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Predicted Chance That Global Warming Will Temporarily Exceed 1.5 °C

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Key Points:

- Early temporary excursions above 1.5 °C would provide a warning that one of the Paris Agreement thresholds is being approached
- Initialized climate predictions indicate a 38% (10%) chance of at least 1 month (year) exceeding 1.5 °C in the 5 year period 2017-2021
- Five-year mean temperatures above 1.5 °C are extremely unlikely in this period

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Abstract The Paris Agreement calls for efforts to limit anthropogenic global warming to less than 1.5 °C above preindustrial levels. However, natural internal variability may exacerbate anthropogenic warming to produce temporary excursions above 1.5 °C. Such excursions would not necessarily exceed the Paris Agreement, but would provide a warning that the threshold is being approached. Here we develop a new capability to predict the probability that global temperature will exceed 1.5 °C above preindustrial levels in the coming 5 years. For the period 2017 to 2021 we predict a 38% and 10% chance, respectively, of monthly or yearly temperatures exceeding 1.5 °C, with virtually no chance of the 5-year mean being above the threshold. Our forecasts will be updated annually to provide policy makers with advanced warning of the evolving probability and duration of future warming events.

Plain Language Summary The Paris Agreement calls for efforts to limit human-induced global warming to less than 1.5 °C above preindustrial levels. Observations of global mean temperature contain both human-induced temperature change and superimposed natural variability. Natural variability may temporarily add to the underlying human-induced warming, leading to observed temperatures that are higher than 1.5 °C for short-term periods. This would not necessarily exceed the Paris agreement, which is usually interpreted to refer to long-term averages, but would give an important indication that the threshold is being approached. If exceedance occurs, policy makers will require guidance regarding how long temperatures will remain above the threshold. Here we develop a new capability to predict the likelihood that global temperature will exceed 1.5 °C above preindustrial levels in the coming 5 years. We use decadal climate predictions that are regularly produced by several international climate prediction centers. Importantly, these predictions take into account the observed present day conditions since this is essential to predict the evolution of natural variability. For the period 2017 to 2021 we predict a 38% and 10% chance, respectively, of monthly or yearly temperatures exceeding 1.5 °C, with virtually no chance of the 5-year mean being above the threshold. We will update our forecasts every year to provide policy makers with advanced warning of the evolving probability and duration of future warming events.

1. Introduction

The Paris Agreement (UNFCCC, 2015) aims to limit global surface temperature rise to "well below 2 °C above preindustrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above preindustrial levels." Although the precise meaning of exceeding a given temperature threshold was not defined, Rogelj et al. (2017) interpret it as human-induced changes in climatological means, averaged over periods of 30 years. However, this will be difficult to verify with observations until well after the event, as natural internal variability may add to human-induced warming to produce temporary threshold exceedances in the observations earlier than would be expected from human influences (Henley & King, 2017; Joshi et al., 2011).

The Paris Agreement (UNFCCC, 2015) also recognizes “the importance of averting, minimizing and addressing loss and damage associated with the adverse effects of climate change, including extreme weather events ….” There is clear evidence that greater global mean warming increases the risk of extreme weather events (Seneviratne et al., 2016), impacting food security (Betts et al., 2018), temperature extremes, and hence mortality rates, in many regions including Europe (Dosio & Fischer, 2018; King & Karoly, 2017), Australia (King et al., 2017), China, and East Asia (Li et al., 2018; Shi et al., 2018), European storms and precipitation extremes (Barcikowska et al., 2018), and coral bleaching events in the Great Barrier Reef (King et al., 2017). Hence, even temporary excursions of global mean temperature above 1.5 °C, with associated increases in the risks of extreme weather events, are relevant for policy makers.

Recent record breaking temperatures (Hu & Fedorov, 2017; Su et al., 2017) highlight the proximity of the 1.5 °C target, and the possibility that it could be exceeded at least temporarily in the near future. If this occurs, policy makers will require guidance regarding the amount of human-induced warming (Haustein et al., 2017) and how long temperatures will remain above the target. Here we develop predictions of the likelihood that global mean temperature will exceed 1.5 °C for different length periods in the coming 5 years. These provide advanced warning of impending risks as well as guidance on the likely duration of exceedance events.

In order to capture natural internal variability, climate predictions must be initialized with the observed state of the climate system. Decadal climate prediction systems have recently been developed for this purpose and have been shown to improve predictions of global mean temperature relative to uninitialized projections (Boer et al., 2013; Doblas-Reyes et al., 2013; Fyfe et al., 2011; Smith et al., 2007). Furthermore, many international forecast centers are now routinely producing and exchanging initialized decadal predictions in near real-time (Smith, Scaife, et al., 2013). We therefore use the multimodel ensemble of initialized real-time decadal climate predictions provided by this international activity to develop and evaluate predictions of the probability of temporarily exceeding 1.5 °C above preindustrial levels. The intention is that these forecast probabilities will be updated annually as new forecasts become available, and made available to policy makers as part of the World Climate Research Program (WCRP) Grand Challenge on Near Term Climate Prediction [https://www.wcrp-climate.org/grand-challenges/gc-near-term-climate-prediction].

2. Data and Methods

2.1. Observations

Observations of global mean near surface temperature are taken as the average of HadCRUT4 (Morice et al., 2012), NASA-GISS (Hansen et al., 2010), and NCDC (Karl et al., 2015). The Paris Agreement (UNFCCC, 2015) did not define the period to be used as the preindustrial reference, and different choices will affect whether the 1.5 °C threshold has been exceeded or not (Schurer et al., 2017; Visser et al., 2018). In common with other studies (Collins et al., 2013; Henley & King, 2017) we take a pragmatic approach (Hawkins et al., 2017) and use the period 1850 to 1900 to represent preindustrial conditions since earlier periods suffer from a lack of direct observations. Estimates of warming for the period 1850–1900 relative to earlier periods range from 0.0 to 0.2 °C (Hawkins et al., 2017; Schurer et al., 2017), which would increase our predicted chance of a temporary excursion over 1.5 °C.

2.2. Models

We analyze global mean surface temperatures from 9 state-of-the-art decadal climate prediction systems (Table 1), all of which have contributed to the international activity to exchange decadal predictions in near real-time that has been ongoing since 2010 (Smith, Scaife, et al., 2013). Decadal climate predictions include the same external forcings (greenhouse gases, anthropogenic and volcanic aerosols, changes in solar irradiance) as centennial timescale projections of climate change (Collins et al., 2013) but are additionally initialized with observations of the state of the climate system. In this way, they are able to predict

Table 1
Summary of Initialized Decadal Forecasts

Name	Institute	Hindcast and forecast start dates	Model and resolution[a] atmosphere (A) ocean(O)	Ensemble size	References
BSC	Barcelona Supercomputing Center, Spain	1st November: 1960, 1961, 1962, …, 2016	EC-Earth A: T255 L 62 O: nominal 1 L 46	5 (10 for the 2017 forecast)	Ménégoz et al. (2018), Doblas-Reyes et al. (2018)
CCCma	Canadian Centre for Climate Modelling and Analysis, Environment and Climate Change Canada	1st January: 1961, 1962, 1963, …, 2018	CanCM4 A: T63 L35 O: 1.4 × 0.9 L40	10	Kharin et al. (2012)
GFDL	Geophysical Fluid Dynamics Laboratory, USA	1st January: 1961, 1962, 1963, …, 2017	GFDL-CM2.1 A: 2.5 × 2.0 L24 O: nominal 1 L50	10	Yang et al. (2013)
MIROC5	University of Tokyo, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan	1st January: 1961, 1962, 1963, …, 2017	MIROC5 A:T85 L40 O:1.4 × 1.4 L50	9	Chikamoto et al. (2012), Mochizuki et al. (2012)
MOHC	Met Office Hadley Centre, UK	1st November: 1960, 1962, 1965, 1968, …, 2008, 2009, 2010, …, 2016	HadGEM3-GC2 A: 0.8 × 0.6 L85 O: 0.25 × 0.25 L75	10 (20 for 2016 forecast)	Dunstone et al. (2016), Sheen et al. (2017)
MPI	Max Planck Institute for Meteorology, Germany	1st January: 1961, 1962, 1963, …, 2017	MPI-ESM A: T63 L47 O: 1.5 × 1.5 L40	10	Pohlmann et al. (2013)
MRI	Meteorological Research Institute, Japan	1st January: 1961, 1966, 1971, …, 2011, 2012, 2013, …, 2017	MRI-CGCM3 A:1.125 × 1.125 L48 O: 1.0 × 0.46 L51	9	
NCAR	National Center for Atmospheric Research, USA	1st November: 1960, 1961, 1962, …, 2015	CESM1.1 A: 1.25 × 0.9 L30 O: nominal 1 L60	10	Yeager et al. (2018)
SMHI	Swedish Meteorological and Hydrological Institute, Sweden	1st January: 1992, 1993, 1994, …, 2009, 2016	EC-Earth A: T255 L 91 O: nominal 1 L 46	9	

[a] Degrees longitude × latitude, or spectral (T159 ≈ 1.125°), L vertical levels.

some aspects of unforced internal variability, and may also improve the simulated response to external forcings.

We assess the likely forecast skill by evaluating hindcasts (retrospective forecasts made using data that would have been available at the time) covering the historical period since 1960. The hindcast start dates for the different systems are given in Table 1, and all available data are used to assess skill. Because decadal forecasts and hindcasts are expensive to produce, especially with high resolution climate models, some systems only extend to 5 years ahead. We therefore restrict our analysis to the first 5 years of each hindcast and forecast for all systems. We also compare with uninitialized climate model simulations from the 5th Coupled Model Intercomparison Project (K. E. Taylor et al., 2012) to assess the impact of initialization. For this we obtained monthly mean global mean surface temperature from 38 models (documented in Appendix A of Hawkins & Sutton, 2016) driven by historical and RCP4.5 radiative forcings.

Because models are imperfect, initialized forecasts drift away from the observations toward the biased model state (Boer et al., 2016; Gangstø et al., 2013; Hermanson et al., 2017; Smith, Eade, et al., 2013). For each individual decadal prediction system, a lead-time dependent drift has therefore been diagnosed from the hindcasts and removed from each month of the initialized model data to produce anomalies relative to the period 1971 to 2000. Each uninitialized simulation is similarly converted into anomalies relative to its average of the period 1971 to 2000 for each month. For both initialized and uninitialized models, values relative to preindustrial conditions are then obtained by adding the observed difference of 0.41 °C between the periods 1971 to 2000 and 1850 to 1900.

We compute the probability of a month (or year) temporarily exceeding 1.5 °C above preindustrial conditions as the fraction of ensemble members that have at least one monthly (or yearly) mean during the 5-year forecast period that exceeds this threshold.

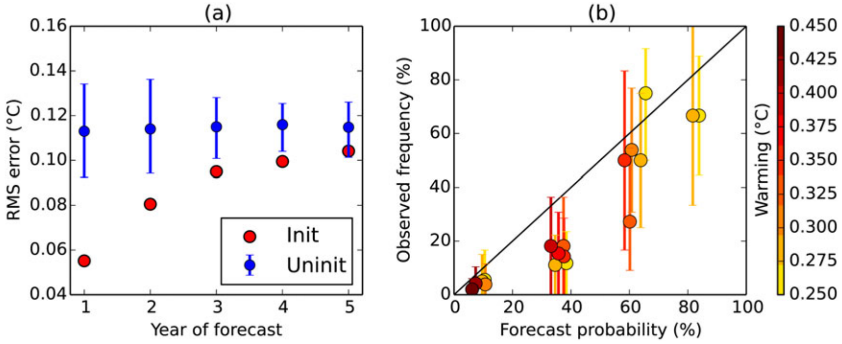

Figure 1. Evaluation of prediction skill and reliability. (a) RMSE as a function of forecast lead time for predictions of annual mean global average temperature. Initialized forecasts (red) are compared with uninitialized simulations (blue, with bars indicating the 5–95% confidence interval where differences could have occurred by chance). (b) Reliability of probabilistic forecasts for exceeding annual mean thresholds defined by increases ranging from 0.25 (yellow) to 0.45 °C (dark red) relative to the annual mean temperature preceding the forecast start date. Exceeding 1.5 °C requires an increase of 0.36 °C relative to the annual mean temperature in 2016. Results are from the initialized hindcasts (Table 1). Bars show the 5% to 95% range of uncertainties in the observed frequencies. RMSE = root-mean-squared error.

2.3. Forecast Quality Measures

We assess the deterministic and probabilistic skill of the forecasts using root-mean-square error (RMSE) and reliability (e.g., Jolliffe & Stephenson, 2003). To assess the impact of initialization we generate 5,000 random samples (with replacement) of the differences in RMSE between initialized and uninitialized hindcasts and compute their 5% to 95% range. Samples are taken in blocks of 3 years to allow for serial autocorrelation.

We cannot directly assess the reliability of forecasts of the probability of exceeding 1.5 °C because this event has not yet occurred in the observations. Instead, we assess the reliability of probabilistic forecasts for exceeding a range of thresholds defined by increases relative to the annual mean temperature preceding the forecast start date. We evaluate increases ranging from 0.25 to 0.45 °C, noting that exceeding 1.5 °C requires an increase of 0.36 °C relative to the annual mean temperature in 2016. Uncertainties in the observed frequencies of occurrence are estimated by computing the 5% to 95% range from 5,000 random samples (with replacement) of the observations. We plot the average of the forecast probabilities within each bin rather than the central bin value to reduce biases in the reliability diagram (Bröcker & Smith, 2007).

3. Results

A positive impact of initialization on the skill of predicting global mean surface temperature has been demonstrated in previous studies (Boer et al., 2013; Doblas-Reyes et al., 2013; Fyfe et al., 2011; Smith et al., 2007) and is reproduced in our results which show lower RMSE in initialized compared to uninitialized forecasts for all of the 5 years of the forecasts, with improvements significant at the 95% level in each of the first 4 years (Figure 1a). In addition, in the initialized ensemble, the forecast probability for exceeding a range of thresholds is generally consistent with the observed frequency of occurrence (Figure 1b). There is a suggestion that forecasts of medium probabilities (e.g., around 30% to 40%) may be slightly overconfident (i.e., forecast probabilities higher than observed frequencies). However, the uncertainties are large and intersect the diagonal (representing perfect reliability) for at least one of the thresholds for all of the probability bins. Overall, the hindcasts show that initialized forecasts are more accurate than uninitialized projections for the coming 5 years and provide reasonably reliable probabilities of exceeding warming thresholds.

Time series of rolling 5-year average global mean surface temperature for the observations along with the initialized and uninitialized hindcasts and forecasts are shown in Figure 2. Consistent with the lower RMSEs (Figure 1a), the initialized hindcasts are generally closer to the observations than are the uninitialized simulations. This is especially clear during the 1998 to 2012 slowdown in the rate of global surface temperature warming (e.g., Fyfe et al., 2016). However, although the initialized hindcasts are cooler than the uninitialized simulations during this period (also noted by Doblas-Reyes et al., 2013, and Guemas et al., 2013), their mean is warmer than the observations, although the observations lie well within the spread of the predictions. The differences between models and observations are caused by a combination of unpredicted internal

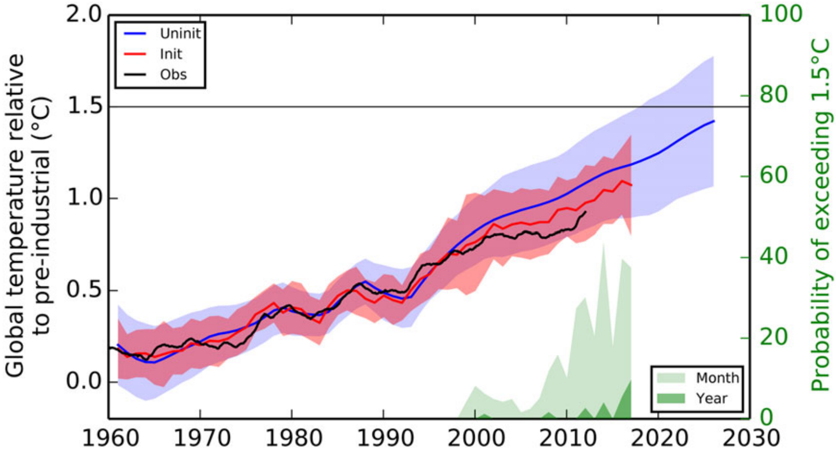

Figure 2. Predicted chance of temporarily exceeding 1.5 °C warming above preindustrial conditions. Time series of rolling 5-year average global mean surface temperature relative to preindustrial (left axis) in observations (black) compared to initialized forecasts (red, solid line showing the ensemble mean and shading the 5–95% ensemble range) and uninitialized simulations (blue, solid line showing the ensemble mean and shading the 5–95% ensemble range). Green shading shows the probability (right axis) from the initialized forecasts of temporarily exceeding 1.5 °C for at least 1 month (light green) and at least 1 year (dark green) during the 5-year forecast period. The date represents the start of each 5-year forecast period.

variability, forcings that are not included in the model simulations (e.g., the early 2000s volcanic eruptions, Santer et al., 2014), and imperfect simulations of external forcings (e.g., Fyfe et al., 2016; Smith et al., 2016). However, recent record breaking global temperatures suggest that the surface warming slowdown is now over (Hu & Fedorov, 2017; Su et al., 2017).

The hindcast and forecast probabilities of temporarily exceeding 1.5 °C are also shown in Figure 2 (green shading). Before 1998 there was virtually no chance that a month or year would exceed 1.5 °C, but the chance has been increasing over the last two decades. In the latest forecast the chances of a month, year, or 5 years exceeding 1.5 °C during the 5-year period 2017 to 2021 are 38%, 10%, and 0%, respectively. For comparison, the uninitialized projections yield probabilities of 89%, 50%, and 23%, respectively, for a month, year, and 5 years (not shown), but these are warmer than the initialized predictions and the observations in recent periods (Figure 2). The forecast probabilities are expected to increase in future: based on the current model trend of 0.2 °C per decade, it is more likely than not that a month will exceed 1.5 °C in the period 2020 to 2024.

It is well recognized that there are different pathways for global warming to reach the thresholds stated in the Paris Agreement (e.g., Goodwin et al., 2018). To investigate the different possible mechanisms through which the climate might temporarily exceed 1.5 °C, we show in Figure 3 the monthly patterns of near surface temperature at the time of maximum global temperature for every ensemble member that exceeds 1.5 °C in the latest forecast from the Met Office decadal prediction system (Met Office Hadley Centre, Table 1). It is well established that global mean temperature is increased by heat released from the tropical Pacific during the positive phase of the El Niño Southern Oscillation (ENSO; e.g., Lean & Rind, 2008; Trenberth et al., 2002). Hence, many of the months show a positive ENSO, characterized by an anomalously warm (cool) eastern (western) tropical Pacific. High global temperatures are also associated with a weakened Southern Annular Mode characterized by high mean sea level pressure (not shown) and high temperatures over Antarctica (Figure 3l), but this link may not be causal because a weaker Southern Annular Mode may itself be driven by ENSO (Fogt & Bromwich, 2006; L'Heureux & Thompson, 2006; Wang & Cai, 2013). Increased global temperatures are also associated with a warm Eurasia (Figure 3l) driven by a positive Arctic Oscillation (AO, not shown), consistent with similar links seen on decadal timescales (Delworth et al., 2016; Iles & Hegerl, 2017). This link is likely to be independent of ENSO which tends to promote a negative AO (e.g., Brönnimann et al., 2007; Ineson & Scaife, 2009). Analysis of CanCM4 provides similar results (not shown) although the link with a positive AO is less clear in this model. Overall, our results suggest that temporary excursions above 1.5 °C are associated with positive phases of ENSO and/or the AO. The first exceedances of 1.5 °C are therefore most likely to occur during the boreal winter and spring since both ENSO and the AO have the largest variance and impact in these seasons.

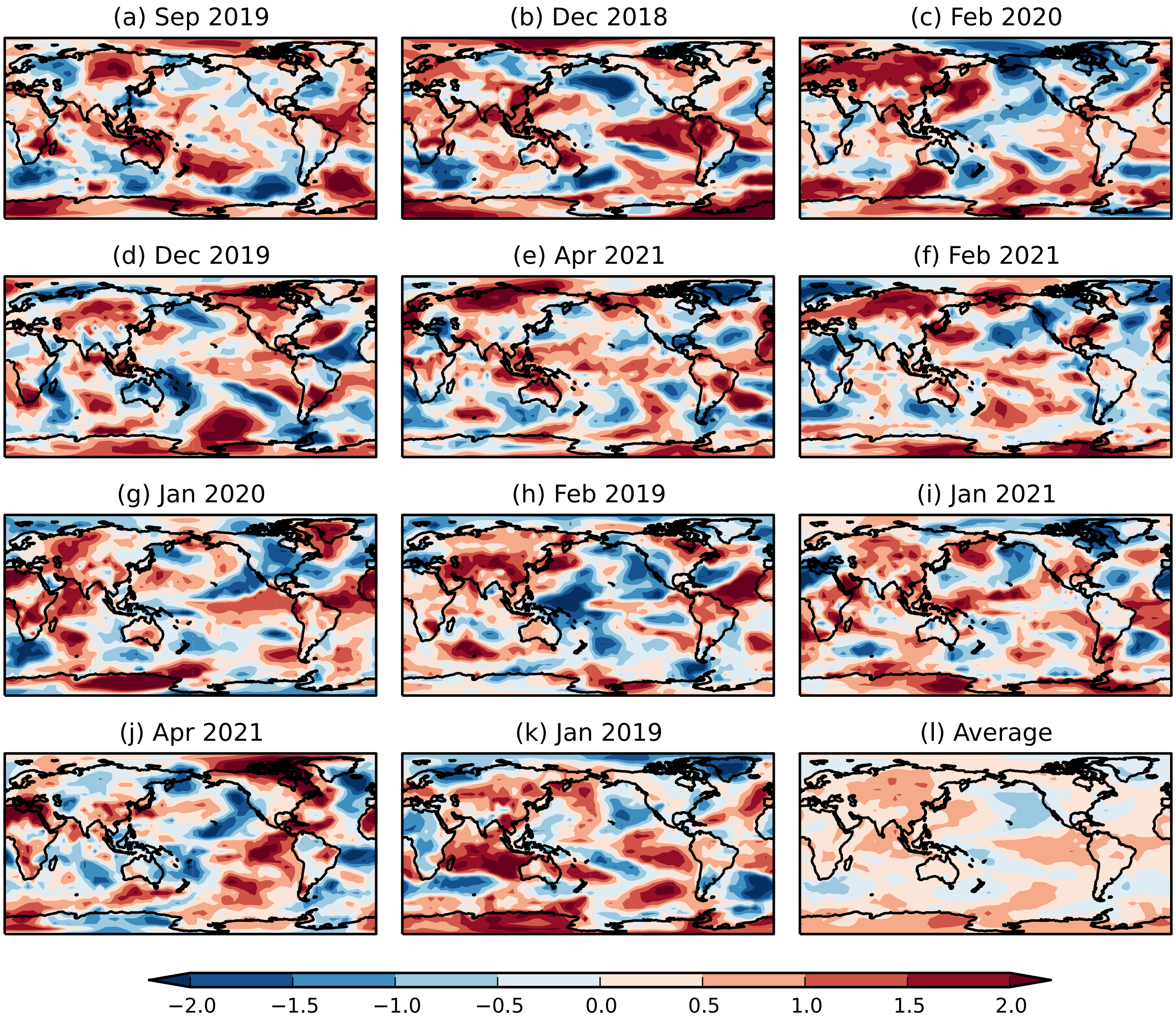

Figure 3. Patterns associated with temporarily exceeding 1.5 °C. (a)–(k) Monthly mean near surface temperature (plotted as standard deviations of the ensemble spread relative to the ensemble mean at each grid point) at the time of maximum global mean temperature for each Met Office Hadley Centre ensemble member that exceeds 1.5 °C in the period 2017 to 2021. The dates are indicated for each month, and their average is shown in the bottom right panel (l). Note that the same date (e.g. April 2021) can occur by chance in different ensemble members.

4. Conclusions

We have developed a new capability to predict the likelihood that global mean temperature will temporarily exceed 1.5 °C above preindustrial levels within the coming 5 years. The forecast utilizes an ongoing international activity to produce a multimodel ensemble of near real-time decadal climate predictions (Smith, Scaife, et al., 2013). In agreement with previous studies we found that these initialized decadal predictions provide more accurate forecasts of global mean temperature than uninitialized climate model projections. We also found that forecast probabilities of exceeding a range of thresholds are reasonably reliable.

For the 5-year period 2017 to 2021 our forecast indicates a 38% and 10% chance, respectively, that an individual month or year will exceed 1.5 °C, with virtually no chance of the 5-year mean being above the threshold. In contrast, the uninitialized model projections show much higher probabilities of 89%, 50%, and 23%, respectively, for a month, year, or the 5-year period. The lower probabilities from the initialized predictions are consistent with improved predictions during the slowdown in surface temperature warming in the early-2000s. However, we note that the initialized predictions were still warmer than observations during the slowdown period and may have also overestimated the probability of exceeding 1.5 °C. Whether this is predominantly caused simply by internal variability, or whether there are errors in forcings or simulated internal variability (e.g., Fyfe et al., 2016; Medhaug et al., 2017), or incorrect model responses to aerosols (Smith et al., 2016), is not fully resolved. Indeed, while decadal climate prediction systems improve near-term predictions compared to uninitialized projections, they do not avoid the need for a fuller understanding of short-term variations in forcings and responses. In particular, modeled circulation responses to several factors including volcanoes, ozone, and solar variability, may be too weak (Scaife & Smith, 2018), and the impacts of stratospheric water vapor (Solomon et al., 2010) on decadal climate are unresolved. The slowdown now appears to be over (Hu & Fedorov, 2017; Su et al., 2017) and our forecast probabilities could be too low in the event of accelerated warming caused either by an unpredicted reversal of internal variability or incorrectly simulated aerosol-induced changes. Conversely, a major volcanic eruption (which is unpredictable) would cool global temperature for several years and render our probabilities too high (Illing et al., 2018; Timmreck et al., 2016).

Our results suggest that temporary excursions above 1.5 °C are most likely caused by positive ENSO and/or AO events. Regional patterns of warming, and hence associated climate impacts, are therefore likely to be very different for temporary excursions than they would be if long-term global temperatures exceed 1.5 °C. In our predictions, short-term warming is also most likely to occur during the boreal winter and spring when ENSO and the AO have the largest variability.

We stress that a temporary excursions over 1.5 °C above preindustrial conditions would not necessarily constitute an exceedance of the Paris Agreement, which has been interpreted to refer to human-induced climate change over periods of at 30 years (Rogelj et al., 2017). Indeed, complying with the Paris Agreement is still achievable (Rogelj et al., 2018) and important, given the impact of further warming on Arctic Sea Ice (Jahn, 2018; Niederdrenk & Notz, 2018; Sigmond et al., 2018), Greenland, and West Antarctic ice sheets and sea level rise (Rasmussen et al., 2018), regional climate (Jacob et al., 2018; M. A. Taylor et al., 2018), and extremes (Dosio & Fischer, 2018; Li et al., 2018). The first temporary excursions above 1.5 °C, if they occur, would not necessarily lead to many of these effects but they would be an important indication of the proximity to the Paris threshold and could generate interest from the media and general public. Our forecasts will therefore be updated annually to provide advanced warning of the likelihood and duration of such events.

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