# Radiative forced enhanced semi-arid warming in cold season over East Asia

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## Abstract

As the climate change occurred over East Asia since 1950s, intense interest and debate have arisen concerning the contribution of human activities to the warming observed in previous decades. In this study, we investigate regional surface temperature change using a recently developed methodology that can successfully identify and separate the dynamically induced temperature (DIT) and radiatively forced temperature (RFT) changes in raw surface air temperature (SAT) data. For regional averages, DIT and RFT make 43.7 and 56.3% contributions to the SAT over East Asia, respectively. The DIT changes dominate the SAT decadal variability and are mainly determined by internal climate variability, such as the North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), and Atlantic Multi-decadal Oscillation (AMO). The radiatively forced SAT changes made major contribution to the global-scale warming trend and the regional-scale enhanced semi-arid warming (ESAW). Such enhanced warming is also found in radiatively forced daily maximum and minimum SAT. The long-term global-mean SAT warming trend is mainly related to radiative forcing produced by global well-mixed greenhouse gases. The regional anthropogenic radiative forcing, however, caused the enhanced warming in the semi-arid region, which may be closely associated with local human activities. Finally, the relationship between global warming hiatus and regional enhanced warming is discussed.

## 1 Introduction

Asia is arguably the most sensitive area to climate change, because it comprises almost 39% of the world’s land area (White and Nackoney, 2003; Huang et al., 2013) and supports four billion people, which accounts for 66.67% of the world population. A great portion of its drylands showed a most significantly enhanced warming in the boreal cold season over mid-to high-latitude areas (Huang et al., 2012). The regional environment change has a close relationship with local population density and economic development level. Jiang and Hardee (2011) found that economic growth technological changes and population growth are the main elements in anthropogenic effects on emission, which cannot be simulated easily by numerical models (Zhou et al., 2010). More recently, there are some studies on understanding the implications of population growth, worker structure and economic intensity for various scenarios of environmental change. The anthropogenic heating resulting from energy consumption has a significant continental-scale warming effect in mid-to high-latitudes in winter based on model simulations (Zhang et al., 2013). The rapid industrialization, urbanization, population growth, and other anthropogenic activities occurred in East Asia.

In the previous studies, dynamic effects induced by greenhouse gases (GHGs) have been proposed to interpret the rapid warming over continents and non-uniformity of local warming distribution (Wallace et al., 2012). The dynamic factors exhibit their influences on surface temperature changes in terms of circulation changes, such as the North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), Atlantic Multi-decadal Oscillation (AMO). Guan et al. (2015) found that the dynamically induced temperature and radiatively forced temperature had opposite contributions to the surface air temperature (SAT) during the process of hiatus over the Northern Hemisphere. Most of the obvious patterns occurred over mid-to high-latitudes where they are known as places having the earliest warming (Ji et al., 2014) and a phenomenon of enhanced warming over semi-arid region (enhanced semi-arid warming, ESAW) (Huang et al., 2012). The ESAW was proposed to be caused by various factors, including changes of atmospheric circulations, sea surface temperature, interaction between land and atmosphere, feedback from snow, and so on (Hu and Gao, 1994; Zhang et al., 2001; Huang et al., 2008; Guan et al., 2009; He et al., 2014). But the roles of different factors in the process of ESAW have not been confirmed.

In this study, the roles of different factors in the process of ESAW will be investigated using a recently developed methodology that can successfully identify and separate the dynamically induced temperature (DIT) and radiatively forced temperature (RFT) changes in the raw temperature data. Section 2 introduces the datasets used in this study. Section 3 provides detailed description of the dynamical adjustment method. Section 4 shows enhanced warming in semi-arid regions and the behaviors of DIT and RFT over different regions of East Asia. It analyzes the variability of DIT and the effects of major natural factors that dominate the dynamic temperature change, and shows the change of RFT. Section 5 lists all the main findings, followed by some discussion.

## 2 Datasets and study area

This study uses monthly precipitation, monthly mean temperature, monthly daily maximum and minimum temperature from the land-only TS3.21 dataset obtained from the Climate Research Unit at the University of East Anglia (Mitchell and Jones, 2005). The data cover the period of 1901-2012 with a high spatial resolution of 0.5°×0.5°. The regionally-average temperature trend of region *k* is calculated using

$$\overline{T}_k = \frac{\sum_{i=1}^{N_k} w_{ki} \times T_{ki}}{\sum_{i=1}^{N_k} w_{ki}} \qquad (1)$$

where $N_k$ is the number of grids in region *k*, $T_{ki}$ is the temperature of grid *i* in region *k*, and $W_{ki} = \cos(\theta_i \times \pi / 180)$, with $\theta_i$ is the latitude of the grid *i*. The temperature trend of region k is calculated by least square method based on the time series of $\overline{T}_k$.

The contribution of RFT (DIT) to raw temperature is calculated as formula (2)

$$CR = \frac{1}{n} \sum_{i=1}^{n} (\tilde{T}_i^2 / T_i^2) \times 100\% \qquad (2)$$

Where n is the number of years of temperature dataset, $\tilde{T}_i$ is the radiatively forced temperature or dynamically induced temperature of year $i$, $T_i$ is the raw temperature of year $i$.

The study area is between 20°N and 53°N, and between 73°E and 150°E, which comprises much of East Asia. The distribution of 30-yr averaged annual precipitation from 1961-1990 (Fig. 1) illustrates most of semi-arid region (annual precipitation between 200-600 mmyr$^{-1}$) located in the northeast, and most of arid region is in the northwest area. It exhibits a generally increase pattern of annual precipitation from Northwest to Southeast. The wet regions are most distributed in the South area. Although precipitation is related to surface temperature, the long-term mean precipitation is the simplest index for classifying climate regions (Huang et al., 2012).

## 3 Dynamical adjustment methodology

The dynamical adjustment method was first proposed by Wallace et al. (2012) and used to analyze non-uniformity of spatial warming over the Northern Hemisphere. The SAT, or the raw temperature data is divided into two parts by the dynamical adjustment method: DIT and RFT. Wallace et al. (2012) claimed the dynamical adjustment method can remove the dynamic component of the SAT induced by atmospheric circulation pattern from the raw SAT in the cold season (November-March) over land areas poleward of 20°N.

The dynamical adjustment methodology used in this study has been improved by Smoliak et al., (2015). The exact process of partial least square (PLS) is to derive monthly dynamical adjustment of Northern Hemisphere land surface temperature field in a pointwise manner, namely, temperature time series of each grid point is a predictand. The data of sea level pressure (SLP) are standardized, and the temperature time series are standardized and high pass filtered prior to carrying out the following dynamical adjustment steps: (1) correlate the grid-point temperature time series with its corresponding SLP to generate a one-point cross-correlation map; (2) project the monthly SLP field onto the correlation pattern, weight each grid point by the cosine of its latitude to obtain the first PLS predictor time series Z1; (3) regress this PLS predictor Z1 out of both the each grid-point temperature time series and its SLP predictor field using conventional least square fitting procedures, which can obtain a residual temperature time series and residual SLP field. Repeat these steps on the residual temperature time series and residual SLP field to obtain the respective PLS predictor Z2 and Z3, ..., Zn, which are mutually orthogonal. In our study, the improved dynamical adjustment methodology (Smoliak et al., 2015) has been applied to the temperature dataset and three predictors are retained, which are determined by cross-validation.

Following the process stated above, the components associated with changes of atmospheric circulation patterns that are expressed in terms of SLP are partitioned, and referred to as DIT variability. The rest is the residual part associated with radiatively forced factors, called the RFT. The RFT is considered as a result of build-up of GHGs, stratospheric ozone depletion, volcanic eruption, aerosol emission, local anthropogenic forcing, and so on. For semi-arid region of East Asia we are interested in, non-radiative factors resulting from thermodynamic processes is also a part of RFT. As their proportion are small over the semi-arid regions, its effects in RFT are ignored in this study. Therefore, we can use the dynamical adjustment method to identify the roles of DIT and RFT in the process of enhanced warming.

## 4 Results analysis

Figure 2 compares the variation of cold season-mean SAT of raw, dynamically and radiatively forced temperatures over East Asia in the period of 1902-2011. The curves exhibit a warming trend in the past century as a whole and an obvious warming from the 1970s to the 1990s. Then, the raw temperature change (black line) appeared a stoppage since about 2000 until now. The DIT (blue line) exhibits obvious decadal variability, with a relatively warming period from the 1970s to the 1990s and an obvious cooling period from 2000 to 2011 in the cold season. The RFT (red line) shows a rapid increasing rate since the late 1970s, which is consistent with the raw temperature data. The different evolutions of DIT and RFT indicate that the time series of DIT and RFT had different roles in the process of raw temperature variability.

Figure 3 shows the spatial distribution of raw, DIT and RFT trends over East Asia in the period of 1902-2011. Figure 3a exhibits a gradually increasing warming pattern from south to north and a strong warming trend located over northern East Asia, especially in Mongolia and Northeast China. The rate of warming was less than 0.005$^{o}$C/year in the south of 40$^{o}$N, with a small scale of cooling region over the southwest. The distribution of DIT trend (Fig. 3b) shows a basic warming background of East Asia. The warming rate over most areas was less than 0.01$^{o}$C/year, with a higher value in the northern part than in the southern part as a whole, and a cooling scale was located in the Northeast of East Asia. The distribution of RFT trend (Fig. 3c) exhibits a similar distribution as that of the raw temperature. It shows an obvious warming over the northern area, which reached 0.025$^{o}$C/year in some regions. A larger scale of cooling located in the southern region demonstrates that the cooling in the raw temperature was due to the radiative factors. The difference of DIT trend distribution from RFT indicates that the influence of radiative forcing on regional temperature changes is much higher than dynamic factor.

The discrepancy of distributions between DIT and RFT trends demonstrates the roles of DIT and RFT were different. Figure 4 gives the distributions of contributions of DIT and RFT to the raw temperature in the cold season over East Asia in the period of 1902-2011. It exhibits quite different locations of high contribution for DIT and RFT. The dynamic contribution to the raw temperature change (Fig. 4a) has high values over the northwest and along the coastal area of Southeast China, but the peak value is much less than its radiative value. In the spatial distribution of RFT contribution (Fig. 4b), the positive centres were located over the northeast and southwest areas, and the values were much higher than those in Fig. 4a. The difference between Fig. 4a and Fig. 4b illustrated the regional temperature is mainly contributed by RFT. This regional discrepancy is confirmed by the contributions of DIT (blue line) and RFT (red line) to the raw temperature as a function of annual precipitation in the cold season over East Asia (Fig. 5). Figure 5 shows that the RFT made a greater contribution than the DIT over the whole region. The contribution of RFT increased as the annual precipitation increased. Opposite to the radiative contribution, the dynamical contribution decreased with the increase of annual precipitation.

According to Huang et al. (2012), the enhanced warming occurred over the semi-arid regions. Figure 6 provides the long-term trends of DIT and RFT as a function of annual-mean precipitation. It illustrates that the RFT had a major contribution to the regional variation and showed a similar curve as the raw temperature over different regions. Both the raw data and RFT reached the peak in the area of 300-400 mmyr$^{-1}$. The fact that the peaks of temperature trend of both raw data and RFT occurred over semi-arid regions indicates that the radiative factors had dominated roles in the process of enhanced warming over the semi-arid regions. However, the DIT trend did not show obvious difference over different areas. It kept a mean rate of 0.005$^{o}$C/year, which is far away from the 0.017$^{o}$C/year of the highest value in the drylands of the RFT trend. The greater warming rate in semi-arid region appeared in both raw temperature and RFT indicated that enhanced warming occurred in drylands is mainly leaded by RFT. It improves the understanding of the ESAW (Huang et al., 2012), and suggests that role of radiative forced part in the process of warming East Asia.

These results are not limited to the monthly-mean temperatures, the daily minimum and maximum temperatures expressed different variability of DIT and RFT as well. Figure 7 shows the distributions of raw, dynamically induced and radiatively forced daily minimum temperature trends over East Asia in the period of 1902-2011. The raw daily minimum temperature illustrates a similar distribution as the raw monthly-mean temperature, with a stronger warming trend over northern East Asia, especially over Mongolia and Northeast China. The dynamically induced daily minimum temperature (Fig. 7b) shows a warming pattern over most areas, with a small cooling in the area along the Northeast China. The RFT trend (Fig. 7c) had an obvious warming over the northern area, with a smaller cooling over South China than in the monthly-mean temperature.

Figure 8 is the distributions of raw, dynamically and radiatively of daily maximum temperature trends over East Asia in the period of 1902-2011. The raw daily maximum temperature trend (Fig. 8a) had a warming trend over Northern East Asia, especially over Mongolia. But the warming extent was apparently less than that in the daily minimum temperature. The cooling in the southern part was larger than that in the daily minimum temperature. The dynamically induced daily maximum temperature (Fig. 8b) shows a slight warming over most areas, with a cooling located in the area along of Northeast China. The RFT trend (Fig. 8c) had an obvious warming over the northern area, with a small cooling scale over South China, which is similar with the raw daily minimum temperature. But the scale of cooling area was much larger than the radiatively forced daily minimum temperature in Fig. 7c.

In order to distinguish the regionally-averaged temperature changes, the daily minimum and maximum of raw, DIT and RFT as a function of annual-mean precipitation are shown in Fig. 9 and Fig. 10, respectively. The daily minimum (Fig. 9) had a higher warming rate than the daily maximum (Fig. 10) over different regions, especially in the drylands. The peaks of RFT over the drylands in both daily minimum and maximum temperatures indicate the dominated roles of radiative effects in the regional warming. But, the DIT trend did not show a similar variability over different area in both daily minimum and maximum temperatures. The higher values of RFT of both daily minimum and maximum temperatures in the drylands emphasize the major roles of RFT in the local enhanced warming process.

The DIT was mainly dominated by major dynamic factors, such as the NAO (Li et al., 2013), PDO (Trenberth and Hurrell, 1994; Kosaka and Xie, 2013) and AMO (Wyatt et al., 2012; Wyatt and Curry, 2014). The correlation coefficients between DIT and NAO/PDO/AMO (Fig. 11) illustrate the influences of these dynamic factors. Figure 11a shows the distribution of the correlation coefficient between the NAO and the DIT. It exhibits positive patterns cover most of the East Asia area, with a 95% confidence level over Mongolia, Inner Mongolia and Northeast China; and negative patterns over India and Southwest China, with a 95% confidence level. It suggests the strong positive influence of the NAO on the DIT over the northern area and the negative effect over the southwest of East Asia. Figure 11b is the correlation coefficient between PDO and DIT. Only the negative correlation coefficients over boundary of China and India pass the confidence level of 95%. In South China and North China, there were positive and negative patterns, respectively. Meanwhile, the negative correlative coefficient of AMO index and DIT (Fig. 11c) covered the most area of East Asia, except for a small positive region in the southwest of East Asia. The general spatial distribution is opposite with the distribution of the NAO.

The RFT variability is always considered as a result of GHGs, but more climate effects of aerosols were revealed in the recent decades (Li et al., 2011). The fast industrialization process over East Asia produced more anthropogenic GHGs and aerosols, and impacted the local climate change (Qian et al., 2009, 2011). The temperature of Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2012) is always marked with its correspondence to the concentration of the GHGs. In order to manifest the effects of GHGs in RFT, a comparison between RFT and a 20-model ensemble mean of CMIP5 simulations (Table 1) over the East Asia is plotted (Fig. 12), which shows that the time series of the CMIP5 simulations are smoother than the observed SAT curve. But, the notable consistent exists between RFT and simulated SAT in the warming period from the 1970s to the late 1990. The consistent curve of RFT and CMIP5 indicated the simulation reflect radiative part of raw temperature.

The distributions of correlation coefficients of DIT and RFT with simulated temperature of CMIP5 are expressed in Fig. 13. Figure 13a exhibits a negative pattern over most of the area except for the boundary between Northwest China and Russia and southwest. But in Fig. 13b, the correlation coefficient of RFT with CMIP5 ensemble mean temperature has a positive pattern over most of China, which passes the 95% confidence level, excluding the northeast of China and Mongolia. It indicates the temperature of CMIP5 has a closer relationship with RFT than DIT, namely, CMIP5 models reflect part of raw temperatures. The high positive correlation coefficient between RFT and ensemble mean of CMIP5 indicates the radiatively forced influence take a major proportion in simulated temperature change. The ensemble mean temperature trend as a function of annual precipitation (Fig. 14) highlights the regional RFT over the drylands (Fig. 6). It illustrates that the enhanced warming over the semi-arid regions led by the RFT does not appear in the ensemble mean temperature, which demonstrates the CMIP5 simulations prefer a uniform temperature change over all the regions. The significant difference between RFT and simulated temperatures over the drylands indicates that the enhanced warming over semi-arid region was not mainly related to radiative forcing produced in models, such as GHGS, land cover change, aerosol and so on. It is more related with regional factors not totally considered in the models.

## 5 Summary and discussion

Our results suggest that the enhanced warming in the drylands was induced by the RFT. The DIT and RFT extracted from the raw temperature had different contributions in the process of temperature change. For the regionally averaged values, the DIT and RFT contributed 43.7 and 56.3% to the SAT over East Asia, respectively. The DIT that was dominated by the NAO, PDO and AMO was on decadal time scales. The RFT changes were the major contributions to the global-scale warming trend and the regional-scale enhanced warming in the semi-arid regions. Previous studies (Guan et al., 2015) pointed out the well mixed GHGs took a continuous warming effect over globe in the radiatively forced temperature change. The local processes dominated the enhanced warming in the semi-arid regions. These possible local processes have been listed in Fig. 15.

The regional RFT was mainly induced by the interaction among atmosphere, land surface, snow/ice and frozen ground cover change, and regional human activities. For example, the drying of sandy or rocky soil by higher temperatures would increase surface albedo, reflecting more solar radiation back to the space. And the substantially declining of snow/ice and frozen ground change in the past 30 years, particularly from early spring through summer (Zhai and Zhou, 1997) may cause the surface temperature to increase in the cold season via the influence on albedo. The thickness of seasonally frozen ground has decreased in response to winter warming (Lemke et al., 2007), which will emit more CO2 into the atmosphere. The net radiation in the semiarid regions will become a radiation sink of heat relative to the surrounding regions. Besides, Multiza et al. (2010) found that local anthropogenic dust aerosols associated with human activities (Huang et al., 2015) such as agriculture and industrial activity accounted for 43 % of the total dust burden in the atmosphere. The radiatively forced effect of aerosol maybe another key process in enhanced warming of semi-arid area. More investigations are needed to quantify the contribution of different local process.

Our results also well explained the co-existence of regional warming and hiatus of the Northern Hemisphere. The major interpretation of the warming trend slowdown (WTS) claimed that natural variability played an important role in global temperature variability (Easterling and Wehner, 2009; Wyatt et al., 2012, Wyatt and Curry, 2014; Kosaka and Xie, 2013). The RFT had a warming contribution offset the cooling effect of DIT, and result in hiatus over the Northern Hemisphere (Guan et al., 2015). According to the results of our study, the RFT had made a major contribution to global warming, where the most obvious warming appeared in the drylands. And we conclude that the long-term global-mean SAT warming trend was mainly related to the radiative forcing produced by the global, well mixed GHGs. But, the regional anthropogenic radiative forcing caused the enhanced warming in the semi-arid regions. Therefore, the hiatus as a phenomenon of global scale was not in conflict with the regionally enhanced warming in the semi-arid regions.

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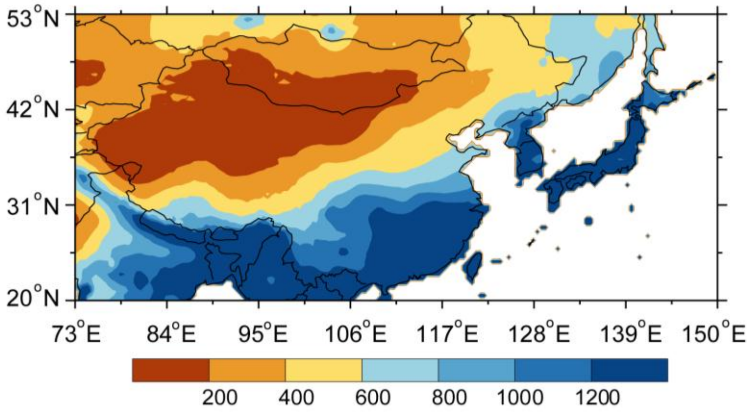

**Figure 1.** Spatial distribution of annual mean precipitation from 1961-1990 (mmyr$^{-1}$)

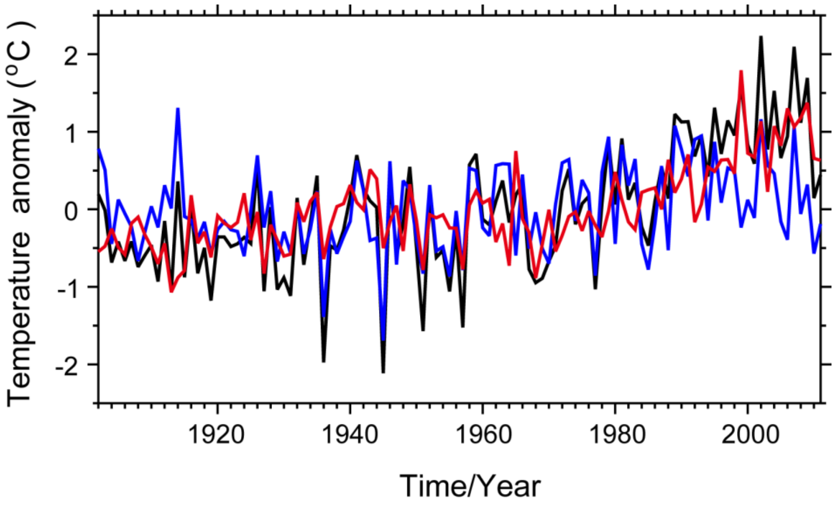

**Figure 2.** Time series of regionally averaged temperature anomalies of raw (black), dynamically induced (blue) and radiatively forced (red) temperatures in the cold season (November to March) from 1902 to 2011 over East Asia.

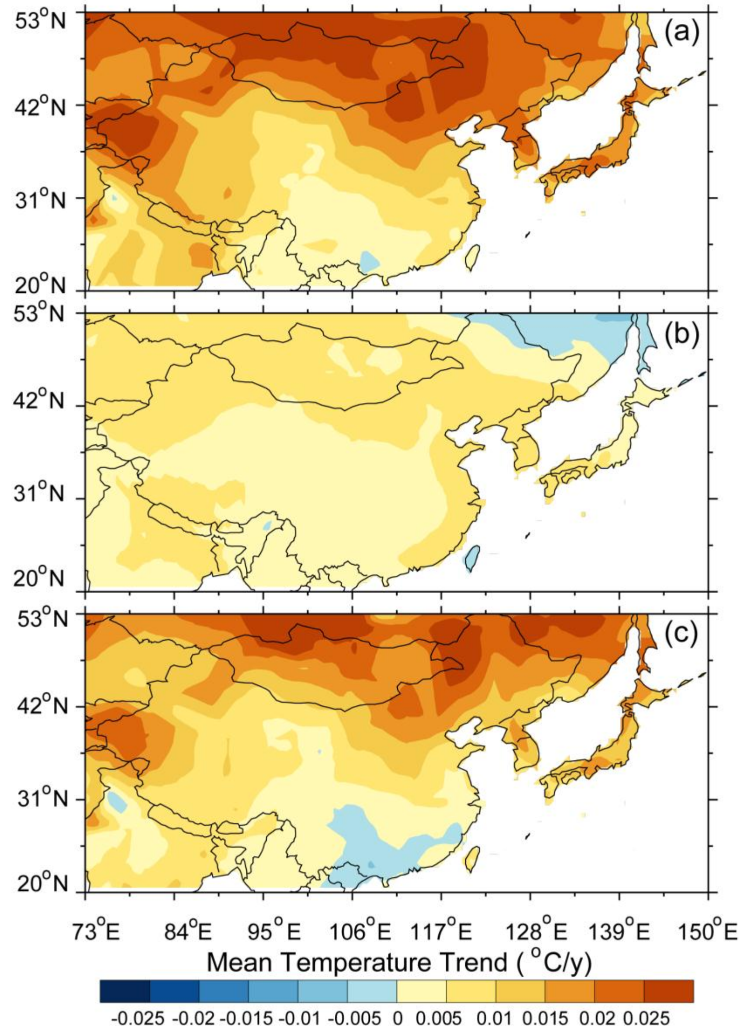

**Figure 3.** Spatial distribution of trend of raw (a), dynamically induced (b) and radiatively forced (c) temperatures in the cold season from 1902 to 2011 over East Asia.

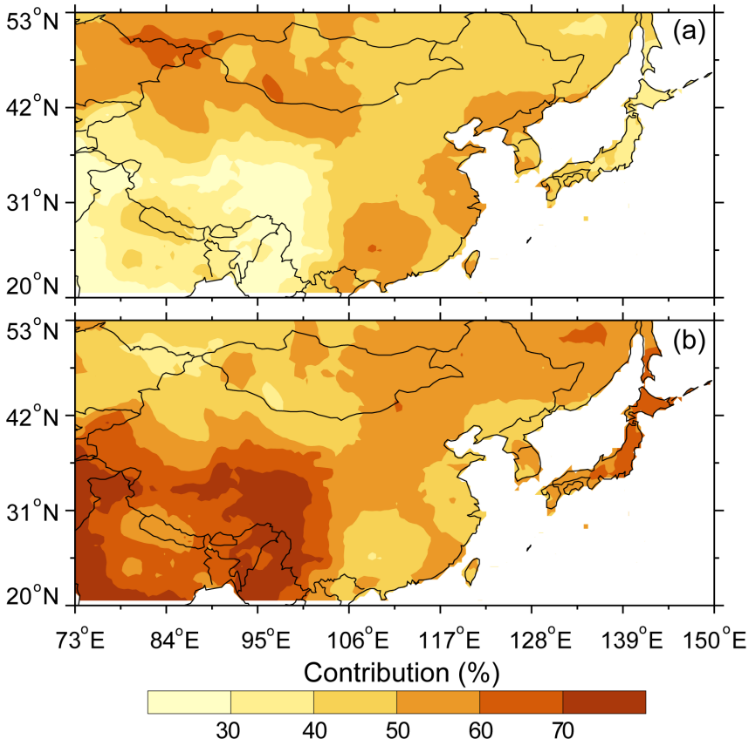

**Figure 4.** Spatial distribution of contribution of dynamically induced (a) and radiatively forced (b) temperatures to raw temperature in the cold season from 1902 to 2011 over East Asia.

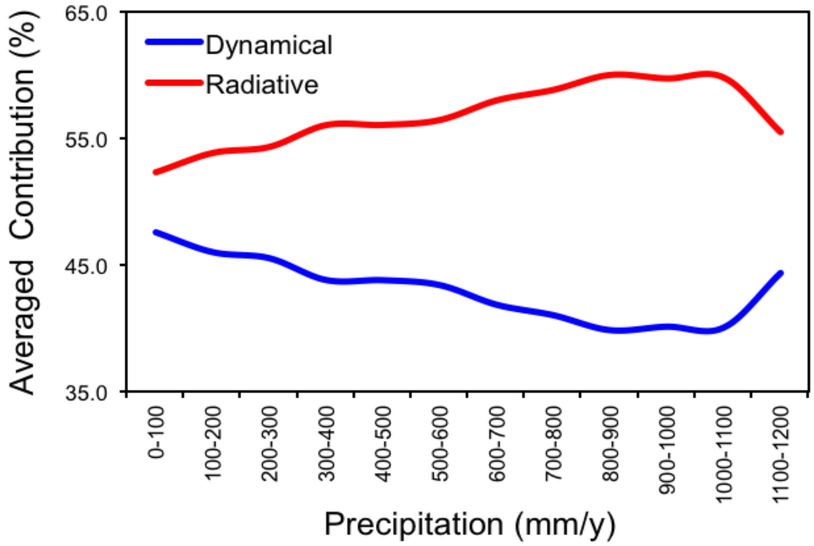

**Figure 5.** Contributions of dynamically induced (blue) and radiatively forced (red) temperatures to the raw temperature as a function of annual precipitation in the cold season from 1902 to 2011 over East Asia.

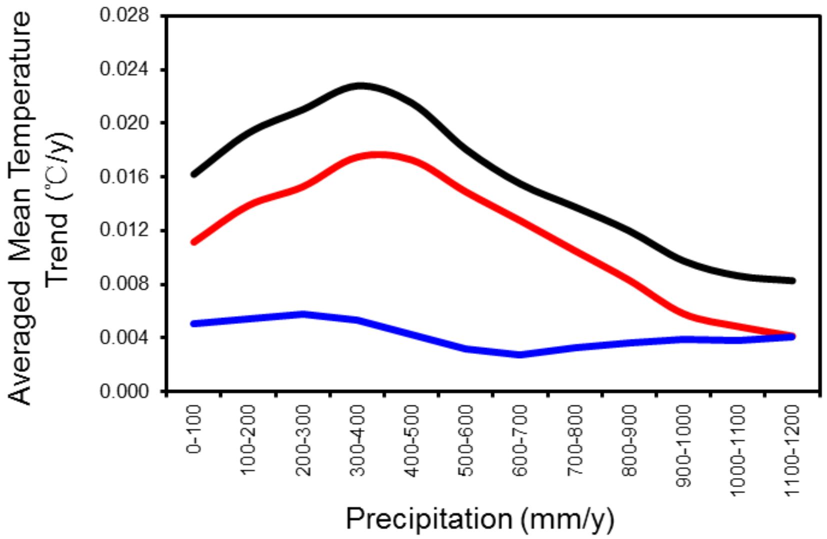

**Figure 6.** Regionally averaged temperature trend as a function of annual precipitation for raw (black), dynamically induced (blue) and radiatively forced (red) temperatures in the cold season from 1902 to 2011 over East Asia.

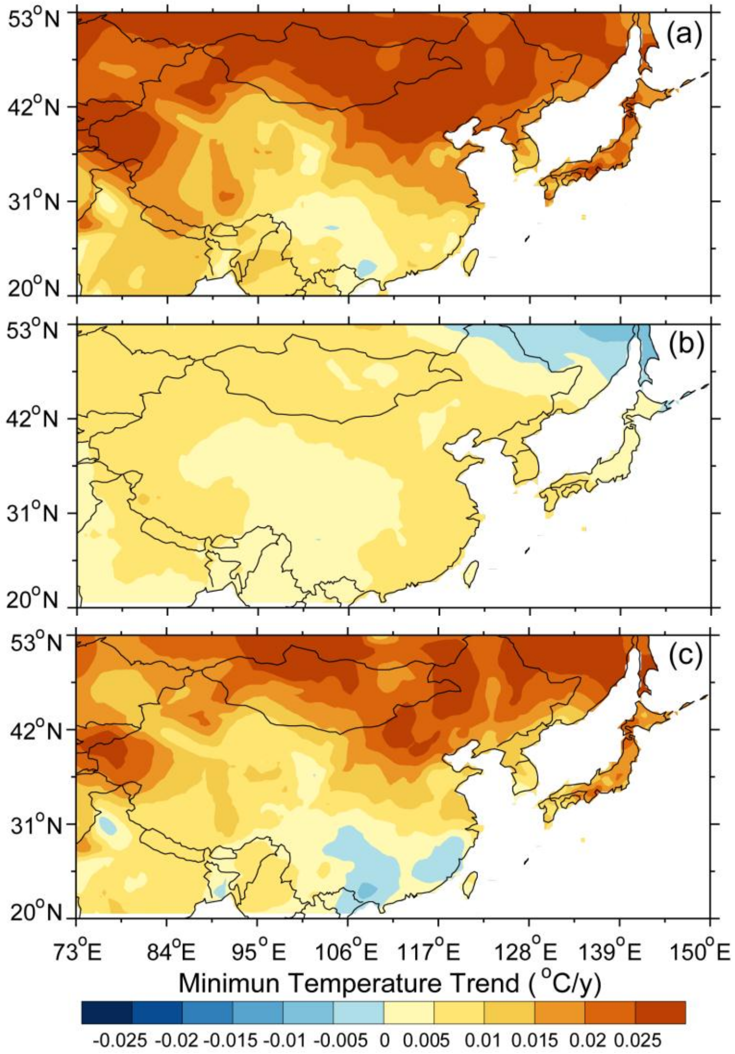

**Figure 7.** Same as Fig. 3, except for daily minimum temperatures.

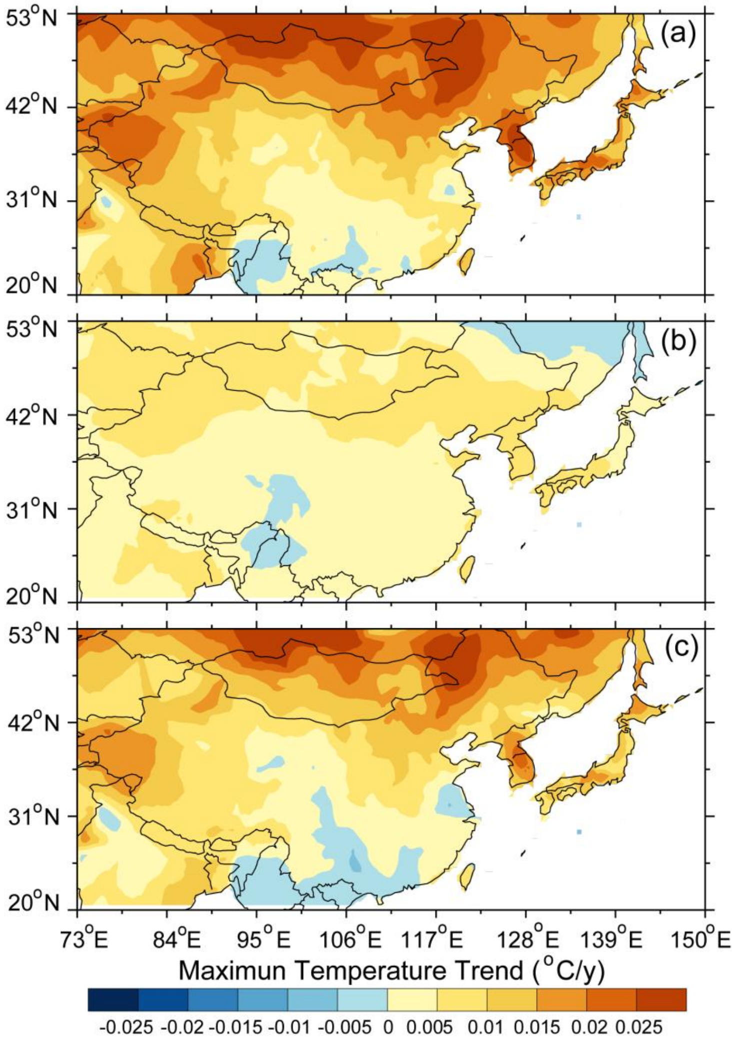

**Figure 8.** Same as Fig. 3, except for daily maximum temperatures.

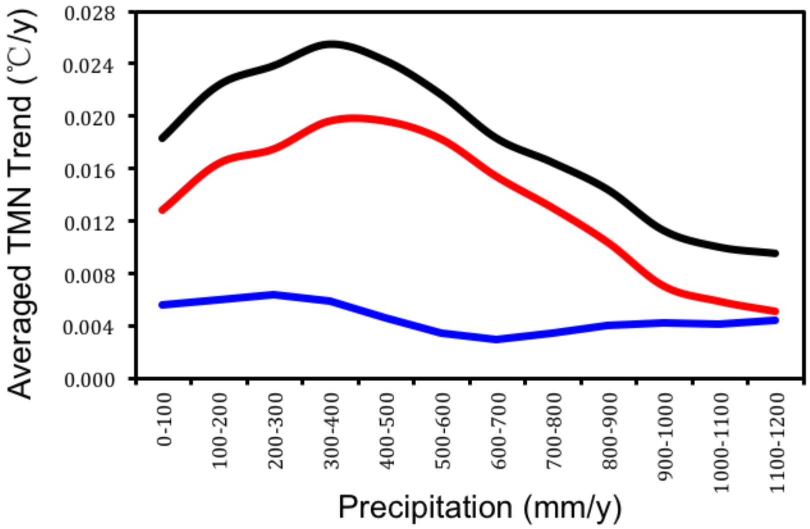

**Figure 9**. Same as Fig. 6, except for daily minimum temperature.

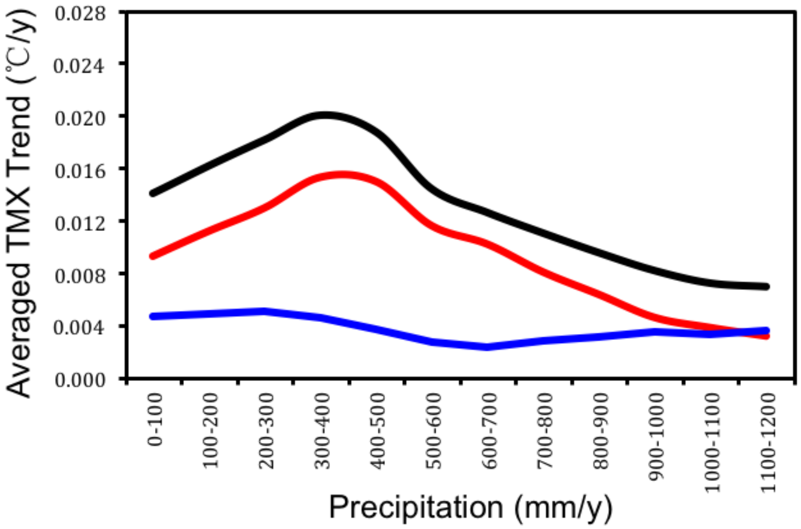

**Figure 10.** Same as Fig. 6, except for daily maximum temperature.

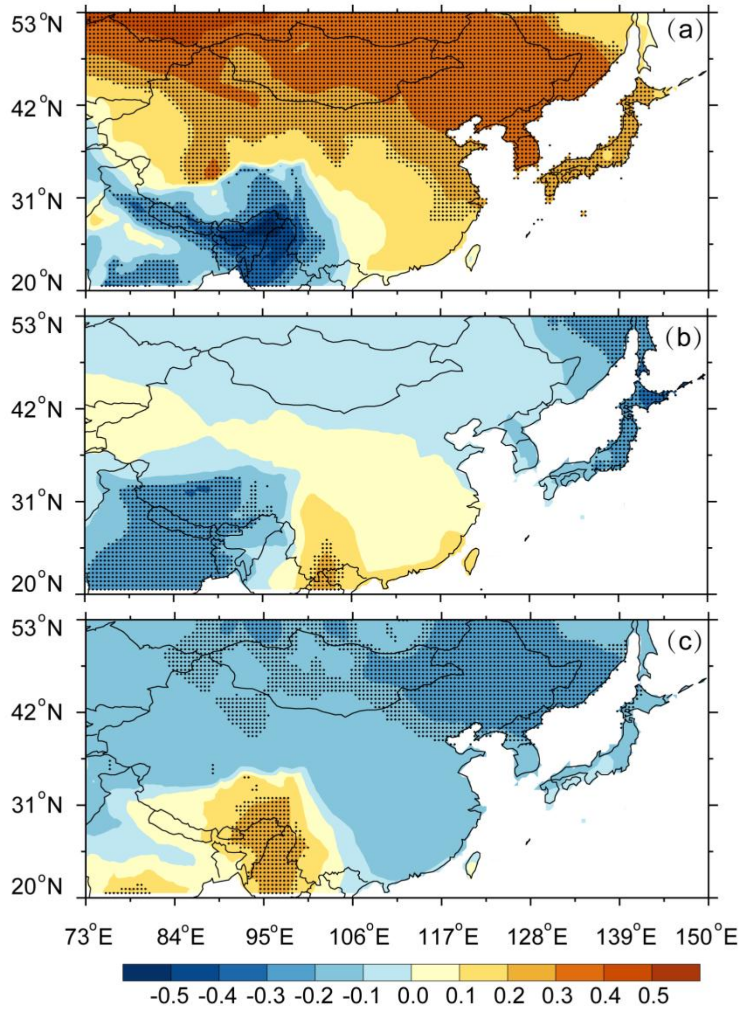

**Figure 11.** Spatial distribution of the correlation coefficient between detrended dynamically induced temperature and detrended NAO (a), PDO (b), and AMO (c) in the cold season from 1902 to 2011 over East Asia. The stippling indicates the 95% confidence level according to a two-tailed Student's *t* test.

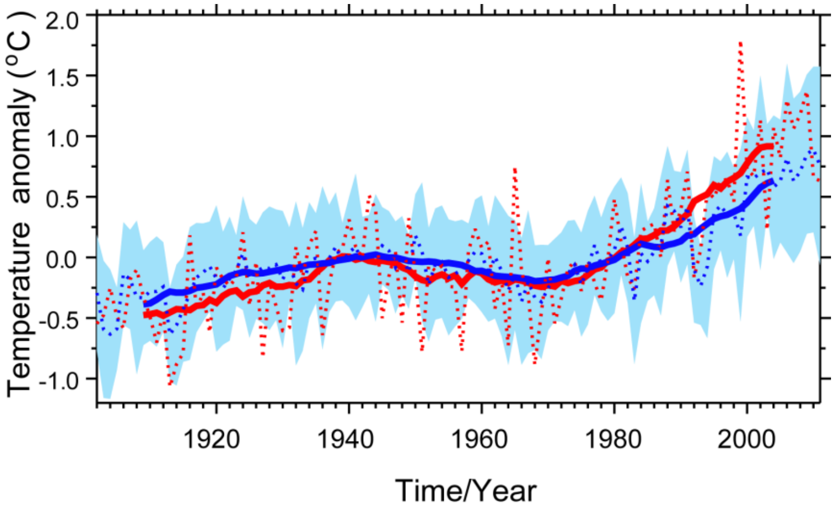

**Figure 12.** Time series of radiatively forced temperature (red) and ensemble-mean CMIP5 simulations (blue) based on 15-yr running mean in the cold season from 1902 to 2011 over East Asia. The blue shading indicates the standard deviation of the CMIP5-simulated field.

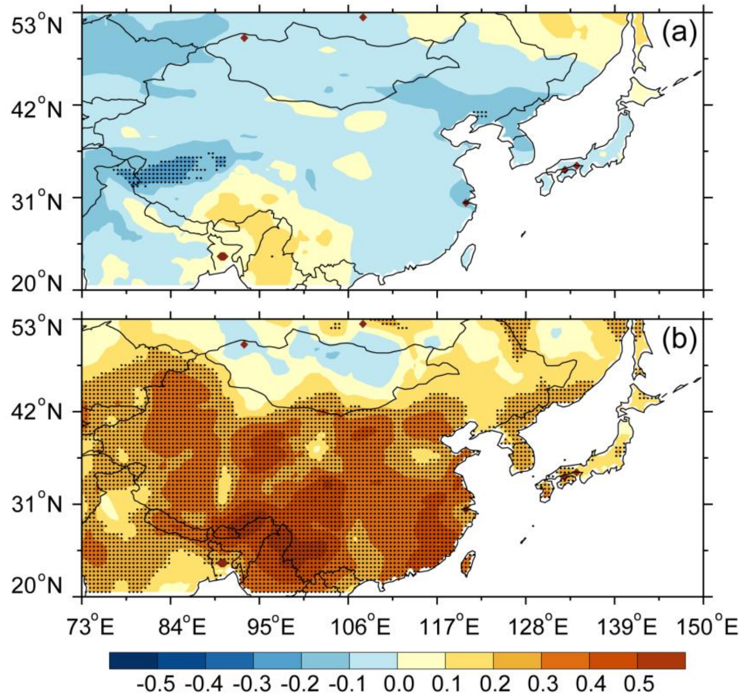

**Figure 13.** Spatial distribution of correlation coefficient between ensemble-mean CMIP5 simulations and dynamically induced temperature (a), and between ensemble-mean CMIP5 simulations and radiatively forced temperature (b) in the cold season from 1902 to 2011 over East Asia.

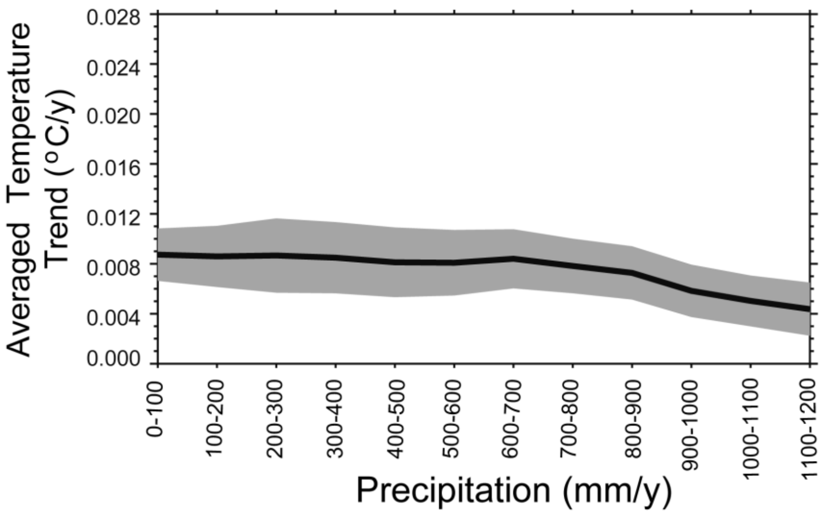

**Figure 14.** Regional averaged temperature trend as a function of climatological annual mean precipitation over East Asia for ensemble-mean CMIP5 simulations in cold season from 1902 to 2011, shading denotes 95% confidence intervals.

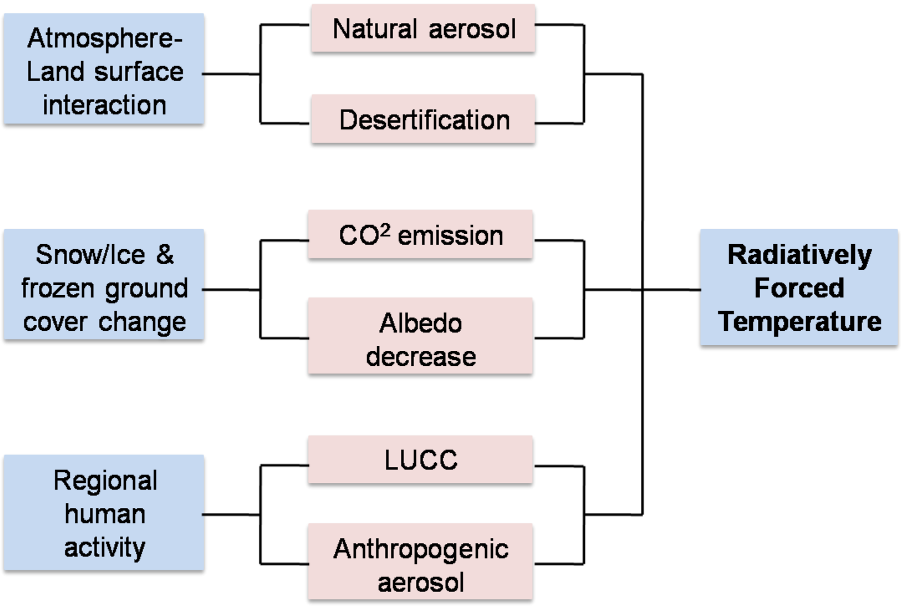

**Figure 15.** Schematic diagram of radiatively forced temperature.

Table 1. CMIP5 models examined in this study.

| Model name | Modelling centre |
|---|---|
| BCC-CSM1.1 | Beijing Climate Center, China |
| CanESM2 | Canadian Centre for Climate, Canada |
| CanESM2 | Canadian Centre for Climate, Canada |
| CCSM4 | National Center for Atmospheric Research, USA |
| CNRM-CM5 | Centre National de Recherches Meteorologiques, France |
| CSIRO-Mk3.6.0 | Commonwealth Scientific and Industrial Research, Australia |
| GFDL-CM3 | Geophysical Fluid Dynamics Laboratory, USA |
| GFDL-ESM2G | Geophysical Fluid Dynamics Laboratory, USA |
| GFDL-ESM2M | Geophysical Fluid Dynamics Laboratory, USA |
| GISS-E2-R | NASA Goddard Institute for Space Studies, USA |
| HadGEM2-CC | Met Office Hadley Centre, UK |
| HadGEM2-ES | Met Office Hadley Centre, UK |
| INM-CM4 | Institute for Numerical Mathematics, Russia |
| IPSL-CM5A-LR | Institute Pierre-Simon Laplace, France |
| IPSL-CM5A-MR | Institute Pierre-Simon Laplace, France |
| MIROC-ESM | Japan Agency for Marine-Earth Science and Technology, Japan |
| MIROC-ESM-CH | Japan Agency for Marine-Earth Science and Technology, Japan |
| MIROC5 | Atmosphere and Ocean Research Institute, Japan |
| MPI-ESM-LR | Max Planck Institute for Meteorology, Germany |
| MRI-CGCM3 | Meteorological Research Institute, Japan |
| NorESM1-M | Norwegian Climate Centre, Norway |