Diurnal Variations in Cloud Frequency over the Gulf Stream Locale

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ABSTRACT

This paper documents evidence of a diurnal variability in cloudiness over the Gulf Stream locale. The Gulf Stream locale (GSL) is defined as the region covering 31°–38°N, 82°–71°W. The Gulf Stream, which occupies a portion of the GSL, is a warm current of water that flows south to north along the east coast of the United States and provides conditions conducive for the development of cloudiness. Cloud heights derived from the GOES VISSR (Visible–Infrared Spin Scan Radiometer) Atmospheric Sounder (VAS) are obtained and used to produce a 7-yr climatology of the diurnal variation in the frequency of low-, middle-, and high-level cloudiness. The climatology is segregated into summer and winter seasons.

Diurnal variations are found during the summer and winter. Satellite observations over land indicate a maximum in the frequency of low cloudiness during daytime and a minimum at night. In addition, high cloudiness is found to increase significantly late in the afternoon and evening. Over the Gulf Stream region, high cloudiness is found most frequently in the mid- to late morning hours. A midafternoon maximum in low cloudiness is found along the coastline of Georgia and South Carolina and north of the Gulf Stream east of Virginia. Nocturnal minimums in low cloudiness are reported in these regions. Results suggest that summertime low and high cloudiness over the GSL are related to prevalent convective activity. An analysis of the diurnally oscillating pattern of boundary layer convergence, derived from analyses from the National Meteorological Center's eta step coordinate model, indicates a strong relationship to the presence of high cloudiness. The strong correspondence between the timing of these two parameters suggests that atmospheric dynamics play a significant role in the diurnal cycle in high cloudiness.

In winter, when convective activity is suppressed there is less detectable response of the atmosphere to the 24-h solar cycle manifest in the diurnal variations of clouds. Nevertheless, low- and midlevel cloudiness are found most frequently in the predawn hours, except over the Gulf Stream where low clouds exhibit an afternoon maximum and a nocturnal minimum. Surface observations of cloudiness support the diurnal variations reported by VAS.

1. Introduction

Clouds are actively involved in modulating the radiation budget in the earth's climate system. Variations in the amplitude and phase of both seasonal and diurnal cycles of the outgoing longwave radiation have been physically interpreted as variations in cloudiness (Short and Wallace 1980). It follows that the first step toward fully understanding the role of clouds in the earth's climate is increasing our knowledge of the temporal and spatial variability of the amounts, types, and radiative properties of clouds. One important timescale of cloud variability that is not adequately understood is the diurnal cycle. Cloudiness is involved in a number of physical processes in the atmosphere, therefore, these processes will have diurnal components if cloudiness varies on a 24-h cycle. Diurnal variations in cloudiness have been well established in the literature particularly for the tropical regions (e.g., Gray and Jacobson 1977; Ball et al. 1980; Ackerman and Cox 1981; Menzel et al. 1990). It has been demonstrated that diurnal variations in cloudiness, particularly in the Tropics, are highly dependent on the geographic location and prevalent convective activity. Therefore, generalizations about diurnal cloud variations may be applicable only to a specific portion of the earth during a particular season. This observation demonstrates the need for monitoring cloud cover at spatial and temporal scales sufficient to account for seasonal and regional changes in diurnal cloud variability. Diurnal cloud variations have also been shown to exist in the midlatitudes. Wallace (1975) has shown significant diurnal variations in precipitation and thunderstorm frequency over the United States during both the summer and winter months. Most notably thunderstorm frequency was found to be strongly modulated by the diurnal cycle. Over the central United States, a nocturnal maximum in the frequency of convective storms and precipitation was found. A strong diurnal cycle in the frequency of low cloudiness was observed off the coast of California (Simon 1977). Short and Wallace (1980) inferred cloudiness from averaged morning to evening mea-

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surements of outgoing longwave infrared radiation. Over land regions and coastal waters it was reported that 12-h differences in outgoing longwave radiation were dominated by middle and high clouds, probably of convective origin. Differences in their patterns are consistent with widely held views concerning the modulation of convection by diurnally oscillating, thermally driven boundary layer circulations.

Accordingly, this paper examines the variation in diurnal cloudiness over the Gulf Stream locale (GSL). The geography in the GSL is unique in the sense that a cool continent (foothills and piedmont) is bounded by the relatively warmer shelf waters of the Atlantic Coast, which is joined to the east by the consistently warmer Gulf Stream. The slightly cooler Sargasso Sea region borders the Gulf Stream to the east (see Fig. 1, Alliss and Raman 1995). Each of these underlying surfaces have been shown to cause different responses in the boundary layer growth and structure as a result of changes in stability and surface roughness (Huang and Raman 1990; 1991). The Gulf Stream flows northward approximately 100 km off the United States east coast. North of Cape Hatteras, North Carolina, the Gulf Stream makes a seaward turn and can meander substantially. The heat loss by the fast moving warm core of the Gulf Stream is greater than in any other oceanic region (Budyko 1963). This heat loss (heat gain to the atmosphere) is the result of the rapid advection of warm water (>26°C) from the subtropics into an area dominated by cold dry continental air masses much of the year. The resulting large surface heat fluxes act to condition the atmosphere and allow for the formation of clouds. Recently, Alliss and Raman (1995) reported that high frequencies of cloudiness exist over the GSL. Clouds were found approximately 75% of the time between the years of 1985 and 1993. The seasonal variations in cloud frequency were also shown to have a distinct relationship to gradients in sea surface temperature (SST). The diurnal cycles in cloudiness that appear in the summer and winter averages appear in

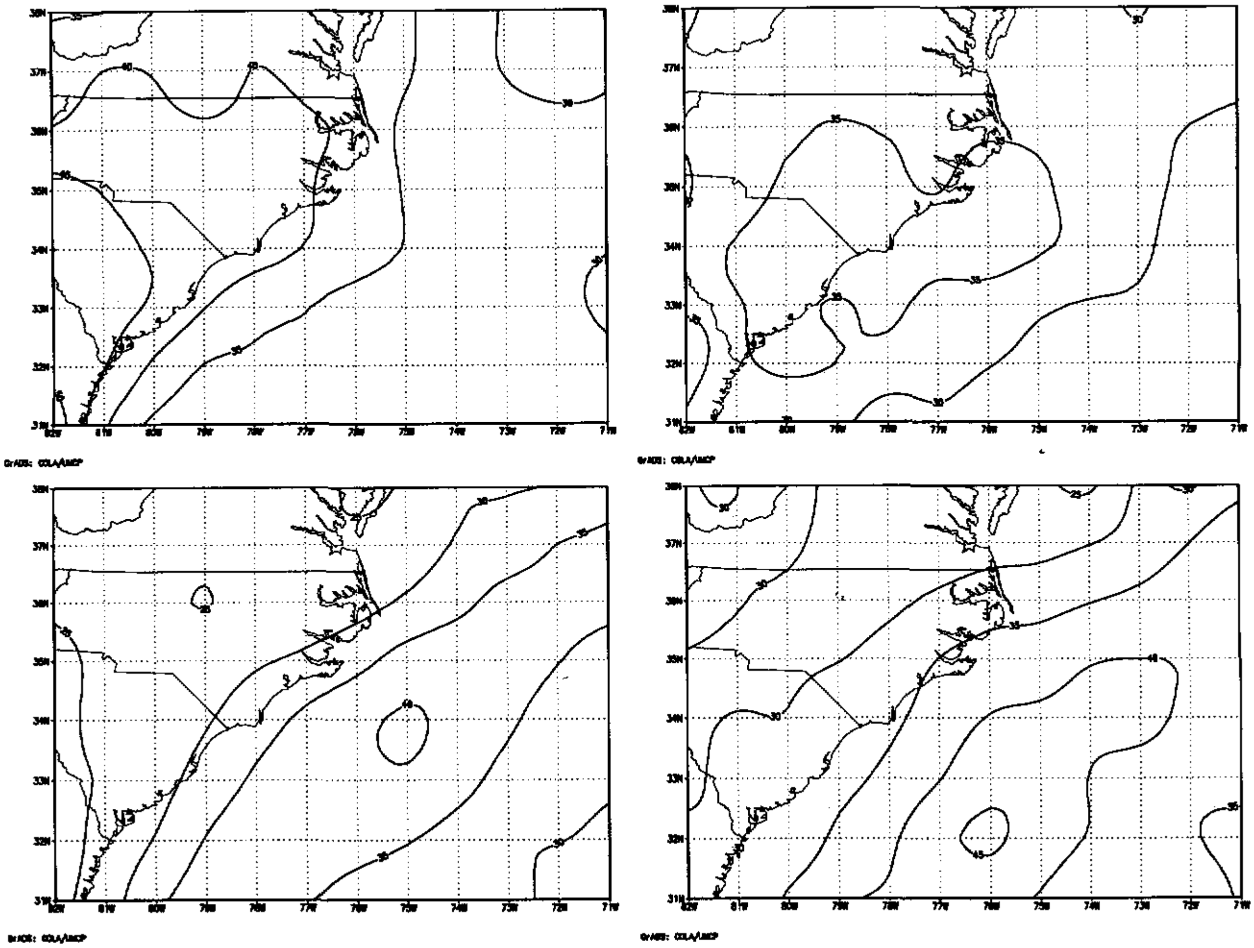

FIG. 1. (a) The mean diurnal variation in the frequency of high-level clouds over the Gulf Stream locale for the 18 months June–August 1987–92: (a) 1900 EST (evening), (b) 0100 EST (night), (c) 0700 EST (morning), and (d) 1300 EST (afternoon). Contour intervals of 5% are shown. The maximum occurrence in high clouds is found near 1900 EST with a minimum 12 h later.

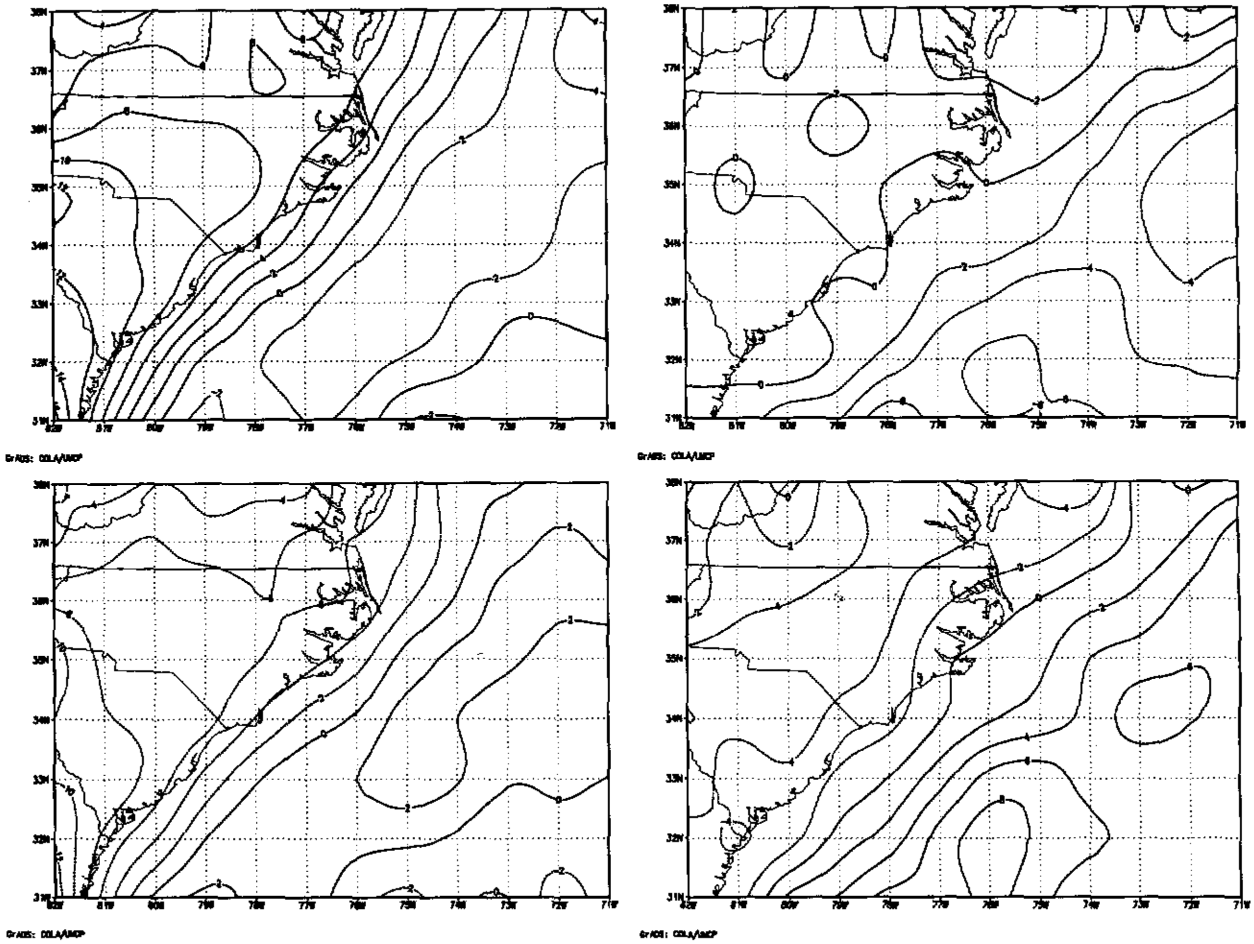

FIG. 2. The mean diurnal variation in the deviation of high cloudiness from the summertime mean: (a) 1900 EST, (b) 0100 EST, (c) 0700 EST, and (d) 1300 EST. Contour intervals of 2% are drawn. High clouds are found more (less) frequently than the mean over land (Gulf Stream) at 1900 EST and less (more) frequently than the summertime mean over land (Gulf Stream) at 0700 EST. High cloudiness over land increases more than 15% between 1300 and 1900 EST and approximately 5%–10% over the Gulf Stream between 0700 and 1300 EST. Solid (dotted) lines indicate a positive (negative) deviation from the mean.

each year individually. Furthermore, the diurnal cycle for the summer of 1994 (not included in this study) was recently computed and shows variations similar to previous years. Thus, we conclude that these variations are significant from a climate perspective.

An accurate assessment of the diurnal variation in cloudiness on a global, hemispheric, or regional scale may best be obtained through the use of satellites. Therefore, a comprehensive documentation of the diurnal variations of low, middle, and high cloudiness over the GSL will be presented for both the winter and summer seasons between 1985 and 1994. For the most recent summer (1993) and winter (1993/94), comparisons of satellite-derived cloudiness to objective analyses of related meteorological data are performed. In addition, surface observations of the diurnal variation in the frequency of cloudiness will be compared to satellite estimates.

2. Data and analysis

The cloud dataset used in this study is a subset of the satellite-derived cloud climatology produced by Wylie and Menzel at the University of Wisconsin. Their cloud climatology focused on high transmissive clouds over the continental United States and is reported in Wylie and Menzel (1989) and Menzel et al. (1992). The method used to derive this dataset is the CO_2 slicing technique, which uses satellite radiances from the Geostationary Operational Environmental Satellite (GOES) Visible–Infrared Spin Scan Radiometer (VISSR) Atmospheric Sounder (VAS). The CO_2 slicing technique utilizes differing partial CO_2 absorption in three infrared channels (13.3, 14.0, and 14.2 μm). Because each channel is sensitive to a different level in the troposphere, cloud heights may be established by determining which CO_2 channel ratios best satisfy the radiative transfer equation. Cloud-top pressures (CTP)

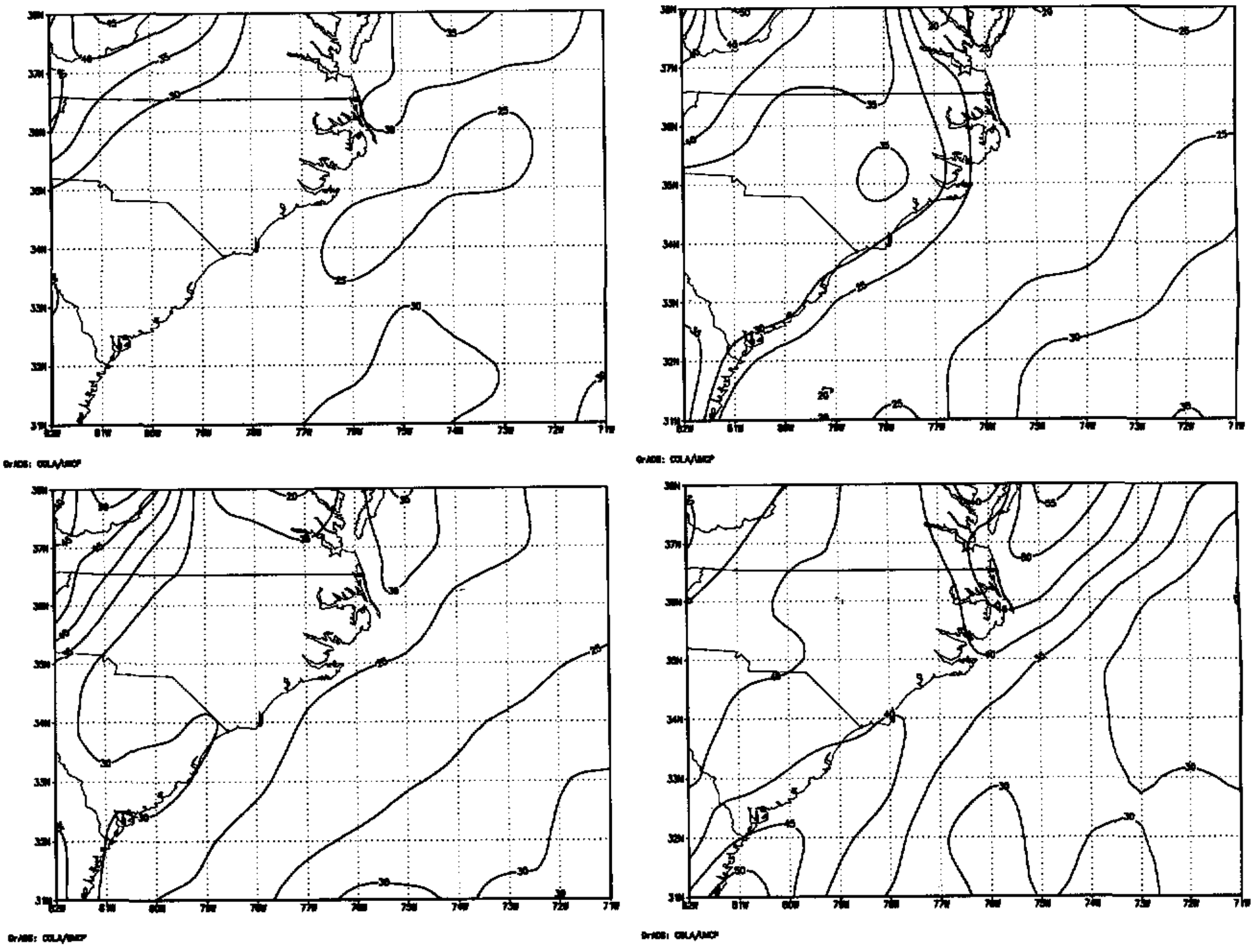

FIG. 3. The mean diurnal variation in the frequency of low-level clouds: (a) 1900 EST, (b) 0100 EST, (c) 0700 EST, and (d) 1300 EST. Contour intervals of 5% are shown. The maximum in low clouds is found over land during the afternoon hours. A large diurnal variation is found off the coasts of Virginia and North Carolina where low-level clouds vary by as much as 35% in 24 h. Maximum low clouds are also observed along the Georgia–South Carolina coastline.

less than 650 mb are computed using this technique. For those CTP greater than 650 mb, cloud heights are calculated directly from the infrared window channel (11.2 μm) radiances and temperature profile estimates. This dataset also includes information on the effective fractional cloud cover (also referred to as effective cloud amount) for each field of view using the IR window channel observations. This information has been shown to be useful in separating opaque clouds from transmissive clouds but is not included in this study. A complete discussion on the cloud retrieval techniques and retrieval errors may be found in the cited references.

Since the purpose of this paper is to describe the diurnal variations of cloud frequency, a dataset with sufficient temporal resolution is essential. In this dataset, cloud parameters are available at approximately 6-h intervals (0100, 0700, 1300, and 1900 EST). The eastern standard time (EST) reference will be used in this study to facilitate discussions on diurnal variations. VAS observations are available twice during day (0700, 1300) and night (1900, 0100) in winter and approximately three times during daylight (0700, 1300, 1900) in summer. Another important consideration is the spatial resolution. The Gulf Stream is a relatively narrow feature spanning 200 km at its maximum width. Therefore, it is imperative to describe cloudiness at scales at least equal to the Gulf Stream dimensions. This dataset affords us the luxury with a spatial resolution of approximately 50 km. This is superior to other cloud climatologies whose horizontal resolutions are as coarse as 250 km (Rossow and Schiffer 1991; Warren et al. 1986, 1988). In addition, VAS cloud heights are derived between 1000 and 100 mb. The VAS CO_2 cloud heights have been found to be reliable for most cloud types, including thin cirrus clouds where other techniques have been inconsistent (Wylie and Menzel 1989). In this study, the term frequency of cloudiness is used to describe the diurnal variations. The frequency of cloudiness is defined as the number of observations,

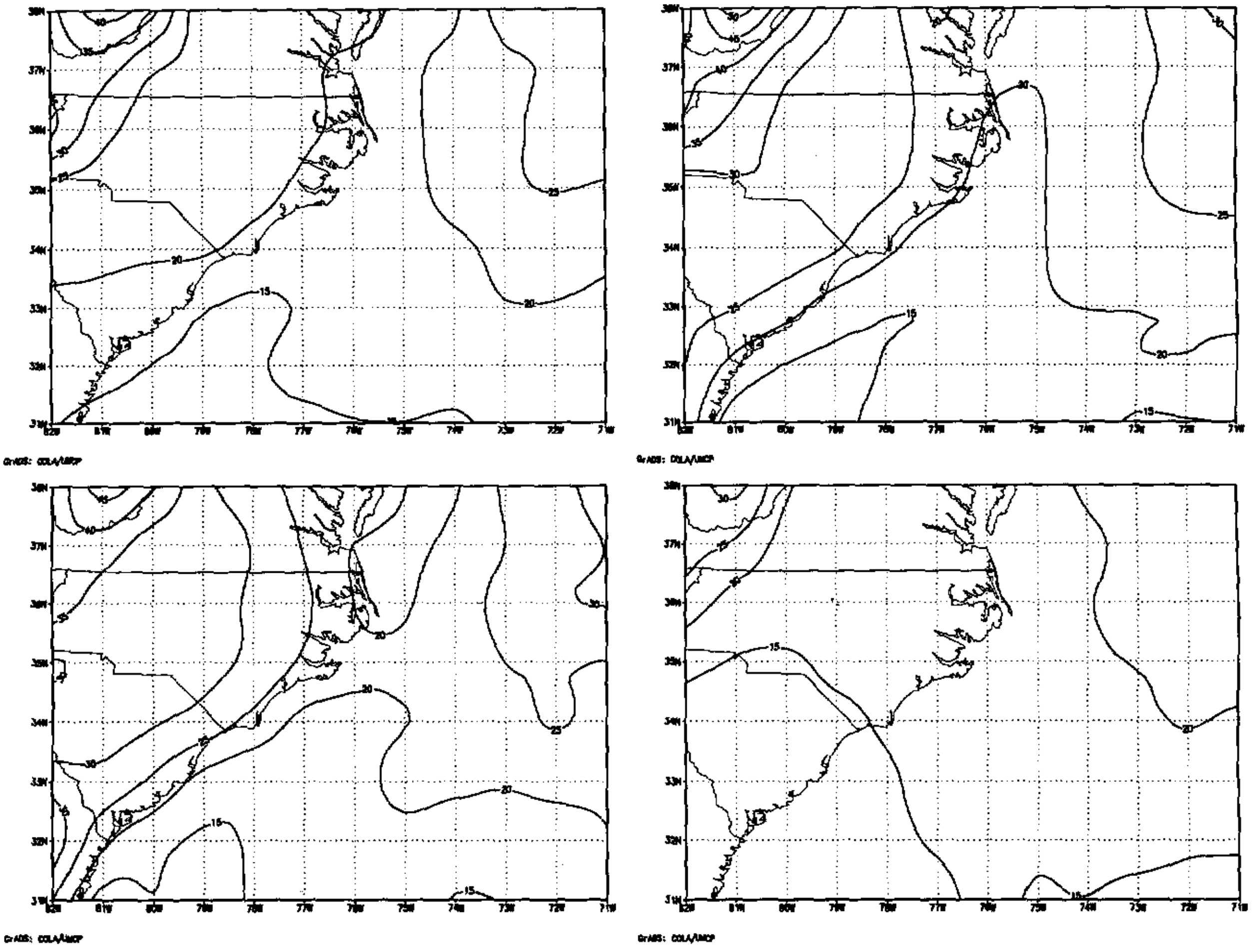

FIG. 4. The mean diurnal variation in the frequency of midlevel cloudiness over the Gulf Stream locale for the 21 winter months, December–February 1985–93: (a) 1900 EST, (b) 0100 EST, (c) 0700 EST, and (d) 1300 EST. Contour intervals of 5% are shown. The maximum occurrence of midlevel clouds is found prior to sunrise, over land. A minimum in the afternoon is observed when these clouds are reported only 15% of the time.

for example, of low clouds in a given grid box divided by the number of all observations in that box. These calculations are performed for each grid point in the domain.

Hourly surface observations of cloudiness for June, July, and August of 1993 (JJA 1993) and December 1993, and January and February of 1994 (DJF 1994) were obtained for the National Weather Service (NWS) reporting stations located in Raleigh (RDU) and Cape Hatteras (HAT), North Carolina. Comparisons are made to VAS frequencies of cloudiness at 0100, 0700, 1300, and 1900 EST, respectively. No explicit information on cloud height is contained in the surface data; however, the frequency of cloudiness, independent of cloud height, is derived. Analyses from the National Meteorological Center's (NMC) eta step-coordinate model are also obtained for JJA 1993 and DJF 1994. This dataset is used to explore the relationship of cloudiness to related meteorological factors. Eta analyses are available at 1900 and 0700 EST. Six-hour forecasts are available at 0100 and 1300 EST. The analyses and forecasts are available at approximately 80-km resolution. Information in the vertical is available at the surface and at 50-mb intervals from 1000 to 100 mb. Fields of temperature, moisture, and horizontal winds are contained in the analyses and forecasts. Even though the analyses and 6-h forecasts cannot be verified over the ocean portion of the GSL, for our purpose the eta provides an adequate representation of the basic meteorological fields. For a complete description of the eta model, the reader is referred to Mesinger et al. (1988).

3. Diurnal variations during summer

Throughout the text the term GSL will refer to the entire study domain and the term Gulf Stream region will refer to the area over and surrounding the Gulf Stream. We present the aggregation of six summer seasons [June–August (JJA) 1987–92] of the frequencies

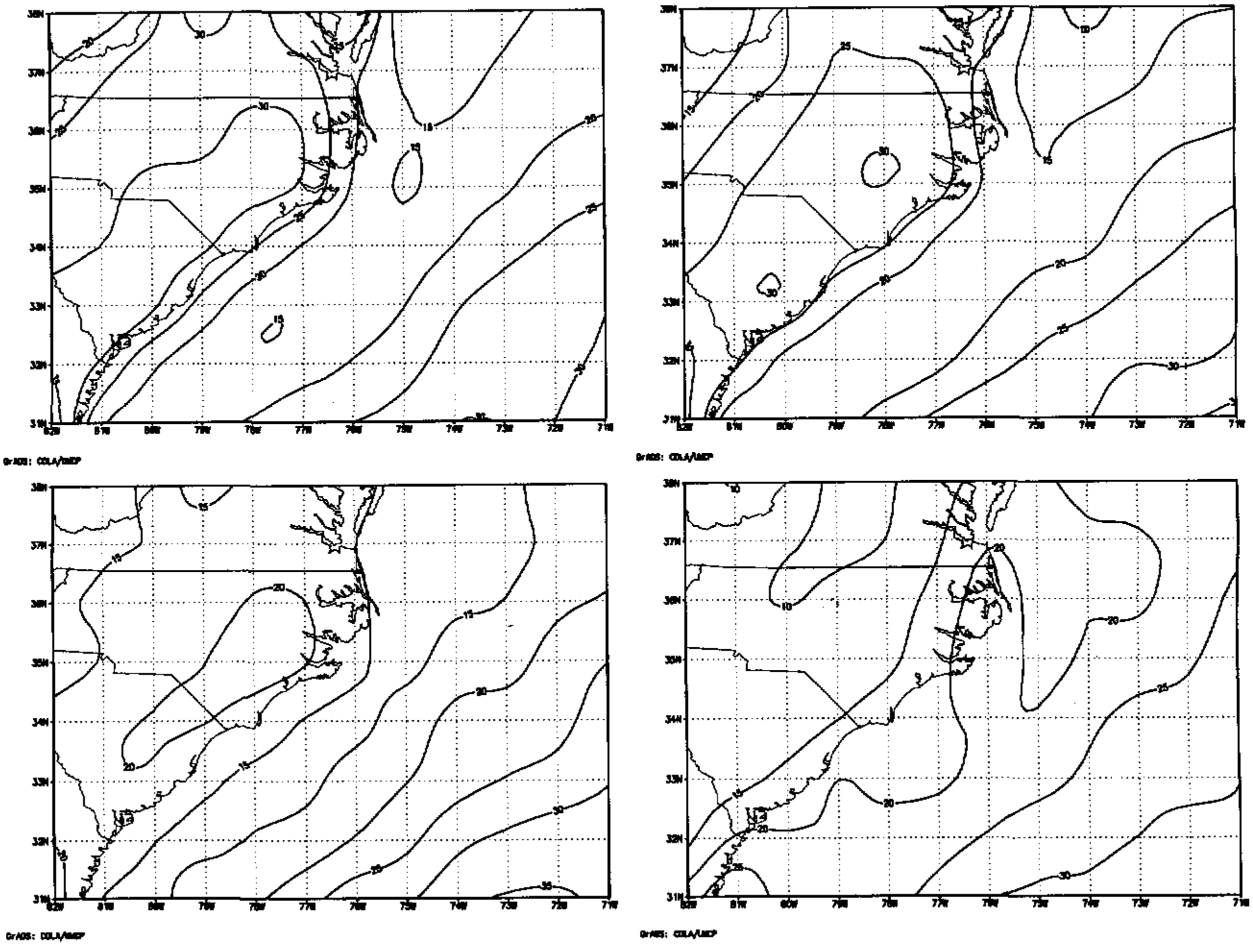

FIG. 5. The mean diurnal variation in the frequency of wintertime low clouds at (a) 1900 EST, (b) 0100 EST, (c) 0700 EST, and (d) 1300 EST. Contour intervals of 5% are shown. Low cloudiness shows a nighttime bias over land. Over the Gulf Stream area, low clouds are found most often around 1300 EST.

of high and low cloudiness stratified into four times. In this study, June, July, and August (JJA) are used to describe the summer months. High clouds are defined as those with CTP less than 400 mb, whereas low clouds are defined as those with CTP greater than 650 mb. Figures 1a–d, show the summertime diurnal changes in the frequency of high cloudiness over the GSL. Results indicate the maximum frequency of high cloudiness over land occurs near 1900 EST with a decrease observed thereafter through approximately 0700 EST. A small increase is noted between 0700 EST and 1300 EST. Conversely, over the ocean very little change in high cloudiness is found between 1900 and 0100 EST. However, an increase in occurrence is noted in this region between 0100 and 1300 EST. Note that by 1300 EST the frequency of high cloudiness exceeds 40% over a large area of the Gulf Stream region. In a study of tropical convective cloudiness derived from GOES data, Meisner and Arkin (1987) found a maximum in JJA convection during the late morning off the southeast coast of the United States. The diurnal change in the frequency of high cloudiness may be more clearly discerned in terms of its deviation from the summertime mean. In Figs. 2a–d the frequencies of occurrence for all four times have been averaged, and the deviations from the average for each time are displayed. High clouds are found more (less) frequently than the mean over land (Gulf Stream) at 1900 EST and less (more) frequently than the summertime mean over land (Gulf Stream) at 0700 EST. It is also apparent that with respect to the mean values, high cloudiness over land increases by as much as 18% between 1300 and 1900 EST and approximately 5%–10% over the Gulf Stream region between 0700 and 1300 EST. Wallace (1975) reports that in this same area (over land) thunderstorm and precipitation frequency show a strong bias toward afternoon and early evening. The study that made use of 10 years of surface data over the continental United States indicates that the diurnal cycle in convective activity is most noticeable during the summer when the overall frequency of convection is highest.

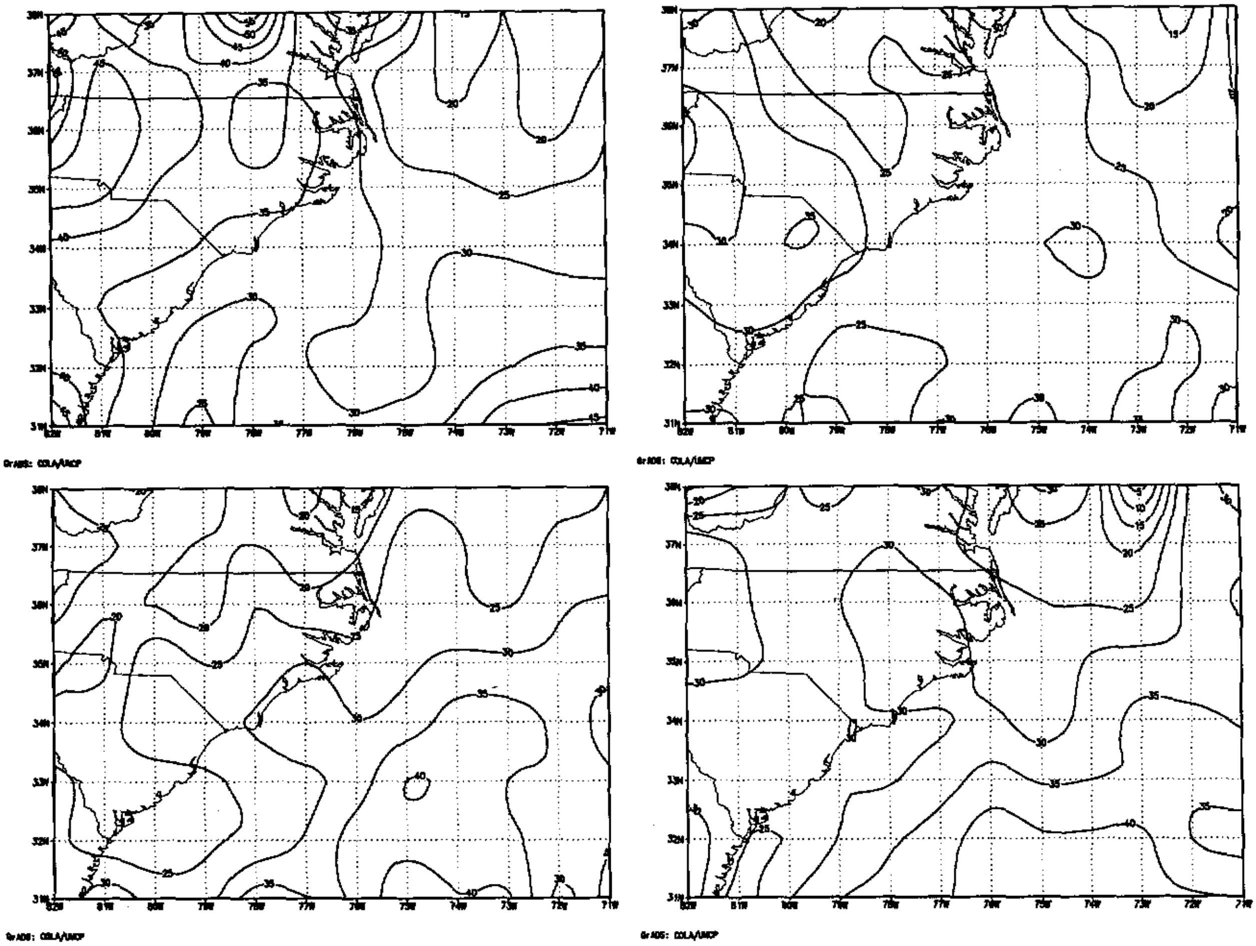

FIG. 6. The mean diurnal variation in high cloudiness for June–August 1993: (a) 1900 EST, (b) 0100 EST, (c) 0700 EST, and (d) 1300 EST. Contour intervals of 5% are shown. High clouds are most prevalent over land at 1900 EST and over water during the morning and early afternoon hours. A minimum is observed over land near sunrise and over water in the late evening.

Figures 3a–d show the diurnal change in the frequency of low cloudiness. More geographical variations are found in the low-cloud frequencies than for the high clouds. As anticipated, the maximum in low cloudiness is found over land during the afternoon. The frequency of low cloudiness is highest over the northwest portion of the GSL. This area is centered over the Appalachian mountains where orographic lifting may play a role in enhancing cloudiness. Although little diurnal variation is present, low clouds are observed more than 40% of the time.

Over the coastal ocean region of the GSL, low clouds vary by as much as 35% on the 24-h solar cycle. This is particularly the case along the coasts of Virginia, northeast North Carolina, and the coasts of South Carolina and Georgia. In these areas low clouds are observed most frequently in the early afternoon (>40%) followed by a decrease toward evening. Very little change is observed through the night with frequencies of 25%–30% observed. In a 5-yr (1987–90, 1992) rainfall climatology derived from the Special Sensor Microwave/Imager (SSM/I) data, Negri et al. (1994) found a late afternoon maximum in precipitation along the coastal sections of Georgia (200–400 mm month^{-1}) and Virginia. Unfortunately their study area did not extend east of 75°W, so comparisons to cloudiness east of the Virginia coast could not be made. The Negri et al. (1994) study also reported an early morning maximum in convective precipitation (200–400 mm month^{-1}) off the coasts of the Carolinas; an area where VAS detected low clouds 25% of the time. Deviations in low cloudiness (−15%) from the summertime means are found at 0100 EST (where the negative sign indicates values less than the mean). A 20% deviation from the mean is noted at 1300 EST. These large deviations, however, are limited to the coastal areas. It should be noted that the CO_2 technique is underestimating the frequency of low cloudiness over land in the late afternoon and evening and over the ocean during the morning and afternoon. The underestimate is found at times when high clouds are reported most often. At these times the satellite's capability of sensing low

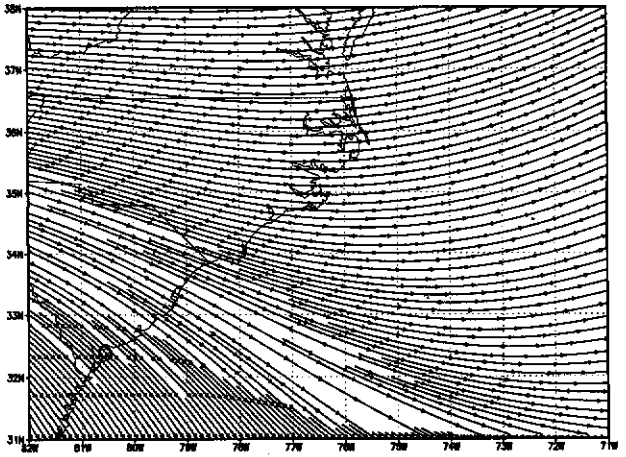

FIG. 7. The mean 200–300-mb layer streamlines derived from eta analyses for June–August 1993. The average wind speed in this layer is approximately 12 m s^{-1}. This wind pattern may play a role in the advection of convective high cloudiness from land to the Gulf Stream region.

clouds is reduced. Despite this deficiency, the increase in the frequency of low clouds coincides with an increase in high cloud. It is important to note that not all low clouds produce high clouds through convective processes. However, during summer, when convective activity dominates, this relationship may be valid.

4. Diurnal variations during winter

The amplitude in the diurnal cycles in cloudiness during winter are much smaller than those of summer but a signal is still present. The winter months in this study are an aggregation of seven winter seasons [December–February (DJF), 1985–93 not including 1986/87] stratified into four times that describe the diurnal cycle. The 1986/87 data were unavailable because VAS operations were restricted for a reconfiguration of the data transmission system. Unlike the summer months, high clouds in winter vary no more than 5%. This is associated with the large increase in the frequency of midlatitude cyclones (Colucci 1976) where high clouds are often found over areas of large-scale rising motion. Midlevel cloudiness, defined as 650 mb < CTP ≤ 400 mb, show some evidence of a diurnal variation. Figures 4a–d show the mean diurnal evolution for midlevel clouds during the winter. From this data it is evident that midlevel clouds show a maximum in the frequency of occurrence around sunrise. This peak is found predominantly over land where they are observed approximately 30% of the time at 0700 EST. By 1300 EST the frequency decreases by one-half as the mean is shown to be 15%. As nighttime approaches the frequency of midlevel clouds increases again. A nocturnal and predawn maximum in the occurrence of precipitation was found in this region by Wallace (1975). Hann (1901) describes that over much of western continental Europe winter precipitation exhibits a nocturnal maximum. These results suggest there may be some connection between the nocturnal maximum in midlevel clouds and precipitation within the GSL.

Low clouds exhibit a stronger diurnal cycle than midlevel clouds in the GSL. A nocturnal maximum over land can be seen in Fig. 5a. Low clouds over land are observed as often as 30% during nighttime (1900–0100 EST). The frequency increases rapidly at night followed by a slow decrease in occurrence by morning (Fig. 5c,d). Low clouds are detected 20% of the time at 0700 EST. We suspect that the satellite may be underestimating their frequency since midlevel clouds are also present at this time. Over the Gulf Stream area, low clouds are found most often near 1300 EST. Here a 20% frequency of occurrence is observed. A small but rather distinct decrease takes place over the Gulf Stream at night. In a narrow band about 100 km in width, low clouds are reported approximately 15% of the time between 1900 and 0700 EST. East of the Gulf Stream no diurnal variation is noted as frequencies in low clouds are observed between 20% and 30% of the time. In this area, known as the Sargasso Sea, SSTs are uniform during winter varying no more than 1°–2°C $(500\ \mathrm{km})^{-1}$ (Fig. 3a, Alliss and Raman 1995). These low clouds are not maintained by radiative cooling at cloud top like their counterparts in the eastern Pacific Ocean. Often, there are higher-level clouds present that tend to suppress such radiative processes. Conversely, it is well known that surface fluxes play a much more important role than cloud-top radiative cooling in the buoyancy production of turbulent kinetic energy and the maintenance of low clouds (Schubert et al. 1979). This is particularly true for convective boundary layers produced during cold air outbreaks.

Since large shields of high clouds show no diurnal variation and are persistent during winter, the actual magnitude in the frequency of low clouds may be underestimated. As indicated by Menzel et al. (1992), for over 50% of satellite reports of upper tropospheric opaque cloud, the ground observer indicated additional cloud layers. Satellite observations of low opaque clouds are more likely to be in error over land than over water due to the false identification of clear sky as low cloud (Wylie and Menzel 1989). This is particularly the case at night during the cold months when strong nocturnal inversions develop. The result is the development of stable boundary layers where little mixing occurs (Mahrt 1985; Parker and Raman 1993). In these instances low clouds may be overestimated. Satellite-derived low clouds over a nocturnal marine boundary layer (MBL), however, are considered more reliable. In this case sea surface temperatures show little diurnal variation, therefore surface fluxes are sufficient to keep the MBL well mixed.

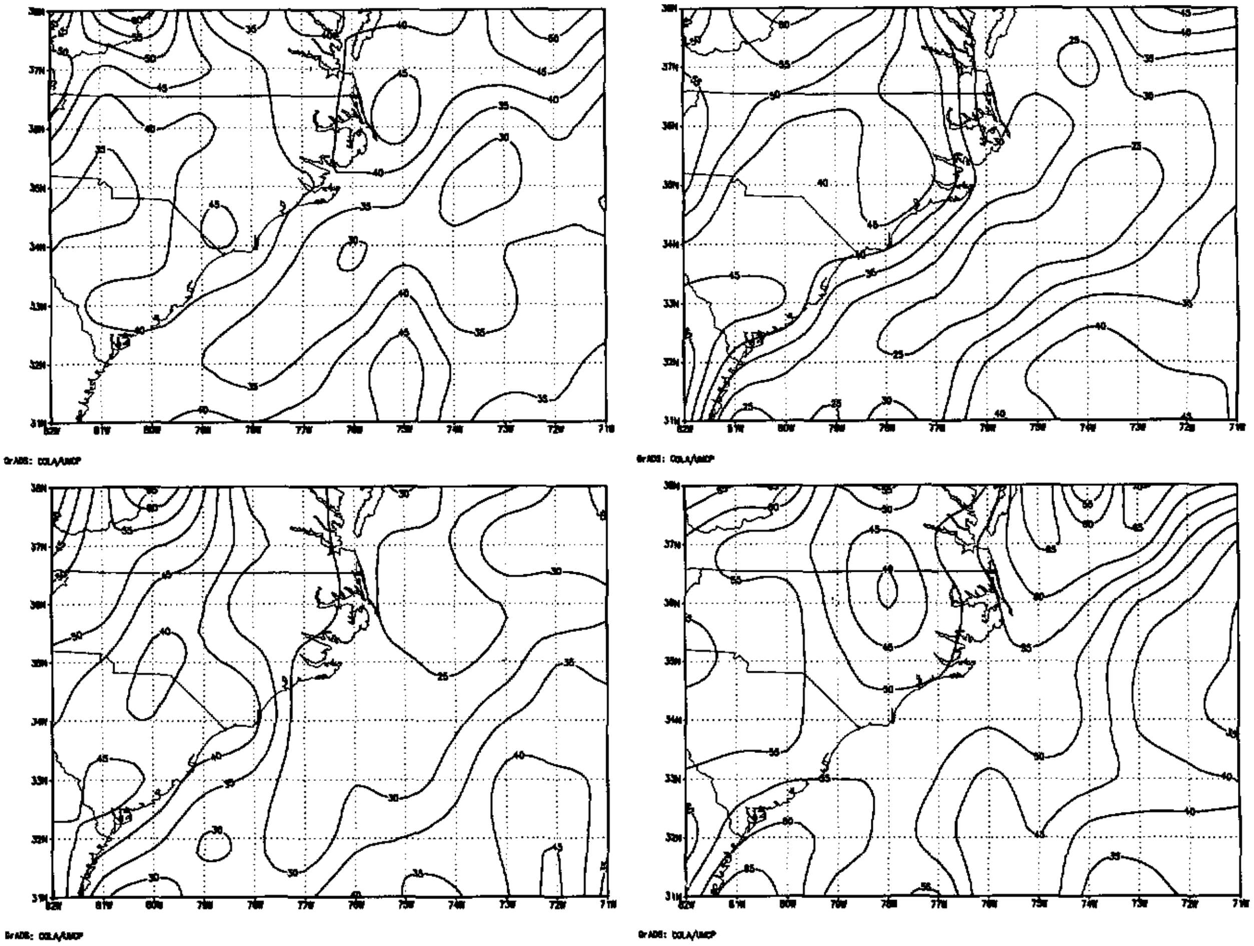

FIG. 8. Same as Figs. 6a–d except for low cloudiness. A maximum in low cloudiness is found over land during the afternoon. A minimum develops along the Gulf Stream area around sunset and is most prevalent at 0100 EST. This nocturnal minimum is replaced by an afternoon maximum.

5. Comparisons with model analyses and surface observations

On the basis of the results presented in sections 3 and 4, we compare eta model analyses and surface observation to the diurnal variations observed in cloudiness.

a. Summer 1993

Figures 6a–d show the mean diurnal cycle of high cloudiness for JJA 1993. Similar to the 6-yr climatology, high clouds tend to be most prolific over land at 1900 EST and over water at 1300 EST. Maximum frequencies of occurrence exceed 35% over land and water during JJA 1993. High clouds are observed least often over land at 0700 EST and over the Gulf Stream region at approximately 1900 EST. Gray and Jacobson (1977) point out that high- and midlevel cloudiness are persistent for hours after the diurnal peak in convection. This diurnal peak is found in the late afternoon hours over land (Wallace 1975). If the observed high cloudiness over land is a result of convection, then it is possible that a relationship exists between the diurnal maximums in high cloudiness over land and the Gulf Stream region. Indeed, approximately 18 h separates the maximum in high cloudiness over land and the Gulf Stream region. Since advection may be one possible factor that could explain the 18-h difference, analyses of upper-level winds from the eta model are investigated. The mean wind speed and direction for JJA 1993 are calculated for the 200–300-mb layer. Results indicate a westerly wind direction over most of the GSL (Fig. 7). In the southwestern portion of the GSL, the mean wind direction is more northwesterly. Additionally, the mean wind in this layer is approximately 12 m s^{-1}. It would, therefore, take an air parcel 16 h to travel a distance of 700 km (distance from central North Carolina to the Gulf Stream region), assuming a 12 m s^{-1} ambient wind. Thus, if high clouds peaked in the early evening over land, they would appear over the Gulf Stream region by the following

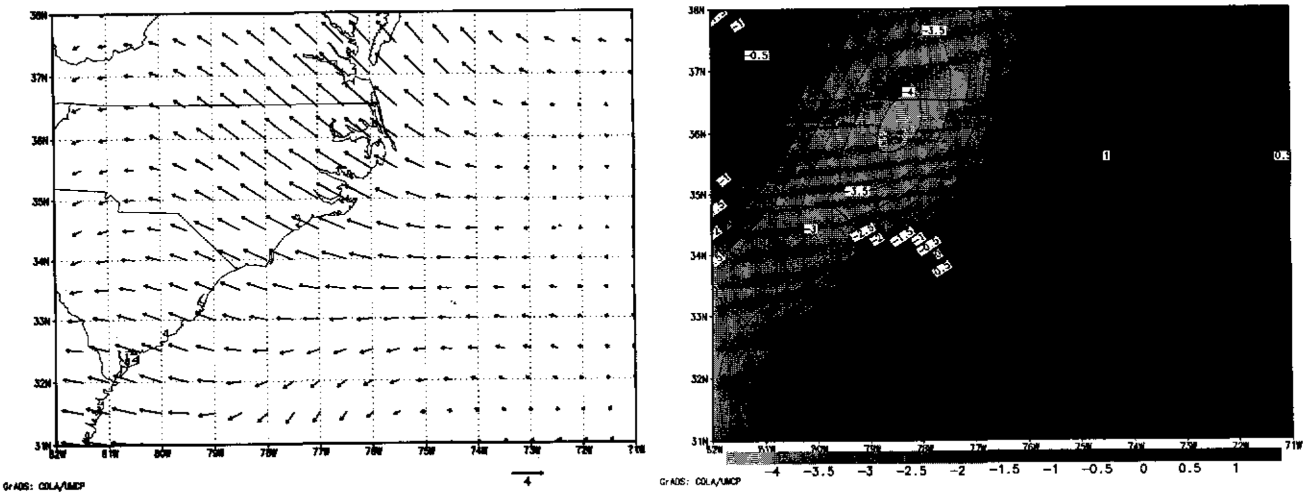

FIG. 9. (a) The mean 12-h difference field (1900 EST minus 0700 EST) in 950-mb wind vectors over the Gulf Stream locale during June–August 1993. The unit arrow represents a 4 m s^{-1} wind. This field is representative of the mean diurnally oscillating component of the wind field at 1900 EST. The wind field is strongly convergent over land and divergent over the Gulf Stream area. (b) The mean difference in lower-tropospheric stability (°C) between evening (1900 EST) and morning (0700 EST) during June–August 1993. Negative (positive) values indicate unstable (stable) conditions. The reduction in lower tropospheric stability is quite evident over land during the evening compared with morning. Overwater stable conditions prevail in the evening compared with the morning.

morning. As pointed out previously, advection is only one possible scenario and other explanations should be considered.

The frequency of low cloudiness is also similar to the climatology; however, more geographical detail is present (Figs. 8a–d). This is likely since it represents only a 90-day period; thus, peaks and valleys in the frequencies are not smoothed out. Maximum low cloudiness is reported near 1300 EST over land. This includes the low cloudiness observed along the Georgia–South Carolina coastlines. Low cloudiness over land decreases from a maximum of over 50% in afternoon to near 40% during nighttime. A minimum with respect to the rest of the GSL develops over the Gulf Stream region around 1900 EST and continues into the night. Frequencies less than 25% are observed along the Gulf Stream area at 0100 EST. This area tends to disappear during the morning hours and is replaced with an afternoon maximum.

The interesting afternoon maximum in low clouds found in the 6-yr climatology off the Virginia and northeast North Carolina coastlines is also seen in the

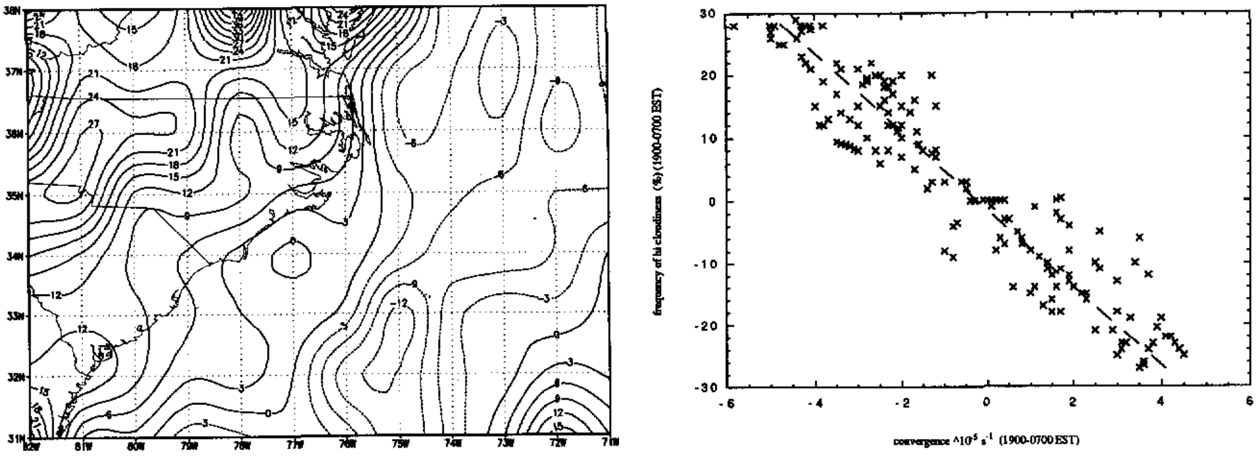

FIG. 10. (a) The evening–morning (1900 EST minus 0700 EST) mean difference field in the frequency (%) of high cloudiness. Positive (negative) values indicate an increase (decrease) in high cloudiness at 1900 EST with respect to 0700 EST. Over land a maximum is found in the evening, whereas over water a minimum is observed. (b) Scatterplot of the evening–morning (1900 EST minus 0700 EST) difference in high cloudiness versus 950-mb convergence. Positive (negative) values indicate divergence (convergence). An increase in the diurnally oscillating frequency of high cloudiness is coincident with an increase in 950-mb convergence.

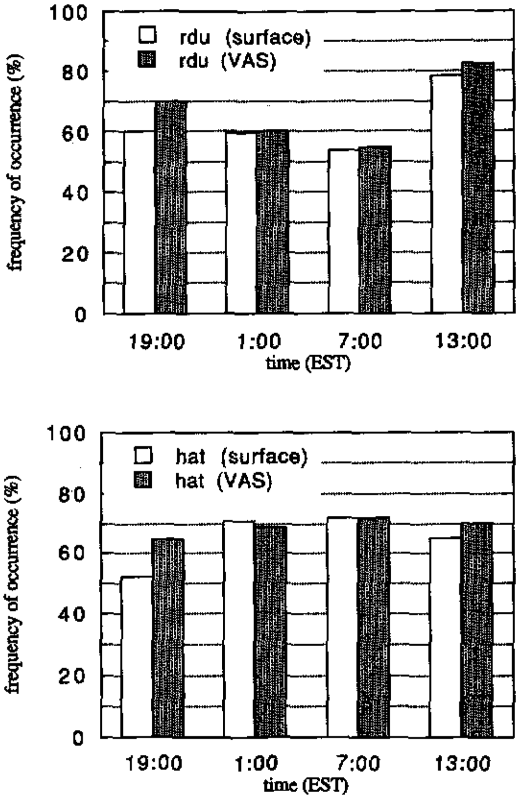

FIG. 11. (a) Comparisons of VAS derived total cloudiness to surface cloud observations at Raleigh, North Carolina (RDU), during June–August 1993. VAS observations agree well with surface observations at each analysis time. Both show the afternoon maximum in cloudiness and the early morning minimum. (b) Same as (a) except at Cape Hatteras, North Carolina (HAT). With the exception of 1900 EST, where a 10% discrepancy is noted, comparisons between VAS and surface observations compliment each other. A morning maximum in total cloudiness is found in both VAS and surface observations.

1993 data. This afternoon maximum is followed by a decrease in occurrence through 0100 EST. Analyses of the eta model wind fields indicate that at the time of maximum low cloudiness (1300 EST) the boundary layer winds are light (less than 2 m s^{-1}). Boundary layer winds are 20% greater at night (0100 EST) when low clouds are found least often compared to 1300 EST. With the existing data, however, it is difficult to explain the observed diurnal cycle in low cloudiness. Certainly this is an area where atmospheric dynamics are complicated by the juxtaposition of the Gulf Stream and return flow of the cold Labrador current. Since there are no surface-based observations of cloudiness to confirm the existence of an afternoon maximum, we may only rely on VAS. It is suggested that a modeling study be conducted to see what role the two currents may have on the diurnal cycle of low clouds in this area.

The diurnal cycle in convective activity and its influence on cloudiness is most noticeable during summer when the overall frequency of convection is highest. The mechanisms that have been proposed to explain the diurnal cycle in convective activity may be grouped into two distinct regimes: those based on thermodynamical processes that affect the static stability and those based on dynamics that influence the mass convergence within the planetary boundary layer. To investigate what possible role these mechanisms may have on subsequent convection, an evaluation of the diurnal oscillating pattern of boundary layer convergence and lower-tropospheric stability (LTS) is performed. This is accomplished using the 950-mb winds from the eta 1900 EST (evening) and 0700 EST (morning) analyses. Wind vectors are derived from the 0700 EST analyses and subtracted from those at 1900 EST for each available day during JJA 1993. The result is a mean 12-h difference in 950-mb wind vectors (Fig. 9a). This difference is representative of the diurnally oscillating component of the wind field at 1900 EST. On a typical late afternoon/early evening in summer, the boundary layer wind field is strongly convergent over land and divergent over water. The maximum in convergence over land during the afternoon is partly the result of the differential heating between the land and water. The acceleration of the flow between the ocean and land may also enhance the convergence. Localized convergence not explicitly resolved by this data may exist as a result of outflow boundaries from previous convective activity and land–sea-breeze circulations. The convergence pattern is found after the time when boundary layer stratification has reached its most unstable levels. This is typically prior to 1900 EST. Figure 9b shows the mean evening–morning difference in LTS. LTS is defined as $\theta(900\ \text{mb}) - \theta(800\ \text{mb})$, where θ is the potential temperature. A reduction in LTS over land is reported. Over the piedmont regions the evening–morning LTS is found to be as low as −4 K. Conversely, over the Gulf Stream the mean evening–morning difference in LTS is on the order of +1 K. The strong gradient oriented along the coast is indicative of the differential heating between the two surface types. Thus, unstable (stable) conditions are found most often over land (water) during the late afternoon compared to 12 h before.

Figure 10a shows the mean difference field (1900 EST minus 0700 EST) in the frequency of high cloud.

TABLE 1. The frequency of occurrence of thunderstorm activity at Raleigh (RDU), and Cape Hatteras (HAT), North Carolina, during the summer of 1993.

	Frequency (%)	
Time (EST)	RDU	HAT
1900	21	18
0100	8	24
0700	11	31
1300	39	32

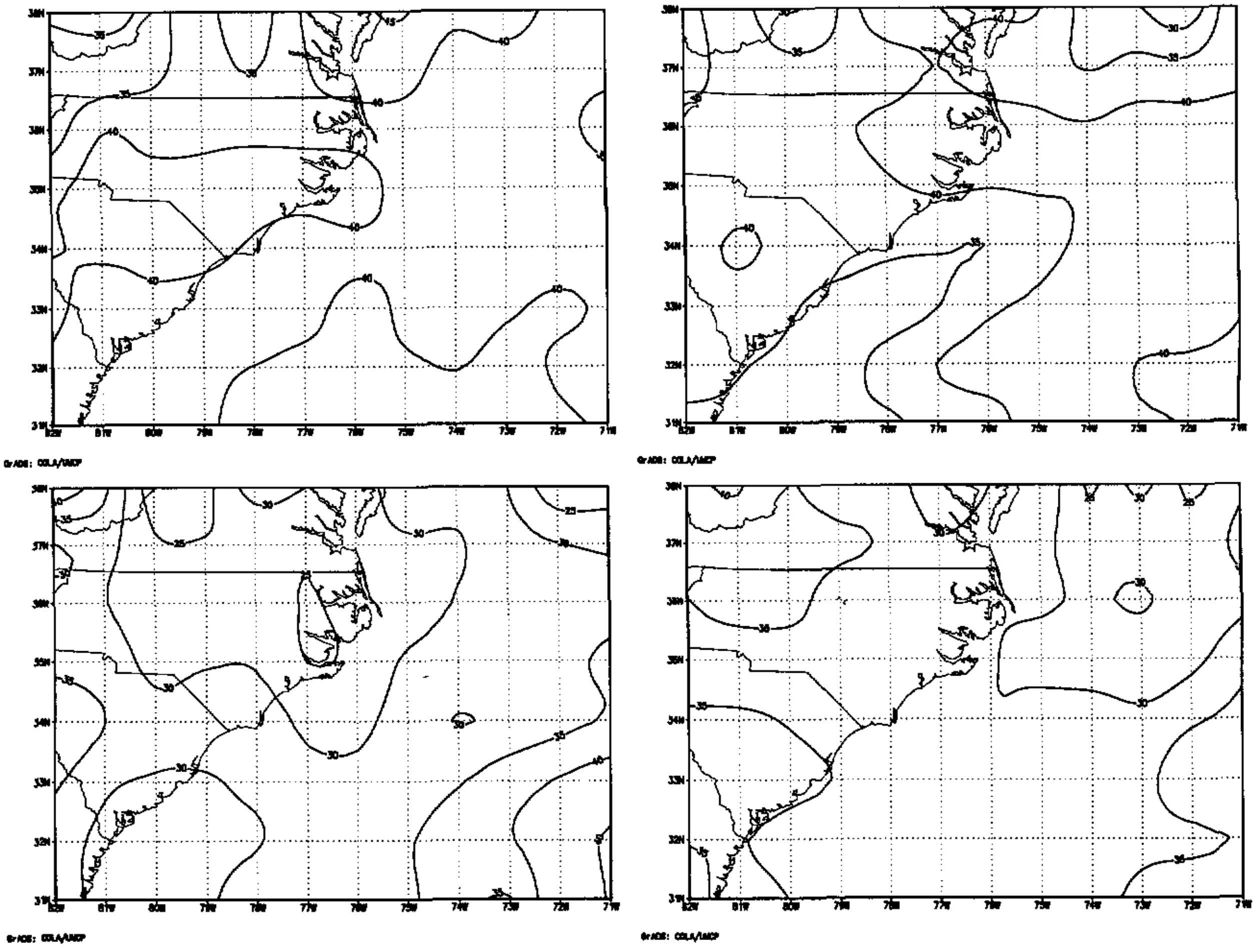

FIG. 12. The mean diurnal variation in high cloudiness for December–February 1994: (a) 1900 EST, (b) 0100 EST, (c) 0700 EST, and (d) 1300 EST. Contour intervals of 5% are shown.

A maximum in high cloudiness over land compared to morning is observed. Over water, a reduction in high cloudiness is evident at 1900 EST compared with 0700 EST. The minimum in convective activity as inferred from the 12-h difference in the frequency of high cloudiness is a result of the relatively stable atmospheric conditions found over the water at this time. These results indicate mean conditions and are associated most frequently with the predominant summertime southwesterly winds. However, during periods when wind directions vary, the process controlling diurnal variations in convective activity and the resulting cloud distributions will be modulated.

A scatterplot of the difference in high cloudiness versus 950-mb evening–morning convergence reveals that high clouds are very strongly correlated with the diurnally oscillating component of boundary layer convergence (Fig. 10b). This scatterplot is produced from a random sample of JJA 1993 eta–VAS data. A single linear relationship applies that suggests as the diurnally oscillating (1900 EST minus 0700 EST) frequency of high cloud increases, an increase in the convergence is noted. A correlation coefficient of 0.94 confirms this relationship. The least-squares fit, which explains approximately 92% of the variance, indicates that high cloud increases nearly 6% per 1×10^{-5} s^{-1} increase in convergence. The strong correspondence between the timing of these two parameters suggests that the diurnal oscillation in high cloudiness is controlled by dynamics. However, the frequency in high cloudiness is also found to be influenced by the diurnal oscillating LTS (Fig. 9b). It is interesting to note that while 92% of the variance in high cloud amount is explained by boundary layer convergence, only 60% is explained by variations in stability.

Diurnal variations in LTS are also compared to variations in the frequency of low cloudiness. A least-squares fit indicates an increase in the frequency of low clouds during the day of about 12% per degree Celsius decrease in LTS. In this case, 74% of the variance in low cloud occurrence throughout the GSL can be attributed to LTS. In the area off the coast of Virginia

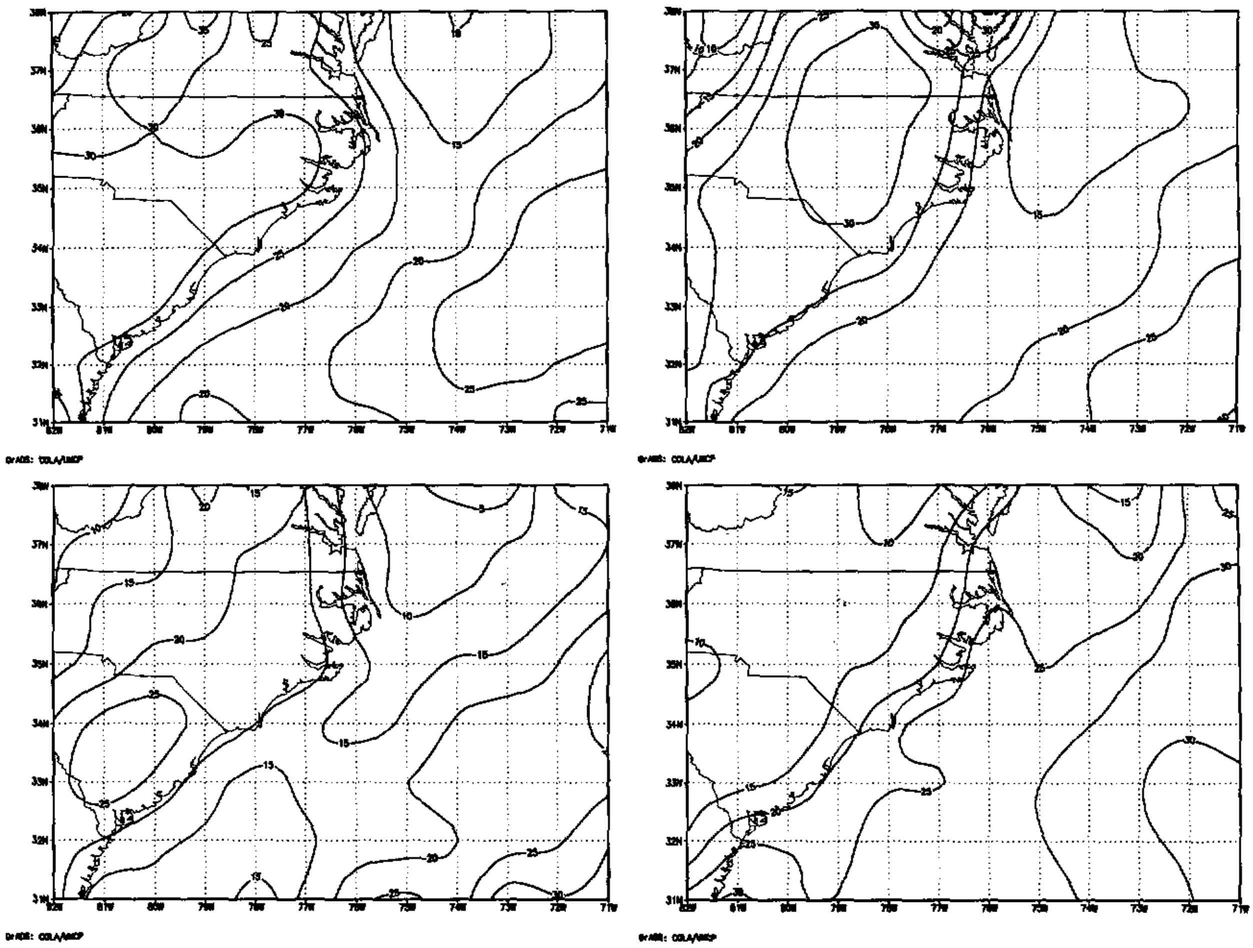

FIG. 13. The same as Fig. 12 except for low cloudiness: (a) 1900 EST, (b) 0100 EST, (c) 0700 EST, and (d) 1300 EST. Contour intervals of 5% are shown.

and northeastern North Carolina, however, an increase in low clouds is correlated with an increase in LTS. The maximum frequency in low clouds in this area, which is observed at 1300 EST, is coincident with a maximum in LTS (stable conditions). Furthermore, the sensible heat flux tends to be negative in the afternoon in this region. If this area of the GSL is removed from the overall statistics, then 88% of the variance in low cloud occurrence may be attributed to diurnal changes in LTS.

VAS cloud frequencies are compared with JJA 1993 surface observations from RDU and HAT, respectively. The VAS data were compiled for a 25-km radius around each site and summarized four times daily. Surface observations at RDU indicate a 78% frequency of cloudiness at 1300 EST. VAS observations indicate an 83% occurrence at this time (Fig. 11a). This maximum is also consistent with a maximum in the occurrence of afternoon thunderstorm activity that is observed in the surface data (Table 1). Observations at RDU indicate that convective activity has the expected afternoon maximum. As suggested in Gray and Jacobson (1977), if convective activity is associated with an organized weather system, then the diurnal variation may be modified. A decrease after 1300 EST is observed with a minimum found in both the VAS and RDU data near 0700 EST. A 10% difference in the frequencies is reported at 1900 EST, however, the other comparisons remain within 5%.

At HAT, the maximum frequency of cloudiness is found between 0100 and 0700 EST (Fig. 11b). A minimum around 1900 EST is observed. Differences between VAS and surface observation estimates differ by more than 10% at 1900 EST. At other times, the estimates of cloudiness are more consistent. Gray and Jacobson (1977) found that over coastal waters surrounded by land outgoing IR is higher in the evening than in the morning. Thus, higher outgoing IR at 1900 EST would mainly be a reflection of the relatively greater frequency of high clouds at 0700 EST. They concluded that this feature was suggestive of an early morning enhancement in convective activity over coastal waters in

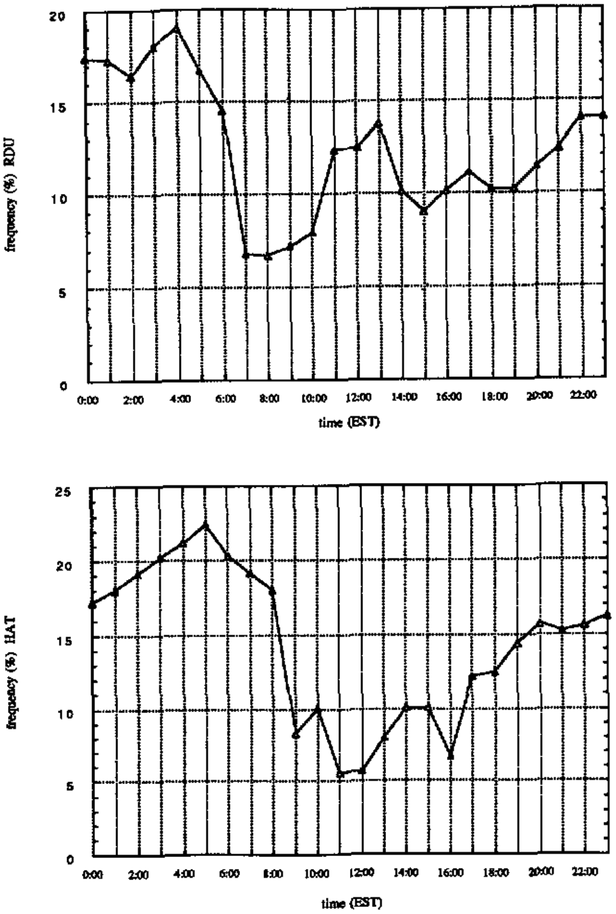

FIG. 14. The frequency of precipitation during the winter of 1994 at (a) Raleigh, North Carolina (RDU), and (b) Cape Hatteras, North Carolina (HAT). Both stations indicate a nocturnal maximum in the frequency of precipitation. The peak frequencies at RDU and HAT are found at 0400 and 0500 EST, respectively. Minimums are observed in the morning and afternoon hours.

association with the land–sea-breeze circulation systems. Indeed, reports of thunderstorm activity at HAT show a double maximum; one between 0100 and 0700 EST and another at 1300 EST (Table 1).

b. Winter 1994

The GSL had an above normal number of cold-air outbreaks and East Coast cyclones during DJF 1994. For the entire domain, cloudiness is found nearly 10% more often than in the 7-yr climatology. Unlike the climatology, high cloudiness during DJF 1994 shows a variation with a maximum of 40% near 1900 EST and a minimum in occurrence (25%–30%) at 0700 EST (Figs. 12a–d). Midlevel clouds show a maximum in occurrence in the early morning both over the ocean and land (not shown). The nighttime maximum is followed by an afternoon minimum. Low clouds over land are observed most frequently during the night and least frequently during the afternoon (Figs. 13a–d). Conversely, low clouds over the Gulf Stream are reported more often during the day and least frequently at night. The minimum over the Gulf Stream first develops sometime after 1300 EST and becomes most pronounced 12–18 h later when frequencies of 10%–15% are observed.

The prevalence of a nocturnal maximum in wintertime cloudiness over land requires a different explanation than was given for summer; however, it is possible that it may also be interpreted in terms of dynamical processes. Wallace (1975) reports that most wintertime precipitation in the central and eastern United States is associated with the passage of developing cyclones. In the warm sector of these systems, nighttime inversions are common. According to Blackadar (1957), who found changes in frictional drag to be associated with the diurnal variation in static stability at the top of the planetary boundary layer, winds should be stronger during the late night hours. This is verified from the DJF 1994 eta analyses, which indicate that winds at the top of the planetary boundary layer average 20% stronger at 0100 EST (night) compared

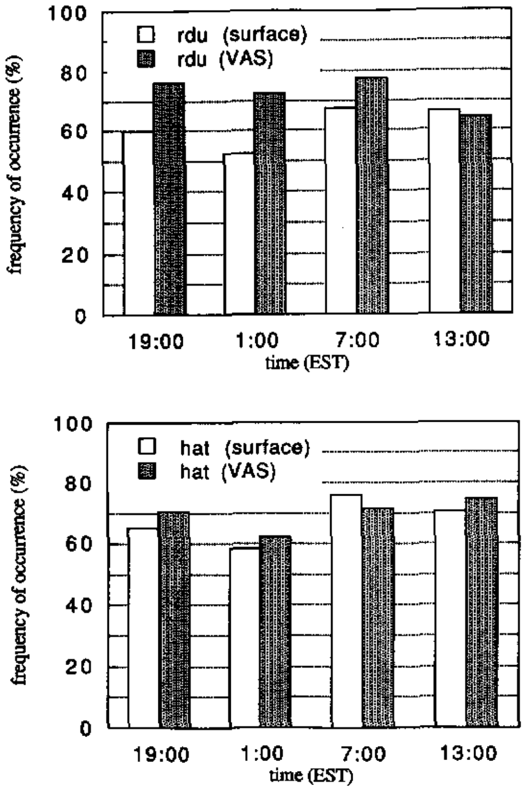

FIG. 15. (a) Comparisons of VAS derived total cloudiness to surface cloud observations at Raleigh, North Carolina (RDU) during the winter of 1994. During winter nights VAS observations tend to overestimate the total occurrence in cloudiness by 10%–15%. (b) Same as (a) except for HAT. The frequency of total cloudiness is greatest in morning and is confirmed by satellite observations. For each analysis time, VAS observations agree to within 5% of surface observations.

to 1300 EST (day). According to Wallace (1975), an increase in wind speeds (within the warm sector boundary layer) will contribute to the amount of lifting above the warm frontal surface, thus enhancing cloudiness and precipitation. This mechanism may serve as one important factor in the observed nighttime cloudiness over land in the GSL. Indeed, surface data from RDU and HAT both indicate a nocturnal maximum in precipitation frequency (Figs. 14a,b). These figures indicate the frequency of occurrence of all forms of precipitation during DJF. At RDU, the maximum in occurrence is found near 0400 EST followed by a rapid decrease by 0700 EST. At HAT, the maximum frequency increases from 12% at 1700 EST to a nocturnal maximum of approximately 22% by 0500 EST. Thereafter, a decrease is observed with frequencies less than 10% found by 1100 EST.

The diurnal variations in the frequency of low cloudiness over the Gulf Stream are compared to variations in the sensible heat fluxes derived from the eta analyses. According to these analyses, the sensible heat flux over the Gulf Stream is greatest at night when the air–sea temperature difference is largest. The heat flux is found to be approximately 25% (15–20 W m^{-2}) greater at night compared to day. The times of maximum and minimum heat flux are 0700 and 1300 EST, respectively. During daytime, the sensible heat flux is found to decrease in association with a reduced air–sea temperature difference. Surface winds from the eta analyses are also found to decrease during this period. VAS observations show an increase in the frequency of low-level clouds between the early morning minimum reported at 0700 EST (maximum heat flux) and the diurnal maximum reported at 1300 EST (minimum heat flux). It is hypothesized that the increase (decrease) in the flux may be one important factor in the future formation (dissipation) of low clouds. Using a random sample of DJF 1994 VAS–eta data, a 6-h lag between the maximum sensible heat flux and maximum occurrence of low clouds is established. A correlation coefficient of 0.81 is computed and the least-squares fit explains 85% of the variance. Assuming the MBL is well mixed (as is likely over the Gulf Stream), the timescale for mixing within the boundary layer may be on the order of several hours. Unfortunately, the time resolution of this data is insufficient to account for a meaningful lag. Furthermore, it is suggested that the diurnal cycle in low clouds is responding to factors other than the sensible heat flux. Clearly, a modeling study and or an analysis of in situ data is necessary to better understand this diurnal cycle.

The surface wind direction is also considered as an important factor controlling the production and maintenance of low clouds. During winter, the surface wind can vary greatly over the Gulf Stream and is essentially a function of synoptic conditions. During the winter of 1994, surface winds had an offshore component more than 68% of the time. This is a condition that leads to the advection of cold, dry continental air over the warm Gulf Stream waters (25°C). As documented in Vuckovich et al. (1991) when the height of the marine boundary layer equals the height of the lifted condensation level convective elements produce low clouds. Surface winds the remaining 32% of the time had some onshore (easterly) component and were also coincident with a high occurrence of low cloudiness.

VAS comparisons to total cloudiness reported at RDU indicate a 10%–15% overestimate by the satellite technique except at 1300 EST, when only a 1% discrepancy is found (Fig. 15a). The overestimate by VAS at night has been discussed in section 2. The trends are the same, however, as maximum cloudiness is found near 0700 EST both in VAS and the surface observations. It is also important to note that the diurnal variation in total cloudiness is 20% less than that for JJA 1993. Comparisons at HAT also show the frequency of cloudiness is greatest in the morning (Fig. 15b). VAS observations in this comparison agree much better than those at RDU. Since HAT is a coastal station, the VAS false identification errors of clear sky as low cloud are less of a problem than those at RDU. In all instances, VAS determinations agree to within 5% of HAT surface observations.

6. Conclusions

In this paper, the diurnal variations in cloudiness over the Gulf Stream locale (GSL) have been documented. In most regions of the GSL there is some response of the atmosphere to the 24-h solar cycle. However, the degree of regularity often varies. Remote-sensed cloud-top heights are used to examine diurnal variations present in summer and winter. Even during winter when midlatitude storms and cold air outbreaks frequently occur, diurnal variations are still reported. The results of this study have shown general trends regarding cloud variability on the diurnal cycle. These trends are supported by surface observations of cloudiness and model analyses. In this study, 6-h resolution cloud data was available, making it possible to infer diurnal changes. It is clear, however, that monitoring diurnal cloud cycles in the GSL requires better temporal resolution.

During the summer months both high- and low-level cloudiness were found to vary greatly on the 24-h cycle. The frequency of low and high clouds over land are found to increase together during daytime. High cloudiness was found most often over land and least often over the ocean during the evening hours. This is the time of day when convective activity was observed most frequently. Surface observations during the summer of 1993 also confirm an increase in total cloudiness and thunderstorm activity during the afternoon and evening. Between the evening and the morning hours a decrease in high cloud was found over land while an increase was observed over the Gulf Stream region. A strong relationship between the occurrence of high cloud in the evening over land and those over the Gulf Stream region 18 h later is reported. Advection is shown to be one important factor. The relationship between the modulation of high cloud on the diurnal cycle and boundary layer convergence was investigated. A single linear relationship was found indicating that the diurnally oscillating frequency of high cloud increases as boundary layer convergence increases. The strong correspondence between the timing of these two parameters suggest that the diurnal oscillation in high cloudiness is mainly controlled by dynamical processes associated with afternoon convection. The diurnal oscillation of high cloud was also shown to be related to the diurnally oscillating lower tropospheric stability although the relationship was not as strong. The diurnal variations in low cloudiness over land were found to be strongly related to the diurnal heating cycle. This is partially the result of the diurnal oscillation of lower tropospheric stability, which is found to be lowest during daytime. Large diurnal variations in low cloudiness were detected off the coasts of Virginia and northeast North Carolina although the diurnal cycle could not be explained by this data.

During the winter months, diurnal variations in mid- and low-level cloudiness were found. Midlevel clouds are indicated most often in the predawn hours followed by a 50% decrease in occurrence by afternoon. The morning maximum in midlevel cloudiness is consistent with the nocturnal maximum in precipitation frequency found during the winter months by Wallace (1975). Low-level clouds also exhibit a nocturnal maximum, particularly over land. The nocturnal maximum in cloudiness over land is shown to be related to nighttime inversions and the subsequent increase in winds at the top of the planetary boundary layer. Satellite observations indicate, however, that over the Gulf Stream region low clouds are found most often during daytime when the sensible heat flux is least and least often at night when the heat flux is greatest. A lag of approximately 6 h was observed between the maximum heat flux and minimum in low cloud, although if a true lag does exist it is believed to be on the order of an hour or two.

The data used in this investigation represent only a small geographical area. The relatively long averaging period gives us confidence in the statistical reliability of the results. Because it is a climatological feature, diurnal cloud variability may be a function of geography and season. Since the Gulf Stream modulates atmospheric conditions on the diurnal cycle physical interpretations of diurnal cloud variations becomes quite complex. Therefore, any comprehensive understanding of this subject requires further research utilizing more observations, comparisons, and modeling work.

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