Observations of Pressure Jump Lines in the Midwest, 10–12 August 1976

Jack H. Shreffler[1] and Francis S. Binkowski[1]

Meteorology and Assessment Division, Environmental Sciences Research Laboratory, EPA, Research Triangle Park, NC 27711

(Manuscript received 22 October 1980, in final form 8 May 1981)

ABSTRACT

Strong thunderstorm activity over Iowa on two successive afternoons was the apparent source of pressure-jump lines (PJL's) which moved SSE at 50 km h^{-1} through the nocturnal boundary layer and were detected by National Weather Service (NWS) stations as far away as Paducah, Kentucky. Rainshowers and thunder were reported at many NWS stations as the PJL's passed.

The Regional Air Monitoring System (RAMS) network at St. Louis provided detailed information on the PJL's. Arrival there was indicated by an abrupt pressure rise of 1.5 mb, a near reversal of the surface flow, and a vertical displacement of 750 m extending through the lower 4 km of the atmosphere. The passage of each PJL was coincident with the turbulent collapse of the nocturnal jet. The observations of the PJL events seem indicative of an internal bore and are similar to those of the Morning Glory seen in northern Australia. We speculate that the bore originates from a late afternoon convergence produced by thunderstorm outflow and opposing low-level winds involving the nocturnal jet.

1. Introduction

Pressure fluctuations ranging from 0.1–10 mb frequently have been attributed to gravity waves propagating outward from distant frontal or severe storm activity. Local effects also may include changes in winds, as well as cloud enhancement or desiccation. As described by Wagner (1962), a large-scale wave over New England resulted in a pressure rise of 2–4 mb in about 2 h, although no other local changes in weather were noted. A possible source of the disturbance was convective activity over eastern Texas on the previous day. Uccellini (1975) presented observations of waves over the Midwest with amplitudes up to 2.5 mb and periods of 3 h. Intensification of existing storm cells or formation of new cells appeared to follow the passage of each wave trough.

A much more rapid pressure rise (2.3 mb in 5 min) was seen in the pressure-jump line (PJL) described by Tepper (1950). Tepper proposed that the PJL was indicative of a wave generated by, and moving well ahead of, a cold front. The passage of the wave would be coincident with a strong upward motion of the air, possibly inducing condensation of water vapor through adiabatic cooling. Tepper inferred that such a process caused the squall-line activity which he observed within minutes after the first indication of a pressure rise. However, as in the case of the large-scale waves described by Wagner and Ucellini, the pressure change may occur alone; the initiation of convective activity would depend on the local thermodynamic state of the atmosphere. Although the interpretation of PJL's as waves and their possible link to squall lines is interesting, there is a surprising paucity of further documentation on this phenomenon. Recently, however, Christie *et al.* (1979) have published a large number of pressure-jump records taken by a microbarometer array in the interior of Australia. While noncommittally referring to the observed phenomenon as "intrusive disturbances" propagating on the nocturnal inversion and generating atmospheric solitons, they point to a resemblance with internal undular surges in the ocean. They find little evidence for disruption of the surface flow fields, and, of course, no precipitation in this very arid region.

In this paper, we present observations of two PJL's which passed the St. Louis region in August 1976 while the Regional Air Monitoring System (RAMS) was operational. The data are unique in including detailed upper air measurements as well as surface winds, temperature and pressure. The probable source of the PJL's was intense thunderstorm activity in a quasi-stationary front across Iowa, and the pressure perturbations could be detected over 500 km from their origin.

2. Observations in the St. Louis area

As an integral part of the Regional Air Pollution Study (RAPS) a network of 25 meteorological towers was established in the St. Louis vicinity. These sta-

---

[1] On assignment from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

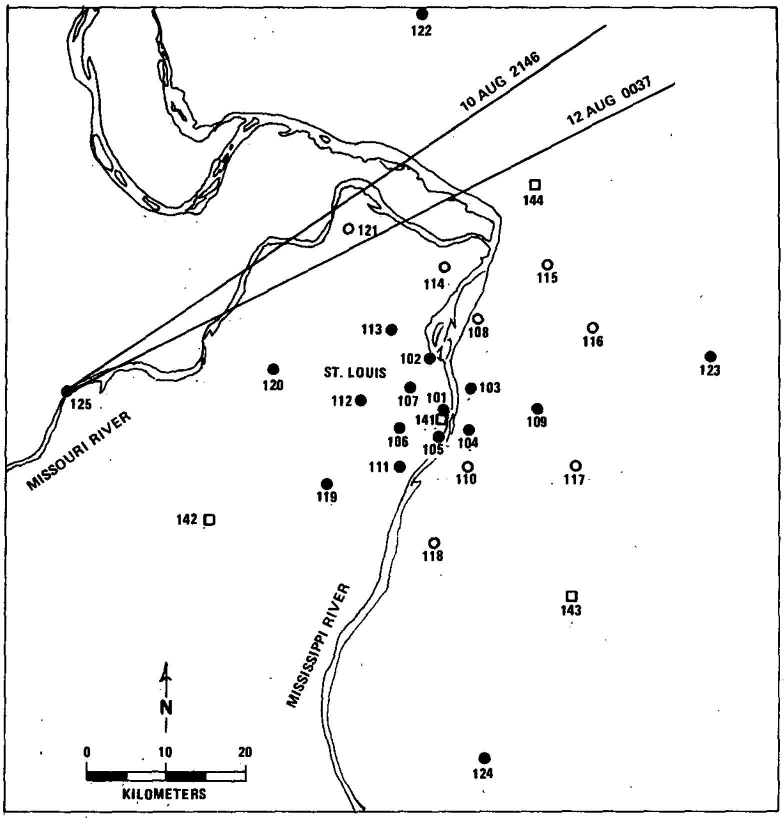

FIG. 1. Locations of the RAMS sites in the St. Louis metropolitan area. Solid dots indicate 30 m towers, open circles 10 m towers, and squares the upper air stations. Lines show the approximate leading edges of the observed pressure jump events moving from the northwest to the north-northwest.

tions comprised the Regional Air Monitoring System (RAMS). Measurements recorded as 1 min averages included wind speed and direction, temperature, barometric pressure, vertical temperature difference and concentrations of various pollutant gases including ozone. In addition, four upper air stations were established. During the period of this study, radiosondes were released simultaneously at 6 h intervals from each station, and PIBALS were released each hour that there were no radiosondes. Fig. 1 shows the layout of the RAMS. Detail on the urbanized areas and a complete description of the RAMS instrumentation are given by Schiermeier (1978).

a. Data from the surface network

On the nights of 10–11 August and 11–12 August 1976 pressure jumps of 1.2–1.8 mb occurring in ~6 min were recorded by the RAMS network. These events on successive nights will be referred to as PJ1 and PJ2. The onset of the pressure rise was accompanied by a temporary change in wind direction but no decline in temperature, as might be expected with a frontal passage or density flow from a thunderstorm downdraft. Pressure measurements were available at only seven of the RAMS stations (101, 109, 112, 122–125), but wind was measured at each. The disturbances clearly covered the entire region and were moving with a nearly linear leading edge toward the southeast to south-southeast.

Figs. 2 and 3 show time series of wind speed, wind direction and pressure for PJ1 and PJ2 at RAMS stations 109 and 122, respectively. Although the records differ somewhat from station to station, these series point out some of the similarities and differences between the two events. On both nights, the southerly flow was nearly reversed, changing to north-northwest. A spike in the wind speed occurred from the new direction, and completion of the pressure rise was coincident with the spike. The pressure rise for PJ1 was less abrupt, but the pressure record shows a distinct wave pattern which is absent from that of PJ2. Also, the PJ1 record shows some indication of a secondary event following the first by ~1 h. Traces of pressure at each available station are presented in the Appendix. The wind direction records are notably different on the two nights. Whereas the wind direction for PJ1 returned rather rapidly to the south through the west, the

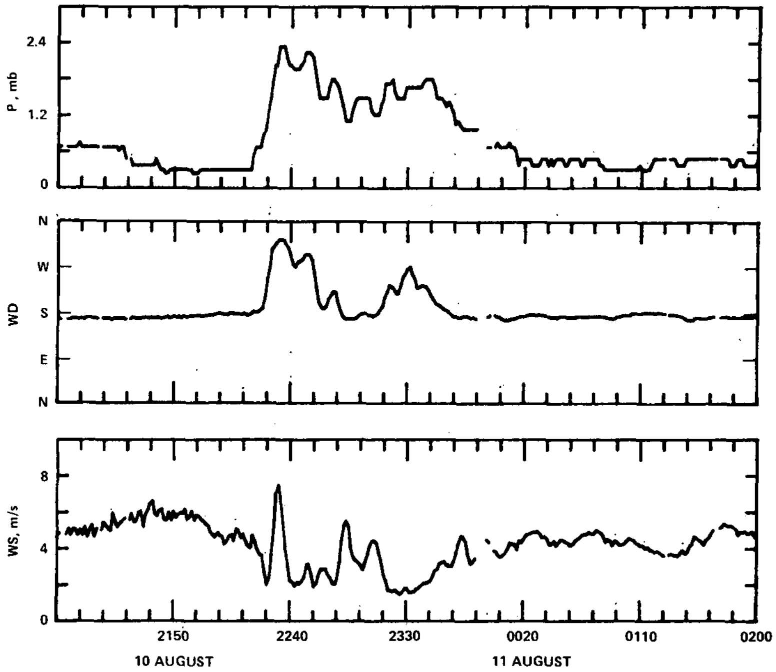

FIG. 2. Time series of wind speed (WS), wind direction (WD) and pressure (P) for the passage of PJ1 as recorded at RAMS 109.

wind direction for PJ2 underwent a clockwise revolution taking several hours to complete. Although the initial changes in wind and pressure were dramatic and rapid, the records show that the entire disturbance was fairly long-lived, ~2 h for PJ1 and 3 h for PJ2. In general, PJ2 appears to be a more intense example of the phenomenon than PJ1.

Listings of 1 min data from each of the RAMS stations were carefully examined to determine the passage times of the PJL's. The time adopted was

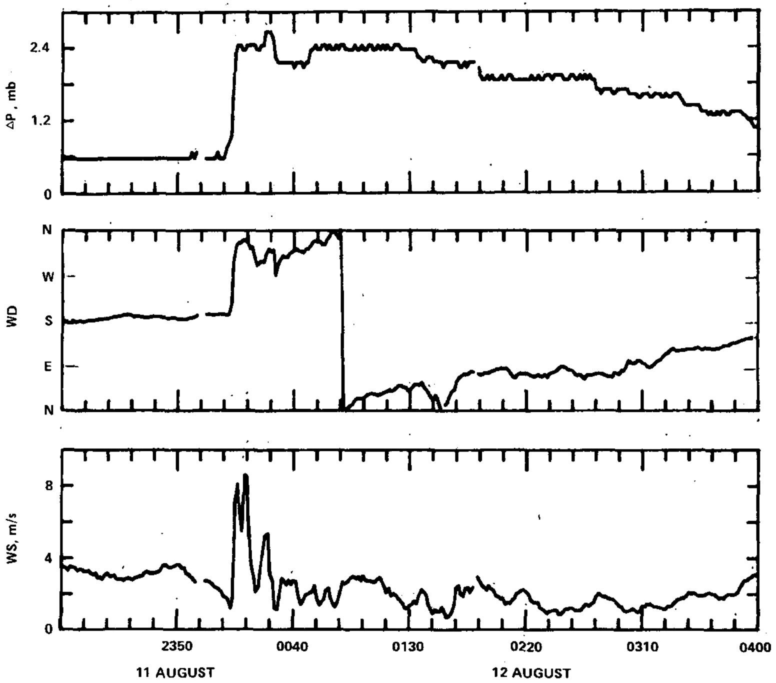

FIG. 3. As in Fig. 2 except for the passage of PJ2 as recorded at RAMS 122.

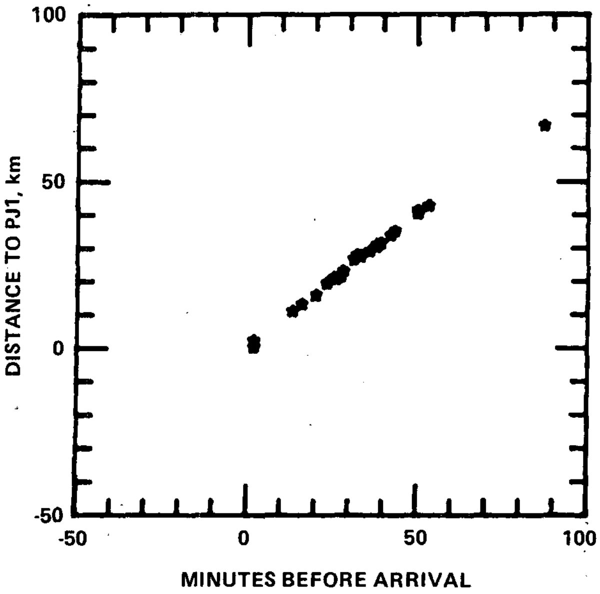

FIG. 4. Distance of each available RAMS site from PJ1 (as given in Fig. 1) plotted against the time of arrival relative to 2146 CST 10 August.

the first minute that the wind direction started its shift, since this effect was adequately sampled and easily identified. Based on these times, it was seen that the leading edge of each PJL approximated a straight line moving from the direction to which the wind shifts. The lines depicted in Fig. 1 were determined by visually matching distances with times of arrival at various stations in the northern section of the network. Having established leading edges of the PJL's, their speeds could then be inferred. Fig. 4 shows the relative passage times at each available station versus the distance from the station to the leading edge of PJ1 as given in Fig. 1. Fig. 5 shows a similar plot for PJ2. Both linear and parabolic least squares fits to these data were made, and results for the former are presented in Table 1. The speeds for the parabolic fits were higher by ~10%, and slight decelerations were indicated. The smoothness of the fits indicates the degree to which the leading edges were actually straight lines, and the standard errors of the estimates are certainly reasonable considering that the establishment of the passage times is only good to 1 min (~1 km). Perhaps the leading edge of PJ2 was a bit more ragged than that of PJ1.

Having given examples of records covering several hours at individual RAMS sites and established the motion and spatial integrity of the disturbances over the region, we now turn our attention to composite records covering the 30 min about the time of arrival. The composite records are formed by averaging data from all available stations in the network using times relative to the local arrival times. The winds are subjected to a vectorial averaging. The composite series of winds and pressure, given in Figs. 6 and 7, show the average effect of the PJL's over the region and give special detail to the arrival time. For PJ1, a 3.5 m s^{-1} wind from 190° just before arrival changed to 5.5 m s^{-1} from 320° at 7 min after arrival. Likewise, for PJ2, a 1.0 m s^{-1} wind from 186° changed to 5.8 m s^{-1} from 338°. The leading edges of the PJL's portrayed in Fig. 1 are moving from 327° for PJ1 and 334° for PJ2. Quite possibly there was a slight decrease in wind speed beginning up to 10 min before arrival. Although only the PJ1 pressure records at individual stations (see Fig. 2) show the distinct wave motion with a period of ~10 min, the composite wind speed series exhibit similar oscillations for both events.

b. Upper air data

A lidar (laser radar) was operated by SRI International (Uthe, 1978) on the night of 10–11 August and recorded the passage of PJ1. (It was not operating during PJ2.) The lidar was co-located with upper air station 141 in downtown St. Louis, and Fig. 8 displays the record. The irregular line at the 3200 m level is an auxiliary measurement of no concern here. The wave motion accompanying PJ1 is clearly evident, and the initial vertical displacement is ~750 m. One rather interesting aspect of the record is the bright cusps near the 3600 m level and just above the wave peaks at lower levels. It is unlikely that these are instrument artifacts, and one immediately thinks of condensation caused by lifting in the disturbance (Uthe, personal communication). To investigate this possibility, the radiosonde

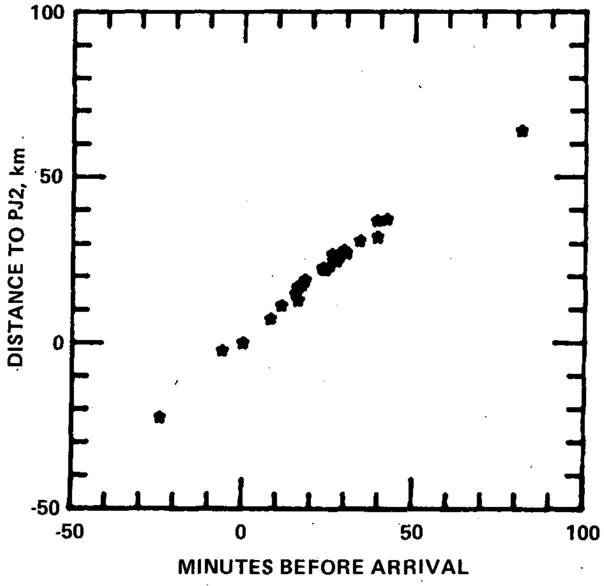

FIG. 5. Distance of each available RAMS site from PJ2 (as given in Fig. 1) plotted against the time of arrival relative to 0037 CST 12 August.

Table 1. Results of linear least square fits to determine the speeds of PJ1 and PJ2 at St. Louis. The data points are plotted in Figs. 4 and 5.

Event	Speed (km h^{-1})	Standard error of estimate (km)
PJ1	46.8	0.95
PJ2	49.8	2.1

release from station 141 at 2148 CST was inspected. If the reflections were from clouds formed at the top of a 750 m displacement, then, given the adiabatic cooling rate, the temperature should exceed the dew point by at least 7.5°C up to a level of about 2900 m. Fig. 9 presents temperature minus dew point as a function of height, and the critical level for saturation is indeed found at 2900 m. The lidar record illustrates two important facts. First, the vertical motion occupies a layer at least 4 km deep, likely much deeper. Second, the magnitude of the vertical displacements obviously could trigger precipitation in a conditionally unstable atmosphere of sufficient depth (Tepper, 1950). However, no precipitation was noted at the St. Louis airport, and the weather radar did not record echoes related in any clear manner to the PJL's.

Figs. 10 and 11 contain information on the vertical structure of the atmosphere from late evening radiosondes. The release prior to PJ1 was only minutes before arrival, although the radiosonde did not actually sense the disturbance. The release in Fig. 11 was nearly 3 h before arrival of PJ2 but, as will be seen from later PIBAL profiles, reflects the same wind structure as existed at the time of the event. On both nights a strong ground-based inversion extended through the first 1 km and was capped by a less stable, nearly adiabatic, layer extending to at least 3 km. RAPS upper air balloons were tracked to only a 3–4 km altitude. Nocturnal jets (Bonner, 1968) were dominant features before the arrival of the PJL's on both nights. Wind speeds at

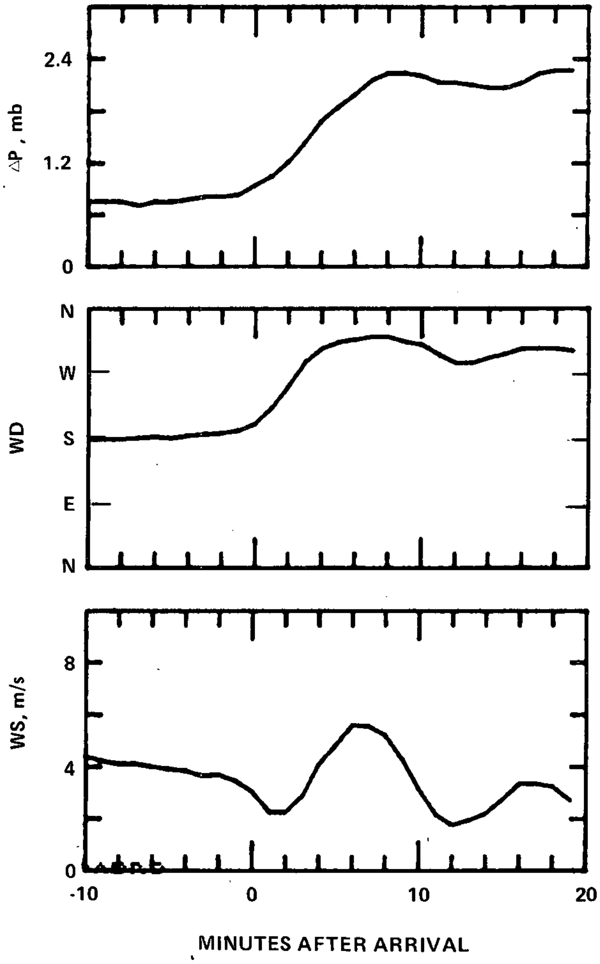

Fig. 6. Time series of wind and pressure formed as averages of data from all RAMS stations operative at the time of PJ1. Times are relative to local arrival.

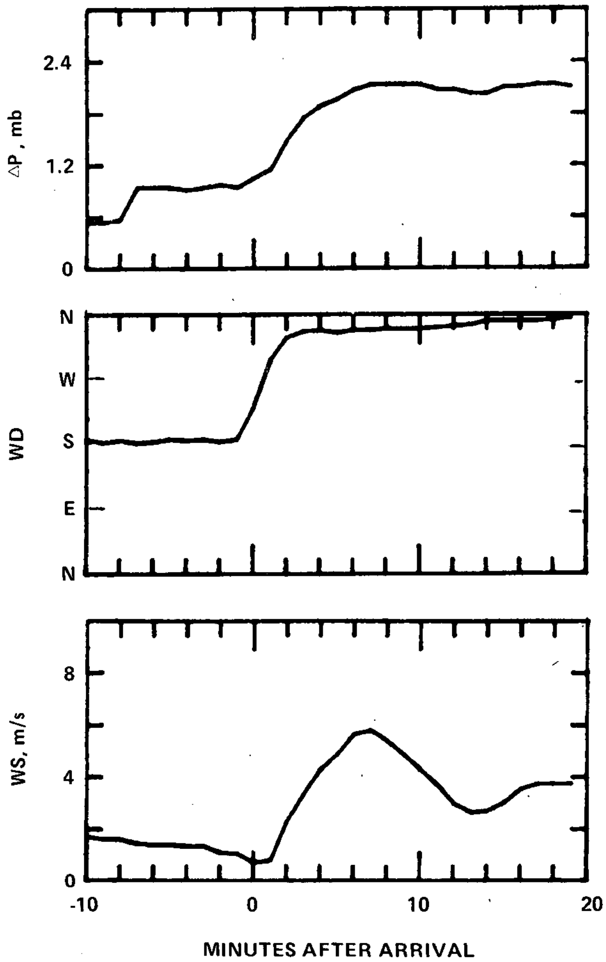

Fig. 7. As in Fig. 6 except for PJ2.

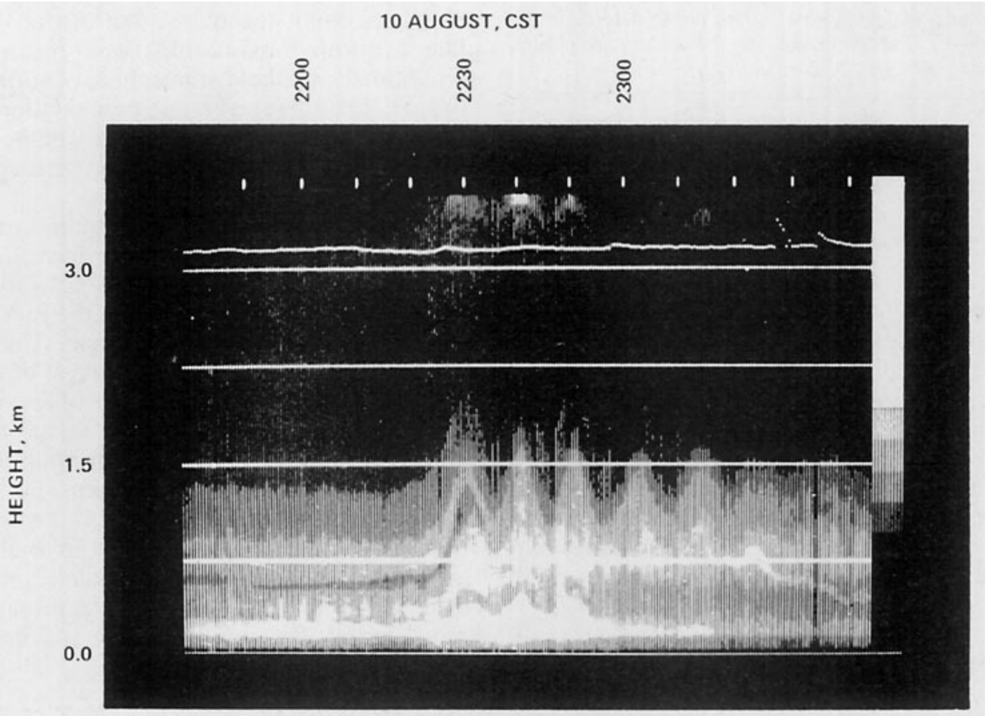

FIG. 8. Lidar record of PJ1, 10 August 1976.

the jet level and above were ~50% higher on the second night, and wind directions were comparable, moving from the south at the surface to west-southwest with height.

An interesting aspect of the passage of the PJL's was the coincident disruption of the nocturnal jet. Fig. 12 shows a sequence of pibal profiles taken before, during, and after the passage of PJ2. From releases near midnight (bottom row of Fig. 12) a maximum jet speed of 20–24 m s^{-1} was evident at ~500 m altitude. For the releases at about 0100 CST, PJ2 had not yet reached site 143, and the jet remained intact. PJ2 had arrived at site 144 about 20 min before the release; the jet was absent, and wind direction was altered through the lower 1 km. From speed and position information previously presented, it appears that the leading edge of PJ2 was within a few kilometers of both sites 141 and 142 at 0100 CST. From the shift in surface wind direction and the absence of a jet over 142, it is inferred that PJ2 arrived there just before release. The 141 release did not show wind direction changes, but the jet speed had decreased by 5 m s^{-1}, perhaps indicating the initiation of the disturbance. (Pibals rise through the first 1 km in ~5 min.) Finally, for the releases at about 0200 CST, the jet was absent at all sites, and the wind direction was still altered through the first 1 km. The clockwise rotation (veering) of the surface wind vector noted in Fig. 3 was restricted to a layer only ~200 m deep.

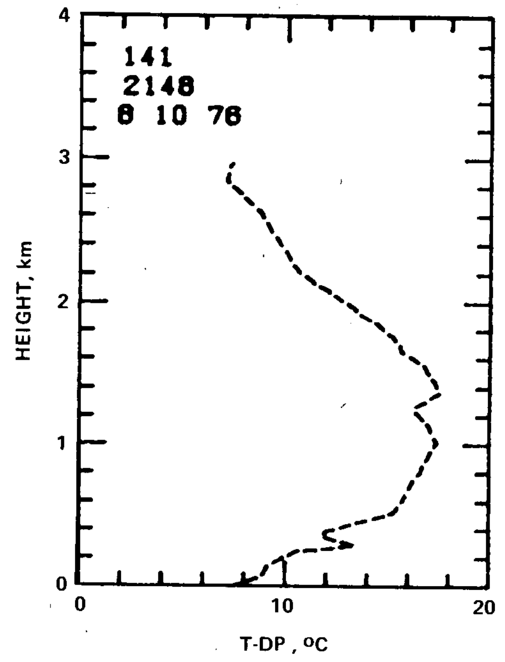

FIG. 9. Vertical profile of dew-point depression from a radiosonde release at site 141 just before PJ1.

It is clear from these pibal records that the nocturnal jet was destroyed at the time of PJ2 passage. Moreover, the destruction was rapid, constituting a turbulent collapse in a matter of several minutes. Indeed, the vertical exchange associated with the collapse is corroborated from RAMS records of ozone and temperature. Ozone concentrations of 70

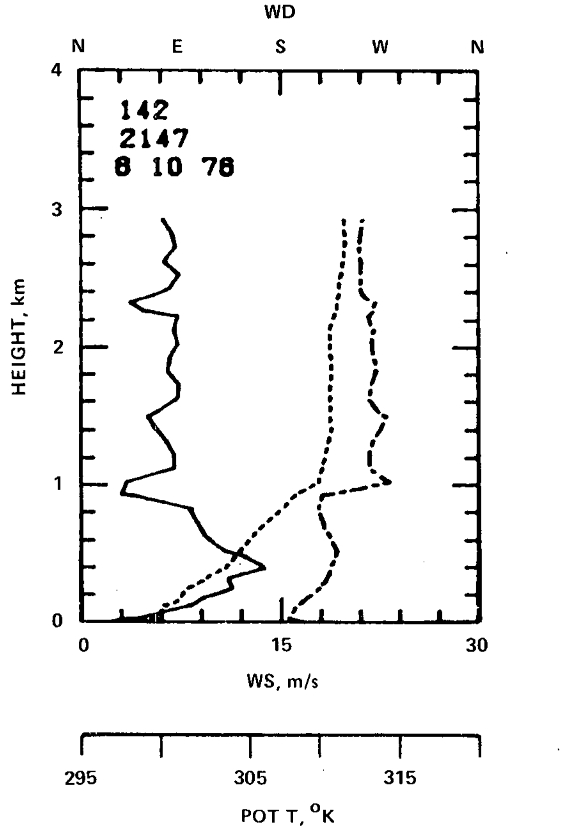

Fig. 10. Vertical profiles of wind speed (solid), wind direction (dot-dashed), and potential temperature (dotted) from radiosonde release at site 142 just before PJ1.

ppb are typically present at night over St. Louis, while close to the ground the pollutant is subject to depletion by dry deposition. Radiosonde profiles (Fig. 11) also indicate potential temperature increasing rapidly with height. Fig. 13 shows the ozone and temperature series at RAMS 122 at the time of PJ2 (compare with Fig. 3). Rapid increases occurred precisely at the arrival time. The rises in temperature and ozone were observed network-wide although the series presented are some of the best examples. Ozone is difficult to use as a tracer because of the presence of nitrogen oxides at most of the RAMS sites.

The jet also was eliminated with the passage of PJ1, but the effect was not as dramatic. From the ozone and temperature records, there is less evidence that the vertical exchange reached to the ground. It should be remembered that the jet was 50% stronger on the second night, and, therefore, contained more than twice as much mean kinetic energy. The likelihood of seeing an increase at a station would depend on the local strength of the inversion and the somewhat random intensity of the downward burst. From available records for PJ1, temperature increased at 11 stations, decreased at 3, and remained the same at 8. For PJ2, temperature increased at 17 stations, decreased at 3, and remained the same at 5. In most cases, increases were abrupt, while in no case was a decrease abrupt. Therefore, the evidence is overwhelming that surface temperature tends to increase with the passage of these phenomena.

3. Synoptic observations

The surface synoptic situation for 10–12 August 1976 may be summarized as follows. A weak, nearly stationary cold front aligned NE to SW remained to the west of Missouri and crossed through Iowa and Minnesota. By 0300 (all times CST) on 12 August, the National Meteorological Center surface map indicated frontolysis for this feature, and a moderate cold front had penetrated into the extreme northern portion of Minnesota and North Dakota. A large anticyclone covered the eastern part of the United States and southeastern Canada with south-southeast flow near the surface over Missouri for most of the period.

Turning to the infrared GOES satellite views, we see that at 1500 on 10 August (Fig. 14a) clouds were situated along the front. By 1630 (Fig. 14b), a bright, nearly circular cloud element had appeared over

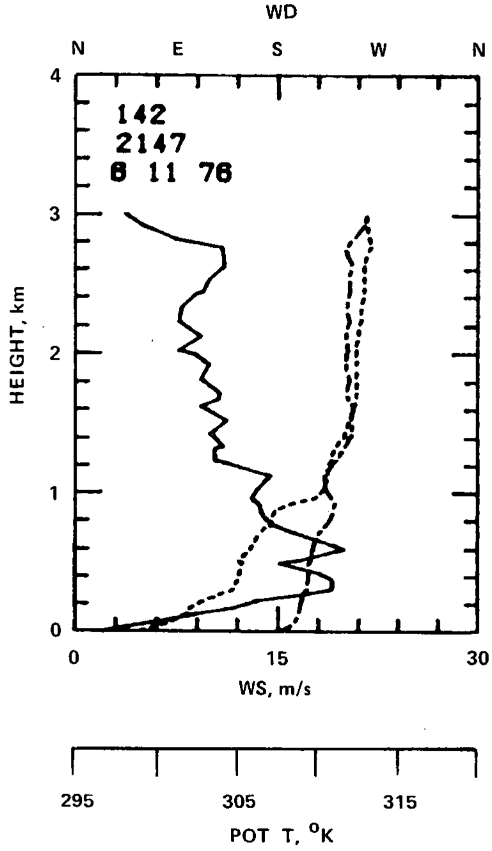

Fig. 11. As in Fig. 10 except from radiosonde release at site 142 ~3 h before PJ2.

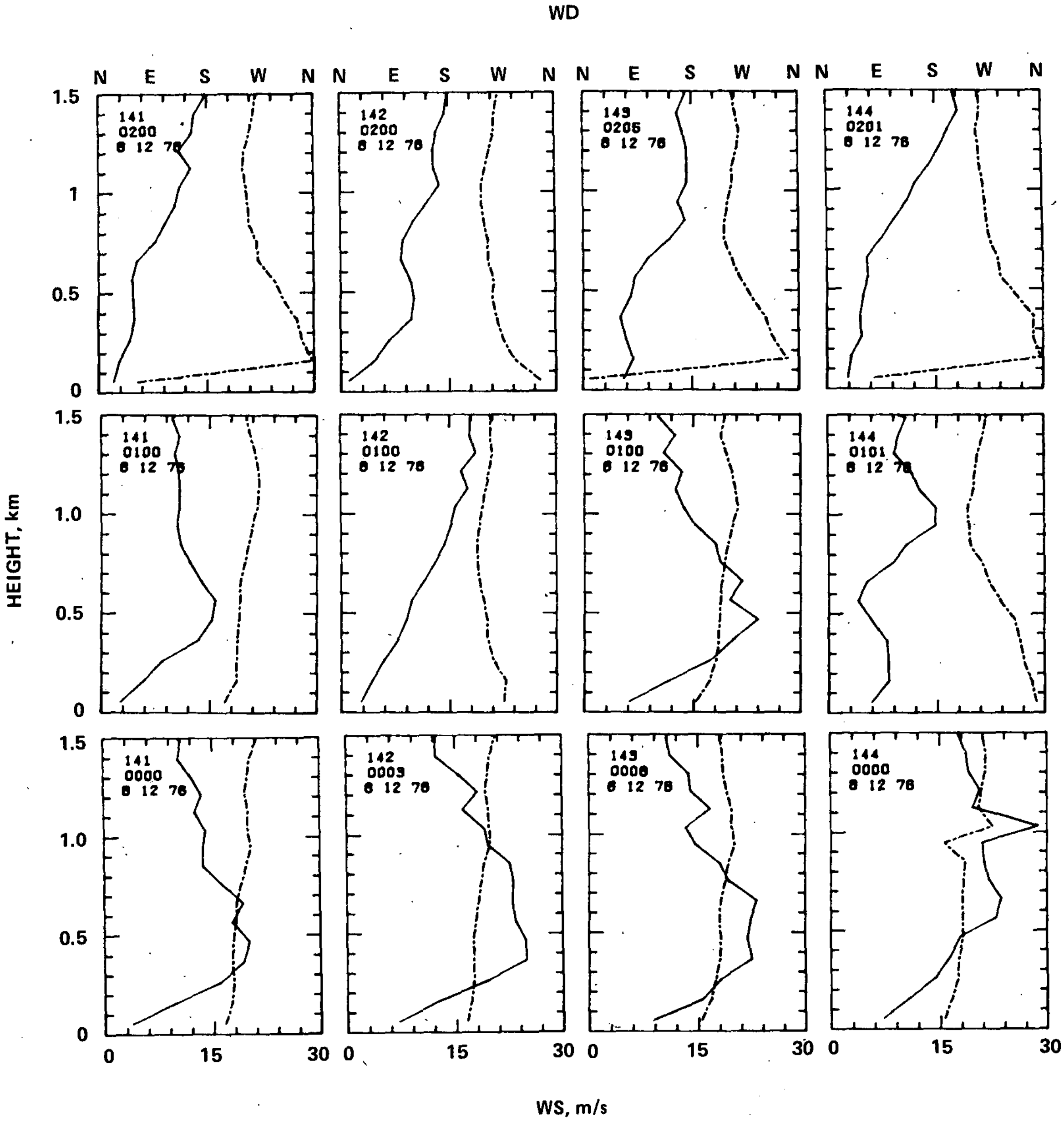

FIG. 12. Vertical profiles of wind speed (solid) and wind direction (dot-dashed) from pibal releases at sites 141–144 near 0000, 0100 and 0200 CST 12 August 1976. This series illustrates the impact of PJ2 on the nocturnal jet.

southeastern Iowa, and it enlarged rapidly during the next hour. The data from National Weather Service (NWS) stations located beneath this feature show rainshower and thunderstorm activity. By 1900, the cloud mass was more diffuse with its southern boundary reaching to the St. Louis region. The situation on the afternoon of 11 August was similar, with a bright cloud element first appearing in northern Iowa at 1400 (not shown). Although other thunderstorm centers were visible on the two afternoons, notably in northern and northwestern Missouri, those over Iowa were positioned so as to be likely initiators of the observed PJL's. While the infrared images show clouds over St. Louis on both nights, post-midnight WBAN remarks of "moon visible" indicate the cover was very thin.

Tables 2 and 3 show the passage times of PJ1 and PJ2 at available NSW stations. Fig. 15 indicates the approximate leading edges of each PJL relative to the station network as well as the centers of thunderstorm activity visible from the satellite views. No curvature of the PJL could be detected from these data and so none is indicated. Particularly for PJ2, rain and thunder were coincident with the passage

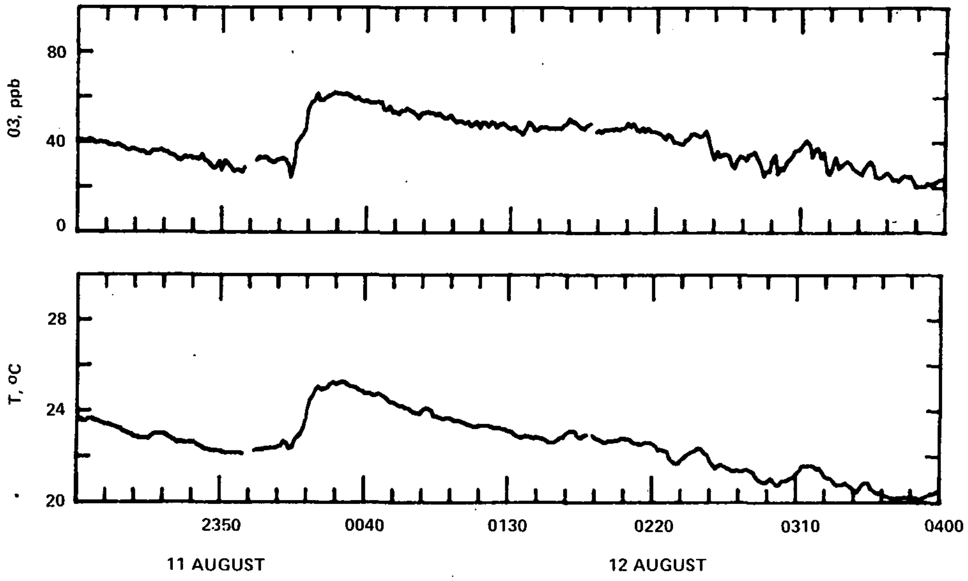

FIG. 13. Time series of temperature (*T*) and ozone (O_3) concentration for passage of PJ2 as recorded at RAMS 122.

at stations north of St. Louis, and this lends support to Tepper's (1950) concept of squall activity associated with the PJL. The average speeds for transit of the PJL's from Quincy, Illinois (UIN), to St. Louis, Missouri (STL), to Cairo, Illinois (CIR), are shown in Table 4. Considering the uncertainties inherent in routine synoptic data, these speeds agree remarkably well with those inferred from the RAMS in St. Louis and presented in Table 1.

Only one station, Kirksville, Missouri (IRK), recorded a pressure jump (PJ1) before the local sunset of about 1900 CST. That record is also unique because it is the only one which shows a sharp temperature drop; in the hour bracketing PJ1, the temperature fell from 35 to 23°C. The event as seen in IRK was likely in its earliest stages, as a severe thunderstorm gust front (Charba, 1974) and not yet as a freely propagating wave. The observation is consistent with the notion that a gust front initiates the wave. The gust front must remain intact long enough to bridge the gap between afternoon convective activity and the formation of the nocturnal inversion, upon which the wave propagation might be assumed to depend.

4. Speculation on the nature of the PJL phenomena

At first glance, the records of pressure and winds shown in Figs. 2 and 3 seem indicative of a density current. Such currents probably were generated in the afternoon thunderstorms. However, the increases in surface temperature at PJL passage do not easily fit this explanation, and the long distances involved are highly unusual in the context of other reports concerning density currents (Charba, 1974). Upon arrival at St. Louis, the disturbances had traveled some 300–500 km (6–10 h) from the centers of storm activity and, if they were density currents, would have long since lost their energy source. Also, if the observations reflect an actual flow of mass, the wind speed should approximate the speed of the PJL. The surface speed spikes as seen in Figs. 6 and 7 reach only ~6 m s^{-1}. Furthermore, the station 144 pibal release at 0101 CST seen in Fig. 12 shows wind shifted to the direction of PJ2 approach but only at a speed of 6–8 m s^{-1}. These values compare with a speed of ~13 m s^{-1} for both PJL's. Considering all data available, the density-current hypothesis is highly improbable.

As an alternative explanation, we propose that the observations are indicative of internal bores, and thus the PJL phenomena reported here are similar in nature to the morning glory observed in northern Australia (Clarke, 1972; Clarke *et al.*, 1981). The data of Clarke show the Morning Glory produces similar effects—a sudden pressure jump followed by a sustained period of high pressure with wavelike undulations, an increase in surface temperature, change in wind direction to the direction of approach, and propagation over long distances. The pressure observations of Christie *et al.* (1979) also may represent internal bores. Their report of only minor perturbations in the surface flow field would seem at variance with that conjecture, although their location may have had very strong nocturnal inversions which prevented involvement of the near-surface winds.

According to Clarke (1972), the Morning Glory is produced when katabatic drainage winds lead to an

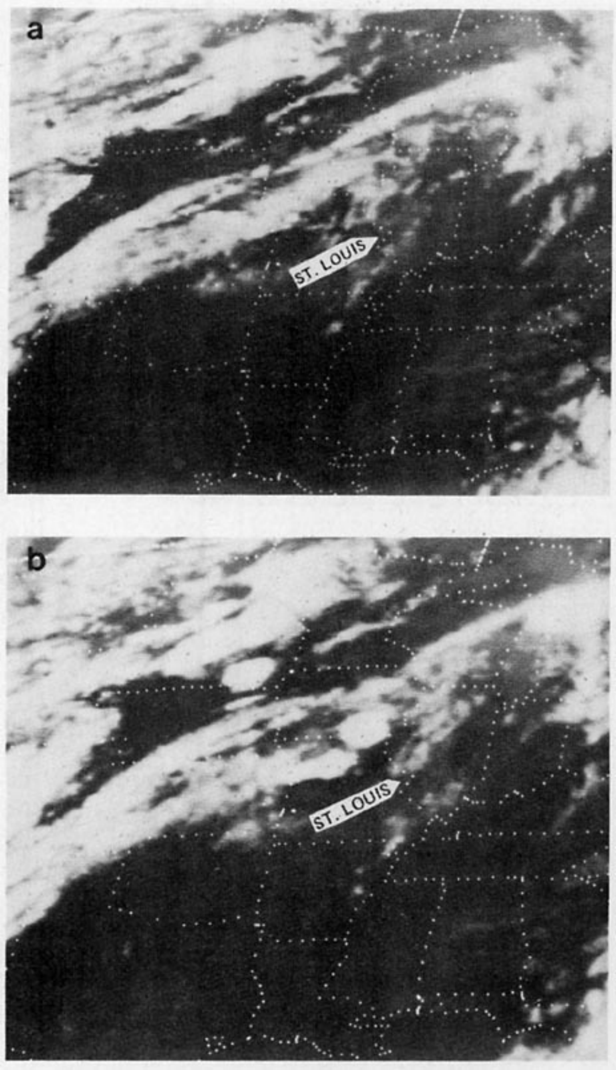

FIG. 14. GOES infrared views, 10 August 1976: (a) 1500 CST, (b) 1630 CST.

accumulation of air at the base of a highland and a consequent formation of a hydraulic jump. While dismissing katabatic effects over the flat terrain of Iowa and northern Missouri, there, nevertheless, were two flow features on which the origin of the PJL events could depend. First, thunderstorm activity was undeniably linked in some manner to the PJL's, and outflows moving to the southeast could be an important factor. Second, low-level winds at St. Louis had a significant component into the advancing PJL's on both nights, and this situation may have existed over an extensive area to the northwest. From balloon profiles taken before PJ1 and PJ2, the winds at jet maximum were oriented 12 and 26°, respectively, into the PJL's. Angles were larger at all lower levels, reaching ~50° at the surface. We deem it plausible that thunderstorm outflow and opposing low-level winds involving the nocturnal jet could lead to an accumulation of air from the lower 500 m and produce a propagating hydraulic jump, in much the same manner as that proposed by Clarke (1972).

Having described the possible origin of the PJL's, we now turn our attention to subsequent interaction between the propagating bore and nocturnal jet. Fully recognizing that the atmosphere as given by profiles in Figs. 10 and 11 is not amenable to treatment as a two-layer system of fluids of constant densities, we will proceed, nevertheless, with some simple calculations that bring the discussion into focus. Fig. 16 depicts a bore (hydraulic jump) moving left to right with speed U. The lower layer fluid has heights h_1 and h_0 with speeds u_1 and u_j on the left and right, respectively. The speed u_j is introduced as the component of the nocturnal jet directed into the advancing bore. If the jet were an ordinary mean flow, then u_j could be subtracted out of the system, and calculations could proceed as if the bore were moving into still fluid. But the jet is not an ordinary mean flow. The tendency for the jet to collapse in turbulence is present because of the sharp speed gradient, and the jet would probably not survive an encounter with the PJL. (Using various lower portions of the radiosonde profiles on the two nights, gradient Richardson numbers of 0.15 to 1 have been calculated.) Following the discussion of Lighthill (1978), the linear theory of bores is based on conservation of mass

TABLE 2. Summary of synoptic observations for PJ1, 10–11 August. Information was derived from barograms, triple registers, and WBAN's. An asterisk indicates the pressure rise was less than abrupt (taking up to 20 min).

Site	Time (CST)	PJ (mb)	Time (CST)	Windshift	Observations and comments
IRK	1720	2.7	1725	S → NW	TRW, T SW-N MOVG ENE
UIN	1852	1.4	1926	SSE → SW	T, LTG SW-NE MOVG E
SPI	2045	0.7*	2134	S → SW	
COU	2100	0.7*	2056	SW → W	T NW-N MOVG E
DEC	2120	0.7			
STL	2155	1.4	2155	SE → W	
EVV	0155	0.7	0155	SE → NW	
CIR	0240	0.7			
PAH	0300	0.7			

TABLE 3. Summary of synoptic observations for PJ2, 11–12 August (as given in Table 2).

Site	Time (CST)	PJ (mb)	Time (CST)	Windshift	Observations and comments
OTM	1930	3.4			TRW, T OVHD MOVG E
MLI	2013	1.4	2015	S → W	TRW, T E-SE MOVG E
IRK	2033	3.4	2030	S → NW	T OVHD
UIN	2205	1.4	2200	S → NNW	TRW, T ALQDS MOVG NE
COU	2300	1.4*	2308	S → NW	RW
SPI	2330	2.0	2330	SW → NW	TRW, T OVHD MOVG ESE
DEC	0000	2.7	0031	SSW → NW	TRW, T OVHD MOVG SE
STL	0040	1.0	0046	SW → NW	
CIR	0510	1.0			

$$\rho(U - u_j)h_0 = \rho(U - u_1)h_1 \qquad (1)$$

and momentum

$$\rho(U - u_j)h_0(u_1 - ru_j) = \tfrac{1}{2}\Delta P h_1. \qquad (2)$$

The factor $0 \leq r \leq 1$ is the proportion of the jet momentum that remains behind the PJL. The use of the observed ΔP obviates the need to deal directly with the varying density and to employ the hydrostatic assumption. Solving for u_1 in (1) and substituting in (2) yields a quadratic equation in U. Approximate parameters based on the St. Louis data are $h_0 = 500$ m, $h_1 = 1250$ m, $u_j = -5$ m s^{-1} and $\Delta P = 1.5$ mb. Results of some test cases are given in Table 5. The computed speeds are in basic agreement with the observed $U = 13$ m s^{-1} and $u_1 = 6$–8 m s^{-1}. Tests show relative insensitivity to h_0/h_1 in the solutions. Although it only may be a mathematical curiosity, the equations predict that U increases as the opposing jet increases for $r = 0$ and $h_0/h_1 > 0.5$.

If the PJL is a line separating a region with a jet from a region without a jet, as the data indicate it is, then the PJL represents a line of horizontal conver-

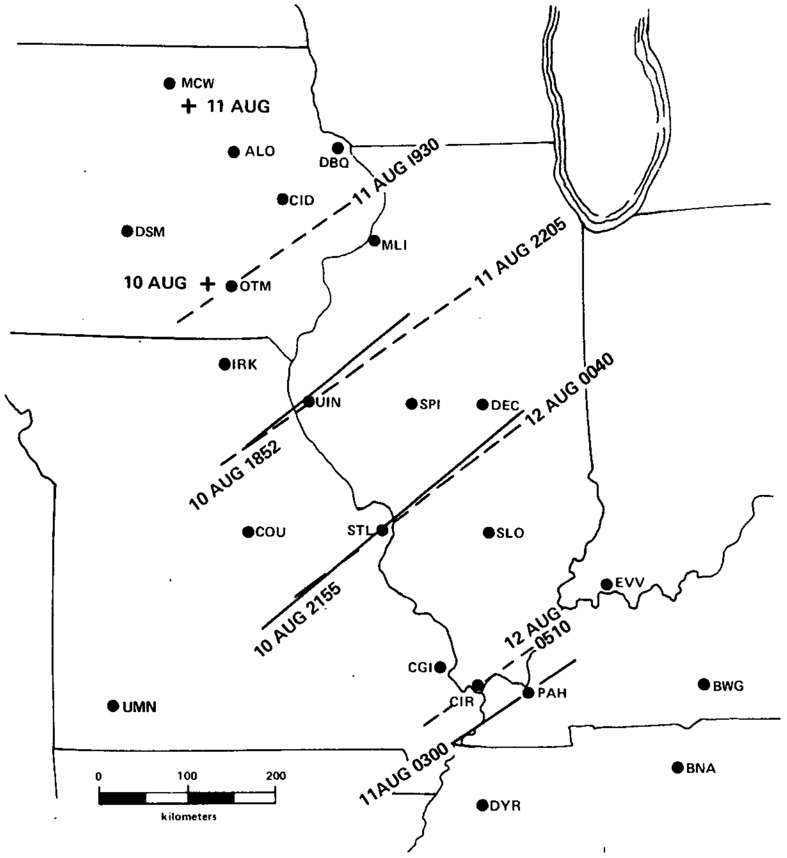

FIG. 15. Map of the upper Midwest showing NWS stations, approximate positions of the PJL's, and the centers (marked by crosses) of strong thunderstorm activity in Iowa on the afternoons of 10 and 11 August.

TABLE 4. Average speeds of PJ1 and PJ2 inferred from synoptic data.

Sites	Separation (km)	Average speeds (km h^{-1}) PJ1	Average speeds (km h^{-1}) PJ2
UIN-STL	149	48	57
STL-CIR	222	44	50
UIN-CIR	371	47	52

TABLE 5. Speeds of the bore (U) and the air behind the bore (u_1) based on mass and momentum principles given by Eqs. (1) and (2).

u_j (m s^{-1})	r	U (m s^{-1})	u_1 (m s^{-1})
0	0	16.1	9.7
−5	0	15.8	7.5
−5	0.5	13.4	6.0
−5	1	11.1	4.7

gence and upward motion. This conclusion holds without regard to the existence of the bore. The role of the bore is to trigger the collapse of the jet, and this could be accomplished by forcing turbulent fluid (from the previously encountered jet) into the jet, where high Reynolds stresses act on the steep speed gradient to transform mean to turbulent kinetic energy. Therefore, there is a tendency for the jet to perform work, adding potential energy along the PJL, which is normally the province of the bore alone, and, in doing so, the jet may reinforce the bore. The net effect is not clear, however. For instance, the creation of high levels of turbulence also may drain energy from the system.

Finally, we note that the characteristics of the PJL and jet were by no means unusual on the two nights in question. Williams (1953) compiled data on waves of elevation (including but not limited to PJL's) in the Midwest and found mode direction as 320–329° and mode speed as 48–54 km h^{-1}. Bonner (1968) found the most frequent jet direction to be from the southwest during the summer. The essence of our proposal on PJL origin implies that these preferred orientations are related in a direct manner.

5. Concluding remarks

The primary purpose of this paper is to fully document the data on two PJL's which passed St. Louis on successive nights in August 1976. This study offers some new insights into the PJL, particularly because of the availability of detailed upper air data and satellite photographs. These PJL's clearly owed their origin to, and moved outward from, areas of strong convective activity along a stationary front. Vertical displacements of 750 m were seen through the lower 4 km at St. Louis. The upward displacements were associated only with cloud formation at St. Louis, while thunderstorms were reported at many NWS stations along the line.

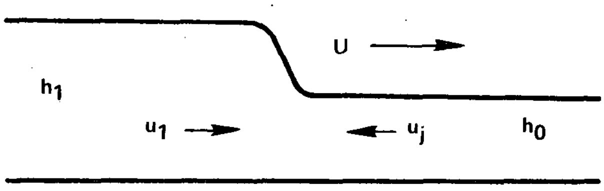

FIG. 16. Schematic of a bore moving left to right at speed U.

The PJL appears to be indicative of an atmospheric bore which maintains its abrupt leading edge while propagating hundreds of kilometers through the nocturnal boundary layer. The passage of each PJL at St. Louis was coincident with the turbulent collapse of the nocturnal jet. As outlined in this paper, we speculate that the jet plays a role in the origin of the bore and could be a significant factor in its energy budget as well.

The present study was initiated specifically to search for evidence of vertical exchange in the nocturnal boundary layer. RAMS records were plotted for each nighttime period in July–August 1976. Evidence for vertical exchange in terms of increases in surface ozone and temperature was spotty and somewhat disappointing. There were occasional increases involving single stations which may indicate isolated, local disruptions of the jet. Certainly the PJL's discussed here were by far the most interesting occurrences, and they were the only such events recorded during the two months.

Acknowledgments. A great many scientists and technicians contributed to the success of the RAPS program. R. Jurgens, G. Smiley and D. Coventry were largely responsible for the archiving of the RAMS data. J. K. S. Ching, J. F. Clarke and J. M. Godowitch made helpful contributions to this study. We thank R. E. Eskridge for reviewing the manuscript. Cecil Winstead prepared the illustrations.

APPENDIX

Individual Pressure Traces

The RAMS pressure network was not designed for study of small pressure fluctuations. The barographs had an intended resolution of 0.27 mb, but it seems clear that this resolution was not routinely maintained under field conditions. Figs. A1 and A2 show the available pressure traces from PJ1 and PJ2, respectively (one station was missing on each night). The tendency of the sensors to "stick" in place and not record minor fluctuations is evident. The choice of the individual records displayed in Figs. 2 and 3 was based on several considerations. There was a need to have complete records of winds and pressure over

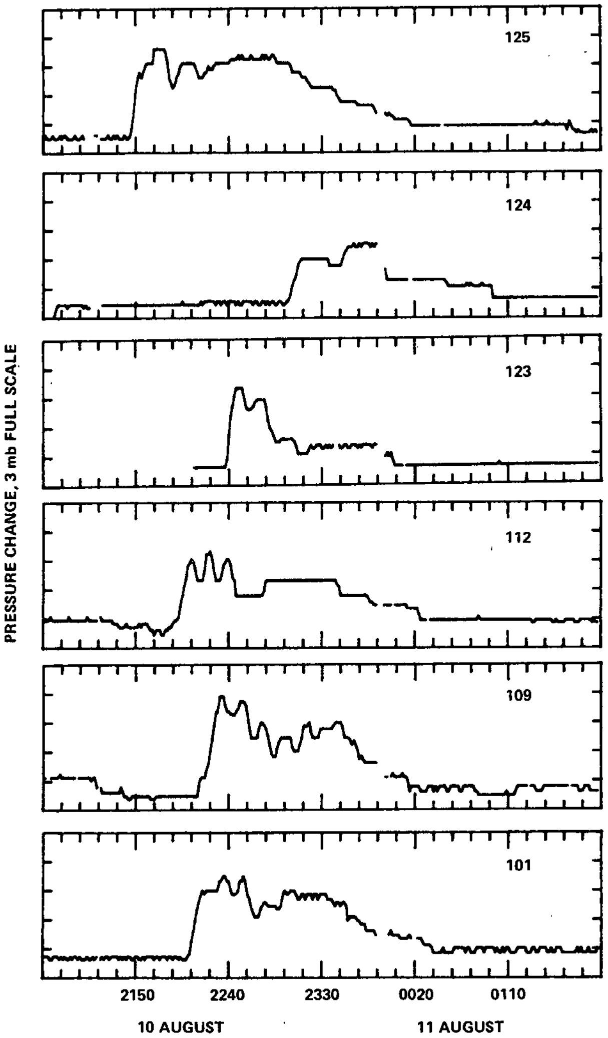

FIG. A1. Time series of pressure at each available RAMS station (indicated on figure) during PJ1. The full vertical scale for each trace is 3 mb.

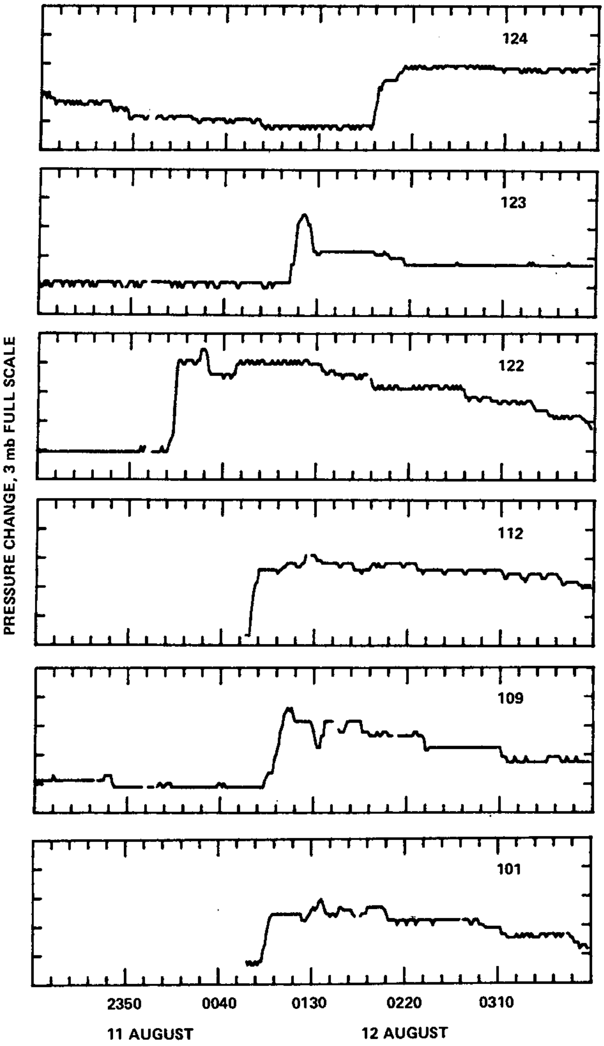

FIG. A2. As in Fig. A1 except during PJ2.

the entire period, with the pressure sensor appearing to work up to designed resolution. The wind records were usually of good quality. For PJ2, the availability of the excellent traces showing ozone and temperature increases at site 122 was the determining factor in the choice of that station. Unfortunately, station 122 did not have a pressure trace for PJ1, so the choice of another rural station (109) was made. The accuracy of the pressure traces precludes using these data to make inferences about the changes in wave form across or with the direction of propagation. The traces do indicate, however, that PJ1 was undular in nature while PJ2 was not.

REFERENCES

Bonner, W. D., 1968: Climatology of the low-level jet. *Mon. Wea. Rev.*, **96**, 833–850.

Charba, J., 1974: Application of gravity current model to analysis of squall-line gust front. *Mon. Wea. Rev.*, **102**, 140–156.

Christie, D. R., K. J. Muirhead and A. L. Hales, 1979: Intrusive density flows in the lower troposphere: A source of atmospheric solitons. *J. Geophys. Res.*, **84**, 4959–4970.

Clarke, R. H., 1972: The morning glory: An atmospheric hydraulic jump. *J. Appl. Meteor.*, **11**, 304–311.

——, R. K. Smith and D. G. Reid, 1981: The morning glory of the Gulf of Carpentaria: An atmospheric undular bore. *Mon. Wea. Rev.*, **109**, 1730–1754.

Lighthill, J., 1978: *Waves in Fluids.* Cambridge University Press, 504 pp.

Schiermeier, F. A., 1978: RAPS field measurements are in. *Environ. Sci. Tech.*, **12**, 644–651.

Tepper, M., 1950: A proposed mechanism of squall lines: The pressure jump line. *J. Meteor.*, **7**, 21–29.

Uccellini, L. W., 1975: A case study of apparent gravity wave initiation of severe convective storms. *Mon. Wea. Rev.*, **103**, 497–513.

Uthe, E. E., 1978: Remote sensing of aerosol properties using lasar radar techniques. Optical properties of the atmosphere. *Proc. Soc. Photo-Opt. Instrum. Eng.*, **142**, 67–77.

Wagner, A. J., 1962: Gravity wave over New England, April 12, 1961. *Mon. Wea. Rev.*, **90**, 431–436.

Williams, D. T., 1953: Pressure wave observations in the central Midwest. *Mon. Wea. Rev.*, **81**, 278–289.