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Discrepancies of surface temperature trends in the CMIP5 simulations and observations on the global and regional scales

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Abstract

Using the fifth Coupled Model Intercomparison Project (CMIP5) model simulations and two observational datasets, the surface temperature trends and their discrepancies have been examined. The temporal-spatial characteristics for the surface temperature trends are discussed. Different from a constant estimated linear trend for the entire simulation period of 1850–2012, a dynamical trend using running linear least squares fitting with the moving 10 yr time windows are calculated. The results show that the CMIP5 model simulations are generally in good agreement with the observational measurements for the global scale warming, but the temperature trends depend on the temporal change and the regional differences. Generally, contrary to the small discrepancies on the global scale, the large discrepancies are observed in the south- and north-polar regions and other sub-regions.

1 Introduction

The fifth Coupled Model Intercomparison Project (CMIP5) provided quantitative datasets for estimating climate change based on a suite of climate models (Taylor et al., 2012). The new climate model products are considered predictions of future climate change, which relies heavily on how well the climate models simulate historical climate change. Each model's reliability impacts the credibility of that model's predictions. Consequently, evaluating climate model results using observational data sets is necessary to understand the capabilities and limitations of climate change simulations.

The surface temperature trends are a very important component to investigate for understanding the state of the global climate. The trends receive a great deal of attention in the climate change community (Hansen, 2001, 2010; Brohan et al., 2006; and many others), because these trends, anomalies, and variations provide evidence of global warming and the possibility of human influence on climate (Intergovernmental Panel on Climate Change, IPCC). However, based on previous studies, two questions have not yet been clearly answered, (1) one is how the temperature trends depend on temporal changes, and (2) another is how discrepancies in the different data sources influence the temperature trends, such as climate model simulations and the different kinds of observations.

Previous studies typically used the overall trends to assess the long-term behavior of temperature time series (Hansen, 1987; Mitchell et al., 2013; Xu and Powell, 2010, 2013; Powell et al., 2012). However, temperature trends change with time period and real time series are generally not well fitted by a straight line because climate may also change abruptly (Alley et al., 2003; Hare and Mantua, 2000). Therefore, the overall linear trend of a temperature time series may conceal some of the temporal characteristics of the temperature change, which is closely linked to changes in dynamic and radiative processes in the atmosphere. To better characterize the temporal change of temperature trends, the annual mean temperature time series are analyzed using the methodology of running linear least squares fits, which can reveal important features of the data, such as long term trends, localized changes and when an abrupt change occurred.

Recently, discrepancies between observations and climate model simulations in the tropical zone have sparked much research. Santer et al. (2005) investigated the altitude dependence of temperature trends in the tropical zone. They compared available observations with 19 of the IPCC CMIP3 models and suggested that any disparities between models and observations are due to residual errors in the observational datasets. From a study of several independent observational datasets, Douglass et al. (2004) confirmed that the disparity was real and arose mostly in the tropical zone. Douglass et al. (2007) examined tropospheric temperature trends based on 67 runs from 22 “Climate of the 20th Century” model simulations and found that the model simulated and observed temperature trends are in disagreement in most of the tropical troposphere. Also, Mitchell et al. (2013) found that the tropical temperature trends in the period of 1979–2008 are not consistent with observations throughout the depth of the troposphere, and this primarily stems from a poor simulation of the surface temperature trends. In this paper, we will investigate both the global and regional characterization of surface temperature trend discrepancies rather than concentrating on tropical zone. This characterization can provide a better understanding of the capabilities and limitations of the climate models in representing climate change on global and regional scales.

For this purpose, the CMIP5 model simulations and observations including HadCRUT4 and GISS reconstructed data sets are compared to characterize the global and regional surface temperature changes since 1850. The goal is to answer the above two questions about the temperature trends in the CMIP5 simulations and other observations. Section 2 describes the datasets and methodologies. The temporal analysis of different geographical regions and the spatial variation pattern of the global temperature trend are presented in Sect. 3. Section 4 provides a final summary and discussion.

2 Data and methodology

2.1 Observations

To assess the global surface mean temperature changes in the CMIP5 climate model simulations, two observational datasets have been used for comparison: (1) the new surface temperature data HadCRUT4 is created by the Met Office Hadley Centre and the Climatic Research Unit at the University of East Anglia (Jones, 1994; Brohan et al., 2006). (2) The new GISS analysis dataset is developed by the National Aeronautics and Space Administration's (NASA) Goddard Institute for Space Studies (GISS) (Hansen et al., 2001, 2010).

2.2 The CMIP5 model simulations

The sixteen (16) CMIP5 model simulations are selected from the 22 available groups' historical run in the IPCC Model archive at the Program for Climate Model Diagnosis and Intercomparison (PCMDI) (Taylor et al., 2012). The detailed information about the

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16 models can be found in the Table 1. The "historical" run is forced by observed atmospheric composition changes (reflecting both anthropogenic and natural sources) including time evolving land cover. Each of the 16 models have been run with multiple ensemble members with between one and nine simulations, and the ensemble mean is used here for each model.

Most of the CMIP5 model datasets spanned the period from 1850 through 2005 (Table 1). GISS begins in 1880 and HADCRUT4 begins in 1850, both of them end in 2012.

2.3 Running linear least square fitting

Running linear least square fitting (L'Heureux et al., 2013) is a form of linear least squares analysis, which is used to estimate the temperature trends with a moving 10 yr temporal window. Different from the traditional linear least squares fitting, in which the rate of trend is constant for the full study period, the running linear least squares fitting technique can provide more detailed information about the trend changes with time.

3 Temporal changes of surface temperature trends

3.1 Global scales

Figure 1 shows the running linear trends of surface temperature over the global (GL), Northern Hemisphere (NH), Southern Hemisphere (SH), Arctic (60–90° N), Antarctic (60–90° S) and the Tropics (20° S–20° N). The grey region shows the temperature trend range among the 16 CMIP5 simulations (minimum and maximum values are range borders). The supplementary figure (Fig. S1) shows the same data as in Fig. 1, but provides the time series of surface temperature averaged over each latitude and regions over land.

At the global scale (Fig. 1a), all the time series tend to capture the same broad features of the warming trends, especially in the two periods with long term persistence

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of warming in the periods of 1910–1940 and 1970–2010. These warming trends are observed in both the observations and all model simulations, which is similar to the analysis in previous studies (Thompson et al., 2008). It is clear that the model simulations have much better agreement with observations in the 40 yr after 1970, but the simulated model warming started around 10 yr earlier and ended 10 yr later than the observed warming during another period 40 yr before 1950. Of particular interest are the opposite trends found in the ~ 10 yr periods at about 1895, 1910, 1930 and 1950. In addition, more subtle differences indicate that almost all the models overestimated cooling in the observed record at around 1880 and 1965, and overestimated warming near 1998.

Apparently, the running temperature trends over the Northern Hemisphere (NH) show a similar temporal characteristic to the global mean in both the model simulations and observations (Fig. 1b). But these variations are quite different from the pattern in the Southern Hemisphere (SH) (Fig. 1c), in which the warming and cooling alternated with around a 20 yr periodic oscillation from 1875 to 1955 in the HadCRUT4 observations. Note that the model simulations did not show this feature. The results tell us that the simulations in the SH have worse temperature trend estimations than their counterparts in NH compared to the observations.

In the tropics, the temperature trends (Fig. 1d) show similar general trending with greater variability than shown as the global change. However, large trends are observed over both polar regions (Fig. 1e and f). It is clear that two extreme warming periods 1915–1925 and 1995–2005 appeared in the Arctic (Fig. 1e), and the warming trends in the Antarctic tend to decrease in the most recent 40 yr. This decrease is consistent with the opposing trends seen in the data between the NH and SH polar regions (Powell et al., 2013). In addition, big discrepancies can be found over the Antarctic before 1965.

It is obvious that the GISS observations (thick, red solid) shows good correspondence in the SH (Fig. 1c) and poor correspondence in the Antarctic (Fig. 1f), particularly prior to 1945.

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3.2 Regional scales

Figure 1g–n shows the running linear trends of surface temperature in 8 sub-regions over land. The 8 sub-regions are defined as follows: United States (US) (25–50° N, 70–125° W), East Asia (EA) (10–50° N, 75–150° E), Europe (EU) (35–60° N, 0–35° E); Russia (RU) (50–75° N, 35–160° E), Australia (AU) (10–40° S, 110–155° E), South America (SA) (55° S–10° N, 35–80° W), South Africa (SAF) (0–30° S, 10–40° E) and North Africa (NAF) (0–30° N, 10–40° E). Similar to the warming on the global scale, the second long term persistent period of warming occurred in 1970–2005 and is found over all 8 sub-regions. However, the trends exist with a significant difference over these sub-regions during the first long term period of persistent warming during the period of 1910–1940. For example, using the global scale warming starting in 1910 from the observational record, the temperature rise over EA, SA, AU and SAF are at the same time, but the temperature did not rise until 5 yr later over US and RU. The EU did not show any warming until 1930. It is worth noting that the different model simulations seem to provide a consistent result although there are differences when compared against the observational record.

3.3 Consistencies between simulations and observations

Based on above results, it is not hard to find that the consistencies between model simulations and observations depend on the global or regional scales. In order to measure those discrepancies, the correlations are calculated between the HadCRUT4 dataset and the models. The results are shown in Table 2, where the correlation coefficient exceeding the threshold value of 0.4 is colored with yellow, it indicates that 16 % or more of the variance in the datasets is explained by the correlation, and satisfies the statistical significant test at the 99 % confidence level. From Table 2, one can see the correlation of the running trend time series between HadCRUT4 and GISS have a higher correlation coefficient except for the Antarctic zone, which reflects the strong consistency for the global and regional surface temperature change in the two observational datasets (GISS and HadCRUT4). Using the HadCRUT4 dataset, the correlations were computed with the 16 CMIP5 model simulations. The results (Table 2) show that the correlations are sharply reduced from global to all sub-regions; the correlation coefficients vary greatly from one region to another region. Approximately 75 % of the model simulations achieved a relatively high correlation with observations at the global scale. It is also found that the NH correlation coefficient is higher than the SH, tropic and both polar regions. This means that the CMIP5 models have much better performance in the NH (excluding the polar region) than their counterparts in the other areas. In addition, the relatively higher global correlation is mainly due to the NH contribution. Note that the Antarctic is the worst region and may be due to the sparse surface observations, the higher elevations in Antarctica and other factors identified in the literature.

For the sub-regions, the correlation coefficient in East Asia is highest of all 8 regions, where there are also 75 % of model simulations exceeding statistical significance test at 99 % confidence level. At the middle-high latitudes, such as Russia, Europe, South America, the model simulations have a relatively poor correlation with the other low-middle latitude regions.

It is not difficult to find that the correlations vary dramatically from one region to another region. The correlation analysis demonstrated that the CMIP5 simulations performance in the NH is better than SH, the Arctic better than the Antarctic, and the low-middle region better than middle-high regions. An interesting fact is all CMIP5 models and observations show better consistency at global scale than the regional scale.

3.4 Discrepancies in the simulations

In order to quantify the discrepancies in the CMIP5 simulations, the ensemble spread is to represent the discrepancies based on the standard deviation among the 16 selected models. The averaged spreads for the period of 1860–2005 derived from those model simulations are shown in Fig. 2. There are substantial variations at the global and regional scales. The trend spread changes from $\sim 0.1\,\mathrm{K\,decade^{-1}}$ at the global scales to $\sim 0.3\,\mathrm{K\,decade^{-1}}$ (or larger) at the regional scales. Both polar regions and

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two high latitude regions including Russia and Europe show a large spread exceeding 0.25 K decade^{-1}, the value is double the amount of spread in the global mean and most other regions. The larger spread of the trend among the simulations reflects the influence of the different climate model systems on climate change estimates. Interestingly, the Southern Hemisphere and tropical latitudes are found to have poor correlations with observations (Table 2), but their spreads among the 16 CMIP5 models show a comparatively small value. In other words, the high consistency among the model simulations in the SH or tropics cannot represent good performance for estimating climate change, because there are the large discrepancies with the observations. The poor correlation with observations and the large spread among the model simulations observed in the polar regions and high latitude regions remind us that the CMIP5 simulations have serious issues over the these areas.

4 Summary and discussion

4.1 Summary

Based on the HadCRUT4 and NASA GISS surface temperature observations, the trends and discrepancies in CMIP5 model simulations have been examined. The results are summarized as follows:

On the temporal variation of the global temperature trends during the period 1850–2012, most of the CMIP5 model simulations captured the two long term persistent warming periods of 1910–1940 and 1970–2005. All 16 of the selected CMIP5 models and observations showed high consistency in the second warming period at both global and regional scales.

On the regional variation of the temperature trends, the CMIP5 model simulations reproduced a common feature with global surface warming, but the trends displayed a significant discrepancy from one region to another region. The simulated warming rate is generally higher than the observations, particularly in the Arctic zone. And, some

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models show a strong cooling trend near 1905 and 1965, which exhibits an opposing result to the observations.

Generally, the temperature trends and spread show marked changes with region. The CMIP5 simulations overestimated the global warming compared to HadCRUT4 observations and remarkably overestimated the warming in the Arctic zone. The results show that most of the regions' spreads remain small, except the Antarctic, Arctic, Europe and Russia. The large spread shows that CMIP5 models have poor consistency in the polar regions and high latitudes.

4.2 Discussion

According to above analysis, it is worth noting that all selected CMIP5 model simulations showed high consistency with observations at the global scale. Generally, NH's consistency is better than SH, and the sub-regions at the low-middle latitudes are better than the regions at the mid-high latitudes. A rather surprising result is that the NH correlation coefficient is remarkably higher than SH, which shows the relatively higher global correlation is mainly due to NH contribution.

Also the largest spread among models appears in the polar regions and high latitudes, which shows that CMIP5 models have poor consistency in these regions. The results give us to consider an important question: why is the consistency between model and observation better at low and middle latitudes in NH? It may have something to do with the spatial coverage of the measuring stations, because most of the meteorological stations are mainly located at low-middle latitudes on the land in the Northern Hemisphere (Brohan, 2006; Hansen, 1987). Thus, the high spatial distribution of observation stations in the NH provides a better result than that in the SH and the high latitudes.

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Supplementary material related to this article is available online at http://www.clim-past-discuss.net/9/6161/2013/cpd-9-6161-2013-supplement.pdf.

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Table 1. The CMIP5/IPCC data sets and selected information.

IPCC I.D.	Model	Center and location	Forcing	Time period
HadCM3	land-surface/vegetation, ocean, atmosphere	Met Office Hadley Centre	GHG, Oz, SA, SI, VI	1860–2005
HadGEM2-AO	atmosphere; sea ice; land atm	Met Office Hadley Centre	Nat, Ant, GHG, SA, Oz, LU, SI, VI, SS, Ds, BC, MD, OC’	1860–2005
HadGEM2-ES	Atmosphere, ocean, land-surface/vegetation, tropospheric chemistry, ocean biogeochemistry	Met Office Hadley Centre	GHG, SA, Oz, LU, SI, VI, BC, OC	1860–2005
MIROC-ESM	atmosphere; ocean; sea ice; land; aerosols; ocean-biogeochemistry; land-biogeochemistry	Japan Agency for Marine-Earth Science and Technology	GHG, SA, Oz, LU, SI, VI, MD, BC, OC	1850–2005
MIROC5	atmosphere; ocean; sea ice; land	The University of Tokyo, Japan National Institute for Environmental Studies and Japan Agency for Marine-Earth Science and Technology	GHG, SA, Oz, LU, SI, VI, SS, Ds, BC, MD, OC	1850–2012
Bcc-Csm1	atmosphere; ocean; sea ice; land	Beijing Climate Center, China Meteorological Administration	’Nat Ant GHG SD Oz SI VI SS Ds BC OC	1850–2012
CESM1-CAM5-1-FV2	atmosphere; ocean; sea ice; land	National Science Foundation, Department of Energy, National Center for Atmospheric Research	GHG, SA, SI, VI, BC, OC	1850–2005
CNRM-CM5	atmosphere; ocean; sea ice; land	Centre National de Recherches Meteorologiques/Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique	GHG, SA, SI, VI, BC, OC	1850–2005
GFDL-CM3 GFDL-ESM2G	atmosphere; ocean; sea ice; land, iceberge	Geophysical Fluid Dynamics Laboratory	GHG, SA, Oz, LU, SI, VI, SS, BC, MD, OC	1860–2005
GISS-E2-H GISS-E2-R	atmosphere; ocean; sea ice; land surface	NASA Goddard Institute for Space Studies	GHG, LU, SI, VI, BC, OC, SA, Oz	1850–2005
MPI-ESM-LR MPI-ESM-P	atmosphere; ocean; sea ice; land, marine	Max Planck Institute for Meteorology	GHG Oz SD SI VI LU	1850–2005
MRI-CGCM3	atmosphere; ocean; sea ice; land; aerosols	MRI (Meteorological Research Institute, Tsukuba, Japan)	GHG, SA, Oz, LU, SI, VI, BC, OC	1850–2005
IPSL-CM5A-LR	ocean, ocnBgchem, seaice, atmos	Institut Pierre-Simon Laplace	Nat, Ant, GHG, SA, Oz, LU, SS, Ds, BC, MD, OC, AA	1850–2005

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Table 2. Correlation of the running linear trend between HadCRUT4 data set and the CMIP5 models and the NASA-GISS (italics indicate a correlation coefficient above 0.4, representing the significant test at 99 % confidence level; bold indicates a negative correlation.

	GL	NH	SH	Tropics	Arctic	Antarctic	US	SA	AU	RU	NAF	SAF	EU	EA
CESM1	0.37	*0.47*	0.13	0.19	0.29	0.18	0.38	0.04	0.27	0.10	*0.49*	0.32	0.37	0.28
CGCM3	0.31	0.25	0.29	0.14	0.18	0.24	0.26	0.07	0.28	0.05	0.33	*0.41*	0.09	0.35
CNRMCM5	*0.55*	*0.57*	0.39	0.22	*0.46*	*0.40*	*0.43*	0.09	0.37	0.25	*0.43*	*0.42*	0.21	*0.40*
GISSE2H	*0.51*	*0.66*	*0.40*	0.22	0.35	0.19	*0.47*	0.08	0.38	0.14	*0.44*	0.36	0.38	*0.56*
GISSE2R	*0.51*	*0.62*	0.34	0.23	0.29	0.34	*0.49*	0.14	0.38	0.20	*0.43*	0.38	*0.45*	*0.60*
IPSL	*0.47*	*0.54*	0.38	0.21	0.29	0.31	*0.43*	0.03	0.24	0.04	*0.41*	0.33	0.15	*0.59*
MIROCESM	0.36	*0.55*	0.33	0.17	*0.44*	**−0.22**	0.36	0.26	0.15	0.29	0.39	0.28	0.38	*0.54*
MPIESMP	*0.47*	*0.50*	*0.40*	0.32	**−0.02**	0.22	0.35	0.13	*0.44*	**−0.12**	0.26	0.18	0.11	*0.45*
MPIESM	*0.41*	*0.48*	0.20	0.26	0.20	**−0.16**	0.20	0.15	0.32	0.26	*0.48*	0.39	0.22	*0.50*
GFDLCM3	*0.47*	*0.60*	0.31	0.14	*0.46*	0.02	*0.48*	0.05	0.04	0.19	0.38	0.30	0.35	*0.54*
GFDLESM2G	*0.46*	0.37	0.37	0.23	0.26	0.06	0.27	0.11	0.32	0.10	0.33	0.27	0.11	0.32
HadCM3	*0.47*	*0.57*	0.34	0.21	0.39	0.31	0.30	0.18	0.22	0.35	0.35	*0.41*	0.29	*0.55*
HadGEM2AO	*0.49*	*0.66*	0.23	0.18	0.23	**−0.03**	*0.42*	**−0.11**	0.37	0.21	0.30	0.35	0.23	0.34
HadGEM2ES	*0.44*	*0.51*	*0.42*	0.19	0.38	0.03	0.30	0.09	0.27	*0.43*	*0.49*	*0.43*	0.21	*0.50*
MIROC5	0.33	*0.61*	0.24	**−0.02**	*0.40*	**−0.08**	*0.42*	**−0.13**	**−0.13**	0.16	0.34	0.16	*0.43*	*0.42*
bcccsm1	*0.49*	*0.56*	0.21	0.24	0.24	**−0.11**	0.20	0.18	0.29	0.27	*0.50*	*0.46*	0.35	*0.46*
GISS	*0.94*	*0.93*	*0.84*	*0.97*	*0.92*	*0.59*	*0.88*	*0.92*	*0.89*	*0.9697*	*0.92*	*0.93*	*0.96*	*0.93*

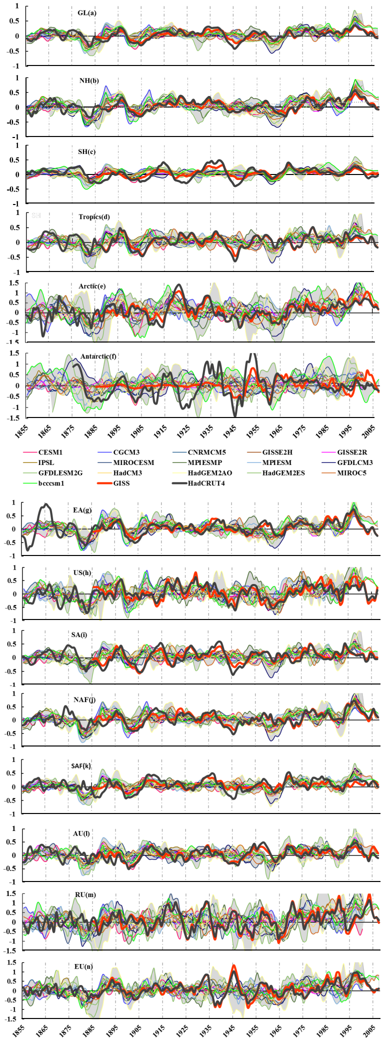

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Fig. 1. Running linear trends for 10 yr moving time window from 1850 to 2012 (the period is 1850–2005 for most CMIP5 simulations) over the global and sub-regions. Grey shading represents the trends range from minimum to maximum in 16 selected CMIP5 models. The x-axis shows the middle year of the 10 yr window, for example, 1855 denotes the trend in the period of 1850–1859. United States (US) (25–50° N, 70–125° W), East Asia (EA) (10–50° N, 75–150° E), Europe (EU) (35–60° N, 0–35° E); Russia (RU) (50–75° N, 35–160° E), Australia (AU) (10–40° S, 110–155° E), South America (SA) (55° S–10° N, 35–80° W), South Africa (SAF) (0–30° S, 10–40° E) and North Africa (NAF) (0–30° N, 10–40° E).

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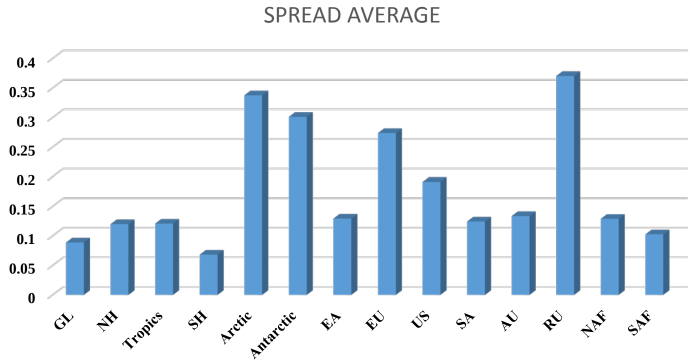

Fig. 2. Average spread of the temperature trend by region in the CMIP5 model simulations from 1860–2012.

CPD
9, 6161–6178, 2013