Climate effects of the deep continental stratus clouds Generated by Tibetan Plateau

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Abstract

Evidence is presented to show that the annual mean cloud optical depth in the leeside of the Tibetan Plateau exhibits a global maximum between 60^{o}S and 60^{o}N. This large cloud optical depth is due to the persistence of 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 over-flow, inducing downstream mid-level divergence; meanwhile it forces the low-level surrounding-flows to converge downstream, generating sustained large scale lifting and stable stratification that maintains the thick stratus clouds.

This 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 observation reveals that the monthly mean anomalous cloudiness and surface temperature vary in tendon. In addition, the surface warming leads to destabilization and desaturation in the boundary layer. These evidences suggest positive feedbacks 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 period of 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 variation over the 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 observation (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. 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. 1996; Waliser 1996). Over the warm pool, both the 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 critical parts 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 the high and low clouds, but the impacts of the middle stratus clouds have received little attention. Klein and Hartmann (1993) noticed that all the regions with a significant fraction of stratus clouds are located over the cold oceans except over China. Distinctive from low marine stratus clouds, the stratus clouds over eastern China are primarily middle[1] 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 with 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 the external forcing. However, our current knowledge of the cloud feedback remains inadequate. The current climate model results suggest that on the global scale clouds have a weak negative feedback; yet, the earlier versions of these models yield large inconsistencies in the nature of the cloud feedbacks with majority of the models suggesting a positive feedback (Cess et al 1990; Zhang et al 1994; Cess et al 1996; Lee et al 1997, Tsushima and Manabe 2001). Previous studies on cloud feedback were primarily focused on tropical ocean regions. Study of the cloud feedback over mid-latitude 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 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 multi-decadal time series of monthly mean total cloud fraction and surface temperature are obtained from the weather database provided by Chinese Meteorological Administration. These data were then interpolated to 1°×1° horizontal grids. The atmospheric general circulation data are derived from the National Centers for Environmental Prediction/ National Center for Atmospheric Research (NCEP/NCAR) reanalysis data (Kalnay 1996) at a horizontal resolution of 2.5° by 2.5° and a vertical resolution of 17 pressure levels.

The short wave and long wave fluxes at the TOA are taken from Earth Radiation Budget Experiment (ERBE) (Barkstrom, 1984). The data archive consists of monthly mean all-sky and clear-sky long wave and short wave radiative fluxes at TOA at 2.5°×2.5°resolutions and available from February 1985 to December 1989. The International Satellite Cloud Climatology Project (ISCCP) products (Rossow and Schiffer 1991; Rossow and Schiffer 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. The ISCCP D-2 dataset (Doutriaux and Seze 1998), used to display the cloud properties related to cloud types, are available in monthly mean from 1984 to 2000 at 2.5°×2.5° resolution.

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 observation are in good agreement. Although systematical deviation between the two datasets exists, it is well within the normal uncertainty contained in the current cloud observations. Figure 1 shows the annual variations of total cloud percentage from 1984 to 2000 over Sichuan basin that adjacent to the Tibet (27°N-32°N, 103°E-108°E). The total cloud amount derived by summing all (15) 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 consistence adds confidence to our analysis of the long time series of the surface observed cloudiness data.

3. Cloud radiative forcing downstream the Tibetan Plateau

Downstream the Tibetan Plateau is located the maximum cloud optical depth in the global tropics and midelatitude between 60°S and 60°N (Fig.2a). Note that this is not due to the total amount of clouds are highest downstream of the plateau. In fact, the annual mean total cloud fraction over the eastern China (about 65%) is less than those in the western Pacific warm pool (where deep cumulus/anvil clouds prevail) and in the eastern Pacific (where marine stratus persists), both are about 75%. Why does the cloud optical depth in the eastern flank of the Tibetan Plateau displays the global maximum?

We found that the largest cloud optical depth downstream the plateau is primarily attributed to its cloud properties. Downstream the plateau, the nimbostratus and altostratus clouds prevail (Fig.2b). The fractional coverage of nimbostratus and altostratus clouds reaches maximum just east of 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°E 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 (103-108E), 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°E to 120°E. Obviously, the nimbostratus and altostratus clouds dominate the zonal variation of cloud optical depth (Fig.5a). Over the Sichuan basin (27°N-32°E, 103°E-108°E), the annual variation of the thick stratus cloud amount is in tendon 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.

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 thick enough to block out the sun entirely. 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 the subtropical East Asia result from the blocking and frictional effects of the Tibetan Plateau. During most period 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 mid-tropospheric westerlies that flow over its mountainous surface, resulting in downstream mid-level divergence. The low-level convergence sustains large-scale steady lifting, while the middle tropospheric divergence confines the lifting to the lower troposphere.

Figure 6 shows the relationships among the total amount of nimbostratus and altostratus clouds and the difference between the mid-level divergence and low-level convergence that signifies the lower tropospheric ascent. All variables are presented in terms of their mean annual cycles and averaged over the leeside of the plateau (103°E to 108°E; 27°N to 32°°E). The vertically differential divergence coincides very well with the amount of nimbostratus and altostratus clouds throughout the year. Results shown in Fig. 6 suggest that the plateau mechanical forcing provides a favorable large-scale environment for formation of deep stratus clouds. Figures 5b and 6 also indicate that the cloud optical thickness and nimbostratus-altostratus cloud amount reach their extremes in cold season when the westerlies are strongest.

In addition to the mechanical forcing of the Plateau, the southern branch of the low-level westerly flows is recharged with moisture in their journeys passing through 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 the stable stratification on the leeside of the plateau, together provide a suitable large-scale condition for maintenance of nimbostratus and altostratus clouds.

5. Stratus cloud-climate feedback over the leeside of the Tibetan Plateau

Over the subtropical eastern China, the cloud amount and surface temperature exhibits a pronounced negative correlation. This can be seen from Fig. 7a that 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 Sichuan basin (103°E-108°E, 27°N-32°N), where the cloud radiative forcing is strongest (Figs. 2, 3, and 5), the correlation coefficient of annual mean cloud amounts and surface temperatures reaches –0.62 for the 50-year period. Figure 7b shows 10-years running mean surface temperature and cloud fraction in the Sichuan basin from 1956 to 1995. Over the Sichuan basin (and the southeastern China in general) the surface temperature variation has a strong opposite tendency with that of the total cloudiness on the monthly to decadal time scales.

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. How does surface temperature affect the continental stratus clouds? Arguably, this is realized through changing the low-level stratification and relative humidity as shown below.

Analysis of the NCEP/NCAR reanalysis data and Chinese surface station data reveals that the surface temperature is highly correlated with the temperature below 850hPa (correlation coefficient reaches 0.7 from 1963 to 1997), but is nearly uncorrelated to the temperature above 600hPa. This implies that a surface warming would destabilize the boundary layer and the lower troposphere and tends to destroy stratus clouds. The analysis also indicates that the relative humidity decreases as the surface temperature rises because the increase of water vapor in the air is slower than the increase of the saturation vapor. The decrease in relative humidity is also destructive to the formation of stratus clouds.

The above evidences lead to two hypothetically positive feedback processes between the cloud physics and large-scale dynamics, i.e., the stratus-surface temperature feedbacks through changing stability and relative humidity. When surface temperature rises, the reduced relative humidity would decrease 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 favor further surface warming.

To confirm the proposed positive cloud feedback mechanisms, we examine the interannual variations. For the period from 1963 to 1997, the correlation coefficient between the surface temperature and the mean relative humidity in the layer between 925 and 700hPa is –0.51; the correlation coefficient between the surface temperature and 850-500hPa differential potential temperatures is –0.49. The annual mean total cloudiness is positively correlated with the mean relative humidity and the differential potential temperature (stability) with the correlation coefficients being 0.78 and 0.53 respectively.

Figure 8 shows 10-years running mean relative humidity and the differential potential temperature. Comparison of Fig. 8 and Fig.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 the 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 in the leeside of the plateau.

To better understand the effects of positive stratus cloud feedback on the surface temperature variation, we present how the cloud radiative forcing changes in response to the 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 contains a sufficiently large signal in the surface temperature that is associated with 1986/87 El Niňo. As shown in Fig. 9a, changes in net CRF at 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 TOA. Comparison of the results shown in Fig. 9a and 9b suggests that the shortwave radiation forcing of the stratus clouds dominates the changes in net CRF at 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 TOA. The positive response of surface radiative forcing to surface temperature change would enhance the climate variation over the eastern flank of the Plateau.

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

a. Impacts on mean climate

The net CRF of the plateau continental stratus exhibits a maximum that is comparable with that of the marine stratus clouds over the southeast 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 TOA (not shown). Although the corresponding longwave CRF is more than twice larger than that of the marine stratus, the net CRF at the eastern flank of the Plateau remains to be dominated by the shortwave CRF. Under the clear sky condition, the annual mean net downward radiative fluxes in this region are around 40 Wm^{-2}. The all-sky net downward radiative fluxes are negative with a minimum below –20 Wm^{-2}, which is located at the Sichuan basin, Therefore, the clouds produce more than 60 Wm^{-2} radiative cooling (Fig. 2c). The zonal variation of shortwave CRF and the net CRF along the Yangtze River coincides well with the zonal variations in nimbostratus-altostratus clouds and the cloud optical thickness. Their annual cycles also match each other quite well (figure not shown), indicating that both the strongest shortwave CRF and net CRF are over Sichuan basin, especially during the cold season.

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, the 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 the Plateau. It is conceivable that the cloud radiative feedback during the surface cooling period could be more robust than that in warming period. When surface cools, the increased static stability favors stratus cloud formation while 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 surface warms, the induced unstable stratification might in part favors cumulus convective clouds that could weaken the positive cloud feedback.

In fact, more robust positive cloud feedback in the cooling period can be inferred from Fig. 9. During the warming period from 1986 to 1987, the surface temperature increased 0.78°C; the net cloud radiative forcing increased 6 Wm-2 (the total cloud fraction decreased by 1%, and the stratus cloud amount decreased by 3.3%). Therefore, the cloud radiative feedback is 7.7 Wm-2K-1. On the other hand, during the cooling period from 1987 to 1989, the surface temperature decreased

0.78°C, the net cloud radiative forcing decreased by 13 Wm-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 Wm-2K-1. Based on this estimation, the positive cloud radiative feedback in the cooling period is more than twice stronger than that during a warming period. The relative weak cloud radiative feedback during warming period is because of the non-stratus cloud formation. During the warming period 1986-1987, 70% of stratus cloud decrease is balanced by non-stratus clouds, while during the cooling period 1987-1989, only 11% of stratus cloud increase is offset by non-stratus clouds. Thus the change of stratus clouds during 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 nimbostratus and altostratus clouds, in particular during the 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 leeside. Meanwhile, the Plateau also slows down the mid-tropospheric westerlies that flow over its mountainous surface, resulting in downstream mid-level 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 global tropics and midelatitude. It produces about 60 Wm^{-2} radiative cooling at TOA over the Sichuan Basin. This prominent radiative forcing makes the eastern China an area of moist static energy sink. This contrasts most other middle-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. 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 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 positive feedback mechanisms are more robust during the period of the surface cooling/stratus cloud increase than during the period of surface warming/stratus cloud decrease. This is because when surface warms, change of the static stability might be in favor of development of cumulus convection (in particular during summer), which can potentially offset the effects of the stratus clouds.

Downstream the Tibetan Plateau the moderate surface cooling in the last century tends to be at odds with most of the rest world (Li et al. 1995, Folland et al. 2001, IPCC TAR 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 prosperities. The two positive feedback mechanisms are instrumental for understanding the fact that the cooling trends from 1950s to mid-1980s in the Sichuan basin is much stronger than elsewhere in the global tropics and mid-latitude (Fig. 7b). Because the positive cloud radiative feedback during cooling period is more effective, the cooling trends from 1950s to mid-1980s in the Sichuan basin was so strong that the overall trend is flat during 1950-200, whereas most of global tropics and midelatitude 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 have implications on the global scale. In the middle and low latitudes, the on-going 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 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 the atmospheric humidity is slower than increase of the saturation water vapor. In addition, previous studies have shown that the 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 the atmospheric temperature in the climate variation (Sun and held 1996; Sun et al 2001; Ingram 2002; Sun et al 2003). Therefore, coupled ocean-atmosphere models might typically overestimate the positive water vapor feedback in amplifying the warming effect of increased greenhouse gas concentrations.

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 unsure cloud feedback processes (Schneider et al 1978; Shukla and Sud 1981; Wetheral and Manabe 1988). Our study suggest 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 albedo effect of the high clouds dominates the greenhouse effects. The cloud liquid water feedback could also be important in some circumstances. Therefore, realistic simulation of the cloud properties and amount is critical for correct representation of the cloud feedback in climate variations.

The present hypothesis is preliminary because of the limitation of data. The uncertainties in above analysis may arise from the fact that we did not consider possible impacts of change in green house gases, aerosols and atmospheric dynamics on the cloud-radiation and surface temperature variations. The hypotheses raised in this study need to be further investigated using numerical experimentations.

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Figure Captions

Fig.1 Annual mean total cloud fraction (in units of percentage) averaged over Sichun basin (27°N-32°N, 103°E-108°E) for the period 1984-2000. Solid line represents cloudiness observed by whether stations. Dashed lines represent the total cloud amount derived by summing all (15) individual clouds in the ISCCP data.

Fig.2 Ten-year (1991-2000) mean cloud optical thickness (a) with contour interval 3, the fractional amount of the nimbostratus and altostratus clouds (b) with contour interval 5%, and the 1985-1999 mean net cloud radiation forcing (CRF) at the top of the atmosphere (TOA) (c) with contour interval 20 Wm^{-2}. The data used in (a) and (b) are derived from the ISCCP and the data used in (c) are from the ERBE data.

Fig.3 Longitudinal cross sections of cloud fraction for different cloud types along 29°N from 100°E to 120°E (a) and along the equator from 140°E to 90°W (b) in units of percentage, which include middle stratus clouds (the nimbostratus and altostratus) (cross), low-level stratus and stratocumulus (filled square), deep convective clouds (filled circle), cirrus and cirrostratus (open circle), and cumulus and altocumulus (open square), derived from the ISCCP D2 data, averaged from 1991 to 2000.

Fig.4 Scattering plots of the fractional amount (percentage) of the middle-level nimbostratus and altostratus clouds (a), low level stratus and stratocumulus clouds (b), and the sum of deep convection and cirrostratus (c) as functions of cloud optical depths in the eastern China (25ºN to 35ºN and 103ºE to 118ºE) derived from the monthly ISCCP data from 1991 to 2000.

Fig.5 (a) Longitudinal cross section of cloud optical thickness (solid), and the percentage of nimbostratus and altostratus cloud amount (dashed) along 29°N from 100°E to 120°E; (b) Annual cycles of the averaged cloud optical thickness (solid), and the percentage of the nimbostratus and altostratus clouds (dashed) averaging over Sichuan basin (103°E to 108°E; 27°N to 32°°E) from 1991 to 2000. The data are derived from the monthly ISCCP data.

Fig.6 1988-1997 mean annual cycles on the leeside of the plateau (27°N to 32°N, 103°E to 108°E;), including nimbostratus-altostratus cloud amount in units of percentage (solid), which is derived from the monthly ISCCP data, and the differential divergence between the mid-level (600-500hPa) and low-level (925-850hPa) in units of $10^6 s^{-1}$ (dashed), which were derived from NCEP/NCAR reanalysis dataset.

Fig.7 (a) Correlation coefficient between monthly mean anomalous surface temperatures and total cloud fraction (after removing the mean seasonal variation) in the Eastern China from 1951 to 2000. (b) 10-years running mean surface temperatures in units of ^oC (dashed) and the total cloud percentage (solid) averaged over (27°N-32°N, 103°E-108°E) from 1951 to 2000 derived from surface station observations.

Fig.8 10-year running mean 925-700hPa averaged relative humidity in units of percentage (dotted line with open square) and 500-850hPa vertical differential potential temperature in units of ^oK (dashed line with filled square) derived from NCEP/NCAR reanalysis products (1967-1992) averaged over (27°N-32°N, 103°E-108°E).

Fig.9 (a) Surface temperature (in units of °C) observed by Chinese weather stations (solid line with open circle) and the net CRF at TOA (in units of wm-2) derived from the ERBE dataset (dashed line with filled square). (b) Percentage of middle-low level stratus clouds (including nimbostratus, altostratus, stratus, and stratocumulus) in ISCCP observations (solid line with open circle), referring to left ordinate outside scale, shortwave CRF at TOA (in units of wm-2) (dotted line with filled square) in ERBE observations. Shown are the yearly mean values averaged over the Sichuan basin (27°N-32°N, 103°W-108°W) from 1985 to 1989.

Fig.10 Schematic diagram illustrating the stratus cloud feedbacks through change of low-level relative humidity and static stability.