Response of Atmospheric Energy to Historical Climate Change in CMIP5

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ABSTRACT

Three forms of atmospheric energy, i.e., internal, potential, and latent, are analyzed based on the historical simulations of 32 Coupled Model Intercomparison Project Phase 5 (CMIP5) models and two reanalysis datasets (NCEP/NCAR and ERA-40). The spatial pattern of climatological mean atmospheric energy is well reproduced by all CMIP5 models. The variation of globally averaged atmospheric energy is similar to that of surface air temperature (SAT) for most models. The atmospheric energy from both simulation and reanalysis decreases following the volcanic eruption in low-latitude zones. Generally, the climatological mean of simulated atmospheric energy from most models is close to that obtained from NCEP/NCAR, while the simulated atmospheric energy trend is close to that obtained from ERA-40. Under a certain variation of SAT, the simulated global latent energy has the largest increase ratio, and the increase ratio of potential energy is the smallest.

Key words: atmospheric energy, CMIP5, historical climate change


1. Introduction

Climate change in recent decades, usually represented as the increase of global surface air temperature (SAT) (Willmott and Legates, 1993; Dixon and Lanzante, 1999; Jones et al., 1999; Watterson et al., 1999; Simmons et al., 2004; Bodri and Cernak, 2005; Zhou and Yu, 2006; Meehl et al., 2007), is also called global warming. Because the entire climate system contains several subsystems (Peixoto and Oort, 1992), there are various climate change indications, e.g., reduction of sea-ice concentration (Ingram et al., 1989; Johannessen et al., 2004), rising sea levels (Meehl et al., 2005; Church and White, 2006), rainforest deforestation (Nobre et al., 1991; Henderson-Sellers et al., 1993), etc. Therefore, it is important to define accurate climate change indices for different purposes (Baettig et al., 2007). For the atmosphere, the vertical thermal structure responses to climate change are also discerned (Santer et al., 1996, 2005; Baldwin et al., 2007; Zhang et al., 2007). These responses in turn modulate the climate energy budget. In this study, atmospheric energy, which represents the integral thermal feature of atmosphere, will be used as an alternative metric to assess the state-of-the-art climate models.

Being a quasi-closed system, the climate system gains positive net energy flux during global warming. Such a change of climate energy budget should be reflected in observations such as Earth Radiation Budget Experiment (ERBE) data (Li and Leighton, 1993; Annamalai et al., 2007) and the Clouds and the Earth’s Radiant Energy System (Wielicki et al., 1996) data. However, because of inaccuracy and uncertainty in re-
mote sensing data, it is difficult to directly calculate exact net energy flux. Kiehl and Trenberth (1997) reported the quasi-balance state among all energy fluxes on top of the atmosphere as well as at the earth’s surface by using the ERBE data. Thereafter, Trenberth et al. (2009) rebuilt the earth’s annual global mean energy budget and reported 0.9 W m$^{-2}$ net radiation flux into the climate system. It is found that enhanced climate energy was originated from the increase of ocean heat content in the last century (Levitus, 2000; Barnett et al., 2001; Hansen et al., 2005; Levitus et al., 2005).

Compared with the ocean, the heat capacity of the atmosphere is much smaller. Therefore, all energy fluxes into the global atmosphere should be approximately in balance (Alessandri et al., 2012). Nevertheless, change of the atmospheric components is essential for modulation of energy flux transmission (Santer et al., 1996; Barnett et al., 1999; Allen et al., 2000; Barnett et al., 2001; Allen and Stott, 2003; Stott et al., 2003; Oreskes, 2004). In particular, changes in the atmospheric thermal state can induce essential climate feedback (Bony et al., 2006). The effect of water vapor on climate change was first considered by Chamberlin (Chamberlin, 1897; Held and Soden, 2000; Fleming, 2005). Soden and Held (2006) estimated the water vapor feedback to be 1.80 ± 0.8 W m$^{-2}$ K$^{-1}$. In this study, water vapor in the atmosphere is represented as atmospheric latent energy. It is understandable that the change of atmospheric energy should be known before a complete description of climate feedback can be presented.

The fifth phase of the Coupled Model Intercomparison Project (CMIP5) is endorsed by the World Climate Research Programme’s Working Group on Coupled Modeling. CMIP5 focuses on understanding of the major gaps in the understanding of past and future climate changes based on a suite of climate simulations (Taylor et al., 2012). The CMIP5 simulations were carefully planned, acknowledging resource limitations for diagnosing and projecting climate change. The historical simulations were carried out to evaluate the ability of climate models to reproduce the climate change in the past 150 years (1850–2005). It is assumed that even with the existence of uncertainty within various climate models, these simulations can be used to compare with observation data.

In this study, we will evaluate 32 coupled CMIP5 models from the viewpoint of atmospheric energy. Two popular reanalysis datasets of NCEP/NCAR and ERA-40 are used as observation data. The paper is organized as follows. Section 2 introduces the data and the atmospheric energy concepts used in this study. The spatial patterns of climatological mean atmospheric energy obtained from various models are compared in Section 3. In Section 4, globally averaged atmospheric energy statistics obtained from models and reanalysis datasets are compared. The relations between different types of globally averaged atmospheric energy are discussed in Section 5. Section 6 presents the main conclusions as well as some discussion.

2. Data and methods

2.1 Data

The monthly mean data from 32 CMIP5 climate models (listed in the right of Fig. 3) are employed in this study. Information on the CMIP5 models can be found at http://cmip-pcmdi.llnl.gov/cmip5/. The first realization has been chosen for all models and additional realizations have been included for some models (total simulations are 46). It should be noted that, although the CO$_2$ concentration has been uniformly prescribed in all the models, the radiative forcing is not identical because of different approaches to atmospheric chemical processes. Despite the differences in models and simulations, some common features of atmospheric energy are expected to be reproduced by CMIP5 models. This is a primary focus of the present study.

As a contrast, the atmospheric energy features derived from ERA-40 (Uppala et al., 2005) and NCEP/NCAR (Kalnay et al., 1996) are also revealed in this study. The atmospheric energy data from these sources should be reliable, although the coverage and duration of the assimilated high-level observation data are limited over some regions. Moreover, it is well known that reanalysis products do not conserve the
mass and energy of the climate system (e.g., Trenberth et al., 2009; Lucarini and Ragone, 2011; Mayer and Haimberger, 2012); therefore, the results can only be considered as a reference. If two reanalysis datasets provide identical descriptions of some features of atmospheric energy, we prefer to believe that this may be the reality in nature. Otherwise, the understanding of atmospheric energy remains uncertain. Considering the duration of the two reanalysis datasets, the comparison between models and reanalysis will be performed for the period 1958–2000.

2.2 Atmospheric energy

The vertically integrated thermal/dynamic features of the atmosphere can be extrapolated from the atmospheric energy. Following Peixoto and Oort (1992), the total atmospheric energy \( E_A \) can be divided into four parts:

\[
E_A = I + P + L + K, \tag{1}
\]

where \( I, P, L, \) and \( K \) denote internal, potential, latent, and kinetic energy, respectively. Column integral mass weighted values are calculated as follows:

\[
I = \int_0^{\infty} \rho c_v T dz = \int_0^{p_0} \frac{c_v T}{g} dp, \tag{2}
\]

\[
P = \int_0^{\infty} \rho g z dz = \int_0^{p_0} z dp = \frac{R d}{c_v} I, \tag{3}
\]

\[
L = \int_0^{\infty} \rho l q dz = \int_0^{p_0} \frac{l q}{g} dp, \tag{4}
\]

\[
K = \int_0^{\infty} \rho \left(\frac{u^2}{2} + \frac{v^2}{2} + \frac{w^2}{2}\right) dz \approx \int_0^{p_0} \frac{u^2 + v^2}{2g} dp. \tag{5}
\]

Here, \( \rho \) is the density of air \( (\text{kg m}^{-3}) \), \( c_v \) is the atmospheric specific heat at constant volume (approximately 717 J kg\(^{-1}\) K\(^{-1}\)), \( R_d \) is the gas constant for dry air (287 J kg\(^{-1}\) K\(^{-1}\)), \( l \) is latent heat of evaporation, \( T \) is air temperature (K), \( z \) is the height of air mass above the earth surface (m), \( q \) is the mass ratio of water vapor \( (\text{kg kg}^{-1}) \), and \( u, v, \) and \( w \) are zonal, meridional, and vertical wind speed, respectively \( (\text{m s}^{-1}) \). The constant proportion between \( I \) and \( P \) in Eq. (3) is accurate only if hydrostatic equilibrium is assumed, and the ratio should be \( R_d/c_v \) only if the effect of water vapor has been neglected. \( L \) is proportional to the precipitable water in the air column. \( L \) also depends on the particular phase transition; in most situations, the main release of latent heat occurs in rain, and \( l = l_c \) \( (2.6 \times 10^6 \text{ J kg}^{-1}) \) will be an appropriate value to use in Eq. (4). To connect the change of atmospheric energy with the climate energy budget, the unit of the linear trend for atmospheric energy has been written as \( \text{W m}^{-2} \) \( (1 \text{ W m}^{-2} = 3.15 \times 10^9 \text{ J m}^{-2} \text{ per 100 yr}) \) in this study.

Kinetic energy will not be considered in this study; consequently, only the thermal features of atmospheric energy are presented. The magnitude of kinetic energy is much smaller than the other three terms. Note that the kinetic energy in atmospheric transient eddies are comparable with that in monthly mean circulations over the midlatitudinal zones (Chang et al., 2013). Therefore, a proper consideration of kinetic energy requires sub-daily simulation data, which is not available for all models used in this study.

3. Spatial patterns of climatological mean atmospheric energy

In this section, the spatial patterns of climatological mean atmospheric energy will be discussed. From Eqs. (2)–(5), it is evident that atmospheric energy is controlled by both the corresponding atmospheric variables (temperature, geopotential height, and specific humidity) and the atmospheric column depth. The local depth of the atmospheric column is primarily determined by the land-surface geopotential height, which does not change significantly over time. Therefore, the distribution of climatological mean atmospheric energy from the models’ ensemble mean is quite close to that from reanalysis (Fig. 1). In particular, atmospheric energy is small over the regions with high altitude terrain, such as the Tibetan Plateau. The largest values for internal energy are given by the models’ ensemble mean and NCEP/NCAR over northern Australia, northern Africa, and central South America. Large potential and latent energy are found over tropical regions; however, the latent energy seems to be modified by the sea surface temperature.

The intercomparison of spatial patterns of clima-
4. Globally averaged atmospheric energy

The standardized series of globally averaged atmospheric energy are given in Figs. 3a–c. For the models’ ensemble mean, all three atmospheric energy values decreased from 1958 to 1964 and then increased continually except for two rapid declines in 1983 and 1992. The decrease of atmospheric energy in 1964, 1983, and 1992 corresponded to the cooling around the same time near the earth’s surface (Fig. 3d) and as likely caused by major volcanic eruptions in low latitudinal zones, i.e., Agung (8°S), Fernandina (0°S), and Mount Pinatubo (15°N), respectively (Robock, 2000). Volcanic aerosols modulate atmospheric aerosol optical depth and alter the energy budget of climate systems (Sato et al., 1993). The simulated globally averaged internal energy is highly correlated with SAT. This suggests that the overall atmosphere temperature has increased because of barotropic effects on the global scale. Because the global atmosphere is generally in hydrostatic equilibrium and follows the Clausius–Clapeyron equation, similar variation of globally averaged potential and latent energy is reasonable.

Regardless of the interannual variation, the internal and potential energy given by the two reanalysis datasets have variations similar to the models’ ensemble mean, especially for the three cooling events. How-
Fig. 2. Taylor diagrams for the climatological mean atmospheric (a) internal energy, (b) potential energy, (c) latent energy, and (d) SAT. The correlation is represented by pattern correlation coefficients between models and reanalysis. The deviation means the difference between the local value and the global mean. The red and blue dots indicate the intercomparison results between models and NCEP/NCAR, and between models and ERA-40, respectively.

However, there is a significant difference in latent energy between productions of the two reanalyses. During the whole period, the latent energy in ERA-40 is linearly increased. The NCEP/NCAR results show a sharp decrease from 1958 to 1964 with no linear increase after 1971. In the following section, globally averaged atmospheric energy statistics from climate models and reanalysis data will be compared in further detail.

4.1 Internal energy

Compared with reanalysis datasets, it seems that most models underestimate the climatological mean internal energy. The climatological mean globally averaged $I$ (Fig. 4a) is approximately $1.72 \times 10^9$ J m$^{-2}$ for most models, which is slightly smaller than that from NCEP/NCAR ($1.73 \times 10^9$ J m$^{-2}$) and ERA-40 ($1.74 \times 10^9$ J m$^{-2}$). One exception is CSIRO-MK-360, which gives a climatological mean internal energy of approximately $1.78 \times 10^9$ J m$^{-2}$.

Compared with climatological mean, the linear trends of simulated internal energy are widely distributed among all models. The largest trend is given by the second realization of IPSL-CM5A-LR ($4.7 \times 10^{-3}$ W m$^{-2}$). The first realization of CSIRO-
MK-360 and the second realization of HadGEM2-ES both give a negative but insignificant trend. It should be noted that the SAT trends for all realizations are positive and significant (Fig. 4d). The weaker warming of the entire atmosphere rather than warming near the earth’s surface can be attributed to cooling in the stratosphere due to ozone reduction (figure omitted, refer to Santer et al., 1996). The trend of the models’ ensemble mean ($1.9 \times 10^{-3}$ W m$^{-2}$) is greater than that in ERA-40 ($1.7 \times 10^{-3}$ W m$^{-2}$) but smaller than
in NCEP/NCAR ($3.1 \times 10^{-3}$ W m$^{-2}$).

4.2 Potential energy

Following the hydrostatic equilibrium assumption for atmosphere (Eq. (3)), the climatological mean globally averaged potential energy should be proportional to internal energy. However, the climatological means of potential energy reproduced by climate models are separated into two groups. There are 20 models in the first group, all of which tend to give a lower climatological mean potential energy of approximately $7.1 \times 10^8$ J m$^{-2}$; the remaining 12 models' climatological mean potential energy is approximately $7.4 \times 10^8$ J m$^{-2}$. The models' ensemble mean result is about
7.2×10^8 \text{ J m}^{-2}, \text{ which is not close to any single model’s result. The cause of the variation in the results of the models cannot be ascertained in this study; however, it has no relation with resolution of the models (neither horizontal nor vertical resolution). The results from the two reanalysis datasets are both approximately } 7.4×10^8 \text{ J m}^{-2}, \text{ which is closer to result from the second group of models.}

The trends of potential energy for most models are within the range of 0.5×10^{-3}–1.0×10^{-3} \text{ W m}^{-2}. The trend from the models’ ensemble mean is 0.9×10^{-3} \text{ W m}^{-2}. This is acceptable because the trend from ERA-40 and NCEP/NCAR is 0.7×10^{-3} and 1.4×10^{-3} \text{ W m}^{-2}, respectively. The potential energy in the first realization of CSIRO-MK-360 decreases linearly, which means that the dry static atmospheric energy decreased between 1958 and 2000. Although with a decrease of internal energy, the potential energy from HadGEM2-ES (first realization) increases linearly. This is against the requirement of the hydrostatic equilibrium.

4.3 Latent energy

Latent energy is the potential energy that is released when water vapor in the atmosphere condenses. Latent energy is essential to climate change because water vapor is one of the most important natural greenhouse gas. The simulated climatological mean latent energy ranges from 4.7×10^7 \text{ (IPSL-CM5A-LR) to } 5.9×10^7 \text{ (CMCC-CESM) J m}^{-2}. \text{ The Inmcm4 model is not included in the analysis because its specific humidity is obviously erroneous (e.g., being negative) at somewhere. The models’ ensemble mean result is } 5.2×10^7 \text{ J m}^{-2}, \text{ which is equal to that in NCEP/NCAR } (5.2×10^7 \text{ J m}^{-2}) \text{ but smaller than in ERA-40 } (5.4×10^7 \text{ J m}^{-2}).

Different from internal and potential energy, all models in this study show a linear increase of latent energy for the whole atmosphere, even for CSIRO-MK-360 and HadGEM2-ES. In other words, the CMIP5 models are more likely to show an atmospheric moistening than global atmospheric warming or expansion during historical climate change. ERA-40 gives a trend of approximately 3.2×10^{-3} \text{ W m}^{-2}, which is close to the result obtained with FGOALS-s2. The trend from NCEP/NCAR is −0.6×10^{-3} \text{ W m}^{-2}. Such a disagreement in the two reanalysis datasets has been reported by Trenberth et al. (2005), and because the result from ERA-40 is supported by that obtained with RSS SSM/I, the linear increase of latent energy seems to be more reliable. Moreover, we also calculated the trend using the 20th century reanalysis datasets (Compo et al., 2011), and a statistically significant (> 95% confidence level) positive trend of 0.89×10^{-3} \text{ W m}^{-2} for global latent energy is suggested. Therefore, it is reasonable to conclude that most models can properly reproduce the moistening of the entire atmosphere for the period 1958–2000.

Although the climatological mean of latent energy is much smaller, its linear trends are comparable to those of internal and potential atmospheric energy. In other words, the increase ratio of latent energy is much greater than that of internal or potential energy. For the models’ ensemble mean, the latent energy of the atmosphere has increased by approximately 7.9% during 1958–2000; whereas the increase ratio of internal and potential energy is approximately 0.4%. This indicates that among internal, potential, and latent energy, atmospheric latent energy is the most sensitive to climate change, which may explain the important role that water vapor has played in climate feedback studies (Held and Soden, 2000, 2006).

4.4 Surface air temperature

SAT is widely used to indicate climate change; therefore, we also need to examine this variable in atmospheric energy simulations. From Fig. 4d, it can be seen that the variation of simulated globally averaged SAT is quite close to the reanalysis results. The model results for climatological SAT mean range from 285.9 \text{ (IPSL-CM5A-LR) to } 288.5 \text{ K (GISS-E2-H). The models’ ensemble mean result is } 286.9 \text{ K, which is quite close to that of NCEP/NCAR } (287 \text{ K}) \text{ and smaller than that of ERA-40 } (287.5 \text{ K). Note that the descriptions of SAT in the two reanalysis products are identical except for the Arctic and Antarctic regions (figure omitted) (Jones et al., 1999; Simmons et al., 2004). Because all climate models’ globally averaged}
SAT shows a positive trend during 1958–2000, air warming near the earth surface appears to be a more confident result than warming of the whole atmosphere. The weakest warming appears in the fifth realization of CSIRO-MK-360 (0.37 K per 100 yr), while the strongest warming appears in FGOALS-s2 (2.4 K per 100 yr). The trend of the models’ ensemble mean is 1.38 K per 100 yr, which is larger than that of ERA-40 (1.1 K per 100 yr) and NCEP/NCAR (0.9 K per 100 yr). Therefore, most models seem to overestimate the increase of SAT during 1958–2000.

For the globally averaged climatological mean atmospheric energy, the results of the models’ ensemble mean are closer to that from NCEP/NCAR. With regard to the linear trend for the period 1958–2000, the result from the models’ ensemble mean seems to be closer to that from ERA-40. These features can also be found in SAT. Note that the identification of globally averaged SAT between the models’ ensemble mean and reanalysis is more significant than that for atmospheric energy. Thus, climate change near the earth’s surface in the past decades seems to be better understood, and therefore can be well reproduced by numerical models. With regard to the thermal state of the entire climate subsystems (e.g., atmospheric energy), considerable uncertainty remains.

5. Globally averaged atmospheric energy connections

On the basis of the above discussion, the globally averaged atmospheric energy and SAT show greater differences than other features in most models. Therefore, before proceeding with the discussion presented in this section, the simulated atmospheric energy needs to be normalized first. Because the globally averaged SAT is often used to represent the thermal state of climate, all atmospheric energy statistical results are normalized with the statistics of SAT.

The climatological mean of internal and potential energy does not demonstrate any connections even after being normalized. The two groups of models with different potential energy values are still significant, as shown in Fig. 5a. However, the normalized mean latent energy shows a linear correlation (at the 95% confidence level for t-test) with internal energy among all models (Fig. 5b); the ratio is approximately $3.6 \times 10^{-2}$. Considering that the difference in the climatological mean globally averaged SAT is small among all models, this linear relationship means that if the climatological mean internal energy in a model is larger than the models’ ensemble mean for 100 J m$^{-2}$, its mean latent energy should be approximately 3.6 J m$^{-2}$ greater. This relationship is also supported by the two reanalyses. Therefore, assuming equal global mean SAT, when the atmosphere has greater internal energy, its latent energy rather than potential energy will also be greater.

The linear connections between normalized atmospheric energy trends are statistically significant (at $>99\%$ confidence level). From Fig. 5c, it can be seen that the ratio between normalized potential energy and internal energy is 0.30. This means that under the same warming rate near the earth’s surface, the increase of atmospheric potential energy is approximately 30% of that of internal energy. This result is well supported by the two reanalysis datasets. Considering that the ratio of climatological mean of potential energy to that of internal energy is approximately 0.4 (Eq. (3)), the ratio of the normalized trend between internal and potential energy implies that the atmosphere will be more compressed and the hydrostatical equilibrium is destroyed in the models’ representation of historical climate change.

The ratio of the trend between simulated latent and internal energy, derived from all models except Inmcm4, is approximately 0.31 (Fig. 5d). This result is statistically significant at the 99% confidence level. Because the climatological mean of latent energy is two orders of magnitude smaller than that of internal energy, such a result indicates that under a certain increase of global SAT, the increase of latent energy is most intensive. However, the two reanalyses do not appear to agree with the models. The result from ERA-40 indicates an even greater increase of latent energy and the result from NCEP/NCAR indicates that the atmosphere has become hot and dry during past decades.
Fig. 5. Distributions of (a, b) climatological mean, (c, d) linear trend, and (e, f) root mean standard deviation (RMSD) between different models (a, c, e: globally averaged internal vs. potential energy; b, d, f: globally averaged internal vs. latent energy). Results for individual models are denoted as black dots. Results from ERA-40 and NCEP/NCAR are denoted as open box and circle, respectively. All atmospheric energy statistics have been normalized with the corresponding SAT statistics (i.e., units for all axes are $10^6 \text{JK}^{-1} \text{m}^{-2}$). The linear fitted line for all models is also given. The slopes of fitted line in (a)–(f) are $-4.8 \times 10^{-2}$, $3.6 \times 10^{-2}$, 0.30, 0.31, 0.30, and 0.31, respectively.

The root mean standard deviation (RMSD) of the atmospheric energy time series is similar to those of the trend (Figs. 5e and 5f). The ratio of RMSD between potential and internal energy as well as that between
latent and internal energy from models are close to that of the trend. Therefore, the change of different global atmospheric energy will maintain a constant ratio on both short (interannual) and longer (decadal) timescales in CMIP5. Note that the RMSD of latent energy from NCEP/NCAR is still much weaker than that of the potential energy.

6. Conclusions and discussion

In this study, we investigated atmospheric energy in historical climate change (1958–2000) to evaluate 32 CMIP5 climate models. The main conclusions are summarized below:

(1) The spatial patterns of climatological mean atmospheric energy reproduced by most models are quite similar to those of the two reanalysis datasets (ERA-40 and NCEP/NCAR).

(2) The globally averaged internal and potential energy from the models’ ensemble mean have similar variations to those of ERA-40 and NCEP/NCAR during 1958–2000, and the globally averaged latent energy from the models’ ensemble mean is close to that of ERA-40.

(3) The climatological mean of globally averaged atmospheric energy from the models’ ensemble mean is close to that from NCEP/NCAR, while the trends from the CMIP5 model simulations are close to that from ERA-40.

(4) Under equal warming conditions near the earth’s surface, the ratio of trends between simulated potential and internal energy is 0.30. The comparable ratio of trends between latent and internal energy is 0.31. Considering the comparison of climatological mean values of atmospheric energy, these two ratios indicate that the proportion of latent energy in the entire atmospheric energy has increased while that of potential energy has decreased under historical global warming.

The significant spread of atmospheric energy in climate models and two reanalysis datasets should be noted. The simulation ability of climate models has improved during the past two decades, which seems to be supported by the more realistic change of SAT in CMIP5 models (Fig. 4d). However, for atmospheric energy, the results from two reanalyses diverge significantly. A significant cause of the uncertainty in atmospheric energy may be that the physical constraint of conservation of dry air mass is violated in the two reanalyses with increasing magnitude prior to the assimilation of satellite data (Trenberth and Smith, 2005). Similarly, a determination of atmospheric mass is also needed to understand the distribution of atmospheric energy among all climate models.

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