NOTES AND CORRESPONDENCE

Future Climate Change Scenarios for Asia as Inferred from Selected Coupled Atmosphere-ocean Global Climate Models

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Abstract

The response of the Asian continent to transient increases in future anthropogenic radiative forcings using the data generated in a set of numerical experiments performed with four coupled atmosphere-ocean global climate models (A–O GCMs) is examined here. These A–O GCMs have demonstrated reasonable skill as regards their ability to simulate the broad features of present-day observed climatological features over the Asian region. A plausible scenario of climate change over Asia and its six sub-regions as inferred from these A–O GCMs due to the future emissions of greenhouse gases and/or sulfate aerosols is presented.

In general, the projected warming over Asia is higher during NH winter than during summer for both the decades 2050s (2040–2069) and 2080s (2070–2099). The rise in surface air temperature is likely to be most pronounced over the North Asia region in all the seasons. Each of the four A–O GCMs considered here simulates an enhanced hydrological cycle and an increase in annual precipitation over most of Asia. The inter-model differences in projections of precipitation are quite large even when averaged for the entire Asian continent suggesting rather limited confidence in the future projections of regional scale precipitation in currently available A–O GCM simulations.

1. Introduction

A number of impact assessments are currently being attempted using the projections of climate change due to anthropogenic radiative forcing provided by transient runs with coupled A–O GCMs (IPCC 1998). The patterns of the model simulated future changes in key climatic elements (such as surface air temperature and precipitation) as a consequence of increased concentrations of greenhouse gases are not likely to be uniform over space and time (IPCC 1996). The rather coarse hori-

zontal resolution in current coupled A–O GCMs, however, limits the feasibility of using regional information for impact assessment studies.

In a study reported earlier, four of the seven A–O GCMs that both reflect the state-of-the-art in numerical experiments and provide a representative range of results from different GCMs have demonstrated some skill as regards their ability to simulate the broad features of present-day observed regional surface climatological features over the Asian continent (Lal & Harasawa 2000). The data generated in transient experiments with these four A–O GCMs, which include the time varying future anthropogenic radiative forcings, are used here to provide plausible projections of climate

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change in terms of the surface air temperature and precipitation over the Asian region.

2. The region of study and climate elements

The data sets generated in transient control and anomaly numerical experiments from four skilled A-O GCMs, namely the CCSR/NIES model (Japan), the CSIRO model (Australia), the ECHAM4 model (Germany) and the HadCM2 model (UK) available at IPCC Data Distribution Centre (see: <http://ipcc-ddc.cru.uea.ac.uk> and <http://www.dkrz.de>), have been used to obtain region specific details on future climate change over Asia and its six sub-regions. Details on these models and appropriate references in the scientific literature on simulation details with individual models can be found at the websites given above.

The geographic region of interest considered in this study is the Asian continent bounded by the latitudes 10°S to 70°N and longitudes 40°E to 180°E. Based on broad climatic and geographical features, the Asian continent has been divided into six sub-regions namely North Asia (50°N–70°N, 40°E–180°E), Central Asia (30°N–50°N, 40°E–75°E), the Tibetan Plateau (30°N–50°N, 75°E–100°E), East Asia (20°N–50°N, 100°E–145°E), South Asia (5°N–30°N, 65°E–100°E) and Southeast Asia (10°S–20°N, 95°E–155°E) regions. We have analyzed the model-generated data on a monthly mean basis, for the Northern Hemispheric winter (December, January and February) season, Northern Hemispheric summer (June, July and August) season as well as on an annual mean basis. The data analyses have been undertaken for the Asian continent as a whole, and also for each of its six sub-regions.

Sulfate aerosols have been identified to affect the climate system by changing the radiative balance of the atmosphere (IPCC 1994; Mitchell et al. 1995). However, considerable uncertainty prevails about the nature and magnitude of aerosol radiative forcing, also the implications of localized forcing due to direct and indirect effects of sulfate aerosols on the deep convection in the tropics and on Hadley circulation (Portmann et al. 1998). In view of this, we have considered here the simulation experiments with greenhouse gas forcing and also with combined greenhouse gas and sulfate aerosol forcing (direct effects only) to obtain the future changes in the mean and/or variance of key climatological elements.

The primary climatic elements considered in this

study from among the model-generated data sets are monthly means of daily maximum, minimum and mean surface air temperatures and precipitation. The fields considered here are chosen based on their relevance for impact assessment purposes and are limited by data availability. Two future 30 year time periods centred around 2050s (2040–2069) and 2080s (2070–2099) have been considered here for scenarios of changes in surface air temperature and precipitation. The time period of 30 years (1961–1990) has been used in generating baseline climatology with reference to which all plausible representations of future climate have been computed.

3. Assessment of future climate change

3.1 Generalized global climate change scenario

In terms of future climates, each of the four skilled A-O GCMs suggest a rise in surface air temperature with the future increases in greenhouse gas concentrations and sulfate aerosols. The projected surface warming is more pronounced over the land regions than over the oceans (Arctic Ocean is an exception) and in the Northern Hemisphere than in the Southern Hemisphere. Maximum surface warming is simulated in all the models during winter at high northern latitudes associated with reduced sea ice and snow cover. An enhanced hydrological cycle and an increase in global mean precipitation is simulated in each of the four models. The maximum increase in annual mean precipitation is along the equatorial belt and in the middle and high latitude regions of both the Hemispheres. The increase in precipitation in the middle and high latitude regions is most pronounced during NH winter. A decrease in the zonal mean precipitation is simulated in the tropical regions of both the hemispheres and is more pronounced during the winter. During NH summer, precipitation change is found to be significant in the Equatorial region. However, the inter-model differences in simulated changes in precipitation over the Equatorial region are rather large. While the inclusion of sulfate aerosols in the simulation experiment tends to reduce the changes in surface air temperature more or less uniformly over the globe, its effect on changes in precipitation has a strong regional bias.

3.2 Region specific climate change scenarios

a. Surface air temperature

The annual and seasonal mean scenarios of future changes (relative to the baseline period of

Table 1. Plausible changes in area-averaged surface air temperature and precipitation over Asia and its Sub-Regions due to future increases in greenhouse gases as inferred from an ensemble of four skilled A-O GCMs (Numbers in bracket are the changes when the direct effect of sulfate aerosols are also included)

Regions	Temperature Change (°C)						Precipitation Change (%)					
	2050s			2080s			2050s			2080s		
	Annual	Winter	Summer	Annual	Winter	Summer	Annual	Winter	Summer	Annual	Winter	Summer
ASIA	3.14 (2.49)	3.43 (2.77)	2.87 (2.23)	4.61 (3.78)	5.07 (4.05)	4.23 (3.49)	7.1 (2.9)	10.9 (6.5)	4.1 (1.5)	11.3 (7.0)	18.0 (12.1)	5.5 (3.5)
North Asia	4.32 (3.52)	5.52 (4.46)	3.29 (2.83)	6.24 (5.30)	8.04 (6.83)	4.82 (4.24)	12.8 (12.0)	23.8 (19.7)	5.1 (7.1)	20.7 (18.9)	39.5 (31.5)	7.7 (10.3)
Arid & Semi-Arid Asia												
(a) Central Asia	3.18 (2.69)	2.81 (2.61)	3.55 (2.59)	4.83 (4.15)	4.41 (3.78)	5.34 (4.36)	1.3 (0.6)	6.9 (1.4)	-2.3 (0.7)	-1.3 (-3.6)	6.9 (1.0)	-4.0 (-1.8)
(b) Tibet	3.38 (2.62)	3.55 (2.94)	3.19 (2.27)	5.04 (4.06)	5.39 (4.32)	4.69 (3.73)	9.0 (7.5)	19.2 (14.8)	4.7 (1.7)	12.8 (11.5)	25.6 (18.8)	5.7 (3.8)
East Asia	2.86 (2.10)	3.26 (2.40)	2.48 (1.72)	4.34 (3.31)	5.11 (3.83)	3.67 (2.77)	7.9 (1.3)	13.3 (4.3)	5.4 (0.7)	10.9 (4.8)	20.1 (7.1)	7.8 (3.1)
Tropical Asia												
(a) South Asia	2.69 (1.92)	3.25 (2.08)	2.19 (1.81)	3.84 (2.98)	4.52 (3.25)	3.20 (2.67)	6.8 (-2.4)	-2.1 (-14.8)	6.6 (0.1)	11.0 (-0.1)	5.3 (-11.2)	7.9 (2.5)
(b) Southeast Asia	2.15 (1.72)	2.28 (1.73)	2.01 (1.61)	3.03 (2.49)	3.23 (2.51)	2.82 (2.34)	4.6 (1.0)	3.5 (2.9)	3.4 (2.6)	8.5 (5.1)	7.3 (5.9)	6.1 (4.9)

1961–90) in surface air temperature and precipitation based on an ensemble of results as inferred from four skilled A-O GCMs for the Asian continent and its sub-regions are presented in Table 1. The projected area-averaged annual mean warming is about 3.1 °C for the decade 2050s and about 4.6 °C for the decade 2080s over the land regions of Asia as a consequence of increases in atmospheric concentration of greenhouse gases. Under the combined influence of greenhouse gas and sulfate aerosols, the surface warming is restricted to only 2.5 °C and 3.8 °C for the decade 2050s and 2080s, respectively. In general, the projected warming over the Asian continent is higher during the NH winter (DJF) than during the NH summer (JJA) for both the time periods. The inter-model differences in projected changes in surface air temperature among the four A-O GCMs are higher during the NH winter than during the NH summer for both the time periods. The differential treatment of ice and snow in high latitude regions and the ice-albedo feedback in A-O GCMs considered here results in rather poor agreement among models on the magnitude of projected changes in surface air temperature during NH winter. The inclusion of sulfate aerosol forcing in the numerical experiments only marginally reduces the magnitude of projected

mean surface warming.

The rise in surface air temperature is likely to be most pronounced over the North Asia region in all the seasons. On an annual mean basis, the warming over the North Asia region is projected to be about 4.3 °C and 6.2 °C during 2050s and 2080s, respectively. In NH winter, the warming could be as high as 5.5 °C and 8.0 °C, respectively, during the decades 2050s and 2080s. The warming in much of the North Asia region is found to be statistically significant at or above the 90% confidence level both during winter and summer in all the models. The magnitude of surface warming projected over the Tibetan Plateau of the Asian region during NH summer is only marginally lower than that projected over the North Asia region. In Southeast Asia, the area-averaged annual mean surface temperature rise is projected to be the least of all the sub-regions of Asia and is statistically insignificant. Moreover, there is no significant seasonal change in the surface temperature rise in this region. Over Central Asia, the rise in surface temperature is highest during NH summer (statistically significant at 90% confidence level) and not during NH winter as observed over the other sub-regions of Asia.

The spatial distributions of annual and seasonal

Fig.1. The spatial distribution of annual and seasonal mean surface air temperature changes (deg C) over the Asian continent as simulated by the CSIRO and the HadCM2 models during the decade 2080s due to greenhouse gas only forcing (Hatched areas indicate the changes are significant at 90% confidence level).

mean surface temperature changes (relative to the baseline period of 1961–90 mean) over the Asian continent due to future increases in greenhouse gases as simulated by the CSIRO and the HadCM2 models for the decade 2080s are depicted in Fig. 1. The choice of these two models for comparing the spatial pattern of simulated surface air temperature was based on the consideration of differences in the vertical resolution of the two models. The CSIRO model atmosphere has only 9 levels in the vertical as against 19 or more vertical levels in the atmosphere in the other three models. The location of maximum surface warming simulated by the HadCM2 model is markedly different from that simulated by the CSIRO model for both time slices, particularly over the South Asian region during the NH summer. This suggests that the complex feedbacks between various physical processes in high altitude regions are strongly dependent on the vertical resolution of the model atmosphere in their response to time-varying radiative forcing factors. Similar non-uniformity, *albeit* not so pronounced and not in the same region, is also observed in the simulated spatial patterns in the other A–O GCMs. This not only leads to larger inter-model spread in the projected surface warming but also enhances uncertainty in regional projections.

b. Diurnal temperature range

Observed warming in surface air temperatures over several regions of the globe has been reported to be associated with the increase in minimum temperatures (accompanied by increasing cloudiness)

and decrease in the diurnal temperature range (Karl et al. 1991). The A–O GCM simulations suggest relatively more pronounced increases in minimum temperature than in maximum temperature over Asia on an annual mean basis, as well as during NH winter for both 2050s and 2080s and hence a decrease in diurnal temperature range (Table 2). During NH summer, however, an increase in area-averaged DTR is projected in simulations with increasing greenhouse gas concentrations suggesting thereby that the maximum temperature would have more pronounced increase relative to the minimum temperature. When combined greenhouse gas and sulfate aerosol forcings are considered, a decrease in area-averaged diurnal temperature range is obtained over the land regions of Asia in both the seasons. The inter-model spread in the projected changes in DTR emphasizes the impact of differential treatment of radiation-cloud feedback processes in the models on the time-varying radiative forcing response.

As seen in Table 2, summer-time increase in DTR over Central Asia is substantially higher (statistically significant at >95% confidence level) relative to the other Asian regions. This is essentially due to a pronounced increase in daytime surface temperature associated with clear skies over the region. Most of the sub-regions follow the same pattern of change in DTR except South and Southeast Asia. A marginal increase in DTR during winter and on an annual mean basis is simulated over Southeast Asia. Over the South Asia region, a decrease in DTR on an annual mean basis and during winter

Table 2. Projected changes in Diurnal Temperature Range over Asia and its Sub-Regions as inferred from an ensemble of four skilled A–O GCMs

Regions	Greenhouse Gases						Greenhouse gases + Sulfate Aerosols					
	2050s			2080s			2050s			2080s		
	Annual	Winter	Summer	Annual	Winter	Summer	Annual	Winter	Summer	Annual	Winter	Summer
ASIA	-0.15	-0.26	1.42	-0.27	-0.45	1.36	-0.17	-0.13	-0.54	-0.27	-0.26	-0.54
North Asia	-0.38	-0.52	1.67	-0.53	-0.81	1.62	-0.45	-0.34	-0.49	-0.57	-0.53	-0.48
Arid & Semi Arid Asia												
(a) Central Asia	0.13	-0.07	4.64	0.17	-0.11	4.75	-0.02	-0.14	2.20	0.09	-0.04	2.36
(b) Tibet	-0.34	-0.60	2.01	-0.46	-0.81	1.91	-0.53	-0.63	0.18	-0.67	-0.80	0.13
East Asia	-0.18	-0.31	0.47	-0.23	-0.43	0.44	-0.19	-0.21	-0.83	-0.28	-0.30	-1.05
Tropical Asia												
(a) South Asia	-0.27	-0.27	-3.06	-0.45	-0.46	-2.89	-0.22	-0.14	-4.97	-0.31	-0.31	-4.95
(b) Southeast Asia	0.15	0.24	-0.50	0.00	0.09	-0.66	0.35	0.42	-0.98	0.18	0.24	-1.09

and a more pronounced decrease in DTR during summer are projected. The decrease in DTR over South Asia during summer (statistically significant at 90% confidence level) is due to the presence of monsoon clouds over the region (Lal et al. 1996). In general, the projected changes in DTR over Asia and its sub-regions are moderated in the presence of sulfate aerosols. A decrease in area-averaged DTR over Asia is projected during both the seasons when the combined effects of greenhouse gases and sulfate aerosols are considered (Table 2). Similar changes are also seen over both North Asia and the East Asia regions.

c. Precipitation

In general, all A-O GCMs simulate an increase in annual mean precipitation over the Asian continent. An area-averaged annual mean increase in precipitation of about 7% for the decade 2050s and about 11% for the decade 2080s over the land regions of Asia is projected due to an increase in greenhouse gases (Table 1). Under the combined influence of greenhouse gas and sulfate aerosols, the increase in precipitation is limited to only 3% and 7% for the decades 2050s and 2080s, respectively. Fig. 2 depicts the changes in precipitation relative to changes in surface air temperature averaged over the land regions of Asia for each of the four skilled GCMs on an annual mean basis as well as during NH winter and NH summer for the decades 2050s and 2080s. The changes in surface air temperature and precipitation simulated in numerical experiments with the A-O GCM developed at the Canadian Centre for Climate Modeling and Analysis (CCCma), which has rather limited skill in simulating the Asian climatology for the present-day atmosphere has also been included in Fig. 2. It is seen that the inter-model differences in precipitation change are significantly large particularly during NH winter even when averaged for the entire Asian continent suggesting rather poor confidence in the future projections of precipitation in current A-O GCMs.

The increase in annual mean precipitation is projected to be highest in North Asia. About 13% and 21% increase in area-averaged annual mean precipitation is projected over this region during 2050s and 2080s, respectively. While the increase in winter precipitation is most pronounced in North Asia, the Tibetan Plateau is also likely to experience substantial enhancement in winter precipitation (Table 1). Over the Central Asia, only an increase

Fig. 2. The projected changes in area-averaged annual and seasonal mean surface air temperature and precipitation over Asia for the decades 2050s and 2080s as obtained in selected A-O GCM simulations.

in winter precipitation and a marginal decline in summer precipitation is projected. While the area-averaged annual mean and winter precipitation is projected to enhance in East Asia, a decline in winter time precipitation is likely over South Asia, more significantly in the presence of aerosols.

The spatial distribution of annual and seasonal mean changes in precipitation (in percent; relative to the baseline period of 1961–90 mean) over the Asian continent due to future increases in greenhouse gases as simulated by the CSIRO and the HadCM2 models for the decade 2080s is depicted in Fig. 3. The winter-time increase in precipitation over North Asia is statistically significant at the 90% confidence level in both the models. The centers of maxima of projected changes in precip-

Fig. 3. The spatial distribution of annual and seasonal mean precipitation change (in percent) over the Asian continent as simulated by the CSIRO and the HadCM2 models during the decade 2080s due to greenhouse gas only forcing (Hatched areas indicate the changes are significant at 90% confidence level).

itation are distinctly different in each of the four A–O GCM simulations with respect to the location as well as magnitude. The presence of sulfate aerosols leads to a reduction in projected increase in area-averaged precipitation over the Asian continent. Also, it induces some shifts in the centers of maxima in spatial distribution of precipitation changes. The A–O GCMs show high uncertainty in future projections of both winter and summer precipitation over South Asia (with or without aerosol forcing). Over the South Asia region, the magnitude as well as the sign of projected changes in monsoon rainfall over the region varies significantly among the models during NH summer. The inter-model differences are largely attributed to differences in treatment of ground hydrology and cloud-radiation interactions in these models (Giorgi & Francisco 2000).

4. Discussion

The scenarios of likely changes in climate of Asia and its sub-regions presented above are suggestive of substantial increases in precipitation over some regions e.g., North Asia. Under such a scenario, the increases in runoff of major Siberian rivers during winter and summer-autumn periods will be most pronounced. Over Central Asia, the most crucial impact of climate change is likely to be an acute shortage of water resources associated with significant increases in surface air temperature. Since the precipitation over this arid and semi-arid region is already low, severe water stress conditions leading to expansion of deserts are possible here. Over South Asia, the current general understanding based on the A–O GCM results presented above is that the length of the dry season is expected to marginally decline as a consequence of greenhouse gas induced rise in surface air temperature and enhanced precipitation. Under the combined influence of greenhouse gases and sulfate aerosols, a rather weak summer monsoon circulation could, however, lead to a decline in rainfall over South Asia. The projected summer-time decrease in DTR could adversely affect the patterns of agricultural productivity in South Asia.

The treatment of the complex interactions of atmospheric physics and planetary scale dynamics and the coarse horizontal resolution in the A–O GCMs restricts confident simulation of climate and its spatial variability required for regional impact assessments. Much of Tropical Asia is intrinsically linked with the annual monsoon cycle and a better

understanding of the future behavior of the temporal and spatial variability in monsoon precipitation is crucial. In order to gain a higher degree of confidence in the projected scenarios of changes in precipitation in tropical monsoon Asia, the basic differences in parameterization of physical processes in the A–O GCMs and their effects on the simulation of regional precipitation need to be further investigated. In this respect, the model sensitivity to the treatment of interaction between monsoon clouds and radiative processes appears to be a key factor.

5. Conclusions

The data from simulation experiments with a set of A–O GCMs using transient increases in anthropogenic radiative forcings have been analyzed to assess future changes in climate of the Asian continent. A plausible climate change scenario for six Asian sub-regions are developed for the decades 2050s and 2080s. The study is confined to the assessment of expected changes in two key climatic elements, namely the surface air temperature and precipitation.

In general, the projected warming over Asia is higher during NH winter than during summer for both the time periods. The rise in surface air temperature would be most pronounced over the North Asia region in all the seasons. During summer, an increase in DTR is likely which would be significantly higher over Central Asia. Over South Asia, a pronounced decrease in DTR during summer is projected for the future. All the A–O GCMs considered in this study simulate an increase in mean precipitation over most of Asia. The increase in annual mean precipitation is projected to be highest in North Asia. While the area-averaged annual mean precipitation is projected to enhance in East Asia, a decline in summer precipitation is likely over Central Asia. The models show high uncertainty in future projections of both winter and summer precipitation over South Asia (with or without aerosol forcings).

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