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Ionospheric Observation of Gravity-Waves Associated With Hurricane Eloise

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Abstract. An experiment conducted by using a continuous wave-spectrum high frequency radio wave Doppler sounder array with three sites and nine transmitters (each site with three transmitters) was carried out to observe the coupling of energy between the troposphere and the ionosphere during the period of Hurricane Eloise. The analysis of the Doppler sounder records indicated that gravity waves were detected when the eye wall of Hurricane Eloise was located at the Gulf of Mexico. A group ray tracing has been used in an attempt to locate the sources of these waves. Wave sources are located along the storm track and near the storm center. The wave excitation mechanism is discussed.

Key words: Hurricanes – Gravity waves – Ionosphere.

1. Introduction

In the past decade, observations made by Georges (1968), Baker and Davies (1969), Davies and Jones (1972), Georges (1973), Hung et al. (1975), Smith and Hung (1975), and Hung and Smith (1977a; 1977b) show a correlation between ionospheric wave-like disturbances and severe weather activity. A recent study of Hung et al. (1978a, 1978b) and Hung and Smith (1978a, 1978b) indicated a close correlation of atmospheric gravity waves and tornado activity. The present study reveals the correlation of gravity waves observed in ionospheric height and the activity of Hurricane Eloise.

The correlation of the atmospheric acoustic-gravity waves and severe storms has been investigated in the past twenty years. Tepper (1950, 1954) proposed that the pressure jump lines effectively lifted the lowest layers of the atmosphere and appeared to initiate squall line development in convectively unstable air. Matsumoto and Akiyama (1969); Matsumoto and Tsuneoka (1969); and Matsumoto et al. (1967a, 1967b) contended that acoustic-gravity waves were responsible for a pulsating tendency of winter and summer convective storms in Western

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Japan. Recently Uccellini (1975) proposed that acoustic-gravity waves are an important mechanism for the initiation of severe convective storms. He also suggested that the study of acoustic-gravity waves could reveal the development of thunderstorms.

It is also suggested that the spiral bands of hurricans and typhoons behave like gravity waves. Tepper (1958) and Abdullah (1966) hypothesized that the bands are gravity waves similar to pressure jumps. Based on numerical simulation, Kurihara (1976) shows that a spiral band of tropical cyclone, which propagates outward, can grow in the presence of the horizontal shear of the basic azimuthal flow. The horizontal wavelength of the band is 200 km, and the characteristics of waves behave like gravity modes.

Gravity waves are also important in understanding the behavior of ionospheric irregularities (Hines, 1960). The ionospheric irregularities known as TID's (traveling ionospheric disturbances) observed by Munro (1950, 1958) have been identified as gravity waves in the form of the fluctuations of ionization in the F region (e.g., Rishbeth and Garriot, 1969). TID's, in general, can be divided into two categories, large scale TID's and medium scale TID's based on the characteristics of wave propagation (e.g., Kato, 1976). The large scale TID's have been identified to be the production of Joule heating and of Ampere mechanical force at the auroral zone during magnetic substorms (e.g., Chimonas and Hines, 1970; Testud, 1970). Medium scale TID's have been observed more often than large scale TID's and may be excited by various sources including meteorological severe storm activity and magnetic disturbances. The discussion of the characteristics of gravity waves in lower and upper atmospheres are given by Gossard and Hooke (1975), and we are limiting ourselves to examine the gravity waves associated with severe storms, in particular, hurricanes in this study.

The observation of atmospheric gravity waves (medium scale TID's) associated with severe storms at the ionospheric height is possible when severe thunderstorms with tops (radar heights) in excess of about 12 km occurred within a radius of several hundred kilometers of the ionospheric reflection points (Georges, 1976; Prasad et al., 1975), or only when intense updrafts of clouds penetrate the tropopause. A similar idea was proposed by Saunders (1962), that the convection regions imbedded in the stratiform anvil of the thunderstorms are clearly the overshooting convective cells which penetrate the tropopause. Observations of the hurricane eye wall by radar echoes made by Malkus (1960) also indicate that the eye wall cloud penetrate well above the tropopause. By taking photographs from a U-2 airplane flying over the thunderstorms, Vonnegut et al. (1966) also showed that convective overshooting turrets rose above the anvil cloud and penetrated the tropopause. This may suggest that the penetration of the intense updrafts of convection through the tropopause could be the mechanism of wave generation. In other words, the process of convective overshooting associated with severe thunderstorms (which in turn is associated with tornadoes) or with the wallclouds of hurricanes is responsible for the generation of atmospheric acoustic-gravity waves. Recent observations made by ATS satellites (Fjuita, 1974) and Skylab (Black, 1977) also endorse the correlation of the growth and collapse of convective overshoot-

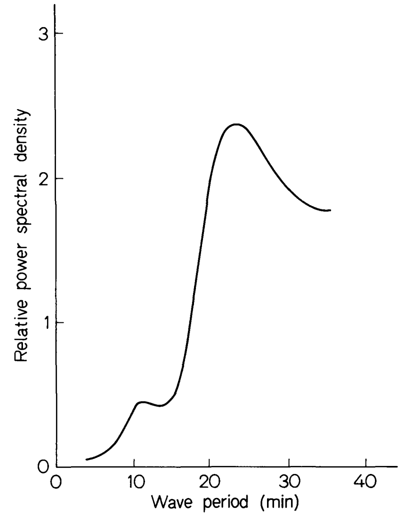

Fig. 1. Power spectral density of waves from Muscle Shoals, Alabama to Huntsville, Alabama at 0200–0340 UT, 9–23–1975

ing turrets associated with severe storms and the generation of gravity waves.

In the present study, we are particularly interested in the investigation of hurricane-associated acoustic-gravity waves which were observed on ground-based ionospheric sounding records as perturbations in electron densities at ionospheric heights. We have employed a continuous wave-spectrum high frequency radio wave Doppler sounder array to observe ionospheric disturbances during the activity of Hurricane Eloise which was located at the Gulf of Mexico on September 23, 1975. The evidence for the coupling of energy from the troposphere into the ionosphere has come from observations of electron density fluctuations which appear as changes of phase and frequency of the ionospherically reflected radio waves.

The results of the coupling between the troposphere and the ionosphere through the upward propagation of gravity waves during the time period of hurricane activity are discussed. The probable errors in computed trajectories of the observed waves will be discussed in Sections 2 and 4.

2. Experiments and Data Analysis

Our Doppler array system consists of three sites with nine field transmitters operating at 4.0125, 4.759 and 5.734 MHz. These sites are located in Northern Alabama and the Tennessee Valley area. A detailed description of the geographical locations and array systems have been given by Hung et al. (1978a) and Hung and Smith (1978a). The propagation characteristics of atmospheric gravity waves can be observed from electron density fluctuations in the ionosphere.

During the time periods of the Hurricane Eloise activity on September 22–23, 1975, wave-like fluctuations were observed at F-region ionospheric heights with wavelengths on the order of 100 km. These observed traveling ionospheric distur-

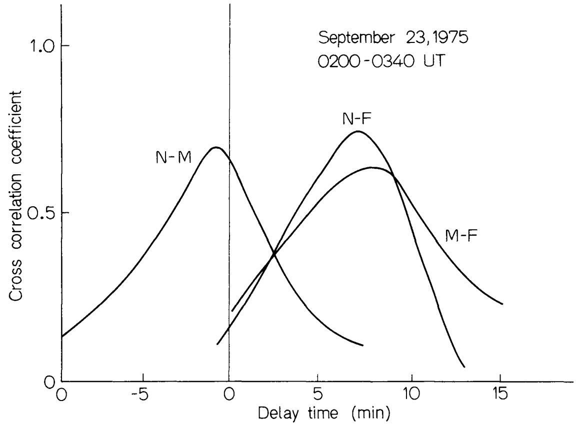

Fig. 2. Cross correlograms at time period 0200–0340 UT, 9–23–1975

bances (TID's) associated with hurricanes belong to medium scale TID's in contrast with large scale TID's associated with geomagnetic activity initiated at the auroral zone (Kato, 1976).

Doppler records observed were subjected to power spectral density analysis and cross-correlation analysis. As an example, Figure 1 shows power spectral density of the ionospheric disturbances from the transmitters at Muscle Shoals, Alabama to the receivers at Huntsville, Alabama, at the observation time 0200–0340 UT, September 23, 1975. The wave period of the disturbances during this time period of observation is 23 min.

The amplitude of the gravity waves is inversely proportional to the square root of the density of the medium (Davies and Jones, 1972). The observed amplitude of the gravity waves associated with severe storms also depends upon the distance from the location of the wave source to the point of the wave observation. The amplitude of waves associated with different types of severe storms, such as severe thunderstorms, tornadoes, and/or hurricanes are all in the order of 0.1 to 0.5 Hz of frequency shift measured at F-2 region ionospheric heights.

As usual, the horizontal phase velocity of the disturbances can be computed from cross-correlograms (detailed description see Hung et al., 1978a). Figures 2 and 3 show cross-correlograms during the time interval 0200–0340 and 0500–0730 UT, September 23, 1975. The accuracy of the determination of the azimuthal angle of wave propagation is within $\pm 5°$, and the horizontal phase velocity is within ± 8 percent of deviation in this set up.

In this experiment, the following characteristics of waves were observed: (1) in the time period 0200–0340 UT, gravity-waves with wave periods of 23 min, azimuthal angle of wave vector 353°, and horizontal phase speed 160 m/s were observed; and (2) in the time period 0500–0730 UT, gravity waves with wave periods of 23 min, azimuthal angle of the wave vector 344°, and horizontal phase speed of 195 m/s were detected.

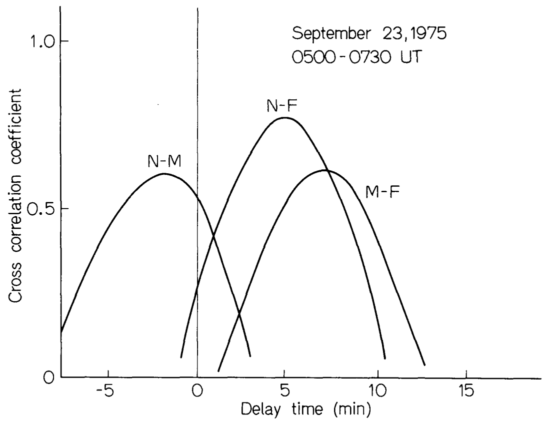

Fig. 3. Cross correlograms at time period 0500–0730 UT, 9–23–1975

3. Reverse Ray Tracing

Theoretical discussions of group rays of atmospheric gravity waves have been carried out by Bretherton (1966), Jones (1969), Cowling et al. (1971) and Bertin et al. (1975). These discussions suggest that the geometrical optics approximation seems valid for the ray propagation of gravity waves if the distance from the source to the point of observation is much longer than the wavelength of the gravity waves. This is approximately true for our case. The wave propagated is assumed to be locally plane so that a local dispersion relation of atmospheric gravity waves, proposed by Hines (1960), is satisfied. Ray tracing, thus, could be carried out by following the group velocity direction in a wind-stratified model atmosphere.

The propagation of wave energy in a lossless transparent medium follows the direction of the group velocity (e.g., Yeh and Liu, 1972). This direction is termed ray direction. In general, in an anisotropic medium the ray direction is different from that of the wave vector. The reverse ray tracing computation is the integration of group velocity with respect to time domain from the ionospheric reflection point back down to the tropopause using the wave period, wavelength, and azimuthal direction of wave propagation obtained from the observational data, the initial vertical wave vector computed from the dispersion relation and appropriate atmospheric parameters. The effect of wind was taken into account by considering the time-space transformation given by the Galilean transformations of displacement vector, time, Doppler-shift of wave frequency, and wave vector. The detailed description of group ray tracing computation has been given in another article (Hung and Smith, 1978a).

In the present paper, the neutral wind is treated as constant in each slab of the atmosphere considered. The values of atmospheric parameters for each altitude are calculated from the U.S. Standard Atmosphere (1962). The profiles of the neutral winds are established using data from the following two sources:

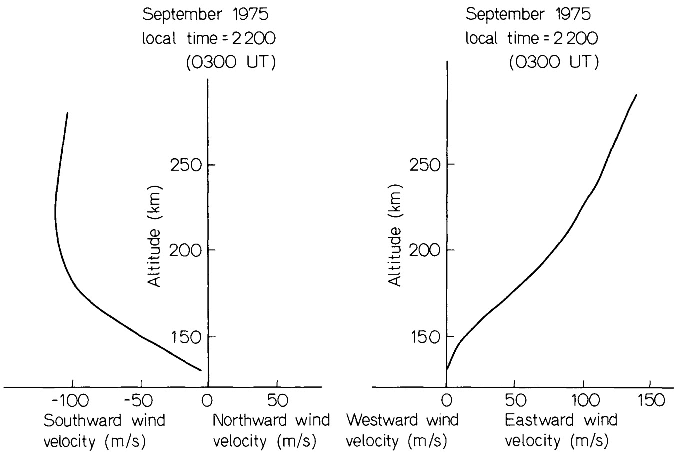

Fig. 4. Computed vertical wind profiles of meridional and zonal components at 2200 local time (0300 UT), September 1975

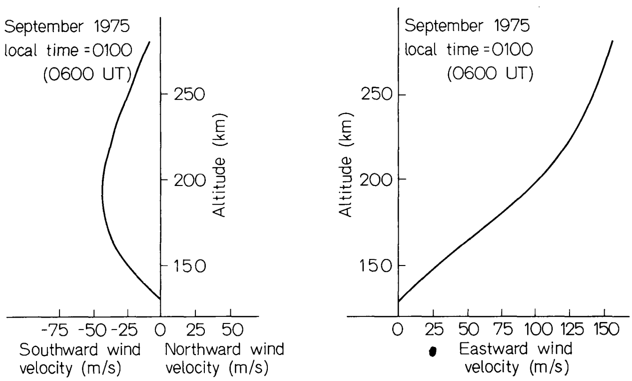

Fig. 5. Computed vertical wind profiles of meridional and zonal components at 0100 local time (0600 UT), September 1975

(1) wind profiles above 100 km altitude are computed from the atmospheric wind model proposed by Kohl and King (1967); (2) at an altitude below 90 km, wind profiles are obtained from meteorological rocketsonde data at Cape Kennedy, Florida.

Figure 4 shows two computed vertical wind profiles from the Kohl and King Model (1967) for zonal component and meridional component at 2200 local time (0300 UT), September 1975. Figure 5 indicates two similar computed vertical wind profiles from the Kohl and King Model (1967) at 0100 local time (0600 UT), September 1975. The observed vertical wind profiles of meridional and zonal components from the meteorological rocketsonde data at 1426 UT, September 23, 1975, at Cape Kennedy, Florida are given in Figure 6.

The wind model proposed by Kohl and King (1967), however, started with

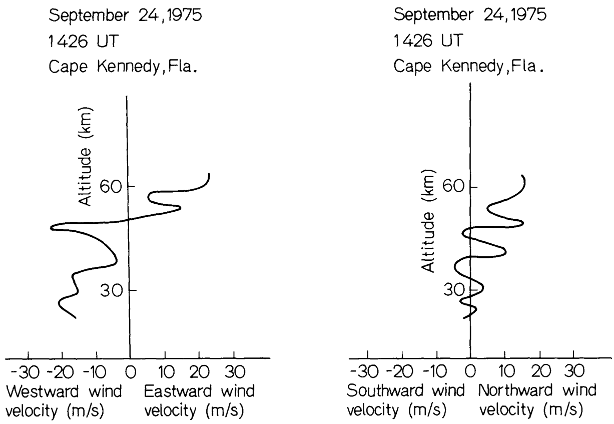

Fig. 6. Observed vertical wind profiles of meridional and zonal components at 1426 UT, 9–24–1975, Cape Kennedy, Florida

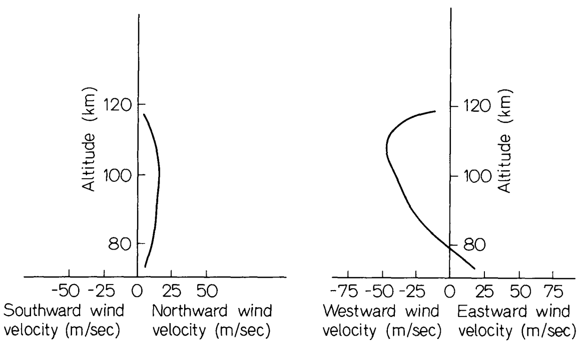

Fig. 7. Wind profiles from altitudes of 70 to 120 km based on 25 sodium cloud experiments from Wallops Island during the summer time

an artificial boundary condition for which the wind velocity is equal to zero at altitude 120 km. To make up this discrepancy, wind profiles based on 25 sodium cloud experiments from Wallops Island (see West et al., 1977), from altitudes of 70 to 120 km as illustrated in Figure 7, were used and faired into meteorological rocketsonde data from Cape Kennedy and computed thermospheric one based on Kohl and King's model. These wind profiles were also checked with the four dimensional wind model (Justus et al., 1974a, 1974b) used by NASA for spacecraft design purposes.

4. Sources of Waves

The reverse ray tracing is started at an altitude of ionospheric reflection height with a frequency of 4.0125 MHz and continues as long as the calculation is

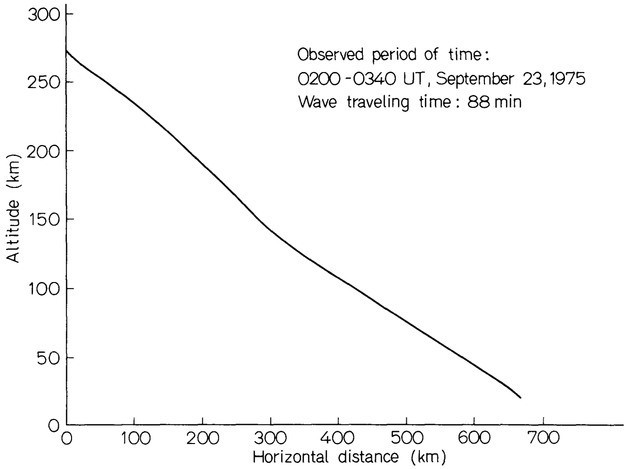

Fig. 8. Trajectory of the computed reverse group ray path for the waves at time periods 0200–0340 UT, 9–23–1975

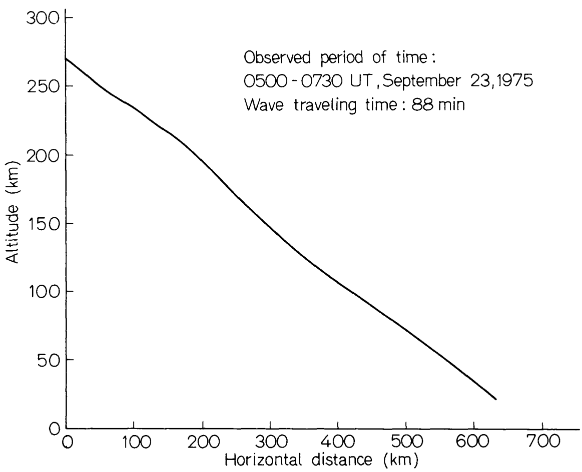

Fig. 9. Trajectory of the computed reverse group ray path for the waves at time period 0500–0730 UT, 9–23–1975

possible to a lower limit of 10 km altitude or the altitude of tropopause. For the purpose of the present study the geographic location of the point at which the calculation is terminated is referred to as the probable source. The probable source of acoustic-gravity waves are then checked with the actual physical features, which is the meteorological observation of storm track of Hurricane Eloise.

It is interesting to review the historical development of Hurricane Eloise. Eloise moved off the coast of Africa as a weak disturbance on September 6, 1975. It then followed a steady westward path across the Atlantic becoming

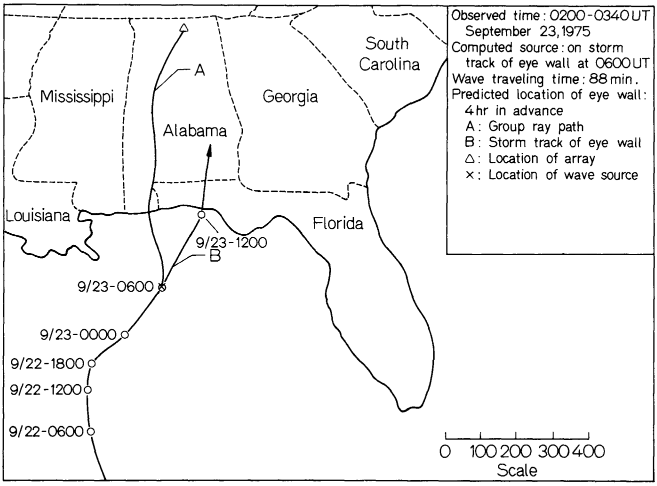

Fig. 10. Geographical map of the trajectory of computed source of waves at time period 0200–0340 UT, 9–23–1975

a tropical depression 600 km east of the Leeward Island on September 13, was named a tropical storm and subsequently a hurricane north of Puerto Rico on the 16th. The westward track carried the center or eye over eastern Cuba and as it moved out over the water, Eloise became a tropical storm once again. After crossing the northeastern tip of the Yucatan Penisula, Eloise turned northward into the Gulf of Mexico on the 21st reaching hurricane force once more on the morning of the 22nd. By that evening, Eloise turned rather abruptly northeastward towards the Florida coastline.

Figure 8 shows trajectory of the computer reverse ray path for the waves observed during time period 0200–0340 UT, September 23, 1975, in terms of height against horizontal distance. Figure 9 shows another trajectory of the computer reverse ray path observed during the time period 0500–0730 UT, September 23, 1975 for the similar profile. Again the group ray paths in the horizontal distance are projected in the map to show the geographical location of the probable sources of waves.

Figure 10 shows the horizontal ray path and the geographical location of the probable source of the wave which was detected in the ionospheric height with receivers at Huntsville, Alabama, at 0200–0340 UT, September 23, 1975. The computed location of the wave source is located right on the storm track of the eye wall at 0600 UT, September 23, 1975. The calculated traveling time of this wave from the probable source to the receiver at Huntsville, Alabama was 88 min. Thus, in this particular case, the location of the wave source was along the storm track and about 90 km distance from the storm center or 4 h in advance of the location of the eye wall.

Figure 11 presents another geographical location of the probable source of the wave which was observed at 0500–0730 UT, September 23, 1975. In this case, the computed probable source of the wave is located right on the

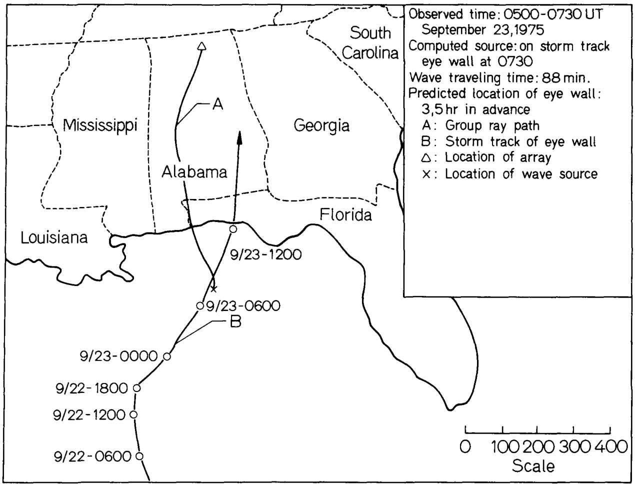

Fig. 11. Geographical map of the trajectory of computed source of waves at time period 0500–0730 UT, 9-23-1975

storm track of the eye wall at 0730 UT, September 23, 1975. The calculated traveling time of this wave from the probable source to the receiver at Huntsville, Alabama was also 88 min. Thus, the wave source was located along the storm track of Hurricane Eloise, and about 80 km distance from the storm center or approximately 3.5 h in advance of the location of the eye wall.

The determination of probable errors or ranges in the reverse ray tracing computation due to the accuracy of the determining of the azimuthal angle of wave propagation and horizontal phase velocity are rather standard. However, it is not easy to determine the errors due to the uncertainty of the wind profiles, in particular, the lacking of real time measurements of the thermosphere part of wind profiles. Hung and Smith (1978a) has estimated the probable errors caused by double the wind velocity, reduce the wind velocity to half, rotate 90° the direction of wind velocity counterclockwise, and rotated 180° the direction of the wind velocity for horizontal distance around 400 km and found that, even under the situation as mentioned, the probable errors are within ± 12 km per 100 km of the horizontal distance. The total probable errors can be estimated based on more than twenty cases of reverse ray tracing computations, compared with physical features of storm data, that the computed probable errors are less than ± 20 km per 100 km of the horizontal distance of ray tracing in our cases. If the probable errors less than ± 20 km per 100 km of the horizontal distance is taken into account, the location of the probable sources of waves was around the outer layer of the wall cloud and 70 to 150 km distance from the storm center. This result agrees with outward propagating gravity waves in the numerical model developed by Kurihara (1976) in which the gravity waves excited around the inner layer of the wall cloud propagate inward with a higher damping rate and the gravity waves developed around the outer layer of the wall cloud propagate outward with a low damping rate.

In addition to the work by Georges (1976), Prasad et al. (1975), Saunders (1962), and Malkus (1960), Vonnegut et al. (1966) using photographs from a U-2 airplane flying over the thunderstorms, showed that convective overshooting turrets rose above the anvil cloud and penetrated the tropopause. This may suggest that the penetration of intense updrafts through the tropopause could be the wave generation mechanisms. Recent Skylab observations (Black, 1977) based on stereophotographs taken from tropical storm Ellen also indicated the overshooting turrets above the tropopause in the wall clouds.

From a fluid dynamics point of view, Lighthill (1952, 1954, 1962, and 1967), Townsend (1968, 1969), and Deardorff et al. (1969) show that gravity waves can be generated by tongues of turbulence penetrating above the turbulent convective zone. This suggests that the overshooting and ensuing collapse of the convective turrets may be responsible for the generation of the atmospheric acoustic-gravity waves. Recently, Shenk (1974) made extensive observations of strong convective cells of severe storms using geosynchronous satellite data and U-2 photographs. When the results of Shenk's analysis are used in the model proposed by Lighthill (1952, 1954, 1962, and 1967), waves with the same periods as those waves associated with severe storms observed by the Doppler array are excited (Hung and Smith, 1977b). Furthermore, by using relative cloud heights of hurricane wall clouds based on photographic enhancement techniques computed from Skylab photographs (Black, 1977) and the growth rate of turrets estimated by Fujita (1974), in Lighthill's model, the wave period in the range of 20 to 25 min associated with hurricanes in the present observation can be generated. The detailed description of the wave generation mechanism will be published in subsequent papers.

George (1960) reported that hurricanes tend to move toward the location where the K-instability index[1] is a maximum with a higher index being related to a higher moisture content and a higher temperature. Results of this study seem to indicate that this is the location of the source of the waves. The possibility of using a combination of these facts as a prediction technique will be the subject of future investigations. This study suggests that the analysis of ionospheric Doppler sounder observations of gravity associated with hurricanes, together with the study of the growth and collapse of convective overshooting turrets based on satellite photographs, can contribute to the understanding of the dynamical behavior of hurricanes.

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[1] Definition of K index is

K = (850-mb temp − 500-mb temp) +
(850-mb dewpoint) − (700-mb dewpoint depression)

which has been widely used by meteorologist to predict severe weather (George, 1960)

References

Abdullah, A.J.: The spiral bands of a hurricane: A possible dynamic explanation. J. Atmos. Sci. **23**, 367–375, 1966

Baker, D.M., Davies, K.: F2-region acoustic waves from severe weather, J. Atmos. Terr. Phys. **31**, 1345–1352, 1969

Bertin, F., Testud, J., Kersley, L.: Medium scale gravity waves in the ionospheric F-region and their possible origin in weather disturbances. Planet. Space Sci. **23**, 493–507, 1975

Black, P.G.: Some aspects of tropical storm structure revealed by handheld-camera photographs from space, in Skylab Explores the Earth, ed. by V.R. Wilmarth, NASA SP-380, pp. 417–461, 1977

Bretherton, F.P.: The propagation of groups of internal gravity-waves in a shear flow. Quant. J. Roy. Meteor. Soc. **92**, 466–480, 1966

Chimonas, G., Hines, C.O.: Atmospheric gravity waves launched by auroral currents. Planet. Space Sci. **18**, 565–582, 1970

Cowling, D.H., Webb, H.D., Yeh, K.C.: Group rays of internal gravity waves in a wind stratified atmosphere. J. Geophys. Res. **76**, 213–220, 1971

Davies, K., Jones, J.E.: Ionospheric disturbances produced by severe thunderstorms, NOAA Professional Paper 6, U.S. Dept. of Commerce, NOAA, Rockville, Md., pp. 47, 1972

Deardorff, J.W., Willis, G.E., Lilly, D.K.: Laboratory investigation of non-steady penetrative convection. J. Fluid Mech. **35**, 7–31, 1969

Fujita, T.T.: Overshooting thunderheads observed from ATS and Learjet. NASA CR-13859T, 1974

George, J.J.: Weather Forecasting for Aeronautics, pp. 673. New York: Academic Press 1960

Georges, T.M.: Short-period ionsopheric oscillations associated with severe weather, Proc. Symp. Acoustic-Gravity Waves in the Atmosphere, Govt. Printing Office, Washington, D.C., pp. 171–178, 1968

Georges, T.M.: Infrasound from convective storms: Examining the evidence. Rev. Geophys. Space Phys. **11**, 571–594, 1973

Georges, T.M.: Infrasound from convective storms, Part II: A critique of source candidates, NOAA Tech. Rep. ERL 380-WPL49, pp. 59, 1976

Gossard, E.E., Hooke, W.H.: Waves in the Atmosphere-Atmospheric Infrasound and Gravity Waves, Their Generation and Propagation, pp. 456. Netherland: Elsevier Scientific Publ. Co. 1975

Hines, C.O.: Internal atmospheric gravity waves at ionospheric heights, Can. J. Phys. **38**, 1441–1481, 1960

Hung, R.J., Phan, T., Smith, R.E.: Observation of gravity waves during the extreme tornado outbreak of April 3, 1974, J. Atmos. Terr. Phys. 1978a (in press)

Hung, R.J., Phan, T., Smith, R.E.: Ionospheric Doppler sounder as remote sensing for detection and prediction of severe storms. AIAA Paper, No. 78–250, 1–6, 1978; also AIAA Journal, **16**, 763–766, 1978b

Hung, R.J., Smith, R.E.: Observation of upper atmospheric disturbances caused by hurricanes and tropical storms. Space Res. **17**, 205–210, 1977a

Hung, R.J., Smith, R.E.: Study of stratospheric-ionospheric coupling during time periods of thunderstorms and tornadic storms. Space Res. **17**, 210–216, 1977b

Hung, R.J., Smith, R.E.: Ray tracing of gravity waves as a possible warning system for tornadic storms and hurricanes. J. Appl. Meteorol. **17**, 3–11, 1978a

Hung, R.J., Smith, R.E.: Dynamics of severe storms through the study of thermospheric-tropospheric coupling. J. Geomag. Geoelectr., 1978b (in press)

Hung, R.J., Smith, R.E., West, G.S., Henson, B.B.: Detection of upper atmospheric disturbances in Northern Alabama during extreme tornado outbreak of April 3, 1974, Ninth Conference on Severe Local Storms, Amer. Meteor. Soc., Boston, Mass., pp. 294–300, 1975

Jones, W.L.: Ray tracing of internal gravity waves. J. Geophys. Res. **74**, 2028–2033, 1969

Justus, C.G., Woodrum, A.W., Roper, R.G., Smith, O.E.: Four-D Global Reference Atmosphere Technical Description, Part I, pp. 106, NASA TM-X-64871, 1974a

Justus, C.G., Woodrum, A.W., Roper, R.G., Smith, O.E.: Four-D Global Reference Atmosphere Technical Description, Part II, pp. 206, NASA TM-X-64872, 1974b

Kato, S.: Thermospheric Waves – a Review. J. Geomag. Geolectr. **28**, 189–206, 1976

Kohl, H., King, J.W.: Atmospheric winds between 100 and 700 km and their effects on the ionosphere. J. Atmos. Terr. Phys. **29**, 1045–1062, 1967

Kurihara, Y.: On the development of spiral bands in a tropical cyclone. J. Atmos. Sci. **33**, 940–958, 1976

Lighthill, M.J.: On sound generated aerodynamically, I. General theory. Proc. Roy. Soc. A **211**, 564–587, 1952

Lighthill, M.J.: On sound generated aerodynamically, II. Turbulence as a source of sound. Proc. Roy. Soc. A **222**, 1–32, 1954

Lighthill, M.J.: Sound generated aerodynamically. Proc. Roy. Soc. A **267**, 147–182, 1962

Lighthill, M.J.: Prediction on the velocity field coming from acoustic noise and a generalized turbulence in a layer overlaying a convectively unstable atmospheric region. I.A.U. Symposium **28**, 429–469, 1967

Malkus, J.S.: Recent developments in studies of penetrative convection and the application to hurricane cumulonimbus towers. Cumulus Dynamics, pp. 65–84. New York: Pergamon Press 1960

Matsumoto, S., Akiyama, T.: Some characteristic features of the heavy rainfalls observed over the Western Japan on July 9, 1967, Part I: Mesoscele structure and short period pulsation. J. Meteorol. Soc. Japan **47**, 255–266, 1969

Matsumoto, S., Ninomiya, K., Akiyama, T.: A synoptic and dynamic study on the three-dimensional structure of mesoscale disturbances observed in the vicinity of a cold vortex center. J. Meteorol. Soc. Japan **45**, 64–81, 1967a

Matsumoto, S., Ninomiya, K., Akiyama, T.: Cumulus activities in relation to the mesoscale convergence field. J. Meteorol. Soc. Japan **45**, 292–304, 1967b

Matsumoto, S., Tsuneoka, Y.: Some characteristic features of the heavy rainfalls observed over the Western Japan on July 9, 1967, Part II: Displacement and life cycles of mesoscale rainfall cells. J. Meteorol. Soc. Japan **47**, 267–278, 1969

Munro, G.H.: Traveling disturbances in the ionosphere. Proc. Roy. Soc. (London) **A202**, 208–223, 1950

Munro, G.H.: Traveling ionospheric disturbances in the F region. Australian J. Phys. **11**, 91–112, 1958

Prasad, S.S., Schneck, L.J., Davies, K.: Ionospheric disturbances by severe tropospheric weather storms. J. Atmos. Terr. Phys. **37**, 1357–1363, 1975

Rishbeth, H., Garriot, O.K.: Introduction to Ionospheric Physics, pp. 331. New York: Academic Press 1969

Saunders, P.M.: Penetrative convection in stably stratified fluids. Tellus **14**, 177–194, 1962

Shenk, W.E.: Cloud top height variability of strong convective cells. J. Appl. Meteorol. **13**, 917–922, 1974

Smith, R.E., Hung, R.J.: Observation of severe weather activities by Doppler sounder array. J. Appl. Meteorol. **14**, 1611–1615, 1975

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

Tepper, M.: Pressure jump lines in Midwestern United States, January–August 1951. Research Paper No. 37, pp. 70, U.S. Weather Bureau, Washington, D.C., 1954

Tepper, M.: A theoretical model for hurricane radar bands. Preprints Seventh Weather Radar Conf., Miami, Amer. Meteor. Soc., K56–65, 1958

Testud, J.: Gravity waves during magnetic substorms. J. Atmos. Terr. Phys. **32**, 1793–1805, 1970

Townsend, A.A.: Internal waves produced by a convective layer. J. Fluid Mech. **24**, 307–319, 1966

Townsend, A.A.: Excitation of internal waves in a stably-stratified atmosphere with considerable wind-shear. J. Fluid Mech. **32**, 145–171, 1968

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

United States Committee on Extension to the Standard Atmosphere: U.S. Standard Atmosphere 1962, pp. 278, U.S. Govt. Printing Office, Washington, D.C., 1962

Vonnegut, B., Moore, C.B., Espinola, R.P., Blau, H.H., Jr.: Electric potential gradients above thunderstorms. J. Atmos. Sci. **23**, 764–770, 1966
West, G.S., Wright, J.J., Euler, H.C.: Space and Planetary Environment Criteria Guideline for Use in Space Vehicle Development, 1977 Revision, pp. 450, NASA Tech. Memo. 78119, 1977
Yeh, K.C., Liu, C.H.: The Theory of Ionospheric Waves, pp. 467. New York: Academic Press 1972

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