DEFINING A NEW NORMAL FOR EXTREMES IN A WARMING WORLD

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The term "new normal" is defined and applied to 2015 record-breaking temperatures. A new normal can be useful for understanding and communicating extremes in a changing climate when precisely defined

BACKGROUND. The term "a new normal" has been used to describe various aspects of recently observed climate and weather. This term is widely used in mainstream media reports to succinctly categorize observed extreme weather and climate events as both unusual and influenced, in some regard, by anthropogenic climate change (e.g., Lewis and Perkins-Kirkpatrick 2016; Franz Prein 2016). The use of this terminology to indicate that climatological events represent a new normal is also used in scientific literature focused on understanding recent extreme climate events. Trenberth et al. (2015, p. 729) argue

> The climate is changing: we have a new normal. The environment in which all weather events occur is not what it used to be. All storms, without exception, are different. Even if most of them look just like the ones we used to have, they are not the same.

Other analyses have attempted to distinguish whether new normal climatic conditions have emerged in a specific region (Diaz et al. 2010; Wood et al. 2013). These studies implicitly define the observational record as the "old normal" and delineate observed contemporary climatological characteristics as the new normal, which provides a diagnostic of an unprecedented change in climate due to greenhouse warming. However, such terminology tends to be descriptive and used ambiguously without precise definition in both scientific literature and public commentary on climate change. In this study, we explore the concept of a new normal for climate and propose a framework for its calculation. Specifically, what is meant by a new normal and is this term a useful concept for understanding climatic change?

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The abstract for this article can be found in this issue, following the table of contents.
DOI:10.1175/BAMS-D-16-0183.1

In final form 17 October 2016

Although a new normal has been applied to describe a diversity of weather and climate phenomena, we focus our specific exploration on a specific set of climate events. Directing our analysis of a new normal to extreme temperatures in the first instance is motivated by several factors. First, extreme weather and climate events occurring on subdaily to multiyear time scales have significant socioeconomic costs and impacts on natural systems. Furthermore, there has been an observed increase in heat extremes on various temporal scales in the observed record (Perkins et al. 2012; Coumou and Rahmstorf 2012). As a result, understanding the causes and potential future changes in the frequency, intensity, and spatial extent of temperature anomalies has become an active research direction (National Academies of Sciences, Engineering, and Medicine 2016). Extreme temperatures are also appropriate for exploring the concept of a new normal, as this term is popularly applied following extreme or record-breaking temperature events. For example, Australian heat waves (Perkins and Pitman 2014) and anomalously warm months (Lewis and Perkins-Kirkpatrick 2016) and record-breaking global-average temperatures have been referred to as a new normal. In summary, the public and scientific interest in extreme observed temperatures and the common discussion of such events as indicative of a new normal enforces the need for a clear definition of this term.

Extreme climate events have increasingly been explored from an attribution perspective, now forming the basis for a dedicated annual report investigating the contributing factors to observed extremes (e.g., Peterson et al. 2012). Attribution studies provide insight into the relative contributions of natural and anthropogenic forcings to a specific observed extreme weather or climate event (Stott et al. 2004). The results of event attribution studies are described as potentially useful for providing information for preparing for future climatic change. For example, the likelihood of hot Australia summers, such as the record-breaking high temperatures of 2012/13, was found to have increased fivefold owing to anthropogenic forcings, including greenhouse gases (Lewis and Karoly 2013). As a corollary, an increase in the frequency of hot summers is expected under increased greenhouse warming, although such results around future probabilities are not typically within the purview of attribution analyses. A review of attribution approaches states that "By determining the causes of extreme weather events being observed now, robust information can also be provided on the extent to which a specific extreme event is a harbinger of the future, and therefore an impact against which a society, which the recent event has shown to be vulnerable to, may want to develop further resilience" (Stott et al. 2012, p. 10). However, without a specific focus on providing insight into future projections about the characteristics of contemporary extremes, attribution studies alone are limited in informing adaptive decision-making.

A further category of climatological studies has attempted to address questions around extremes by posing the idea of "time of emergence" (Mora et al. 2013; King et al. 2015). These studies investigate when the signal of climate change will emerge distinctly from the background noise of climate variability (Hawkins et al. 2014), arguing that the time of emergence (ToE) metric is potentially important for adaptation planning. For example, Mora et al. (2013) determined the projected year in which the mean climate of a given location moves to a state continuously outside the bounds of simulated historical variability. Recognizing the importance of extremes for societal impacts, King et al. (2015) proposed the alternative time of anthropogenic emergence (TAE) and calculated the emergence for various extreme indices in historical and future model simulations relative to a quasi-natural state.

Both attribution and time of emergence approaches have a collective overarching aim of informing adaptation planning. However, these approaches only go partway to doing so. Attribution studies quantify the influence of a specific forcing (e.g., anthropogenic greenhouse gases) on current climate records, but do not specifically address questions around the

Table 1. Details of CMIP5 experiments analyzed.

Model experiment	Major forcings
Historical	Anthropogenic (greenhouse gases, aerosols, ozone) and natural (solar, volcanics)
HistoricalNat	Solar and volcanics
RCP2.6	Anthropogenic (greenhouse gases, aerosols, ozone scenarios) and natural (solar); radiative forcing reaches a maximum near the middle of the twenty-first century before decreasing to 2.6 W m^{-2}
RCP4.5	Anthropogenic (intermediate greenhouse gases, aerosols, ozone scenarios) and natural (solar)
RCP6.0	Anthropogenic (intermediate greenhouse gases, aerosols, ozone scenarios) and natural (solar)
RCP8.5	Anthropogenic (greenhouse gases, aerosols, ozone scenarios) and natural (solar); radiative forcing reaches a level of about 8.5 W m^{-2} at the end of the century

occurrence of such records in the future, which depends on the nature of future changes in temperatures, both through the rate of warming and higher-order changes in the shape of the temperature distributions. Similarly, time of emergence studies have largely focused on determining when future mean climates can be considered outside the range of historical variability but typically do not focus on specific events and their future occurrence. Hence, the potential of the information these studies provide for informing decision-making around future planning for potentially high-impact events is inherently limited.

TIME OF EMERGENCE OF NEW NORMAL.

Previous studies have begun to specifically investigate the incidence of historical heat records in future greenhouse gas emissions scenarios (Christidis et al. 2014). One such recent study examined the incidence of historical record summers in the future, determining that historically hot summers will be the norm for large areas globally within the next 20 years (Mueller et al. 2016). This supports previous model-based findings centered on exploring changes in heat regimes. For example, Diffenbaugh and Scherer (2011) previously determined the point in time at which the coolest warm season of the twenty-first century became hotter than the hottest warm season of the late twentieth century in simulations, indicating a new and permanent climate regime shift. Such approaches extend information provided by event attribution analyses and explicitly indicate that historical temperature records on seasonal time scales occur more frequently under increased greenhouse gas warming. While these future heat records approaches demonstrate that contemporary extremes occur more frequently in the future, they are also limited in providing insight into current extremes broadly. Furthermore, an examination of the widely used concept of a new normal more broadly has not yet been made.

Our study builds on this set of prior studies in examining the concept of a new normal by combining aspects of attribution, time of emergence, and future heat records analytical approaches. We note that from a purely statistical viewpoint, a new normal may be viewed as having limited utility. An extreme event is typically reported as a new normal when its occurrence is considered to have been influenced by anthropogenic warming and will likely become more frequent under future warming. However, by definition the climate system under the influence of anthropogenic warming is nonstationary and exhibits a nonconstant mean (i.e., a warming trend). Here in a true statistical sense "new" and "normal" are essentially oxymoronic; such extremes cannot be considered as categorical evidence of a distinct state. However, moving beyond semantics, the concept of a new normal is persistent and widely employed for framing and understanding observed weather and climate phenomena. Hence, we instead propose the more precise concept of the time of emergence of a new normal (ToENN).

The time of emergence of a new normal is defined here as having occurred when more than 50% of future anomalies exceed a reference event in magnitude or intensity. This definition can be applied broadly to a diversity of events. We begin by applying this general ToENN framework using the record-breaking global-average 2015 temperatures as a reference event. When will years as hot as 2015 become the norm? We focus

Table 2. CMIP5 models and observational datasets analyzed.

Models
Beijing Climate Center, Climate System Model, version 1.1 (BCC_CSM1.1)
Community Climate System Model, version 4 (CCSM4)
Community Earth System Model, version 1 (Community Atmosphere Model, version 5 [CESM1(CAM5)]
Geophysical Fluid Dynamics Laboratory Earth System Model with Modular Ocean Model, version 4 component (GFDL-ESM2M)
Goddard Institute for Space Studies Model E2, coupled with Hybrid Coordinate Ocean Model (GISS-E2-H)
GISS Model E2, coupled with the Russell ocean model (GISS-E2-R)
L'Institut Pierre-Simon Laplace Coupled Model, version 5A, low resolution (IPSL-CM5A-LR)
L'Institut Pierre-Simon Laplace Coupled Model, version 5A, mid resolution (IPSL-CM5A-MR)
Model for Interdisciplinary Research on Climate, Earth System Model (MIROC-ESM)
Meteorological Research Institute Coupled Atmosphere–Ocean General Circulation Model, version 3 (MRI-CGCM3)
Norwegian Earth System Model, version 1 (intermediate resolution) (NorESM1-M)
Observations
GISS Surface Temperature Analysis (GISTEMP)
Climate Research Unit temperature dataset, version 4 (CRUTEM4)

on annual- and seasonal-scale events, rather than short-duration, high-impact extremes such as heat waves, as such large-scale observed record-breaking events have been widely discussed in the public domain using a new normal framing. However, our proposed methodology is intended to be applied to investigating events across spatial and temporal scales.

CASE STUDY: 2015 TEMPERATURES. We investigate the ToENN$_{2015}$ in phase 5 of the Coupled Model Intercomparison Project (CMIP5) climate projections (Taylor et al. 2012). Using a key element of the event attribution approach, we focus on an observed extreme event, defined as the magnitude of the highest global annual average mean temperature (Tmean) anomaly recorded in the observational record (ΔT_{2015}). We combine this attribution-derived focus with a key element of the time of emergence approach to explore the timing of when extreme contemporary annual- and seasonal-scale temperatures become statistically normal. We formally define and assess the concept of a new normal relative to present based around extreme temperatures, which pose a significant risk of societal impacts (IPCC 2012).

We demonstrate ToENN by using a single realization from each of 18 models participating in CMIP5 with temperature data (tas) available for standard historical and historicalNat experiments, and representative concentration pathway (RCP) experiments RCP2.6, RCP4.5, RCP6.0, and RCP8.5 (Taylor et al. 2012) (see Table 1). Global-mean annual land-only temperature anomalies are calculated for land surface

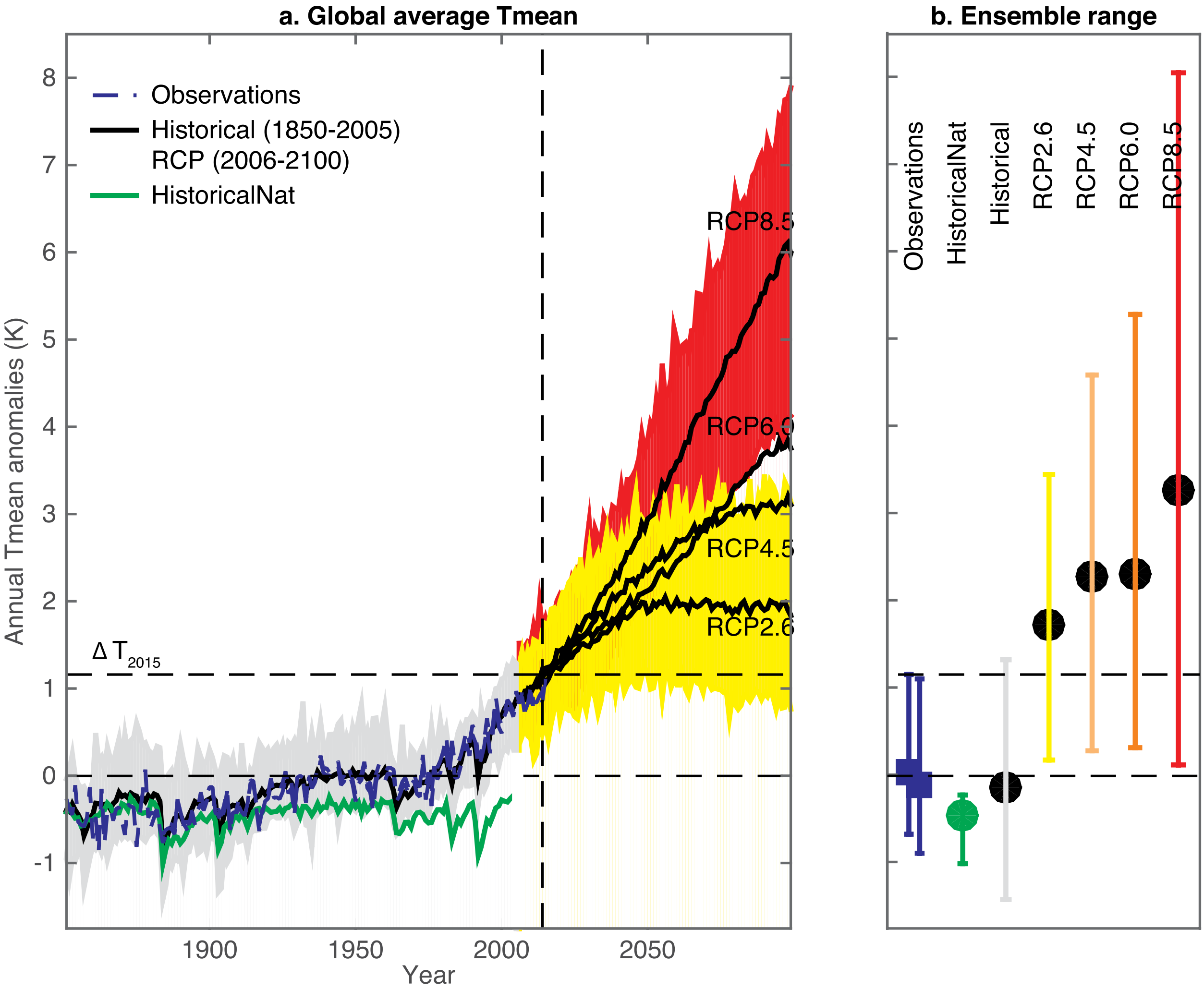

Fig. 1. Multimodel mean global temperature change relative to 1961–90 for CMIP5 historicalNat, historical (1850–2005), and RCP (2006–2100) scenarios. The 5th–95th-percentile model range is shown for the historical and RCP scenarios. The multimodel mean values area shown in (a) solid lines for each CMIP5 experiment and (b) black dots for means across the entire time period. The horizontal line indicates the global annual-average temperature anomaly observed in 2015 (ΔT_{2015}).

grid boxes relative to each model's 1961–90 climatology. Models are regridded onto a uniform 1.5° latitude by 1.5° longitude horizontal grid. In addition to determining ToENN$_{2015}$, we also explore the time of emergence of seasonal and regional-scale temperatures. Regional area-mean temperatures are calculated for Australia (50°–10°S, 110°–155°E), Europe (30°–70°N, 10°W–60°E), Asia (10°–70°N, 60°–170°E), and North America (20°–70°N, 160°–50°W). Seasonal [December–February (DJF) and June–August (JJA)] data are also analyzed for regions. Observations are derived as the mean from the Goddard Institute for Space Studies (GISS) Surface Temperature Analysis (GISTEMP) (Hansen et al. 2010) and Climate Research Unit temperature dataset, version 4 (CRUTEM4) (Morice et al. 2012), global temperature datasets (Table 2).

We apply a model evaluation step demonstrated in CMIP5-based attribution studies and compare model variability in historical simulations against observed variability (Lewis and Karoly 2013; Lewis et al. 2014). Using a Perkins skill score (Perkins et al. 2007), we assess the similarity of probability density functions (PDFs) of modeled and observed regional average temperatures. A skill score is determined for each model as a measure of the common area between simulated and observed distributions, which ultimately provides a simple measure of the similarity of models to observations across the entire PDF. We compare each CMIP5 model's historical realization to both GISTEMP and CRUTEM4 for annual, DJF, and JJA global averages. Models with skill score below 0.5 when compared to either

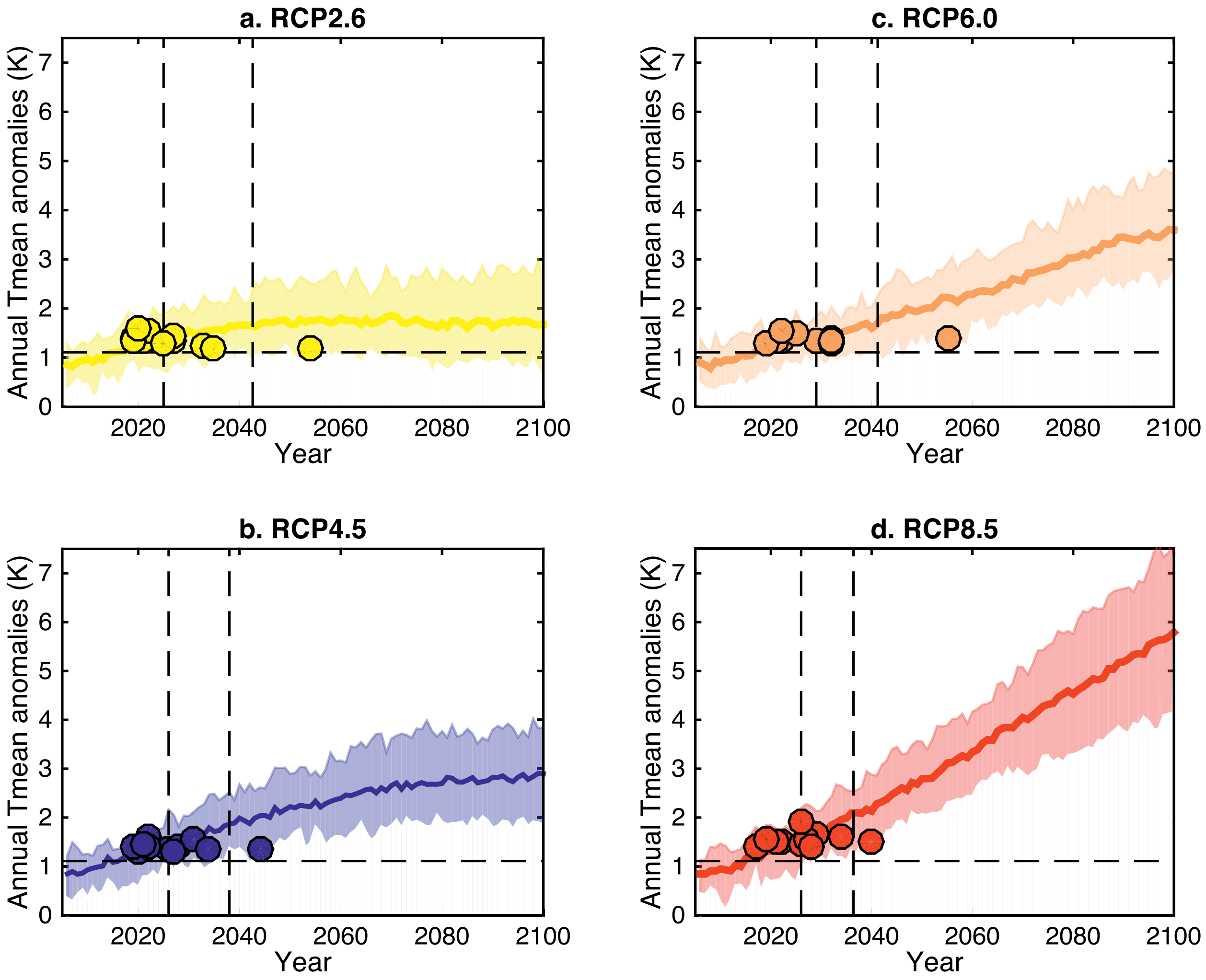

FIG. 2. Emergence of new normal for global annual-mean temperatures. Global-average temperature changes are shown for each RCP scenario for multimodel mean (and 5th–95th-percentile range) relative to 1961–90. Circles indicate the time of emergence of a new normal in each model realization and the corresponding average annual-mean temperature in the 20-yr period centered on the year of emergence. The horizontal line shows the highest observed anomaly ΔT_{2015}. Vertical lines show the median (>50%) and very likely (>90%) time of emergence of new normal in each scenario for the multimodel ensemble (where $n = 11$).

Table 3. Projected return times (yr) of global-mean annual-, DJF-, and JJA-average temperature anomalies exceeding the largest magnitude in the observed record. Return times are expressed as >N where the probability of occurrence of temperatures above this threshold are too small to be accurately estimated or do not occur at all in *N* simulated years and as <2 where simulated temperatures greater than the most extreme observed are very likely to occur more frequently than in every second projected year.

		Return times				
		2006–25	**2026–45**	**2046–65**	**2066–85**	**2086–2100**
Annual						
HistoricalNat	>*N*					
Historical (1976–2005)	150					
RCP2.6		2.5	<2	<2	<2	<2
RCP4.5		2.5	<2	1	1	1
RCP6.0		2.5	<2	1	1	1
RCP8.5		2.5	<2	1	1	1
DJF						
HistoricalNat	>*N*					
Historical (1976–2005)	>*N*					
RCP2.6		3.2	<2	<2	<2	<2
RCP4.5		3.4	<2	1	1	1
RCP6.0		3.3	<2	1	1	1
RCP8.5		3.3	1	1	1	1
JJA						
HistoricalNat	>*N*					
Historical (1976–2005)	75					
RCP2.6		<2	<2	<2	<2	<2
RCP4.5		<2	<2	1	1	1
RCP6.0		<2	1	1	1	1
RCP8.5		<2	1	1	1	1

observational dataset for any of these temporal averages are excluded from further analysis. This resulted in 11 of 18 models (Table 2) available for further analysis, and a multimodel mean, and 5th- and 95th-percentile values are calculated for each experiment using these 11 models (Fig. 1). Following this evaluation step, the historical experiment is analyzed for years 1976–2005 and the historicalNat 1900–2005. While further CMIP5 models are available beyond the 11 utilized, we assert that greater confidence in establishing a ToENN occurs when models capture observed variability over the historical period.

To determine the time that 2015 emerges as the new normal using a multimodel ensemble, we start by calculating ToENN$_{2015}$ for each model realization. For this case study, the ToENN future state is the subsequent 20-yr period. To account adequately for multidecadal variability (Hawkins et al. 2014), the ToENN in each model realization is the year that for any subsequent 20-yr period, 50% of anomalies exceed the reference event. We take the multimodel average median across the 11-member ensemble (Fig. 2). For global and regional area-mean ToENN calculations, we additionally report a very likely ToENN value if an event has emerged as a new normal in >90% of model realizations. This provides an assessment of the spread of ToENN values in the model realizations. We note that the year for differing reference events will also be different in most cases, such that, for example, the hottest DJF in Australia occurred in 2013 and hence ToENN$_{2013}$ would be explored for this event at this location.

Following Knutti and Sedláček (2013), we apply a measure of robustness R to ToENN calculations, which combines measures of ranked probability skill score and the ratio of model spread to the predicted change. Here R is defined as

$$R = 1 - \mathrm{A1}/\mathrm{A2},$$

where A1 is the integral of the squared area between two cumulative density functions (each RCP model realization and the multimodel mean) and A2 is the integral of the squared area between two cumulative density functions (the RCP multimodel mean and the historical multimodel mean). A higher robustness score corresponds to a relative model agreement on sign and magnitude, with $R = 1$ representing perfect model agreement, and stippling in Fig. 2 indicating robustness of >0.8.

Return times of heat events in the various regions (Australia, Europe, Asia, and North America) are also calculated to allow comparison with previous studies.

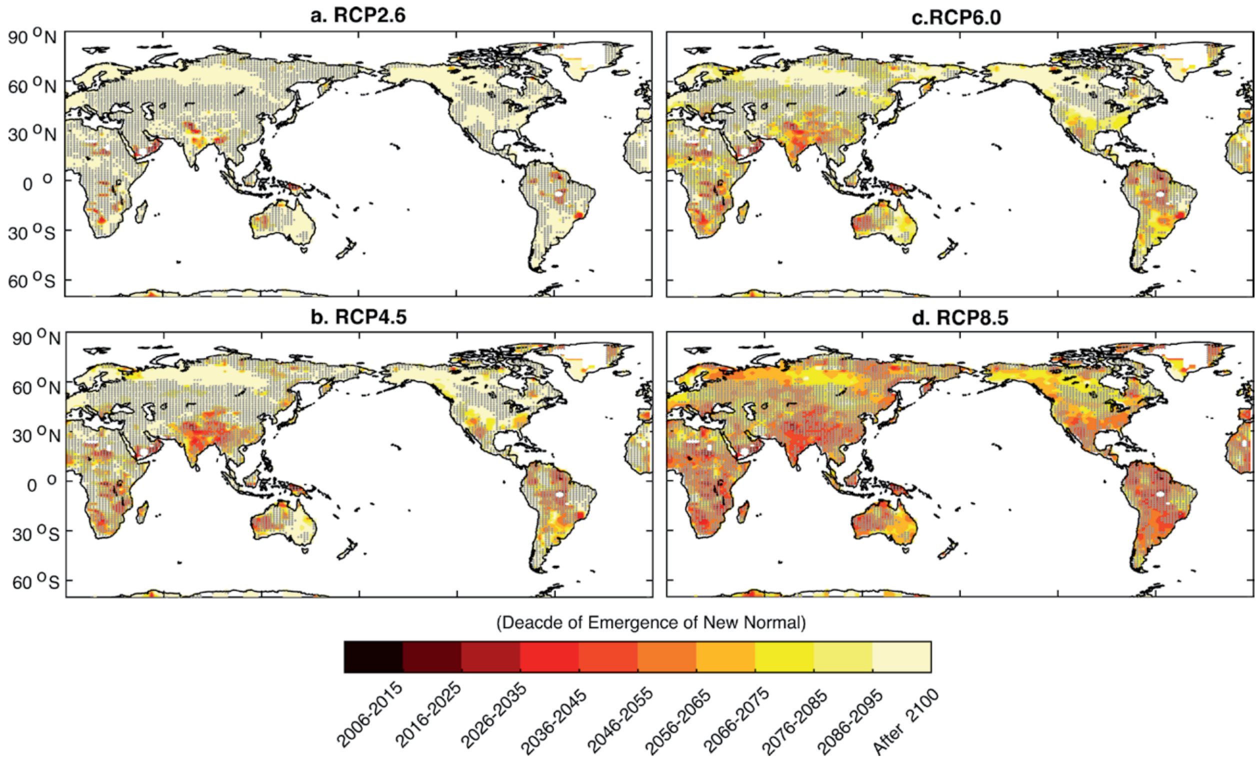

Fig. 3. Maps of the multimodel median decade of emergence of a new normal for annual-average temperatures in each grid box for various RCP scenarios. Gray stippling marks areas of high robustness (>0.8), which corresponds to a relatively high level of model agreement on sign and magnitude. White areas (where no ToENN value is shown) indicate areas of missing data in observational temperature products, and Antarctica is excluded because of poor observational coverage.

Following Christidis et al. (2014), return times are based on distributions of temperature anomalies. The probability of exceedance of ΔT_{2015} is calculated and the return time computed as the inverse of the probability. Return times were estimated using a bootstrap resampling technique, whereby subsamples of 50% of model data were resampled 10,000 times, with replacement, for each experiment suite and a spread of probability values determined with 90th-percentile values presented in this study as the calculated return time. In several cases, the precise return time could not be reliably quantified as such temperatures anomalies were very rare or did not occur in model realizations. In this case, return times are reported as greater than the number of simulated years >*N*.

Finally, a more detailed investigation of ToENN uncertainties is made to determine the impact of experimental design on the concept of a new normal for extreme seasonal- and annual-mean temperature anomalies. The ToENN and return times calculated here are robust to changes in definition and experimental design. For example, including the full set of 18 CMIP5 models does not impact the emergence patterns of annual- and seasonal-scale regional and global temperatures. The ToENN for annual-average global-mean temperatures was reexamined using an ensemble defined using multiple realizations from models {in this case three realizations each from Model for Interdisciplinary Research on Climate, version 5 (MIROC5); Community Earth System Model, version 1 (Community Atmosphere Model, version 5) [CESM1(CAM5)]; and Commonwealth Scientific and Industrial Research Organisation Mark 3.6.0 (CSIRO Mk3.6.0)}. This ensemble produced ToENN values similar to the ensemble constitute by single realizations of 11 models, though a new normal tended to occur slightly earlier.

A NEW NORMAL FOR EXTREME TEMPERATURES.

The time series of annual-average global Tmean shows that the 2015 record occurs outside the simulated range in the historicalNat multimodel ensemble and near the limit of the historical experiment terminating in 2005 (Fig. 1). However, such global anomalies fall well below the multimodel mean for all representative concentration pathway scenarios, indicating ToENN will occur. The time of emergence of a new normal is explored using

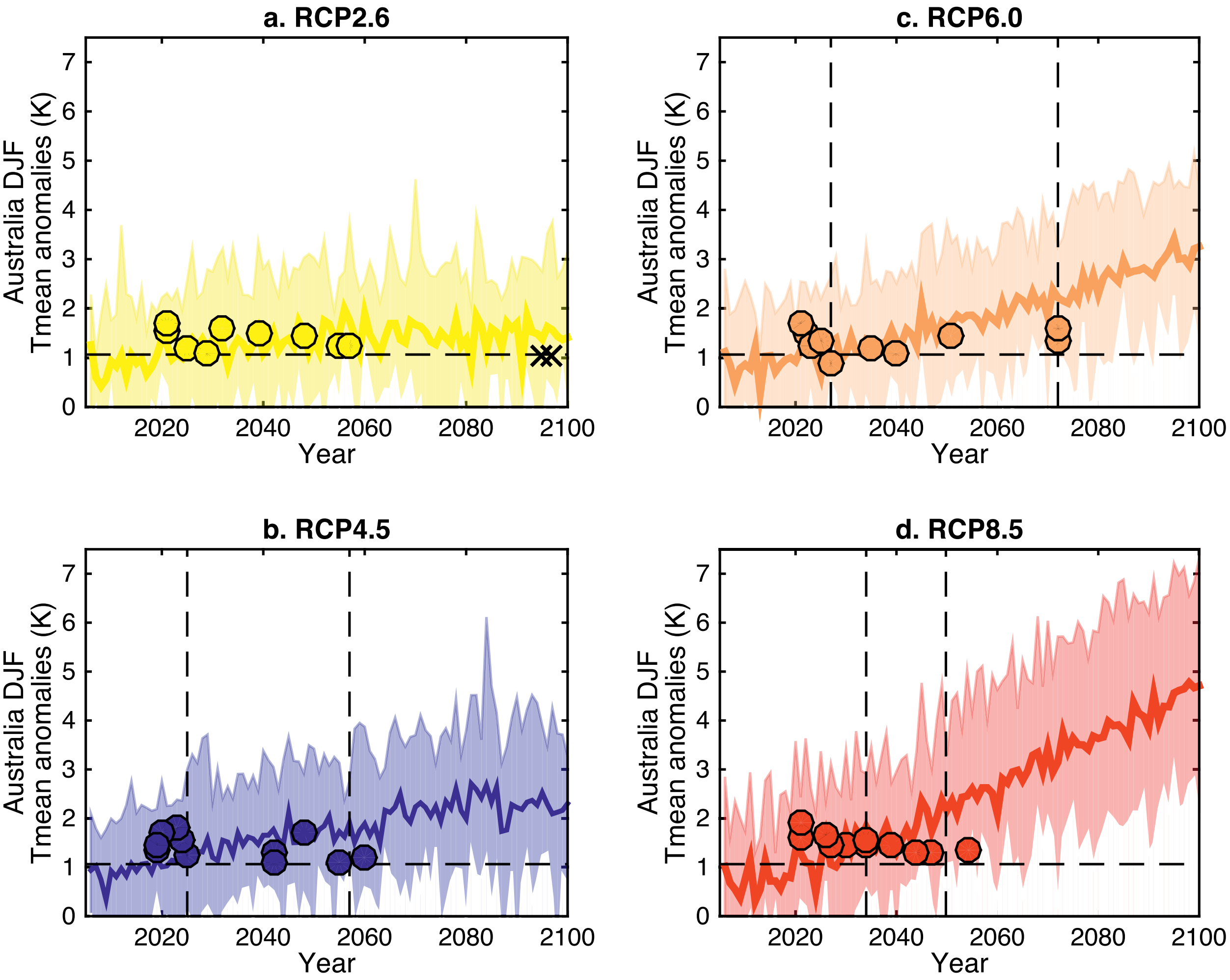

Fig. 4. As in Fig. 2, but showing the emergence of new normal for Australian DJF temperatures. A black cross at the end of the century represents model realizations where emergence does not occur prior to 2100. In this case, vertical mean and "very likely" lines are not shown for that experiment (i.e., RCP2.6). In cases where ToENN occurs between 2090 and 2100, markers are plotted at the corresponding mean temperature over this decade.

individual model realizations for the RCP scenarios (Fig. 2), which demonstrates that 2015 emerges as the new normal in all RCP scenarios for >90% of models by 2040. The median time of emergence of 2015 as the new normal occurs between 2020 and 2030 under all emissions trajectories. The small contribution of scenario uncertainty in near-term projections has been reported elsewhere (Hawkins and Sutton 2009). The spread of ToENN values in individual model realizations is lowest in the high-end RCP8.5 emissions scenario, where in all models a new normal for ΔT_{2015} is reached by 2040.

When framed in terms of return times (Christidis et al. 2014) of future temperature anomalies exceeding ΔT_{2015}, exceedance of this threshold very likely (>90% confidence) has a return period of 1–2 yr in all RCP scenarios by 2006–25 (Table 3) but occurs infrequently in the historical simulations for 1976–2005. By 2026–45, such a temperature event occurs every year in the higher-end pathways (RCP8.5, RCP6.0, and RCP4.5). While it should be noted that the lack of volcanic eruptions necessarily required within the RCP forcing suite may be important in simulated temperatures in the near past and near future, the frequent occurrence of contemporary extremes and emergence of a new normal of 2015 in the early part of the RCP pathways demonstrates rapid warming after the historical experiment finishes in 2005 (see Fig. 1).

The ToENN for annual-mean temperatures is next explored at lower spatial scales. The time of emergence of a new normal is first calculated for each model land surface grid box for annual-average temperatures (Fig. 3) using the current maximum temperature anomaly observed for each grid box (as available up to 2015). An ensemble robustness assessment was also applied based on relative model

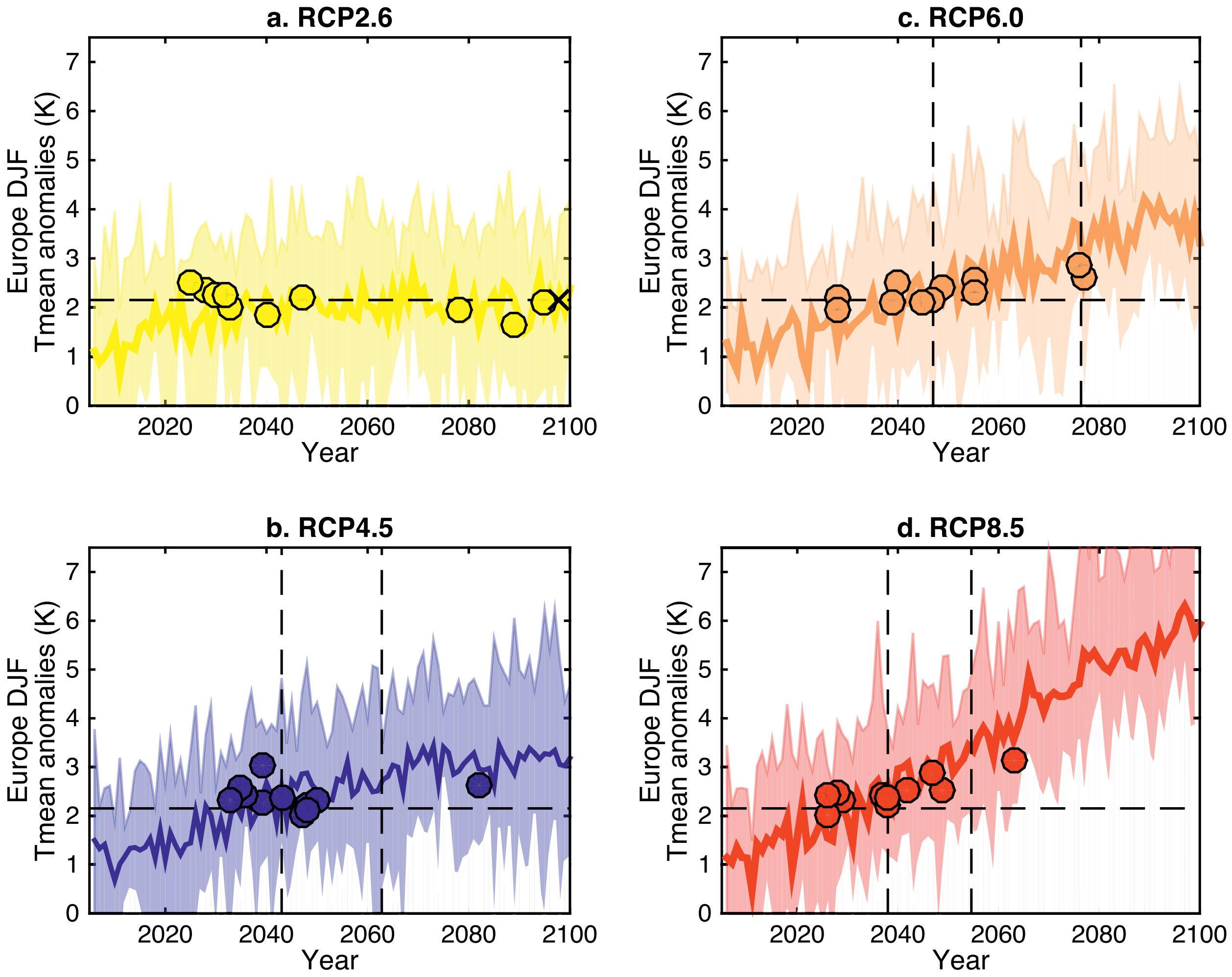

Fig. 5. As in Fig. 4, but for European DJF temperatures.

agreement of sign and magnitude, demonstrating large spatial areas of model agreement on the sign and relative magnitude of simulated temperature changes, with the most notable exceptions over Antarctica where observations are poor, and hence the results are not shown in Fig. 3. While all scenarios show that a new normal for annual Tmean occurs for the majority of land surfaces (>70%) before the end of the century, there is a clearer scenario dependence in the time of emergence of a new normal on the gridbox scale, where the signal-to-noise ratio is likely to be lower than for the global average. Under aggressive greenhouse gases emission cuts (RCP2.6 scenario), emergence occurs for 72% of land areas by 2100, but only for 1% of land areas in the first half of the century. In contrast, for the CMIP5 high-level emissions scenario, RCP8.5, which represents our current emissions trajectory (Peters et al. 2013), the ToENN is consistently earlier than lower-end emission scenarios, and a robust emergence of a new normal occurs over most land surfaces (98%) by the end of the century and in 12% of locations before 2045 (Fig. 3d).

In contrast to annual-average temperatures, the corresponding ToENN results for seasonal Tmean for various regions show a greater sensitivity to the various emissions scenario used in the model experiments (Figs. 4–7). We focus on DJF (austral summer/boreal winter) regional-mean temperatures as an example. ToENN occurs comparatively earlier for Australia (Fig. 5) than for Northern Hemisphere regional DJF ToENN values, which are generally later in the twenty-first century and a larger model spread is simulated. In Australia, record summer (DJF) temperatures ΔT_{2013} (Lewis and Karoly 2013) are a new normal in the majority of model realizations by 2035 in all scenarios. On these shorter temporal and lower spatial scales, the emergence of a new normal can be avoided in low-emission pathways in some model realizations. For example, the mean ToENN for DJF temperatures in Europe and Asia, and particularly for North America, occurs later in the twenty-first century, or not at all, in the RCP2.6 scenario, compared

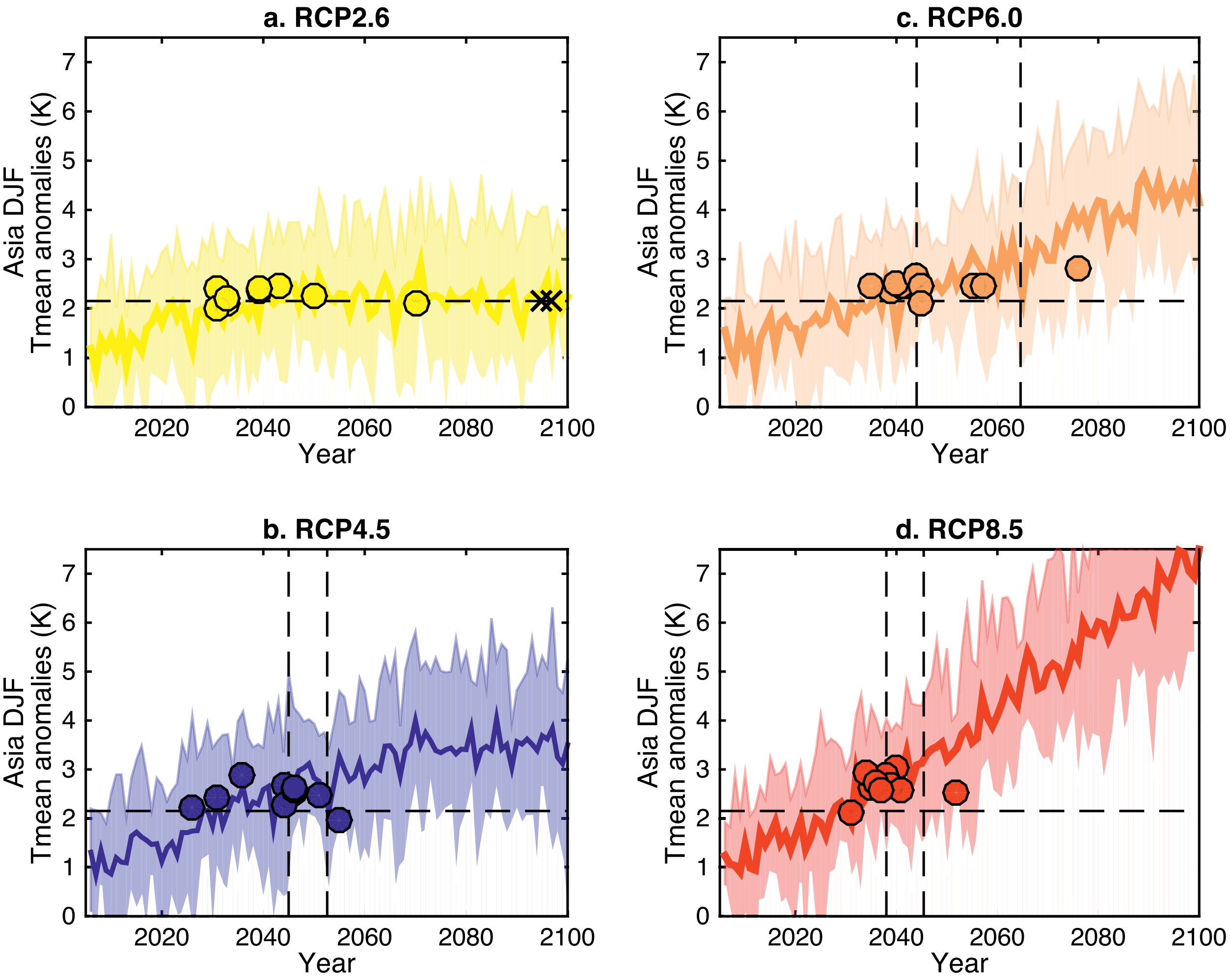

Fig. 6. As in Fig. 4, but for Asian DJF temperatures.

with RCP6.0 or RCP8.5. The scenario dependence of regional ToENN is more complicated in the JJA (boreal winter) season in Asia and Europe, owing to the complexity of the emissions trajectories in the RCP in the near term (Peters et al. 2013). While the RCP2.6 scenario has a lower greenhouse gas forcing than RCP4.5, the near-term warming projected is greater and more variable as a result of aerosol contributions that affect these highlighted regions (Chalmers et al. 2012).

This result demonstrates that at the regional scale, a new normal for contemporary extremes can be avoided for certain seasonal-scale extremes with aggressive greenhouse gas emission reductions. The larger model spread of ToENN on regional and seasonal scales occurs as the signal-to-noise ratio is lower regionally than for global annual-average temperatures. Furthermore, the temporal and spatial-scale dependence of extremes is widely noted in attribution approaches that largely focus on large-scale phenomena such as coherent heat waves (e.g., Stott et al. 2004; Schär et al. 2004) or continental-scale seasonal heat (e.g., Lewis and Karoly 2014; Knutson et al. 2014). Previous studies investigating the time of emergence of mean and extreme climate indices also identify regional and seasonal-scale differences that are dependent on variability (Mora et al. 2013; King et al. 2015).

COMMUNICATING CHANGING EXTREMES.

We have proposed a formal definition of a new normal based on when a particular extreme event emerges as a new normal in future climate states, which we call the time of emergence of a new normal. We have demonstrated this general framework for a new normal using the case study of the record-breaking global-average 2015 temperatures. Based on CMIP5 simulations of alternative future emission scenarios and realizations of multiple contributing models, we show 2015 global annual-mean temperature anomalies will emerge as the new normal by 2040 at the latest and are unavoidable even in emissions scenarios representing aggressive greenhouse gas cuts (i.e., RCP2.6; Peters

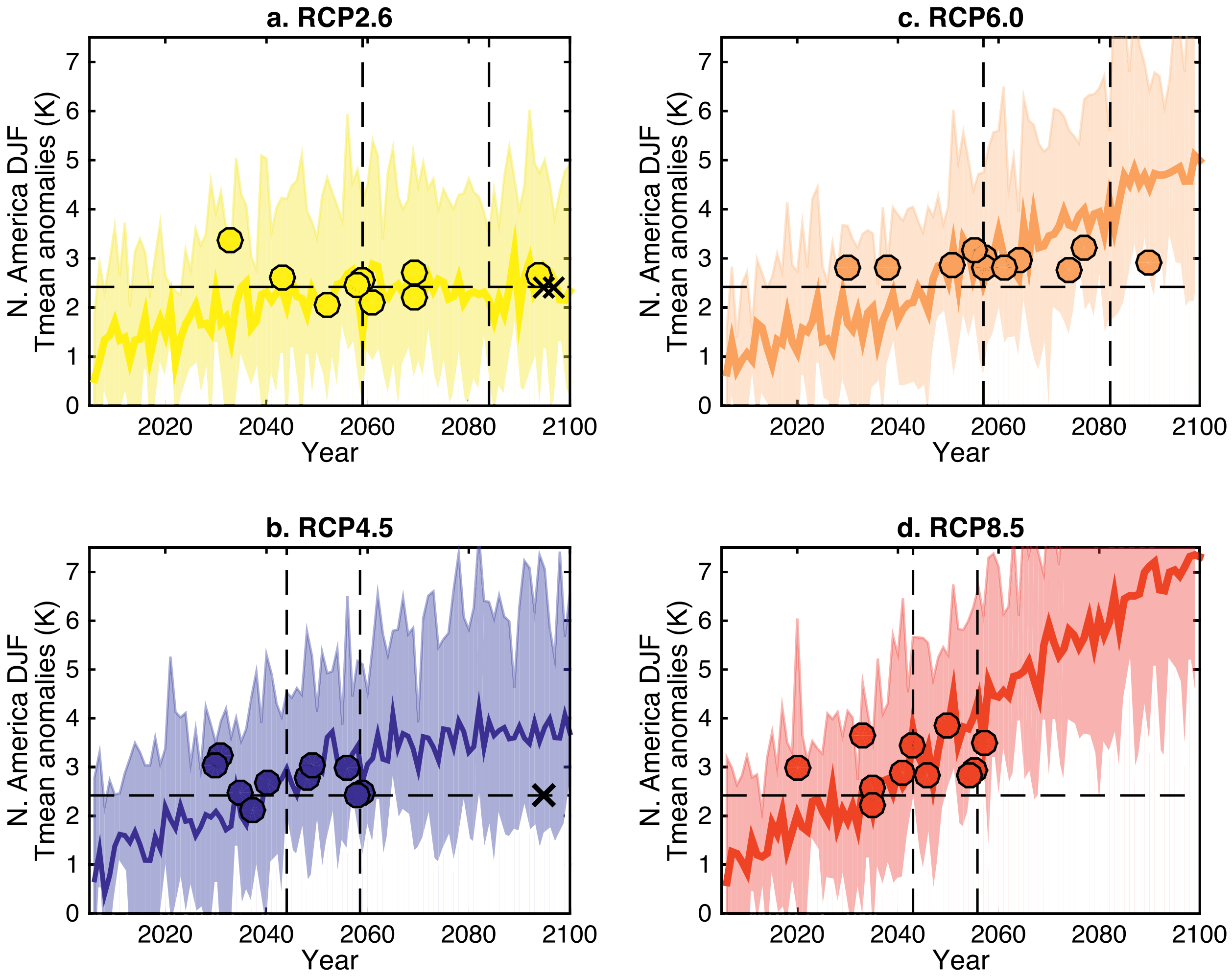

Fig. 7. As in Fig. 4, but for North American DJF temperatures.

et al. 2013). In contrast, a new normal in local- and regional-scale temperatures can be delayed in low-emissions scenarios, suggesting that if greenhouse gas emissions were to fall, the majority of places would benefit, as the extremes of the world today would not become the new normal in the future. This framework can be employed at a multitude of spatial and temporal scales and for a variety of extreme event types in order to understand the occurrence of contemporary extremes of high societal and economic risk in the future.

The results of this specific case study support previous examinations of historical records in future projections under varying emissions scenarios. For example, Mueller et al. (2016) examined summer-mean temperatures and determined that historically hot summers would be the norm within the next 20 years for half the world's population. Furthermore, many areas are likely to move into a new seasonal heat regime within the next four decades (Diffenbaugh and Scherer 2011). On a regional scale, historically hot summers are projected to be the norm in eastern China within two decades in the CMIP5 midrange RCP4.5 scenario (Sun et al. 2014). Later dates were determined by Mora et al.'s (2013) analysis; however, this instead focused on a distinct emergence from the range of historical variability, rather than on changing frequency of contemporary extremes in future projections.

The consistency of these results looking at the increased frequency of historical record-breaking temperatures occurring on regional and seasonal scales in future projections, together with our ToENN example presented here, collectively demonstrate the value of the concept of a new normal. While event attribution studies are increasingly useful for understanding and disentangling the multiple contributing factors to observed extremes, they are limited in providing insight into climate extremes in the future. That is, attribution studies determining that anthropogenic climate change substantially influenced an observed event infer that type of event will occurring more frequently in a future of enhanced warming (Lewis and

Karoly 2013) and focus narrowly on the frequency of historical extremes. Alternatively, studies centered on the future occurrence of historical extremes (Mueller et al. 2016; Sun et al. 2014) encompass an assessment of both event frequency and the increasing magnitude of events, relative to a historical baseline. This is demonstrated in Fig. 1, where the 2015 record-breaking global-average temperatures are projected to rapidly become cooler than average in the near future.

Our case study of the 2015 global-average record temperatures also demonstrates the utility of the new normal concept for the communication of climate change, where it is clearly defined. This is one proposal for understanding this concept from a scientific perspective, prompted by the description of observed seasonal- to annual-scale extremes as a "new normal" (Lewis and Perkins-Kirkpatrick 2016). Alternative definitions to the time of emergence of a new normal are possible and potentially equally useful. For example, a new normal could alternatively be defined using the variability in observed climates and future climate projections. Other useful explorations could investigate specific classes of events, such as so-called extreme extremes like heat waves (e.g., Perkins and Pitman 2014) or floods, or holistically examine climatic conditions in a specific region (e.g., Wood et al. 2013). The generic framework provided here is ideal for expansion to other categories of events and their definition and for exploration in other model datasets.

The term new normal has been used widely to redress the misplaced perception that climate change impacts will occur only as a future problem, rather than as an influence on present climates (Perkins and Pitman 2014). Framing contemporary phenomena as a new normal readily encapsulates the contribution of climate change to current weather and climate events (Trenberth et al. 2015). However, the use of the term without precise definition in both scientific literature and public commentary on climate change limits its utility. First, the vague use of the term negates the importance of natural climate variability. From a simple perspective, if 2015 is a new normal for global temperatures, what if 2016, 2017, or 2018 are cooler? Second, the use of the term without definition provides limited information about climate change impacts and risks, which are circumvented by a precise description. Applying the new normal definition based on a time of emergence approach and the case study that we offer here, we expect with high confidence that global-average temperatures greater than those observed in 2015 will occur at least every second year by 2040. This precisely defined new normal effectively communicates the influence of climate change in the record-breaking temperatures and their changing occurrence in the future. In combination with attribution and time of emergence studies, this approach can help inform adaptation strategic for climate change.

ACKNOWLEDGMENTS. This research was supported by ARC DECRAs 160100092 to S.C.L. and DE140100952 to S.E.P.-K, the ARC Centre of Excellence for Climate System Science (Grant CE 110001028), and the NCI National Facility. We thank the Bureau of Meteorology, the Bureau of Rural Sciences, and CSIRO for providing AWAP data. We acknowledge the WCRP's Working Group on Coupled Modelling, which is responsible for CMIP. The U.S. Department of Energy's PCMDI provides CMIP5 coordinating support.

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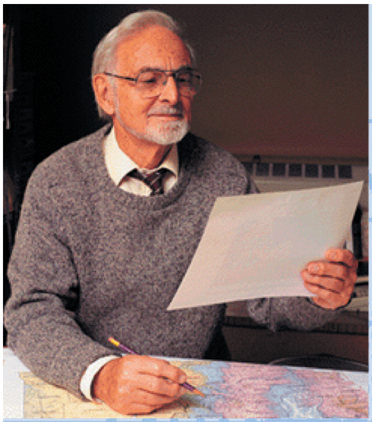

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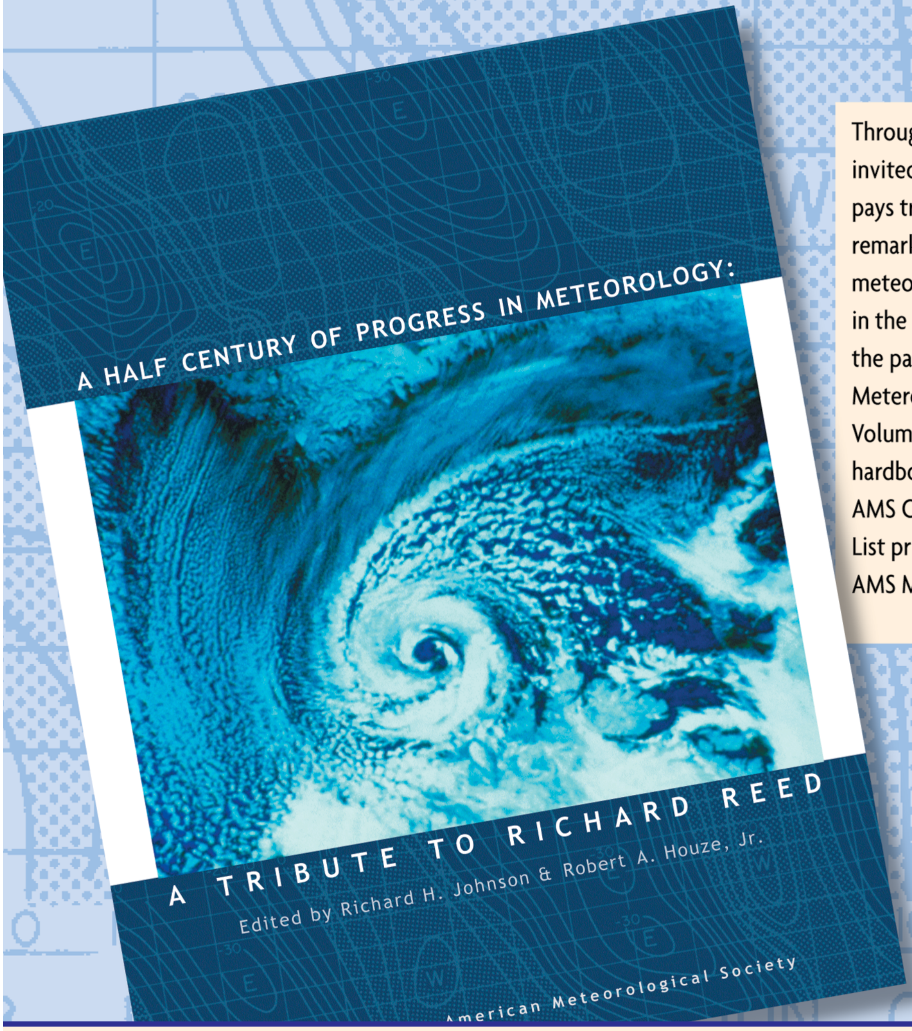

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