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To cite this article: I Mahlstein *et al* 2011 *Environ. Res. Lett.* **6** 034009

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Early onset of significant local warming in low latitude countries

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Received 31 March 2011

Accepted for publication 12 July 2011

Published 25 July 2011

Online at stacks.iop.org/ERL/6/034009

Abstract

The Earth is warming on average, and most of the global warming of the past half-century can very likely be attributed to human influence. But the climate in particular locations is much more variable, raising the question of where and when local changes could become perceptible enough to be obvious to people in the form of local warming that exceeds interannual variability; indeed only a few studies have addressed the significance of local signals relative to variability. It is well known that the largest total warming is expected to occur in high latitudes, but high latitudes are also subject to the largest variability, delaying the emergence of significant changes there. Here we show that due to the small temperature variability from one year to another, the earliest emergence of significant warming occurs in the summer season in low latitude countries ($\approx 25^\circ\text{S}$ – 25°N). We also show that a local warming signal that exceeds past variability is emerging at present, or will likely emerge in the next two decades, in many tropical countries. Further, for most countries worldwide, a mean global warming of 1°C is sufficient for a significant temperature change, which is less than the total warming projected for any economically plausible emission scenario. The most strongly affected countries emit small amounts of CO_2 per capita and have therefore contributed little to the changes in climate that they are beginning to experience.

Keywords: local detection

 Online supplementary data available from stacks.iop.org/ERL/6/034009/mmedia

1. Introduction

Detecting and attributing a climate change signal using the optimal fingerprinting method which includes signal to noise considerations globally and regionally (Barnett and Schlesinger 1987, Hegerl *et al* 1996, 1997, Santer *et al* 1995) has been done for a number of variables and on different regional scales (Stott and Tett 1998). Such studies have shown that attribution of surface warming is now possible not only on global but also on continental scales and few studies exist focusing on smaller scales (Stott *et al* 2000, Stott 2003, Gillett *et al* 2008, Zhang *et al* 2006), and improved approaches have allowed attribution not only of warming but

also of some other climate-related variables and impacts such as regional rainfall patterns and wildfires (Zhang *et al* 2007, Santer *et al* 2003, Gillett *et al* 2003). The anthropogenic trends are superimposed on natural fluctuations, and the ratio of the two depends on spatial and temporal scales. For example, while the largest anthropogenic warming is expected at high latitudes, the largest variability also occurs there. Here we use climate model output to approach the question of the emergence of significant anthropogenic climate changes from a local and scenario independent point of view in a manner that complements global attribution studies: taking account of spatial and temporal variability, we evaluate at what global temperature increase a particular place experiences a significantly different temperature regime compared to early 20th century conditions. Large-scale detection and attribution

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studies rely on regions with a high signal to noise ratio in order to detect an anthropogenic warming signal as early as possible (Hansen *et al* 1998, Baettig *et al* 2007, Giorgi and Bi 2009, Williams *et al* 2007, Barnett and Schlesinger 1987, Karoly and Wu 2005, Madden and Ramanathan 1980, Wigley and Jones 1981). For the first time we consider both the ‘noise’ of local variability and the ‘signal’ of global warming to specifically identify the locations and seasons where new temperature regimes emerge. We show that tropical regions display the earliest significant warming based on current models, broadly consistent with available data. Such an analysis is important not only for understanding how humans experience climate change in different locations, but also because a range of climate impacts (e.g. on ecosystems) can generally be expected to increase as climate changes exceed past variability. Ecoregions in the tropics are likely to be particularly vulnerable to anthropogenic climate change, as a smaller increase in temperature will lead to larger future extremes in tropical ecoregions based on an A1B scenario as shown by Beaumont *et al* (2011) and may lead to food insecurity (Battisti and Naylor 2009).

2. Results and discussion

Twenty-three atmosphere ocean general circulation models (AOGCM) are used in the analysis; only one run from each model is used, to avoid heavier weights for models that ran ensembles. As will be shown, a key focus is the low latitudes in the summer season. A subset of models was also chosen according to the quality of their ability to simulate tropical variability (see supplementary material available at stacks.iop.org/ERL/6/034009/mmedia). However, the results are not changed significantly by the selection of models (see supplementary material (available at stacks.iop.org/ERL/6/034009/mmedia) for a comparison of results from the two model sets) and therefore all results shown are based on all models available. The models are compared to gridded global observations for the period from 1900–99 from the NASA analysis (GISTEMP, see <http://data.giss.nasa.gov/gistemp/references.html> and section 3). Note that the results of GISTEMP are consistent with other observational datasets (see supplementary available at stacks.iop.org/ERL/6/034009/mmedia).

The noise of interannual variability and the signal of anthropogenic warming are calculated separately for each grid cell (all models are regridded to a common grid of T42). The spatial scale of a grid cell is small enough to detect local changes, because (unlike rainfall) regional temperature variations extend over areas bigger than a single grid cell (Mahlstein and Knutti 2010, Jones *et al* 1997). One measure of the noise in summer surface temperature (TAS) is the interannual summer variability, shown in the top panel of figure 1 (see section 3). Note that the left column of figure 1 shows the model results whereas the right column represents the observational data (which is gridded at a resolution of $2.8^\circ \times 2.8^\circ$). The summer (defined as the three warmest consecutive months during the time period 1900–50) signal of anthropogenic warming is indicated by the difference between

1990–99 and 1900–99, as shown in the middle panel of figure 1. Models indicate that the warming signal is more pronounced over land than ocean, and is stronger in the Northern high latitudes, the US and the subtropics. But the noise of interannual variability of surface temperature of the models is also highest in the higher latitude land areas and lowest in the tropics (panel (a)). Figure 1(c) indicates that many middle and high latitude places showing a strong absolute summer warming signal (including the high latitudes and much of the US) are characterized by a low warming to variability ratio, due to large local variability. During the winter season, variability is higher at middle and high latitudes, leading to lower warming to variability signals in nearly all regions despite higher warming; thus we focus here on summer. The low latitudes, with very low interannual variability, contain large areas where people live that show high warming to variability ratios (particularly in many coastal and island regions). A region of high warming to variability is also obtained in the data and models in some uninhabited or sparsely inhabited parts of the Southern Ocean. For annual average conditions, similar results to those of summer are obtained in the tropical regions, but the high latitudes show even lower warming to variability ratios (see supplementary material available at stacks.iop.org/ERL/6/034009/mmedia). The observed summer variability is broadly similar to that obtained in the models in many regions, with notable exceptions such as the behaviour obtained in Australia and southern Africa. Note that the observed local variability is smaller than that generally found in the models, as noted in previous studies (Gleckler *et al* 2008). Generally the patterns in the observations are less smooth than those obtained in the models, but this is not surprising since the observations provide only one realization, whereas the model results are based on more than twenty realizations. The warming to variability ratio of the models compares well with the observations over most regions with higher warming to variability ratios (greater than 1), although differences are seen over parts of the Atlantic, northern North America, and near the Antarctic Peninsula.

The results are robust across all models considered, the only exception being the northwest coast of South America (probably due to differences in how models represent the topography of the Andes). Note that the qualitative results are not sensitive to the time periods used in the 20th century. For example, the patterns do not change if data are restricted to the period after 1950 (see supplementary material available at stacks.iop.org/ERL/6/034009/mmedia).

The signal to noise ratio is an important parameter for climate impacts. For example, changes in climate in a location with large variability may have less severe impacts on those ecosystems and species that are adapted to large changes on short timescales (Williams *et al* 2007). In contrast, species with limited ability to adapt to environmental changes such as some tropical plants, insects, and reptiles (Deutsch *et al* 2008, Sinervo 2010) may be quite vulnerable to climate change. Changes in the mean temperature are relevant to ecosystems as many species show climate change impacts due to the warming trends of the past (Parmesan and Yohe 2003).

The increase in global temperature required for the signal of change to emerge from the noise can be estimated by

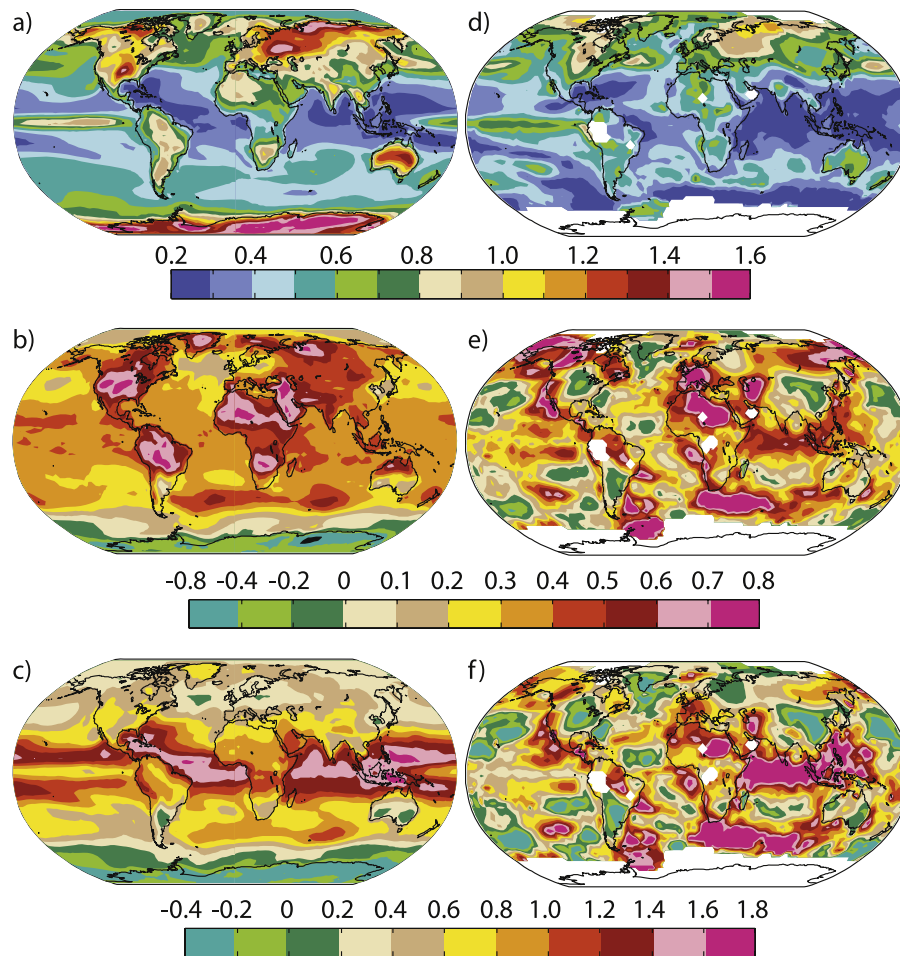


Figure 1. (a)–(c) are based on model results and show (a) interannual variability (noise) of summer average surface temperature (TAS) in °C, (b) signal of summer TAS trend (°C), calculated as the difference between 1990–99 and 1900–99, (c) warming to variability ratio of the summer trend to the summer variability. (d)–(f) are the same as (a)–(c) but for the observations (GISTEMP). Note that there are small regions outside the colour scale on (e) and (f).

comparing the TAS distributions of different time periods. Two samples of summer or warm season temperatures of two different time periods are significantly different when they do not originate from the same distribution at the 95% confidence level (see section 3 and supplementary material (available at stacks.iop.org/ERL/6/034009/mmedia) for three different statistical tests used, and the robustness of results among them). Figure 2 depicts the mean global temperature increases for which 80% of the models show a significant summer warming over different countries (see section 3). The pattern of the results is similar to the interannual warming to variability ratio shown in figure 1(c). During summer, a number of countries in the low latitudes (e.g. Indonesia, parts of the Middle East and Central America, and large parts of Africa) should already be experiencing significant changes based upon this analysis. These results are robust to how the interannual variability is characterized and to the rate of warming in models (see supplementary material available at stacks.iop.org/ERL/6/034009/mmedia). Figure 2 also demonstrates that for many locations worldwide, less than 1 °C global annual mean warming compared to 1900–29 is sufficient for local summer warming to exceed natural variability. A constant

composition or ‘commitment’ scenario (IPCC 2007) projects a global average warming of about 1.2 °C, but studies of economically plausible scenarios predict a warming of near 2 °C or more in the long-term (Rogelj *et al* 2010, Meinshausen *et al* 2009), which would cause significant summer changes worldwide. Thus, these results demonstrate that the globe is committed to significant local changes in summer TAS in all countries, with the earliest emergence occurring in tropical regions.

The question of whether a significant local warming has already been measured is complicated by the fact that many local high quality observational records extend only to about 1950. Data are also sparse in many tropical countries. Therefore, when working with limited observations the local detectability may only be achieved with a larger global warming as part of the signal is already included in the time series which is used for testing. If records are even shorter, this would further delay the point when changes can be identified as significant. However, the pattern of the results is not sensitive to changes in the baseline time period or the transient climate response of the scenario, nor is the pattern significantly changed when annual means are used instead of summer means

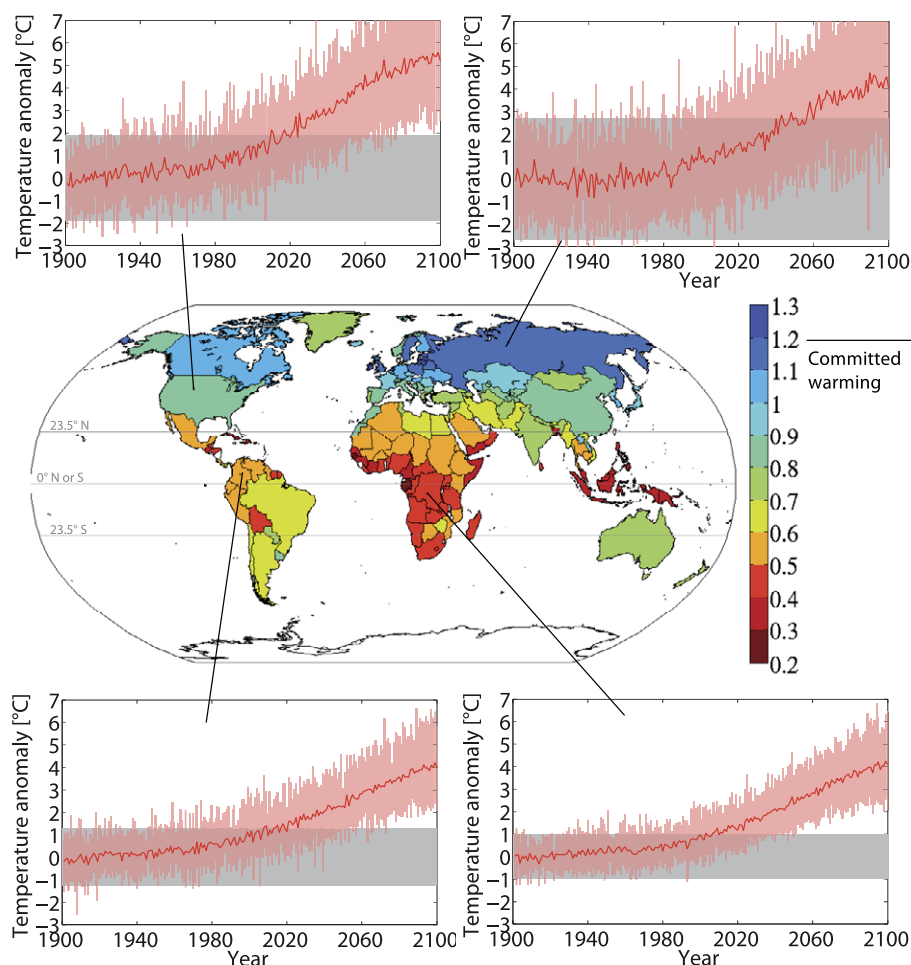


Figure 2. The map shows the global temperature increase (°C) needed for a single location to undergo a statistically significant change in average summer seasonal surface temperature (TAS), aggregated on a country level. The black line near the colour bar denotes the committed global average warming if all atmospheric constituents were fixed at year 2000 levels. The small panels show the interannual summer-season variability during the base period (1900–29) (± 2 standard deviations shaded in grey) and the multi-model mean summer temperature (red line) of one arbitrarily chosen grid cell within the specific country. The shading in red indicates the 5% and 95% quantiles across all model realizations.

(see supplementary material available at stacks.iop.org/ERL/6/034009/mmedia). One recent observational study (Collins 2011) suggests that significant changes are indeed emerging in parts of tropical Africa, especially in summer.

Figure 3 shows the warming to variability of the summer warming on an aggregated country level versus the emission per capita for the countries shown in figure 2. The striking result is that the two happen to be anti-correlated. Most of the countries showing the most significant changes at a small global warming have low CO₂ emissions per capita (http://www.iea.org/publications/free_new_Desc.asp?PUBS_ID=2143). In contrast, some of the largest emitters in the past and present are among the least affected countries thus far as measured by warming to variability. In short, those countries affected most by the warming are not the ones that are the most responsible for it (Schneider 2003). The fact that locally significant warming emerges first in countries with low emissions has no underlying economic or societal cause. To estimate the risks associated with climate changes, the local impacts, vulnerability and adaptive capacity need to be considered. It is frequently stated

that the low latitude countries are the most vulnerable due to limited financial resources and hence low adaptive capacity, but here we have documented a key aspect of tropical vulnerability that is physically based (rather than linked to the economical issues in these countries): the size of the warming signal relative to interannual noise.

3. Methods

3.1. Climate model data

The climate model data are available from the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project Phase 3 (CMIP3) (Meehl *et al* 2007). All data are regridded to a T42 grid, and for each model only the first run available in the CMIP3 archive is used for the analysis.

3.2. Observations

The gridded temperature data from the NASA analysis (GISTEMP, see Hansen *et al* 2006 and <http://data.giss.nasa>.

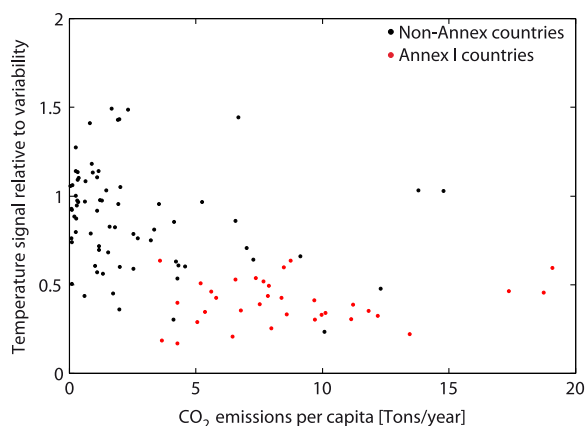


Figure 3. Warming to variability ratio (local summer temperature signal relative to interannual summer temperature variability) for each country versus CO₂ emissions per capita in year 2009.

gov/gistemp) are shown in figure 1. The data were gridded to T42 resolution using the provided Fortran program. Since GISTEMP only provides the anomalies, the summer season at each grid point was determined using the NCEP/NCAR reanalysis surface temperatures (Kalnay *et al* 1996) during 1950–60.

3.3. Interannual summer variability

The interannual summer variability is estimated by first linearly detrending the model and data values for the time period 1900–99. For each year the average summer TAS is then calculated and the standard deviation of the time series is obtained. The interannual variability is calculated individually for each model before averaging across models. Other approaches to quantifying variability do not change the basic conclusions (see supplementary material, especially figure S5, available at stacks.iop.org/ERL/6/034009/mmedia).

3.4. Significance tests

Whether temperatures of two time periods are significantly different is tested in several different ways. The primary test on summer TAS is applied using 30-year moving windows at 10-year steps, starting with 1900–29 as a baseline and ending in 2070–99 for the SRES A1B model runs. This procedure is applied to each model and grid cell. The results are not significantly different for different lengths of the moving window. The local warming is considered statistically significant (i.e. detected) when a Kolmogorov–Smirnov test rejects with 95% significance that the samples of the two 30-year windows are drawn from the same distribution. The last year of the moving window is taken as the year of emergence in one model. Changes are considered significant in the year when the signal is detected in 80% of the models. This procedure is done for each grid point. The year is then used to estimate the corresponding global temperature change based on the A1B simulation in each model. Figure 2 averages the global temperature threshold across countries for comparison with figure 3. Alternative statistical tests considered include

the Student t-test and a simple test which detects a significant change when the difference of the mean temperature of the two time windows exceeds twice the interannual variability. The results are not materially affected by the test applied (see supplementary material available online at stacks.iop.org/ERL/6/034009/mmedia).

Acknowledgments

We gratefully acknowledge the modelling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP's Working Group on Coupled Modelling (WGCM) for their roles in making available the WCRP CMIP3 multi-model dataset. Support of this dataset is provided by the Office of Science, US Department of Energy.

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