ENERGY BUDGET BIAS IN GLOBAL COUPLED OCEAN-ATMOSPHERE-LAND MODEL*

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ABSTRACT

The energy budget of the two versions of the GOALS model (GOALS-1.1 and GOALS-2) is described and compared to observational estimates. The results illustrate that the simulated surface net shortwave radiation flux is underestimated in the high-latitude regions while the surface net longwave radiation flux is substantially overestimated in that region, which results in the lower surface air temperature (SAT) of the polar region and the stronger negative sensible heat flux in high latitudes. The overestimated sensible heat flux from surface to atmosphere in the continents causes the much warmer SAT centers, which may be the reason for the bias of the model SAT. The bias that the simulated precipitation is less than observation in most regions is closely related to the underestimated latent heat flux over most of the Eurasian Continent and the oceans, especially over the subtropical oceans. It can be seen that the bias in the OLR of the two models lies in low and middle latitudes, where the absorbed solar shortwave radiation flux at the top of the atmosphere is comparable to the NCEP reanalysis, but much less than ERBE data. This indicates that the improvement of cloud-radiation parameterization scheme in low and middle latitudes is of critical importance to the simulation of global energy budget. The simulated cloud cover from the GOALS-2 model with diagnosed cloud scheme is generally less except at equatorial areas, especially in the mid-latitude areas, which causes the large bias of energy budget there. It is suggested that the refinement of cloud parameterization is one of the most important tasks in the model's future development.

Key words: climate system, coupled model, energy budget, cloud parameterization

I. INTRODUCTION

Successful climate system models and their components should adequately simulate energy budget through the climate system. The net flux of energy at the top of the atmosphere determines the available energy for the complete climate system (i. e., atmosphere and underlying surfaces). Meanwhile, this radiative energy is transformed into other forms—such as kinetic, latent, and sensible—with the vertical and horizontal redistribution of these forms of energy. Several previous observational studies have examined the global atmospheric energy budget using either historic or contemporary data. The overviews of these studies are given by Kiehl and Trenberth (1997) and Trenberth

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(1997). Yang et al. (1999) presented an evaluation of the National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) reanalysis (the reanalysis) by comparing its components of the earth radiation budget to satellite data. Yu et al. (1999) conducted a consistency study of the atmospheric energy budget based on the available data sets. They have pointed out that on an average, the atmosphere needs an additional energy source of about 20 W m^{-2} to balance its budget. These observational studies have provided some useful references for our analysis of the energy budget in the climate system models.

The earlier simulation of energy budget is presented by Kiehl and Ramanathan (1990), who have discussed the earth radiation budget for the Community Climate Model (CCM1) at NCAR. Kiehl et al. (1994) analyzed the energy budget for the second version of the CCM (CCM2). The recent study of Kiehl et al. (1998) not only describes the radiation budget of the latest version of CCM (CCM3), but carries out a more extensive analysis of the entire energy budget of the atmospheric model at both the top of the atmosphere and the surface. However, the aforementioned numerical studies are only limited to the analysis of individual atmospheric model.

The climate system is a complicated system with five interacting subsystems, which consist of atmosphere, ocean, lithosphere, cryosphere and biosphere linked together by energy cycles. An important verification of the validity of the climate system model, in particular the coupled ocean-atmosphere-land model, is to objectively reproduce the energy budget on a global scale. Great efforts have been contributed to the development of the climate system model at the State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics (IAP) for many years. Since the mid 1990s, a Global Ocean-Atmosphere-Land System Model (GOALS) has been established in IAP/LASG (Wu et al. 1997; Zhang et al. 2000). The model, which joined the Coupled Model Intercomparison Project (CMIP), has been broadly used in climate research.

The purpose of this paper is to compare the energy budget of two versions of the GOALS model (GOALS-1.1 and GOALS-2), in terms of the fact revealed in the evaluation of NCEP and NCAR reanalysis, Earth Radiation Budget Experiment (ERBE) data, and Surface Radiation Budget (SRB) data. Guo et al. (2000) presented a systematic evaluation of the variables of several versions of the GOALS model, including the atmospheric variables (surface air temperature (SAT), sea level pressure (SLP), and precipitation) and oceanic variables (sea surface temperature (SST) etc.). The accurate simulation of these variables is closely related to that of the energy budget in the model, therefore, a deep understanding of the model's capability and weakness will be gained by the analysis of energy budget in the climate system model. The aim of choosing the specific two versions of GOALS model (GOALS-1.1 and GOALS-2) for this study is to investigate the effect of cloud parameterization schemes (prescribed cloud and diagnosed cloud) on the simulation of the energy budget in the model and provide some references for the model's further improvement.

The paper is organized as follows. Section II provides a brief description of the observed data and model-generated data sets from two versions of the GOALS model, Section III describes the global and zonal-mean energy budget from the model and makes comparisons to observations, Section IV considers the geographic distribution of the annual mean energy terms, and finally Section V contains the summary and discussion in the study.

II. MODEL AND OBSERVATION DESCRIPTION

There is the same dynamical frame in the two versions of GOALS model. Its atmospheric component is a revised spectrum model. The horizontal discretization is conducted based on a rhombic spectral truncation with a zonal wavenumber of fifteen (R15), which approximates to a grid size of about 7. 5°× 4. 5°. There are nine uneven layers in vertical direction with σ-coordinates, of which three layers are located in the planetary boundary layer. In order to reduce the spectral truncation error, a standard stratification deduction of global-mean air temperature and geopotential height is applied to the model (see Wu et al. 1996). The fitting scheme of radiative heating in the model is adopted by the transmission function on the absorption of the entire longwave and infrared shortwave bands (K-distribution) (see Shi 1981; Wang 1996). An advanced land surface process model, which includes three soil layers and one vegetation layer with twelve types of vegetation (see Xue et al. 1991), is incorporated in the AGCM component of the GOALS model.

The oceanic component of GOALS model is a primitive equation grid model. There are twenty uneven layers in vertical direction with η-coordinates, of which nine layers are located in the thermocline, with the largest depth of 5500 m. The variables are distributed in the B grid system of the model with its horizontal resolution of 5° (longitude) × 4° (latitude). The sea-land distribution and sea bottom topography of the model is close to the reality and the North Pole in the ocean model is treated as an isolated island due to the difficulty in defining the velocity of the pole in spherical coordinate (see Zhang et al. 1996). A thermodynamical sea-ice model is coupled with the ocean component to predict the pattern and thickness of sea-ice in the polar area (see Parkinson and Washington 1979).

The coupling between the oceanic component and atmospheric component takes into account the exchange of heat flux and momentum flux, and the coupling scheme used in the two versions of GOALS model is the modified monthly flux anomaly exchange (MMFA) scheme (see Yu and Zhang 1998).

The difference between the GOALS-2 and GOALS-1. 1 lies in the atmosphere model in which the diagnosed cloud (see Liu et al. 1998) from the GOALS-2 is developed to replace the prescribed cloud obtained from International Satellite Cloud Climatology Project (ISCCP, see Rossow and Schiffer 1991) in the GOALS-1. 1. There are long-time integrations from both the two versions, and the ten years of data of each version are used to calculate their climatological means.

NCEP/NCAR monthly reanalysis data (including the surface sensible heat, surface latent heat, radiation data at the surface and at the top of the atmosphere) from January of 1980 to December of 1989, are employed to calculate the observed global and zonal-mean energy budget. To add more reliability to our analysis, some other results, such as the estimate of Kiehl and Trenberth (1997) and the ensemble of international Atmospheric Model Intercomparison Project (AMIP), will also be compared with the global mean results of the two versions. For the annual and zonal-mean analysis, ERBE data are used to make comparisons with the simulation of the energy budget at the top of the atmosphere in the models. In addition, SRB data are compared to the zonal-mean surface radiation budget in the GOALS model simulations. It should be noted that we only use the available NCEP/NCAR reanalysis data as observations for the analysis of the geographic distribution of the annual mean energy terms.

III. GLOBAL AND ZONAL-MEAN BUDGETS

Table 1 presents all lands, all oceans, and the globally averaged ensemble annual mean energy budgets for the GOALS-1.1 and GOALS-2. Table 2 shows the annual mean energy budgets of the AMIP ensemble, the NCEP reanalysis, and the estimate of Kiehl and Trenberth (hereafter referred to as K&T). The positive indicates downward flux and the negative means upward flux in these two tables. The net shortwave radiative flux at the top of the atmosphere (TOA) is firstly considered. The ensemble-mean from AMIP is 239 W m^{-2}, which is very close to the estimate of K&T (235 W m^{-2}) and slightly different from the NCEP reanalysis (226.34 W m^{-2}). The net shortwave radiative flux at TOA in the GOALS-2 approaches the AMIP ensemble, while that in the GOALS-1.1 nears the NCEP reanalysis. However, for TOA net flux, namely, the earth's balance, the result from the GOALS-1.1 (2.91 W m^{-2}) is consistent with the AMIP ensemble (4.10 W m^{-2}) and closer to the estimate of K&T than that from the GOALS-2 (23.17 W m^{-2}).

By comparison between the two tables, it can be seen that the earth's balance is positive in the models (GOALS-1.1, GOALS-2, and AMIP ensemble) but it is negative for the NCEP reanalysis (−10.87 W m^{-2}). The negative balance of NCEP reanalysis is unrealistic and it is not ideal in the view of the model as well. The earth-atmosphere system can not be an energy radiator due to the long-term friction dissipation in the model. Study of Kim* suggests that all GCMs consume the resolved-scale kinetic energy through the friction but do not convert to their internal energy. Under this situation, the model atmosphere is of energy imbalance so as to compensate the friction dissipation, which means the positive earth's balance. The atmospheric balance is positive for both models, and has the comparative magnitude in the two models (13.31 W m^{-2} in GOALS-1.1 versus 15.86 W m^{-2} in GOALS-2), being qualitatively consistent with the positive absorption of AMIP (2.90 W m^{-2}). It is inferred from the tables that the way in which friction dissipation is being balanced in two versions of the GOALS model is different. Specifically, the friction dissipation in the GOALS-2 is characterized by the offset of the difference between the net flux at TOA and the net flux downward into the surface, which is in agreement with the AMIP ensemble. But the friction dissipation in the GOALS-1.1 is characterized by the compensation with the sum of the net flux at TOA and the net flux upward from the surface. It can be concluded that the "zero" balance from the estimate of

* Kim Jeong-Woo. Simulation of the SAT, precipitation and energy fluxes over the global lands and oceans (personal communication).

K&T only exists in the real world, not in the model climate.

Table 1. Global Annual Mean Energy Budgets at the Top-of-Atmosphere (TOA) and at the Surface (SFC) from the Two Versions of the GOALS Model (GOALS-1.1 and GOALS-2). Fluxes are in W m^{-2}

	GOALS-1.1			GOALS-2		
	all lands	all oceans	global	all lands	all oceans	global
SFC sensible heat flux	−40.13	−18.25	−24.89	−51.91	−11.77	−23.94
SFC latent heat flux	−46.77	−90.69	−77.33	−48.52	−81.76	−71.68
SFC net longwave radiative flux	−68.47	−47.42	−53.85	−94.67	−63.18	−72.73
SFC net shortwave radiative flux	137.25	149.35	145.67	157.74	183.45	175.66
Surface Balance	−18.12	−7.01	−10.40	−37.36	26.74	7.31
TOA OLR	−216.89	−217.40	−217.19	−215.41	−217.62	−216.95
TOA net shortwave radiative flux	204.14	227.10	220.10	216.23	250.52	240.12
Earth's Balance	−12.75	9.70	2.91	0.82	32.90	23.17
Atmospheric Balance	5.37	16.71	13.31	38.18	6.16	15.86

Table 2. Global Annual Mean Energy Budgets at the Top-of-Atmosphere (TOA) and at the Surface (SFC) from the AMIP Ensemble, the NCEP Reanalysis, and the Estimate of Kiehl and Trenberth (K&T). Fluxes are in W m^{-2}

	AMIP ensemble			NCEP	K&T
	all lands	all oceans	global	global	global
SFC sensible heat flux	−29.85	−15.11	−19.51	−15.50	−24
SFC latent heat flux	−49.65	−105.05	−88.65	−79.97	−78
SFC net longwave radiative flux	−69.82	−60.13	−62.98	−61.29	−66
SFC net shortwave radiative flux	152.26	180.78	172.25	161.94	168
Surface Balance	2.94	0.49	1.20	5.18	0
TOA OLR	−227.37	−238.11	−234.90	−237.21	−235
TOA net shortwave radiative flux	213.66	249.77	239.00	226.34	235
Earth's Balance	−13.71	11.66	4.10	−10.87	0
Atmospheric Balance	−16.65	11.17	2.90	−16.05	0

It can be seen from Table 1 that there is not much difference between outgoing longwave radiation (OLR) at TOA over all oceans and over all lands in the two versions of the GOALS model. The slight overestimation of OLR over all oceans versus all lands should be related to the primary standing high over the oceans as was found by Kim (personal communication). Similar results are also presented in the AMIP ensemble as shown in Table 2.

In a word, as far as the global annual mean top-of-atmosphere (TOA) energy budget is concerned, the AMIP ensemble is for the most part close to the estimate of K&T, and the main problem of the NCEP reanalysis and GOALS-1.1 is the underestimation of TOA net shortwave radiative flux. The common weakness of the two versions of the GOALS model is the underestimation of TOA OLR. The OLR of the NCEP reanalysis agrees well with that of the estimate of K&T, although the underestimation of the TOA net shortwave radiative flux from the NCEP reanalysis results in its unreasonable negative earth's balance.

The greater bias in the GOALS model exists in the simulation of the surface energy balance. There is large difference between the two versions and the AMIP ensemble for the surface energy balance including the over-ocean and over-land balance, except that the positive global surface balance of the GOALS-2 is qualitatively consistent with that of the NCEP reanalysis and the AMIP ensemble. The overestimation of the energy absorbed at the sea surface of GOALS-2 (26.74 W m^{-2}) is mainly attributed to the lower upward latent heat flux from the sea surface. On the other hand, the negative over-land balance (-37.36 W m^{-2}) is basically due to the overestimation of the upward sensible heat flux and the surface net longwave radiative flux that are about 22 W m^{-2} larger than the corresponding flux from the AMIP ensemble, indicating the strong heating from the land surface into the atmosphere. The over-land warmer center of the surface air temperature (SAT) (see Guo et al. 2000) in GOALS-2 is chiefly due to the above-mentioned surface energy bias, which suggests the need to improve the pertinent physical process in the land surface component model. The negative surface balance either over land or over ocean in the GOALS-1.1 is associated with the underestimation of the net shortwave radiative flux into the surface. In contrast to the GOALS-1.1, the GOALS-2 has a better simulation in the surface net shortwave radiative flux and TOA net shortwave radiative flux (over land and over ocean) in consistent with the AMIP ensemble. We also note that the TOA OLR bias in the GOALS-1.1, which is 20 W m^{-2} smaller than that in the NCEP reanalysis and the AMIP ensemble, still exists in the GOALS-2 with the diagnosed cloud. It is suggested that the introduction of the diagnosed cloud scheme in the GOALS-2 makes the simulation of the net shortwave radiative flux at the surface and at the TOA improved as a whole, but is still incapable of simulating the longwave radiative flux which should be drawn to our attention in the further development of the cloud scheme.

The above discussion is the analysis of the global annual mean energy budgets, and the following discussion will further depict the latitudinal feature of the energy terms by the analysis of zonal averaged fluxes.

Figure 1 shows the zonal- and annual-mean absorbed shortwave flux, outgoing longwave flux, and net radiative flux (shortwave minus longwave) at the TOA from the GOALS-1.1, GOALS-2, NCEP reanalysis, and ERBE (missed in high latitudes). Generally, both of the two versions are capable of yielding a reasonable simulation of the gradual poleward decrease in the three TOA radiation fluxes, and of reproducing the observed feature that absorbed shortwave flux is larger in low and middle latitudes and smaller in high latitudes than outgoing longwave flux. However, TOA OLR from the GOALS-1.1 and GOALS-2 is about 20 W m^{-2} lower in low and middle latitudes than that from the NCEP reanalysis and ERBE, also about 15 W m^{-2} lower in the northern high

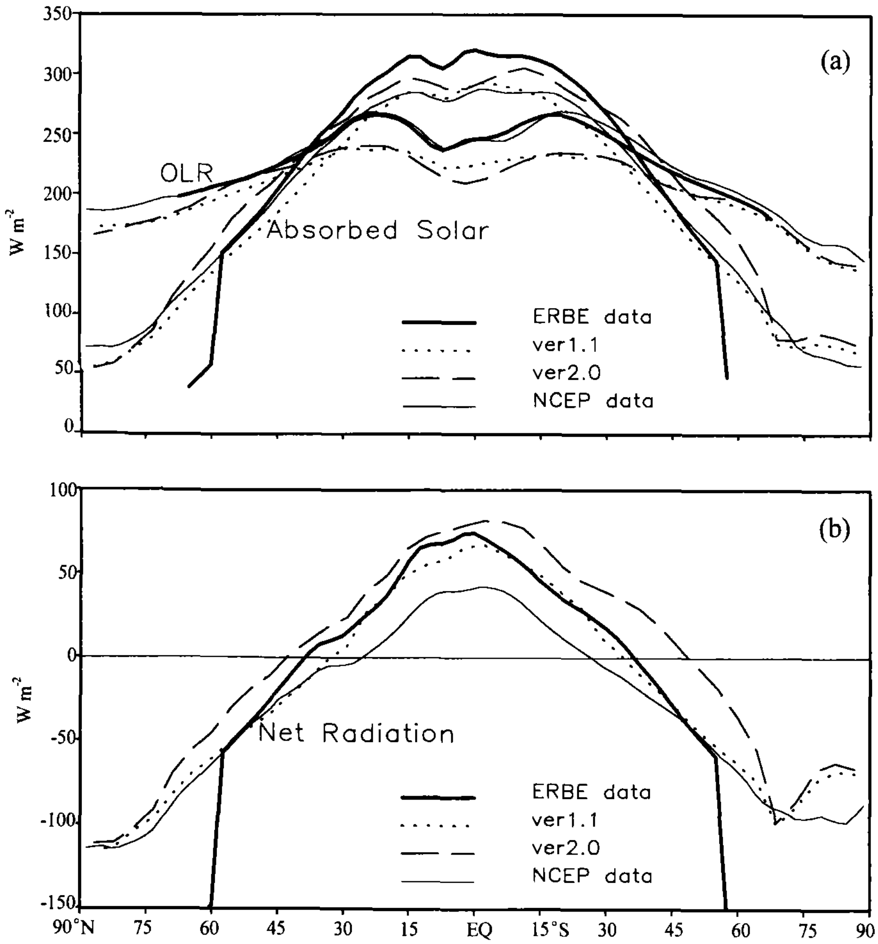

Fig. 1. Annual and zonal-mean top-of-atmosphere (a) outgoing longwave radiative flux (OLR) and absorbed shortwave flux, (b) net radiative flux (W m^{-2}) from the two GOALS versions and observations (the NCEP reanalysis and ERBE data).

latitudes than that from observations. It can be seen that the bias of the lower TOA outgoing longwave radiative flux (OLR) from the two versions presented in Table 1 is mainly located in low latitudes, where the OLR is even less in GOALS-2 than in GOALS-1.1 from 15°S to 15°N (Fig. 1a). The absorbed shortwave flux at TOA from the GOALS-1.1 is very close to but a little smaller than that from the NCEP reanalysis, while the shortwave flux from the GOALS-2 is almost slightly higher in the whole latitude band than that from the NCEP reanalysis. It should be noted that the three data sets (GOALS-1.1, GOALS-2, and NCEP reanalysis) are much lower in low and middle latitudes than ERBE for the absorbed shortwave flux at TOA. In addition to the underestimation of the simulated OLR, it is inferred that low and middle latitudes are the regions in which there is a greater bias in the simulation of the energy budgets. The net effect of the absorbed shortwave flux and outgoing longwave flux at TOA is presented in Fig. 1b. One can see that the net radiative flux from the two versions shows an energy overplus (positive) in low and middle latitudes and an energy deficit (negative) in high latitudes and polar region, which suggests an agreement with observation that the heat flux is transported poleward from low latitudes through the atmospheric and oceanic circulations. There is a good agreement between the GOALS, especially GOALS-1.1 and ERBE for TOA net radiative flux, but the simulation of the two versions is larger than the NCEP reanalysis, in particular, that of the GOALS-2 far exceeds the ERBE data, which may explain the larger earth's balance (23.17 W m^{-2}) of GOALS-2 in Table 1. The negative global mean earth's balance (−10.98 W m^{-2}) of the NCEP reanalysis in Table 2, is mainly attributed to the too low net radiative flux and the resulting insufficient heating in low and middle latitudes of the earth-atmosphere system (Fig. 1b), which results from the underestimation of absorbed shortwave flux over that area.

The zonal- and annual-mean surface net longwave radiative flux and net shortwave radiative flux from the two GOALS versions and observations (the NCEP reanalysis and SRB data) are shown in Fig. 2, where the negative indicates direction upward. From

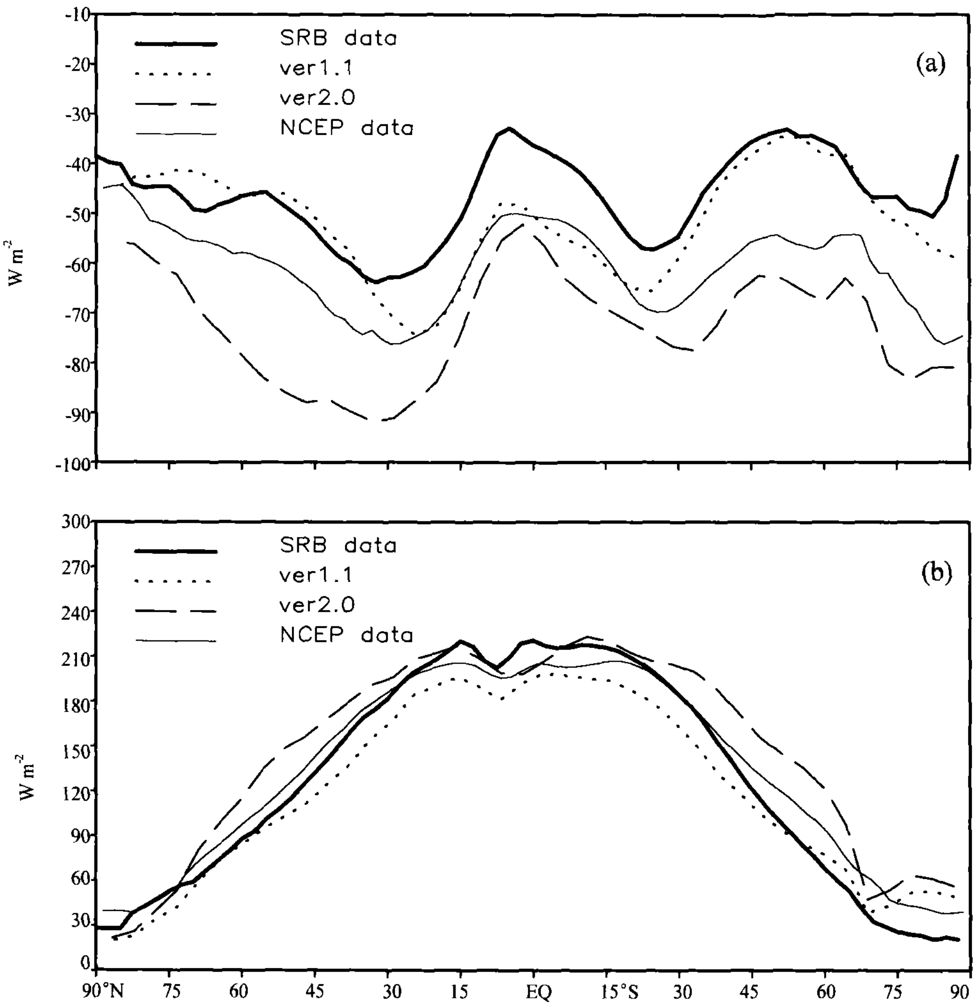

Fig. 2. Annual and zonal-mean surface (a) net longwave radiative flux and (b) net shortwave radiative flux (W m^{-2}) from the two GOALS versions and observations (the NCEP reanalysis and SRB data).

Fig. 2a, it can be seen that the surface net longwave radiative flux from the two GOALS versions reaches its maximum (absolute value) in the subtropical region of both hemispheres and falls to its minimum (absolute value) in the tropical region, which shows an agreement with the NCEP reanalysis and SRB data. In spite of the consistent tendency of the latitudinal variation, there is quantitative difference between the NCEP reanalysis and SRB data almost in the whole latitude band, which is understandable as the uncertainty (about 20 W m^{-2}) in the surface net longwave radiative flux noted by the observational study of Rossow and Zhang (1995). There is a good agreement in the tropics and large bias in the rest regions between the GOALS-1.1 and the NCEP reanalysis, while there is large bias in the tropics and good agreement in the rest regions between the GOALS-1.1 and the SRB data. The greater bias in surface net longwave radiative flux between GOALS-1.1 and GOALS-2 is located in extratropics. This is because the downward surface longwave radiative flux from the GOALS-2 is lower than that from the GOALS-1.1 in extratropics (figure not shown), which leads to the much larger surface net longwave radiative flux (upward minus downward) from the GOALS-2 versus the GOALS-1.1 in that region, especially in middle latitudes. Kiehl et al. (1998) pointed out that the surface net longwave radiative flux depends critically upon cloud-base height, cloud fraction, and lower-tropospheric moisture. The annual-mean, zonally averaged total cloud fraction from the GOALS-1.1 and the GOALS-2 is also given in this study (Fig. 3). The cloud of International Satellite Cloud Climatology Project (ISCCP) in Fig. 3 is the prescribed cloud used in the GOALS-1.1. In general, the total cloud fraction of ISCCP is higher than that of the GOALS-2, especially in middle latitudes of the extratropical region, where the GOALS-2 simulated total cloud fraction is obviously underestimated. This may be the dominant reason why there is so much difference between GOALS-2 and GOALS-1.1 in the simulation of surface net longwave radiative flux within that region shown in Fig. 2a. The surface net shortwave radiative flux from the GOALS-1.1 is lower than that from the GOALS-2 and observations (the NCEP reanalysis and SRB data),

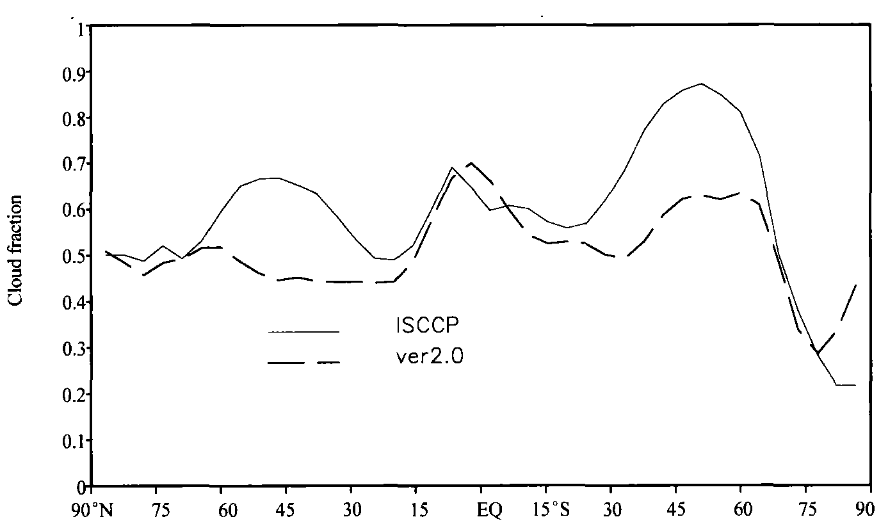

Fig. 3. Annual-mean zonally averaged total cloud fraction from GOALS-1.1 (ISCCP) and GOALS-2.

particularly in the region between 55°S and 55°N (see Fig. 2b). However, except for a slight underestimation around the equator compared to the SRB data, the surface net shortwave radiative flux from the GOALS-2 is larger than that from observations (the NCEP reanalysis and SRB data) at most latitudes with an obvious large bias in middle latitudes, which is directly related to the underestimation of GOALS-2 simulated cloud fraction and is also leading to the higher global mean surface net shortwave radiative flux in the GOALS-2 than the NCEP reanalysis shown in Table 1.

All in all, through the comparison of the surface net shortwave radiative flux between GOALS-2 and GOALS-1. 1, it can be seen that the difference between the two versions is primarily located in middle latitudes where the simulation of GOALS-2 is apparently overestimated due to the lower cloud fraction over there. The absorbed shortwave flux at TOA from the GOALS-2 is overestimated in middle latitudes (see Fig. 1a), which is also attributed to the bias in the simulated total cloud fraction. With the addition of the overestimation of the surface net longwave radiative flux from GOALS-2, it is suggested

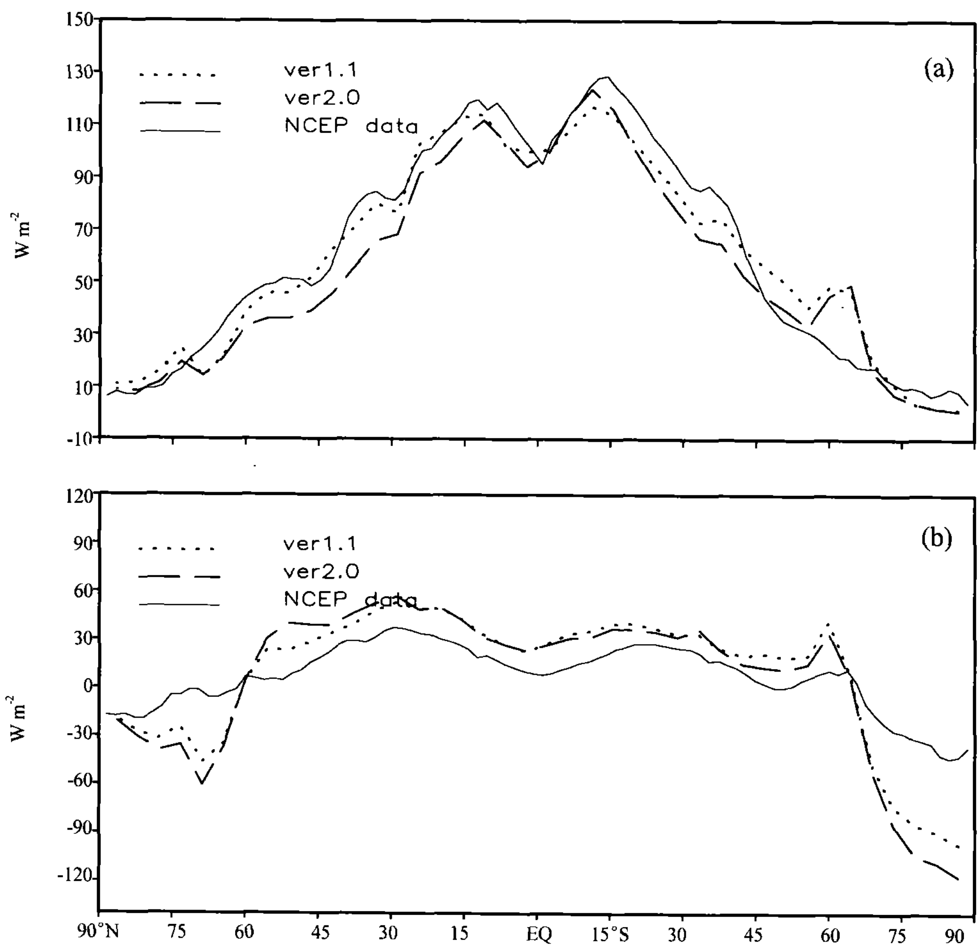

Fig. 4. Annual-mean zonally averaged surface (a) latent heat flux and (b) sensible heat flux (W m^{-2}) from the two GOALS versions and observations (the NCEP reanalysis).

that the refinement of diagnosed cloud parameterization is one of the most important tasks in the model's future development.

Surface latent heat flux and sensible heat flux are two fundamental heating sources. Their zonally averaged patterns in the simulation as well as reanalysis are shown in Fig. 4. In general, two maximums of latent heat flux are found to be at 15°N and at 15°S separately, and the slightly larger maximum is in the Southern Hemisphere, which is well simulated in the two GOALS versions. But the latent heat flux from the two versions is underestimated from 40°S to 70°N, especially in middle latitudes of both hemispheres for the GOALS-2 simulation with a significant underestimation, compared to the NCEP data. Whereas in the mid- to high latitudes of the Southern Hemisphere, the two GOALS versions tend to greatly overpredict the latent heat flux than NCEP data (Fig. 4a). As shown in Fig. 4b, there is a good agreement between GOALS-1. 1 and GOALS-2 in the simulation of the sensible heat flux, which is 15 W m^{-2} larger in the region between 60°S and 60°N, and is negative but much larger (absolute value) in high latitudes, with respect to the NCEP data. The comparison between the observed and modeled surface radiative flux (see Fig. 2a and Fig. 2b) suggests that the net effect of weaker surface net shortwave radiative flux and stronger surface net longwave radiative flux from the GOALS model in the high latitude region of both hemispheres will impose a stronger cooling on the surface, which leads to the underestimation of modeled surface air temperature in high latitudes (see Guo et al. 2000) and results in the stronger negative flux over there by transporting the sensible heat flux from the near-surface atmosphere towards the surface.

IV. GEOGRAPHIC ENERGY DISTRIBUTION

Zonally averaged fluxes of energy are significant in describing the meridional structure that plays a crucial role in poleward heat transport. However, the climate system is forced by the three-dimensional distribution of energy (see Trenberth and Solomon 1994). Moreover, zonal averaging can mask regional biases in energy fluxes. Thus, to better understand the GOALS model global energy budget, we present the geographic distribution of the various energy fluxes at both the top of the atmosphere and the surface, and to summarize, we focus on the annual mean energy budget.

The geographic distributions of the annual mean outgoing longwave flux at the TOA from the NCEP data and the two GOALS versions as well as their difference (model minus observation) are shown in Fig. 5. The observed three centers (viz., the equatorial Africa center, the Asian-central and western equatorial Pacific center, and the tropical America Continent center) (see Fig. 5a) of low outgoing longwave flux associated with tropical deep convection and extensive anvil cloud system are well presented in the GOALS-2 (Fig. 5c) but somewhat overestimated (Fig. 5e), whereas the three low centers are not reproduced in the GOALS-1. 1 (Fig. 5b). The two versions produce the lower outgoing longwave flux over the eastern Pacific basin, which results in a significant negative OLR bias (Fig. 5d and Fig. 5e). In general, the simulated OLR from the GOALS-1. 1 and GOALS-2 is underestimated almost globally with the largest bias in the tropics, which is consistent with the zonal-mean results aforementioned.

The geographic distribution of the TOA annual mean absorbed shortwave flux is

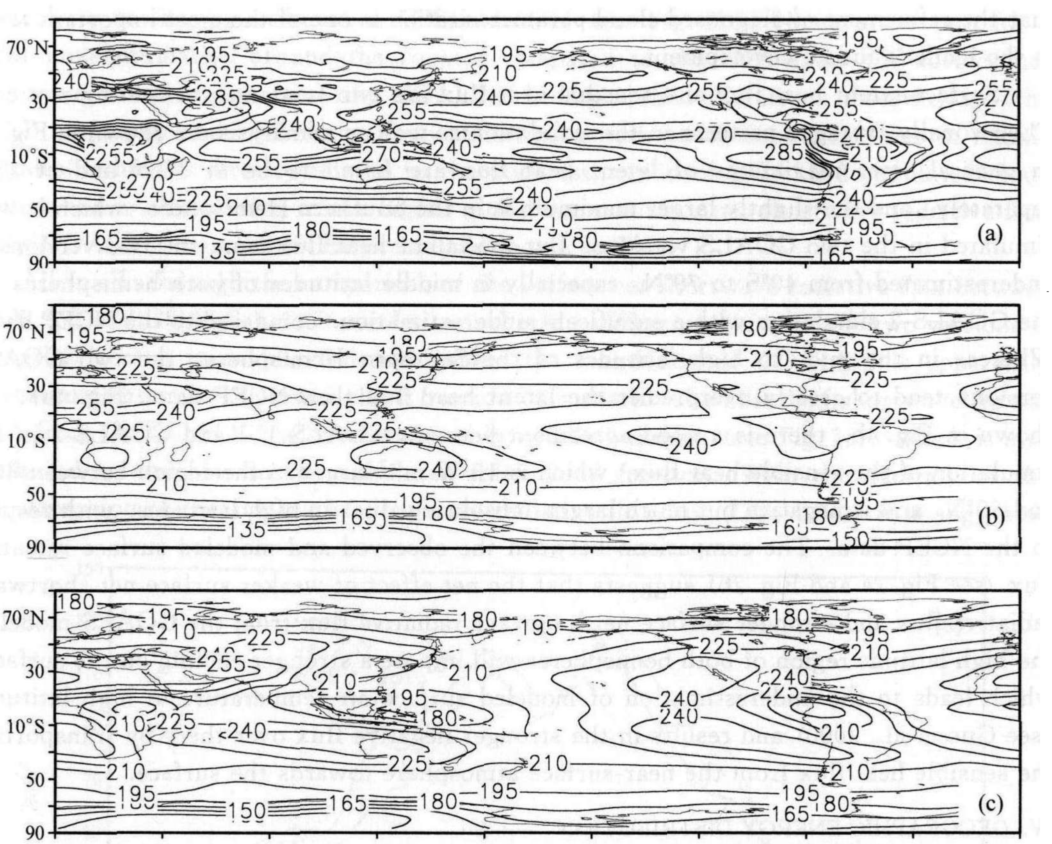

Fig. 5. Geographic distribution of ensemble-mean, annual mean outgoing longwave flux (W m^{-2}) at the TOA from (a) NCEP data, (b) GOALS-1.1, (c) GOALS-2, (d) difference between GOALS-1.1 and NCEP, and (e) difference between GOALS-2 and NCEP.

shown in Fig. 6. Generally, the GOALS model is capable of reproducing the main feature of the top of atmosphere annual mean absorbed shortwave flux. The tropical eastern Pacific maximum center, the equatorial Africa low center, and warm pool low center of the western Pacific (see Fig. 6a) are simulated quite well in GOALS-2 (Fig. 6c). However, the obvious bias in the absorbed shortwave flux at the TOA from GOALS-2 is over oceans, where the simulated flux is 40 W m^{-2} larger than the NCEP data, especially in the tropical Atlantic, the eastern Pacific, and the southern Indian Ocean, but this flux is underestimated in the warm pool of western Pacific and the Antarctica, to some extent (Fig. 6e). The bias over oceans in GOALS-2 is apparently ameliorated in GOALS-1. 1 that shows a stronger negative bias over land, especially in the Asian Continent and Australia. Similar to GOALS-2, GOALS-1. 1 it also shows a weaker absorbed shortwave flux in high latitudes (Fig. 6d).

Figure 7 shows the geographic distributions of the annual mean net surface energy flux (the total of surface latent heat flux, sensible heat flux, net longwave radiative flux and net shortwave radiative flux) in the GOALS model and NCEP data. There is a remarkable agreement in the spatial patterns of net energy flux into the oceans (positive) and net energy flux from the ocean into the atmosphere (negative). The GOALS model can simulate the input of energy into the equatorial region, but overestimate this flux in the Indian Ocean region compared to the NCEP data. In the analysis of the energy budget of CCM3, Kiehl et al. (1998) also noted that CCM3 overestimated the net surface energy flux in the Indian Ocean region compared to the Large et al. (1997) data. It is suggested that the bias in the Indian Ocean region may be the common problem to the modern models. The energy losses (negative) from the ocean areas of Kuroshio and Gulf Stream are simulated quite well in the GOALS-1. 1 (Fig. 7b), but not clearly captured in the GOALS-2 (Fig. 7c). Furthermore, the heat flux into the ocean in GOALS-2 is larger in the equatorial Atlantic and eastern Pacific than that estimated in GOALS-1. 1 and NCEP data. From Fig. 7a, it can be seen that the surface net energy flux for the NCEP data is close to zero over land and in high latitudes of both the two hemispheres. However, the two GOALS versions show the stronger net energy flux from the surface into the atmosphere (negative) in the American Continent, South Africa, Arabian and North India Peninsulas and most of China, and the apparent input of energy from the atmosphere into the surface (positive) over land in high latitudes (Fig. 7b and Fig. 7c). These biases in surface net energy flux may result in the lower surface air temperature (SAT) over land in high latitudes and warmer SAT centers over South America, South Africa, southern North America and India Peninsulas, which are revealed in the evaluation of the GOALS model by Guo et al. (2000).

Figure 8 shows the geographic distributions of the annual mean surface latent heat flux from observations and the GOALS models, and their difference. There is an agreement between the GOALS surface latent heat flux and NCEP data, which is characterized as a better simulation of the latent heat flux minimum in the equatorial region, including the low center over cold tongue in the equatorial eastern Pacific (Figs. 8a, 8b, 8c). The two versions have the same bias coming from the lower latent heat flux over the oceans, especially much lower flux over the subtropical oceans. The

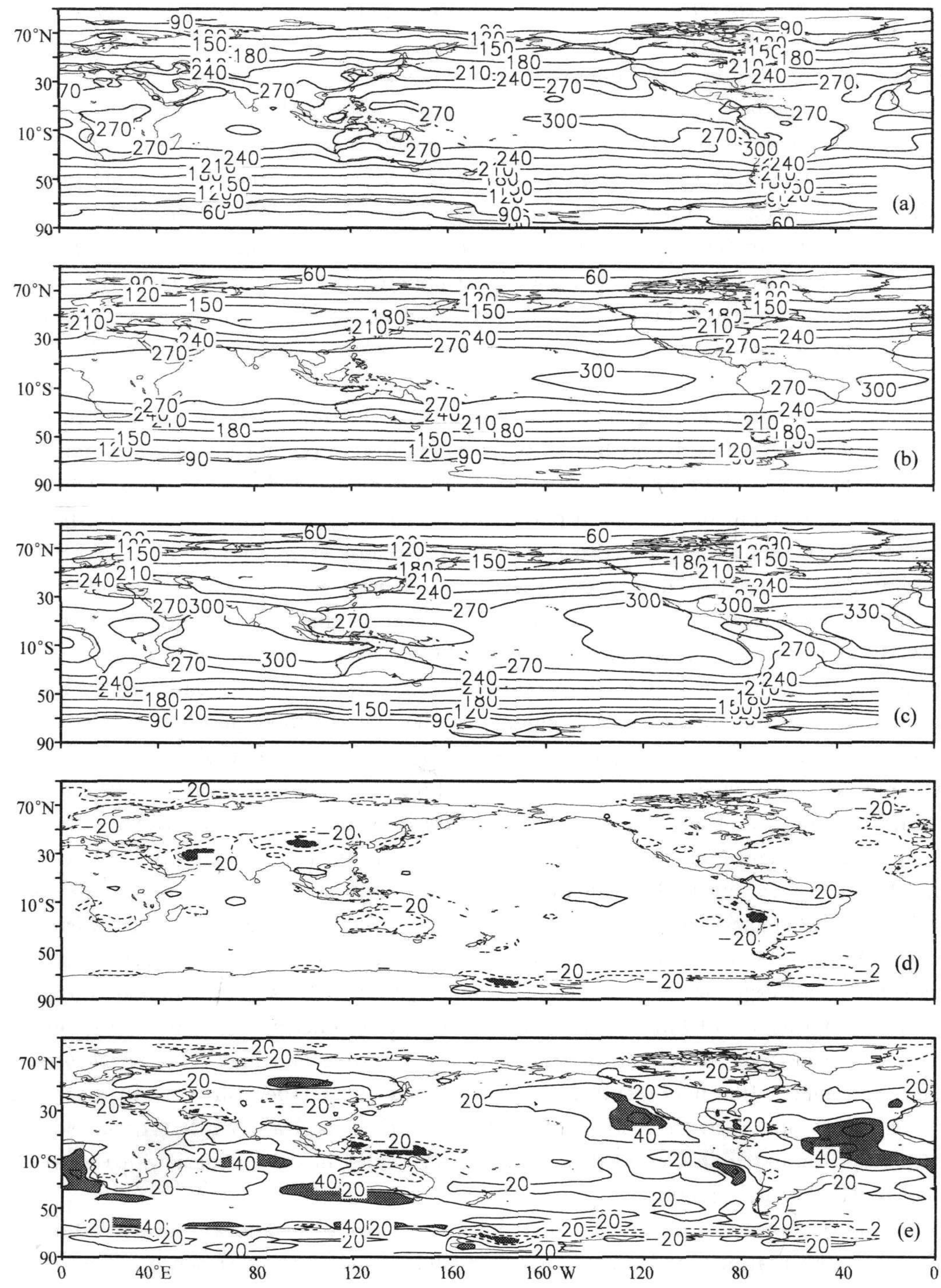

Fig. 6. As in Fig. 5 but for the absorbed shortwave flux at the TOA (W m^{-2}).

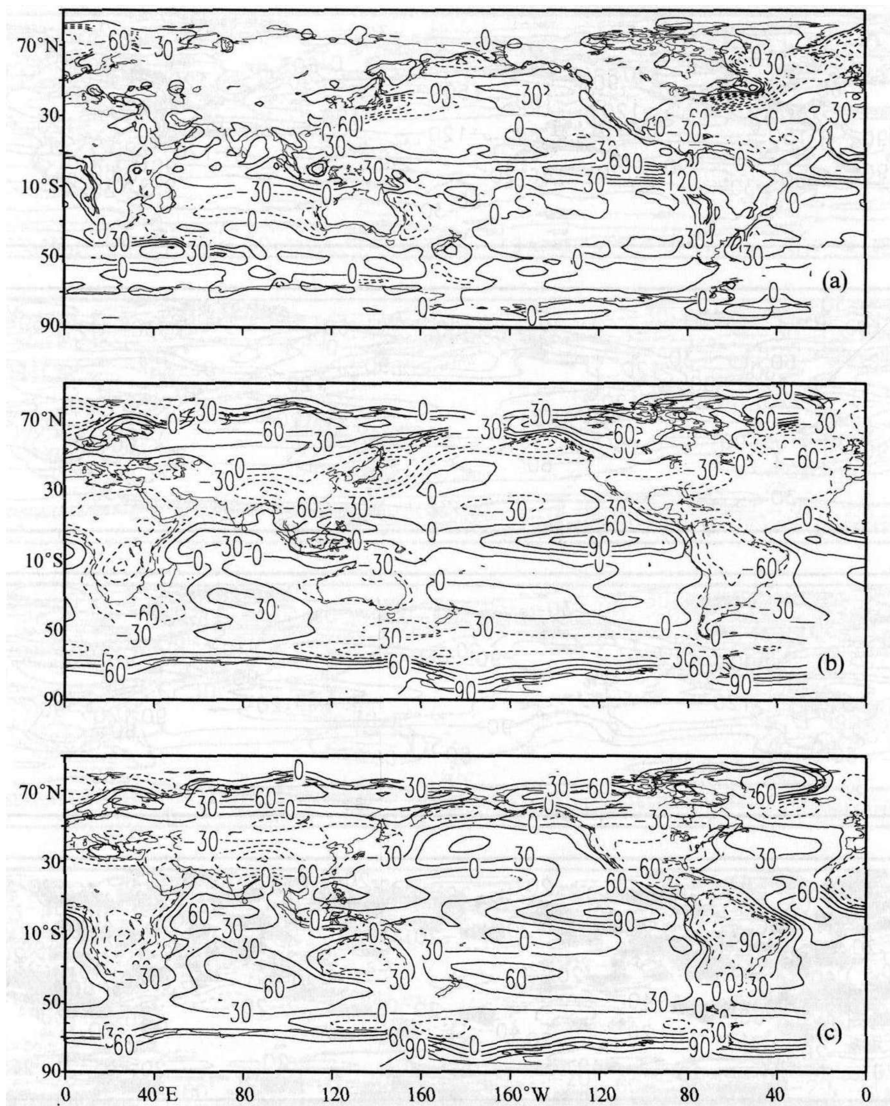

Fig. 7. Geographic distribution of ensemble-mean, annual mean net surface energy flux (W m^{-2}) (the total of surface latent heat flux, sensible heat flux, net longwave radiative flux and net shortwave radiative flux) from (a) NCEP data, (b) GOALS-1. 1, and (c) GOALS-2. The positive denotes direction downward.

same bias over land in the two versions also includes the overestimation of latent heat flux mainly in the African Continent, southern and northern China, and most of South America, and the underestimation in most of the Eurasian Continent and North America, especially in the Northern Continent (Figs. 8d and 8e). These biases in the surface latent heat flux may be the reason for the underestimation of model precipitation in many areas (see Guo et al. 2000). From the distribution of annual mean surface sensible heat flux (Fig. 9), one can see that the observed positive sensible heating centers, such as Australia center, South America center, southern North America center, southern Africa center and India Peninsulas center are well simulated in the GOALS model (Figs. 9a, 9b and 9c).

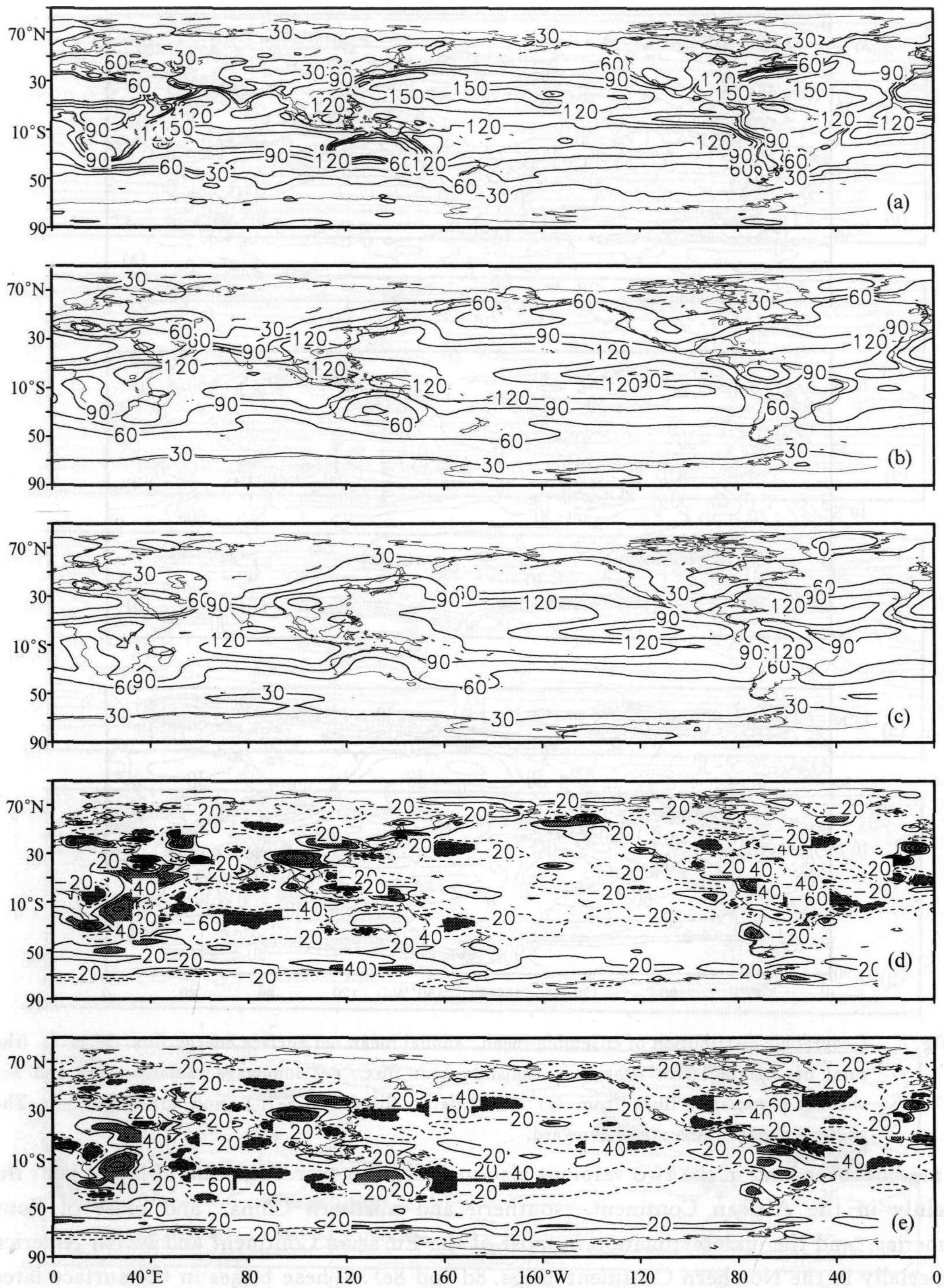

Fig. 8 As in Fig. 5 but for the surface latent heat flux (W m^{-2}).

The sensible heat flux shows a very similar pattern of the bias between two model versions and observations, as is shown in the comparison of the latent heat flux. The reason may be that the change in surface sensible heat flux and latent heat flux is not sensitive to the

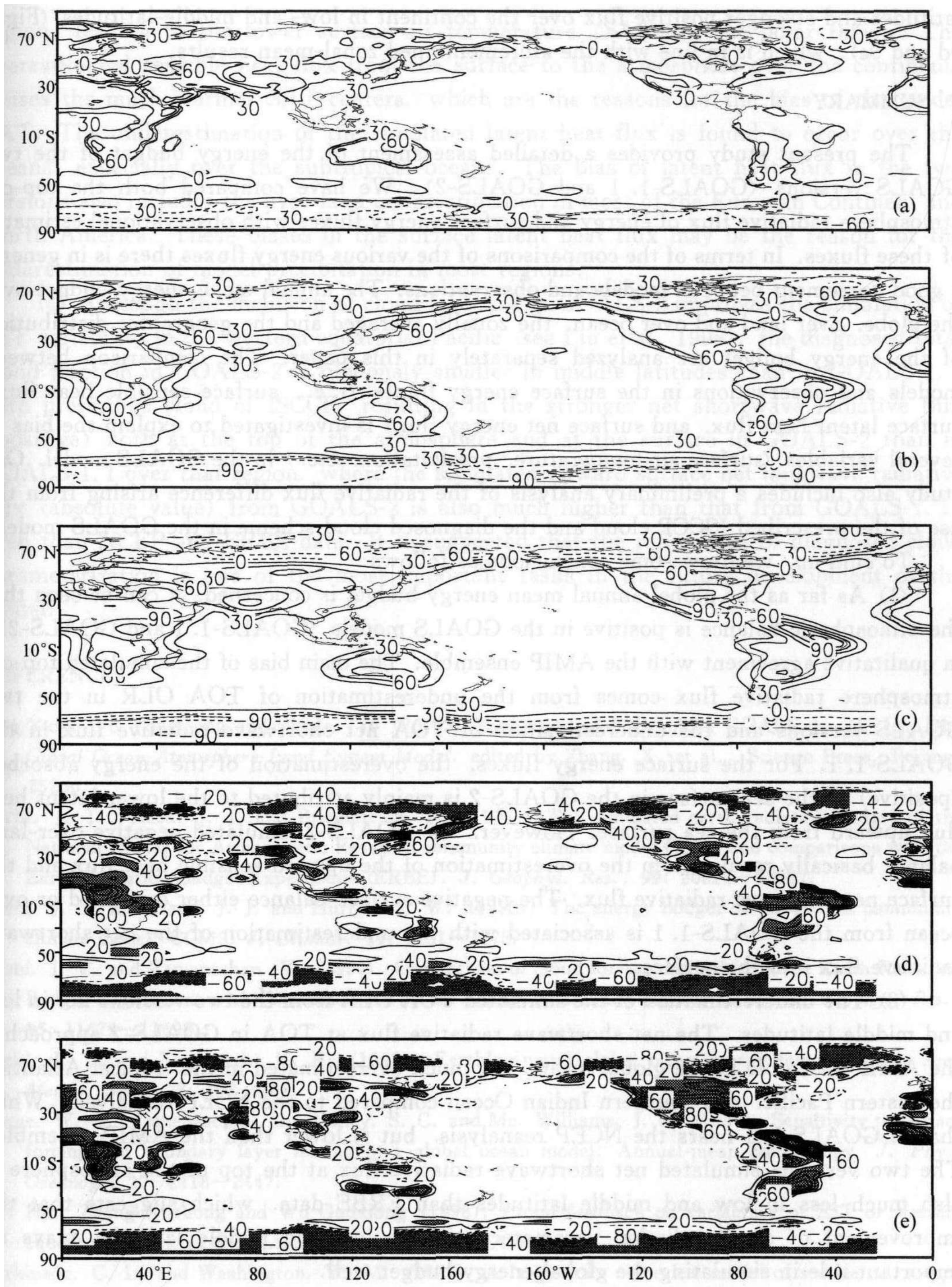

Fig. 9. As in Fig. 5 but for the surface sensible heat flux (W m^{-2}).

change in cloud scheme from GOALS-1. 1 to GOALS-2. The significant bias of the sensible heat flux in the GOALS model comes from the stronger negative flux in high latitudes and stronger positive flux over the continent in low- and middle-latitudes (Figs. 9d and 9e), which is in line with the aforementioned zonal-mean results.

V. SUMMARY

The present study provides a detailed assessment of the energy budget of the two GOALS versions (GOALS-1.1 and GOALS-2). We have compared both the top-of-atmosphere radiative flux of energy and surface energy fluxes with observational estimates of these fluxes. In terms of the comparisons of the various energy fluxes there is in general a good agreement between models and observations. The annual mean energy budget over the globe, over land and over ocean, the zonally averaged and the geographic distribution of the energy budget are analyzed separately in this paper. The comparison between models and observations in the surface energy fluxes (i.e., surface sensible heat flux, surface latent heat flux, and surface net energy flux) is investigated to explain the bias of several variables (surface air temperature, precipitation, etc.) in the GOALS model. Our study also includes a preliminary analysis of the radiative flux difference arising from the use of the prescribed ISCCP cloud and the diagnosed cloud scheme in the GOALS model.

To sum up, we draw some conclusions as follows:

(1) As far as the globel annual mean energy budget is concerned, it can be seen that the atmospheric balance is positive in the GOALS models (GOALS-1.1 and GOALS-2), in qualitative agreement with the AMIP ensemble. The main bias of the simulated top-of-atmosphere radiative flux comes from the underestimation of TOA OLR in the two GOALS versions and the underestimation of TOA net shortwave radiative flux in the GOALS-1.1. For the surface energy fluxes, the overestimation of the energy absorbed (positive) at the sea surface in the GOALS-2 is mainly attributed to the lower latent heat flux upward from the sea surface. However, the GOALS-2 simulated negative over-land balance basically results from the overestimation of the upward sensible heat flux and the surface net longwave radiative flux. The negative surface balance either over land or over ocean from the GOALS-1.1 is associated with the underestimation of the net shortwave radiative flux into the surface.

(2) The underestimation of the simulated TOA OLR from the two versions lies in low and middle latitudes. The net shortwave radiative flux at TOA in GOALS-2 approaches the AMIP ensemble in the global mean, but much overestimated in the tropical Atlantic, the eastern Pacific, and southern Indian Ocean compared to the NCEP reanalysis. While that in GOALS-1.1 nears the NCEP reanalysis, but is lower than the AMIP ensemble. The two versions simulated net shortwave radiative flux at the top of the atmosphere is also much less in low and middle latitudes than ERBE data, which suggests that the improvement of cloud-radiation parameterization in low and middle latitudes plays an important role in simulating the global energy budget well.

(3) In terms of the geographic distribution, the two GOALS versions show the similar distribution characteristic and bias region in the simulations of both the surface sensible heat flux and latent heat flux. The modeled negative sensible heat flux in high latitudes is associated with the underestimation of the simulated surface net shortwave radiation flux and the overestimation of the surface net longwave radiation flux over that

region, leading to the lower surface air temperature (SAT) in the polar region. The overestimated sensible heat flux from the surface to the atmosphere over the continents causes the much warmer SAT centers, which are the reasons for the bias of the model SAT. The underestimation of the simulated latent heat flux is found to occur over the oceans, especially over the subtropical oceans. The bias of latent heat flux in the two versions also includes the over-land underestimation in most of the Eurasian Continent and North America. These biases in the surface latent heat flux may be the reason for the underestimation of model precipitation in most regions.

(4) Although the inclusion of cloud feedback in GOALS-2 improves the simulation of SST variability in the western equatorial Pacific (see Liu et al. 1998), the diagnosed total cloud fraction in GOALS-2 is obviously smaller in middle latitudes than in GOALS-1.1 with prescribed cloud of ISCCP, resulting in the stronger net shortwave radiative flux (positive) both at the top of the atmosphere and at the surface in GOALS-2 than in GOALS-1.1 over that region, where the simulated upward surface net longwave radiative flux (absolute value) from GOALS-2 is also much higher than that from GOALS-1.1, even than NCEP and ERBE data. It is suggested that the refinement of diagnosed cloud parameterization is one of the most important tasks in the future development of the model.

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