Forecasting Note

Gravity Waves: Those Important to Operational Weather Forecasting

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1. Introduction

We have all seen evidence of gravity waves at times. They occasionally appear as rippled patterns in clouds, or in satellite imagery as shock waves emanating from a central source such as a mesoscale convective complex. These waves do have the effect of changing the original state of the atmosphere in a limited area, and thus are important for atmospheric modeling. A certain type of gravity wave produced in mid-tropospheric regions of highly non-geostrophic flow is the topic of this note. Most of the material presented here is from research work by Steven E. Koch, an expert in gravity waves, who coined the term mesoscale gravity waves for these phenomena.

The mesoscale gravity waves of interest are most common from late fall through early spring. Research by Uccellini and Koch (1987) suggests that they are generated in mid levels where a jet streak rounds the base of a negatively tilted trough, and the flow immediately downstream is highly difluent. After a wave is generated, there has to be a low-level stable layer present downstream to act as a duct for the wave energy. This could be an inversion associated with a warm front or a stationary front. Another possible source is the low-level inversion formed during overrunning events, when surface high pressure wedges into Alabama from the east.

Although the understanding of these waves is incomplete, it is believed that the process of geostrophic adjustment in the region of highly diffluent flow generates the waves. It is further argued that the waves can organize and enhance existing areas of precipitation or deep convection. Precipitation areas are not always present when gravity waves are acting. But if they are, there is usually at least one arc-shaped band of rain or showers preceding the wave trough. Some studies (e.g., Trexler and Koch, 1999) have noted increases in intensity of precipitation bands in the presence of a gravity wave. While that alone is interesting, it is the ability of these waves to sometimes bring sudden damaging wind gusts down to the surface that is the main focus here.

A notable Alabama gravity wave case that occurred on February 22, 1998 was documented in a study by Bradshaw et al. (1999). That gravity wave event was responsible for widespread wind damage due to gusts that were around 60 mph at times over central and northern Alabama. There were numerous reports of structural damage and large trees toppled. The gravity wave in that case traveled north at around 60 mph, just to the rear of a broad band of precipitation, and north of a surface warm front across southern Alabama. In another case during the fall of 2002, just a few weeks before the Huntsville office opened, a gravity wave moved east across northern and central Alabama late one evening, producing brief wind gusts of 40 to 50 mph. The timing of the strong gusts, as later deduced from surface observations, indicated that the gravity wave was moving at 50 to 60 mph. There were several reports the next day of minor wind damage such as lawn furniture being blown around. Since that gravity wave event, the author has witnessed five or six more events across northern Alabama, only two of which produced wind gusts over 40 mph. The gravity waves in all cases had speeds of 50 to 60 mph. The weaker events only had surface wind gusts in the 20- to 30-knot range.

The main purpose of this note is to acquaint the reader with the synoptic situation favorable for gravity wave generation. Unless the potential for gravity waves is determined, there is little hope of recognizing when they are present. When it is determined that gravity waves might occur, detecting and tracking them is difficult without a network of 5-minute ASOS pressure data (Koch and O'Handley, 1997). Likewise, the issuance of advisories and warnings is problematic.

One problem is the uncertainty of precisely when and where the first effects will be felt. Another is the movement or phase velocity of the wave. It appears that most of these waves move fast. As a result, lead times are limited, and individual locations in the wave's path usually experience the highest squalls or gusts for just a few minutes. In the case studied by Bradshaw et al. (1999), the damaging winds lasted 10 to 20 minutes at any given spot. Yet another problem is that more than one wave might occur. Assuming reasonably good early detection of an initial wave, it is uncertain when the next one will occur, since the period between waves usually varies from 1 to 4 hours, but can be as much as 6 hours.

The next sections expand on the conditions favorable for wave generation, and describe some general wave characteristics. Then an example of a recent weak gravity wave event in Alabama is given. In the summary section, the main points are restated along with tips for determining when a gravity wave event is actually starting or is in progress.

2. Precursor Synoptic Conditions

a. Generation.

Mesoscale gravity waves are apparently generated by geostrophic adjustment that occurs in mid-tropospheric regions of highly non-geostrophic flow, usually where the flow is highly difluent in the base of negatively tilted troughs. Fig. 1 is a conceptual model by Uccellini and Koch (1987) of a typical 300-mb height field and wind pattern overlaying a favorable surface pattern. The basic surface pattern has many variations as shown in Fig. 2.

In Fig. 1, it is in the region where the jet streak (V) becomes sharply non-geostrophic, and the flow becomes sharply diffluent, that the wave(s) are believed to originate as the atmosphere adjusts to the imbalance of forces caused by the jet streak. Once generated, the waves tend to move downstream toward the upper ridge axis. The most favorable region for wave occurrence and propagation is in the shaded area, near and north of a surface boundary, and between the trough and ridge inflection point and the ridge axis.

b. Ducting the wave energy

Once a gravity wave is generated, it needs a favorable vertical structure in the atmosphere to maintain itself and keep propagating, otherwise it will quickly dissipate. One key ingredient for survival of the wave is a deep low-level inversion or stable layer, such as found north of a surface warm front. The statically stable inversion layer effectively traps or ducts the wave. This keeps wave energy from propagating vertically and dissipating, while also providing a good medium for continued horizontal propagation.

For a gravity wave to propagate with minimal loss of energy, there are theoretical requirements (as put forth by Lindzen and Tung, 1976) for the stable layer, as well as for the thermodynamic structure above the inversion. For example, the static stability of the stable layer must be large, and the layer must be deep enough to contain at least a quarter of the vertical wavelength. Furthermore, the layer immediately above the inversion must be conditionally unstable in order to prevent the wave from propagating its energy out of the stable duct layer. Most studies of gravity wave events have found that these criteria were met.

Obviously, the operational meteorologist does not have time to diagnose these details. However, there is now within AWIPS a product called duct function (originally named duct factor in the literature). It is located in the Volume Browser under Plan View, under the Sfc/2D field, and then at the bottom of the Misc drop-down menu. According to Koch and O'Handley (1997), the duct factor (DF) is a measure of the stable layer or duct strength, and the degree to which the 400- to 700- mb layer is conditionally unstable. Their equation for DF is

$$\mathrm{DF} = \Theta\ (800\ \mathrm{mb}) - \Theta\ (950\ \mathrm{mb}) + \Theta_e\ (800\ \mathrm{mb}) - \Theta_e\ (400\ \mathrm{mb}). \qquad (1)$$

where Θ is potential temperature (°K), and Θ_e is the equivalent potential temperature (°K).

In general, concentrated areas of positive DF values represent regions of strong ducting. Apparently, no minimum positive value of DF has been established as a lower threshold. Koch and Saleeby (2001) suggest that a DF of 10 to 15 is enough for strong ducting. However, gravity waves have been shown to occur in DF environments of 5 to 10 (e.g., Gaffin, 1999).

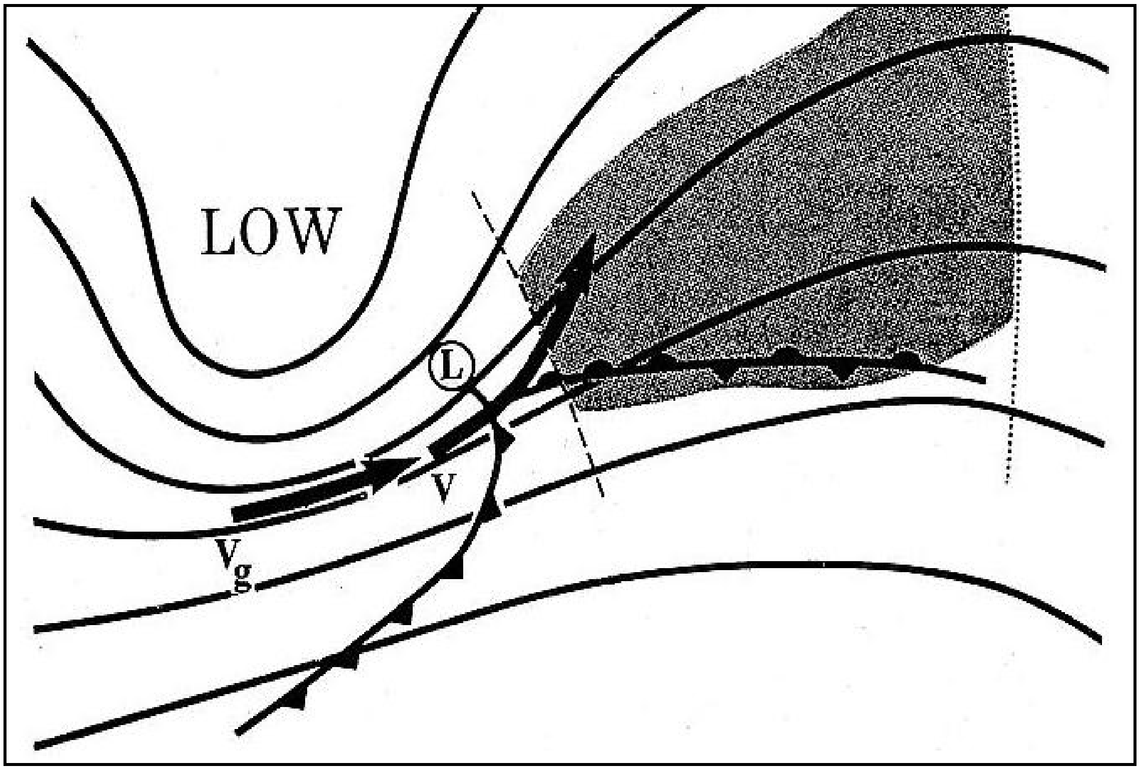


Fig. 1. The typical 300-mb pattern favorable for mesoscale gravity wave generation, atop a favorable surface pattern of cyclone (L) and fronts. A quasi-geostrophic jet streak max (V_g) in the base of the trough becomes highly non-geostrophic (V) as it cuts across geopotential height contours (bold lines). It is in the region near the axis of inflection of the trough and ridge (dashed line) where the flow becomes highly difluent that the waves are believed to originate. Microbarograph observations have shown that gravity wave occurrence and propagation is within the shaded area, along and north of a surface boundary, between the axis of inflection and the 300-mb ridge (dotted line). In practice, the 500-mb pattern often looks similar. Adapted from Koch and Saleeby (2001).

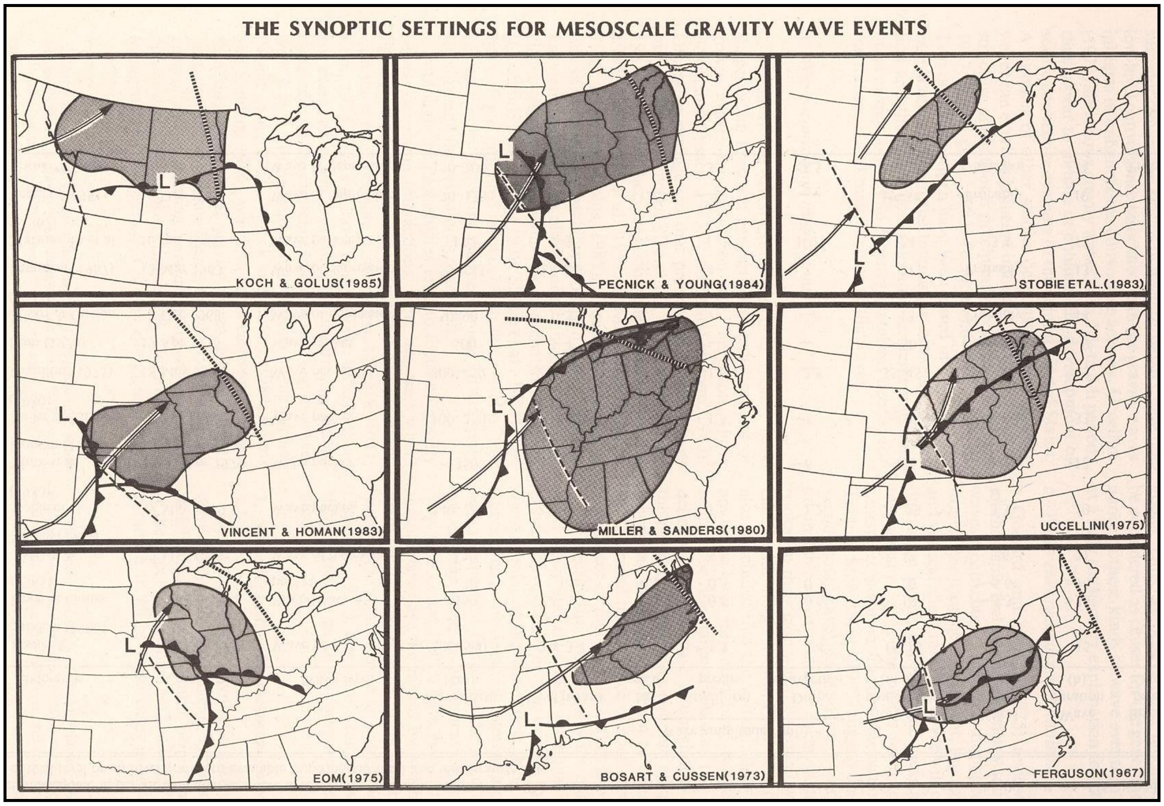


Fig. 2. Assorted types of surface synoptic patterns in which mesoscale gravity waves have occurred. Positions of synoptic features are approximate means during the first half of the events. Shaded areas encompass the entire event in each case. Arrows indicate the paths of jet streaks. The axis of inflection between the 300-mb trough and ridge, and the axis of the 300-mb ridge, are shown as dashed and dotted lines, respectively. Note that the surface pattern in the center of the bottom row occurs when high pressure wedges in from the east. Adapted from Uccellini and Koch (1987).

3. Wave Characteristics

According to Uccellini and Koch (1987), mesoscale gravity waves typically have amplitudes of 1-15 mb, wavelengths of 50-500 km, and periods of 1-4 hours. It was later noted by Koch and O'Handley (1997) that most studies of gravity wave events in the literature indicated wave lengths greater than 150 km. Also, the period for some waves can be up to 6 hours, as observed by Koch and Siedlarz (1999). Individual waves can last for several hours, as can the generation source for the waves. Kaplan et al. (1997) showed that the geostrophic balance process has several complex steps and that it can last up to 12 hours. For purposes of this forecasting note, a look at the structure and speed of gravity waves is important for understanding where to expect gusty surface winds and how to time them.

a. Vertical and horizontal structure

Figure 3 shows a conceptual model from Eom (1975) of a trapped, non-tilted gravity wave of wavelength 160 km, moving east at phase velocity C, with wind patterns represented by horizontal and vertical vectors. Although variations on this idealized model occur, observed gravity waves have confirmed the basic pressure and wind patterns.

The wind field in Fig. 3 shows that a convective band would form close to where upward vertical motion is maximized at nodal points just preceding the wave crest. Also, the greatest downward motion and pressure falls occur at nodal points just ahead of the wave trough, a distance behind the convective band. Initial reports of pressure falling rapidly in ASOS surface observations usually occur after a crest passes and toward the trailing edge of the precipitation. Sometimes reports of pressure rising rapidly are seen near the leading edge of the precipitation. A rise and fall couplet separated by several miles is a good clue that a mesoscale phenomenon is present.

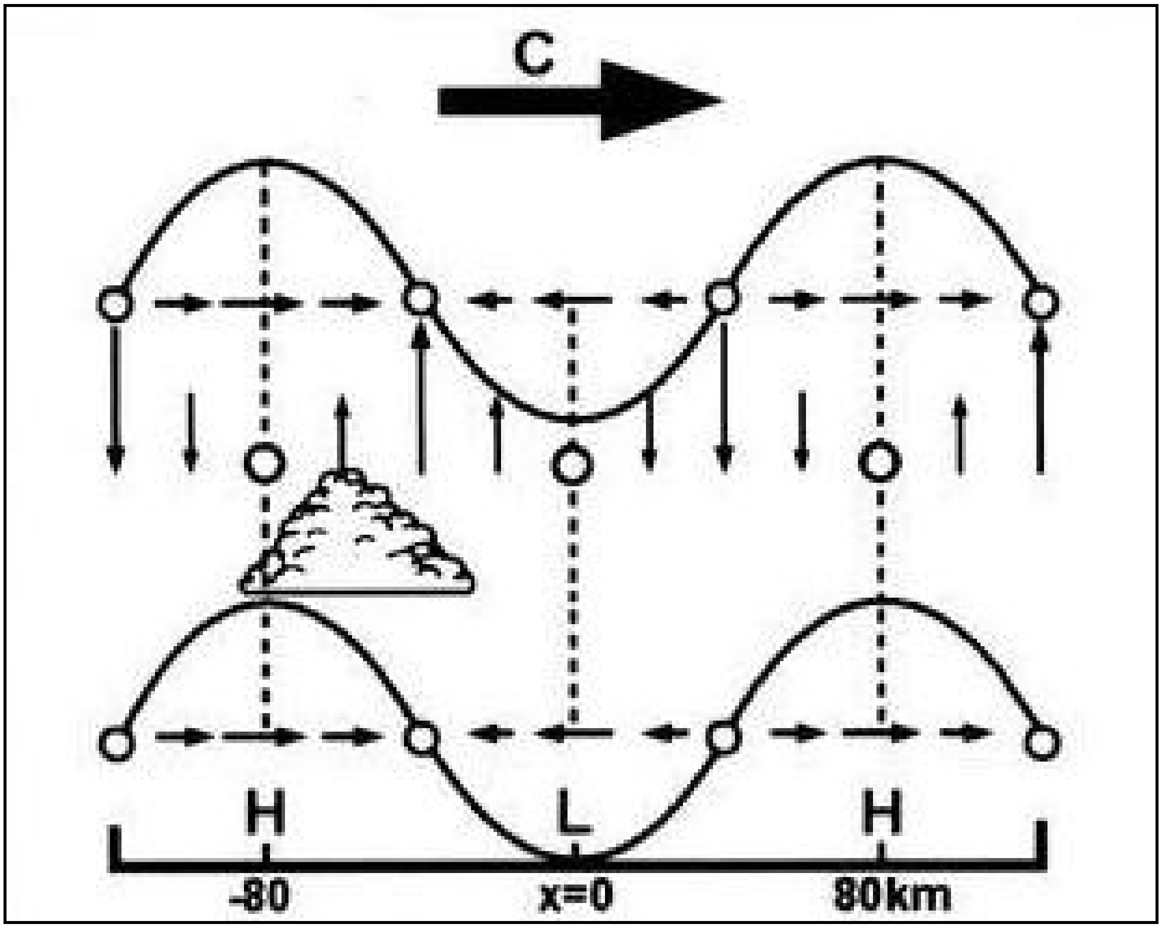
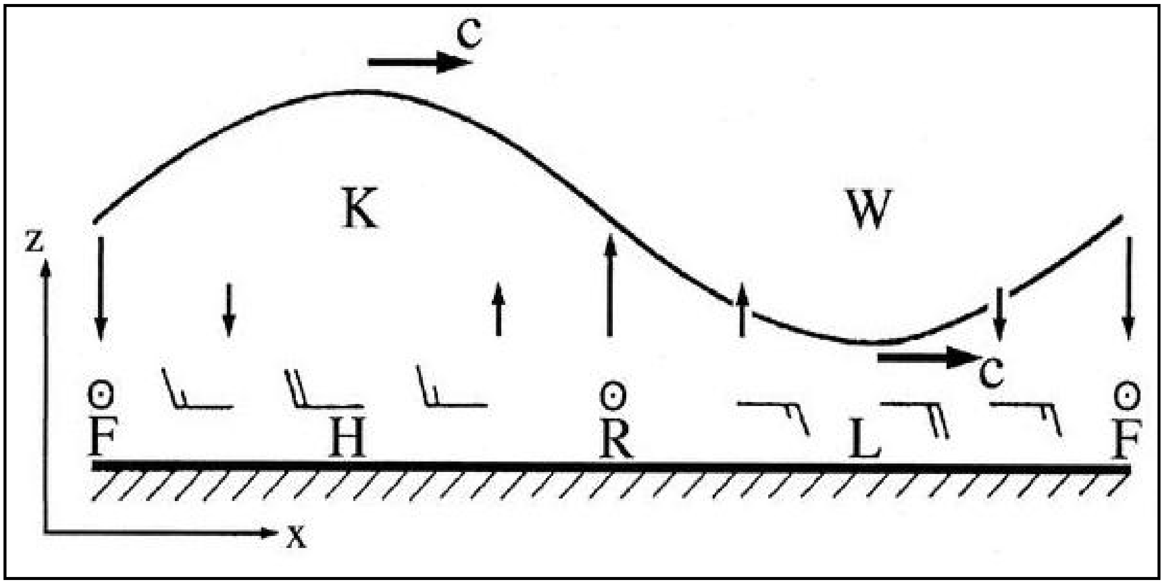


Fig. 3. Idealized non-tilted (trapped) gravity wave with a wavelength of 160 km moving along at phase velocity (speed) C. Nodal points on the wave are shown as open circles. Horizontal and vertical arrows represent the wind field, with high and low surface pressure given by H and L, respectively. After the conceptual model of Eom (1975). Adapted from Koch and Saleeby (2001).

Figure 4 from Trexler and Koch (1999) provides more detail on wind and pressure tendencies near the surface. Note that the approach of a wave trough is heralded by a sudden fall in surface pressure, followed by an increase in surface winds toward the wave trough. It is in that zone from the maximum pressure fall (F) to the wave trough that strong wind squalls or gusts are possible at the ground. In real cases, the direction of strong winds is usually several degrees in opposition to the movement of the wave. The cases seen thus far in our area have had strong winds from the southeast for waves that appeared to be moving from the southwest through west. The typical sequence with a gravity wave trough is: approach of wave trough, sharp surface pressure drop, period of gusty southeast surface winds, approach of wave crest, sharp surface pressure rise.

Returning to Fig. 3, it is very important to note the position of the convective band with respect to the area of potentially strong surface winds. Studies have shown that in virtually all cases where precipitation systems were present, the precipitation area or band was out ahead of the wave trough, with the back edge of precipitation closely coinciding with the sudden pressure falls and increase in surface winds. In other words, the pressure falls and wind increases were accompanied by an abrupt end of precipitation.

A good rule of thumb, given an environment conducive to gravity waves, is that a gravity wave should be suspected if rapid surface pressure falls and increases in surface winds are occurring near the back edge of a precipitation area or band. In general, the strong winds will be near or up to 25 miles behind the trailing edge of the precipitation. However, as already mentioned, not all gravity wave events have precipitation systems to follow. In those cases, where the potential exists for gravity waves, one needs to keep an eye on upstream observations for reports of sudden pressure falls or gustiness.



Fig, 4. Another view of a trapped gravity wave moving along at speed C within the x-z plane. The K and W indicate cold and warm air regions, respectively. Arrows represent the vertical wind field, while conventional shafts and barbs represent the low-level winds. High (H) and low (L) surface pressure are also shown, along with locations of maximum pressure rises (R) and falls (F). Adapted from Trexler and Koch (1999).

b. Typical speeds

The speed or phase velocity of a gravity wave will be largely dependent on the mean flow in which it is embedded. Koch and O'Handley (1997) suggested that the mean wind direction and speed within the stable layer be used to estimate the direction of motion and speed of a wave. Bradshaw et al. (1999) calculated this from the Birmingham sounding for the event they studied. The wave speed was found to be very close to the speed they determined by tracking arrival times of strong winds at specific locations along the wave's path.

It seems that the speed of gravity waves is highly variable due to the variety of synoptic situations in which they can occur. Observed gravity waves mentioned in the introduction moved at speeds of 50-60 mph, but other cases documented in the literature (e.g., Bosart and Cussen, 1973, and Bosart and Seimon, 1988) reported gravity wave propagation speeds of around 30 mph.

Obviously, the faster the wave, the harder it is to forecast. For example, a wave trough moving east out of northern Mississippi at 50 mph would get across northern Alabama in about 4 hours. It would be difficult to provide much lead time on wind advisories or warnings for the first counties affected. Also, the strong winds would be of short duration at any given point as the wave progressed. This reemphasizes the importance of keeping an eye on upstream observations to hopefully catch the first occurrences of large surface pressure falls or increases in surface winds.

4. Recent Example of a Weak Gravity Wave Event in Alabama

Following is an example of observations made after a recent weak gravity wave event in Alabama. This example is presented to help tie together the information in sections 2 and 3 above. The event occurred during the morning of February 3, 2005. Precursor conditions included:

- A negatively tilted 500-mb trough was over Texas at 02/0000Z with a 70-knot jet streak swinging through the base of the trough over southern Texas. Further ahead over the Arklatex, the 500-mb flow was highly difluent.
- At the surface, a high pressure wedge with its easterly winds had pushed all the way across Alabama. A low-level inversion was in place over Alabama with veering lower-tropospheric winds.
- The midnight shift forecasters were following a band of light to moderate rain moving east over Mississippi and Alabama. The band demonstrated a general arc shape, and toward daybreak on the 3rd, a definite back edge was curved from northwest Alabama down to south-central Alabama.
- Unfortunately the 03/12Z sounding for Birmingham was not available, but the Peachtree City, Georgia sounding at that time showed a strong low-level inversion and stable layer from 900 mb through 700 mb, topped by a conditionally unstable layer from 700 mb through 300 mb. A calculation of DF from Eq. 1 gave a value of positive 8, which implies that a good duct for the wave existed over northern Georgia, and probably over Alabama as well.

The following are short sections of observations from Birmingham (KBHM), Montgomery (KMGM), and Huntsville (KHSV), Alabama. They show how pressure falls, gusty winds, and an abrupt end of rain occurred as the weak gravity wave trough on the trailing edge of the precipitation moved across the state.

METAR KBHM 021153Z VRB04KT 4SM RA BR SCT015 BKN020 OVC027 05 / 03 A3026 RMK A02 RAB01 SLP247 P0020 60036 70044 T00500033 10056 20050 53012
SPECI KBHM 021217Z 11012G18KT 4SM -RA BR FEW015 BKN032 OBV060 04 / 03 A3022 RMK A02 **PRESFR** P0004
SPECI KBHM 021242Z **13016G23KT** 6SM -RA BR FEW009 BKN042 OVC085 04 / 03 A3021 RMK A02 P0006
METAR KBHM 021253Z 11011G23KT 8SM -RA SCT012 BKN070 OVC080 04 / 03 A3021 RMK A02 SLP232 P0006 T00440033
SPECI KBHM 021310Z 14015G21KT 100V170 9SM –RA BKN014 BKN065 OVC080 04 / 03 A3023 RMK A02 P0000
METAR KBHM 021353Z 11012G20KT 8SM OVC014 05 / 03 A3023 RMK A02 **RAE18** SLP238 P0000 T00500033

METAR KMGM 021353Z 08014KT 3SM +RA BR FEW010 BKN015 OVC025 05 / 04 A3027 RMK A02 SLP252 P0027 T00500039
SPECI KMGM 021358Z 06010KT 2SM +RA BR BKN010 BKN017 OVC025 05 / 04 A3030 RMK A02 P0003
METAR KMGM 021453Z 11018G28KT 10SM SCT010 BKN048 06 / 04 A3021 RMK A02 **PK WND 11028/1445 RAE49** SLP230 P0013 60063 T00560039 50003
SPECI KMGM 021515Z 11016KT 10SM BKN010 BKN090 06 / 04 A3024 RMK A02 PK WND 11027/1500
METAR KMGM 021553Z 10012KT 10SM OVC012 07 / 04 A3024 RMK A02 PK WND 11027/1500 RAB40E50 SLP241 P0000 T00670044

METAR KHSV 021353Z 13013KT 2SM -RA BR OVC016 05 / 04 A3024 RMK A02 TWR VIS 2 1 / 2 SLP241 P0006 T00500039
SPECI KHSV 021414Z 12018G22KT 4SM -RA BR OVC014 05 / 04 A3024 RMK A02 P0001
SPECI KHSV 021427Z 13016G21KT 7SM -RA OVC016 05 / 04 A3023 RMK A02 P0001
METAR KHSV 021453Z 13020G25KT 2SM R18R/6000VP6000FT +RA BR OVC016 05 / 04 A3022 RMK A02 SLP234 P0002 60021 T00500039 56015
SPECI KHSV 021457Z 13019G24KT 1 1 / 2SM R18R/6000VP6000FT +RA BR OVC016 04 / 04 A3022 RMK A02 P0000
SPECI KHSV 021511Z 13018G25KT 2 1 / 2SM -RA BR OVC016 04 / 04 A3023 RMK A02 **PK WND 10028/1501** PNO $
METAR KHSV 021553Z 13017G23 7SM OVC016 04 / 03 A3023 RMK A02 PK WND 10028/1501 **RAE53** SLP237 P0012 T00440033 $

These observations all showed the same trend as the gravity wave trough moved through. Certain parts of the observations for each station are bolded to illustrate a pattern. Notice that only the Birmingham observations happened to record the rapidly falling pressure. However, it can be safely assumed that the other two stations actually did also in their 5-minute pressure data. Besides that, the fact that all three locations showed an increase in winds, followed shortly afterward by an abrupt end to the precipitation, confirms both theory and observation. Based on the precipitation trends at Montgomery and Huntsville, one could argue that the rain intensity increased along with the winds.

5. Summary

In this review on mesoscale gravity waves, it was pointed out that the waves tend to develop in a preferred synoptic setting that displays the following features:

- At 300-mb, there is a negatively tilted trough with a jet streak rounding its base. The pattern at 500 mb is often similar.
- The flow is highly difluent immediately downstream from the jet streak. The waves are believed to originate there as part of a geostrophic adjustment process.
- At the surface, a cyclonic system with associated fronts is present. Along and to the north of the warm front, a low-level inversion or stable layer exists.

It is in the area along and north of the surface warm front, bounded on the left by the 300-mb (or 500-mb) trough and ridge inflection point, and on the right by the downstream upper ridge axis, that gravity waves can occur. They usually move from the source region toward the upper ridge axis, while the low-level stable layer traps them and ducts their energy. The wave speeds vary (e.g., 30-60 mph), but an estimate of their direction of movement and speed can be obtained from the mean direction and speed within the stable layer.

Since the emphasis of this review was on the capability of gravity waves to produce significant surface winds at times, an example was presented of a gravity wave event in Alabama. Although the event was relatively weak, it still displayed a sequence that has been documented in numerous gravity wave studies. First came a sharp drop in surface pressure as the wave trough approached. That was followed by a period of gusty winds, with an abrupt end to the precipitation shortly afterward.

Here are a few suggestions to keep in mind after deciding that gravity waves are possible in our area. Perhaps the monitoring of surface observations is most important of all, because not all gravity wave events have associated precipitation systems. At least with those that do, there is a precipitation area or band that can be tracked to determine what observations to watch, and how fast the system is moving. The following suggestions assume that gravity waves with associated precipitation systems are possible.

- The majority of gravity waves that affect our area will approach from the west and south quadrants. Keep a constant watch on surface observations several miles upstream, perhaps out as far as Memphis, Tennessee to the west, Jackson, Mississippi to the southwest, and Montgomery, Alabama to the south.
- Examine the current and projected mid level flow over our area to estimate the direction and speed that a wave could have. Also recall that the mean flow in the low-level stable layer is a good estimate.
- Monitor precipitation systems both upstream and in the immediate area that have already organized or appear to be doing so.
- Pay particular attention to observations near the leading and trailing edges of precipitation areas or bands.
- A good clue that a gravity wave is present is the PRESRR remark in observations near the leading edge, and the PRESFR remark near the back edge.
- Detailed pressure observations are not always available in the routine ASOS observations. Therefore, a watch for sudden increases in surface winds at or just to the west of the back edge of the precipitation is also needed.
- If the PRESFR remark is close to the start of increasing winds, and precipitation ends shortly after the significant winds, this is a very good clue that a gravity wave is involved.

- Obviously, timing of the back edge of precipitation will help with advising the public about significant winds. Otherwise, in the absence of precipitation, make the best use of PRESFR and gusty wind reports.

6. Concluding Comments

The proverb, "Forewarned is forearmed", applies in the case of mesoscale gravity waves. By recognizing patterns favorable for gravity wave development, and with conscientious meteorological watch, we should be able to at least have a chance of dealing with their effects. Local archives and case studies of gravity waves will also go a long way toward increasing our ability to forecast these phenomena.

Acknowledgments

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