

Climate Changes in the 21st Century over the Asia–Pacific Region Simulated by the NCAR CSM and PCM

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(Received September 1, 2000)

ABSTRACT

The Climate System Model (CSM) and the Parallel Climate Model (PCM), two coupled global climate models without flux adjustments recently developed at NCAR, were used to simulate the 20th century climate using historical greenhouse gas and sulfate aerosol forcing. These simulations were extended through the 21st century under two newly developed scenarios, a business-as-usual case (BAU, $\text{CO}_2 \approx 710$ ppmv in 2100) and a CO_2 stabilization case (STA550, $\text{CO}_2 \approx 540$ ppmv in 2100). The simulated changes in temperature, precipitation, and soil moisture over the Asia–Pacific region (10° – 60°N , 55° – 155°E) are analyzed, with a focus on the East Asian summer monsoon rainfall and climate changes over the upper reaches of the Yangtze River.

Under the BAU scenario, both the models produce surface warming of about 3 – 5°C in winter and 2 – 3°C in summer over most Asia. Under the STA550 scenario, the warming is reduced by 0.5 – 1.0°C in winter and by 0.5°C in summer. The warming is fairly uniform at the low latitudes and does not induce significant changes in the zonal mean Hadley circulation over the Asia–Pacific domain. While the regional precipitation changes from single CSM integrations are noisy, the PCM ensemble mean precipitation shows 10% – 30% increases north of $\sim 30^\circ\text{N}$ and $\sim 10\%$ decreases south of $\sim 30^\circ\text{N}$ over the Asia–Pacific region in winter and 10% – 20% increases in summer precipitation over most of the region. Soil moisture changes are small over most Asia. The CSM single simulation suggests a 30% increase in river runoff into the Three Gorges Dam, but the PCM ensemble simulations show small changes in the runoff.

Key words: Climate simulation, Climate change, Asian monsoon, Ensemble simulation

1. Introduction

Human activities such as fossil fuel combustion and deforestation have caused a sharp rise in atmospheric concentrations of greenhouse gases (CO_2 , CH_4 , etc.) and aerosols since the late 19th century (Watson et al., 1990; Schimel et al., 1996). A large number of climate model experiments predict substantial climate changes (including surface warming) in response to increased concentrations of CO_2 and other greenhouse gases (e.g., Mitchell et al., 1990; Kattenberg et al., 1996). With projected growth in the world economy and population in the 21st century, the atmospheric loading of greenhouse gases is likely to continue to rise. This could induce significant climate changes in the 21st century. Meaningful predictions of these changes using comprehensive climate models have many practical applications (e.g., for climate impact assessments and to

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^②The National Center for Atmospheric Research is sponsored by the U. S. National Science Foundation.

guide future emission controls).

Various general circulation models (GCMs) of the Earth's climate system, including those with coupled atmosphere, ocean and land components, have been developed to study natural climate variability and the climate responses to increased greenhouse gas and aerosol loadings (see Mitchell et al., 1990 and Kattenberg et al., 1996, and references therein). Reliable predictions of future climates are, however, still a big challenge for current climate models. The uncertainties arise from models' deficiencies in simulating the earth's mean climate and variability and from the large uncertainty in the projected future greenhouse gas and industrial aerosol emissions.

Because projections of future emissions usually have large uncertainties, a standard GCM experiment is to assume an arbitrary rate of increase for CO₂, such as a 1% compound increase per year (e.g., Manabe et al., 1991; Mitchell et al., 1995; Russell and Rind, 1999; Boer et al., 2000; Meehl et al., 2000a, b). Climate changes from these experiments are not normally linked to specific years in the future and thus are not presented as quantitative predictions of future climates. Other GCM experiments (e.g., Cubasch et al., 1992; Roeckner et al., 1999) have predicted future climate changes using concentrations based on independently-determined emission scenarios.

Recently, we used the National Center for Atmospheric Research (NCAR) Climate System Model (CSM) and the Parallel Climate Mode (PCM) to simulate (with 5 ensemble runs for the PCM) the 21st century climate under two newly developed scenarios of future emissions of CO₂, SO₂ and other trace gases (Dai et al., 2001a,b). The CSM and PCM are comprehensive global climate models with coupled atmosphere, ocean, land and sea-ice components (Boville and Gent, 1998; Washington et al., 2000). The CSM and PCM share the same atmospheric and land component models, but they have different ocean and sea-ice models. The CSM and PCM differ from some other coupled GCMs in that they do not use conventional flux adjustments to produce a stable surface climate. The two future emission scenarios, an existing policies (ACACIA Business As Usual, or ACACIA-BAU, henceforth BAU) scenario and a policy (CO₂ stabilization, or STA550) scenario, were generated using an energy-economics model driven by regionally-specific assumptions with regard to population growth, economic growth, energy use per capita, technology developments, etc. The main results from these simulations have been summarized in Dai et al. (2001a, b, c). In this paper, we analyze the simulated changes in temperature, precipitation, soil moisture, and the atmospheric circulation over the Asia-Pacific region (55°–155°E, 10°–60°N), with a focus on the East Asian summer monsoon.

In the following, we first briefly describe the models, simulations and future scenarios in Section 2, which also includes a summary of the model-simulated 20th century climate compared with observations. The predicted 21st century climates are presented in Section 3. A summary is given in Section 4. We emphasize that the climate changes for the 21st century reported in this study, as in other similar studies, have large uncertainties (especially regarding regional changes). They should be considered only as members within a wide spectrum of possibilities. Other forcings, such as future variations in solar radiation and volcanic eruptions, are not included in these experiments and are likely to induce additional climate changes.

2. Models, simulations and future emissions scenarios

The CSM is described in detail by Boville and Gent (1998) and other papers in that issue of *Journal of Climate*. The CSM is a coupled global climate model consisting of an atmospheric GCM (the Community Climate Model Version 3, CCM3; Kiehl et al., 1998), an ocean GCM (the NCAR CSM Ocean Model, NCOM; Gent et al., 1998), a land surface biophysics model (LSM 1.0; Bonan, 1998), and a sea-ice model (Weatherly et al., 1998). These component models are coupled through a "flux coupler" (Bryan et al., 1996), which computes interfacial fluxes between components. The ocean component, NCOM, is based on the GFDL MOM-1.1 z -coordinate model incorporating new parameterizations of the effects of mesoscale eddies and the upper-ocean boundary layer. The version of the CSM used in this study is CSM-1.3 described in Boville et al. (2001), which incorporates several changes to either greatly reduce the deep ocean drift found in earlier versions of the CSM (through a reduction of the aerodynamic roughness length of sea ice) or add new capabilities for transient climate simulations (through an introduction of prognostic greenhouse gas distributions and an interactive sulfur cycle).

The PCM is described in detail by Washington et al. (2000). It uses the same atmospheric and land models but different ocean and sea-ice component models. The PCM uses the Los Alamos National Laboratory Parallel Ocean Program (POP) for the ocean component and the Naval Postgraduate School sea-ice model. The PCM codes are designed to run on parallel computers efficiently. Both the CSM and PCM have an equilibrium sensitivity of about 2.1°C global-mean warming for a doubling of atmospheric CO_2 content since this number is derived using the CCM3 coupled to a slab ocean (Meehl et al., 2000a).

The atmospheric component, CCM3, is a spectral model with horizontal T42 truncation ($\sim 2.8^{\circ}$ horizontal resolution). CCM3 has 18 layers in the vertical (3 in the planetary boundary layer) with the top layer centered at 4.8 hPa. The integration time step (Δt) for CCM3 is 20 min (1 h for radiation). The CSM ocean component, NCOM, has 2.4° resolution in longitude and variable resolution in latitude, with smallest grid spacing of 1.2° at the equator and in the Arctic and largest spacing of 2.3° at midlatitudes. In the vertical, NCOM has 45 levels, with 4 equal depth levels in the upper 50 m and 25 levels in the upper kilometer of the ocean. Δt is 30 min for NCOM. The land surface model, LSM, runs on the same grid as CCM3 with a time step of 20 min. The PCM ocean component, POP, has $2/3^{\circ}$ average horizontal grid spacing with 32 vertical levels (2 layers in the top 50 m). One of the major advantages of the POP is that it produces realistic ocean circulations over the high latitude oceans because of a displaced North Pole over North America.

The component models of the CSM and PCM were first run separately during a spinup period (Boville and Gent, 1998), and then run in coupled mode with no anthropogenic forcing for 40 or more years before the first model year (1870) of the historical simulation (1870–1999). Four sets of climate simulations were completed. These are

- 1) a 230-year control run with trace gas concentrations appropriate for 1870,
- 2) historical runs for the period 1870–1999 using historical forcings of greenhouse gases and aerosols,
- 3) 21st century runs for 2000–2099 under the BAU scenario, and

4) 21st century runs for 2005–2099 under the STA550 scenario (before 2005 STA550 is identical to BAU).

For the CSM, each of the above simulations has only one single run, whereas for the PCM, there are 10 ensemble runs for the historical simulation and 5 ensemble runs for each of the two future scenarios (BAU and STA550). Each of the historical ensemble run started from different conditions separated by one or two decades from the coupled spin-up simulation. The future simulations are a continuation of corresponding historical runs with projected future greenhouse gas concentrations and sulfate loadings. The PCM results reported here are ensemble averages.

The greenhouse gas (CO_2 , CH_4 , N_2O , O_3 , and CFCs) concentrations and atmospheric sulfate (SO_4) loadings are described in detail by Dai et al. (2001a). For the historical run, they were derived based on observations. The two greenhouse gas and sulfate scenarios for the 21st century were designed to have a “matched” pair, an existing-policies (ACACIA–BAU) scenario and a policy of CO_2 stabilization (STA550) scenario. Internally-consistent emissions for the two most important gases, CO_2 and SO_2 , were generated using the MiniCAM integrated-assessment / energy-economics model of Edmonds et al. (1997), driven by regionally-specific assumptions with regard to population growth, economic growth, energy use per capita, technology developments, etc.

Figure 1 shows the global-mean CO_2 concentration and anthropogenic SO_2 emissions under the BAU and STA550 scenario. The IPCC SRES A1 and IS92a scenarios are also included in Fig. 1 for comparison (the IS92a CO_2 is similar to that for the BAU). The 2100 CO_2 level is about 540 ppmv under the STA550 scenario and 710 ppmv in the BAU case, which represents an approximate doubling of the level around 1991. The SO_2 emission under both the BAU and STA550 scenarios peaks around 1990 and declines steadily until 2080 when it stabilizes around 30 Tg S / yr (1 Tg = 10^{12} g).

The performance of the CSM in simulating present climate has been evaluated extensively in a number of papers published in the June 1998 issue of *Journal of Climate* and by Dai et al. (2001a). Using observed historical greenhouse gas concentrations and sulfate aerosol loadings, the CSM (version 1.3) simulates many of the spatial and temporal variations of the 20th century climate. Specifically, the CSM simulates the following reasonably well (Dai et al., 2001a): 1) geographical, seasonal, and year-to-year variations in global surface air temperature and precipitation, 2) latitude–height distributions of zonal–mean air temperature, specific humidity, and winds (including the regions of vertical motion that characterize the Hadley and Ferrel cells), 3) global distributions of 2–8 day synoptic storms, 4) ENSO-induced precipitation anomalies over the globe, 5) the pole–midlatitude oscillations (such as the NAO) in sea–level pressure fields, 6) the rapid rise in global and zonal–mean surface temperatures since the late 1970s, and 7) increasing precipitation over northern middle- and high-latitude land areas during the 20th century.

The CSM also has a number of systematic biases in simulating the current climate. These include: 1) a cold bias ($2\text{--}6^\circ\text{C}$) in surface air temperature over land areas, 2) overestimates of cloud amount (by 10%–30%) over land areas, 3) underestimates of cloud amount over the marine stratus regions west of North and South America and Africa, 4) reduced variability of equatorial Pacific SSTs (Meehl and Arblaster, 1998) and overestimates of tropical precipitation south of the equator in the Pacific, 5) a cold bias in the simulated surface air temperature at $50^\circ\text{--}70^\circ\text{N}$ from the 1920s to the 1940s (which may be partly due to absence of solar forcing in the simulations), and 6) a negative

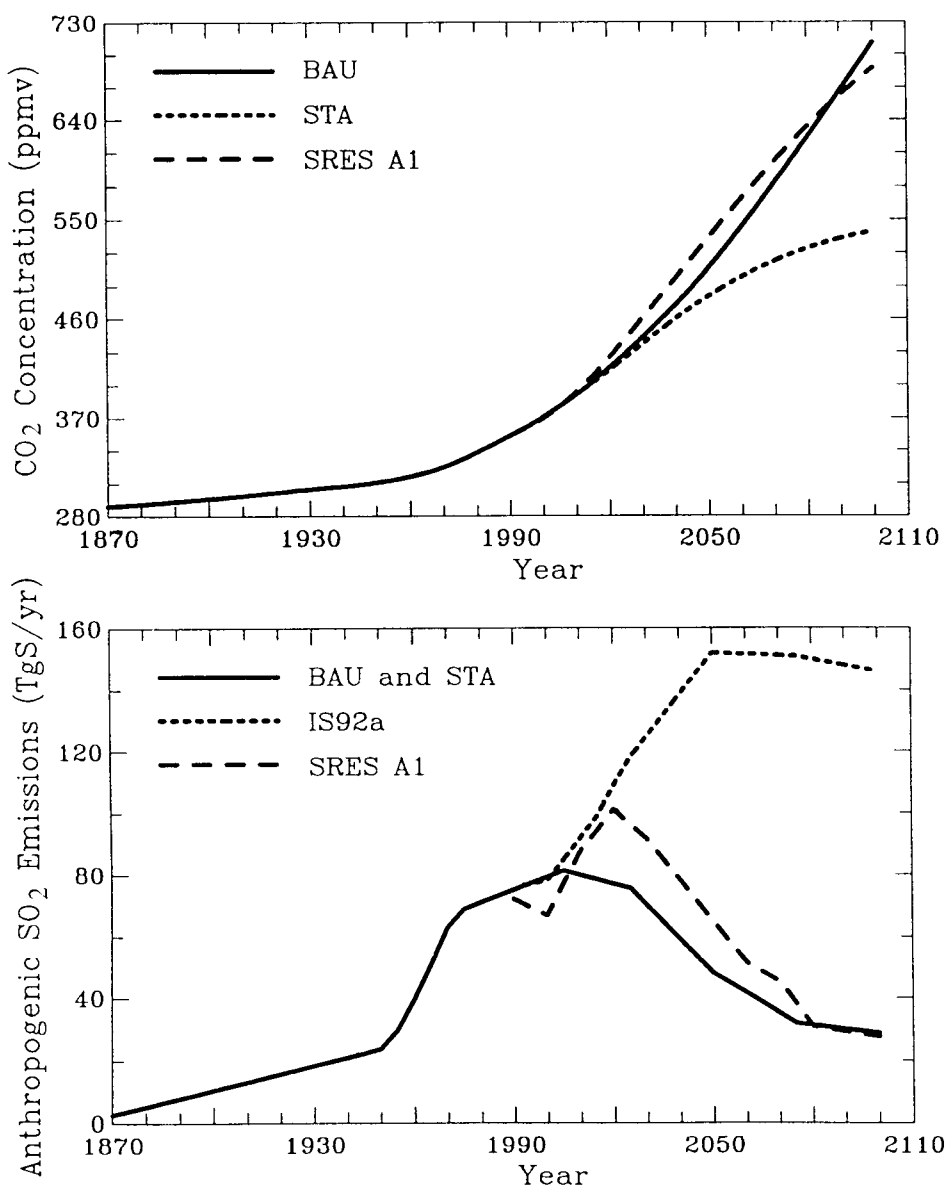


Fig. 1. Global mean values of atmospheric CO₂ concentrations (ppmv, upper panel) and anthropogenic SO₂ emissions (TgS / yr, 1 Tg = 10¹² g, lower panel) from 1870 to 2100. Data before the 1990s are observations and thereafter are projected values under different scenarios (see text for more details).

(positive) bias in surface (deep) ocean salinity, and excess sea ice in the North Pacific and the subarctic North Atlantic Oceans.

The PCM has similar biases as in this version of the CSM. However, the PCM produces ENSO SST anomalies closer to the observed than in the CSM (Meehl et al., 2001), and a more realistic Arctic Ocean circulation (Washington et al., 2000). In the PCM, adding solar forcing to the historical run improves the agreement between the observed and simulated global mean surface temperature, especially during 1920–1950.

3. Simulated climate changes in the 21st century

3.1 *Global temperature and precipitation changes*

The global climate changes simulated by the CSM and PCM are discussed in detail by Dai et al. (2001a) and Dai et al. (2001b,c), respectively. To provide a context for the regional changes discussed below, here we briefly summarize the global temperature and precipitation changes simulated by the two models.

In both the CSM and PCM, the projected global surface warming from the 1990s to the 2090s is $\sim 1.9^{\circ}\text{C}$ under the BAU scenario and $\sim 1.5^{\circ}\text{C}$ under the STA550 scenario. As in other coupled models, the surface warming is largest at winter high latitudes ($\geq 5.0^{\circ}\text{C}$ from the 1990s to the 2090s) and smallest ($\sim 1.0^{\circ}\text{C}$) over the southern oceans, and is larger over land areas than ocean areas. The PCM differs from the CSM in that it produces a moderate cooling (of $1\text{--}2^{\circ}\text{C}$ under the BAU and $\sim 1^{\circ}\text{C}$ under the STA550 scenario) over the central North Atlantic during December–February (DJF), and larger warming than in the CSM over the Arctic in DJF and annual temperature. Under the STA550 scenario, the warming patterns are comparable to those for the BAU case, except that the warming is reduced by about $0.5\text{--}1.5^{\circ}$ over land and by about $0.2\text{--}0.5^{\circ}\text{C}$ over ocean.

Globally-averaged precipitation increases by $\sim 3.5\%$ (3.0%) from the 1990s to the 2090s in the BAU (STA550) case in the CSM and by $\sim 3.3\%$ (2.4%) in the PCM. Under the two scenarios, both the models produce large precipitation increases (up to 50%) over northern mid- and high-latitudes and the Antarctic, especially during winter. Precipitation changes are noisy at low latitudes. Large differences occur between the BAU and STA550 regional precipitation changes in the single CSM run. However, the regional patterns of PCM ensemble-mean precipitation changes become stable and similar under the two future scenarios. This suggests that meaningful regional climate changes may be obtained through ensemble simulations using present coupled GCMs. The PCM ensemble simulations show general increases of precipitation over the central equatorial Pacific and Indian Oceans and decreases of precipitation over the subtropical (around 30° latitude) oceans. In the PCM ensemble simulations, June–August (JJA) precipitation increases over India, Australia, eastern China, but decreases over the western United States, eastern Brazil, and southern (south of $\sim 15^{\circ}\text{S}$) Africa (Dai et al., 2001b).

3.2 *Model simulated East Asian monsoon*

Meehl and Arblaster (1998) showed that the CSM reproduces most major features of the Asia–Australian monsoon system, including its negative correlation with equatorial sea surface temperature in the Pacific. Since we will focus on the model simulated changes in summer rainfall over the Asia–Pacific region, we should first evaluate the models' performance in simulating present-day mean rainfall and atmospheric circulation associated with the Asian summer monsoons, especially the East Asian summer monsoon.

Figure 2 compares the 1979–1998 mean precipitation for months May to September from the CSM (similar for the PCM) to that of the Xie–Arkin climatology (Xie and Arkin, 1997 and updates). It can be seen that the broad features of the northward-moving rain-belt (the hatched area) are roughly reproduced by the CSM, especially over the western Pacific, the South China Sea and Southeast Asia. However, precipitation over

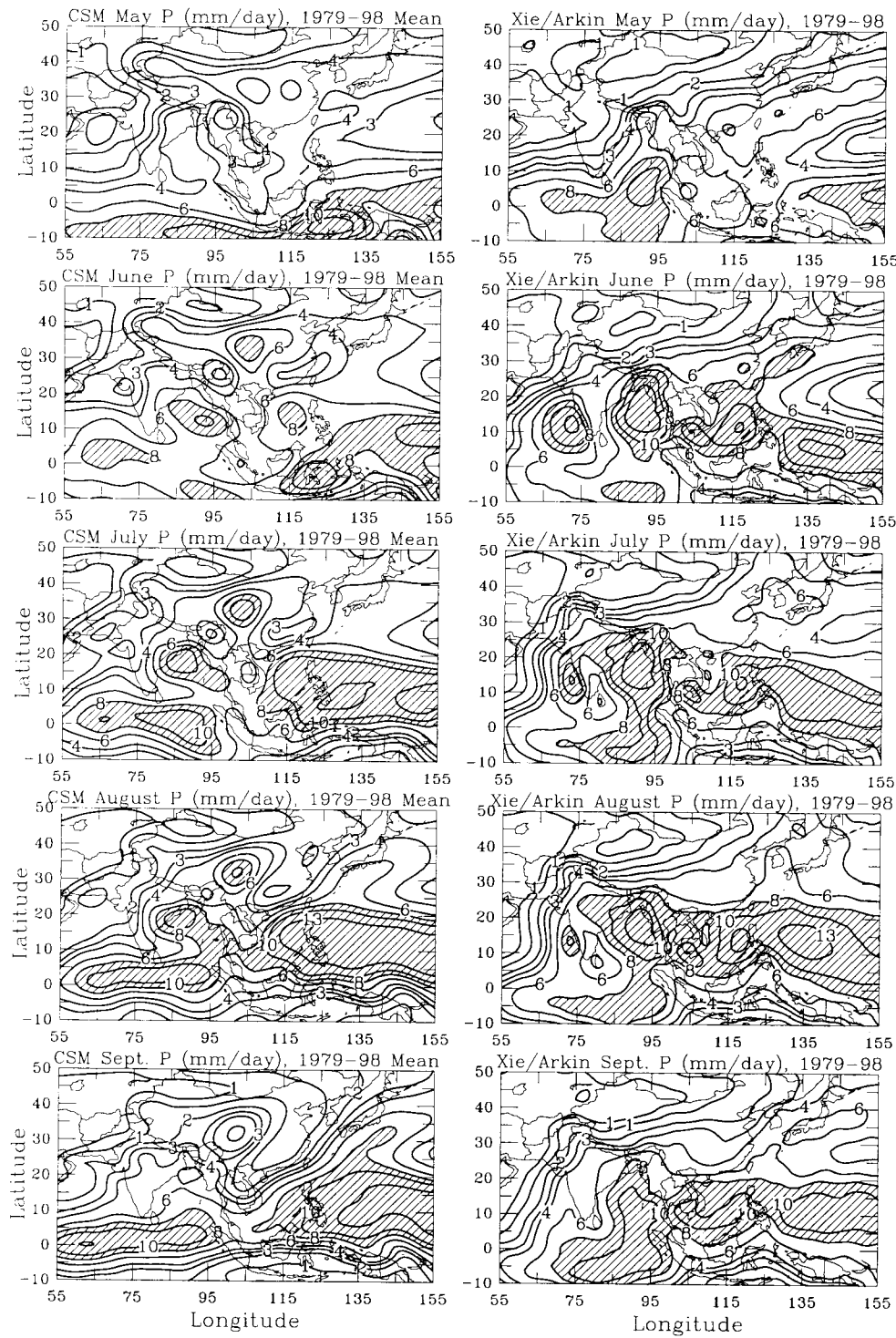


Fig. 2. CSM simulated (left column) and observed (right column: from Xie and Arkin, 1997 and updates) 1979–1998 mean precipitation (mm / day) over the Asia–Pacific region for months May (top panels) to September (bottom panels). Areas with precipitation ≥ 8 mm / day are hatched.

coastal eastern China, the East China Sea, Japan and the Korean Peninsula is lower in the CSM than the observed. Also, Indian monsoon rainfall is not well simulated by the CSM.

The dry bias over eastern Asia in the CSM is related to the fact that the summer Pacific Subtropical High (PSH) in the model is too strong compared with the NCEP/NCAR reanalysis (Kalney et al., 1996). As a result, the 1014 isobar of the PSH extends too far to the west in the CSM (Fig. 3). The low pressure center over the South China Sea and the Philippines is also too strong in the CSM. These biases in SLP fields are accompanied (in the lower troposphere) with weak southerly winds (thus less moisture for precipitation) over eastern China and East and South China Seas from May to July, and strong north-easterlies over eastern China in August and September (Fig. 3). These circulation biases contribute to the summer dry bias over eastern Asia in the CSM.

3.3 Climate changes over Asia-Pacific

Figure 4 shows the DJF, JJA, and annual surface air temperature changes from 1980–1999 (i.e., using 20-yr average) to 2080–2099 under the BAU scenario over the Asia-Pacific region simulated by the CSM (left column) and PCM (right column). It can be seen that the warming is above 3°C over most Asia during DJF and about 2–3°C during JJA in both the CSM and PCM. The warming is fairly uniform during JJA, whereas it generally increases with latitude during DJF, especially over the Sea of Japan and the North Pacific (due to strong feedback of sea ice). The PCM shows (~1–2°C) less warming during DJF over central Asia and Russia than the CSM. The difference is within the ensemble range (~1.0–2.5°C) over these regions (Dai et al., 2001b) and thus insignificant statistically.

The warming patterns under the STA550 scenario (not shown) are very similar to those for the BAU scenario. The slower increase of CO₂ concentration in the STA550 case reduces the warming during 2080–2099 by about 0.5–1.0°C in DJF and 0.5°C in JJA over most Asia (Dai et al., 2001b).

Figure 5 shows the percentage changes in DJF, JJA, and annual precipitation from 1980–1999 to 2080–2099 under the BAU scenario simulated by the two models. It can be seen that regional precipitation changes can differ substantially between the CSM and PCM. On regional scales ($\leq 10^3$ km), the CSM-simulated precipitation changes are noisy and can differ greatly between the BAU (Fig. 5) and STA550 run (not shown) due to large intra-ensemble variability on regional scales. The regional changes are more stable in the ensemble averages of the PCM runs and are comparable between the two scenarios. Therefore, we shall focus on the precipitation change patterns in the PCM ensemble mean.

The PCM ensemble mean (Fig. 5) shows that from 1980–1999 to 2080–2099 DJF precipitation increases by 10%–30% north of ~30°N and decreases by ~10% south of ~30°N, whereas JJA precipitation increases (by 10%–20%) over most of the Asia-Pacific region. The increase of JJA precipitation over western India, southern Pakistan, and the Arabian Sea is especially large (40%–50%). This belt of increased precipitation extends westward to northern Africa (Dai et al., 2001b).

Area-averaged summer rainfall is often used as an index for the strength of Asian summer monsoons (Ding, 1994). Figure 6 shows the time series of JJA precipitation averaged over the East Asian monsoon region (10°–40°N, 100°–130°E) from 1870 to 2099 simulated by the CSM and PCM. It can be seen that both the models produce some

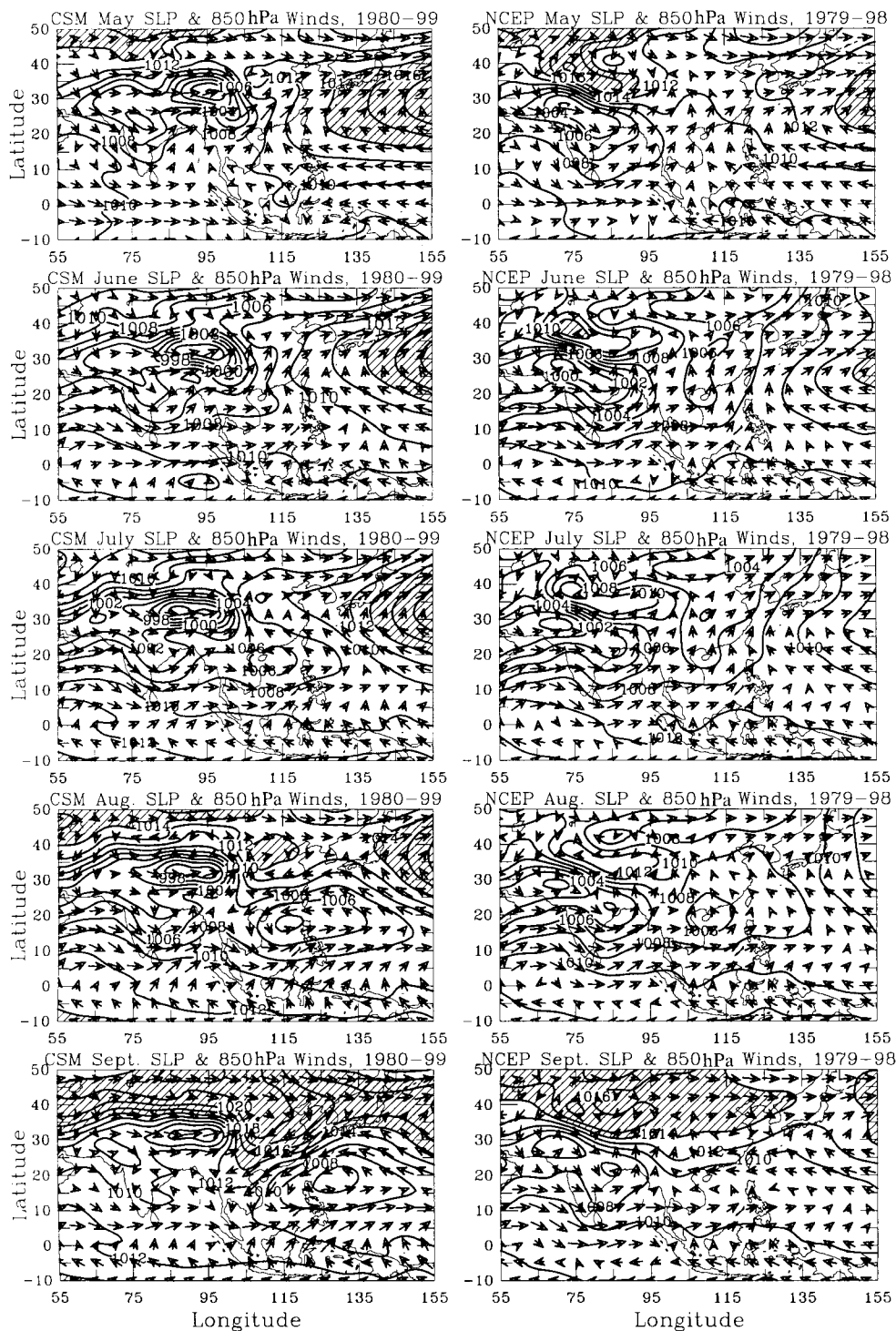


Fig. 3. Same as Fig. 2 but for mean sea level pressure (contours, hPa) and 850 hPa winds (arrows, maximum length $\cong 10$ m/s) from the CSM historical simulation (left column) and NCEP/NCAR reanalysis (right column; Kalnay et al., 1996). Contours over 1014 hPa are hatched.

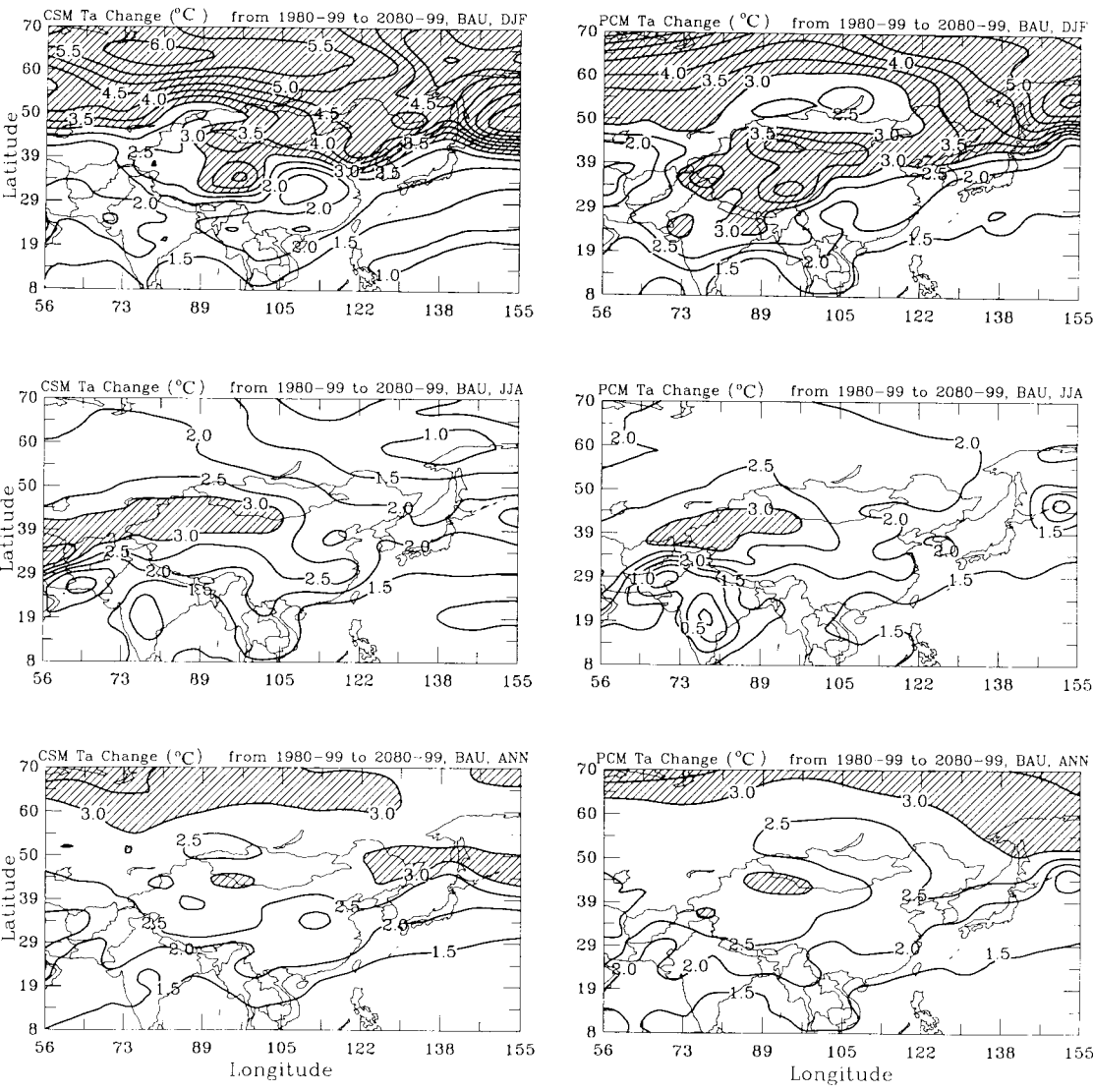


Fig. 4. CSM (left column) and PCM (right column, 5-ensemble average) simulated DJF, JJA, and annual surface air temperature changes (°C) from 1980–1999 to 2080–2099 under the business as usual (BAU) scenario. Values over 3.0°C are hatched. All changes are statistically significant at the 5% level (Dai et al., 2001a).

increases ($\sim 7\%$ from present level) in the East Asian monsoon rainfall by the later part of the 21st century. Both the models suggest that flooding years will become more frequent in the 21st century, as shown by those annual peaks that are well above the historical levels in Fig. 6. The year-to-year variability of the monsoon rainfall, which is depicted by the annual anomalies relative to the decadal mean in Fig. 6, appears to be relatively stable over the 230-yr period, while large inter-decadal variations exist through the entire period. Compared with the rainfall from the CSM single run, the interannual variations in the ensemble averaged PCM rainfall are greatly reduced as expected from

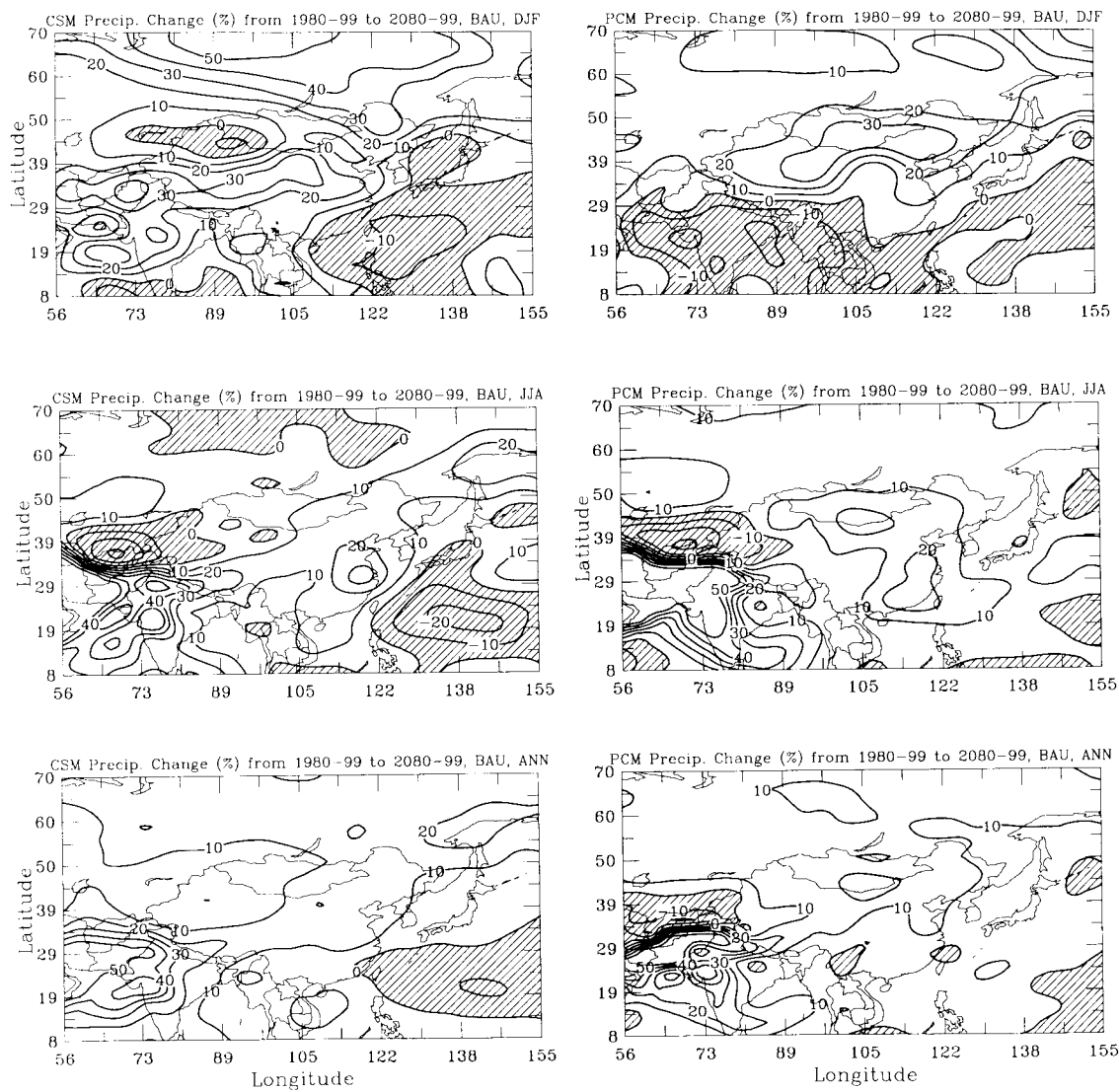


Fig. 5. Same as Fig. 4 but for percentage precipitation change. Negative values (i.e., decreases) are hatched. Changes within about $\pm 20\%$ (10% for annual mean) are statistically insignificant (Dai et al., 2001b).

the ensemble averaging (Fig. 6). Since the earth climate will be a single realization, interannual variability will be more comparable to the CSM simulation than the PCM ensemble mean.

Convective rainfall is the dominant form of summer precipitation over the East Asian monsoon region in the CSM (and PCM) (Fig. 7), as one would expect. Figure 7 shows that the increases in the East Asian monsoon rainfall result entirely from the increases in the convective rainfall, and the large-scale stratiform precipitation changes little as the surface temperature increases, which suggests small changes in relative humidity in the CSM (Dai et al., 2001a).

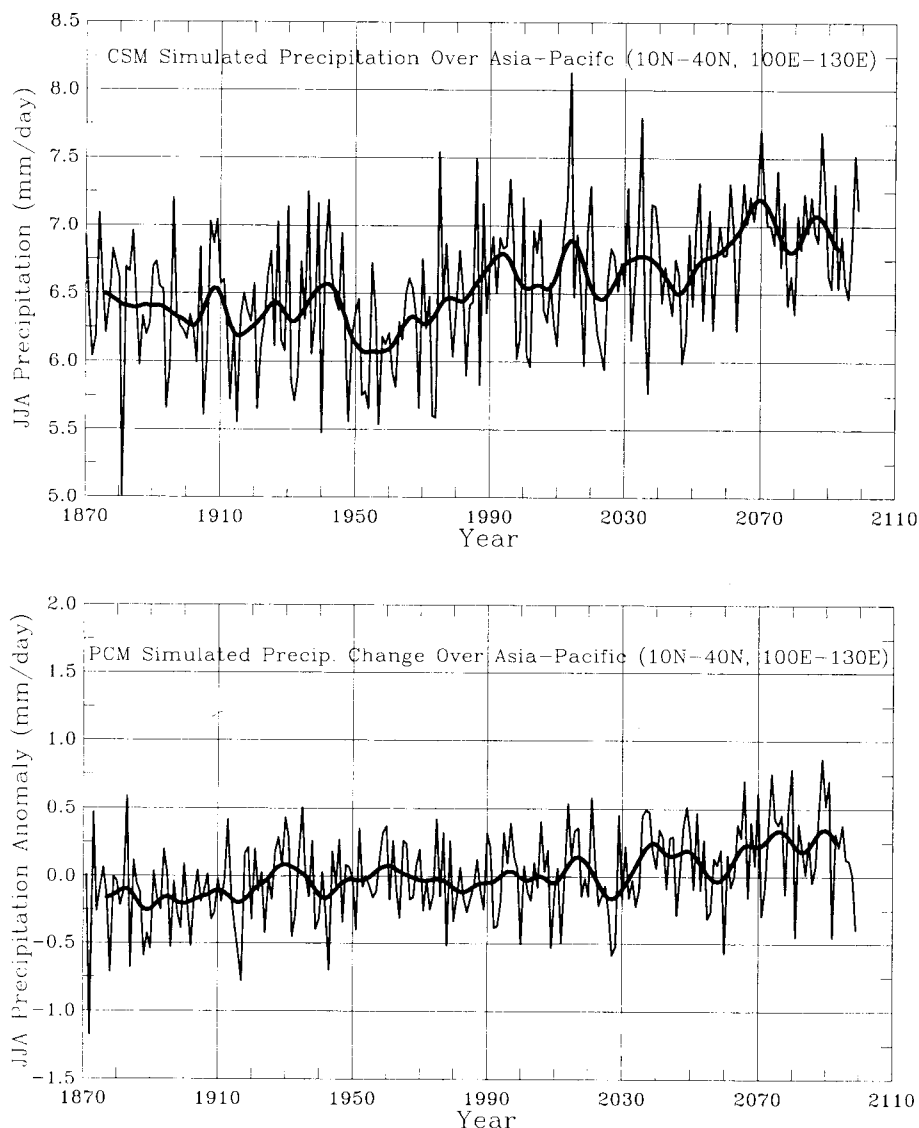


Fig. 6. CSM (upper panel) and PCM (lower panel, 5-ensemble average) simulated summer (June–August) precipitation variations (mm/day) from 1870 to 2099 averaged over the East Asian monsoon region (10° – 40° N, 100° – 130° E) under the BAU scenario (for the 21st century). The thick solid curve is the smoothed value using a 20-yr low-pass filter. Long-term changes above the interannual variation range may be regarded as statistically significant.

Soil moisture changes are small ($\pm 5\%$) over most Asia (including China, Southeast Asia, the Korean Peninsula, and Japan) in both the CSM and PCM simulations (not shown). In general, both the models suggest 2%–5% increases in root zone (top 70 cm) soil moisture during DJF over Russia and much of western Asia due to increased precipitation (not shown). During JJA, the CSM suggests small increases over these areas while the PCM ensemble mean shows some decreases over the same areas. Both the models show large (10%–30%) increases in soil moisture over western India, southern Pakistan,

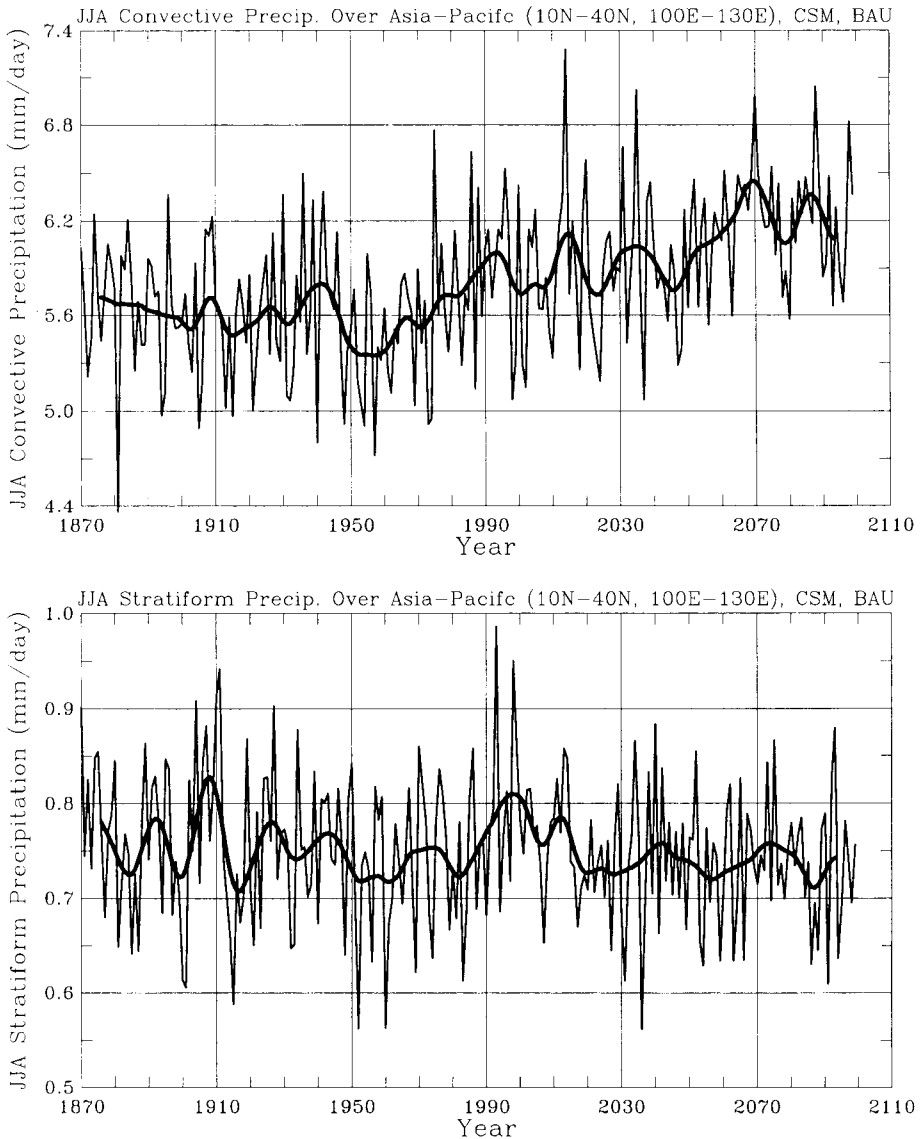


Fig. 7. Same as Fig. 6 but for CSM simulated convective(upper panel) and stratiform (lower panel) precipitation.

southern Afghanistan, and southern Iran through the year resulting from precipitation increases.

Latitude–height plots (not shown) of zonal mean stream–function and vertical velocity (ω) averaged over the 60° – 140° E domain revealed small ($\pm 5\%$) changes in the strength of the zonal mean Hadley circulation over the Asia–Pacific region. This is consistent with the small latitudinal gradient in the warming over low latitudes (cf. Fig. 4).

3.4 Climate changes over the upper reaches of the Yangtze River

Because of its enormous environmental, social, and economical impacts of the Three Gorges Dam, which is located at the middle reaches of the Yangtze River, future climate

change over the upper reaches of the Yangtze River is of great interest and concern to the Chinese people and government, and environmentalists around the world. The CSM and PCM simulations provide an estimate for the potential climate changes due to anthropogenic forcing in the 21st century over this region.

Figure 8 shows the time series of JJA surface air temperature averaged over the upper reaches of the Yangtze River (25° – 33° N, 94° – 114° E) simulated by the CSM and PCM under the BAU scenario. Both the models show a warming of $\sim 2^{\circ}\text{C}$ in the next 100 years over this region. The model results suggest that by about 2020 surface air temperature over this region will reach levels not seen since 1870. The steady warming increases surface evaporation over the region by about 7% during the next 100 years (Fig. 9). The year-to-year variations in both the temperature and evaporation remain fairly

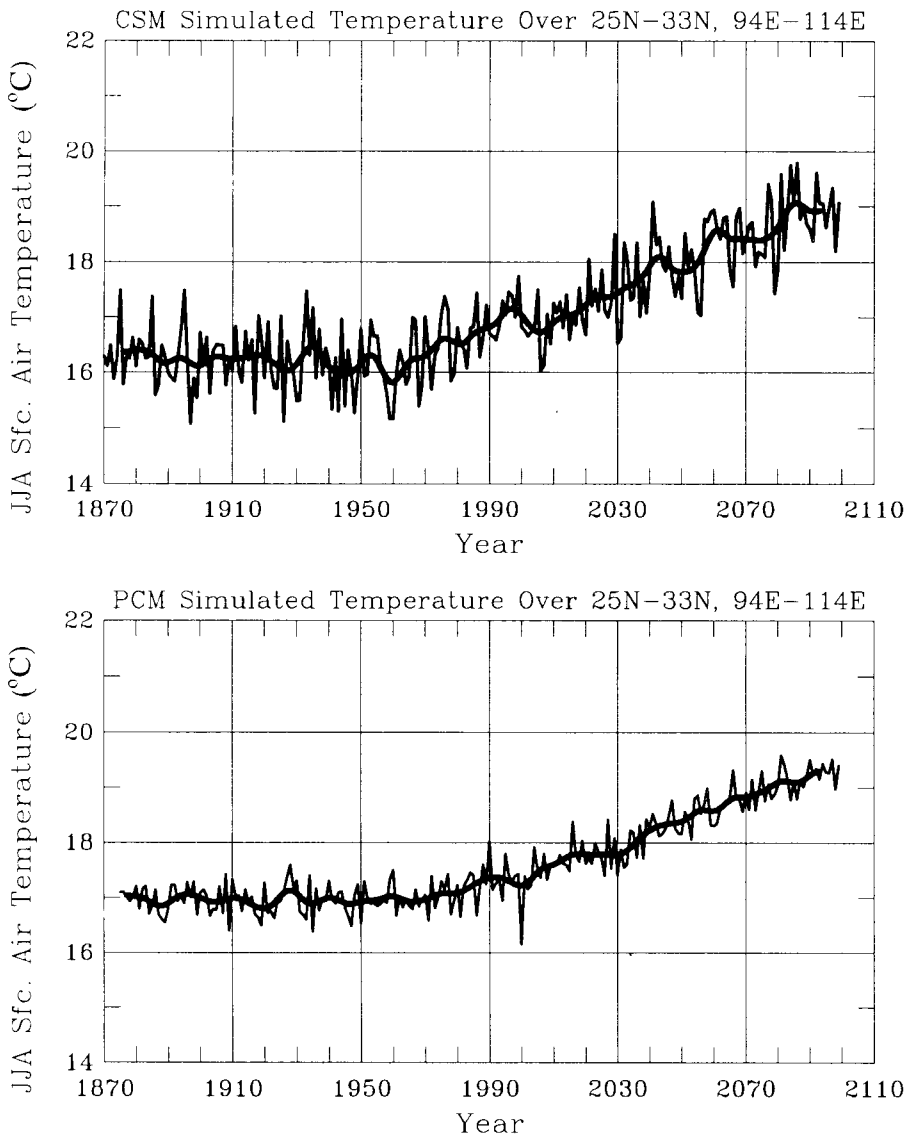


Fig. 8. Same as Fig. 6 but for summer surface air temperature ($^{\circ}\text{C}$) averaged over the upper reaches of the Yangtze River (25° – 33° N, 94° – 114° E).

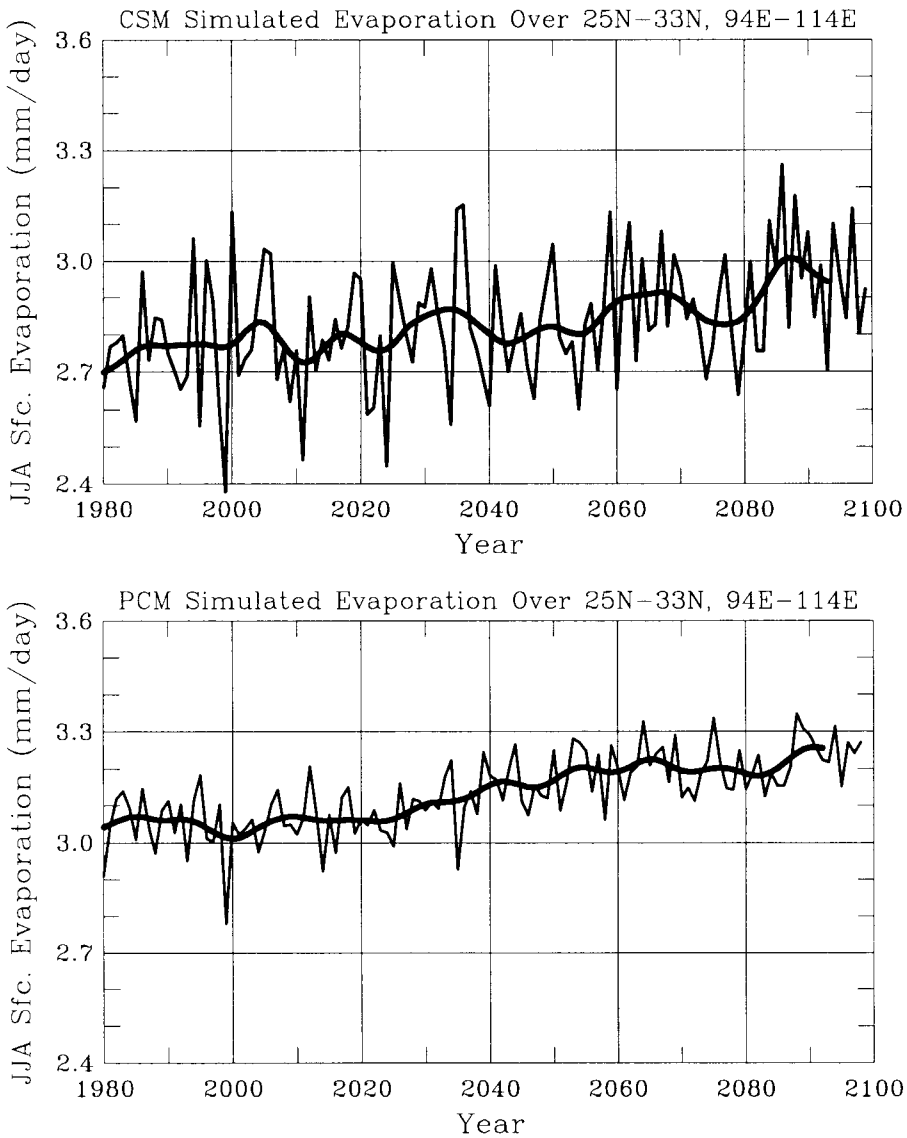


Fig. 9. Same as Fig. 8 but for summer surface evaporation (mm / day).

stable in these simulations (Figs. 8 and 9).

Figure 10 shows the simulated time series of JJA precipitation averaged over the upper reaches of the Yangtze River. The CSM produces $\sim 14\%$ increases of JJA precipitation in the next 100 years, whereas the PCM ensemble mean suggests a smaller increase ($\sim 5\%$). In both the models, the interannual variations (relative to local mean) remain comparable during the entire integration period.

Since JJA soil moisture changes over the upper reaches of the Yangtze River are within $\pm 2\%$ (not shown), precipitation minus evaporation ($P-E$) is a good proxy of river runoff over this region. Figure 11 shows that the inferred river runoff into the Three Gorges Dam increases by $\sim 30\%$ from 1980–1999 to 2080–2099 in the CSM simulation

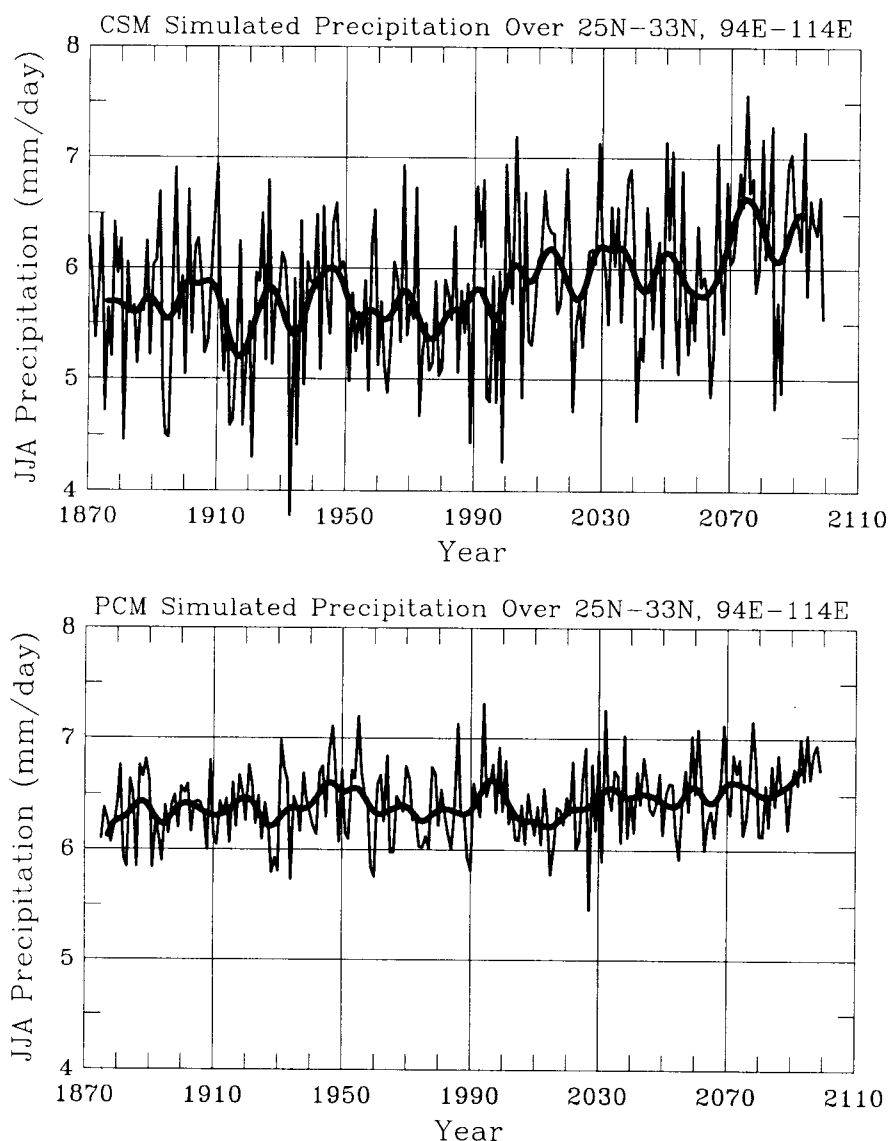


Fig. 10. Same as Fig. 8 but for summer precipitation (mm / d).

(mainly due to precipitation increases). Flooding years become increasingly frequent as the mean river runoff increases steadily in the 21st century in the CSM simulation. Although some of the PCM ensemble runs showed increases in the P-E over the region, the ensemble mean P-E changes little during the 21st century. This suggests that there are uncertainties (resulting mostly from precipitation changes) in model simulated regional changes of river runoff.

4. Summary and conclusions

The CSM and PCM produce a stable surface climate without flux adjustments that are used in some other coupled GCMs (Kattenberg et al., 1996). Using observed histori-

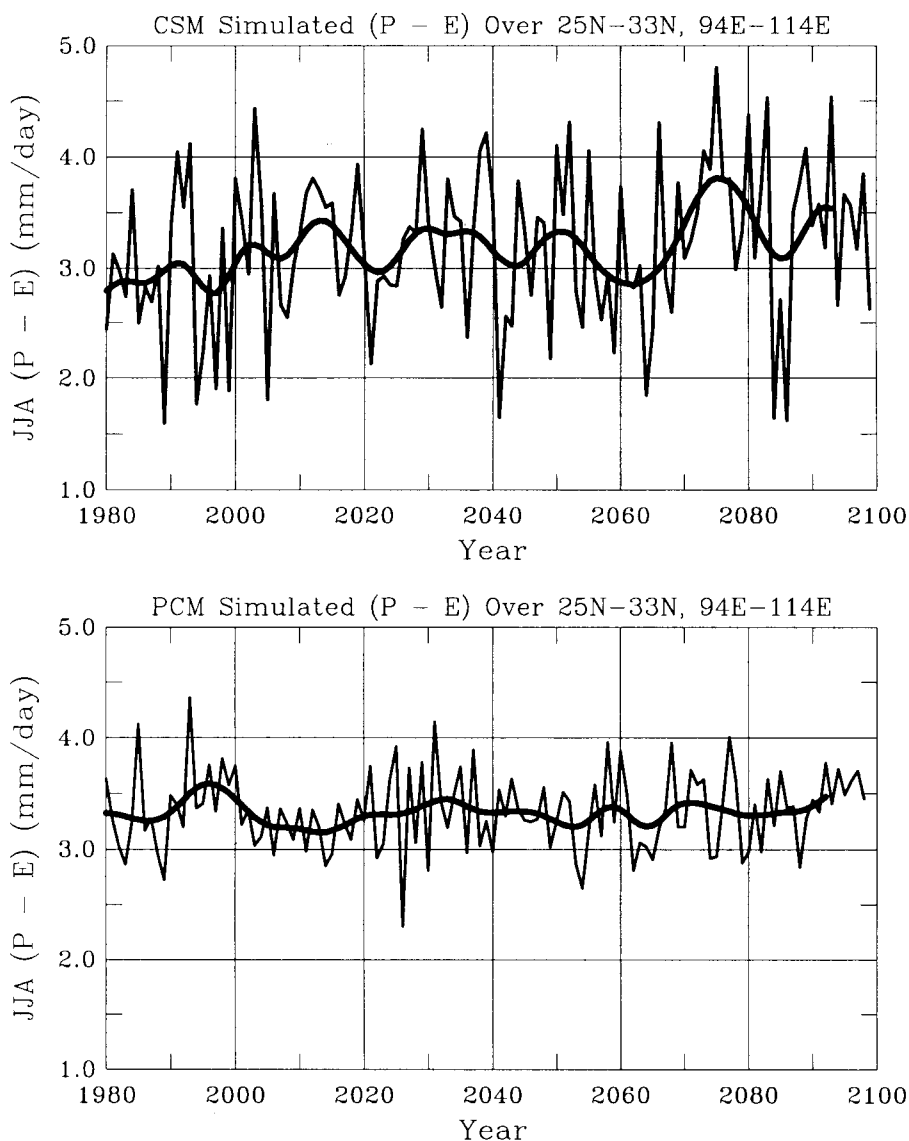


Fig. 11. Same as Fig. 8 but for summer precipitation minus evaporation (mm/day).

cal greenhouse gas concentrations and sulfate aerosol loadings, the CSM and PCM simulates many of the spatial and temporal variations of the 20th century climate (Dai et al., 2001a,b,c). Over the Asia-Pacific region (10° – 60° N, 55° – 155° E), the broad features of the East Asian summer monsoon rainfall is reproduced by the two models.

The CSM and PCM are used to simulate the climate of the 21st century under two different scenarios for future greenhouse gas concentrations and sulfur dioxide emissions, a business as usual case (BAU, $\text{CO}_2 \approx 710$ ppmv in 2100) and a CO_2 stabilization case (STA550, $\text{CO}_2 \approx 540$ ppmv in 2100). In both cases, we used a future SO_2 emissions scenario that is more realistic than any used previously in similar studies. We recognize that these simulations of future climate change have large uncertainties, which exist both in the forcing scenarios and in the model response to the forcing. Other climate forcings

such as changes in solar irradiance and volcanic eruptions are not included in these simulations.

Under the BAU scenario, the two models produce surface warming of about 3–5°C in winter and 2–3°C in summer over most Asia. Under the STA550 scenario, the warming is reduced by 0.5–1.0°C in DJF and by 0.5°C in JJA. The warming over the low-latitude Asian–Pacific region is fairly uniform and has little latitudinal gradient, which is consistent with the small changes in zonal mean Hadley circulation over the Asia–Pacific domain.

Regional precipitation changes have large intra-ensemble variations and a single realization such as the CSM simulation reported here may not be representative of the most-likely changes. The 5-ensemble mean from the PCM simulations, however, shows stable regional patterns of precipitation changes that are comparable under the BAU and STA550 scenario. The PCM ensemble mean shows that over the Asia–Pacific region, DJF precipitation increases by 10%–30% from 1980–1999 to 2080–2099 north of ~30°N and decreases by ~10% south of ~30°N, whereas JJA precipitation increases by 10%–20% over most of the region. In both the models, JJA rainfall over the East Asian monsoon region (10°–40°N, 100°–130°E) increases by ~7% by the later part of the 21st century, during which flooding conditions are likely to occur more frequently than in the past over the region.

Soil moisture changes are small ($\pm 5\%$) over most Asia, except for western India, southern Pakistan, southern Afghanistan, and southern Iran where root zone moisture increases by 10%–30% by the end of 21st century in all the seasons.

Over the upper reaches of the Yangtze River (25°–33°N, 94°–114°E), both the CSM and PCM suggest ~2°C surface warming and ~7% increases in surface evaporation for JJA in the next 100 years. The JJA precipitation changes over this region are, however, larger in the CSM simulation (+14%) than in the PCM ensemble mean (+5%). Because of this difference, the CSM simulation shows an implied ~30% increase in JJA river runoff into the Three Gorges Dam from 1980–1999 to 2080–2099, whereas the PCM ensemble mean simulation produces only small changes in this river runoff.

J.W. Weatherly, T.W. Bettge, W.G. Strand, J.M. Arblaster, V.B. Wayland and A.P. Craig contributed to the PCM simulations. B.A. Boville, J.T. Kiehl, and L.E. Buja contributed to the CSM simulations. The PCM simulations are supported by the U.S. Department of Energy and the U.S. National Science Foundation (NSF). The CSM simulations were supported by NSF Special Funds (NCAR CGD 98–110, Amendment #63) and the ACACIA Consortium (CRIEPI, Japan; EPRI, CA; KEMA Nederland B.V., the Netherlands; and the National Center for Atmospheric Research (NCAR), CO).

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