Comparison of Model-Calculated and ERBE-Retrieved Clear-Sky Outgoing Longwave Radiation

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ABSTRACT

In order to validate radiative transfer models and identify sources of errors in the satellite retrieval of radiation budgets, model calculations of clear-sky outgoing longwave radiation (OLR) over oceans are compared with data from ERBE (Earth Radiation Budget Experiment). The NASA GEOS-1 (Goddard Earth Observing System) and the NCEP/NCAR (National Center for Environmental Prediction and National Center for Atmospheric Research) reanalyses of temperature and humidity and the SAGE (Stratospheric Aerosol and Gas Experiment) retrieval of the stratospheric humidity are used in the model calculations.

Averaged over time (1985-1989) and space (60˚S - 60˚N), the model-calculated clear-sky OLR has a positive bias of 2.0 - 2.4 W m^{-2} when compared to that of ERBE. Nearly all of the bias can be accounted for by the inclusion of the absorption due to CO_2 in the 4.3 µm band and to the weak CO_2 and O_3 molecular lines distant from band centers. The use of the two different reanalyses has only a small effect on the flux calculations (≈ 0.4 W m^{-2}). Consistent with suggestions by previous studies, ERBE is found to overestimate the clear-sky OLR over high humidity regions. The importance of the upper tropospheric humidity in affecting the earth radiation budget is also investigated. Although only ≈ 15% of the atmospheric humidity is contained in the region above the 600-hPa level, the upper troposphere is as important as the lower troposphere in contributing to the clear-sky OLR.

1. INTRODUCTION

The effect of clouds on the radiation budgets at the top of atmosphere (TOA) derived from the Earth Radiation Budget Experiment (ERBE) [Barkstrom *et al*. 1989] has been widely used to validate climate models and to improve cloud parameterization schemes. This so-called cloud radiative forcing is defined as the difference between the all-sky flux and the clear-sky flux. The zonal-mean value of the cloud radiative forcing in the outgoing longwave radiation (OLR) at TOA is ≈ 20-40 W m^{-2}, which is small compared to the clear-sky OLR (≈ 240-300 W m^{-2}). Since a small error in the clear-sky OLR could have a large relative error in the cloud forcing, it is important to accurately derive the clear-sky OLR either from satellite measurements or from radiative transfer models.

Previous studies assessing the accuracy of the ERBE clear-sky OLR over oceans yielded mixed results. Slingo and Webb [1992] found that global-mean ERBE clear-sky OLR was 3-4 W m^{-2} greater than their model calculations using the European Centre for Medium-Range Forecasts (ECMWF) temperature and humidity analyses. In contrast, Collins and Inamdar [1995] found that the ERBE values were ≈ 4 W m^{-2} lower than model calculations using ship radiosonde measurements in the tropics. Also using the ECMWF temperature and humidity fields, Kiehl and Briegleb [1992] found that agreement between the clear-sky OLR computed from a radiation model and the ERBE OLR is within ± 5 W m^{-2}. A common conclusion from these studies is that the ERBE clear-sky OLR has a large positive bias (5-15 W m^{-2}) in regions of deep convection or high humidity. As suggested by Hartmann and Doelling [1991], this bias may be related to the ERBE scene identification scheme, which could identify a high humidity clear scene as a partly cloudy scene. This misidentification of clear scenes leads to an overestimate of the clear-sky OLR.

The clear-sky OLR calculated from radiative transfer models depends strongly not only on the vertical distributions of temperature and humidity but also on the parameterization of the absorption of longwave (LW) radiation due to water vapor, CO_2, O_3, and other minor trace gases. Slingo and Webb [1992] used a Malkmus narrow-band radiation scheme with a spectral resolution of 10 cm^{-1}, whereas Kiehl and Briegleb [1992] used the radiation scheme of Briegleb [1992]. Both schemes included the radiative effects of water vapor, CO_2, O_3, CH_4, N_2O, and CFCs. The absorption in the minor CO_2 (9.4 and 10.4 μm) and O_3 (14 μm) bands was also included. Collins and Inamdar [1995] used a LOWTRAN 7 radiative transfer model [Kneizys *et al*. 1988]. The LOWTRAN 7 includes the absorption due to CH_4 and N_2O but not the absorption in the CFCs and the minor CO_2 and O_3 bands.

The motivation of this study is to re-evaluate the clear-sky OLR both from radiation model calculations and from ERBE. Studies of the difference between the model-calculated and the satellite-derived OLR will provide useful information on the error characteristics of the temperature and humidity analyses, the satellite retrieval scheme, and the radiative transfer parameterization. In the present study, two temperature and humidity fields obtained from the NASA GEOS-1 (Goddard Earth Observing System) reanalysis [Schubert *et al*. 1993] and the NCEP/NCAR (National Centers for Environmental Predictions / National Center for Atmospheric Research) reanalysis [Kalnay *et al*. 1996] are used. The reanalysis of specific humidity in the stratosphere and the upper troposphere has a large uncertainty because of the lack of observations and the difficulty in global model simulations. The humidity in the stratosphere and the upper troposphere has been retrieved from the SAGE (Stratospheric Aerosol and Gas Experiment) solar occultation measurements [Chiou *et al*. 1996]. Limited by the SAGE satellite orbital configuration, the density of the humidity retrievals is very low, and only the monthly- and zonal-mean humidity profiles are useful. Since high-altitude moisture is either unavailable or unreliable in the reanalyses, the SAGE-retrieved monthly- and zonal-mean stratopheric water vapor is used in the flux calculations. The clear-sky OLR is calculated only over oceans because of a large uncertainty in the land surface temperature.

2. DATA SOURCES AND RADIATIVE TRANSFER MODEL

2.1. *Data Sources*

The ERBE S-4 data archive [Barkstrom *et al*. 1989] contains clear-sky and all-sky LW and SW (shortwave) radiative fluxes at TOA for a period of 5 years from January 1985 to December 1989. The spatial resolution is 2.5˚ x 2.5˚ latitude-longitude, and the temporal resolution is one month. The ERBE fluxes have a number of systematic errors due to inadequate spatial and temporal sampling and incorrect identification of satellite scenes (i.e. clear, partly cloudy, overcast, etc.). Flux errors in individual clear and overcast scenes are estimated to be less than 2% and are much reduced when taking time and space averages [Harrison *et al*. 1990]. Constrained by the length of the ERBE S-4 data archive, the period of this study is limited to January 1985 - December 1989.

The atmospheric temperature and tropospheric water vapor are taken from the NASA GEOS-1 and the NCEP/NCAR reanalyses. The NASA GEOS-1 reanalysis has a horizontal resolution of 2.0˚ x 2.5˚ latitude-longitude, 18 vertical levels, and a temporal resolution of 6 hour. Currently, the data are available for 1980-1993. The NCEP/NCAR reanalysis has a horizontal resolution of 2.5˚ x 2.5˚ latitude-longitude, 17 vertical levels, and a temporal resolution of one day. The data are available for 1979-1996. The two reanalyses have identical pressure levels except for the top level and a few levels near the surface. The top pressures of the GEOS-1 and NCEP/NCAR are 20 hPa and 10 hPa, respectively. The stratospheric and upper tropospheric humidity (above the 300-hPa level) of both analyses is unreliable. In the NCEP/NCAR reanalysis, the specific humidity at 300 hPa often has a zero value. In the GEOS-1 reanalysis, the upper tropospheric humidity is overestimated in the tropics and underestimated in the extratropics as compared to radiosonde observations [Starr *et al*. 1995]. But it is always overestimated when compared to the SAGE data. In this study, we replace the stratospheric and upper tropospheric (pressure < 150 hPa) humidity of the reanalyses by the SAGE retrievals. Below the 150-hPa level, the SAGE humidity retrieval might have a large uncertainty due to cloud contamination in the SAGE radiance measurements. Therefore, the logarithm of specific humidity between 150 hPa and 300 hPa is interpolated linearly in the logarithm of pressure from the SAGE retrieval at 150 hPa and the reanalyses at 300 hPa. Zero specific humidity at 300 hPa in the NCEP/NCAR reanalysis is replaced by 10^{-6} g g^{-1}. Because of the low data density, only the monthly- and zonally-averaged SAGE humidity is used.

Figure 1 shows differences in the zonal-mean temperature and humidity between the two reanalyses (NCEP/NCAR minus GEOS-1) for the northern winter season (December, January, February, DJF) and the summer season (June, July, August, JJA) in the ERBE period (1985-1989) over oceans. Compared to the GEOS-1 reanalysis, the NCEP/NCAR temperature is much higher in the stratosphere for both seasons, with a magnitude increase from 0 K at ≈100 hPa to >7 K at the top of the model atmosphere (20 hPa) (Figs. 1a and b). Generally, the NCEP/NCAR temperature is lower than the GEOS-1 temperature in the troposphere by < 2 K. These differences are also noted by Higgins *et al.* [1996]. Differences in the zonal-mean humidity are shown in Figs. 1c and d. In order to emphasize values in the upper troposphere, the difference in the logarithm of the specific humidity is shown. Specific humidity exponentially decreases with height in the troposphere (not shown) and remains relatively constant within 1×10^{-6} - 3×10^{-6} in the stratosphere for all seasons and latitudes [Chiou *et al.* 1996]. Except in some high latitude regions, the humidity difference between the two reanalyses is less than 25% ($\Delta \log_{10} q < 0.1$). Overall, the NCEP/NCAR humidity is higher than the GEOS-1 humidity in the lower troposphere, and the reverse is true in the upper troposphere.

The daily values of sea surface temperature (SST) use in GEOS-1 are available with a horizontal resolution of 2.0° x 2.5° latitude-longitude, and the daily values of SST use in NCEP/NCAR are available on a T62 Guassian grid (≈ 1.87° x 1.87° latitude-longitude). We degraded the spatial resolution of the NCEP/NCAR SST to 2.5° x 2.5° latitude-longitude by using a linear interpolation to be consistent with the spatial resolution for the atmospheric temperature and humidity. In the horizontal interpolation of the NCEP/NCAR SST, the nearest grid point to the coastline in latitude and longitude is taken as missing in order to avoid contamination by land surface temperatures. The differences in the SSTs between the two reanalyses are very small.

The vertical distribution of O_3 mixing ratio is obtained from Rosenfield *et al*. [1987], and the amount of CO_2 is assumed 330 ppmv (parts per million by volume). Mixing ratios of the uniformly distributed gases in the atmosphere are taken from the IPCC report [IPCC 1994]: 0.31 ppmv for N_2O , 1.75 ppmv for CH_4, 0.3 ppbv (parts per billion by volume) for CFC-11, 0.5 ppbv for CFC-12, and 0.1 ppbv for CFC-22.

2.2. *Longwave Radiative Transfer Model*

In computing the LW fluxes, the spectrum is divided into nine bands [Chou and Suarez 1994]. A k-distribution function with linear pressure-scaling for the absorption coefficient is used to compute water vapor and CO_2 transmission functions. For the 9.6 μm band, a table look-up is used to compute the O_3 transmission function. The radiation model also includes the absorption due to minor trace gases such as N_2O, CH_4, and CFCs, as well as the two minor CO_2 absorption bands centered at 9.4 μm and 10.4 μm [Kratz *et al*. 1997]. Comparisons of fluxes computed using the parameterization and using a line-by-line model are given in Section 4.

3. RESULTS

In this section, the clear-sky OLR flux calculated from the radiative transfer model is compared to that retrieved from ERBE. Fluxes are calculated using the 6-hourly GEOS-1 reanalysis and the daily NCEP/NCAR reanalysis of temperature, tropospheric humidity, and SST. The effect of diurnal variations of the GEOS-1 temperature and humidity on the LW flux calculation is found to be small (< 1 W m^{-2}). We can expect, therefore, that not resolving the diurnal cycle in the NCEP/NCAR reanalysis will not affect the conclusions of this study. A similar result was also found by Slingo and Webb [1992].

3.1. *Model-Calculated Minus the ERBE-Retrieved Clear-Sky OLR*

Figure 2a shows the annual cycle of the zonal-mean clear-sky OLR fluxes over the oceans retrieved from ERBE. Fluxes larger than 290 W m^{-2} straddle the equator, with a maximum occurring in the winter hemisphere. The maximum follows the seasonal march of the Intertropical Convergence Zone (ITCZ), but on the opposite side of the equator where the atmosphere is not as humid. As can be seen in the figure, the clear-sky OLR decreases poleward, consistent with the variations in the extratropical SST and atmospheric temperature. Differences in the clear-sky OLR are shown in Figs. 2b and c, respectively, for GEOS-1 minus ERBE and NCEP/NCAR minus ERBE. It can be seen that the two reanalyses produce quite similar results, in spite of the differences in temperature and humidity shown in Fig. 1. Overall, the model-calculated clear-sky OLR is larger than the ERBE. The maximum positive bias is found between 20˚ and 30˚ latitude in the summer hemisphere, with a magnitude of ≈ 6 W m^{-2}. The bias becomes weaker and even changes to negative at higher latitudes. The magnitude of the positive bias in the tropics is consistent with that of Collins and Inamdar [1995]. Averaged over the region 60˚S - 60˚N and the five-year period (1985-1989), the biases are +2.4 W m^{-2} and +2.0 W m^{-2} for the calculations using the GEOS-1 and the NCEP/NCAR reanalyses, respectively.

To understand the positive bias of the ERBE clear-sky OLR in moist regions as suggested in a number of studies [e.g., Hartmann and Doelling 1991, Slingo and Webb 1992, Collins and Inamdar 1995], we show in Fig. 3 the latitudinal distributions of the clear-sky OLR difference between the model calculations and the ERBE retrieval as a function of the mean relative humidity. The mean relative humidity represents the relative humidity of the reanalyses averaged over the troposphere below the 300-hPa level and over the five-year period. It can be seen in the figure that the patterns of the OLR difference are very similar for the two sets of flux calculations. The positive bias of the model calculations, relative to the ERBE OLR, systematically decreases with increasing humidity. It even changes to negative, reaching -8 W m^{-2}, for relative humidities greater than 60%. This is consistent with the suggestion that the ERBE clear-sky OLR might have a positive bias over high humidity regions due to incorrect identification of the clear scenes. Over dry regions, however, the model estimate is considerably higher than ERBE's, the difference reaching 10 W m^{-2} at 30% relative humidity over tropical region. This difference may be caused by the underestimation of the humidity used in the model calculations or by the incorrect identification of scenes with thin clouds or small cloud amount as clear scenes in the ERBE retrievals. In the latter case, the ERBE clear-sky OLR would be underestimated, and thus the difference shown in the figure is positive.

The horizontal distributions of the model bias for the five-year period are shown in Fig. 4 for the two reanalyses. For JJA, the clear-sky OLR calculated using the GEOS-1 temperatures and humidities is higher than that of ERBE over most of the tropics (30˚S - 30˚N) (Fig. 4a). However, there is a relatively weak negative bias in some equatorial regions, for example, the western Pacific in the Northern Hemisphere, the central Pacific and Indian Ocean in the Southern Hemisphere. Compared to the tropics, a much weaker bias is found in the midlatitudes . For the clear-sky OLR calculated using the NCEP/NCAR analyses (Fig. 4b), the peak-to-peak amplitude of the bias is two times larger than that of the GEOS-1 in the tropics. A large positive bias (> 8 W m^{-2}) occurs in the tropical eastern Pacific and over the ocean to the east of the Philippines. On the other hand, a large negative bias (< -8 W m^{-2}) is found in the central and eastern equatorial Pacific in the Southern Hemisphere. For DJF (Figs. 4c and d), the spatial distributions of the bias for both analyses are quite similar. Overall, the bias is much reduced when compared to that of JJA.

3.2. *Comparison of the Two Reanalyses*

Although the main purpose of the present study is not to compare the two reanalyses, a brief comparison of the reanalysed temperature and humidity fields is needed to discuss the discrepancy of the model biases over the tropics for JJA (see Figs. 4a and b). Figure 5 shows the difference (NCEP/NCAR minus GEOS-1) in the vertical profiles of temperature and in the logarithm of specific humidity, as well as the model-calculated clear-sky OLR for JJA at 20˚N. There is a significant temperature discrepancy of up to 12 K in the lower stratosphere between the two reanalyses (Fig. 5a). Compared to GEOS-1, the NCEP/NCAR temperatures are higher in the stratosphere and lower in the troposphere over the central Pacific, whereas NCEP/NCAR has a higher humidity over the central and eastern Pacific and a lower humidity in the western Pacific (Fig. 5b). Except in the western Pacific, the middle tropospheric humidity of the NCEP/NCAR reanalysis is a factor of 3-4 ($\Delta \log_{10} q > 0.5$) higher than that of the GEOS-1 reanalysis. However, NCEP/NCAR has less humidity in the lower troposphere over the entire Pacific.

The difference in clear-sky OLR (Fig. 5c) is positive over the western Pacific and negative over the eastern central Pacific. In the western Pacific (130-160˚E), it is clear that the higher temperature and lower humidity in the NCEP/NCAR lead to a larger clear-sky OLR. This large positive difference decreases eastward and changes to negative in the central Pacific, associated with the increase in the middle and upper tropospheric humidity, even though the temperature is higher in the stratosphere and the humidity is lower in the lower troposphere. The negative OLR difference in the central and eastern Pacific is related to the higher NCEP/NCAR humidity in the middle and upper troposphere. These results show clearly the importance of the upper tropospheric humidity even though it is much smaller than the lower tropospheric humidity.

4. DISCUSSION AND CONCLUSION

To identify the possible sources of the discrepancies between the model calculations and the ERBE retrieval of clear-sky OLR, the radiation model calculations are compared to line-by-line calculations [Ridgway *et al*. 1991]. The line-by-line calculations use the Air Force Geophysical Laboratory (AFGL) 1993 edition of the molecular line parameters [Rothman *et al*. 1987]. Table 1 shows the clear-sky OLR for individual spectral bands from line-by-line calculations and from the radiative transfer model for the midlatitude summer atmosphere [McClatchey *et al*. 1972]. There are two sets of line-by-line calculations for bands 3, 6, and 9. The first set includes the same absorbers used in the model, and the second set includes additional absorption which has some radiative effect but is not included in the radiation model. As can be seen from the first row of each band in the table, the error between the line-by-line calculation and the model is less than 1 W m^{-2}, both for individual bands and for the total spectrum. The additional absorption in the calculation, as shown in the second row for each band, includes the 4.3 μm CO_2 band (Band 9), the weak 14 μm O_3 band (Band 3), and weak O_3 absorption lines outside the major 9.6 μm O_3 band (Band 6). The total effect of these minor absorption bands is to reduce the clear-sky OLR by 2.0 W m^{-2} (286.6 W m^{-2} vs. 284.6 W m^{-2}). Compared to the line-by-line calculation, the radiative transfer model overestimates clear-sky OLR by 0.7 W m^{-2} (285.9 W m^{-2} vs. 286.6 W m^{-2}).

As shown earlier, the domain-averaged discrepancies of the clear-sky OLR for the five year period (1985-1989) between the model calculations and the ERBE were 2.4 W m^{-2} when the GEOS-1 analysis was used and 2.0 W m^{-2} when the NCEP/NCAR analysis was used. Thus, much of these discrepancies can be accounted for by the minor absorptions that are not included in our radiative transfer model (2.0 W m^{-2}). If we used CO_2 concentration of 350 ppmv (IPCC, 1994) instead of 330 ppmv, the discrepancies will be further reduced by ≈ 0.25 W m^{-2}. Although the global-mean model bias is small, locally the differences can be much larger and are correlated with the local humidity. The largest differences are found in the tropics, where the model underestimates the clear-sky OLR by ≈ 4 W m^{-2} when the column-mean relative humidity is high and overestimates it by ≈ 10 W m^{-2} when the mean relative humidity is low. The positive model bias over dry atmospheric regions was reported by Collins and Inamdar (1995).

If the difference in the GEOS-1 and NCEP/NCAR analyses represents typical uncertainty in temperature and humidity, then the uncertainty in the global clear-sky OLR calculation due to the uncertainty in temperature and humidity is ≈ 0.4 W m^{-2}. However, there are large regional discrepancies in the clear-sky OLR due to large differences in the middle and upper tropospheric humidity. The upper tropospheric humidity has a significant effect on the clear-sky OLR and the climate sensitivity to external radiative forcing [Lindzen 1990], but is very difficult to derive either from a climate model or from radiosonde and satellite observations. The percentage contribution of the atmosphere below a certain pressure level to the clear-sky OLR for three atmospheres taken from McClatchey *et al.* [1972] is shown in Fig. 6. A larger slope of the curves at the given level indicates a greater contribution from that level. It can be seen that the stratosphere contributes ≈ 10% to the clear-sky OLR, primarily from the 15 µm CO_2 band. The slopes are rather uniform between 300 and 800 hPa, indicating that layers in this region are equally important in contributing to the clear-sky OLR. For all three atmospheres, about 40 % is contributed from the region above the 600-hPa level, which contains only ≈15% of the total water vapor. The contribution of the atmosphere below the 800-hPa level increases as humidity increases. For the moist tropical atmosphere, the contribution from the near surface atmosphere (pressure > 800 hPa) is 12%, while the surface contribution is 17%. The surface contribution increases to 37 % for the dry midlatitude winter atmosphere.

The difference in the model-calculated and the ERBE-derived clear-sky OLR is small (≈2 W m^{-2}) when averaged over global oceans. This difference can be accounted for by the absorption in the 4.3 µm CO_2 band and the weak CO_2 and O_3 molecular lines distant from major absorption band centers, which are not included in the radiation model calculations. However, large differences greater than 10 W m^{-2} do occur in the monthly and regional (2.5˚x2.5˚ latitude-longitude) clear-sky OLR. Generally, negative bias (model minus ERBE) is found in regions of high humidiy, and large positive bias occurs in dry regions. A large portion of these biases is attributable to the incorrect identification of clear scenes in the ERBE retrieval processes; clear scenes with high humidity might be identified as cloud-contaminated in the former case, while scenes with thin and small cloud amount might be identified as clear in the latter case. Based on the results of radiation calculations using different temperature and humidity analyses and on the comparison between the radiation parameterization and the line-by-line calculation, we can conclude that large clear-sky OLR difference (exceeding 8 W m^{-2}) between model and ERBE in both very dry and very humid regions is not caused by the uncertainty in radiative transfer calculations.

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TABLE 1. Spectral Bands, Absorbers, and Longwave Radiation Fluxes at the Top of Atmosphere Calculated from the Line-by-Line Method and the Parameterization for a Midlatitude Summer Atmosphere. Units are W m^{-2}.

Band	cm^{-1}	Absorber	Line-by-Line	Model
1	0-340	H_2O(line)	34.30	34.10
2	340-540	H_2O(line)	60.73	60.23
3	540-800	H_2O(line+continuum)+CO_2+N_2O	65.87	66.70
		H_2O(line+continuum)+CO_2+N_2O+O_3	65.44	
4	800-980	H_2O(line+continuum)+CO_2	58.25	58.28
5	980-1100	H_2O(line+continuum)+O_3+CO_2	21.55	21.13
6	1100-1250	H_2O(line+continuum)+CH_4+N_2O	21.00	20.92
		H_2O(line+continuum)+CH_4+N_2O+O_3	20.57	
7	1250-1380	H_2O(line)+CH_4+N_2O	12.40	12.28
8	1380-1900	H_2O(line)	7.38	7.33
9	1900-3000	H_2O(line)	5.11	4.90
		H_2O(line)+CO_2	4.00	
Total	0-3000	Major and trace gases	286.59	285.87
			284.62	

Figure Captions

Fig. 1. Latitude-pressure cross sections for the difference between the NASA GEOS-1 reanalysis and the NCEP/NCEP reanalysis for 1985-1989 : (a) temperature during December-January-February, (b) temperature June-July-August, (c) specific humidity December-January-February, and (d) specific humidity June-July-August. The specific humidity combines tropospheric humidity taken from the two reanalyses with stratospheric humidity obtained from SAGE retrievals. The units are K for temperature and g g^{-1} for specific humidity (q). The contour interval is 1 K in temperature and 0.1 in $\log_{10} q$. The negative values are shaded.

Fig. 2. (a) Latitude-month distribution of the zonal-mean clear-sky OLR from ERBE (a) and the difference between the ERBE OLR and that calculated using the NASA GEOS-1 reanalysis (b) and the NCEP/NCAR reanalysis (c). The unit is W m^{-2}, and the contour interval is 10 W m^{-2} in (a) and 2 W m^{-2} in (b) and (c). Negative values are shaded.

Fig. 3. Differences between the ERBE-retrieved clear-sky OLR and the model-calculated clear-sky OLR using the NASA GEOS-1 reanalysis (a) and the NCEP/NCAR reanalysis (b) as functions of latitude and height-mean relative humidity. The height-mean relative humidity is a vertically averaged value below the 300-hPa level. The unit is W m^{-2}, and the contour interval is 2 W m^{-2}. Negative values are shaded.

Fig. 4. (a) Horizontal distributions of the difference between the ERBE-retrieved fluxes and the model-calculated fluxes using the reanalyses of the NASA GEOS-1 for June-July-August (a), the NCEP/NCAR for June-July-August (b), the NASA GEOS-1 for December-January-February (c), and the NCEP/NCAR for December-January-February (d). The unit is W m^{-2}, and the contour interval is 4 W m^{-2}. Negative values are shaded.

Fig. 5. Differences in the reanalyses (NASA GEOS-1 minus NCEP/NCAR) at 20˚N in the Pacific for temperature (a), the logarithm of the specific humidity (b), and the calculated clear-sky OLR (c). The units are K for temperature, g g^{-1} for specific humidity q, and W m^{-2} for OLR.

Fig. 6. Contribution to the clear-sky OLR integrated from the top of atmosphere to a certain pressure level.