# Storm Following Climatology of Precipitation Associated with Winter Cyclones Originating Over the Gulf of Mexico

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ABSTRACT

A storm-following climatology was compiled for the precipitation distributions associated with winter cyclones that originate over the Gulf of Mexico and adjacent coastal region. The goal of this research is to investigate the roles of the Gulf of Mexico and Atlantic Ocean as sources of moisture for these storms, and to investigate geographic/orographic influences on the precipitation distributions. A second objective of this research is to provide forecasters with a potential guide with which to evaluate numerical model forecasts of quantitative precipitation for these storms. A 24-y climatology (1960–1983) was compiled of storms that originated over the Gulf of Mexico and adjacent coastal region, and produced wide-spread areas of precipitation (totals ≥ 25 mm). Sixty-six storms satisfied these criteria, and three dominant storm tracks were identified. Six-h totals of hourly precipitation data were objectively analyzed for individual storms belonging to each of the three tracks, and grid-point values were composited in a storm-following coordinate system. Charts of mean precipitation distributions and frequency of occurrence were constructed to display the evolving precipitation fields surrounding storms belonging to each track. The resulting climatology is presented.

To provide an example of the application of the precipitation climatology, results from a GALE case study are presented.

## 1. Introduction

In the past a number of climatologies of surface cyclone types, frequencies, and tracks over North America have been summarized to explain general patterns of formation, movement and dissipation (Loomis 1874; Miller 1946; Petterssen 1956; Klein 1957; Colucci 1976; Reitan 1979; Zishka and Smith 1980; Whittaker and Horn 1981). The most complete cyclone climatology was done by Klein (1957). Like Pettersen, Klein looked at the frequency of cyclones and anticyclones over the Northern Hemisphere for the period 1899 to 1939. Unlike Petterssen, however, Klein's study covered all 12 months. Miller (1946) studied 208 winter (October–April) cyclones that originated over the Atlantic coastal region during a period of ten years. Colucci (1976) found that there is a concentration of winter storms in a band from Cape Hatteras to New England over the northern edge of the Gulf Stream. Deepening is favored over the North and South Carolina coasts, and along the northern edge of the Gulf Stream, while the northeastern Gulf of Mexico is a poor region for cyclone deepening. A study by Zishka and Smith (1980) of January and July surface cyclones from 1950 to 1977 also concluded that cyclogenesis occurs most frequently along the east coast of the United States and in the lee of the Rocky Mountains (lee cyclogenesis).

Several studies (Reitan 1979; Zishka and Smith 1980; Whittaker and Horn 1981) have noted a statistically significant decline in the frequency of North American cyclogenesis in recent years. However, a principal-component analysis of cyclone frequencies (Hayden 1981) for North America and the adjacent Western Atlantic for the period 1885–1978 indicates that the number, severity, and duration of Atlantic Coast cyclones increased between 1942 and 1974.

A particular challenge to operational weather forecasters is precipitation forecasting. Few climatological studies, however, have attempted to relate precipitation patterns to the location and/or movement of low pressure centers. Jorgensen (1963) compiled a precipitation climatology for winter storms centered over Missouri, while Jorgensen et al. (1967) compiled a climatology for precipitation associated with 700-mb lows centered over the intermountain west. Tasaka (1980) composited precipitation patterns associated with cyclones that cross Japan in winter. The value of a storm-following climatology to the forecaster is that it provides a composite precipitation distribution for a given surface-low position. Significant forecast deviations from the typical (composite) precipitation distribution can alert the forecaster to an unusual or infrequently occurring situation. The forecaster's own experience may suggest the degree of believability in the aberration.

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In this paper, a storm-following climatology is presented for precipitation associated with winter cyclones that originate over the Gulf of Mexico and adjacent coastal region. The climatology is comprised only of storms that produced heavy, widespread precipitation during winter months (January, February, and March) from 1960 to 1983. Precipitation associated with midlatitude cyclones that originate over the Gulf of Mexico and adjacent coastal region contributes significantly to the total annual precipitation over the southeastern United States, especially in winter (*National Climatic Data Summary,* 1960–80).

An objective analysis technique was used to transform raw data from observation stations in the hourly precipitation data (HPD) network to an equally-spaced grid. All significant storms that originated over the Gulf of Mexico and adjacent costal region were charted to identify common storm tracks. Precipitation data from storms that follow common tracks are then composited, resulting in a storm-following precipitation climatology for the dominant storm tracks.

The goal of this research is to investigate the roles of the Gulf of Mexico and Atlantic Ocean as sources

TABLE 1. Significant precipitation producing cyclones (Jan.–March, 1960–1983).

| Origin of low | Number with precipitation ⩾ 25 mm | % of all lows w/precip. ⩾ 25 mm | % of total lows |
|---|---|---|---|
| Midwest | 33 | 25 | 7 |
| Gulf Coast | 66 | 51 | 15 |
| Atlantic | 31 | 24 | 7 |
| Total | 130 | | |

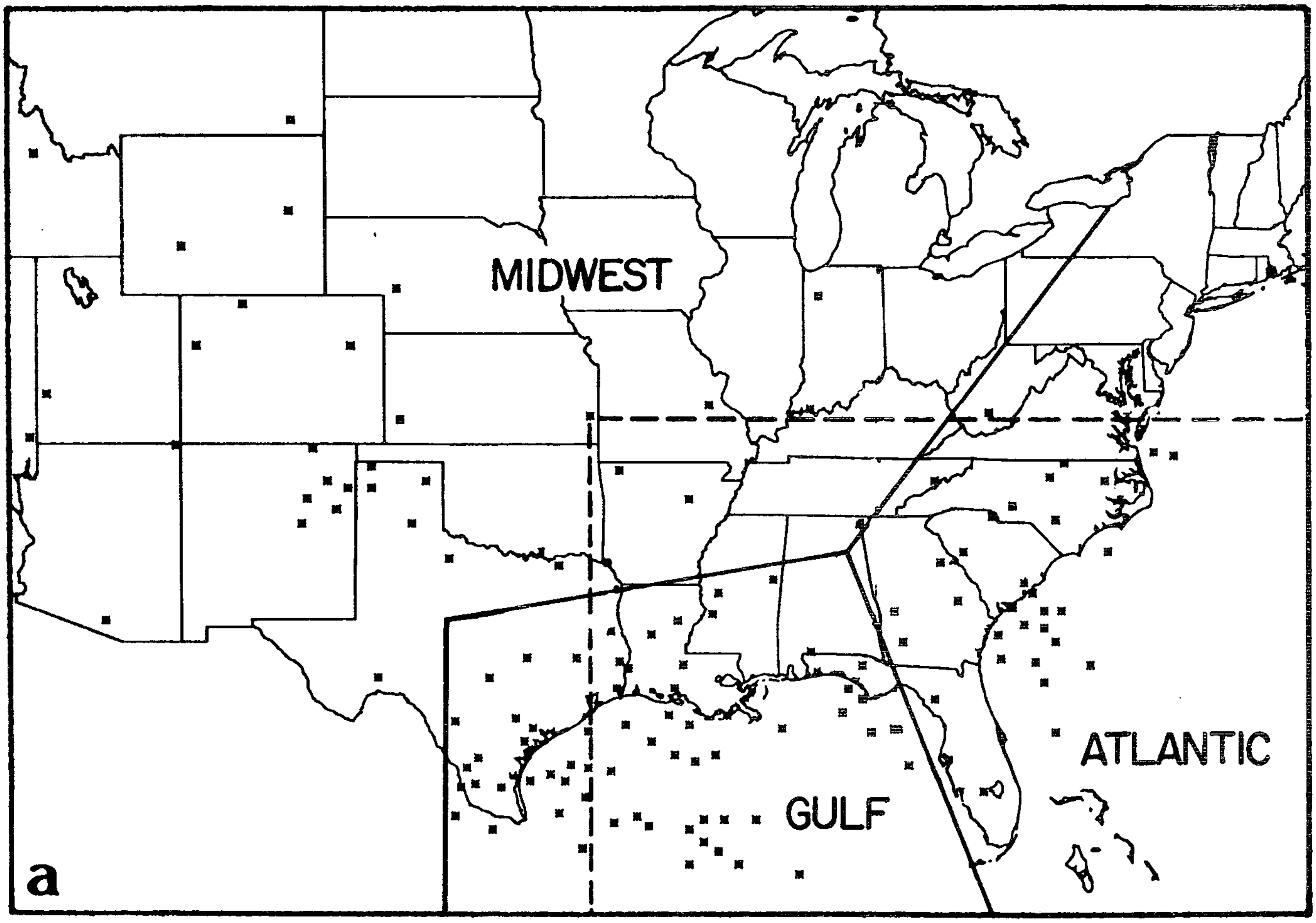



FIG. 1. a) Geographic areas of cyclogenesis; asterisks indicate locations of low centers when closed isobars were first analyzed on surface charts for significant precipitation producing cyclones. Dashed line indicates boundary across which cyclones must traverse to be included in the climatology. b) Composite storm Tracks A, B and C, and geographic regions numbered 1 through 5. The "L"s indicate the locations along each composite track closest to the centers of geographic regions (indicated by solid dots), and appear in subsequent composite figures for reference. Regional legs along Tracks A, B, and C are indicated by the small numbers. c) Hourly Precipitation Data (HPD) stations. Asterisks indicate locations of stations whose precipitation histograms are shown in Fig. 8. d) Results of interpolation of the HPD precipitation data (contours every 5 mm), with reported HPD precipitation totals for a sample six-hour period.

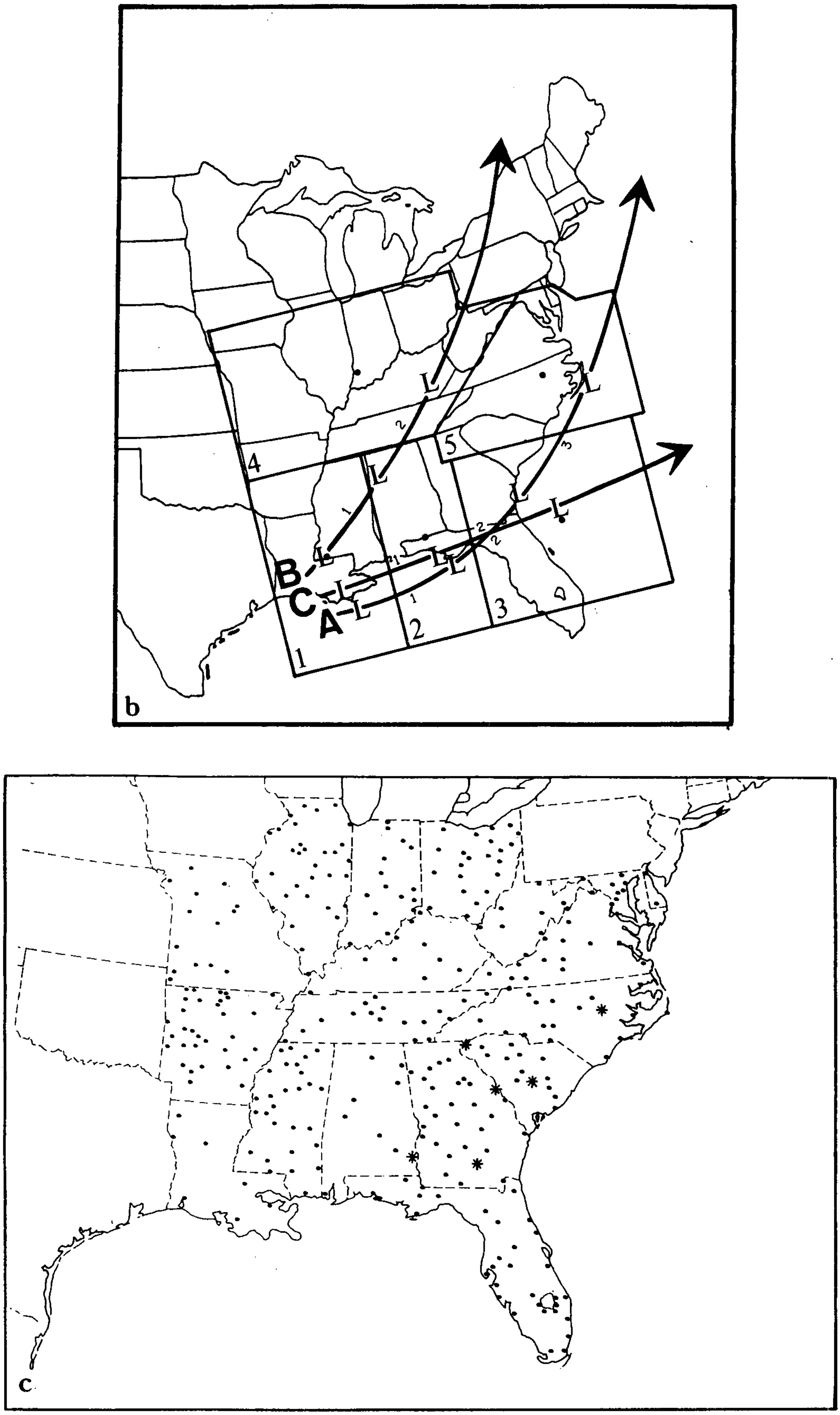



FIG. 1. (*Continued*)

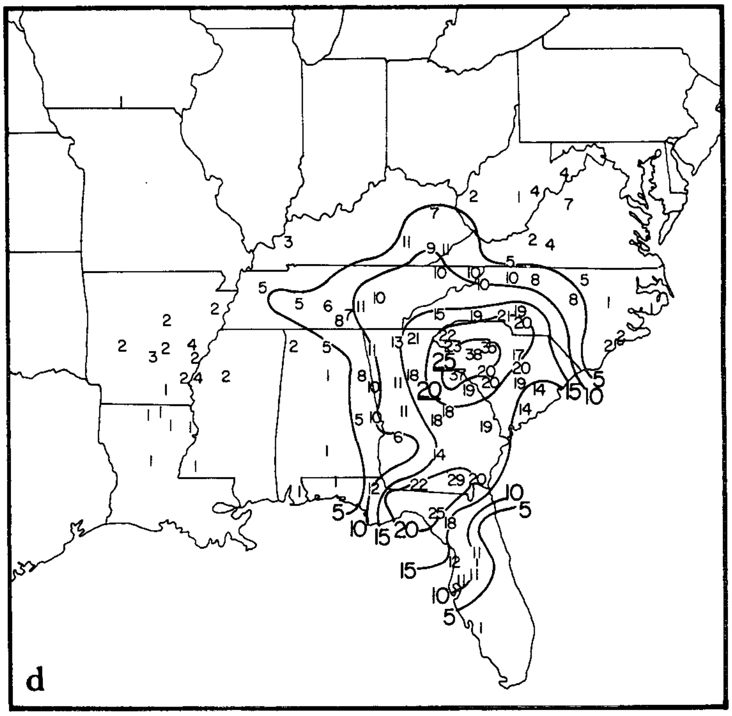



FIG. 1. (*Continued*)

of moisture for these storms, and the influence of geography/orography on the precipitation patterns. A second goal of this research is to provide forecasters with a composite precipitation envelope that can be used to gauge climatologically the extent and intensity of precipitation when a winter storm is forecast by numerical models to occur along a similar storm track.

Criteria for selecting storms for the climatology are discussed in section 2 of the paper. Storm tracks are discussed in section 3. Data sources and analysis procedures are detailed in section 4, and the results of the climatology are presented in section 5. In section 6, a case study is presented of the synoptic-scale precipitation distribution associated with a storm that formed over the Gulf of Mexico coastal region and tracked along the coast to North Carolina during the Genesis of Atlantic Lows Experiment (GALE). A comparison with the climatology is then presented.

Questions that will be addressed in this paper include:

1) What are the dominant tracks for heavy precipitation producing storms that originate over the Gulf of Mexico?

2) Where are the greatest precipitation rates and totals located with respect to the storm centers and storm tracks?

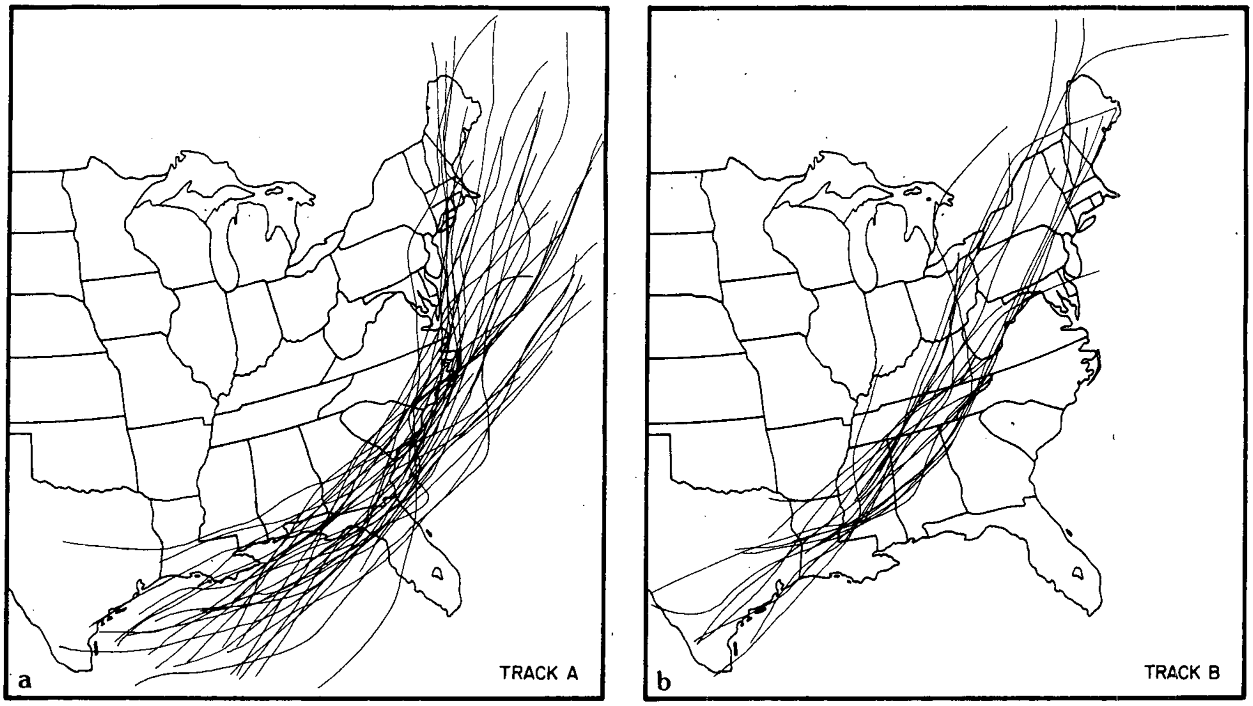
3) What roles do the Gulf of Mexico, Atlantic Ocean, and Appalachian Mountains play in the precipitation distributions following these storms?

## 2. Storm selection

Winter storms tracking across the southeast United States must have passed within the area bounded to the west by 95°W and to the north by 38°N (dashed line in Fig. 1a), to be considered in the climatology. Only those low pressure centers that could be identified for 24 hours or more were included. Cyclone track charts contained in the *National Climatic Data Summary* and *Mariners Weather Log* were used to identify 453 lows that traversed the designated area during winter from 1960 to 1983. Storms originating over the Atlantic Coast Region comprised 40% of the total, while those originating over the Gulf Coast Region comprised 32% of the total (Fig. 1a).

To reduce the impact of: i) variations in storm intensity, ii) small variations in location of the lows composited, and iii) problems interpreting results from composites in which scattered light precipitation totals from weak systems are included, the selection of lows was further restricted to those that produced significant precipitation over a large area. Only those storms producing $\geq$25 mm ($\sim$1 in.) of precipitation per 24 hours at a minimum of three reporting stations and covering roughly a two state area ($\geq$4° lat. $\times$ 6° long.) along the storm tracks were included in the climatology.

Precipitation summary charts from the National Oceanographic and Atmospheric Administration (NOAA) were reviewed, and of the original 453 winter lows identified, 130 (29%) were found to satisfy the above criterion. The distribution of locations where a closed surface isobar was first analyzed for the 130 lows shows three preferred areas of cyclogenesis for the heavier precipitation producing storms (Fig. 1a): i) in the lee of the Rocky Mountains (lee cyclogenesis), ii) over the northwest Gulf of Mexico, and iii) over the western Atlantic Ocean, off the South Carolina and Georgia coast. These results are consistent with those of Colucci (1976) and Zishka and Smith (1980). Of the significant precipitation producing storms the majority (66) originated over the Gulf of Mexico and its coastal region (see Table 1). The magnitude of the numbers in Table 1 depend to some degree on the choice of the boundaries of the cyclogenesis areas in



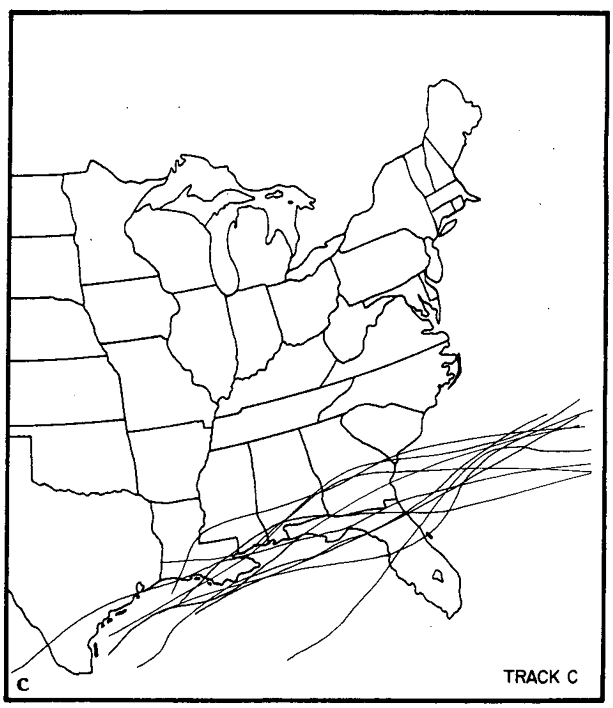




FIG. 2. Storm tracks of the 66 lows that originated over the Gulf of Mexico and its coastal region (area labeled "Gulf" in Fig. 1a). a) Tracks of lows that comprise composite Track A. b) Tracks of lows that comprise composite Track B. c) Tracks of lows that comprise composite Track C.

TABLE 2. Track statistics.

SPEED is given in km/hr.
$\delta p/\delta t$ = change in pressure (mb/hr) following the storm.
$\delta \zeta/\delta t$ = change in surface geostrophic relative vorticity ($\times 10^{-5}$ s$^{-1}$/hr), where $\zeta = (\alpha/f)\nabla^2 p$.

| Track | | Leg 1 | Leg 2 | Leg 3 |
|---|---|---|---|---|
| A | Speed | 48 | 76 | 55 |
| | $\delta p/\delta t$ | −0.3 | −0.3 | −0.4 |
| | $\delta \zeta/\delta t$ | −0.4 | −0.2 | 1.0 |
| B | Speed | 23 | 58 | |
| | $\delta p/\delta t$ | −0.6 | −0.3 | |
| | $\delta \zeta/\delta t$ | −0.01 | 0.2 | |
| C | Speed | 45 | 52 | |
| | $\delta p/\delta t$ | −0.2 | −0.3 | |
| | $\delta \zeta/\delta t$ | 0.2 | −0.3 | |

Fig. 1a. The northeastern Gulf of Mexico is found to be a sparse region of cyclogenesis, a finding that is consistent with Colucci's (1976) conclusion that this area is not conducive to cyclogenesis. The lack of cyclogenesis over the Appalachians, reflects the inhibition of low development over mountains, and confirms the results of Colucci (1976) and Zishka and Smith (1980).

The remainder of this paper will focus on the climatology of the majority of significant cyclones that originated over the Gulf of Mexico and adjacent coastal region.

## 3. Storm track climatology

To further refine the results of the precipitation climatology, dominant storm tracks were identified (Fig. 1b) by tracing the individual tracks of each of the 66

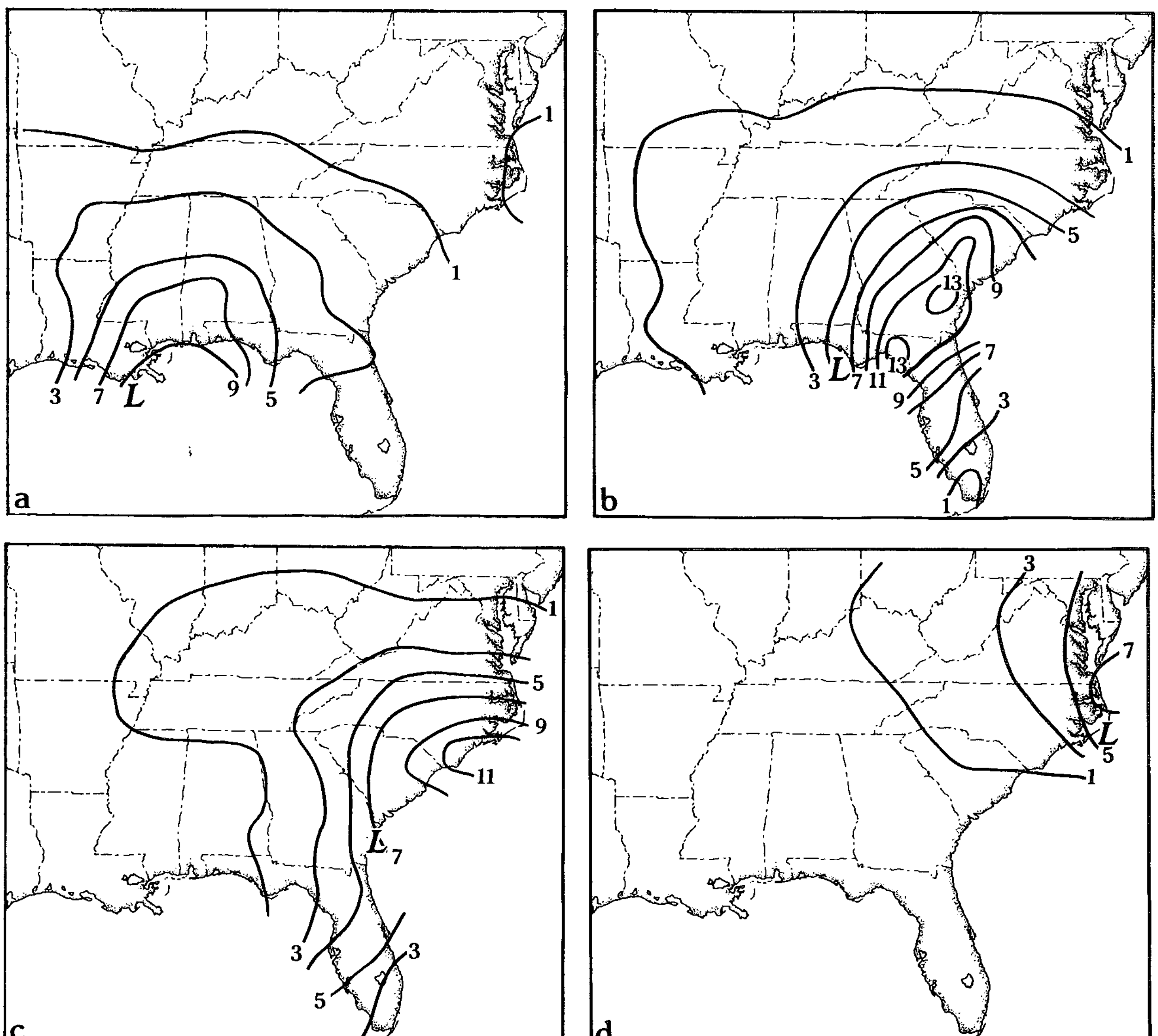



FIG. 3. a–d) Mean six-hour precipitation totals (mm) for lows in Track A. The "L"s indicate the points where Track A passed closest to the centers of the respective geographic regions, and are for reference only.

lows as they moved from the coastal regions of the Gulf of Mexico (Fig. 2). One of the objectives of the current research is to relate observed changes in the synoptic-scale precipitation patterns to moisture sources and topographic factors as the lows evolve and progress. The size and shape of the regions shown in Fig. 1b were chosen to match this objective. Composite tracks were identified with geographical considerations in mind by noting the regions through which the individual low centers passed (Fig. 1b). The composite tracks represent the mean axes of the individual tracks shown in Fig. 2. The locations along each composite track closest to the center of a geographic region are labeled "L" in Fig. 1b. For reference, these "L"s also appear in the composite figures of section 5 of this paper. It should be noted that the composite tracks and "L"s are for schematic illustration only, and are not used directly in the calculation of the composites. Precipitation data from the time that an individual low's track passed closest to the center of a geographical region were used in calculating the composites.

The three composite tracks correspond to lows passing primarily along the United States coast east of the Appalachian Mountains (Track A), passing inland west of the Appalachian Mountains (Track B), and passing due east across northern Florida (Track C). Tracks A, B, and C, account for ~58%, ~27%, and ~15% of the 66 storm tracks, respectively (Fig. 1b). The composite precipitation patterns presented in section 5 of this paper, confirm that these three tracks result in distinct precipitation patterns, whose characteristics are influenced by geographical factors.

Table 2 lists propagation speed, central pressure changes ($\delta p/\delta t$), and geostrophic relative vorticity changes ($\delta\zeta/\delta t$) following cyclones on Tracks A, B, and C for each segment depicted in Fig. 1b. Storms along Leg 2 of Track A experience the highest mean propagation speed and deepening rate ($\delta p/\delta t < 0$), yet they also experience weakening ($\delta\zeta/\delta t < 0$). Maximum deepening rates occur along Leg 1 of Track B; relatively slow storm motion and no intensification also characterize this leg. The region of greatest intensification occurs along Leg 3 of Track A, which is an area well-known for cyclogenesis. Storms tend to weaken along Tracks A and C as they move across the northeastern Gulf of Mexico to the Florida peninsula.

## 4. Precipitation data and processing

Past climatological studies (Jorgensen et al. 1967; Klein et al. 1968; Korte et al. 1972; and Tasaka 1980) based their findings on 12- or 24-h precipitation totals for each low. Jorgensen's 1967 study based its findings on precipitation totals for 12-h periods centered at upper-air observation times. The chosen period over which precipitation totals are calculated must be long enough to reveal the synoptic precipitation pattern, but short enough to resolve major evolutionary changes. Twelve-hour periods are too long for this purpose, since the propagation speeds of the faster storms would allow them to pass across more than one region during this period (Table 2). Therefore, 6-h precipitation totals were chosen. Precipitation totals were calculated centered at the observation time at which an individual low located within a defined geographic region was closest to the center point of that region (Fig. 1b).

Raw data for the climatology consists of hourly precipitation data (HPD) at principal (primary) stations, secondary stations, and cooperative observer stations operated by the National Weather Service and the Federal Aviation Administration. The Fischer-Porter precipitation gauge and the Universal Rain Gauge are the primary instruments used to create the historical HPD files at the National Climatic Data Center (NCDC), Asheville, North Carolina. The Fischer-Porter

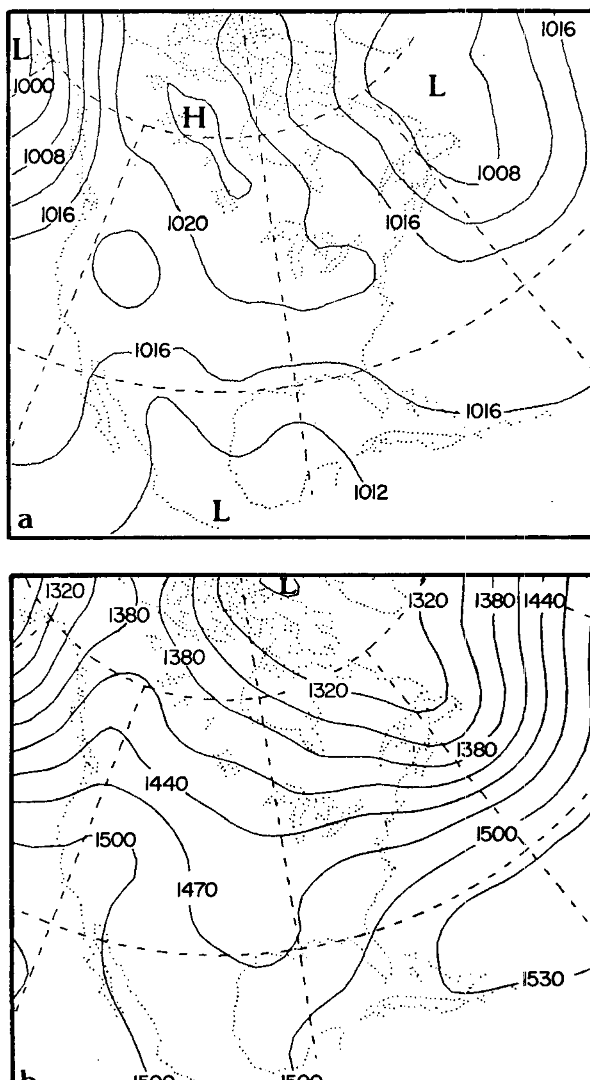



FIG. 4. a) Sea-level pressure composite (contours every 4 mb) and b) 850 mb height composite (contours every 30 m) for 40 Track A storms whose mean position was just south of Louisiana.

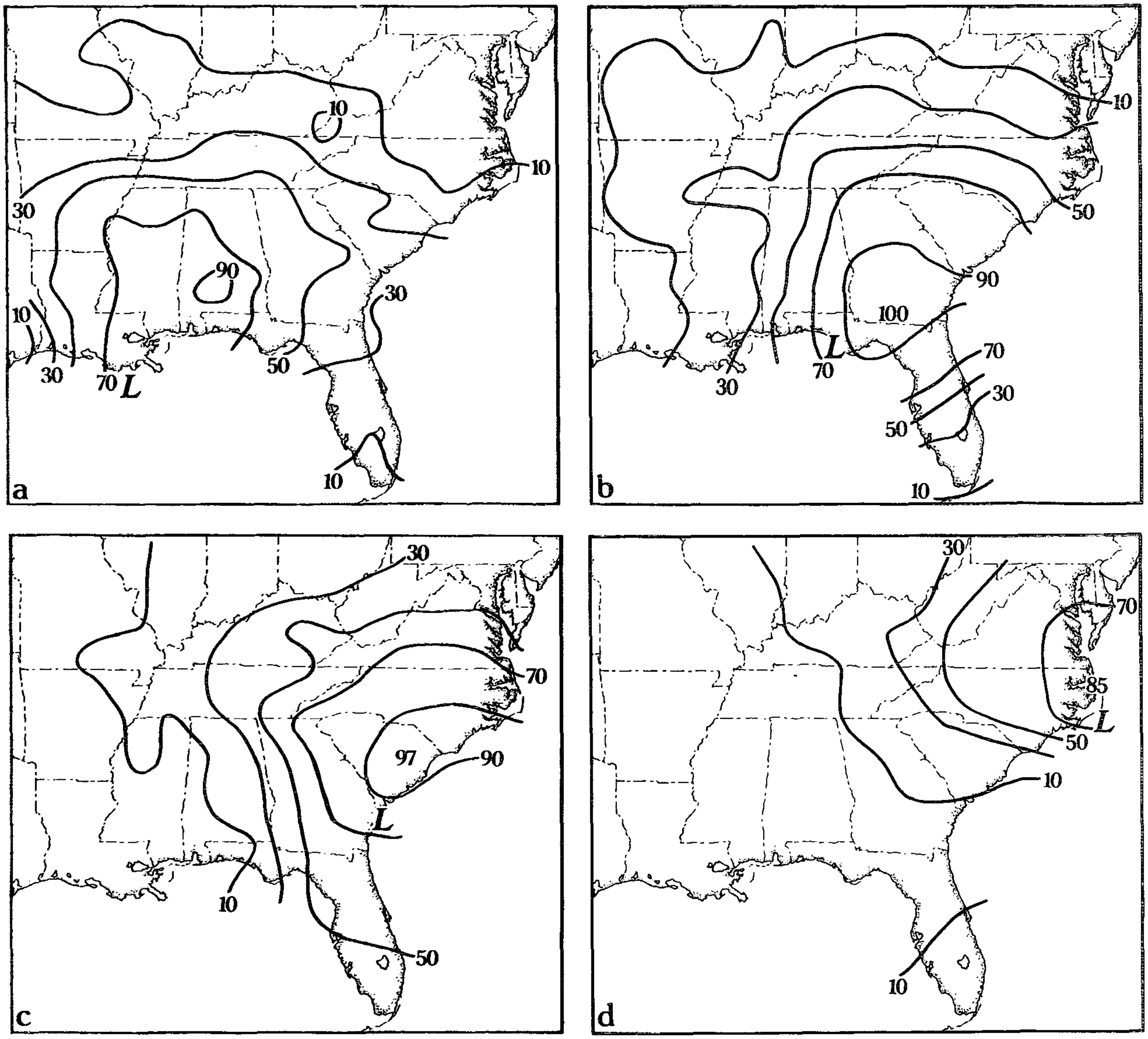



FIG. 5. a–d) Same as Figs. 3a–d except, contours are values of percent frequency of occurrence for precipitation totals ≥ 1 mm.

gauges store precipitation amounts in hundredths of inches, but usually report to tenths only. For this study, amounts recorded in hundredths of inches are rounded to the nearest tenth of an inch. The Universal gauges also report in tenths of inches.

The hourly precipitation station inventory (by state) lists the number of days each month when a station was unable to report HPD values (for whole or part of each day). This inventory was used to determine which stations would be the most reliable. In particular, it was important to determine whether no precipitation at a station meant just that, or whether the station was not reporting at all. Stations were deleted from the climatology data base based on the percentage of time they were listed as closed on the Station Inventory. If a station was closed for more than 15 days from January to March of a particular year (or >20% of the time), and this occurred for five years or more from 1960 to 1983, then that particular station was eliminated from the study. The locations of the final 316 stations meeting the criterion are plotted in Fig. 1c. It should be noted that precipitation that occurred over the coastal waters was not included in this study due to a lack of data.

Non-uniformity in the HPD was reduced as much as possible by using data from only those stations with the most consistent station histories and by computing 6-h cumulative precipitation totals, as discussed above. However, data-sparse regions existed in Louisiana, Alabama, Kentucky, West Virginia, and parts of Virginia, the Carolinas, and southeastern Georgia. To compensate for this, and to emphasize synoptic-scale features (rather than local details) of the precipitation distribution around the surface lows, a Cressman-like (1959) objective analysis scheme was employed to interpolate the data.

Hourly precipitation data were interpolated onto a regular grid whose grid point spacing (0.5° lat. by 0.5° long.) was defined by computer, and based on the density of HPD station network in Fig. 1c. The objective analysis can be expected to yield reasonable interpolations in regions of adequate data coverage. The radius of influence $R$ was chosen to guarantee that at least one data value would be found in at least five octants around each grid point [$R \sim 100$ km in data dense regions (e.g. Georgia), and $R \sim 200$ km in data sparse regions (e.g., Alabama)]. An example of the contoured results of the interpolation, with raw HPD reporting totals for a particular 6-h period appears in Fig. 1d. The isohyet pattern is faithful to the data though values are smoothed at the two maxima.

For each station in Fig. 1c, 6-h precipitation totals were calculated at all 316 stations centered at the time an individual low located within a defined geographic region was closest to the center point of that region. The precipitation-totaling program ensured that all stations conformed to the same UTC time periods. Six-hour gridded data from lows belonging to each of the three composite tracks, were averaged for each geographic region through which the lows passed.

The rationale behind the chosen methodology is to keep a geographically fixed compositing scheme, while minimizing the scatter introduced by variations in low positions being composited. Important geographically

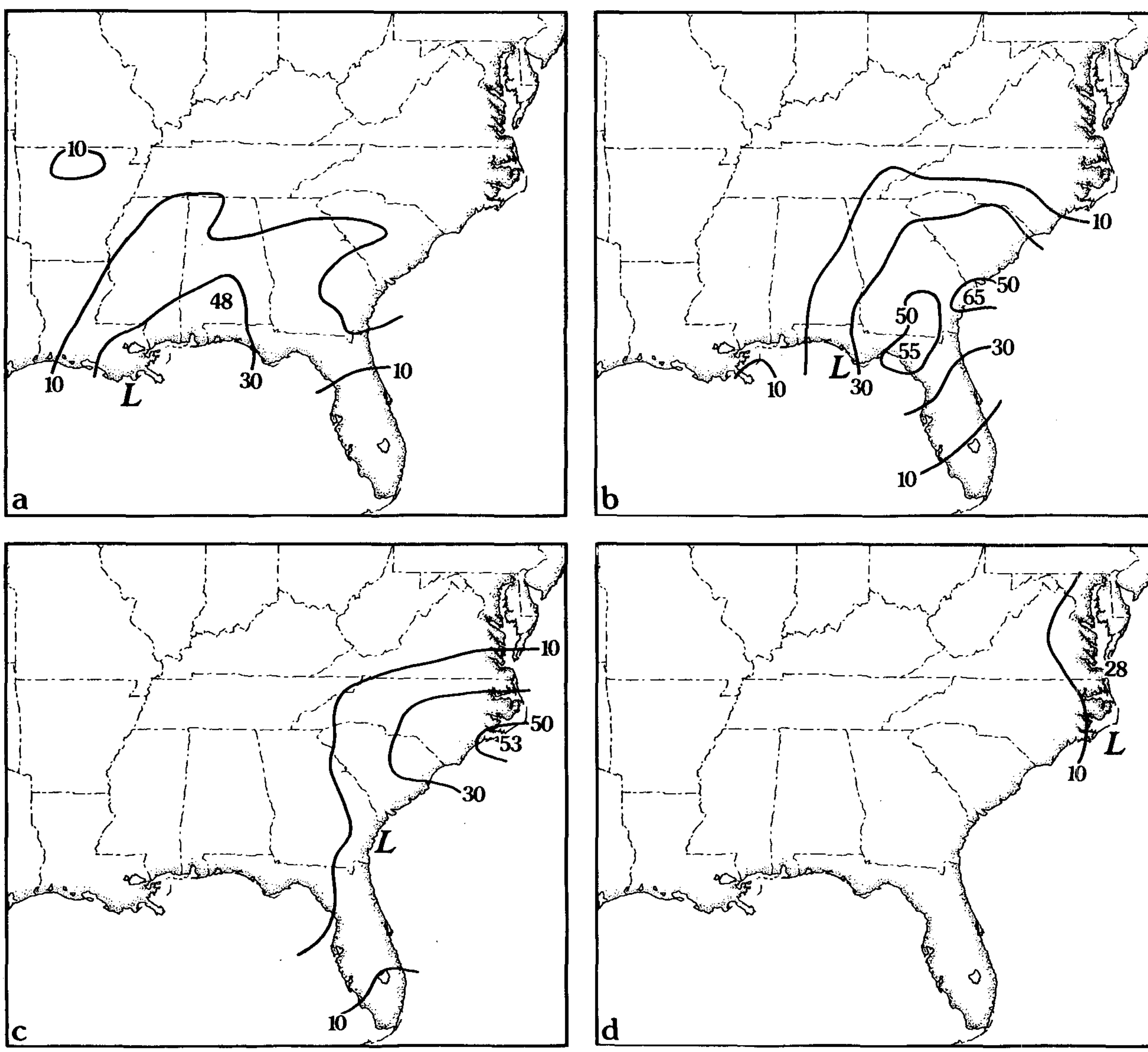



FIG. 6. a–d) Same as Figs. 5a–d for precipitation totals ≥ 10 mm.

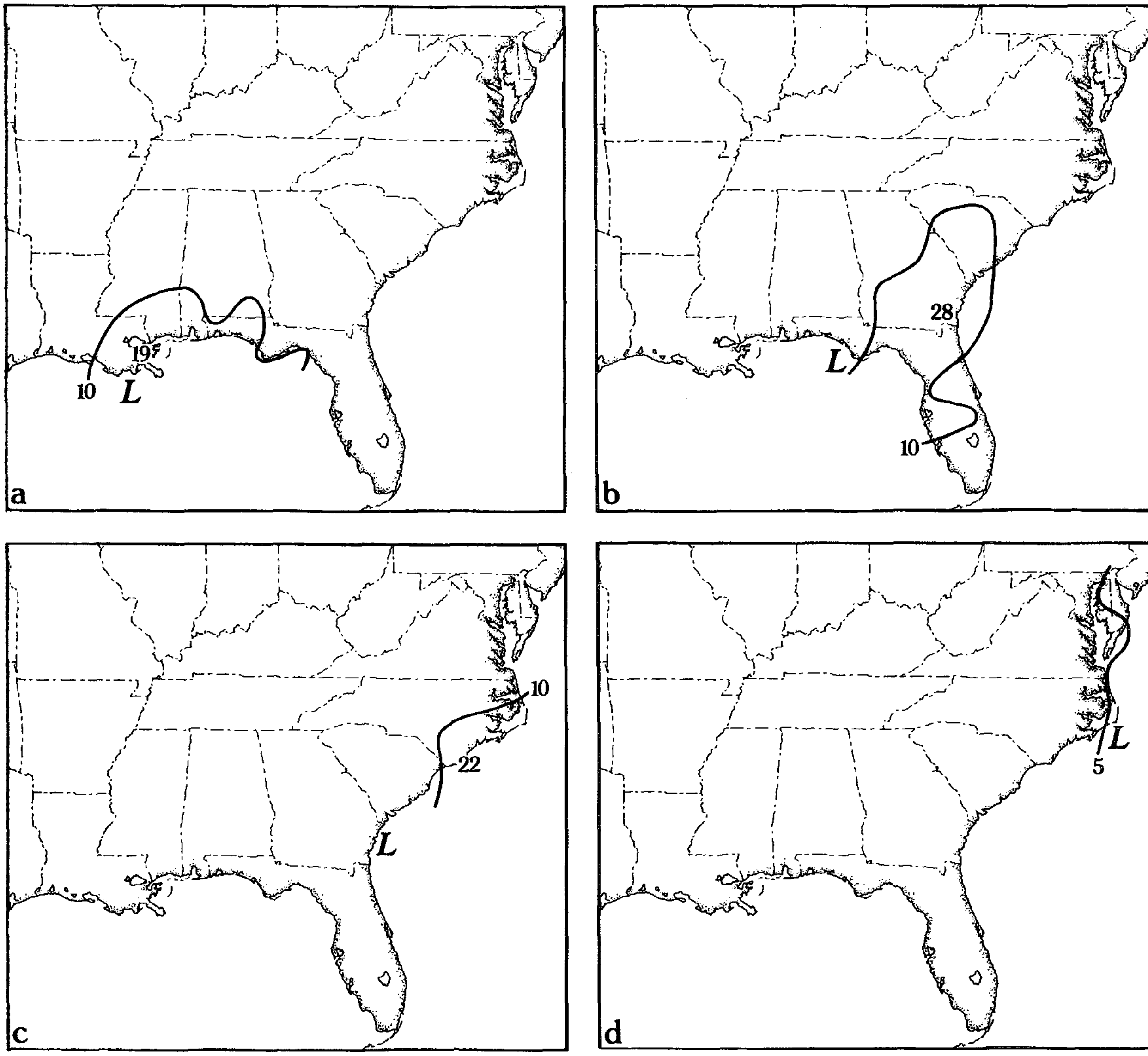



FIG. 7. a–d) Same as Figs. 5a–d for precipitation totals ≥ 20 mm.

fixed influences on the precipitation patterns that would be smeared using a truly storm following compositing scheme are thus revealed.

## 5. Storm-following precipitation climatology

Figures 3a–d depict the evolution of the mean precipitation pattern around Track A storms. Precipitation amounts maximize at 13 mm over 6 hours in Region 3 (Fig. 3b), as the lows cross the Gulf Coast region. The double maximum of precipitation in Fig. 3b suggests that the Atlantic joins as a second moisture source as the storms cross the Florida panhandle in Region 3. Although, there is a lack of data along the Georgia coast, raw HPD data support the presence of two distinct maxima. Moisture feeding into the storms from the Gulf of Mexico is diminished by the time they reach the Atlantic coast (Fig. 3c) as suggested by sea-level pressure and 850-mb height composites at this stage in the mean storm track (not shown). Precipitation amounts decrease over land to 7 mm in 6 hours just north of the mean low in Fig. 3d, as the precipitation pattern moves northeastward and offshore with the low. Precipitation distributions over the coastal waters were not investigated in this study due to a lack of data.

Composites of the sea-level pressure and 850-mb height fields (Figs. 4a and b, respectively) for the early stage of Track A storms were computed using the NMC gridpoint dataset (grid spacing ~321 km at 35°N). NMC gridpoint data are available at 12-h intervals (0000 UTC and 1200 UTC). Data from the time closest to the composite times used in Fig. 3a were used in

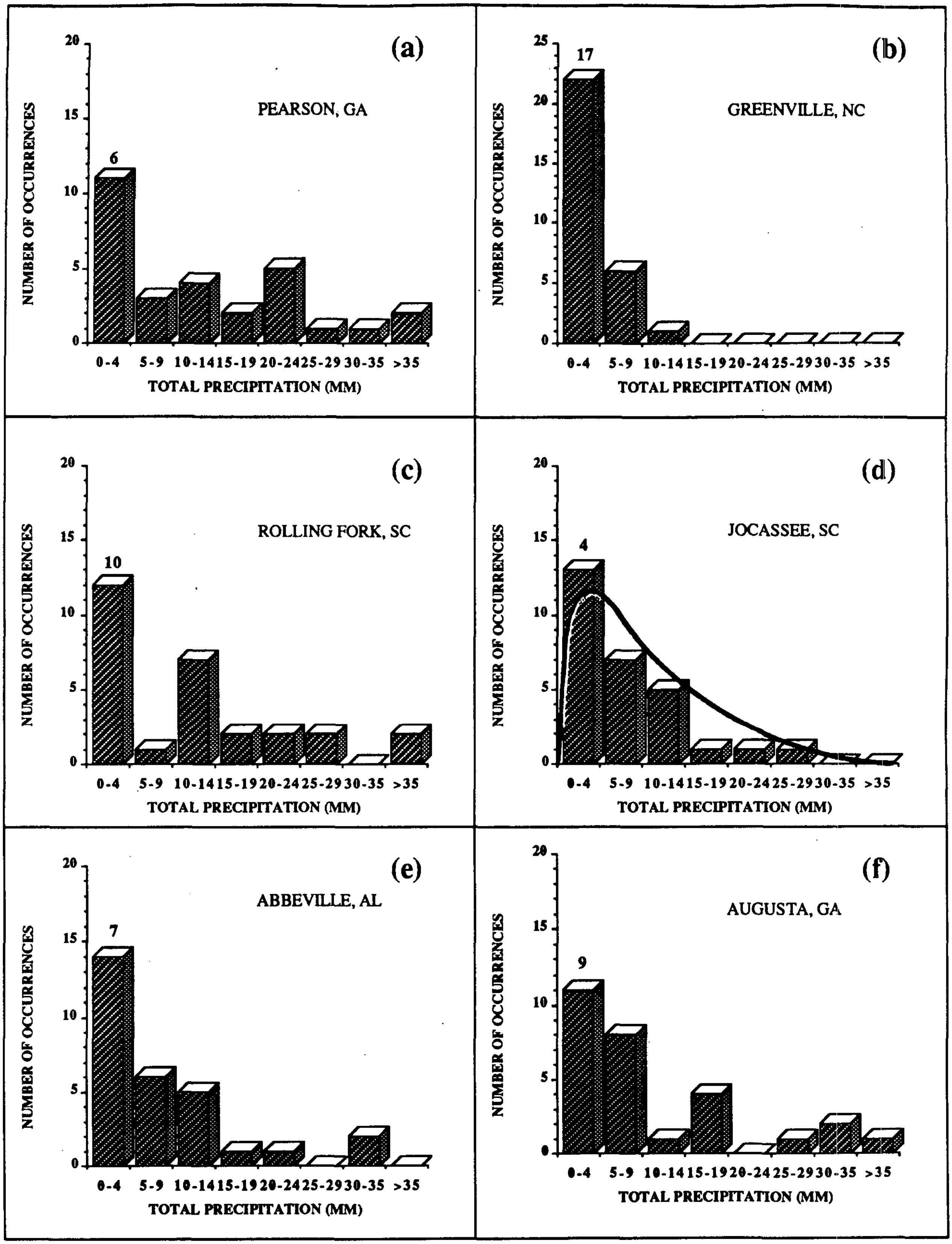
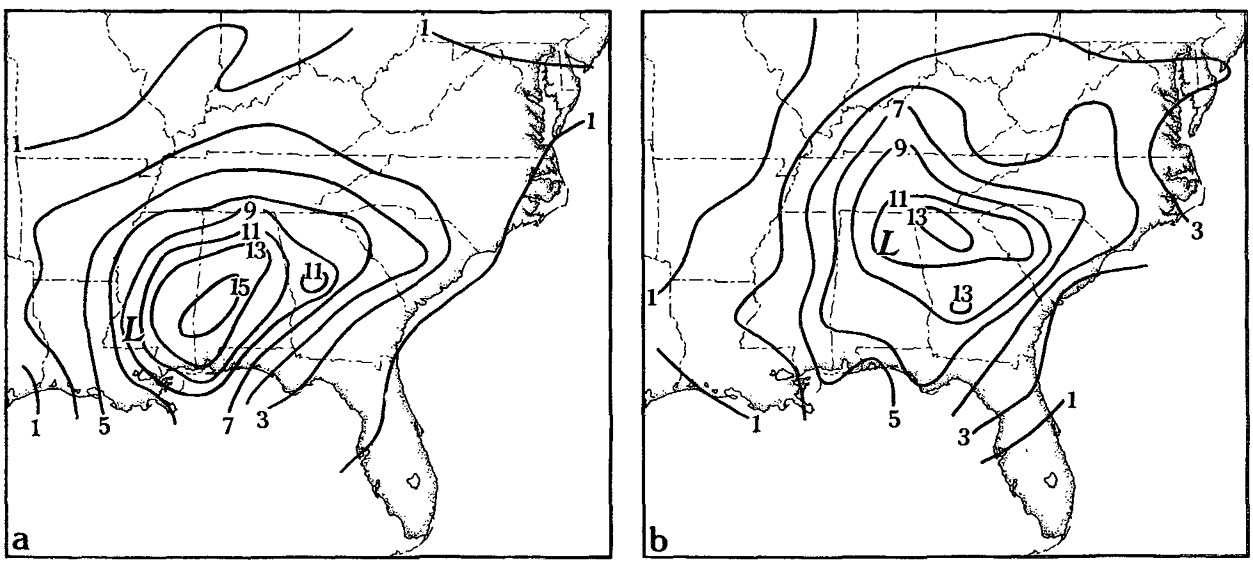



FIG. 8. a–f) Histograms of occurrence of six-hour precipitation totals for six selected HPD stations for Track A in Region 2 (Fig. 3b). The locations of the six HPD stations are shown in Fig. 1c. The abscissa is precipitation category (5 mm width), and the ordinate shows the frequency of occurrence in each category. The number at the top of the first column in each panel gives the frequency of occurrence of no precipitation reported.

constructing the composites. The composites show a broad flow of air from the Gulf of Mexico across the eastern half of the United States. The lack of a closed isobar in the surface-pressure composite (Fig. 4a) is due to a combination of the weakness of the incipient lows, scatter in their initial positions, and smoothing introduced by poor temporal resolution in the NMC gridpoint dataset.

Insight into the variability of the precipitation intensity surrounding the mean low tracks is provided by the frequency of precipitation occurrence. The frequency charts are divided into three categories: light (≥1 mm in 6 hours), moderate (≥10 mm), and heavy (≥20 mm). Since the data used in compiling the percent frequencies are derived from a dataset that has been filtered by the storm selection criteria, caution should be exercised in applying these charts in forecasting applications.

The contour patterns showing the percent frequency of precipitation occurrence (Figs. 5 to 7) for Track A reflect the quantitative precipitation patterns seen in Fig. 3. The three intensity categories for Track A storms all exhibit a growth in the areal extent of the maximum frequency of occurrence from Regions 1 to 2, followed by a gradual decrease as storms cross to the Atlantic in Region 3 and northeastward in Region 5. Nearly the entire southeastern United States experiences light precipitation at least 10% of the time when the Gulf of Mexico is the major moisture source (Figs. 5a and b). As storms travel from Region 3 to Region 5, the extent of light precipitation over land west of the Appalachians decreases by the time lows reach the North



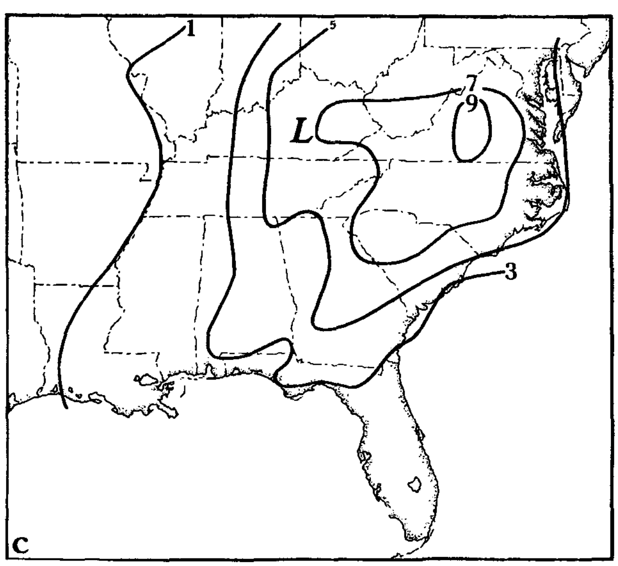




FIG. 9. a–c) Mean six-hour precipitation totals (mm) for lows in Track B. The "L"s indicate the points where Track B passed closest to the centers of the respective geographic regions, and are for reference only.

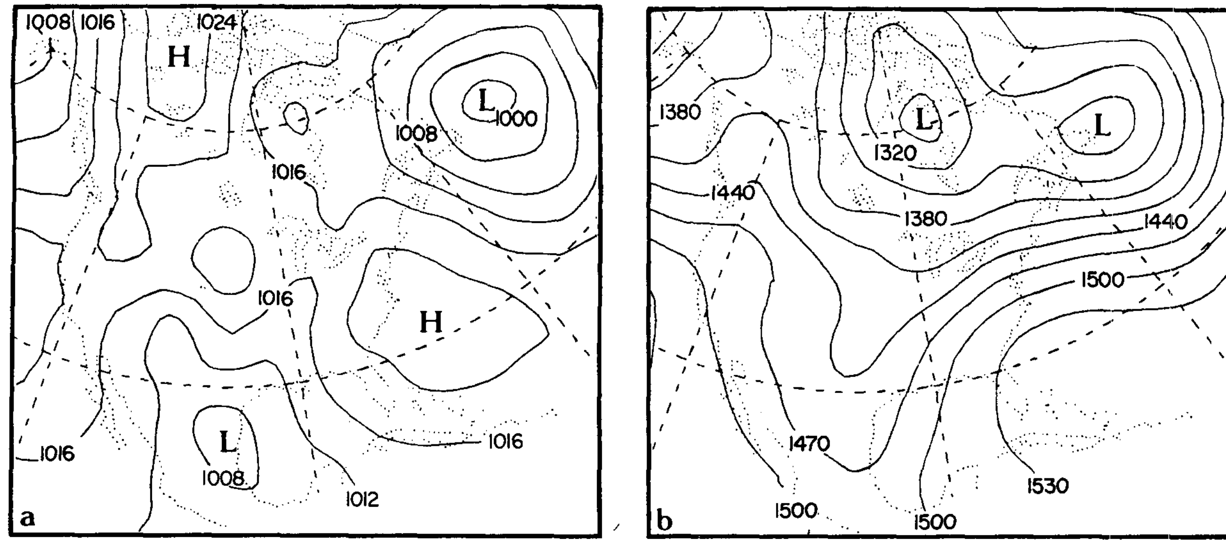
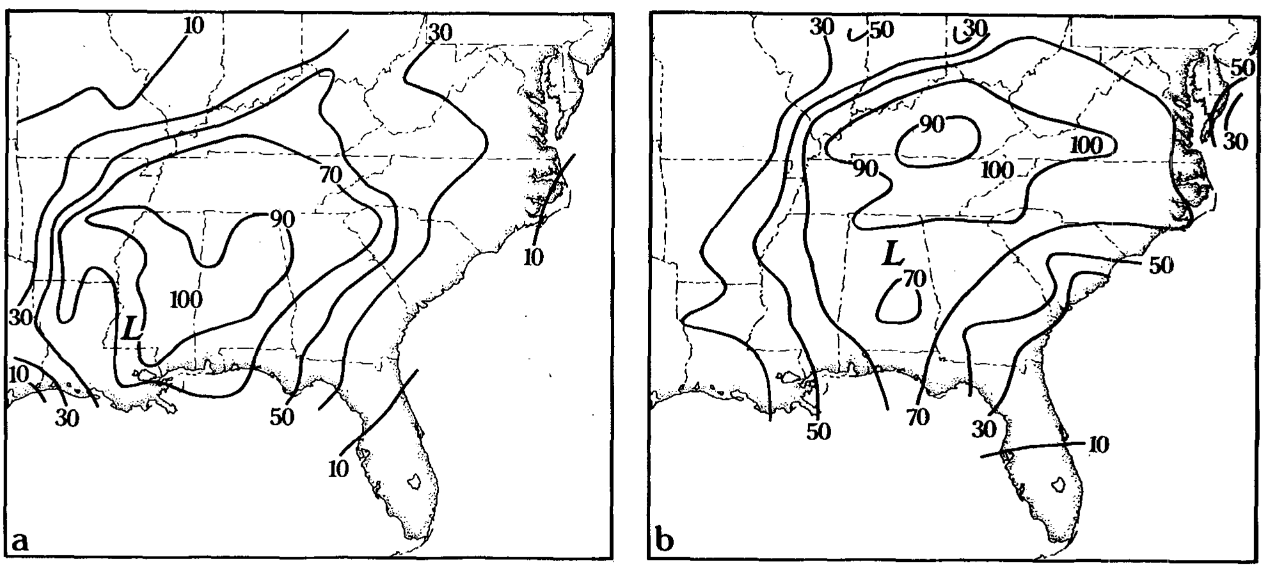



FIG. 10. a) Sea-level pressure composite (contours every 4 mb) and b) 850 mb height composite (contours every 30 m) for 17 Track B storms whose mean position was over Alabama.



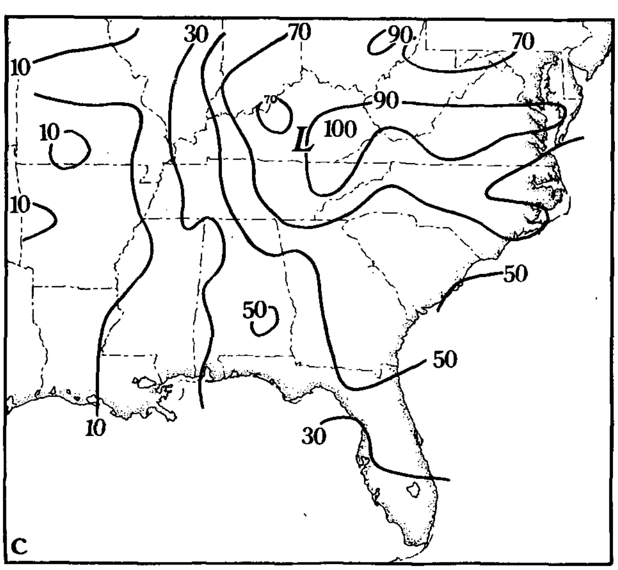




FIG. 11. a–c) Same as Figs. 9a–c, except contours are values of percent frequency of occurrence for precipitation totals ≥ 1 mm.

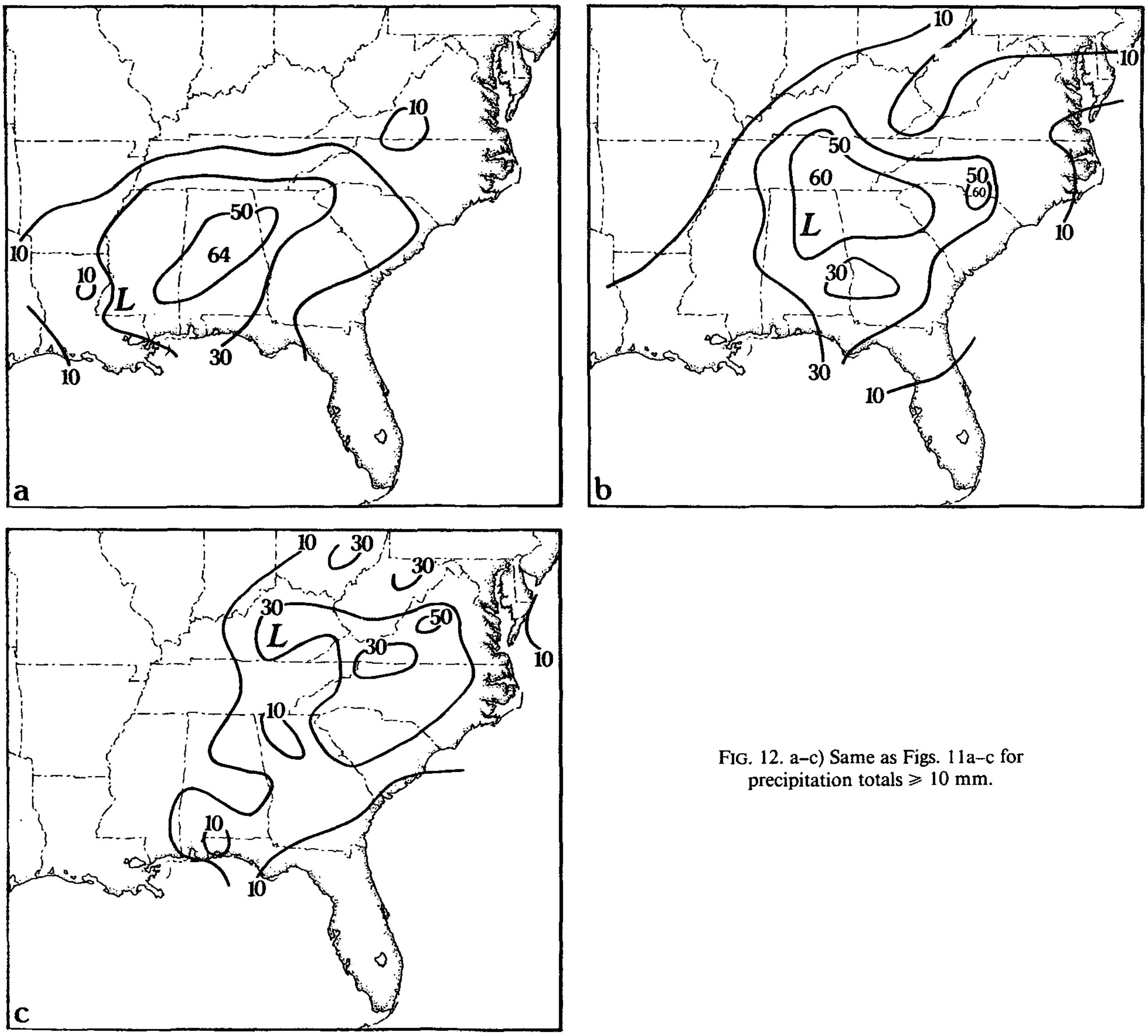



FIG. 12. a–c) Same as Figs. 11a–c for precipitation totals ≥ 10 mm.

Carolina coast (Fig. 5d). Frequency of moderate to heavy precipitation is generally highest northeast of the storm center. The greatest frequency of moderate precipitation is ≤65%, while that of heavy precipitation is <30% (Figs. 6 and 7).

To further evaluate the variability of the precipitation amounts comprising the composites for Track A in Region 2, histograms were constructed for six HPD stations (Fig. 8). The locations of the six stations are shown by the asterisks in Fig. 1c. It is clear from the histograms that the variability in the precipitation totals is large, reflecting variability from storm to storm, both intrinsically and because of a small scatter in the locations of individual storms comprising the composite for Region 2. Observations from Pearson, Georgia (Fig. 8a), located near the composite maximum over Georgia (Fig. 3b), show six-hour precipitation totals ranging from zero to 37 mm. This variability illustrates the difficulty encountered in making quantitative precipitation forecasts, and the caution that must be exercised when applying the composite to particular storms. By contrast, Greenville, NC (Fig. 8b), located in a region of light precipitation in the composite (Fig. 3b), is dominated by light rainfall totals or the absence of precipitation; the greatest precipitation total reported at Greenville was only 10 mm. At the outskirts of the composite precipitation distribution, the range of observed precipitation totals narrows, and the question becomes whether or not light rain will fall. Distributions for Rolling Fork, South Carolina, Abbeville, Alabama, and Augusta, Georgia are shown to further illustrate the precipitation variability.

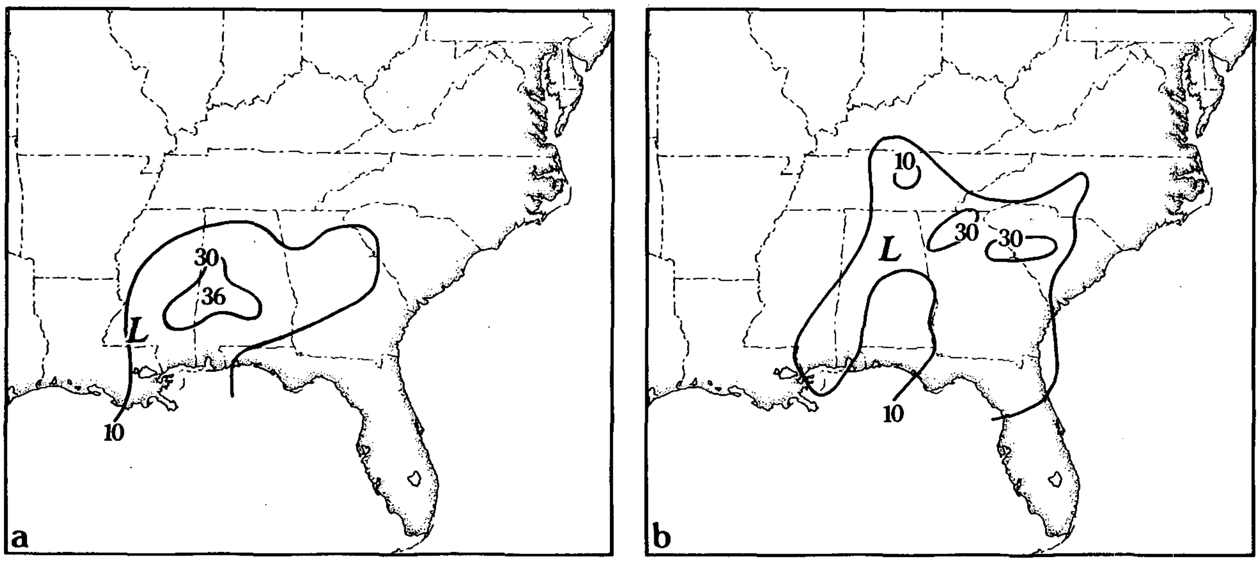
Standard deviations were calculated for the precipitation distributions of a number of the HPD stations.

The results will only be qualitatively discussed since precipitation occurrence was not normally distributed (as evidenced in Fig. 8). The results were qualitatively the same as those obtained using a gamma distribution (Thom 1958) to describe rainfall distributions. A gamma curve is fit to the precipitation distribution for Jocassee, South Carolina (Fig. 8d). The results of these calculations revealed that the ratio of the variance to the precipitation totals is least in regions where the probability of precipitation and the mean precipitation totals are greatest. Included in these regions are those in which orography (Appalachians) has an obvious influence.

Track B storms are predominantly fed by Gulf of Mexico moisture during their early stages (Figs. 9a and b). However, a local maximum in precipitation occurring east of the Appalachians over Virginia, as the storms move northward, provides evidence that Atlantic moisture is involved at this latter stage in the storms' evolution (Fig. 9c). Composites of sea-level pressure and 850-mb heights for Track B storms early in their development suggests that moisture in the lower troposphere is advected from the Gulf of Mexico across the eastern half of the United States (Figs. 10a and b).

Maximum values in the mean precipitation patterns (Figs. 9a–c) decrease from 15 mm to 9 mm as lows track away from the Gulf of Mexico (from Region 1 through 2 and into 4), yet the general area of precipitation (≥1 mm) continues to cover virtually the entire map area. This pattern is also evident in Figs. 11a–c showing the frequency of light precipitation occurrence.

Moderate precipitation occurs at least 50% of the time across a wide area north and east of the lows in Regions 1 and 2 (Fig. 12a) early in the development



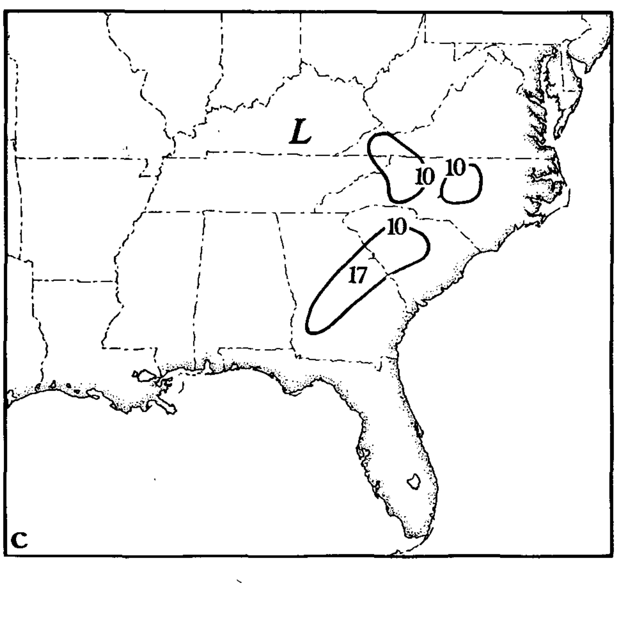




FIG. 13. a–c) Same as Figs. 11a–c for precipitation totals ≥ 20 mm.

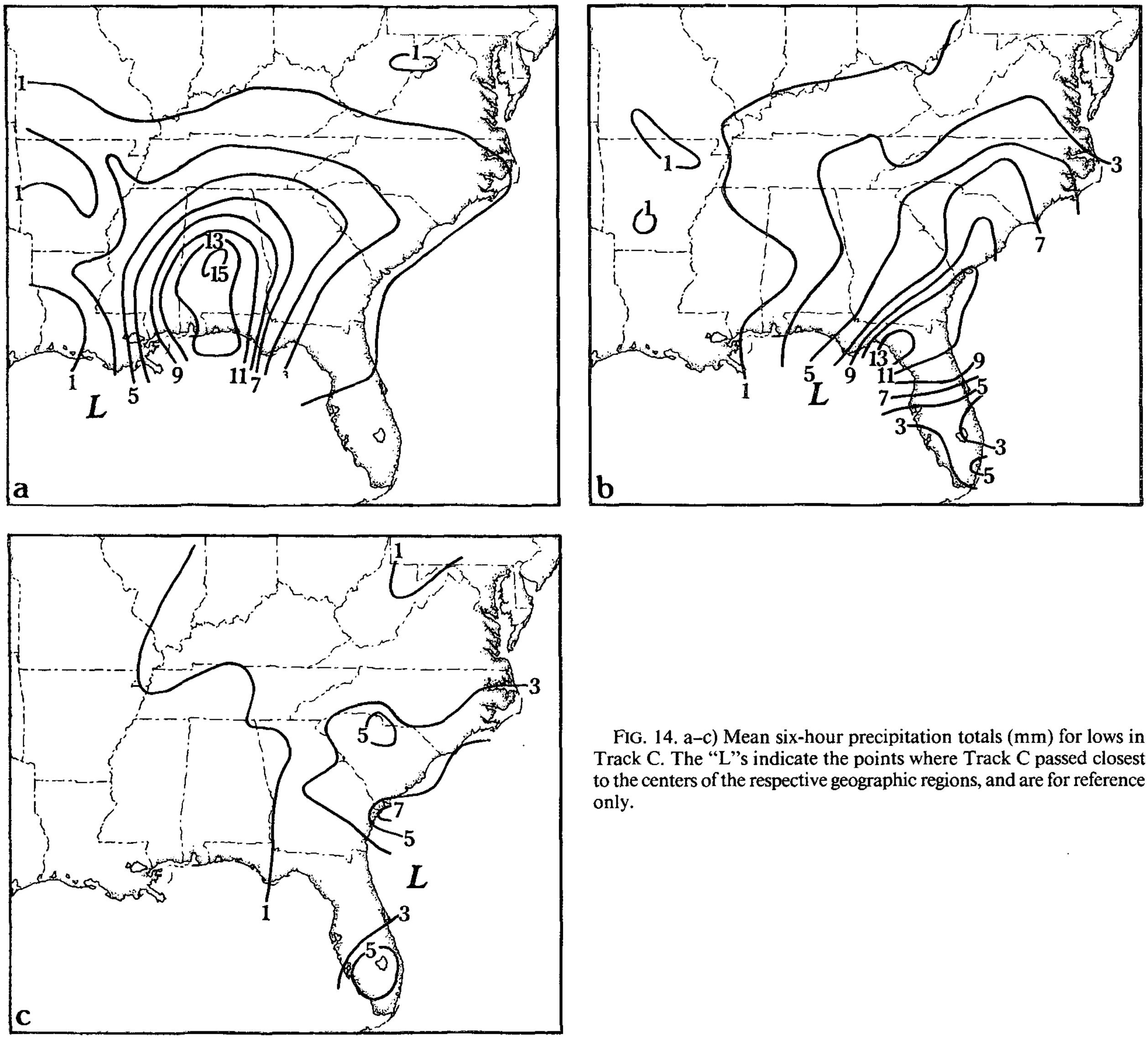



FIG. 14. a–c) Mean six-hour precipitation totals (mm) for lows in Track C. The "L"s indicate the points where Track C passed closest to the centers of the respective geographic regions, and are for reference only.

of the storms. The local maximum of moderate occurrence over the North and South Carolina border in Fig. 12b is likely associated with the propensity of this area for frontogenesis under synoptic conditions conducive for cold-air damming (Bosart et al. 1972). Moisture from the Atlantic comes into play locally in this situation. The area of moderate occurrence decreases as the low moves into Region 4, with maxima occurring over and to the east of the Appalachian Mountains, indicative of orographic influences, and the effects of warm air over running the southern edge of cold-air damming (Fig. 12c).

The frequency of heavy precipitation maximizes near the border of Regions 1 and 2 (Fig. 13a) early in the storm's history. As the lows track northeastward into Region 4, local maxima spread northeastward over and to the east (windward) side of the Appalachians (Fig. 13b and c). These maxima may be related to the outbreak of thunderstorms in the warm sector and provide further evidence for the role of moisture from over the Atlantic in the latter stages of the storms.

Once mature Track B storms reach Region 4, they tend to spawn "Type B" cyclones along the Atlantic coast (Miller 1946). A check of the 12 storms compromising Track B revealed that secondary lows formed along the Atlantic coast in 42% of the cases. Secondary cyclogenesis occurring from South Carolina to Virginia advects moist air from the Atlantic Gulf Stream northwestward, contributing to the precipitation maximum observed east of the Appalachians. Evidence for a northwestward flow from over the warm waters of the Gulf Stream can be seen in the composite 850-mb height field for the latter stage of the Track B storms (not shown).

Storms in Track C tend to mimic the precipitation patterns of those in Track A for Regions 1 and 2, though Track C precipitation amounts and frequencies of occurrence tend to be slightly greater (Figs. 14 to 17). Maximum precipitation values over 6 hours were 15 mm and 13 mm, respectively, as lows track through Regions 1 and 2 (Fig. 14a and b). By the time these storms reach Region 3 and continue eastward, they are too far south and moving away from the Atlantic coast to produce significant precipitation totals over land (Fig. 14c). In Figs. 15 and 16 maxima in the occurrence of light and moderate precipitation are restricted to the southern states and Florida. Southern Mississippi, southern and central Alabama, and the Florida panhandle tend to receive the brunt of the heavy precipitation from these storms (Fig. 17).

*a. Storm track precipitation totals*

Forecasting river levels and flood potential depends not only on precipitation rate, but also on the total precipitation over the duration of a storm. Therefore, a storm-total precipitation climatology (Fig. 18) was constructed for cyclones following each of tracks A, B, and C. Hourly precipitation data for all HPD stations were totaled for the duration of each storm. To produce the storm-total precipitation climatology, storm totals were averaged for all storms in each track. Contoured results appear in Figs. 18a–c, with actual precipitation totals given for selected stations identified in Fig. 18a.

Storms that follow Track A produce the maximum totals (>25 mm) along the Atlantic coast south of Virginia and over Florida (Fig. 18a). Values decrease to

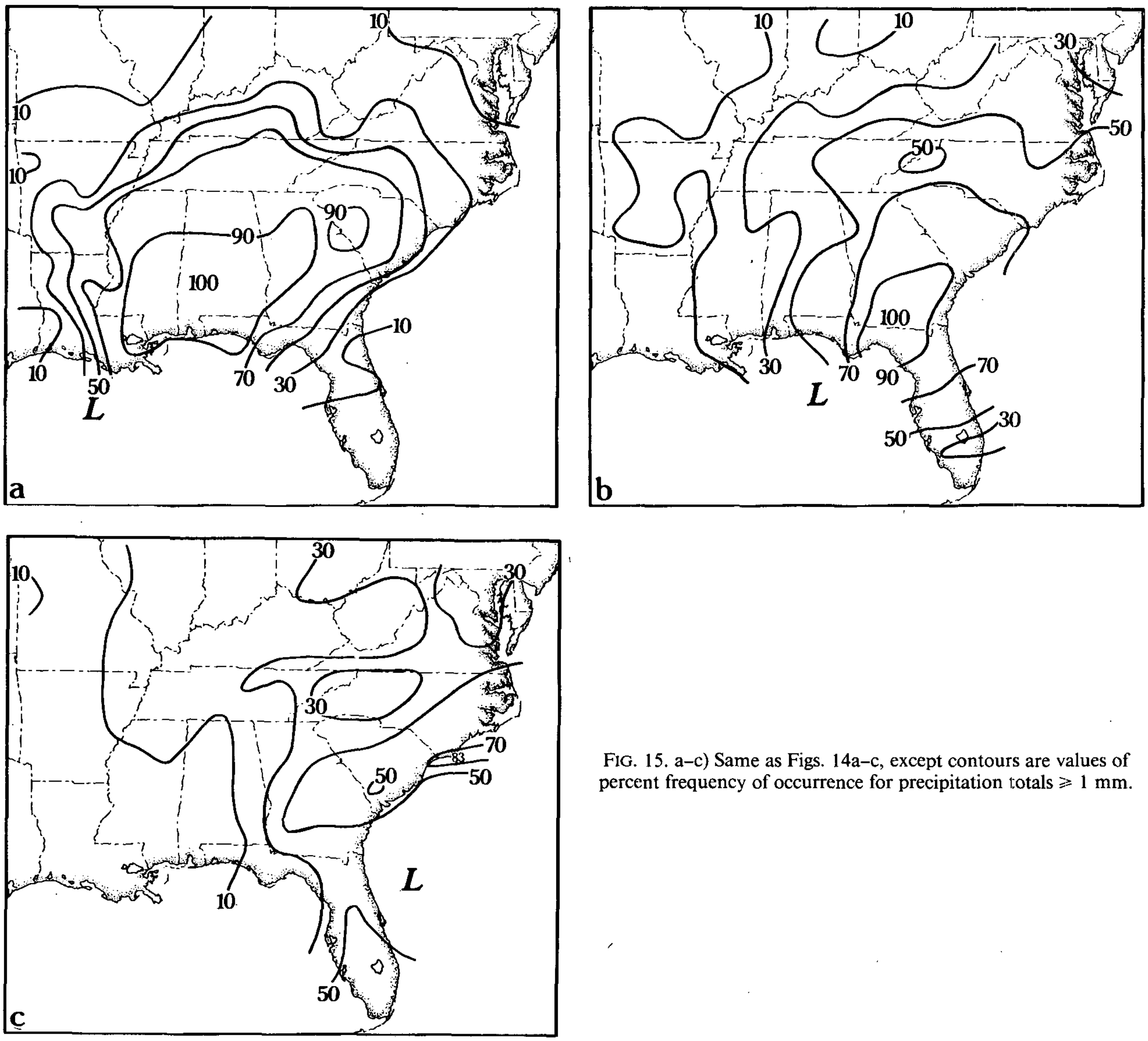



FIG. 15. a–c) Same as Figs. 14a–c, except contours are values of percent frequency of occurrence for precipitation totals ≥ 1 mm.

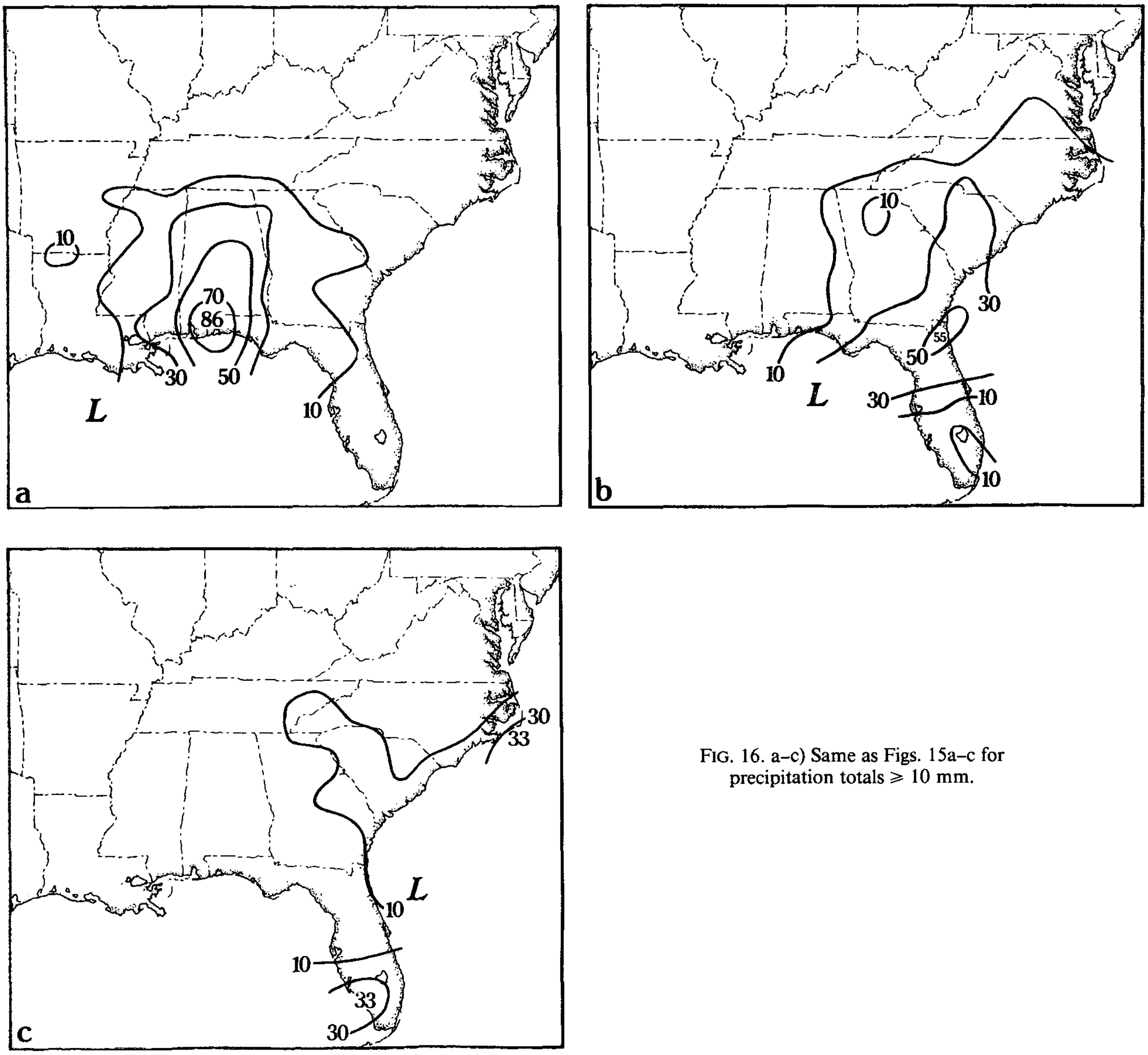



FIG. 16. a–c) Same as Figs. 15a–c for precipitation totals ≥ 10 mm.

the northwest, with <5 mm observed north of the Ohio River. Track B cyclones produce the greatest precipitation totals over land of the three tracks, with an axis of maximum precipitation across Mississippi, Alabama, and northern Georgia (Fig. 18b). The tongue of maximum precipitation extending across the Appalachians into North Carolina and Virginia suggests the combined influence of orography, and moisture from over the Atlantic, and the effects of secondary cyclogenesis along the Atlantic coast. Storms in Track C (Fig. 18c) produce higher precipitation totals than those in Track A, consistent with their slower propagation velocities (Table 2) and greater mean 6-h precipitation totals (Fig. 14). The large precipitation gradient from a maximum of 39 mm at Atlanta, Georgia to 13 mm at Nashville, Tennessee indicates Gulf of Mexico moisture has not reached as far north as for Track B lows.

## 6. GALE case study

To provide an example of the application of the results of the storm-following climatology, a brief case study of the precipitation patterns associated with a cyclone that paralleled Track A is presented in this section of the paper. The case chosen occurred during the field phase of the Genesis of Atlantic Lows Experiment (GALE) conducted during the winter of 1986, and therefore, is not included in the climatology. Data from special observation networks deployed during GALE (Dirks et al. 1988) were incorporated in the study.

Southwesterly flow dominated the middle troposphere over the eastern half of the United States on 11 February 1986 (Fig. 19a). The surface cyclone located over central Alabama (Fig. 19b) developed during the previous 6 hours and is the storm of interest in this case study. Thunderstorms, light rain, and fog occurred along a stationary front ahead of the low. Light rain, drizzle, and fog extended northward into southwest Virginia.

A review of sounding data compiled from 0300 UTC to 0900 UTC 11 February revealed the existence of a low-level jet (LLJ) between 900 mb and 700 mb. Analysis of 300-mb and 500-mb data from the special sounding network deployed during GALE (not shown) indicates that the LLJ formed in response to dynamical forcing associated with the entrance region of a jet streak in the upper troposphere (Uccellini and Johnson 1979; Uccellini and Kocin 1987). The LLJ was located approximately 100–300 km ahead of the surface cold front, approaching and eventually crossing, the quasi-stationary warm front. Analyses of pressure, wind, and moisture fields on isentropic surfaces and cross-section analyses (not shown) were used to locate the extent of this jet.

Isentropic analysis is useful in that air parcels follow isentropic surfaces when potential temperature is conserved, and vertical motion can be estimated from cross isobaric components of the wind field, neglecting diabatic effects and the motion of the pressure surface (Homan and Uccellini 1987). The 300°K-isentropic surface (Fig. 20) reveals wind speeds $\geq$35 m s$^{-1}$ at 0600 UTC 11 February. Cross-isobaric flow towards lower pressure over most of Carolinas, implies upward vertical motion. Trajectory analysis revealed that the low-

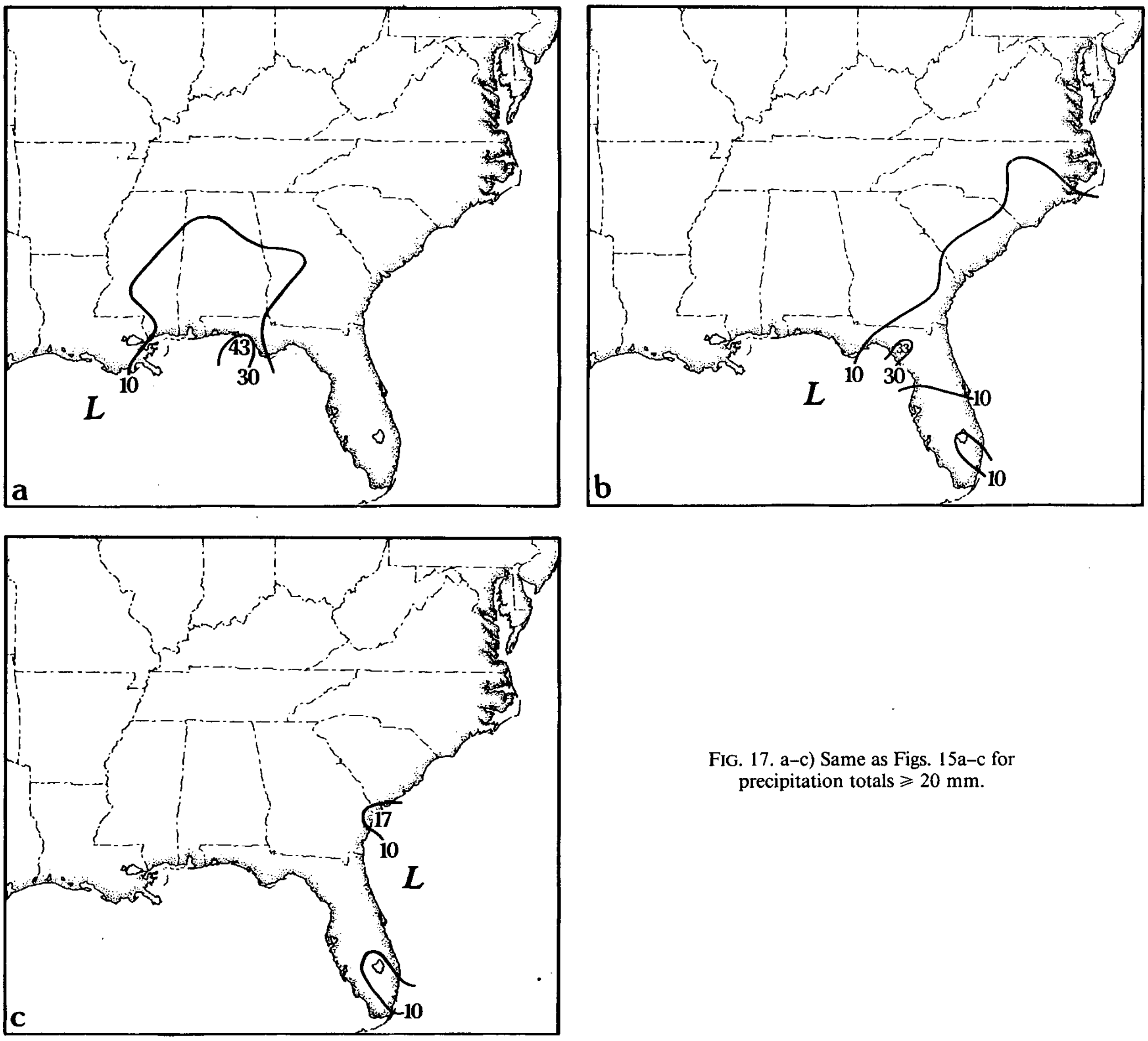



FIG. 17. a–c) Same as Figs. 15a–c for precipitation totals $\geqslant$ 20 mm.

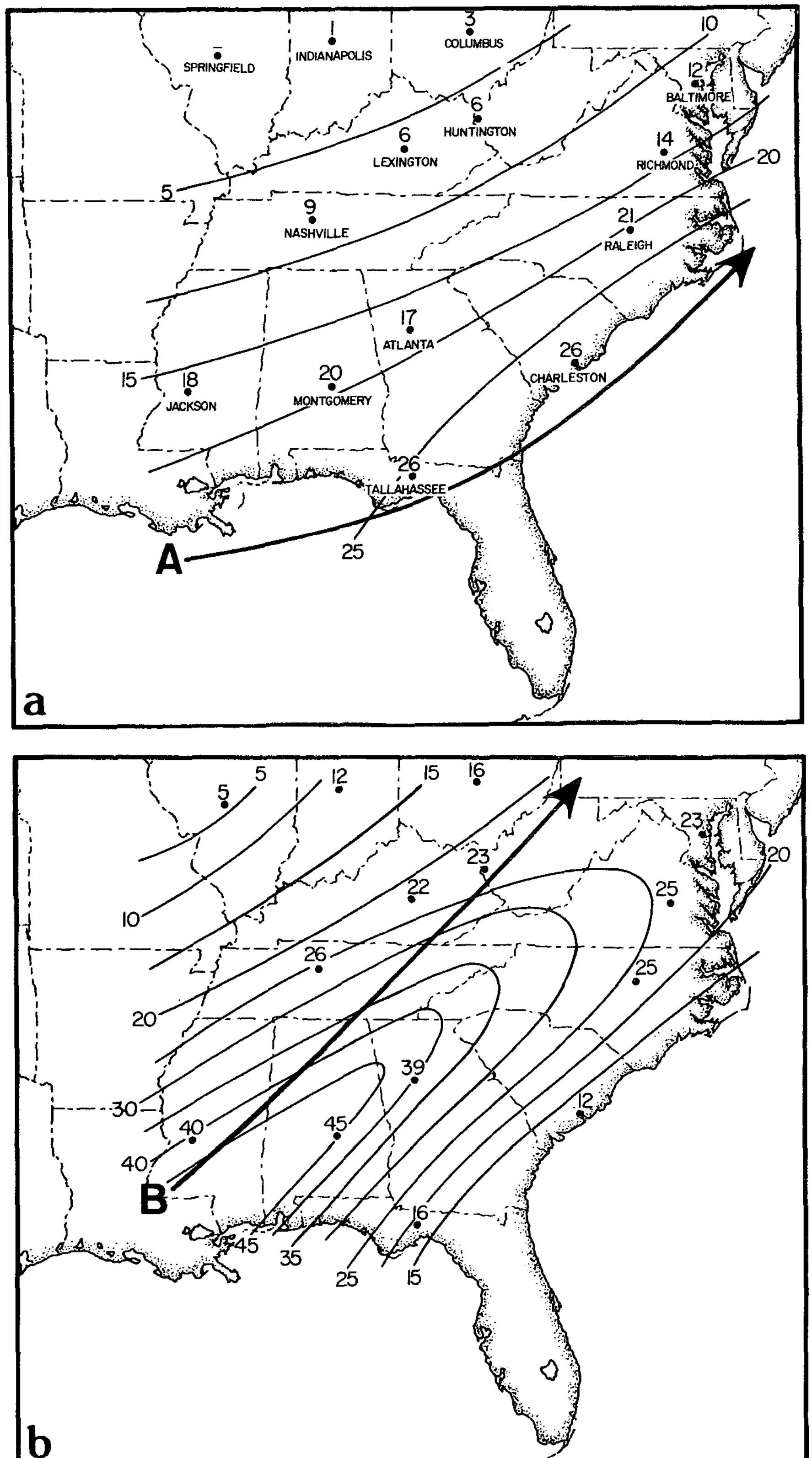



FIG. 18. a) Contours of storm total precipitation (mm) for Track A lows, with selected stations for which precipitation totals (in mm) are shown. b) Same as (a) for Track B lows. c) Same as (a) for Track C lows.

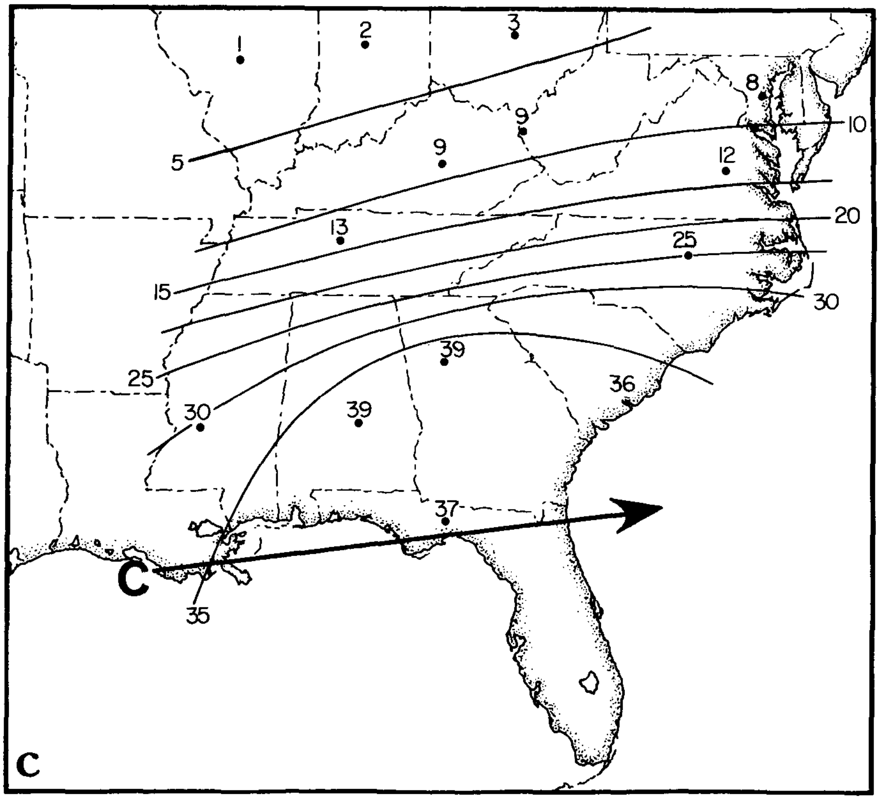



FIG. 18. (*Continued*)

level jet originated within the planetary boundary layer over the Gulf of Mexico, crossed central Georgia and moved off the Atlantic coast by 0900 UTC 11 February. This finding supports the evidence in the climatology of the importance of the Gulf of Mexico as a moisture source for storms over the southeastern United States.

To compare the precipitation distribution associated with the case study to the results of the precipitation climatology for Track A storms, hourly precipitation data were composited into 6-h totals (Fig. 21). The composites were centered at times when the location of the low-pressure center in the case study was closest to the mean low position in the Track A climatology (Fig. 3).

The six-hour precipitation composite centered at 1800 UTC on 10 February (Fig. 21a) (the low is located just south of Louisiana) shows light precipitation across most of the analysis region, with maximum over southern Alabama, Mississippi and over southern Georgia and northern Florida. This pattern is similar to that of the climatology (Fig. 3a), which also has precipitation across southern Alabama, Mississippi, with a tongue of higher values across northern Florida. The precipitation composite for 0300 UTC 11 February (Fig. 21b) shows an axis of heavier precipitation from northern Florida across southern Georgia and South Carolina, with a distinct maximum over southern Georgia, associated with convective activity during the period. Although, the averaging process of the climatology smooths the influence of individual convective events, the pattern of precipitation (Fig. 3b) is remarkably similar to that of the case study. The composite for 0900 UTC (Fig. 21c) shows light precipitation across the southeastern United States, with the greatest precipitation along the Atlantic coast over North Carolina and northern Florida. The corresponding climatology (Fig. 3c) shows a similar distribution, with the greatest precipitation along the North Carolina coast and over Florida. The final composite for 1500 UTC (Fig. 21d) shows very light precipitation lingering over Delaware, Virginia and the Carolinas, with the low along the mid-Atlantic coast, consistent with the climatology (Fig. 3d).

Storm total precipitation for the 36-h period: 0900 UTC 10 February–2100 UTC 11 February is presented in Fig. 22. Comparison with the storm total precipitation for Track A storms (Fig. 18) reveals a similar distribution, with an axis of precipitation along the Atlantic coast, and generally decreasing precipitation totals to the northwest. The maximum of ~60 mm over Georgia in the case study total (Fig. 21) is due to convective activity, and is underestimated in the climatology.

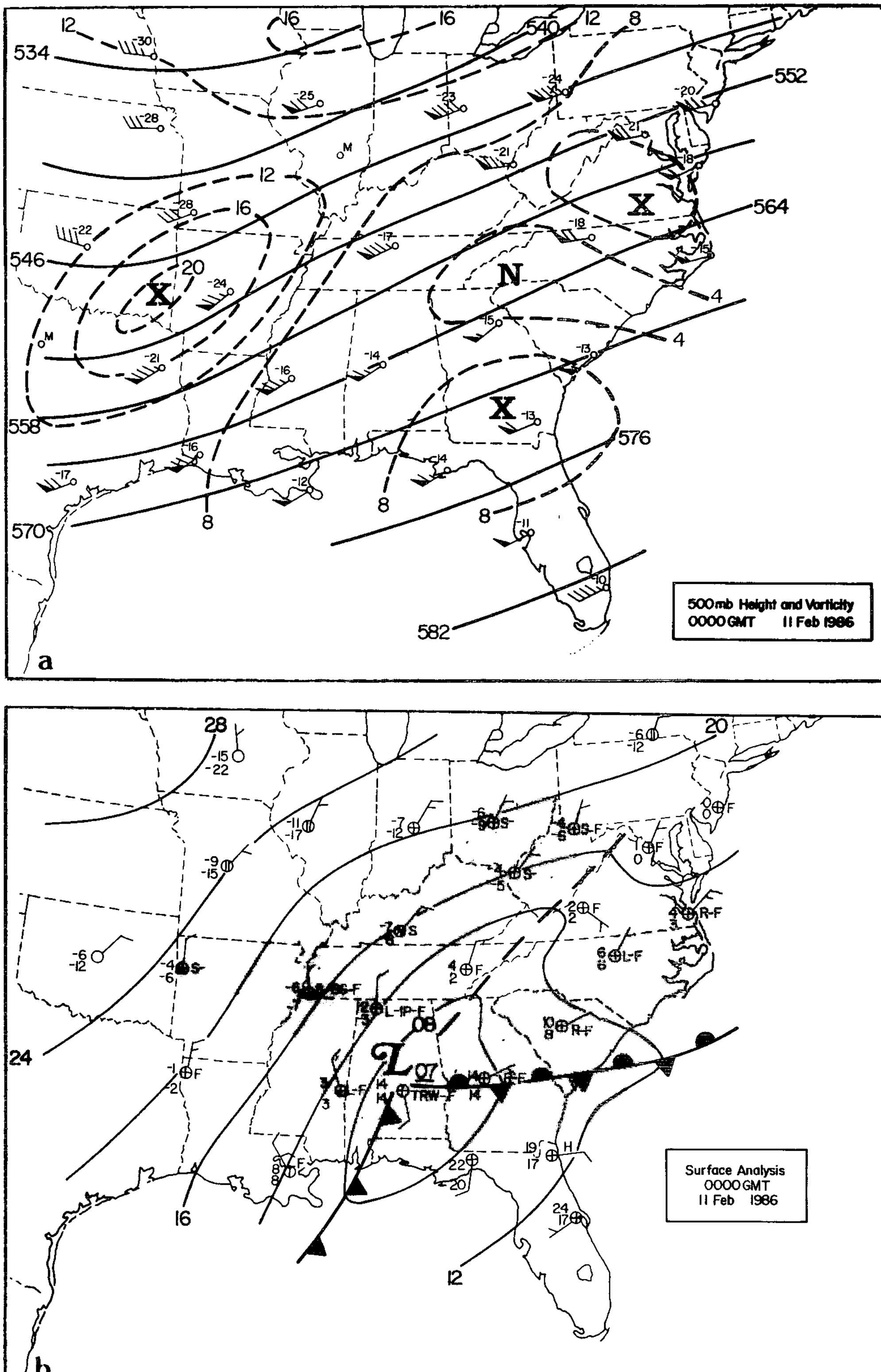



FIG. 19. a) 500 mb analysis for 0000 UTC 11 February 1986. Solid contours are heights (in dm) and the "X" and "N" denote locations of vorticity maxima and minima ($\times10^{-5}$ s$^{-1}$), respectively. Station reports include temperature (°C) and wind velocity (barb = 5 m s$^{-1}$; flag = 25 m s$^{-1}$). b) Surface analysis for 0000 UTC 11 February 1986 (contours every 4 mb). Station reports include temperature and dewpoint (°C), observed weather, cloud cover, and wind velocity. Shading depicts areas of precipitation.

## 7. Summary and conclusions

A storm-following climatology has been constructed of storm-scale precipitation patterns associated with 66 large wintertime lows that originated over the Gulf of Mexico and adjacent coastal area. One objective of this research is to investigate the influence of moisture sources (Gulf of Mexico and Atlantic Ocean) and orography (Appalachian Mountains) on synoptic-scale precipitation patterns associated with winter storms. A second objective is to provide forecasters with a potential guide with which precipitation forecasts by numerical models can be evaluated.

A 24-y inventory of storms that produced significant widespread precipitation over the eastern half of the United States revealed 130 storms. Of these, the majority (66) originated over the Gulf of Mexico Region, outnumbering storms that originated along the Atlantic Coast or Midwest Regions roughly by two-to-one.

By investigating the tracks of the 66 Gulf lows three dominant storm tracks were identified (Tracks A, B, and C). Hourly precipitation data compiled at 316 HPD observation sites across the southeast U.S. were totaled in six-hour intervals, and objectively analyzed. Storm-following precipitation patterns were then composited along the three dominant storm tracks. The precipitation climatology was not extended over the coastal waters in this study due to a lack of data.

Results from the precipitation composites combined with composite sea-level pressure and 850-mb height fields provide evidence that in their early stages storms along all three tracks draw significant moisture from the Gulf of Mexico. As Track A lows cross the Florida panhandle, the extension of precipitation across eastern Georgia, South and North Carolina suggests that the Atlantic provides a second significant moisture source.

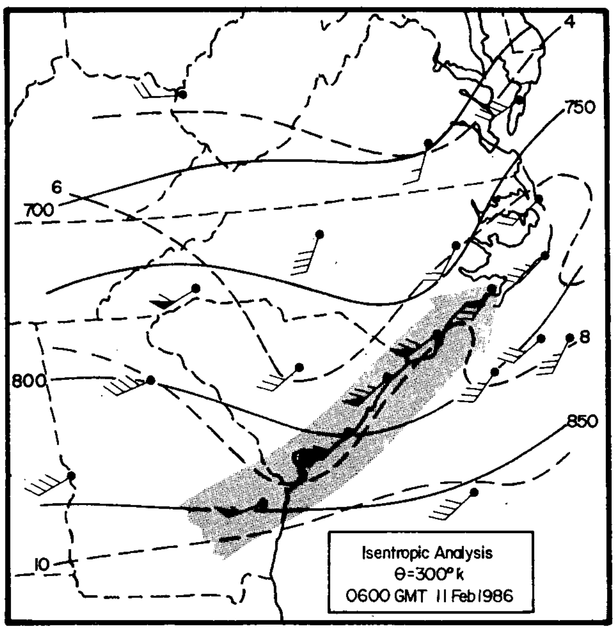



FIG. 20. Isentropic analyses of pressure, wind, and mixing ratio on the 300°K surface for 0600 UTC 11 February.

The frequency of moderate to heavy precipitation was highest northeast of the storm centers at all times along Track A. Track B storms experienced a gradual decrease in precipitation totals as they advanced northeastward, although widespread light precipitation continued to cover most of the southeast United States. As lows in this track moved northeastward into Tennessee and Kentucky, precipitation and frequency maxima over and to the east of the Appalachian mountains were enhanced by Atlantic moisture. Upward vertical velocities are enhanced by a combination of forcing mechanisms under the synoptic conditions of Track B. These include upslope flow, and enhanced low-level convergence associated with the southern edge of cold-air damming and secondary cyclogenesis along the Mid-Atlantic coast.

The central Gulf coast received the greatest precipitation from Track C lows, with precipitation over land diminishing rapidly after the lows passed eastward across the Florida panhandle.

Caution must be exercised when applying the precipitation climatology to quantitative precipitation forecasts, due to the inherent variability in observed precipitation totals, smoothing introduced by the compositing methodology, and the storm selection criteria used in this study.

Storm-total precipitation distributions were also computed for each dominant storm track. Storms that follow Track A produce storm total precipitation > 25 mm along the Atlantic coast south of Virginia, tapering off northward to a minimum north of the Ohio River. Of the three tracks, Track B cyclones produce the greatest composite storm-total precipitation over land, with an axis of maximum precipitation across Mississippi, Alabama, and northern Georgia. Storm precipitation totals for slow moving storms in Track C exceeded those for Track A storms, with the greatest precipitation totals occurring across southern Alabama, Georgia and northern Florida.

Based on the climatological research presented in this paper (for midlatitude cyclones that passed east of 95°W, south of 38°N, and resulted in significant precipitation over the southeastern United States during January, February and March), the following conclusions were drawn:

1) Most of these storms initially formed over the Gulf of Mexico or adjacent coastal region (Fig. 1a).

2) The Gulf of Mexico provides most of the mois-

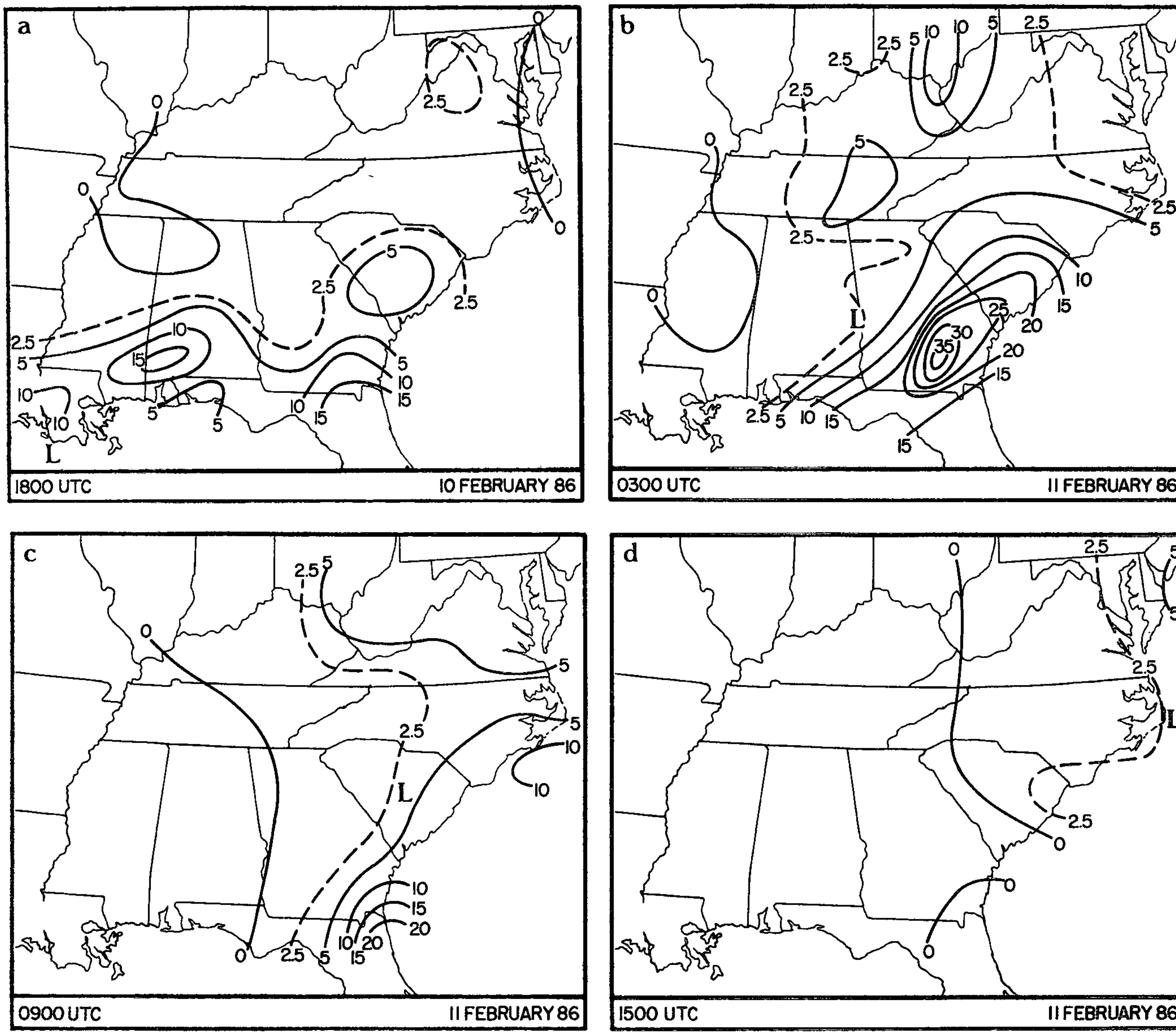



FIG. 21. Six-hour centered precipitation totals (mm) for: a) 1800 UTC 10 February 1986, b) 0300 UTC 11 February 1986 c) 0900 UTC 11 February 1986, and d) 1500 UTC 11 February 1986.

ture for all storms that initially form over the Gulf of Mexico or adjacent coastal region, with the greatest totals and highest frequencies generally located north and east of the storm center.

3) Storms that track west of the Appalachians (Track B) tend to produce heavier precipitation totals across wider areas over the eastern half of the United States than those that track south and east of the Appalachian Mountains to the Atlantic coast (Tracks A and C). (Lows following Tracks A and C may produce as much or even more widespread heavy precipitation, but much of this occurs over the coastal waters that are outside the observation area.)

4) The role of the Atlantic Ocean as a moisture source is limited early in the storms' history, and increases as storms move northeastward.

5) The Appalachian Mountains locally enhance precipitation for all three storm tracks.

To provide an example of the application of the precipitation climatology, selected results of a GALE case study (10–11 February 1986) were presented of a sur-

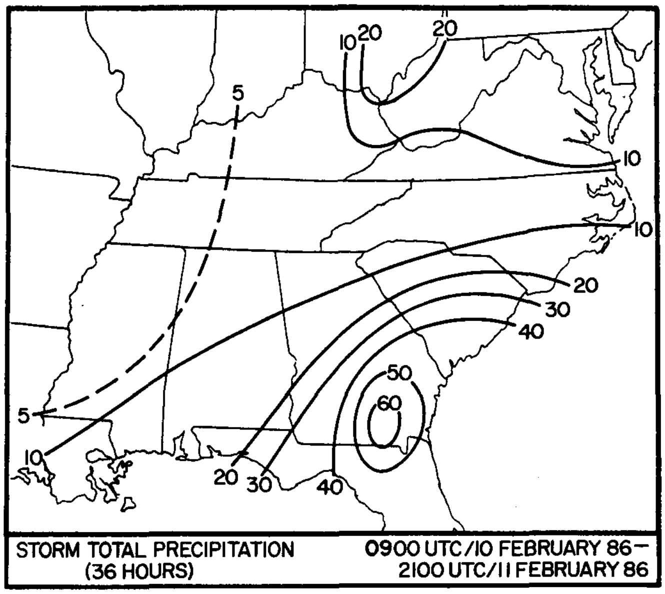



FIG. 22. Storm-total precipitation (mm) for the period 0900 UTC on 10 February 1986 to 21 UTC on 11 February 1986.

face low whose path was close to Track A. The surface low developed over central Alabama at 0000 UTC 11 February and traveled rapidly east-northeastward through the heart of the GALE observation network centered in the Carolinas.

Isentropic analyses revealed the existence of a low-level jet that originated over the Gulf coast and propagated rapidly through central Georgia and the Carolinas and off the Carolina coast. The transport of moisture from over the Gulf of Mexico to the region of precipitation by the low-level jet, is consistent with the climatological evidence of the importance of the Gulf of Mexico as a moisture source for storms over the southeastern United States.

Comparison of 6-h precipitation patterns for the case study and the Track A climatology show good agreement. The similarity of the precipitation patterns provides evidence of the importance of geography (orography of the Appalachians, shape of coastlines, proximity to warm ocean waters) in determining the distribution of precipitation. Discrepancies in the magnitudes of the maximum precipitation totals, however, highlight the limitations of the climatology, and the caution that must be exercised when attempting to apply the precipitation climatology to local quantitative precipitation forecasts.

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