Squall Lines, Pressure Jump Lines and Atmospheric Gravity Waves

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Abstract

A review is given of the nature of squall lines and of their identification and study as pressure jump lines. The theory of steepening atmospheric gravity waves is reviewed and several synoptic patterns associated with the generation of severe storms are presented and shown to produce atmospheric gravity waves dynamically.

The squall line

The surface synoptic weather map contains many features familiar to the meteorologist and layman alike. Among these features there is one, which is relatively common on the synoptic map of the United States, which is commonly referred to as a "squall line". This line is usually seen as an almost solid line of thunderstorms oriented generally NE to SW, and very often oriented parallel to the surface position of a cold front.

Some of the most severe weather experienced in the United States is associated with the squall lines—severe wind storms, severe hail storms, heavy downpours, and the most violent of all storms, the tornado. Despite its exceedingly dramatic manifestations, the nature and particularly the dynamics of the squall line are as yet not completely understood, and we find that there are almost as many theories on the genesis and life history of squall lines as there are investigators who study this problem.

In its most pronounced state, the passage of the squall line produces very spectacular weather events at the surface (fig. 1):

(1) A marked pressure rise of several mbs. in an extremely short period of time. Values of 3 to 5 mbs. in less than 5 minutes are quite common.

(2) A pronounced temperature fall. A drop of about 10° F in 5 to 10 minutes is not rare.

(3) An increase in relative humidity, usually associated with the temperature fall.

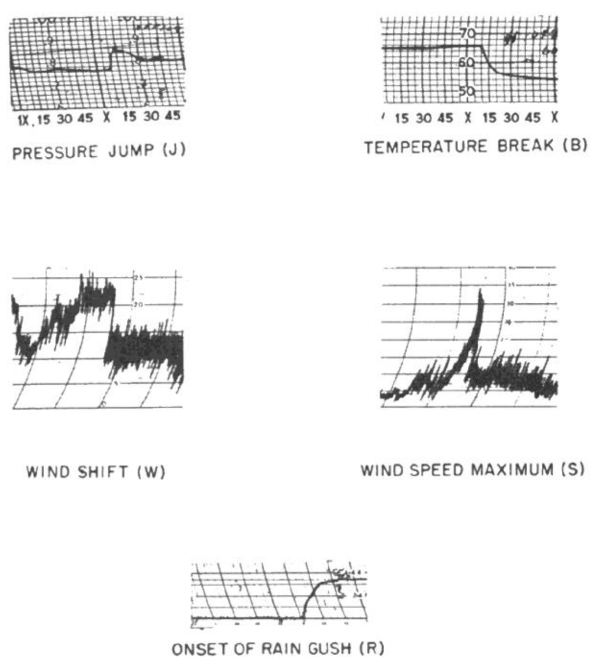

Fig. 1. Behavior of surface elements with passage of "ideal" squall line

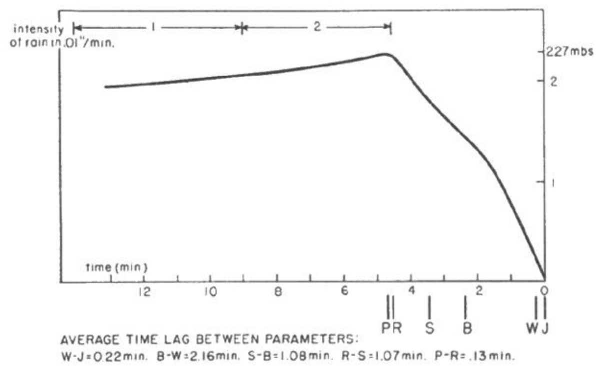

Fig. 2. Average conditions associated with the squall line of May 16, 1948 over the Thunderstorm Project network in Wilmington, Ohio. Letters refer to elements in fig. 1

(4) A very sharp wind shift which is usually associated with extreme gustiness. This wind shift, too, is very pronounced and usually takes place in less than 5 minutes, with the gustiness of the winds reaching as high as 60 mph. (about 100 km/h) representing an increase of from 10 to 50 mph. or more, over a previous wind speed.

(5) Heavy precipitation appearing in the form of a rain gush, with perhaps as much as 1/10 of an inch (2.5 mm) of rain over this same short period of time.

Interestingly enough, it is not unusual for the entire life history of the squall line over a geographic point to be concluded in about 20 minutes to 1/2 hour, after which there is a general improvement of conditions and oftimes a return to those conditions which existed before the squall line passage.

The average time lag between the times of onset of the various meteorological parameters just discussed have been found (fig. 2) to suggest the following sequence of events: As the squall line approaches, the rise in pressure and the associated wind shift come first, followed after a few minutes by the temperature break and the maximum wind gust. Precipitation lags behind and comes almost at the time when the pressure trace has reached its maximum, and often times later.

This sequence has been observed many times over, and has suggested that perhaps there is significance to the fact that the rise in pressure preceeds all the other elements at the surface, and as such may yield the clue as to the true nature of the squall line.

The pressure jump line

While the behavior of the meteorological parameters just discussed represents the *idealized* pattern associated with squall lines, it has been observed and reported from time to time, that all of these weather changes need not take place with the passage of the squall line. For example, there may or may not be precipitation, there may or may not be a pronounced wind shift, there may or may not be a pronounced temperature fall, etc.

However, in our investigations of squall lines, one variation seems to be almost universally present, and that is the spectacular rise in pressure preceeding the advent of the other parameters. This spectacular rise in pressure we have named the "pressure jump", and the line along which pressure jumps are occurring we have named a "pressure jump line". We have found it expedient to set *arbitrarily*, the limits of a pressure jump, as follows:

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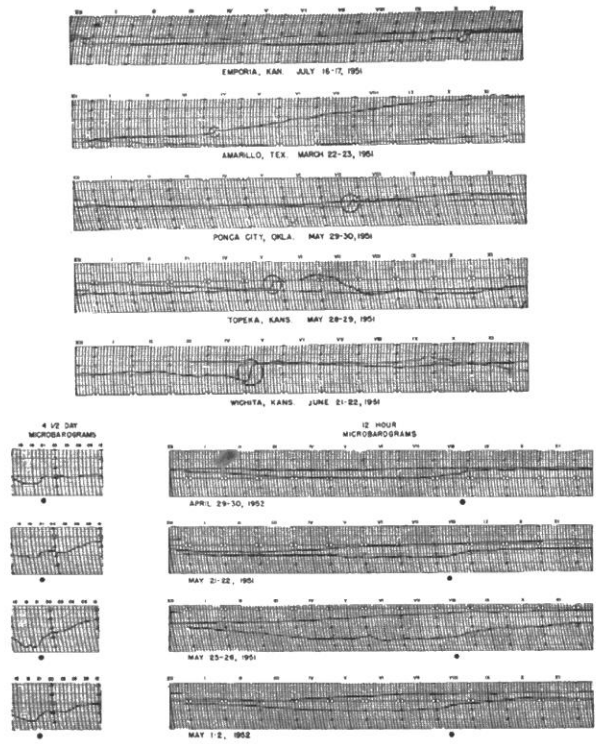

Fig. 3. Examples of pressure jumps as they appear on high speed microbarograms (upper) and comparison of pressure rises on 4½ day and 12 hr. microbarograms (lower). Marked pressure rises (given by black dot) on former do not necessarily appear as pressure jumps on latter

A pressure jump is defined as a rate in the rise of pressure equal to or exceeding 0.125 mm Hg per minute and with a total rise of at least 0.5 mm Hg.

It is clear that in view of the pressure jump criterion mentioned above, the 4½ day trace used in recording pressure on a barograph cannot readily discriminate between pressure jumps and the more gradual rises of pressure, and for that reason we have increased the speed of rotation of the drum on the microbarograph to one revolution in 12 hours (fig. 3).

Moreover, in order to insure continuity in charting the movement of the pressure jump line, it has been found advisable to increase the density of recording stations from their customary spacing in the United States of about 100 miles to a spacing of about 25 to 30 miles. The United Staates Weather Bureau has been maintaining a network of cooperative stations of this density for the past 6 years in the Midwestern states of the United States, where severe local storms are most common (fig. 4). Although the microbarograph is the primary recording instrument in this network, some of the stations are also equipped with hygrothermographs, rain gages and wind recorders.

A review of the statistical nature of pressure jump lines may be found in the United States Weather Bureau Research Paper nº 37, "Pressure Jump Lines in Midwestern United States, January—August 1951", by M. Tepper, and other staff members of the Severe Local Storms Research Unit. Of these the most significant are:

(1) The pressure jump line has relatively small dimensions. For example, the median area swept out by such a line can be approximated roughly by a rectangle 125 miles long, and 100 miles wide (1 mile = 1.6 km) (fig. 5).

It is our belief that much of the difficulty that has been experienced in the identification and tracking of squall lines—or pressure jump lines as we are considering them here—is due to the lack of recognition on the part of the synoptic meteorologist of the scale of the phenomena. The synoptic meteorologist has been attempting to follow the progress of squall lines on the ordinary synoptic map where the distribution of stations can hardly be expected to yield the resolution required of a phenomenon whose size is comparable to the spacing of the recording stations.

(2) The duration of the pressure jump line is relatively short, measured in terms of hours. In half the cases studied the duration was 3 to 4 hours or less.

(3) The median speed of propagation of pressure jump lines is in excess of 30 mph.

(4) There is a definite tendency on the part of pressure jump lines to propagate with a speed in excess of the component of wind in their direction of motion at most levels below the tropopause.

(5) Severe storms (including tornadoes) have been found to occur in both time and place with the passage of pressure jump lines (fig. 6).

(6) In comparison with radar echo lines, pressure jump lines describe a more systematic organization of events and represent more clearly the propagation of squall lines (fig. 7). "Precursors" have been found ahead of radar echo

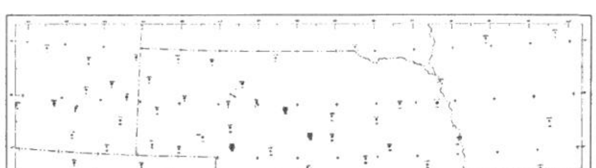

Fig. 4. 1954 special surface cooperative observational network in midwestern United States. Network is centered in the State of Kansas in 1954

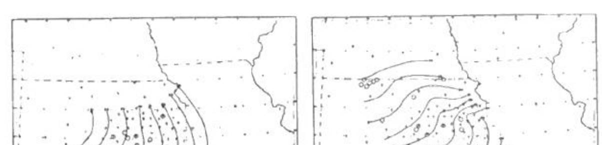

Fig. 5. Examples of pressure jump lines in special network (1951). Open circles refer to reported severe local storms

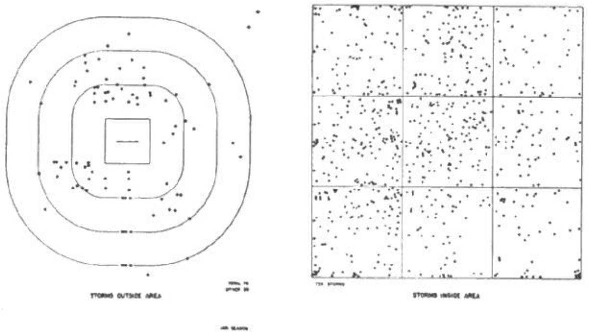

Fig. 6. Position of severe storms relative to 1951 season pressure jump lines, in midwest network. Large square to right and small square to left represent area swept out by pressure jump lines and each black dot a reported storm

lines which have been timed to occur exactly with the passage of the pressure jump line. It has been suggested that these precursors may be due to a gradient in refractive index, caused either by temperature or humidity gradients associated with pressure jump lines.

Pressure jump indicator

Due to the fact that the pressure jump lines seem to be so closely related to severe local storm occurrences, the Weather Bureau experimented, and by now has developed a device to respond automatically whenever the criteria mentioned above occur. This instrument which is called a "pressure jump indicator", is essentially a variagraph which responds only when the total change in pressure exceeds the minimum criteria (fig. 8). When in operational use this indicator is installed at places where a 24-hour watch is normally maintained, such as fire-houses, police stations, jails, etc. When the indicator is set off due to the passage of a pressure jump in the atmosphere, an alarm is sounded and the man on duty calls the control weather station by telephone. In this way the progress of the pressure jump line may be followed on a current basis.

Atmospheric gravity waves

So far, we have discussed the squall line, or the pressure jump line merely from the point of view of observations, i. e., how it is manifest in meteorological records. We shall now discuss briefly the hypotheses that pressure jump lines are steepened atmospheric gravity waves.

This hypothesis is based on an analogy to the flow of liquids (fig. 9). It is known that in long-wave theory, gravity waves can be set up either on a free surface or on an interface between two liquids (fig. 9a), and when one considers the full non-linear problem the waves develop very marked slopes along the leading edges. An example of such a breaking wave is the tidal bore.

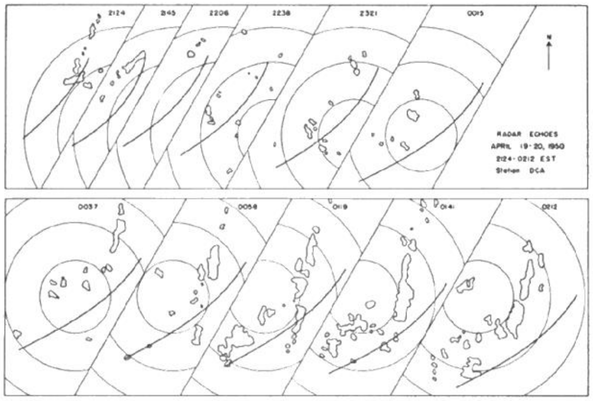

Fig. 7. Comparison between analyzed position of pressure jump line and radar echo presentations in vincinity of Washington, D. C., April 1950

Essentially what is required in order to arrive at such a phenomenon is:

(1) A stable layer along which the gravity waves can travel and

(2) Significant accelerations in the fluid.

It has been shown on several occasions that the atmosphere, if it is considered as consisting of two autobarotropic stratified layers, can be handled as analogous to the above incompressible model (fig. 9b, 9c). Thus, whenever we have situations wherein the atmosphere can be approximated by two autobarotropic layers, and where significant accelerations are possible (fig. 9d), we might look for gravity waves to form. Obviously, other things being equal, the magnitude of the gravity waves will depend on the magnitude of the accelerations involved. At the surface a barogram will record a pressure jump as a steepened gravity wave passes (fig. 9e, 9f). In numerical computations which we have been conducting reasonable atmospheric motions and reasonable atmospheric accelerations associated with these motions were able to produce, theoretically at least, gravity waves of significant amplitude.

The hypothesis states that once the steepening gravity wave has been produced in the atmosphere the propagation speed is determined by the laws of finite wave motion, consisting essentially of the local long wave speed plus the fluid speed. We might expect then, gravity wave to travel with a speed in excess of the actual value of the wind. Secondly, whenever the atmospheric gravity wave is produced and has significant amplitude, its effect on the atmospheric layer below and above it, is such as to produce violent upward motion. It is this characteristic that is considered responsible for the extreme nature of convection

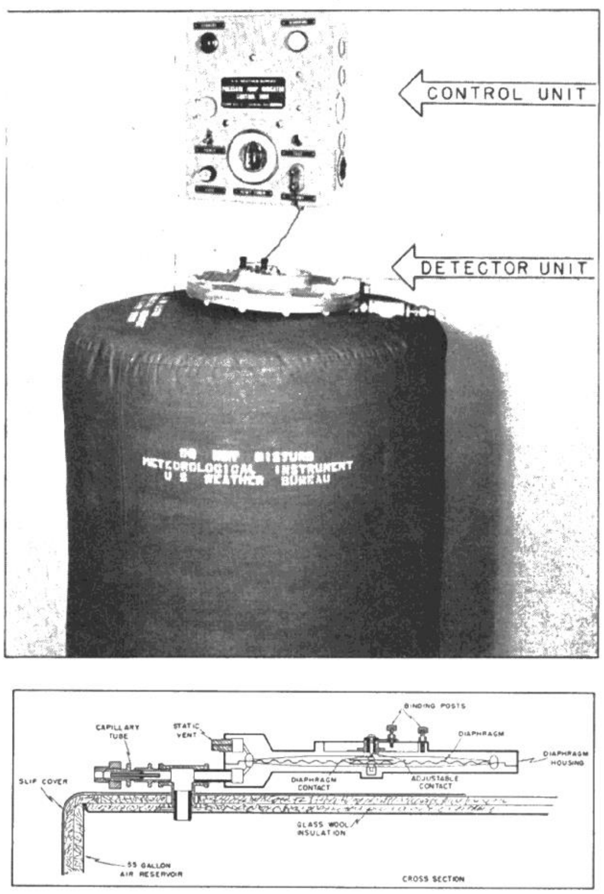

Fig. 8. Pressure Jump Indicator showing "detector" resting on 55 gal air reservoir and connected to "control" unit. Sketch is cross section of "detector"

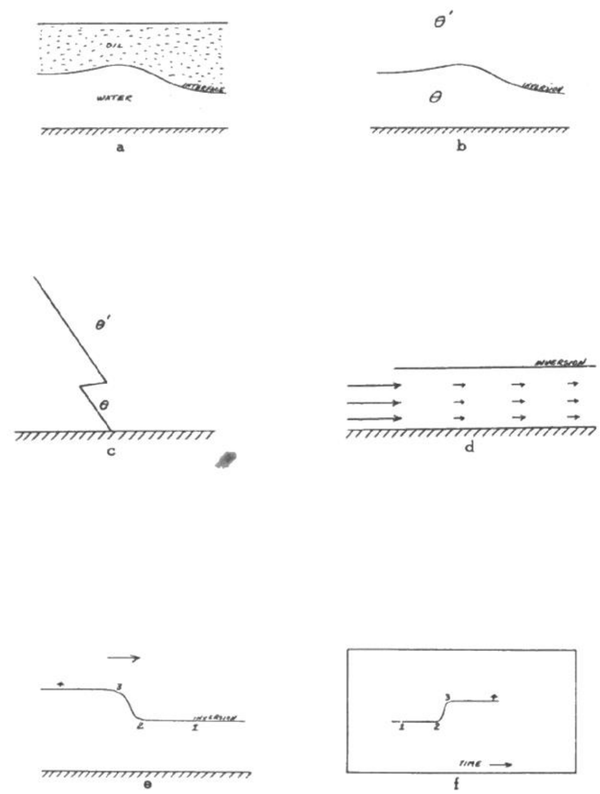

Fig. 9. Analogy between (a) gravity waves in stratified liquids and (b) atmospheric gravity waves. (c) Postulated vertical stratification in the atmosphere containing (d) accelerations. The passage of (e) the steepened atmospheric gravity wave is recorded as (f) a pressure jump on the microbarogram

associated with the squall line. Also, this would account for the fact that the pressure rise is noted to preceed the actual squall line itself, that is, the line of thunderstorms.

Certain synoptic patterns have been mentioned in the literature as favorable for squall line and/or severe storm formation (fig. 10). We have been constructing physical models based on these synoptic patterns in order to determine whether pressure jump lines might be formed dynamically in these models. Three essentially different models have been studied:

(1) Pressure jump lines produced by accelerating cold fronts (fig. 10a).

(2) Pressure jump lines produced by the addition of momentum to a simple current (fig. 10b).

(3) Pressure jump lines produced by the transit of an isotach maximum aloft (fig. 10c).

Summary and conclusions

A squall line is a line along which marked convection takes place and is recognized as an almost solid line of thunderstorms. Of all meteorological variations that take place with the passage of the squall line, including variations of wind, temperature, pressure, precipitation, relative humidity, and radar echo patterns, there seems to be one parameter that is very conservative, and that is the abrupt rise in pressure which has been defined as the *pressure jump*. The pressure jump line is a relatively small scale meteorological event whose entire dimensions are about the dimensions of the distribution of current surface observation reports. Consequently, in order to study the life history pattern of pressure jump lines, it is necessary to utilize dense networks of stations.

Unfortunately, the upper air observations have not been plentiful, and as a result we have lacking a very necessary bit of information—the behavior of the upper air pattern with the passage of the pressure jump line. We hope that in our subsequent years of research, to be able somehow to increase the number of upper air observations, possibly by means of swarms of upper air soundings, frequent soundings taken at selected stations, or aircraft observations.

Finally, we have indicated that we might explain many of the peculiarities and characteristics of pressure jump lines (or squall lines) by considering them to be propagating and steepening atmospheric gravity waves. Also, we have shown how we might start with some synoptic patterns associated with severe weather outbreaks and dynamically produce steepening atmospheric gravity waves.

This raises a very interesting point which we will touch on just briefly, and that is that there exists quite a gap between the large scale atmospheric motions (and by that we mean the types of motions that meteorologists usually analyze on a day to day basis), and the weather locally. It is important that meteorologists think in terms of linkages between the larger scale motions and the weather locally. It is proposed here that the atmospheric gravity wave is one of these linkages and that early identification by the meteorologist of conditions which produce atmospheric gravity waves will assist him in localizing those areas where severe storms may be expected.

Bibliography

Byers, H., and *Braham, R.*, 1949. "The Thunderstorm", U. S. Government Printing Office.

Fujita, T., 1955. "Results of Detailed Synoptic Studies of Squall Lines", Tellus, Vol. 7.

Fujita, T., *Newstein, H.*, and *Tepper, M.*, 1956. "Mesoanalysis—An Important Scale in the Analysis of Weather Data", U. S. Weather Bureau Research Paper No. 39.

Fulks, J. R., 1951. "The Instability Line", Compendium of Meteorology, American Meteorological Society.

Harrison, H. T., and *Orendorff, W. K.*, 1954. "Pre Cold Frontal Squall Line", United Air Lines Meteorology Department Circular +16.

Newton, C. W., 1950. "Structure and Mechanism of Pre Cold Frontal Squall Line", Journal of Meteorology, Vol. 7.

Tepper, M., 1950. "A Proposed Mechanism of Squall Lines", "The Pressure Jump Line", Journal of Meteorology, Vol. 7.

Tepper, M., 1952. "The Application of the Hydraulic Analogy to Certain Atmospheric Flow Problems", U. S. Weather Bureau Research Paper No. 35.

Tepper, M., 1954. "Pressure Jump Lines in Midwestern U. S., January—August 1951", U. S. Weather Bureau Research Paper No. 37.

Tepper, M., 1955. "On the Generation of Pressure Jump Lines by the Impulsive Addition of Momentum to Simple Current System", Journal of Meteorology, Vol. 12.

Tepper, M., 1956. "The Generation of Internal Atmospheric Gravity Waves by the Transit of a Steady Isotach Maximum above an Inversion Surface" (in manuscript).

Williams, D. T., 1948. "A Surface Micro Study of Squall Line Thunderstorms", Monthly Weather Review, Vol. 76.

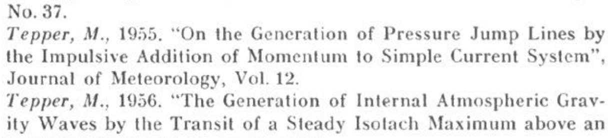

Fig. 10. Three examples of synoptic situations which produce atmospheric gravity waves. Schematic vertical cross sections are below the corresponding synoptic pattern