Historical Perspective on the Research and Operational Application of Weather-Significant Gravity Waves

Dr. Louis W. Uccellini
Director, National Weather Service
NOAA Assistant Administrator for Weather Services

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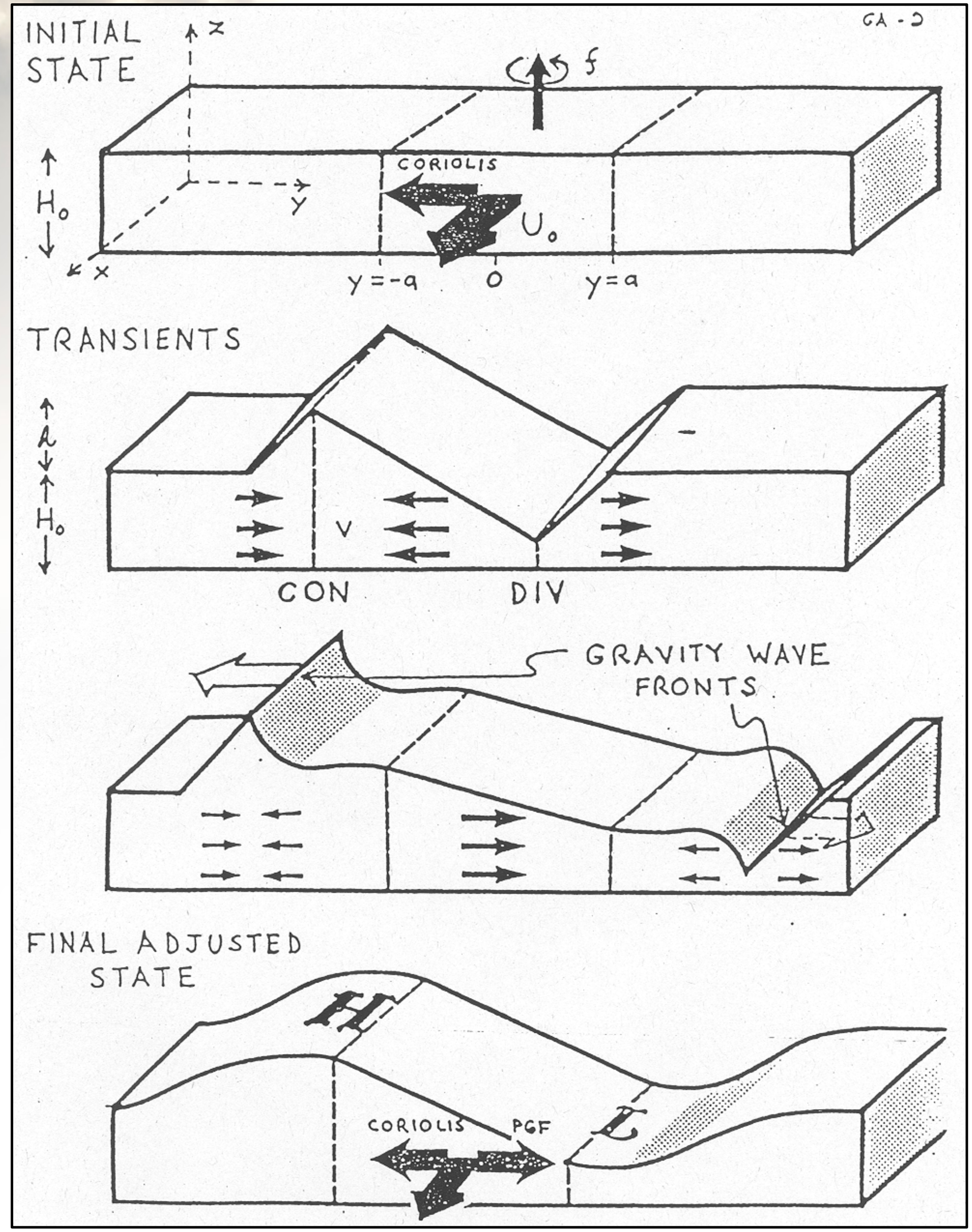
Outline

- Historical overview (1940s-1950s)
- Gravity wave research reemerges (1970s-1980s)
  - 2-4 hour 400-500km wavelength gravity waves exist!
  - Large scale gravity waves can initiate convective storms (Uccellini, 1975)
- Spectrum of atmospheric mass-momentum adjustment to unbalanced flow: From cyclones to gravity waves
- Who gets lost in the shuffle (and certainly deserves recognition)
- Concerns and opportunities
- Summary

Historical Overview (1940s-1950s)

1940s

- Interest in larger scale gravity waves limited to inertial-gravity wave concepts generated by an initial unbalanced flow (Rossby, 1938)
- Transient solution (Cahn, 1945)



An Early Look at a Large-Scale Pressure Pulsation

- Brunk (1949) investigated a singular wave associated with thunderstorm system

THE PRESSURE PULSATION OF 11 APRIL 1944

By Ivan W. Brunk

U. S. Weather Bureau, Chicago

(Manuscript received 17 July 1948)

"The pressure pulsation is shown to be an exceptional case of a phenomenon which is frequently overlooked, and about which as yet our knowledge of the physical process involved is very incomplete."

Surface Pressure and Wind Characteristic of the Brunk Pressure Pulsation

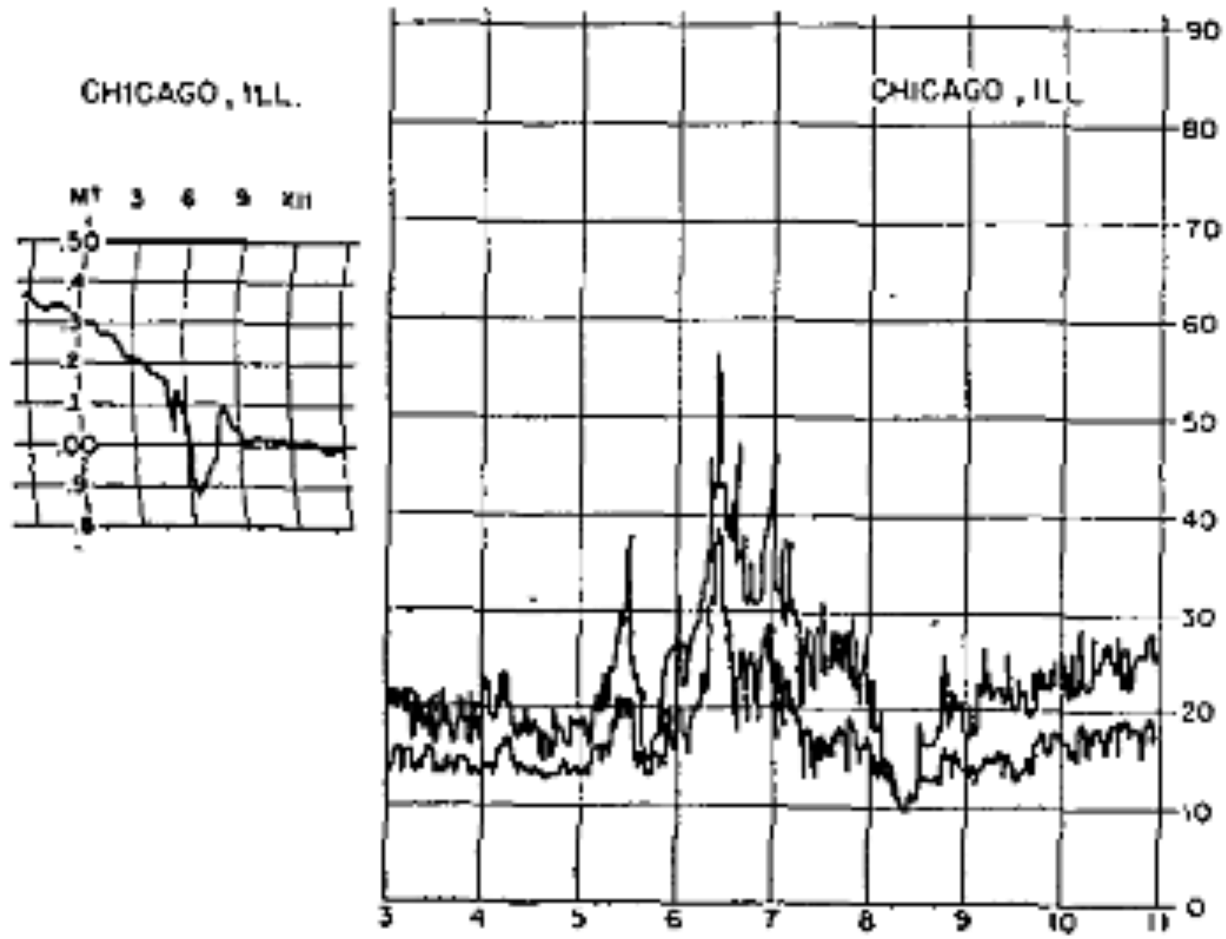


FIG. 3. Barograph record and outline of Dines pressure-tube anemometer record at Chicago 11 April 1944 (CST).

Brunk, 1949

Relationship of the Mesoscale Event to the Synoptic Surface Features

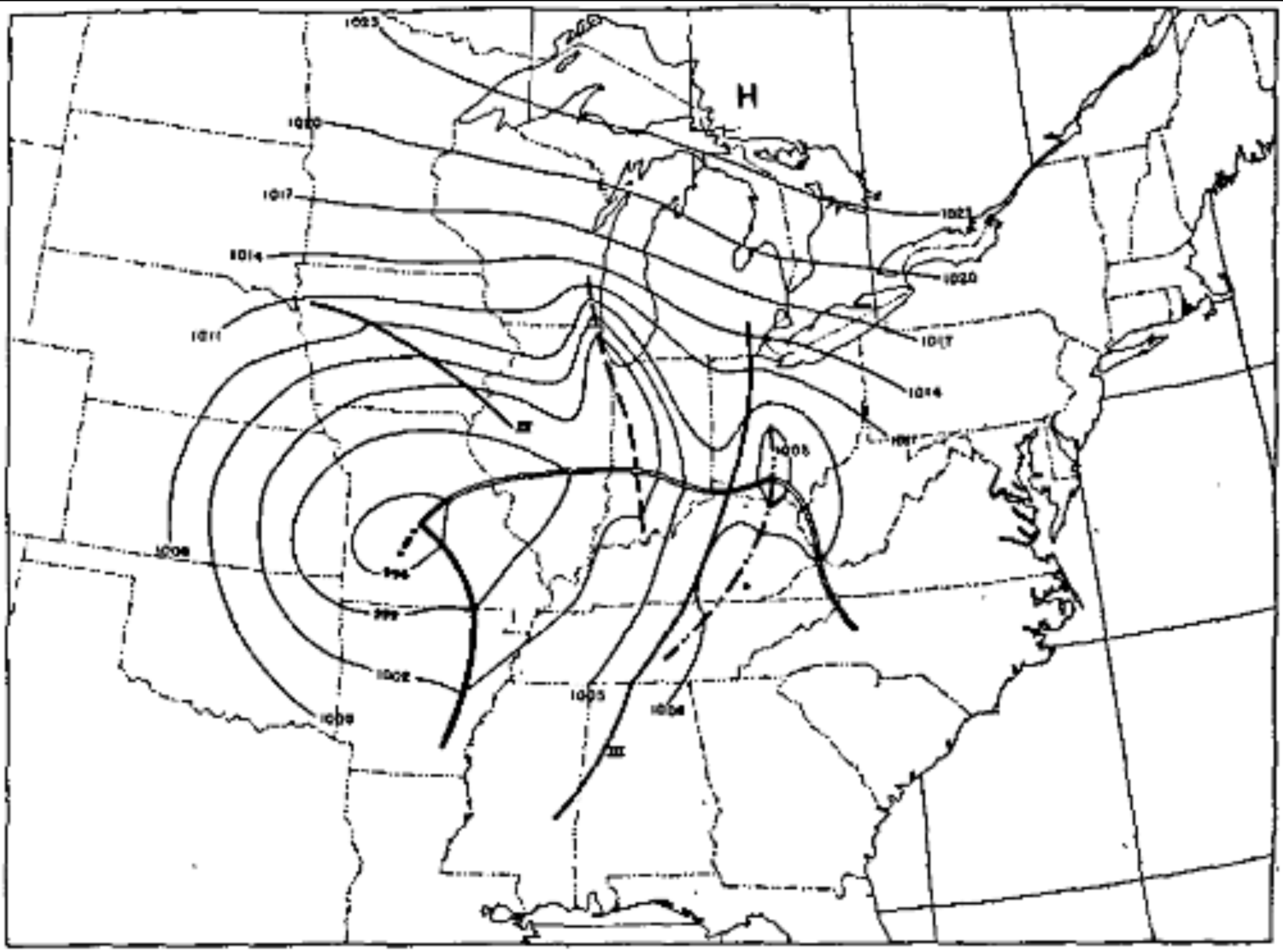
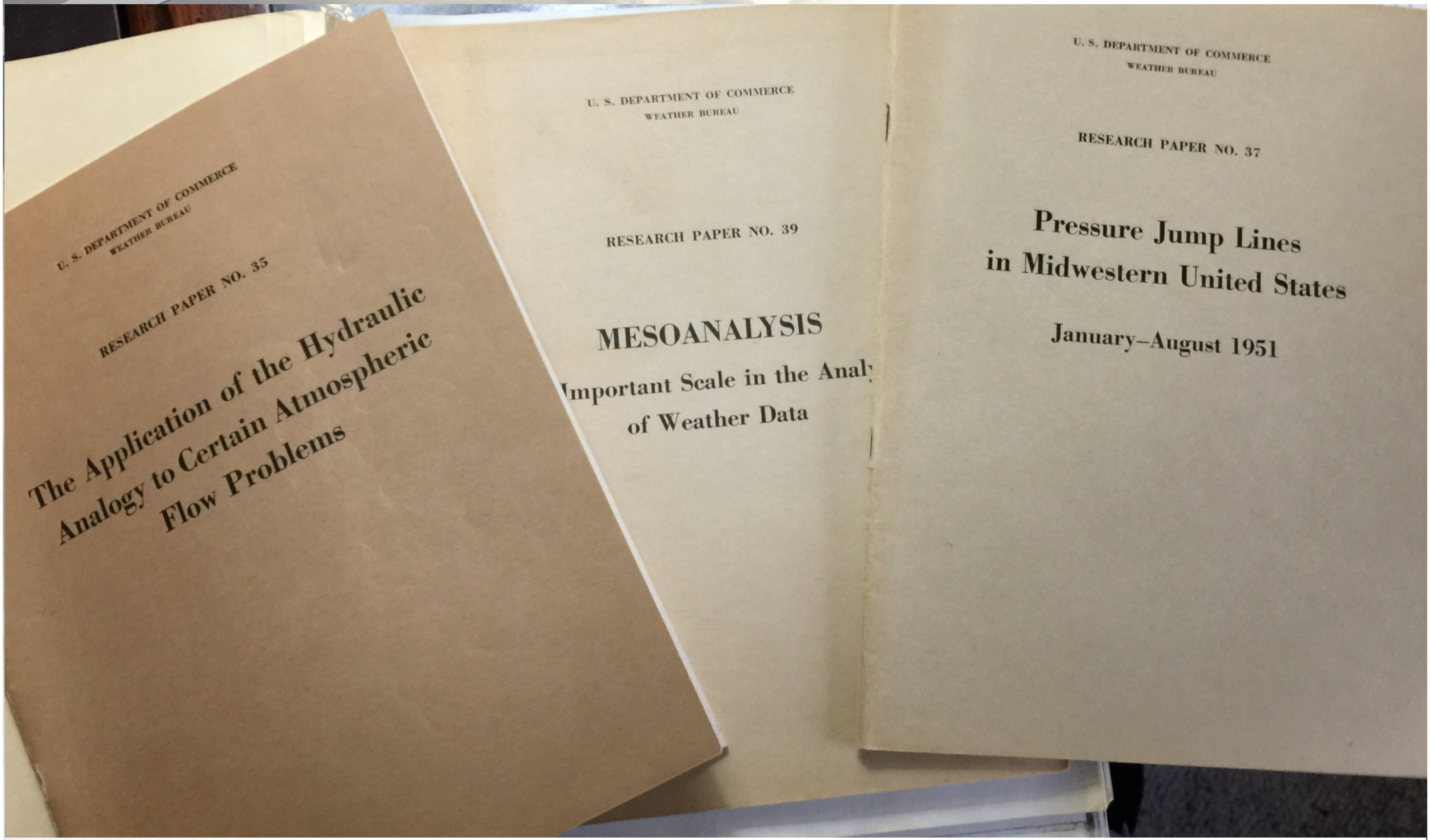


FIG. 4. Enlarged section of surface map, 0630 CST 11 April 1944.

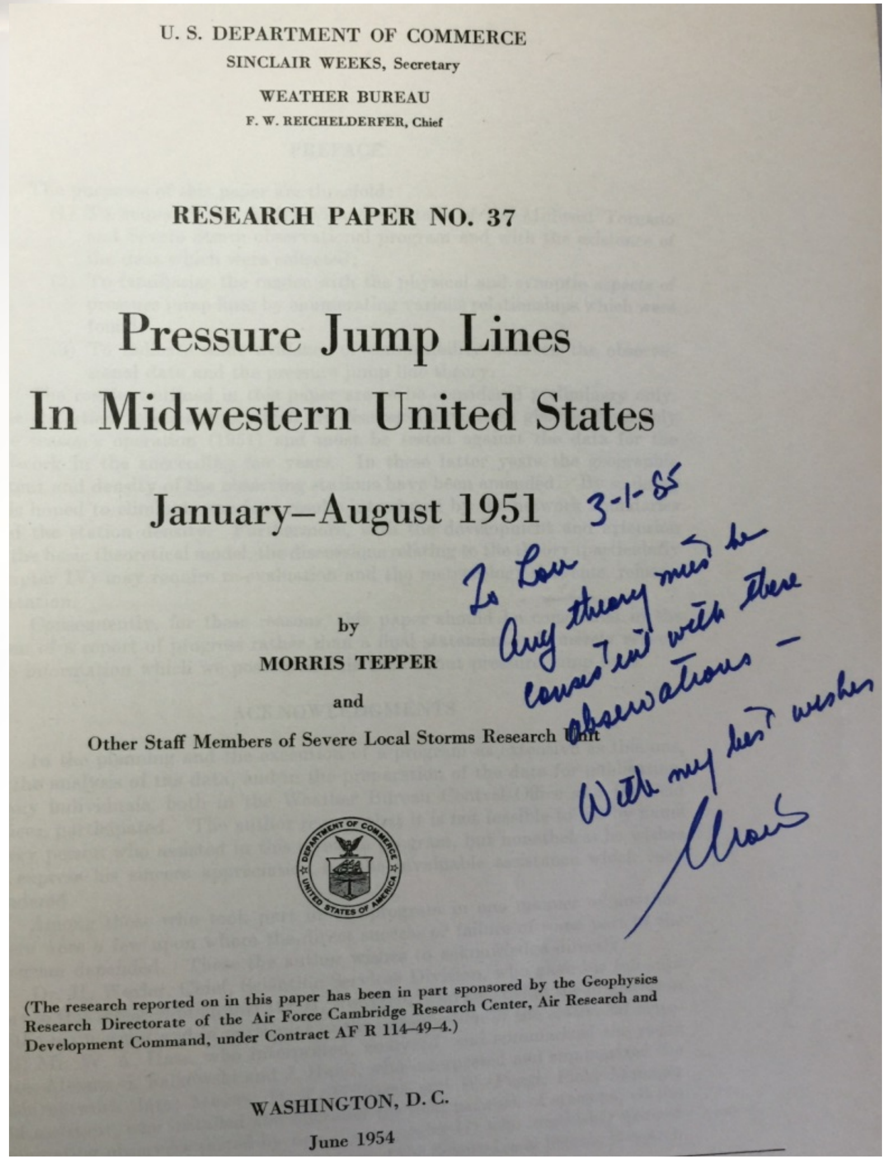
Brunk, 1949

The Influence of Morris Tepper



Morris Tepper

- Mesocale analysis
- Theoretical framework for pressure jumps
- Design and implementation of a field program



The "Pressure Jump" Singular Wave

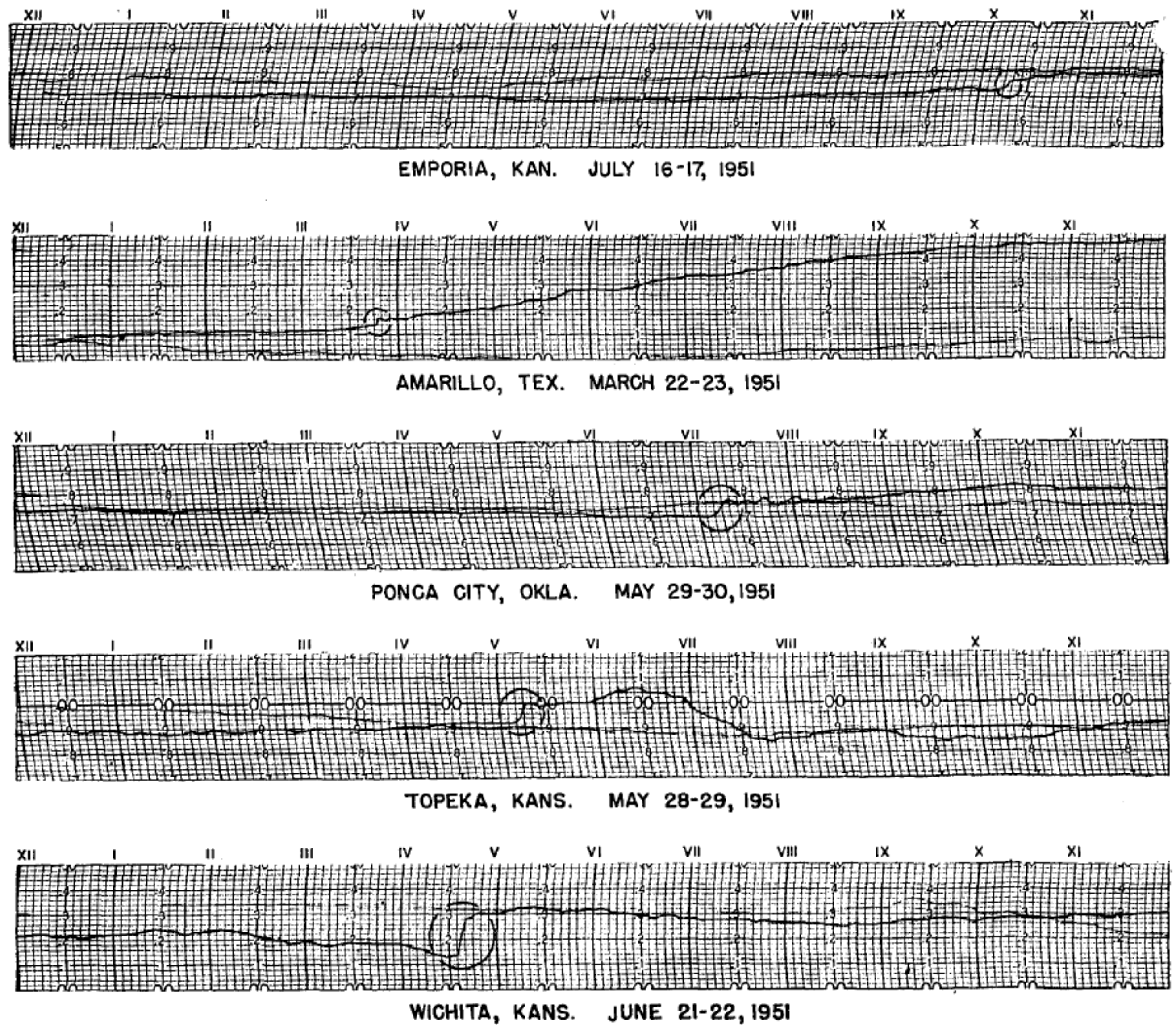


FIGURE 3.—Sample microbarograms of pressure jumps recorded on high speed microbarographs (one revolution every 12 hours). Time interval between two vertical thin lines is 5 minutes.

Tepper, 1954

- Pressure jump lines can be tracked over hundreds of kilometers
- A number of these pressure jumps were initially dry
- Pressure jumps were later associated with thunderstorms

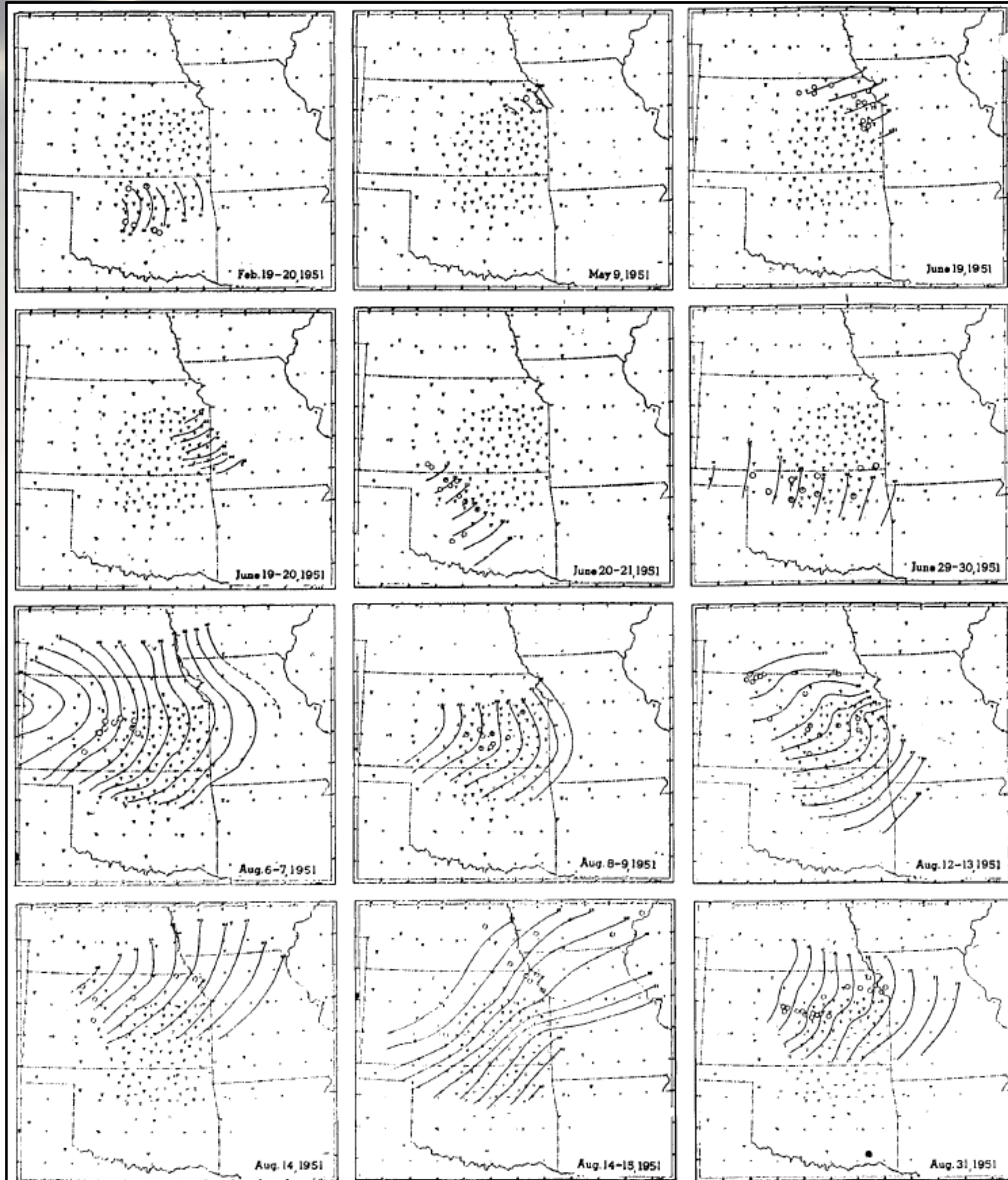
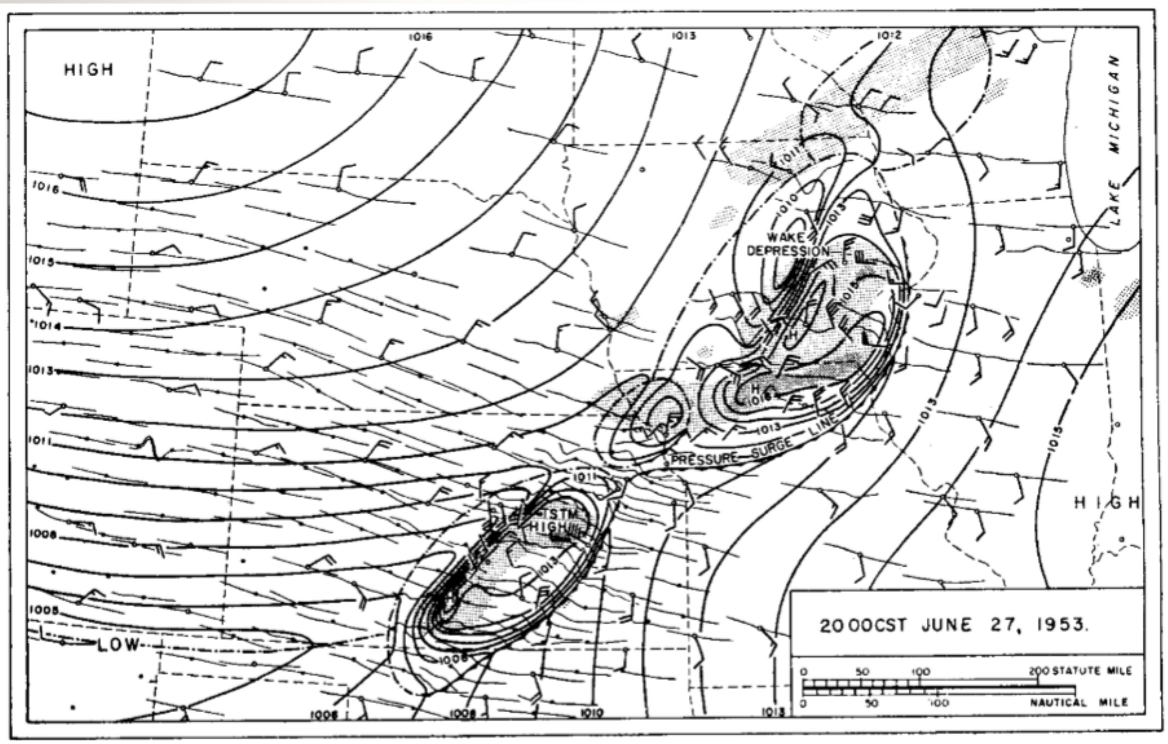


FIGURE 5.—Examples of pressure jump lines. Curves are hourly isochrones. Large open circles are reports of severe local storms.

Tepper, 1954

Fujita Shuts Down Tepper and Interest in Large-Scale Gravity Waves

- Ted Fujita widely known for mastering the mesoanalysis of the thunderstorm environment
- Diagnosed the "thunderstorm high"
- He then took aim at Tepper



Fujita, 1955

Fujita Takes Aim at Tepper

"The intense system of storms was initiated *before* a pressure-surge line was organized. This suggests the futility of seeking a trigger mechanism in the pressure field at the initial stage."

– Fujita, 1955, page 435

Gravity Wave Research Reemerges (1970s-1980s)

- 2-4 hour 400-500km wavelength gravity waves exist!
- Large scale gravity waves can initiate convective storms

- Bosart and Cussen, 1973
- Eom, 1975
- Uccellini, 1975

Lance Bosart and John Cussen

Gravity Wave Phenomena Accompanying East Coast Cyclogenesis

LANCE F. BOSART and JOHN P. CUSSEN, JR.—*Department of Atmospheric Science, State University of New York at Albany, N.Y.*

"A remarkable example of gravity wave propagation over the southeastern United States on Dec. 3, 1968, is described."

Analysis of Waves

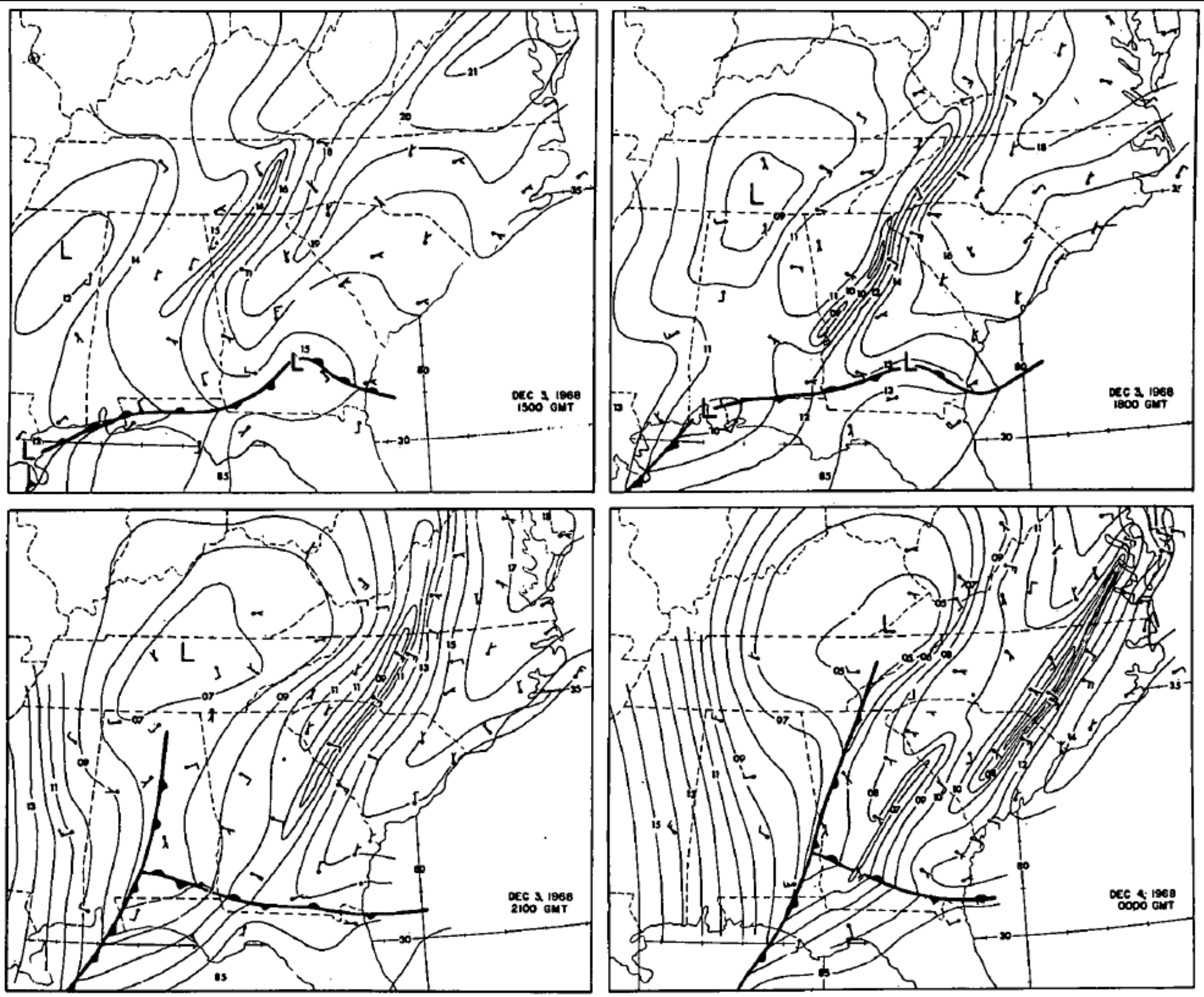


FIGURE 3.—Detailed surface maps at 3-hourly intervals for time periods indicated. Isobars are drawn for every 1 mb and winds are in knots, plotted according to the conventional station model.

Bosart and Cussen, 1973

Analysis of the Internal Gravity Wave Occurrence of 19 April 1970 in the Midwest

Analysis of the Internal Gravity Wave Occurrence of 19 April 1970 in the Midwest

JAE KYUNG EOM[1]

Department of Meteorology, University of Wisconsin, Madison, Wisc. 53706

(Manuscript received 23 October 1973: in revised form 15 November 1974 and 20 December 1974)

"An analysis is made of high frequency fluctuations of surface pressure and wind with a period of 3-4 h observed in the midwestern United States in the early morning hours of 19 April 1970."

"Solutions from a simple model of atmospheric dynamics for a compressible and hydrostatic flow are compared with the observations. It is shown that the fluctuations in the atmosphere correspond well to simple gravity wave concepts and in particular to internal gravity waves propagating to the northeast with an approximate speed of 50m/s and an average wavelength of 500 km."

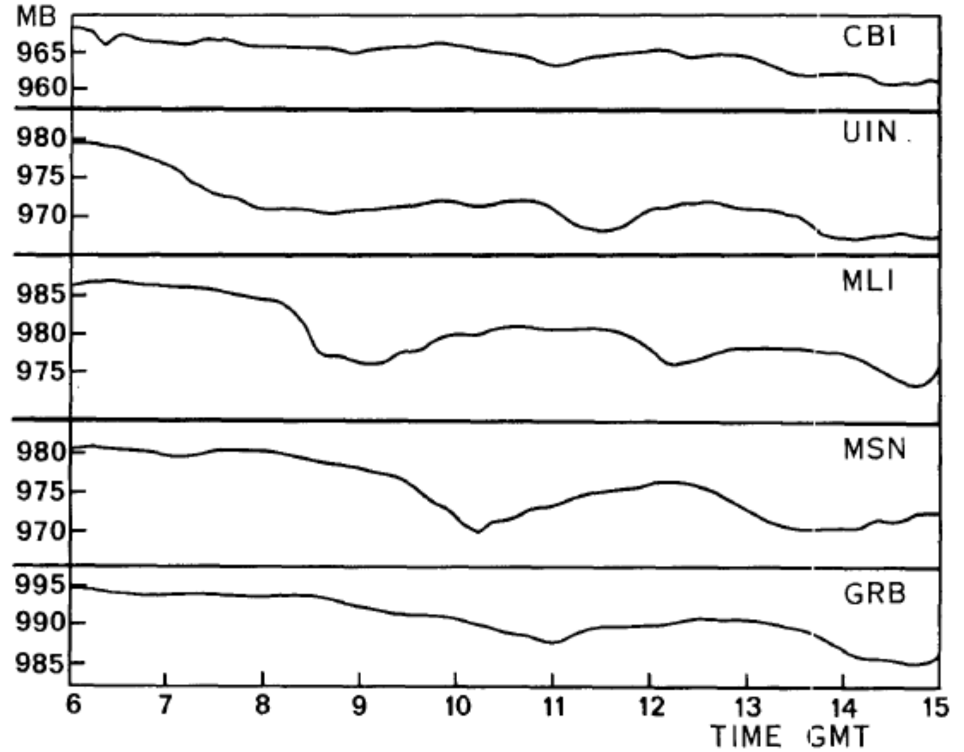
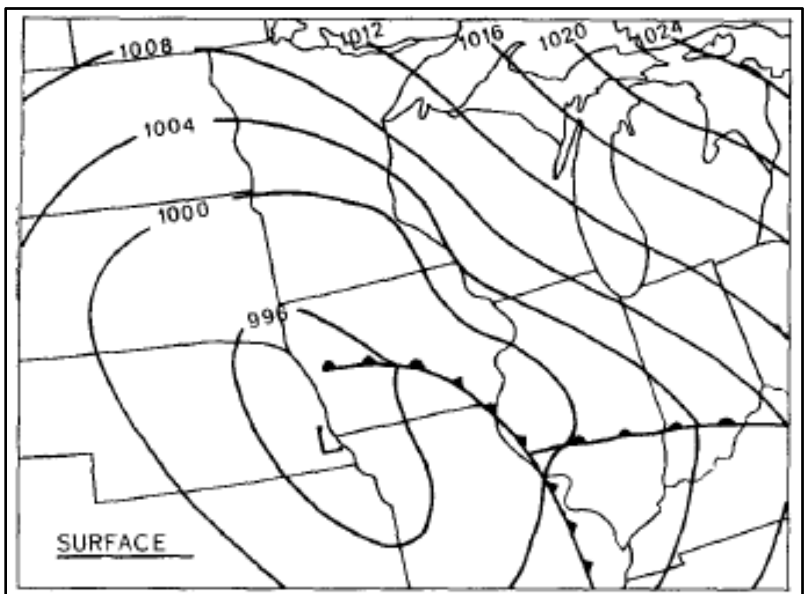
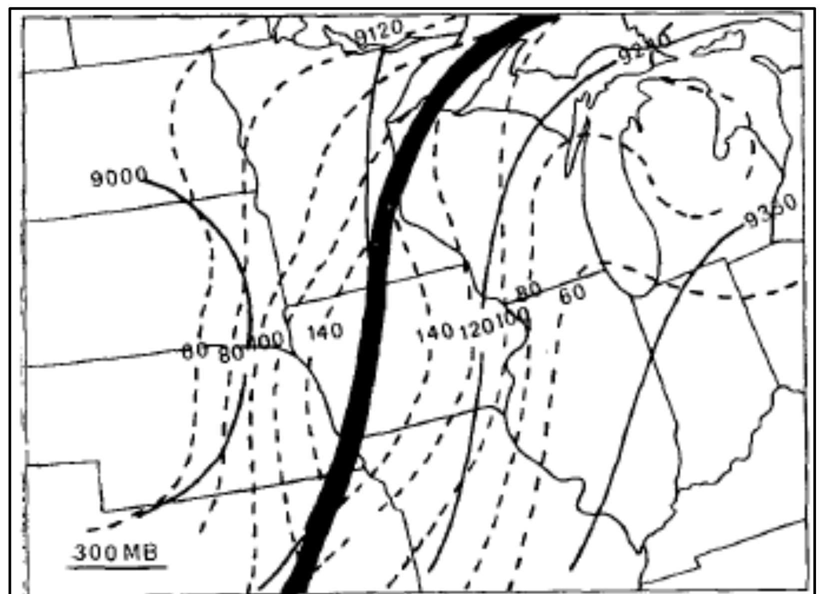


FIG. 1. Barogram traces of the station on the wave path in the order of Columbia, Quincy, Moline, Madison, and Green Bay from top. The traces are for the interval from 0600 to 1500 GMT 19 April 1970.





Eom, 1975

Schematic of the Model

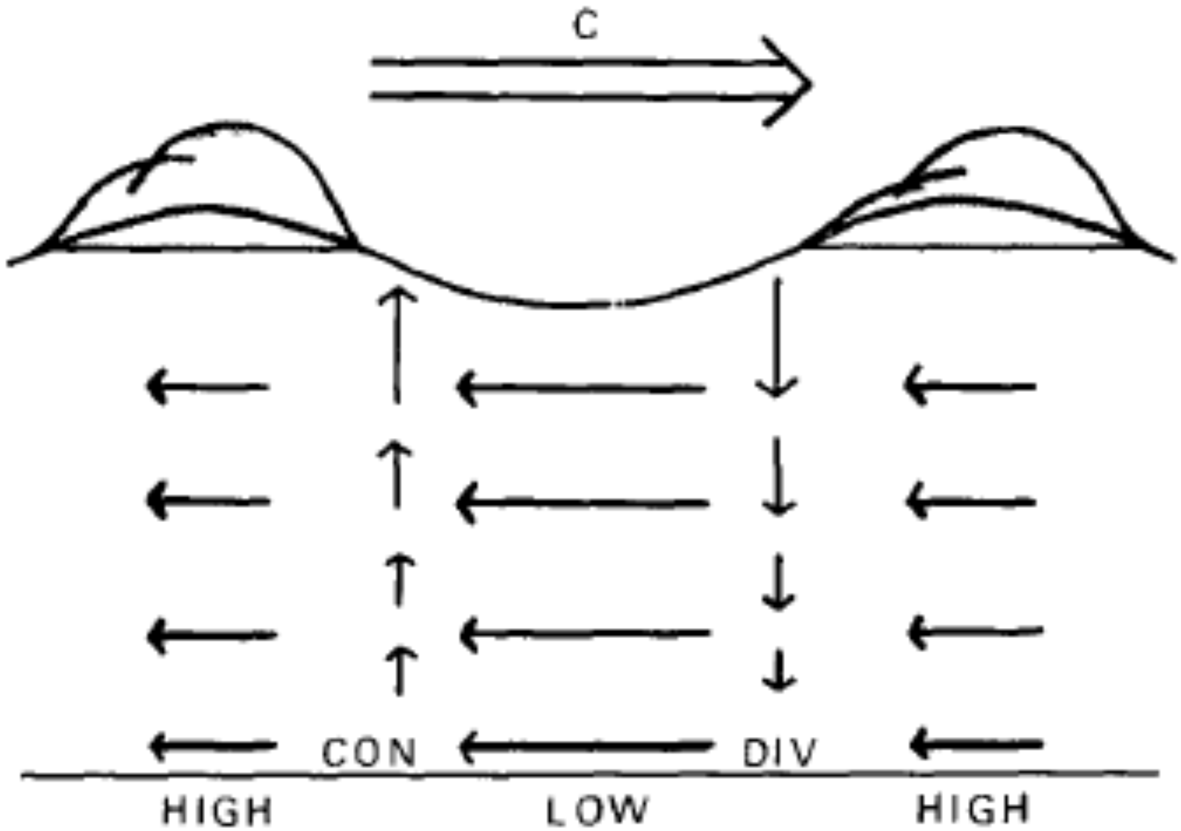
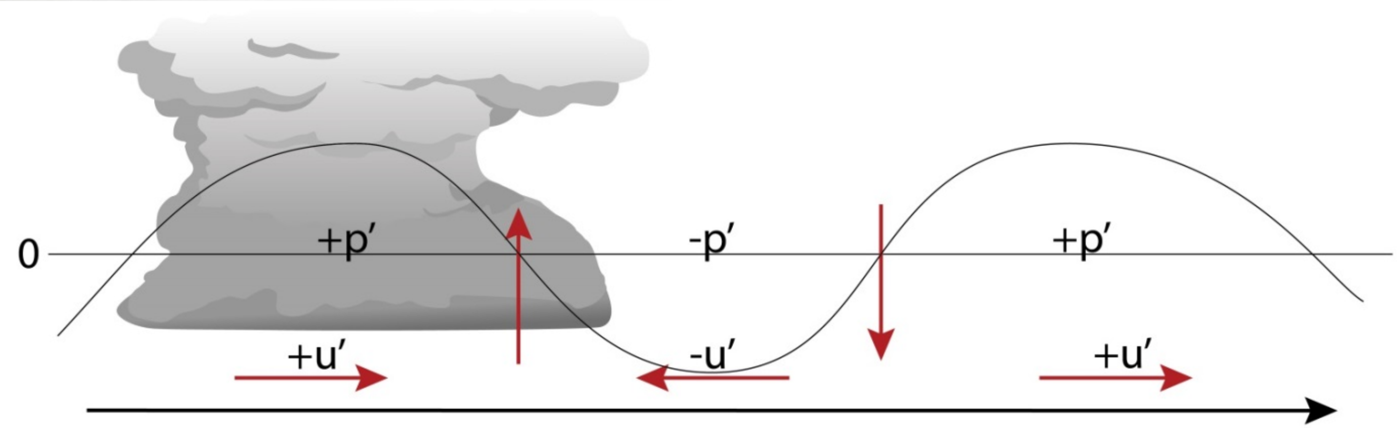


FIG. 7. Schematic view of the wave. The arrow labeled C indicates the propagating direction. The other arrows suggest the velocity distribution associated with the wave. HIGH and LOW refer to the surface pressure distribution, and CON and DIV the horizontal convergence and divergence. Regions of cloudiness enhancement are indicated schematically.

Eom, 1975

My Interest in Gravity Waves

- A discussion with Ogura in 1970 directed me to Matsumoto and Akiyama (1969), Matsumoto and Tsuneuka (1969)
- Bosart and Cussen (1973) and Eom (1975): Gravity wave door is reopened
- All my research started/completed with operational data
- Initial focus on the release of convective instability:
  - 3-hour periodic nature of storms as diagnosed with surface convergence and radar data (Senior Thesis, 1971)
  - Isolated the role of 2 to 4 hour period gravity waves in the release of the convective instability using detailed p’ analysis (Master’s Thesis, 1972)



A Case Study of Apparent Gravity Wave Initiation of Severe Convective Storms

"Analyses of surface weather reports, radar data, surface wind convergence, and surface *p'* fields revealed that the intensity of the convective systems pulsated with periods ranging from 2 to 4 h; and that the gravity waves were a precursor to storm development in Iowa and Wisconsin and appeared to initiate convection in those areas. Reintensification of preexisting storm cells or the development of new cells generally followed the passage of the wave trough, with maximum storm cells or the development of new cells generally followed the passage of the wave trough, with maximum rainfall intensity coinciding with the passage of the ridge. The cycle is completed with a general weakening of the convective storms as the next trough approaches."

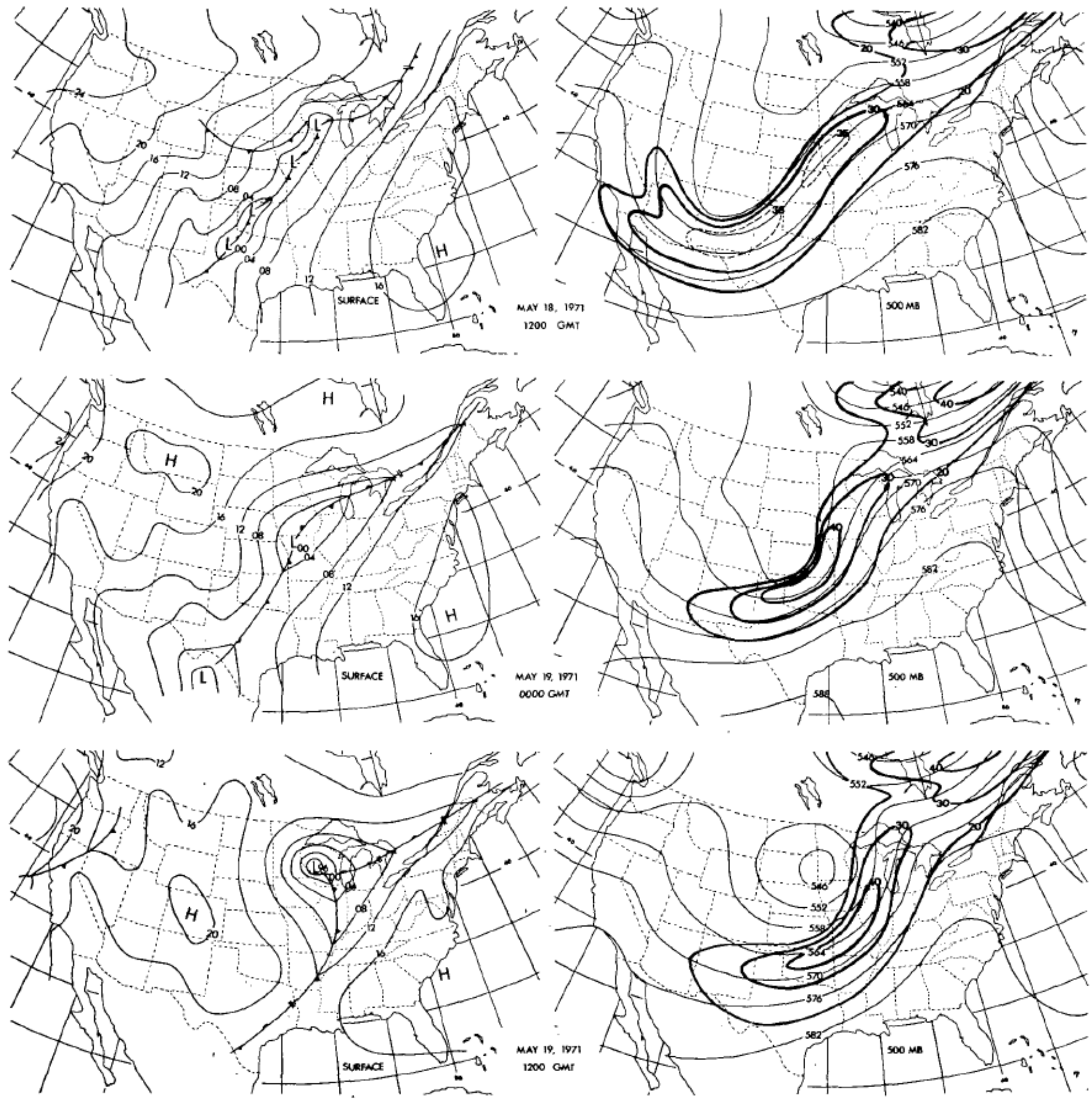


FIG. 1. Surface and 500 mb maps from 1200 GMT 18 May 1971 through 1200 GMT 19 May 1971. Isobars are drawn for every 4 mb. Heights (thin solid) are at 6 dam intervals and isotachs (thick solid) are at 10 m s^{-1} intervals.

Uccellini, 1975

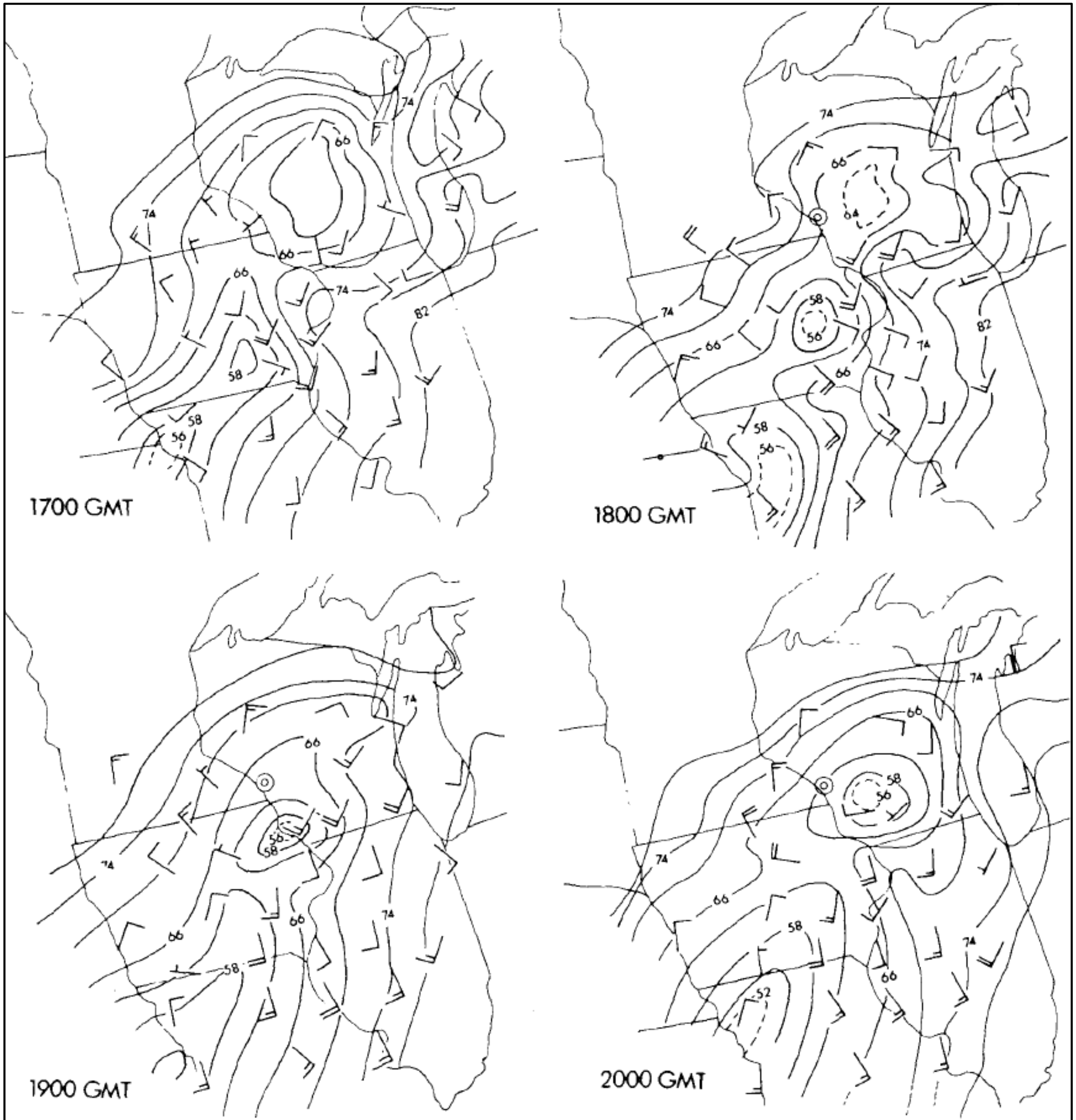


FIG. 3. Surface isobaric analyses, using altimeter settings (inches of mercury; 58=29.58 in. of Hg) and surface wind barbs for 1700 GMT through 2000 GMT 18 May 1971.

Uccellini, 1975

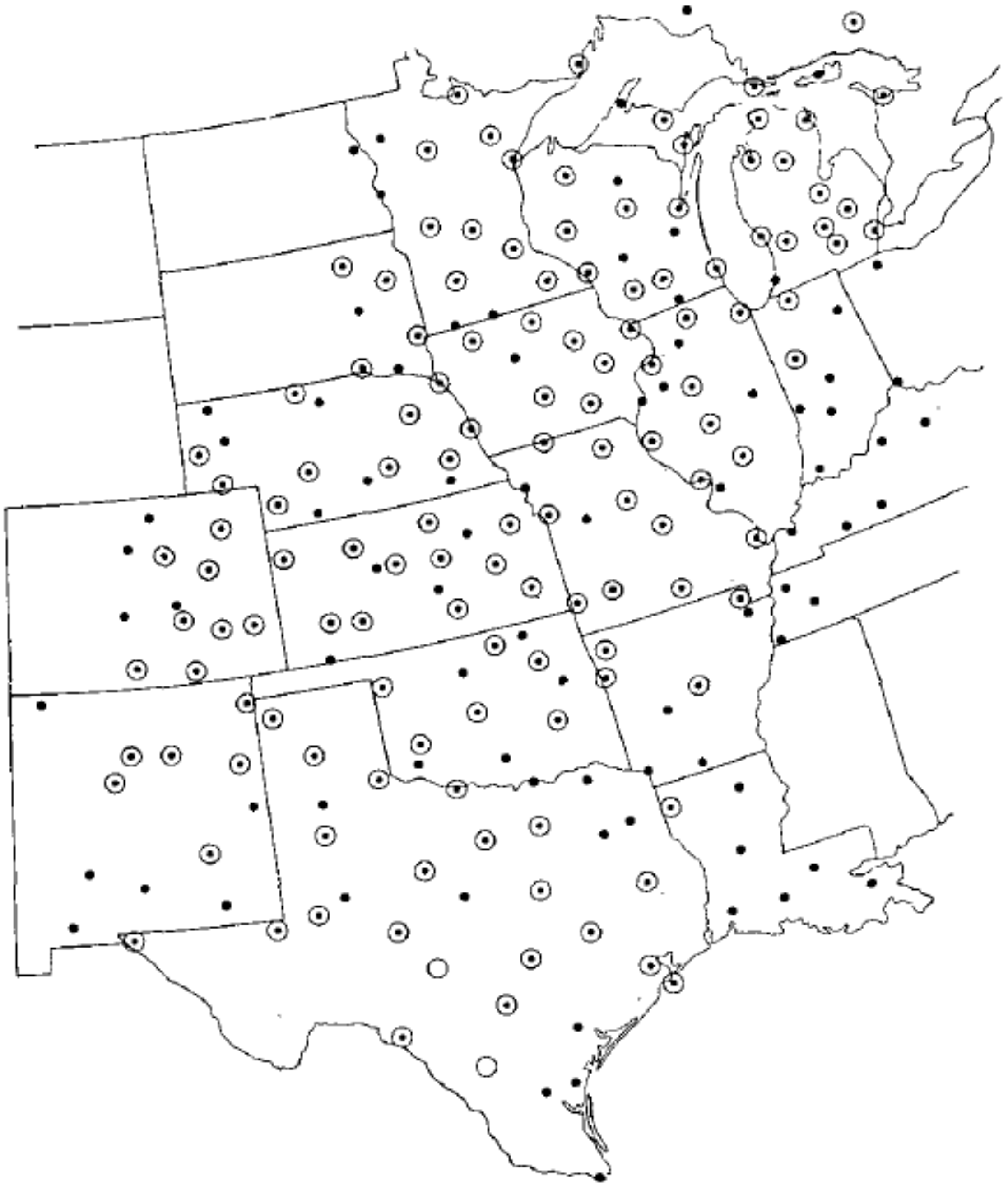
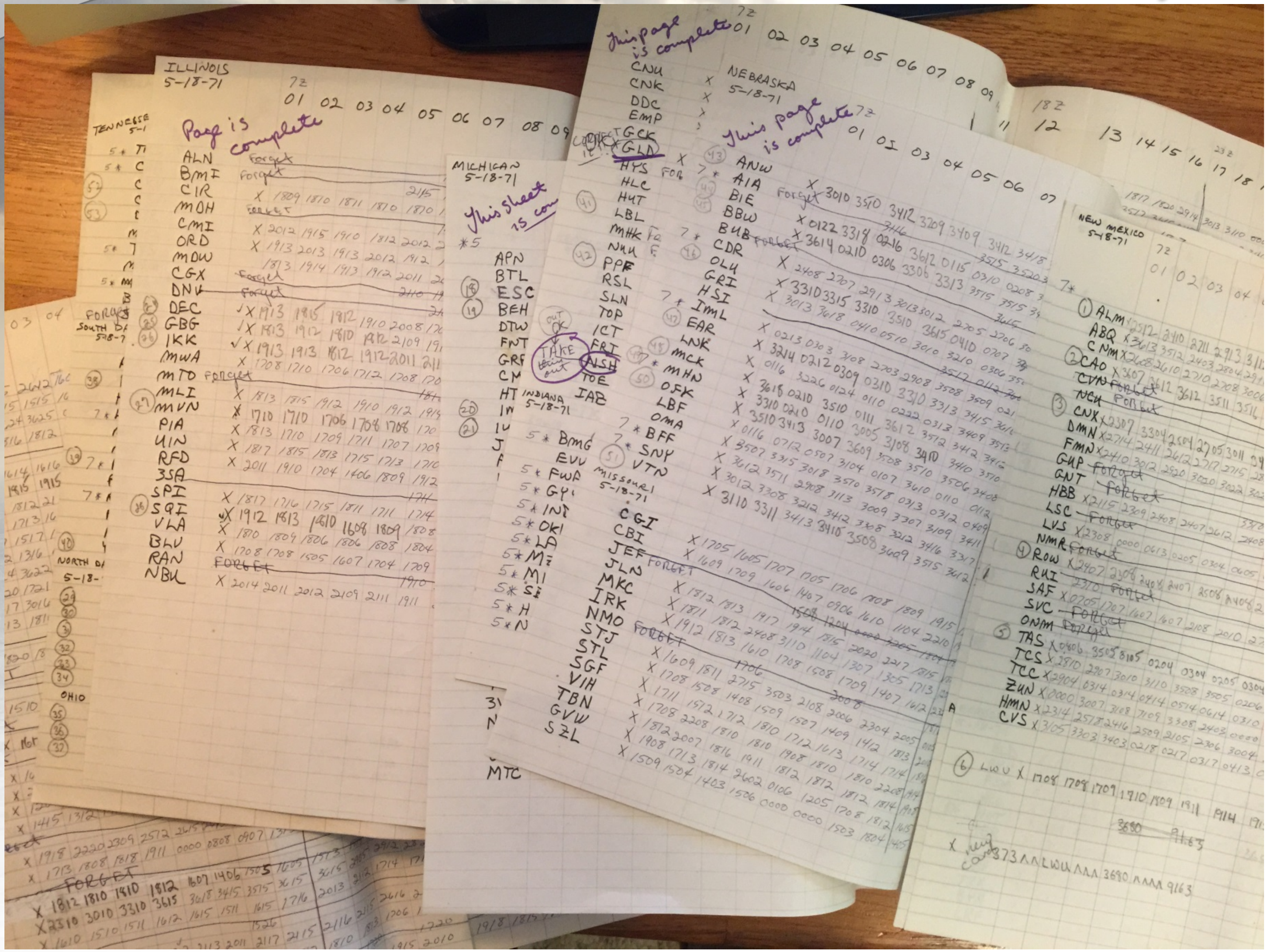


FIG. 4. Location of stations used in diagnostic study from which barograph traces ○ and surface observations ● were available.

Uccellini, 1975

All Operational Pressure Traces Read and Tabulated by Hand (at 15 Minute Intervals)



- Tabulated pressure traces then passed through a band pass filter

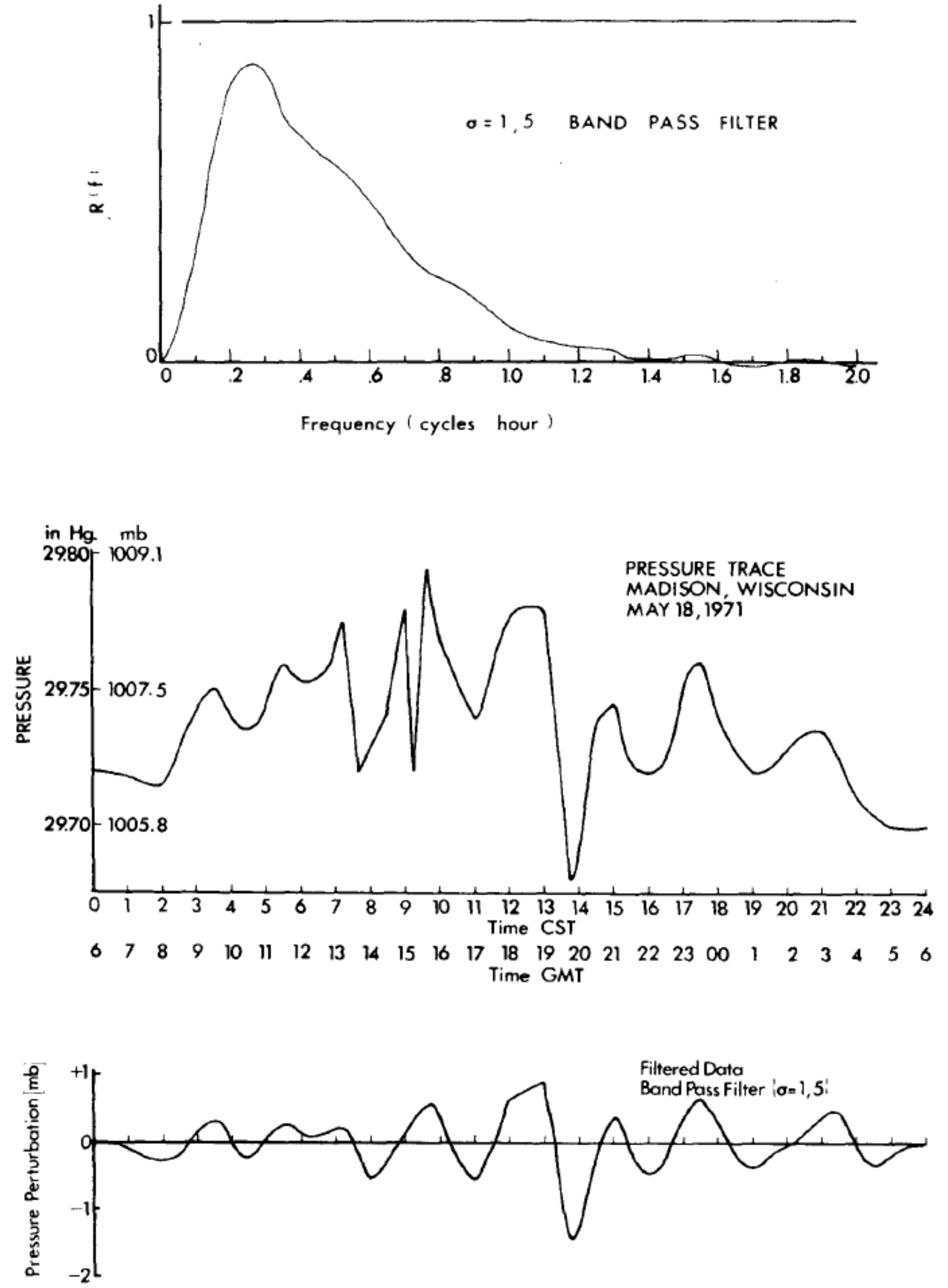


FIG. 5. Response function $R(f)$ for the band pass filter (top). Presented also is the original pressure trace for Madison, Wis., (middle) and the filtered pressure perturbation trace (bottom).

Uccellini, 1975

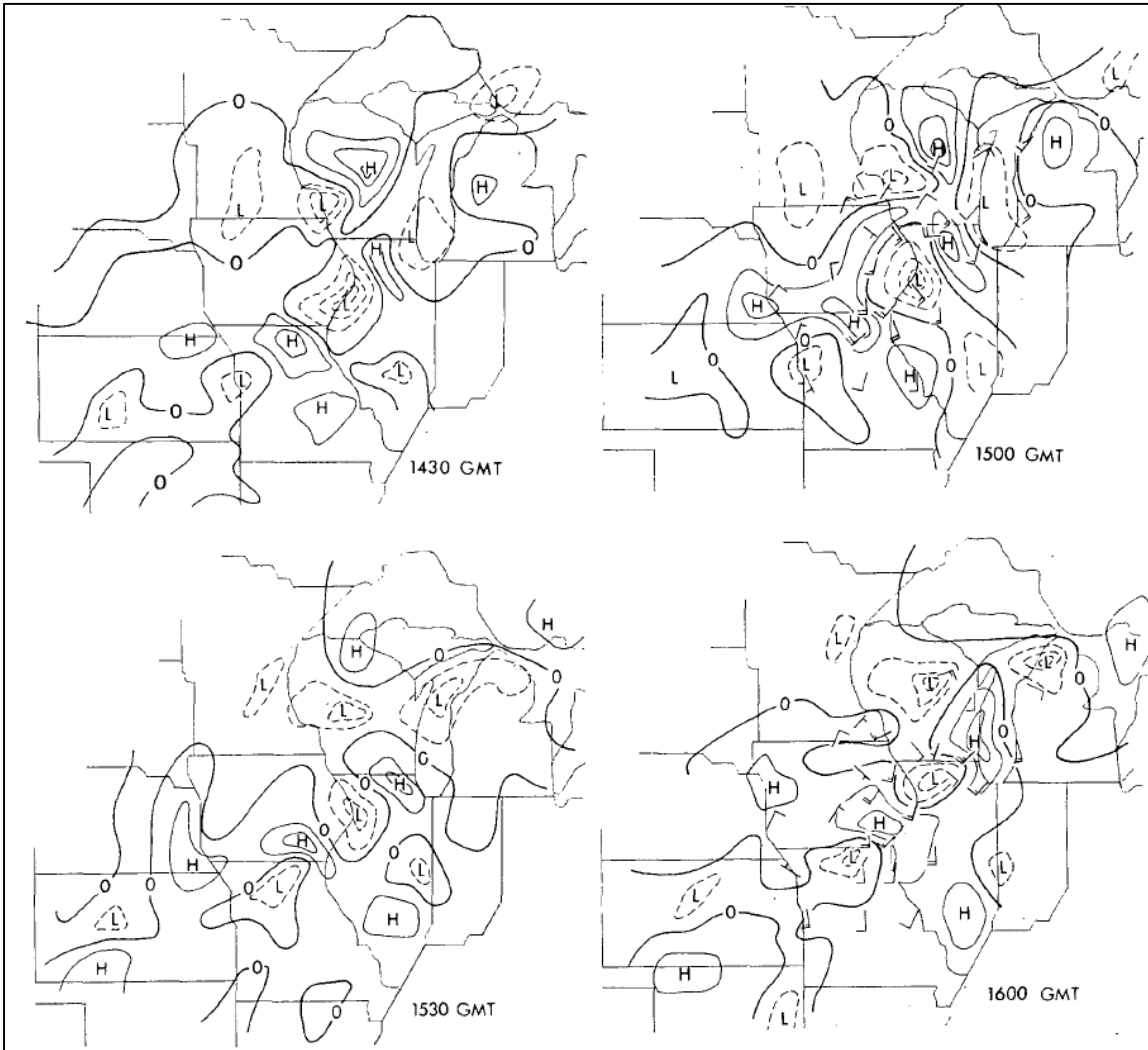


FIG. 6. Successive p' maps analyzed at 0.5 mb interval and surface wind barbs. Negative p', thin dashed; positive p', thin solid; $p'=0$, thick solid. The locations of the minimum and maximum p' values are indicated by L and H respectively.

Uccellini, 1975

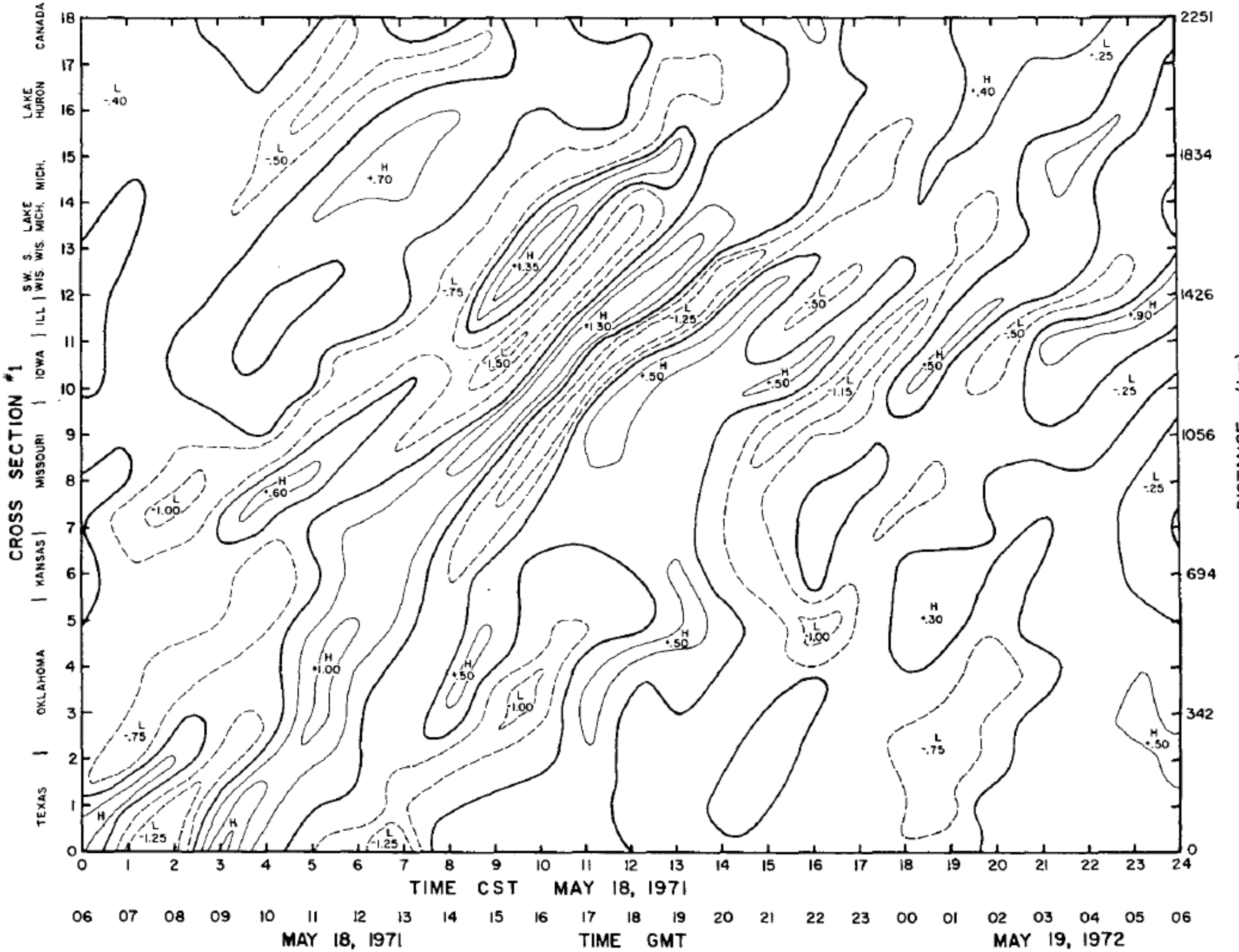


FIG. 9a. Time cross section # 1 of p' values (see details in caption of Fig. 6) analyzed along central track (see Fig. 8).

Uccellini, 1975

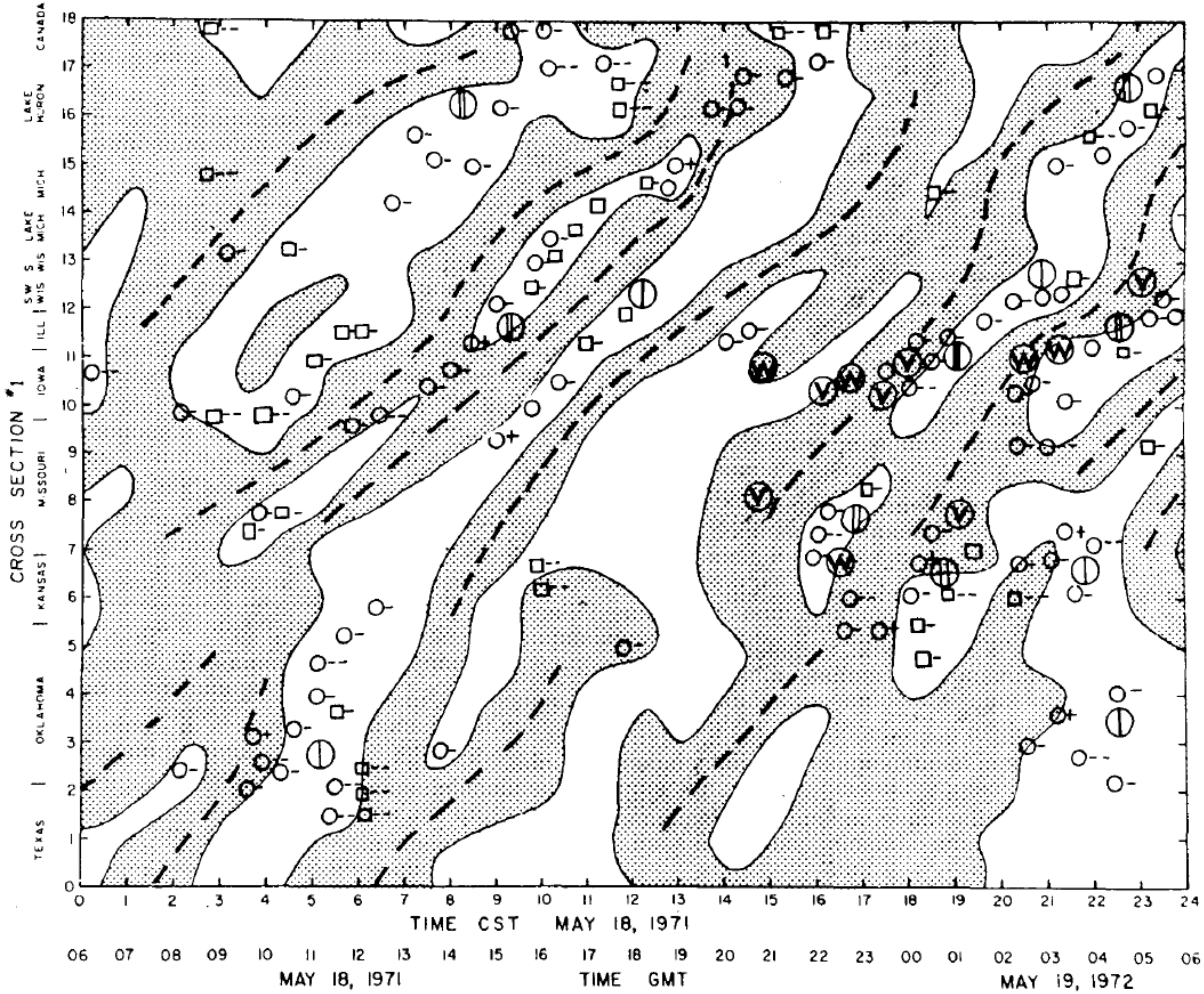
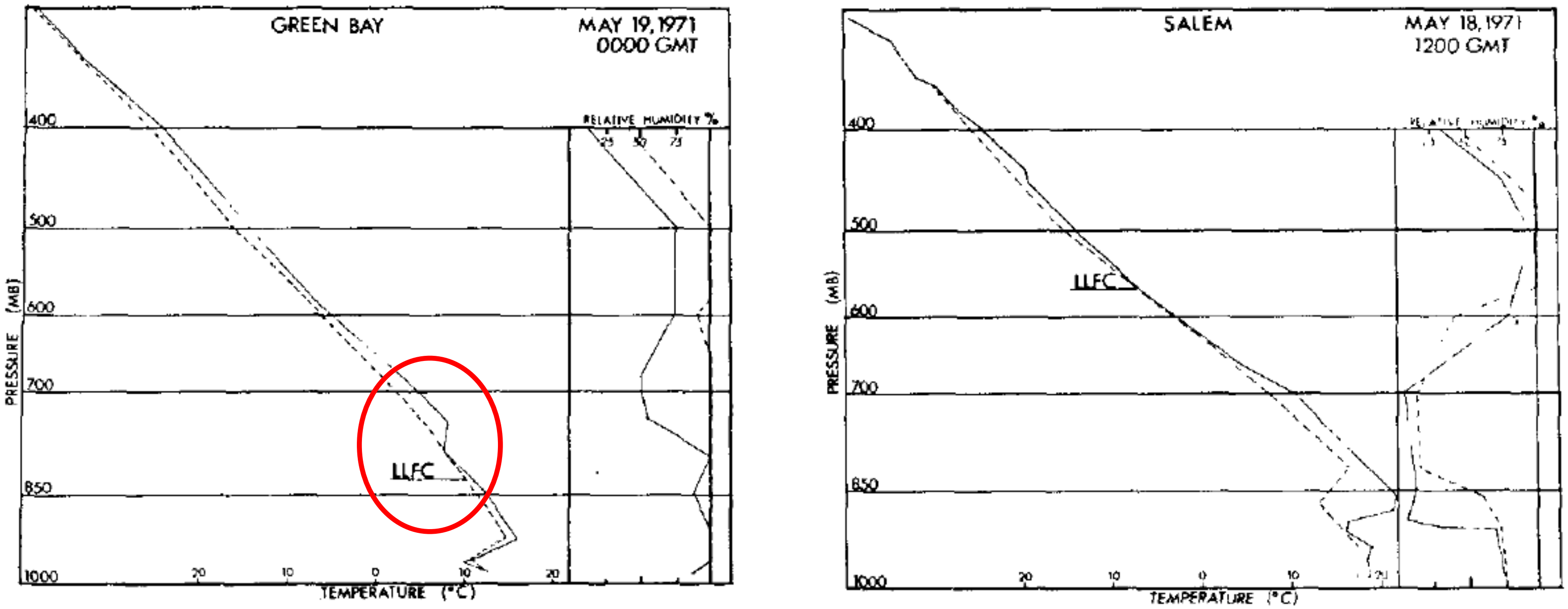


FIG. 9b. Time cross section #1 with surface weather reports. The shaded area is negative p', with the progression of the gravity waves represented by the dashed lines. Surface weather reports: ○ thundershower □ rainshower; Intensity: (– –) very light, (—) light, ( ) moderate, (+) heavy; Ⓦ windstorm; Ⓥ tornado; ⦶ one station reporting precipitation; ⊕ two or more stations reporting precipitation concurrently.

Uccellini, 1975

Displacement Applied to Green Bay Sounding



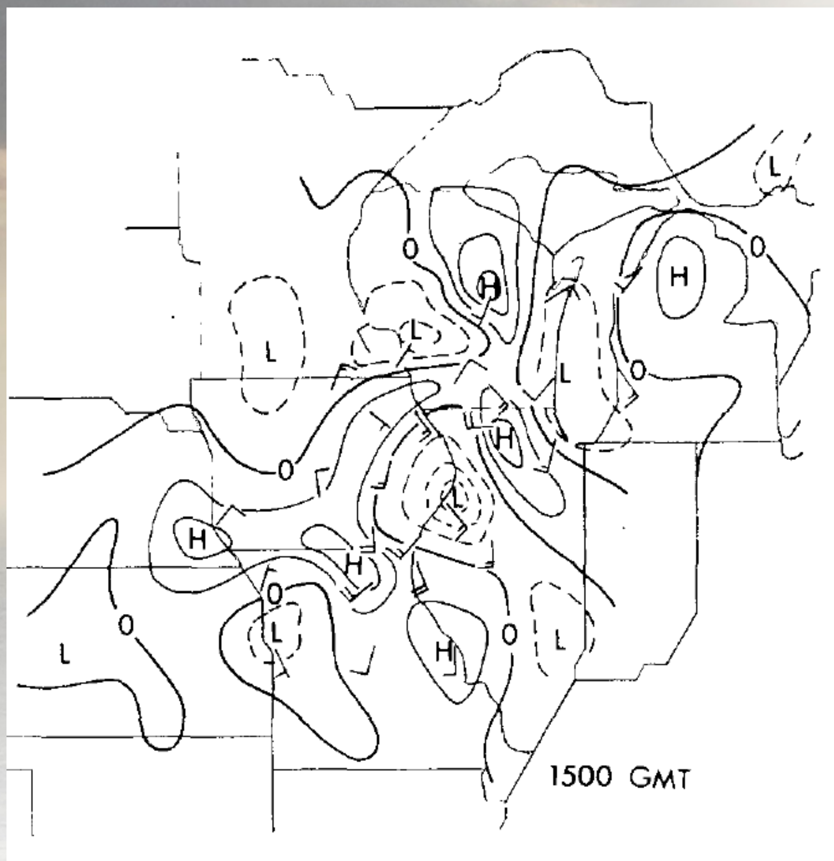
	W_k[850–700]	W_k[850–500]	LLFC (MB)
ORIGINAL SOUNDING	$-6 \cdot 10^1$	$5 \cdot 10^1$	
SOUNDING AFTER GRAVITY WAVE	$8 \cdot 10^1$	3×10^2	830

	W_k[850 700]	W_k[850 500]	LLFC (MB)
ORIGINAL SOUNDING	$-1 \cdot 10^2$	$4 \cdot 10^2$	
SOUNDING AFTER GRAVITY WAVE	$3 \cdot 10^2$	$-6 \cdot 10^2$	570

FIG. 13. Atmospheric soundings for Green Bay, Wis., 0000 GMT 19 May 1971 and Salem, Ill., 1200 GMT 18 May 1971. Original sounding (solid line), hypothetical sounding following maximum displacement due to modeled gravity wave (dashed line). LLFC is the lowest level of free convection. Tables below the sounding list the work W_k done on or by parcels before and after the maximum displacement has occurred (see text).

Uccellini, 1975

Great Uproar!



Surface p' analysis
1500 UTC 18 May 1971
(Uccellini, 1975)

- 3-hourly, 250 to 400 km wavelength gravity waves, cannot exist (Lindzen, Lilly, Anthes, etc.)
- Gravity waves don't initiate convection – "*…futility of seeking a trigger mechanism in the pressure field at the initial stage*" (Fujita, 1955)
- And even if you can show that gravity waves are important – no way to isolate in real time and *no forecast value* (Maddox and others)

A Case Study of Gravity Waves-Convective Storms Interaction: 9 May 1979

"One of the two wave trains developed in regions of weak or no convection and appeared to initiate more intense convective clusters downstream from the point of origin. It is shown that the characteristics of the wave trains are consistent with those gravity waves generated in a region of strong vertical shear associated with the jet. It is suggested that the wave trains continue to extract energy from the basic state all along their track through critical level interaction."

Improved band pass filter with cross correlation technique – analysis points to continuous extraction of wave energy from basic state (shear/instability); not ducting!

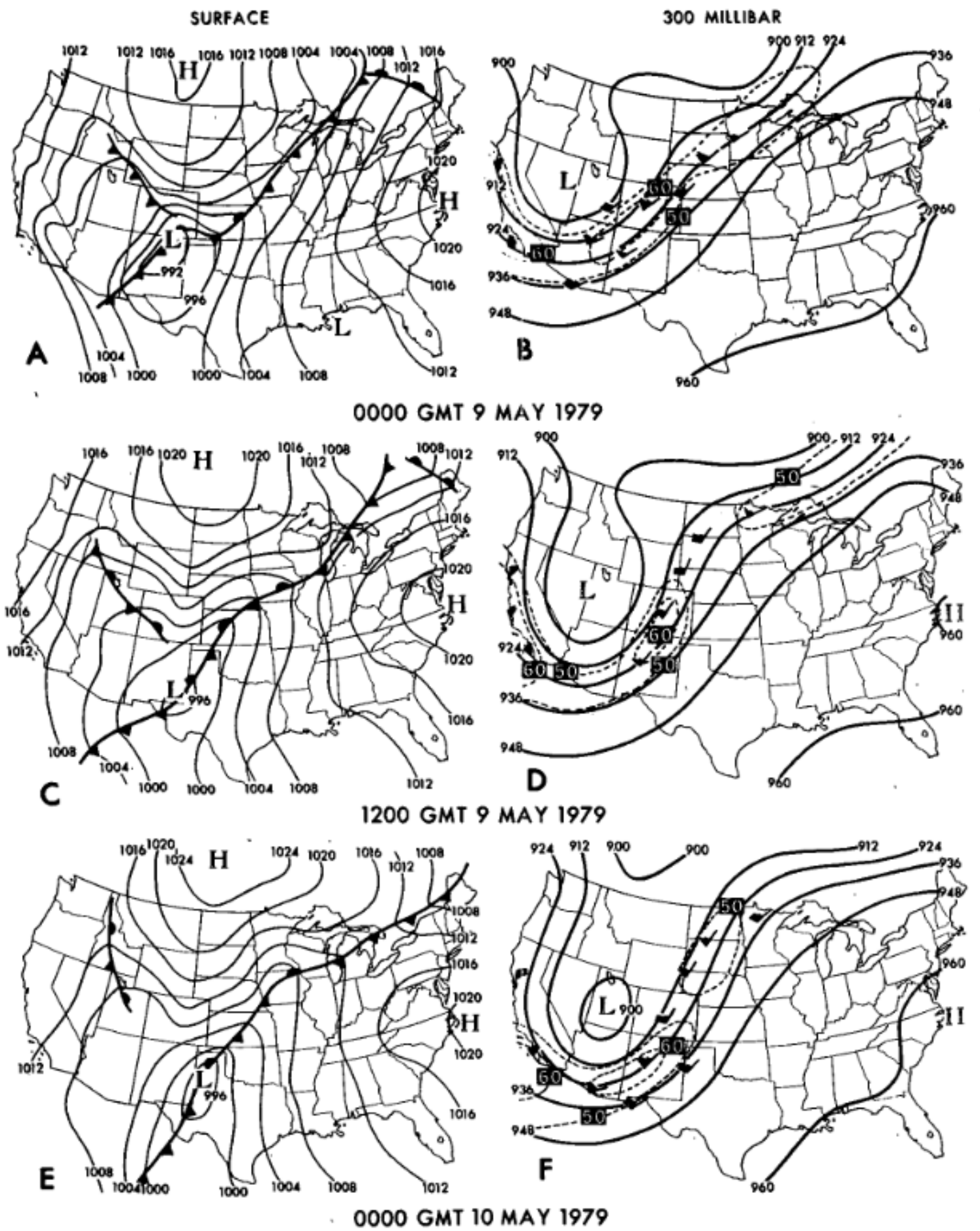


FIG. 1. Surface and 300 mb analyses for 0000 GMT and 1200 GMT, 9 May 1979 and 0000 GMT 10 May 1979.

Stobie et al., 1979

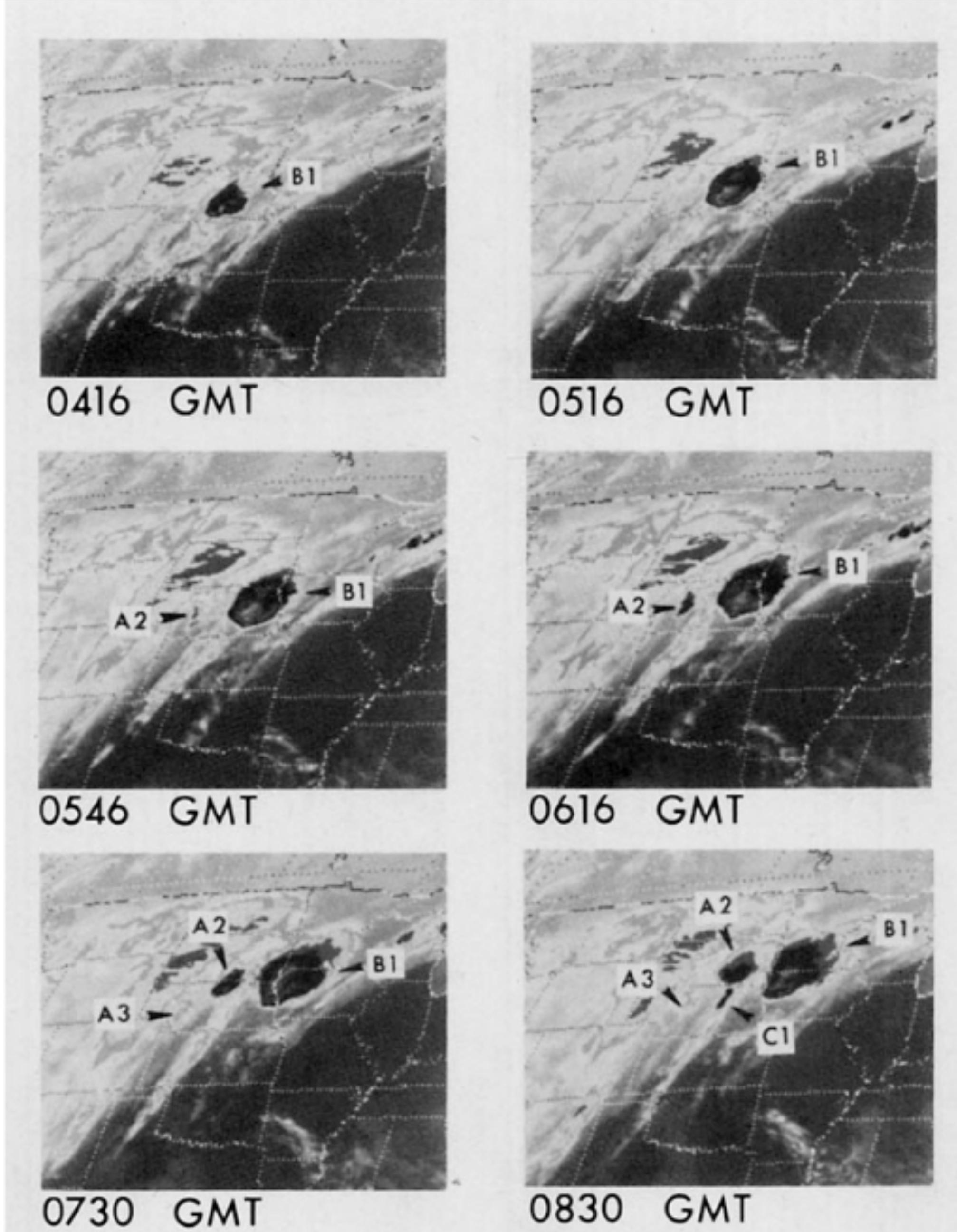


FIG. 3. Enhanced infrared GOES satellite pictures from 0416 GMT to 1430 GMT, 9 May 1979.

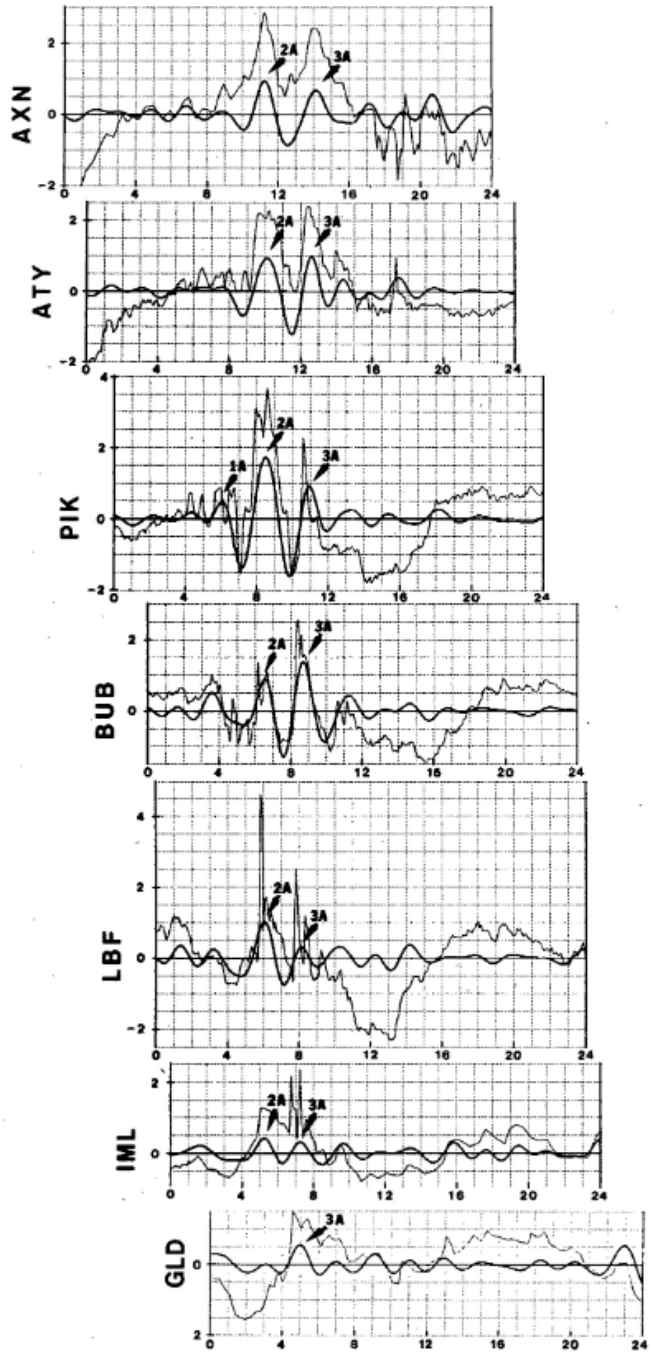


FIG. 8. Pressure traces from stations along track A. For each station the ordinate is pressure (mb) while the abscissa is time (GMT). Dark traces are the bandpass filtered traces while the thin traces are the raw data with the mean and trend removed. The labels A1, A2 and A3 identify the three main pressure maxima that propagated along track A.

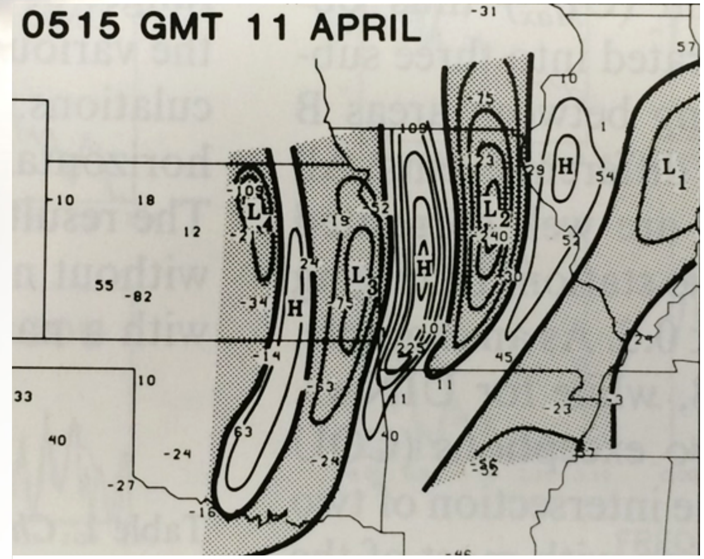
Stobie et al., 1979

Gravity Wave Research Revs Up

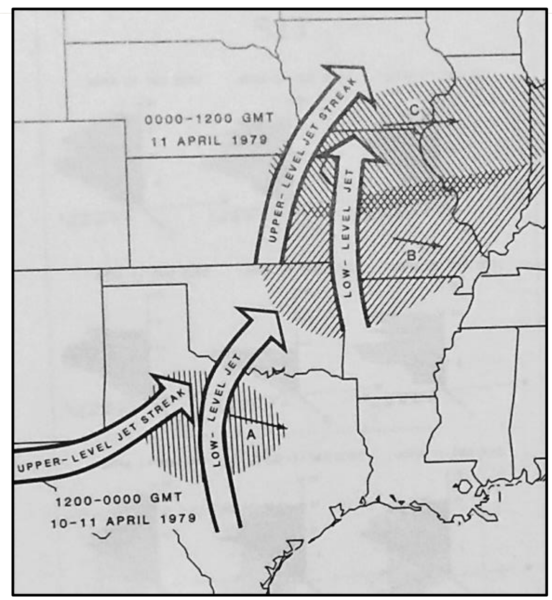
- (Lindzen and Tung, 1975): 2 to 4 hour gravity waves exist! They are “ducted” by temperature/wind profiles
- (Ferretti et al, 1988): Shear/moisture profile provides critical level and energy source for 2 to 4 hour period gravity waves within 3 wave packets
- Along with Kocin et al. (1986) best analyzed jet-GW case (3-h soundings)

Today:

- Many studies: Gravity waves are ubiquitous – can generate convection! (Koch et al. and others)
- Gravity waves considered part of overall spectrum of atmospheric response to unbalanced flow



P’ analysis for gravity wave event 10-11 April 1979



Ferretti et al., 1988

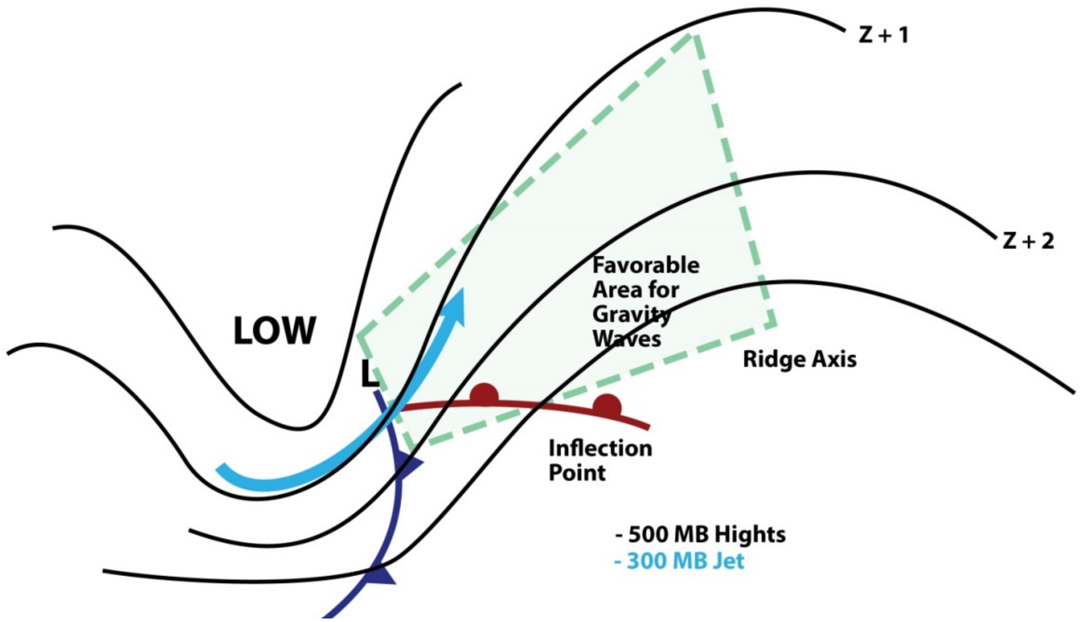
Gravity Wave Research Summary Comments

“Gravity waves are not isolated events whose occurrence is confined to those few cases in which atmospheric conditions favor observable cloud modulation by the waves; they are virtually ubiquitous. With appreciation for the pervasive character of gravity waves has come an appreciation for their dynamical importance…” (Bill Hooke, 1986)

“As such, they are the fundamental building blocks of mesoscale dynamics. All mesoscale circulations, no matter how complex, can be represented as a superposition of nonlinear, interacting gravity waves.” (Bill Hooke, personal communication)

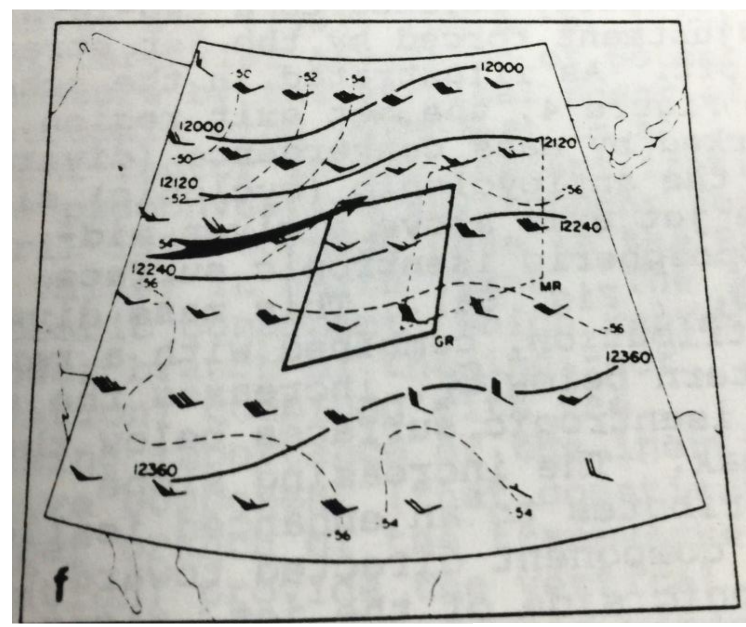
Spectrum of Atmospheric Mass-Momentum Adjustment to Unbalanced Flow: From Cyclones to Gravity Waves

Synoptic Environment for Large Scale Gravity Waves



Uccellini and Koch, 1987
(review of 13 cases of gravity waves published in literature)

- Clear preference for gravity waves to exist near jet exit region – approaching downstream ridge crest



Maddox, 1983

- Same framework for cyclogenesis and mesoscale convective complexes

Large-Amplitude Mesoscale Wave Disturbances Within the Intense Midwest Extratropical Cyclone of 15 December 1987

RUSSELL S. SCHNEIDER

Department of Meteorology, University of Wisconsin, Madison

(Manuscript received 15 December 1989, in final form 24 August 1990)

ABSTRACT

On 15 December 1987 several long-lived, large-amplitude mesoscale wave disturbances embedded within a rapidly intensifying extratropical cyclone traversed the Midwest and created life-threatening blizzard conditions. Within the wave disturbances, which likely were atmospheric gravity waves, pressure falls of up to 11 mb in 15 min were accompanied by winds in excess of 30 m s^{-1} (60 kt), cloud-to-ground lightning and heavy snowfall. One of the large-amplitude mesoscale wave disturbances, characterized by a surface pressure minimum lower than the cyclone's central pressure, propagated through the cyclone center during the rapid intensification stage of the storm system. The rapid changes in weather conditions associated with these wave disturbances played havoc with attempts to make short-range forecasts at the height of the 15 December 1987 snowstorm. To help forecasters anticipate and identify mesoscale wave disturbances, basic forecast guidelines based on gravity wave principles and recent research results are discussed.

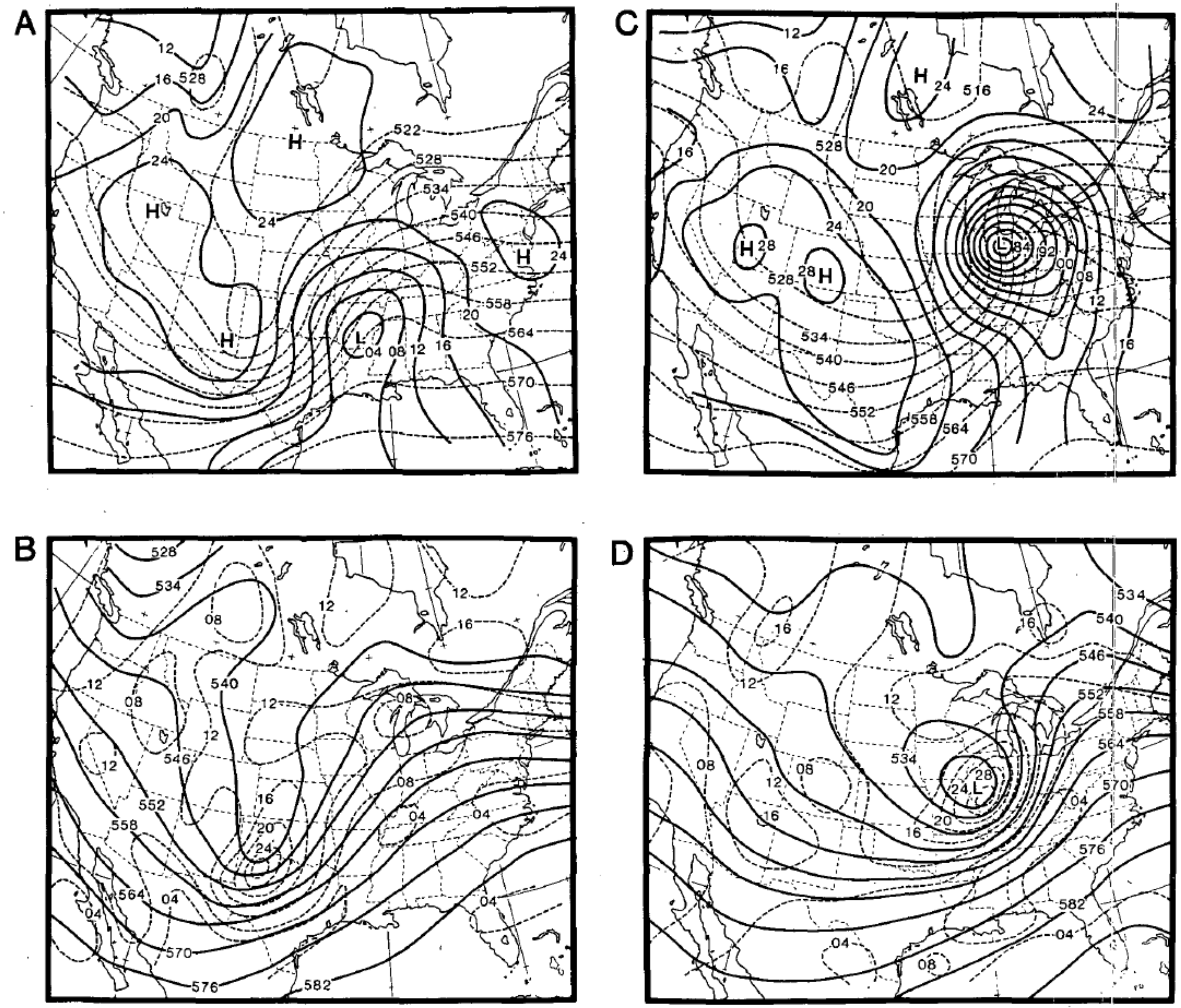


FIG. 1. Subjective analyses of: (A) mean-sea-level pressure (solid; contoured every 4 mb) and 1000–500-mb thickness (dashed; contoured every 6 dam) and (B) 500-mb heights (solid; contoured every 6 dam) and absolute vorticity (dashed; contoured every $4 \cdot 10^{-5}\ s^{-1}$) for 0000 UTC 15 December 1987. (C) and (D) are the same as (A) and (B) but for 1200 UTC 15 December 1987.

Schneider, 1990

Large amplitude gravity wave passes through synoptic low center during period of "rapid deepening"

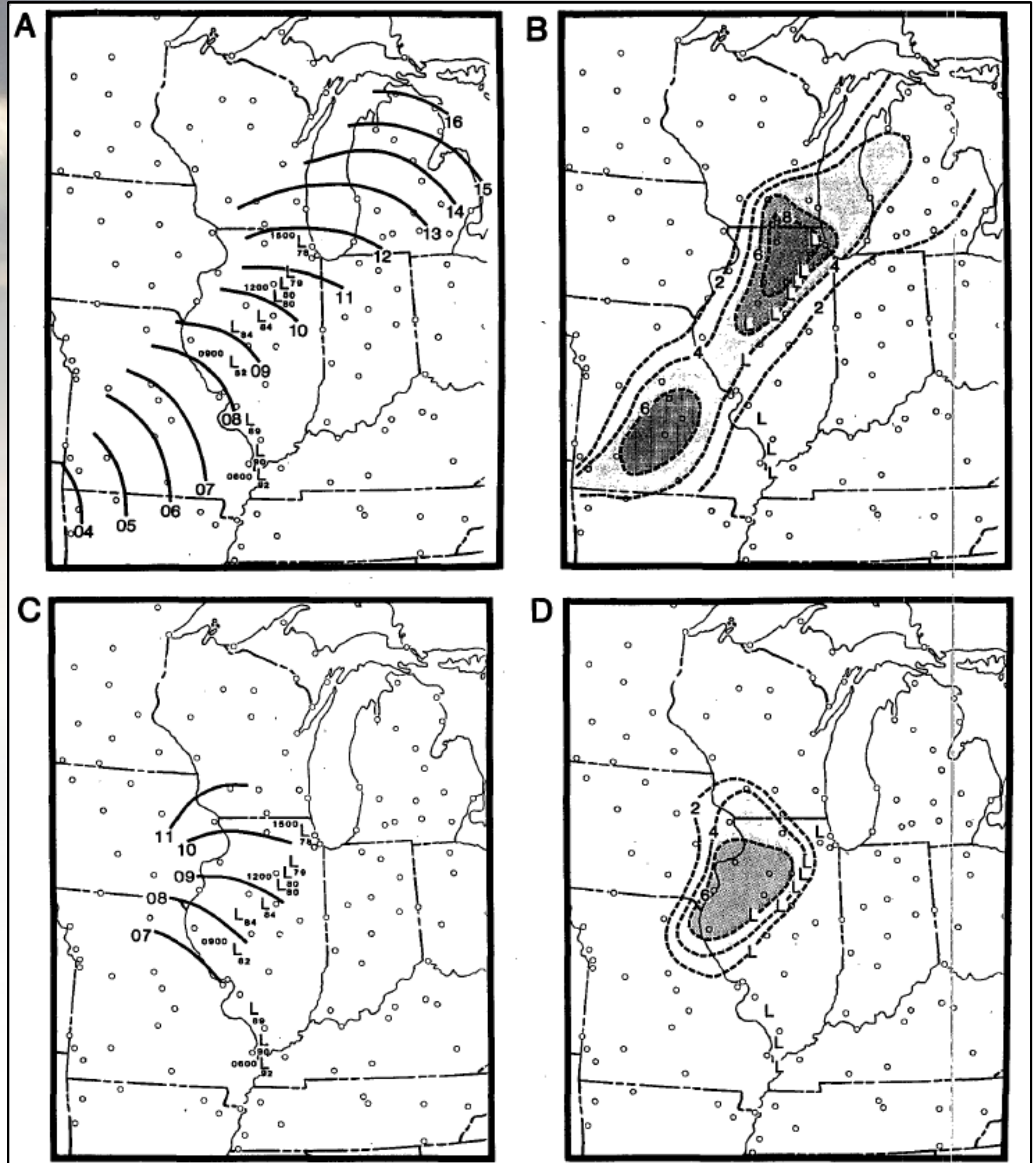
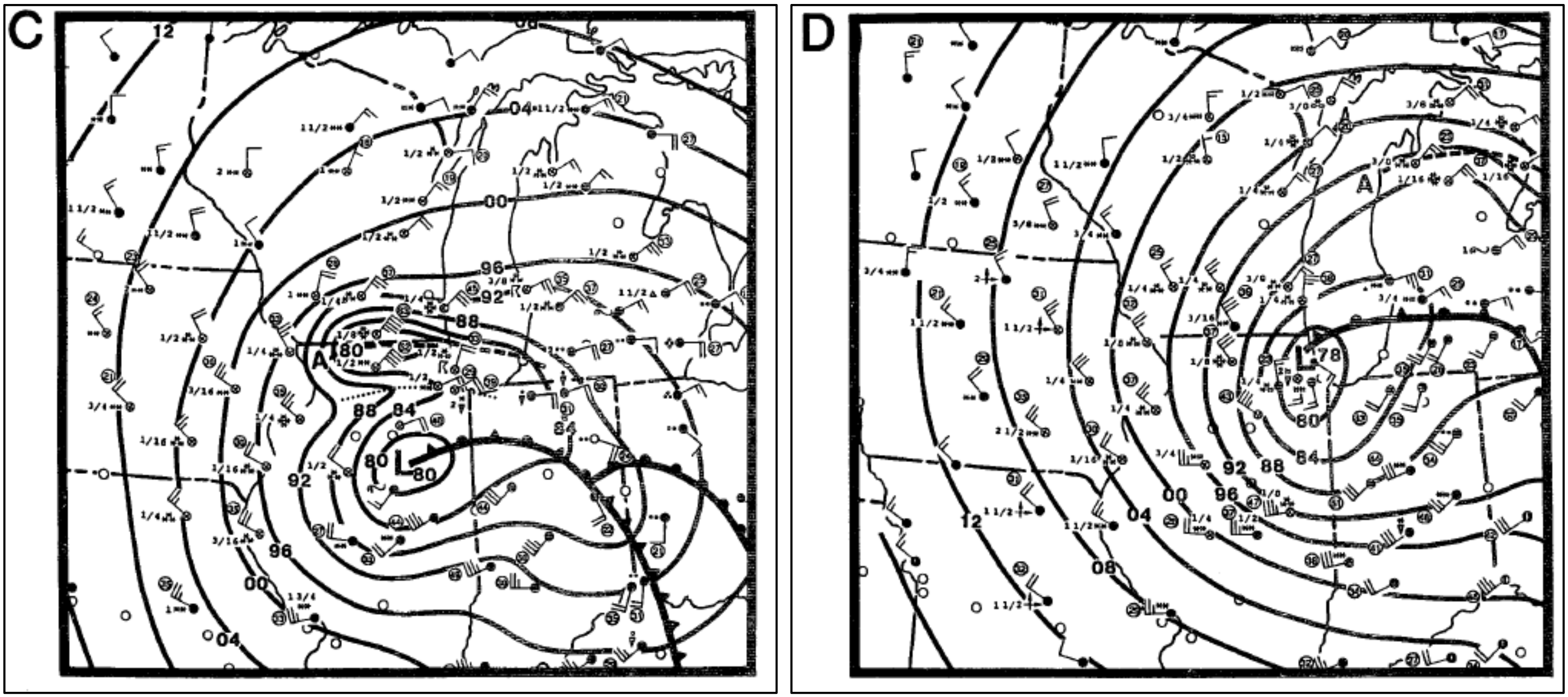


FIG. 7. (A) Isochrones of the location of wave-trough A (solid, UTC) on 15 December 1987. The position of the extratropical cyclone ('L'), the minimum sea-level pressure (below 'L'; mb; lead '9' or '10' omitted), and the time at 3-h intervals (above and left of 'L'; UTC) are plotted. To match synoptic observations, the position of each isochrone is the estimated wave location 10 min before the labeled hour. (B) Peak-to-peak amplitude of wave-trough A (dashed, mb) (see text for definition). (C) and (D) are the same (A) and (B) except the data is for wave-trough B.

Schneider, 1990



Schneider, 1990

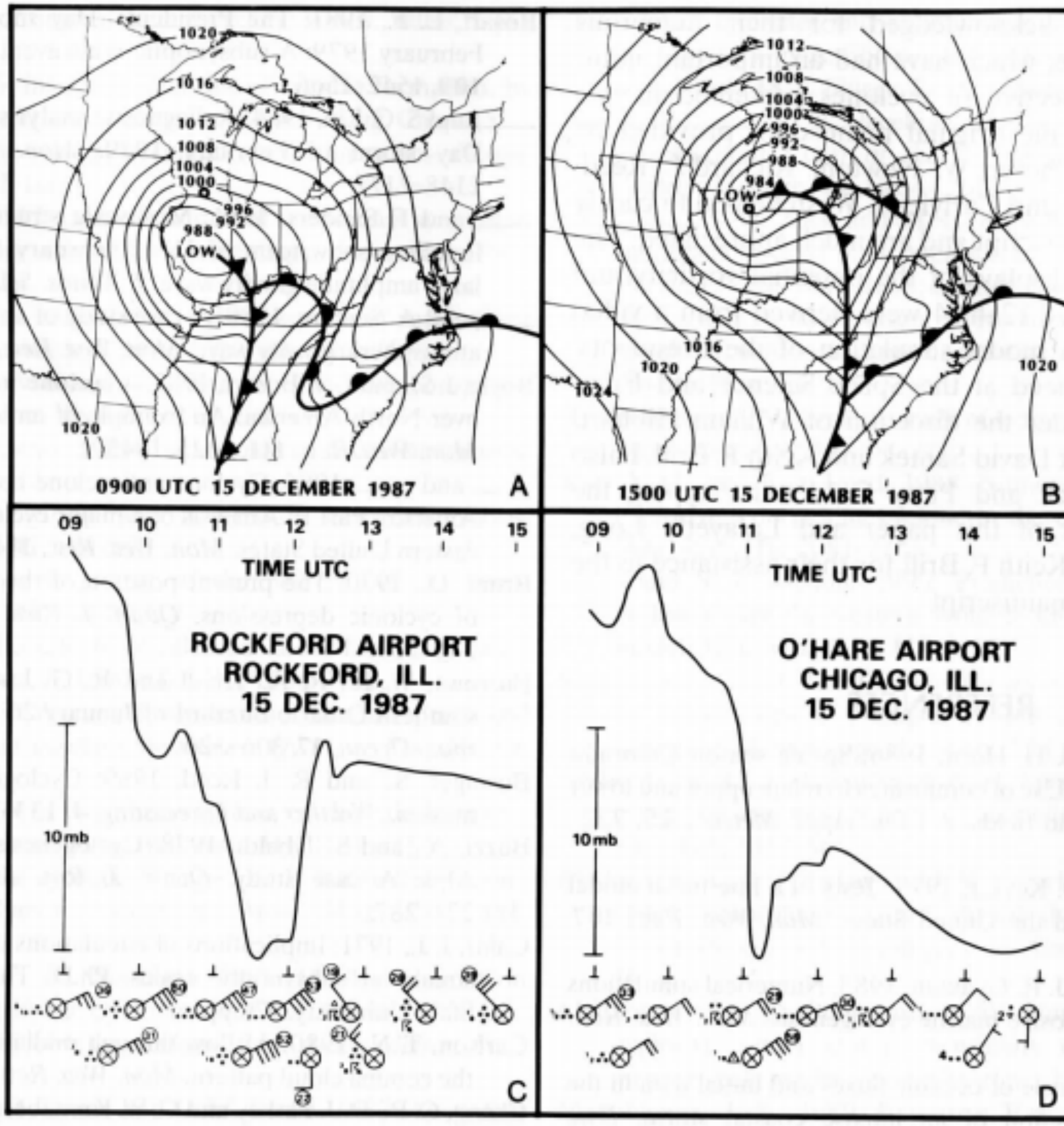
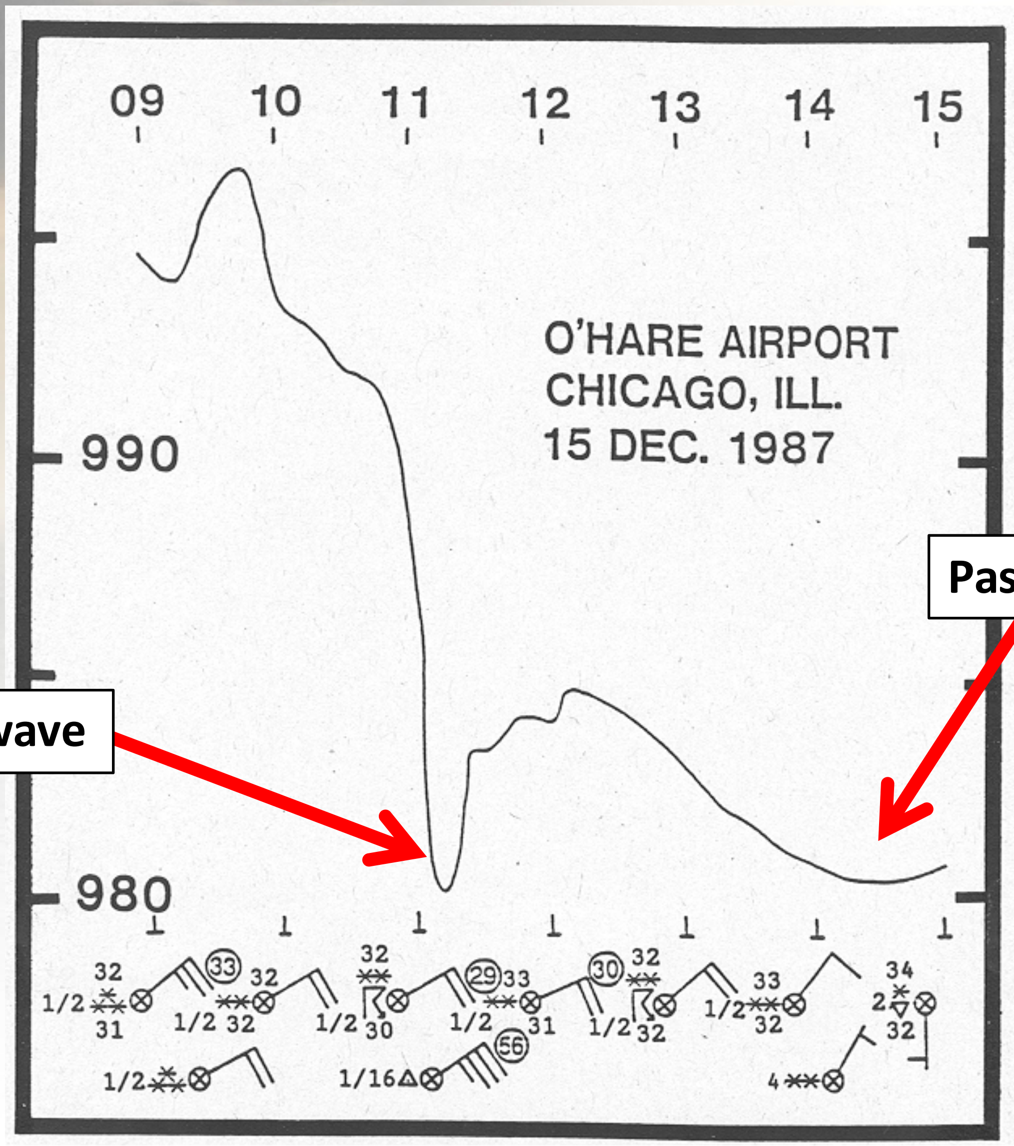


FIG. 6.23. Sea-level pressure (mb) and surface front analyses for (a) 09 UTC and (b) 15 UTC 15 December 1987. Pressure traces and hourly surface observations for (c) Rockford, Illinois and (d) Chicago O'Hare International Airport; locations indicated by circles in (a) and (b), respectively. Surface observations include wind direction and speed, gusts (kn) encircled, visibility (miles) and weather (symbols standard). (Figure derived from Schneider 1990.)

Schneider, 1990

Pressure Trace through Chicago O'Hare



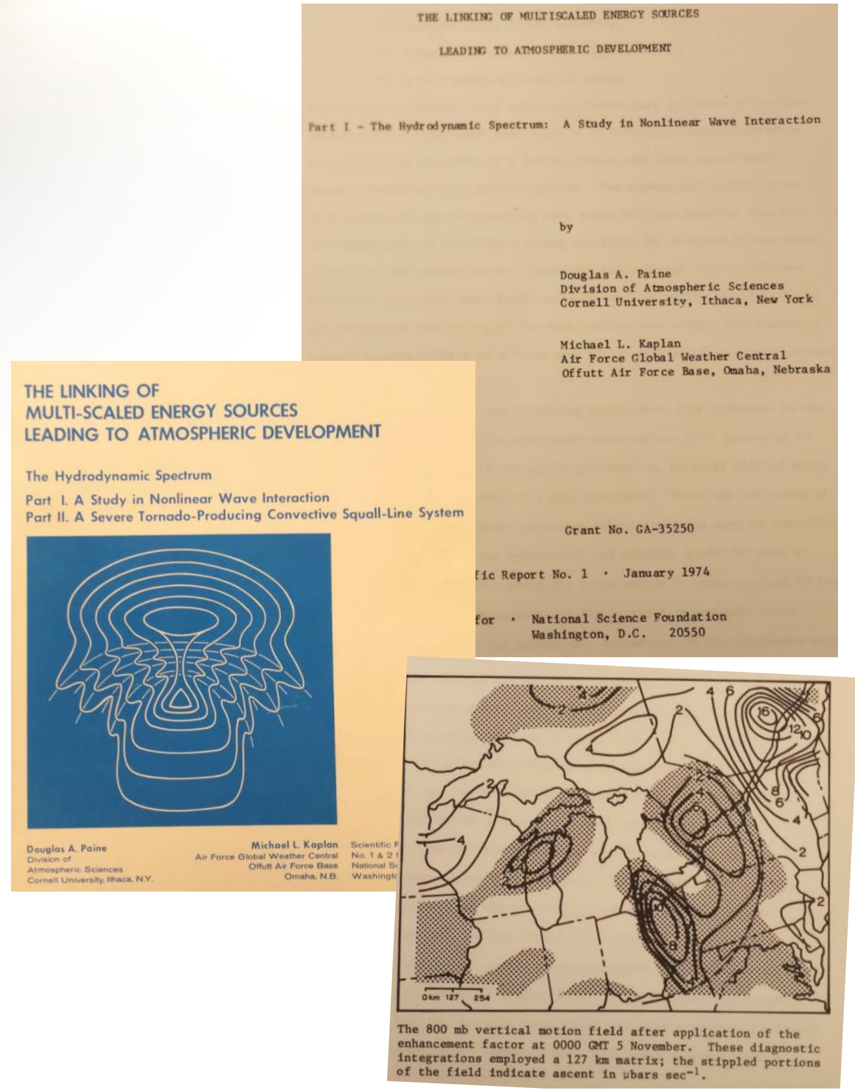
Passage of gravity wave

Passage of synoptic low

Schneider, 1990

Who Gets Lost in the Shuffle

- Morris Tepper
- Jae Eom
- Douglas Paine/Michael Kaplan
  - First to model gravity wave in severe weather event
  - Unbalanced flow described in terms of the divergence equation: Momentum surge (negative Jacobian) directed towards a "geopotential negative Laplacian" works towards an unbalanced state
  - This is simply a jet propagating towards the ridge crest



Paine and Kaplan, 1974

Concerns and Opportunities

- In order to understand larger scale gravity waves and their influence on the weather, need to do the work!
  - Need the p’ (and u’) analyses mapped against the vertical shear and moisture profiles
- Opportunities:
  - New observations (Lidar)
  - Ability of the finer scale non-hydrostatic model
  - Coming soon: 1 minute improved ASOS data

Why is This Important?

- Forecasters are already starting to account for gravity waves in forecast and warnings

Example from WFO Raleigh, NC:

(1:54 PM) nwsbot: RAH issues STRONG WIND GUSTS POSSIBLE IN THE SANDHILLS AND SOUTHERN PIEDMONT EARLY THIS AFTERNOON for Alamance, Chatham, Davidson, Durham, Forsyth, Franklin, Granville, Guilford, Orange, Person, Randolph, Vance, Wake, Warren [NC] till 5:00 PM EST

(2:28 PM) nwsbot: RAH issues STRONG WIND GUSTS POSSIBLE ACROSS THE PIEDMONT AND COASTAL PLAIN THIS AFTERNOON for Chatham, Cumberland, Durham, Edgecombe, Franklin, Granville, Halifax, Harnett, Hoke, Johnston, Lee, Moore, Nash, Orange, Sampson, Vance, Wake, Warren, Wayne, Wilson [NC] till 5:00 PM EST

(2:34 PM) nws-barrett.smith: We issued an SPS for the apparent gravity wave that has been tracking north from Georgia earlier this moring. there was a repor of damage in Darlington, SC earlier this hour, and several observations of 35-40kt accompanying the pressure/rise couplet.

TRACK OF THE MID-LEVEL LOW AND NORTHERN STREAM WAVE PASSING TO OUT NORTHWEST) AND ALSO EAST OF I-95 (NEAR AND EAST OF THE SURFACE LOW). ADD IN A POSSIBLE GRAVITY WAVE NOTED IN SURFACE OBS IN SOUTHWEST GEORGIA THIS MORNING...WHICH MAY BE A PART OF WHY THE HRRR SHOWS A RAPID SPLIT IF QPF WITH NORTHERN EXTENT THIS AFTERNOON. HIGHS WILL RANGE FROM MID 40S NW TO MID 50S SE.

Summary

- History of gravity wave research and application is a wild one – honored to be a part of it
- 2-4 hour gravity waves are an important component of the overall spectrum of adjustment to unbalanced flow (from cyclone to mesoscale convective complex to turbulence)
- Gravity waves have significant impact on weather (winds, convection, turbulence…)
- Forecaster interest – gravity wave concepts now being applied in real time
- Models illustrate consistent wave/weather connections (stay tuned)
- Life should be good for gravity wave research – structure evolution, energy sources, weather influences. Lots of problems left to be solved!

Sources

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