Surface Wind–Pressure Gradient Relationships in Central Florida

ROBERT A. MADDOX

NOAA, Environmental Research Laboratories, National Severe Storms Laboratory, Norman, Oklahoma

HUGO F. BEZDEK

NOAA, Environmental Research Laboratories, Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida

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ABSTRACT

An extended series of surface observations is used to compare observed surface winds with winds computed using the geostrophic relationship. These computations are done for both steady and unsteady wind regimes. Large differences are found in the comparisons of observed to computed winds. The differences exhibit pronounced seasonal and diurnal variability that appear to reflect both boundary layer stability and small-scale wind and pressure fields—for example, those attending land–sea breezes and thunderstorms.

The results of this study may be useful to those engaged in studying global datasets and to modelers, who are continually challenged to improve the treatment of parameterization of turbulent processes. However, it is not obvious that any simple parameterization can be applied to obtain an accurate estimate of the surface wind in central Florida, given only the large-scale pressure gradient or a model-predicted wind above the surface as input. The use of the pressure field to estimate surface winds is an uncertain exercise at best.

1. Introduction

The degree to which the winds approach geostrophic balance has long been of interest in studies of the atmospheric boundary layer (e.g., Blackadar 1957; Wexler 1961; Hasse and Wagner 1971; Schaefer and Doswell 1980; Garratt et al. 1982; Joffre 1985). The relationship between the surface wind and computed geostrophic wind has also been investigated over the German Bight (at sites 15 and 60 km offshore) by Luthardt and Hasse (1981). Hoxit (1975) examined boundary layer wind profiles for a dataset from three stations in the southeast United States. As he and many others have noted, the angle between the surface wind and the surface isobars increases with increasing stability; this coincides with a decreasing Ekman layer depth. Hoxit further concluded that the geostrophic departure method for computing surface stress is valid only in the afternoon hours. However, he did not attempt to compare observations of surface wind to estimates of wind derived from the surface pressure field using the geostrophic relation. This study extends his approach by examining hourly surface data over the Florida peninsula and comparing observed winds with geostrophic winds derived from the surface pressure field.

The relationship between the surface wind and the concurrent geostrophic wind can be quite important for a variety of situations. For example, can accurate surface wind speeds be estimated over large data-void areas of the globe, given only analyzed pressure gradients or model-predicted surface pressures and winds at some level above the surface? Attempts to answer this question motivated the work by Luthardt and Hasse (1981).

In most numerical prediction models, the wind is explicitly predicted at a discrete level above the surface (typically 40–100+ m—see Klemp and Wilhelmson 1978; Hansen et al. 1983; Warner and Seaman 1990). The surface wind is then estimated via some simple parameterization of turbulence and mixing. (Departure from geostrophic balance is a measure, among other processes, of the effects of turbulent processes acting on the flow.) Treatment of these processes in models can be critical for model-based studies of air–sea interactions, where the surface wind stress is of substantial importance to the sensible and latent heat fluxes. Hansen et al. (1983) demonstrate the importance of properly representing these processes by comparing model runs with two different wind stress parameterizations; winter temperatures can change by as much as 10 K in northern latitudes and energy transports can vary by a factor of 3 at low levels.

The principal motivation for this study originated from an examination of data from the Comprehensive Ocean–Atmosphere Data Set (COADS) (Woodruff et

Corresponding author address: Dr. Robert A. Maddox, National Severe Storms Laboratory, 1313 Halley Circle, Norman, OK 73069.

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al. 1987). It is well known that observed winds from COADS have decadal trends; however, the validity of these trends has been questioned (Cardone et al. 1990, and references cited therein). To provide a simple test of the validity of the trends in the observations, Hansen and Bezdek (1994) used shipboard surface pressure measurements to estimate surface winds in order to compare these trends with those from the observations. During the course of that study, it was found that observed surface winds varied widely when compared to winds expected from geostrophic balance constraints. However, the COADS dataset contains monthly means of observed wind speed and direction in addition to the corresponding sea level pressure, all of which are derived from individual measurements contained in a 2° × 2° latitude–longitude grid. Unfortunately, the individual measurements are not uniformly distributed in either space or time.

With a view toward better understanding the nature of the relationship between observed and pressure-derived winds, an attempt was made to find a dataset with improved internal consistency. Unfortunately, such datasets exist only over land and not over the ocean. Surface data from Florida were examined for an extended period, because the results could provide a baseline for interpreting the COADS data within the framework of geostrophic balance. Recognizing that the diurnal heating and widely varying surface character of the land presents a vastly different boundary condition than does the ocean, we expect worst-case results relative to ocean observations.

2. Observations and methodology

Observational data from the Florida peninsula were used since there are several stations with long periods of record, continental effects should be minimal, and elevations of stations considered are all very close to sea level. The stations in this study were chosen so that the geometry was roughly the same as that used for calculations based on the 2° × 2° latitude–longitude grid of COADS. As noted above, it is obvious that surface characteristics over land are vastly different than over the ocean. However, the significant advantage of the land measurements is that these observations are made in a consistent and uniform manner.

Five surface observing stations in central and northern Florida were chosen: Gainesville (GNV), Jacksonville (JAX), Daytona Beach (DAB), Tampa (TPA), and Tallahassee (TLH) (see Fig. 1). For each of the five stations, six years of hourly surface data were obtained from the National Climatic Data Center. This amounts to more than 52 000 hours of data per station. The sea level observations at the four outside stations were used to fit a plane, in the least-squares sense, to the pressure field from which were obtained the east and north pressure gradients at GNV. These pressure gradients, computed across a distance of approximately

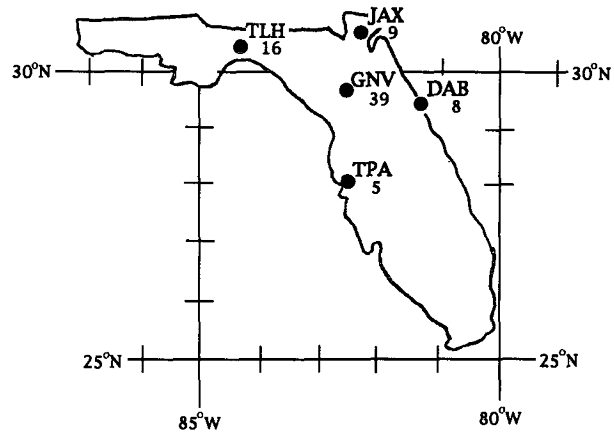

FIG. 1. Map showing locations and elevations (m) of observing sites used in this study.

350 km, were then used to calculate a surface wind estimate using the geostrophic equation. (Note that we did not attempt to parameterize surface stress or drag, and the geostrophic wind computed reflects a simple balance between the surface pressure and Coriolis forces.)

The geostrophic assumption is most valid for synoptic scales, and the station spacing here is adequate for estimating the large-scale pressure gradient. Small-scale gradients will of course cause the local wind to deviate from geostrophic balance. It is also important to realize that more closely spaced observing stations are not appropriate for this type study for two reasons. The first is the condition on the geostrophic assumption noted above; the second is that the imprecision of routine, operational pressure measurements precludes accurate estimation of the geostrophic wind if stations are closer than about 150 km (C. Doswell 1994, personal communication).

The computed geostrophic surface winds were compared to the measured winds at the central station, GNV. Before making the comparisons, those cases for which the wind speed was zero at GNV were removed from the dataset. This was done to allow realistic comparison of actual winds with computed geostrophic winds: we did not examine the cases in which the surface layer was calm and completely decoupled from the overlying atmosphere. There were about 11 500 hours of calm wind observations (slightly more than 20% of the sample) at GNV. These calm wind cases exhibit a diurnal and seasonal distribution in accord with expectations related to stability of the boundary layer (i.e., stable, calm boundary layers prevail at night and during the cool season). The final dataset contained observations for more than 40 000 hours at each of the five stations.

The observed wind directions and speeds at GNV (Fig. 2) show that much of the year is dominated by pronounced northeasterly to easterly winds associated

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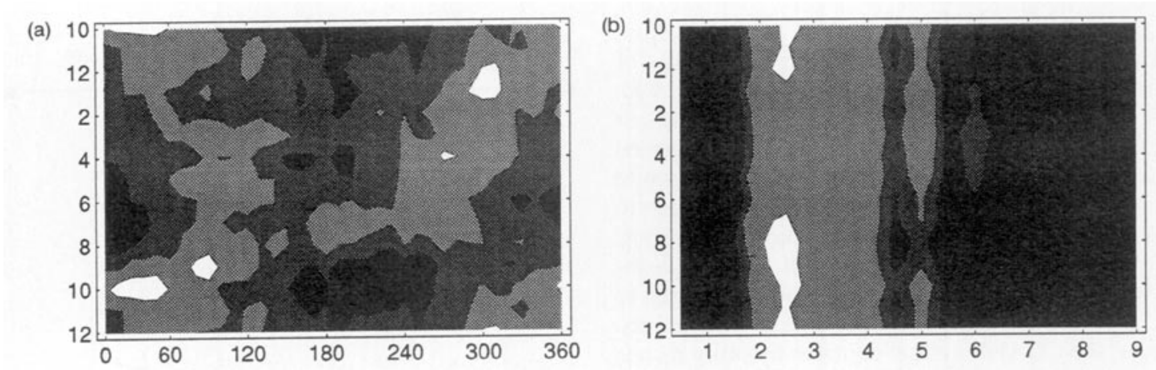

FIG. 2. (a) Frequency of occurrence of observed wind direction (increments of 10°): black is less than 50; medium gray is 50–99; light gray is 100–199; and white is 200 or more. (b) Frequency of occurrence of observed wind speed (in increments of 0.5 m s^{-1}) as functions of the month at Gainesville: black is less than 50; dark gray is 50–149; medium gray is 150–249; dark gray is 250–699; and white is greater than 700. Months 10–12 are repeated to emphasize the structure of the seasonal cycle.

with the subtropical band of trade winds. A secondary flow regime with westerly to northerly winds occurs during the cool half of the year when midlatitude cold fronts occasionally penetrate southward across Florida. The geostrophic winds (Fig. 3) are somewhat consistent, except that the directions are clustered more tightly around easterly and northwesterly directions. The geostrophic speeds tend to be higher. The wind speeds increase in the winter and early spring and then decrease in late spring and summer. It should be noted that easterly flow prevails over Florida, even during the cool months of the year.

Comparisons between the observed and calculated geostrophic winds were made for two stratifications of the wind observations at GNV. These were chosen to distinguish between steady and unsteady wind regimes. Periods of steady winds are felt to be most representative of synoptic-scale forcing—that is, of situations where the geostrophic approximation is most applicable and where it is more likely that the observed winds would approach geostrophic balance. The regimes were determined by finding runs of consecutive observations, within the dataset remaining after calm winds were removed, that had hour-to-hour changes of 20° or less in wind direction. Steady wind regimes were arbitrarily chosen to be those with runs of 20 hours or more. Unsteady regimes constituted the remaining dataset—that is, observations remaining after the calm winds and steady regimes were extracted. Interestingly, more than 16 000 hourly observations occurred during steady wind regimes, indicating the persistent nature of the subtropical trade-wind pattern that is often in place over Florida. (As will be shown later, the steady wind regime is dominated by winds from the north to east-southeast.)

3. Regime calculations

The computed hourly differences between the observations and the geostrophic wind direction (see Figs. 4 and 5) indicate that the steady regime data are more centrally distributed about a turning angle of approximately −40° (i.e., observed wind blowing down the

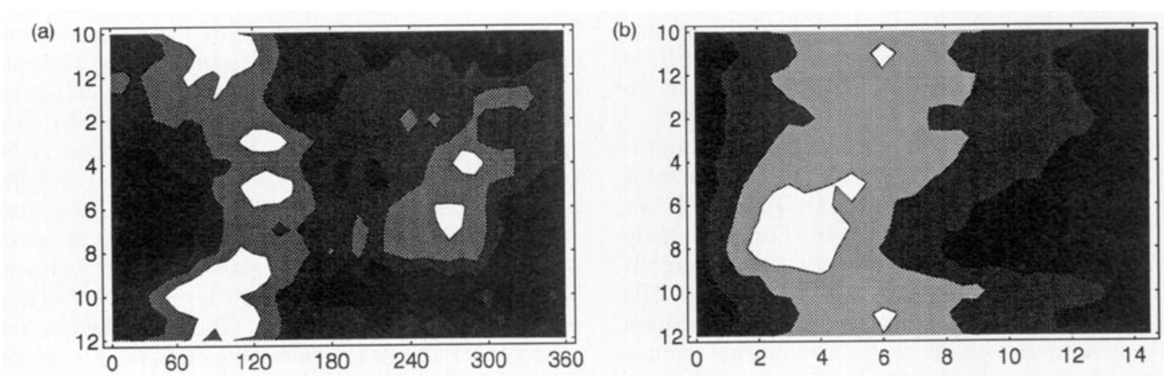

FIG. 3. (a) Frequency of occurrence of geostrophic wind direction (increments of 10°): black is less than 50; medium gray is 50–99; light gray is 100–199; and white is 200 and greater. (b) Frequency of occurrence of geostrophic wind speed (in increments of 0.5 m s^{-1}) as a function of the month at Gainesville: black is less than 50; medium gray is 50–149; light gray is 150–249; and white is 250 and greater.

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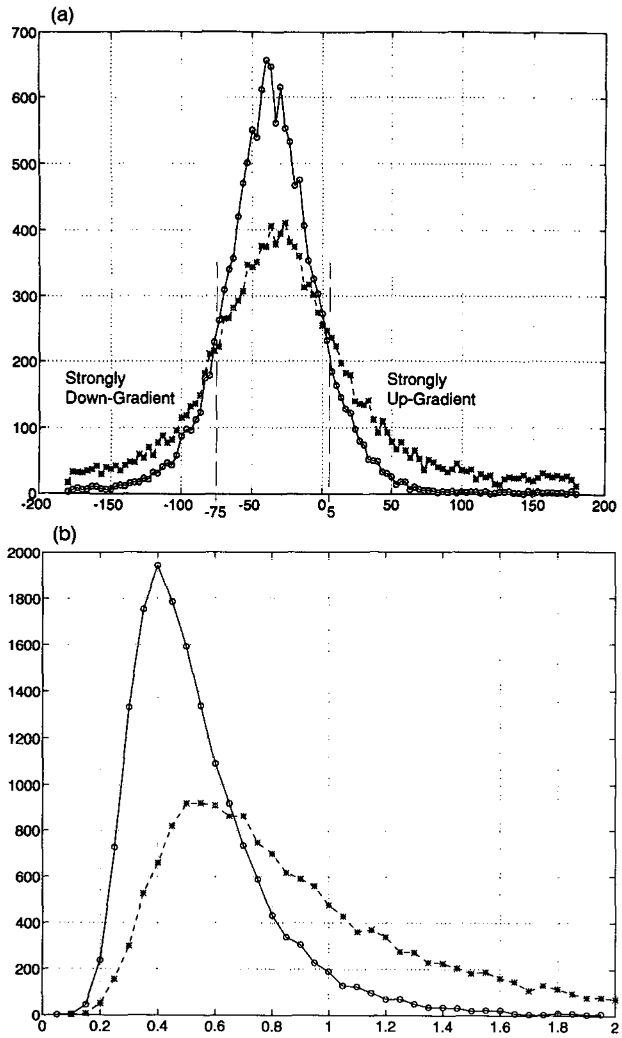

FIG. 4. Histogram of (a) turning angle and (b) speed ratio (observed/geostrophic). The solid line is for observations during steady wind regimes, and the dashed line is for unsteady periods.

pressure gradient; 0° corresponds to observed wind parallel to geostrophic wind). The variable wind regime was less well behaved and showed much greater deviations from geostrophic conditions. This is to be expected, since unsteady regimes suggest wind characteristics that would be less amenable to the geostrophic approximation. It is interesting that a substantial number of observations were characterized by winds apparently blowing strongly up or down the pressure gradient, and we will discuss the possible physical causes of this result a bit later. The steady regime ratio of observed to geostrophic wind speed (Fig. 4b) is sharply peaked at a value of 0.4; the unsteady regime is broadly distributed.

a. Seasonal and diurnal aspects

There are several obvious aspects of the distribution of steady wind regime observations by month and time of day (Fig. 6a): the steady wind regimes occur most frequently during the fall (October and November); these regimes tend to exclude observations taken in the middle of the day during the summer; and steady run hours minimize during the summer months of June, July, and August. This seems plausible if "steadiness" requires strong large-scale pressure gradients that are more typically present in Florida during the cool season. Similarly, unsteady wind regimes (Fig. 6b) tend to occur much more frequently during the daytime, when heating and mixing tend to cause variable winds, and during the summer, when pressure gradients tend to be weak. Note also that thunderstorms and associated small-scale wind and pressure fields tend to occur more frequently in the summer.

The maximum observed speeds relative to geostrophic values tend to occur during late morning to early afternoon (see Fig. 7a), when heating and mixing are maximizing, and during the summer season. Ratios are generally 0.4 or less during the nighttime when the boundary layer is stable and there is less vertical mixing. The turning angles (Fig. 7b) show a corresponding behavior in that values tend to be minimized when heating and mixing is likely to be greatest. It is of interest to note that the observed winds are closest to geostrophic for steady wind regimes during the summer, when these regimes are least likely to occur.

These results are generally similar to those of Hoxit (1975) for surface stations in the southeast. (Note that his three stations were well inland.) The diurnal range of turning angle at GNV is greatest in summer and fall, remaining relatively large through the year, whereas Hoxit's results show reduced diurnal ranges during the winter and spring for more continental stations.

b. Large upgradient and downgradient flow

The large number of ageostrophic observations at GNV suggests that an examination of the wings of the

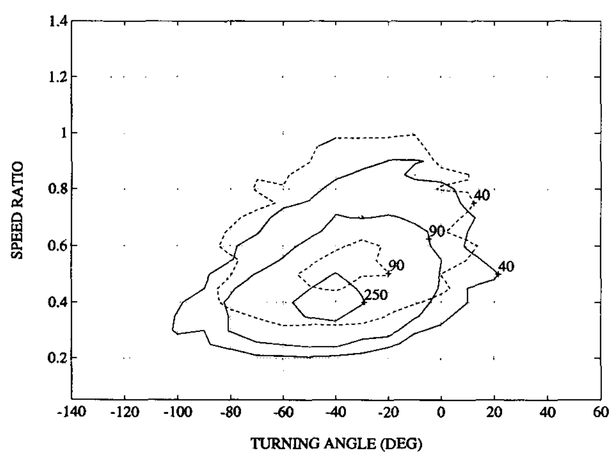

FIG. 5. Contours of frequency of occurrence of speed ratio as function of turning angle for steady cases (solid) and unsteady cases (dashed).

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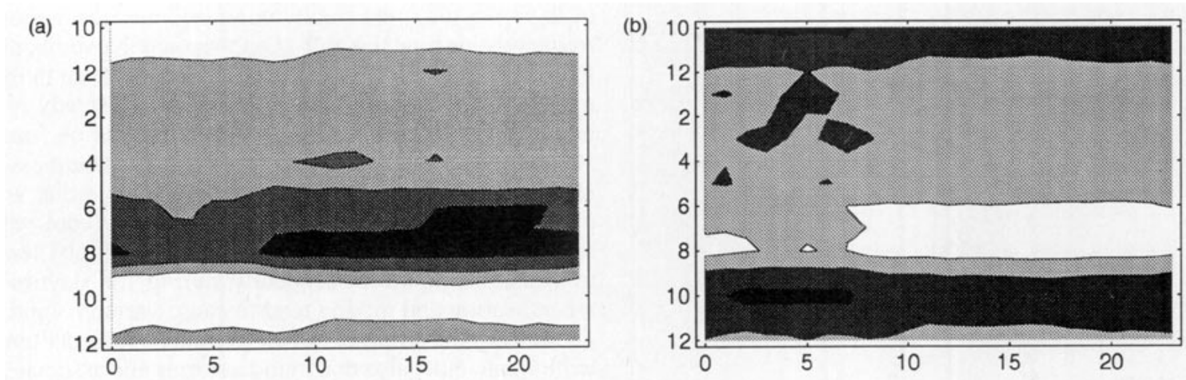

FIG. 6. Frequency of occurrence of observations during (a) steady and (b) unsteady wind regimes as functions of the month and hour of day. (Plots show LST hour of day to illustrate the diurnal heating cycle.) The gray scale is the same in (a) and (b): black is less than 25; medium gray is 25–49; light gray is 50–74; and white is 75 and greater.

data distribution might provide further insight into the causes. The monthly and diurnal distribution of strongly upgradient wind directions (turning angles of +5° or more) is presented in Fig. 8a. These cases clearly occur most often during the fall and spring, with distinct peaks in September, November, and April. Further, they tend to occur most frequently from about 0900 through 1600 LST, the period of diurnal heating.

In contrast, the cases of strongly downgradient flow [turning angles of −75° or less (Fig. 8b)] exhibit a minimum during the midpart of the day in the summer but show a strong preference to occur during the fall and winter. This result seems physically plausible since large downgradient flow occurs within the southern sectors of large anticyclones (Hoxit 1975). Florida is most likely to be in this synoptic environment (i.e., large anticyclone moving from the northwest to the northeast with the cool air mass covering Florida) during the cool season. This physical picture is apparently confirmed by the distributions of observed wind direction versus computed turning angle shown in Fig. 9 for both wind regimes. Strongly downgradient flow tends to occur when the surface wind direction ranges from about 300° to 090° through the north—that is, when Florida is in the cool air south of the center of anticyclones.

However, Fig. 9 does little to help elucidate the reasons for cases of strongly upgradient flow (refer to Fig. 8a). These cases tend to be characterized by two distinct windows of wind direction: from about 240° to 300° and also from about 080° to 180°. Since these cases occur principally during the daytime, two possible causes suggest themselves. First, the strongly upgradient winds could result from thunderstorm outflows that would reflect the local pressure forcing and thereby could be strongly out of phase with the large-scale gradient. However, thunderstorm activity over Florida predominates during the summer, not during the cool season.

A second mechanism could be that the inland character of Gainesville leads to stronger diurnal heating and pressure decreases than those that occur at the coastal ''corner'' stations. During weak large-scale gradient situations, the observed wind in central Florida

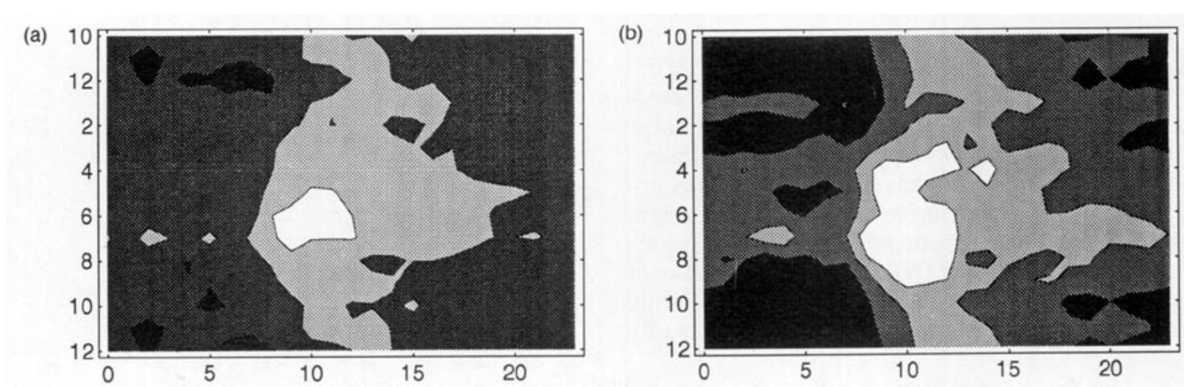

FIG. 7. (a) Contours of mean speed ratio: black is less than 0.4; medium gray is 0.4 to less than 0.6; light gray is 0.6 to less than 0.8; and white is 0.8 and greater. (b) Contours of a vector average turning angle as functions of the month and hour of day for the steady cases: black is greater than −15°; medium gray is −15° to greater than −30°; light gray is −30° to greater than −45°; and white is −45° and less.

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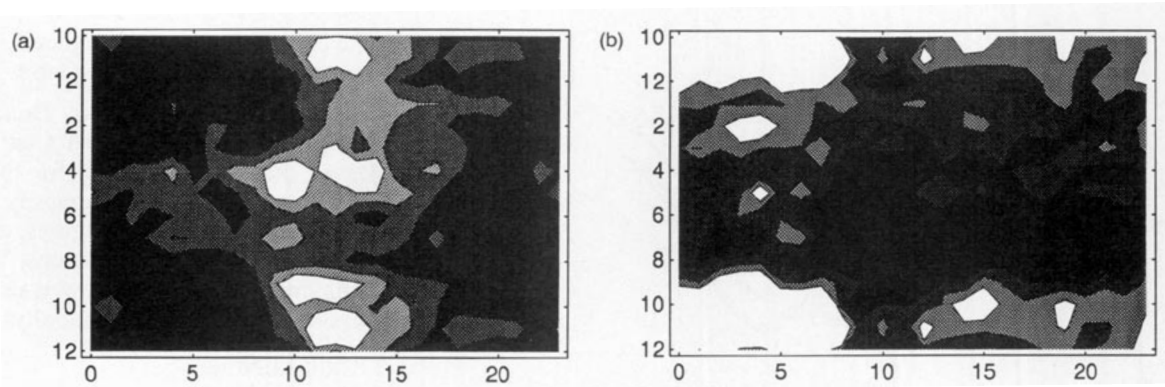

FIG. 8. (a) Frequency of occurrence of turning angle greater than 5°: black is less than 5; medium gray is 5 to less than 10; light gray is 10 to less than 15; and white is 15 or greater. (b) Frequency of occurrence of turning angle less than −75° as functions of the month and hour of day for the steady cases. The gray scale is the same as for (a).

could reflect local pressure gradients that differ substantially from the synoptic situation (i.e., the apparent cases of strongly upgradient flows could reflect the frequent occurrence of local, thermally driven circulations inland over Florida). Figure 10 shows the annual average diurnal pressure curves for the five stations involved and lends support to this hypothesis, since the peak-to-peak changes in the amplitude of the GNV and TLH curves are greater than that of the other three stations. [Note that the observation site at TLH is somewhat inland relative to TPA, DAB, and JAX (Fig. 1).]

Furthermore, since the GNV and TLH average pressure traces *cross* the TPA and DAB curves during the afternoon, it is apparent that the relationship of observed to computed geostrophic winds can change dramatically during the day due to local pressure changes. The effects of the diurnal pressure tendency on our calculations should be most apparent during the late morning/early afternoon when the largest average pressure falls of 2–3 mb occur—that is, from 1000 to 1600 LST (in agreement with both Figs. 8b and 10).

4. Discussion

The comparison of observed winds with those derived from the surface pressure gradients, calculated across a distance of several hundred kilometers, and the geostrophic approximation illustrates the complexity of the surface geostrophic wind relationship. The variability of speeds and directions relative to those computed for the geostrophic wind is quite large. This study is somewhat hindered by having only surface wind data. However, the results are in general agreement with what would normally be expected: turning angles tend to be greater, that is, more negative, and speeds tend to be considerably less than geostrophic values at night when the boundary layer is more stable with suppressed vertical mixing.

Given a simple starting hypothesis that the winds over Florida should be relatively well behaved, at least in synoptically dominated steady wind regimes, with respect to observed pressure gradients and the geostrophic approximation, the results of the calculations

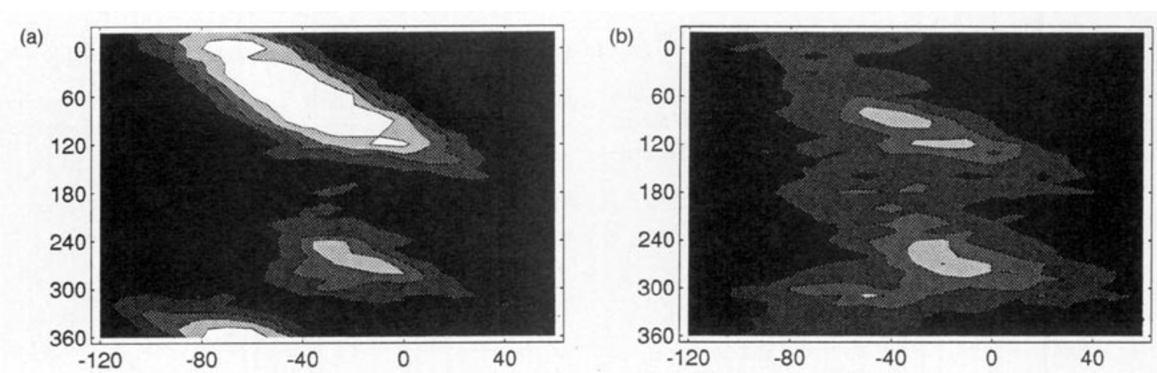

FIG. 9. (a) Frequency of occurrence of observed wind direction (increments of 10°) at Gainesville as a function of turning angle (increments of 10°) for steady regimes: black is less than 20; dark gray is 20–39; medium gray is 40–59; light gray is 60–99; and white is 100 and greater. (b) Frequency of occurrence of unsteady regimes: the gray scale is the same as (a), with no counts reaching the white level.

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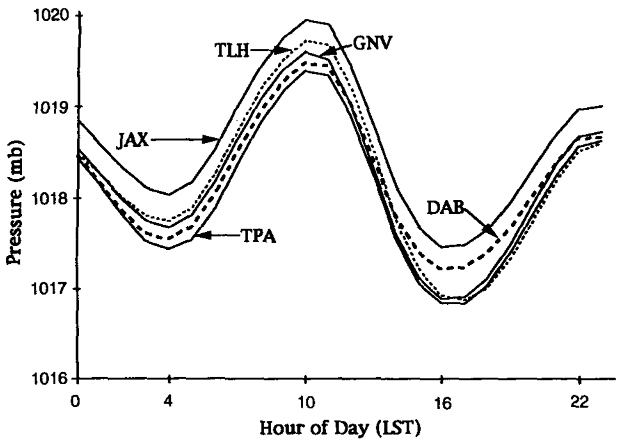

FIG. 10. Average diurnal cycle of sea level pressure at the five stations used in this study.

show a large variance with geostrophic balance. Small-scale pressure gradients, such as those associated with land and sea breezes and thunderstorms, undoubtedly cause much of this variance. The results show that use of the pressure field to estimate surface winds is an uncertain exercise at best, which is in concert with the conclusions of Hoxit (1975) and Doswell (1988). It is not obvious that any simple parameterization could be applied to obtain an accurate estimate of the surface wind at Gainesville, given only the large-scale pressure gradient as input, or, by implication, given a model-predicted wind at some level above the surface.

Interestingly, Luthardt and Hasse (1981) also concluded that the surface wind–surface pressure relationship was not well behaved for the German Bight area. For the ocean, these conclusions are unfortunate indeed. Datasets from platforms with stable spatial and temporal characteristics (such as used in this study) are rare and simply do not exist for oceanic areas. This means that wind stress at the ocean surface, the principal forcing for ocean circulation, must be estimated in some indirect manner. It is clear that the surface pressure field will not provide a particularly good estimate.

One more point is worth noting. The value of data summaries for wind and pressure fields, such as in COADS, might be improved greatly if atmospheric stability and geostrophic consistency were considered and somehow included in the summarizing procedures.

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