Climate Effects of the Deep Continental Stratus Clouds Generated by the Tibetan Plateau

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ABSTRACT

Evidence is presented to show that the maximum annual mean cloud optical depth between 60°S and 60°N is located on the lee side of the Tibetan Plateau. This largest cloud optical depth is produced by persistent deep stratus clouds (primarily the nimbostratus and altostratus) during winter and spring. These deep stratus clouds are generated and maintained by the frictional and blocking effects of the Tibetan Plateau. The plateau slows down the overflow, inducing downstream midlevel divergence; meanwhile it forces the low-level flows to converge downstream, generating sustained large-scale lifting and stable stratification that maintain the thick stratus clouds.

These stratus clouds produce extremely strong cloud radiative forcing at the top of the atmosphere, which fundamentally influences the local energy balance and climate change. Analysis of the long-term meteorological station observations reveals that the monthly mean anomalous cloudiness and surface temperature vary in tandem. In addition, the surface warming leads to destabilization and desaturation in the boundary layer. This evidence suggests a positive feedback between the continental stratus clouds and surface temperature through changing lower-tropospheric relative humidity and stratification. It is shown that the positive feedback mechanism is more robust during the period of the surface cooling than during the surface warming. It is suggested that the positive climate feedback of the continental stratus cloud may be instrumental in understanding the long-term climatic trend and variations over East Asia.

1. Introduction

Clouds are important modulators of climate. Distribution of clouds has profound impacts on radiative energy balance and in turn on the atmospheric circulations and climate (Schneider 1972; Hartmann and Short 1980; Hartmann et al. 1992). The effect of clouds on radiation budget is measured by cloud radiative forcing (CRF), which represents the difference between cloud-free radiative fluxes and the average of all-sky observations (Ramanathan et al. 1989). The net CRF at the top of atmosphere (TOA) depends on the balance between the cloud albedo and greenhouse effects.

The effects of clouds depend on their properties (Slingo 1989). Deep convective and cirrus clouds play an important role in regulating sea surface temperature (SST) over the tropical warm pool (Arking and Ziskin 1994; Ramanathan et al. 1995; Lau et al. 1997; Waliser 1996). Over the warm pool, both shortwave and longwave CRFs are strong, but the net CRF at the TOA is negligible because of cancellation between them (Kiehl 1994). The low-level marine stratus clouds, on the other hand, produce net radiative cooling due to the dominance of the negative shortwave CRF. These low-level clouds play a critical part in establishing the cold tongues of SST and the equatorial asymmetry of the tropical convergence zone in the tropical Pacific and Atlantic Oceans (Philander et al. 1996; Yu and Mechoso 1999).

So far much attention has been paid to the CRF of high and low clouds, but the impacts of middle stratus clouds have received little attention. Klein and Hartmann (1993) noticed that all of the regions with a sig-
nificant fraction of stratus clouds are located over cold oceans except over China. Distinctive from low marine stratus clouds, the stratus clouds over eastern China are primarily middle clouds (Yu et al. 2001). In this study, we focus on the climatic impacts of the middle stratus clouds downstream of the Tibetan Plateau. We will describe its unique cloud radiative characteristics and its formation mechanism.

Another motivation of the present study concerns the climate feedback of the continental stratus clouds. Within a climate system the feedback processes that involve clouds and water vapor have foremost influences on the climate system in response to changes in external forcing. However, our current knowledge of cloud feedback remains inadequate. The current climate model results suggest that on a global scale clouds have a weak negative feedback (Cess et al. 1996); yet, the earlier versions of these models yield large inconsistencies in the nature of cloud feedbacks with a majority of the models suggesting a positive feedback (Cess et al. 1990). Previous studies on cloud feedback were primarily focused on tropical ocean regions. Study of the cloud feedback over midlatitude land area is rare. The Tibetan Plateau provides a natural laboratory for understanding the feedback between continental stratus clouds and surface temperature. One of the major purposes of the present study is to investigate the nature of this feedback.

After a brief description of the data used in this study in section 2, we will describe unique features of the continental stratus deck downstream of the Tibetan Plateau (section 3), elaborate mechanisms responsible for the formation of these continental stratus clouds (section 4), and investigate the nature of the stratus cloud–climate feedback (section 5), as well as its impacts on the mean climate and climate variation (section 6). In the last section, we summarize the major points and discuss the implications of present results on global warming.

2. Data

The data used in this study include meteorological station observations, reanalysis data, and satellite observations. The multidecadal time series of monthly mean total cloud fraction and surface temperature are obtained from the weather database provided by the Chinese Meteorological Administration (CMA). To facilitate climate studies, 160 surface stations, which are distributed reasonably evenly over mainland China, are selected. The monthly data include precipitation, surface temperature, and cloud fraction. The locations of 145 stations in eastern China are marked by heavy dots in Fig. 7. a. These station data were then interpolated to 1° × 1° horizontal grids by averaging the station data with weights proportional to the inverse of the square distances between the grid and stations. The atmospheric general circulation data are derived from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) re-

analysis data (Kalnay et al. 1996) at a horizontal resolution of 2.5° × 2.5° and a vertical resolution of 17 pressure levels. The NCEP–NCAR reanalysis data are currently available for the period starting January 1948. However, because the quality of the analysis over Asia may be low before the 1960s (Yang et al. 2002), the data used in this study are for 1963–2000.

The shortwave and longwave fluxes at the TOA are taken from the Earth Radiation Budget Experiment (ERBE) (Barkstrom 1984). The data archive consists of monthly mean all-sky and clear-sky longwave and shortwave radiative fluxes at the TOA with 2.5° × 2.5° resolution available from February 1985 to December 1989. Uncertainties in the ERBE data arise mainly from instrument errors, sampling biases, and errors from the conversion of radiance to irradiance using bidirectional models. Barkstrom et al. (1989) gave an error bound of 5 W m−2 for the monthly regional fluxes. A more detailed analysis of the uncertainties in ERBE data has been made by Rieland and Raschke (1991). Part of the errors, such as sampling errors and the bidirectional model errors, is random. The impact of random errors is negligible when time and space averages are performed (Yu et al. 1999). The International Satellite Cloud Climatology Project (ISCCP) products (Rossow and Schiffer 1991, 1999) were also used, which provide cloud optical thickness and cloud amount for various cloud types. These cloud types are defined by the visible spectrometry/infrared (VIS/IR) cloud-top pressure and optical thickness or by the IR cloud-top pressure alone. Based on cloud top-pressure, clouds are classified into low-level cloud (including cumulus, stratocumulus, and stratus), middle-level cloud (altocumulus, altostratus, and nimbostratus) and high-level cloud (cirrus, cirrostratus, and deep convection). The specific cloud types listed above are determined further by classifying optical thickness into three categories, below 3.6 for cumulus, altocumulus, and cirrus, above 23 for stratus, nimbostratus, and deep convection, and between 3.6 and 23 for stratocumulus, altostratus, and cirrostratus. The ISCCP D2 dataset (Doutriaux-Boucher and Seze 1998), used to display the cloud properties related to cloud types, is available as monthly means from 1984 to 2000 at 2.5° × 2.5° resolution.

The surface-observed cloud amounts suffer from artificial errors and the accuracy of the ISCCP cloud properties are limited by intersatellite calibration error and by errors from estimating cloud properties from radiance. Changes in the ISCCP precessing produced significant differences between versions of the ISCCP dataset (Doutriaux-Boucher and Seze 1998), and a number of artifacts remain in the D2 data. We have examined the consistency between the cloud amounts observed from the surface station and from satellites. The interannual variations of total cloudiness obtained from the ISCCP data and from the station observations are in good agreement. Although systematic deviation between the two datasets exists, it is well within the normal
We found that the largest cloud optical depth downstream of the plateau is primarily attributed to its cloud properties. Downstream of the plateau, nimbostratus and altostratus clouds prevail (Fig. 2b). The fractional coverage of nimbostratus and altostratus clouds reaches a maximum just east to the Tibetan Plateau.

Figure 3 further compares two longitudinal cross sections of cloud fraction for different cloud types, one is along 29°N from 100° to 120°E and the other along the equator from 140°E to 90°W. Along 29°N and to the east of the Tibetan Plateau, especially over the Sichuan basin (103°–108°E), the amount of nimbostratus and altostratus clouds exceeds the amounts of all other types of clouds that have large optical thickness (e.g., deep convective, low-level stratus, and stratocumulus clouds) (Fig. 3a). In contrast, along the equator the marine stratus (stratus and stratocumulus) dominates in the eastern Pacific, whereas the cirrus and cirrostratus clouds prevail in the western Pacific (Fig. 3b).

The nimbostratus and altostratus clouds are responsible for the extremely large cloud optical thickness of the Tibetan Plateau stratus cloud deck. This proposition is further confirmed by the results shown in Figs. 4 and 5. As shown in Fig. 4, the nimbostratus and altostratus clouds exhibit the best correlation with the total cloud optical thickness. Figure 5 compares zonal variations of cloud optical depth and nimbostratus–altostratus cloud amount along 29°N from 100° to 120°E. Obviously, the nimbostratus and altostratus clouds dominate the zonal variation of cloud optical depth (Fig. 5a). Over the Sichuan basin (27°–32°N, 103°–108°E), the annual variation of the thick stratus cloud amount is in tandem with that of the cloud optical thickness (Fig. 5b), confirming that the nimbostratus and altostratus clouds are major contributors to the large cloud optical thickness. The correlation coefficient between annual-mean variations of the nimbostratus–altostratus cloud amount and the cloud optical thickness in Sichuan basin is 0.674 from 1984 to 2000.

4. Formation mechanism of the nimbostratus and altostratus clouds

Nimbostratus and altostratus clouds generally cover a vast area and have a bulky vertical extent. The nimbostratus is sometimes thick enough to block out entirely the direct solar beam. The nimbostratus clouds have low cloud base and considerable vertical development, bringing the tops into the middle tropospheric level. The nimbostratus and altostratus often form when stably stratified moist air is forced by steady mechanical lifting over a large area. This often happens at a warm or cold front with gentle slope, occlusion, or in the presence of other large-scale forcing. Usually the atmosphere is stably stratified, and turbulence mixing in the clouds is weak.

We put forward that the persistent nimbostratus and altostratus clouds over subtropical East Asia result from uncertainty contained in current cloud observations. Figure 1 shows the annual variations of total cloud percentage from 1984 to 2000 over the Sichuan basin, which is adjacent to Tibet (27°–32°N, 103°–108°E). The total cloud amount derived by adding all individual clouds in the ISCCP data is systematically (about 2%) larger than the total cloudiness observed by surface meteorological station (Fig. 1). The correlation coefficient between them is 0.90. This consistency adds confidence to our analysis of the long time series of the surface-observed cloudiness data, although the consistency between cloud amount from surface stations and satellite data is not enough to entirely dispel the limitation of both data. The agreement in the interannual variations between the two cloud datasets should result from the time and space averages, which result in random errors being negligible. Previous studies have also shown that these two independent cloud datasets could produce comparable climatological patterns in cloud distribution and cloud movement in low and middle latitudes (Lau and Crane 1997; Hahn et al. 2001).

3. Cloud–radiative forcing downstream of the Tibetan Plateau

Based on ISCCP data, 1991–2000 mean cloud optical thickness and fractional amount of the nimbostratus and altostratus clouds are shown in Figs. 2a and 2b, respectively. The maximum cloud optical depth in the global Tropics and midlatitudes between 60°S and 60°N is located downstream of the Tibetan Plateau (Fig. 2a). Note that the maximum total amount of clouds is not located downstream of the plateau. In fact, the annual mean total cloud fraction over eastern China (about 65%) is less than those over the western Pacific warm pool (where deep cumulus/anvil clouds prevail) and over the eastern Pacific (where marine stratus persists); both are about 75%. Why is the cloud optical depth over the eastern flank of the Tibetan Plateau the largest?
the blocking and frictional effects of the Tibetan Plateau. During most of the year, in particular from November to May, the Tibetan Plateau is continuously exposed to tropospheric westerlies. The elevated plateau bifurcates upstream low-level westerly flows and forces the surrounding flows to converge downstream. Meanwhile, the plateau also slows down the midtropospheric westerlies that flow over its mountainous surface, resulting in downstream midlevel divergence. The low-level convergence sustains large-scale steady lifting, while the middle tropospheric divergence confines the lifting to the lower troposphere.

Based on NCEP–NCAR reanalysis data, Fig. 6a shows the 1991–2000 annual mean westerly speed at 500 hPa and winds at 850 hPa. It is clear that the westerly flow is considerably slowed down when flowing over the Tibetan Plateau, which induces a strong divergence in the middle troposphere leeward of the plateau. The 850-hPa surrounding flows converge downstream of the plateau. The 1991–2000 annual-mean vertical profile of divergence averaging in the region ($27^\circ$–$32^\circ$N, $103^\circ$–$118^\circ$E) is shown in Fig. 6b, which clearly displays the low-level convergence and middle and high tropospheric divergence downstream of the Tibetan Pla-
Fig. 3. Longitudinal cross sections of cloud fraction for different cloud types along (a) 29°N from 100° to 120°E and (b) along the equator from 140°E to 90°W in units of percentage, which include middle stratus clouds (the nimbostratus and altostratus) (crosses), low-level stratus and stratocumulus (filled squares), deep convective clouds (filled circles), cirrus and cirrostratus (open circles), and cumulus and altocumulus (open squares), derived from the ISCCP D2 data, averaged from 1991 to 2000.

Fig. 4. Scatterplots of the fractional amount (percentage) of (a) the middle-level nimbostratus and altostratus clouds, (b) low-level stratus and stratocumulus clouds, and (c) the sum of deep convection and cirrostratus as functions of cloud optical depths over eastern China (25°–35°N, 103°–108°E) derived from the monthly ISCCP data from 1991 to 2000.

tau. Figure 6c shows the relationships among the total amount of nimbostratus and altostratus clouds and the midlevel divergence. Both variables are presented in terms of their mean annual cycles and averaged over the lee side of the plateau (27°–32°N, 103°–108°E). The midtropospheric divergence coincides very well with the amount of nimbostratus and altostratus clouds throughout the year. Results shown in Fig. 6 suggest that mechanical forcing by the plateau provides a favorable large-scale environment for formation of deep stratus clouds. Figures 5b and 6c also indicate that the cloud optical thickness and nimbostratus–altostratus cloud amount reach their extremes in the cold season when the westerlies are strongest.

In addition to the mechanical forcing by the plateau, the southern branch of the low-level westerly flows (Fig. 6a) is recharged with moisture due to their trajectories passing across the warm Indian subcontinent and the Bay of Bengal. The moist, southern branch of the low-level westerly is constantly uplifted by the Yun-Gui Plateau, a highland extending from the southeast corner of the Tibetan Plateau to Indochina. The sustained ascent, increased moisture transport, and stable stratification on the lee side of the plateau, together provide a suitable large-scale condition for maintenance of nimbostratus and altostratus clouds.
5. Stratus cloud–climate feedback over the lee side of the Tibetan Plateau

Over subtropical eastern China, the cloud amount and surface temperature exhibits a pronounced negative correlation. This can be seen from Fig. 7a, which shows the spatial pattern of the correlation coefficients between the observed anomalous monthly cloud fractions and the anomalous surface temperatures from 1951 to 2000. The most significant negative correlation is found along the Yangtze River valley. Over the Sichuan basin (27°–32°N, 103°–108°E) from 1991 to 2000. The data are derived from the monthly ISCCP data.

The negative correlation between the surface temperature and stratus cloud amount suggests a coupling between the surface temperature and the cloud radiative forcing. It is well understood that the clouds can affect surface temperature through changing CRF (Chen et al. 2003). How does surface temperature affect the continental stratus clouds?

Analysis of the NCEP–NCAR reanalysis data and Chinese surface station data reveals that the surface temperature is highly correlated with the temperature below 850 hPa (correlation coefficient reaches 0.72 from 1963 to 2000), but is nearly uncorrelated to the temperature above 600 hPa. This implies that a surface warming would destabilize the low troposphere and reduce the relative humidity in the boundary layer because the increase of water vapor in the air is slower than the increase of the saturation vapor over most of the land area.

The above analyses lead to two hypothetically positive feedback processes between the cloud physics and large-scale dynamics, that is, the stratus–surface temperature feedbacks through changing stability and relative humidity. When surface temperature rises, the reduced relative humidity would reduce stratus cloud fraction, allowing more radiative fluxes into the earth system and resulting in further surface warming. Meanwhile, the surface warming would also reduce the lower-tropospheric static stability, which in turn reduces the potential for stratus cloud formation and favors further surface warming. In addition, the reduction in static stability could stimulate stronger mixing with drier air above and could further induce the reduction in low-level humidity, which could enhance the feedback.

To confirm the proposed positive cloud feedback mechanisms, we examine interannual variations. For the period from 1963 to 2000, the correlation coefficient between the surface temperature and the mean relative humidity in the layer between 925 and 700 hPa is −0.48; the correlation coefficient between the surface temperature and 850–500-hPa differential potential temperatures is −0.42. The annual mean total cloudiness is positively correlated with the mean relative humidity and the differential potential temperature (stability) with the correlation coefficients being 0.73 and 0.50, respectively.

Figure 8 shows 10-yr running mean relative humidity and the differential potential temperature. Comparison of Figs. 8 and 7b indicates that a significant negative (positive) correlation between the surface temperature (total cloud amount) and lower-troposphere relative humidity or static stability exists on decadal time scales. The strong coupling among the surface temperature, clouds, relative humidity, and static stability indicates the important contributions of the stratus cloud feedback (through changing relative humidity and static stability) to the climate variations on the lee side of the plateau.

To better understand the effects of positive stratus cloud feedback on the surface temperature variation, we present an example to illustrate how the cloud radiative forcing changes in response to surface temperature changes. Combining the ERBE data, ISCCP data, and Chinese station observation data, the surface temperature induced changes in cloud radiative interaction is examined from 1985 to 1989. Although the ERBE data is available only for this short period, it nevertheless
Fig. 6. (a) The 1991–2000 annual-mean westerly wind speed at 500 hPa (contour interval is 2 m s\(^{-1}\)) and the winds at 850 hPa (vectors with maximal length for 6 m s\(^{-1}\)). The dashed contours denote wind speed below 10 m s\(^{-1}\). The shading denotes mountain heights, and the edges of light and dark shading denote the contours of 2000 and 3500 m, respectively. (b) 1991–2000 annual-mean vertical profile of horizontal divergence averaging in the region (27°–32°N, 103°–118°E) in units of 10\(^{6}\) s\(^{-1}\). (c) 1991–2000 mean annual cycles on the lee side of the plateau (27°–32°N, 103°–108°E), including nimbostratus–altostratus cloud amount (percentage) (solid), which is derived from the monthly ISCCP data, and the divergence in the midlevel (600–500 hPa) in units of 10\(^{6}\) s\(^{-1}\) (dashed). The circulation data are derived from the NCEP–NCAR reanalysis dataset.

contains a sufficiently large signal in the surface temperature that may be associated with the 1986/87 El Niño. As shown in Fig. 9a, changes in net CRF at the TOA positively correlated with changes in the surface temperature, and both of them negatively correlate with total cloud amount (Fig. 1). Figure 9b shows the yearly mean variations of the stratus cloud amount with large cloud optical depths (including nimbostratus, stratus, altostratus, and stratocumulus), and the associated shortwave CRF at the TOA. Comparison of the results shown in Figs. 9a and 9b suggests that the shortwave radiation forcing of the stratus clouds dominates the changes in net CRF at the TOA. Since the amount of solar radiation energy absorbed by the atmosphere is small, the surface radiative forcing change is almost the same as that at the TOA.

6. Impacts of the Tibetan Plateau stratus cloud deck on east China climate

a. Impacts on mean climate

The negative net CRF of the plateau continental stratus exhibits a maximum that is comparable with that of marine stratus clouds over the southeastern Pacific (Fig. 2c). This is expected from the radiative properties of the nimbostratus and altostratus clouds. Corresponding to the largest cloud optical depth, the Tibetan Plateau stratus deck produces strongest shortwave CRF at the
The extremely strong negative CRF of the plateau stratus deck has prominent impacts on the climate in eastern China. It affects profoundly the local energy balance. To compensate the radiative cooling induced by the negative net CRF at the TOA, the atmospheric
column there must gain energy from the moist static energy convergence. Therefore, eastern China becomes an area of energy sink. This is in sharp contrast to other subtropical regions where the atmosphere exports moist static energy (Yu et al. 1999).

b. Impacts on the surface temperature variation

The positive feedback between the surface temperature and the Tibetan Plateau stratus deck may help to explain the climate variation downstream of the plateau. It is conceivable that the cloud radiative feedback during the surface cooling period could be more robust than that in the warming period. When the surface cools, the increased static stability favors stratus cloud formation while it restrains deep convection and related cirrus cloud formation, which results in more intensified solar radiative cooling that dominates the cloud-induced greenhouse warming. However, when the surface warms, the induced unstable stratification might, in part, favor cumulus convective clouds that could weaken the positive cloud feedback.

Figure 9 illustrates more robust positive cloud feedback in the cooling period. During the warming period from 1986 to 1987, the surface temperature increased 0.78°C; the net cloud radiative forcing increased by 6 W m$^{-2}$ (the total cloud fraction decreased by 1%, and the stratus cloud amount decreased by 3.3%). Therefore, the cloud radiative feedback is only 7.7 W m$^{-2}$ K$^{-1}$ if changes in cloud are entirely related to the changes in surface temperature. On the other hand, during the cooling period from 1987 to 1989, the surface temperature decreased 0.78°C, and the net cloud radiative forcing decreased by 13 W m$^{-2}$ (the total cloud fraction increased by 5.5% and stratus clouds increased by 6.2%). Thus, the cloud radiative feedback amounts to 16.7 W m$^{-2}$ K$^{-1}$ if changes in cloud are entirely related to the changes in surface temperature. Based on this estimation, the positive cloud radiative feedback during the cooling period is obviously stronger than that during a warming period. The relatively weak cloud radiative feedback during the warming period could be due to the nonstratus cloud formation. During the warming period of 1986–87, 70% of the stratus cloud decrease is balanced by nonstratus clouds, while during the cooling period 1987–89, only 11% of stratus cloud increase is offset by nonstratus clouds. Thus the change of stratus clouds during the cooling period more effectively dominates the total cloudiness variation than that during a warming period.

7. Conclusions and discussions

It is shown that on the eastern flank of the Tibetan Plateau the annual mean cloud optical depth exhibits a maximum in the global Tropics and extratropics (between 60°S and 60°N). This maximum cloud optical thickness is due to the persistence of the thick nimbo-stratus and altostratus clouds, in particular during winter and spring. The nimbostratus and altostratus clouds determine the cloud radiative properties of the continental stratus cloud deck in the wake of the Tibetan Plateau.

We propose that the thick stratus cloud deck results from the blocking and frictional effects of the Tibetan Plateau on the prevailing westerlies. The elevated plateau bifurcates the upstream low-level westerly flows and forces the surrounding flows to converge on its lee side. Meanwhile, the plateau also slows down the midtropospheric westerlies that flow over its mountainous surface, resulting in downstream midlevel divergence. As such, the plateau constantly generates and maintains middle stratus clouds, resulting in the maximum cloud optical depth.

The persistent plateau stratus deck generates strongest cloud radiative forcing at the TOA in the global Tropics and midlatitudes. It produces about 60 W m$^{-2}$ radiative cooling at TOA over the Sichuan basin. This prominent radiative forcing makes eastern China an area of moist static energy sink. This contrasts with most other mid–low latitude regions where the atmosphere exports moist static energy.

In the regions covered by the plateau stratus deck, the total cloud amount and the surface temperature exhibit a pronounced negative correlation. Surface cooling is found to stabilize the lower troposphere and increase the relative humidity in the boundary layer and the lower troposphere. The opposite is true for the surface warming.

Based on these observed facts, we propose that there exist two positive feedback processes between the surface temperature and stratus clouds: one through change of the relative humidity and the other through change of the static stability (Fig. 10). Rising surface temperature leads to a reduction of the stratification and decrease of relative humidity; both suppress the formation of continental stratus clouds. Reduction of the stratus clouds would, in turn, reduce cloud radiative cooling and favor further surface warming. Similarly, surface cooling would increase the amount of stratus clouds and further enhance the surface cooling.

The results shown in Fig. 9 suggest that the two pos-

![Schematic diagram illustrating the stratus cloud feedbacks through change of low-level relative humidity and static stability.](image-url)
itive feedback mechanisms are more robust during the period of surface cooling and stratus cloud increase, than during the period of surface warming and stratus cloud decrease. This is because, when the surface warms, change of the static stability might favor the development of cumulus convection (in particular during summer), which can potentially offset the effects of the stratus clouds. Of course, a longer dataset is required to confirm these findings.

Downstream of the Tibetan Plateau the moderate surface cooling in the last century tends to be at odds with most of the rest of the world (Li et al. 1995; Folland et al. 2001; Houghton et al. 2001). Previous studies have emphasized effects of anthropogenic aerosols (Lou et al. 2001; Menon et al. 2002). Considering the critical role of clouds in regulating climate and the persistence of the continental stratus deck, we propose that the distinctive climate trend may be attributed to the unique regional cloud radiative properties. Chen et al. (2003) showed a significant increase in the middle and low cloud amount in the winter half-year over the east periphery of the Tibetan Plateau responding to doubled CO₂ simulation and mentioned that cloud radiative interaction is the primary cause of the change in surface temperature in the regions with elevations below 3 km around the Tibetan Plateau. The two positive feedback mechanisms could be instrumental for understanding the fact that the cooling trends from the 1950s to mid-1980s in the Sichuan basin is much stronger than elsewhere in the global Tropics and midlatitudes (Fig. 7b). Because the positive cloud radiative feedback during the cooling period is more effective, the cooling trends from the 1950s to mid-1980s in the Sichuan basin were so strong that the overall trend is flat during 1950–2000, whereas most of the global Tropics and midlatitude regions are characterized by considerable warming during the same period.

Although the analysis in the present study is focused on the Yangtze River valley, the conclusions concerning the cloud–climate feedback may highlight a mechanism that may apply globally. In middle and low latitudes, the ongoing enhanced warming trend has been attributed to the greenhouse gas effects and water vapor feedback (Yang and Tung 1998; Schneider et al. 1999; Hall and Manabe 1999; Larson et al. 1999; Slingo et al. 2000). The water vapor feedback is based on the assumption that during surface warming the relative humidity remains constant. This assumption is not always supported by our diagnostic analysis. Although the global-mean water vapor is positively correlated with surface temperature, the mean relative humidity is negatively correlated with the lower-tropospheric temperature because the increase of atmospheric humidity is slower than the increase of saturation water vapor, especially over the middle–high latitude continent. Some previous studies have shown that most existing climate models overestimate the positive correlation between the surface temperature and the temperature above the boundary layer.

They also overestimate the correlation between water vapor and atmospheric temperature in climate variation (Sun and Held 1996; Sun et al. 2001, 2003; Ingram 2002). Therefore, coupled ocean–atmosphere models might typically overestimate the positive water vapor feedback in amplifying the warming effect of increased greenhouse gas concentrations. However, Bauer et al. (2002) argued that the discrepancy between observed and simulated correlations between temperature and humidity are substantially reduced when consistent sampling is introduced, and Soden et al. (2002) provided quantitative evidence of the reliability of water vapor feedback in current climate models by comparing water vapor feedback in the Geophysical Fluid Dynamics Laboratory model and observations following the eruption of Mount Pinatubo. The uncertainty of humidity in the NCEP reanalysis is arguable to display the long-term global changes (Trenberth et al. 2001).

Cloud effects in the current climate models exhibit a range of positive and negative feedback depending on the physical parameterizations of models. Consequently, model-based predictions of global warming include both a strong amplifying effect of water vapor feedback and a significant uncertainty due to uncertainty of cloud feedback processes (Schneider et al. 1978; Shukla and Sud 1981; Wetherald and Manabe 1988). Our study suggests that cloud radiative feedback could be positive in the stratus deck region due to the associated changes in stratification and relative humidity in the lower troposphere. It is important to point out that the nature of the cloud radiative feedback on surface temperature depends on the properties of the clouds. The cloud–climate feedback could be negative when the albedo effect of high clouds dominates the greenhouse effects. The cloud liquid water feedback could also be important in some circumstances. The complexity of cloud feedback in different area arises from large different responses of different cloud types to the changes in surface temperature. Over a cold oceanic area, for example, in the eastern equatorial Pacific, the low-level stratus cloud dominates the total cloud (Fig. 3b), but the interannual variability of total cloud is regulated strongly by cirrus cloud (not shown). The El Niño warming reduces the static stability in the lower troposphere, which results in a low-level stratus cloud decrease and cirrus cloud increase and the cirrus cloud–induced greenhouse effect dominates the change in the net CRF at TOA. Although the 1987 El Niño warming also involved a positive feedback in the eastern equatorial Pacific; which is consistent with Sun et al. (2003), the physical process is very different from that downstream of the Tibetan Plateau. Therefore, realistic simulation of cloud properties and amount is critical for correct representation of the cloud feedback in climate variations.

The present hypothesis is preliminary because of the limitations of the data used. The uncertainties in the above analysis may arise from the fact that we did not consider possible impacts of changes in greenhouse gas-
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