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Gravity Wave Phenomena Accompanying East Coast Cyclogenesis

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ABSTRACT—A remarkable example of gravity wave propagation over the southeastern United States on Dec. 3, 1968, is described. The wave developed within the cold air north of a quasi-stationary front along the coast of the Gulf of Mexico in apparent response to convective activity associated with a weak cyclonic disturbance on the front. The wave maintained its identity for 14 hr while propagating east-southeastward at 13 m/s in a direction nearly opposite to the low-level flow. Gravity-wave-related pressure drops exceeded 7 mb over an average period of 1 hr. Strong and gusty winds blowing perpendicularly to the isobars toward lower pressure accompanied the wave-related pressure fall. Precipitation of several hours duration ceased abruptly with the wave passage, along with increases in the ceiling and horizontal visibility. Comparison is made with results from other papers dealing with wave propagation along frontal surfaces.

1. INTRODUCTION

During the period Dec. 3–5, 1968, a complex low-pressure system evolved over the southeastern United States and moved northeastward. This system was characterized by a chaotic surface-pressure distribution for the first 24 hr with several separate Low centers on both sides of the Appalachian Mountains. Considerable gravity wave activity was observed in the southeastern United States within the cold air north of a quasi-stationary front during this period. The direction of propagation was nearly parallel to the orientation of the quasi-stationary front and opposite to the direction of the low-level easterly flow. This paper focuses on a detailed description of the gravity wave phenomena and on how the principal wave interacted with the larger scale synoptic environment in terms of the pressure, wind, temperature, and precipitation fields. The gravity wave under investigation had an amplitude of a 3.5 mb, a propagation speed of 10–15 m/s, and a life cycle of nearly 15 hr. The wave was discernible from a careful analysis of existing hourly surface teletype reports. Barogram records suggested that the wave period varied from 1 to 2 hr.

2. BACKGROUND

Brunk (1949) investigated pressure pulsations apparently triggered by intense thunderstorms that swept across the central and eastern United States in April of 1944. He was able to follow four separate eastward-moving waves associated with rainfall peaks within the cold air. Strong, gusty easterly winds accompanied the passage of the pressure pulsations. Pothecary (1954) tried to relate observed surface pressure and wind changes within a cold air mass over southern England to motion along a quasi-horizontal frontal surface. He hypothesized that cold air outflow from intense thunderstorms initiated the wave propagation by interfering with the prevailing low-level easterly flow. The propagation direction was parallel to the frontal zone and nearly opposite to the low-level flow. Pothecary also found that the observed wind and pressure variations for his case were in reasonable agreement with theoretical values given by Goldie (1925). Goldie's equations were derived for the case of two superimposed incompressible fluids of differing velocity flowing over a rigid surface. The upper layer was assumed to be of unlimited depth. Pothecary's hypothesis could not be substantiated, however, because of the sparsity of synoptic observations over the ocean to the southeast of England.

Ferguson (1967) examined a winter case of gravity wave propagation over the Great Lakes area similar in nature to the cases of Brunk and Pothecary mentioned previously. However, Ferguson's case was noteworthy for wave amplitudes of several millibars. He concluded that the gravity wave was associated with a squall line

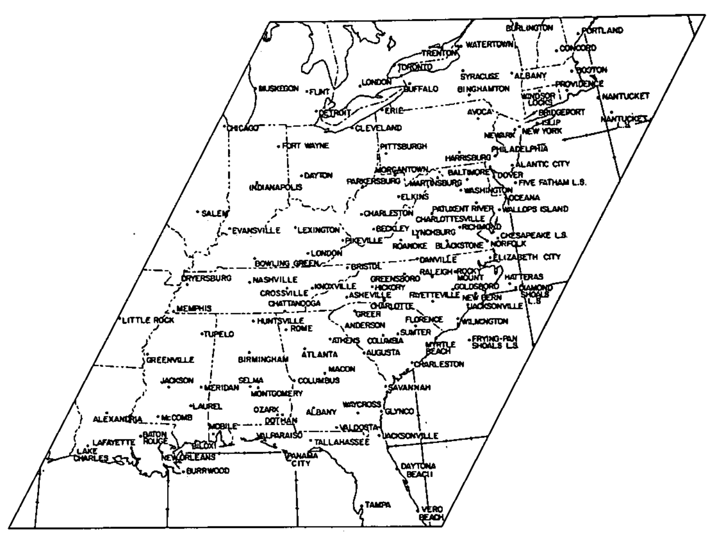

FIGURE 1.—Locations of pertinent stations mentioned in the text.

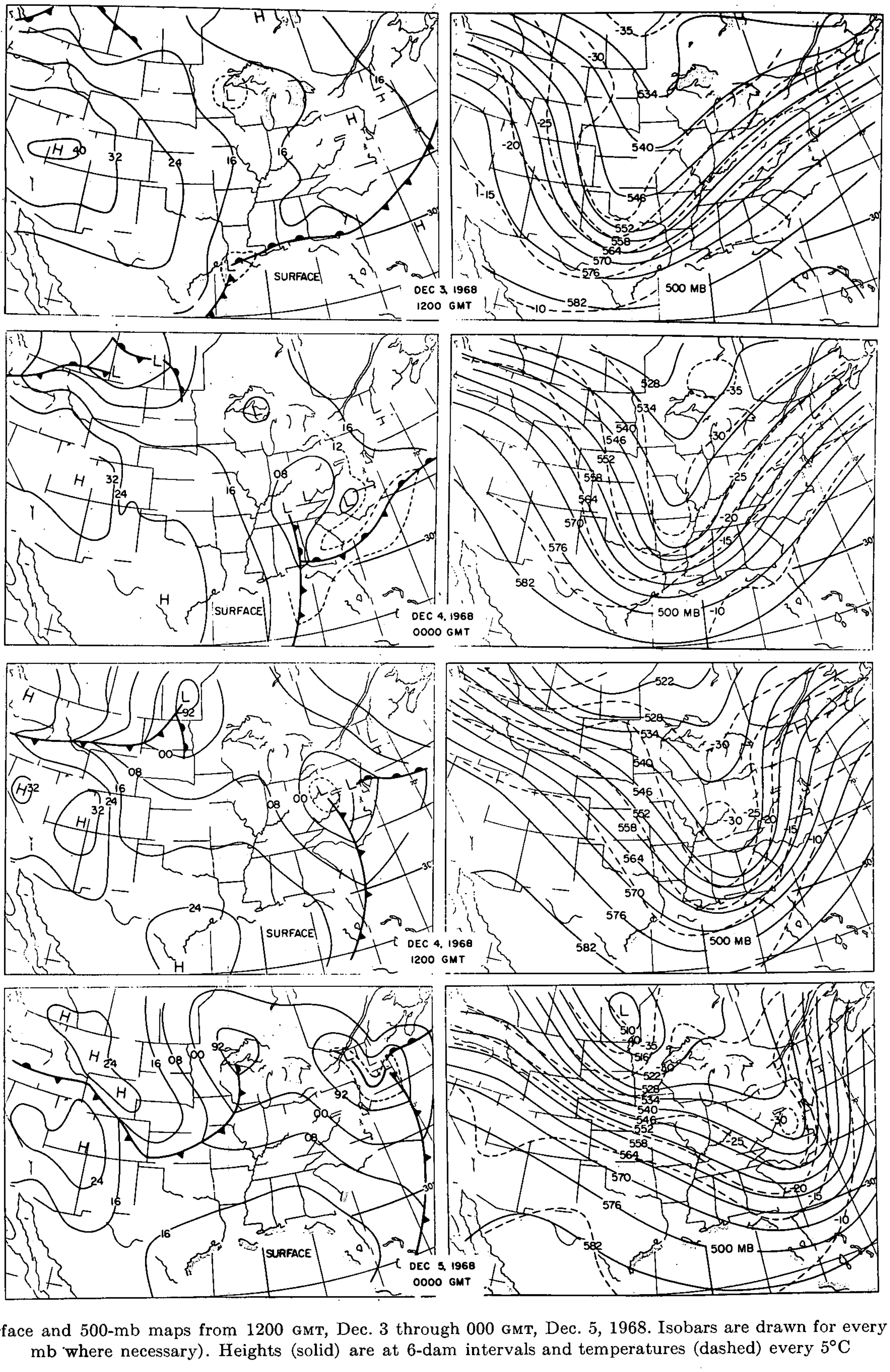

FIGURE 2.—Surface and 500-mb maps from 1200 GMT, Dec. 3 through 000 GMT, Dec. 5, 1968. Isobars are drawn for every 8 mb (every 4 mb where necessary). Heights (solid) are at 6-dam intervals and temperatures (dashed) every 5°C

probably triggered by convective activity farther to the southwest. Reasonable agreement was obtained with the theoretical equations of Goldie. In related work, detailed investigations by Matsumoto and Akiyama (1970) and Matsumoto and Ninomiya (1969) have concentrated on the linkage between gravity wave phenomena and the vertical transport of momentum with a corresponding influence on mesoscale precipitation fields.

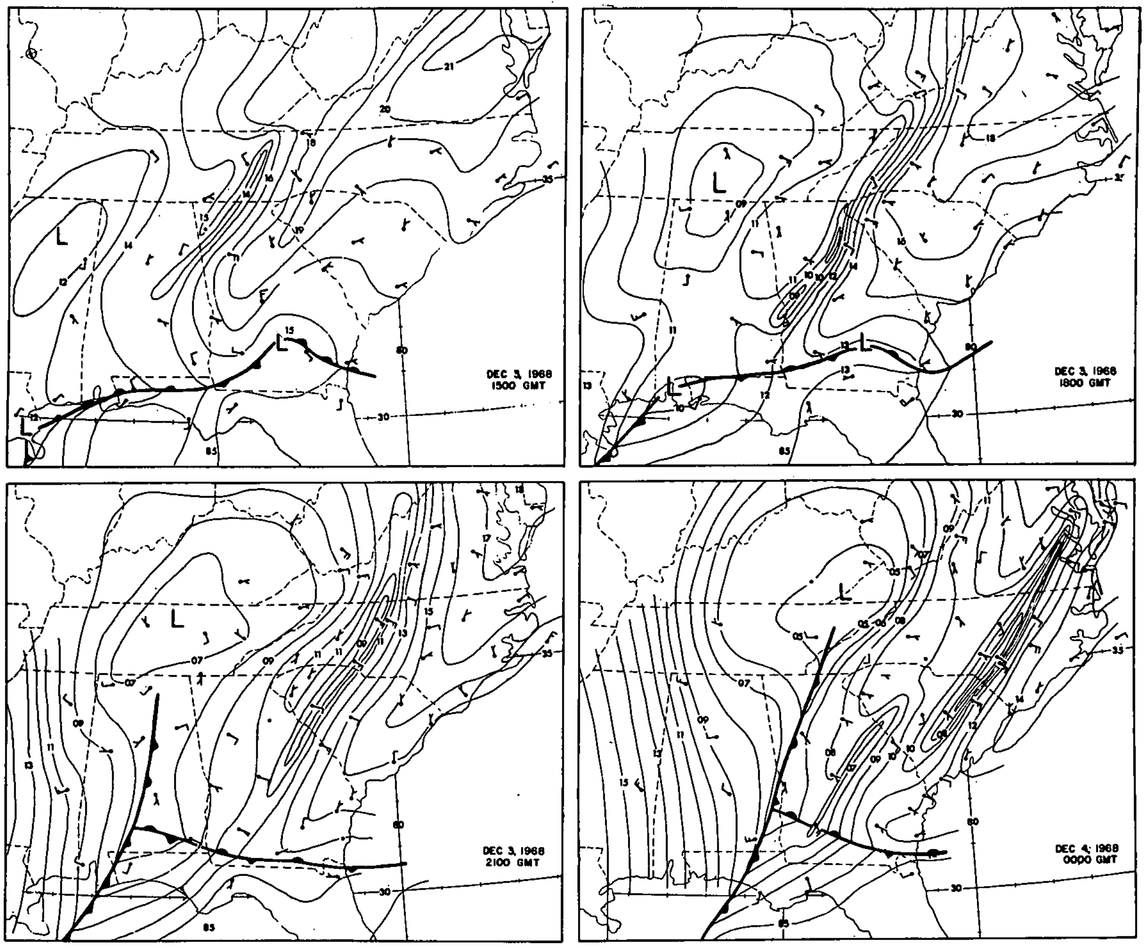

FIGURE 3.—Detailed surface maps at 3-hourly intervals for time periods indicated. Isobars are drawn for every 1 mb and winds are in knots, plotted according to the conventional station model.

3. SYNOPTIC SITUATION

A key station location map is shown in figure 1, and the surface and 500-mb synoptic situations for Dec. 3–5, 1968, are shown in figure 2. At 1200 GMT on Dec. 3, 1968, a weak surface trough is evident over the Mississippi Valley with a ridge axis from James Bay, Canada, to Cape Hatteras, N.C. At 500 mb, a pronounced trough is located over the Great Plains. Cold advection into the trough suggests continuing intensification.

Twelve hours later the surface map is quite complex. There are separate low-pressure centers over the upper Michigan peninsula and southeastern Kentucky with the suggestion of a center east of the Appalachian Mountains over North Carolina. Considerable gravity wave activity took place in the Georgia, Carolina, and Virginia regions in the preceding 12 hr. Our study focuses on the 12-hr period ending at 0000 GMT on Dec. 4, 1968. Additional aspects of mesoscale weather features accompanying this storm as it moved up the Atlantic coast can be found in papers by Bosart (1973) and Bosart et al. (1972).

4. DATA

Data used in this paper were obtained from the National Climatic Center of the National Oceanic and Atmospheric Administration in Asheville, N.C. These included surface WBAN observations, 4-day and, where available, 12-hr microbarograms, triple recorder traces, and *Hourly Precipitation Data* publications. Additionally, teletype data from service "A" and service "C" were used to augment information in the fringe areas.

5. OBSERVED CHARACTERISTICS OF THE GRAVITY WAVE

Figure 3 presents surface maps analyzed every 1 mb at 3-hr intervals, which show many of the characteristics of the gravity wave. Mesoanalysis techniques described by Fujita (1955) were used in the construction of these charts. The details of the analysis as well as the existence of the wave structure itself were understandably not evident from the conventional 3-hourly surface maps analyzed every 4 mb and routinely transmitted over national facsimile. The important features to be noted from these maps include the following: (1) the east-southeast motion of the wave front in a direction nearly opposite to the low-level flow, (2) strongest surface winds blowing perpendicular to the isobars toward low pressure in the region of greatest pressure fall, (3) elongation and intensification of the wave-front northeastward with time, and (4) the development of a synoptic scale cyclonic circulation center to the west of the Appalachian Mountains. Observe that the wave front, which marks the leading edge of the

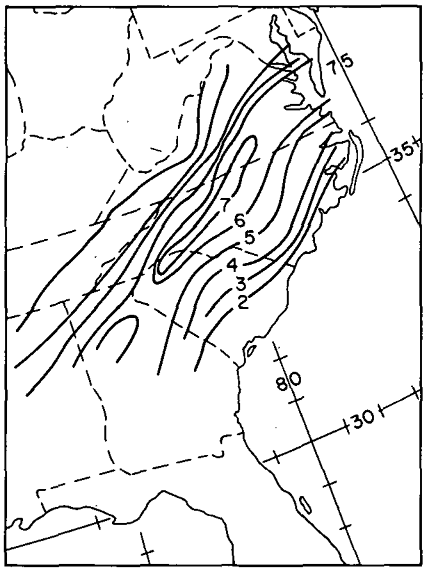

FIGURE 4.—Total pressure drop (mb) associated with the passage of the gravity wave.

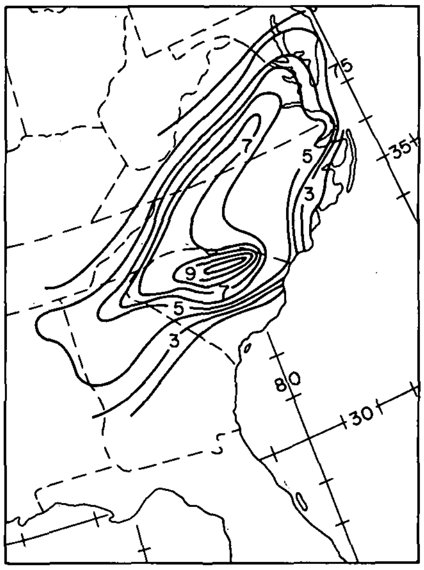

FIGURE 5.—Rate of pressure fall (mb/hr) as derived from the time of commencement of rapid fall to the time of the wave pressure minimum.

gravity wave, existed in the cold air north of a quasi-stationary front along which several minor low-pressure waves progressed. Furthermore, the gravity wave was first detected west of the mountains shortly before 1200 GMT on December 3 and appeared to maintain its identity crossing the mountains.

The character of the wave passage was a rapid drop in pressure approaching 7 mb at some locations, usually followed by several oscillations with periods that varied from about 5 to 12 min. These oscillations were analyzed on barograms from those few stations where high-speed traces (one turn of the drum every 12 hr) were available. On the other 4-day traces, which constituted the majority of the data, the oscillations following the initial drop were not as easily separated due to the short periods involved. The initial pressure drop is still evident, however, and the time of occurrence and rate of fall may be determined from the trace. At some stations, the pressure drop was preceded by a slight rise of about 10 percent of the total drop, while other stations had no detectable rise immediately prior to the fall from ambient pressure. As we shall see later, the strength and depth of the low-level inversion are correlated to the total pressure drop and the rate of pressure fall.

The limits of accuracy for the 4-day traces are assumed to be 15–20 min. The accuracy of the pressure reading on the trace is not critical since it is the change in pressure that is under investigation. The trace is assumed accurate in pressure changes to within 1 mb.

To separate the pressure change associated with the gravity wave from the overall synoptic situation, we used the time of the increased rate of pressure fall to the lowest pressure to determine the magnitude of the pressure change and the rate of fall. Care was taken to prevent confusion between any real change in the rate of pressure fall and the semidiurnal pressure change. Wave-related pressure changes of less than 2 mb are neglected due to the difficulty of separating them from the ambient trace.

Figure 4 shows the total pressure drop associated with the wave passage; values in excess of 7 mb were measured. Figure 5 shows the rate of fall in mb/hr as determined from barograms. For comparison, the normal semidiurnal pressure changes occur at a maximum rate of about 0.5 mb/hr in this region.

The wave-related pressure drop approaches a rate of 7.5 mb/hr at several stations in the Carolinas and central Virginia with an average fall rate of 5 mb/hr in the area east of the mountains. An exception is noted in northeastern South Carolina, where extremely sharp but brief falls exceed 10 mb/hr. The length of time it takes the pressure to fall from the point where it first starts its rapid descent to the time the first pressure minimum is reached varies from station to station but is usually about 65 min. Isochrones of wave front passage obtained from an analysis of the time of pressure drop from microbarograms and barograms were plotted on a base map. This procedure established that the primary wave was traveling from 300° at 13 m/s. Figure 6 shows the hourly positions of the wave front from 2 hr after detection until 1 hr before dissipation.

Note that the pressure drop maximum seems to exhibit a movement relative to the moving pressure wave itself. This can be seen by comparing Figures 4 and 6. At about 1600 GMT on Dec. 3, 1968, the maximum pressure changes are occurring in northern Georgia. As the wave travels toward the coastline, the maximum pressure drop appears to travel along the wave such that by 2200 GMT the maximum change is located in south-central Virginia.

Figure 7 shows a cross section of station barograms along a line parallel to the direction of the path of the gravity wave from the mountains to the coast. The gravity wave is detected at Roanoke, Va., just prior to 2100 GMT. Increasing wave amplitude is observed toward the coast with the pressure trough becoming more pronounced at Newport News and Norfolk, Va., before nearly disappearing at Cape Hatteras. Observe the small pressure

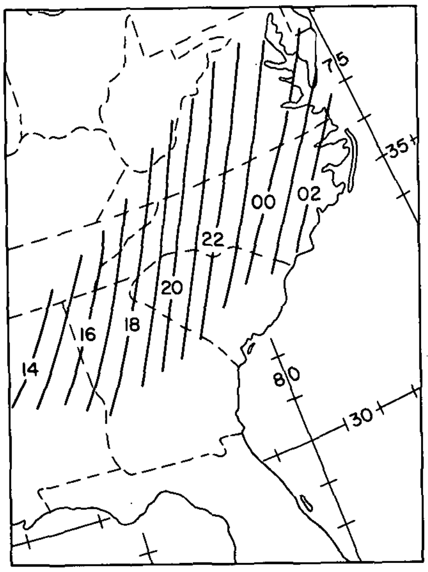

FIGURE 6.—Hourly location and extent of the leading edge of the pressure drop associated with the primary gravity wave. All times are GMT on Dec. 3–4, 1968.

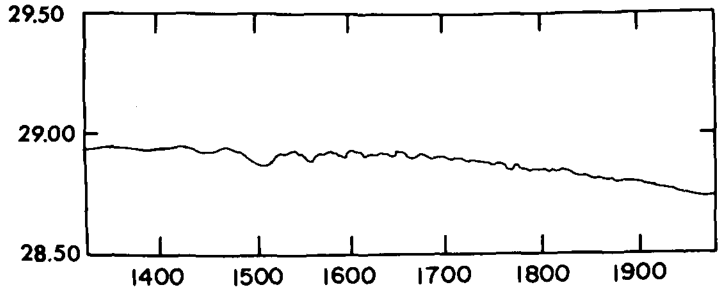

FIGURE 8.—Portion of Knoxville, Tenn., station pressure trace in inches of mercury for Dec. 3, 1968, obtained from a 12-hr clock recorder. All times are GMT.

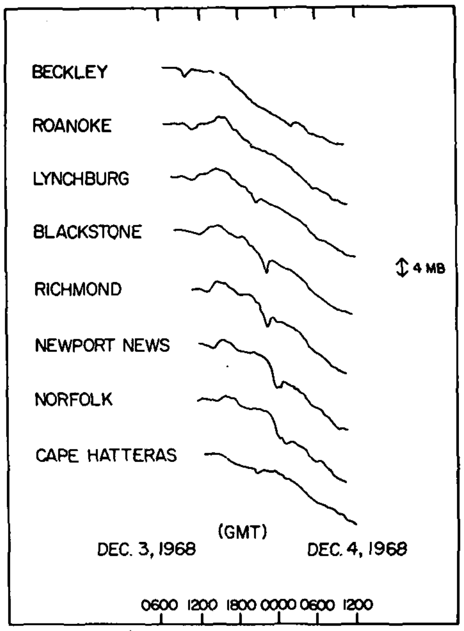

FIGURE 7.—Four-day barograms for a station cross-section parallel to the direction of motion of the primary gravity wave.

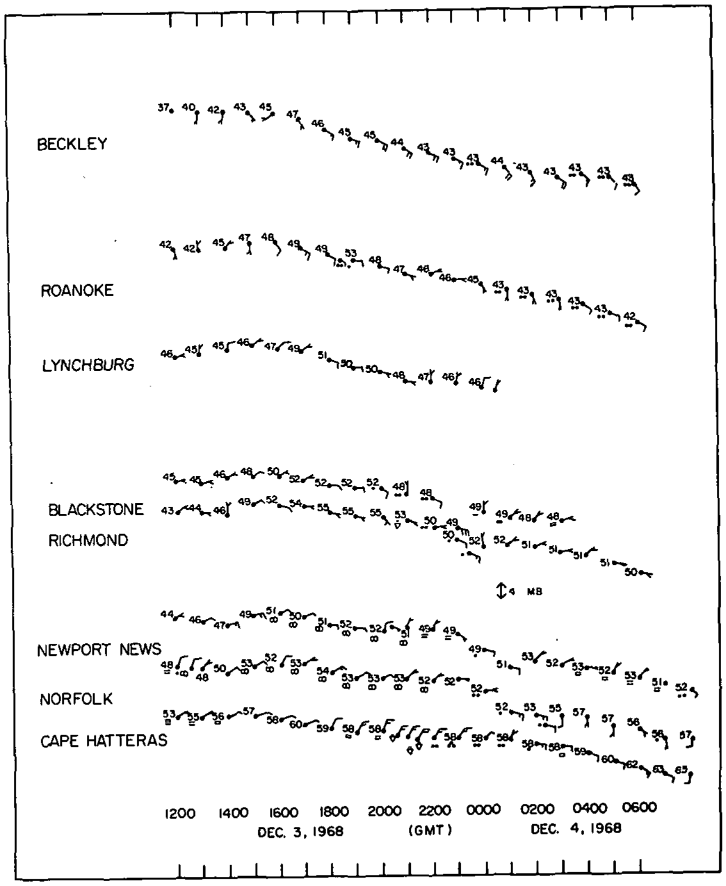

FIGURE 9.—Hourly weather, temperature (°F), and wind (kt) for same stations as in figure 7. For reference, a 4-mb vertical pressure scale is indicated between Richmond and Newport News, Va. Note that the 2300 GMT observation at Blackstone (30-kt wind) is a reflection of the large 1-hr pressure change and as such appears to be with the Richmond data.

oscillations of less than ± 1 mb to the rear of the wave as several locations. This behavior shows up in other crost sections, but there is no consistent pattern. It is difficult to draw any definite conclusions, however, because the 4-day traces obscure features with periods of 5–10 min. On the other hand, a 12-hr trace for Knoxville, Tenn., (fig. 8) shows small-scale oscillations persisting for 3 hr after the primary wave passage at 1500 GMT. Consequently, the pressure field to the rear of the pulse is not as smooth as indicated in figure 3. Evidence of an earlier gravity wave prior to 1200 GMT is noted from the Beckley and Roanoke traces (fig. 7). This wave, which dissipated as it moved across Virginia, could be followed across the Ohio Valley in advance of a weakening cold front over the Mississippi Valley.

Some of the gross features of the wind field in relation to the gravity wave have been described in connection with figure 3. Figure 9 presents the hourly weather, temperature, and wind direction in cross-section form for the same stations as figure 7. The ordinate is scaled according to station distance. Individual hourly reports are plotted according to station pressure with relevant nonhourly specials included. The onset of gusty ESE winds from 20 to 30 kt is evident in association with the strong pressure fall accompanying the wave passage. At a few

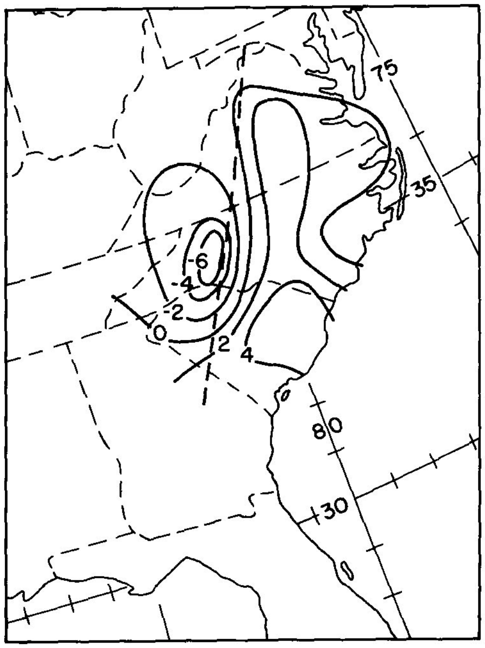

FIGURE 10.—Surface divergence (10^{-5} s^{-1}) computed kinematically from the wind field at 2100 GMT, Dec. 3, 1968. Heavy, dashed line marks the leading edge of the pressure drop associated with the primary gravity wave.

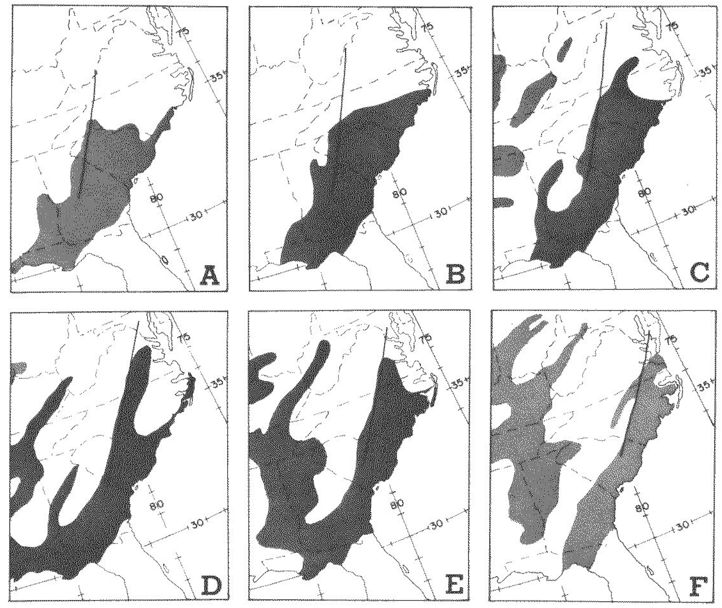

FIGURE 11.—Area of hourly precipitation equal to or greater than 0.01 in. for hourly periods, (A) 1800–1900, (B) 1900–2000, (C) 2000–2100, (D) 2100–2200, (E) 2200–2300, and (F) 2300–0000 GMT, Dec. 4, 1968, is indicated by stippling. Location of pressure minimum at the end of each hourly period is indicated by a heavy solid line.

stations, such as Blackstone, Va., reported gusts exceeded 30 kt. One of the most striking features is the uniformity of observed wind directions as the wave approaches from the west-northwest; almost all stations report winds from 120°–130°, with a few reports of 140°.

Figure 10 shows the surface divergence computed kinematically from surface wind data at 2100 GMT on Dec. 3, 1968. Comparison with figure 6 shows that an area of convergence of 6×10^{-5} s^{-1} occurs in the hour following the passage of the wave front marking the leading edge of the pressure drop associated with the primary gravity wave. Likewise, an area of divergence precedes the wave front. Consequently, a strong ageostrophic component reinforces the synoptic scale geostrophic wind resulting in a strong, gusty wind period during the time of rapid surface pressure fall to the rear of the wave front. After passage of the wave-related pressure minimum, the ageostrophic component opposes the synoptic component, resulting in reduced wind speeds and even a reversal in direction at some locations. Note the light northwesterly winds at some stations following the wave passage (figs. 3, 9). While caution must be exercised in interpreting the results of these computations because of the irregular topography and the resultant effects on surface wind directions, the results appear physically reasonable. An attempt was made to correlate the time of strongest wind with the time of lowest pressure in the wave but without success. A few stations show this correlation, but most of them do not because other stronger winds are observed during the calendar day in association with synoptic scale features such as the cold front passage. These stronger winds are in turn reported on the WBAN 10 forms. In addition, the density of stations making triple recorder observations including wind direction and speed is too low to shed any light on this question.

6. SURFACE WEATHER CHARACTERISTICS WITH THE WAVE PASSAGE

It is extremely difficult to deduce any significant change in the temperature field during the passage of the gravity wave. A tendency for an in-phase temperature and surface pressure relationship accompanying the wave passage is evident. However, these temperature changes are probably related to the precipitation field. Several stations in figure 9 report precipitation just prior to and accompanying the initial wave-induced pressure drop ending abruptly as the gusty easterly winds subside. Decreases in temperature during this period are probably the result of evaporational cooling of precipitation falling into relatively dry air. The 5°F drop at Richmond between 2000 and 2200 GMT is offset by a 6°F rise in the dew-point temperature as the initial temperature–dew-point temperature spread of 16° is reduced to 5°F. Similar behavior is noted at Blackstone. With the passage of the pressure minimum, temperatures recover toward ambient values as the precipitation ceases. This effect is not as pronounced at coastal locations, where the initial temperature–dew-point temperature spread is considerably less.

Hourly precipitation maps showing areas of rainfall of 0.01 in. or more for 6 consecutive hourly periods beginning 1800–1900 GMT and ending 2300–0000 GMT on Dec. 4, 1968, are presented in fig. 11. The position of the axis of minimum pressure is superimposed on each map. In general, the rain area remains to the east of the eastward-traveling pressure minimum with the result that there appears to be a "shutting off" of precipitation after the wave passage. Rainfall at any one station usually lasted for 3–4 hr resulting in about 0.25 in. of water.

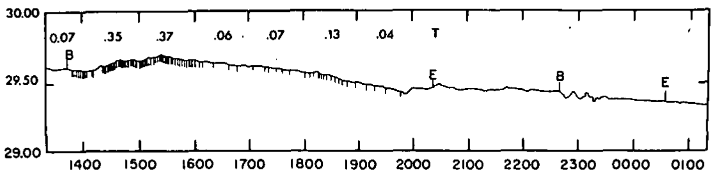

FIGURE 12.—Station pressure (in. of mercury) and precipitation (10^{-2} in.) versus time (GMT) at Macon, Ga., for a portion of Dec. 3, 1968. Each thin, solid, vertical line below the pressure trace represents 0.01 in., of precipitation. Cumulative hourly precipitation totals are indicated above the pressure trace. B and E refer to time of beginning and ending of precipitation.

Comparison with figure 10 shows that there is fair agreement between the location of the rain area and the region where surface divergence yields to surface convergence with the resultant enhancement of low-level upward motion. The rapid decrease in surface convergence after the passage of the pressure minimum is evidently enough to suppress precipitation. Figure 12 shows this sequence in greater detail. Macon, Ga., was the only station in the path of the gravity wave that had both a 12-hr barogram trace and a triple register precipitation record. Rainfall amounted to 0.48 in. from 1526 to shortly before 2000 GMT during the period of pressure fall ahead of the wave passage and then ceased abruptly. The situation at Macon is not clear cut, unfortunately, as this station lies close to the southern end of the path of the gravity wave. Thunderstorm rainfall provided a complicating analysis factor at Macon before the onset of the pressure drop. Note the intense rainfall between 1408 and 1526 GMT when a pressure rise of 3.73 mb was observed. During this period, Macon was on the northern fringe of an area of thunderstorms traveling eastward along a quasi-stationary front.

Finally, most stations observed a definite improvement in the visibility and ceiling after the passage of the gravity wave. Visibilities of 1–3 mi with ceilings of 500 ft in light rain and fog gave way to visibilities of 5–10 mi and overcast ceilings of 2,000 ft after the wave passage.

7. DISCUSSION

The gravity wave under investigation in this paper appeared to originate over northern Alabama and Mississippi prior to 1200 GMT on Dec. 3, 1968. Thunderstorm activity in connection with an evolving wave disturbance just off the Louisiana coast between 0600 and 1200 GMT appears to be the initial triggering mechanism. Table 1 lists the times of reported thunderstorms in the southeastern United States on December 3 from the hourly station network. A concentration of thunderstorm activity in south-central Alabama and Mississippi, southern Louisiana, and the Florida panhandle is to be noted from 0600 to 1200 GMT. An inspection of the radar reports for this region suggests that the convective activity is considerably more extensive than would appear from the hourly network. Speculative arguments on the role of convective activity in initiating gravity waves has also appeared in papers by Goldie (1925), Pothecary (1954), Wagner (1962), and Ferguson (1967).

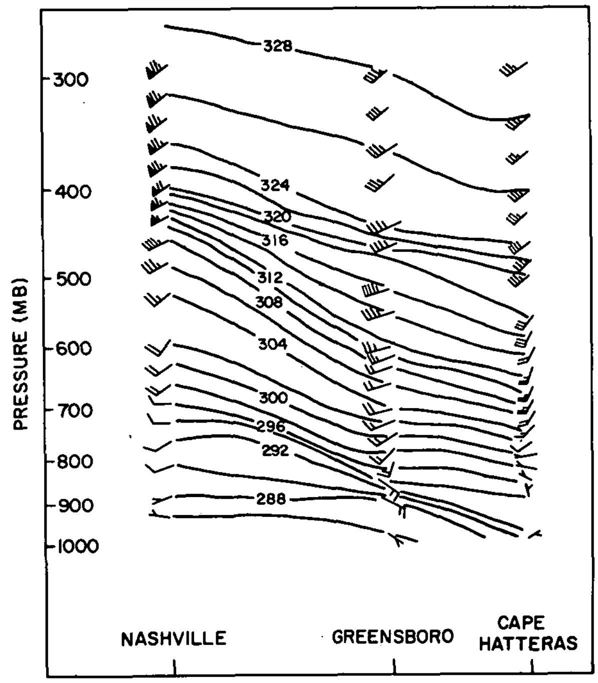

FIGURE 13.—Cross section of potential temperature (solid) every 2°K and winds (m/s) from Nashville, Tenn., to Cape Hatteras, N.C., for 0000 GMT, Dec. 4, 1968.

TABLE 1.—*Stations reporting thunderstorms in the southeastern United States on Dec. 3, 1968*

Station	Time (GMT)
Louisiana	
Lake Charles	1030–1152
Lafayette	0650–0732
New Orleans	OCNL LTG SW 0956
Burrwood	0810–0935; 1015–1230, 1510–1615
Mississippi	
McComb	0600–0959
Meridian	0713–0920
Biloxi	1103–1143, 1456–1518
Georgia	
Augusta	PIREP LRG TSTM 10 n.mi. S at 2122
Alabama	
Selma	1016–1112
Montgomery	1053–1133
Ozark	HOOK SHAPED ECHO 33–46 n.mi. S-SSE 1540–1600
Florida	
Valparaiso	1431–1458
Panama City	1109–1141
Tallahassee	1330–1401
Tennessee	
Crossville	2144–2215

The propagation medium in the present case appears to be a low-level inversion representing overrunning of cold air by tropical air just north of the quasi-stationary front along the gulf coast. Figure 13 is an east–west cross-section of potential temperature at 0000 GMT on December 4, representative of a time when the primary gravity wave is reaching the Atlantic coast. The lower tropospheric inversion is especially pronounced at Greensboro,

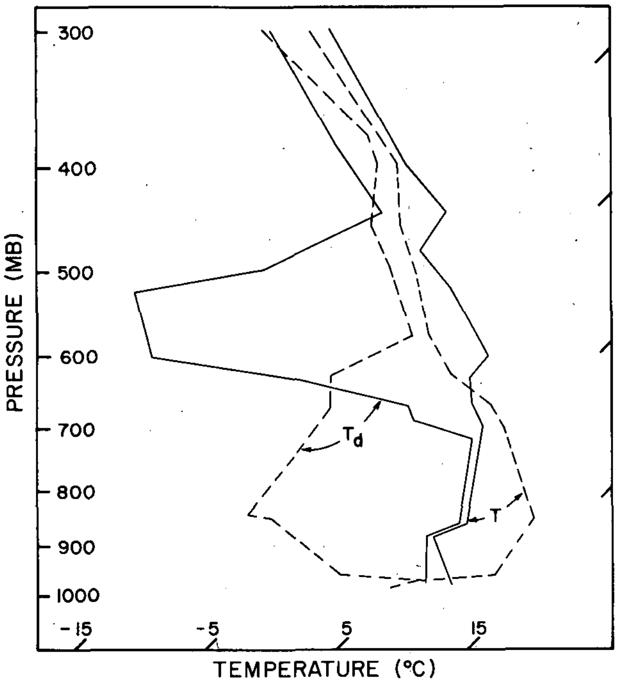

FIGURE 14.—Greensboro, N.C., temperature and dew-point temperature profiles for 1200 GMT, Dec. 3, 1968 (dashed) and 0000 GMT, Dec. 4, 1968 (solid) on a skew T–log p diagram.

TABLE 2.—*Computed and observed wave parameters at selected stations*

	Athens, Ga.	Greensboro, N.C.
Time of wave passage on Dec. 3, 1968 (GMT)	1800	2100
Mean potential temperature of cold air (°K)	299	298
Mean potential temperature of warm air (°K)	326	323
Height of inversion above ground (m)	739	967
Phase velocity from eq(1) (m/s)	±24. 4	±27. 0
Mean wind at inversion resolved along observed direction of wave propagation (m/s)	−10. 1	−9. 8
Phase velocity corrected for advection (m/s)	14. 3 −34. 5	17. 2 −36. 8
Observed phase velocity (m/s)	13. 4	13. 4

N.C., and slopes downward and weakens toward Cape Hatteras. Likewise, the low-level inversion weakens westward across the Appalachian Mountains. A similar low-level inversion is noted somewhat farther south 12 hr earlier (not shown). A more detailed picture of this inversion can be seen in figure 14, which shows temperature and dew-point temperature soundings taken at Greensboro 9 hr before (1200 GMT on December 3, dashed) and 3 hr after (0000 GMT on December 4, solid) the passage of the primary gravity wave. The 1200 GMT plot depicts the surface inversion formed by radiational cooling in a weak high-pressure region (fig. 2). Note the exceptional dryness of the lower troposphere. A rapid moisture increase and corresponding cooling in 12 hr is seen in this layer as an inversion develops between 850 and 900 mb.

Tepper (1950) used an expression of the form

$$c=\left[\left(1-\frac{\theta_1}{\theta_2}\right)gh\right]^{1/2} \tag{1}$$

to compute the phase velocity of a squall line propagating along a density discontinuity between two fluids. Here, h is the height of the discontinuity, g is gravity, c is the phase velocity of the wave, and θ_1 and θ_2 are the mean potential temperatures of the lower and upper fluid, respectively. The equation assumes homogeneous, adiabatic fluids with the upper fluid of infinite extent. Surface friction and topography are neglected. One-dimensional motion is assumed in the lower layer and no motion at all in the upper layer. The effect of the earth's rotation is likewise ignored. Table 2 shows computations using eq (1) at two stations in the path of the gravity wave for which upper air data can be used. A correction was made for advection by the horizontal wind resolved along the observed direction of the wave at the height of the inversion. An averaging of the 1200 and 0000 GMT soundings was also necessary. The mean potential temperature of the warm air was averaged from the top of the inversion to the tropopause.

The positive root (in the phase velocity) corresponds to the more physically realistic situation of the progressive wave. It was not possible to detect the regressive wave (negative root) with the data in hand. A well-defined horizontal density discontinuity did not exist in the much deeper cold air over the Mississippi Valley. Although agreement between theory and observation is reasonably good for the progressive wave, we are more inclined to believe that this may be due to fortuitous circumstances. The fluids are clearly not adiabatic (fig. 14) and vertical wind shear is important. Likewise, the 12-hr time scale for the wave existence suggests that the Coriolis acceleration may not be negligible. It is of interest to note that the wave disturbance dissipated rapidly as it approached the North Carolina coast where the inversion lowered and weakened.

Ferguson (1967) applied Goldie's (1925) equations to his study of a squall line situation over the Great Lakes. The results were reasonable in terms of surface-pressure amplitude. However, the equations predicted rising surface pressure coupled with wave-induced strong ageostrophic flow. Likewise, in our case, Goldie's equations predicted rising surface pressure together with the strong easterly flow with the approach of the gravity wave. This is erroneous; the strong, gusty winds were definitely associated with sharply falling pressure. A close inspection of Ferguson's table 1 and figure 5 suggests that gusty surface winds normal to the wave front took place with rapidly falling surface pressure for his case also.

A feature of considerable interest that could not be investigated here were the numerous small pressure oscillations discernible on the few and far-between 12-hr barograms (fig. 8). As the initial wave neared the coast, a trailing wave appeared to become organized over eastern Georgia and South Carolina as can be seen in figure 3.

It is not clear whether this new wave development came at the expense of the trailing minor pressure oscillations or was influenced by renewed convective activity around 2100 GMT on December 3 just south of Augusta, Ga. Radar indicated that this convective activity was extensive with cloud tops in excess of 40,000 ft. The second wave was more difficult to follow, but it appeared to track more eastward and then east-northeastward at 10–13 m/s reaching into eastern North Carolina and southeastern Virginia by 0600 GMT on December 4 as an enhanced pressure fall region that gave the appearance of a secondary storm formation along the Virginia coast. The resulting weak cyclonic circulation persisted for 6–12 hr over Chesapeake Bay and the Delmarva Peninsula before beginning a steady intensification as a coastal Low.

In any detailed case study such as presented here, a valid question can be raised about the representativeness of the results. Our case is probably one of the most dramatic examples of gravity wave propagation in connection with east coast storms in the last several years. In particular, the Georgia, Carolinas, and Virginia area is one of the most favored locales with shallow cold air trapped east of the mountains to the north of an active frontal zone. We have also examined in detail the case of Mar. 3, 1971, which preceded major east coast cyclogenesis by 6–12 hr. Details on the precipitation field associated with this storm can be found in Bosart (1973).

In the March 1971 case, a series of two gravity waves 3–4 hr apart moved east-northeastward from Georgia to the Virginia coast at 10–13 m/s. Wave amplitudes ranged from 2–5 mb with a pressure fall period of 75–80 min and a wavelength of 55–60 km. As in the December 1968 case, the strongest winds occurred with rapidly falling pressure ahead of the wave and at an angle of nearly 90° to the isobars. The wave activity was apparently triggered by intense convection along and just north of a surface warm front in advance of a weak low-pressure area.

From a forecasting standpoint, it would probably be difficult to generate short-term forecasts of rapid changes in meteorological conditions. Yet, the changes in wind direction and speed, ceiling, visibility, and precipitation that occurred with the December 1968 case are undoubtedly of importance to aviation interests. Turbulence with the period of the gusty surface winds is clearly of concern. Several pilot reports indicated moderate to severe turbulence in the location of the gravity wave for the December 1968 case. One can, however, determine possible gravity wave activity by analyzing maps of hourly pressure change from observed teletype data. This technique was of value for the March 1971 case and should be useful in general if the gravity-wave-induced pressure falls occur on time scales of 1 hr or more.

From a theoretical standpoint, we have the question of what role, if any, do gravity wave phenomena play in cyclogenesis. A number of speculations were raised by Bosart (1973) on the possible role of cold air convective activity in bringing the synoptic scale environment closer to saturation, which would in turn aid cyclogenesis, given favorable conditions aloft. The role of the gravity wave in the vertical transport of moisture, momentum, and energy needs to be explored further. Bretherton (1969) has carried out a theoretical study in which gravity waves are generated or further excited by a stably stratified air flow over hilly terrain in north Wales. He finds that in selected cases these waves can vertically transport momentum and energy as high as 20 km. Further observational and theoretical work is required in this area.

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REFERENCES

Bosart, Lance F., "Detailed Analysis of Precipitation Patterns Associated With Mesoscale Features Accompanying United States East Coast Cyclogenesis," *Monthly Weather Review*, Vol. 101, No. 1, Jan. **1973**, pp. 1–12.

Bosart, Lance F., Vaudo, Cosmo J., and Helsdon, John H. Jr., "Coastal Frontogenesis," *Journal of Applied Meteorology*, Vol. 11, No. 8, Dec. **1972**, pp. 1236–1258.

Bretherton, Francis P., "Momentum Transport by Gravity Waves," *Quarterly Journal of the Royal Meteorological Society*, Vol. 95, No. 404, London, England, Apr. **1969**, pp. 213–243.

Brunk, Ivan W., "The Pressure Pulsation of 11 April 1944," *Journal of Meteorology*, Vol. 6, No. 3, June **1949**, pp. 181–188.

Ferguson, Howard L., "Mathematical and Synoptic Aspects of a Small-Scale Wave Disturbance Over the Lower Great Lakes Area," *Journal of Applied Meteorology*, Vol. 6, No. 3, June **1967**, pp. 523–529.

Fujita, Tetsuya, "Results of Detailed Synoptic Studies of Squall Lines," *Tellus*, Vol. 7, No. 4, Stockholm, Sweden, Nov. **1955**, pp. 405–436.

Goldie, Archibald H. R., "Waves at an Approximately Horizontal Surface of Discontinuity in the Atmosphere," *Quarterly Journal of the Royal Meteorological Society*, Vol. 51, London, England, **1925**, pp. 239–246.

Matsumoto, Seiichi, and Akiyama, T., "Mesoscale Disturbances and Related Rainfall Cells Embedded in the 'Baiu Front' With a Proposal on the Role of Convective Momentum Transfer," *Journal of the Meteorological Society of Japan*, Series II, Vol. 48, No. 2, Tokyo, Apr. **1970**, pp. 91–102.

Matsumoto, Seiichi, and Ninomiya, K., "On the Role of Convective Momentum Exchange in the Mesoscale Gravity Wave," *Journal of the Meteorological Society of Japan*, Series II, Vol. 47, No. 2, Tokyo, Apr. **1969**, pp. 75–85.

Pothecary, I. J. W., "Short Period Variations in Surface Pressure and Wind," *Quarterly Journal of the Royal Meteorological Society*, Vol. 80, No. 345, London, England, July **1954**, pp. 395–401.

Tepper, Morris, "A Proposed Mechanism of Squall Lines: The Pressure Jump Line," *Journal of Meteorology*, Vol. 7, No. 1, Feb. **1950**, pp. 21–29.

Wagner, A. James, "Gravity Wave Over New England, April 12, 1961," *Monthly Weather Review*, Vol. 90, No. 10, Oct. **1962**, pp. 431–436.

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