

Future Changes in Surface Temperature and Precipitation in Arid and Semi-arid Regions Revealed by the Multi-Model Ensemble (MME) Dataset for the IPCC AR4

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Abstract: Characteristics of climate change in arid and semi-arid regions have been investigated using the Multi-Model Dataset (MMD), where data submitted for IPCC AR4 by many research centers are compiled under the project CMIP3, WCRP. Five arid and semi-arid regions (Central Asia, Middle East, South West United States, Sahara and Australia) are selected and future changes in surface temperatures and precipitation are investigated using MME data. A significant increase in surface temperature in the five regions is found, but precipitation change is noticed only in winter and in the central Asia and Sahel regions. As our understanding of the climate system in an arid region is limited and many unknown processes operate, it is still questionable as to whether these simulation results are reliable. Therefore, it is necessary to estimate the reliability, for which the relationship between the time-averaged error in the present climate and the future change due to a doubling of CO₂ is examined. The relationship to surface temperature has been examined over the Central Asia and the Sahara regions. After screening MME data, 14 models are selected, and a meaningful correlation in the annual and seasonal means is found in those regions. This is because the surface temperature is considered to be governed by the radiative energy balance. In contrast, a significant correlation to change of annual mean precipitation could not be found over these regions. This is because precipitation is governed by a rainfall event and convective systems. A relationship is found only in winter, because precipitation in winter may be controlled by disturbances in the mid-latitude.

Key words: Global warming, climate model, IPCC, MMD.

The Fourth Assessment Report (AR4) of the IPCC (Intergovernmental Panel for Climate Change), published in 2007, has noted that "most of the observed increase in global average temperature since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations" (IPCC, 2007) and concluded that contribution by human activities to the recent raising of surface temperature has a more than 90%

confidence level. Based on the increase in scientific knowledge since IPCC TAR (Third Assessment Report), mitigation and adaptation of the greenhouse gas has become a political agenda item in the international diplomatic world. In international negotiations, it is critical and essential to present a pathway towards a sustainable society for both developed and developing countries. In this sense, climate change in the regions becomes important. In chapter

Table 1. A list of participating models in the MME data set. Most of abbreviations consist of the name of the research center and -the model name. However, MIROC (Model Inter-disciplinary for Research On Climate) is the model name developed by CCSR, NIES, and JAMSTEC. For abbreviations refer to Table 2

Bccr_bcm2_0	giss_model_e_h	mri_cgcm2_3_2°
cccma_cgcm3_1	lap_fgoals1_0_g	ncar_ccsm3_0
cccma_cgcm3_1_t63	ingv_echam4	ncar_pcm1
cnrm_cm3	inmcm3_0	ukmo_hadcm3
csiro_mk3_0	ipsl_cm4	ukmo_hadgem1
Gfdl_cm2_0	miroc3_2_hires	
gfdl_cm2_1	miroc3_2_medres	
giss_aommpi_echam5		

The percentage change in precipitation for each region during summer (JJA), the ensemble mean value and standard deviation between models are shown in Fig. 4. According to it, precipitation will increase in Central Asia, but will decrease in

South-West US, the Sahara and Australia. There is no clear tendency in the Middle East. However, both positive and negative standard deviations between models are found for all cases, making it difficult to conclude about the change. In other words,

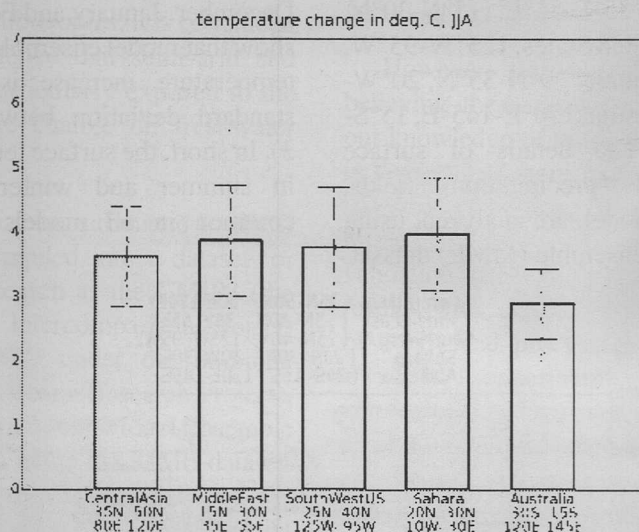


Fig. 2. Temperature change for each arid region in degrees Celsius. Changes are defined as the difference between 1980-1999 means and 2080-2099 means. The scenario for the 21st century is SRES A1B. Arid areas are defined in Fig.1. Each bar indicates an ensemble mean of the percentage change in precipitation for each area for June-July-August. The error bar denotes the inter-model standard deviation. Light-dark circles represent each model result, showing a significant scatter in many cases.

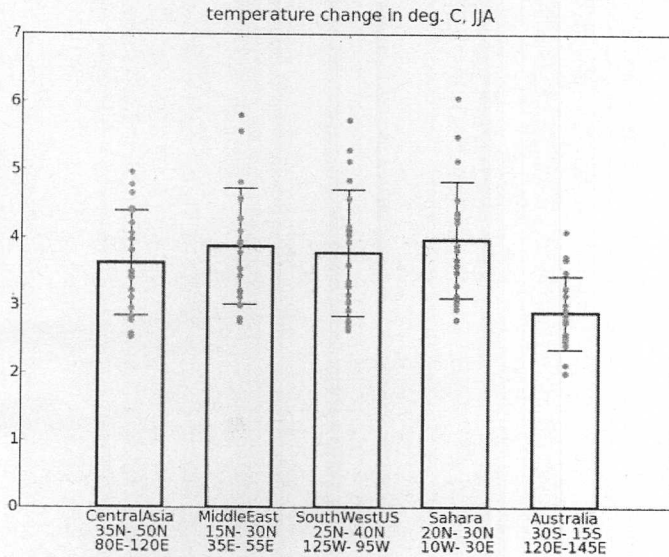


Fig. 3. As in Figure 2 but for December-January-February.

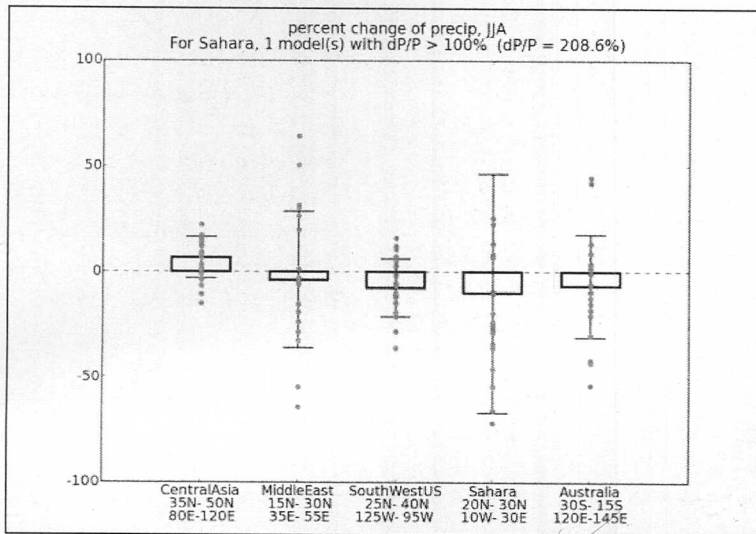


Fig. 4. Percentage change in precipitation for each arid region. Changes are defined as the difference between 1980-1999 means and 2080-2099 means. The scenario for the 21st century is SRES A1B. Arid areas are defined in Fig. 1. Each bar indicates an ensemble mean of percentage change in precipitation for each area for June-July-August. The error bar denotes the inter-model standard deviation. Light-dark circles represent each model result, showing a significant scatter in many cases.

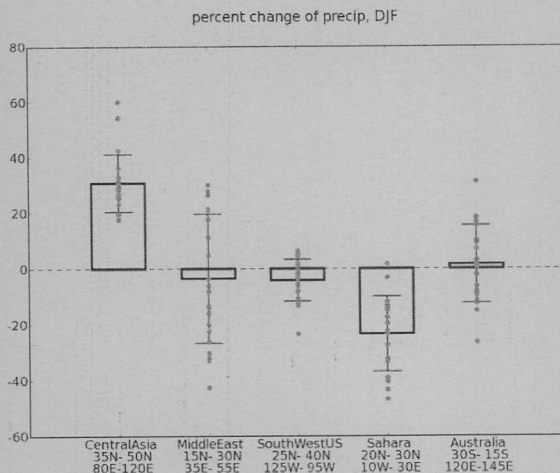


Fig. 5. As in Figure 3 but for December-January-February.

we cannot say whether precipitation in the arid and semi-arid regions is increasing with warming due to CO₂ doubling.

Similarly, the percentage change in precipitation for each region during winter (DJF) shows increase over Central Asia and decrease in the Sahara Desert (Fig. 5). Standard deviation between models in these two regions is located in positive or negative regions and it is concluded that these two changes are significant. As for the other three regions, it is impossible to derive definite conclusions. In summary, surface temperature increase is common in 5 regions, but precipitation differs. Therefore, detailed analysis of the Central Asia and the Sahara is conducted in the following sections.

How Reliable are the Changes?

Although many simulation results have been presented, there still remains a question regarding reliability of the results. In particular, precipitation and land surface processes play very important roles in the

climate of arid and semi-arid regions, and it is important to see how well these processes are represented in an atmospheric General Circulation Model (GCM).

Different schemes and algorithms have been used for a land surface process in the GCM. There are many types of land surface models, such as the bucket model (Manabe, 1965), BATS (Dickinson *et al.*, 1993), etc. Characteristics of these models have been reviewed by Pitman and Henderson-Sellers (1998).

In order to improve the performance of a land-surface model, many intensive validation programmes have been conducted. As a land-surface model, PILPS (the Project for Intercomparison of Land-Surface Parameterization Scheme) was launched in 1992 under the umbrella of WCRP (World Climate Research Programme). It covers many different regions, such as a forest and a grassland in both the tropics and mid-latitudes. In particular, the PILPS semi-arid experiment was conducted for the arid and semi-arid regions. However, it should

be noted that model results are influenced by many processes and improvement of a single scheme does not directly contribute to the improvement of total performance of the model. Climate in the arid and semi-arid regions is strongly influenced by the change in large-scale circulation, which is influenced by the model performance at the global-scale. The total performance of the model should be carefully examined. Analysis of the spread of model results are considered to contribute to evaluation of limits of performance of the models, although this is not straightforward.

Another important process in determining climate in arid and semi-arid regions is the precipitation process, which is controlled by the convective process and atmospheric circulation. In the large-scale GCM, precipitation process is represented by a parameterization scheme, and there remains an uncertainty in the parameterization of convective processes. As large-scale circulation is better simulated than the convective process, it is considered that precipitation, associated with the large-scale motion, is better represented in GCM. Usually, validation of model results is conducted by comparing model results with observed values and, so far, it is concluded that the present GCM well represents a large-scale precipitation field in the present climate.

Nevertheless, there exists an error in simulated fields, which is considered to be a reflection of model insufficiency. Therefore, careful examination of model results may shed insight on model performance.

For example, time-averaged errors are considered to be related to a model response of forcing, because transient errors may

be cancelled out by the time-averaging process. On the other hand, climate change in a warmer climate, due to CO₂ doubling, is considered to be a response to increased forcing, and it is natural to consider whether there exists some relation between the two values. The relationship can be considered as follows.

The present observation is assumed to be represented by:

$$O + \epsilon_0 = M_t * F_t + G_t \quad \text{.....(1)}$$

Here, O is an observed climate value and ϵ_0 is an error in observation. Observation is considered to be a sum of a free mode and a response due to a forcing. In this paper, the response to forcing is assumed to be approximated to a linear process. G_t is the free modes component which, in other words, is the variability without forcing in the climate system. Then, a simulated climate value from the i -th model, $S(i)$, is represented as:

$$S(i) = (M_t + \epsilon(i))(F_t + \epsilon F(i)) + G_t + \epsilon G(i) \quad \text{.....(2)}$$

where, $S(i)$ is a simulated climate value and $\epsilon(i)$ is the error in the i -th model; $\epsilon F(i)$ is the forcing error in the i -th model; $\epsilon G(i)$ represents an error in the i -th model in the variability in the climate system. In general, $\epsilon G(i)$ is complex and could be large in amplitude, but, in this paper, it is assumed to be neglected. Then, the time-averaged error is:

$$\Delta E(i) = S - O = \epsilon(i)F_t + M_t * \epsilon F(i) \quad \text{.....(3)}$$

here, the time-average operator is neglected.

On the other hand, the future climate, $W(i)$, due to global warming in the i -th model is estimated as follows:-

$$W(i) = (M_t + \varepsilon(i))(F_t + \varepsilon F(i) + \Delta F_w(i)) + G't + \varepsilon G'(i) \quad \dots(4)$$

where, $\Delta F_w(i)$ is a forcing due to CO_2 increase in the i -th model. Again, it should be noted that a change in $G_t + \varepsilon G(i)$ due to CO_2 doubling is assumed to be small. In other words, $G_t + \varepsilon G(i) = G't + \varepsilon G'(i)$. Then, the climate change due to the CO_2 increase, $\Delta W(i)$, is computed as:

$$\Delta W(i) = W(i) - S(i) = (M_t + \varepsilon(i)) \Delta F_w(i) \quad \dots(5)$$

Therefore, when $\varepsilon F(i)$ in (3) is small, i.e., forcing error in the present climate system is small in the models, $\Delta E(i)$ and $\Delta W(i)$ has the relationship,

$$\Delta W(i) - M_t \Delta F_w(i) = \frac{\Delta F_w(i)}{F_t} \times \Delta E(i) \quad \dots(6)$$

As $\Delta F_w(i)$ is not very different between models, $\Delta W(i)$ and $\Delta E(i)$ have a linear relationship.

It should be noted that contribution of natural variability is assumed to be small. Therefore, there is no guarantee as to whether the relationship described above holds good. This relationship is examined in the next section.

Relationship between Systematic Error in the Present Climate and the Future Climate Change

Significant increase in the surface temperature is noted over the five regions, but significant precipitation change in winter is noted only in the Central Asian and the Sahara regions. Therefore, these two regions are selected for examination of the assumption highlighted.

Before discussing the details, it is beneficial to describe the manner in which annual cycles of surface temperature and precipitation occur. For temperature observations, we employ the long-term monthly mean of the NCEP/NCAR reanalysis (Kalnay *et al.*, 1996). We use two datasets for precipitation: the long-term monthly mean from the Xie and Arkin (1997) dataset for the Central Asia, and the 1998-2005 monthly average from the TRMM 3G68 (TMI-PR-combined) precipitation product for Sahara (Kummerow *et al.*, 1998). Strictly speaking, the averaging period differs between the MME and observational datasets, but as we will see, the effect of different averaging periods should be minor relative to model errors. First, the annual cycle of surface temperature in Central Asia is displayed in Fig. 6(a), as a monthly mean value, time-averaged between 1980 and 1999 in the 20C3M run in 21 models, which simulate the general characteristics of the annual cycle well, although there are biases of a few degrees. The annual cycle, averaged between 2080 and 2099 in the SRES A1b, is shown in Fig. 6(b). The profile of the annual cycle in the warmer climate is similar to that in the present climate, but an upward shift is noted, which means that a relatively uniform warming, independent of season, is occurring. This can be clearly seen in the difference between 2080-2099 and 1980-1999 in Fig. 6(c). Similarly, the annual cycle of surface temperature over the Sahara region is shown in Fig. 7(a), where the model results are scattered around the observations and differences between model results and observations are within a few degrees. Thus, the general features of the annual cycle are depicted in the

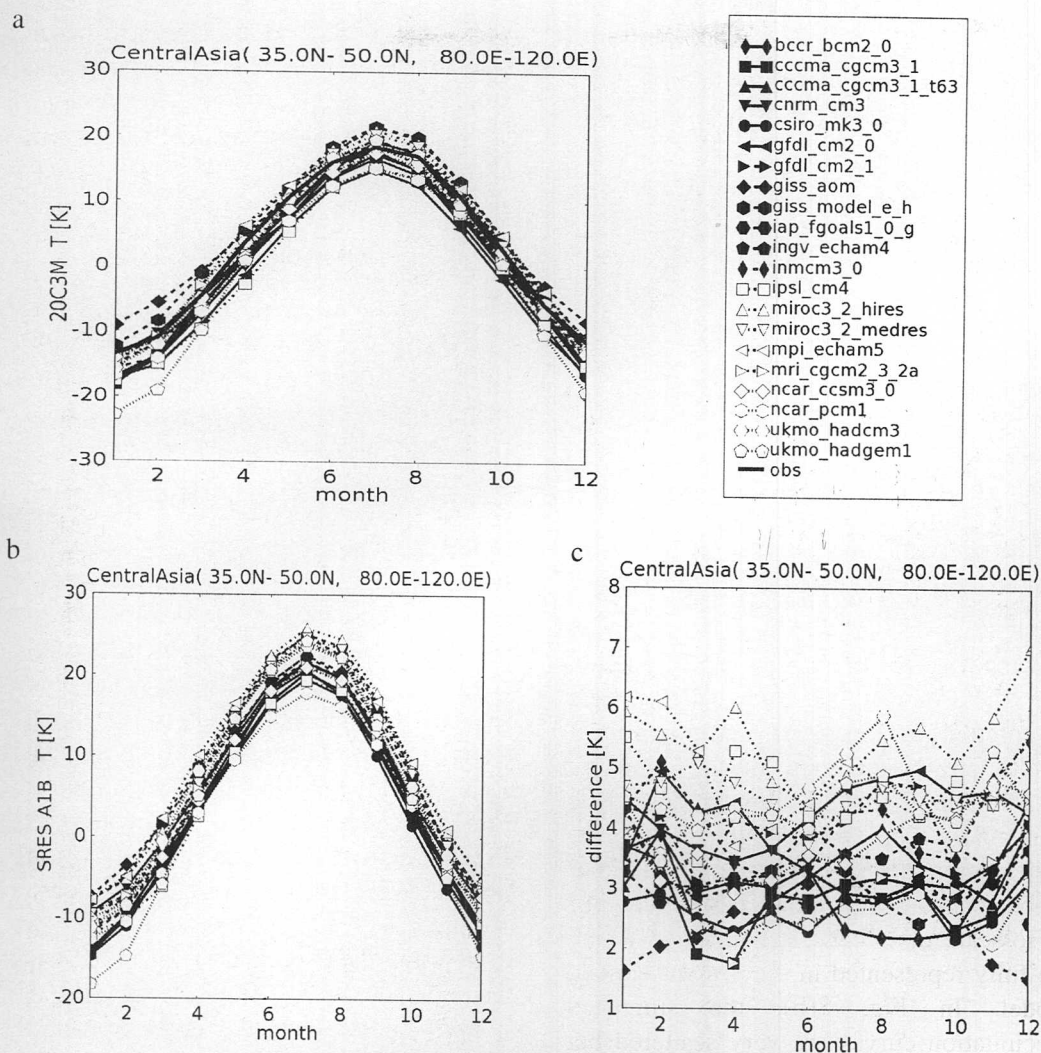


Fig. 6. (a) Annual cycle of surface temperature over Central Asia in the present climate(1980-1999) from MME data. Unit is $^{\circ}\text{C}$.

(b) Annual cycle of surface temperature over the warmer climate(2080-2099) in the SRES A1B scenario.

(c) Increase in surface temperature due to global warming over Central Asia. Unit is $^{\circ}\text{C}$.

models, but there remains significant biases. The increase in the surface temperature, is also shown in Fig. 7(b). It is noted that the monthly variability in the difference

is small, compared to the change in the annual mean temperature. All model results show an increase in surface temperature, but inter-seasonal variability is small,

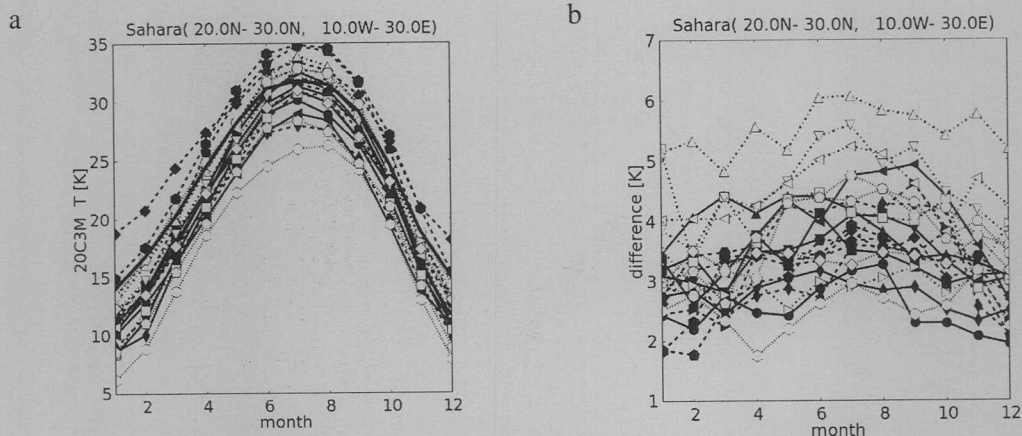


Fig. 7. (a) Same as Figure 6 (top), except for the Sahara region.
(b) Same as Figure 6 (bottom), except for the Sahara region.

compared with the annual mean. The seasonal difference tends to become greater in summer and autumn.

Model results for changes in precipitation over the Central Asia due to 21 models are plotted in Fig. 8(a). All the model results are larger than those found by observation. Errors in summer are larger than those in winter. It should be remembered that precipitation in summer is associated with thunderstorms and/or meso-scale disturbances, neither of which are fully represented in the present climate model. In Fig. 8(b), the simulated precipitation curves are very scattered but appear to converge in the winter. This is because the winter precipitation in Central Asia is mainly influenced by large-scale circulation, which is controlled by large-scale atmospheric dynamics. Present models can well represent the phenomena governed by the large-scale dynamics. By contrast, precipitation in the summer is controlled by small-scale phenomena, whose representation is not so good in the present large-scale models.

The annual cycle over the Sahara is shown in Fig. 9. Most models cannot reproduce the annual cycle of precipitation over the Sahara, where slight differences tend to be exaggerated. Since there are very few reliable observations to estimate precipitation amounts over the region, data from satellite-borne TRMM (Tropical Rainfall Measurement Mission) PR (Precipitation Radar) sensor, measuring rainfall over land as well as the ocean (Kummerow *et al.*, 1998) is taken for observation data-set. Based on TRMM PR data, Harada *et al.* (2003) estimated the monthly rainfall over the Sahara from 1998 to 2001, where precipitation in the summer was greater than that in the winter. In particular, it was shown that May, 2000 and September, 2001 had a maximum of $\sim 90 \text{ mm month}^{-1}$. Therefore, it cannot be concluded that early summer and early autumn peaks in precipitation, simulated by models, are wrong, although attention should be paid to the amount of precipitation. Again, it should be noted that rainfall in the dry season results from several

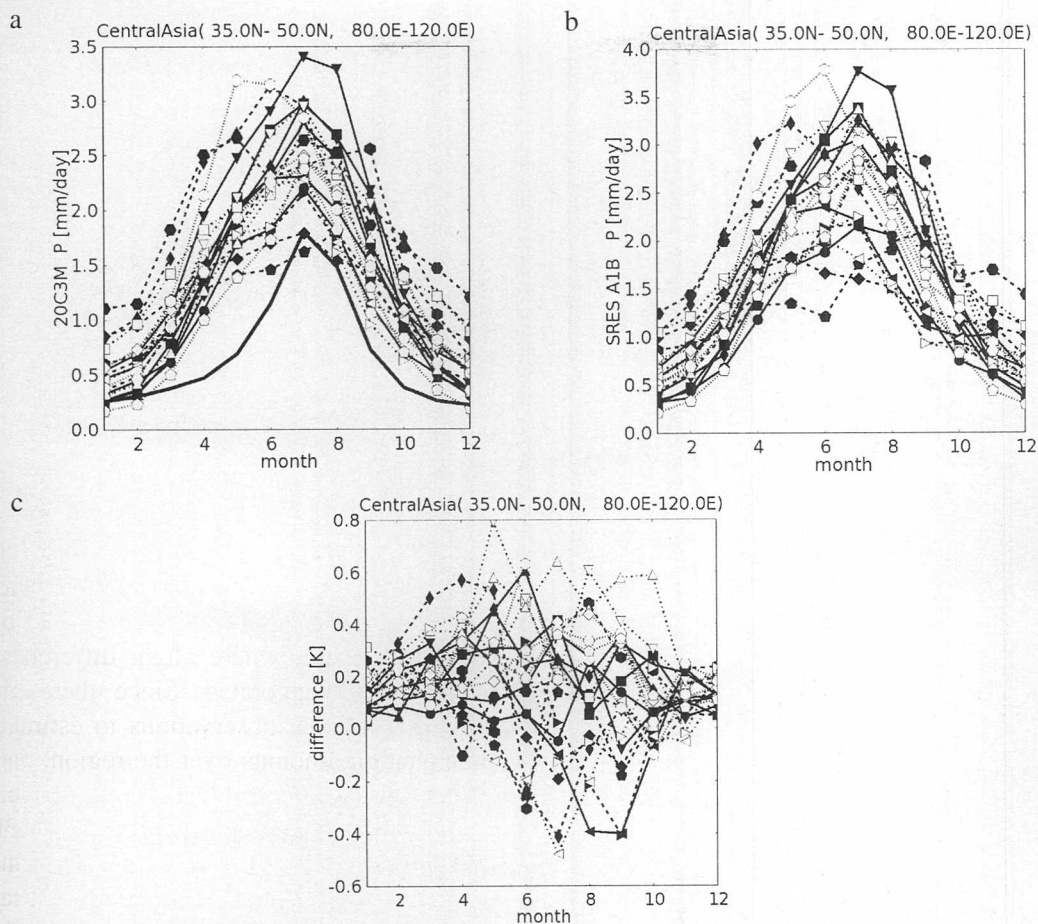


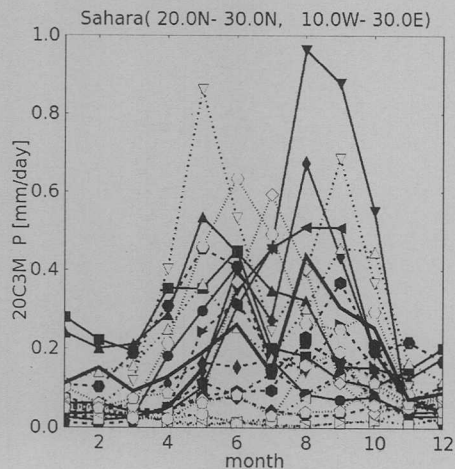
Fig. 8. Same as Figure 6, except for precipitation in the Central Asia region.

thunderstorms, which are not well represented in the present model. On the contrary, cyclones in the mid-latitude move southwards and the rainfall associated with weather fronts becomes dominant in the winter. This is why precipitation in the winter converges amongst in the models. This is a common feature of the performance of climate models in a desert area.

Although the increase in surface temperature in a warm climate is robust in the models, their reliability is doubtful, because model's performance in desert

conditions is not expected to be so good. The relationship between temperature increase (dT) in the warming climate and temperature bias (T_{bias}) in the present climate need also to be examined. As explained earlier, T_{bias} represents the inadequacy of a model performance for the present climate, which may be related to future climate change. This is because the surface temperature is mainly controlled by the averaged radiational balance in the large scale and is not so sensitive to land surface processes.

a



b

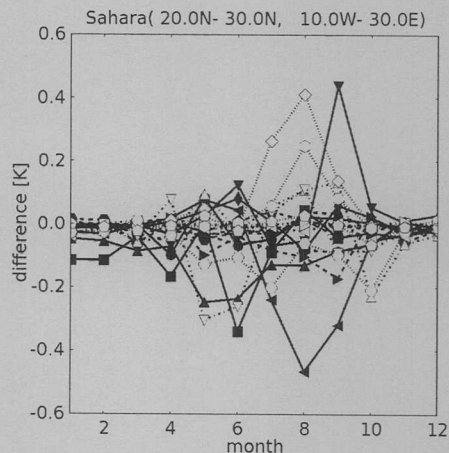


Fig. 9. (a) Annual cycle of surface temperature over the Sahara region in the present climate(1980-1999) from MME data. Unit is $^{\circ}\text{C}$.
(b) Increase in surface temperature due to global warming over Central Asia. Unit is $^{\circ}\text{C}$.

The annual averaged temperature increase (dT) and temperature biases (T_{bias}) of 21 models are shown in Fig. 10(a) which reveal no correlation ($r=-0.02$) between dT and T_{bias} . However, it is noted that there are two groups, one being highly correlated, whilst the other comprises outliers. Outliers, which are subjectively judged, include *gfdl_cm2_1*, *ingev_echam4*, *giss_aom*, *giss_model_e_h*, *hadgem1*, *inmcm3.0* and *ipsl_cm4*, whilst 7 model results are omitted. These model results are outlier from many model results in other regions, which suggests that these model performances are somewhat different from the others and that the assumption described in earlier section is not valid for all models. It is uncertain as to why GFDL CM2.0 and CM2.1 are so different and further detailed examination of model performance is necessary. The scatter diagram for 14 models shows that the

correlation increases from -0.02 to 0.83 (Fig. 10b). In order to confirm that this selection is reasonable, the case of the Sahara region is displayed in Fig. 11. In this case, the correlation increases from 0.18 (21 model cases) to 0.63 (14 models). It suggests that the selection is reasonable and, hereafter, we concentrate on the 14 model data.

The scatter diagrams of dT and T_{bias} in winter and summer are examined for both regions. A similar trend is found in both the winter and summer cases. In the Central Asia case, the correlation coefficient in JJA rises from 0.08 to 0.47 and the correlation coefficient in DJF rises from -0.18 to 0.6. In the Sahara case, the correlation coefficient increases from 0.28 to 0.64 (JJA) and from 0.07 to 0.51 (DJF). In other words, a future increase in surface temperature over the central Asia and Sahara due to CO_2 doubling has a correlation with

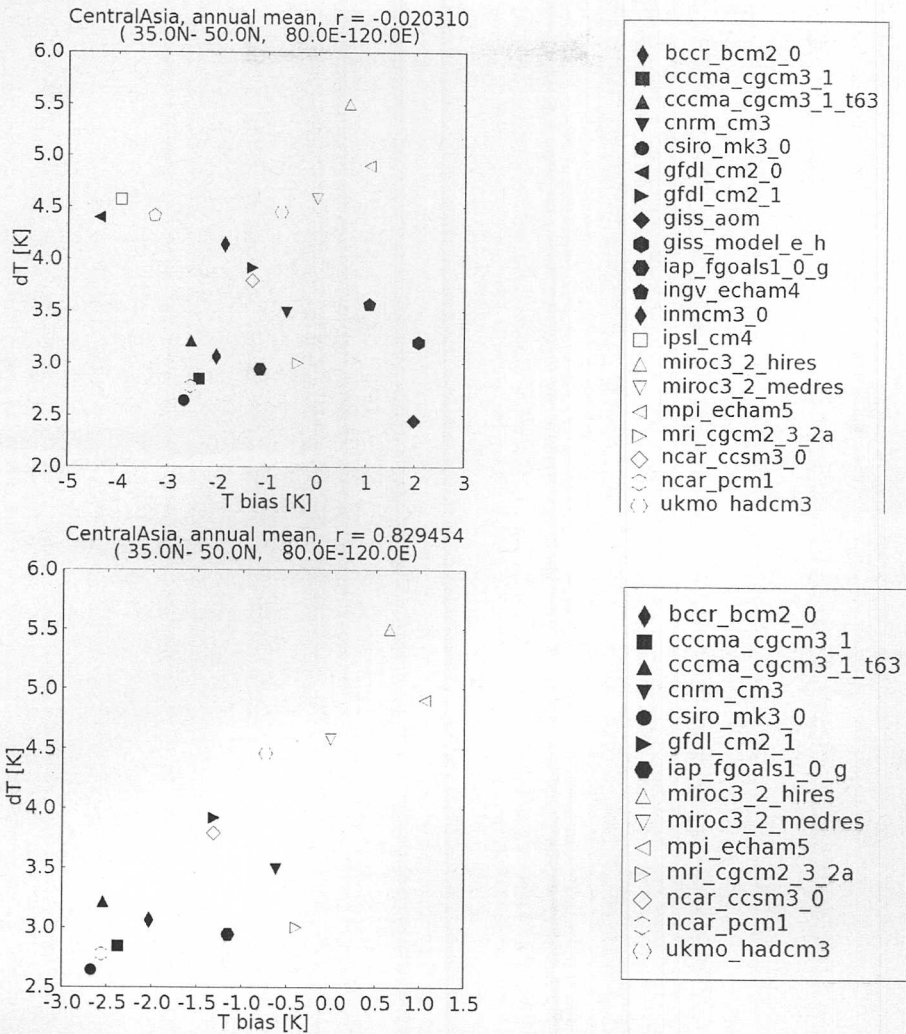


Fig. 10. (top) Time-averaged error(horizontal axis) and increase, due to CO_2 doubling, of surface temperature over Central Asia for MME data. (bottom) Same as above, except for eliminating 6 model results.

systematic error in the present climate in summer and winter, and with the annual mean, which may be related to differences in the model architecture.

Next, precipitation is examined. It is considered that a precipitation field is different from a temperature field. Temperature has a continuous value and

is considered to be related to the energy balance. However, precipitation is an event with a positive-definite value and is related to atmospheric motion. Annual mean precipitation increase (dP) and precipitation bias (P_{bias}) over the Central Asia and the Sahara are shown in Fig. 12(a) and (b), respectively. In these cases, correlation is

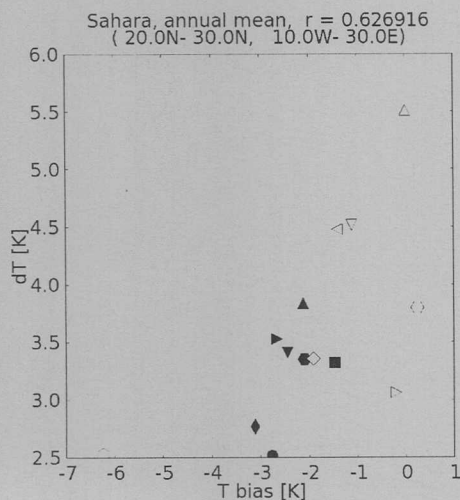


Fig. 11. Same as Figure 10 (bottom), except for the Sahara region.

not high and exclusion of 7 model results does not give a significant impact, i.e., from 0.16 (21 models) to 0.14 (14 models) in Central Asia and from -0.36 (21 models) to -0.33 (14 models) in the Sahara. A precipitation field is related to a rainfall

event, which is controlled by many processes and it is considered that the assumption made earlier does not work so well.

The relationship in summer and winter is also examined. The Central Asia and the Sahara cases for, winter only, are shown in Fig. 13(a) and (b), respectively. Both show a linear relationship, but the inclination is different. A positive correlation in summer in central Asia is also noted, but there is no meaningful correlation in the Sahara case. This is because the precipitation in winter may be controlled by disturbances in the mid-latitude and is strongly influenced by atmospheric dynamics. On the other hand, rainfall in summer is strongly controlled by convection and meso-scale phenomena and its representation is considered to be diverse. It is considered that there are two mechanisms for increasing rainfall, i.e., (1) an increase in precipitation intensity and (2) an increase in the number of rainy days. These two aspects were examined for the Central Asia and the Sahara cases. Increase

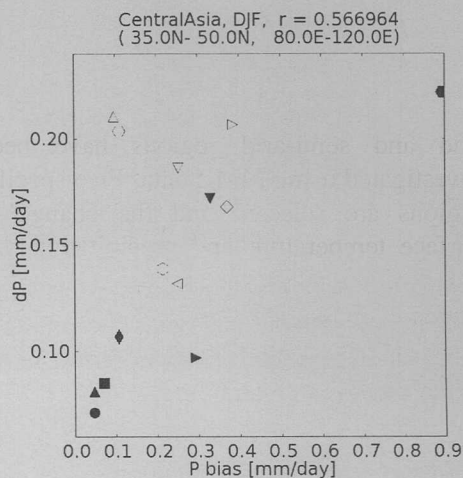
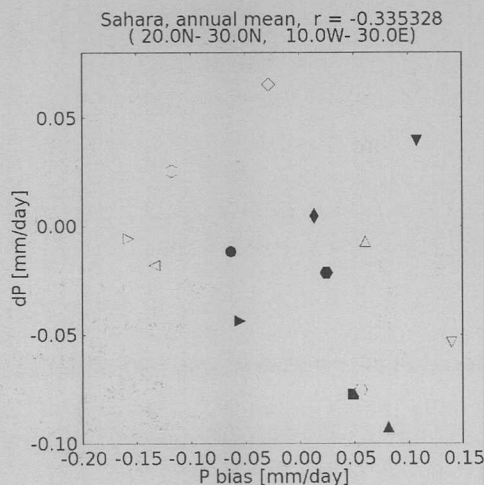


Fig. 12. Same as Figure 10, except for the precipitation.

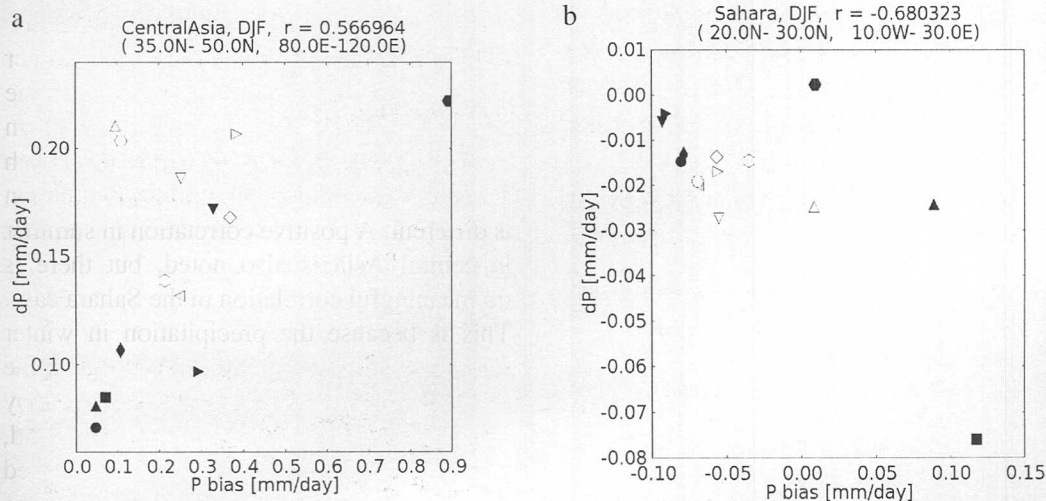


Fig. 13. (a) Same as Figure 10, except for the precipitation in winter over Central Asia, (b) Same as above, except for the Sahara region.

in precipitation intensity is noted in the Central Asia, but no significant increase is noted in other regions. Regarding precipitation days, a significant decrease in the number of rainy days is noted in all regions.

Summary

Surface temperature and precipitation in arid and semi-arid regions have been investigated using MME data. Five specific regions are selected and the change in surface temperature and precipitation due to CO_2 doubling are examined. A significant increase in the surface temperature is noted in all models. This increase is greater than the standard deviation between models. However, change in precipitation differs between models, and a significant increase (decrease) is noted only in the Central Asia (Sahara) regions, respectively.

The reliability of these results is examined for the Central Asia and the Sahara regions. An assumption that the systematic

error and the future climate change are correlated is examined over these two regions. The assumption was found to be invalid for 21 models, but when the models were screened, the assumption held good. Future change in surface temperature is positively correlated with the time-averaged error in the present climate. In other words, a model, which simulates a higher surface temperature in the desert region in the present climate, tends to show larger increase in the future warmer climate. This is valid for the annual mean, as well as for both winter and summer pweriods. This is because temperature field is determined by an energy balance and climate in an arid region is not very much influenced by other factors, such as clouds.

On the other hand, the precipitation process is complex and influenced by many processes. There is no clear relationship between mean error in the present climate and future climate change. A relationship is found only in the winter. It may be

suggested that winter precipitation is governed by mid-latitude disturbances, and there may exist some correlation between them. However, further study of this aspect is necessary.

Abbreviations for research organizations are shown in Table 2. For more information,

Table 2. Abbreviation of research organizations

BCCR	Bjerknes Center for Climate Research, Norway
CCSM	Community Climate System Model, National Center for Atmospheric Research, USA
CCCMA	Canadian Center for Climate Modelling and Analysis, Canada
CCSR	Center for Climate System Research, the University of Tokyo, Japan
CNRM	Center National de Recherches Meteorologies/Meteo-France, France
CSIRO	Commonwealth Scientific and Industrial Research, Australia
	ECHAM5/MPI-OM, Max Planck Institute for Meteorology, Germany
MIUB	Meteorological Institute of the University of Bonn, Germany
GFDL	Geophysical Fluid Dynamics Laboratory/NOAA, USA
GISS	Goddard Institute for Space Studies/NASA, USA
IAP	Institute for Atmospheric Physics, China
INM	Institute for Numerical Mathematics, Russia
INGV	Institute National for Geophysics and Volcanology, Italy
IPSL	Institute Pierre Simon Laplace, France
JAMSTEC	Japan Agency for Marine Earth Science and Technology
MRI	Meteorological Research Institute/JMA, Japan
NIES	National Institute of Environmental Studies, Japan
UKMO	UK Meteorological Office, UK

refer to www-pcmdi.llnl.gov/ipcc/about_ipcc.php.

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References

- Cook, E.R., Seager, R., Cane, M.C. and Stahle, D.W. 2007. North American drought: Reconstructions, causes and consequences. *Earth-Science Review* 81: 93-134.
- Dickinson, R., Henderson-Sellers, A. and Kennedy, P.J. 1993. Biosphere Atmosphere Transfer Scheme(BATS) for the NCAR Community Climate Model, NCAR Tech. Note NCAR/TN275+STR, 69 pp.
- Harada, C. and Sumi, A. 2003. Seasonal and year-to-year variations of rainfall in the Sahara desert region based on TRMM PR data. *Geophysics Research Letters* 21: 1-4.
- Held, I.M., Delworth, T.L., Lu, J., Findell, K.L. and Knutson, T.R. 2005. Simulation of Sahel drought in the 20th and 21st centuries. *PNAS* 102: 17891-17896.
- Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R. and Joseph, D. 1996. The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society* 77: 437-471.
- Kummerow, C., Barnes, W., Kozu, T., Shiue, J. and Simpson, J. 1998. The Tropical Rainfall Measuring Mission (TRMM) sensor package. *Journal of the Atmospheric and Oceanic Technology* 15: 809-817.
- Manabe, S., Smagorinsky, J. and Strickler, R.F. 1965. Simulated climatology of a general circulation model with a hydrologic cycle. *Mon. Wea. Rev.*, 93: 769-798.
- Meehl, G.A., Covey, C., Delworth, T., Latif, M., McAvaney, B., Mitchell, J.F.B., Stouffer, R.J. and Taylor, K.E. 2007. The WCRP CMIP3

- multimodel dataset. *Bulletin of the American Meteorological Society* 88:1383-1394, doi: 10.1175/BAMS-88-9-1383.
- Nicholis, N. 2004. The changing nature of Australian droughts. *Climate Change* 63: 323-336.
- Pitman, A.J. and Henderson-Sellers, A. 1998. Recent progress and results from the project for the intercomparison of landsurface parameterization scheme. *Journal of Hydrology* 212: 128-135.
- Seager, R., Ting, M., Held, I., Kushnir, Y., Lu, J., Vecchi, G., Huang, H-P., Harnik, N., Leetma, A., Lau, N-C., Li, C., Velez, J. and Naik, N. 2007. Model Projections of an Imminent Transition to a More Arid Climate in Southwestern North America. *Science* 316: 1181-1184.
- Sheffield, J. and Wood, Eric F. 2008. Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. *Climate Dynamics* 31: 79-105. DOI 10.1007/s00382-007-0340-z
- Wang, G. 2005. Agricultural drought in a future climate: Results from 15 global climate models participating in the IPCC 4th assessment. *Climate Dynamics* 25: 739-753. DOI 10.1007/s00382-005-0057-9.
- Xie, P. and Arkin, P.A. 1997. Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. *Bulletin of the American Meteorological Society* 78: 2539-2558.