



Can Current AGCMs Reproduce Historical Changes in the Atmospheric Diabatic Heating over the Tibetan Plateau?

Duan An-Min, Xiao Zhi-Xiang & Hu Jun

To cite this article: Duan An-Min, Xiao Zhi-Xiang & Hu Jun (2014) Can Current AGCMs Reproduce Historical Changes in the Atmospheric Diabatic Heating over the Tibetan Plateau?, *Atmospheric and Oceanic Science Letters*, 7:2, 143-148

To link to this article: <https://doi.org/10.3878/j.issn.1674-2834.13.0084>



© Institute of Atmospheric Physics, Chinese Academy of Sciences



Published online: 12 Aug 2015.



Submit your article to this journal



Article views: 46



View related articles



View Crossmark data

Can Current AGCMs Reproduce Historical Changes in the Atmospheric Diabatic Heating over the Tibetan Plateau?

DUAN An-Min^{1,3}, XIAO Zhi-Xiang^{1,2}, and HU Jun^{1,2}

¹ State Key Laboratory of Numerical Modelling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China

² University of Chinese Academy of Sciences, Beijing 100049, China

³ Key Laboratory of Meteorological Disaster, Nanjing University of Information Science and Technology, Ministry of Education, Nanjing 210044, China

Received 19 October 2013; revised 16 November 2013; accepted 18 November 2013; published 16 March 2014

Abstract Recent studies have demonstrated a persistent decreasing trend in the spring sensible heat (SH) source over the Tibetan Plateau (TP) during the past three decades. By comparing simulations from nine state-of-the-art atmospheric general circulation models (AGCMs) driven by historical forcing fields with both observational data and five reanalysis datasets, the authors found that the AGCMs are unable to reproduce the change in the SH flux over the TP. This deficiency arises because the observed decreasing trend in SH flux depends primarily on the change in surface wind speed according to the bulk formula, whereas in the models it is also influenced largely by changes in the land-air temperature difference related to the systematic cold bias. In addition, an obvious discrepancy exists in other aspects of the diabatic heating simulated by the models, suggesting that a significant improvement is required in the physical schemes associated with land surface processes and diabatic heating over the complicated topography.

Keywords: Tibetan Plateau, AGCMs, diabatic heating, trend

Citation: Duan, A.-M., Z.-X Xiao, and J. Hu, 2014: Can current AGCMs reproduce historical changes in the atmospheric diabatic heating over the Tibetan Plateau? *Atmos. Oceanic Sci. Lett.*, 7, 143–148, doi:10.3878/j.issn.1674-2834.13.0084.

1 Introduction

The mechanical and thermal forcing effects of the Tibetan Plateau (TP) are important factors in the formation and evolution of hemispheric circulation and climate (Yeh et al., 1957; Hahn and Manabe, 1975; Luo and Yanai, 1983; Li and Yanai, 1996; Duan and Wu, 2005; Wu et al., 2012). Prior to the rainy season, a strong sensible heat (SH) flux dominates the total diabatic heating over the TP and regulates both the timing of the establishment of the tropical Asian summer monsoon (Wu et al., 1997; Wu and Zhang, 1998) and the interannual variation of the East Asian summer monsoon (EASM) (Duan and Wu, 2005; Zhao and Chen, 2001).

In parallel with the warming climate, the atmospheric heat source, especially the spring SH flux over the TP, has shown a clear weakening trend during the past three dec-

ades (Zhu et al., 2007; Yang et al., 2011). This weakening trend in the spring SH flux over the TP is directly related to the persistent decelerated surface wind, which can be considered as a regional response to the relatively larger amplitude of warming over northern parts of Eurasia and smaller amplitude of warming over southern parts of Eurasia, its spatially non-uniform warming effect, and the resultant decelerated subtropical westerly jet (Duan and Wu, 2009). Moreover, the suppressed TP atmospheric diabatic heating has been further linked to the decadal abating of the EASM, and the resultant southward retreat of the monsoon rainfall belt in China (Liu et al., 2012; Duan et al., 2013).

It is unfortunate that in the third phase of the Coupled Model Intercomparison Project (CMIP3), only a few air-sea coupled general circulation models (AOGCMs) could reproduce the decelerated westerly jet (Duan and Wu, 2009), suggesting a generally low ability of AOGCMs in simulating regional climate change. After some years of further development, it is now thought that the ability of these models has been improved in certain respects, and that the forcing fields in the historical experiments in the fifth phase on CMIP (CMIP5) are now more reliable (Taylor et al., 2012). In particular, the sea surface temperature (SST) bias in AOGCMs may be partially responsible for the bias in the regional warming pattern. This raises the question: can we expect state-of-the-art atmospheric general circulation models (AGCMs) driven by historical SST and other forcing fields to reproduce the observed declining spring SH flux and the total atmospheric diabatic heating over the TP? In this study, we address this issue by comparing simulations from nine current AGCMs with station-based observational data and five reanalysis datasets.

2 Data and models

There are few directly observed long-term and large-scale SH datasets available globally, and particularly for the TP due to the complex terrain and extreme environment there. Routine monitoring stations are distributed mainly in the central and eastern TP (CETP), whereas only a few are located in the western TP. The data used here include the regular surface meteorological observations from 71 stations over the CETP supplied by the China Meteorological Administration (CMA). Observa-

tions were made four times each day from 1980 to 2005 and included surface skin temperature (T_s), surface air temperature (T_a), and 10-m wind speed (V). The daily mean T_a , T_s , V , and SH flux fields during the same period were also obtained from five reanalysis products: National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) (Kalnay et al., 1996), NCEP-Department of Energy(NCEP/DOE) (Kanamitsu et al., 2002), Japanese 25-year Reanalysis(JRA-25) (Kazutoshi et al., 2007), Interim European Centre for Medium Range Weather Forecasts Reanalysis (ERA-Interim) (Dee et al., 2011), and Modern Era Retrospective-Analysis for Research and Applications(MERRA) (Rienecker et al., 2011), which have global horizontal resolutions of $2.5^\circ \times 2.5^\circ$, $1.875^\circ \times 1.88^\circ$, $1.125^\circ \times 1.12^\circ$, $1.5^\circ \times 1.5^\circ$, and $\left(\frac{2}{3}\right)^\circ \times \left(\frac{1}{2}\right)^\circ$, respectively.

The SH flux at the 71 stations was calculated using the bulk aerodynamic method:

$$SH = C_p \cdot \rho \cdot C_{DH} \cdot V \cdot (T_s - T_a), \quad (1)$$

where $C_p = 1005 \text{ J kg}^{-1} \text{ K}^{-1}$ is the specific heat of dry air at constant pressure, ρ is the air density that decreases exponentially with increasing elevation, C_{DH} is the drag coefficient for heat, see Duan and Wu (2008) for more details.

Simulations in the nine AGCMs were based on the integrations from CMIP5 produced for the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5). The horizontal grids of the AGCMs varied from 360×576 ($0.5^\circ \times 0.625^\circ$) in Geophysical Fluid Dynamics Laboratory global High Resolution Atmospheric model (GFDL-HIRAM-C180) to 64×128 ($2.8^\circ \times 2.8125^\circ$) in Beijing Normal University-Earth System Model(BNU-ESM) and Canadian Atmospheric Global Climate Model

(CanAM4). The forcing factors used were combinations of greenhouse gases, sea ice, volcanic aerosols, ozone, historical SST, black carbon, sulfate aerosols, and solar variability derived from the dataset for the period 1850–2005. As most of the simulation results end in 2005, and the most significant trend over the TP was observed after the 1970s, including the SH and V (Duan and Wu, 2008), the period 1980–2005 was used for comparisons among the models and also with observations.

3 Results

The spring mean SH flux over the CETP from 1980 to 2005 from the 71 stations, calculated using Eq. (1), and that archived in the five reanalysis datasets are shown in Fig. 1. Consistent with previous findings (Yeh and Gao, 1979; Zhao and Chen, 2001; Duan and Wu, 2008), in spring, a strong SH flux dominates the western and central TP (about 120 W m^{-2}) and gradually diminishes eastward (to about 50 W m^{-2} around the eastern corner). Over the TP, the SH varies greatly from the central plateau to the eastern TP because of the unique underlying surface characteristics and complex orography. The basic pattern of the spring SH flux over the TP is also reflected in the JRA-25, ERA-Interim, MERRA, and NCEP/DOE reanalysis data, although there is a significant discrepancy in the magnitude. However, the NCEP/NCAR data do not show an SH center at around 90°E .

The ability of the AGCMs to simulate the climate mean state is a prerequisite if past climate change is to be reproduced and future climate trends projected. Figure 2 shows the spring mean SH, V , $T_s - T_a$, T_s , and T_a averaged over the 71 stations, and the results from the reanalysis data and AGCMs extended to cover the locations of these stations via bilinear interpolation. The average SH flux

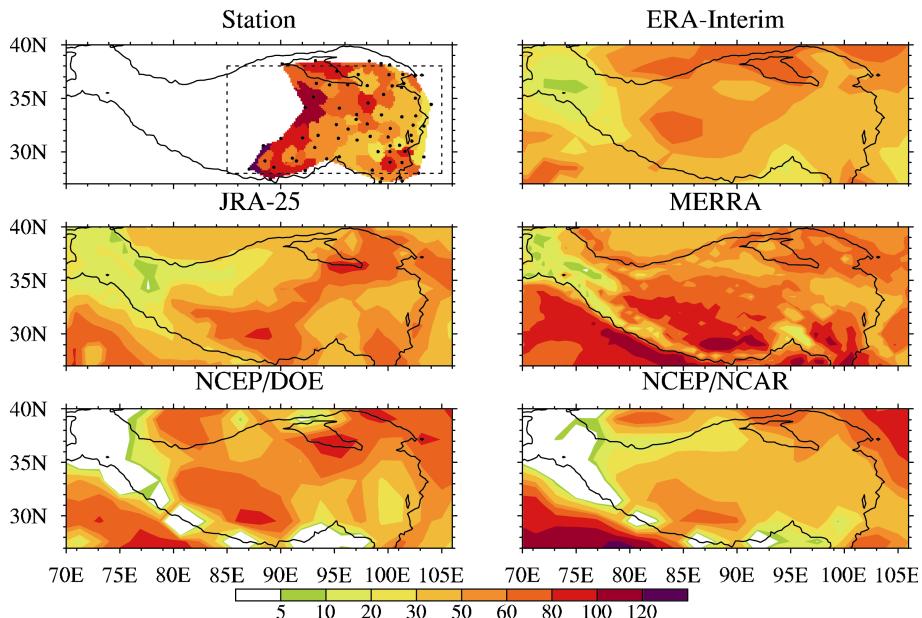


Figure 1 Spatial distribution of spring mean (March–May) sensible heat (SH) flux over the Tibetan Plateau (TP) for 1980–2005 (W m^{-2}). The thick lines indicate the area of the TP with an average altitude higher than 3000 m. In the top left panel, the locations of the 71 meteorological stations are shown by the dots, while the dashed rectangle denotes the domain of the central and eastern TP (CETP) ($28\text{--}38^\circ\text{N}, 85\text{--}105^\circ\text{E}$).

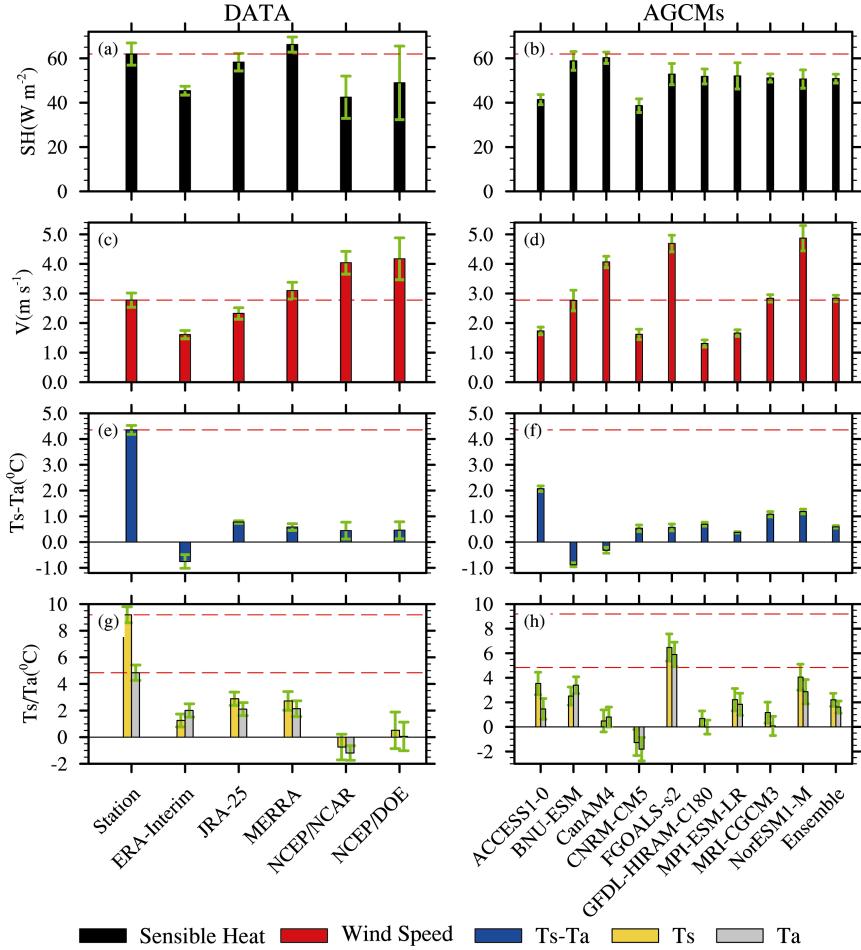


Figure 2 Average for the 71 stations, and results from the five reanalysis datasets and nine AGCMs (interpolated onto the locations of 71 stations) for: (a) and (b) spring mean SH flux (W m^{-2}), (c) and (d) 10-m wind speed V (m s^{-1}), (e) and (f) $T_s - T_a$ ($^{\circ}\text{C}$), and (g) and (h) T_s and T_a ($^{\circ}\text{C}$) for 1980–2005. The red dashed lines denote the corresponding station values and the green bars denote the standard deviation.

from the 71 stations is 62 W m^{-2} . Apart from MERRA, which gives a value of 66 W m^{-2} , the reanalysis data systematically underestimates the average SH flux, which varies from roughly 42 W m^{-2} for NCEP/NCAR to 58 W m^{-2} for JRA-25. The SH flux is also systematically underestimated by the AGCMs, with the CanAM4 generating the most realistic average value of 60 W m^{-2} . The differences among the various data sources might be related to the significant altitude differences between the model grid cell and the corresponding stations.

The details of the physical schemes governing the land surface processes vary among the different models, but the underestimated SH flux over the TP is directly related to the low value of $T_s - T_a$, because the magnitude of V in the five reanalysis datasets and most of the models is similar to or even larger than that in the observations. Low values of $T_s - T_a$ might be related to the distinct surface cold bias in the reanalysis data and models. In fact, the 71-station-averaged spring mean T_s reaches 9.2°C , whereas that in the reanalysis data is less than 3.0°C and in the AGCMs is typically less than 4.0°C . This situation is also true for T_a , because the magnitude of T_a depends largely on T_s .

In the reanalysis data, the cold bias in the daily air temperature can be mainly ascribed to the higher surface

altitude (Frauenfeld et al., 2005; Wang and Zeng, 2012), while Yang et al. (2007) attributed the substantial surface cold bias over the TP in land models to the absence of diurnal variations in C_{DH} . Zeng et al. (2012) suggested that revising the coefficients used to compute the roughness length for heat can markedly reduce the underestimation of daytime T_s , and that limiting the minimum friction velocity and soil thermal conductivity helps to make the nighttime T_s larger under light winds and dry soil situations in land models. Both identifying the cause of the surface cold bias and improving the land model in the AGCMs are beyond the scope of this paper, but the related bias in $T_s - T_a$ does influence the trend in SH, as shown below.

Figure 3 shows the trend and corresponding error bar for the averaged SH, V , and $T_s - T_a$ based on the 71 observation stations, as well as the averaged results over the CETP derived from the reanalysis data and AGCMs from 1980 to 2005. A significant weakening trend in the SH flux appears in both the observations and all five reanalysis datasets. By comparing the trend in SH with that in V and $T_s - T_a$, we can conclude that the downward trend in SH based on station observations is induced primarily by the decline in V , because the trend in $T_s - T_a$ shows an opposite (upward) trend. Liu et al. (2012) discussed the rela-

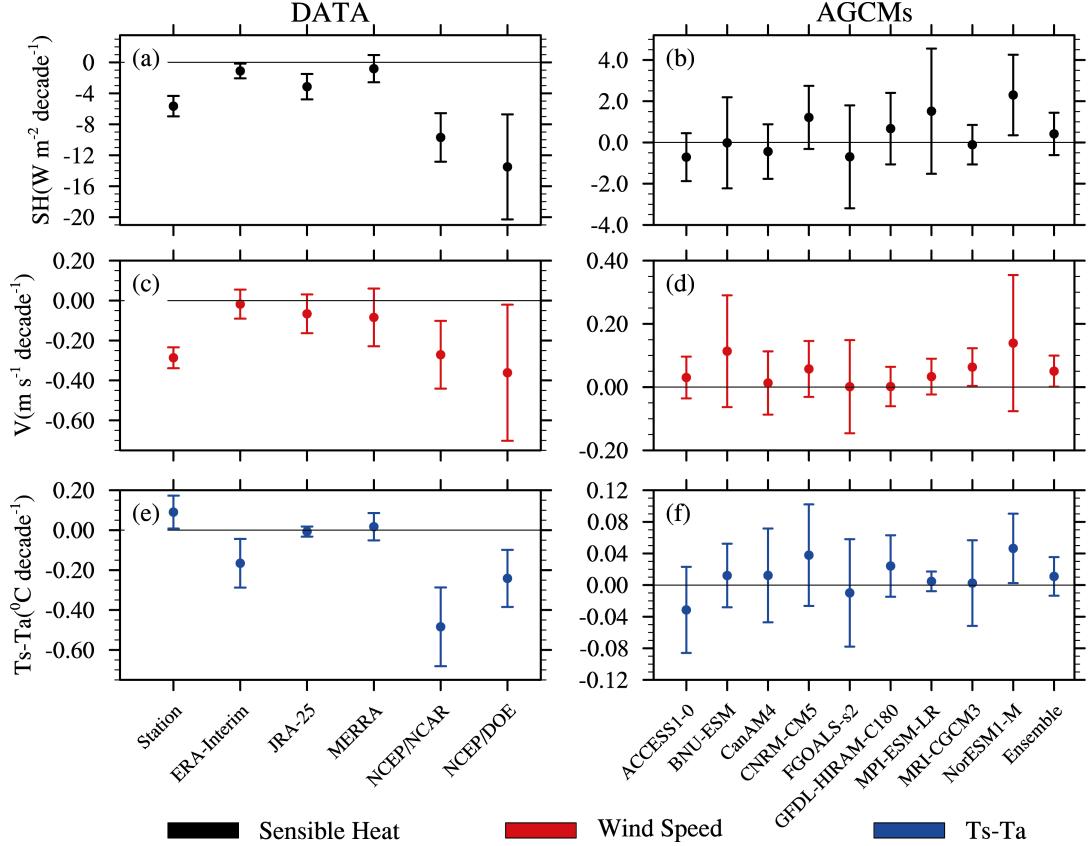


Figure 3 Average for the 71 stations, and results from the five reanalysis datasets and nine AGCMs (interpolated onto the locations of 71 stations) for spring linear trends in: (a) and (b) SH flux (W m^{-2} per decade), (c) and (d) V (m s^{-1} per decade), and (e) and (f) $T_s - T_a$ ($^{\circ}\text{C}$ per decade) for 1980–2005. The solid lines denote the zero values and the bars indicate the uncertainty at the 95% confidence level based on the standard error.

tive contribution of changes in V and $T_s - T_a$ to the downward trend in SH over the TP, and their results indicated that the relative change in $T_s - T_a$ is about one-tenth of the change in V over decadal timescales, because the climate mean value of $T_s - T_a$ over the TP is much larger than the surrounding plain regions, and its relative change is small.

In the reanalysis data, due to the assimilation procedure that takes into account the in situ observations, the declining trend in V is consistent with the observations over the TP, which helps to obtain the observed downward trend in SH. However, with regard to $T_s - T_a$, only MERRA shows a slightly increasing trend, and the decreasing trend in the other four other reanalysis datasets further enhances the weakening trend in the SH. Note that the trends in SH, V , and $T_s - T_a$ averaged over the 71 stations exceed the 95% confidence level, and this is also the case for NCEP/NCAR and NCEP/DOE.

The changes simulated in the SH, V , and $T_s - T_a$ by the nine AGCMs show a remarkable degree of divergence and uncertainty. Among them, only one model (Norwegian Earth System Model (NorESM1-M)) exhibits a significant trend in SH, but the sign is opposite to the station data. This result is not surprising for two reasons. Firstly, unlike the reanalysis data, the in situ observations are not included in the AGCMs and the historical forcing fields. Secondly, the small value of the climate mean $T_s - T_a$ related to the cold bias in the models might also be impor-

tant in the trend of the SH compared to the observation, as shown in the right panels of Fig. 3.

Based on various reanalysis datasets, recent studies by Zhu et al. (2007) and Wang et al. (2012) suggested that, over the TP, there has been a decreasing trend in the total atmospheric heat source, which agrees with the results derived from in situ and satellite observations (Duan and Wu, 2008). To test the models' abilities to reproduce the trend in the total diabatic heating over the TP, in Fig. 4 we plot the trend in each individual component of diabatic heating over the CETP derived from the JRA-25 reanalysis data and the nine AGCMs. It is evident that in the JRA-25 data a significant decreasing trend in the atmospheric diabatic heating occurs from 1980 to 2005 due to the weakened SH flux and enhanced radiative cooling effect, despite it being offset somewhat by a slight increase in latent heat. In the AGCMs, the decreasing trend in the total atmospheric diabatic heating occurs in only a few models (NorESM1-M, GFDL-HIRAM-C180, Meteorological Research Institute-coupled climate model (MRI-CGCM3), and Centre National de Recherches Meteorologiques/Centre European de Recherche et Formation Avancees en Calcul Scientifique (CNRM-CM5), in order of amplitude), and most are not statistically significant. Moreover, the trend is induced mainly by the reduced latent heat release rather than the SH flux. Two AGCMs (CanAM4 and The Flexible Global Ocean-Atmosphere-

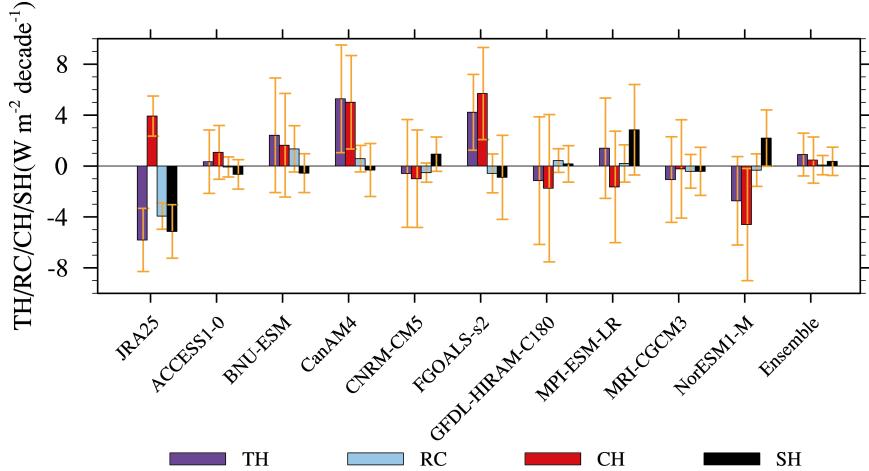


Figure 4 Linear trends in the total atmospheric heat source (TH) and each component, i.e., SH, heat release due to condensation of precipitation (CH), and the net radiative cooling of the air column (RC) for 1980–2005 in CETP domain-averaged results from the JRA-25 data and the nine AGCMs. All results were regridded onto $2.5^\circ \times 2.5^\circ$ grids to facilitate the comparison. Units: W m^{-2} per decade. The bars indicate the uncertainty at the 95% confidence level based on the standard error.

Land System model, Spectral Version 2 (FGOALS-s2) even show a significant increasing trend in the total atmospheric diabatic heating, due to the remarkable increase in the release of latent heat. Therefore, the current AGCMs have almost no skill at reproducing changes in either the SH flux or the total atmospheric heat source over the CETP.

4 Summary

In this paper, we have examined the ability of state-of-the-art AGCMs to simulate recent trends in the spring atmospheric diabatic heating over the CETP. By comparing simulations from nine AGCMs driven by historical forcing fields, with observational records, and five reanalysis datasets, we found that the AGCMs are unable to reproduce the observed weakening trend in the spring SH flux and the total atmospheric diabatic heating over the CETP. According to the bulk formula, the observed trend in the SH over the CETP depends chiefly on the change in V due to the distinct $T_s - T_a$. The decelerated V is thereby responsible for the downward trend in SH. However, in the models, the trend in the SH is determined by the change in both V and $T_s - T_a$ for the systematic surface cold bias. As a result, most of the AGCMs cannot reproduce the observed trend in either V or $T_s - T_a$, which leads to their inability to simulate the trend in SH. In addition, the simulated trends in the other two components of the total atmospheric diabatic heating (i.e., the release of latent heat due to precipitation and the net radiative cooling of the air column) also showed a large discrepancy. Therefore, it is necessary to improve the physical schemes that simulate land surface processes and atmospheric diabatic heating, such as cumulus convective and cloud-radiation feedback mechanisms, if we wish to realistically reproduce local climate change.

As revealed by our previous study (Duan and Wu, 2009), the trend in surface wind speed over the TP is directly related to the large-scale warming pattern and the

resultant change in the westerly jet in the upper troposphere. The intrinsic link between regional and large-scale climate changes around the TP, together with the interactions among the components of the atmospheric diabatic heating, require further investigation.

Acknowledgements. This work was supported jointly by the Strategic Priority Research Program—Climate Change: Carbon Budget and Related Issues of the Chinese Academy of Sciences (Grant No. XDA-05110303), the Chinese Ministry of Science and Technology (Grant No. 2010CB951703), the National Natural Science Foundation of China (Grant No. 41175070), Special Fund for Public Welfare Industry (meteorology) administered by the Chinese Ministry of Finance and Ministry of Science and Technology (Grant No. GYHY201406001), and Key Laboratory of Meteorological Disaster, Nanjing University of Information Science and Technology, Ministry of Education (Grand No. KLME1309).

References

- Dee, D. P., S. Uppala, A. Simmons, et al., 2011: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system, *Quart. J. Roy. Meteor. Soc.*, **137**, 553–597.
- Duan, A. M., M. R. Wang, Y. H. Lei, et al., 2013: Trends in summer rainfall over China associated with the Tibetan Plateau sensible heat source during 1980–2008, *J. Climate*, **26**, 261–275.
- Duan, A. M., and G. X. Wu, 2005: Role of the Tibetan Plateau thermal forcing in the summer climate patterns over subtropical Asia, *Climate Dyn.*, **24**, 793–807, doi:10.1007/s00382-004-0488-8.
- Duan, A. M., and G. X. Wu, 2008: Weakening trend in the atmospheric heat source over the Tibetan plateau during recent decades. Part I: Observations, *J. Climate*, **21**, 3149–3164.
- Duan, A. M., and G. X. Wu, 2009: Weakening Trend in the atmospheric heat source over the Tibetan Plateau during recent decades. Part II: Connection with Climate Warming, *J. Climate*, **22**, 4197–4212.
- Frauenfeld, O. W., T. Zhang, and M. Serreze, 2005: Climate change and variability using European Centre for Medium-Range Weather Forecasts reanalysis (ERA-40) temperatures on the Tibetan Plateau, *J. Geophys. Res.*, **110**, D02101, doi:10.1029/2004JD005230.
- Hahn, D. G., and S. Manabe, 1975: The role of mountains in the south Asian monsoon circulation, *J. Atmos. Sci.*, **32**, 1515–1541.

- Kalnay, E., M. Kanamitsu, R. Kistler, et al., 1996: The NCEP/NCAR 40-Year reanalysis project, *Bull. Amer. Meteor. Soc.*, **77**, 437–471.
- Kanamitsu, M., W. Ebisuzaki, J. Woollen, et al., 2002: NCEP-DOE AMIP-II reanalysis (R-2), *Bull. Amer. Meteor. Soc.*, **83**, 1631–1643.
- Kazutoshi, O., T. Junichi, K. Hiroshi, et al., 2007: The JRA-25 reanalysis, *J. Meteor. Soc. Japan*, **85**, 369–432.
- Li, C. F., and M. Yanai, 1996: The onset and interannual variability of the Asian summer monsoon in relation to land-sea thermal contrast, *J. Climate*, **9**, 358–375.
- Liu, Y. M., G. X. Wu, J. L. Hong, et al., 2012: Revisiting Asian monsoon formation and change associated with Tibetan Plateau forcing: II. Change, *Climate Dyn.*, 1183–1195, doi:10.1007/s00382-012-1335-y.
- Luo, H., and M. Yanai, 1983: The large-scale circulation and heat sources over the Tibetan Plateau and surrounding areas during the early summer of 1980. Part I: Precipitation and kinematic analyses, *Mon. Wea. Rev.*, **111**, 922–944.
- Rienecker, M. M., M. J. Suarez, R. Gelaro, et al., 2011: MERRA: NASA's Modern-Era retrospective analysis for research and applications, *J. Climate*, **24**, 3624–3648.
- Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2012: An overview of CMIP5 and the experiment design, *Bull. Amer. Meteor. Soc.*, **93**, 485–498, doi:10.1175/BAMS-D-11-00094.1.
- Wang, A. H., and X. B. Zeng, 2012: Evaluation of multireanalysis products with in situ observations over the Tibetan Plateau, *J. Geophys. Res.*, **117**, D05102, doi:10.1029/2011JD016553.
- Wang, M. R., S. W. Zhou, and A. M. Duan, 2012: Trend in the atmospheric heat source over the central and eastern Tibetan Plateau during recent decades: Comparison of observations and reanalysis data, *Chinese Sci. Bull.*, **57**, 548–557, doi:10.1007/s11434-011-4838-8.
- Wu, G. X., W. P. Li, H. Guo, et al., 1997: Sensible heat driven air-pump over the Tibetan Plateau and its impacts on the Asian Summer Monsoon, in: *Collections on the Memory of Zhao Jiuzhang*, D. Ye et al. (Eds.), Chinese Science Press, Beijing, 116–126.
- Wu, G. X., Y. M. Liu, J. L. Hong, et al., 2012: Revisiting Asian monsoon formation and change associated with Tibetan Plateau forcing: I. Formation, *Climate Dyn.*, 1169–1181, doi:10.1007/s00382-012-1334-z.
- Wu, G. X., and Y. S. Zhang, 1998: Tibetan Plateau forcing and the timing of the monsoon onset over south Asia and the South China Sea, *Mon. Wea. Rev.*, **126**, 913–927.
- Yang, K., X. F. Guo, J. He, et al., 2011: On the climatology and trend of the atmospheric heat source over the Tibetan Plateau: An experiments-supported revisit, *J. Climate*, **24**, 1525–1541.
- Yang, K., M. Rasmy, S. Rauniar, et al., 2007: Initial CEOP-based review of the prediction skill of operational general circulation models and land surface models, *J. Meteor. Soc. Japan*, **85A**, 99–116.
- Yeh, T. C., and Y. X. Gao, 1979: *Meteorology of the Qinghai-Xizang (Tibet) Plateau* (in Chinese), Science Press, Beijing, 278pp.
- Yeh, T. C., S. W. Lo, and P. C. Chu, 1957: On the heat balance and circulation structure in troposphere over Tibetan Plateau (in Chinese), *Acta Meteor. Sinica*, **28**, 108–121.
- Zeng, X. B., W. Zhuo, and A. H. Wang, 2012: Surface skin temperature and the interplay between sensible and ground heat fluxes over arid regions, *J. Hydrometeorol.*, **13**, 1359–1370.
- Zhao, P., and L. X. Chen, 2001: Climate features of atmospheric heat source/sink over the Qinghai-Xizang Plateau in 35 years and its relation to rainfall in China, *Sci. China Ser. D-Earth Sci.*, **44**, 858–864.
- Zhu, Y. X., Y. H. Ding, and H. G. Xue, 2007: The decadal relationship between atmospheric heat source of winter and spring snow over Tibetan Plateau and rainfall in east China, *Acta Met. Sinica* (in Chinese), **65**, 947–958.