (140 m) on Karkar Island. The results are given in Fig. 5.8, where it can be seen that open sun radiant temperatures can rise to 65°C at Kaul and to 60°C at Lufa. For comparative purposes, screen temperatures at the nearest climate stations have been included on the figure.

Low screen temperatures and frosts

The occurrence of low mean minimum temperatures is related directly to altitude and the occurrence of extreme minima to particular meteorological conditions, of which the most important is high radiation loss at night resulting from clear skies. This situation occurs most frequently during those periods when a strong outflow from the southern high pressure zone has brought dry air to the PNG area. At higher altitudes such conditions can result in ground frosts which, if prolonged, can be associated with drought conditions. An excellent review of the meteorological conditions during one major frost/drought occurrence, that of 1972, has been prepared by the Bureau of Meteorology (1972b).

In PNG the occurrence of low temperatures is important in determining the upper limit of highland agriculture based on the sweet potato *(Ipomoea batatas)*. Low temperatures result in increased crop maturation time and decreased yield

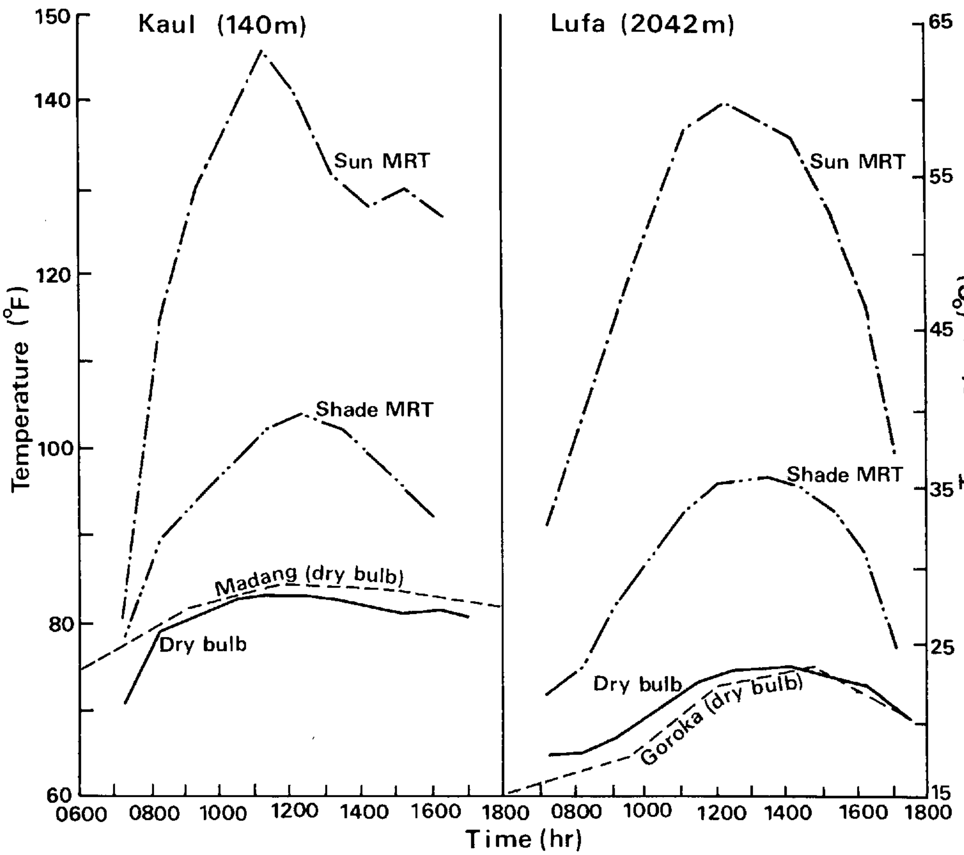
Fig. 5.7
Maximum temperature cumulative probability curves. Each curve shows the number of days per fortnight, averaged over all years of record, when temperatures at the particular station were less than or equal to the stated temperature.



per unit area, setting the marginal limit for sweet potato culture at approximately 2600-2800 m. Climatically this limit has two components. The first is the broad constraint set by low mean temperatures, which is, secondly, compounded by the incidence of frosts. These latter, being of a periodic nature, can occur at altitudes well below the marginal upper limit of cultivation set by mean climatic conditions. As a result, they are effectively perturbations from a mean which is reasonably constant and reliable, and hence frosts are commonly viewed as disasters. When it occurs, frost damage to crops may vary from slight to catastrophic, depending on the length and severity of the cold period. Major frost occurrences have been recorded for 1941, 1950, 1962 and 1972, with only the last being the subject of any documentation.

Frost probability increases with height, particularly over 2000 m. As there are no official climate recording stations above this altitude the determination of frost probability is unreliable. Reference to the data which do exist may give some indication of the situation. Ground frost risk appears to commence at altitudes of about 1500 m (Fitzpatrick 1965) and increases with altitude. Frosts are likely to be indicated by screen minima of 4.4°C (Fitzpatrick 1965; Brookfield 1964), and Waddell (1972) suggests that in the presence of temperature

Fig. 5.8
Daily cycle of mean radiant temperature (MRT) recorded in sun and shade compared with dry bulb temperature at the same location and at the nearest climate station (from Budd *et al.* 1974).



inversions they may also occur at screen temperatures up to 5.5°C. After analysing Wabag (1980 m) minimum screen temperatures for a 10-year period (1957-1966), Waddell (1972) arrives at a probability of 2.1 days per annum with temperatures below 5.5°C and 0.6 days below 4.4°C. For Sirunki (2653 m) he suggests that 'mild ground frosts are an annual occurrence'. An indication of ground climatic conditions during a major frost occurrence has been provided by Brown and Powell (1973, 1974). These authors analysed minimum temperature data taken in a shed at Tambul (2250 m) during the 1972 frost/drought sequence and found that 17 days with minima below 4.4°C occurred in August, followed by 8 days in September, while on two occasions in October the temperature fell to -1.1°C.

Physiographic conditions play an important role in the occurrence and severity of frost at both micro- and meso-scale levels. Waddell (1972) presents direct evidence of inversions near the ground and within the micro-relief of gardens in the Wabag area. Larger inversions almost certainly occur in physiographic situations where cold air drainage is impeded in a down-slope direction, such as in basins or 'frost hollows'.

6 Humidity and Evaporation

Water enters the atmosphere by evaporation from the earth's land and water surfaces and by transpiration from plants. It is returned to the earth as precipitation, so completing the hydrologic cycle. In the PNG region vast amounts of water vapour are evaporated continuously from the surrounding tropical oceans and from the land surface itself, and the high dew point temperature of the warm tropical air causes absolute levels of atmospheric moisture, as well as relative humidities, to be high throughout the year. The combination of high air temperatures and humidities is an important factor in controlling rates of evaporation, and in determining the degree of human comfort or discomfort as expressed by comfort indices (see Chapter 9).

Humidity

Wet and dry bulb temperatures, from which humidity values can be calculated, are recorded at 0900 and 1500 hr at thirty-nine locations in PNG. Mean monthly summaries of these data, and the relative humidities derived from them, have been presented by McAlpine *et al.* (1975). Three-hourly observations of wet and dry bulb temperatures are made at a further eleven stations, and the relative humidities calculated from these data are presented below. The daily cycle of dry bulb temperature in PNG based on the 3-hourly observations has been discussed in Chapter 5.

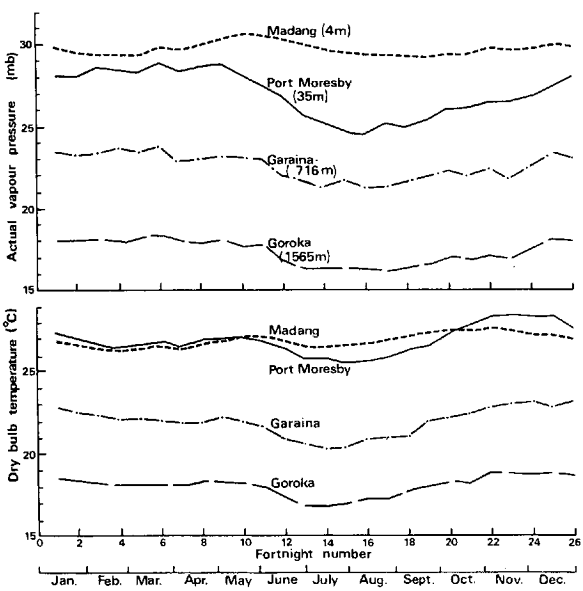


Fig. 6.1
Mean 0900 hr dry bulb temperatures and vapour pressures for four stations. Vapour pressure follows a similar seasonal cycle to air temperature, with coastal locations having the highest levels of atmospheric moisture throughout the year.

The mass of water present per unit volume of unsaturated air is approximately proportional to the vapour pressure. Consequently, vapour pressures calculated from wet and dry bulb temperature data provide an indication of the variation in total moisture content of the air at different times of the year and between different locations on the PNG landmass. Figure 6.1 shows mean 0900 hr vapour pressures and dry bulb temperatures for two coastal stations, Madang (4 m), and Port Moresby (35 m), and for two highland stations, Garaina (716 m) and Goroka (1565 m). The graphs indicate that vapour pressure follows a similar seasonal cycle to air temperature and, while a noticeable decrease in vapour pressures occurs at Port Moresby during the south-east season when rainfall is at a minimum, the two coastal locations have the highest levels of atmospheric moisture measured at surface level throughout the year. A comparison of values at Garaina and Goroka indicates the decrease in vapour pressure that occurs with altitude.

In the following discussion reference will be made to the relative humidity index, as well as to relative humidities calculated for specific hours of the day. This index, which is calculated from wet and dry bulb, and maximum and minimum temperatures, is defined as 'the ratio of the average 9 a.m. vapour pressure to the saturation vapour pressure at the average mean temperature' (Bureau of Meteorology 1969). Because of its relation to the mean temperature, this index can be taken as a good approximation of the daily mean (24 hr) relative humidity.

Fig. 6.2
Mean monthly relative humidity index. Relative humidities are highest in the wet lowland regions and decrease slightly in the drier lowlands. At altitudes between 500 and 2000 m, values are also slightly lower than in the lowlands.

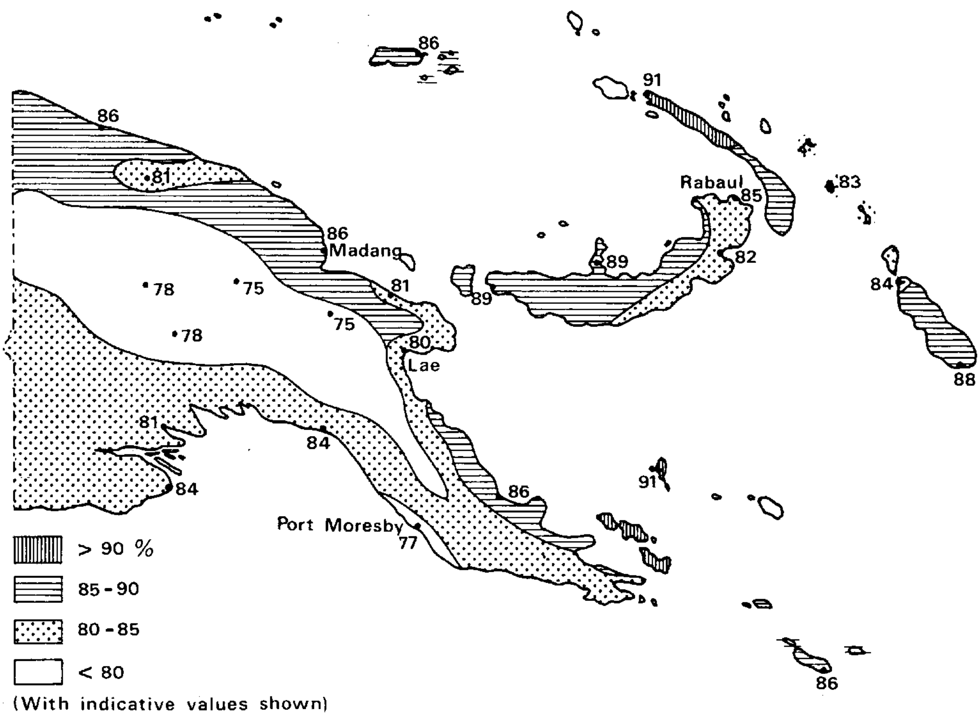


Fig. 6.2a—January

Spatial variation in relative humidity

Consistently high levels of atmospheric moisture prevail throughout the year in PNG, a consequence of its equatorial position and the vast areas of tropical ocean that surround it. The broad pattern of distribution of the mean monthly relative humidity index for January and July is mapped in Figs. 6.2a and b, and Fig. 6.3 shows the annual cycle of relative humidity for selected stations. The comparative lack of variation in this parameter across PNG indicates the overall humid nature of the climate. There are, however, some interesting, if not marked, regional differences.

It can be seen that the highest relative humidity indices are found in the wet lowland regions, where the mean monthly relative humidity ranges between 80 per cent and 90 per cent for most of the year. Slightly lower mean monthly relative humidities are found in the drier lowland regions around Port Moresby and in the Markham Valley, where values generally lie between 75 per cent and 85 per cent. At altitudes between 500 and 2000 m, the mean monthly relative humidity indices are slightly lower than in the lowlands, a consequence of the decreased midday relative humidity minima found at higher altitudes. In these highland areas, values of the index are generally in the range 70-85 per cent.

Seasonal variation in relative humidity

As is the case with spatial variation, seasonal variation in the mean monthly relative humidity index is slight throughout PNG, generally ranging between 2 per cent and 10 per cent in lowland areas and between 3 per cent and 7 per cent at altitudes above 500 m. Apart from this more limited range at higher altitudes,

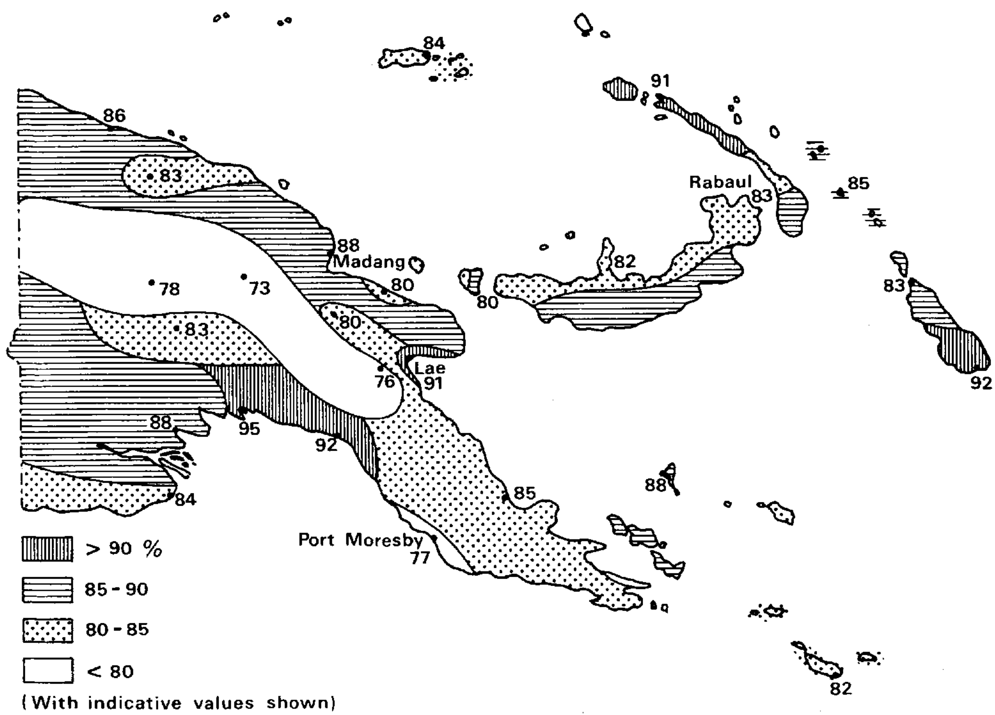


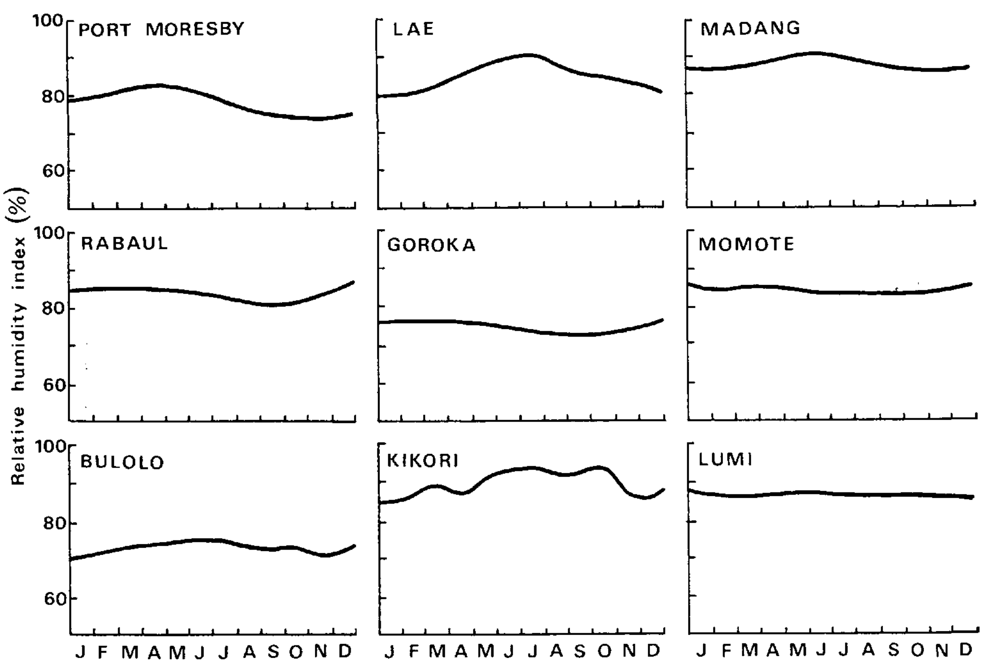
Fig. 6.2b—July

seasonal variation in relative humidity shows no change with elevation up to 2000 m, as shown in Fig. 6.4. The amplitude of the annual cycle of relative humidity is in fact far less than the amplitude of the daily cycle, which will be discussed in a later section. This differential is greatest in the highland areas, where the mean seasonal variation in the mean monthly relative humidity index is 5 per cent and the mean diurnal variation in relative humidity is 35 per cent.

The very low seasonal variation in relative humidity index to some extent precludes meaningful comparisons between the annual cycles of relative humidity index, rainfall and temperature. For example, at stations where the seasonal variation in the mean monthly relative humidity index is only 2-5 per cent, such as Kavieng and Vanimo in the lowlands and Lumi, Wau and Goroka at higher altitudes, maximum values of the mean monthly relative humidity index can occur in a number of months of the year and there is virtually no discernible annual cycle.

In the wet lowland areas, however, the annual cycles of rainfall and relative humidity index show considerable parallelism at stations where the seasonal variation in relative humidity index exceeds 5 per cent, such as at Rabaul and Lae. In the drier lowland areas such as at Port Moresby and Erap, the annual cycle of relative humidity index shows less parallelism with the annual rainfall cycle in spite of the comparatively large seasonal variation of 8 per cent in the relative humidity index. In these areas, and at higher altitudes, an inverse relationship between annual cycles of relative humidity index and temperature is generally apparent. Thus the annual cycle of the mean monthly relative humidity index tends to reach its peak during April to August, the time of year at which air temperatures reach their lowest values (see Chapter 5). Conversely, the lowest

Fig. 6.3
Annual cycle of relative humidity index for selected stations. There is comparatively little variation throughout the country, indicating the overall humid nature of the climate.



mean monthly relative humidity indices normally occur between September and March, during which period the annual cycle of monthly temperature reaches its maximum.

Effect of altitude

Little can be said about the effect of altitude on relative humidity in PNG except that there is a difference of about 10 per cent between the ranges of mean monthly values in the lowlands (below 200 m) as compared with the highlands (200-2000 m). While relative humidities are in general uniformly high in the mornings (0900 hr), there is a difference of around 10 per cent between the ranges of the mean monthly 1500 hr relative humidity values at coastal and lowland stations compared with higher altitude locations. This greater diurnal variation in relative humidity in the highlands, which will be discussed more fully in the following section, leads to a differential of around 10 per cent in the ranges of the mean monthly relative humidity index at lowland as compared with highland stations, as shown in Fig. 6.5 for the months of January and July. Between 200 m and 2000 m there is, however, no noticeable decrease in the mean monthly relative humidity index with increasing altitude. This reflects a similar uniformity in mean monthly 0900 and 1500 hr relative humidity values for stations in this altitudinal range.

Daily variability of relative humidity index

The relative humidity index displays very little daily variability throughout PNG. Figure 6.6 shows the annual cycle of the mean daily relative humidity index by fortnights, together with standard deviations and extreme values, for four lowland and two highland stations. These data summarise 20 years of daily records for the coastal stations Lae, Madang, Port Moresby and Rabaul, and 14 years of daily records for the highland stations Garaina (716 m) and Goroka (1565 m).

It can be seen that the standard deviations of the daily values are low, ranging between 5 per cent and 8 per cent at all stations except Madang, the most humid station, where daily variability is even lower. Recorded extreme maximum values reach 100 per cent at all four coastal stations and at Garaina, and reach 98 per cent at Goroka.

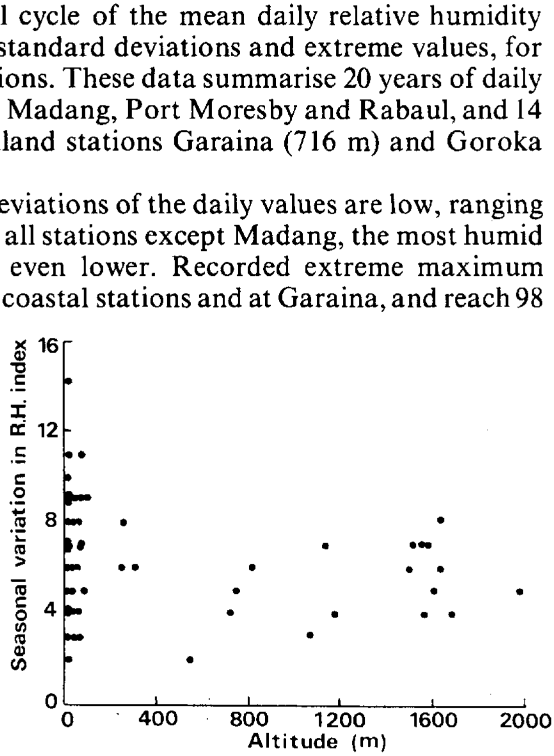


Fig. 6.4
Effect of altitude on seasonal variation in relative humidity index. The seasonal range is more limited at altitudes above 500 m, but there is no further change with elevation up to 2000 m.

Extreme minimum values of the relative humidity index are higher at the coastal stations than at the highland stations. The lowest daily relative humidity index recorded at Madang is 59 per cent, and extreme minima for other coastal stations lie between 45 per cent and 50 per cent. In the highlands, the lowest recorded relative humidity index at Garaina is 33 per cent and at Goroka it is a very low 28 per cent. Under such extremely dry atmospheric conditions evaporation rates are much accelerated and the stress on plant life in the highland areas is at its greatest.

Daily cycle of relative humidity

Figure 6.7 presents graphs of mean 3-hourly relative humidity values for January and July at nine coastal and two highland locations. It can be seen that relative humidity reaches its daily peak at dawn (0600 hr), when temperatures are lowest and the air is close to saturation in all regions except the highest peaks. As temperatures increase during the morning, and the difference between dry bulb and dew point temperature increases, relative humidities decrease steadily, the rate of decrease being less marked in the islands and wet coastal areas than in the drier lowlands and inland regions. Relative humidities reach their lowest daily values early in the afternoon, during the period when air temperatures and hence saturation vapour pressures reach their daily maxima. Subsequently, the onset of night brings lower temperatures and rising relative humidities which climb steadily until dawn of the following day.

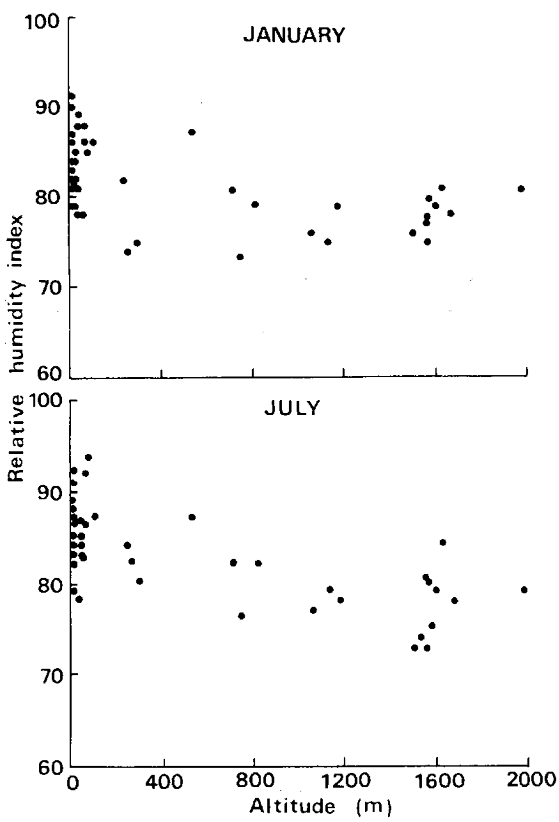
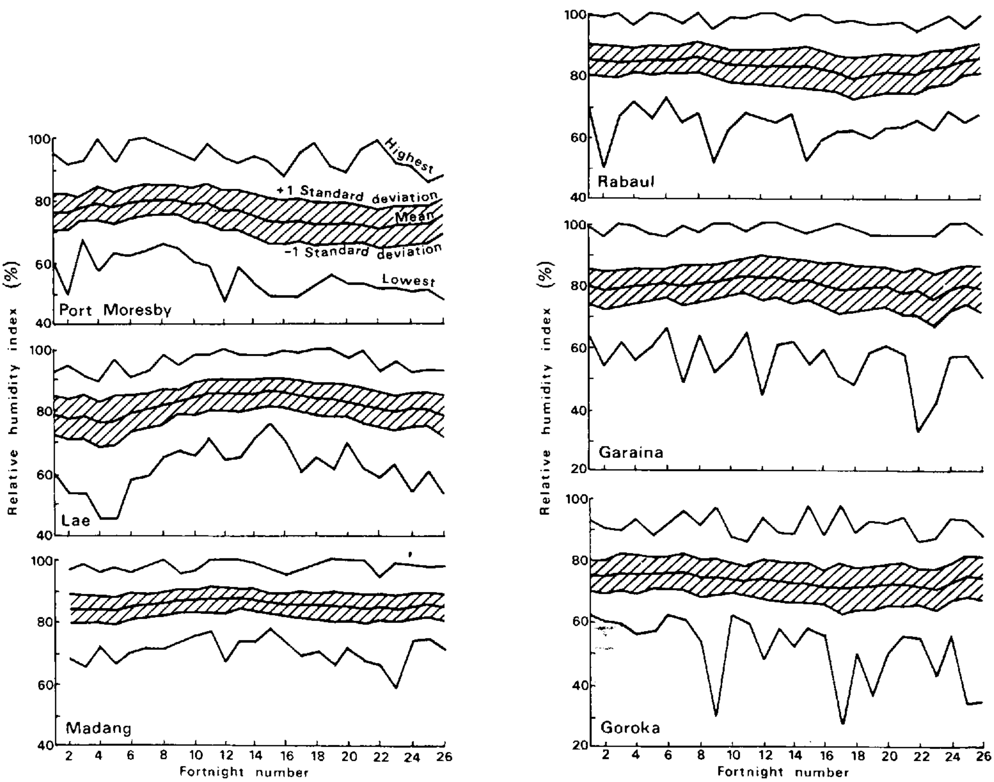


Fig. 6.5
Effect of altitude on mean monthly relative humidity index for January and July. The range of values is lower in the highlands than in the lowlands, but there is no noticeable decrease with increasing altitude between 200 m and 2000 m.

While the amplitude of the daily cycle at any particular location generally varies by only a few per cent throughout the year, there are marked variations in the diurnal range of relative humidity between different regions of PNG. The amplitude is least in the islands and the wetter coastal areas where maximum and minimum daily relative humidities differ by about 20 per cent, the cycle ranging from around 95 per cent at dawn to 75 per cent in the early afternoon. In the drier coastal areas such as around Port Moresby the diurnal range increases to around 30 per cent, with maxima of 95 per cent at dawn falling to minima of 65 per cent during the day.

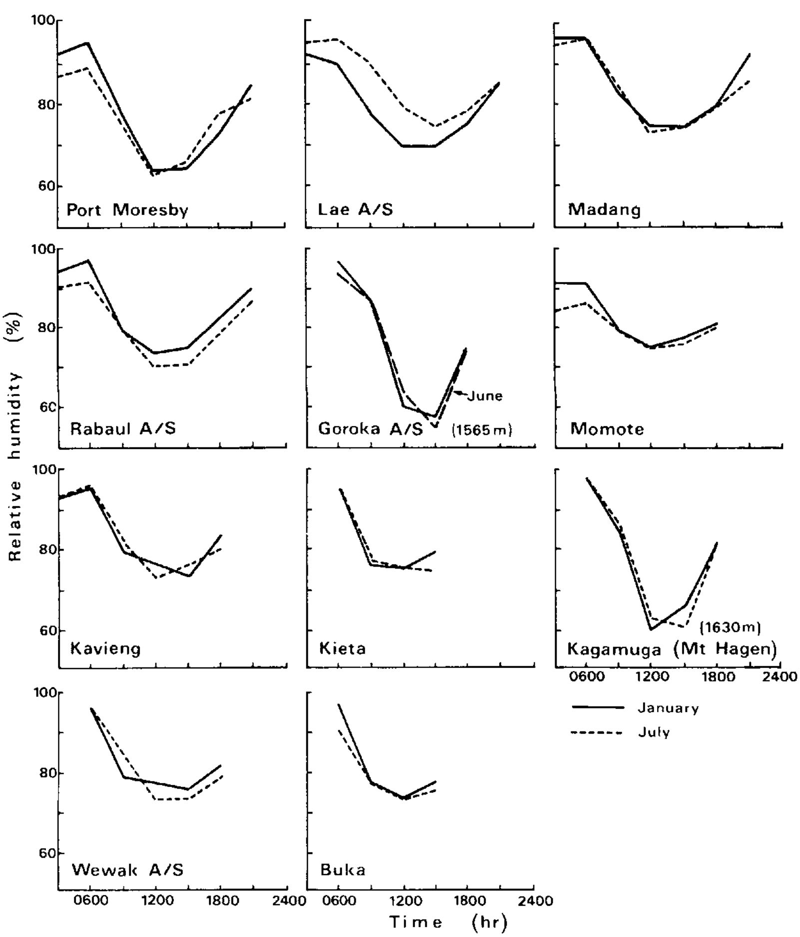
At inland lowland stations the diurnal range of relative humidity is even greater. This cannot, however, be illustrated by reference to measurements of relative humidity made at 3-hourly intervals throughout the day, as these data are available for only 11 stations in PNG, none of which is located in an inland lowland area. Comparisons must therefore be made by using the differences between the 0900 hr and 1500 hr relative humidity measurements, as these data are available for an additional thirty-nine PNG climate stations (see McAlpine *et al.* 1975). As a comparison, the (0900 hr-1500 hr) difference in relative humidity at Port Moresby is close to 12 per cent for most of the year while at six inland lowland stations the (0900 hr-1500 hr) difference remains at around 20 per cent throughout the year.

Fig. 6.6
Daily variation in relative humidity index by fortnights for selected stations. Hachured area encloses mean plus and minus one standard deviation. Lines outside hachured area are highest and lowest values on record.



Three-hourly measurements of relative humidity are available for only three stations above 500 m. These are Goroka (1565 m) and Kagamuga (Mt Hagen) (1630 m), and Pindaunde (3480 m on Mt Wilhelm), where incomplete hygrograph data have been recorded (Hnatiuk *et al.* 1976). Diurnal ranges of relative humidity derived from the 3-hourly data for Goroka and Kagamuga are close to 35 per cent throughout the year, with daily maxima of around 95 per cent at dawn falling to minima of 60 per cent during the day. This would indicate that the amplitude of the daily cycle of relative humidity is greater at higher altitudes than on the coast. As further confirmation of this observation, the (0900 hr-1500 hr) difference in relative humidity can be derived for a total of thirteen stations above 500 m. Although wide variation is encountered between stations at similar altitudes, the figures are generally higher than for coastal locations, while exhibiting no clear trend with increasing altitude up to 2000 m (Fig. 6.8). The relative

Fig. 6.7
Mean three-hourly relative humidities for January and July at nine coastal and two highland (Goroka and Kagamuga) stations. The diurnal range is least in the islands and wetter coastal areas, and increases in the drier lowlands and inland. In the highlands, diurnal ranges are generally higher than at coastal stations.



physiographic position of a highland station, which may be on a valley floor or slope, and its distance from surrounding mountains, are clearly of major importance in determining the magnitude of the diurnal range of relative humidity. This is illustrated by comparison of figures for Goroka, Kainantu and Aiyura, three stations at similar altitudes (1565 m) where the (0900 hr-1500 hr) differences in relative humidity are of the order of 28 per cent, 16 per cent and 9 per cent respectively.

The only measurements of relative humidity recorded at an altitude greater than 2000 m in PNG are provided by McVean (1968) and Hnatiuk *et al.* (1976), who discuss hygrograph traces taken at irregular intervals over a period of four years at Pindaunde (3480 m) on Mt Wilhelm. The traces did not show the normal diurnal cycle of relative humidity found at lower altitudes, but rather an almost continuous record of near maximum (100 per cent) relative humidities which was interrupted by irregular fluctuations occurring at any time of day or night.

Evaporation

Evaporation, the rate at which water is transferred from land, open water and vegetated surfaces to the atmosphere, is of importance in itself and also in so far as it is a main component of the hydrologic cycle (see Chapter 8).

Before 1967 the only evaporation records in PNG were for Australian standard sunken tanks at Port Moresby and Bubia, and for two lysimeters on Mt Wilhelm which were used for a short period to measure evapotranspiration at high altitudes (McVean 1968; Hnatiuk *et al.* 1976). For this reason, estimates of

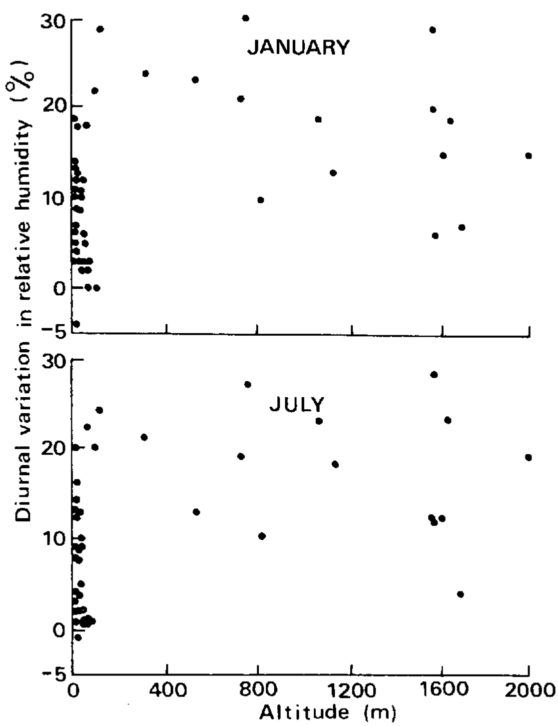


Fig. 6.8
Effect of altitude on diurnal variation in relative humidity (0900-1500 hr) for January and July. There is no clear trend with increasing altitude up to 2000 m.

Australian standard sunken tank evaporation calculated by the method of Fitzpatrick (1963) from screen temperature and humidity data provided the only basis for all previous work requiring evaporation inputs (for example SMEC 1970; McAlpine 1970). Unfortunately, apart from Port Moresby which is in any case atypical, and Bubia, the estimates could not be validated and so they will not be referred to again in the following discussion. They have, however, been tabulated elsewhere (McAlpine *et al.* 1975).

Since 1966 a network of seven US Class A pan evaporimeters has been installed gradually at stations now controlled by the PNG National Weather Service and more recently a further three US Class A pans have been installed by Bougainville Copper Limited (BCL) to monitor evaporation at key sites for their Bougainville Island operations. Seven of these ten instruments are at coastal locations, and the remainder are inland, at altitudes of 655, 750 and 1630 m. By using the evaporimeter data from this network and other climatic data from the climate station network it has been possible to make a comprehensive broad-scale study of evaporation rates in PNG. This study is described in a paper (Keig *et al.* 1979), which provides the basis for the following discussion of PNG evaporation regimes.

It was also possible in the course of this study to calculate mean monthly and annual estimates of evaporation for a limited number of stations using the Penman method (Penman 1948), which is one of several that fall into the category of 'combination' methods. These stations cover a total of seventeen locations (see Fig. 6.9), but this network is insufficient to allow reliable spatial extrapolation and construction of maps of Penman evaporation for PNG. The steps taken in deriving the Penman estimates, and the resulting values, are included in the paper by Keig *et al.* (1979). The values were found to correlate significantly at the 1 per cent confidence level (r=0.84) with the Class A pan estimates discussed below.

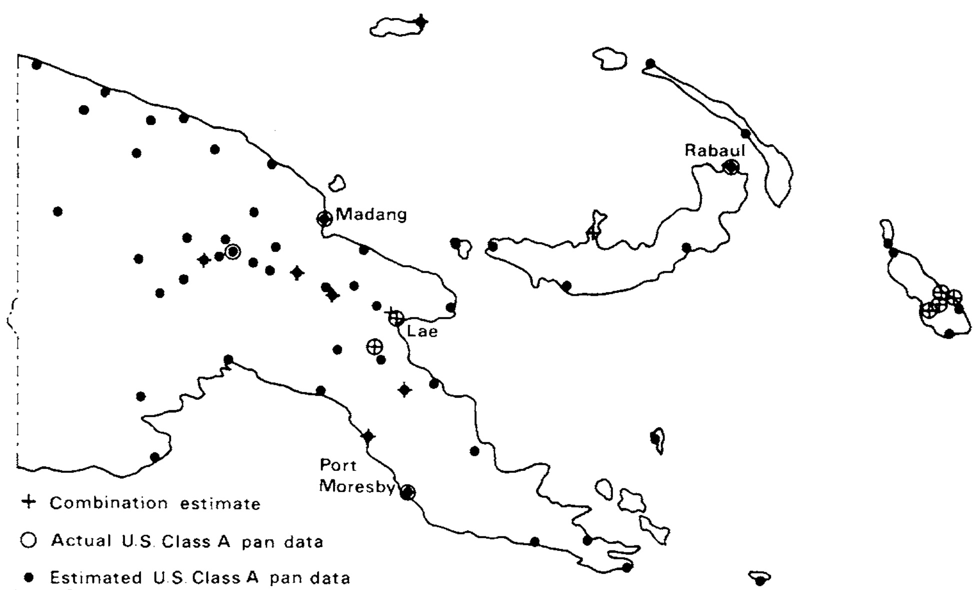


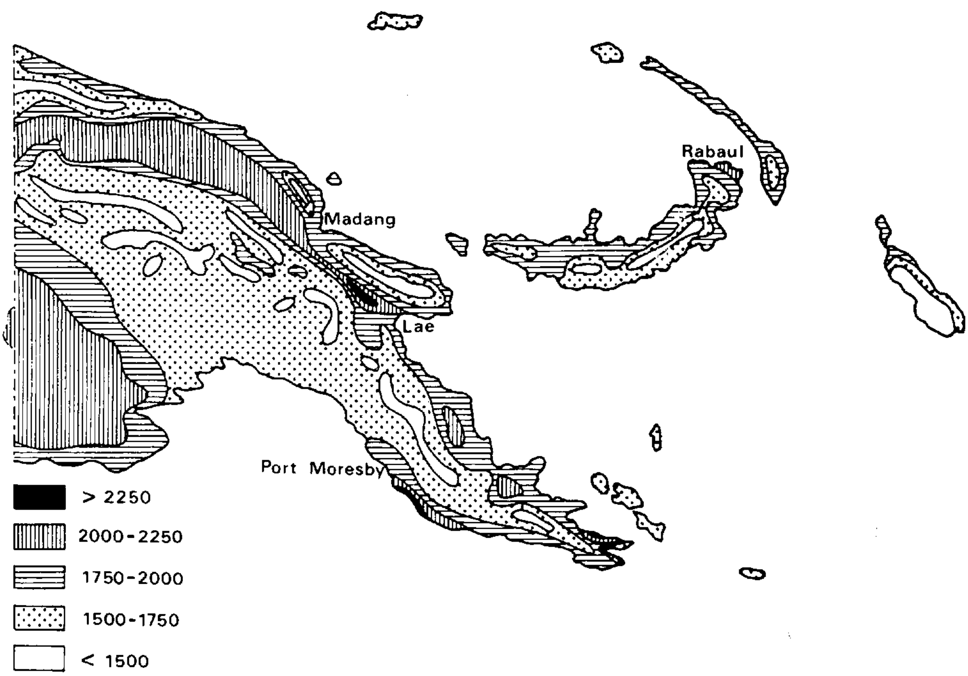
Fig. 6.9
Location of PNG stations for which actual evaporation data are available or estimates have been calculated (after Keig *et al.* 1979).

US Class A pan evaporation estimates

Estimates of mean monthly and annual US Class A pan evaporation at sixty-four stations in PNG have been derived by applying Christiansen's (1968) method to mean monthly temperature, relative humidity, sunshine and wind data. The locations of these stations are shown in Fig. 6.9. As described by Keig *et al.* (1979), the method was calibrated for seven stations where US Class A pan evaporimeters are installed, and the coefficients so derived were then applied to the climatic data for other stations not equipped with evaporimeters. The particular set of coefficients which was to be applied to each station was determined on the basis of physiographic location and rainfall amount and seasonality. The resulting estimates of US Class A pan evaporation for sixty-four reasonably well-distributed locations were then used to construct a map of annual evaporation rates for PNG (Fig. 6.10). The estimates have been tabulated by McAlpine *et al.* (1975).

The validity of the estimation method was investigated by comparing estimated and actual evaporation for three evaporimeters which were not included in the initial calibration procedure. The correlation coefficient between actual and estimated data was significant at the 1 per cent confidence level (r=0.84), indicating that the Christiansen method could be regarded as an effective estimator of evaporation. The paper by Keig *et al.* (1979) also demonstrated that US Class A pan evaporation in PNG was approximately equal to evaporation from extensive free water surfaces, as estimated by the Penman equation. This con-

Fig. 6.10
Estimated annual US Class A pan evaporation for PNG (mm). Rates are highest in lowland areas, particularly in the dry coastal regions and the inland lowland valley systems.



trasts with the situation in temperate regions, where Penman estimates and actual measured evaporation from large water surfaces are assumed to be 70 per cent of pan evaporation. This is caused by changed relativities of the energy balance components under humid tropical conditions.

Spatial variation in evaporation rates

The US Class A pan estimates indicate that annual evaporation rates in the PNG lowlands are of the order of 2300-2400 mm per annum and that lower rates could be expected at higher altitudes. The distribution of estimated annual evaporation is mapped in Fig. 6.10 and will be discussed in terms of broad geographic regions.

Lowlands. The most extensive occurrences of the lowland areas are those that occupy the major inland valley systems (for example, Sepik, Fly and Ramu Rivers) and which experience north-west season rainfall maxima. Estimated US Class A pan evaporation in these areas ranges in annual total from 2000 to 2300 mm.

The remainder of lowland PNG comprises a coastal and an adjacent narrow foothill zone. Within this zone differing evaporation regimes can be distinguished. The highest rates occur in the limited dry coastal and lowland areas with annual rainfalls less than 2000 mm, where average annual evaporation ranges from 1900 to 2400 mm. The most extensive coastal climate has a north-west season rainfall maximum, an annual average rainfall greater than 2000 mm, and a reasonably distinct degree of rainfall seasonality. Here mean annual US Class A pan evaporation varies from 1800 to 2200 mm. Those lowland areas with either a south-east season rainfall maximum or no seasonality at all have the lowest estimates of US Class A pan evaporation. In areas of south-east season rainfall maximum annual rates range from 1400 to 1900 mm, while in the uniform rainfall regions annual totals range from 1300 to 1700 mm.

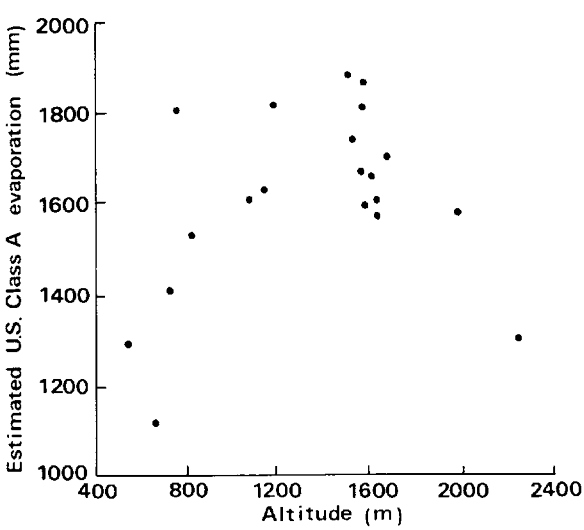


Fig. 6.11
Effect of altitude on estimated annual US Class A pan evaporation. There is no clear trend with increasing altitude between 400 m and 2000 m.

Highlands. The relationship between evaporation and altitude is complex. Theoretically the decrease in atmospheric pressure with increasing altitude should cause an increase in evaporation rates if all other factors remained constant. However, the decrease in temperature with altitude more than offsets the effect of falling pressure and the overall result is a general decrease in evaporation with increasing height above sea level. Superimposed on this general trend are the effects of local variations in other climatic elements such as relative humidity and wind. These can become the dominant factors that determine local evaporation rates, effectively masking any expected general altitudinal trend. It is therefore inappropriate to develop a relationship linking evaporation solely with elevation. This has also been demonstrated in the equatorial highlands of East Africa where 'no clear trend is discernible' in estimates of evaporation between 1000 and 3000 m (Brown and Cochemé 1973).

A similar situation occurs in the PNG highlands, where estimates of US Class A pan evaporation derived by the Christiansen method show poor altitudinal relationships (see Fig. 6.11). However, there is clearly an eventual decrease in evaporation with altitude since the most common annual evaporation regimes in the lowlands lie between 1700 and 2000 mm while limited lysimeter data recorded at 3480 m on Mt Wilhelm (McVean 1968; Hnatiuk *et al.* 1976), when adjusted to an approximate free water equivalent, give an annual evaporation of about 500 mm.

All estimates of US Class A pan evaporation in the highland areas relate to stations with altitudes varying from 500 to 2240 m and include a wide range of topoclimatic situations with considerable variations in mean daily relative humidity, a factor to which the Christiansen formula is particularly sensitive. For instance, stations at lower altitudes (500-1200 m) situated on coastal ranges (for example Lumi, Panguna) have particularly high relative humidities (86, 89 per cent) and consequently low annual evaporation rates (1100-1300 mm). Stations at similar altitudes but situated within the central highlands (for example Menyamya) have lower relative humidities (75, 76 per cent) and rates of evaporation similar to higher inland stations.

The total US Class A pan evaporation per annum at stations between 1200 and 2000 m is generally in the range of 1600-1800 mm. All these stations are located in the floors and lower slopes of the large populated intramontane valleys of the central highlands and have relative humidities of 75-80 per cent, which are lower than those of the coastal ranges. Although no data are available, evaporation on the more frequently clouded mountains which surround these intramontane valleys could be assumed to be less than on the valley floors, a result of the diurnal pattern of moisture movement in these intramontane valleys (see Chapters 2 and 3).

Above 2000 m, estimates of US Class A pan evaporation are available for only one station, Tambul (2240 m), where annual evaporation falls to 1300 mm.

Seasonal variation in evaporation

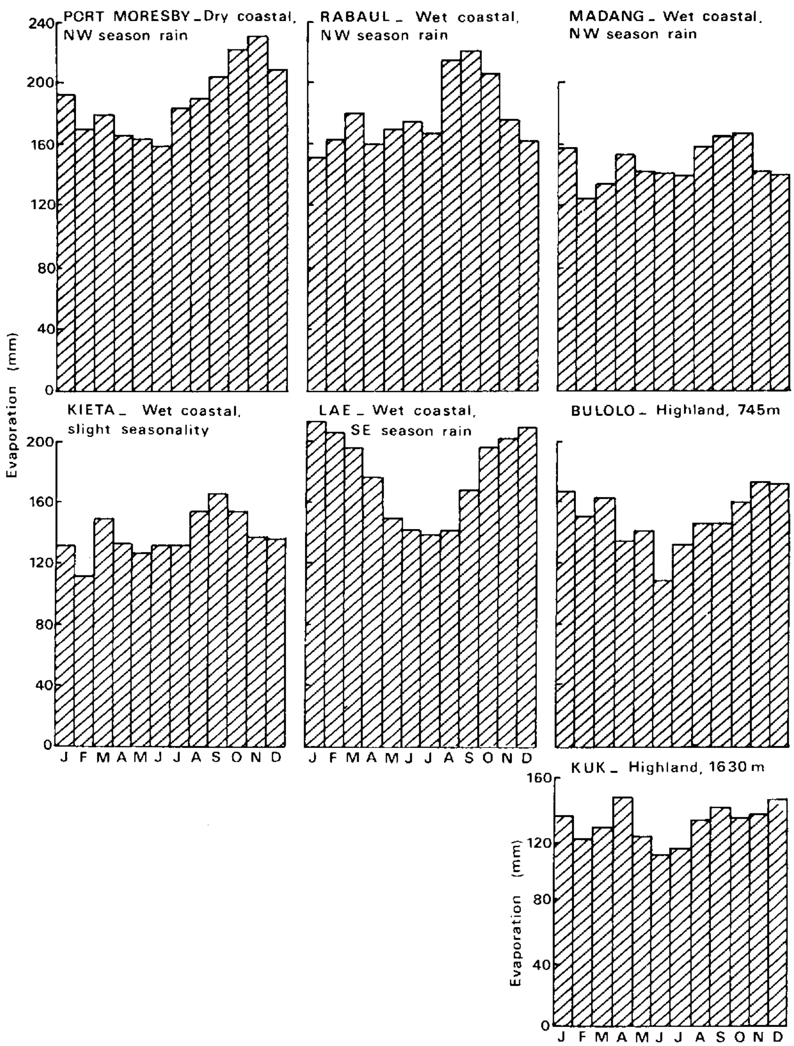
The monthly US Class A pan estimates indicate that there is little seasonal variation in evaporation rates. The difference between the maximum and minimum monthly evaporation, that is, the seasonality, is greatest for stations located in the dry lowland areas around Port Moresby and in the drier Markham

Valley, where it reaches about 70 mm. In other coastal and inland lowland areas, and at altitudes up to 1200 m, seasonal variation in evaporation rates is about 50 mm. This value drops to about 35 mm for stations between 1200 and 2240 m.

Figure 6.12 shows mean monthly US Class A pan evaporation for seven stations for which actual data are available. The following discussion of monthly variation in evaporation rates is based on average values derived from the monthly estimates for stations in similar physiographic locations and having similar rainfall amounts and seasonalities.

Monthly evaporation reaches a peak of about 210 mm in November in the dry coastal and lowland regions and falls to a minimum of about 145 mm in June. At

Fig. 6.12
Seasonal variation in measured US Class A pan evaporation (mm). Seasonality is generally low, with minimum monthly evaporation rates occurring in December-May in areas with north-west season rainfall maxima, and in July-September in areas with south-east season rainfall maxima



the wet coastal and inland lowland stations experiencing their highest rainfall in the north-west season, monthly evaporation rises to about 200 mm in August-November, and falls to about 150 mm in December-May. Those wet coastal stations experiencing rainfall maxima in the south-east season show similarly reversed seasonality in evaporation regimes, and lower monthly evaporation rates than the north-west season stations. At the south-east season stations, monthly evaporation reaches a maximum of about 165 mm in November-January and falls to a minimum of about 120 mm in July-September. The lowest monthly evaporation rates in the lowlands are found at those stations located in zones of high rainfall with little or no seasonality. Here monthly evaporation reaches about 155 mm in August-October and drops to about 115 mm in February-June.

At mid-altitude stations located between 500 and 1200 m, monthly evaporation rises to about 145 mm in October-January and falls to about 90 mm in June. As discussed in the preceding section, evaporation shows no clear trend with altitude up to 2240 m, and monthly evaporation rates at stations between 1200 and 2240 m are actually somewhat higher than corresponding values for stations between 500 and 1200 m. Thus in the populated highland valleys monthly evaporation reaches a maximum of about 160 mm in September-December and falls to a minimum of about 120 mm in February-June.

7 Daylength, Cloudiness, Sunshine and Radiation

Papua New Guinea is located close to the equator, in a region where seasonal differences in daylength and extraterrestrial radiation are slight. However, the broad-scale meteorological controls operating over PNG (see Chapters 2 and 3) and the rugged physiography of the country itself give rise to considerable seasonal, synoptic and local-scale variability in the amount and extent of cloud cover. This in turn regulates the reception of radiation and sunshine at the earth's surface. The following discussion will deal in turn with each of these various factors affecting the reception of solar energy in the PNG region.

Daylength, sunrise and sunset

The PNG mainland and islands lie within the latitudinal range 0-12°S. Consequently, only very slight variation is found in the duration of daylight between the northernmost and southernmost regions. As shown in Fig. 7.1, the longest day, occurring in December, varies from 12 hours 14 minutes at Lorengau (2° 1'S) to 12 hours 40 minutes at Port Moresby (9°27'S), a difference of only 26 minutes. Similarly, the shortest day, which occurs in June, is 12 hours 0 minutes long at Lorengau, and 11 hours 34 minutes long at Port Moresby. The difference between the longest and shortest days at Lorengau is only 14 minutes, and at the higher latitude of Port Moresby this difference increases to 1 hour 6 minutes.

Papua New Guinea lies entirely within time zone 'K', which is 10 hours ahead of Greenwich Mean Time. Local times of civil sunrise and sunset at five locations are plotted for each month in Fig. 7.2a and b. While there is little difference between Port Moresby, Lae and Lorengau (longitudes 147°12'E, 147°0'E, 147°19'E respectively), the times of civil sunrise and sunset at Kieta in the east (6°13'S, 155°38'E) are about one hour in advance of those at Vanimo (2°41'S, 141°17'E) in the west. Sunrise is earliest in November, when it occurs at 0511 hr at Kieta and 62 minutes later (0613 hr) at Vanimo, while in July sunrise is latest, occurring at 0550 hr at Kieta and 52 minutes later (0642 hr) at Vanimo. Times of civil sunset range from 1729 hr at Kieta to 1832 hr at Vanimo in May, a difference

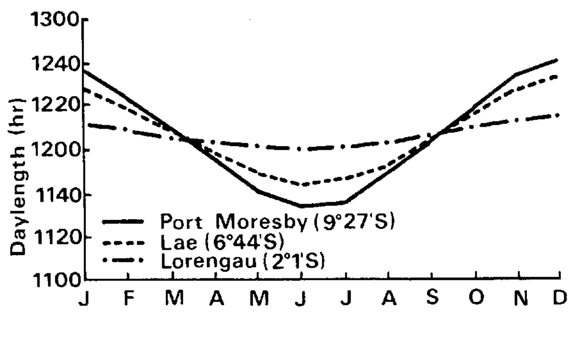


Fig. 7.1
Monthly variation in duration of daylength. Because of its location close to the equator, PNG experiences only very slight variation between the northernmost and southernmost regions.

of 63 minutes, and from 1801 hr at Kieta and 1855 hr at Vanimo in February, a difference of 54 minutes. These data were calculated using computer routines developed by Goodspeed (1975).

Cloudiness

Meteorological satellite imagery has been used to derive maps and charts of relative cloudiness on both world and regional bases averaged over varying time periods (Taylor and Winston 1968; Sadler 1967; Godshall *et al.* 1969; Atkinson and Sadler 1970; Miller *et al.* 1971). On all such maps the Melanesian region is shown to be covered by cloud for most of the year, with maximum cloudiness occurring at the height of the north-west and south-east seasons (see Chapter 2, Fig. 2.4). This is shown very clearly in the imagery presented by Miller *et al.* (1971) showing three-monthly means of relative cloud cover for the period 1967-70. These indicate that at 1400-1600 hr local sun time cloudiness exceeds 5 oktas over most of PNG during December-February and June-August. The orographic influence of the central highlands and the island mountain chain is evidenced by their persistently heavier cloud cover and in March-May mean cloudiness exceeds 5 oktas only in these mountainous regions. Somewhat cloudier conditions occur during September-November than during March-May, although the south-western plateau inland from Daru still remains relatively cloud-free while the central highlands, Torricelli Ranges and New Britain mountain chain are all covered by cloud in excess of 5 oktas at 1400-1600 hr.

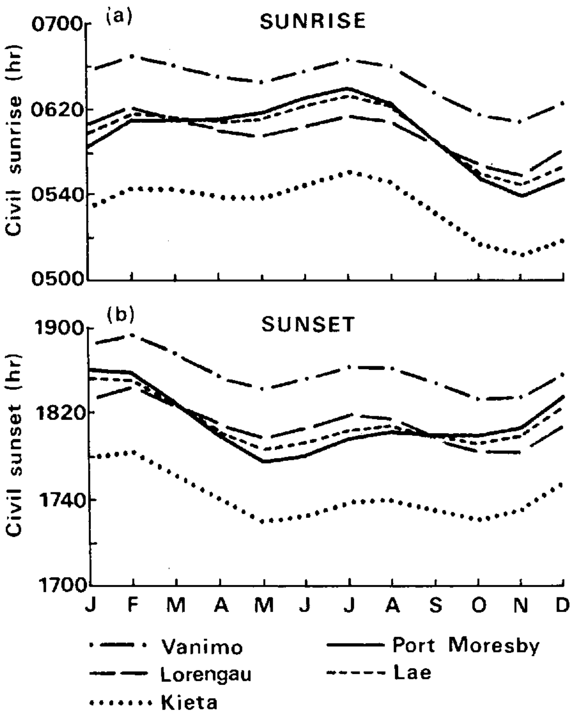


Fig. 7.2
Monthly variation in times of civil sunrise and sunset for selected stations. Times at Kieta in the east are about one hour in advance of those at Vanimo in the west.

Fig. 7.2a—Civil sunrise

Fig. 7.2b—Civil sunset

The information on cloud cover provided by the satellite imagery is supplemented by surface observations at 0900 and 1500 hr local time for some sixty-four locations in PNG (McAlpine *et al.* 1975), which broadly agree with the summarised satellite data. In Fig. 7.3, cumulative frequency distributions of total cloud cover at 0900 and 1500 hr are plotted by fortnights for six stations. In all cases it is clear that greatest cloudiness occurs during the north-west season, and at Lae a second cloudiness maximum occurs during the south-east season when

Fig. 7.3
Cumulative probabilities of cloudiness (oktas) by fortnights for selected stations. Each curve shows the number of days per fortnight, averaged over all years of record, when cloud cover at the particular station was less than or equal to the stated amount.

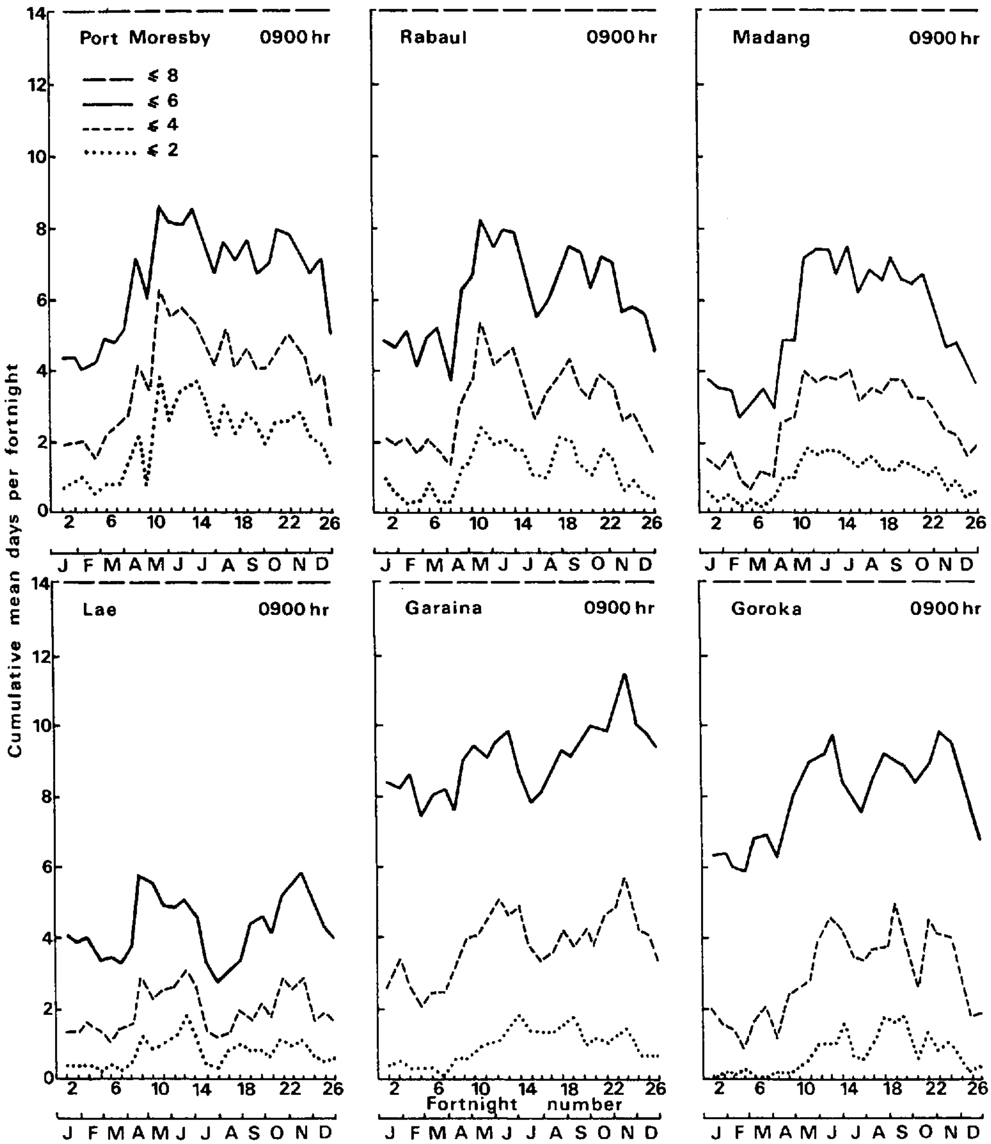


Fig. 7.3a—0900 hr

rainfall at Lae reaches the peak of its annual cycle. Of the four lowland stations, cloudiness is less at 0900 hr at Port Moresby and Rabaul than at Madang and Lae during corresponding periods of the year, Lae being the cloudiest of the four locations. During the course of the year at Port Moresby and Rabaul, cloud cover does not exceed 4 oktas on approximately 2-6 days per fortnight, while at Madang cloud cover does not exceed 4 oktas on 1-4 days per fortnight and at Lae on 1-3 days per fortnight.

Whether a particular location has heavier cloud cover in the mornings or in the afternoons depends on the results of the superimposition of the daily cycle of local effects on the broad-scale circulation. Of the coastal stations shown in Fig. 7.3, there is little difference between the cloud cover at 0900 hr and 1500 hr at

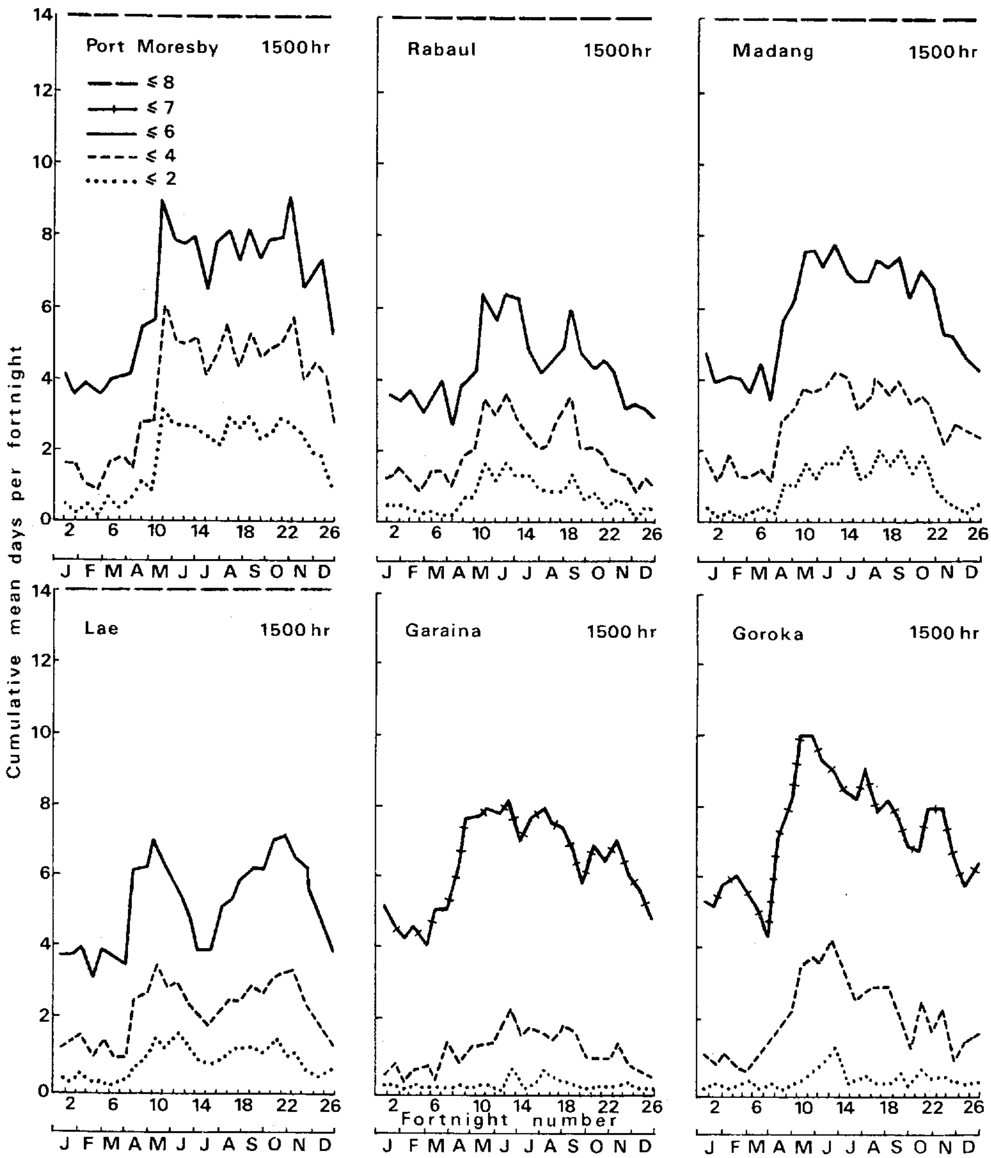


Fig. 7.3b—1500 hr

Port Moresby and Madang, while Rabaul is cloudier at 1500 hr, when cloud cover does not exceed 4 oktas on approximately 1-3 days per fortnight during the course of the year.

Lae is generally less cloudy at 1500 hr than at 0900 hr, a consequence of the fact that rainfall is higher during the night-time hours than during the day at Lae (see Chapter 4). Differences in the daily pattern of cloudiness are particularly marked between highland locations, although these areas are generally cloudier than lowland and coastal stations in the afternoons. Of the two examples of highland stations shown in Fig. 7.3, Garaina (716 m) is considerably more cloudy at 1500 hr than at 0900 hr, with cloud cover not exceeding 4 oktas on only 1-2 days per fortnight during the course of the year. At Goroka (1565 m), however, cloud cover at 1500 hr follows relatively the same frequency pattern throughout the year as at 0900 hr.

Fogs are a frequent occurrence in the mountainous regions of PNG, although there are insufficient recorded data to provide a quantitative indication of their frequency. They also occur more rarely on coastal and inland lowland plains. The colder, rarefied mountain air, nocturnal radiational cooling, and high moisture content from diurnal shower activity supplemented by moisture from swamps and lakes, all contribute to the formation of fog and mist in highland valleys and basins during the early morning. As a result, airfields in the highlands are subject to closure before about 0900 hr because of fog.

Fogs are comparatively rare in most coastal regions of PNG, except along the Gulf of Papua coast between Kerema and Port Moresby, where they often present a serious hazard to aircraft and coastal shipping, particularly in the south-east season. On coastal and inland plains such as the Sepik and Fly River basins, fogs may form on clear nights after rain, or on swamps, marshes, or about river mouths. Over the open ocean, however, fogs are practically unknown owing to high sea temperatures in the area which contribute to marked instability of the air in the low layers, which in turn tends to inhibit fog.

On most days clouds can envelop the mountain peaks and higher slopes, particularly during and immediately subsequent to a rainy spell, causing sudden, and often prolonged, periods of poor visibility. Sometimes under such conditions the cloud does not lower sufficiently to close the well-known 'gaps' between mountain ranges. Light aircraft pilots have been known to take advantage of this to maintain flying operations but there is a very real risk that the cloud base will suddenly lower, thus closing the 'gap' with little or no warning. In some places, Edie Creek for example, fog occurs almost every afternoon due to the enveloping of the slopes by cloud.

Sunshine

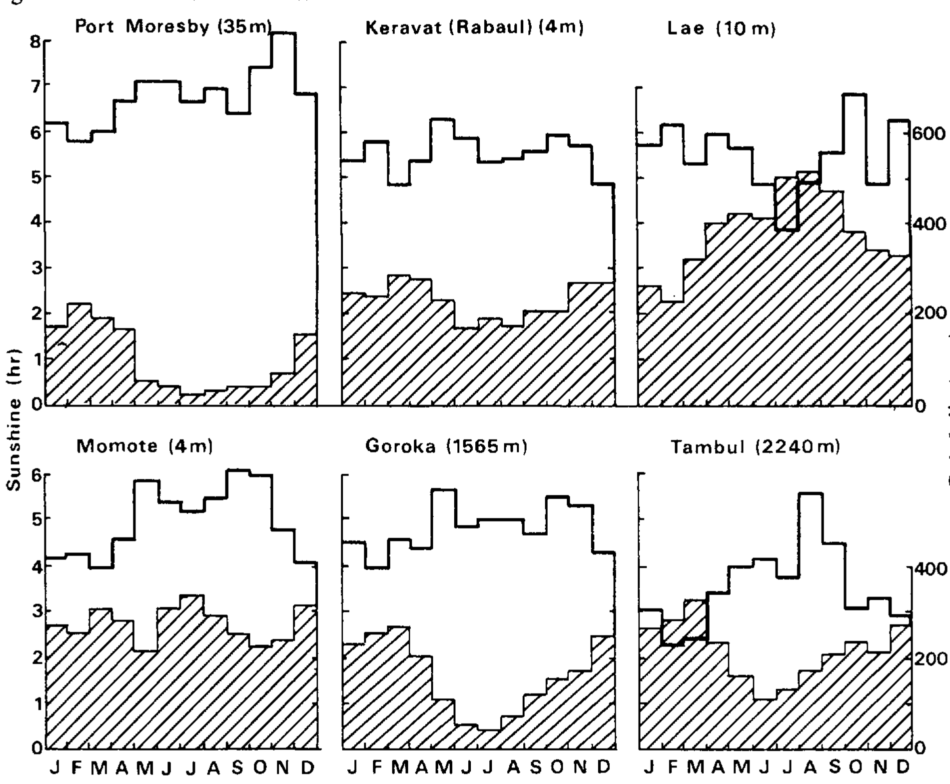
The number of hours of bright sunshine per day is recorded at some twenty-three locations in PNG, by stations operated either by the National Weather Service or the Department of Primary Industry (DPI), formerly the Department of Agriculture, Stock and Fisheries (DASF). Monthly means for all National Weather Service stations, and for some DPI/DASF stations, have been presented by McAlpine *et al.* (1975). Data for additional DASF stations are given by Mendham (1971b).

Figure 7.4 shows monthly variation in daily sunshine hours for four coastal and two highland stations, together with mean monthly rainfall for these stations. It will be seen that there is an inverse relationship between sunshine hours and rainfall at all six locations, the highest sunshine hours per day being recorded in those months in which rainfall is least, and vice versa. The driest station, Port Moresby, received the most sunshine, ranging from a monthly minimum of 5.8 hr per day in February, the month of highest rainfall, to a monthly maximum of 8.2 hr per day in November, with a mean annual total of 2478 hr. Of the two island stations, more sunshine is recorded at Keravat on New Britain (2034 hr per annum) than at Momote on Manus Island (1829 hr per annum), which also shows more seasonal variation in sunshine values.

The south-east season rainfall maximum at Lae is reflected in the monthly sunshine minimum of 3.5 hr per day in July, while the monthly sunshine maximum of 6.9 hr per day occurs in October. The mean total annual sunshine for Lae is 2012 hr.

Sunshine figures are lowest at the two highland stations, ranging from 4.0 hr per day in February to 5.7 hr per day in May at Goroka (1565 m), and from 2.3 hr per day in February to 5.6 hr per day in August at Tambul (2240 m). Mean total annual sunshine hours are 1764 at Goroka, which is only slightly less than the corresponding figure for Momote (1829 hr). However, a mean of only 1292 hr of sunshine is recorded annually at Tambul. These lower sunshine figures in the

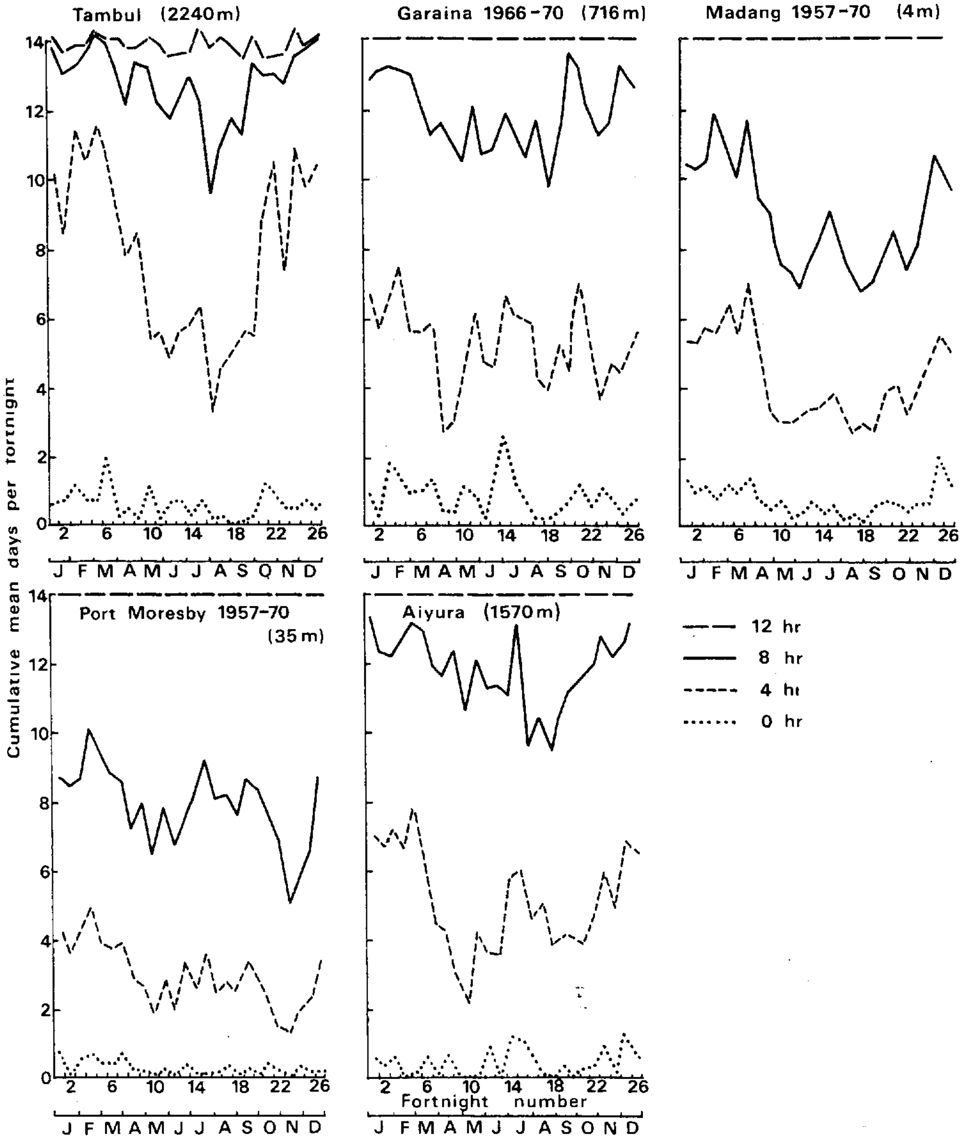
Fig. 7.4
Monthly variation in mean daily sunshine hours (dark line) and mean monthly rainfall (shaded) for selected stations. There is an inverse relationship between sunshine hours and rainfall in both highland and coastal locations.



highlands are reflected in Kalma's (1972) estimations of lower annual global solar radiation levels over the central highlands (see Fig. 7.11). They result from the frequent occurrences of fogs and mists in the early mornings, which can last until about 0900 hr, and the heavy cloud cover over the central highlands during most of the year.

Figure 7.5 shows the cumulative number of days per fortnight on which sunshine duration reaches specified levels at five PNG stations. The probability of days with no sunshine is low at all locations, being less than two days per fortnight throughout the year at Madang, Garaina, Aiyura and Tambul, and less

Fig. 7.5
Cumulative probabilities of sunshine duration by fortnights for selected stations. Each curve shows the number of days per fortnight, averaged over all years of record, when sunshine duration at the particular station was less than or equal to the stated number of hours.



than one day per fortnight at Port Moresby. This is the sunniest of the five stations, with the highest probability of daily sunshine durations between eight and twelve hours. The three highland stations, Garaina, Aiyura and Tambul, record less sunshine than do Port Moresby and Madang, the highest altitude station—Tambul (2240 m)—being least sunny of the five.

As discussed earlier, sunshine duration shows an inverse seasonal relationship with rainfall, and this is evidenced in Fig. 7.5 by the fact that the probabilities of lower sunshine durations are highest during the north-west season, when monthly rainfall at all five stations reaches the peak of its annual cycle.

Relations between sunshine, daylength and cloud cover

The relation between mean daily recorded sunshine hours per month (n) and daily maximum possible duration of bright sunshine (daylength) for each month (N) is shown in Fig. 7.6 for four locations: Port Moresby, Lae, Goroka and Momote. Comparison with Fig. 7.1 shows that the regular annual variation in daylength is entirely masked by the more irregular fluctuations in recorded sunshine hours when n/N is considered. The general pattern of monthly variation in n/N is similar to that shown by the sunshine data for the four stations, as discussed in the preceding section. Values of n/N are highest at Port Moresby, ranging from 0.47 in February to 0.65 in November. The patterns for Momote and Goroka are relatively similar, with n/N values for Momote ranging from 0.33 in March to 0.50 in September, and values for Goroka ranging from 0.33 in February to 0.48 in May. The reversed seasonality at Lae is again evident in the annual cycle of n/N values, which range from 0.30 in July to 0.56 in October.

For each month, that part of a day during which bright sunshine is obscured by cloud cover can be calculated as 1—n/N. Using data for sixteen stations where twice-daily cloud cover measurements were made in addition to measurements of duration of bright sunshine, Kalma (1972) calculated by linear regression the approximate relationship $n/N = 1.101 - 0.884\ c_{av}$, where c_{av} is mean monthly cloud cover.

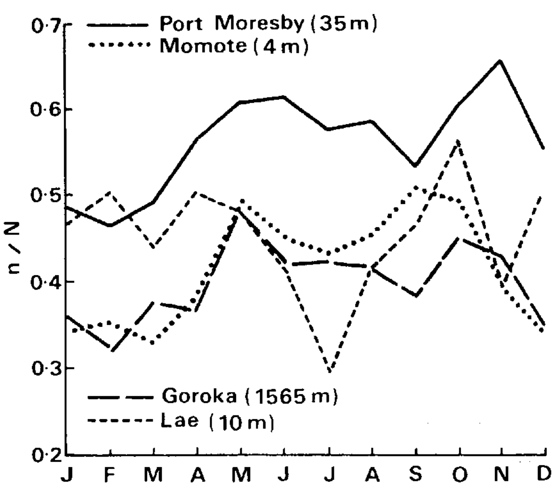


Fig. 7.6
Annual variation in value of n/N, where n is the mean daily recorded sunshine hours per month, and N is the daily maximum possible duration of bright sunshine (daylength) for the same month

Radiation

The low-latitude regions of the earth's surface receive more extraterrestrial radiation in the course of a year than do the higher latitudes, and there is only slight variation throughout the year in the amount of radiation received. The earth's energy balance is maintained by the poleward movements of the general circulation which transport heat energy away from tropical areas. Measurements of incoming solar radiation are not, however, widely recorded, as the necessary instrumentation is complex and expensive. Kalma (1972) has used radiation and sunshine data for Port Moresby, Rabaul-Kerevat and Jayapura-Sentani in Irian Jaya to establish the relationships between total radiation received on a horizontal surface on earth and radiation received on a horizontal surface extraterrestrially, and also between the actual duration of bright sunshine and the maximum possible duration of bright sunshine. In another study involving radiation measurements, Mendham (1971a) has compared radiation and sunshine data recorded at Keravat (West New Britain) and Mosa (East New Britain) and related them to oil palm growth.

As discussed by Kalma (1972), there is little difference in extraterrestrial radiation in the PNG region over the course of a year. If the extraterrestrial radiation at 12° S is expressed as the ratio of that at the equator, the calculated values are 1.10 in January, 0.92 in April, 0.85 in July and 1.03 in October. Extraterrestrial radiation values at Port Moresby, Rabaul and Jayapura-Sentani in Irian Jaya are tabulated by McAlpine *et al.* (1975). Because of the similarity of these values throughout PNG, the observed spatial and temporal variations in global solar radiation levels can be attributed mostly to differences in cloud cover, as discussed earlier, rather than in extraterrestrial radiation.

Figure 7.7 shows mean daily global solar radiation for each month at Port Moresby, Rabaul and Jayapura-Sentani. These data have been presented in tabular form by McAlpine *et al.* (1975). Radiation is lowest in May to July,

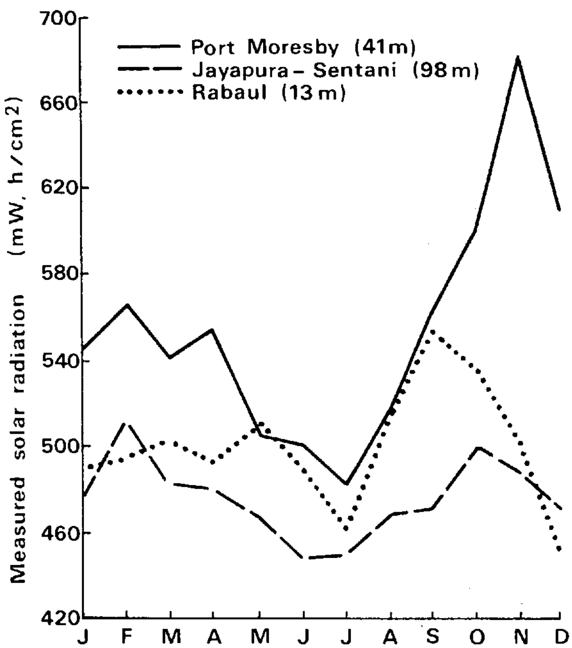


Fig. 7.7
Mean daily global solar radiation per month at three New Guinea stations. Radiation is lowest in May to July, and thereafter increases steadily until heavy cloud cover associated with the onset of the north-west season lowers radiant energy levels in the last months of the year

values of 483 mW-h/cm² and 462 mW-h/cm² being recorded in July at Port Moresby and Rabaul respectively. Later in the year there is a steady increase in radiation levels, until the heavy cloud cover associated with the onset of the north-west season results in lower radiant energy during December and the early months of the year. Radiation levels are at their highest in September at Rabaul (552 mW-h/cm²) and in November at Port Moresby (683 mW-h/cm²). Less radiation is received throughout most of the year at Jayapura-Sentani than at the two stations in PNG, where Rabaul receives considerably less radiation than does Port Moresby. These differences reflect the higher precipitation rates at Jayapura-Sentani (2523 mm annually) and Rabaul (2014 mm annually), which are associated with heavier cloud cover and less pronounced seasonality than at Port Moresby (1214 mm).

Figure 7.8 demonstrates a similar relationship between the three stations when mean daily global solar radiation per month (Q) is expressed as a ratio of mean daily total radiation per month received extraterrestrially (Q_A). The Q/Q_A values for Port Moresby vary from 0.50 to 0.63, while at Rabaul only 0.44 to 0.56 of extraterrestrial radiation is received at the earth's surface during the course of the year.

During the months of lower rainfall in the second half of the year, some indication of the widely-found time lag of about one month between the annual cycle of global solar radiation and mean air temperature (Prescott and Collins 1951) is seen at both Rabaul and Port Moresby (Fig. 7.9). This simple relationship is, however, masked during the higher rainfall, and hence cloudier, months early in the year.

From these radiation data, together with sunshine and cloudiness records for additional locations, Kalma (1972) has constructed maps of global solar radiation for January, April, July and October, as well as the annual total global solar radiation. The portions of these maps covering PNG are reproduced in Figs. 7.10a to 7.10d, and in Fig. 7.11.

In his discussion of the annual variation in global solar radiation over New Guinea, Kalma finds that the orientation of belts of equal insolation is approximately NW-SE throughout the year, although a zonal pattern would be expected from the seasonal migration of the zone of maximum extraterrestrial insolation. Fitzpatrick *et al.* (1966) have noted a similar asymmetric distribution of rainfall regimes in PNG, and they attribute this to the contrasting effects on the general atmospheric circulation of the proximity of the Australian continent, the vast sea surfaces of the Pacific and the major meteorological barrier of the central

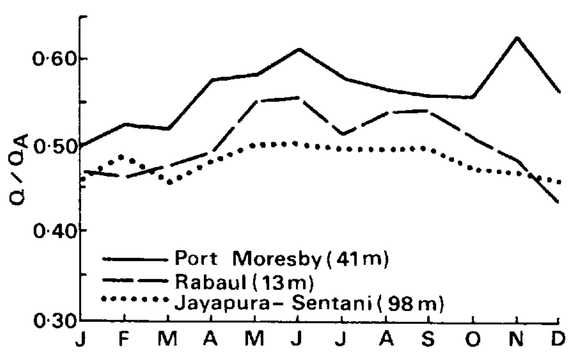


Fig. 7.8
Ratio of mean daily global solar radiation per month (Q) to mean daily total radiation per month received extraterrestrially (Q_A)

highlands of New Guinea. These factors also contribute to the asymmetric patterns of cloudiness and insolation.

In January (Fig. 7.10a) at the height of the north-west season, the belt of low radiation associated with the location of the inter-tropical convergence zone (ITCZ) reaches its most northerly position. Lowest daily values of about 410 mW-h/cm² are found over New Britain, with the exception of the Gazelle Peninsula. Daily values are highest along the coastal strip from Bereina to Port Moresby, reaching about 600 mW-h/cm² at Bereina. The major portion of the central highlands received between 450 and 475 mW-h/cm².

In April (Fig. 7.10b), maximum daily values are found in the Port Moresby region (540 mW-h/cm²) and around Kavieng (540 mW-h/cm²). The belt of low radiation associated with the ITCZ has moved southwards from its position in January, and minimum values are found over most of the central highlands.

By July (Fig. 7.10c), the middle of the south-east season, the belt has reached its most southerly position and minimum daily values of radiation (325-350 mW-h/cm²) are found around Kikori. The highest daily values of about 520 mW-h/cm² are found in the Kavieng area and values of 470 mW-h/cm² occur around Port Moresby.

In October (Fig. 7.10d), the belt of low radiation has moved northwards again and occupies an intermediate position over the central highlands, where minimum daily values of 475-500 mW-h/cm² are found. Maximum daily values of

Fig. 7.9
Comparison of annual cycles of global solar radiation, mean temperature and rainfall

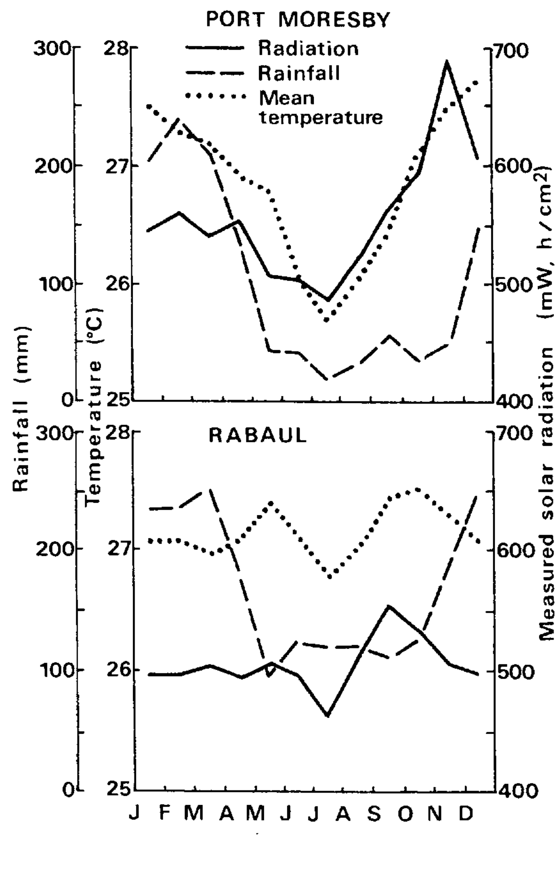


Fig. 7.9a—Port Moresby

Fig. 7.9b—Rabaul

Fig. 7.10

Distribution of global solar radiation for January, April, July and October expressed as mean daily values in mW-h/cm² (from Kalma 1972). The belt of low radiation associated with the location of the ITCZ reaches its most northerly position in January and its most southerly position in July

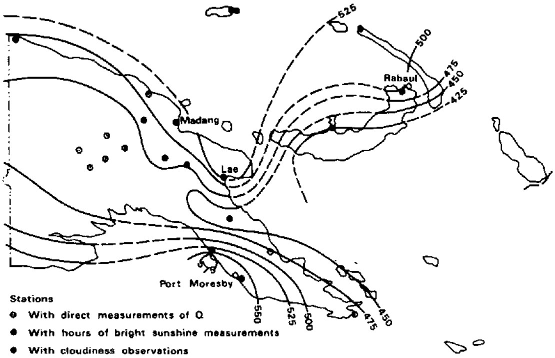


Fig. 7.10a—January

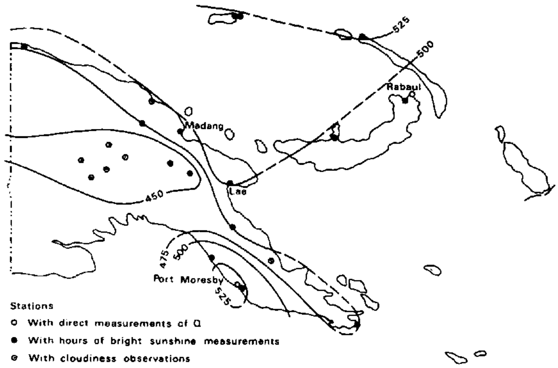


Fig. 7.10b—April

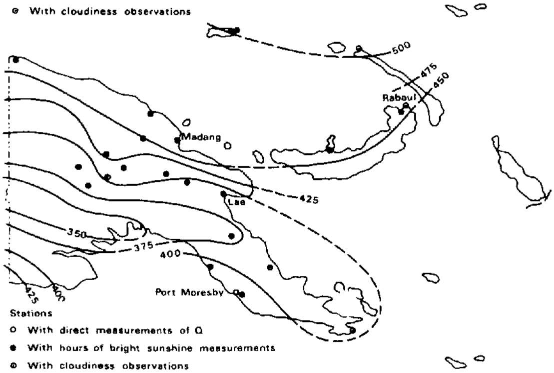


Fig. 7.10c—July

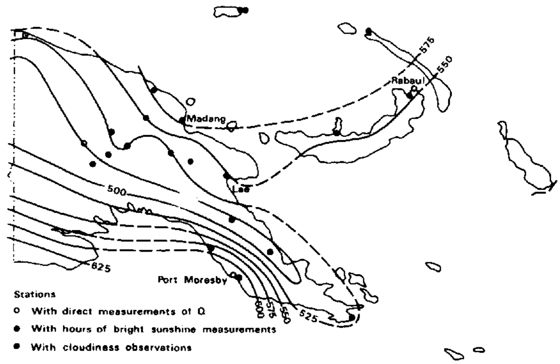


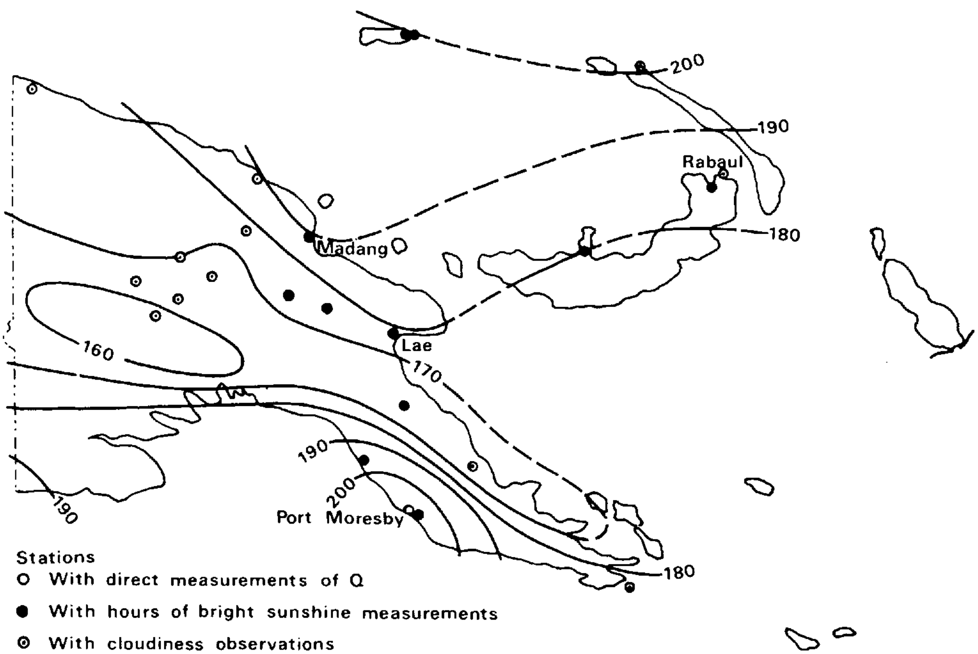
Fig. 7.10d—October

insolation are reached in the Daru coastal strip (625 mW-h/cm²).

The map of the annual total of global solar radiation (Fig. 7.11) shows that most of PNG receives less than 200 mW-h/cm² per year, with the exception of Kavieng and the Port Moresby area. Considerable areas of the central highlands receive as little as 160 mW-h/cm².

The broad-scale radiation distribution can, however, be highly modified at particular locations by slope and aspect. Given the rugged nature of the physiography, effective radiation receipt at the earth's surface can vary considerably over short distances. Smith (1975) and Barry (1978b) refer to the differences in soil temperature on 30° slopes on Mt Wilhelm (at 3480 m). East facing slopes at this location are warmer than west facing slopes, as the former are exposed to clearer atmospheric conditions in the mornings. Slope and aspect differences of this nature could be expected to occur throughout PNG, as a consequence of local diurnal patterns of cloudiness.

Fig. 7.11
Distribution of total annual global solar radiation expressed as mean daily values in W-h/cm² (from Kalma 1972). Most of PNG receives less than 200 W-h/cm² per year.



8 The Water Balance

The preceding chapters have dealt separately with the individual elements of climate such as rainfall, temperature and wind. The elements discussed were those which are most widely known and for which data are regularly recorded from instruments that are easily read and maintained. Data for these individual elements can be used to produce estimates of other important climatic parameters which are either not measured, as a result of instrumentation difficulties or costs, or for which data are limited in extent. An example of this, mentioned in a previous chapter, is the use of temperature and humidity data to extend the limited information available from a restricted network of evaporimeters. A further example would be the calculation of human comfort indices using temperature, humidity and wind data.

One of the most important and frequently used sets of climatic information that can be estimated from analysis of readily available climatic data is that relating to the water balance. Briefly, the water balance of an area (or at a point) is based on the principle of conservation of matter, in that the amount of precipitation falling on an area must be equivalent to the losses of water from that area plus the water stored within it. The major part of the precipitation stored within an area is held as soil moisture or in lakes, ponds and dams. The losses of water from an area are of two types. First, evaporation and plant transpiration are responsible for water loss to the surrounding atmosphere and, second, surface runoff and deep percolation result in water loss to the surrounding land area.

This balance between inputs and outputs of water from an area can be used to produce estimates of unknown components of the water budget from the available data. In its most unusual form, water balance accounting integrates precipitation and evaporation data to produce estimates of runoff and soil moisture deficits for a specified area and time period.

Information concerning derived water balance parameters is of considerable practical importance. For instance, estimates of runoff are essential in engineering for flood estimation, erosion control and assessments of hydro-electric potential. Information on soil moisture regimes is vital for evaluation of land for agricultural use, irrigation design and control and, more broadly, in understanding the vegetation patterns present in an area.

In Papua New Guinea a number of studies using the ability of water balance accounting techniques to estimate runoff and soil moisture have been undertaken for a variety of purposes. Annual runoff has been estimated and assessed for hydro-electric potential and flood estimation procedures have been developed for use in a range of engineering applications (SMEC 1970, 1973; Ribeny and Brown 1968). At a more theoretical level, models have been established to simulate daily runoff from drainage basins (Pickup 1976). The rainfall situation during the 1972 drought has been investigated for the Fly River area (SMEC 1973) and for the highlands (Bureau of Meteorology 1972). Water balance techniques have been used to investigate soil moisture for drought and plant growth incidence in a number of regional resource studies (Fitzpatrick 1963;

McAlpine 1973) and in a study of the agricultural potential of the Markham Valley (Holloway 1973). A study of the biogeography of Northern Australia and New Guinea (Nix and Kalma 1972) included a water balance for the region. This is a key reference for water balance in relation to plant growth in this area.

The former investigations were all of a broad-scale nature. Only a few detailed studies have been made using water balance techniques. One of these concerned itself with the soil moisture regime for one type of highland agriculture in which soil is formed into mounds and composted before planting (Waddell 1972). Another study has investigated the water balance of an alpine vegetation community (McVean 1968).

All of these studies were undertaken for specific purposes and each required some investigation of particular components of the water balance. None aimed to investigate regional or point water balances as such, or regimes for the country as a whole, in order to establish the main differences between places and variations over time.

The water balance model

To overcome this lack of a comprehensive view of the water balance for the whole of the country, a model was applied to the data from rainfall stations for which a 15-year standard period of record was available. This set of stations covers most of Papua New Guinea (see Fig. 1.5) and, as discussed in Chapter 1, it encompasses most of the temporal variation in rainfall found within the country. The aim in applying the model was principally to derive estimates of changes in the level of soil moisture held in store, and to estimate seasonal and annual water surpluses and runoff.

Briefly, the model operates on a time interval of one week and, because it is based on rainfall station observations, it produces weekly estimates for a series of points. Changes in the storage of moisture in the soil are estimated by using actual weekly rainfall as input to the store and estimated weekly evaporation as withdrawal from it. The soil is assumed to have a maximum storage of water or field capacity of 1500 mm. The weekly estimate for water surplus, if any, is calculated to be the amount by which weekly rainfall is in excess of the requirement to recharge soil moisture to its maximum capacity after having met the evapotranspiration demand. This demand is calculated as 0.8 times mean weekly evaporation from an Australian standard sunken tank evaporimeter, when soil moisture in the preceding week was above 75 mm (i.e. 50 per cent of maximum storage), and 0.4 times evaporation when soil moisture falls below this level. The calculations are similar to those used by Fitzpatrick (1965) and SMEC (1970) in earlier water balance investigations in Papua New Guinea. The model is described in more detail by McAlpine (1970) and the computer programs used for the analysis have been documented previously (Keig and McAlpine 1974). At the time the analyses were carried out, estimates of US Class A pan evaporation were not available. The use of Australian standard sunken tank evaporation rather than US Class A pan observations would not have affected the results discussed below. Detailed results of the water balance analyses have been reported elsewhere (McAlpine and Short 1974). The following discussion presents a brief overview of those results, emphasising soil moisture and runoff regimes.

Before proceeding further, it is useful to consider the various components of the water balance for particular places. Figures 8.1 and 8.2 compare the four major components of the mean monthly water balance for two different stations. These are Port Moresby, which is located in a dry area of the country, and Madang, in a humid area. Of the four components, rainfall and evaporation are known, while runoff and soil moisture are estimates.

At Port Moresby (Fig. 8.1), mean weekly rainfall exceeds evaporation by a significant amount, on average, from late December to May. For the remainder of the year the reverse is the case, Of the two components which the model estimates, soil moisture storage has a possible upper limit of 150 mm (maximum storage), while mean weekly point water surplus or runoff can take any value. From late December to mid May, the level of moisture in the soil is on average above 75 mm (50 per cent of maximum storage), rising close to the limit of 150 mm during February and March. After May the level decreases rapidly to less than 25 mm in July, and it remains low until November. Thus, soil water deficits which may seriously affect plant production are common for at least six months of the year. Conversely, soil water availability is fairly well assured for the other six months. The curve of mean weekly water surplus follows a similar pattern to that of soil moisture, with low to negligible values being estimated from May to

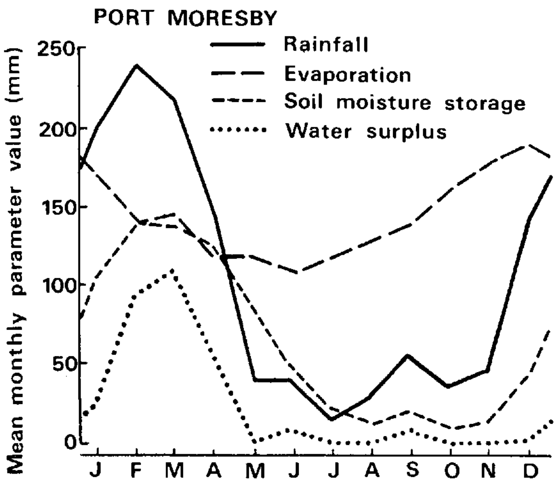


Fig. 8.1
Mean monthly water balance component values for Port Moresby

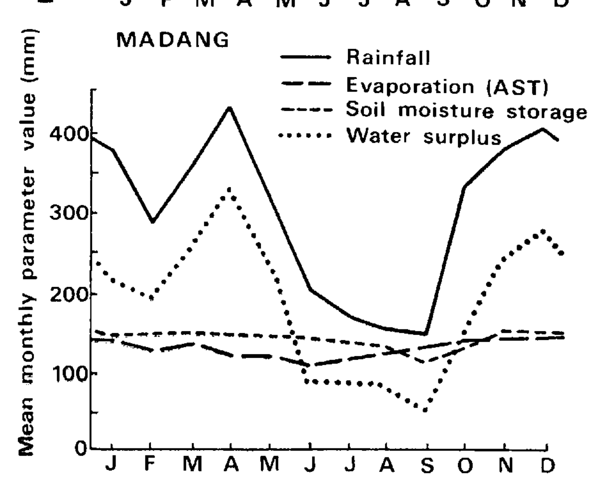


Fig. 8.2
Mean monthly water balance component values for Madang

December, rising to monthly values of 100 mm in March. In summary, the general pattern shown for Port Moresby is typical of a tropical monsoon or savanna climate.

At Madang (Fig. 8.2), rainfall exhibits a seasonal pattern which is less pronounced than in Port Moresby and precipitation exceeds evaporation for all months of the year. As a consequence, mean weekly soil moisture levels remain close to the maximum storage of 150 mm throughout the year. Water surplus closely follows the rainfall plot.

These two figures illustrate the interaction of the main components of the water balance at both a dry and a moderately wet station. In this context, it should be noted that, whereas mean values are excellent in distinguishing one station from another, they conceal temporal variations which can be important in interpreting the estimated means.

As this treatment of the water balance is more concerned with the unknown parameters—soil moisture and runoff—the remainder of the discussion will be in terms of these parameters rather than in terms of separate components of the water balance for particular places as in Figs. 8.1 and 8.2.

Soil moisture

Curves showing estimated mean levels of soil moisture for a number of stations are shown in Fig. 8.3. The stations have been selected to indicate the range of soil moisture regimes, irrespective of their areal coverage. Since the drier regimes are of limited areal extent, some idea of true spatial perspective is provided by the hachuring on the diagram, which indicates the soil moisture regimes typical of most of the country.

Distinct differences between drier stations are evident from the figure, as is the seasonality in soil water levels. It can also be seen that, in the wet season, mean weekly soil moisture levels even at the driest stations do not fall below 75 mm (50

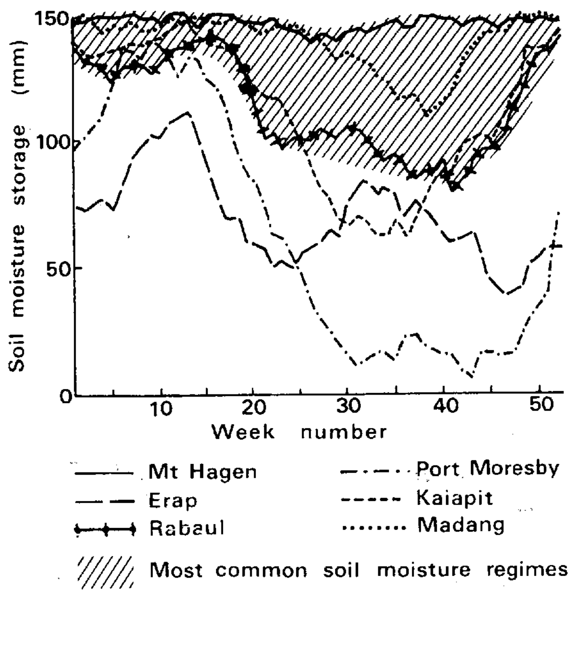


Fig. 8.3
Mean weekly soil moisture storage for a range of stations. The hachured area indicates the range in which the most common and widespread soil moisture regimes occur.

per cent of maximum storage). As well, the mean weekly levels in the dry season are not significantly depleted over most of the country. Nevertheless, analysis of the 15-year standard period data has indicated that, in fact, there is a probability of some level of soil moisture depletion at most places, and an obviously higher tendency for this to occur in the drier season.

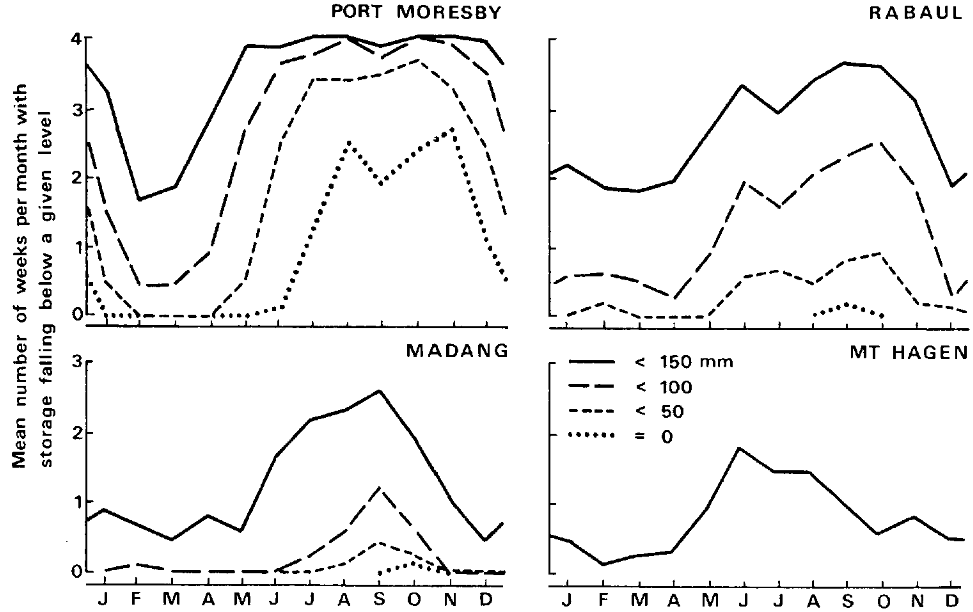
The probability of a station experiencing some level of soil moisture depletion is shown in Fig. 8.4, where plots indicating the mean number of weeks per month with soil moisture storage falling below a specified level are presented. Of the levels specified, that shown as equal to zero can be taken as indicating a severe drought situation; the level of less than 50 mm indicates reduced plant growth conditions, which would be serious for crops such as taro with high water demands. Depletion to levels between 50 and 100 mm could affect yields of high water demanding crops such as sugar, while levels between 100 and 150 mm would indicate periods of no effective limitation to growth in terms of water demand.

The figure indicates that serious droughts occur regularly in Port Moresby and would be of such a nature as to severely limit the potential for agricultural production without irrigation in that area during the dry season. At Rabaul there is some risk of significant levels of depletion, which could result in lower yields for some crops, while at Madang the seasonal occurrence of significant levels of depletion is shorter than at Rabaul and occurrences are less frequent and severe. In the highlands, Mt Hagen does not reveal any level of soil moisture depletion of any significance to agriculture during the standard period analysed.

From the foregoing it is apparent that significant levels of depletion of soil moisture (or drought) are both rare and brief for most of the country. Nevertheless, it should be noted that the model assumes a maximum soil moisture capacity

Fig. 8.4

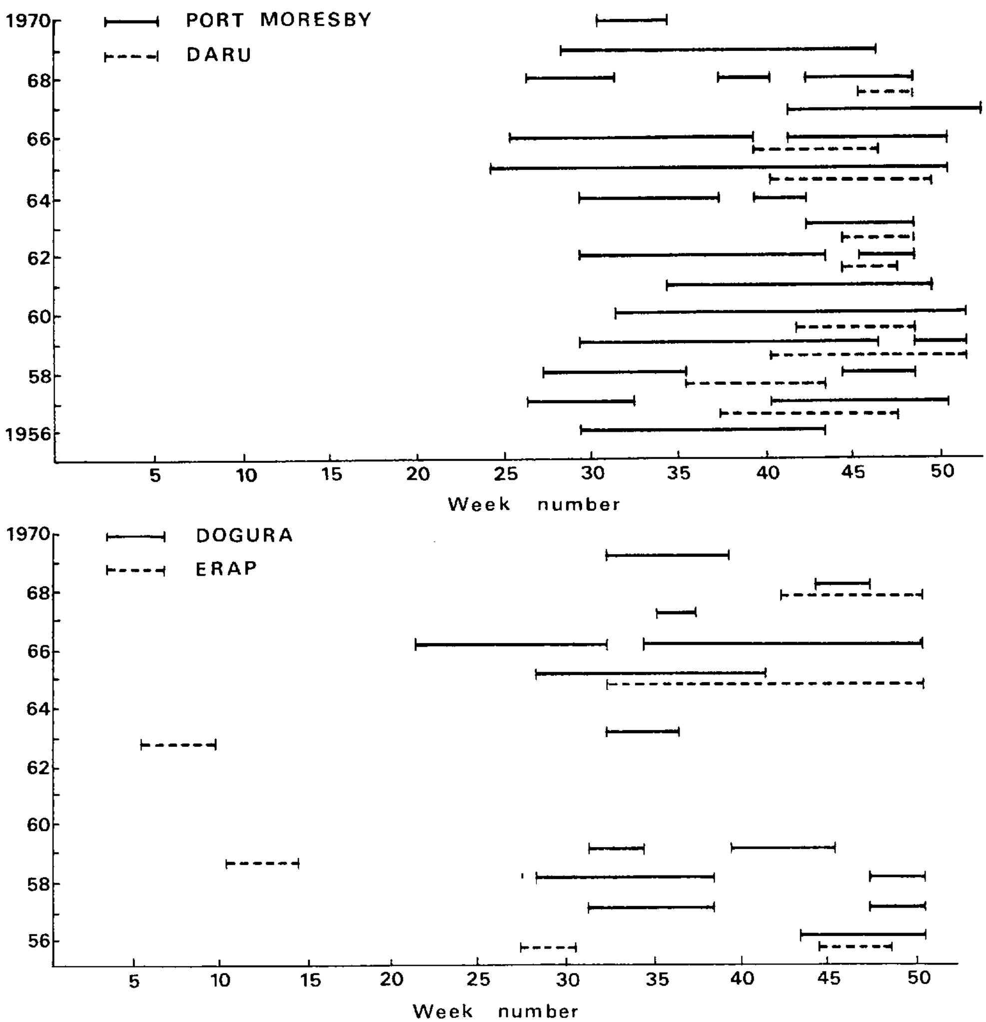
Frequency distribution of specified levels of soil moisture for a range of typical stations. Frequency is expressed as the average number of weeks per month when soil moisture would be less than the specified level.



of 150 mm and, in situations where actual capacity is less than this value (as would frequently be the case on steeper slopes and poorer soils), drought occurrences would be more frequent and of longer duration. Over most of the country, and in all but the wettest areas, soils with water holding capacities of less than 50 mm would be subject to soil water deficiencies of sufficient magnitude to limit plant growth or at least to result in short wilting periods.

In those limited areas with average soil moisture regimes falling outside and below the hachured area in Fig. 8.3, serious soil moisture depletion is common even with an assumed maximum available soil water capacity of 150 mm. The most extensive occurrences of this type of regime are found along the southern central coast around Port Moresby, in the most southern portion of the Western Province including Daru, in the Markham Valley near Erap and along a portion of the north coast of Milne Bay Province near Dogura. The actual frequency and

Fig. 8.5
Sequences of drought periods at four stations during the standard 15-year period. A drought is a consecutive period of weeks in which soil moisture is entirely depleted. Droughts of less than 2 weeks are not shown.



length of severe droughts in these areas, when available soil moisture was entirely depleted, are illustrated by plotting the year by year occurrence of droughts for a typical station in each area (Fig. 8.5), excluding droughts of two weeks or less. While the drought-prone nature of these areas is clearly indicated, it should be noted that, for those soils possessing available water capacities of less than the assumed maximum of 150 mm, the number and length of droughts would be greater than those shown in Fig. 8.5. As such soils are not uncommon in these areas, dry season agriculture based on tropical crops with high water demands would be hazardous without supplementary irrigation. In fact, dry season agricultural cropping is rare in these areas.

While lack of soil water is a limitation to plant growth, long periods of excessive water supply are also a hazard. The water balance model can be used to give an indication of this situation by assuming that saturation (or levels of water above the field capacity of the soil) can occur in those weeks when soil moisture is at a maximum and water surplus exceeds a specified value, say 50 mm. As an example, an analysis of this type has been carried out for Kikori in the Gulf of Papua region and the frequency of possibly saturated soil conditions is shown in Fig. 8.6. It is clear that at this location excess soil water would be a problem every year, particularly within the period between weeks 15 and 25.

It is significant that, in higher rainfall areas where this type of soil moisture regime occurs, population is light and livelihood was traditionally gained from other forms of subsistence than agriculture.

The soil moisture regimes calculated for the standard period rainfall stations have been classified according to the intensity and frequency of levels of soil moisture depletion. This classification is presented as a map in Fig. 8.7, which shows that the areas of significant and serious levels of soil moisture drought are of limited extent. By contrast, a large proportion of the country experiences varying degrees of modest soil water deficits, either on a regular seasonal or occasional basis. It is interesting to note that most of the population engaged in agricultural production lives in areas characterised by seasonal levels of moderate soil moisture depletion. Significantly, the main exceptions occur in areas that are wetter but that have freely draining ash soils over limestone.

Runoff

Runoff and streamflow are usually described as hydrological phenomena. They can also be viewed as the end products of the climatological processes involving evaporation, precipitation and the water balance of a region. Point water balance models of the type employed here produce estimates of weekly water surplus as well as estimates relating to soil moisture status. These water surplus estimates can be used directly to give an indication of point runoff, especially in areas such as Papua New Guinea, where rainfall is high in relation to evaporation and soil moisture storage.

Using a similar model to the one applied here, SMEC (1970, 1973) prepared point estimates of mean annual runoff for a large number of stations for which annual rainfall figures were available. These estimates were validated against observed runoff measured at a number of stream gauging stations and the two data sets were shown to be in good agreement. On this basis, a map of mean annual runoff for Papua New Guinea was prepared. The mean annual estimates

Fig. 8.6
Frequency and lengths of periods of possibly saturated soil conditions at Kikori defined as sequences of weeks when soil moisture is at its maximum and water surplus exceeds 50 mm per week

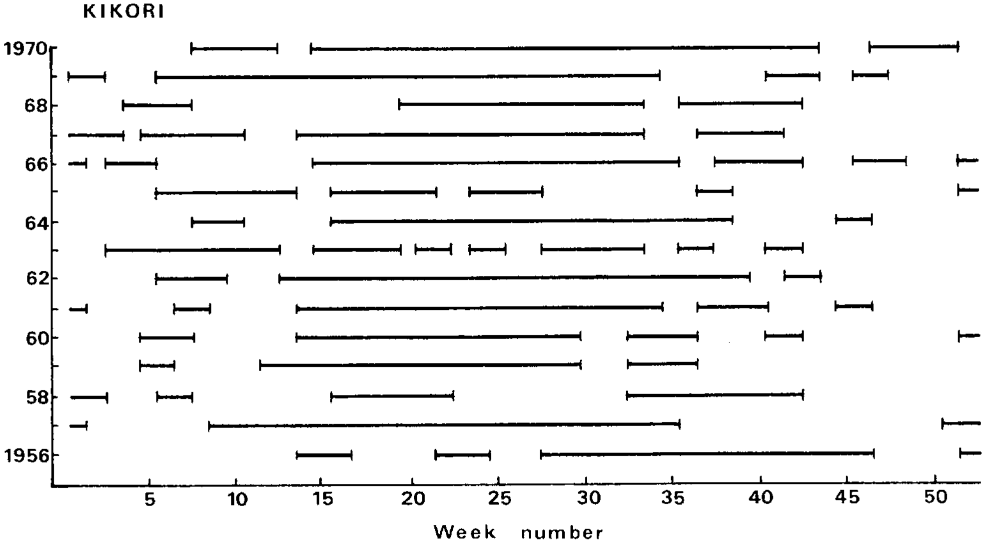
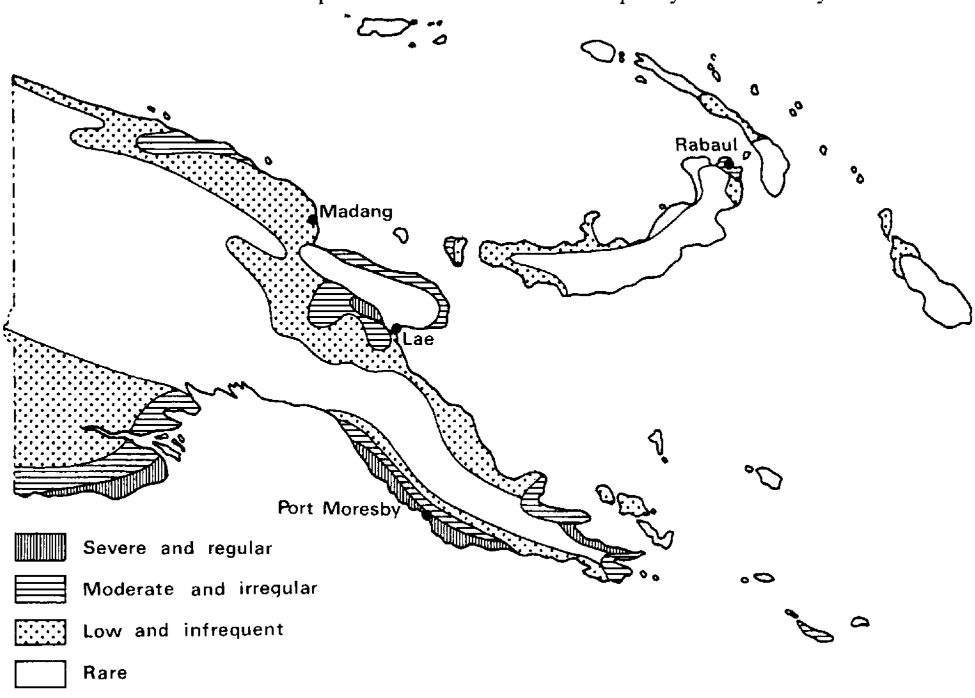


Fig. 8.7
Frequency and intensity of soil moisture deficiencies in PNG. *Severe and regular*—soil moisture depleted below one third of capacity for 10-25% of the length of most dry seasons and in which periods of entire depletion are not uncommon. *Moderate and irregular*—soil moisture storage depleted to below one third of capacity for 10-25% of the length of most dry seasons. Short periods of depletion below two thirds of capacity may occur. *Low and infrequent*—soil moisture storage depleted to below one third of capacity for only 1-10% of the length of occasional dry seasons. *Rare*—levels of soil moisture depletion below one third of capacity are extremely rare



of water surplus derived from the model used in this chapter were also found to be in good agreement with the stream gauge data and hence with the SMEC map published in 1970.

It is not the purpose here to deal with the hydrology of Papua New Guinea, but simply to deal with the water surplus or runoff component of the water balance. The reader is referred to the two SMEC reports for a more detailed treatment of runoff and stream flow. The following discussion provides general information concerning the seasonal distribution of water surplus (runoff) and its monthly and annual variability by reference to the estimates of weekly water surplus derived from the model.

As could be expected from the distribution and amount of rainfall over most of Papua New Guinea, runoff is generally high and exhibits weak to relatively strong differences in seasonal distribution. Mean weekly water surplus (runoff) curves for a representative group of stations are shown in Fig. 8.8. The hachured section of the figure represents the most common and widespread runoff regimes. Drier areas of the country obviously have lower runoff than is found throughout the remainder, and runoff is at its lowest in the dry season. Those areas such as Lae, which experience rainfall maxima in the middle of the year (i.e., south-east trade wind season maxima) have particularly high runoffs both in seasonal and annual terms. As the data varied somewhat around the seasonal trend, the curves presented in Fig. 8.8 have been fitted to the actual mean weekly data by harmonic analysis.

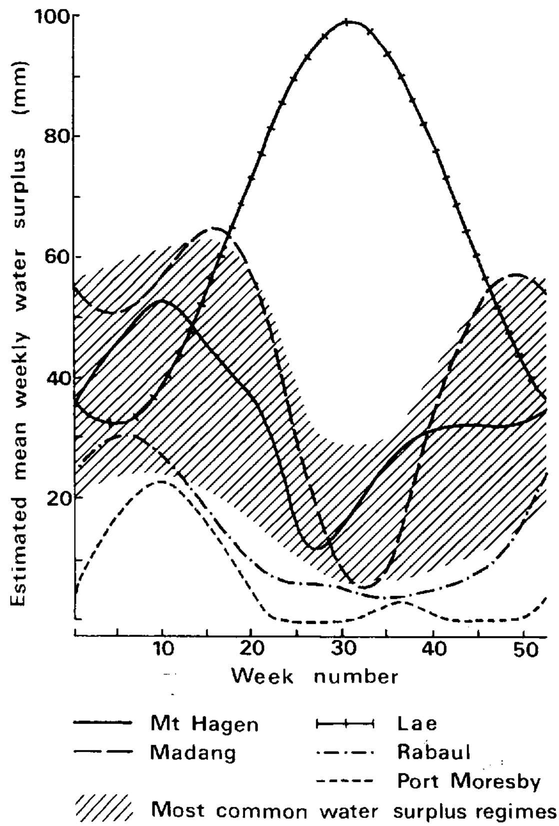


Fig. 8.8
Mean weekly water surplus (runoff) for selected stations. The curves have been smoothed by harmonic analysis.

Figure 8.9 presents, for a selection of stations covering the range of mean annual runoff, the frequency in weeks per month of specified levels of runoff. It can be seen that at the dry station, Port Moresby, the number of weeks per month when runoff exceeds 100 mm is relatively low. By contrast, events of this magnitude are not uncommon elsewhere, while weekly runoffs exceeding 150

Fig. 8.9
Frequency distribution of specified levels of water surplus (runoff) for a range of stations. Frequency is expressed as the average number of weeks per month when water surpluses would exceed the specified levels.

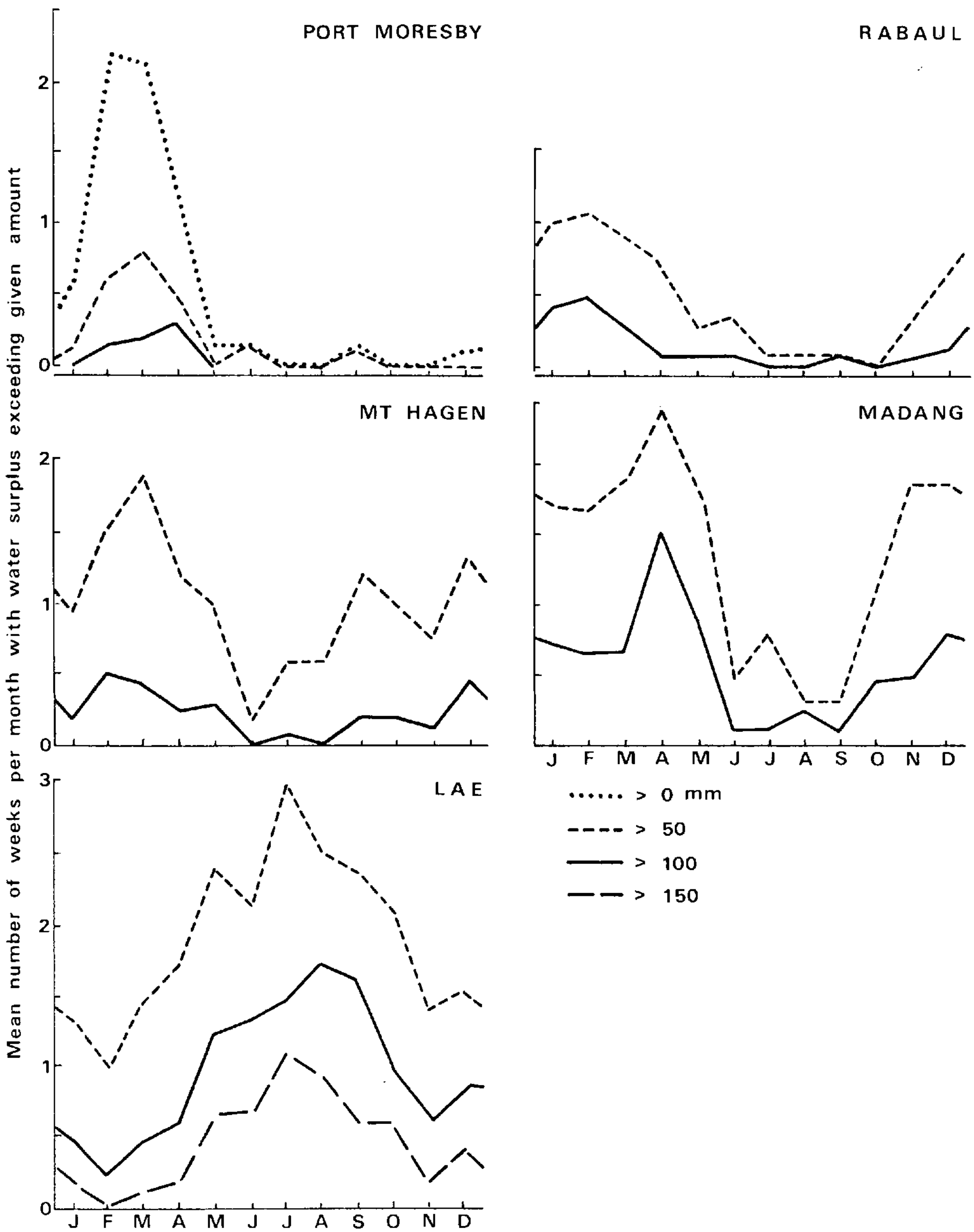
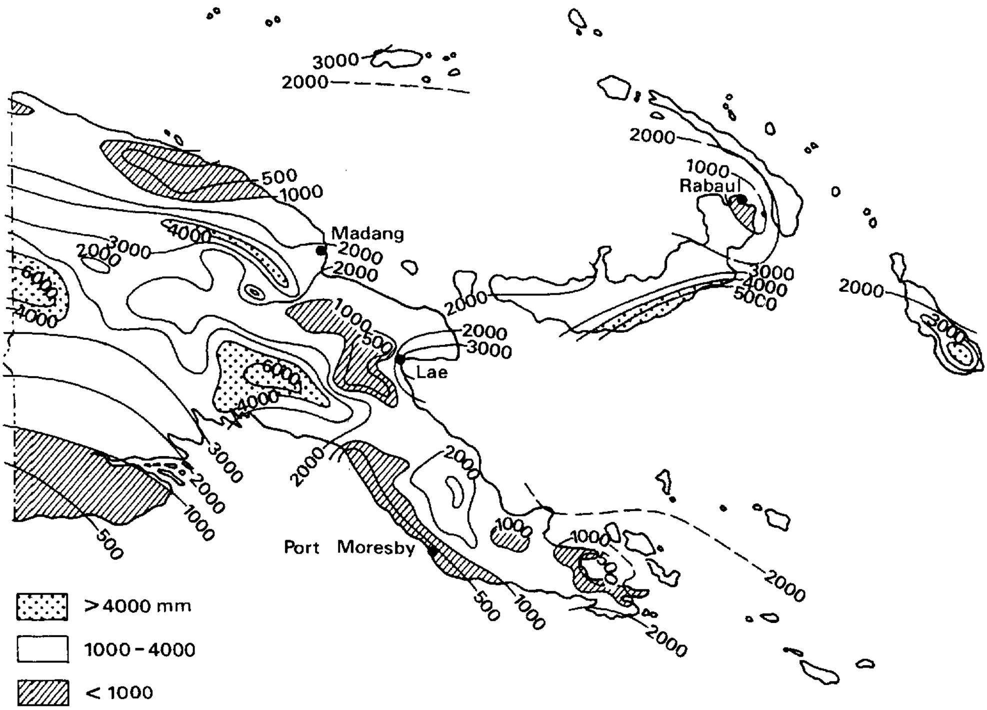


Fig. 8.10
Mean annual water surplus (runoff) for PNG (mm)



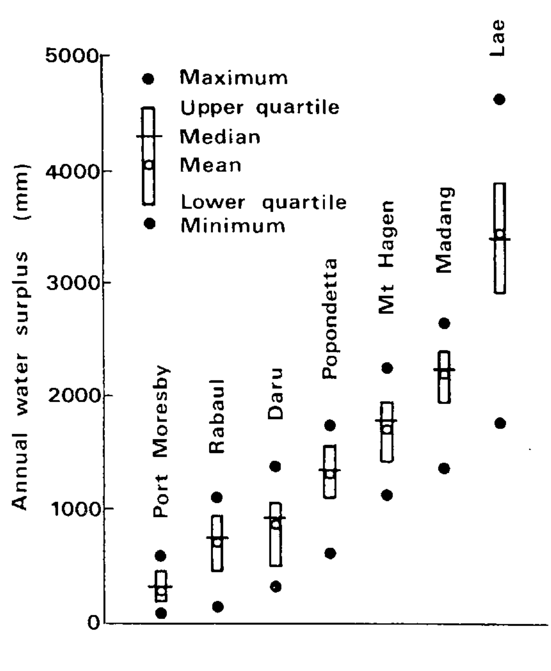


Fig. 8.11
Variability of annual water surplus (runoff) for a range of stations

mm occur only once every 7 to 15 years, except at Lae, where such events are more common.

The overall pattern of mean annual runoff for Papua New Guinea is shown in Fig. 8.10 and this map is based on the earlier SMEC map (1970). Areas with relatively higher runoff (i.e., greater than 4000 mm per annum) and also with relatively lower runoff (i.e., less than 1000 mm per annum) are distinguished by hachuring. It should be noted that the extrapolation inland of the runoff isolines on the main islands is very tentative, owing to the absence of rainfall data.

As is the case with rainfall, the variability in the estimated mean annual runoff for the greater part of the country is low. This variability is shown in Fig. 8.11 using bar charts. The total range of the variability of mean annual runoff experienced at most stations during the fifteen years of the standard period is less than the value of the median. Half of the yearly runoff values vary from the median by only 10-20 per cent. This low variability enhances the reliability of the mean runoff map.

9 Climatic Classification

The perceived climate of a particular place or region is a synthesis of the contributing effects of various elements. In considering such a climate as a whole, and its associations with other features of both the physical and biological environments, a means must be found of quantitatively integrating the individual climatic elements to provide a satisfactory representation of what is observed and felt to be the climate of the particular location.

Various climatic classifications, based on associations of climatic elements in specific numerically-defined systems, have been devised. These are methods for identifying collectively certain features of climate considered to be significant in terms of their associations with particular spatially-defined occurrences of non-climatic factors, such as vegetation and human comfort. Four major global climatic classificatory systems, namely those devised by Köppen and Geiger (1936), Thornthwaite (1948), Holdridge (1947, 1971) and Terjung (1967, 1968) have been applied to climatic data for the PNG region, and the results will be discussed in the following sections. As all climate stations below 2000 m fell into Köppens 'A' classification on the basis of temperature, it was possible to use the larger rainfall station network to obtain a denser distribution of points for this classification than was possible with the other three. These all required both rainfall and temperature data as inputs, and therefore the smaller climate station network was used. The Terjung classification requires both wet and dry bulb temperature data, and so the network of stations used for this classification was limited to those climate stations for which wet and dry bulb temperatures were available.

It was found, however, that none of the global classifications could distinguish all the major climatic types which are generally and locally recognisable parts of the overall continuum of climate in PNG. For this reason, a special classification has been devised which categorises, by means of subjectively-defined classes, the major PNG climatic types in a manner which demonstrates more clearly their association with observed spatial variations in non-climatic parameters, particularly in vegetation. A discussion of the resulting climatic types to be found in PNG and descriptions of representative stations for each type are presented in the later sections of this chapter.

Köppen classification

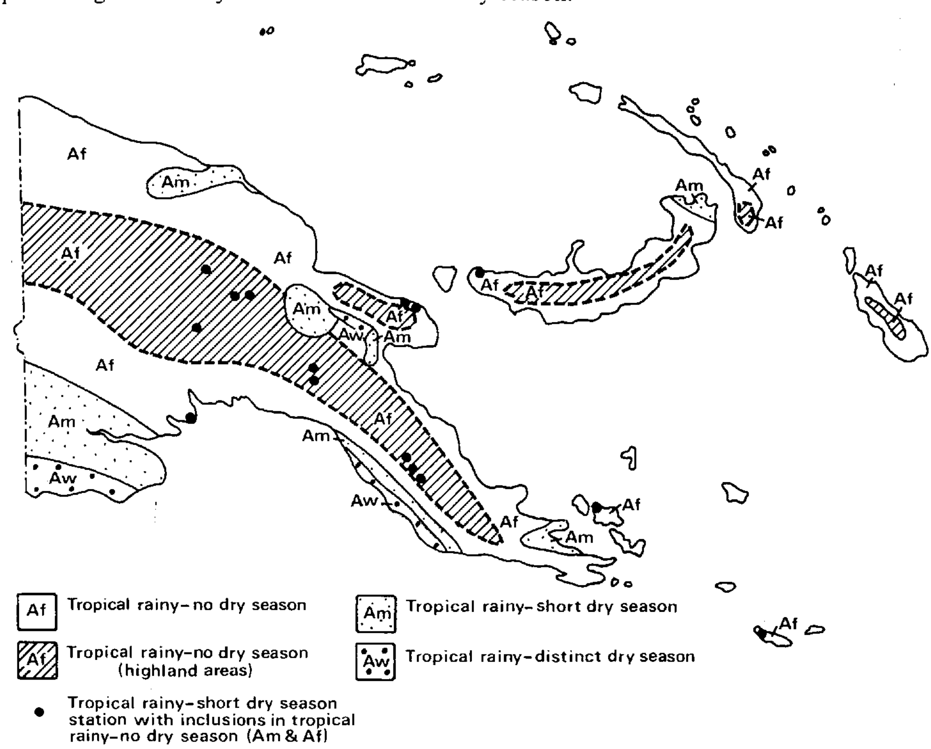
The Köppen and Geiger (1936) classification of climates for PNG is shown in Fig. 9.1. At all climate stations below 2000 m, the mean temperature of the coldest month exceeds 18° C, indicating their classification as tropical rainy 'A' climates. While Köppen does not give special consideration to tropical highland climates, which above 2000 m in PNG approximate 'C' climates but lack seasonal range, the 'A' climates have been mapped in Fig. 9.1 with the main highland cooler zones distinguished by hachure. Since temperature data were not required within the 'A' classification by the Köppen system, all rainfall stations were classified, providing a much denser network of values than would otherwise have been possible.

As can be seen in Fig. 9.1, the major portion of PNG is classified as Af, representing continually wet climates with no dry season. These climates extend from the coast into highland regions (indicated by hachure on the map). Monsoonal climates with a short dry season (Am) are found in smaller widely-separated areas, the largest being the Fly River basin of south-western Papua. Stations which are classified as Am appear to be limited in extent, but this may be an artefact of station record length. Those Am stations located in generally Af areas are so indicated on the map. Three small regions having Aw climates with a distinct dry season are found in coastal south-western Papua, in the Port Moresby area and inland along the Markham River valley.

Thornthwaite classification

Thornthwaite's (1948) classification was applied to rainfall and temperature data for the PNG climate station network and the results have been mapped in Fig. 9.2. Since this classification required temperature as well as rainfall data, the network of stations was much less dense than that used for Köppen's classification, which required only rainfall data at altitudes below 2000 m. It is probable, therefore, that not all minor isolated occurrences of one particular climatic type within another have been identified on the Thornthwaite map.

Fig. 9.1
Köppen's classification of climates for PNG. The major portion of the country is classified as Af, representing continually wet climates with no dry season.

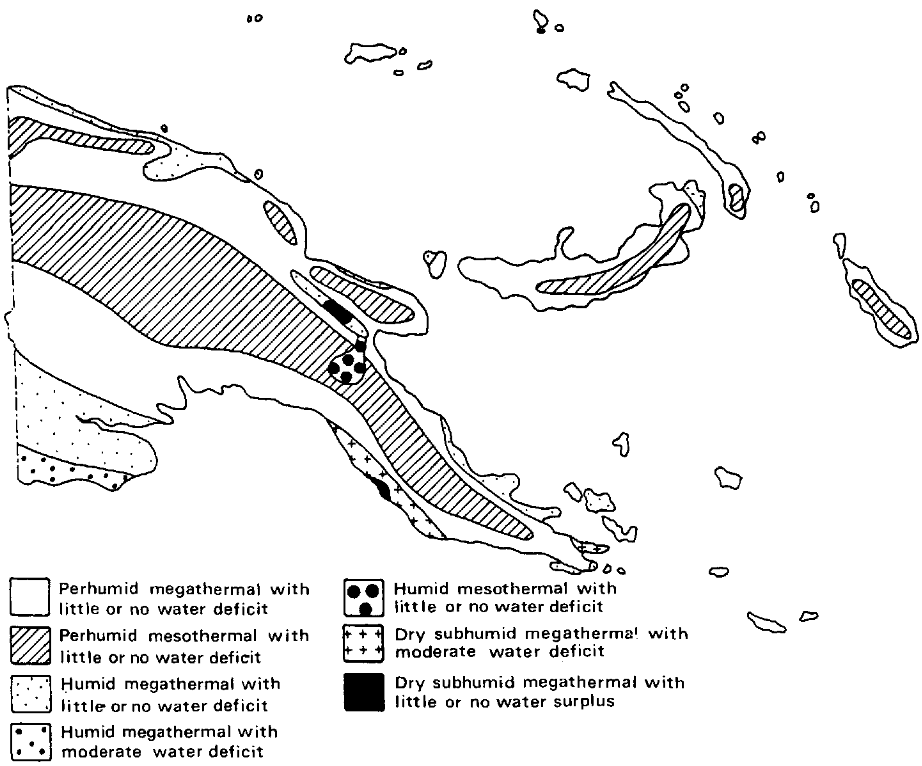


The greater part of the country falls into the perhumid megathermal and mesothermal classifications with little or no water deficiency. The humid megathermal and mesothermal areas with little or no water deficiency generally correspond with or encompass those areas designated Am in the Köppen system. Coastal south-western Papua is the only region of PNG with a Thornthwaite humid mesothermal classification, with moderate water deficiency. Dry subhumid megathermal classifications, with moderate water deficiency, are found on the north coast of eastern Papua near Dogura and along the eastern coast of the Papuan Gulf, while the driest areas in the immediate vicinity of Port Moresby, and at Erap in the Markham River valley, are classified as dry subhumid megathermal, with little or no water surplus.

Holdridge classification

The Holdridge life zone system (Holdridge 1947; Holdridge *et al.* 1971), developed in tropical America, was specifically devised to relate tropical vegetation with climate, although it can also be used in other regions of the world. Figure 9.3 shows the Holdridge climatic classification for PNG which was derived using temperature and rainfall data for sixty-eight climate stations.

Fig. 9.2
Thornthwaite's classification of climates for PNG. The greater part of the country falls into the perhumid megathermal and mesothermal classifications, with little or no water deficiency.

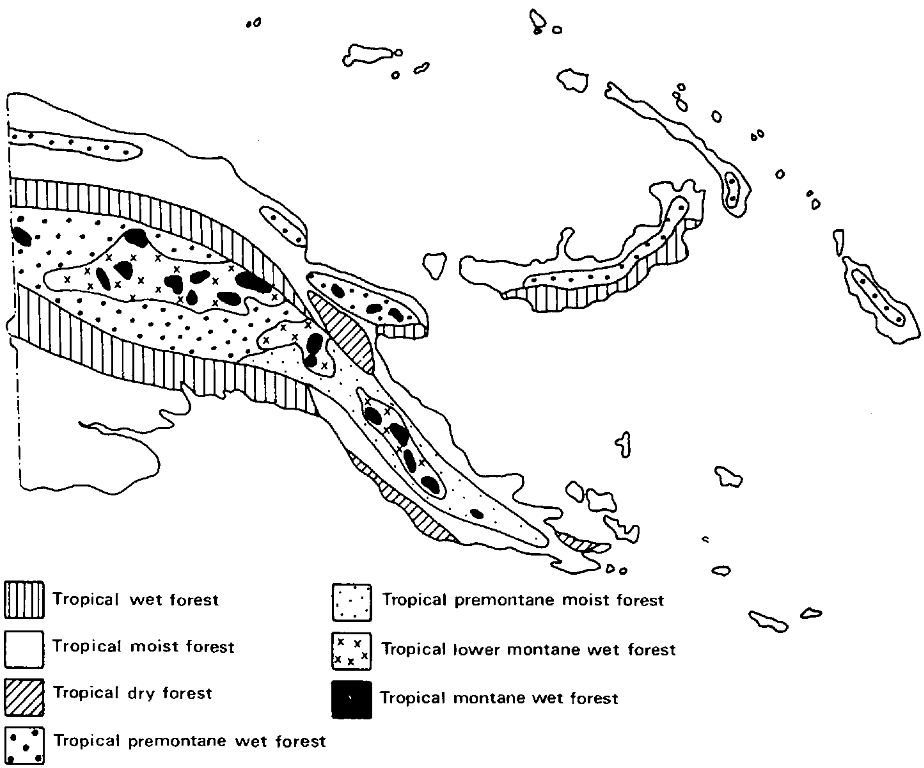


The major portion of lowland PNG falls into the Tropical Moist Forest classification, with regions of Tropical Wet Forest on the coast of western New Britain, and bordering the northern and southern flanks of the western portion of the central highlands. A small area of Sub-tropical Moist Forest occurs in the Amazon Bay region of south-eastern Papua. Tropical Dry Forest is found in two small areas around Port Moresby and at Erap in the Markham River valley.

The higher altitude regions in the eastern half of the mainland are classified as Tropical Premontane Moist Forest and as annual precipitation rates increase towards the west this classification grades to Tropical Premontane Wet Forest. The transition from Premontane to Lower Montane Wet Forest would occur at approximately 1700 m, and higher altitude areas between 1700 and 2700 m would be classified as Tropical Lower Montane Wet Forest. No attempt has been made to show the boundaries or extent of this class, owing to the lack of climatic data at these altitudes.

Areas having mean annual biotemperatures of less than 12° C, and so falling into the Tropical Montane Rain Forest classification, occur above approximately 2750 m. At 3480 m on Mt Wilhelm, where mean annual precipitation is in excess of 3000 mm and mean annual biotemperature is 7.6° C (McVean 1968; Smith 1975, 1977), this classification would apply. Further high altitude areas

Fig. 9.3
Holdridge's classification of climates for PNG. Most of lowland PNG falls into the Tropical Moist Forest classification, with some regions of Tropical Wet Forest on the coast of West New Britain and bordering the central highlands in the west. Higher altitude regions are mainly Tropical Premontane Moist Forest in the east, grading to Tropical Premontane Wet Forest in the west



(above 3000 m) which would also be classified as Tropical Montane Rain Forest have been indicated on the map in Fig. 9.3. Smith (1975, 1977) provides a discussion of the Holdridge life zone classification for higher altitudes on Mt Wilhelm and its relation to observed vegetation zones.

Terjung classification

A climatic classification which relates monthly maximum and minimum temperatures and their associated vapour pressures to human comfort has been proposed by Terjung (1967, 1968). The subjectively-derived categories of comfort are represented by two symbols, the first, which is alphabetic, indicating the prevailing daytime conditions, and the numeric subscript indicating the degree of diurnal variation. Figures 9.4a and b show the Terjung classification for PNG in January and July, as derived from mean monthly temperature data for forty-seven climate stations.

Altitude is again the major cause of variations in classification. In January, lowland PNG is classified as Sultry (S), the most 'uncomfortable' regions being found in the northern islands of the Bismarck Archipelago and in the Milne Bay area, where diurnal variation is least (S_1). Generally the lowland Sultry daytime conditions moderate to Warm conditions at night (S_3). On the coastal ranges and

Fig. 9.4
Terjung's classification of climates in terms of human comfort for PNG. Lowland areas are Sultry, moderating to Warm and then to Mild with increasing altitude

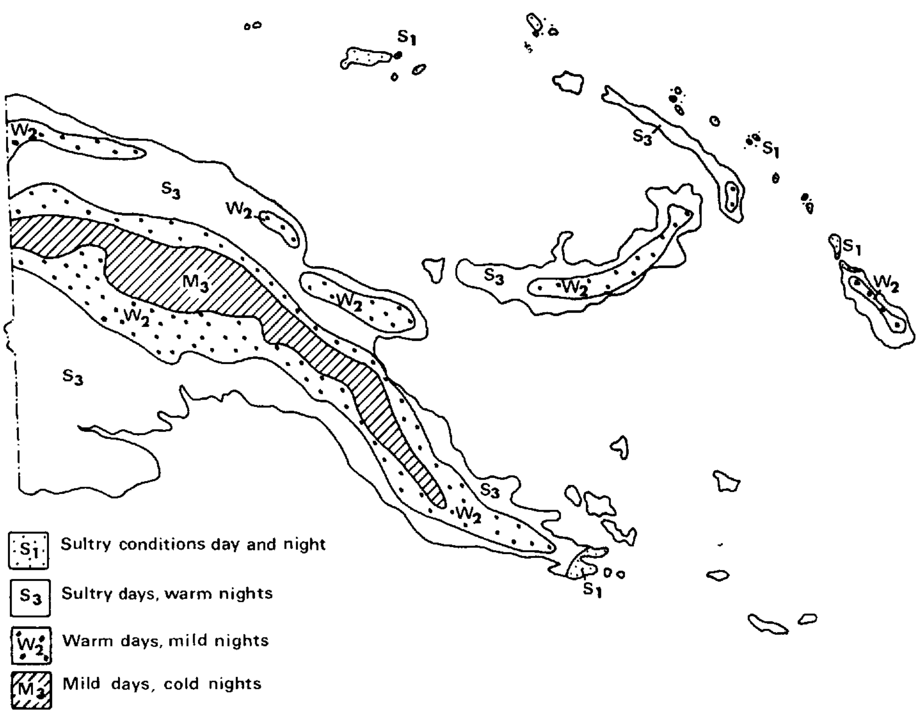


Fig. 9.4a—January

at altitudes up to 1500 m in inland areas the climate is modified to Warm days and Mild nights (W_2). Above 1500 m, data were only available for stations at altitudes up to 2000 m, and these were classified as having Mild days and Cold nights (M_3). No attempt has been made to show on the map the Terjung classifications for areas above 2000 m in the central highlands.

In July there is a trend to greater diurnal variation and hence somewhat more comfortable climatic conditions. The most noticeable change occurs in the Milne Bay area, where the very uncomfortable (S_1) conditions of January moderate to Warm (W_1) conditions in July.

A climatic classification for PNG

There are many different global climatic classifications, of which four of the more widely-used systems have been applied to PNG and the results discussed in the preceding sections. These show varying regionalisations of climate in PNG, which result from differences in the aims of the classifications and their associated data inputs. An example of these variations is seen by comparing the Terjung human comfort map (Fig. 9.4) with the three vegetation-oriented maps in those areas where rainfall amounts are less. However, none of these global classifications can satisfactorily distinguish all the major climatic types which are generally and locally recognised as contributing to the overall pattern of climate in PNG. Consequently a further classification system has been devised, using

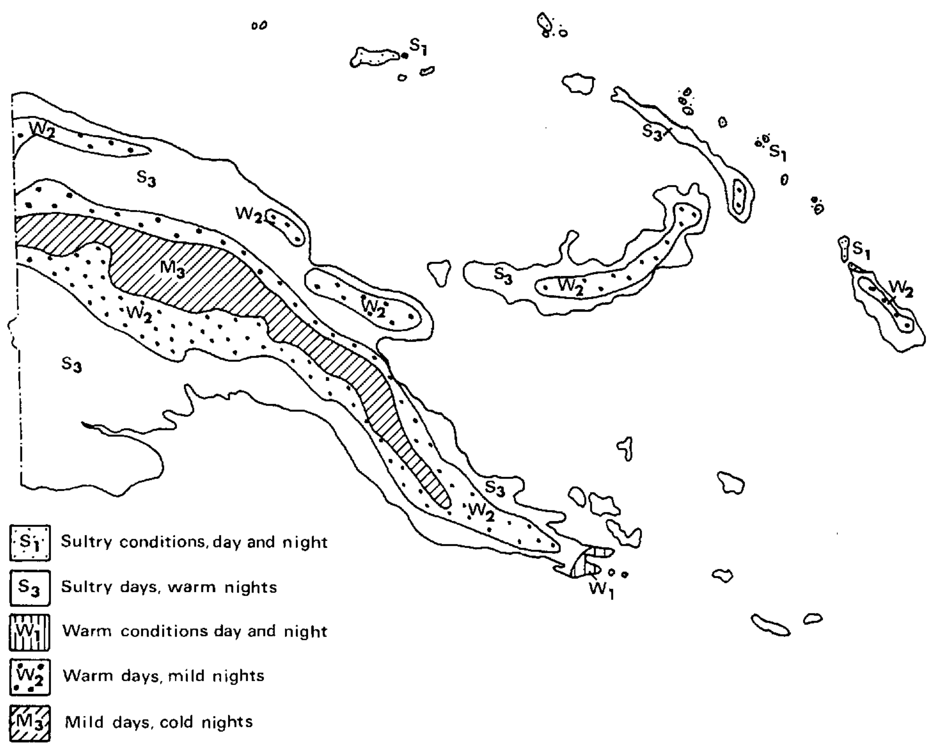


Fig. 9.4b—July

subjectively-chosen class intervals, in an attempt to categorise the various climatic types which are subjectively recognised. While the climate itself is a continuum, in some areas it changes so rapidly in a short distance—as at Sogeri near Port Moresby—that it is a relatively simple matter to differentiate climatic types and map their boundaries. In other areas, however, the gradients of climatic change are far more gradual, and it becomes more difficult to recognise where one climatic type becomes another. Thus the breakpoints in the classification to be discussed in this and following sections are subjectively selected, but they take into account the major types of PNG vegetation as observed during surveys carried out in PNG over the past twenty years (see, for example, Paijmans (1975, 1976), Blake *et al.* (1973), Smith (1975, 1977)). A simplified map of vegetation distribution is shown in Fig. 9.6.

The classification is based first on altitude as the determinant of temperature regimes and second on mean annual rainfall. Altitudinal class intervals have been selected to correspond with recognised changes in vegetation (Paijmans, 1975, 1976) and each class can be broadly described in terms of particular vegetation types. Table 9.1 shows the eleven classes which comprise the classification system, and indicates the ranges of altitude and mean annual rainfall for each class. The average of the mean annual rainfall values for stations falling within the same class is also shown in the column relating to precipitation. In addition, an extended set of related but not determining parameters are shown in the table. These include average values or ranges of the estimated mean annual US Class A pan evaporation and of the ratio of mean annual precipitation to mean annual evaporation (P/E) for stations in each of the classes, together with average figures for mean annual maximum and minimum temperature. In the following discussion of the climatic classes reference is also made to seasonality where this is a significant factor.

It will be seen that only limited climatic data are available for some of the classes, particularly those occurring at higher altitudes. The lack of sufficiently long and well-distributed rainfall records also precluded the use of the more sophisticated classification devised by McAlpine and Short (1974) as the basis for classifying water balance over the entire country. This latter system, which is based on the results of weekly water balance accounting procedures, integrates the effects of rainfall and evaporation to provide a more meaningful guide to the length and severity of 'dry' periods than can be obtained from mean monthly rainfall and evaporation data. Water balance studies have, however, been carried out on a number of the stations falling into eight of the eleven classes of the classification system described in Table 9.1 (see preceding chapter). From the results of these calculations, estimates of the range of the mean annual water surplus for each climatic type are given in Table 9.1. Finally, the table lists stations which are representative of each class and provides an indication of the type of vegetation associated with each climatic type. Where the range of stations within a class is relatively large, two or more stations may be listed to give an indication of variation within the class. Figure 9.5 provides a diagrammatic summary of the major climatic elements for each of the representative stations, allowing direct comparison between classes of mean annual temperature and humidity regimes and the main parameters of the water balance—rainfall, evaporation, soil moisture storage and water surplus. It should be noted that the scales of some of the graphs vary between classes.

Table 9.1

Climates of Papua New Guinea

Climate no.	Name	Mean annual precipitation (mm) Mean	Mean annual precipitation (mm) Class range	Mean annual US Class A pan evap. (mm)	P/E ratio	Mean annual water surplus (mm)	Mean annual temperature* (°C) Max	Mean annual temperature* (°C) Min	Representative station/s	Vegetation
LOWLAND CLIMATES 0-500 m										
1	Lowland dry subhumid	1300	1000-1500	2200	<1	<500	32	23	Pt Moresby	Savanna, grassland
2	Lowland subhumid	1800	1500-2000	1600-2000	≃1	500-1000	32	23	Daru	Savanna, dry evergreen forest
3	Lowland humid	2700	2000-3500	1500-1900	1-2	1000-2000	30	23	Ambunti, Rabaul, Madang	Lowland hill and alluvium forest
4	Lowland perhumid	4700	>3500	1400-1800	>2	>2000	30	23	Lae, Kikori	Lowland hill and alluvium forest
PREMONTANE CLIMATES 500-1400 m										
5	Premontane subhumid	1800	1500-2000	1600-2000	≃1	500-1000	29	18	Bulolo	Grassland
6	Premontane humid	2700	2000-3500	1500-1900	1-2	1000-2000	29	18	Lumi, Garaina, Panguna	Hill forest
7	Premontane perhumid	4700	>3500	1400-1800	>2	>2000	29	18	Lake Kutubu	Hill forest
LOWER MONTANE CLIMATES 1400-3000 m										
8	Lower montane subhumid	1800	1500-2000	1600-2000	1	500-1000	25	13	Goroka (1565 m)	Grassland
9	Lower montane humid	2700	2000-3500	1500-1900	1-2	1000-2000	25	13	Mt Hagen (1630)	Lower montane forest

Climate no.	Name	Mean annual precipitation (mm) Mean	Mean annual precipitation (mm) Class range	Mean annual US class A pan evap. (mm)	P/E ratio	Mean annual water surplus (mm)	Mean annual temperature (°C) Max	Mean annual temperature (°C) Min	Representative station/s	Vegetation
10	Lower montane perhumid	8500	>3500	1400-1800	>2	>2000	22	11	Hongkong (2085 m)	Lower montane forest
UPPER MONTANE CLIMATES	>3000 m									
11	Upper montane humid	>3000	–	500	6	–	11	4	Mt Wilhelm (3480 m) (McVean, 1968; Hnatiuk *et al.* 1976)	Upper montane forest, grassland

* For temperatures over the entire range of altitudes see Chapter 5.

A map of this climatic classification for PNG is presented in Fig. 9.7, and the following general discussion of each climatic type arranged on an altitudinal basis summarises the information provided in Table 9.1 and Figs. 9.5 and 9.7.

Lowland climates

The four classes of lowland climate cover that area of PNG which lies between 0 and 500 m. The classes are distinguished on the basis of mean annual rainfall, which ranges from just over 1000 mm to almost 10 000 mm in the lowland areas. Temperatures are the highest in PNG, with mean annual maxima reaching 32° C and minima of 23° C. There is only slight seasonal variation in both temperature and relative humidity, which decreases from almost 100 per cent at dawn to around 70 per cent in mid-afternoon over most of the lowlands.

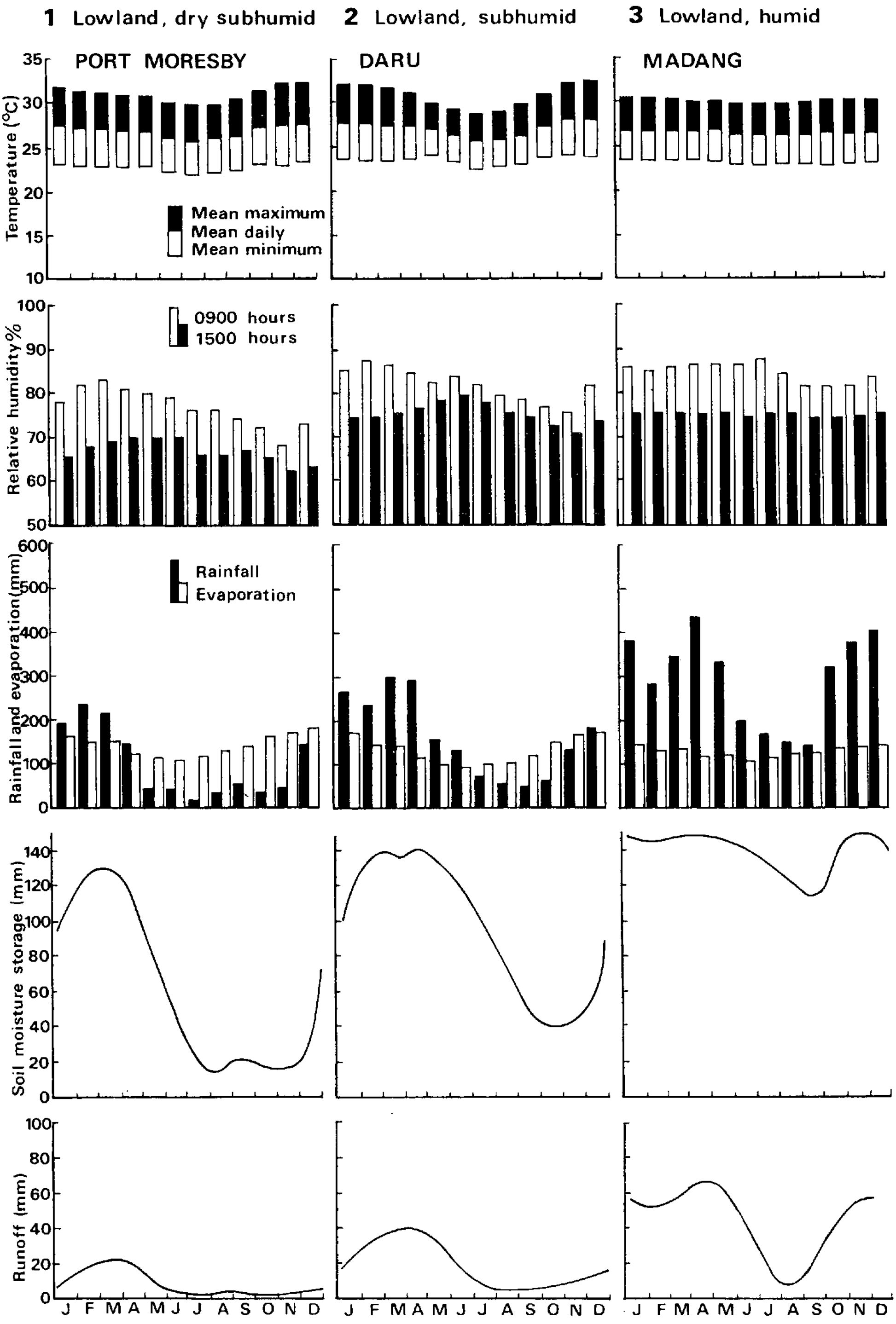
Type 1—Lowland dry subhumid. This is the driest and also the hottest climate in PNG. Extending in a narrow strip along the eastern coast of the Gulf of Papua from Kukipi to Kwikila, it includes the Port Moresby region, and it is also found in a small area of the north coast of eastern Papua around Dogura and at Erap in the Markham River valley. Mean annual rainfall in these regions lies between 1000 and 1500 mm, and there is generally a very high degree of seasonality. A regular prolonged dry season extends from May to November, resulting in soil moisture 'drought' conditions (below 50 mm) for almost half the year. The vegetation in these areas is either grassland or savanna.

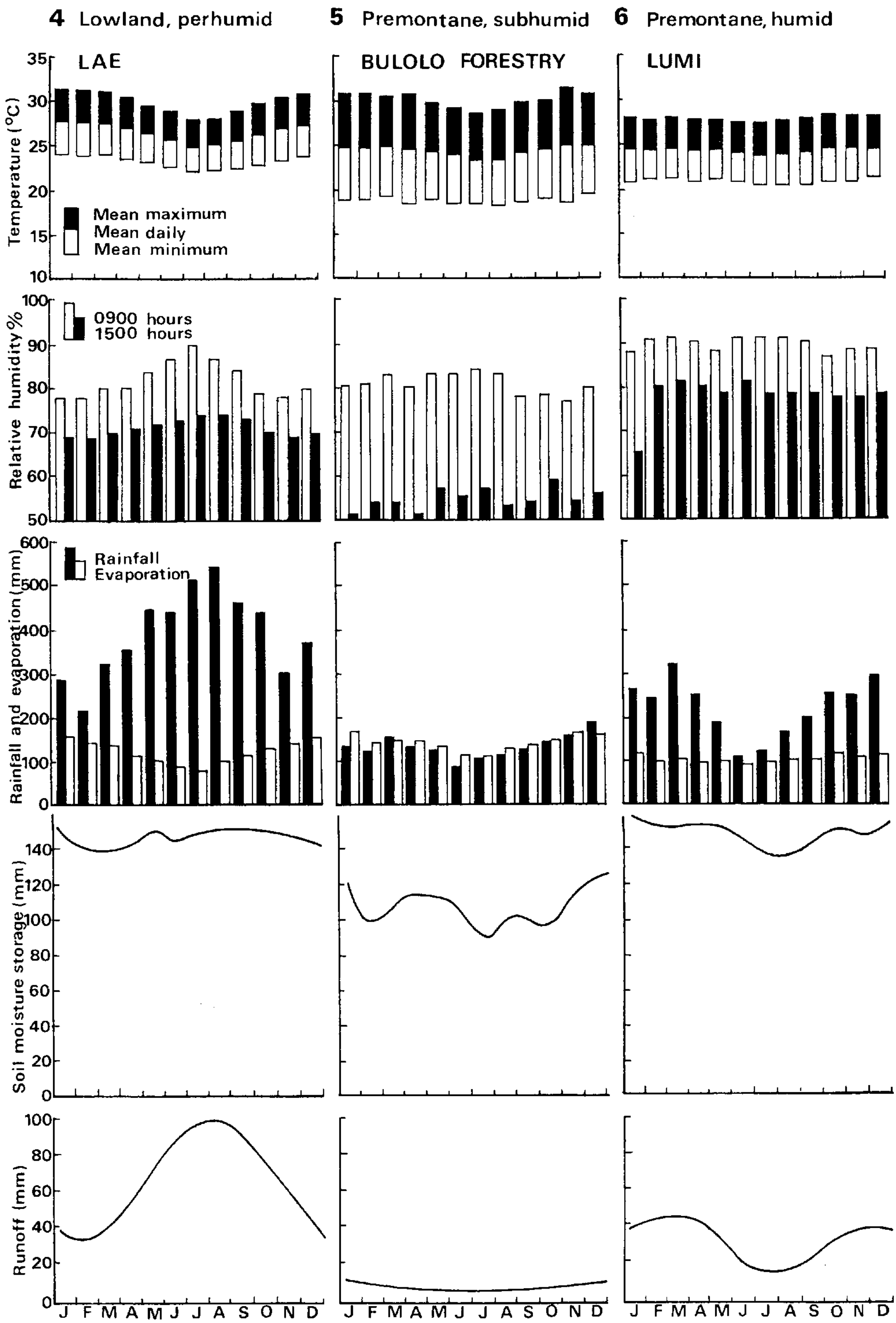
Type 2—Lowland subhumid. This climate is somewhat wetter than Type 1, with mean annual precipitation rates between 1500 and 2000 mm, but it is equally as hot. Its largest area of occurrence is in coastal south-western Papua, but it is also found in other small areas, such as inland from Wewak along the Sepik River, in the Markham River valley, and on the north coast of eastern Papua in the region between Cape Nelson and Cape Vogel, extending inland to Safia. A pronounced dry season occurs between June and October, and although soil moisture falls to drought levels the depletion period is not as regular or as prolonged as for the Type 1 climate. The vegetation in these areas is either savanna or dry evergreen forest.

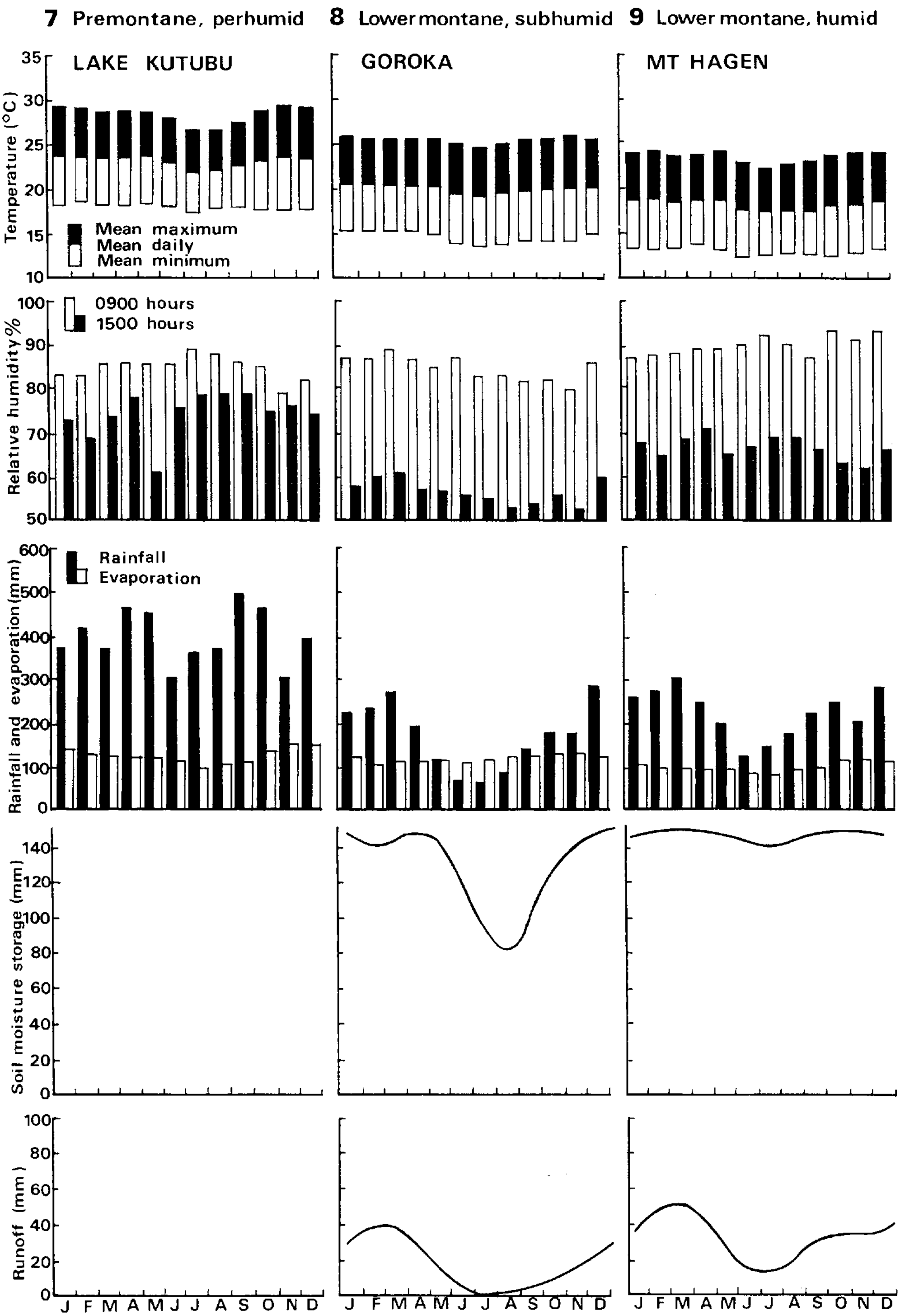
Type 3—Lowland humid. This humid climate, with annual rainfall between 2000 and 3500 mm, covers a large part of coastal and lowland PNG, as shown in Fig. 9.6. Annual maximum temperatures are slightly cooler than for the drier lowland climates. Rainfall regimes range from highly seasonal at some stations, such as Gizarum and Saidor, to only very slightly seasonal at other stations such as Wewak and Momote. Stations falling within this climatic type have their rainfall maxima during the north-west season from December to March.

A few stations classified as Type 3 have rainfall maxima during the south-east season between May and October, but show only moderate seasonality. They include Samarai in the Milne Bay area of eastern Papua, Aropa on the coast of Bougainville Island and Karlai on the south-eastern coast of New Britain. These stations are located in transition zones between those regions having north-west season rainfall maxima and those which experience very high rainfall during the south-east season and are classified as Type 4.

Fig. 9.5
Summary of major climatic parameters for representative stations in climatic classes 1 to 9. Insufficient data are available to permit inclusion of stations in classes 10 and 11, or water balance statistics for class 7.




4 Lowland, perhumid
5 Premontane, subhumid
6 Premontane, humid
LAE
BULOLO FORESTRY
LUMI
Temperature (°C)
Mean maximum
Mean daily
Mean minimum
Relative humidity %
0900 hours
1500 hours
Rainfall and evaporation (mm)
Rainfall
Evaporation
Soil moisture storage (mm)
Runoff (mm)
J F M A M J J A S O N D



7 Premontane, perhumid
8 Lowermontane, subhumid
9 Lower montane, humid
LAKE KUTUBU
GOROKA
MT HAGEN
Temperature (°C)
Mean maximum
Mean daily
Mean minimum
Relative humidity %
0900 hours
1500 hours
Rainfall and evaporation (mm)
Rainfall
Evaporation
Soil moisture storage (mm)
Runoff (mm)
J F M A M J J A S O N D

Mean annual water surpluses in Type 3 areas are moderately high. There may be rare cases of soil moisture depletion to drought levels, but these periods are of short duration. The vegetation in these areas is generally classed as lowland hill or alluvium forest.

Type 4—Lowland perhumid. This is the wettest of the lowland climates, with mean annual precipitation rates in excess of 3500 mm. The majority of stations in Type 4 areas, particularly those on the coast, experience south-east season rainfall maxima and have a high degree of seasonality. These south-east season areas occur along the southern coast of New Britain, along the coast of the Huon Gulf including Finschhafen and Lae, at the southern end of Bougainville Island and along the coast at the head of the Gulf of Papua. This latter area extends westward and inland in a strip bordering the southern flank of the central highlands, but the rainfall maxima in the inland areas occur during the north-west season. A similar lowland perhumid area having north-west season rainfall maxima borders the northern fall of the central highlands from Aiome to Amboin.

Lowland perhumid climates are characterised by high annual water surpluses and the absence of soil moisture drought conditions. The vegetation is either lowland hill or alluvium forest.

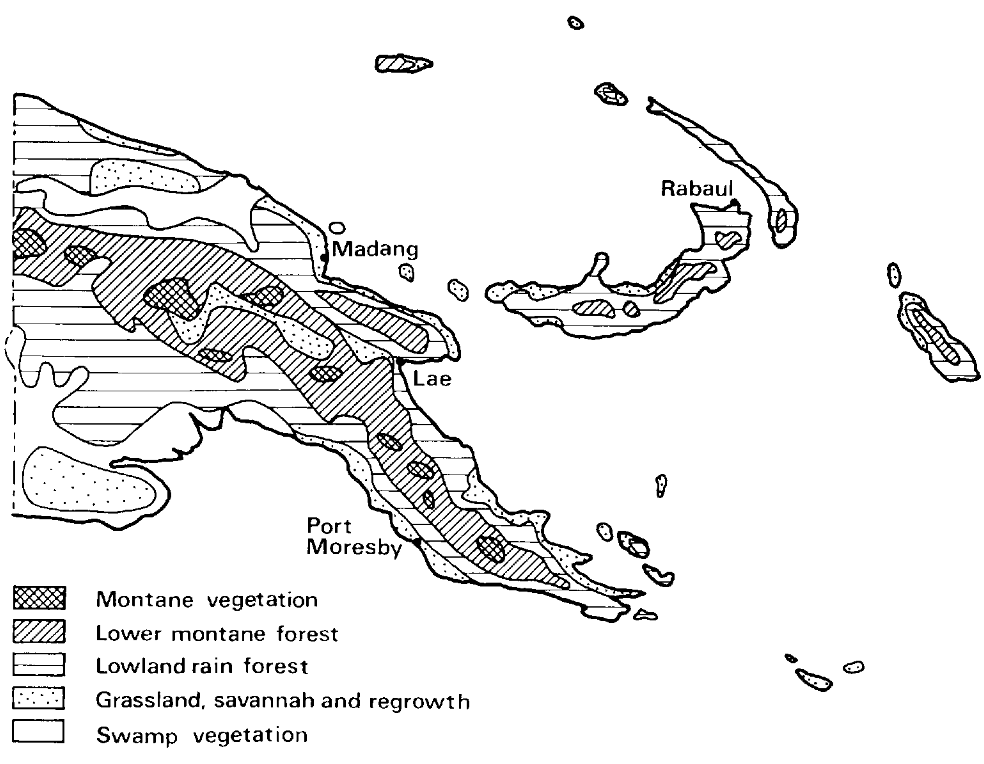


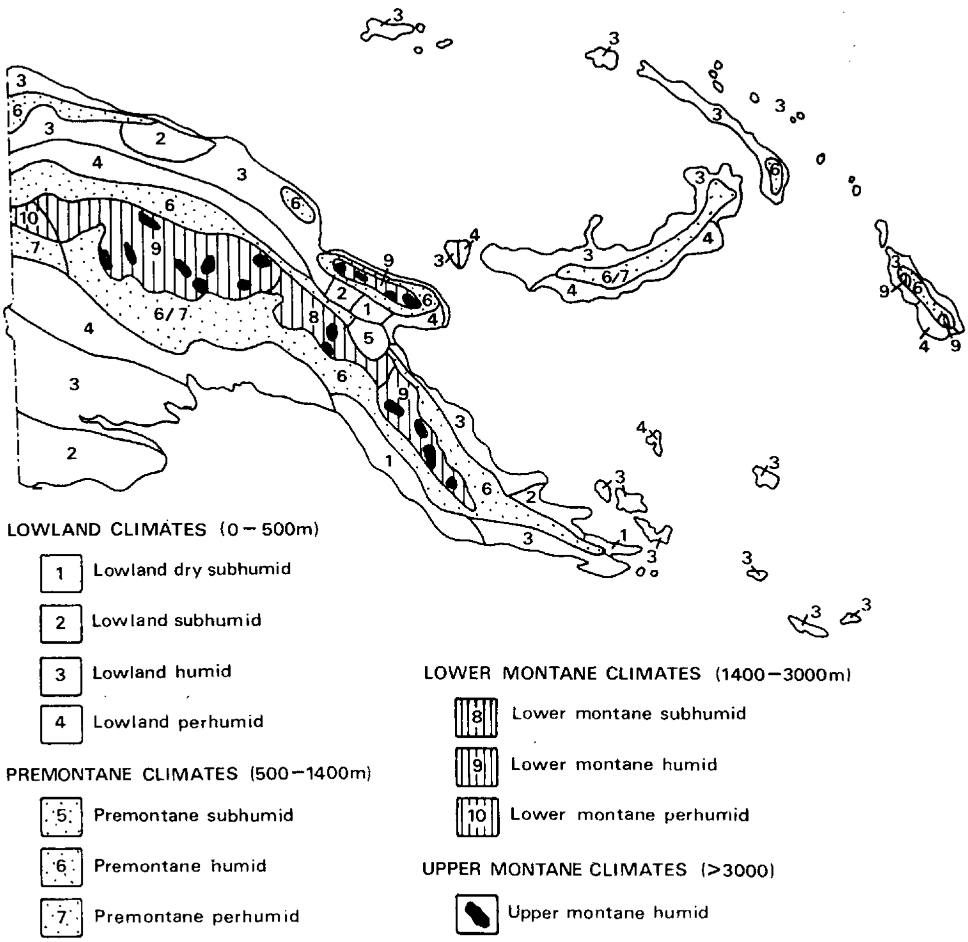
Fig. 9.6
Vegetation distribution in PNG (simplified from Paijmans [in press]).

Premontane climates

The premontane climates extend from 500 to 1400 m in altitude, and are again subdivided into classes on the basis of mean annual rainfall, which ranges from about 1500 mm to at least 5000 mm in these areas. The increased altitude causes a reduction in temperatures, particularly in the minima. Mean annual maxima are around 29° C, while the minima are around 18° C, and hence diurnal variation is greater than in the lowlands. While relative humidities show little seasonal variation, there are considerable differences in the mid-afternoon humidity levels between stations in this altitudinal range, due mainly to the effects of physiographic location.

Type 5—Premontane subhumid. The subhumid Type 5 is the driest of the premontane climates, having a mean annual rainfall of between 1500 and 2000 mm. Mid-afternoon relative humidities fall to comparatively low levels around 60 per cent throughout the year. This climatic type is found in a small area surrounding Bulolo and Wau, extending south as far as Menyamya. Rainfall

Fig. 9.7
Climatic classification of PNG based on altitide and mean annual rainfall



regimes show only moderate seasonality, with maxima occurring during the north-west season. Mean annual water surpluses are relatively low, but soil moisture is never depleted to drought levels at Wau or Menyamya, and only very rarely falls to below 50 mm for short periods at Bulolo during August to November. The area is mainly covered by grassland.

Type 6—Premontane humid. This climatic class covers those premontane areas where mean annual rainfall is between 2000 and 3500 mm. It occurs in the higher inland regions of Bougainville Island and New Britain, on the northern coastal ranges of the mainland, and in an almost continuous strip bordering the highest regions of the central highlands and extending eastwards almost as far as Alotau. Rainfall regimes are moderately seasonal, with maxima occurring during December to March, and there is an absence of soil moisture drought conditions. Vegetation throughout these areas is classed as hill forest.

Type 7—Premontane perhumid. This climatic type is similar to Type 6, except that mean annual rainfall exceeds 3500 mm and consequently mean annual water surpluses would be greater. In practice, it is difficult to distinguish areas which would be classified as Type 7, as data are available for only a few stations which fall into this class. However, some of those areas which have been mapped as Type 6 are likely to include areas of Type 7, and this probability has been indicated by regions marked as 6/7 on the map. One continuous area of Type 7 appears to occur in the Ningerum-Olsobip region along the southern fall of the central highlands close to the Irian Jaya border. Because of the scarcity of data, it was not possible to carry out water balance studies for any station falling within Type 7, but it is probable that mean annual water surpluses exceed 2000 mm.

Lower montane climates

The lower montane climatic types range in altitude from 1400 m to 3000 m, exceeding by some 400 m the general upper limit of cultivation at 2600 m. Mean annual maximum temperatures decrease to around 24° C in these regions and mean annual minima are about 13° C. While seasonal variation in both temperature and humidity regimes is not marked, diurnal variation is greater than in lowland areas. Ground frosts are likely to occur above about 1500 m, their incidence and severity increasing with elevation and in physiographic locations conducive to their development (Fitzpatrick 1965).

Type 8—Lower montane subhumid. An area in the eastern highlands around Goroka and Henganofi experiences relatively low annual rainfall (1500-2000 mm) with moderately high north-west seasonality. While mean annual water surpluses are not large soil moisture is only very rarely depleted to drought levels. Short periods of drought sometimes do occur at Goroka in late July and August. The area classed as Type 8 is mainly covered by grassland.

Type 9—Lower montane humid. This climate class extends over most of the western part of the central highlands and also covers the high altitude regions of eastern Papua. Rainfall in these areas is between 2000 and 3500 mm annually, with slight to moderate north-west seasonality. Mean annual water surpluses are high and there are no occurrences of soil moisture droughts. The vegetation is described as lower montane forest.

Type 10—Lower montane perhumid. Data are available for only one station—Hongkong (2085 m)—which falls into this perhumid class with mean annual rainfall exceeding 3500 mm. It is probable that small areas of Type 10 are found as inclusions in the regions marked as Type 9 on the map, particularly in the western highland areas where rainfall tends to be higher.

Upper montane climate

Type 11—Upper montane humid. This quasi-alpine upper montane climate extends from 3000 m to 4509 m, the height reached by Mt Wilhelm, the highest mountain in PNG. Climatic data are available for only one location, this being at 3480 m in the Pindaunde Valley on the flank of Mt Wilhelm (McVean 1968, 1974; Hnatiuk *et al.* 1976). Here the mean annual maximum temperature is around 11° C and the mean annual minimum is around 4° C.

Relative humidities are generally close to 100 per cent. However, when the clouds are below Pindaunde in the early mornings, relative humidities can fall below 50 per cent, but in the afternoons they are seldom below 70 per cent. Ground frosts occur on almost 50 per cent of days. Annual rainfall is in excess of 3000 mm and maximum monthly rainfall occurs during December to March.

Limited lysimeter data for Pindaunde, when adjusted to an approximate free-water equivalent, indicate that annual evaporation is about 500 mm. Thus the P/E ratio is high, and it is therefore probable that soil moisture droughts do not occur.

There are marked changes in vegetation within this altitudinal range (Smith 1975, 1977; Paijmans 1975, 1976; Paijmans and Löffler 1972). Upper montane forest reaches its limit at approximately 3900 m, above which low shrubs grade to grassland communities at about 4100 m.

Local variation within climatic types

This classification describes the broad range of climatic types occurring within Papua New Guinea. The intricate pattern of landform and its interaction with local atmospheric circulation ensure that within each climatic type there will be a considerable degree of local variation, frequently over quite short distances. This variation will be more pronounced in hilly and mountainous regions, and hence within the premontane, lower montane and montane climates.

Knowledge of local climatic variation within the major climatic types is of considerable importance in land resource utilisation, yet the nature and degree of such variation is unlikely to be revealed either by the climate reporting station network or by synoptic meteorology. There is little doubt that traditional knowledge of local circulations can provide a reasonable basis for describing local variation in climate, and this has been confirmed in a number of areas by field experience.

Climate and land use

The classification presented above provides a means by which possible associations between climate, population and land use can be discussed. Although economic development is proceeding rapidly, land use type and distribution is still strongly related to traditional patterns and practices. There are three main types of subsistence livelihood in Papua New Guinea. The first and most widespread is agricultural production based on root crops. The second is the collection and processing of sago. Both groups hunt, forage or fish for other food and can combine any of these activities to obtain a livelihood.

A very broad picture of the distribution of population and land use is presented in Fig. 9.8. Between one-third and one-half of the population lives in the inland highland valleys at altitudes above 1000 m, and mostly between 1500 and 2000 m. Their agricultural systems are intensive and based on sweet potato as the staple. Arabica coffee and tea are the main export cash crops. In the lowlands, people who live on the inundated alluvial plains form the main sago subsistence groups. Elsewhere in hillier terrain normal agricultural practice is based on shifting cultivation, with the main root crops being taro, yams, sweet potato and cassava. Coconuts, cacao, robusta coffee and rubber are the main cash crops.

Environmental conditions, of which climate is a major determinant, limit the range of crops which can be grown in any particular place. Temperature is one of these limiting factors, and Fig. 9.9 indicates the temperatures within which the main crops can be grown (as expressed in the relation between altitude and temperature). In addition, the areal distributions of many animal and bird species are similarly confined within altitudinal ranges (Kikkawa and Williams 1971). The following discussion relates land use and climate using the climatic classification presented above. It is not intended that the indicated relationships be considered in the sense of climatic determinism, but simply as a set of observed associations between climate and land use.

Lowland climates

The dry subhumid type of lowland climate is little used for agriculture, except for catch crops during the wet season. Traditionally, the bulk of the population occupying this type of environment lived on the coast or had access to sago in nearby swamps, which were watered from surrounding higher rainfall areas. More recently, these swamps and associated alluvial plains have been used for dry season cropping.

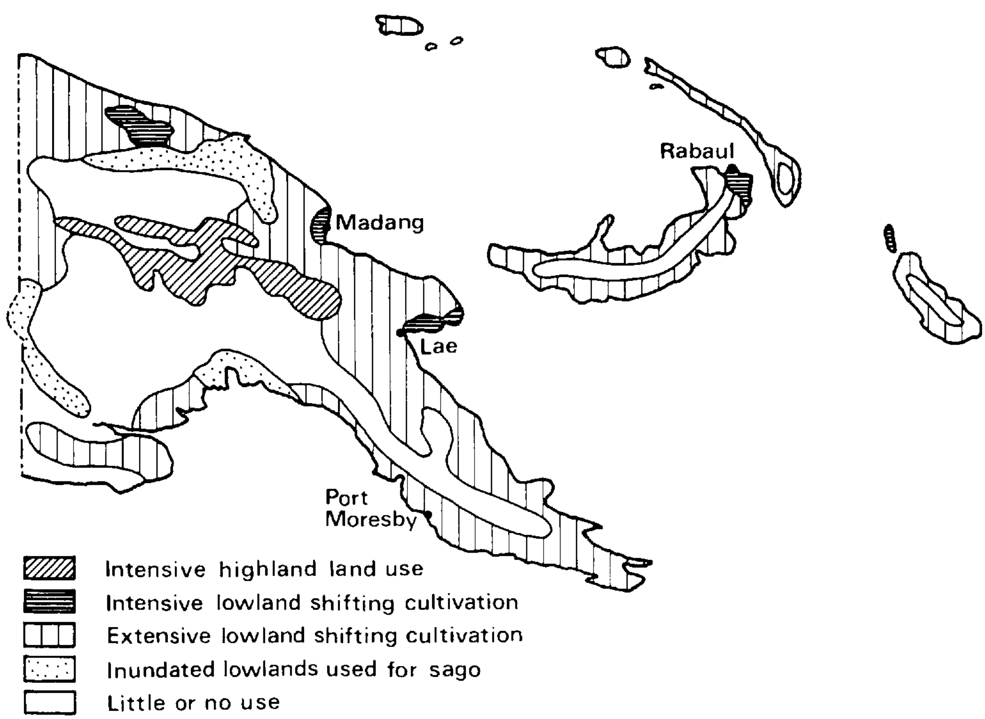
Agriculture in the subhumid lowlands varies widely in intensity. In the south-west of the country near Daru, the subhumid areas are either unused or support very light populations. By contrast, the most intensive and heavily populated of all PNG lowland agricultural systems is found within the same climatic type, but in the north near Maprik. While there will be other than climatic explanations for this difference, water balance accounting does reveal that the probability, duration and severity of soil moisture drought is significantly lower in the north near Maprik than in the south-west near Daru.

Within the subhumid lowlands, agriculture is based mainly on yam as the staple root crop. Of all the root crops apart from cassava, yam appears to be the most drought-tolerant. This climatic type also covers the large sago-based population living on the Sepik River and its tributaries. For much of the wet season the land available to this group is inundated, and consequently the people have developed trading links and agricultural systems to ensure a supply of plant food other than sago. These agricultural systems include the production of crops on levees when the river subsides and into the dry season.

The bulk of lowland agriculture takes place within the humid climatic type. The most intensively used areas are those either towards the lower end of the rainfall range for this type (2000 mm), such as near Rabaul, or towards the upper end of the range (3500 mm), such as near Madang where the higher wet season rainfall is associated with significant levels of soil moisture deficiency during the dry season.

The lowland perhumid climatic type is virtually unused, except for those areas subject to south-east season rainfall maxima, such as the south of Bougainville Island, New Britain, Finschhafen and Lae. Traditionally, these have all been taro-growing areas, although the occurrence of taro blight *(Phytophera colocasiaea)* has led to replacement of taro by sweet potato in recent years.

Fig. 9.8
Generalised land use map for PNG. Almost one-half of the population lives in the inland highland valleys, where agricultural systems are intensive and based on sweet potato as staple. In the lowlands, people living on inundated alluvial plains form the main sago subsistence groups. Elsewhere in the lowlands, shifting cultivation is practised to grow taro, yams, sweet potato and cassava for subsistence.



Premontane climates

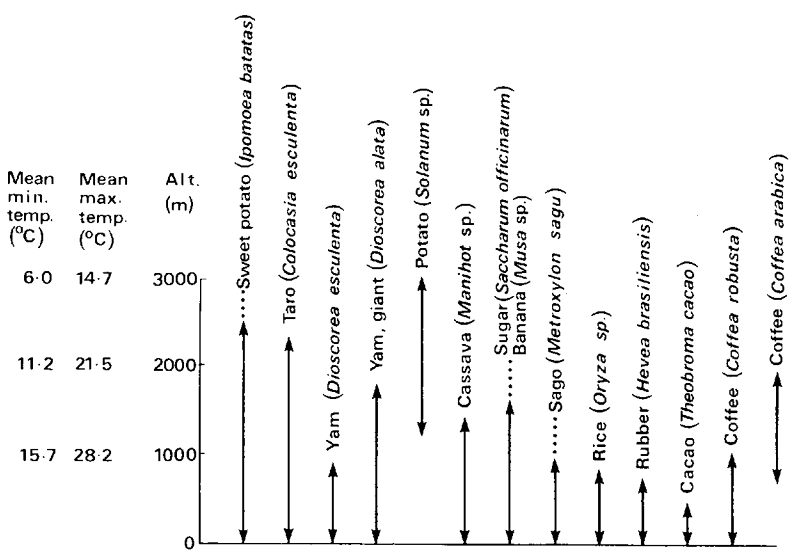
For the most part these climatic types are unpopulated, except for the subhumid area covering Bulolo, Wau and Menyamya. In this drier area, yam and sweet potato are again the root crop staples. One of the reasons most commonly advanced for the lack of occupation of this climatic zone is that it encompasses the environmental temperature limits for the main crops grown in PNG. The zone is too cold for optimal production from lowland crops and too warm for highland crops.

Lower montane climates

The major part of the agriculture within the lower montane zone is found in the central cordillera. The coastal and island ranges are little used at this altitude and within the central cordillera, the perhumid areas to the west are also little used. Most agriculture takes place in the humid areas. The agriculture found in the small subhumid area between Goroka and Henganofi is at the lower end of the rainfall range for the subhumid type (2000 mm) and associated with a lower evaporation regime than is found in lowland subhumid areas. The staple is sweet potato, which in the drier eastern highlands is grown in soil given only light tilling. In the wetter western highland areas, the crop is drained by ditches or grown on artificial soil mounds.

The upper altitudinal limit of sweet potato-based agriculture occurs around 2800 m, but cultivation usually ceases at 2600 m, where the risk of frost and increase in maturation time cause planting to become risky and non-productive. Within the lower montane climatic zone a significant additional agroclimatic boundary occurs at about 2000 m, where temperatures have decreased to a level at which a number of crops such as sugar, bananas and coffee are no longer productive.

Fig. 9.9
Altitudinal ranges of major food and cash crops. Temperatures are those determined from generalised lapse rates for PNG.



Montane climates
In terms of subsistence activity, these areas are only used for hunting and foraging.

Climate and resource assessment

These associations between climate and land use clearly indicate the major importance of climate as a factor in resource assessment and utilisation. Many agricultural practices represent responses to climatic effects. For example, the almost universal use of hilly terrain for traditional agriculture is most likely a response to the need for adequate drainage in a wet environment. Flatter alluvial plains, even if more fertile, present drainage hazards without considerable engineering modification.

Consideration of climatic factors raises a complex issue for land development. Large-scale agricultural production involves mechanisation, and of necessity mechanised agriculture must largely be restricted to areas of low slope. Except in the highland valleys, such areas have few people living on them and in addition have higher malarial prevalence rates. Thus the requirements of large-scale agriculture make it difficult to organise within a local village context. The development of smallholder cash cropping in association with subsistence agriculture has become common in many areas of PNG and in a sense this can be seen partly as an indirect response to climate.

More direct issues linking climatic factors with resource use are covered in studies by Kalma (1979) on the use of wind as a source of local electrical power and, at a much wider scale, by Dirkis (1974) on the use of the country's extensive water resources for hydro-electric power.

Resource and infrastructural development involve a need for the expansion of knowledge of climate and its variability, both in space and in time. From the information currently available, this book has attempted a comprehensive description of the climate of Papua New Guinea. It is hoped that the book will provide a basis for the much needed expansion of climatological knowledge of that country.

Appendix

Selected Climatic Tables for Papua New Guinea

MONTHLY VECTOR MEAN WINDS TO 80 MILLIBARS

LAE — 1960-69 — 6 DEG. 43 MIN. LAT.S. 147 DEG. 0 MIN. LONG.E. 8 METRES

PRESSURE MB	HEIGHT KM		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
SURF	0.0	DIRECTION (DEG.)	306	306	303	303	309	314	326	315	297	304	302	303	306
		SPEED (KNOTS)	7	7	6	4	2	2	1	1	1	2	3	4	3
950	.6	DIRECTION (DEG.)	303	304	301	301	311	310	319	325	298	303	299	301	304
		SPEED (KNOTS)	10	10	9	5	2	2	1	1	1	1	4	6	4
900	1.0	DIRECTION (DEG.)	285	284	277	262	155	144	134	129	145	149	262	273	246
		SPEED (KNOTS)	8	8	6	2	2	2	4	4	3	2	2	3	2
850	1.5	DIRECTION (DEG.)	284	284	279	248	138	132	134	132	137	145	245	271	206
		SPEED (KNOTS)	7	7	6	2	3	5	5	6	4	3	2	3	1
750	2.6	DIRECTION (DEG.)	281	279	278	224	116	119	117	124	117	122	187	269	143
		SPEED (KNOTS)	6	6	6	1	5	6	8	8	6	4	1	3	2
700	3.1	DIRECTION (DEG.)	273	274	264	81	89	97	99	99	99	97	138	258	100
		SPEED (KNOTS)	4	4	2	2	7	10	11	11	8	5	2	2	9
600	4.4	DIRECTION (DEG.)	285	46	173	82	78	87	86	85	90	84	130	287	65
		SPEED (KNOTS)	1	1	0	2	6	10	12	12	8	4	2	1	5
500	5.8	DIRECTION (DEG.)	55	83	65	80	83	83	82	80	84	77	94	69	81
		SPEED (KNOTS)	1	5	3	3	6	9	11	12	9	6	2	1	6
400	7.6	DIRECTION (DEG.)	87	88	86	82	85	93	91	86	91	80	90	72	88
		SPEED (KNOTS)	3	6	6	4	5	8	13	12	11	7	2	3	7
300	9.6	DIRECTION (DEG.)	93	91	87	83	82	92	90	83	89	80	61	70	80
		SPEED (KNOTS)	5	9	7	5	3	8	13	12	13	7	2	4	7
250	10.9	DIRECTION (DEG.)	91	95	85	64	42	73	73	71	75	61	27	65	74
		SPEED (KNOTS)	8	13	10	6	3	8	15	15	15	9	5	5	9
200	12.4	DIRECTION (DEG.)	95	98	87	82	11	60	62	63	64	51	26	68	68
		SPEED (KNOTS)	11	16	14	9	2	9	17	16	18	13	8	8	11
150	14.2	DIRECTION (DEG.)	99	100	91	60	280	60	59	67	69	53	41	76	75
		SPEED (KNOTS)	16	26	18	10	2	8	16	13	18	12	9	11	12
100	16.5	DIRECTION (DEG.)	94	98	96	102	230	114	98	94	101	91	74	88	96
		SPEED (KNOTS)	23	26	20	4	4	4	6	9	7	8	7	18	10
80	17.8	DIRECTION (DEG.)	93	101	102	126	254	263	269	268	250	230	94	94	126
		SPEED (KNOTS)	17	13	14	3	4	6	9	5	3	1	1	8	2

MONTHLY VECTOR MEAN WINDS TO 80 MILLIBARS

PORT MORESBY 1960-69 9 DEG. 26 MIN. LAT.S. 147 DEG. 13 MIN. LONG.E.
35 METRES

PRESSURE MB	HEIGHT KM		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
SURF	0.0	DIRECTION (DEG.)	342	344	342	61	133	142	144	148	145	147	107	351	128
		SPEED (KNOTS)	3	4	3	0	2	5	6	5	4	3	1	2	1
950	.6	DIRECTION (DEG.)	341	343	341	40	127	141	142	145	141	145	114	346	112
		SPEED (KNOTS)	6	7	5	1	3	8	8	7	6	4	1	3	2
900	1.0	DIRECTION (DEG.)	316	317	316	121	125	125	124	119	114	113	39	319	40
		SPEED (KNOTS)	11	12	7	1	4	8	8	5	5	3	0	3	1
850	1.5	DIRECTION (DEG.)	309	310	311	339	112	114	119	118	111	106	341	310	335
		SPEED (KNOTS)	12	13	6	1	3	6	6	5	4	3	1	5	1
750	2.6	DIRECTION (DEG.)	308	305	311	351	84	96	86	98	99	106	241	302	335
		SPEED (KNOTS)	11	12	7	1	3	4	4	4	2	3	0	4	2
700	3.1	DIRECTION (DEG.)	300	296	312	83	71	81	84	82	103	107	150	278	45
		SPEED (KNOTS)	8	8	3	1	4	6	6	7	3	3	4	2	12
600	4.4	DIRECTION (DEG.)	309	293	70	76	57	73	81	76	66	49	136	277	65
		SPEED (KNOTS)	4	3	1	2	5	7	8	10	4	3	2	1	3
500	5.8	DIRECTION (DEG.)	328	32	92	43	68	61	76	75	59	34	120	34	64
		SPEED (KNOTS)	2	2	3	2	4	5	8	9	5	2	1	1	3
400	7.6	DIRECTION (DEG.)	31	74	97	71	78	61	88	81	83	17	241	55	79
		SPEED (KNOTS)	1	3	5	2	3	3	8	10	7	1	1	2	3
300	9.6	DIRECTION (DEG.)	88	101	100	57	191	179	100	94	92	327	295	44	93
		SPEED (KNOTS)	2	6	5	2	1	1	7	8	6	3	2	2	3
250	10.9	DIRECTION (DEG.)	121	112	96	353	276	288	59	57	56	326	331	45	38
		SPEED (KNOTS)	2	8	3	2	4	3	6	8	7	7	6	2	2
200	12.4	DIRECTION (DEG.)	113	109	64	4	292	312	22	39	39	332	338	18	14
		SPEED (KNOTS)	5	10	2	6	7	5	9	10	11	9	9	4	4
150	14.2	DIRECTION (DEG.)	119	102	73	8	289	315	9	35	43	332	355	44	24
		SPEED (KNOTS)	8	16	4	9	9	5	10	7	12	6	9	6	5
100	16.5	DIRECTION (DEG.)	108	95	107	41	250	198	134	101	106	78	88	87	102
		SPEED (KNOTS)	22	27	13	3	9	2	5	9	9	4	6	17	7
80	17.8	DIRECTION (DEG.)	103	91	98	84	229	198	202	177	219	268	113	83	108
		SPEED (KNOTS)	24	23	15	6	5	1	2	2	3	3	3	10	5

MONTHLY VECTOR MEAN WINDS TO 80 MILLIBARS

RABAUL 1960-69 4 DEG. 12 MIN. LAT.S. 152 DEG. 11 MIN. LONG.E.
4 METRES

PRESSURE MB	HEIGHT KM		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
SURF	0.0	DIRECTION (DEG.)	306	302	305	125	124	126	129	128	131	131	132	261	130
		SPEED (KNOTS)	2	2	1	1	4	5	7	6	6	5	3	0	3
950	.6	DIRECTION (DEG.)	299	300	302	148	135	138	141	140	139	138	142	281	144
		SPEED (KNOTS)	4	4	3	2	6	7	9	8	8	6	3	1	3
900	1.0	DIRECTION (DEG.)	292	292	290	187	139	139	143	145	142	143	171	265	161
		SPEED (KNOTS)	7	7	6	2	6	9	11	11	9	6	3	3	4
850	1.5	DIRECTION (DEG.)	287	283	284	270	110	116	126	126	119	126	208	264	153
		SPEED (KNOTS)	8	7	6	1	5	7	8	8	6	4	3	4	2
750	2.6	DIRECTION (DEG.)	280	282	280	320	102	103	111	105	101	107	205	264	114
		SPEED (KNOTS)	6	5	4	0	6	9	9	9	7	4	3	4	3
700	3.1	DIRECTION (DEG.)	284	303	282	68	94	90	99	94	99	92	211	272	95
		SPEED (KNOTS)	3	1	2	1	8	10	11	11	9	4	2	3	4
600	4.4	DIRECTION (DEG.)	59	85	73	97	85	80	88	86	89	79	19	358	83
		SPEED (KNOTS)	3	6	4	4	9	13	14	15	12	6	1	1	8
500	5.8	DIRECTION (DEG.)	74	78	78	93	82	81	83	81	83	77	64	61	80
		SPEED (KNOTS)	9	11	9	7	7	13	15	17	14	8	2	5	10
400	7.6	DIRECTION (DEG.)	73	78	76	90	86	87	86	82	83	83	85	70	83
		SPEED (KNOTS)	11	13	10	10	6	12	16	18	15	10	3	8	11
300	9.6	DIRECTION (DEG.)	76	75	79	88	84	96	84	81	87	85	78	76	84
		SPEED (KNOTS)	11	16	10	9	5	9	14	17	14	9	4	7	11
250	10.9	DIRECTION (DEG.)	88	82	80	85	87	87	79	78	85	75	104	74	82
		SPEED (KNOTS)	13	17	12	7	4	10	15	16	15	8	4	8	11
200	12.4	DIRECTION (DEG.)	88	90	90	91	74	84	75	70	83	73	74	76	80
		SPEED (KNOTS)	12	20	13	7	3	9	14	18	17	9	5	7	11
150	14.2	DIRECTION (DEG.)	91	89	100	99	308	88	65	71	75	54	58	84	76
		SPEED (KNOTS)	19	23	15	7	3	7	16	16	17	11	6	13	11
100	16.5	DIRECTION (DEG.)	95	86	95	168	241	126	72	113	80	94	61	84	99
		SPEED (KNOTS)	17	29	14	5	6	9	10	8	9	10	8	14	8
80	17.8	DIRECTION (DEG.)	82	85	91	217	255	169	218	157	187	87	82	86	108
		SPEED (KNOTS)	16	24	13	4	5	3	1	5	2	6	11	13	4

MONTHLY AND ANNUAL RAINFALL (MM) PROBABILITY BY PERCENTILES AND QUARTILES

Station		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
AIOME														
STATION NO. 200291	LOWEST	279	366	428	424	152	108	50	74	144	199	300	431	5197
(1958-70)	10	392	498	497	444	202	121	78	131	158	232	352	432	5197
	25 L.Q.	583	532	628	506	300	128	125	144	181	284	391	483	5316
	30	583	656	628	506	300	184	180	144	181	284	391	483	5316
	50 MED.	634	829	727	617	404	197	212	165	213	318	459	564	5527
	70	834	835	872	682	520	267	306	221	302	375	473	591	5651
	75 U.Q.	834	837	890	682	520	272	312	221	302	375	495	601	6302
	90	1006	912	949	762	621	321	342	333	479	463	507	607	6441
	HIGHEST	1037	943	1161	765	638	322	413	384	589	616	803	899	6441
	NO. OF RECORDS	13	11	12	13	13	11	11	13	13	13	12	12	8
AIYURA														
STATION NO. 200003	LOWEST	56	50	137	33	28	11	30	37	36	50	97	100	1563
(1937-70)	10	124	140	181	129	62	50	47	58	56	56	131	128	1831
	25 L.Q.	184	216	202	185	81	61	71	72	96	109	142	205	1905
	30	186	221	214	189	81	69	79	86	102	130	169	208	1917
	50 MED.	239	252	249	226	119	80	90	120	136	157	189	240	2184
	70	260	309	297	261	152	107	118	170	176	193	233	272	2301
	75 U.Q.	266	319	322	266	158	115	130	175	176	205	239	280	2310
	90	352	394	420	354	195	151	184	218	220	265	285	355	2497
	HIGHEST	427	474	440	399	240	173	266	390	252	322	307	400	2565
	NO. OF RECORDS	30	30	30	30	30	31	30	30	30	29	30	30	29
BAINYIK														
STATION NO. 200169	LOWEST	68	97	144	78	22	26	14	13	69	57	89	82	1292
(1950-69)	10	92	100	145	84	54	33	20	16	71	83	130	87	1402
	25 L.Q.	129	119	166	130	88	52	39	66	77	107	141	132	1529
	30	138	137	170	169	93	63	56	76	78	112	149	145	1538
	50 MED.	162	181	194	186	114	90	78	90	100	136	177	167	1692
	70	173	204	211	209	120	100	93	117	147	166	208	187	1787
	75 U.Q.	175	211	235	210	125	102	95	136	148	179	223	192	1826
	90	275	330	308	249	177	146	146	162	197	248	265	272	2110
	HIGHEST	292	395	353	266	183	147	179	181	242	291	268	350	2378
	NO. OF RECORDS	19	18	18	18	18	18	19	19	19	19	19	18	17

MONTHLY AND ANNUAL RAINFALL (MM) PROBABILITY BY PERCENTILES AND QUARTILES

Station		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
DARU														
STATION NO. 200024	LOWEST	99	46	53	27	35	11	5	6	6	0	0	12	1163
(1894-70)	10	141	128	162	106	80	34	25	15	12	4	6	50	1348
	25 L.Q.	185	201	239	187	113	48	32	25	18	12	22	96	1689
	30	216	208	261	215	129	50	46	28	20	16	26	104	1742
	50 MED.	264	245	299	328	175	76	67	39	30	29	70	169	2077
	70	291	293	384	410	287	124	104	47	46	50	128	226	2247
	75 U.Q.	307	308	397	451	303	147	112	66	53	57	141	271	2317
	90	413	366	548	582	397	242	191	115	101	101	291	427	2785
	HIGHEST	1248	634	658	673	748	382	509	347	163	472	502	688	3972
	NO. OF RECORDS	70	72	69	72	71	72	70	70	70	71	71	69	57
GOROKA A/S														
STATION NO. 200197	LOWEST	27	29	138	75	23	4	5	16	22	42	57	55	1375
(1948-70)	10	120	157	169	114	35	21	9	36	57	65	94	116	1576
	25 L.Q.	166	196	217	164	66	28	24	45	85	107	133	154	1734
	30	183	211	218	183	73	32	25	46	87	119	133	170	1819
	50 MED.	220	242	289	223	102	53	47	62	101	155	175	255	1907
	70	310	314	325	243	141	72	58	84	167	172	203	310	2046
	75 U.Q.	327	318	339	263	141	75	68	101	172	181	213	315	2054
	90	346	363	345	276	195	96	99	138	176	264	254	363	2213
	HIGHEST	403	402	359	289	369	115	127	196	276	303	310	421	2379
	NO. OF RECORDS	22	21	22	22	23	23	22	23	23	22	22	21	19
KAVIENG														
STATION NO. 200048	LOWEST	71	43	105	109	99	49	12	0	29	14	66	93	1631
(1916-70)	10	143	124	148	193	128	123	105	84	52	102	90	190	2531
	25 L.Q.	214	207	190	254	179	170	177	128	137	151	155	262	2759
	30	224	234	224	266	198	179	188	152	140	157	169	273	2966
	50 MED.	335	270	298	283	250	216	233	206	168	220	231	326	3078
	70	375	339	369	306	322	275	271	274	224	280	316	358	3327
	75 U.Q.	385	347	372	321	323	307	282	315	246	315	338	368	3611
	90	543	480	420	403	439	407	325	380	359	401	393	465	3955
	HIGHEST	905	550	676	680	549	503	518	624	463	653	495	660	4865
	NO. OF RECORDS	40	39	39	41	40	41	40	39	43	43	43	43	34

MONTHLY AND ANNUAL RAINFALL (MM) PROBABILITY BY PERCENTILES AND QUARTILES

Station		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
KIKORI STATION NO. 200054 (1913-70)	LOWEST	112	90	144	93	103	75	109	105	76	19	36	73	3011
	10	177	218	209	267	382	354	284	242	245	113	113	202	4416
	25 L.Q.	261	257	250	328	586	441	422	375	343	290	185	217	5294
	30	274	269	285	343	596	508	484	391	360	312	217	232	5419
	50 MED.	309	314	363	420	717	748	644	470	554	466	312	296	5881
	70	368	398	426	513	888	895	799	736	731	601	393	352	6298
	75 U.Q.	384	418	438	539	910	916	848	753	812	659	404	373	6316
	90	435	462	524	658	1067	1083	1060	880	1097	788	590	440	7033
	HIGHEST	475	582	645	795	1462	1508	1434	1324	1844	1088	856	515	7935
	NO. OF RECORDS	50	51	51	54	55	55	55	55	52	52	53	52	43
LAE A/S STATION NO. 200065 (1925-70)	LOWEST	36	53	140	237	67	115	143	161	193	72	128	37	3109
	10	159	94	191	303	162	168	333	303	274	176	196	192	4141
	25 L.Q.	183	156	226	337	271	266	366	376	354	275	263	253	4207
	30	199	166	252	346	366	289	388	404	364	277	275	276	4411
	50 MED.	258	254	335	399	423	413	503	484	466	391	328	323	4553
	70	282	276	362	426	500	530	559	629	569	516	396	366	4867
	75 U.Q.	283	285	395	458	532	544	611	682	606	532	424	390	4904
	90	432	372	457	539	667	628	722	781	649	610	513	471	5445
	HIGHEST	522	403	524	602	840	770	1058	863	922	695	577	605	6062
	NO. OF RECORDS	33	32	34	34	35	34	35	35	36	36	35	34	30
MADANG AGRIC. STATION NO. 200070 (1916-70)	LOWEST	85	88	126	122	18	70	1	1	2	17	163	112	2333
	10	158	160	211	241	187	117	56	24	32	95	228	194	2717
	25 L.Q.	226	244	270	309	266	163	117	53	79	185	293	257	3289
	30	289	258	288	326	278	165	119	68	89	202	306	290	3368
	50 MED.	346	322	357	422	365	221	147	107	134	250	351	381	3592
	70	419	362	443	509	438	285	200	176	188	292	418	444	3811
	75 U.Q.	458	370	458	528	508	300	235	179	198	309	437	462	3893
	90	501	472	531	681	621	367	341	260	279	485	545	592	4124
	HIGHEST	555	616	709	797	775	702	436	382	562	729	660	808	4569
	NO. OF RECORDS	48	49	49	49	49	48	47	46	45	45	45	44	42

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Station		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MT. HAGEN STATION NO. 200243 (1951-70)	LOWEST	122	89	130	83	63	30	24	67	109	89	80	85	2078
	10	197	217	182	123	100	62	48	78	162	148	143	108	2132
	25 L.Q.	225	223	215	185	139	86	100	122	170	168	170	219	2394
	30	225	224	218	207	146	106	100	127	179	177	173	226	2401
	50 MED.	258	236	286	255	195	114	136	168	208	203	185	274	2579
	70	301	306	327	326	220	138	176	231	269	260	257	304	2741
	75 U.Q.	310	352	388	331	240	143	182	231	278	268	266	337	2866
	90	412	418	414	396	255	207	218	279	351	342	333	452	3243
	HIGHEST	428	431	469	453	334	230	234	280	366	496	376	453	3337
	NO. OF RECORDS	20	20	20	20	20	20	20	20	20	20	20	20	20
PORT MORESBY KONEDOBU STATION NO. 200108 (1891-41)	LOWEST	52	28	7	0	0	0	0	0	0	0	0	0	574
	10	72	73	64	15	2	1	0	0	1	0	0	15	723
	25 L.Q.	119	124	101	49	7	6	2	3	5	3	10	53	857
	30	122	142	116	55	11	8	3	4	7	4	13	55	871
	50 MED.	158	169	162	83	39	22	12	7	15	11	35	87	939
	70	217	221	195	117	75	41	22	15	33	33	74	131	1102
	75 U.Q.	224	239	239	120	81	44	36	19	41	42	81	140	1128
	90	297	401	288	217	135	63	98	37	75	83	141	203	1280
	HIGHEST	471	465	404	595	589	191	198	174	136	246	211	442	1829
	NO. OF RECORDS	49	49	49	49	49	46	47	48	48	49	48	49	42
PORT MORESBY JACKSONS STRIP STATION NO. 200286 (1945-70)	LOWEST	26	60	28	9	2	0	0	1	0	2	0	25	869
	10	69	82	70	49	8	2	1	2	3	5	7	82	998
	25 L.Q.	114	149	125	73	14	7	2	6	11	10	25	112	1060
	30	124	149	129	74	15	9	4	10	12	17	32	116	1087
	50 MED.	148	228	173	132	36	23	13	27	28	28	53	161	1154
	70	197	268	228	154	51	40	27	44	34	50	97	205	1319
	75 U.Q.	211	295	240	183	54	40	28	44	39	52	103	213	1395
	90	262	371	358	332	147	100	45	93	83	112	140	236	1480
	HIGHEST	465	434	442	728	187	313	70	138	344	181	234	268	1569
	NO. OF RECORDS	25	25	25	25	25	25	25	26	26	26	26	26	25

MONTHLY AND ANNUAL RAINFALL (MM) PROBABILITY BY PERCENTILES AND QUARTILES

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
RABAUL A/S STATION NO. 200340 (1946-70)	LOWEST	24	37	93	93	5	19	10	8	8	3	62	116	1490
	10	127	112	134	134	28	34	42	25	24	31	94	132	1596
	25 L.Q.	165	158	192	169	67	52	56	48	49	88	129	182	1715
	30	168	169	215	171	71	52	57	61	51	106	149	185	1737
	50 MED.	192	215	261	190	119	95	100	95	99	116	166	236	2010
	70	287	268	297	238	154	132	137	130	129	152	182	259	2202
	75 U.Q.	342	283	303	242	192	135	139	132	149	177	192	275	2255
	90	393	359	408	315	259	246	169	195	161	187	280	344	2449
	HIGHEST	445	808	460	354	286	331	239	350	202	203	345	582	2574
	NO. OF RECORDS	24	24	24	25	25	25	23	23	24	24	24	24	23
SAIDOR STATION NO. 200253 (1952-70)	LOWEST	101	82	156	120	44	23	3	2	2	5	42	114	1853
	10	116	160	237	146	75	53	35	5	11	36	60	119	1872
	25 L.Q.	293	200	316	216	111	93	64	44	43	86	109	142	2380
	30	306	308	321	250	127	94	70	59	55	90	117	173	2583
	50 MED.	347	485	353	292	156	123	111	76	105	192	145	252	2769
	70	421	502	439	354	250	157	144	106	141	220	209	328	2915
	75 U.Q.	498	652	490	368	254	204	154	108	150	226	212	345	2981
	90	600	846	624	525	267	263	211	227	198	260	371	535	3446
	HIGHEST	1066	913	673	831	301	277	256	292	329	466	379	541	3541
	NO. OF RECORDS	17	18	17	17	19	19	19	17	19	18	17	18	14
SAMARAI STATION NO. 200123 (1891-70)	LOWEST	42	42	7	80	66	43	6	21	19	8	14	11	1505
	10	68	59	100	115	110	91	53	58	77	55	52	43	1965
	25 L.Q.	97	103	138	181	209	144	94	80	135	98	89	77	2195
	30	103	107	153	190	211	179	100	84	152	149	109	95	2241
	50 MED.	146	179	226	248	274	245	140	153	209	192	157	129	2441
	70	205	220	289	304	344	359	296	286	307	270	246	166	2943
	75 U.Q.	209	231	315	305	369	394	308	290	326	320	259	184	3071
	90	301	305	415	387	480	542	460	487	428	435	347	254	3709
	HIGHEST	494	367	739	664	668	943	734	903	1124	642	478	408	4549
	NO. OF RECORDS	53	53	51	53	52	55	53	53	55	55	55	53	44

MONTHLY AND ANNUAL RAINFALL (MM) PROBABILITY BY PERCENTILES AND QUARTILES

Station		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
WAU N.G.GOLDFIELDS STATION NO. 200278 (1929-70)	LOWEST	21	45	43	52	25	18	36	3	51	30	40	38	1274
	10	61	72	115	62	49	28	55	24	81	40	125	91	1530
	25 L.Q.	96	122	160	109	76	57	73	64	93	80	144	134	1670
	30	124	147	172	117	89	67	77	65	96	82	152	136	1710
	50 MED.	151	191	210	173	116	83	98	96	118	138	177	207	1816
	70	221	240	268	244	174	102	119	137	132	190	219	282	1911
	75 U.Q.	254	251	284	259	179	108	127	139	139	202	228	282	1956
	90	332	296	312	292	220	129	156	182	181	240	289	336	2251
	HIGHEST	445	341	332	345	275	169	211	303	224	332	362	395	2492
	NO. OF RECORDS	37	37	37	37	38	37	38	38	38	37	37	37	35
WEWAK TOWNSHIP STATION NO. 200499 (1923-69)	LOWEST	21	5	47	35	26	34	67	10	73	90	64	26	1631
	10	38	29	84	57	116	117	69	50	94	119	98	42	1755
	25 L.Q.	89	67	102	110	170	139	122	81	115	176	131	83	2040
	30	103	73	109	124	184	141	124	100	123	177	133	89	2167
	50 MED.	137	105	131	163	238	185	189	160	185	214	204	115	2231
	70	184	133	192	205	255	235	217	179	248	268	221	163	2370
	75 U.Q.	193	157	205	268	290	248	218	195	285	281	229	184	2466
	90	240	220	268	306	318	366	332	354	367	323	300	253	2597
	HIGHEST	265	394	329	518	577	492	461	359	561	399	464	317	2667
	NO. OF RECORDS	28	26	29	31	31	30	29	30	30	29	28	26	17

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STATION NAME	STATION NO.	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
AIOME	200291	681	727	737	606	403	211	228	194	276	347	456	561	5642
AITAPE ST.ANNA	200002	242	270	292	210	216	191	181	134	175	173	214	310	2581
AIYURA	200003	197	246	263	183	111	85	96	131	132	177	187	268	2076
AMBUNTI	200004	277	260	311	265	211	132	163	187	196	217	233	240	2727
ANGORAM	200006	200	210	228	201	142	84	84	84	92	126	225	212	1882
AWELKON	200166	602	692	530	390	247	252	273	286	220	234	233	444	4402
BAINYIK	200169	147	181	197	181	113	76	82	90	108	156	171	173	1684
BAIYER RIVER	200170	281	343	364	261	170	91	101	122	181	205	204	310	2633
BAMU RIVER	200171	296	361	435	363	410	297	179	152	207	211	204	277	3391
BANIARA	200015	271	264	272	207	121	93	44	35	61	78	74	168	1698
BEREINA	200174	204	225	207	135	42	30	18	26	60	51	50	145	1193
BOGIA/AWAR	200175/165	240	235	287	243	140	92	68	53	81	145	201	299	2084
BULOLO FORESTRY	200178	132	125	158	137	127	88	103	111	129	145	156	184	1604
BWAGAOIA	200084	236	248	223	285	223	249	123	172	231	254	237	242	2779
DARU	200024	271	237	302	293	158	133	71	53	51	62	131	184	1891
DOGURA	200025	246	218	217	143	75	80	62	42	80	93	68	122	1447
ERAP	200187	150	158	168	86	60	78	87	104	75	87	77	146	1271
ERAVE	200188	294	328	330	271	258	254	320	307	322	292	236	298	3511
FINSCHHAFEN	200035	146	96	135	332	535	631	681	556	478	489	292	249	4619
GARAINA	200192	233	284	311	241	200	138	140	173	222	310	277	280	2808
GIZARUM	200194	398	436	355	230	126	124	119	121	88	106	150	298	2551
GOROKA A/S	200197	215	237	263	184	110	59	53	78	131	167	170	273	1939
HENGANOFI	200312	232	266	300	172	88	43	29	67	97	171	153	229	1847
ITIKINUMU	200316	290	316	333	327	295	151	98	173	287	296	279	352	3241
KAIAPIT	200043	257	277	356	253	139	63	54	82	127	172	229	357	2366
KANDRIAN	200210	119	98	152	179	327	596	671	631	425	298	158	151	3860

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STATION NAME	STATION NO.	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
KAVIENG	200048	347	281	326	303	261	230	217	208	211	279	236	395	3282
KEREMA	200051	227	286	299	288	452	360	416	348	421	325	179	237	3826
KIKORI	200054	329	355	338	463	683	598	663	597	646	483	273	270	5635
LAE A/S	200065	291	225	332	361	451	447	519	544	463	441	307	373	4753
LUMI	200234	265	247	315	251	191	108	120	166	199	253	249	299	2658
MADANG A/S	200235	382	287	343	436	332	204	172	151	144	324	378	404	3558
MENDI	200339	229	259	286	215	214	195	261	258	266	276	194	226	2806
MENYAMYA	200238	151	181	182	145	121	96	80	100	153	176	175	174	1752
MINJ	200240	236	272	296	214	182	117	130	174	208	205	198	284	2509
MOMOTE	200241	274	253	277	281	224	327	372	314	277	245	230	309	3382
MT. HAGEN	200243	252	264	295	236	190	115	138	168	212	234	190	270	2564
POMIO	200251	223	151	233	268	462	856	1291	1187	723	477	240	235	6195
POPONDETTA	200272	311	263	295	239	171	121	78	101	158	190	235	346	2482
PT. MORESBY A/S	200286	199	239	217	143	41	41	16	31	57	37	48	145	1214
RABAUL A/S	200340	235	233	253	194	93	124	118	122	111	126	184	249	2014
SAIDOR	200253	402	480	398	327	175	131	119	100	119	167	167	275	2742
SAMARAI	200123	160	174	228	305	206	257	133	170	230	213	134	149	2312
SOHANO	200018	338	303	341	271	168	121	183	182	168	185	199	249	2692
TAPINI	200255	229	268	282	184	128	67	51	77	141	172	162	240	2002
TARI	200256	229	251	285	247	242	156	178	187	238	261	230	250	2754
TUFI	200262	381	458	324	305	295	206	108	66	106	164	238	311	2963
VANIMO (ARMY)	200259	271	257	336	232	182	184	203	157	171	188	201	327	2673
WABAG	200265	293	308	353	295	206	134	137	202	276	277	254	325	3056
WAU GOLD RIDGES	200274	183	197	197	169	117	69	104	96	115	176	169	215	1806
WEWAK A/S	200160	143	128	155	173	219	203	184	195	206	225	207	147	2189

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STATION NAME	STATION NO.	YRS. OF RECORD	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
ABAU	200000	15	141	162	205	225	250	215	206	197	210	113	108	145	2211
AIOME	200291	8	681	727	737	606	403	211	228	194	276	347	456	561	5642
AITAPE ST.ANNA	200002	29	256	263	274	246	208	175	172	153	139	156	206	270	2531
AIYURA	200003	29	230	263	265	225	121	90	102	131	135	161	195	241	2156
ALOTAU	200543	6	148	175	196	261	356	329	308	342	501	375	112	121	3199
AMAZON BAY	200446	8	273	196	249	272	234	204	236	154	183	149	67	113	2197
AMBOIN	200456	3	611	582	688	448	282	327	367	277	475	455	492	457	5214
AMBUNTI	200004	16	245	253	298	246	181	119	150	178	205	241	273	276	2554
ANGORAM	200006	13	210	218	235	221	145	87	80	81	88	150	219	239	2101
ARONA	200164	15	208	272	280	180	74	63	73	73	91	162	193	289	1978
AWELKON	200166	21	578	670	562	396	275	275	272	268	221	216	243	407	4444
BAIBARA	200168	14	210	190	231	227	206	270	205	216	245	139	76	161	2491
BAINYIK	200169	17	160	186	204	176	110	81	78	95	120	147	180	176	1721
BAIYER RIVER	200170	16	290	334	370	274	160	90	100	126	174	195	222	304	2614
BALIMO A/S	200297	11	258	323	326	269	243	160	108	70	129	130	132	277	2476
BANIARA	200015	34	268	288	258	206	143	107	71	60	64	88	122	179	1813
BEREINA	200174	14	210	220	210	131	42	28	21	26	55	53	43	172	1182
BUBIA	200176	17	217	193	243	230	263	265	351	325	288	257	185	202	3025
BUIN COAST	200017	15	277	258	308	224	270	318	563	465	366	313	235	205	3776
BULOLO HOSPITAL	200019	27	122	151	180	160	117	73	94	98	117	126	150	179	1544
BUNA BAY	200022	28	329	320	344	294	233	181	133	101	147	211	337	369	3048
BWAGAOIA	200084	35	252	318	269	292	299	248	181	221	237	260	255	227	3012
CAPE NELSON	200023	29	397	466	410	344	295	209	126	101	107	186	309	325	3327
DARU	200024	57	280	258	325	321	223	108	93	52	42	55	111	204	2063

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STATION NAME	STATION NO.	YRS. OF RECORD	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
DOGURA	200025	44	232	221	222	149	91	93	76	65	77	79	88	120	1493
ERAP	200187	16	149	149	179	87	60	78	98	99	68	77	76	135	1248
ERAVE	200188	14	297	335	314	274	257	250	309	292	331	289	238	299	3405
ESA'ALA	200189	14	185	199	233	260	207	203	170	139	199	217	134	134	2272
FINSCHHAFEN	200035	25	140	95	135	301	464	589	655	568	531	402	297	227	4417
GARAINA	200192	22	227	296	291	251	195	131	148	166	220	282	300	303	2806
GASMATA	200036	21	140	143	175	239	646	811	867	1071	827	512	303	192	6051
GIZARUM	200194	23	397	456	404	223	124	132	118	118	94	94	156	284	2562
GOBARAGERE	200049	33	195	174	196	211	108	78	46	51	61	78	129	166	1521
GOROKA A/S	200197	19	230	254	266	204	113	54	49	74	121	154	171	243	1921
HENGANOFI	200312	14	232	266	305	172	88	43	29	67	97	167	142	230	1828
IALIBU	200314	13	331	351	381	297	228	191	258	288	369	373	312	343	3752
ILOLO	200205	28	287	328	305	287	193	123	87	121	174	222	196	258	2575
IOMA	200041	27	446	412	398	344	260	207	160	195	250	292	448	456	3927
ITIKINUMU	200316	39	322	286	363	357	267	166	114	176	230	283	322	338	3255
KAGUA	200319	12	263	272	316	235	209	171	207	233	315	330	223	285	3080
KAIAPIT	200043	26	264	271	363	292	140	64	65	79	121	165	243	335	2425
KAINANTU A/S	200208	16	235	252	285	170	103	69	58	95	116	150	194	267	2037
KAIRUKU	200044	36	240	277	226	134	46	44	28	14	40	40	54	133	1282
KALILI	200045	22	521	383	472	325	275	308	459	419	337	337	340	468	4737
KANDRIAN	200210	15	123	115	142	184	350	556	697	630	468	277	164	140	3885
KEREMA	200051	44	231	232	264	289	437	386	347	331	336	299	209	209	3612
KIETA	200053	27	259	259	301	295	233	250	259	243	210	250	242	233	3020
KIKORI	200054	43	314	330	360	441	750	718	652	556	610	473	329	301	5772
KOKODA	200056	39	336	333	365	328	259	187	180	224	273	321	407	362	3596

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STATION NAME	STATION NO.	YRS. OF RECORD	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
KOKOPO	200057	33	219	189	221	170	120	121	168	148	111	116	162	230	1946
KOMPIAM	200218	12	281	350	398	343	245	165	176	205	308	292	315	348	3421
KOROBA	200328	13	263	267	321	288	328	246	248	289	319	291	219	261	3331
KUNDIAWA	200182	13	249	239	288	241	152	97	84	117	182	200	185	224	2249
KWIKILA	200116	41	156	131	176	149	79	51	44	43	58	50	66	110	1147
LAE A/S	200065	30	267	231	324	403	424	414	501	517	473	386	346	332	4617
LAKE KUTUBU	200226	11	370	412	367	453	446	297	356	364	487	454	299	385	4735
LORENGAU	200075	37	325	297	307	333	275	335	398	367	281	279	285	294	3881
LOSUIA	200069	37	425	431	380	337	332	306	306	270	271	257	239	268	3942
LUMI	200234	15	275	249	311	269	183	107	111	162	198	253	266	285	2646
MADANG AGRIC.	200070	42	340	314	373	439	378	235	176	123	152	267	376	375	3533
MENDI	200339	13	231	267	277	222	213	183	239	253	284	269	204	219	2800
MENYAMYA	200238	16	156	182	175	170	128	84	80	96	151	158	175	186	1769
MINJ	200240	14	245	269	289	217	181	114	127	174	215	191	186	271	2485
MOMOTE	200241	20	270	260	305	287	215	308	335	291	257	230	240	311	3341
MOROBE	200086	18	159	180	179	230	265	244	236	215	265	233	276	255	2769
MT. HAGEN	200243	20	264	271	285	253	184	119	131	171	221	221	208	258	2586
MUMENG	200244	16	176	143	153	130	86	64	84	81	98	114	156	204	1471
NAMATANAI	200088	25	438	407	418	341	211	173	187	154	125	189	299	407	3431
NOMAD RIVER	200484	8	496	522	601	252	313	228	236	309	266	322	262	454	4272
POPONDETTA	200272	14	291	268	294	240	195	112	85	99	171	177	264	335	2482
PT. MORESBY A/S	200286	25	169	221	191	167	51	40	20	34	40	40	69	156	1197
PT. MORESBY KONEDOBU	200108	42	177	199	170	103	62	30	29	16	26	31	49	105	995
RABAUL A/S	200340	23	230	244	256	209	129	114	104	103	94	118	173	238	2003

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STATION NAME	STATION NO.	YRS. OF RECORD	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
RAUA	200113	15	270	284	278	216	164	137	160	131	115	156	205	182	2298
ROUNA HYDRO	200341	13	269	316	300	165	122	55	40	65	136	105	90	208	1867
SAIDOR	200253	14	403	455	401	318	176	139	111	97	107	166	176	266	2714
SALAMO	200122	21	194	177	198	207	269	294	182	187	249	254	188	126	2633
SAMARAI	200123	44	167	177	242	259	291	287	205	225	261	229	183	142	2655
SIMBAI A/S	200345	12	381	404	362	291	193	116	117	163	234	257	287	386	3175
SOHANO	200018	11	342	300	315	278	179	129	171	163	152	174	224	255	2710
TABIBUGA	200317	12	419	434	474	353	205	106	130	149	194	259	288	406	3417
TALASEA	200136	22	738	704	640	460	198	126	113	109	110	166	251	454	4157
TAMBUL	200348	12	266	287	328	239	166	111	136	170	209	233	218	272	2617
TAPINI	200255	20	240	261	275	196	121	60	55	74	128	147	173	226	1956
TARI	200256	15	225	257	270	244	234	155	170	198	232	245	227	225	2693
TELEFOMIN	200257	16	255	286	317	297	304	286	315	326	374	310	232	231	3527
TUFI	200262	16	372	445	350	405	289	190	138	85	109	158	276	320	3097
VANIMO	200150	12	279	337	303	208	217	186	189	152	168	166	200	262	2797
WABAG	200265	18	300	301	343	293	199	136	127	193	265	266	262	310	3015
WABO DAM SITE	200673	2	603	609	721	682	618	914	859	930	925	732	519	542	8700
WANIGELA	200266	16	253	251	224	320	271	143	95	61	136	129	224	308	2388
WAPENAMANDA	200267	14	234	259	297	242	165	104	111	164	214	206	204	241	2488
WAU N.G.G.	200278	35	179	191	212	184	127	84	104	103	121	145	191	211	1843
WEWAK A/S	200160	14	143	128	155	173	219	203	184	195	206	225	207	147	2189

MEAN MONTHLY, ANNUAL AND EXTREME TEMPERATURE CHARACTERISTICS (DEG. C)

STATION NAME	TEMPERATURE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
AMBUNTI	EXTREME MAX.	36.7	36.7	37.3	36.7	35.6	35.6	35.6	36.7	36.9	36.7	37.2	36.7	37.3
STATION NO. 200004	MEAN MAX.	32.3	31.9	32.1	31.9	31.9	31.7	31.2	32.2	32.4	32.1	32.6	32.2	32.0
50 METRES	MEAN	27.4	27.2	27.4	27.4	27.4	27.4	26.8	27.5	27.8	27.5	27.8	27.5	27.4
	MEAN MIN.	22.4	22.5	22.7	22.8	22.9	23.1	22.4	22.8	23.2	22.8	23.0	22.8	22.8
	EXTREME MIN.	15.6	16.7	16.7	18.4	17.8	17.3	17.3	11.1	12.8	18.9	17.3	13.9	11.1
BULOLO FORESTRY SCHL	EXTREME MAX.	34.4	34.4	34.6	33.9	32.9	32.8	32.5	32.8	32.7	33.6	35.5	33.6	35.5
STATION NO. 200590	MEAN MAX.	30.7	30.6	30.7	30.7	29.7	29.1	28.4	28.9	29.7	29.9	31.1	30.6	30.0
745 METRES	MEAN	24.8	24.8	24.9	24.5	24.3	23.8	23.4	23.4	24.1	24.4	24.8	25.0	24.3
	MEAN MIN.	18.8	18.9	19.1	18.2	18.8	18.4	18.3	17.9	18.4	18.8	18.4	19.4	18.6
	EXTREME MIN.	14.0	15.6	14.6	11.6	15.0	12.8	14.2	12.0	12.4	15.6	11.8	11.0	11.0
ERAP	EXTREME MAX.	37.5	37.8	38.9	36.1	36.7	37.5	36.1	35.6	34.7	36.7	37.8	38.9	38.9
STATION NO. 200187	MEAN MAX.	33.8	33.9	34.0	33.6	32.3	32.0	30.9	30.9	31.7	32.3	34.0	33.9	32.8
260 METRES	MEAN	28.0	28.2	28.3	27.7	27.8	26.5	25.7	25.7	26.2	26.7	28.0	28.2	27.2
	MEAN MIN.	22.1	22.4	22.5	21.7	23.3	20.9	20.4	20.5	20.7	21.1	22.0	22.5	21.7
	EXTREME MIN.	16.1	17.8	18.9	17.2	17.5	17.9	16.1	15.0	11.7	16.1	16.7	19.7	11.7
GARAINA	EXTREME MAX.	34.3	32.8	34.4	31.7	30.6	31.9	30.1	31.7	31.2	31.7	32.2	32.8	34.4
STATION NO. 200192	MEAN MAX.	29.4	29.4	29.1	28.7	28.2	27.2	26.8	27.5	28.2	28.6	29.3	29.3	28.5
716 METRES	MEAN	23.8	23.8	23.8	23.2	23.0	22.2	21.9	22.2	22.8	23.1	23.4	23.7	23.0
	MEAN MIN.	18.1	18.2	18.4	17.7	17.7	17.1	16.9	16.9	17.4	17.6	17.4	18.0	17.6
	EXTREME MIN.	12.8	11.8	11.7	10.6	9.4	7.5	8.3	9.1	9.5	11.8	11.7	11.7	7.5
GOROKA A/S	EXTREME MAX.	30.6	29.8	29.4	28.7	30.0	28.9	29.7	29.0	29.4	29.6	30.0	28.3	30.6
STATION NO. 200197	MEAN MAX.	25.9	25.7	25.6	25.8	26.0	25.2	24.8	25.3	25.7	25.8	26.3	25.8	25.7
1565 METRES	MEAN	20.6	20.5	20.5	20.5	20.5	19.6	19.3	19.6	20.0	20.1	20.3	20.5	20.1
	MEAN MIN.	15.2	15.2	15.4	15.2	14.9	14.0	13.8	13.9	14.2	14.3	14.3	15.1	14.6
	EXTREME MIN.	10.7	10.0	9.9	8.9	10.3	7.2	8.3	7.2	6.2	6.1	8.3	9.1	6.1
LAE A/S	EXTREME MAX.	38.2	37.3	38.7	33.9	33.2	33.4	32.2	32.4	32.2	35.2	34.4	35.6	38.7
STATION NO. 200065	MEAN MAX.	31.1	31.2	30.8	30.1	29.4	28.6	27.8	27.9	28.7	29.6	30.3	30.7	29.7
10 METRES	MEAN	27.5	27.5	27.3	26.7	26.2	25.5	24.9	25.0	25.5	26.1	26.7	27.1	26.3
	MEAN MIN.	23.8	23.8	23.7	23.3	22.9	22.4	22.0	22.0	22.2	22.6	23.1	23.5	22.9
	EXTREME MIN.	20.7	21.1	21.7	21.3	19.4	19.4	19.3	19.4	19.1	19.1	20.9	20.3	19.1
LOSUIA	EXTREME MAX.	34.4	34.4	34.4	33.3	35.0	32.2	31.7	37.2	32.4	37.4	35.0	35.6	37.4
STATION NO. 200069	MEAN MAX.	30.3	30.2	30.2	29.6	29.1	28.3	27.8	27.9	28.5	29.1	29.9	30.2	29.3
3 METRES	MEAN	26.9	26.9	26.9	26.8	26.8	26.1	25.8	25.9	26.3	26.6	26.9	27.1	26.6
	MEAN MIN.	23.5	23.6	23.5	24.0	24.4	23.8	23.7	23.8	24.0	24.0	23.9	23.9	23.8
	EXTREME MIN.	20.3	20.0	19.9	20.0	20.6	19.2	18.9	20.1	18.9	18.8	18.8	17.8	17.8
LUMI	EXTREME MAX.	31.9	32.1	31.1	31.7	31.3	32.4	30.6	31.8	32.1	31.7	32.1	30.6	32.4
STATION NO. 200234	MEAN MAX.	27.7	27.4	27.6	27.4	27.4	27.0	26.9	27.2	27.4	27.7	27.6	27.5	27.4
535 METRES	MEAN	24.0	24.0	24.1	23.9	24.0	23.6	23.3	23.5	23.7	23.9	23.9	24.1	23.8
	MEAN MIN.	20.3	20.6	20.6	20.4	20.5	20.1	19.7	19.8	19.9	20.1	20.2	20.6	20.2
	EXTREME MIN.	8.9	11.7	17.2	14.1	15.0	17.3	5.0	15.8	9.4	12.2	17.8	15.6	5.0
MADANG A/S	EXTREME MAX.	33.2	33.3	33.3	33.7	32.2	32.2	31.5	31.7	33.4	31.7	32.5	33.6	33.7
STATION NO. 200235	MEAN MAX.	30.2	30.1	30.1	29.9	30.2	29.8	29.6	29.7	29.9	30.1	30.2	30.1	30.0
4 METRES	MEAN	26.7	26.6	26.7	26.6	26.8	26.4	26.2	26.3	26.4	26.5	26.6	26.7	26.5
	MEAN MIN.	23.2	23.1	23.2	23.2	23.3	22.9	22.8	22.9	22.9	22.9	23.0	23.2	23.1
	EXTREME MIN.	21.0	20.7	20.8	21.1	20.1	19.9	20.0	18.9	20.8	20.3	20.0	19.4	18.9

MEAN MONTHLY, ANNUAL AND EXTREME TEMPERATURE CHARACTERISTICS (DEG. C)

STATION NAME	TEMPERATURE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MOMOTE	EXTREME MAX.	33.3	32.9	32.3	32.8	32.9	31.9	31.7	32.1	32.0	33.3	32.6	32.2	33.3
STATION NO. 200241	MEAN MAX.	30.0	30.0	29.9	30.0	30.3	29.8	29.5	29.6	29.9	30.2	30.2	29.9	29.9
4 METRES	MEAN	27.1	27.1	27.1	27.2	27.7	27.3	27.0	27.1	27.3	27.4	27.3	27.0	27.2
	MEAN MIN.	24.2	24.2	24.2	24.3	25.1	24.7	24.5	24.5	24.6	24.6	24.3	24.0	24.4
	EXTREME MIN.	22.0	21.7	21.9	21.7	22.6	21.7	21.1	21.7	21.7	22.1	21.9	21.1	21.1
MT. HAGEN	EXTREME MAX.	31.1	28.9	27.8	28.1	29.1	27.8	27.6	27.8	27.9	28.8	28.3	30.0	31.1
STATION NO. 200243	MEAN MAX.	24.2	24.4	23.8	23.9	24.3	23.1	22.4	22.7	23.2	23.9	24.3	24.2	23.7
1630 METRES	MEAN	18.8	18.9	18.6	18.8	18.9	17.8	17.5	17.7	17.9	18.2	18.5	18.8	18.3
	MEAN MIN.	13.4	13.3	13.4	13.7	13.4	12.4	12.5	12.7	12.6	12.5	12.7	13.3	13.0
	EXTREME MIN.	8.3	5.0	5.0	7.2	2.8	4.4	5.6	5.4	1.7	3.9	4.4	4.7	1.7
MT. WILHELM	EXTREME MAX.	13.4	11.1	12.8	14.4	13.9	15.0	14.3	15.0	14.4	15.5	14.2	13.2	15.5
* (MCVEAN(1968) AND	MEAN MAX.	11.1	11.1	10.8	10.7	11.2	11.2	11.2	11.7	12.6	11.7	11.5	11.1	11.3
J.SMITH(PERS.COMM.))	MEAN	7.7	7.7	7.8	7.4	7.7	7.5	7.2	7.7	7.7	8.0	7.8	7.7	7.6
3480 METRES	MEAN MIN.	4.2	4.2	4.8	4.0	4.1	3.7	3.2	3.6	2.7	4.2	4.1	4.2	3.9
	EXTREME MIN.	2.7	1.7	3.4	.8	.6	-.4	-.2	-.8	-.3	-.1	-.2	2.7	-.8
PT. MORESBY A/S	EXTREME MAX.	36.2	36.1	35.4	34.2	33.8	33.9	33.3	33.8	34.8	35.5	36.3	36.3	36.3
STATION NO. 200286	MEAN MAX.	31.8	31.5	31.4	31.0	30.8	30.1	29.7	29.9	30.4	31.3	32.1	32.2	31.0
35 METRES	MEAN	27.5	27.3	27.2	26.9	26.8	26.1	25.7	26.0	26.4	27.1	27.5	27.7	26.8
	MEAN MIN.	23.1	23.0	22.9	22.7	22.8	22.1	21.7	22.0	22.3	22.8	22.8	23.1	22.6
	EXTREME MIN.	20.4	18.8	18.3	16.8	14.5	14.5	10.4	14.8	14.4	16.3	16.0	19.6	10.4
RABAUL A/S	EXTREME MAX.	35.4	34.1	36.1	34.4	34.9	35.5	35.0	35.2	36.1	35.9	35.0	34.7	36.1
STATION NO. 200340	MEAN MAX.	30.9	30.9	30.7	30.8	31.2	30.9	30.4	30.7	31.4	31.6	31.3	30.9	31.0
4 METRES	MEAN	27.1	27.1	27.0	27.1	27.4	27.1	26.8	27.0	27.4	27.5	27.3	27.1	27.1
	MEAN MIN.	23.2	23.2	23.3	23.3	23.6	23.3	23.2	23.2	23.4	23.3	23.3	23.2	23.3
	EXTREME MIN.	20.2	20.0	20.3	20.0	20.6	17.8	19.4	19.4	19.3	19.3	20.4	16.1	16.1
SAMARAI	EXTREME MAX.	36.1	36.0	35.3	33.4	34.6	33.3	33.3	32.8	37.2	32.2	34.4	35.1	37.2
STATION NO. 200123	MEAN MAX.	31.4	31.6	30.8	29.6	28.4	27.6	27.0	27.2	27.8	28.4	29.6	30.7	29.2
40 METRES	MEAN	28.0	28.2	27.8	26.9	26.1	25.5	24.9	25.0	25.4	26.0	26.7	27.5	26.5
	MEAN MIN.	24.6	24.7	24.7	24.2	23.8	23.3	22.8	22.8	22.9	23.5	23.8	24.2	23.8
	EXTREME MIN.	20.5	18.3	21.1	21.1	17.2	20.0	17.2	18.3	15.0	19.2	19.4	20.6	15.0
WABAG	EXTREME MAX.	26.1	26.1	25.8	26.1	27.2	26.1	24.4	24.6	29.1	26.1	27.3	25.0	29.1
STATION NO. 200265	MEAN MAX.	22.5	22.4	22.4	22.4	22.5	22.2	21.8	21.7	22.1	22.2	22.6	22.4	22.3
1980 METRES	MEAN	17.1	17.3	17.3	16.9	16.8	16.1	16.1	16.2	16.5	16.6	16.7	16.9	16.7
	MEAN MIN.	11.6	12.2	12.1	11.3	11.0	9.9	10.3	10.7	10.9	10.9	10.8	11.3	11.1
	EXTREME MIN.	6.1	7.9	7.0	3.1	6.1	3.9	5.0	5.5	2.7	4.3	5.4	6.7	2.7

PROBABILITIES OF MAXIMUM AND MINIMUM TEMPERATURE (MEAN DAYS PER FORTNIGHT WITHIN SPECIFIED CLASSES (DEG.C))

GOROKA 1957-70	MAXIMUM TEMPERATURE				
	20.0	25.0	30.0	35.0	40.0
1	.1	3.9	10.0	.0	.0
2	.1	3.7	10.2	.0	.0
3	.0	4.2	9.7	.1	.0
4	.0	4.9	9.1	.0	.0
5	.0	4.9	9.1	.0	.0
6	.1	4.0	10.0	.0	.0
7	.0	5.6	8.4	.0	.0
8	.0	3.9	10.1	.0	.0
9	.1	3.6	10.3	.1	.0
10	.0	2.9	11.1	.0	.0
11	.0	3.9	10.1	.0	.0
12	.0	5.8	8.2	.0	.0
13	.3	6.3	7.4	.0	.0
14	.0	7.1	6.9	.0	.0
15	.2	6.9	6.9	.0	.0
16	.0	6.3	7.7	.0	.0
17	.1	5.2	8.7	.0	.0
18	.0	5.2	8.8	.0	.0
19	.1	4.2	9.6	.0	.0
20	.1	4.6	9.3	.0	.0
21	.3	3.9	9.9	.0	.0
22	.0	3.2	10.8	.0	.0
23	.1	2.1	11.8	.0	.0
24	.1	3.6	10.3	.0	.0
25	.0	4.4	9.6	.0	.0
26	.0	3.9	10.1	.0	.0

GOROKA 1957-70	MINIMUM TEMPERATURE				
	10.0	15.0	20.0	25.0	30.0	35.0
1	.0	5.6	8.4	.0	.0	.0
2	.0	5.4	8.6	.0	.0	.0
3	.0	6.2	7.8	.0	.0	.0
4	.0	5.1	8.9	.0	.0	.0
5	.0	5.1	8.9	.0	.0	.0
6	.0	5.0	8.9	.1	.0	.0
7	.0	5.4	8.5	.1	.0	.0
8	.0	5.7	8.3	.0	.0	.0
9	.1	5.4	8.5	.0	.0	.0
10	.0	6.6	7.4	.0	.0	.0
11	.1	7.2	6.7	.0	.0	.0
12	.2	10.3	3.5	.0	.0	.0
13	.4	10.9	2.7	.0	.0	.0
14	.2	11.4	2.4	.0	.0	.0
15	.1	11.8	2.1	.0	.0	.0
16	.6	9.9	3.5	.0	.0	.0
17	.5	10.8	2.7	.0	.0	.0
18	.4	10.0	3.6	.0	.0	.0
19	.2	10.4	3.4	.0	.0	.0
20	.1	8.9	5.0	.0	.0	.0
21	.4	9.7	3.9	.0	.0	.0
22	.6	8.1	5.4	.0	.0	.0
23	.5	9.4	4.0	.0	.0	.0
24	.2	8.2	5.7	.0	.0	.0
25	.1	5.5	8.4	.0	.0	.0
26	.2	5.6	8.3	.0	.0	.0

MADANG 1951-70	MAXIMUM TEMPERATURE				
	20.0	25.0	30.0	35.0	40.0
1	.0	.0	4.8	9.2	.0
2	.0	.0	6.0	8.0	.0
3	.0	.0	5.6	8.4	.0
4	.0	.0	5.7	8.3	.0
5	.0	.0	5.9	8.1	.0
6	.0	.0	5.8	8.2	.0
7	.0	.0	7.7	6.3	.0
8	.0	.1	6.5	7.4	.0
9	.0	.0	5.0	9.1	.0
10	.0	.0	4.5	9.5	.0
11	.0	.0	5.8	8.3	.0
12	.0	.1	6.0	8.0	.0
13	.0	.0	9.1	4.9	.0
14	.0	.0	9.6	4.4	.0
15	.0	.1	9.5	4.4	.0
16	.0	.0	10.7	3.3	.0
17	.0	.0	9.6	4.4	.0
18	.0	.0	7.7	6.4	.0
19	.0	.0	7.6	6.4	.0
20	.0	.0	6.6	7.4	.0
21	.0	.1	6.4	7.6	.0
22	.0	.0	4.4	9.6	.0
23	.0	.0	4.4	9.6	.0
24	.0	.0	5.3	8.7	.0
25	.0	.0	5.8	8.3	.0
26	.0	.0	5.3	8.7	.0

MADANG 1951-70	MINIMUM TEMPERATURE					
	10.0	15.0	20.0	25.0	30.0	35.0
1	.0	.0	.0	14.0	.0	.0
2	.0	.0	.0	13.9	.1	.0
3	.0	.0	.0	14.0	.0	.0
4	.0	.0	.0	14.0	.0	.0
5	.0	.0	.0	14.0	.0	.0
6	.0	.0	.0	14.0	.0	.0
7	.0	.0	.0	14.0	.0	.0
8	.0	.0	.0	14.0	.0	.0
9	.0	.0	.0	13.9	.1	.0
10	.0	.0	.0	14.0	.0	.0
11	.0	.0	.0	13.6	.4	.0
12	.0	.0	.0	14.0	.0	.0
13	.0	.0	.1	13.6	.4	.0
14	.0	.0	.0	13.9	.1	.0
15	.0	.0	.0	13.5	.5	.0
16	.0	.0	.0	13.3	.7	.0
17	.0	.0	.0	13.3	.7	.0
18	.0	.0	.1	13.4	.6	.0
19	.0	.0	.0	13.8	.2	.0
20	.0	.0	.0	13.7	.3	.0
21	.0	.0	.0	13.5	.5	.0
22	.0	.0	.0	13.6	.4	.0
23	.0	.0	.0	13.8	.2	.0
24	.0	.0	.0	14.0	.0	.0
25	.0	.0	.0	14.0	.0	.0
26	.0	.0	.1	13.7	.2	.0

PROBABILITIES OF MAXIMUM AND MINIMUM TEMPERATURE (MEAN DAYS PER FORTNIGHT WITHIN SPECIFIED CLASSES (DEG.C))

PT.MORESBY A/S 1951-70 MAXIMUM TEMPERATURE

	20.0	25.0	30.0	35.0	40.0
1	.0	.0	1.5	12.3	.2
2	.0	.0	1.3	12.6	.1
3	.0	.0	1.7	12.4	.0
4	.0	.1	1.7	12.2	.0
5	.0	.0	1.7	12.2	.0
6	.0	.1	1.3	12.6	.0
7	.0	.1	2.6	11.3	.0
8	.0	.0	1.5	12.5	.0
9	.0	.0	1.8	12.3	.0
10	.0	.0	1.9	12.1	.0
11	.0	.1	3.4	10.5	.0
12	.0	.0	3.6	10.4	.0
13	.0	.0	5.8	8.2	.0
14	.0	.0	6.3	7.7	.0
15	.0	.0	6.7	7.3	.0
16	.0	.0	5.8	8.3	.0
17	.0	.0	4.6	9.4	.0
18	.0	.0	4.5	9.5	.0
19	.0	.0	4.0	10.1	.0
20	.0	.0	2.0	12.0	.1
21	.0	.0	1.2	12.7	.1
22	.0	.0	.6	13.4	.1
23	.0	.0	.6	13.2	.2
24	.0	.1	.7	13.2	.1
25	.0	.0	.2	13.5	.3
26	.0	.0	1.0	12.8	.2

PT.MORESBY A/S 1951-70 MINIMUM TEMPERATURE

	10.0	15.0	20.0	25.0	30.0	35.0
1	.0	.0	.0	14.0	.0	.0
2	.0	.0	.0	13.9	.1	.0
3	.0	.0	.0	14.0	.0	.0
4	.0	.0	.0	13.9	.0	.0
5	.0	.0	.0	13.9	.1	.0
6	.0	.0	.2	13.8	.0	.0
7	.0	.0	.8	13.2	.0	.0
8	.0	.0	.8	13.3	.0	.0
9	.0	.0	.6	13.4	.0	.0
10	.0	.0	1.2	12.7	.2	.0
11	.0	.1	1.3	12.6	.1	.0
12	.0	.0	1.4	12.6	.1	.0
13	.0	.0	2.8	11.2	.0	.0
14	.0	.0	2.0	12.1	.0	.0
15	.0	.1	2.1	11.8	.0	.0
16	.0	.0	2.4	11.6	.0	.0
17	.0	.0	1.5	12.5	.0	.0
18	.0	.1	1.5	12.5	.0	.0
19	.0	.0	.9	13.1	.0	.0
20	.0	.0	.9	13.0	.2	.0
21	.0	.0	1.1	12.9	.1	.0
22	.0	.0	.8	13.0	.3	.0
23	.0	.0	.6	13.2	.2	.0
24	.0	.0	.2	13.6	.2	.0
25	.0	.0	.1	13.6	.4	.0
26	.0	.0	.0	13.9	.1	.0

RABAUL 1951-70 MAXIMUM TEMPERATURE

	20.0	25.0	30.0	35.0	40.0
1	.0	.1	3.3	10.6	.0
2	.0	.0	3.6	10.4	.0
3	.0	.0	2.7	11.4	.0
4	.0	.0	4.1	10.0	.0
5	.0	.0	3.1	10.9	.0
6	.0	.0	3.0	11.1	.0
7	.0	.0	4.5	9.6	.0
8	.0	.0	3.0	11.0	.0
9	.0	.0	2.0	12.0	.0
10	.0	.0	1.6	12.4	.0
11	.0	.0	1.6	12.4	.0
12	.0	.0	1.9	12.1	.0
13	.0	.0	3.6	10.4	.0
14	.0	.2	4.4	9.5	.0
15	.0	.0	5.4	8.6	.0
16	.0	.1	5.2	8.7	.0
17	.0	.0	3.5	10.5	.0
18	.0	.0	3.0	11.0	.0
19	.0	.0	2.1	11.8	.2
20	.0	.0	2.7	11.1	.3
21	.0	.0	1.8	12.3	.0
22	.0	.0	1.3	12.6	.1
23	.0	.1	1.7	12.2	.0
24	.0	.0	2.1	11.9	.0
25	.0	.0	2.5	11.5	.0
26	.0	.0	3.6	10.4	.0

RABAUL 1951-70 MINIMUM TEMPERATURE

	10.0	15.0	20.0	25.0	30.0	35.0
1	.0	.0	.0	13.8	.2	.0
2	.0	.0	.0	13.7	.4	.0
3	.0	.0	.0	13.8	.2	.0
4	.0	.0	.0	13.6	.5	.0
5	.0	.0	.0	13.6	.4	.0
6	.0	.0	.0	13.8	.3	.0
7	.0	.0	.0	13.7	.4	.0
8	.0	.0	.0	13.4	.6	.0
9	.0	.0	.0	12.9	1.1	.0
10	.0	.0	.0	12.4	1.6	.0
11	.0	.0	.0	12.3	1.7	.0
12	.0	.0	.0	11.9	2.1	.0
13	.0	.0	.0	13.1	1.0	.0
14	.0	.0	.0	13.1	1.0	.0
15	.0	.0	.0	13.3	.6	.0
16	.0	.0	.0	13.2	.8	.0
17	.0	.0	.2	12.9	.8	.0
18	.0	.0	.1	12.3	1.6	.0
19	.0	.0	.0	12.7	1.3	.0
20	.0	.0	.0	13.0	1.0	.0
21	.0	.0	.1	12.7	1.3	.0
22	.0	.0	.1	12.6	1.3	.0
23	.0	.0	.0	13.1	.9	.0
24	.0	.0	.0	13.7	.3	.0
25	.0	.0	.0	13.8	.2	.1
26	.0	.0	.0	13.8	.2	.0

MEAN MONTHLY AND ANNUAL ESTIMATES OF EVAPORATION (MM) FROM A U.S. CLASS A PAN *

STATION NAME	NUMBER	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
AIYURA	200003	131	120	136	135	128	119	124	128	151	132	140	137	1581
BUBIA	200176	168	162	155	165	154	143	161	142	152	172	178	168	1920
BUKA	200179	142	127	133	155	144	159	146	173	172	166	149	148	1814
BULOLO FORESTRY SCHL	200590	167	151	163	136	142	109	132	148	146	162	175	174	1805
ERAP	200187	206	188	193	191	176	155	166	171	181	206	224	213	2270
GARAINA	200192	126	116	129	98	103	81	102	119	119	134	136	140	1403
GOROKA A/S	200197	155	133	152	146	166	134	150	156	177	169	165	163	1866
KAINANTU A/S	200208	144	127	138	133	141	123	127	126	154	148	147	162	1670
KAVIENG	200048	104	114	119	109	103	109	109	129	126	118	121	108	1369
KIETA	200714	131	115	148	132	126	131	130	154	165	153	137	138	1660
KIKORI	200054	149	130	121	140	114	106	112	108	103	114	150	145	1492
KUK	DPI	137	123	130	150	124	112	117	136	144	137	140	149	1599
LAE A/S	200065	212	205	196	176	155	142	139	141	167	196	201	209	2139
LUMI	200234	105	106	121	92	105	82	103	114	111	121	115	118	1293
MADANG A/S	200235	158	126	135	156	143	142	141	160	167	168	143	141	1780
MENYAMYA	200238	142	130	144	115	133	100	119	139	136	157	153	155	1623
MOMOTE	200241	124	126	135	125	132	137	140	172	163	159	139	121	1673
MT. HAGEN	200243	133	119	127	128	136	111	114	124	143	145	144	144	1568
PANGUNA	BCL	106	91	95	79	85	77	85	89	100	102	102	103	1114
PT. MORESBY A/S	200286	192	169	178	165	164	158	182	190	204	222	230	209	2263
RABAUL A/S	200340	151	164	181	160	170	175	168	216	222	207	176	164	2154
VANIMO ARMY	200259	152	140	162	167	160	165	159	182	178	179	157	152	1953
WAU HOMESTEAD	200355	141	131	148	113	129	98	122	135	134	151	152	151	1605
WEWAK A/S	200160	132	126	139	125	124	126	136	161	149	131	136	127	1612

* ESTIMATES FROM KEIG ET AL (1979)

MEAN MONTHLY 0900 AND 1500 HR RELATIVE HUMIDITY (%) AND AVERAGE INDEX OF RELATIVE HUMIDITY

STATION NAME	TIME	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
AIYURA STATION NO. 200003	0900	79	79	79	77	82	82	81	81	80	80	74	77	79
	1500	73	78	75	75	69	70	69	74	75	72	69	80	73
	INDEX	80	79	79	77	84	79	80	81	80	81	78	81	80
BUBIA STATION NO. 200176	0900	83	81	82	83	85	88	90	87	84	84	79	83	84
	1500	73	75	78	73	71	75	77	84	76	70	71	74	75
	INDEX	82	79	82	83	84	85	86	84	83	84	82	82	83
BULOLO FORESTRY SCHL STATION NO. 200590	0900	80	81	83	80	83	83	84	83	78	78	77	80	81
	1500	50	54	54	51	57	55	57	53	54	59	54	56	55
	INDEX	71	72	73	73	75	75	76	74	72	74	71	73	73
ERAP STATION NO. 200187	0900	78	77	83	78	83	86	88	85	84	77	73	80	81
	1500	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
	INDEX	74	74	77	76	80	80	82	81	81	79	75	74	78
GARAINA STATION NO. 200192	0900	85	86	89	88	86	89	89	86	84	81	77	81	85
	1500	64	65	69	70	69	70	70	68	69	69	67	67	68
	INDEX	81	81	82	83	84	84	84	82	82	81	80	80	82
GOROKA A/S STATION NO. 200197	0900	87	87	89	87	85	87	83	83	82	82	80	86	85
	1500	58	60	61	57	57	56	55	53	54	56	53	60	57
	INDEX	75	76	76	75	74	74	73	72	72	73	73	76	74
KAINANTU A/S STATION NO. 200208	0900	77	80	80	80	82	82	81	87	80	77	76	73	80
	1500	57	62	68	69	64	68	69	66	66	65	63	69	66
	INDEX	78	78	80	81	80	78	80	82	79	78	79	75	79
KAVIENG STATION NO. 200048	0900	83	82	82	80	81	79	82	82	79	78	76	80	80
	1500	70	71	76	76	76	76	74	74	71	72	79	79	75
	INDEX	91	89	90	90	91	90	91	90	91	91	89	90	90
KIKORI STATION NO. 200094	0900	92	93	93	87	93	97	96	93	91	92	83	90	92
	1500	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
	INDEX	85	86	90	87	92	93	94	91	92	94	85	87	90
LAE A/S STATION NO. 200065	0900	78	78	80	81	84	87	90	87	84	79	78	80	82
	1500	69	69	70	71	72	73	74	74	73	70	69	70	71
	INDEX	79	78	80	84	86	87	91	85	83	84	82	81	83
LUMI STATION NO. 200234	0900	88	90	91	90	88	91	91	91	90	86	88	88	89
	1500	65	80	81	80	78	81	78	78	78	77	77	78	78
	INDEX	87	85	85	87	87	87	87	86	85	85	86	85	86

MEAN MONTHLY 0900 AND 1500 HR RELATIVE HUMIDITY (%) AND AVERAGE INDEX OF RELATIVE HUMIDITY

STATION NAME	TIME	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MADANG A/S	0900	86	85	86	86	86	86	87	84	81	81	81	83	84
STATION NO. 200235	1500	75	75	75	76	75	74	75	75	74	74	74	75	75
	INDEX	86	85	85	87	88	89	88	87	86	86	86	86	87
MENYAMYA	0900	75	77	78	78	78	82	82	80	76	72	69	72	77
STATION NO. 200238	1500	62	60	65	65	62	62	64	67	62	61	60	58	62
	INDEX	75	76	77	76	75	76	79	75	74	72	73	73	75
MOMOTE	0900	80	80	82	80	79	80	80	80	79	76	78	80	80
STATION NO. 200241	1500	77	77	79	79	78	76	78	76	76	75	77	80	77
	INDEX	86	85	86	86	84	84	84	84	84	83	84	86	85
MT.HAGEN	0900	87	88	88	89	89	90	92	90	87	83	82	83	87
STATION NO. 200243	1500	68	65	69	71	65	67	69	69	66	63	62	66	67
	INDEX	81	80	82	81	82	82	84	83	82	78	79	81	81
PT MORESBY A/S	0900	78	82	83	81	80	79	76	76	74	72	68	73	77
STATION NO. 200286	1500	66	68	69	70	70	70	66	66	67	65	62	63	67
	INDEX	78	79	80	82	81	80	77	76	75	75	74	75	78
RABAUL A/S	0900	79	80	80	80	79	79	80	77	76	75	75	79	78
STATION NO. 200340	1500	75	74	75	75	73	71	74	71	71	72	74	76	73
	INDEX	85	86	86	86	84	84	83	81	79	81	82	86	84
VANIMO (ARMY)	0900	89	87	87	84	83	84	84	86	84	82	81	84	85
STATION NO. 200259	1500	79	78	78	78	77	78	80	80	80	78	78	76	78
	INDEX	85	85	84	85	86	86	85	85	86	85	84	85	85
WAU HOMESTEAD	0900	78	83	83	83	83	84	86	86	81	77	74	77	81
STATION NO. 200355	1500	59	61	64	64	60	62	63	63	61	59	61	61	62
	INDEX	76	76	76	78	76	77	77	77	75	75	75	75	76
WEWAK A/S	0900	81	83	83	82	82	84	83	80	80	80	82	81	82
STATION NO. 200160	1500	74	76	76	76	75	75	74	72	72	72	76	76	75
	INDEX	85	85	86	86	86	86	85	84	87	89	86	86	86

MEAN DAILY RECORDED SUNSHINE (HOURS) PER MONTH AND ANNUAL TOTAL

STATION NAME	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL ANNUAL
AIYURA STATION NO. 200003	3.8	4.1	4.2	4.5	5.4	5.3	4.6	5.6	5.1	4.6	4.8	3.5	1688
BEREINA STATION NO. 200174	5.5	4.8	4.1	5.7	6.1	4.2	5.0	5.2	5.2	6.3	6.6	6.4	1982
GARAINA STATION NO. 200192	4.2	3.9	4.0	5.1	4.7	5.1	4.7	5.6	5.3	5.1	5.7	4.8	1771
GOROKA A/S STATION NO. 200197	4.5	4.0	4.6	4.4	5.7	4.9	5.0	5.0	4.7	5.5	5.3	4.3	1764
KERAVAT STATION NO. DPI	5.4	5.8	4.9	5.4	6.3	5.9	5.4	5.5	5.6	6.0	5.8	4.9	2034
KIETA STATION NO. 200714	5.9	4.9	5.4	6.4	7.2	5.8	5.8	4.4	6.5	6.3	5.7	5.7	2131
LAE A/S STATION NO. 200065	5.8	6.2	5.4	6.0	5.7	4.9	3.5	5.0	5.6	6.9	4.9	6.3	2012
MADANG A/S STATION NO. 200235	5.2	5.1	4.9	5.4	6.7	6.9	6.4	7.1	6.9	6.7	6.4	5.3	2222
MOMOTE STATION NO. 200241	4.2	4.3	4.0	4.6	5.9	5.4	5.2	5.5	6.1	6.0	4.8	4.1	1829
MOSA STATION NO. DPI *	3.2	2.4	4.2	3.9	5.3	5.0	4.5	5.6	5.1	4.9	5.5	3.4	1616
PT. MORESBY A/S STATION NO. 200286	6.2	5.8	6.0	6.7	7.1	7.1	6.7	6.9	6.4	7.4	8.2	6.9	2478
TAMBUL STATION NO. DPI	3.0	2.3	2.4	3.4	4.0	4.1	3.8	5.6	4.5	3.1	3.3	2.9	1292

* DATA OBTAINED FROM MENDHAM(1971B)

PROBABILITY OF SUNSHINE DURATION (MEAN DAYS PER FORTNIGHT WITHIN SPECIFIED CLASSES (HOURS))

GARAINA 1966-70

	0.0	0.1-4.0	4.1-8.0	8.1-12.0
1	1.1	5.7	5.9	1.3
2	.2	5.4	7.5	.9
3	1.8	4.7	6.7	.9
4	1.3	6.3	5.5	.9
5	.9	4.7	7.4	.9
6	1.0	4.6	6.6	1.8
7	1.4	4.5	5.4	2.7
8	.4	2.3	8.9	2.3
9	.4	2.6	7.9	3.0
10	1.2	3.5	5.8	3.5
11	.8	5.3	5.9	2.0
12	.2	4.7	5.9	3.2
13	1.4	3.2	6.2	3.2
14	2.4	4.0	4.8	2.8
15	1.2	4.8	5.2	2.9
16	.8	5.1	4.7	3.4
17	.2	4.1	7.4	2.3
18	.2	3.7	5.9	4.3
19	.4	4.8	6.0	2.8
20	.8	3.6	9.2	.4
21	1.2	5.8	6.2	.8
22	.6	4.7	6.6	2.1
23	1.0	2.6	7.7	2.6
24	.8	3.9	6.9	2.4
25	.4	4.0	8.8	.8
26	.6	4.7	7.5	1.2

MADANG 1958-70

	0.0	0.1-4.0	4.1-8.0	8.1-12.0
1	1.4	3.9	5.1	3.6
2	.9	4.4	5.0	3.6
3	1.1	4.6	4.8	3.6
4	.8	4.8	6.2	2.1
5	1.2	5.1	4.4	3.3
6	1.0	4.5	4.5	3.9
7	1.4	5.5	4.9	2.2
8	.8	4.1	4.5	4.7
9	.5	2.8	5.7	5.0
10	.7	2.3	4.5	6.5
11	.2	2.8	4.3	6.8
12	.4	2.8	3.7	7.1
13	.7	2.6	4.4	6.3
14	.4	3.1	4.8	5.7
15	.6	3.2	5.3	4.9
16	.2	3.1	4.6	6.1
17	.3	2.4	4.6	6.7
18	.1	2.8	3.9	7.2
19	.6	2.2	4.2	6.9
20	.7	3.0	4.1	6.1
21	.6	3.5	4.4	5.5
22	.4	2.8	4.1	6.8
23	.6	2.2	5.1	6.2
24	.6	4.3	4.4	4.7
25	2.1	3.3	5.2	3.5
26	1.3	3.7	4.9	4.1

PT. MORESBY A/S 1957-70

	0.0	0.1-4.0	4.1-8.0	8.1-12.0
1	.7	3.6	4.4	5.3
2	.1	3.5	5.0	5.3
3	.6	3.7	4.4	5.4
4	.7	4.2	5.2	3.8
5	.4	3.5	5.6	4.4
6	.4	3.4	5.2	5.0
7	.7	3.2	4.7	5.4
8	.3	2.6	4.3	6.8
9	.2	2.4	5.3	6.1
10	.1	1.7	4.6	7.7
11	.2	2.5	5.2	6.1
12	.1	1.8	4.8	7.4
13	.4	3.0	4.2	6.4
14	.1	2.5	5.5	5.9
15	.1	3.5	5.6	4.8
16	.1	2.4	5.6	5.9
17	.4	2.4	5.4	5.8
18	.1	2.4	5.1	6.3
19	.2	3.2	5.2	5.4
20	.1	2.8	5.5	5.7
21	.4	1.9	5.2	6.5
22	.2	1.3	5.4	7.1
23	0.0	1.3	3.7	9.0
24	.3	1.7	3.7	8.3
25	.2	2.1	4.0	7.7
26	.2	3.2	5.4	5.2

MEAN DAILY SOLAR AND EXTRATERRESTRIAL RADIATION PER MONTH (MWH/SQ CM) *

STATION NAME	LAT.S. DEG.MIN.	LONG.E. DEG.MIN.	RADIATION	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
(1) PT. MORESBY A/S (41 METRES)	9 29	147 9	SOLAR (MEASURED)	543	567	541	555	507	502	483	516	560	596	683	609
			EXTRATERRESTRIAL	1085	1084	1047	963	871	818	834	911	1001	1062	1082	1080
(2) RABAUL (13 METRES)	4 13	152 15	SOLAR (MEASURED)	491	495	504	494	509	491	462	514	552	538	506	448
			EXTRATERRESTRIAL	1041	1061	1051	996	925	879	892	954	1020	1051	1044	1030

(1) EPPLEY PYRANOMETER, CSIRO DIVISION OF BUILDING RESEARCH

(2) ROBITZSCH ACTINOGRAPH, BUREAU OF METEOROLOGY

* DATA OBTAINED FROM KALMA(1972)

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Figures in bold type indicate the main reference to the subject.