

# Diurnal Cycles of Clouds and How They Affect Polar-Orbiting Satellite Data

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(Manuscript received and in final form 4 May 2007)

## ABSTRACT

Diurnal cycles of clouds were investigated using the NOAA series of polar-orbiting satellites. These satellites provided four observations per day for a continuous 11-yr period from 1986 to 1997. The High Resolution Infrared Radiation Sounder (HIRS) multispectral infrared data were used from the time trend analysis of Wylie et al. The previous study restricted its discussion to only the polar orbiters making observations at 0200 and 1400 LT because gaps in coverage occurred in the 0800 and 2000 LT coverage. This study shows diurnal cycles in cloud cover over 10% in amplitude in many regions, which is very similar to other studies that used geostationary satellite data. The use of only one of the polar-orbiting satellites by Wylie et al. caused biases up to 5% in small regions but in general they were small (e.g.,  $\leq 2\%$  for most of the earth). The only consistently large bias was in high cloud cover over land in North America, Europe, and Asia north of 35°N latitude in the summer season where the 0200 and 1400 LT average high cloud frequency was 2%–5% more than the daily average. This occurred only in the summer season, not in the winter.

## 1. Introduction

Polar-orbiting satellites have commonly been used for studying cloud cover (Heidinger and Pavolonis 2005; Pavolonis et al. 2005; Thomas et al. 2004; Stubenrauch et al. 1999a,b,c; Susskind et al. 1997; Wylie et al. 1994, 2005; Wylie and Menzel 1999). One common criticism they face is that they use sun-synchronous orbits that are affected by the diurnal cycles of clouds. To minimize this problem most studies use two or more satellites, if they are available, and both the daytime and nighttime parts of the orbit. The National Oceanic and Atmospheric Administration (NOAA) planned to operate two polar-orbiting satellites, however, in the early years, 1980–96, there were extended periods of months to years where only one satellite was available. Because of these gaps in coverage the time trend study of Wylie et al. (2005) focused on only one of the polar orbits (0200 and 1400 LT), which gave continuous uninterrupted coverage for 17 yr. All of the available NOAA polar-orbiter data from 1979 to 2001 were analyzed, but the 0800 and 2000 LT data were not included

in their report because of its lack of continuity. This has led to questions about possible biases in the cloud cover they reported, which will be examined here using the larger dataset from all NOAA polar satellites.

The locations and magnitudes of cloud diurnal cycles have been identified using geostationary satellites by Bergman and Salby (1996), Chen and Houze (1997), Kondragunta and Gruber (1994), Kondragunta (1996), Cairns (1995), Hendon and Woodberry (1993), Duvel (1989), Houze and Betts (1981), Gray and Jacobson (1977), and Wylie and Woolf (2002). Some of these studies used cloud retrievals from the International Satellite Cloud Climatology Project (ISCCP; Rossow and Schiffer 1999), which summarized the data into eight uniformly spaced observations per day. Others such as Houze and Betts (1981) and Gray and Jacobson (1977) used their own cloud analyses with more frequent observations.

Significant diurnal cycles were found over land-masses mainly in the summer season, which appear to be driven by solar heating of the land surface. The highest values in cloud cover were usually found just after solar noon from the increase in boundary layer cumulus. Very large diurnal cycles were found in mountainous regions because of cumulus growth on south facing slopes inclined toward the sun. Upper-tropospheric cirrus clouds also show diurnal cycles in the same areas

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(Wylie and Woolf 2002), which come from deep convection. Their time of maxima lags total cloud cover by 4–6 h reflecting the growth of cumulus to anvil cirrus, the spreading of the cirrus, and the long resident time of cirrus in the upper troposphere. Cirrus maxima occur close to sunset.

Over oceans, cloud-cover maxima usually occur in the mornings for low-altitude marine stratus clouds. They grow at night from radiative cooling at their tops destabilizing the sounding and then evaporate during the day from solar insolation inside the clouds. Marine stratus dominates the diurnal cycles of clouds on the eastern sides of oceans in both hemispheres.

Exceptions to these two large diurnal cycles were found. High clouds in the Pacific Ocean have a morning maxima from infrared cooling at the tops of deep convection according to Chen and Houze (1997), which is opposite to the diurnal cycle of cirrus clouds seen over land. Another exception occurs in coastal areas where marine stratus clouds move inland showing a morning maxima opposed to the near solar noon maxima of most land cumulus clouds.

This paper uses the data from High Resolution Infrared Radiation Sounder (HIRS) flown on the NOAA series of operational polar-orbiting satellites. The HIRS data were not used in the ISCCP. Jin et al. (1996) compared cloud cover statistics from the ISCCP to HIRS (Wylie and Menzel 1999 analysis) and found that the HIRS reported 10%–15% more cloud cover from high thin cirrus clouds than the ISCCP.

In the analysis of HIRS, all of the NOAA polar-orbiting data were analyzed even though Wylie et al. (2005) limited their discussion to only the 0200 and 1400 LT orbit. This study adds the 0800 and 2000 LT orbit to give four observations per day. The biases caused by using a subset of the polar satellite data are discussed.

## 2. Cloud diurnal cycles in HIRS observations

The method of detecting clouds in HIRS data is extensively discussed in Wylie et al. (2005). It differs from the ISCCP in that the altitudes of semitransparent cirrus clouds are determined by radiative modeling of the upwelling radiation from 13- to 15- $\mu\text{m}$  wavelength. HIRS has four channels in this part of the spectrum. The HIRS data are not used by the ISCCP because they are not available on most operational weather satellites and this is the main reason why they have been analyzed separately by others (Wylie et al. 1994, 2005; Wylie and Menzel 1999; Stubenrauch et al. 1999a,b,c; Susskind et al. 1997).

At the start of the NOAA polar satellite series, there

were gaps in coverage of the 0800 and 2000 LT orbit. However from the winter of 1986 to 1997, continuing coverage was obtained from both of NOAA's orbits at 0800, 2000, 0200, and 1400 LT. We use these periods to show the diurnal cycles and discuss the biases caused by using only one of the orbits, and/or using only one side of an orbit.

The cloud cover averaged from 1986 to 1997 is shown in Fig. 1. It is very similar to all other summaries of global cloud cover and is broken into the opposite seasons of boreal summer (June–August) and boreal winter (December–February). Clouds are most frequent in the tropics especially over South America and Africa. This is the intertropical convergence zone (ITCZ), which moves north and south with the seasons. Clouds are less frequent north and south of the ITCZ, which is where the subtropical deserts occur over land and the subtropical high pressure centers occur over oceans. Frequent cloud cover is also found in higher latitudes, mainly in the winter hemisphere from cyclone and frontal activity.

The most commonly used data from polar orbiters are the daylight portion of the 1400 LT orbit. Most studies that extract cloud physics information (from other sensors) such as particle size and visible optical depth use this orbit. The deviation of cloud-cover observations at 1400 LT from the average of all four daily observations is shown in Fig. 2. This generally shows where diurnal cycles are present in the boreal summer as it is very similar to what is shown in Bergman and Salby (1996), Kondragunta and Gruber (1994), and Kondragunta (1996). Cloud cover exceeds the daily average in most land areas. The largest values of excess reach 13% in the western North American mountains, central Asia, and the Saharan Desert. Other areas of large afternoon excess cloud cover also appear in eastern Brazil and eastern tropical Africa. These areas are just south of the areas of highly frequent convective clouds associated with the ITCZ. Over the eastern Pacific and Atlantic Oceans large deficits of afternoon (1400 LT) cloud cover appear in areas dominated by marine stratus clouds.

In boreal winter diurnal cycles in cloud cover are small over northern land areas (Fig. 3). Some evidence of diurnal cycles appears in the southern Rocky Mountains in North America, the northern Sahara Desert, and eastern Asia as an excess of clouds at 1400 LT. But the opposite diurnal cycle of cloud deficits at 1400 LT also appear in northern Canada, eastern Europe, and the east Asian coast. The largest depiction of diurnal cycles is the cloud-cover deficits over the eastern tropical oceans mainly in the Southern Hemisphere, which is the austral summer season. A large diurnal cycle also

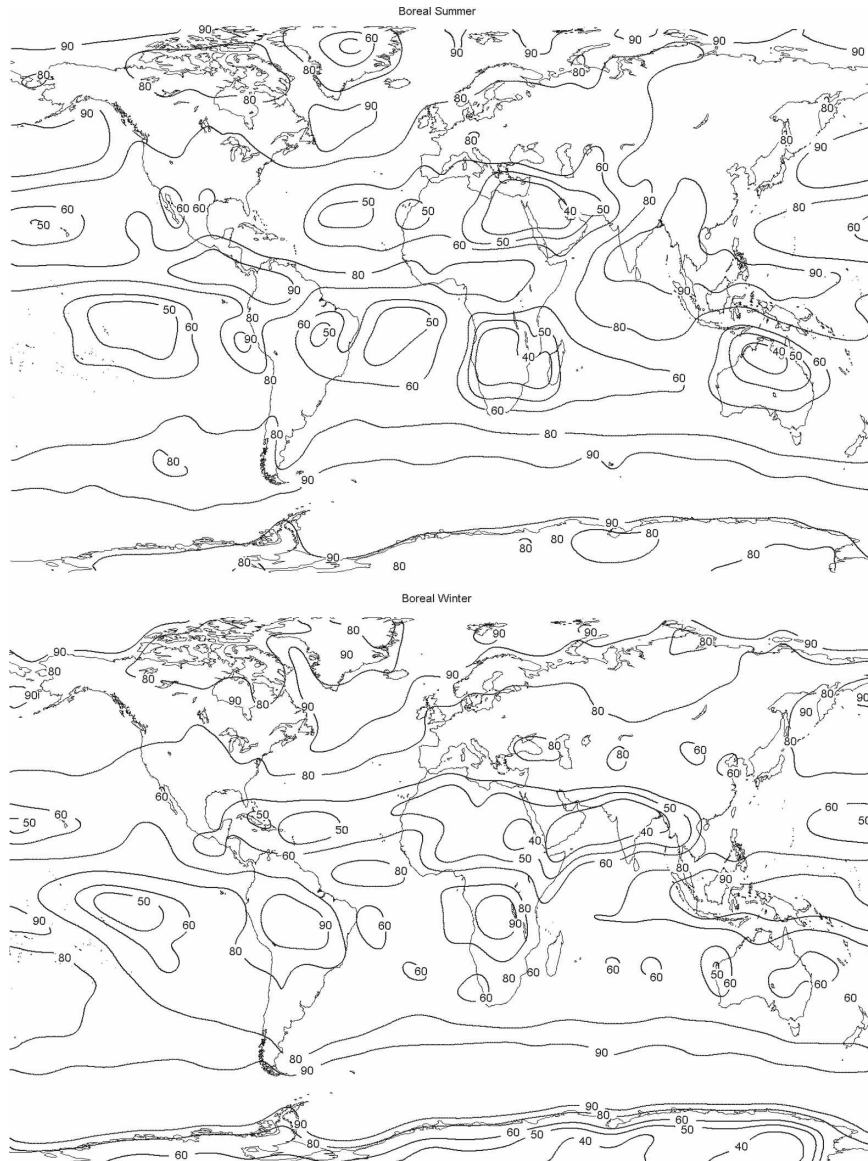


FIG. 1. The frequency (%) of all clouds from the HIRS NOAA polar-orbiting satellite data: boreal (top) summer and (bottom) winter.

appears in the eastern Indian Ocean next to the coast of Australia.

### 3. The affect of zonal averaging

The diurnal cycles of cloud cover appear in zonal averages although their magnitude is tempered from the regional amplitudes shown in Figs. 2 and 3. Since the largest regional cycles were in midlatitudes over land, the zonal average of cloud cover from  $30^{\circ}$ – $60^{\circ}$  to  $0^{\circ}$ – $30^{\circ}$ N are shown in Fig. 4. In the  $30^{\circ}$ – $60^{\circ}$  N average, the 1400 LT cloud cover is only 6.3% above the daily

average. The total range from the minimum at 0200 LT to the maximum at 1400 LT spans only 12.6% while in a two local areas, North America and Asia the range is as high as 24%. In the north tropics,  $0^{\circ}$ – $30^{\circ}$ N, the range is smaller—only 5.1%. However, high clouds have a larger range of 8.2%.

Over tropical oceans (Fig. 5) the range of zonally averaged cloud cover is smaller than land, 7%–9%. High clouds had even smaller diurnal cycle ranges.

A summary of the diurnal ranges (minimum to maximum) of zonally averaged cloud cover is shown in Table 1. They are largest in the midlatitudes ( $30^{\circ}$ – $60^{\circ}$ N–S) in the summer seasons over land. High cloud

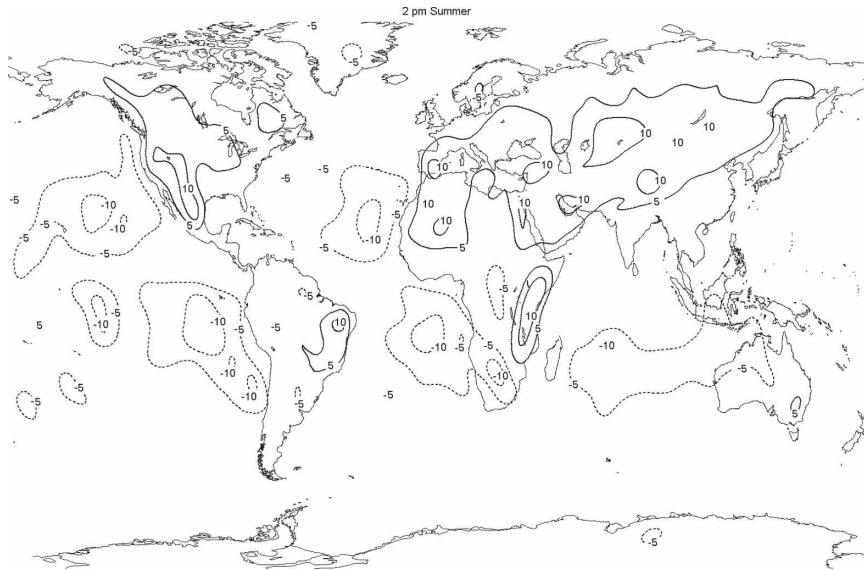


FIG. 2. The deviation of cloud cover (%) of the 1400 LT orbit from the daily average of four observations during boreal summer (June–August) from 1986 to 1997.

diurnal cycles are generally weaker than the total cloud cover. Over oceans, the large areal averaging offsets the fairly large regional diurnal cycles shown in Figs. 2 and 3.

Another notable feature in Figs. 4 and 5 is that the high cloud diurnal cycles peak later than the total cloud cover. In these data the largest value is usually found in the 2000 LT orbit. Wylie and Woolf (2002) were better able to resolve the time lag with a similar cloud detection scheme using 13–15- $\mu\text{m}$  data from geostationary

satellites. But that study was limited in area mainly to the conterminous United States (CONUS) with a very small sample from the tropics because of the limited availability of the 13–15- $\mu\text{m}$  data from geostationary satellites. This study finds similar behavior of high clouds.

#### 4. Biases of the 0200 and 1400 LT orbit

The average of both sides of the 0200 and 1400 LT orbit significantly reduces the bias from the daily mean.

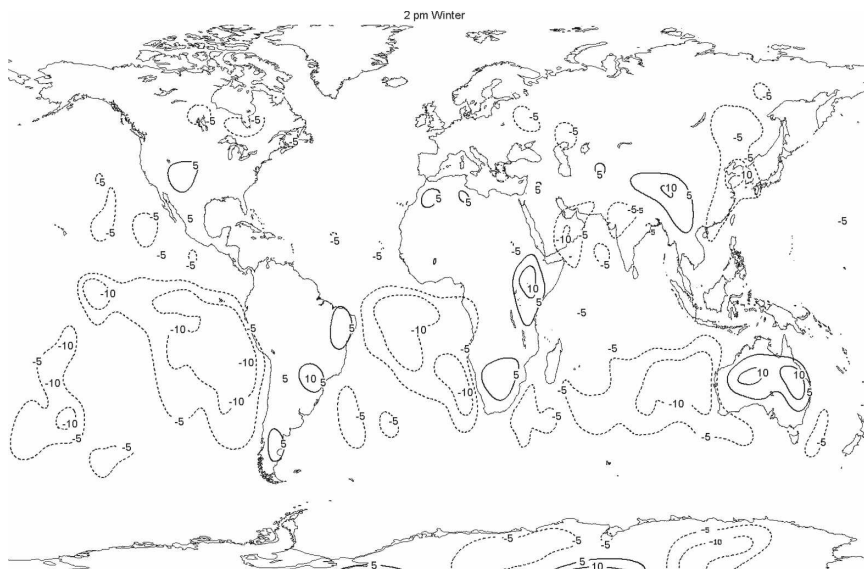


FIG. 3. As in Fig. 2, but for the boreal winter (December–February).

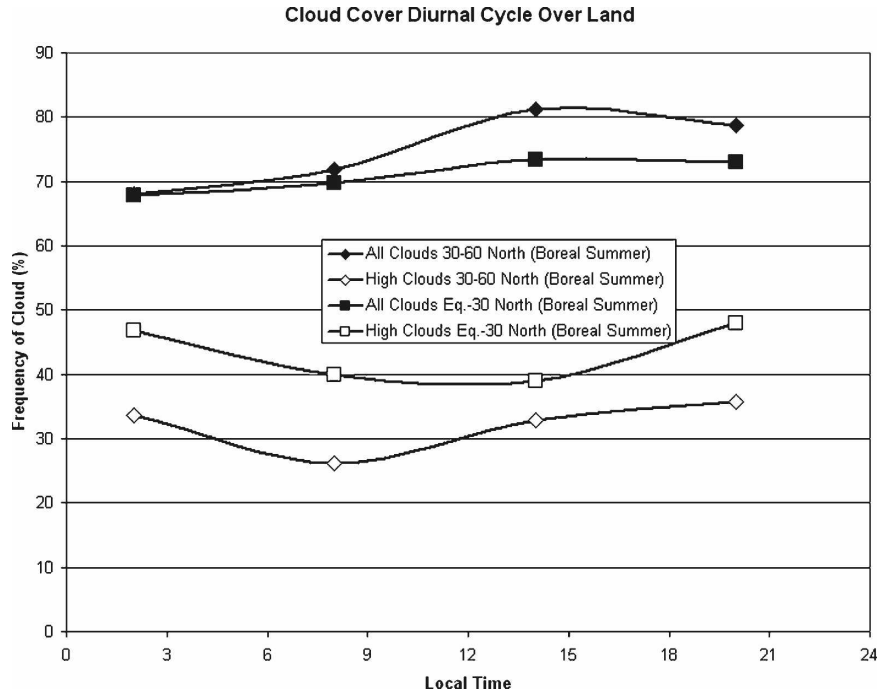


FIG. 4. The frequency of cloud cover (%) averaged from 30° to 60°N vs local time over land.

Figure 6 shows this bias for the summer months of the 1986–97 record. These biases are generally  $\leq 2\%$ . Over oceans, the 0200 and 1400 LT average generally under-reports cloud cover by 2% in most of the marine stratus

clouds. Over land, cloud cover is underreported by up to 5% in North and South Africa especially in the Sahara, and in South America. In a few local areas of central Asia, Brazil, and in South America, cloud cover

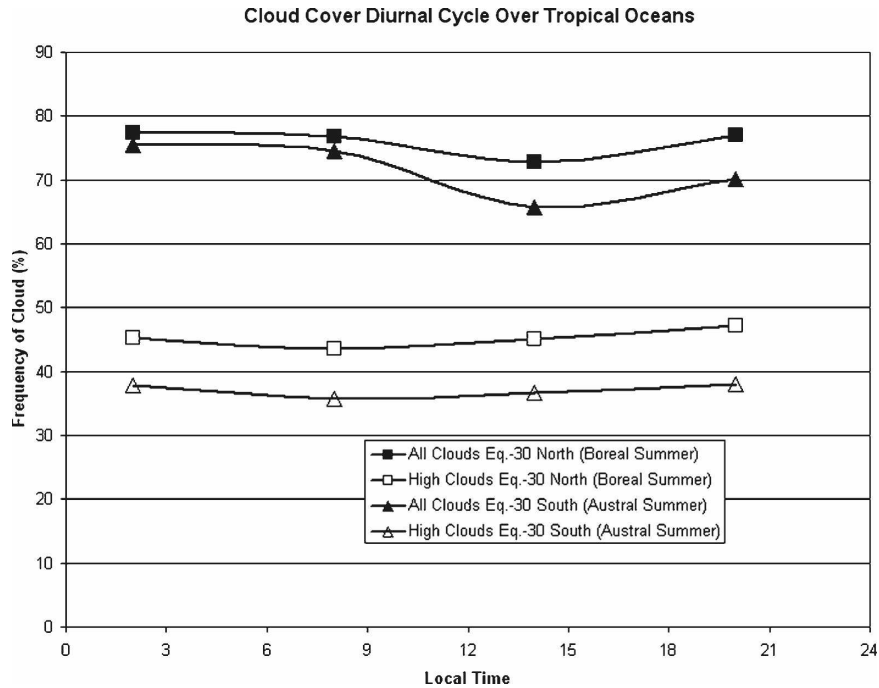


FIG. 5. The frequency of cloud cover (%) averaged from 0° to 30°N vs local time over the oceans.

TABLE 1. The diurnal range of cloud-cover frequencies (%) zonally averaged over 30° latitude.

All clouds	Boreal summer		Boreal winter	
	Land	Oceans	Land	Oceans
30°–60°N	12.6	3.2	2.9	2.6
0°–30°N	5.1	4.3	7.3	4.6
0°–30°S	4.1	7.1	3.8	9.5
30°–60°S	3.2	2.0	8.5	6.0
<b>High clouds</b>				
30°–60°N	9.3	1.9	2.6	1.6
0°–30°N	8.2	4.1	5.1	2.7
0°–30°S	4.2	1.8	9.5	2.8
30°–60°S	2.9	0.6	7.5	1.8

is overreported by 2%. The zonal averages, however, have almost no biases (i.e., <1%).

High clouds show different bias patterns (Fig. 7). They are generally overreported by 2% north of 35°N over land. In a few areas, the overreporting reached 5%. Over tropical oceans many locations show a slight overreporting of 2%. But these areas are mixed and near some areas of underreporting. There is a pattern

in the western CONUS in that high clouds are slightly overreported in the Rocky Mountains while slightly underreported to the east. This indicates that the high cloud diurnal cycle peaks earlier in the afternoon in the mountains than to their east, which was also seen in Wylie and Woolf (2002).

Since Wylie and Woolf (2002) showed a late afternoon peak in high clouds for most locations, one may expect the 0200 and 1400 LT average to underreport these clouds. However, a lot of the high clouds appeared in the 0200 LT analysis along with the 1400 LT analysis and the 0800 LT analysis tended to have a minimum. This resulted in the 0200 and 1400 LT average being slightly higher than the daily mean.

## 5. Summary and conclusions

The diurnal cycles are significantly strong and >10% in amplitude in some areas. Zonal averages show these strong diurnal cycles if land and water are analyzed separately. However, these diurnal cycles may be missed if land and water areas are combined in zonal averages because maxima occur at opposite phases in time.

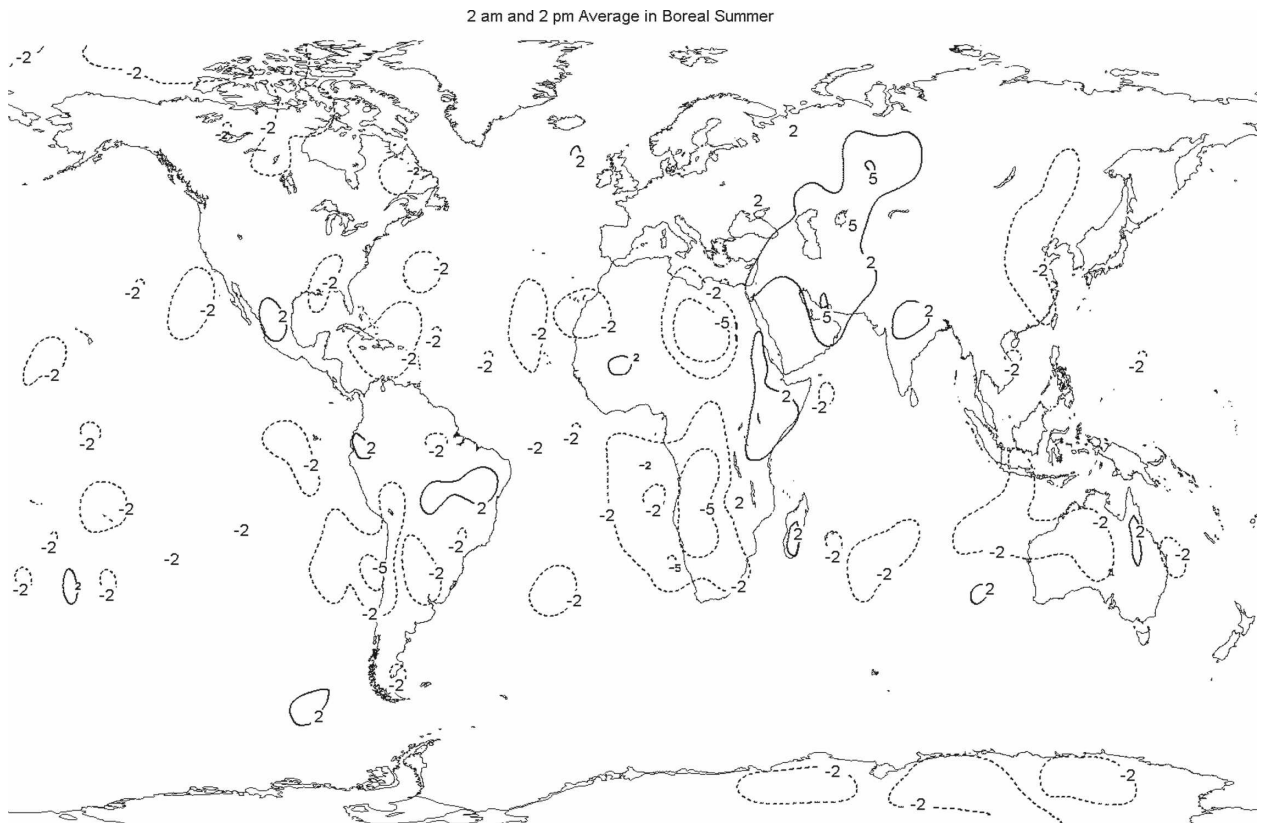


FIG. 6. The biases of cloud cover frequency (%) of the 0200 and 1400 LT average from the daily mean from 1986 to 1997 (which included the 0800 and 2000 LT observations).

2 am 2 pm Average of High Clouds in Boreal Summer

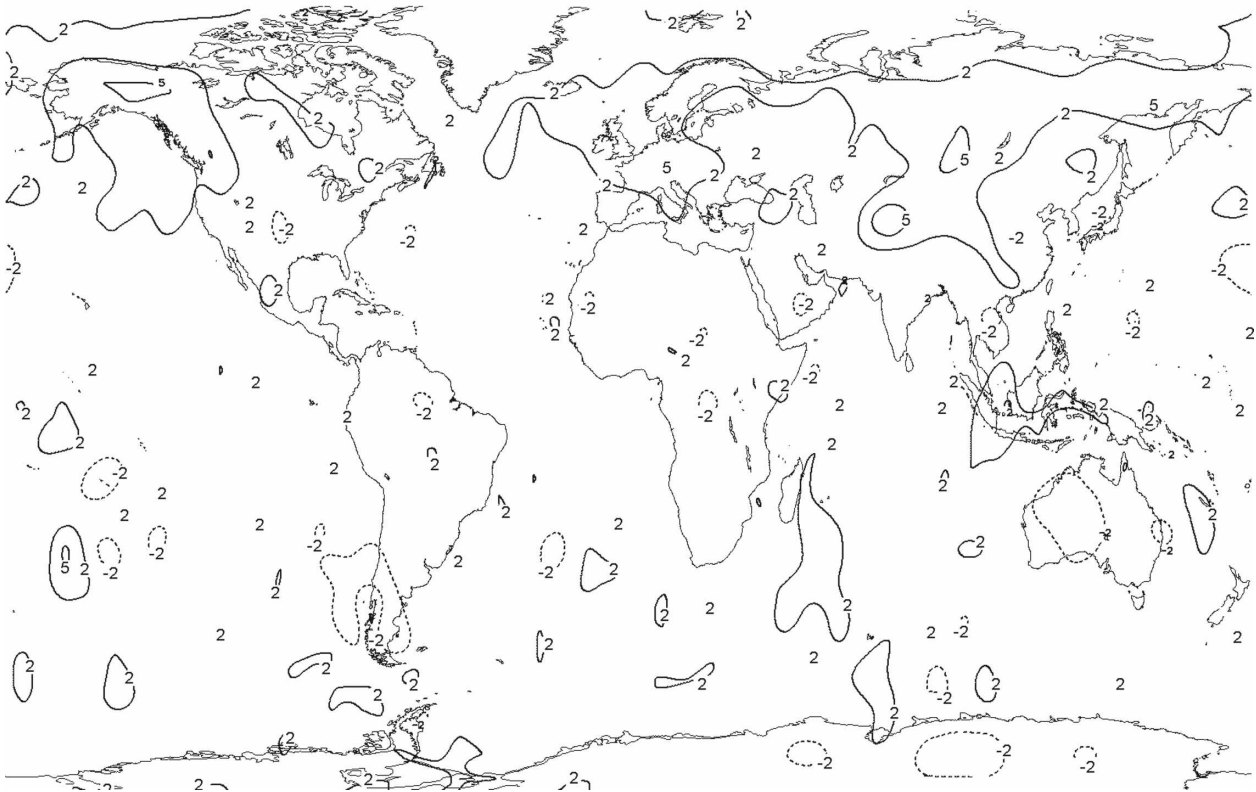


FIG. 7. As in fig. 6, but only for high clouds.

The averaging of both the ascending and descending NOAA satellite orbits reduces the affect of diurnal cycles but does not entirely eliminate them. The 0200 and 1400 LT average underestimates cloud cover by 2% in many regions of the oceans and in some land areas (e.g., the Sahara of Africa, southern Africa, Western Australia, southern South America, and part of the North American Gulf Coast). These areas in general also have lower cloud frequencies than the ITCZ and midlatitude storm belts.

The 0200 and 1400 LT average also has some biases in high cloud frequency. The largest bias was poleward of 35°N over land in the summer season (but not in the winter season). Other smaller areas of biases around  $\pm 2\%$  were also scattered around the oceans and tropical regions of South America and Africa.

The biases of general cloud cover and high clouds were very small when averaged longitudinally (i.e.,  $< 1\%$ ) because regions of biases of opposite signs occurred at similar latitudes.

*Acknowledgments.* The author thanks Drs. Eric Smith and Song Yang for organizing this issue dedicated to studies of diurnal cycles.

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