Simulation of the Diurnal Cycle of Outgoing Longwave Radiation with an Atmospheric GCM

A. SLINGO*, R. C. WILDERSPIN AND S. J. BRENTNALL

Meteorological Office, Bracknell, Berkshire, England

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ABSTRACT

Results are presented from an integration of the U.K. Meteorological Office 11-Layer Atmospheric General Circulation Model, with emphasis on the simulation of the diurnal cycle of the outgoing longwave radiation. The model reproduces many of the features which have been noted from observational studies with satellite data. It is argued that such comparisons between models and observations have considerable potential not only for validating the cloud and other parameterization schemes used in models but also for understanding the origin of the observed variations.

1. Introduction

Observations of the Earth's radiation budget (ERB) from satellite platforms have proved to be invaluable for studies of climate and for validating climate models (Hartmann et al., 1986). These data show directly the horizontal distribution of radiative heating which is the energy source for the earth's climate system. In addition, because that heating is strongly influenced by the cloud cover, the data also contain information on the distribution and radiative properties of clouds. These observations therefore provide one of the most important sources of validation for assessing the schemes used to predict cloud fields in Atmospheric General Circulation Models (AGCMs). Such assessments have traditionally concentrated on mean climatologies derived from several years of data, but the observed variations on a wide range of time scales could also be used. In particular, several recent studies have demonstrated that in many regions there are substantial systematic variations in the ERB and cloud fields in response to the diurnal cycle of solar heating. Data from the GOES (Minnis and Harrison, 1984) and METEOSAT (Duvel and Kandel, 1985) geostationary satellites and from various polar orbiters (Hartmann and Recker, 1986) have been analyzed. In this note, results from an AGCM are used to demonstrate that such data have considerable potential for further validating the cloud and other parameterization schemes employed in models.

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2. Model and integration

The U.K. Meteorological Office 11-Layer Model is a finite difference AGCM which is formulated in sigma coordinates on a regular latitude/longitude grid. An early version was used to study the climate of the Saharan region by Cunnington and Rowntree (1986), who also described the convection scheme. More recently, studies have been made of the model's response to sea surface temperature anomalies associated with El Niño (Palmer and Mansfield, 1986) and to envelope orography and a parameterization of orographic gravity wave drag (Palmer et al., 1986; Slingo and Pearson, 1987). Basic details of the model are given by Slingo and Pearson (1987) and the development of the longwave part of the radiation scheme is described by Slingo and Wilderspin (1986). A comprehensive handbook of the model is also available (Slingo, 1985). The model has since been modified to improve the quality of the cloud and ERB simulations, through various changes including revised convection, boundary layer and cloud prediction schemes. A paper describing those changes and presenting results from a control simulation with the new model is in preparation. The results shown here are from a development version which differs only in minor respects from the new model.

For most applications, the model is integrated with a resolution of 2.5° in latitude by 3.75° in longitude. The model predicts the fractional coverage both by layer clouds (which occupy a single model layer) and by a convective cloud tower (which may be any number of model layers deep). The layer cloud amounts are calculated by a quadratic dependence on the environmental relative humidity, rising from zero at the threshold relative humidity (typically 90 percent) to full cover at saturation. The convective cloud amount is proportional to the vertically integrated mass of condensed water calculated in the penetrative convection scheme, and the cloud base and top required in the radiation computations are determined by the layers in which the moist convection begins and ends. The radiation and cloud prediction schemes are called every three hours of model time in order to resolve the diurnal cycle.

In the version used here, the land surface temperature is computed by considering the energy balance of a single slab. The net energy flux at the surface is converted into a temperature increment by assuming that the surface thermal capacity is equivalent to that of 5 cm of water. This is intended to give a reasonable amplitude and phase response to the diurnal cycle, although its response to other frequencies is poor. A more advanced parameterization, incorporating four layers of different depths, has recently been developed, and this gives a good response to forcing from diurnal to interannual frequencies (Warrilow, 1987, in preparation).

The model was integrated through a complete annual cycle using initial conditions taken from the end of June of a previous integration. The results shown here are meaned over the month of January.

3. Results

The mean outgoing longwave flux from the model for the month of January is compared with Nimbus 7 data (Jacobowitz et al., 1984) for January 1980 in Fig. 1. The model reproduces the major features in the observed distribution, notably the minima in the tropical regions due to deep convective clouds over South America, southern Africa, Indonesia, the intertropical convergence zone (ITCZ) and the South Pacific convergence zone (SPCZ). There are maxima in the subtropics, where the clouds are much lower or absent. The values also decrease realistically towards the poles.

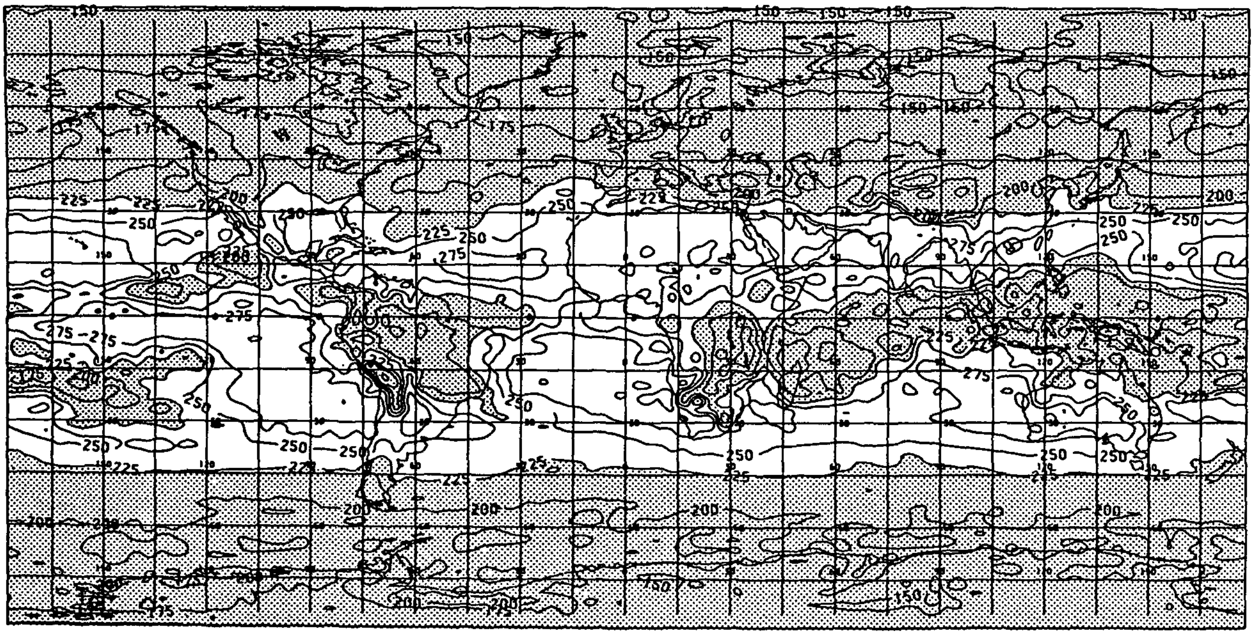
The good agreement between the observed and modeled mean outgoing longwave flux indicates that the cloud prediction scheme is working satisfactorily, at least as regards the cloud associated with deep convection. However, as noted in the introduction, additional information can be gleaned from the simulation of the diurnal cycle, as will now be discussed.

Satellite data on the diurnal cycle of the outgoing longwave flux were presented by Minnis and Harrison (1984) and Hartmann and Recker (1986) in the form of maps in which the phase of the first harmonic of the diurnal cycle at each grid point was represented by the direction of an arrow on an imaginary 24 hour clock, based on local time. The amplitude and phase were obtained by an harmonic analysis of the data. This is an attractive way to present the results, although it was recognized that the observed diurnal cycle rarely follows a pure sine wave. A slightly different method is employed here, which is explained in Fig. 2. The advantage of this representation is that it does not assume that the form of the diurnal variation is sinusoidal. A coherent, but nonsinusoidal, diurnal variation appears as a bent arrow, while a sinusoidal variation leads to a straight arrow. As will be seen, over much of the globe the model's diurnal variation is not sinusoidal and it would be interesting to see the satellite data analyzed in the same way to establish whether this behavior is realistic.

The mean diurnal cycle in the outgoing longwave flux for January from the model is shown in Figs. 3a and 4a, using the notation illustrated in Fig. 2. In addition, Figs. 3b and 4b show the diurnal variation of the clear-sky contribution to the flux. Archiving the clear-sky flux separately makes it possible to isolate the cloud radiative forcing of the general circulation, by subtracting this component from the total flux (Ramanathan, 1987; Hartmann et al., 1986). For the present study, the diurnal variation in the clear-sky flux is itself of considerable interest because it is dominated by the diurnal variation in the surface temperature. Over the oceans, the use of prescribed sea surface temperatures leads to a very weak diurnal cycle in the clear-sky flux as this responds only to changes in atmospheric temperature and moisture content. The variation is also weak over land at high latitudes because the surface insolation is small. However, elsewhere over land there is a substantial diurnal variation due to changes in the land surface temperature. The amplitude of the variation is greatest in those regions where there is little cloud cover and the soil moisture content (which is a prognostic variable of the model) is lowest, because here the evaporation is lowest and so the surface temperature responds most strongly to changes in insolation. This may be seen by comparing the contours of the amplitude on Figs. 3b and 4b with the mean flux shown in Fig. 1a. At low latitudes, where the precipitation is mainly convective, there is a strong correlation between high soil moisture content and high precipitation and hence with low outgoing longwave flux. The diurnal variation is thus strongest over the Sahara desert (where it exceeds 40 W m^{-2} over large areas) and over the deserts of southern Africa and south Australia. Over North and South America, the pattern is in reasonable agreement with the same diagnostic derived by Minnis and Harrison (1984) from GOES data (their Fig. 14 from Part III), with a minimum in the Amazon Basin and maxima over the Andes and Rockies. For most of the areas where the diurnal variations are significant, the minimum occurs in the early morning and the maximum in the late afternoon. This is consistent with the variations one would expect in the surface temperature, although the maximum is somewhat later in the day than was found in the satellite studies.

Variations in the cloud cover lead to greater complexity in the diurnal cycle of the total longwave flux (Figs. 3a and 4a) compared with the clear-sky component. Over land, the clear-sky signature can still be

(a) Model



(b) Nimbus 7

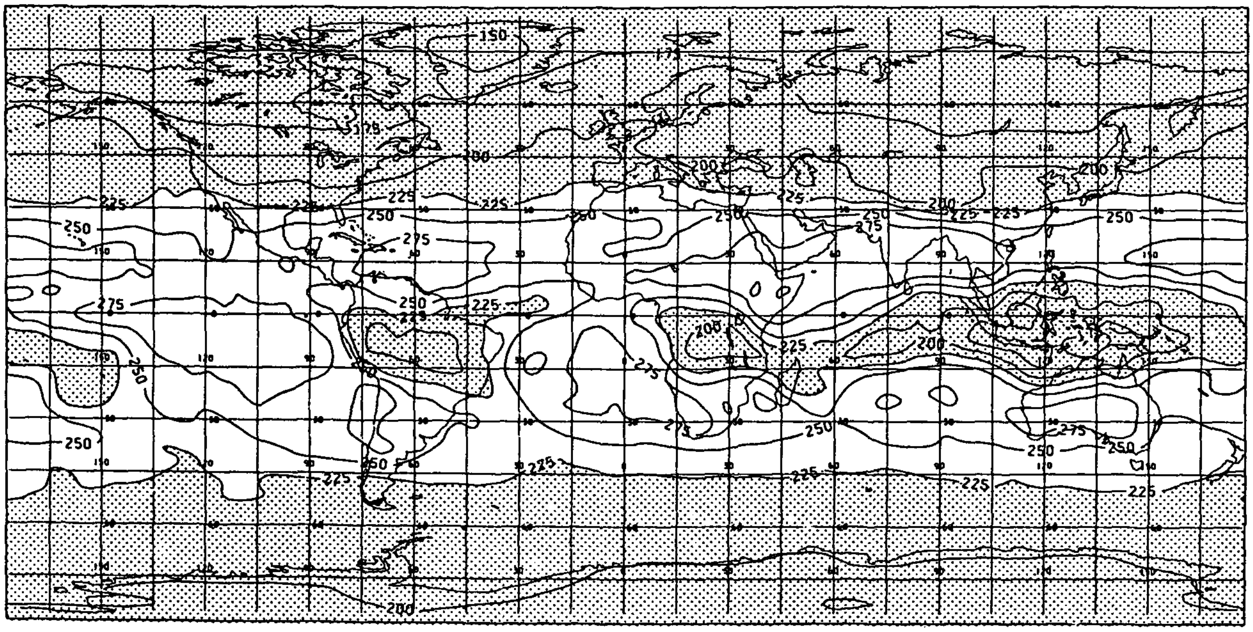


FIG. 1. Mean outgoing longwave flux in W m^{-2} for January from (a) the model and (b) Nimbus 7 Narrow Field Of View data for 1980. The contour interval is 25 W m^{-2} with shading below 225 W m^{-2}.

seen in areas where the cloud amounts are small, notably the Sahara. Elsewhere, the patterns are much more complicated. Over South America there are maxima in excess of 40 W m^{-2} associated with changes in the convection in the Amazon Basin and Northeast Brazil, as was also found by Minnis and Harrison (1984, Part III, their Fig. 22). Their data show a maximum in the outgoing longwave flux at around local noon (their Fig. 17), although Hartmann and Recker show earlier maxima in this season (their Fig. 1a). In

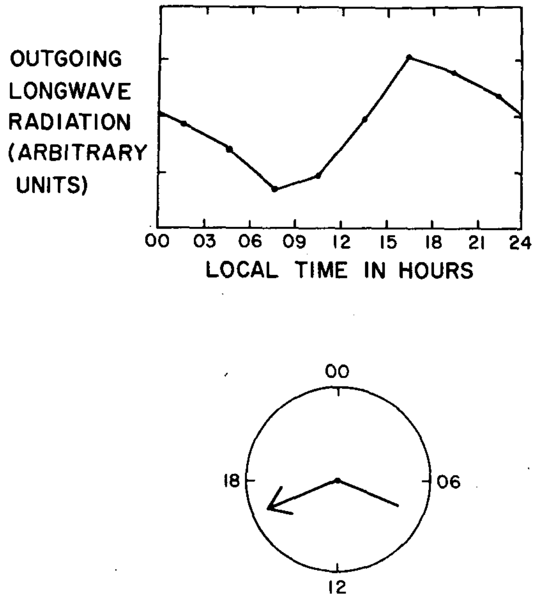


FIG. 2. The graph at the top illustrates schematically the variation of the outgoing longwave flux through the day at a typical model gridpoint, with a minimum at 0730 local time and a maximum at 1630 local time. This coherent, but nonsinusoidal, behavior may be represented by an arrow on an imaginary 24-hour clock. The tail of the arrow points at the local time of the minimum and the head points at the local time of the maximum. Thus the variation shown on the graph is represented as in the lower diagram.

the model, there are less coherent variations with maxima at various local times.

Of particular interest in Figs. 3a and 4a are the oceanic areas with coherent diurnal variations in excess of 20 W m^{-2}. Comparison with the clear-sky maps shows that these variations are almost entirely due to changes in the cloud cover, as was also found in the observations. The largest variations are in the Indian Ocean, Indonesia and in the Pacific ITCZ extending from 150°E across the dateline to 150°W. Similar patterns are shown by Hartmann and Recker (1986). In the Pacific ITCZ there is a maximum in the outgoing longwave flux around noon and a minimum at night. This is in broad agreement with the phase of the diurnal cycle found by Hartmann and Recker. It suggests that the high cloud cover is a maximum during the night, although both Albright et al. (1985) and Hartmann and Recker (1986) argue that the cloudiness variations are much more complicated than this simple picture, with changes in cloud cover at different levels producing partly compensating changes in the outgoing longwave flux.

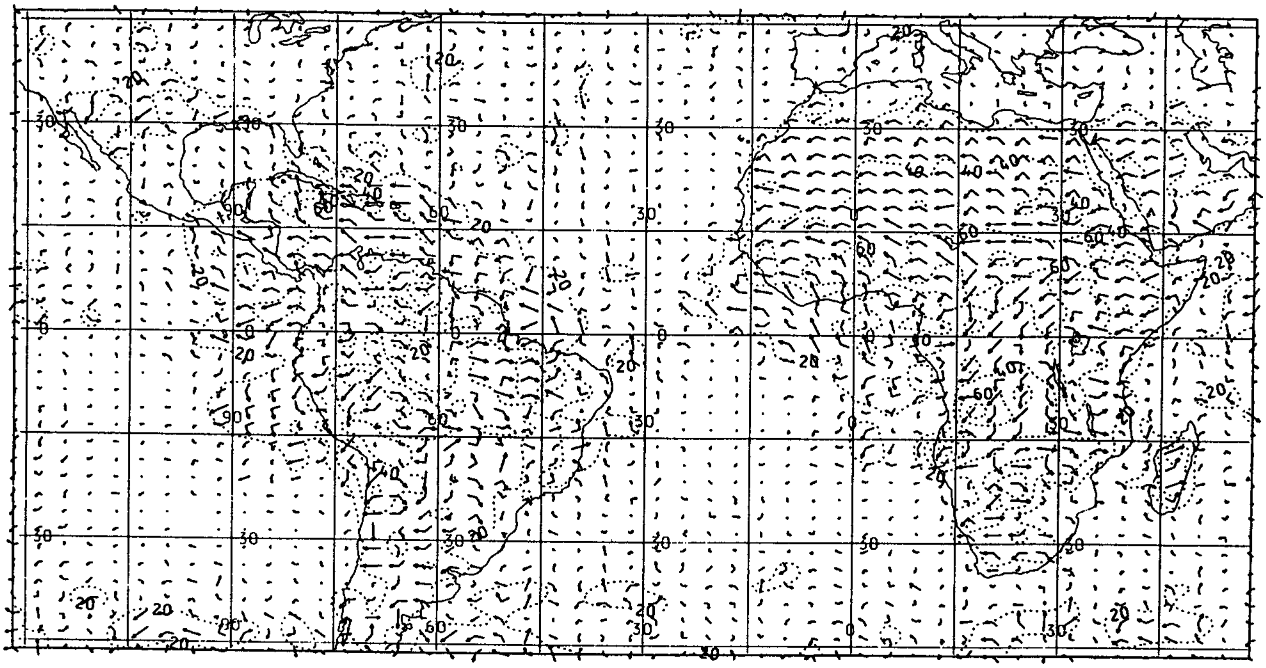
Both Minnis and Harrison (1984) and Hartmann and Recker (1986) show that there are significant diurnal variations in the low cloud cover and outgoing longwave flux in the stratocumulus regimes of the Southeast Pacific and Atlantic oceans. These variations are probably forced by the diurnal cycle in the absorption of solar radiation within the cloud (Turton and Nicholls, 1987). While Fig. 3a shows some variations in these areas, they are primarily due to changes in higher cloud layers and there is little evidence for coherent diurnal variations in those regions where the model predicts substantial low cloud cover unobscured by higher cloud (i.e. close to the coasts of South America and South Africa between about 15°S and 30°S). It is not yet known whether this is due to a failure to represent the cloud cover variations themselves or to the cloud top temperature being too close to the sea surface temperature for a signal to appear in the outgoing longwave flux. Further work is planned to study this aspect of the simulations, given the importance of these clouds in the radiation budget.

4. Discussion

The purpose of this note is to demonstrate the value of comparisons between model simulations and satellite observations of the diurnal cycle in the earth's radiation budget and to encourage further such studies. By separating the clear-sky contribution from the total outgoing longwave flux, it is possible to study the diurnal cycle in the land surface temperature, which may yield useful information on the realism of the methods used to represent land surface processes in models. For example, it will be interesting to compare the results from the present model with that incorporating the new land surface temperature scheme mentioned in section 2. Additionally, since the diurnal cycle in the outgoing longwave flux is strongly influenced by changes in the cloud cover, it should also be possible to assess the cloud parameterization, particularly in regions where the cloud is convective in origin. Over the oceans, the observed diurnal variations in the ITCZ are presumably the result of subtle interactions between radiative and convective processes, and there may be information here which would be of value in developing a closer link between the model parameterizations for these processes. The significant observed diurnal variation in the areas of marine subtropical stratocumulus may indicate the need for such a link between the radiation, turbulence and condensation parameterizations (Turton and Nicholls, 1987). It should also be noted that failure to include the diurnal cycle or to resolve it adequately can lead to a degradation in the quality of model simulations (Randall et al., 1985; Wilson and Mitchell, 1986).

The successful simulation of the observed diurnal cycle would thus enhance considerably the credibility of a model for climate studies. Such a model would also be a powerful tool for understanding the processes which control the observed diurnal variations. Models used for numerical weather prediction could also benefit from such comparisons, particularly if the evolution of the modeled diurnal cycle during a forecast could

(a) Total



(b) Clear-Sky

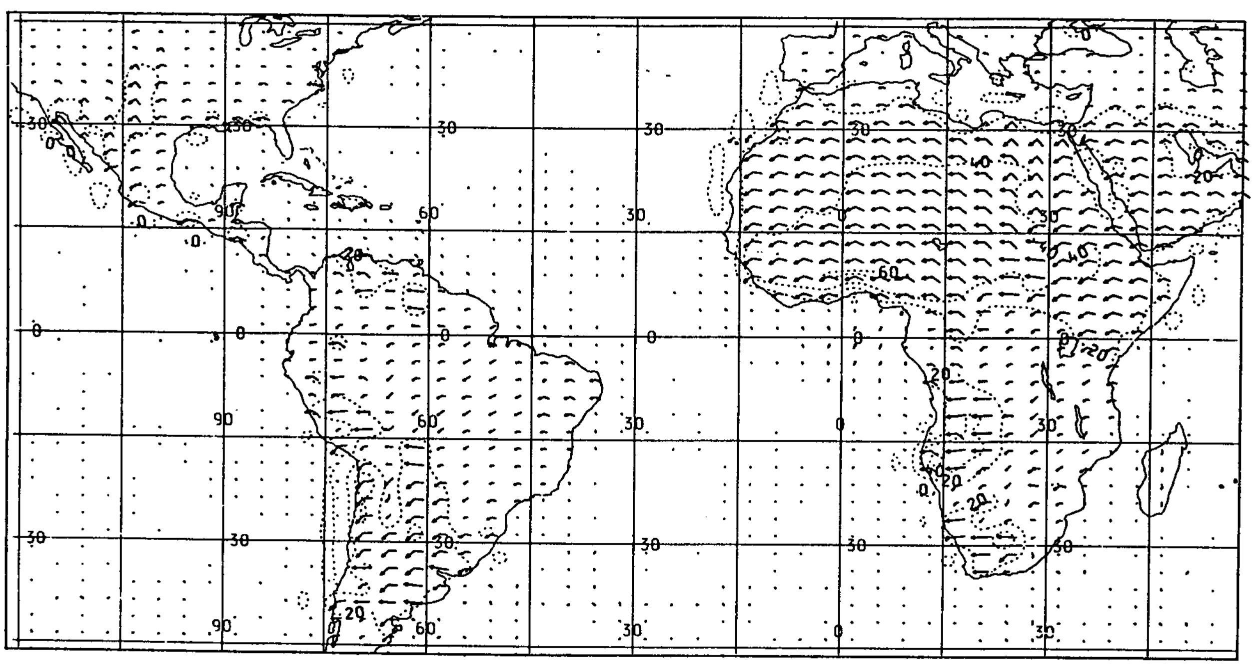


FIG. 3. (a) Mean diurnal variation of the total outgoing longwave flux from the model for January, using the representation explained in Fig. 2. The length of the arrow is proportional to the amplitude of the variation up to 30 W m^{-2} and is constant for larger variations. In addition, contours of the amplitude are shown dotted, with a contour interval of 20 W m^{-2}. No arrows are plotted if the amplitude is less than 2 W m^{-2}. The map is for the area 45°N to 45°S, 120°W to 60°E. Latitude and longitude lines are plotted every 15°. (b) As in (a) except for the clear-sky contribution.

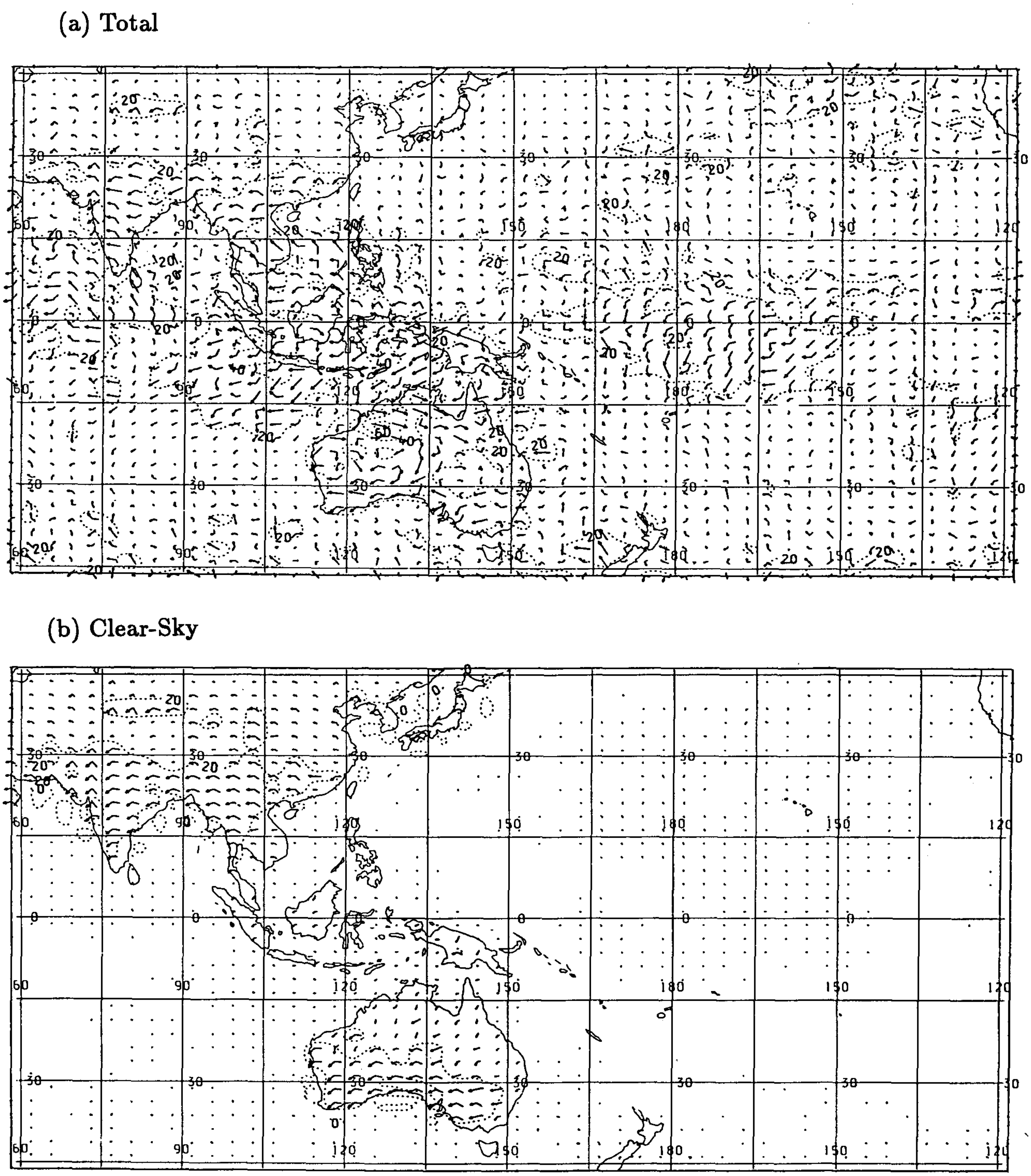


FIG. 4. As in Fig. 3 except for the other hemisphere.

be compared with satellite data for the same time period.

The averaging period used here is only 30 days. This is probably long enough to define the diurnal cycle in the clear-sky flux, as that is dominated by the strong and coherent variation in the land surface temperature. Over the tropical oceans, however, a component of the apparent diurnal cycle in the total flux may be spuriously generated by aliasing of the much larger synoptic variations. A longer time period is probably needed to study such regions. It would also be interesting to determine whether the character of the modeled diurnal cycle varies with time of year (as was found by Hartmann and Recker, 1986) or synoptic conditions.

This preliminary study has demonstrated that the model shows some success in reproducing the observed diurnal variations. A more detailed investigation is planned with extensive diagnostics, particularly of the cloudiness and related fields. Clear and total outgoing longwave fluxes and their diurnal variation are also being obtained as part of ERBE (Barkstrom and Smith, 1986), so this investigation should make a timely contribution to this fascinating area of research.

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