

Diurnal Surface-Pressure Variations over the Continental United States and the Influence of Sea Level Reduction

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ABSTRACT

This paper presents the results of a detailed study of the diurnal and semidiurnal pressure variations at the surface across the continental United States. Using a larger dataset than preceding studies and a variety of analysis approaches, the spatial and temporal variations in the diurnal and semidiurnal components of station and sea level pressure are described, and the influence of current pressure reduction techniques on the characteristics of sea level pressure is evaluated. It is shown that the temperature-averaging scheme currently used in sea level pressure reduction creates a bogus semidiurnal signal in sea level pressure over high terrain. This paper also describes the summertime mesoscale evolution of station pressure over the northeast United States and presents 3-h pressure-change maps for the continental United States during the summer and winter seasons.

1. Introduction

Diurnal and semidiurnal variations are important contributors to the overall variance of pressure at the earth's surface. These variations obscure pressure changes associated with the movement and evolution of transient synoptic and mesoscale systems and dominate the pressure signal under quiescent conditions. A detailed knowledge of the spatial and temporal variability of the diurnal and semidiurnal pressure signals would not only be useful for isolating the pressure changes associated with transient systems, but would also contribute to our knowledge of topographically fixed phenomena such as sea-land breezes and mountain-valley circulations. Diurnal and semidiurnal pressure variations are also of interest because of their relationship to variations in cloudiness and precipitation (Riehl 1947; Brier 1965; Brier and Simpson 1969).

By the end of the nineteenth century it was well known that the mean surface-pressure variations at virtually any location consist primarily of diurnal and semidiurnal components (Hann 1889; Cole 1892). Figure 1, which displays the annual-mean diurnal sea level pressure evolution at three low-elevation stations, illustrates this fact. At all three locations the semidiurnal component is evident, with amplitude increasing toward the equator. By the turn of the century it was also recognized that the diurnal component is spatially irregular and that the semidiurnal variation reflects

some type of global tidal phenomena, with the largest amplitude near the equator. Studies of that era could not clearly describe the geographical variability of the diurnal and semidiurnal variations because of the sparsity of pressure data. For example, in perhaps the earliest study of diurnal pressure variations across the United States, Cole (1892) determined the seasonal variation of the first four harmonics of the diurnal pressure evolution at six locations. As more data became available during the twentieth century, various investigators attempted to more clearly delineate the geographic variations of the diurnal and semidiurnal surface pressure components.

The classic reference on diurnal surface-pressure changes across the continental United States is Weather Bureau Technical Paper No. 1; published in 1943. This work¹ presents an atlas of monthly mean diurnal pressure traces at 100 stations across the continental United States. Without superior successor studies, it has remained the basic reference used by synoptic and mesoscale meteorologists. Applying the same 100-station dataset, Spar (1952) examined the semidiurnal pressure component at the surface across the United States. He found that the amplitude of the semidiurnal pressure signal generally increased toward the equator and that amplitude isolines ran approximately east-west across the continent with somewhat enhanced amplitude over regions of high terrain. Furthermore, the semidiurnal pressure signal possessed an annual variation with

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¹ Based on the laborious digitizing and analysis efforts sponsored by the Work Project Administration (WPA).

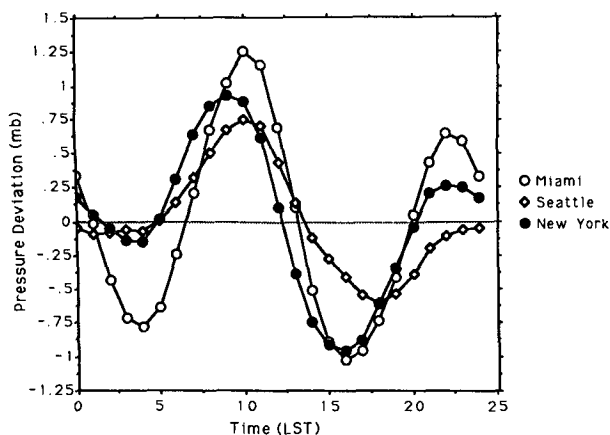


FIG. 1. Annual-mean diurnal sea level pressure variations at three low-level stations of varying latitude. Pressures are expressed as deviations (mb) from the long-term mean for each station (see section 2 for details).

minimum amplitude during the late spring and early summer. Haurwitz and Cowley (1973) examined the diurnal and semidiurnal pressure components at the surface on a global scale, using data from nearly 300 stations. They found that the amplitude of the diurnal component was largest over land and that the isopleths of semidiurnal amplitude possessed the zonal orientation noted by Spar. At most locations, the amplitude of the semidiurnal pressure component was larger than that of the diurnal.

There is extensive literature on the origin of semidiurnal and diurnal pressure variations at the surface. The works of Siebert (1961), Lindzen (1967), Chapman and Lindzen (1970), among others, have shown that the semidiurnal surface-pressure component is the result of the response of the upper stratosphere and mesosphere to forcing by the diurnal solar thermal wave. The theoretical amplitude of this semidiurnal pressure variation is largest at the equator (approximately 1 mb) and lessens toward the poles.

A diurnal surface-pressure component is also created by upper-atmospheric thermal forcing but is substantially weaker than the semidiurnal mode at the surface. Diurnal pressure change at the surface can also be forced by heating and cooling in the lower troposphere and by the resulting diurnal circulations. In areas of large surface diabatic forcing, diurnal pressure changes can be quite large; in some cases they exceed 1.5 mb in amplitude. For example, a large diurnal pressure variation is observed during the summer within the Central Valley of California, where daytime heating in the lower troposphere results in substantial pressure falls (Mass et al. 1986).

This paper presents the results of a detailed study of the diurnal and semidiurnal pressure variations at the

surface across the continental United States. Using a larger dataset than preceding studies and a variety of analysis approaches, the spatial and temporal variations in the diurnal and semidiurnal components of station and sea level pressures are documented. The influence of current pressure reduction techniques on the characteristics of sea level pressure is also evaluated. Finally, 3-h station-pressure-change maps are provided to serve as a reference for synoptic and mesoscale analyses.

2. Data acquisition and initial processing

In this study, both station pressure (pressure reported at the actual elevation of the observing site) and sea level pressure (station pressure reduced to mean sea level) for stations across the continental United States are examined. The source of data for this study is the U.S. Hourly Surface Observation Dataset maintained by the Data Support Section of the National Center for Atmospheric Research (NCAR). Station pressure was available every 3 h and sea level pressure was generally available hourly. For each station, the hourly (or three-hourly) pressures were expressed as deviations from the monthly mean (of the month the observations were taken). This procedure removes any long-term drift in the mean pressures; such drift could be real or the result of inaccuracies or movement of the measuring instrument.

The next step was to average the pressure deviations into monthly, seasonal,² and annual averages for each hour. To determine the minimum number of years of data required to produce representative results (i.e., results that would be virtually indistinguishable from those calculated using a much larger dataset), the following approach was used. For 15 geographically well-distributed stations, the seasonal and annual averages of the pressure deviations for progressively longer periods were compared with the mean of the complete records (generally 15–25 years). Averaging more than four years of data for the seasonal means and one year of data for the annual means produced results indistinguishable from longer-term averages. These results were confirmed statistically using the standard *t* test. Specifically, it was found that there was no statistically significant difference (at the 5% level) between the seasonal (annual) averages computed using 4 (1) years worth of data and the values calculated from all available data. These results are consistent with those found during a study of diurnal precipitation variability (Wallace 1975) in which it was determined that at least 200 observations were required for stable results. For

² The seasons were defined as winter (DJF), spring (MAM), summer (JJA), and autumn (SON).

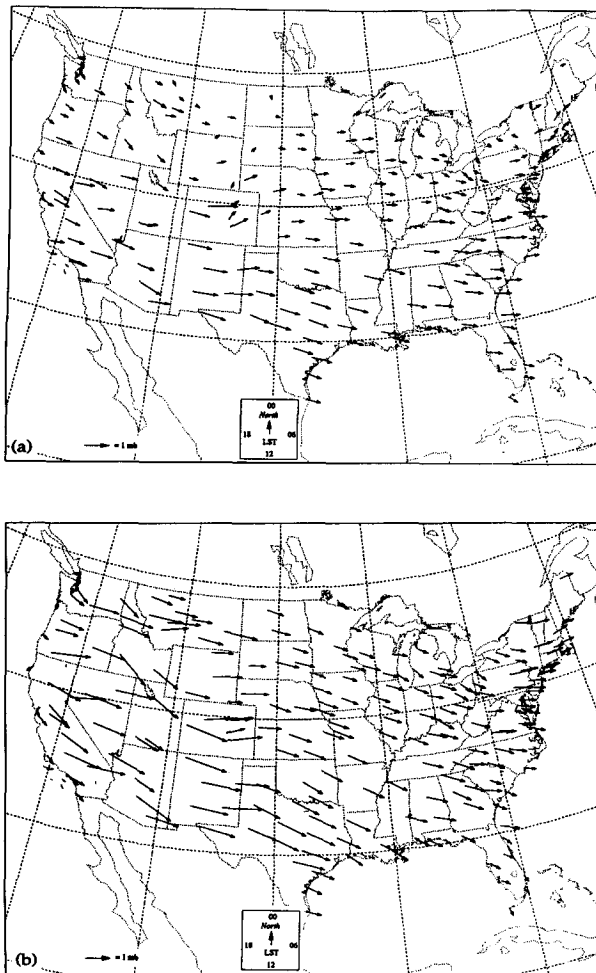


FIG. 2. Winter (a) and summer (b) diurnal sea level pressure variations across the continental United States. The length of the arrows are proportional to the amplitude of the first harmonic (see legend) and the direction relative to true north indicates the phase (time of the maximum of this component in LST). As noted in the legend, northward-directed arrows indicate a midnight maximum, eastward-directed arrows indicate a 0600 LST maximum.

sea level (station) pressure, these procedures resulted in a dataset of 208 (213) stations.³

3. Harmonic analyses

a. Diurnal component

Sea level and station pressure observations were analyzed harmonically to determine the amplitude and

phase of the diurnal⁴ component across the United States. Although station pressure was available only every 3 h and provides less resolution (0.3 mb) than sea level pressure (0.1 mb), it was found that harmonic analyses of either station or sea level pressure were virtually indistinguishable for stations near sea level. In this study, the phase of the first harmonic is given by the local standard time (LST) that this component reaches its maximum. The amplitude and phase of the diurnal component of sea level pressure for the winter and summer seasons are presented in Figs. 2a and 2b. In these figures, the length of the arrow is proportional to the diurnal amplitude, and the direction of the arrow (relative to true north) gives the time of the maximum in LST using a 24-h clock. Figure 3 presents the amplitude of the diurnal component of sea level pressure during summer. In winter (Fig. 2a) there is a general decrease in amplitude of the first harmonic with proximity to water and increasing latitude, with amplitudes ranging from ~1–1.5 mb in the Southwest to less than 0.25 mb along the Canadian border and the coastal sections of the Pacific Northwest. The phase of the first harmonic is relatively uniform, with most stations reaching a maximum at approximately 0700 LST. Distinctly different phasing is apparent along the eastern slopes of the Rockies and coastal New England; in these locations the maxima in the first harmonic occur at approximately 0300 LST. Phasing irregularities are also obvious in regions where the diurnal amplitudes are small. The diurnal amplitudes in sea level pressure for summer (Fig. 2b and Fig. 3) are considerably larger than those of winter, especially along the northern tier of states. The largest amplitudes, exceeding 1.75 mb at several locations, are found over the interior of the western United States. Weak amplitude and irregular phasing are noted along the stratus-laden Pacific coast, where diurnal temperature variations are small. Although phase variability is generally less during the summer than during the winter, the two regions of early phasing (along the eastern slopes of the Rockies and coastal New England) are still evident.

Figure 4 presents a vector plot of the diurnal component of station pressure for summer, which can be compared with the corresponding sea level pressure display (Figure 2b). As with sea level pressure, the diurnal amplitude appears to be greatest in the interior of the western United States where the daily temperature range is large and smaller in regions of maritime influence. Compared to sea level pressure, the diurnal amplitudes of station pressure are modestly reduced (20%–30%) over higher terrain. Figure 5 presents a scattergram for the summer season of the amplitude

³ In the search for sufficiently long time series at each station the study was begun at the year 1960 and proceeded forward in time until sufficient pressure data was acquired.

⁴ Or more precisely, the first component (or harmonic) of the daily pressure variation.

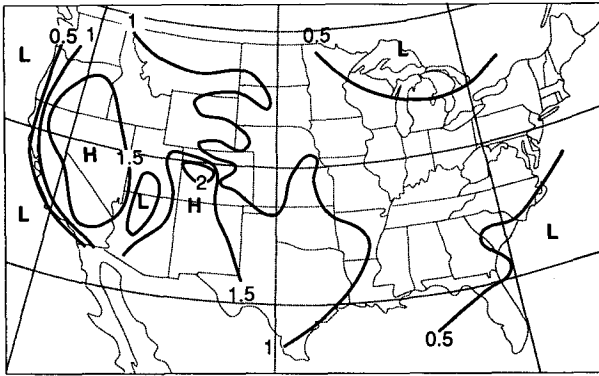


FIG. 3. Amplitude of the diurnal component of sea level pressure during summer in millibars.

of the diurnal component of station pressure versus daily temperature range. This figure suggests an approximately linear relationship between these two parameters; the linear correlation between them is 0.71.

Table 1 presents a summary of amplitudes and phases of the first (diurnal) harmonics of sea level and station pressures as season and latitude vary. The amplitude of the first harmonic of sea level pressure averaged over the entire continental United States is largest (0.90 mb), and the phasing is latest (07.28 LST, note that times are given in decimal fractions of an hour) during the summer months. The diurnal amplitude and phase for station pressure are quite similar to those of sea level pressure except for generally weaker amplitude (except winter) and earlier phasing (except spring).

The latitude of maximum amplitude of the first harmonic varies systematically during the year. Figure 6

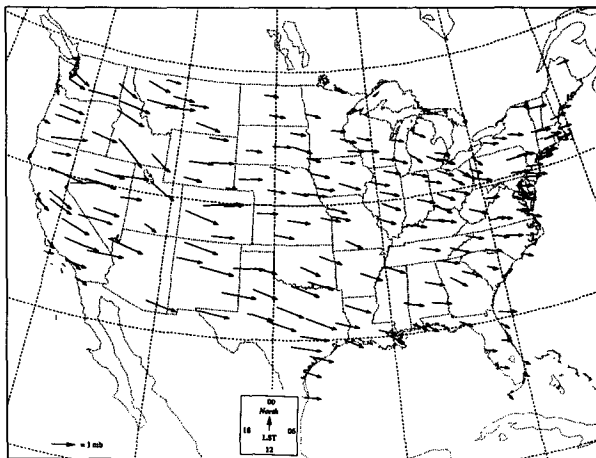


FIG. 4. Amplitude of the diurnal component of station pressure during summer in millibars.

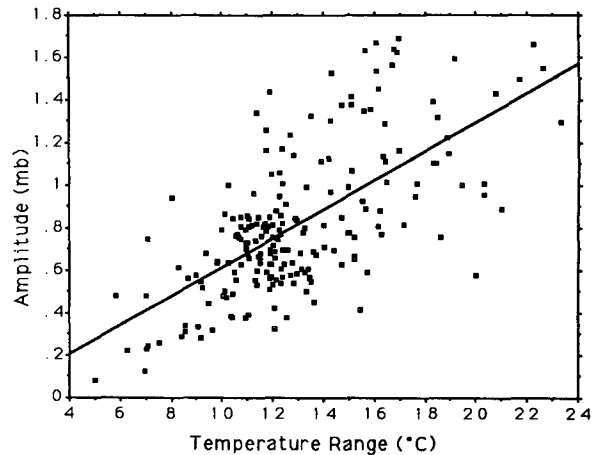


FIG. 5. Scattergram of the amplitude of the diurnal harmonic of station pressure versus temperature range for the summer season.

presents scattergrams of the diurnal amplitude of station pressure versus latitude for the four seasons. Also plotted is a least-squares fit second-order polynomial. During winter, the amplitude peaks at $\sim 31^\circ\text{N}$ and declines rapidly to the north. During spring and summer, the peak migrates to approximately $35^\circ\text{--}37^\circ\text{N}$, and both the scatter and amplitude ranges increase considerably. By autumn, the amplitude peak shifts southward and the amount of scatter lessens. The tendency for a decrease in amplitude south of 30°N (for all seasons) reflects the fact that most of the stations south of the latitude are located on the coast, where the diurnal temperature range is reduced. More quantitatively, Table 2 shows that the linear correlation between the diurnal amplitude of station pressure and latitude varies from -0.56 during the winter to only -0.05 during the summer; sea level pressure correlations follow a similar seasonal variation. These findings indicate that the latitudinal variation of the first harmonic is large during the winter season when there is a strong gradient in solar insolation (and temperature) over the continental United States; progressing into the summer, the dependence of the first diurnal harmonic on latitude weakens and the maximum shifts northward as solar forcing (and temperature) becomes more uniform across the United States.

b. Semidiurnal pressure component

The annual-mean semidiurnal component of sea level pressure is presented in Fig. 7 (vector plots of amplitude and phase) and Fig. 8 (amplitude only). The time (LST) of the first maximum was used to determine the phase of this harmonic. The phase of the semidiurnal harmonic is relatively uniform across the domain (certainly more so than the diurnal com-

TABLE 1. Amplitude and phase of the diurnal component of sea level and station (in parentheses) pressures.

Region	Number of stations	Amplitude (mb)					Phase* (LST)				
		Annual	Winter	Spring	Summer	Fall	Annual	Winter	Spring	Summer	Fall
Whole United States	208 (213)	0.70 (0.66)	0.51 (0.52)	0.76 (0.75)	0.90 (0.82)	0.67 (0.57)	06.94 (06.64)	06.60 (06.34)	06.86 (06.92)	07.28 (06.99)	06.83 (06.31)
20°–30°N	13 (15)	0.58 (0.57)	0.60 (0.61)	0.64 (0.60)	0.61 (0.54)	0.50 (0.54)	07.75 (07.08)	07.22 (06.71)	07.98 (07.58)	08.48 (07.60)	07.41 (06.53)
30°–40°N	97 (89)	0.85 (0.82)	0.67 (0.69)	0.91 (0.92)	1.01 (0.93)	0.81 (0.74)	07.01 (06.76)	06.55 (06.37)	07.01 (07.03)	07.38 (07.06)	06.93 (06.45)
40°–50°N	99 (101)	0.58 (0.56)	0.32 (0.37)	0.62 (0.65)	0.82 (0.77)	0.55 (0.44)	06.77 (06.51)	06.57 (06.21)	06.57 (06.62)	07.02 (06.91)	06.67 (06.10)

* Note that phase values are in decimal fractions of an hour.

ponent), with the first maximum at approximately 1000 LST, and amplitude generally decreasing toward the north. Somewhat earlier phasing is apparent along the Continental Divide and the eastern slopes of the Rockies. The largest amplitudes occur over the western United States, especially over Colorado and New Mexico. Other regions of enhanced amplitude are approximately coincident with the Appalachian and Sierra Nevada mountains. The seasonal semidiurnal components are quite similar to the annual averages presented above and thus are not displayed.

The annual semidiurnal component of station pressure is presented in Fig. 9 (vector plots of amplitude and phase) and Fig. 10 (amplitude analysis only). Phase is nearly uniform across the entire nation with the isopleths of semidiurnal amplitude being far more zonal for station pressure (Fig. 10) than for sea level pressure (Fig. 8). This distribution of semidiurnal station-pressure amplitude is quite similar to that of Spar (1952), which made use of a substantially smaller dataset. Both Fig. 10 and Spar's Fig. 1 show maxima over the continental divide, the interior of California, and along the eastern coast of the United States.

A summary of the semidiurnal components of sea level and station pressures for varying season and latitude is presented in Table 3. The semidiurnal component of station pressure averaged over the entire dataset is relatively constant in amplitude throughout the year (~ 0.57 mb), whereas the sea level pressure semidiurnal amplitude is smallest during the summer (~ 0.56 mb) and largest during the fall and winter (~ 0.75 mb).⁵ Phase does not change appreciably either by season or latitude band for either sea level or station pressure. For both sea level and station pressure the

amplitude of the semidiurnal pressure component decreases with latitude. This relationship is further illustrated in a scattergram of annually averaged semidiurnal amplitude of station pressure versus latitude (Fig. 11), which indicates a nearly linear dependence. As shown in Table 4, the correlation between the semidiurnal amplitude of station pressure and latitude remains high throughout the year with little variation. In contrast, the correlation of the semidiurnal component of sea level pressure with latitude varies substantially by season, varying from ~ -0.58 during the winter and fall to ~ -0.84 during the spring and summer. As discussed in section 7, this seasonal variability is predominantly the result of problems with the National Weather Service algorithm for reducing station pressure to sea level.

c. Relative contribution of the diurnal and semidiurnal components to the mean daily pressure variation at the surface

Nearly all of the variance of the mean daily station-pressure variation can be explained by the superposition of the diurnal and semidiurnal components. The third component is generally negligible for all seasons, except winter. During the winter, the third component explains less than 10% of the variance across the lower two-thirds of the United States and only approaches 20% in the far northern sections of the Midwest and northern Plains. Figure 12 presents the percentage of variance explained by the semidiurnal harmonic of station pressure for the winter and summer seasons across the United States. (Since the variance explained by the diurnal component is approximately the difference between 100% and the magnitude of semidiurnal component, the variance explained by the diurnal component is not shown.) During the winter (Fig. 12a) a complex pattern is evident with neither component dominating. There is some tendency for larger semidiurnal amplitudes to be observed along the Southeast

⁵ In contrast, Spar (1952) found that the amplitude of the semidiurnal component in station pressure possesses a substantial seasonal variation with minimum amplitude during the late spring and summer months.

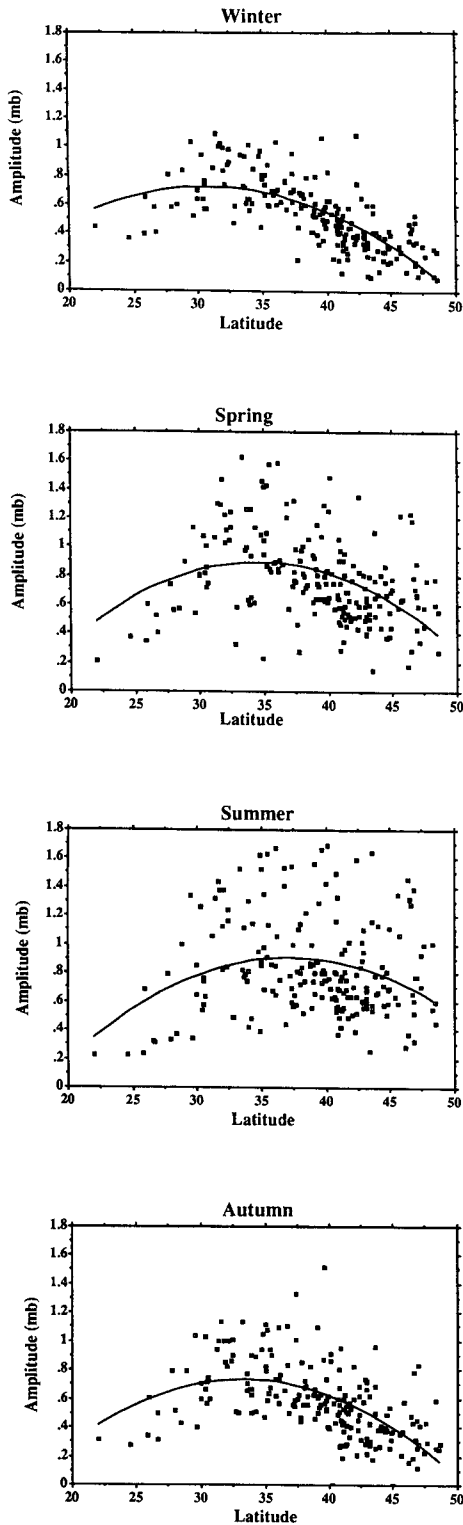


FIG. 6. Scattergrams of the amplitude of the diurnal component of station pressure (mb) versus latitude for winter, spring, summer, and autumn. Also shown are curves that represent best-fit second-order polynomials.

TABLE 2. Linear correlation coefficients between the amplitudes of diurnal sea level and station-pressure variations and latitude.

	Annual	Winter	Spring	Summer	Fall
Sea level pressure	-0.33	-0.66	-0.32	-0.04	-0.27
Station pressure	-0.33	-0.56	-0.28	-0.05	-0.40

coast, the northern Great Plains, and the coast of the Pacific Northwest. During the summer (Fig. 12b) the diurnal component dominates most of the nation except for the Southeast coast, where the semidiurnal variability explains more than 70% of the variance.

4. Regional daily pressure variations for the northeast United States

The surface-pressure signatures of diurnal circulations have been clearly documented in only a handful of locations (Ferber and Mass 1990). In this section, the project database is used to examine the response of station pressure to the regional diurnal circulations of the northeast United States during the summer. This region was selected for several reasons. First, in this area there is a relative abundance of reporting stations and a general simplicity of terrain. Second, the diurnal circulations appear to be particularly strong in this region during the summer, perhaps because of the proximity of a relatively cool ocean surface to a well-heated continental area.

Figure 13 displays the diurnal variation of station pressure over the northeast United States during the summer season. Plotted on these maps are the seasonally averaged deviations from the daily mean of station pressure at four times during the day. At 0400 LST positive pressure deviations dominate inland, with

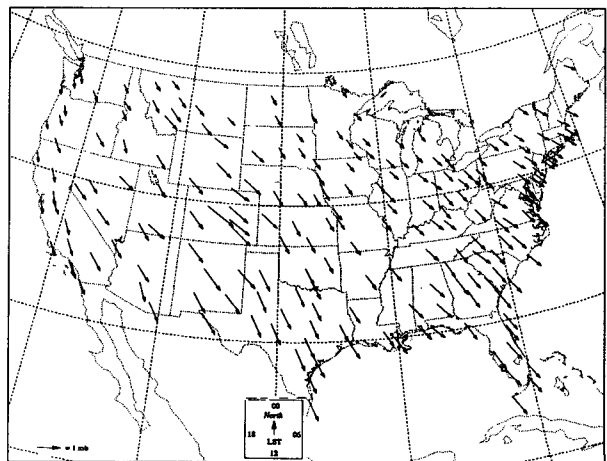


FIG. 7. Annual semidiurnal sea level pressure variations across the continental United States. Arrows plotted as in Fig. 2.

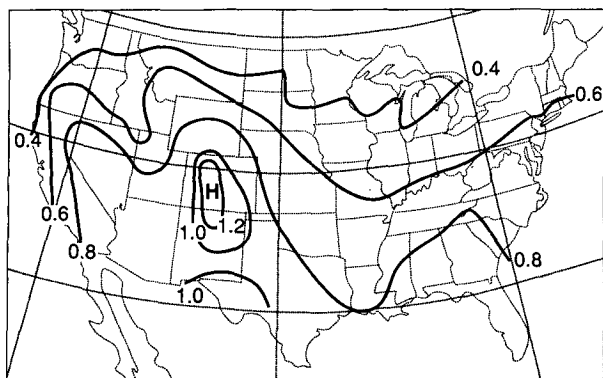


FIG. 8. Amplitude of the annual semidiurnal component of sea level pressure in millibars.

negative deviations along the coast. Such a pressure distribution is consistent with an offshore, land-breeze circulation. Six hours later at 1000 LST there is still an offshore pressure gradient, although significant alterations in the pressure pattern have occurred. At 1600 LST, near the time of maximum air temperature over land, the pattern has completely reversed from the nighttime pressure distribution. Low pressure (i.e., enhanced negative deviations) dominates the interior, with higher pressure along the Atlantic coast and Lake Ontario. Such a pressure pattern is consistent with an onshore, sea-breeze circulation. Finally, at 2200 LST a weakened onshore pressure gradient is apparent. It is of interest to note that the diurnal mesoscale pressure pattern shown for New England in Fig. 13 is similar in amplitude (~ 0.5 – 1 mb) and phasing to that found over Washington state in the study of Ferber and Mass (1990).

5. Three-hour pressure-change analyses

To aid the interpretation of surface synoptic charts, a series of maps of 3-h station-pressure change for the winter and the summer seasons were prepared. These figures, presented in the Appendix, can assist synoptic analysts in separating the pressure variability produced by transient synoptic and mesoscale disturbances from the changes created by topographically fixed circulations and upper atmospheric oscillations and tides.⁶ Pressure changes during some 3-h periods are quite large, reaching over 2 mb at some locations. For example, during the winter, 3-h pressure declines exceeding 2 mb are observed at many stations of the southwest United States for 1800–2100 UTC (Fig. A1). Summertime changes are less intense but still quite significant (Fig. A2).

⁶ Note: the station model used on surface synoptic charts indicate the 3-h station-pressure change.

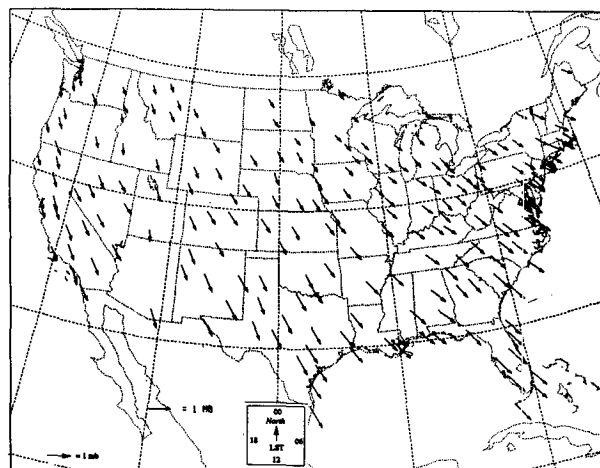


FIG. 9. Annual semidiurnal station pressure component across the continental United States. Arrows plotted as in Fig. 2.

Such large diurnal station-pressure variations can easily complicate the diagnosis of frontal positions. As an example, consider the hypothetical case of a cold front over eastern Texas at 2100 UTC on a winter's day. As shown in the Appendix, over this region and to the west pressure falls between 2 and 3 mb are typical from 1800 to 2100 UTC. Such an isallobaric pattern can attenuate or eliminate the pressure rises behind a weak or moderate cold front.

6. Daily pressure evolution at some selected observing sites

Another approach to understanding the daily pressure evolution at the surface is to examine the seasonal variations in the diurnal pressure traces at individual sites. Figure 14 presents the diurnal sea level pressure variations at four sites: Seattle, Washington; Denver, Colorado; St. Joseph, Missouri; and Miami, Florida.

At Seattle (Fig. 14a), there is a large difference in

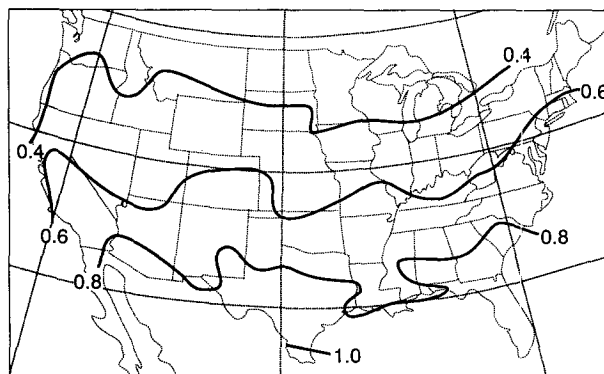


FIG. 10. Amplitude of the annual semidiurnal component of station pressure in millibars.

TABLE 3. Amplitude and phase of the semidiurnal component of sea level and station (in parentheses) pressures.

Region	Number of stations	Amplitude (mb)					Phase* (LST)				
		Annual	Winter	Spring	Summer	Fall	Annual	Winter	Spring	Summer	Fall
Whole United States	208 (213)	0.67 (0.57)	0.74 (0.59)	0.66 (0.56)	0.56 (0.55)	0.75 (0.60)	09.63 (09.65)	09.55 (09.46)	09.72 (09.86)	10.14 (09.95)	09.54 (09.44)
20°-30°N	13 (15)	0.90 (0.91)	0.97 (0.97)	0.93 (0.89)	0.78 (0.85)	0.95 (0.97)	10.14 (09.78)	10.03 (09.78)	10.22 (09.98)	10.43 (10.08)	09.93 (09.52)
30°-40°N	97 (89)	0.79 (0.68)	0.89 (0.72)	0.77 (0.65)	0.66 (0.65)	0.87 (0.71)	09.69 (09.64)	09.52 (09.45)	09.79 (09.87)	10.24 (09.9)	09.50 (09.39)
40°-50°N	99 (101)	0.51 (0.44)	0.56 (0.45)	0.51 (0.44)	0.42 (0.43)	0.60 (0.46)	09.50 (09.56)	09.51 (09.31)	09.57 (09.76)	10.00 (09.89)	09.54 (09.3)

* Note that phase values are in decimal fractions of an hour.

the pressure evolution for the four seasons. During the winter a single, narrow maximum centered at ~1000 LST appears, while during the summer a more sinusoidal-appearing curve is evident with a well-defined minimum around 1800 LST. The phase of the primary maximum (minimum) shifts progressively earlier (later) as summer approaches. The Denver daily sea level pressures (Fig. 14b) do not evince as large a seasonal variability as Seattle, and the pressure range is actually larger in winter than summer. The Denver pressure trace is also characterized by a large semidiurnal component. As discussed in section 7, much of this semidiurnal amplitude can be traced to problems with the sea level pressure reduction algorithm used by the National Weather Service. St. Joseph, Missouri, located at nearly the same latitude as Denver (Fig. 14c), possesses a far smaller semidiurnal amplitude for all seasons and, in contrast to Denver, has a larger range in the summer than winter. At Miami (Fig. 14d), a strong semidiurnal oscillation is evident with relatively little seasonal variability. The largest pressure range is observed during the winter months at this location.

7. Discussion

A major finding of the harmonic analyses presented above is the existence of large differences in amplitude and phasing between the semidiurnal components of station and sea level pressure over the higher elevations of the western United States. Significant, but lesser, discrepancies were noted between the diurnal components of station and sea level pressure over these regions. As shown below, these discrepancies are probably produced by the pressure-reduction method used by the National Weather Service (NWS). Specifically, the manner in which surface temperature is averaged for use in the pressure reduction creates an artificial semidiurnal variation in sea level pressure.

For stations below 300 m, the NWS uses the hypsometric equation to reduce the observed surface pressure (i.e., station pressure) to mean sea level (see Saucier 1972 for a more detailed description of the pressure-reduction techniques used by the National Weather Service). At higher-elevation stations, additional corrections to the hypsometric reduction are made. Surface temperature is used in the hypsometric calculation and is temporally averaged in an attempt to remove surface diurnal temperature variations, since such variations would not be representative of the free air in which the reduction is supposedly taking place. The averaging technique applied by the NWS is a simple one in which the surface temperature at the observing time is averaged with the surface temperature 12 h before.

If the surface temperature variation could be described by a pure sinusoid with an exact period of

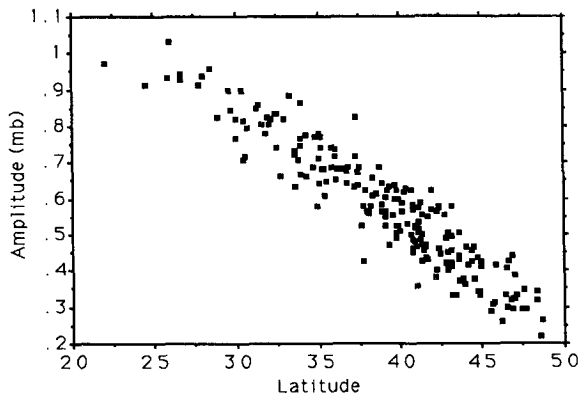


FIG. 11. Scattergram of the annual-average amplitude of the semidiurnal component of station pressure versus latitude.

TABLE 4. Linear correlation coefficients between the amplitudes of semidiurnal sea level and station-pressure variations and latitude.

	Annual	Winter	Spring	Summer	Fall
Sea level pressure	-0.75	-0.57	-0.83	-0.84	-0.59
Station pressure	-0.80	-0.79	-0.76	-0.77	-0.77

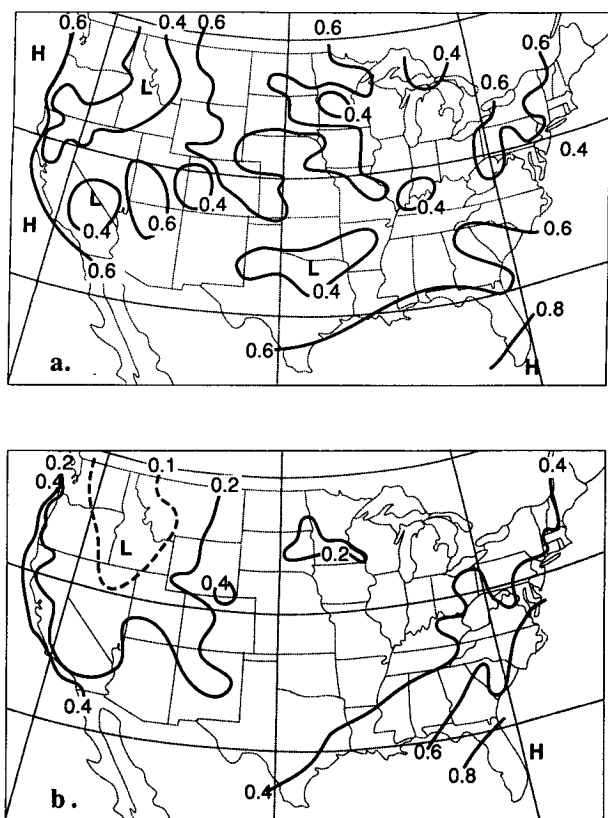


FIG. 12. Percent variance of the daily variation of station pressure for the winter (a) and summer (b) seasons explained by the semidiurnal component.

24 h there would be little problem with the NWS 12-h averaging scheme. This is because a simple average of points 12 h apart will always produce the correct daily mean for such a pure sinusoid. However, the typical diurnal temperature evolution at the surface is generally characterized by relatively uniform temperatures at night and rapid temperature increases and declines during the morning and early evening, respectively. With such a variation the above averaging scheme creates a significant semidiurnal variation in the "diurnally averaged" temperatures.

To illustrate this point consider Fig. 15, which presents the August 1986 monthly mean, diurnal temperature variation at Stampede Pass, Washington—a station of relatively high altitude (~ 1200 m MSL) but relatively modest diurnal temperature range. Note that the temperature remains at $\sim 13^{\circ}\text{C}$ from 2200 through 0700 LST, followed by a rapid rise during the morning hours. Also shown in this figure is the temperature averaged using the method applied in the NWS pressure-reduction algorithm. Note how a significant semidiurnal temperature signal is established. Assuming a simple hypsometric reduction to sea level, this semi-

diurnal temperature signal (amplitude of $\sim 1^{\circ}\text{C}$) would be expected to produce a spurious semidiurnal variation in sea level pressure of approximately 0.5 mb in amplitude at this location. Stampede Pass is hardly a worst case example of this problem. Many stations in the western United States experience a far larger diurnal temperature variation (of similar nonsinusoidal shape) and are found at equal or greater elevations. Thus, it is clear why significant enhancement of the semidiurnal sea level pressure signal is observed over the western United States and why this discrepancy disappears when station pressure is considered.

The bogus semidiurnal temperature wave used in the reduction to sea level both increases the amplitude and advances the phase of the semidiurnal sea level pressure variations at high-altitude stations. The influence on phase can be understood by noting that the semidiurnal variation in 12-h mean temperature (using the NWS temperature-averaging technique) reaches minima at approximately 0700 and 1900 LST and maxima around 0100 and 1300 LST (e.g., Fig. 15). Since higher (lower) temperatures will result in lower (higher) sea level pressures using the hypsometric formula, the semidiurnal variation in mean temperature contributes to higher sea level pressures around 0700 and 1900 LST and lower pressures at 0100 and 1300 LST. Superposing this reduction-induced pressure variation on a typical station pressure daily evolution (with maxima at ~ 1000 and 2200 LST) will tend to advance the phase and amplify the semidiurnal component.

To further illustrate many of the above points, consider Fig. 16a, which presents the annual-mean daily sea level pressure variations at Denver, Colorado (1625 m MSL); St. Joseph, Missouri (262 m MSL); and Wilmington, Delaware (24 m MSL), expressed as deviations from their long-term means. All of these stations are at a similar latitude ($\sim 39^{\circ}40'\text{N}$) and thus their semidiurnal pressure amplitudes should theoretically be nearly identical. It is immediately apparent from this figure that the sea level pressure evolutions at the lower-elevation stations (i.e., St. Joseph and Wilmington) are similar with maxima at ~ 1000 and 2200 LST and minima at ~ 0300 and 1600 LST. In contrast, the diurnal sea level pressure variation at Denver possesses considerably higher amplitude and earlier phasing than the lower elevation stations. Figure 16b presents the difference in sea level pressure between Denver and St. Joseph; a semidiurnal oscillation of approximately 0.75 mb is found with peaks at ~ 0700 and 1700 LST and minima at ~ 0200 and 1300 LST.

It is easy to demonstrate that the semidiurnal difference between Denver and St. Joseph sea level pressures (Fig. 16b) can be explained by the temperature-averaging scheme used in the NWS sea level pressure-reduction method. Figure 17 displays the diurnal tem-

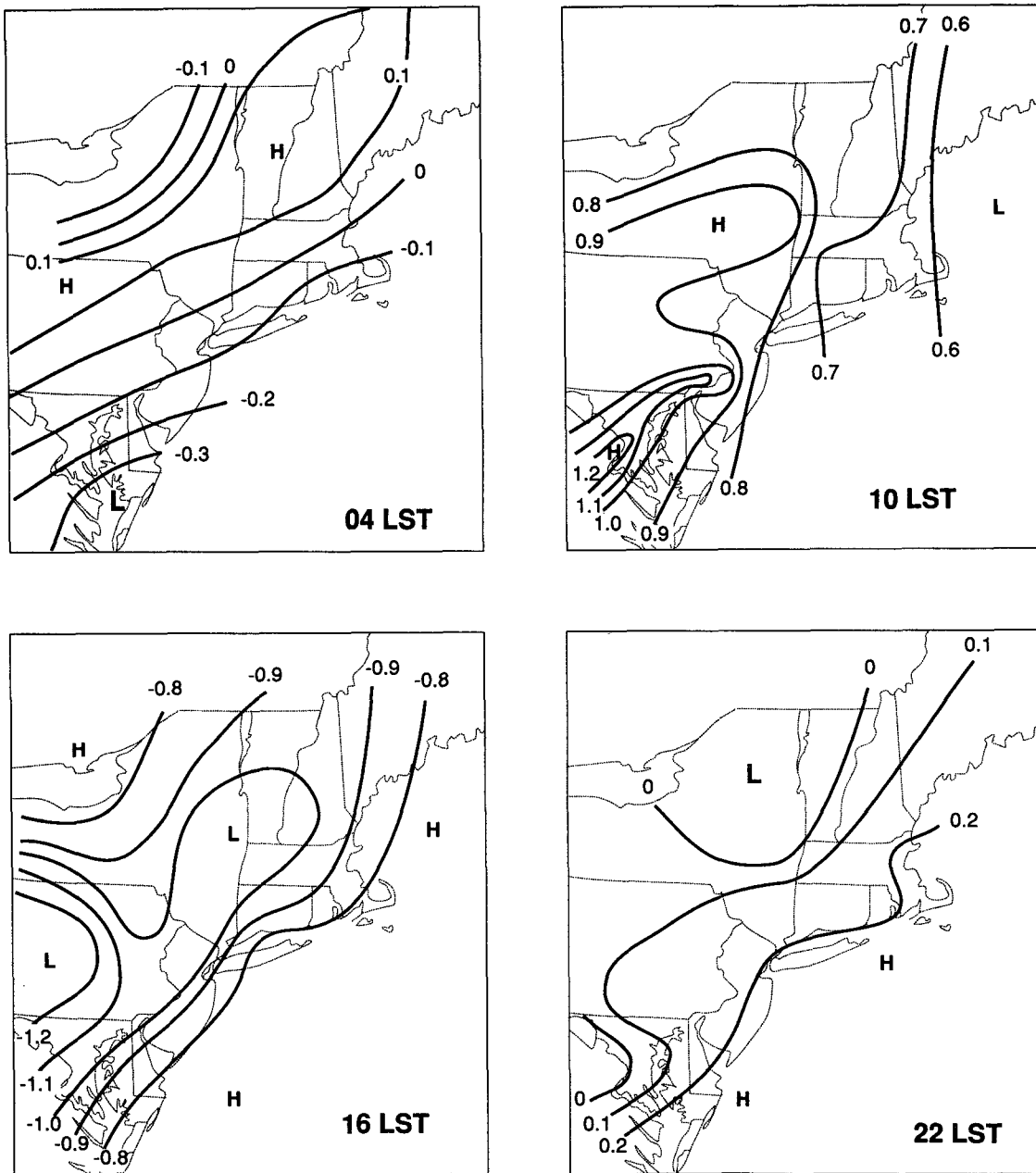


FIG. 13. Deviations of station pressure from the daily mean for the summer season for the northeast United States for 0400, 1000, 1600, and 2200 LST.

perature variation at Denver for 15 August 1987, a day embedded within a period of rather static synoptical-scale and mesoscale conditions. This day also had a temperature range (17°C) that was relatively close to the annual average (16°C) and hopefully provides a first approximation to the shape of the annual-average diurnal temperature variation. Applying the NWS surface-temperature-averaging technique (dashed line)

produces a semidiurnal oscillation with a range of ~2°C and broad minima centered near 0600 and 1800 LST, and broad maxima at approximately 0100 and 1200 LST. Since warm temperatures should be reflected in lower sea level pressures and vice versa, this average temperature evolution is consistent with the phasing of the pressure difference between Denver and St. Joseph. A simple calculation using the hypsometric

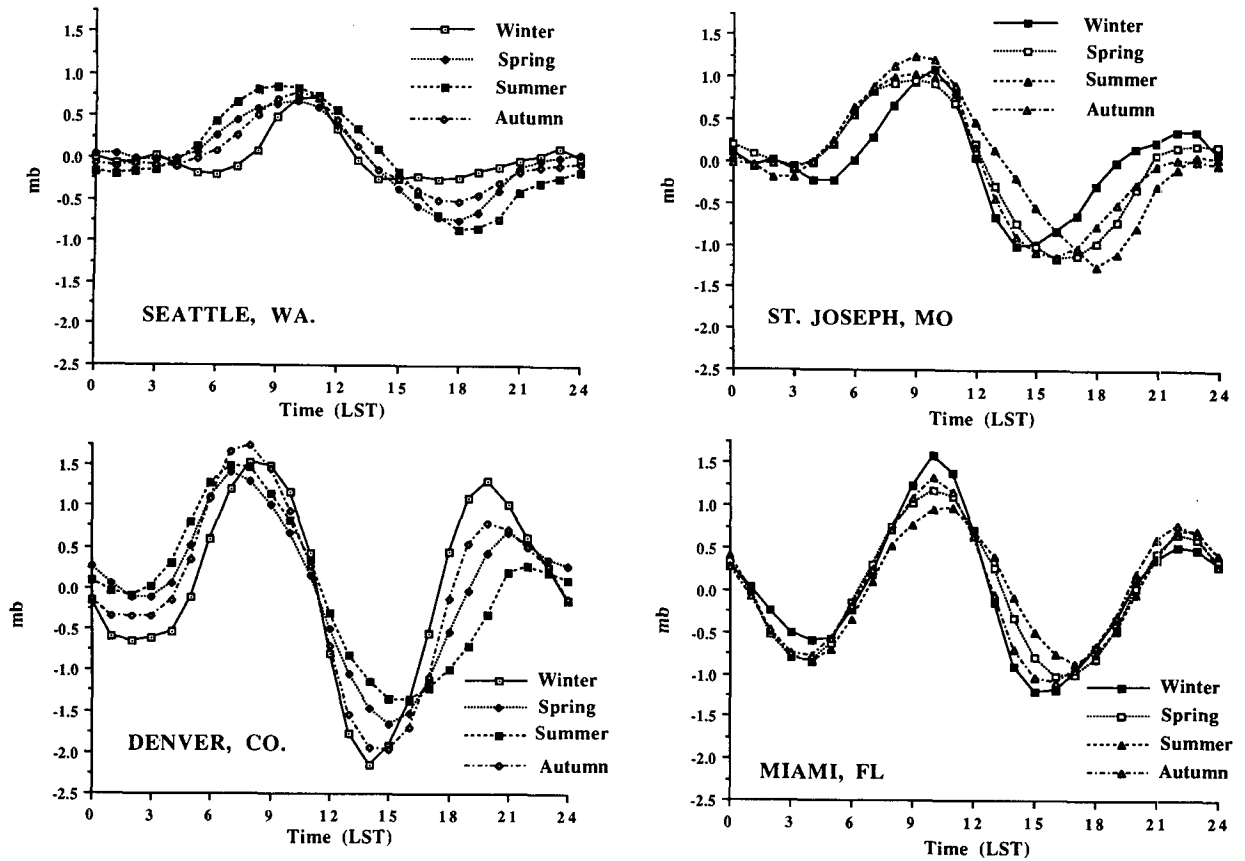


FIG. 14. Mean daily sea level pressure traces for four seasons at Seattle, Washington; Denver, Colorado; St. Joseph, Missouri; and Miami, Florida.

equation indicates that the above semidiurnal temperature wave would be expected to produce a semidiurnal pressure signal with an amplitude of 0.75 mb—a value quite close to the amplitude of the Denver–St. Joseph

pressure difference found above. (The predicted amplitudes are shown in Fig. 16b with stippled lines.) Figure 18, which displays the 3-h station pressures for the above three stations, indicates that the large amplitude and phasing differences between Denver and the lower elevation stations virtually disappear when station pressure is considered.

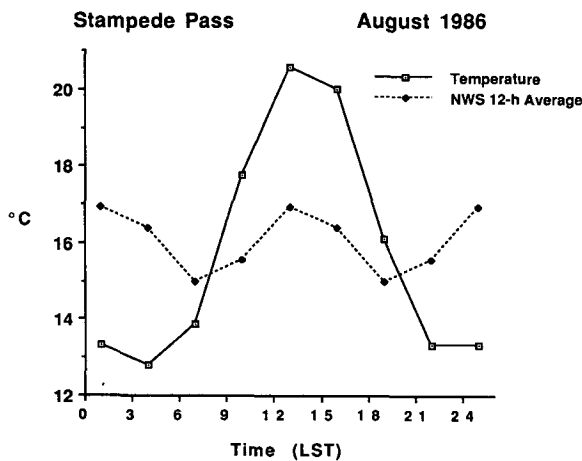


FIG. 15. Mean daily temperature variation for August 1986 at Stampede Pass, Washington (solid line) and the result of the National Weather Service temperature-averaging scheme (dashed line).

In section 3 it was shown that the semidiurnal amplitude of sea level pressure varies significantly by season, in contrast to the lack of seasonality in the station-pressure semidiurnal component. The bogus semidiurnal pressure signal produced by the simple temperature-averaging scheme described above contributes to this seasonal variation in sea level pressure semidiurnal amplitude. Assuming a similar daily temperature range for winter and summer, the simple two-point averaging scheme used by the NWS will tend to produce a larger bogus semidiurnal temperature signal during the winter, with its short period of warming, than during the summer, when the temperature evolution is more sinusoidal. To illustrate this point, the Denver temperature evolution shown in Fig. 17 was modified to have a shorter period of daytime heating as would be observed during the winter (the diurnal

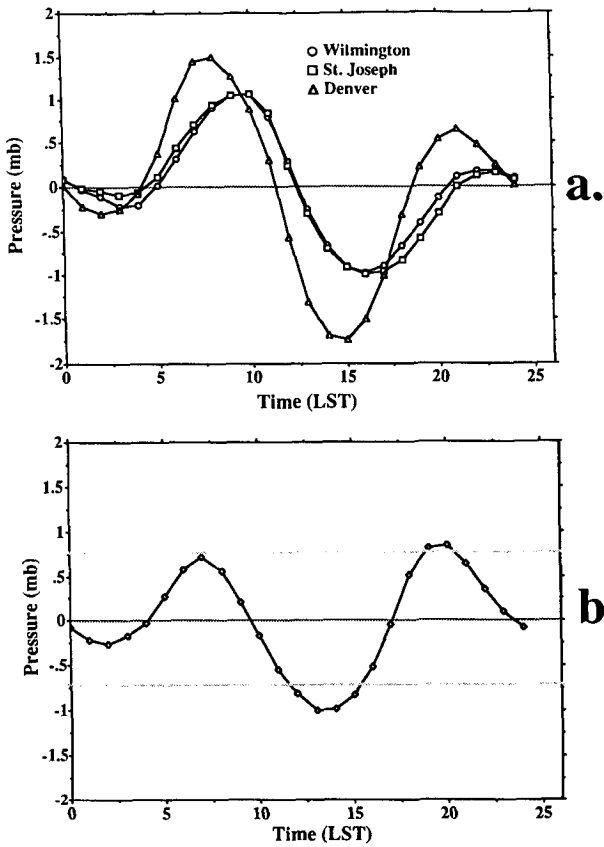


FIG. 16. Annual-mean diurnal sea level pressure variation at Denver, Colorado; St. Joseph, Missouri; and Wilmington, Delaware, expressed as deviations from long-term means (a). The difference in sea level pressure deviations between Denver and St. Joseph (solid line) and the amplitude predicted by a simple calculation using the hypsometric formula (stippled lines) are shown in (b).

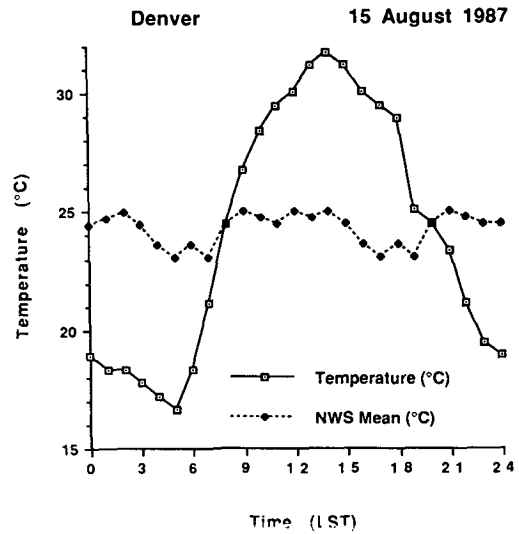


FIG. 17. The hourly surface temperature evolution at Denver, Colorado, on 15 August 1987 (solid line). Also shown is the mean temperature produced by the National Weather Service averaging scheme (dashed line).

Colorado and New Mexico, and decreases to less than a millibar over the coastal sections of the Pacific Northwest. Discrepancies between sea level and station-pressure range reach 2–4 mb over the higher elevations. Since the station-pressure range represents the true physical variation in pressure at the surface, it is clear that the sea level reduction process has contributed a large error in the daily sea level pressure variation. The summertime sea level pressure range (Fig. 20c) exceeds 4 mb over the interior of California, parts of Nevada and Idaho, and in a band stretching from New Mexico

temperature range remained the same). This modified temperature curve and the resulting two-point NWS temperature average are shown in Fig. 19. Significantly, the amplitude of the bogus semidiurnal signal has been enhanced by approximately a factor of 2 compared to the previous unmodified results. Some simple experiments conducted for this paper suggest that at higher elevation stations, such as Denver, the wintertime amplification of the semidiurnal temperature signal, because of the above shape-related effects, more than compensates for the decreased temperature range observed during the winter months.

A final illustration of the significant error produced by the current reduction algorithm is found in Fig. 20, which presents the daily pressure ranges for the winter and summer seasons over the continental United States for both sea level and station pressure. During the winter, the daily range of sea level pressure (Fig. 20a) is clearly enhanced (compared to station pressure, Fig. 20b) over the western United States, especially over

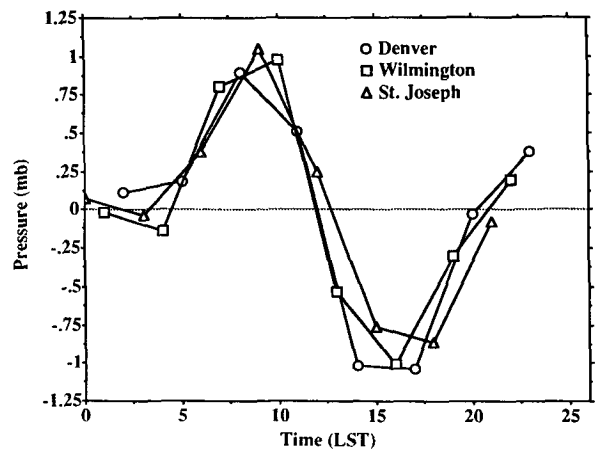


FIG. 18. The annual-average daily station-pressure evolution at Denver, Colorado; St. Joseph, Missouri; and Wilmington, Delaware.

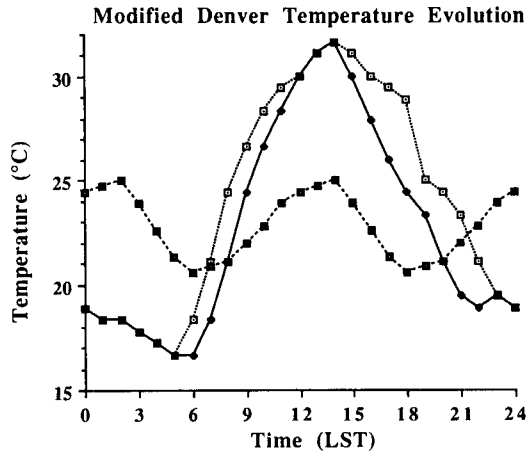


FIG. 19. The hourly surface temperature evolution at Denver, Colorado, on 15 August 1987 (dotted line), a modified winterlike temperature curve (solid line), and the National Weather Service two-point diurnal averaging scheme applied to the modified temperature evolution (dashed line).

into western Colorado. The summer station-pressure diurnal range (Fig. 20d) is similar to the sea level pattern except for ~25% less amplitude over higher elevations.

An additional problem with the current two-point temperature-averaging technique occurs when a sig-

nificant synoptic change occurs during the 12-h averaging period. For example, consider a situation in which a strong cold front passes through a site and brings large temperature falls over a period of 6 h. The current averaging technique would then average the temperature at the time of the pressure observation with a far warmer temperature 12 h earlier that would not be representative of the new regime at any time of the day. The result would be a sea level pressure that would be too low.

There are a number of approaches that might be used to reduce or eliminate the bogus semidiurnal pressure signal noted above. For example, by creating a diurnal temperature average using hourly or three-hourly values the semidiurnal temperature signal would be greatly suppressed and the spurious semidiurnal pressure signal would be attenuated. Such a procedure would not significantly reduce the number of stations providing sea level pressure since virtually all sites that report sea level pressure in the United States are 24 h stations. Furthermore, this approach (i.e., using a better diurnal average) will become increasingly practical as automated 24-h surface observing sites spread throughout the United States. Another possibility would be to use altimeter setting (pressure reduced hypsometrically to sea level using the U.S. Standard Atmosphere) instead of the traditional sea level pres-

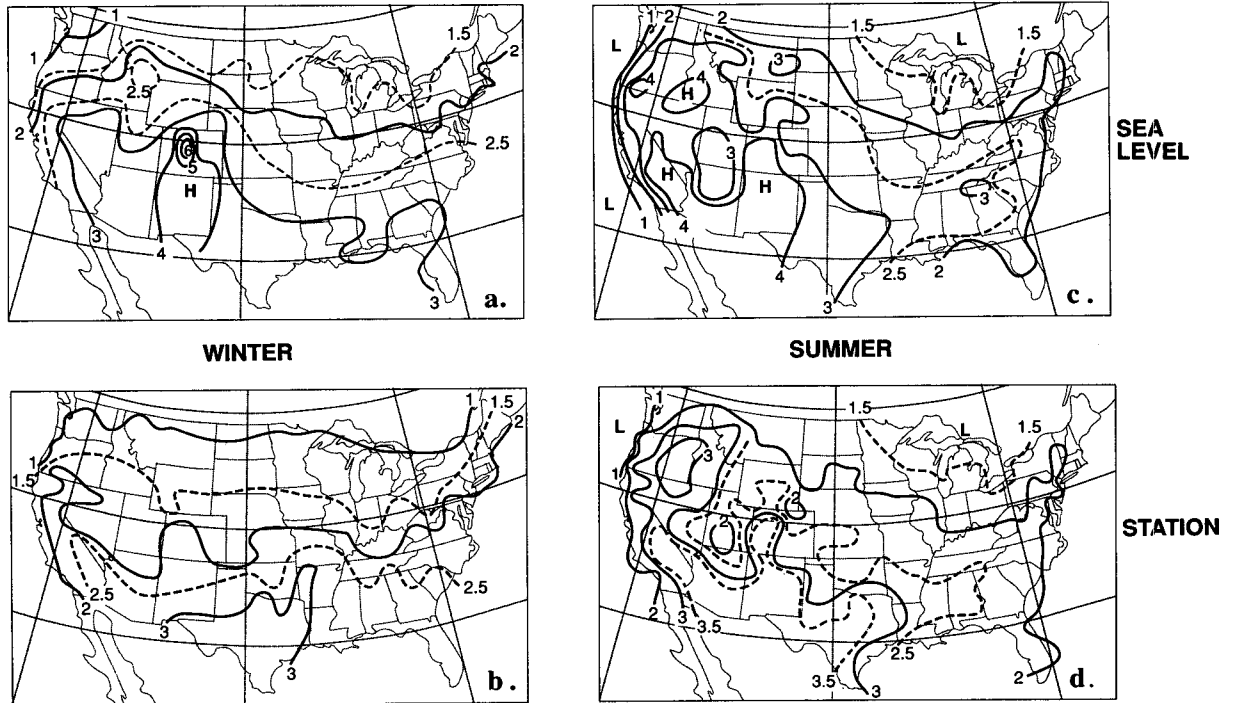


FIG. 20. Daily pressure range during the winter season for sea level (a) and station (b) pressures. Daily pressure range during the summer season for sea level (c) and station (d) pressures.

sure. Although this method would remove the diurnal temperature averaging problem, it could potentially contribute other deficiencies, such as when the temperature soundings are significantly different from the U.S. Standard Atmosphere. Other possible approaches include the use of a free atmospheric level (e.g., 700 mb) instead of the surface as the starting point for the pressure reduction (Benjamin and Miller 1990), presenting the surface geostrophic stream and potential functions instead of a reduced pressure (Sangster 1960, 1987), and deriving a surface-pressure field utilizing the geostrophic wind defined on a terrain-following coordinate system (Pielke and Cram 1987). A careful evaluation of the above approaches in both operational and research environments should be made.

Looking toward the future, it is clear that a far more comprehensive and detailed examination of diurnal pressure variations at the surface will be possible in a few years. This optimism is based on the imminent deployment of over 1000 automated surface observing stations (ASOS) as part of the National Weather Service modernization effort. Not only will the number of observing sites be increased, but all of these locations will take observations 24 hours a day, which is not the case with the present observing network. The enhanced surface station network should allow clearer definition of mesoscale pressure variations associated with diurnal circulations forced by topography and land-sea contrasts.

8. Conclusions and summary

This paper describes the diurnal and semidiurnal variability of station and sea level pressure across the continental United States using data from approximately 200 stations. It was shown that during the winter the diurnal components of station or sea level pressure generally decrease in amplitude with increasing latitude and that at most stations the diurnal component of surface pressure reaches a maximum at approximately 0700 LST. During the summer, the amplitude of the diurnal component increases and the dependence on latitude decreases. For all seasons, the semidiurnal component of sea level pressure increases in magnitude toward the south and is substantially enhanced over the higher elevations of the western United States. The first semidiurnal maximum typically occurs at ~ 1000 LST, with earlier phasing over the Continental Divide and the eastern slopes of the Rockies. The semidiurnal component of station pressure is more uniform across the United States than the same component of sea level pressure.

The daily variation in station pressure is dominated by the diurnal and semidiurnal components. Over the United States, these two components are roughly equal

in importance during the winter; during the summer the diurnal component dominates. The third diurnal component is generally negligible for all seasons except winter when it can explain up to 20% of the variance over the northernmost tier of states.

This paper also presents regional maps of the diurnal station-pressure variations over the northeast United States during the summer. During the night, station pressure is higher inland than over the coast. Such a pressure distribution is consistent with a regional land-breeze circulation. The opposite situation (i.e., a sea-breeze circulation) is observed during the day.

The current method used by the National Weather Service to reduce station pressure to sea level possesses a significant flaw in the algorithm used to calculate the diurnal-mean surface temperature. Specifically, using an average of two temperatures, 12 h apart, produces a significant semidiurnal oscillation in the resulting mean temperatures; through the hypsometric formula used in the reduction this oscillation creates a bogus semidiurnal sea level pressure variation. Various solutions to this problem are discussed in the text. Finally, this paper presents the 3-h station-pressure changes observed for the summer and winter seasons to assist synoptic analysts in separating the pressure variability produced by transient synoptic and mesoscale disturbances from the diurnal changes created by upper-atmospheric oscillations and topographically fixed circulations.

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APPENDIX

Three-hour Station-Pressure-Change Maps

One of the goals of this project has been to create 3-h station-pressure-change maps that could aid in the interpretation of the 3-h pressure changes plotted on standard surface synoptic charts. In this section, such maps (in UTC) are displayed for both the summer and winter seasons (see section 2 for an explanation of the data handling procedures used in this study). A cursory examination of these maps reveals that large 3-h vari-

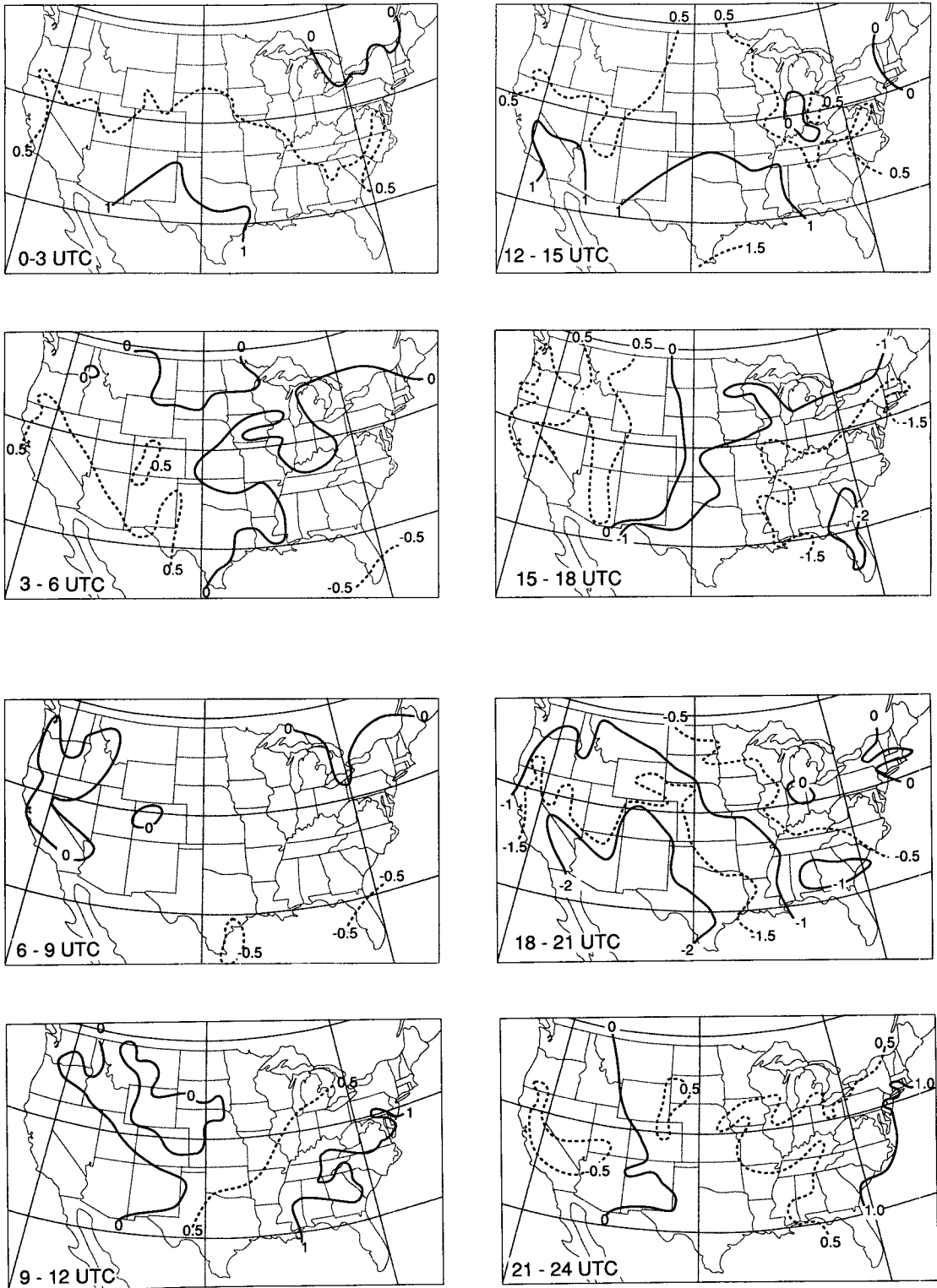


FIG. A1. Three-hour station-pressure change maps for the winter season. Pressure changes are in millibars (positive values indicate increasing pressure during the period).

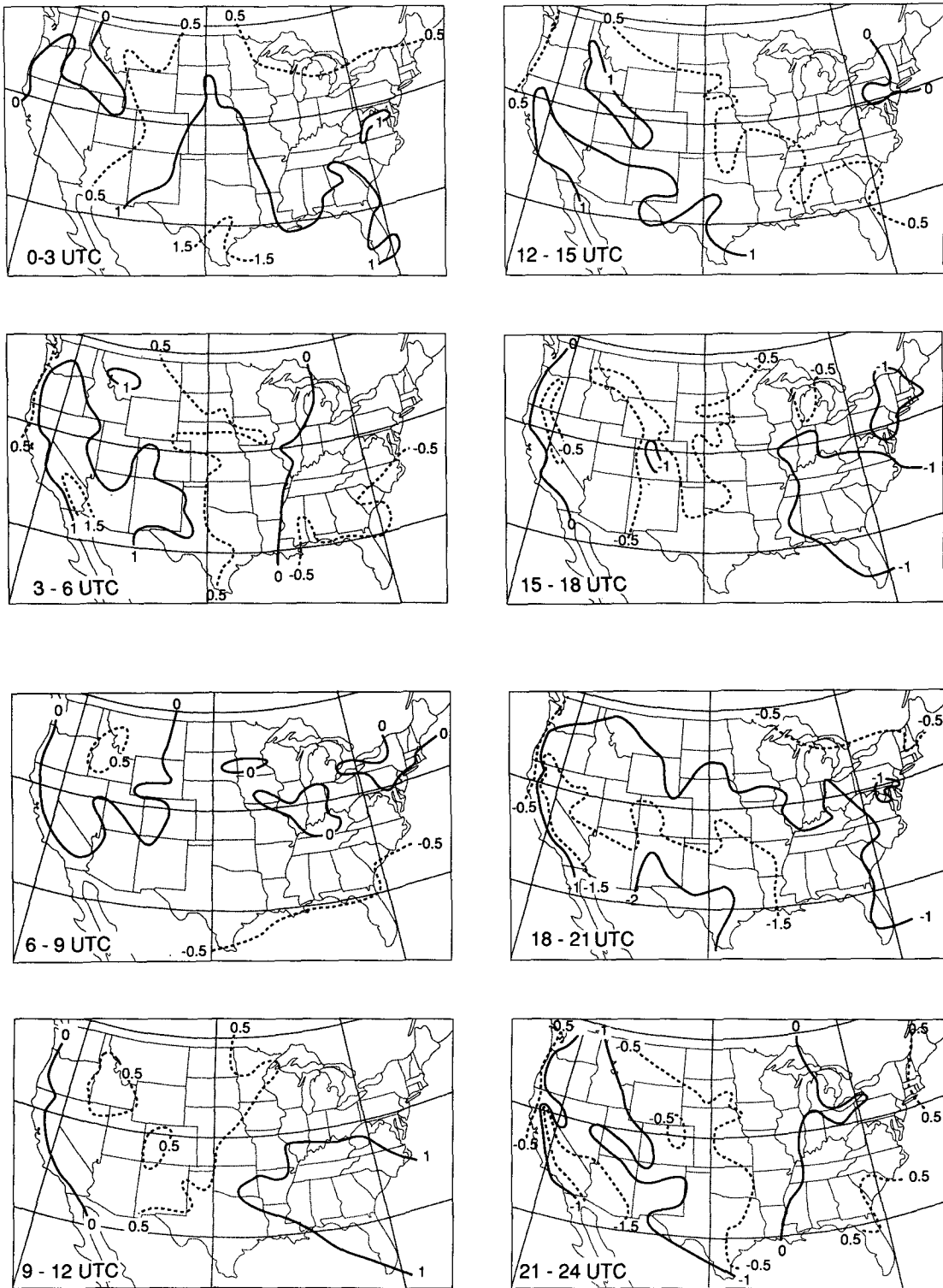


FIG. A2. Three-hour station-pressure-change maps for the summer season. Same plotting convention as Fig. A1.

ations unconnected with mobile synoptic or mesoscale disturbances do exist and potentially could mask or obfuscate meteorologically significant phenomena. As noted in the text, these station-pressure changes are the superposition of meteorological phenomena of various scales (e.g., the global semidiurnal pressure oscillation based in the upper troposphere and lower-tropospheric mesoscale circulations).

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