Chapter 4

Conclusions and future directions

4.1 Summary of this work

4.1.1 Canopy-scale model

A canopy model combining biochemical and inverse Lagrangian approaches has been presented. Source distributions of CO_2, $^{13}CO_2$, $C^{18}O^{16}O$, H_2O and sensible heat within the canopy as well as their fluxes at the ground were predicted. Ground flux magnitudes and six parameters relating to photosynthetic capacity, stomatal conductance, radiation penetration and turbulence structure were optimised to minimise the difference between modelled and measured concentration profiles. Modelled total fluxes (canopy plus ground) agreed reasonably well with measured eddy covariance fluxes when a stability correction was applied to morning and evening periods. CO_2 fluxes were overestimated by the model compared to the measurements by about 10%, while modelled H_2O and sensible heat flux showed no systematic difference from eddy covariance measurements.

Parameter optimisation was hindered by co-dependence of parameters; little structure in the water vapour concentration profiles; and possible insufficient utilisation of gradients near the ground, especially for water vapour. Calculation of the equilibrium evaporation rate appeared to give a more reliable estimate of soil evaporation than that obtained by the model optimisation procedure. Model estimates of soil carbon dioxide efflux and heat flux were reasonable. Parameter estimates deviated considerably from prior estimates in some cases, but the demonstrated ability of the model to reasonably reproduce canopy fluxes of CO_2, H_2O and sensible heat suggests the estimates obtained were realistic.

The optimised value found for marginal water loss per marginal carbon gain was substantially lower than other estimates for this biome. Relating to this result, the model predicted low stomatal conductance, intercellular CO_2 concentration and carbon isotope discrimination. This is likely a result of hydraulic limitation caused by the low temperatures experienced during the study, which was undertaken during snow melt in May. Maximum photosynthetic capacity was also modelled to be quite low, probably also relating to the emergence from winter.

Optimisation of radiation extinction coefficients resulted in greater penetration into the canopy than theoretical predictions for point source light and random leaf arrangements. The values found partially account for the effects of leaf clumping and penumbra.

The low optimised value for the Lagrangian time scale was thought to be compensating in part for stability effects in the lower canopy, as well as throughout the canopy for the morning and evening periods. The idea of T_L evolving during the day and through the canopy depending on stability conditions was explored and model predictions were found to behave sensibly when the diurnal variation in wind speed and stability was high.

The model approach presented here represents an advance in characterisation of leaf and soil fluxes within a canopy. Interesting insights into parameters controlling plant-atmosphere exchange were revealed, as well as their relationship with environmental variables.

4.1.2 Regional-scale model

Two CBL budget methods were compared to infer average regional surface fluxes of CO_2 as well as carbon and oxygen isotope discrimination during CO_2 assimilation over a two-day period in July 1998 over a central Siberian forest and bog region. The first method was also used to infer regional sensible and latent heat fluxes.

CO_2 fluxes estimated from the integral CBL budget method (Equation (3.4)) agreed very well with eddy covariance flux measurements from the forest tower representing the dominant ecosystem type in the region. Estimates of Δ^{13}C for both afternoon periods were close to that expected from knowledge of C_3 plant carbon isotopic discrimination and measurements of leaf δ^{13}C. Estimates of Δ^{18}O were more variable and hard to interpret quantitatively without better knowledge of isotopic composition of plant leaf and source water. The large variation in modelled Δ^{18}O may be explained by the contrasting influences of the two different ecosystem types in the region. Compared to the forest, the bog region was characterised by relatively high evaporation rates, low assimilation rates, and high humidity. Accounting for possible large differences in intercellular CO_2 concentration and its isotopic composition between the forest and bog dramatically altered the interpretation of modelled oxygen isotope discrimination in terms of isotopic composition of source water. The effect would be less marked in the afternoon periods as c_i is drawn down and leaf water becomes more enriched. Disequilibrium between chloroplast water and intercellular vapour is also likely to be important: chloroplast water composition should reflect source water composition overnight if the stomata are closed but become close to the steady-state value modelled for water at the sites of evaporation in the late afternoon.

Estimates of regional sensible and latent heat flux were in fair agreement with the eddy covariance measurements. Modelled fluxes were generally close to measurements in the forest, except for high latent heat flux modelled for the first afternoon being closer to the bog measurements. Oxygen isotope composition measured over the bog region also suggested the bog may have been most influential for that period.

The height integration method (Equation (3.7)) was generally less successful than the ICBL budget method at predicting surface CO_2 fluxes. Isotopic discriminations obtained by the height integration method were also more variable but reasonably close to values obtained by the ICBL budget method. Both the integral CBL budget method and the height integration method are very sensitive to measurement error since the contributing terms are of similarly large magnitude but opposite sign. The height integration method is perhaps more error-prone because variations in measured concentrations which may arise from measurement error or natural patchiness are treated as real and horizontally extensive, while the ICBL budget method smooths these variations to find average concentrations within and above the CBL. A more serious deficiency in the height integration method was shown to be in the assumption of constant scalar concentration at the top of the integrating column. Accounting for time variation in free troposphere concentrations in the two-layer height integration method made it essentially identical with the ICBL method.

Investigation of differences between the two-layer height integration and ICBL methods revealed that the ICBL method as applied to the morning period on 24 July had not properly accounted for the difference in height of the residual layer and the fully developed convective boundary layer. The magnitude of this term was quantified and may be incorporated into the ICBL budget equation for cases involving residual layers.

4.2 Limitations to the models

Many of the physiological and physical processes incorporated into the models here have been greatly simplified. To some extent, this is a necessary measure in inverse modelling because detailed interactions of the forward processes are lost in the inversion. For the same reason, the inversion can compensate for flaws in the simplified representation of the system, by requiring the model output to match the observations through adjustment of parameters. In general, the advantage of simplification is that more detailed treatments generally require additional observational information about the system, which may be difficult or impossible to acquire. Simplification of various sub-components of a system also helps to minimise the computational demand when modelling the whole system. For these reasons and because of widespread success of simplifications found in varied applications in the literature, many of these were adopted in the present study. For example, no rigorous attempt was made to account for effects such as mesophyll conductance in the photosynthesis and isotopic discrimination models. The parameters involved in these models, however, were assigned values determined from experimental evidence with this simplification in place, which reduces the resulting error to a minimum (de Pury and Farquhar, 1997; Brugnoli and Farquhar, 2000).

Probably the most significant simplifications applied in the study here were modelling radiation penetration as an exponential decline with leaf area in the canopy model, and neglecting advection in the regional model. As discussed extensively in §2.4.4, there have been many detailed studies investigating shoot and canopy structure and radiation interception in order to produce rigorous treatments of radiation penetration within plant canopies, particularly coniferous canopies. This is especially relevant to the present study site because fir and spruce, the dominant species here, exhibit needle clumping to a greater extent than pine. Furthermore, radiation penetration is perhaps the most important process to represent correctly in the canopy model presented here, because leaf radiation interception is the fundamental driver of all leaf to air fluxes: photosynthesis, transpiration, and heat exchange. It is evident, however, that some kind of parameterisation of the process describing radiation penetration was necessary. To represent the system in the model to the degree of detail that is present in the real system would require a three dimensional treatment with extensive observations of shoot structure, needle orientation and arrangement, and shoot and tree distribution. The intent of this study was not to produce such a model. The approximation of exponential decline was therefore applied as the best option given the available observations and priority of investigation. The importance of the effects of leaf clumping and penumbra were recognised by allowing the extinction coefficients to be optimised. This gave an independent verification based on indirect observations (scalar concentrations within the canopy) of the reduction in extinction rate caused by these effects that had been seen in other direct investigations. Further work in the area of modelling radiation penetration in plant canopies where clumping and penumbra are important will likely lead to more sophisticated general parameterisations than were applied here, which have the potential to provide considerable improvement in performance of models such as this.

The extent to which advection is important in regional boundary layer budgets depends on the heterogeneity of the surface and the rate of advective transport. Neglect of this term in the present study was rationalised by the low wind speeds during the study and extensive coverage of the forest and bog ecosystem types. Unfortunately, the appropriateness of this approximation could not be verified due to lack of suitable upwind and downwind observations. Variation in CO_2 and H_2O concentrations and temperature above the boundary layer during the day (Table 3.1) suggested that significant advective transport was occurring there. It is difficult, however, to make inferences from this about advection within the boundary layer because the two regions are subject to very different airflow regimes and are not closely coupled. Perhaps the best evidence that neglect of advection was warranted is the excellent agreement between model CO_2 flux predictions with eddy covariance measurements. Sensible and latent heat predictions were less successful, but the quality of the temperature and water vapour concentration measurements were correspondingly inferior. In summary, while the contribution of the advective term should generally be quantified in studies such as this, indirect evidence suggested that neglect of this term here probably introduced little error.

4.3 Further applications of multiple constraint and multiple scale approaches

The models described above represent a step forward in utilising cross-scale information and multiple constraints in inverse modelling. The models combine atmospheric inversions with physiological descriptions to find the optimum solution for vegetation fluxes. In the canopy-scale study five different tracers were used to simultaneously solve for parameters defining leaf-level fluxes and to partition ecosystem fluxes between the canopy and ground. Both the canopy and regional-scale studies utilised simplified models of carbon and oxygen isotope discrimination during CO_2 assimilation to interpret isotopic fluxes implied by the atmospheric concentrations: in the canopy model as an integrated feedback on model fluxes and in the regional model for quantitative interpretation of model fluxes.

The use of isotopic data in these studies provided additional constraints on the inferred CO_2, H_2O and heat fluxes in the canopy model, and for both models it allowed physiological parameters to be explored and interpreted within the context of environmental conditions. For the regional model, interpretation of the oxygen isotope data was particularly interesting as it reflected the contrasting influences of two very different ecosystem types. The nonlinear combination of these two influences could help to explain the low oxygen isotope discrimination inferred for one integrating period, whereas interpreting this result using bulk parameters for the heterogeneous landscape led to implausible estimates of source water composition.

A further step that could be taken with a study such as this would be to nest the canopy-scale model within the boundary layer budget model so that the concentration measurements at both scales could work in tandem to further constrain the flux parameters. At present the canopy model has no time dependence, while the regional model relies on changes in concentration with time to infer flux contributions. Linking the two models would provide an efficient means to utilise the information available in the diurnal changes in canopy concentrations, forcing the inferred canopy fluxes at different times to be consistent with observations in the atmospheric boundary layer above. Similarly, the boundary layer budget would be constrained to provide flux estimates consistent with those inferred at the canopy level. Information on the surface heat flux obtained from the combined model could be used to drive a model of boundary layer evolution during the day. Landscape heterogeneity would have to be addressed, perhaps using a number of canopy-level profiling sites. Such a step remains to be done in future work, however, as the two studies presented here were undertaken in different ecosystems and different seasons.

The use of multiple constraints in inverse modelling is gaining popularity amongst modellers today. The term “multiple constraints” is all-encompassing, and may include multiple tracers (CO_2, H_2O, temperature, isotopes of CO_2, CH_4, radiation, and many more); multiple sources (eg. flux measurements, concentration profile measurements, absolute concentration measurements, radiative exchange measurements, nitrogen content measurements); multiple scales (sub-leaf, leaf, canopy, region, globe; and seconds to decades); and multiple modelling approaches (forward and inverse or process-based and observation-based submodels). The idea of incorporating data from a variety of sources and scales is attractive because each observation we make presents a slightly different window onto the processes that influence the whole set of observations. The simultaneous interpretation of each observation within a larger modelling framework can therefore provide much greater insight into the mechanisms underlying plant-atmosphere exchange processes than would be available from observations in isolation. It seems likely that as computational capability continues to increase and collaborations between researchers of complementary expertise thrive, we will see much progress in our understanding of plant-atmosphere interaction achieved through multiple constraint approaches.