The Diurnal Cycle of Upper-Tropospheric Clouds Measured by GOES-VAS and the ISCCP

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ABSTRACT

A comparison of diurnal cycles in high clouds (<440 hPa) measured by the Geostationary Operational Environmental Satellite Visible Infrared Spin Scan Radiometer (VISSR) Atmospheric Sounder (GOES-VAS) and the International Satellite Cloud Climatology Project (ISCCP) was made. The GOES-VAS longwave infrared data allow uniform detection of upper-tropospheric cirrus clouds from daylight into night without effects from solar reflections. It is sensitive to thin cirrus, which are difficult to detect. But it is not available globally because the sounder instrument is flown only on geostationary satellites operated by the United States. The ISCCP, however, is a global dataset using five to seven geostationary satellites.

Large diurnal cycles were found in the Rocky Mountains and along the northern coast of the Gulf of Mexico mainly in the summer season. In the Tropics substantial diurnal cycles also were found in central Brazil and the Atlantic ITCZ. In the winter over the continental United States, diurnal cycles were very small or nearly absent.

The ISCCP found similar diurnal cycles over land. The amplitudes of the cycles were about 1.5 times larger in the VAS data than the ISCCP (IR only) data over land because of the former's sensitivity to thin cirrus. The phase relationships were very similar. In the western tropical Atlantic ITCZ, the VAS found dual maxima in the diurnal cycle (morning and later afternoon), which the ISCCP could not detect. These changes in high cloud cover probably were driven by radiative cooling of the cloud tops over the ocean. Over land the obvious cause of diurnal cycles in high clouds is deep convection from solar surface heating.

1. Introduction

The diurnal cycle of upper-tropospheric clouds has traditionally been studied with satellite data in the 11-μm window channel (Bergman and Salby 1996; Chen and Houze 1997; Duvel 1989; Gray and Jacobson 1977; Hendon and Woodberry 1993; Houze and Betts 1981; Kondragunta and Gruber 1996). Satellite platforms provide global coverage and a top-down view of upper-tropospheric clouds unobstructed by lower clouds. But detection of transmissive clouds in the 11-μm channel is difficult because the blackbody radiative temperature measured by satellite sensors may be warmer than the air temperature at the cloud altitude. Optically thin cirrus clouds in the upper troposphere transmit terrestrial radiation making them appear warmer than the air temperature at their altitude. Estimates of the coverage of IR transmissive clouds range from 20% to 30% of the earth. Wylie and Menzel (1999) reported 30% coverage of IR transmissive clouds above 6 km using High-resolution Infrared Radiometer Sounder (HIRS) data while the International Satellite Cloud Climatology Project (ISCCP; Rossow and Schiffer 1999) reported 20% coverage of these clouds. The ISCCP uses the imaging sensors on the geostationary and polar orbiting weather satellites.

Very few upper tropospheric cirrus clouds are opaque to terrestrial radiation. Wylie and Menzel (1999) found only 5% of the clouds above 6-km altitude were opaque in the HIRS data and Rossow and Schiffer (1999) reported only 2.6% in the ISCCP dataset. This indicates that IR transmission occurs in about 85% of the high cloud data, covering 17%–25% of the earth.

To account for IR transmission in the 11-μm window channel, solar reflection measurements in the 0.7-μm visible channel are commonly used by the ISCCP and others (Rossow and Schiffer 1999; Minnis et al. 1993). A correction for the 11-μm measurements is made using the 0.7-μm data along with a radiative transfer model that estimates the increase in the 11-μm blackbody radiative temperature caused by IR emission and transmission.

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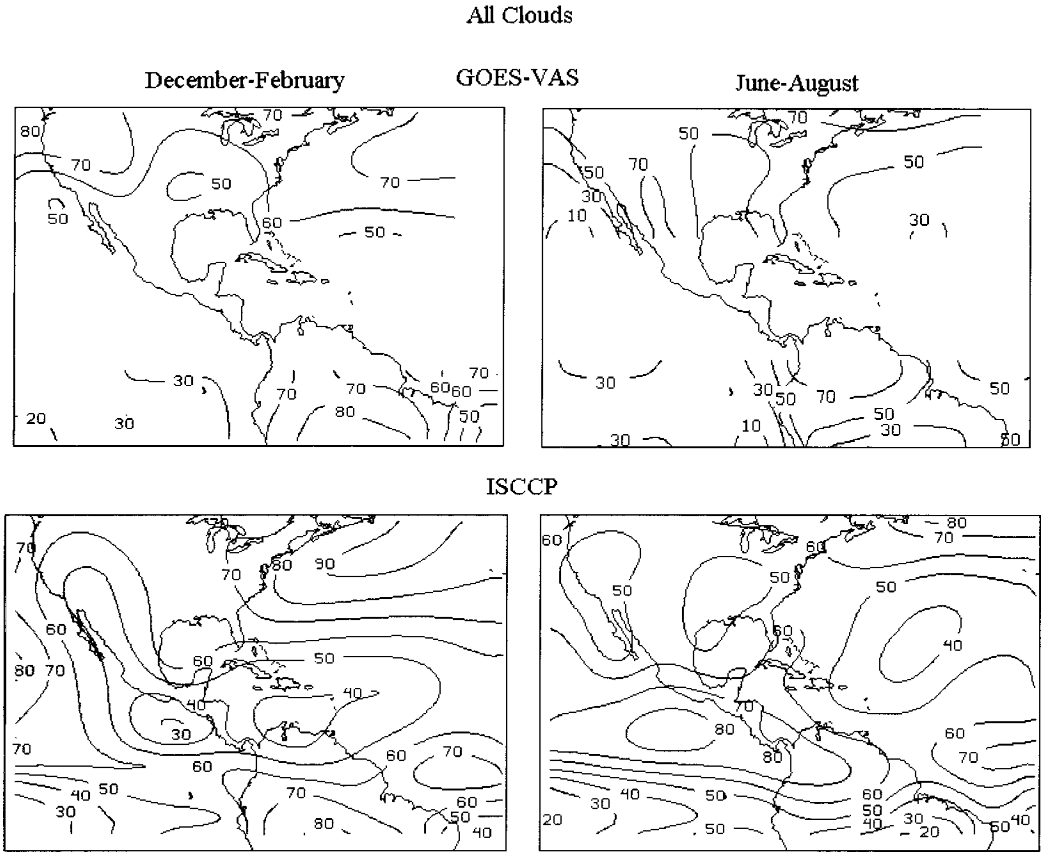

FIG. 1. The frequency of clouds (all altitudes) detected using the GOES-VAS data (upper panels) and the ISCCP (lower panels) for Dec 1987–Feb 1988 (winter) and Jun–Aug 1998 (summer).

The problem with using 0.7-μm data for diurnal studies of upper-tropospheric cirrus clouds is that the correction for IR transmission cannot be applied to the entire diurnal cycle. At night, only the single-channel 11-μm data are available on many geostationary satellites. The previous studies have been limited at night to the use of the single-channel detection technique (11 μm) for upper-tropospheric clouds.

Few alternative data for studying diurnal cycles of clouds can be found. Hahn et al. (1995) evaluated cloud diurnal cycles using National Weather Service surface-based observations. They took advantage of nighttime data where moonlight or twilight was available for the ground observers. They found differences in diurnal cloud cycles between land and oceanic areas. Cloud maxima were commonly found during daylight over land but over oceans, nighttime maxima also were common. The diurnal cycles of upper-tropospheric clouds were not evaluated by Hahn et al. (1995), but significant changes in estimates of total cloud cover of 3%–4% were made with the incorporation of nighttime surface observations.

The problem of diurnal cycles in upper-tropospheric clouds also will haunt the future sensors planned for the Earth Observing System. These sensors will provide better information on cloud radiative properties but will be flown on sun-synchronous satellites that will sample only a few points in the diurnal cycle. To understand cloud radiative properties for studies of global heat budgets, we must account for the behavior of all cloud forms over the full diurnal cycle.

In this paper we take advantage of a limited dataset from a geostationary sounder instrument flown only on United States satellites. The Visible Infrared Spin Scan Radiometer (VISSR) Atmospheric Sounder (VAS) was flown on the Geostationary Orbiting Environmental Satellites (GOES) from 1978 to 1994. It has three channels from 13.3 to 15.0 μm that are sensitive to different levels in the troposphere depending on the amount of CO_2 absorption in each channel. There is no solar reflection in these longwave IR channels so uniform detection can be obtained throughout the entire diurnal cycle. Cloud heights are calculated by comparing the measured upwelling radiation in each channel to results from a forward calculation. Partially transmissive clouds will affect each channel differently depending on the height of the cloud and the level of sensitivity of the channel. The algorithm used here is described in Wylie and Woolf (2000). It is a modification of algo-

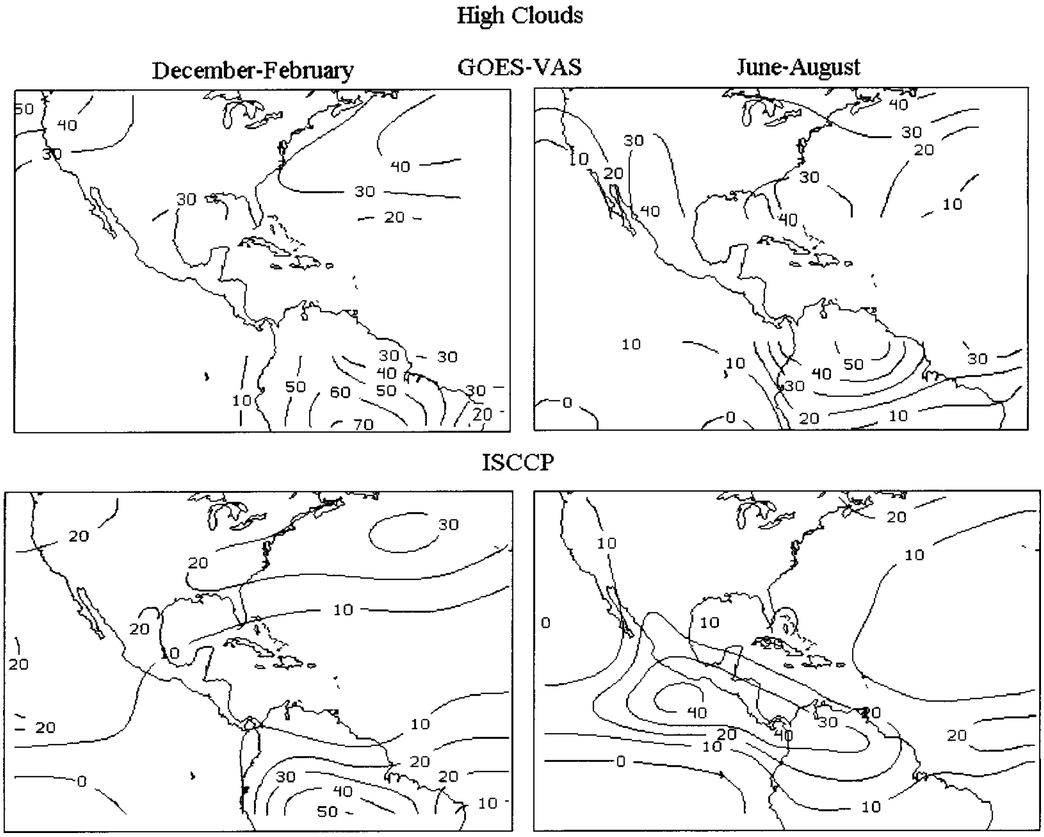

FIG. 2. The frequency of high clouds above 440 hPa detected in the GOES-VAS and ISCCP (IR-only single channel) data for the same months as Fig. 1.

rithms applied to the same VAS data in previous studies by Wylie and Menzel (1989) and Menzel et al. (1992).

This paper builds on Wylie and Woolf (2000) by studying one winter and one summer, each three months in length. The previous paper described the algorithm and validation studies by making comparisons to rawinsondes and the ISCCP for a limited dataset of 7 days. This paper expands that study to two seasons.

A description of the algorithm will not be given here because it is available in Wylie and Woolf (2000). We begin by discussing the bounds of the dataset, its areal coverage, and time span in section 2. Seasonally averaged cloud frequency statistics are compared to the ISCCP for the same time period in section 3. In section 4 the amplitudes of the diurnal cycles measured by both the VAS and ISCCP datasets are compared. A discussion of similarities to other studies is presented in section 5.

The objective of this study is to assess the utility of ISCCP data for evaluating the diurnal cycle of upper-tropospheric clouds globally. The ISCCP and the 11-μm data from the geostationary satellites that the ISCCP uses will continue to be the main source of data for global diurnal cycle studies. The GOES-VAS and the GOES-Sounder on the current United States platforms are the only sounding instruments expected to fly on geostationary satellites. Their coverage will continue to be limited to only part of the area viewed by the two operational geostationary spacecraft, which is a small fraction of the earth. Some additional coverage may be possible with future Meteosat satellites over Europe and Africa. However the sensors planned for Meteosat will not carry the full complement of longwave IR channels needed for cloud height and temperature sounding retrievals. They will carry only one longwave IR channel from which cloud height retrievals may be possible, but require a more complicated algorithm that will have to make assumptions about IR radiative transfer properties of clouds. These assumptions are not needed with the GOES-VAS and GOES-Sounder instruments.

2. The area studied

The GOES-VAS covered a smaller region than seen by the imaging instrument (VISSR), which scanned the entire hemisphere in view from the satellite's position. VISSR scans were routinely made every 30 min, or more frequently if requested for monitoring severe weather events. The VAS scans were made after the VISSR images in the 10-min period between VISSR scans. This time restriction limited the size of the area that could be scanned. The VAS also contained more

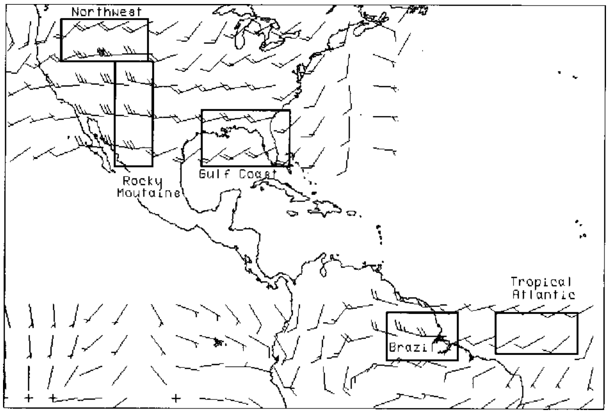

FIG. 3. The amplitude (max − min) of the diurnal cycle of high cloud (<440 hPa) frequencies detected in the GOES-VAS data in the summer, Jun–Aug 1988. The regional boxes are for reference to Figs. 4–8.

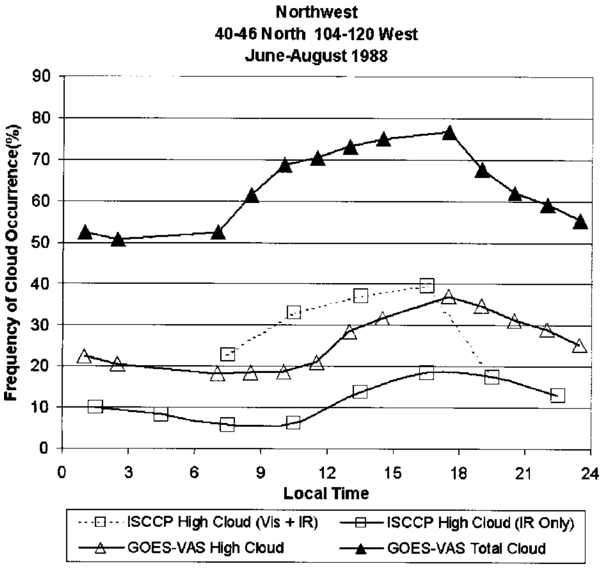

FIG. 4. The frequency of clouds in the northwestern United States during Jun–Aug 1988.

channels than the VISSR, which increased the time needed for scanning. The VAS repeated scan lines in its image to reduce instrument noise through averaging. All of these factors limited the coverage of VAS data. The locations and times of the VAS coverage were adjusted seasonally according to the needs for satellite sounding data at the National Oceanic and Atmospheric Administration/National Environmental Satellite, Data, and Information Service (NOAA/NESDIS). In this study, we choose two areas where the *GOES-7* VAS provided nearly continuous coverage for full 3-month seasons.

The first area studied is over the continental United States and parts of bordering oceans from 25° to 48°N and 40°–130°W (called the CONUS). Fourteen measurements per day were made by paired VAS scans. The paired scans were 0.5 h apart followed by gaps of 1.0–1.5 h. The second study area was in the Tropics from 10°S to 5°N and 20° to 130°W (called the TROPICS). It was scanned five to eight times per day. Both of these areas are contained in the region plotted in Figs. 1 and 2.

The months studied were December 1987 plus January and February 1988, for the winter case, and June, July, and August 1988 for the summer case. Ninety days' of data were collected in each season. All of the VAS data had previously been extracted from the GOES archive by the National Aeronautics and Space Administration's (NASA) Pathfinder project.

3. Seasonally averaged frequency of clouds

The seasonally averaged frequency of occurrence of all cloud forms (total cloud cover) is shown in Fig. 1, while Fig. 2 shows the frequency of clouds above 440 hPa in the upper troposphere. In this study we refer to ''high clouds'' as having tops above the 440-hPa level following the classification of the ISCCP. Cloud-base altitudes are not measured by this system or the ISCCP. The frequencies of clouds detected in the VAS data are compared to similar statistics produced from the ISCCP in the bottom panels of Figs. 1 and 2. Season averages over the CONUS and TROPICS areas are also given in Table 1.

Data from the most recent ISCCP cloud detection algorithm, the D1, were used. Details of the ISCCP algorithm are described in Rossow and Schiffer (1999).

The Wisconsin VAS analysis reports lower occurrences of all clouds (total cloud cover) than the ISCCP but greater occurrences of high clouds (see Figs. 1 and 2, and Table 1). The VAS reported occurrence of all (total) clouds is 4%–5% less than the ISCCP over the regions studied except for the TROPICS in summer where VAS was 10% less. The largest differences are in the eastern Pacific Ocean along the coasts of North and South America (Fig. 1). The VAS analysis also found lower total cloud cover in the western Atlantic and the Gulf of Mexico. We suspect that the VAS analysis missed many of the low-level marine stratus and cumulus clouds in these areas. The VAS reported more cloud cover in a few mountainous areas of the western United States: Idaho, Montana, Nevada, and Utah.

The VAS data reported high cloud occurrences 6%–14% greater than the ISCCP. The largest differences were over land in South America and in the northern CONUS region. It should be noted that Fig. 2 shows the ISCCP high cloud occurrences from their single-channel IR-only technique. The ISCCP high cloud occurrences from their visible-IR technique are 7%–12% greater and closer to the VAS statistics.

A comparison of the HIRS data with the ISCCP data made by Jin et al. (1996) found similar differences in high cloud statistics. The HIRS data contain infrared channels from 13 to 15 μm similar to the VAS data,

TABLE 1. The frequencies of all clouds and high clouds (above 440 hPa) detected with the Wisconsin algorithm applied to VAS data compared to the results of the ISCCP D1 monthly averages. The CONUS covers 25°–50°N, and 40°–130°W. The TROPICS cover 10°S–5°N and 20°–130°W.

	CONUS			TROPICS		
		ISCCP			ISCCP	
	VAS	Visible and IR	IR only	VAS	Visible and IR	IR only
All Clouds						
Winter	63%	70%	68%	53%	61%	57%
Summer	49%	57%	53%	39%	54%	49%
High clouds						
Winter	30%	28%	19%	28%	22%	14%
Summer	24%	24%	12%	15%	18%	9%

and its data are processed by a similar algorithm. Jin et al. (1996) found the Wisconsin analysis of HIRS data contained 14%–16% greater high clouds occurrences than the ISCCP. Most of this difference was attributed to a higher sensitivity of the HIRS algorithm to optically thin cirrus clouds. These VAS data also appear to be finding more optically thin clouds.

4. Diurnal cycles

The main purpose of processing the VAS data is to quantify the diurnal cycle of high clouds. A previous study by Menzel et al. (1992) found a diurnal cycle of high clouds only in the summer months along the coast of the Gulf of Mexico and in the southern Rocky Mountains. However, that study was limited to only four VAS observations per day. The present study used 12–14 observations per day.

The amplitude of the diurnal cycle in high clouds during the summer of 1988, June–August, is shown in Fig. 3. High clouds have their largest diurnal cycles in the summer. High cloud occurrences change by 30%–50% in the Rocky Mountains and eastern Brazil. Substantially large diurnal cycles of 30% also were found along the coast of the Gulf of Mexico and Florida. A slightly weaker diurnal cycle was found in the Atlantic Ocean intertropical convergence zone (ITCZ) east of Brazil.

Several regions where large diurnal cycles appeared were selected for detailed study. The boxes in Fig. 3 show the locations of these regions and the full diurnal cycles in these regions are plotted in Figs. 4–8. In each of the regional plots (Figs. 4–8) we show data for the occurrence of all clouds (total cloud cover) and high clouds (above 440 hPa). For the ISCCP high clouds we show the cloud frequencies from both of their techniques, their visible-IR two-channel method, and their single-channel IR-only method. The symbols indicate the local times of the satellite observations while the lines are only smooth connections between the observations.

In the northwestern United States, Fig. 4, the ISCCP

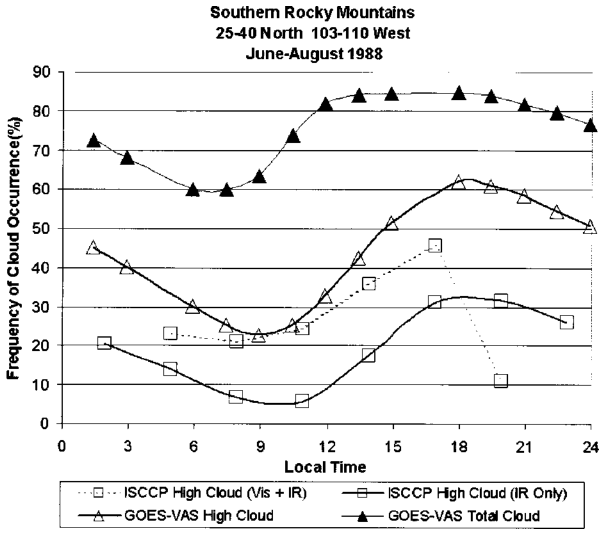

FIG. 5. The frequency of clouds in the southern Rocky Mountains during Jun–Aug 1988.

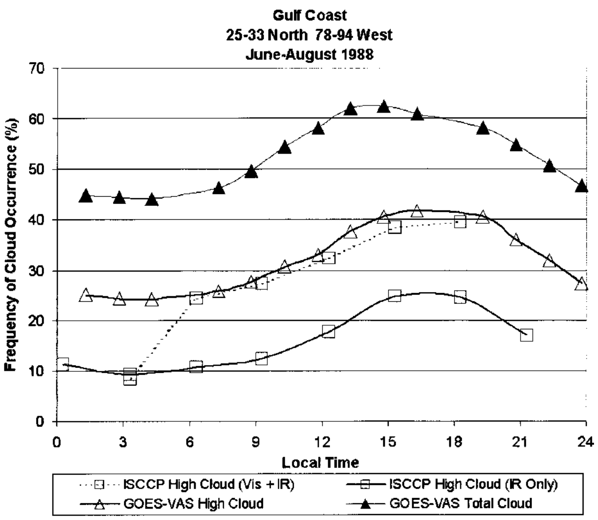

FIG. 6. The frequency of clouds on the coast of the Gulf of Mexico during Jun–Aug 1988.

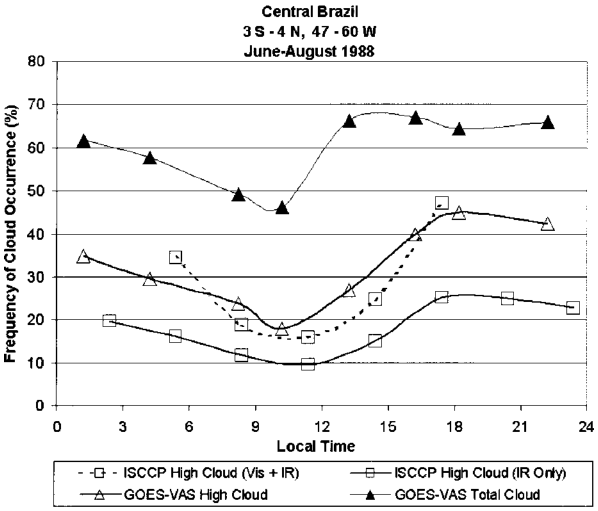

FIG. 7. The frequency of clouds in central Brazil during Jun–Aug 1988.

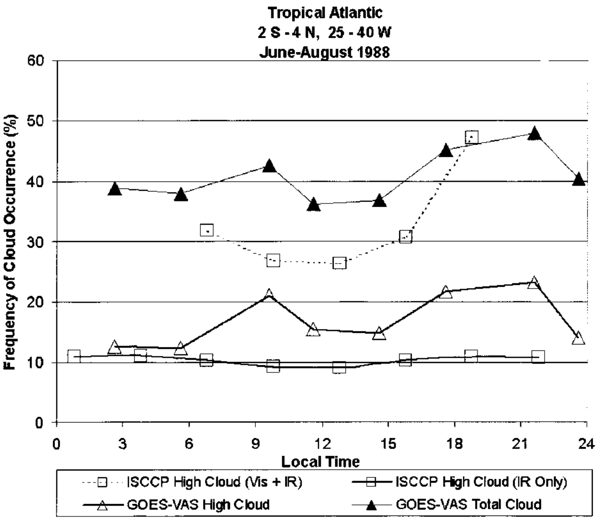

FIG. 8. The frequency of clouds in the tropical Atlantic Ocean during Jun–Aug 1988.

found a very large diurnal cycle in total clouds from the minimum of 31% at 0430 local time (LT) to the maximum of 69% at 1330 LT—a 38% amplitude. The VAS data had a slightly smaller diurnal amplitude of 26%. The high cloud diurnal cycle in the ISCCP visible-IR combination two-channel data had a 16% amplitude between 0700 and 1630 LT while the single-channel IR-only data had a smaller 12% amplitude. The ISCCP two-channel data also had an anomalously low value at 1930 LT probably because of insufficient solar illumination for use of the visible channel reflectance. The amplitude of the GOES-VAS high cloud diurnal cycle is 19%, slightly higher than the ISCCP. Both the GOES-VAS and ISCCP single-channel (IR only) high cloud data also lag the total cloud cover data by about 4 h. The time lag of high clouds from total cloud occurrences is probably from the growth of small cumulus clouds in the morning to large cumulonimbus clouds with cirrus anvils covering large areas in the afternoon.

In the southern Rocky Mountains, Fig. 5, similar relationships between the VAS and ISCCP cloud data were found. The peak in frequency of high clouds lagged the total cloud cover by about 4 h, similar to the northwestern United States. The ISCCP dual-channel high cloud data also track the VAS data except for the last ISCCP point at 1950 LT, which was anomalously low from the data at the preceding times. The VAS diurnal cycle in high clouds also has a larger amplitude than the ISCCP IR-only data, 39% for the VAS versus 26% of the ISCCP.

In the Gulf coast region, Fig. 6, the VAS and ISCCP show similar amplitudes in diurnal cycles. The high cloud frequencies from the ISCCP and GOES-VAS agree very well except for the first point at 0318 LT where the ISCCP high cloud frequency was anomalously lower than the other times. The ISCCP IR-only data have smaller high cloud frequencies but a very similar diurnal cycle to the GOES-VAS.

In central Brazil, Fig. 7, the diurnal cycle of high cloud occurrence also is large with VAS and ISCCP reporting diurnal changes. The ISCCP high cloud diurnal cycle from their two-channel visible-IR technique has a 31% amplitude, which is slightly larger than the VAS amplitude of 27%. The ISCCP IR-only high cloud occurrence data have a smaller diurnal cycle amplitude of 16%.

In the tropical Atlantic Ocean, Fig. 8, the diurnal cycles were small and complicated. Small dual maxima were found in the VAS occurrences of total cloud cover. A morning maxima appeared at 0930 LT and late afternoon maxima appeared at 2130 LT. The dual maxima also were found in high cloud occurrences by the VAS but not in the ISCCP data. The ISCCP dual-channel data report a large diurnal change of 22% in high cloud occurrence. However the last value of 47% (high cloud occurrence) at 1848 LT may be inaccurate because of low solar illumination. The ISCCP single-channel IR high cloud occurrence data have no discernable diurnal cycle. The VAS data are probably more accurate since they do not use any solar reflection measurements.

In the winter, December–February, diurnal cycles were very small (see Fig. 9). Most of the VAS data show amplitudes around 10%, which is about the noise level of these data. In the northwestern United States, Fig. 10, the VAS data show 8%–10% changes between successive times in the middle of the day for both all clouds and high clouds. These changes appear to be from an unknown problem in the VAS data. We doubt that cloud cover fluctuates as shown by the VAS data. The ISCCP high cloud data show diurnal small diurnal cycles but disagree on the phase of the cycle between the two-channel visible-IR and IR-only data. The two-channel cloud occurrence data probably have problems

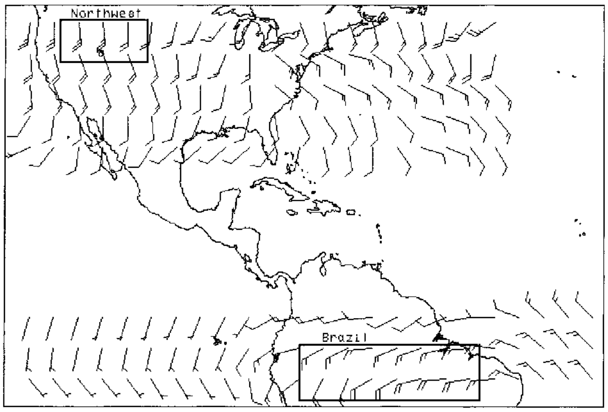

FIG. 9. The amplitude (max − min) of the diurnal cycle of high cloud (<440 hPa) frequencies detected in the GOES-VAS data in the winter: Dec 1987–Feb 1988. The regional boxes are for reference to Figs. 10 and 11.

with low solar illumination in this area in the winter. The ISCCP IR-only high cloud occurrence data show a slight maxima in the morning from 0500–0800 LT, which appears to be reasonable.

In south-central Brazil in December–February substantial diurnal cycles were found in total cloud and high cloud occurrences in both the VAS and ISCCP data (Fig. 11). The first data point of the ISCCP dual-channel technique at 05:00 LT appears to be anomalously lower from the data at the center of the day, probably because of low solar illumination. The ISCCP IR-only high cloud data follow similar changes seen in the VAS data. However, the VAS did not take data between 0648 and 1548 LT missing the minimum. If the first ISCCP dual-channel data point is ignored, the ISCCP reported a 24% change in high cloud frequencies from a low of 35% at 1100 LT to a high of 59% at 1700 LT. This is greater than the 14% diurnal change in high cloud occurrence reported by the VAS data.

5. Similarity to other studies

The GOES-VAS data show high cloud diurnal cycles similar to the Bergman and Salby (1996) analysis of 7 yr of ISCCP data, from 1984 to 1990. Bergman and Salby (1996) found the largest diurnal cycles in high cloud cover over land in the Tropics, primarily South America and Africa. The GOES-VAS data also report similar diurnal cycles to the study of GOES VISSR made by Soden (2000). Other large diurnal cycles in high clouds were found over the western Pacific ITCZ around Malysia and Indonesia. Chen and Houze (1997) also found diurnal variations in high cloud cover in this area with their own analysis of the Japanese Meteorological Satellite data independent of the ISCCP. No geostationary sounder data are available for Africa or the western Pacific Ocean. Thin cirrus in these areas may increase the diurnal cycles of high clouds as seen in the CONUS area.

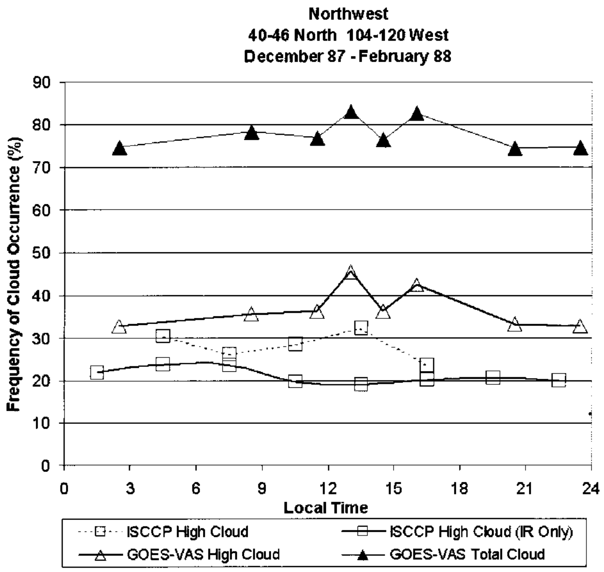

FIG. 10. The frequency of clouds in the northwestern United States (same region as in Fig. 4) during Dec 1987–Feb 1988.

Bergman and Salby (1996) and Gray and Jacobson (1977) reported the largest diurnal variance in high cloud cover occurred in the areas of greatest high cloud occurrence and also the strongest deep convection. The same trend can be found in the VAS data over the limited area that it covered.

The phases of the maxima and minima are nearly constant globally according to Bergman and Salby (1996). In the data analyzed here, small phase differences were observed. Most regions peaked in high cloud cover between 1800 and 2000 LT, which is very similar to what Bergman and Salby (1996) reported. The Gulf coast region, however, peaked about an hour earlier.

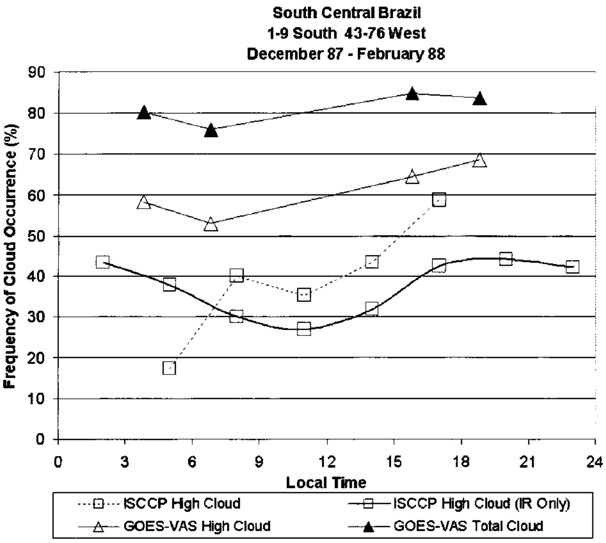

FIG. 11. The frequency of clouds in south-central Brazil during Dec 1987–Feb 1988.

Chen and Houze (1997) and Gray and Jacobson (1977) found the largest cloud systems in the Pacific Ocean peaked in the early morning hours from 0300 to 60600 LT. We found a similar behavior in the tropical Atlantic ITCZ (Fig. 8) where two maxima occurred, one in the morning at 0930 LT and a second in the afternoon at 2030 LT. The time of the morning maximum is later than in the western Pacific reported by Chen and Houze (1997) and Gray and Jacobson (1977). Duvel (1989) studied the ITCZ in Africa and the eastern Atlantic and found that diurnal cycles varied in the times of their maxima, occurring generally in the afternoon over land and becoming earlier with westward movement over the Atlantic Ocean.

The daily increases in total cloud cover generally lead high clouds by 2–4 h in the VAS data. Bergman and Salby (1996) also found low clouds over land peaking in the early afternoon and leading high clouds by about 5–6 h with ISCCP data. The phase relationship between low clouds, or total cloud cover, and high clouds indicates the building of deep convection and the spreading of cirrus anvils from it. This relationship was also found in a prior study by Menzel et al. (1992) using a subset of VAS data of only four observations per day.

The previous studies of diurnal cycles (Bergman and Salby 1996; Chen and Houze 1997; Duvel 1989; Gray and Jacobson 1977) used only single-channel IR satellite data. Similar data from the ISCCP IR-only technique are shown in Figs. 4–8 and 10 and 11. High cloud frequencies from this technique are generally 10%–15% lower than the VAS or the ISCCP dual-channel technique because thin cirrus are mistakenly assigned lower altitudes in the ISCCP IR-only data. However, this study shows that the ISCCP IR-only high cloud data show similar diurnal cycles of high clouds. The only location where this relationship did not hold was in the tropical Atlantic where the VAS found double maxima in the diurnal cycle of high clouds whereas the ISCCP-IR only technique failed to detect a diurnal cycle in high clouds.

6. Summary and conclusions

The diurnal cycles in high cloud occurrence measured by the GOES-VAS and ISCCP single channel (IR only) are similar even though the ISCCP IR data reported smaller amplitudes. The ISCCP IR (only) data is not able to find the thin cirrus that the GOES-VAS detects, causing smaller cloud occurrences and weaker diurnal variations.

Both the VAS and ISCCP datasets indicated that the largest diurnal cycles are over land in areas where deep cumulus convection occurs—the Rocky Mountains, the Gulf coast and Florida, and central Brazil. In the CONUS they occur in summer and are absent or extremely weak in the winter. These are the areas where solar insolation also is large (Bergman and Salby 1996; Hendon and Woodberry 1993). In Brazil the areas of the largest diurnal cycles move between the seasons following the solar insolation.

The only area of significant disagreement was in the western Atlantic ITCZ where the VAS found dual maxima in the diurnal cycle and the ISCCP IR-only data had no diurnal cycle. There was a hint of this cycle in ISCCP dual-channel (visible and IR) data as discussed in section 5.

The amplitude of the diurnal cycle of high clouds found by the GOES-VAS was greater than that of the ISCCP (IR only) data by a factor of ~1.5 in the land areas where the largest diurnal cycles were found. The ISCCP IR data may be useful in estimating bias errors in cloud datasets from sun-synchronous satellites over land if a statistical correction is used for the deficiency of the ISCCP single-channel IR technique. This would improve the use of datasets from polar orbiters. Over oceans, the ISCCP IR data has difficulty in finding the diurnal cycles of high clouds. Other studies of oceanic areas by Chen and Houze (1997), Duvel (1989), and Gray and Jacobson (1977) have indicated that diurnal cycles are driven more by radiative cooling of the cloud tops than the surface solar insolation, which drives the land diurnal cycles.

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