

The Diurnal Distribution of Lightning over North Florida and Its Relation to the Prevailing Low-Level Flow

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ABSTRACT

Six years (1989–94) of cloud-to-ground lightning data are used to examine the distribution of lightning across the Florida panhandle and adjacent coastal waters and its relationship to the prevailing low-level flow. Only warm season data between 1 May and 31 October are used. The prevailing flow is determined by subdividing the low-level (1000–700 mb) vector mean wind into categories that are either parallel or perpendicular to various parts of the coastline. Moderate wind speeds ($2\text{--}5\text{ m s}^{-1}$) generally are found to be more conducive to producing lightning than stronger speeds. Wind speeds stronger than 5 m s^{-1} likely inhibit the formation of the sea breeze, the main focus for summertime thunderstorms in the region.

Onshore, offshore, and parallel flows are found to play important roles in determining the patterns of flash locations in each flow regime. The complexity of the coastline also is found to have a major impact on the flash distributions. The prevailing wind direction is shown to be related to the time of peak afternoon lightning occurrence as well as the frequency of nighttime storms.

1. Introduction

Lightning is a deadly and frequent phenomena over many parts of the United States. Much of the recent research about lightning in the United States has used data from the National Lightning Detection Network (NLDN) (Cummins et al. 1998). Orville (1994) performed a nationwide study of lightning distribution between 1989 and 1991. Florida was found to have the greatest flash densities, followed by portions of Oklahoma, Texas, Alabama, and the Carolina coast. A more detailed study of summertime lightning in the southeastern United States was conducted by Watson and Holle (1996) in preparation for the 1996 Summer Olympic Games. Highest concentrations of lightning were found over the Florida peninsula, with other local maxima scattered along coastal sections of the Florida panhandle, Georgia, and South Carolina. A recent 10-yr monthly lightning climatology of Florida (Hodanish et

al. 1997) showed that July is the most active period, with the greatest concentrations located in the center of peninsula, that is, inland of both coasts.

Much of the lightning in Florida and other coastal regions can be attributed to sea-breeze-induced convection. Lightning data have been used to study sea breezes over the Florida peninsula. For example, López and Holle (1987) examined the distribution of lightning over the central Florida peninsula as a function of the low-level, large-scale flow.

The impact of the prevailing synoptic-scale flow on sea-breeze development has been studied extensively. Estoque (1962) found that offshore flow produced a stronger sea-breeze circulation than did onshore flow. He also noted that certain parallel flows enhanced the sea breeze more than others. Specifically, parallel flow with lower pressure offshore produced a stronger sea breeze than did parallel flow with lower pressure onshore.

Arritt (1993) recently performed two-dimensional numerical simulations of the sea breeze for a wide range of wind speeds, for both onshore and offshore scenarios. The maximum offshore wind speed that still allowed the sea breeze to penetrate inland was found to be 6 m

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s^{-1} . Upward vertical motion along the sea-breeze front was maximized at this speed. On the other hand, offshore wind speeds greater than 6 m s^{-1} kept the sea-breeze circulation entirely offshore, and its vertical motion was small. Arritt's model indicated that sea-breeze vertical motions were weaker for onshore flow than offshore flow. Ascending motion for cases of onshore flow occurred only for speeds less than 5 m s^{-1} .

Three-dimensional numerical models also have been used to examine the influence of the prevailing wind on the sea breeze. McPherson (1970) modeled the effects of an irregular coastline on sea-breeze development. Vertical motions early in the day were found to be maximized at the inland corners of a simulated square bay. However, an asymmetry developed later, with the strongest vertical motions occurring over its northwest corner. Pielke (1974) showed that the sea-breeze convergence pattern exerts primary control over the general location of thunderstorm development over the Florida peninsula.

Gibson and Vonder Haar (1990) conducted a satellite-derived climatology of clouds over the southeastern United States. Their findings also suggested that small-scale features, such as bays and inlets, have an impact on sea-breeze formation. Gould and Fuelberg (1996) found similar results over north Florida using satellite-derived cloud data.

Our objective is to examine the distribution of lightning over north Florida as a function of the prevailing low-level wind velocity and time of day. While extensive lightning studies have been conducted for central Florida (e.g., López and Holle 1987), none has focused on north Florida. In addition, few studies anywhere have considered lightning as a function of the prevailing wind. Physiographic differences between the Florida peninsula and panhandle motivate this study. Specifically, the coastline of the Florida panhandle is more complex than the relatively straight coasts of the peninsula. In addition, the panhandle lacks the multiple sources of moisture that surround the peninsula; the Gulf of Mexico is its only major source of moisture. The present study has similarities to that of Gould and Fuelberg (1996). However, our use of lightning data focuses more on the locations of deep convection than the locations of clouds.

2. Data

The NLDN currently consists of 106 sensors located across the United States (Cummins et al. 1998). The network is managed by Global Atmospheric, Inc. The sensors and detection methodology are described in detail by Cummins et al. (1998) and Orville (1987, 1994). Only cloud-to-ground (CG) flashes are detected. Each NLDN flash record contains time, location, polarity, intensity, and the number of return strokes. Six years of data are used in this study, that is, the warm seasons between 1 May and 31 October of 1989–94. This is the

period when deep convection over the Florida panhandle is most likely due to mesoscale circulations such as the sea breeze.

The NLDN does not detect every CG flash. Instead, the network's detection efficiency during the period 1989–94 has been estimated to be 65%–80% (Cummins et al. 1998). We did not apply any correction to account for this detection efficiency. Although 33% of all flashes produce more than one return ground contact point (Watson and Holle 1996), we included only the location of the initial stroke in this study. The average location accuracy for lightning flashes improved steadily over the period, going from 4–8 km between 1989 and 1991 to 2–4 km through 1994 (Cummins et al. 1998).

The domain of this study consisted of a 3° latitude \times 4° longitude box centered just west of Tallahassee, Florida, at 30.5°N , 85°W . Individual flashes within this domain were superimposed onto a grid whose individual grid cells were $5 \text{ km} \times 5 \text{ km}$. The 78×67 array of 25 km^2 grid cells covered southwest Georgia, southeast Alabama, all but the far western Florida panhandle, the Florida "Big Bend," and the adjacent coastal waters of the Gulf of Mexico (Fig. 1).

The prevailing low-level flow for each study day was determined from the daily 1200 UTC soundings from Tallahassee (13 June 1991–94) or nearby Apalachicola (1989–12 June 1991). These sounding data were available on a CD-ROM (Radiosonde Data of North America) provided by the National Climatic Data Center. The 1000–700-mb vector mean wind was calculated for each day and used to determine the appropriate wind classification for that day. This layer corresponds to that used over central Florida by López and Holle (1987) and over south Florida by Woodley et al. (1982). Precipitable water and temperature lapse rate also were calculated for each study day to describe moisture content and stability.

The flow regimes created for this study were based on the 1000–700-mb vector mean wind. Specifically, our five directional categories are denoted northeast, east, south, southwest, and northwest (Fig. 1). Our objective was to create flow regimes so that the wind within each would be approximately parallel or perpendicular to the various coastlines of the study region. This goal was motivated by previous studies of the sea breeze and associated lightning, for example, Estoque (1962), López and Holle (1987), and Arritt (1993). However, with the many undulations that compose the north Florida coastline, such orientations were not always achieved. Each regime was subdivided into moderate ($\geq 2 \text{ m s}^{-1}$ and $\leq 5 \text{ m s}^{-1}$) and strong ($> 5 \text{ m s}^{-1}$) categories based on the mean speed in the layer. A classification for light winds ($< 2 \text{ m s}^{-1}$) also was created; it included all directions.

3. Results

a. All flow regimes—All hours

Before categorizing the lightning data into the five wind regimes, all data from the study period were com-

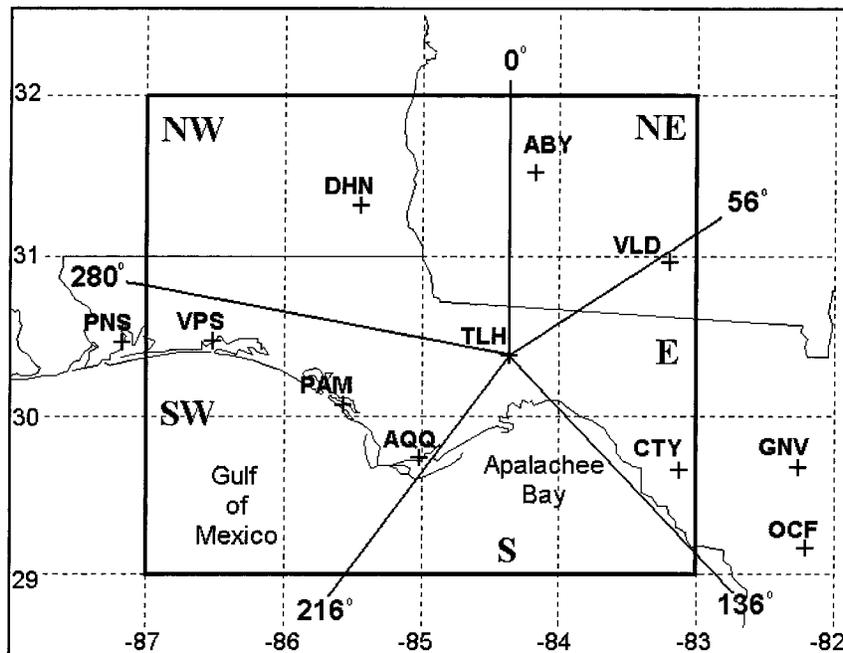


FIG. 1. Outline of study area and divisions for the five flow regimes (NE, E, S, SW, NW). Geographical features and observing sites also are indicated.

bined to determine those locations most prone to lightning. For the months May–October from 1989 to 1994, a total of 2 237 189 flashes was recorded in the study region. Figure 2 depicts the distribution of average warm season flash density (flashes per square kilometer) during the study period. Greatest flash densities (exceeding four flashes per square kilometer, brown color) are concentrated along the panhandle coastline from Panama City (PAM) to Valparaiso (VPS), and also in the Cross City (CTY) area of the eastern Big Bend (see location identifiers in Fig. 1). These locations suggest that the lightning is closely linked to the sea breeze. Noticeably smaller flash densities extend from southeastern Alabama into central Georgia. Flash densities offshore generally are smaller than those onshore. However, relatively large flash densities are located over Apalachee Bay, especially its easternmost sections.

b. Individual flow regimes

A total of 1007 out of the possible 1104 days had both the radiosonde and lightning data needed to categorize the days by their 1000–700-mb vector mean wind. Figure 3 shows the distribution of days within each wind regime. Days with southwesterly flow (SW) are most common, while days with northeasterly (NE) winds are least common. Table 1 lists the number of days in each of the 11 categories along with their total number of flashes, the mean and median number of flashes per flow day, and other statistical parameters. The distribution in each category is highly skewed, as

evidenced by large differences between the means and medians. Therefore, we will use the median as the measure of central values.

The strong southwesterly flow category (Table 1) has the largest number of study days (183), the most flashes (440 867), and the greatest median number of flashes per flow day (1301). Conversely, the strong northeasterly category includes the fewest number of days (33) as well as the smallest median number of flashes per day (0). This regime is the least conducive to lightning and deep convection. One should note the large maximum number of flashes on individual days, for example, 32 553 flashes in the moderate northwesterly (NW) category and 21 090 flashes in the light category.

1) LIGHT FLOW

The light flow (<2 m s⁻¹) category includes all wind directions. The 155 light flow days are associated with 351 960 flashes (Table 1), with the maximum number of flashes occurring near 2100 UTC, and the minimum number occurring between 0700 and 0800 UTC (Fig. 4a). This category ranks sixth in the median number of flashes per day (475).

The spatial distribution of flash densities for light flow is shown in Fig. 5a. Several notable maxima are evident across the region. The largest area of flash densities greater than one flash per square kilometer (yellow and red) stretches just inland from west of Apalachicola (AQQ) to the western edge of the domain. The linear orientation and placement of this feature suggest that

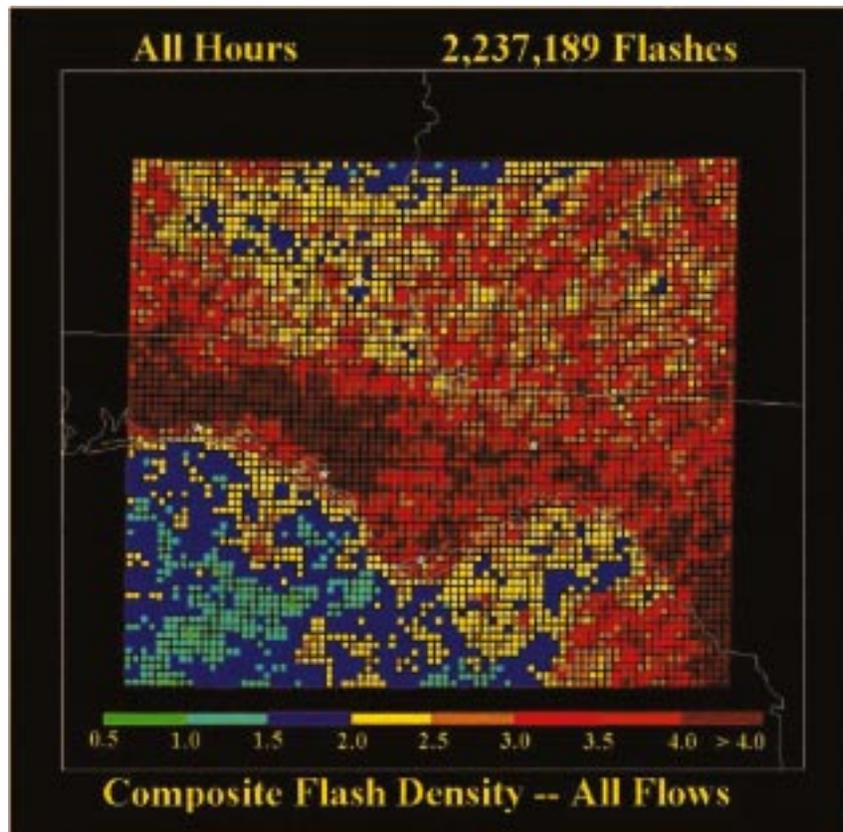


FIG. 2. Composite warm season flash density (flashes per square kilometer) from May to October of 1989–94. Flashes from all hours and wind regimes are combined.

the deep convection is maximized along the sea-breeze front. Another area of relatively large flash densities is located between Apalachicola and Tallahassee (TLH). This maximum may be due, in part at least, to the convergence of sea breezes from the opposing coastlines in the Apalachicola area. Areas of large densities also are located south of Valdosta (VAD) northward into central Georgia and in the southeast corner of the domain near Cross City (CTY). Our examination of lightning in the Jacksonville, Florida area (not shown) indicates that the large densities over eastern Georgia (Fig. 5a) are due to the westward progression of the Atlantic Coast sea breeze that reaches this area late in the day.

Smallest inland values of flash density are located over southeastern Alabama and southwestern Georgia. Our operational experience indicates that the gulf coast sea breeze seldom penetrates into Alabama or Georgia on days of light flow. This probably explains why there is relatively little thunderstorm activity in that area. A secondary minimum also is noted along the coast southeast of Tallahassee. The concavity of the coastline in this area likely leads to weaker convergence and less formation of deep convection compared to adjacent coastal regions. Offshore, flash densities are small, except for somewhat greater values over the southeastern portion of Apalachee Bay.

Careful analysis of hourly flash densities for days of light flow provides useful insight into favored areas for thunderstorm development. Figure 6 shows hourly densities for a 6-h period of light flow (1600–2100 UTC). At 1600 UTC, convection is beginning to form near Apalachicola (Fig. 6a). By 1700 UTC (Fig. 6b), there is a large area of relatively large flash densities in the vicinity of Apalachicola. One also should note the activity surrounding Choctawatchee Bay (near Valparaiso, VPS) and, to a lesser extent, around West Bay (near Panama City, PAM). These regions of enhanced lightning are in good agreement with the numerical modeling results of McPherson (1970) and the satellite cloud climatology of Gibson and Vonder Haar (1990) and Gould and Fuelberg (1996). At 1800 UTC (Fig. 6c), three distinct areas of concentration are evident. The area between Panama City, Apalachicola, and Tallahassee continues to expand, as does the area north of Choctawatchee Bay. Flash densities also are increasing along the coast near Cross City.

Greatest flash densities move inland later in the afternoon (1900–2100 UTC, Figs. 6d–f). The gap in the distribution southeast of Tallahassee is clearly evident. Conversely, greatest densities are located northeast of Panama City at 1900–2000 UTC. The relatively small flash densities along the immediate coast of the pan-

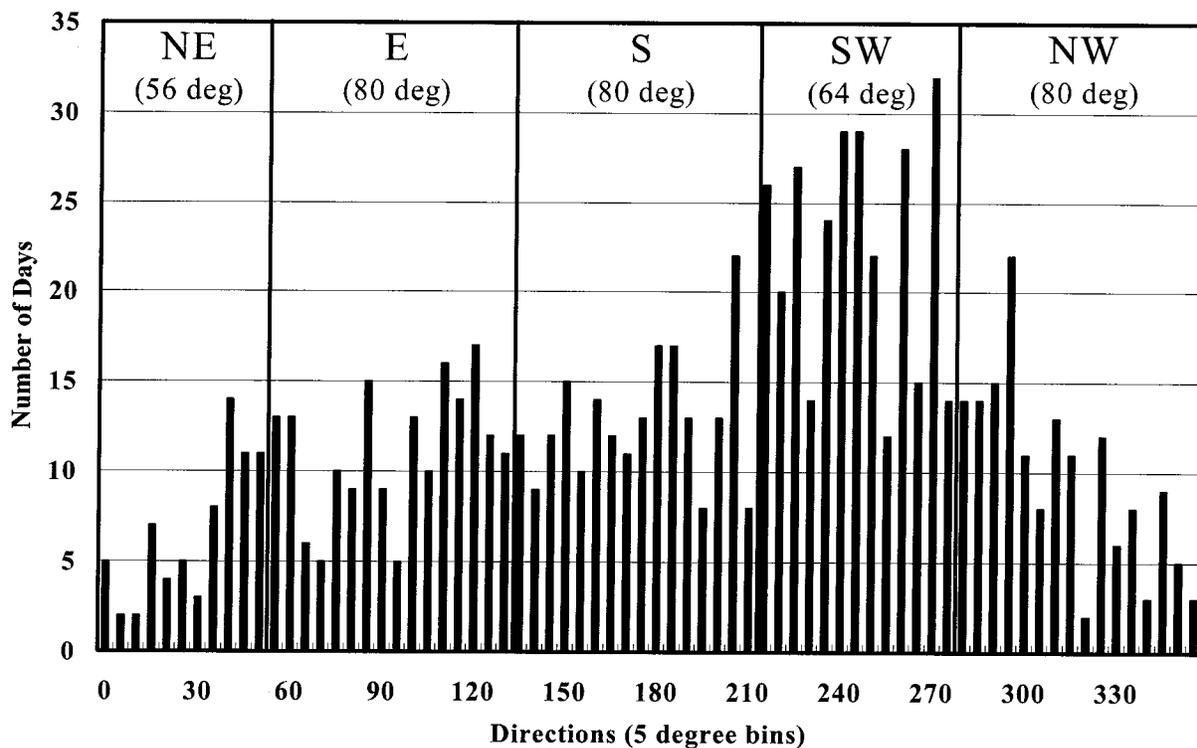


FIG. 3. Distribution of days according to flow regime. Days are grouped in 5° bins, with the widths of the flow regimes indicated.

handle suggest that sea-breeze-induced thunderstorms have progressed inland. Greatest flash densities over southeastern Georgia during this period occur at the last time (2100 UTC). Beyond 2100 UTC (not shown), the density patterns become more disorganized, suggesting that the locations of thunderstorms later in the day are due to forcing mechanisms other than the sea breeze, for example, outflow boundaries from earlier activity.

2) NORTHEASTERLY FLOW

Moderate northeasterly flow is rare over north Florida, with only 41 days during the 36-month period (Table 1). Its median of 32 flashes per day ranks ninth out

the 11 categories. The maximum number of flashes occurs around 2200 UTC—the latest of all categories (Fig. 4b). Flash densities (Fig. 5b) are concentrated in two areas: one along the gulf coast from Apalachicola to Valparaiso and the other near Cross City. The proximity of the flashes to the coastlines suggests that the sea breeze does not progress far inland due to the opposing northeasterly flow. The locations of these maxima agree with the results of Estoque (1962) and Arritt (1993), that is, strongest sea-breeze-induced vertical motions occur along the coasts that have well-defined offshore flow.

There are fewer days (33) with strong northeasterly flow (>5 m s⁻¹) than any other category (Table 1). This flow regime also has the fewest number of flashes (9321)

TABLE 1. Flash characteristics for each flow regime. Relative rankings are given in parentheses for the median number of flashes (fls) per flow day.

Wind regime	No. flashes	No. flow days	Mean fls day ⁻¹	Min fls day ⁻¹	25 percentile	Median fls day ⁻¹	75 percentile	Max fls day ⁻¹
Light	351 960	155	2270	0	6	475 (6)	2752	21 090
NE-mod	82 729	41	2017	0	0	32 (9)	2273	15 716
NE-stg	9321	33	282	0	0	0 (11)	3	4335
E-mod	139 911	81	1727	0	8	273 (7)	1690	13 287
E-stg	91 145	92	990	0	1	137 (8)	1239	6312
S-mod	196 814	101	1948	0	193	1091 (2)	3360	9950
S-stg	199 341	98	2034	0	139	908 (4)	3048	14 216
SW-mod	253 839	85	2986	0	19	920 (3)	3736	19 142
SW-stg	440 867	183	2409	0	314	1301 (1)	3492	16 438
NW-mod	277 171	78	3553	0	1	892 (5)	3155	32 553
NW-stg	107 169	60	1786	0	0	12 (10)	1269	18 151

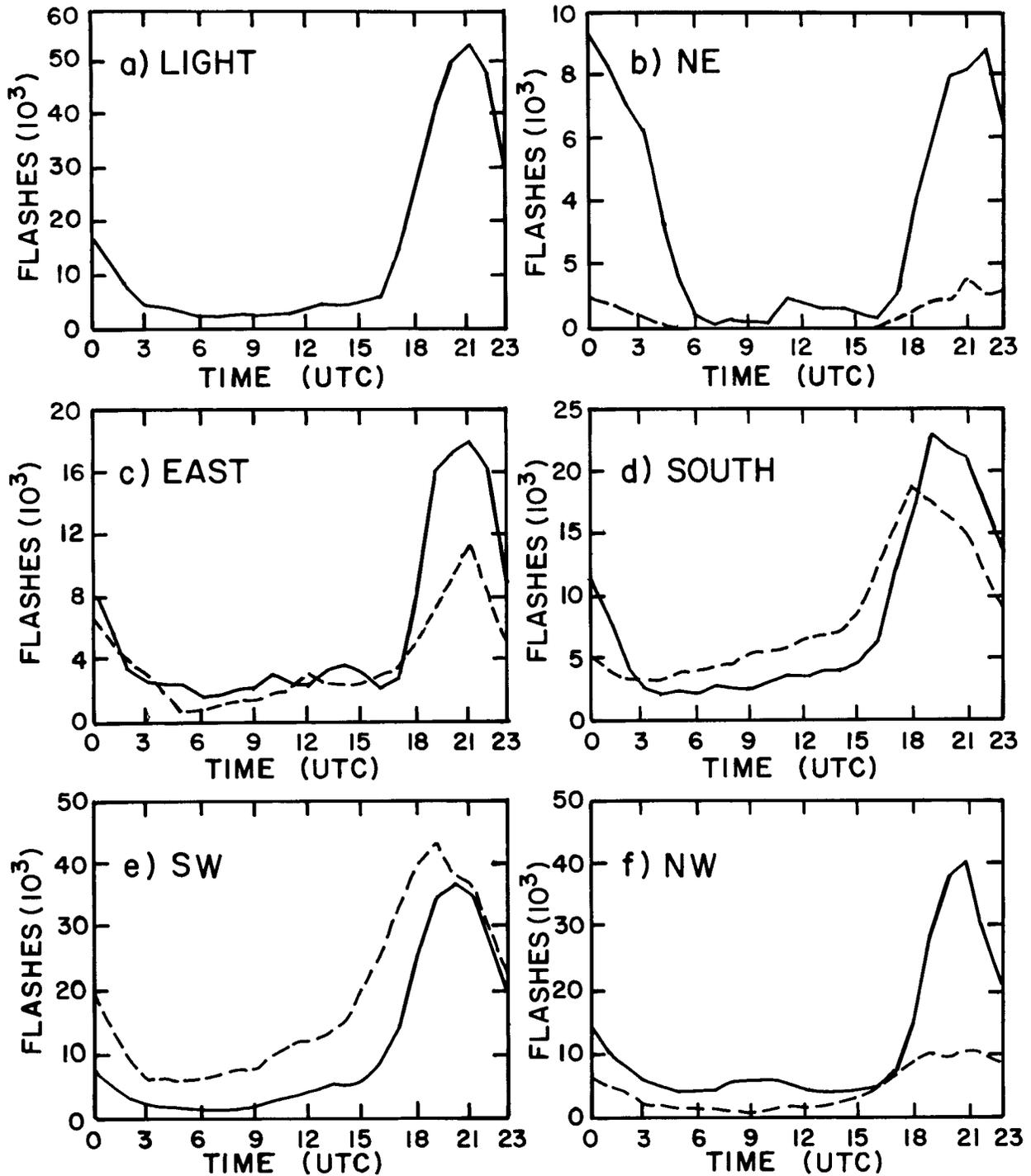


FIG. 4. Diurnal flash profiles for (a) light flow, and strong (solid) and moderate flows (dashed) for the (b) NE, (c) E, (d) S, (e) SW, and (f) NW categories.

as well as the smallest median number of flashes per day (0). These small values are attributable to the thermodynamics of this flow. Table 2 lists values of 1000–700-mb lapse rates and precipitable water for each flow regime. Since the soundings were taken during the early

morning (1200 UTC), the lapse rates probably do not represent afternoon conditions when deep convection is most likely. Nonetheless, with an average lapse rate of 4.2°C/km and precipitable water of 25.2 mm, the days with strong northeasterly flow are least conducive to

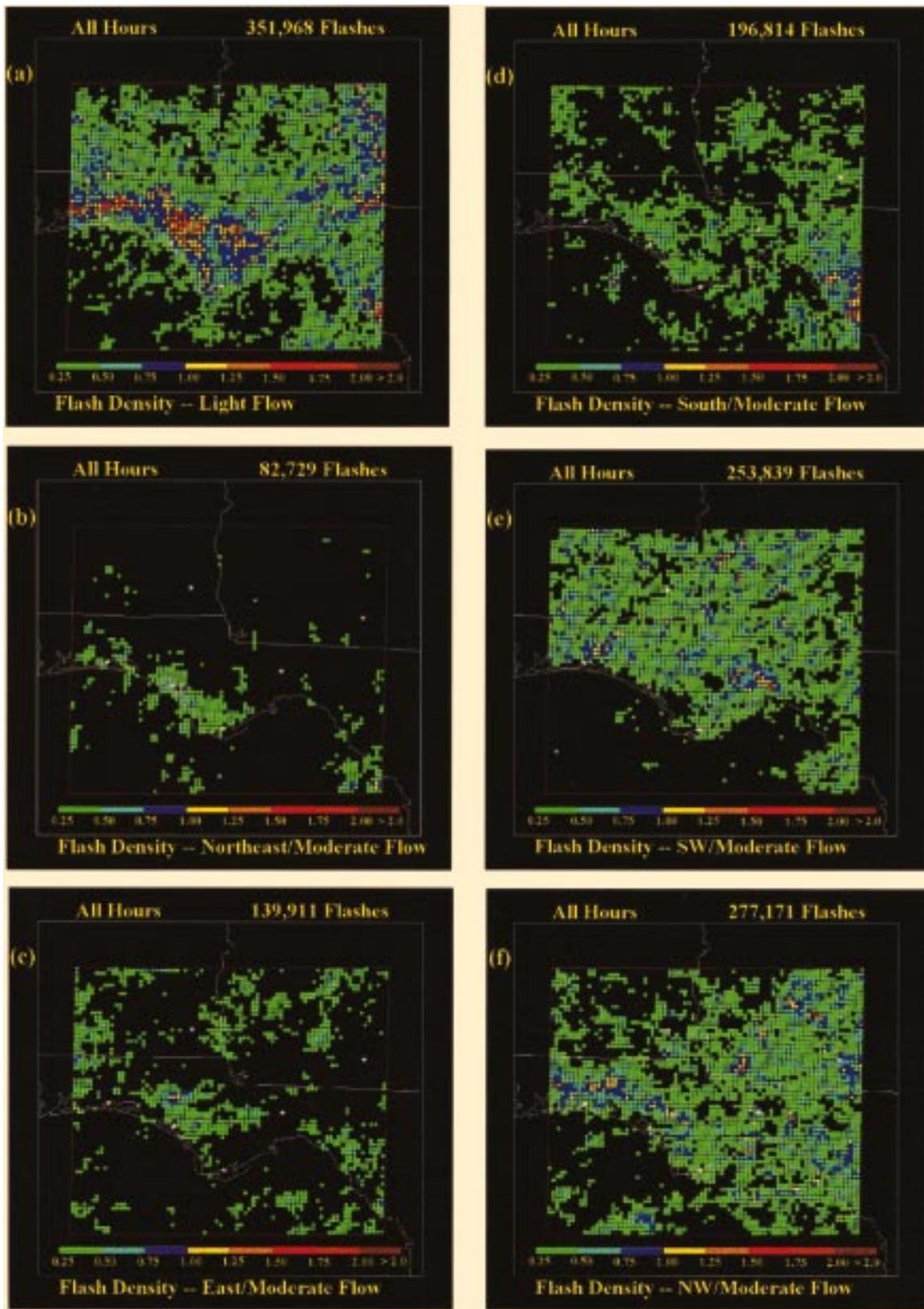


FIG. 5. Average warm season flash density (flashes per square kilometer) for all hours of May–October from 1989 through 1994 for (a) light flow, (b) NE–moderate flow, (c) E–moderate flow, (d) S–moderate flow, (e) SW–moderate flow, and (f) NW–moderate flow.

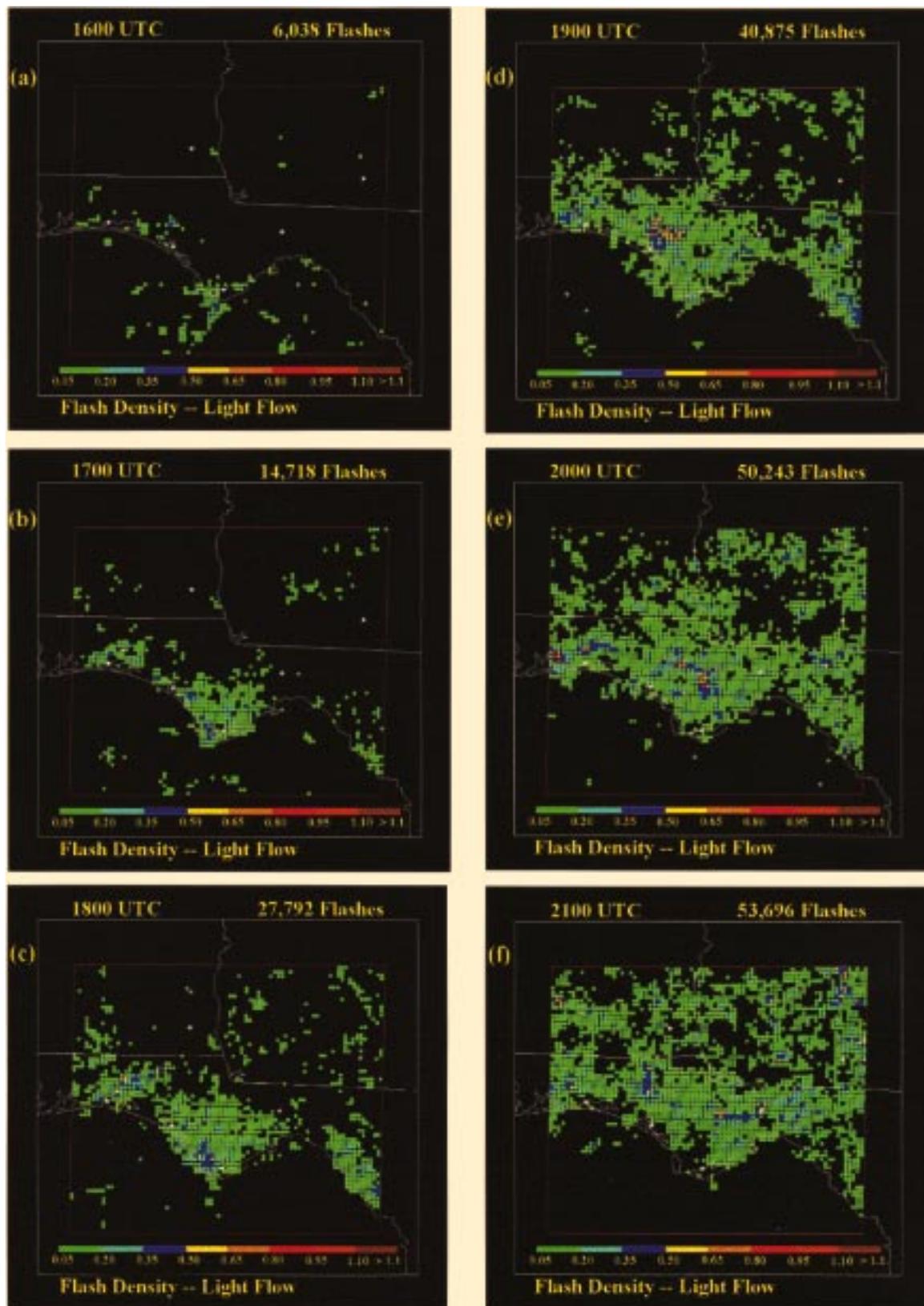


FIG. 6. Average warm season flash density (flashes per square kilometer) for light flow during May–October from 1989 through 1994 at (a) 1600, (b) 1700, (c) 1800, (d) 1900, (e) 2000, and (f) 2100 UTC.

TABLE 2. Average moisture and stability characteristics for each flow regime. Relative rankings are given in parentheses. Calculations are based on 1200 UTC soundings at either Tallahassee or Apalachicola.

Flow regime	No. flow days	1000–700-mb lapse rate (°C/km)	Precipitable water (mm)
Light	155	5.1 (5)	38.8 (5)
NE–mod	41	4.9 (7)	36.0 (8)
NE–stg	33	4.2 (11)	25.2 (11)
E–mod	81	5.0 (6)	37.2 (7)
E–stg	92	4.7 (9)	38.3 (6)
S–mod	101	5.3 (1)	40.5 (2)
S–stg	98	5.3 (1)	41.4 (1)
SW–mod	85	5.2 (4)	39.3 (4)
SW–stg	183	5.2 (3)	40.1 (3)
NW–mod	78	4.9 (8)	35.3 (9)
NW–stg	60	4.3 (10)	28.7 (10)

convection. Figure 7 depicts the average sounding for days with strong northeasterly flow (dashed) and strong southerly flow (solid). The strong northeasterly flow days are drier than those with strong southerly flow (the most humid, 41.4 mm; Table 2). These relatively dry, stable conditions do not favor the development of thunderstorms. In addition, strong offshore flow probably deters sea-breeze development and pushes the entire sea-breeze circulation offshore (Arritt 1993), further reducing the likelihood of convection over land.

3) EASTERLY FLOW

Moderate easterly flow (E) produces a total of 139 911 flashes over 81 days (Table 1), ranking seventh in the median number of flashes per flow day (273). Figure 5c shows the average warm season flash density for this category. Relative maxima are noted along the coasts that are oriented southeast to northwest. Scattered areas of relatively large flash densities are located over southwest Georgia and along the western edge of the study area. The maximum number of flashes occurs between 2100 and 2200 UTC (Fig. 4c).

The strong easterly flow category ranks eighth in the median number of flashes per day (137; Table 1). This flow is relatively moist and unstable (Table 2). Offshore flash densities are more concentrated over Apalachee Bay than over any inland areas (not shown). The only inland area of relatively high flash densities is located near Cross City (not shown).

4) SOUTHERLY FLOW

Moderate southerly flow (S) produces 196 814 flashes over 101 study days, ranking second in the median number of flashes per day (1091; Table 1). Figure 5d shows the average warm season flash density for this regime. The most notable maximum is located near Cross City, in the southeast corner of the domain. A much weaker relative maximum stretches from near Apalachicola to northwest of Panama City.

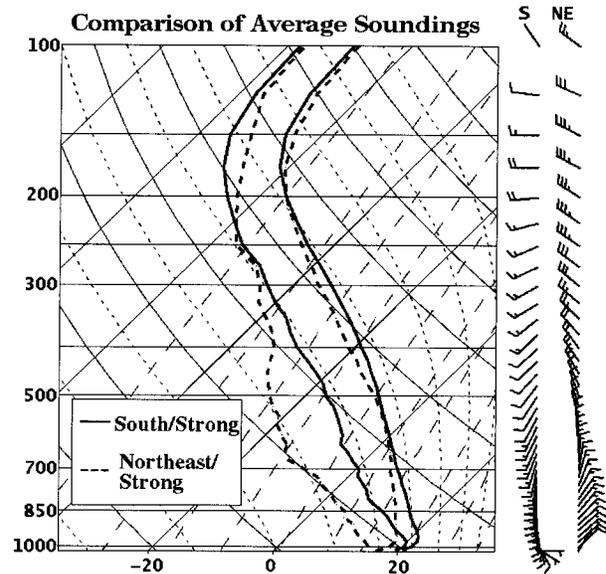


FIG. 7. Average soundings for the strong southerly (solid) and strong northeasterly (dashed) flow regimes. Data are plotted at 25-mb intervals. Soundings were taken at 1200 UTC at either Tallahassee or Apalachicola.

It is interesting to note that coastlines where the southerly flow is directly onshore exhibit a rather diffuse pattern of flash density, for example, near Tallahassee and Valparaiso (Fig. 5d). This suggests either that few thunderstorms form in these regions or that the thunderstorms that do form along the coasts are pushed inland rapidly, thus spreading their lightning flashes over a large area. In contrast, those portions of the coastline that are more parallel to the flow have the greatest flash densities, for example, near Cross City.

Strong southerly flow ranks fourth in the median number of flashes per flow day (908), with 199 341 flashes over 98 flow days (Table 1). It is the most humid and unstable of the 11 flow regimes (Table 2, Fig. 7). A significant amount of offshore lightning occurs with strong southerly flow, more than with any other category. The offshore maxima are located over Apalachee Bay and over the Gulf of Mexico south of Panama City and Valparaiso (Fig. 8a). Hourly flash densities (not shown) indicate that the majority of these offshore flashes are associated with nocturnal thunderstorms. These nocturnal storms are more evident for strong southerly flow than for moderate southerly flow. Specifically, the time series (Fig. 4d) shows that the moderate category (dashed) has more flashes between 1800 and 2100 UTC than does strong flow (solid). However, the strong flow results in many more flashes during the overnight hours and early morning. The times of maximum afternoon flashes (1800–1900 UTC) are earlier than for any other category. This abundance of offshore, nocturnal storms and the relatively early hour of afternoon maximum flashes implies that synoptic-scale systems, and not just the sea breeze, are important forcing mechanisms for much of this convection.

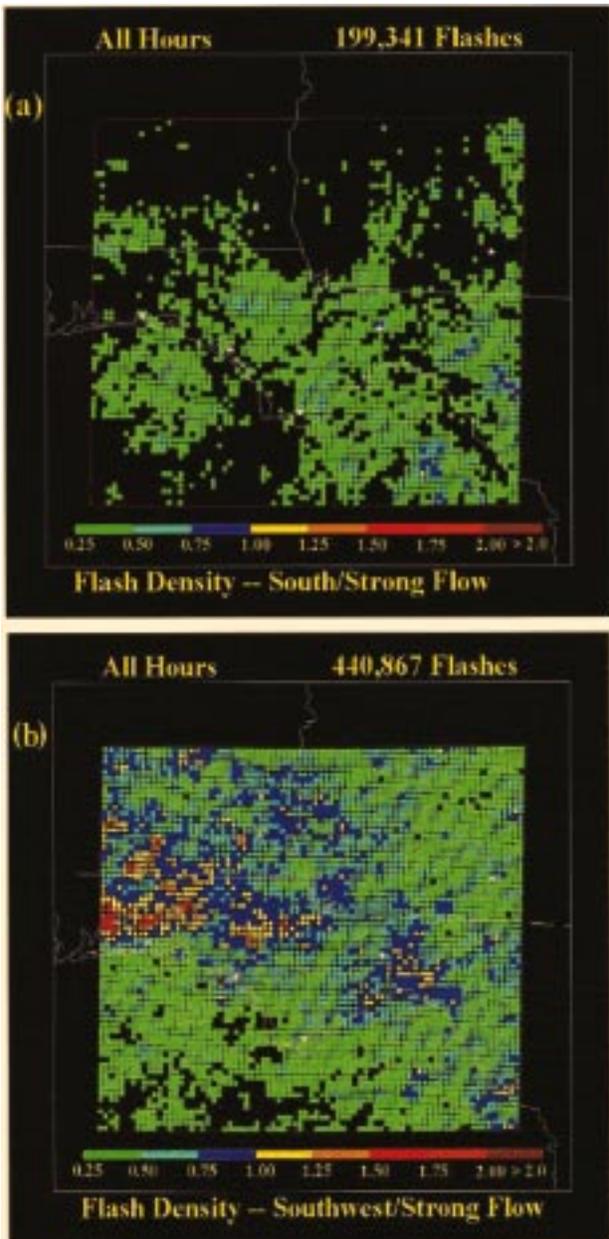


FIG. 8. Average warm season flash density (flashes per square kilometer) for all hours of May–October from 1989 through 1994 for (a) strong southerly flow and (b) strong southwesterly flow.

5) SOUTHWESTERLY FLOW

Moderate southwesterly flow ranks third in the median number of flashes per flow day (920; Table 1). Most flashes occur over land (Fig. 5e). The only exception is near Cross City where many flashes extend offshore. Flashes are most common near 2000 UTC (Fig. 4e), the second earliest of the moderate flow categories (behind southerly).

The areas of greatest concentration along coastal areas (Fig. 5e) are located south of Tallahassee as well as north of Choctawatchee Bay. The latter maximum may

result from increased convergence due to the bay. The maximum near Tallahassee extends nearly parallel to the coastline toward Apalachicola. Similar to the distribution for moderate southerly flow (Fig. 5d), the flash densities for moderate southwesterly flow are greatest along the coasts that are more parallel to the flow.

The strong southwesterly flow category has the largest number of flashes of any flow regime (440 867; Table 1), the greatest number of flow days (183), and the greatest median number of flashes per day (1301). Flashes occur over virtually the entire study region (Fig. 8b). One area of relatively large flash densities, with values exceeding one flash per square kilometer, extends from near the triple point of Alabama, Georgia, and Florida, westward to the edge of the domain. Another area of relatively large flash densities is located along the coast south of Tallahassee. There is considerable offshore lightning, similar to that observed for strong southerly flow (Fig. 8a). And, the strong flow category exhibits more nighttime lightning than does the moderate category (Fig. 4e), also similar to strong southerly flow regime (Fig. 4d).

Of all 11 categories, strong southwesterly flow is most likely to be associated with synoptic-scale forcing, for example, frontal systems and upper-level troughs located west of the study area. Thus, the sea-breeze signal may be dominated by larger-scale processes. The strong southerly flow category probably is second most influenced by synoptic-scale systems.

6) NORTHWESTERLY FLOW

Moderate northwesterly flow exhibits an average number of lightning flashes. With a median of 892 flashes per flow day, it ranks fifth among the 11 categories (Table 1). The most pronounced area of maximum density (Fig. 5f) is located along the Florida panhandle from northeast of Panama City to the western edge of the domain. Other areas of relatively large density are scattered across south Georgia. Flashes are most common during the late afternoon, near 2100 UTC (Fig. 4f).

One might expect maximum flash densities to be located between Apalachicola and Tallahassee (Fig. 5f), that is, where the northwesterly flow is directly offshore. Two-dimensional numerical models have shown that such a region should exhibit a strong sea breeze with significant vertical motion at its leading edge as well as little inland penetration (e.g., Estoque 1962; Arritt 1993). However, that flash distribution is not indicated in Fig. 5f. Instead, greatest flash densities occur along the coasts of the panhandle that are almost parallel to the northwesterly flow. This same distribution also is present, but to a less obvious extent, along the coast from Tallahassee to Cross City, a region that also is parallel to the northwesterly flow. To determine whether these flashes occurred on days having a more westerly wind component (more parallel) or a more northerly component (offshore), the northwest regime (Fig. 1) was

subdivided into two equal directional sectors. The results (not shown) indicate that the observed flash pattern (Fig. 5f) mostly is attributable to westerly flow, that is, more parallel flow. Conversely, the northwesterly flow does not generate a maximum of flashes along that portion of the coastline to which the flow is perpendicular.

Strong northwesterly flow results in a significantly smaller median number of flashes per day (12) than does moderate northwesterly flow (892), ranking 10th relative to the other regimes (Table 1). However, the pattern of flash densities (not shown) is similar to that of moderate northwesterly flow, with maxima located along the panhandle coastline and also near Cross City. Once again, few flashes are indicated along the coast between Tallahassee and Apalachicola, the region perpendicular to the northwesterly flow.

4. Conclusions

The distribution of lightning over the northeastern gulf coast of Florida during the warm season has been found to depend, in part, on the direction and speed of the prevailing low-level flow. Wind speeds of 2–5 m s⁻¹ generally were more conducive to lightning flashes than speeds stronger than 5 m s⁻¹. Specifically, for every wind regime except southerly flow, the 2–5 m s⁻¹ speed category had the larger number of median flashes per flow day. Speeds greater than 5 m s⁻¹ apparently suppress thunderstorm formation by inhibiting formation of the sea breeze, the main focus for summertime thunderstorms in this area.

The complexity of the coastline within the study area was found to have a major impact on the flash distribution. Several bays, as well as convex or concave portions of the coastline, appear to enhance or diminish flash densities in adjacent areas. Each of the five wind regimes in this study contained flow that was parallel or perpendicular to some portion of the coastline. The results indicate that lightning distributions near coastlines parallel to the flow are different from those of coastlines perpendicular to the flow.

Wind direction was found to be associated with differences in the stability and moisture content of the atmosphere. Days with strong northeasterly flow were the driest and most stable, and this flow regime had the smallest median number of flashes per day. The southerly flow regime was most humid and unstable. It ranked in the upper third of the categories in the median number of flashes per day.

The southerly and southwesterly flow categories had the earliest times of maximum flashes (1800–2000 UTC). Conversely, the moderate northeasterly category had the latest maximum (2200 UTC). Offshore lightning was most common for strong southerly flow and strong southwesterly flow. These offshore storms probably are due mostly to the effects of synoptic-scale forcing.

Many previous numerical studies on the formation and strength of the sea-breeze circulation have been two-

dimensional, focusing on the effects of onshore or offshore flow. Results of the current study suggest the need for additional three-dimensional modeling that focuses on the effects of complex coastlines. Future research also should investigate interactions between the sea breeze and smaller-scale circulations such as river breezes or “swamp breezes.” We believe that research, and local climatological studies such as presented here, will be useful to operational meteorologists in their quest to improve short-term forecasts in coastal areas.

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