Weather and Climate Extremes 18 (2017) 55–64

Contents lists available at ScienceDirect

Weather and Climate Extremes

journal homepage: www.elsevier.com/locate/wace

Transient response of the global mean warming rate and its spatial variation

James S. Risbey[a,*], Michael R. Grose[a], Didier P. Monselesan[a], Terence J. O'Kane[a], Stephan Lewandowsky[a,b,c]

[a] *CSIRO Oceans & Atmosphere, Hobart, Australia*
[b] *University of Bristol, Bristol, UK*
[c] *University of Western Australia, Perth, Australia*

ARTICLE INFO

Keywords:
Climate variability
Climate projection
Transient response
Extreme warming

ABSTRACT

The Earth has warmed over the past century. The warming rate (amount of warming over a given period) varies in time and space. Observations show a recent increase in global mean warming rate, which is initially maintained in model projections, but which diverges substantially in future depending on the emissions scenario followed. Scenarios that stabilize forcing lead to much lower warming rates, as the rate depends on the change in forcing, not the amount. Warming rates vary spatially across the planet, but most areas show a shift toward higher warming rates in recent decades. The areal distribution of warming rates is also changing shape to include a longer tail in recent decades. Some areas of the planet are already experiencing extreme warming rates of about 1 °C/decade. The fat tail in areal distribution of warming rates is pronounced in model runs when the forcing and global mean warming rate is increasing, and indicates a climate state more prone to regime transitions. The area-proportion of the Earth displaying warming/cooling trends is shown to be directly related to the global mean warming rate, especially for trends of length 15 years and longer. Since the global mean warming rate depends on the forcing rate, the proportion of warming/cooling trend areas in future also depends critically on the choice of future forcing scenario.

1. Introduction

The Earth is undergoing long term warming in response to increases in greenhouse gas concentrations in the atmosphere (Houghton et al., 1990). The warming can be characterised by the total change or *amount* of warming from a base period (usually pre-industrial), and by the *rate* of change of warming over a specified interval of time. Both the *amount* and *rate* of warming are important variables for adaptation to climate change. This is because some species, ecosystems, crops, or sectors of the economy are sensitive to the actual temperature (and therefore amount of change), and some are sensitive to the rate of change because of the need to migrate or adapt to maintain similar environments as temperatures change (Thomas et al., 2004; Quintero and Wiens, 2013; Oppenheimer et al., 2014; Burke et al., 2015). So far there has been more attention in the climate community to quantifying the *amount* than *rate* of warming.

The rate of global mean surface warming (warming rate) has increased in the modern period (since about 1970) (Stocker et al., 2013; Lewandowsky et al., 2015; Hansen et al., 2012). The transient response of the climate system is not uniform in space or time (Schneider and Thompson, 1981). The global mean surface temperature (GMST) exhibits fluctuations in time, where some decades warm more rapidly than others (Houghton et al., 1990; Marotzke and Forster, 2015; Risbey, 2015). The processes responsible for variation in warming rate through time (on time scales shorter than the greenhouse response of many decades and longer) include natural internal variability of the coupled climate system and changes in external forcing associated with variable solar forcing and aerosol loading (Houghton et al., 1990). Such variations always occur and are evident in Fig. 1a throughout the instrumental record. This work addresses variations in the warming rate through time in observations and projections of the rate in models.

We also examine the degree to which the warming rate is uniformly expressed in space. There is considerable regional (spatial) heterogeneity in the warming (Hansen et al., 2012; Sutton et al., 2015). There are good reasons why all regions of the Earth do not warm at the same rate. These include:

Land/ocean contrast: It is well known that the oceans, with higher heat capacity and the ability to store heat, respond more sluggishly than the land regions (Schneider and Thompson, 1981).

---

[*] Corresponding author. CSIRO Oceans & Atmosphere, Box 1538, Hobart, Tas 7001, Australia.
E-mail address: james.risbey@csiro.au (J.S. Risbey).

https://doi.org/10.1016/j.wace.2017.11.002
Received 23 July 2016; Received in revised form 14 November 2017; Accepted 15 November 2017

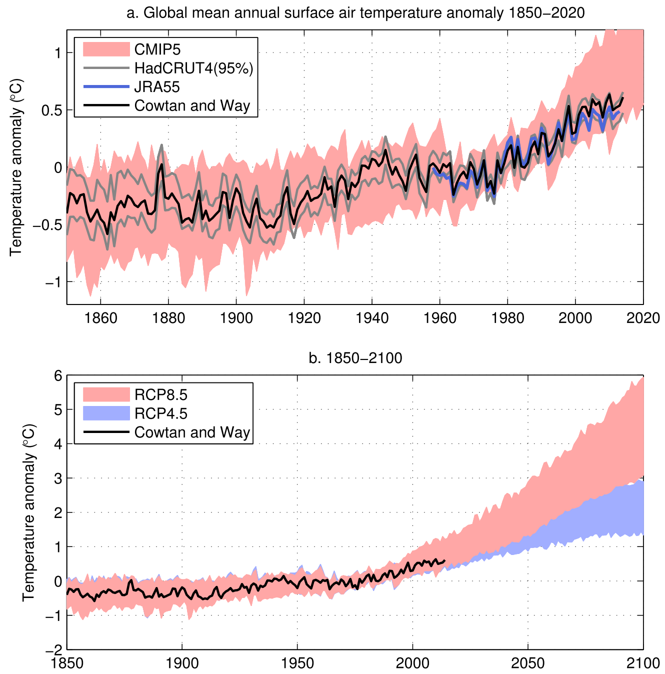

Fig. 1. Global mean surface temperature series a) for HadCRUT4 observations (grey), JRA55 reanalysis (blue), Cowtan and Way (black) and the 2.5–97.5 percentile distribution from the CMIP5 historical and RCP8.5 series; b) projections of GMST to 2100 for the CMIP5 2.5–97.5 percentile distribution in RCP4.5 (blue) and RCP8.5 (red), with Cowtan & Way observations (black).

Ocean circulation: Persistent ocean currents may keep some regions cooler or warmer than the average. Changes in ocean circulation will change the distribution of regions with different heating rates (Held, 1993).

Atmospheric circulation: Meridional (north-south) flows in the atmosphere are induced by persistent blocking modes (O'Kane et al., 2013, 2016). Changes in the locations of preferred blocking regions over decades can change warm/cold advection over a region, changing the local rate of warming.

Cryosphere response: Changes in the cryosphere in high latitudes through changes in albedo, sea ice, and meltwater can change the surface temperature, lapse rate, and meridional temperature gradient, which can induce local and larger scale changes in warming rate (Hansen and Takahashi, 1984; Held, 1993).

Heterogeneous radiative forcing: Atmospheric radiative forcing differs from one region to another due to differences in aerosol loading and distributions of some trace gases (Ramanathan et al., 1987; Ramaswamy et al., 2001).

Given the clear reasons for differences in regional warming rates, one should not expect all regions to warm together. Relevant questions are: what is the distribution of warming rates in space, and how much of the Earth is undergoing warming at any given point in time. The latter question is relevant to how strongly one can generalise regional expectations from the global mean (Grenier et al., 2015). If a region shows little or no warming, is that unusual and what does that imply in evaluating climate projections? (Grose et al., 2017). We do not explore specific regional responses here as that is done elsewhere (Grenier et al., 2015; Sutton et al., 2015; Grose et al., 2017).

2. Data and methods

A range of different data sets are used here to represent GMST. For instrumental data, we use HadCRUT4 (Morice et al., 2012); Cowtan and Way (2014), and GISTEMP (Hansen et al., 2010). In some cases we also compare this data with GMST from the NCEP-NCAR 20th century reanalysis (Compo et al., 2011) and the JRA55 reanalysis (Kobayashi et al., 2015). The reanalyses are used to provide gridded surface temperature, along with Cowtan & Way. Cowtan & Way is a conservative choice because it relies on HadSST3, which shows slower warming than the ERSSTv4 and COBE-SST version 2 reconstruction (Kent et al., 2017; Hausfather et al., 2017).

We calculate a number of diagnostics here based on spatial analyses of surface temperature in gridded surface temperature datasets. Our purposes are best served by a surface temperature dataset with fuller spatial coverage using optimal interpolation. Among the most complete datasets in this regard is Cowtan & Way, who have used a kriging method for optimal interpolation to provide gridded data back to 1850, from which we can do spatial analyses (calculate area proportions showing warming/cooling in given periods). While other surface temperature datasets also provide gridded data, they have not all provided the same focus on data coverage and interpolation procedures needed to minimise the consequences of missing data cells through the earlier part of the temperature record.

The sparser data in the earlier part of the temperature record is potentially an issue for the kinds of spatial analysis carried out here. To provide a measure of this uncertainty we have employed different datasets and different types of data in the analysis. For example, we repeated all analyses here with the 20th century reanalysis, which is a gridded product with full grids through the earlier period like Cowtan & Way. The 20th century reanalysis is perhaps regarded as a less reliable product for surface air temperature than dedicated instrumental products because it relies on model reanalysis with surface and atmospheric data. Despite this, the results for the 20th century reanalysis are qualitatively similar with relatively minor quantitative differences for the analyses presented here. This increases our confidence that the larger uncertainties in the earlier part of the record for the spatial analyses are probably not critical for the outcomes shown.

GMST is also taken from Coupled Model Intercomparison Project (CMIP5) models (Taylor et al., 2012) with one run per model generating a multi-model ensemble. Note that for the CMIP5 models we use surface air temperature to represent GMST, which is different from the observed GMST records that contain a blend of surface air temperatures over land and sea surface temperatures over ocean. Over the recent instrumental period, this introduces a slight underestimate of temperature changes in the observed GMST series (Cowtan et al., 2015).

The CMIP5 ensemble is typically represented here by a band covering the 2.5–97.5 percentile range of results. The CMIP5 ensemble runs span 1850–2100, with historical forcing for the period 1850–2005, and Representative Concentration Pathway (RCP) RCP2.6, RCP4.5, and RCP8.5 (Moss et al., 2010) forcing from 2006 to 2100. The number of model runs varies depending on the RCP used and is 22, 27, and 32 for RCP 2.6, 4.5, and 8.5 respectively. The profile of each of the RCP scenarios is shown in Fig. 2 and corresponds to a complete phase out of greenhouse gas emissions and an arrest in the forcing increase for RCP2.6, eventual reduction in greenhouse emissions and a stabilisation of forcing at a higher level for RCP4.5, and continued rise in greenhouse emissions and radiative forcing to much higher levels for RCP8.5.

The response of GMST to the RCP 4.5 and 8.5 forcings is shown in Fig. 1b for the period out to 2100. The response is fairly similar through about 2020, and then the RCP8.5 scenario exhibits faster warming. For the RCP4.5 scenario the forcing stabilizes (Fig. 2) and the rate of warming eventually decreases, as shown by the reduction in gradient of the blue envelope near the end of the series in Fig. 1b and in section 3.1. In some cases we wish to illustrate variability in the CMIP5 model runs more specifically than in the collective ensemble. In that case we use either the ACCESS1.0 model (Dix & coauthors, 2013) or the CCSM4 (Gent et al., 2011). The latter model includes an RCP2.6 run whereas the former does not.

A key metric assessed in this study is the area-proportion of the Earth that exhibits positive or negative warming trends over a specified period. Results are mostly displayed for negative trends (cooling area-