NOTES AND CORRESPONDENCE

The Synoptic Setting and Possible Energy Sources for Mesoscale Wave Disturbances

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ABSTRACT

Thirteen case studies of mesoscale wave disturbances (characterized by either a singular wave of depression or wave packets with periods of 1–4 h, horizontal wavelengths of 50–500 km, and surface pressure perturbation amplitudes of 0.2–7.0 mb) are reviewed to isolate common synoptic features for these cases and to shed light on possible energy sources for the waves. A strong thermal inversion in the lower troposphere (north of a frontal boundary) and a jet streak propagating toward a ridge axis in the upper troposphere are commonly observed in all the cases. In general, the area of wave activity is bounded by the jet axis to the west or northwest, a surface front to the southeast, an inflection axis (between the trough and ridge axes) to the southwest and the ridge axis to the northeast.

The conditions specified by Lindzen and Tung as being necessary to form a wave duct, which include the existence of the lower-tropospheric inversion, seem to be met in many of these cases. This suggests that a ducting mechanism contributes to the long duration of these wave events by preventing the vertical propagation of wave energy.

Questions are raised concerning the role of either convection or shear instability as source mechanisms for the generation of these mesoscale wave disturbances. The observed development of the waves within the exit region of a jet streak propagating toward an upper-level ridge axis is shown to be consistent with the hypothesis that the actual energy source needed to initiate and sustain these wave events may be related to a geostrophic adjustment process associated with upper-tropospheric jet streaks.

1. Introduction

At least 13 case studies have revealed the existence of mesoscale wave disturbances which appear to have significant effects upon the intensity and distribution of precipitation. These wave events (listed in Table 1) possess periods $\tau > 1$ h, horizontal wavelengths $\lambda > 50$ km, and surface pressure perturbation amplitudes $p' > 0.2$ mb. The waves can either take the form of a singular "wave of depression," or a "wave packet" (a series of progressive disturbances). Since in all of these cases the investigators attempt to show that both types of wave disturbances were gravity waves, we will frequently apply that term in this paper to these wave events, although there remains some uncertainty about the true nature of the waves in at least some of the studies. Internal gravity waves displaying these values of τ and λ pose a perplexing problem since, theoretically, the wave amplitude should diminish rapidly through the vertical propagation of energy (as will be discussed in section 4). Nevertheless, the wave disturbances reviewed here have a long duration (3–16 wave periods), affect large areas (10^4–10^6 km^2), and have a significant impact on the surface wind, cloud cover and precipitation rates.

The primary purposes of this paper are 1) to identify a common synoptic-scale environment within which these mesoscale waves are generated and maintained for several cycles and 2) to discuss the issue of wave generation mechanisms that could be related to the synoptic environment identified for the 13 cases. Section 2 contains a historical review and a brief discussion of gravity wave source mechanisms for the 13 wave events. Following this, the synoptic setting for 9 of the 13 case studies is described in section 3. The likelihood of a wave duct operating to maintain the wave coherence in all 13 cases is discussed in section 4. Vertical wind shear and geostrophic adjustment processes associated with upper-level jet streaks are further examined in section 5 as possible source mechanisms for the gravity waves. Geostrophic adjustment is strongly emphasized in order to encourage future research in this area, as discussed in section 6.

2. Historical review

The wave disturbances in each of the case studies listed in Table 1 have been shown to influence the mesoscale structure of precipitation systems, including rain, sleet, snow and thunderstorms. Brunk (1949) provides detailed analyses that indicate an association between severe convective storms and waves of depression. Tepper (1950, 1954) emphasizes that preexisting pressure jumps can provide the mechanical lift necessary for the initiation of squall lines. Matsumoto et al. (1967a, 1967b), Matsumoto and Akiyama (1969) and Matsumoto and Tsuneoka (1969) present evidence that internal gravity waves with periods near 3 h are responsible for a pulsating tendency in the winter and summer convective storms in western Japan where the low-level convergence associated with the gravity waves initiates or enhances the convective activity. Uccellini (1975) also shows gravity waves with 2.5- to 4-h periods that appear to initiate or enhance the development of severe convective systems in the central United States. A number of other studies demonstrate that gravity waves can exert a significant influence on the mesoscale structure of stratiform precipitation events (Ferguson, 1967; Stobie et al., 1983; Pecnick and Young, 1984). Two questions which have been raised in many of the case studies concern the interaction between convection and the waves, and the more fundamental issue of an energy source and other mechanisms needed for the initiation and maintenance of the waves.

a. Wave–convection interactions

Several of the investigations listed in Table 1 have suggested an apparent generation or enhancement of gravity waves by convection (e.g., Ferguson, 1967; Bosart and Cussen, 1973; Vincent and Homan, 1983). Others have suggested that preexisting gravity waves may initiate convection (Uccellini, 1975; Stobie et al., 1983), and still others mention both processes (Brunk, 1949; Matsumoto et al., 1967a,b; Miller and Sanders, 1980; Koch and Golus, 1985).[1] Quantitative application of various linear stability models to local soundings has demonstrated the ability of ascent patterns associated with gravity waves to release potential instability (Uccellini, 1975; Koch, 1979; Stobie et al., 1983). The waves force saturated air parcels to their level of free convection by providing the mechanical lift necessary to eliminate the restraining inversion.

Although the case studies tend to focus on gravity wave–convection interactions, there are cases where significant convection is not observed coincidentally with the surface pressure perturbations (Tepper, 1951; Eom, 1975; Pecnick and Young, 1984). Indeed, there are examples where rain, sleet or snowstorms are associated with the existence of diagnosed gravity waves with 2 to 5 mb pressure perturbations at the surface (Stobie et al., 1983; Pecnick and Young, 1984; Bosart and Sanders, 1986), which in some cases are stronger than the amplitude of gravity waves associated with deep convective storms. *Hence, the observations do not generally show a strong correlation between wave amplitude and the presence of convection. This would seem to suggest that convection is not an energy source for the development of many of the largest-amplitude wave events.* Thus, we believe other mechanisms must also be considered as causes for the generation and maintenance of these kinds of wave events in order to arrive at a fully satisfactory explanation for their occurrence.

b. Wave energy source mechanisms

Gossard and Hooke (1975) review the following mechanisms that can act as energy sources for gravity waves: convection, density impulses (accelerating fronts), geostrophic adjustment, topographical forcing and vertical shear instability. We will concentrate our discussion in this paper on the shear and adjustment mechanisms since the others seem less plausible as general explanations for the observations presented in Table 1. Stobie et al. (1983) suggest that although convection could have played an important role in selecting an unstable wave mode, the energy source for the wave packet in their case was the vertical wind shear associated with the jet stream. Pecnick and Young (1984) also concluded that the vertical shear associated with an upper-level jet could have provided the energy source for the large-amplitude (5.1 mb) wave of depression in their case, although they also recognized the possibility that a geostrophic adjustment process downwind of the jet could not be ruled out. Uccellini (1975) found the presence of a jet streak to be a common factor in many of the earlier gravity wave cases.

Jet streaks are associated with enhanced vertical wind shear and thus their relationship to diagnosed gravity waves could help to explain the occurrence of these events. At the same time, there is a strong likelihood that geostrophic adjustment processes may also be an important factor for the occurrence of gravity waves near a jet, as numerical experiments by Van Tuyl and Young (1982) have revealed. Since gravity–inertia waves are the means by which mass and momentum are redistributed so as to ultimately achieve geostrophic balance from an initially unbalanced state (Blumen, 1972), there are strong reasons to consider this alternative as an important wave source mechanism.

3. Synoptic setting for mesoscale wave events

Figure 1 depicts the synoptic setting for 9 of the 13 wave cases listed in Table 1. These are the cases for which adequate geopotential height and wind analyses of the upper troposphere are available.[2] Surface features common to all of these cases include a surface low

[1] Curry and Murty (1974) and Balachandran (1980) have also noted the possibility for a gravity wave characterized by $\lambda < 50$ km and $\tau < 1$ h to be initiated by a convective system. Conversely, Koch (1979) showed that gravity waves with similar characteristics could explain the periodic development of thunderstorms along a dryline. It is not our intention to discuss such studies of small-scale gravity waves.

[2] The recent case study of the 11 February 1983 East Coast snowstorm by Bosart and Sanders (1986) is not included in Fig. 1 because of its recent publication. However, this study provides evidence for the existence of large-amplitude, long-period gravity waves, which had a significant effect on snowfall rates and occurred within a synoptic environment essentially identical to those appearing in Fig. 1.

TABLE 1. Characteristics of mesoscale wave disturbances and their environment as determined from published case studies (see text). References marked with an asterisk are those for which inadequate upper air data analyses were available for inclusion within Fig. 1. The qualitative statement "probably" represents subjective evaluations by the authors of the likelihood of a critical level or an inversion from available tropospheric wind and temperature data.

Reference	Case date	Wave type	Wavelength (km)	Wave period (h)	Wave amplitudes (mb)			Horizontal phase speed (m s^{-1})	Critical level (km)	Wave duration (h)	Inversion below 2 km?
					No precip	Stratiform precip	Deep convection				
1) Bosart & Sanders (1986)	11–12 Feb 1979	Wave packet	100–500	2.4–3.4	—	1.5	3.4	15–23	~7.0	15	Yes
2) Koch & Golus (1985)	11–12 Jul 1981	Bimodal wave packet	160 70	2.6–3.2 1.0	0.2 0.2	0.5 0.3	0.6 0.5	18 20	~5.3 ~5.6	>33 >16	Yes
3) Pecnick & Young (1984)	27 Mar 1975	Wave of depression	120	1.3	5.1	5.1	—	32	8.6	21	Yes
4) Stobie et al. (1983)	9 May 1979	Wave packet	240–265	2.5–3.3	—	1.5	1.2	20–29	3.3	10	Yes
5) Vincent & Homan (1983)	10–11 Apr 1979	Wave packet	~350	~4	—	~2	~6	~25	Probably	>12	Yes
6) Miller & Sanders (1980)	3 Apr 1974	Wave packet	100–250	2.5–3.0	—	1.5	~5	~15	Unknown	33	Yes
7) Uccellini (1975)	18 May 1971	Wave packet	300–450	2.5–4.0	0.5	1.0	2.5	35–45	C > U	10	Yes
8) Eom (1975)	19 Apr 1970	Wave packet	500	3–4	~4	—	—	~50	Unknown	9	Yes
9) Bosart & Cussen (1973)	3 Dec 1968	Wave of depression	50–90	1–2	7	7	—	13	Probably	14	Yes
10) Ferguson (1967)	13 Mar 1963	Wave of depression	55–185	0.8–2.3	—	4	?	21	Probably	13	Yes
11) Matsumoto et al *(1967)	16 Jan 1965	Wave packet	170	2–3	—	1–2	1–2	24	~3.3	15	Yes
12) Tepper *(1951)	6 Dec 1949	Wave of depression	~70–120	~1	1.2	—	—	19–34	Probably	10	Yes
13) Brunk *(1949)	11 Apr 1944	Wave of depression	~150–200	~2.5	—	3.5	<3.5	16–22	Unknown	24	Probably

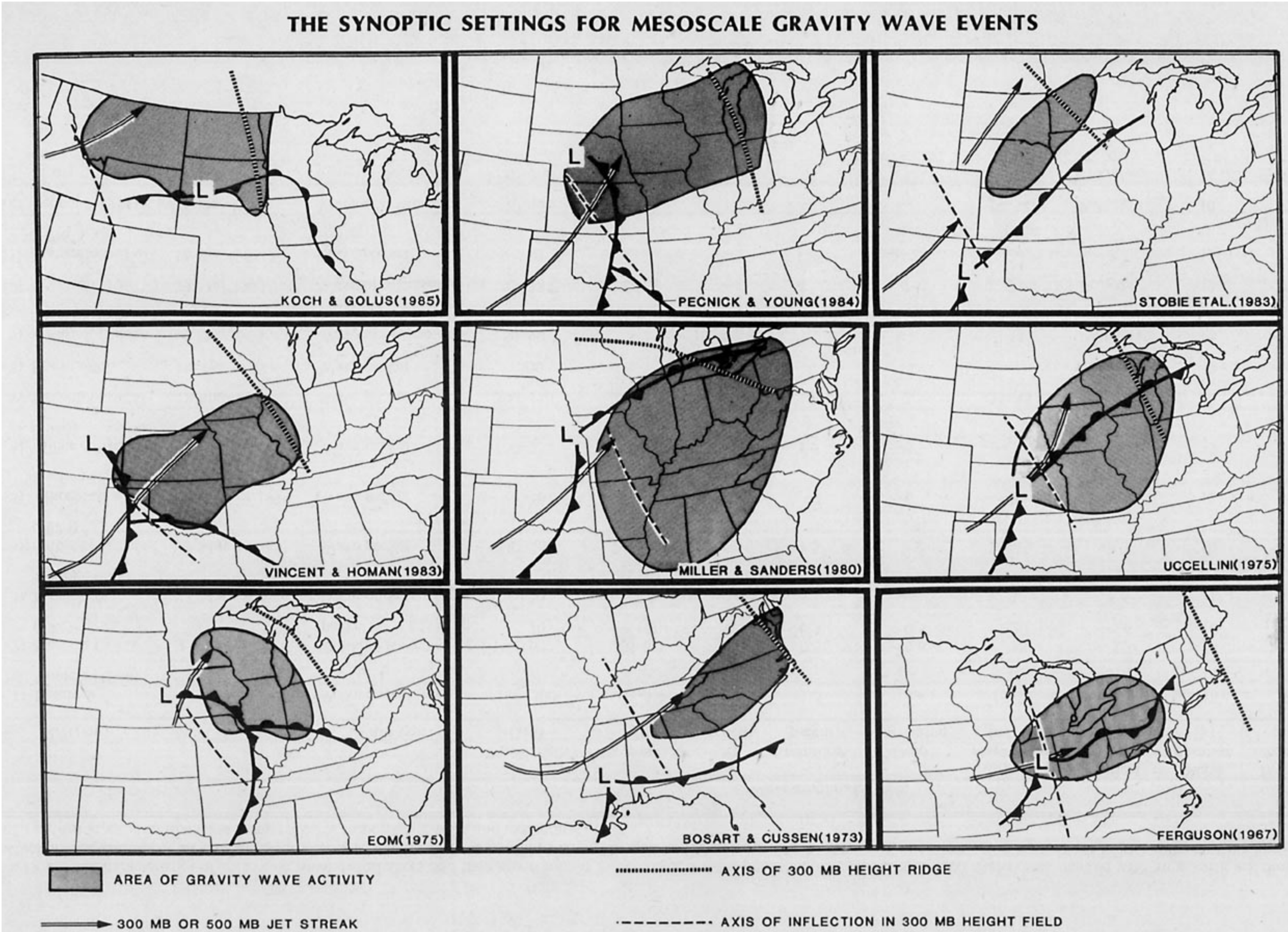

FIG. 1. The synoptic settings for wave cases 2 through 10 listed in Table 1. Positions of all atmospheric features shown on maps are approximate means during first half of wave episode, during which wave source mechanisms are assumed to operate most efficiently. Shaded regions represent areas of wave activity during entire wave episode as determined from surface microbarograph analyses. Jet streak positions (double arrow) represent core of maximum wind speeds within the 300 mb jet stream (if unavailable, 500 mb data are used). Dotted line refers to the ridge axis. Dashed line refers to the inflection axis between the trough and ridge in the 300 mb height field.

pressure system upstream of the area of wave activity [with the exception of an inverted trough in the Koch and Golus (1985) case] and a distinct frontal boundary extending northeast to southeast from the surface low. The waves tend to be confined to a region marked by the presence of a lower-tropospheric temperature inversion, usually on the cold side of the warm or stationary front and also for those few cases where gravity waves were diagnosed in the warm sector (Uccellini, 1975; Miller and Sanders, 1980). The climatological study by Gedzelman and Rilling (1978) also emphasizes the presence of a lower-tropospheric inversion during short-period (<30 min) gravity wave events.

There are also features in the upper troposphere which are common to all the wave cases depicted in Fig. 1. First, the waves are found exclusively in the exit region of a jet streak and preferentially on its right (anticyclonic shear) side. Furthermore, they are confined to a region between the axis of inflection and the downstream ridge axis in the 300 mb height field. Thus, in general, the area of wave activity appears to be bounded by the inflection axis to the southwest, the jet axis to the west or northwest, the ridge axis to the northeast, and the surface frontal boundary to the southeast. The only exception to the frontal location observation is the gravity wave event reported by Miller and Sanders (1980). However, they did not statistically filter surface barograph traces, a procedure which helps to unambiguously identify the wave packet and diagnose the propagation of individual waves.

4. Maintenance of wave coherence

It was noted in the Introduction that the class of waves being considered here can propagate freely, assuming for this discussion that they are internal gravity waves. They would, in fact, have a vertical group velocity fast enough to remove most of their energy before traveling even a single wavelength horizontally, so that little if any wave coherence should be expected. This behavior can best be appreciated by considering the Taylor-Goldstein wave equation for an incompressible, Boussinesq, nonrotating[3] atmosphere (Gossard and Hooke, 1975),

$$\frac{d^2W(z)}{dz^2}+n^2W(z)=0, \tag{1}$$

where $W(z) = W[\rho(z)/\rho_0]^{1/2}$ is a density-normalized vertical velocity perturbation and

$$n=\left[\frac{N^2}{[U(z)-C]^2}-\frac{U''(z)}{U(z)-C}-k^2\right]^{1/2} \tag{2}$$

is the vertical wavenumber. The various quantities in Eq. (2) are the Väisälä-Brunt frequency (N) defined by $N^2 = gd(\ln\theta)/dz$, where θ is the potential temperature; the ambient wind and its second derivative with respect to height z (U and U'', respectively); the phase velocity of the wave disturbance (C); and the horizontal wavenumber (k) for a disturbance which propagates in the x-direction. Upon ignoring the term involving the second derivative of wind shear, employing the Doppler-shifted (intrinsic) frequency defined by

$$\omega=k(U-C), \tag{3}$$

and making the WKB approximation for the local vertical wavenumber, the wave dispersion equation can be rewritten as

$$n^2=k^2\left[\left(\frac{N}{\omega}\right)^2-1\right]. \tag{4}$$

This relation shows that real vertical wavenumbers ($n^2 > 0$) are possible only when $\omega < N$, i.e., for long intrinsic wave periods characteristic of the mesoscale waves being considered in this paper. (The criterion for $n^2 > 0$ becomes $F < W < N$ upon considering Coriolis effects.) These waves can propagate energy vertically and are thus termed "untrapped waves," a conclusion which can be drawn from consideration of the expression for the vertical group velocity (C_{gz}). This expression can be derived (Gossard and Hooke, 1975) by differentiating (4) with respect to n to arrive at

$$C_{gz}=\frac{-n\omega^3}{k^2N^2}, \tag{5}$$

which shows that real, nonzero values for C_{gz} (and hence the vertical energy flux) are possible only for real values of n (requiring $\omega < N$). An actual estimate for C_{gz} was made by Pecnick and Young (1984), who used the estimated wave slope defined by

$$s\equiv dz/dx=k/n \tag{6}$$

to rewrite (5) for a hydrostatic wave ($s^2 \ll 1$) as simply

$$C_{gz}\approx[U(z)-C]s. \tag{7}$$

They obtained values of C_{gz} which decreased from -5 m s^{-1} at low levels to -0.5 m s^{-1} above 400 mb, due to the increase of winds with height. It follows that untrapped waves quickly lose most of their energy since the energy can propagate vertically through the entire depth of the troposphere during the time it takes for the wave to propagate less than one horizontal wavelength (about 3 h, according to Table 1). Thus, some mechanism must exist which either acts to impede this rapid energy loss or continuously provides for a source of the wave energy to account for the long duration of the wave events observed in so many case studies (Table 1).

The common occurrence of mesoscale gravity waves in the presence of a lower-tropospheric inversion (sec-

[3] The following discussion assumes no Coriolis effects on the gravity waves. However, it may be more appropriate to consider several of the wave events (with periods greater than 3 h) as gravity–inertia waves, for which the Coriolis parameter would have to be accounted.

tion 3) raises the question of whether a wave duct can act as such a mechanism in these cases. A duct is formed when a stable lower atmosphere underlies a layer of lower stability capable of reflecting the vertically propagating waves. Jones (1968) shows that ducting acts to both a) confine the direction of wave propagation to that perpendicular to the direction of vertical wind shear and b) maintain the wave amplitude without significant energy loss due to vertical leakage and so permit wave propagation over large horizontal areas and many wave cycles. Lindzen and Tung (1976) emphasize that most observed inversions are, in and of themselves, too thin to act as an efficient wave duct for wave events with the long wavelengths and high phase speeds being considered here. However, they show that the presence of an overlying layer characterized by the presence of conditional instability, a critical level (where $C = U$), and sufficiently strong shear that the Richardson number (Ri) decreases to a value $\mathrm{Ri} < 0.25$ can result in strong reflectance properties for long wavelength modes. The existence (or probable existence) of a critical level in the mid- to upper troposphere is observed in most of the cases (Table 1). In addition, the Ri criterion seems to have been met in those studies where such a calculation was actually performed (Stobie et al., 1983; Pecnick and Young, 1984; Koch and Golus, 1985). Although it is not our purpose to fully investigate whether all the necessary conditions specified by Lindzen and Tung (1976) were actually met in all of these cases, our findings do *support* the ducting mechanism concept for *maintaining* a wave disturbance once it has been generated.

5. Wave source mechanisms

Though the synoptic analyses appear to show the importance of a ducting mechanism for trapping wave energy for an extended period of time, other mechanisms must be isolated which actually *excite* the unstable wave mode and provide a source of energy for the wave activity. Given the existence of jet streaks near the region of the observed waves (Fig. 1), two source mechanisms for gravity waves are discussed: shearing instability and geostrophic adjustment processes.[4]

a. Shearing instability

The close association between mesoscale wave disturbances and upper-level jet streaks observed for many of the cases suggests that the vertical wind shear associated with the jet could provide an energy source for the waves. The shear mechanism has been shown to be applicable through linear stability analyses (Lalas and Einaudi, 1976; Stobie et al., 1983; Pecnick and Young, 1984). Table 1 indicates that a critical level is frequently observed in mesoscale wave events. This observation is an additional piece of evidence in support of the shear mechanism since the critical level can not only act to duct gravity wave energy but can also serve as a generation level for the waves, provided the local shear is sufficiently strong that $\mathrm{Ri} < 0.25$ (Gossard and Hooke, 1975; Stobie et al., 1983).

A problem encountered with shear instability as a source mechanism is that most theoretical models predict a wavelength much smaller than those observed in mesoscale wave events (Lalas and Einaudi, 1976). In fact, even smaller-scale gravity waves apparently generated by shear instability are characterized by a wavelength which is many times larger than approximately seven times the shear layer thickness ($\lambda \approx 7D$) predicted by the models. The extensive data presented by Greene and Hooke (1979) comparing D to λ derived from highly sensitive microbarographs also supports the contention that $\lambda \gg D$. One explanation is that the atmosphere acts to filter out small-scale waves which decay in amplitude away from the shear zone more rapidly than mesoscale waves, due to the fact that they are typically "trapped waves" [$n^2 < 0$ in (4)]. Thus, only the larger wavelength phenomena would be detected at ground level. However, Lalas and Einaudi (1976) were able to show theoretically that consideration of a rigid lower boundary (such as the earth's surface) introduces an unstable mode characterized by very long wavelengths which closely match observations summarized in Table 1. It is therefore possible that the existence of jet streaks provides the shear instability needed to generate mesoscale gravity waves with the characteristics being discussed here.

On the other hand, a critical level was not evident in the case studied by Uccellini (1975). Furthermore, the very large phase speed reported by Eom (1975) also raises doubts about a critical level in that case. Even more disturbing is the recent gravity wave analyses using wind data obtained from MST-radar wind profilers, which have revealed that gravity waves can exist without the presence of a critical level (Einaudi et al., 1987). With this recent finding, the prospect that the wave disturbance could extract energy from the mean flow and thus grow rapidly in the presence of shearing instability is diminished. These observations seem to suggest that other mechanisms, not related to shear instability, may also act to generate the gravity waves for these particular cases, such as the geostrophic adjustment processes associated with a finite-length jet streak.

b. Geostrophic adjustment

Gravity-inertia waves have time and space scales large enough for the Coriolis force to be important.

[4] Ley and Peltier (1978) have proposed that gravity–inertia waves can be generated during surface frontal collapse (the later stages of frontogenesis, when highly nongeostrophic conditions develop). None of the wave events (Fig. 1) occurred in the immediate vicinity of the surface cold front, although it remains possible that the stationary or warm front to the southeast of most of the wave regions was actively frontogenetical.

Rossby (1938) and Cahn (1945) showed that these waves are excited in local regions of geostrophic imbalance resulting from an initial addition of momentum to a rotating fluid. The resulting wave train is highly dispersive and propagates perpendicular to the current in a two-dimensional flow regime, eventually damping out as the current approaches a state of geostrophic balance (Cahn, 1945). Matsumoto (1961) further shows that the pressure field would adjust to the velocity disturbance (e.g., a propagating jet streak) when the disturbance scale is small compared to the Rossby radius of deformation (λ_R), which is typically of magnitude $\lambda_R > 1000$ km in the atmosphere (Rossby, 1938). A gravity–inertia wave in a barotropic fluid should display a horizontal wavelength $\lambda \approx \lambda_R$. However, Blumen (1972) shows that the Rossby radius of deformation (hence, the gravity–inertia wavelength) in a *stratified* atmosphere is given by

$$\lambda_N \sim \frac{NH}{2\pi f}, \qquad (8)$$

where H is the atmospheric scale height and f the Coriolis parameter. The wavelengths listed in Table 1 are contained within the range specified by (8), namely $\lambda \approx 100$–500 km. Yet, despite this agreement, the local energy source for gravity–inertia waves related to the geostrophic adjustment process remains unknown.

These linear theoretical studies did not treat the alongstream variations in the mass and momentum fields that characterize actual jet flows. This factor is considered by Van Tuyl and Young (1982), who utilize a two-layer, primitive equation model in a study of the geostrophic adjustment process for a propagating, finite-length jet streak. They show that gravity–inertia waves are generated in regions of unbalanced flow near the jet core, where the criterion needed to apply the balance equation (discussed later) is not satisfied. The amplitude of the unbalanced motions increases with the square of the Rossby number (Ro), *particularly around and just downwind of the jet core.* They suggest that for sufficiently high Ro, "such as those encountered near strong jet streaks, the secondary circulations predicted by quasi-geostrophic and balance theories would be unable to maintain the balance condition which existed initially. Gravity–inertia waves, or related unbalanced motions, should therefore result" (Van Tuyl and Young, 1982, p. 2041).

House (1961), Paine et al. (1975), Kaplan and Paine (1977) and Uccellini et al. (1984) all show that, as a jet streak approaches an upper-level ridge, an increasingly unbalanced situation appears to develop, resulting in a significant increase in the upper-level wind divergence. This process is diagnosed with the divergence equation, which in pressure coordinates is written in the form

$$\frac{d\delta}{dt} = -\delta^2 + f\zeta - \beta u - \tilde{\nabla}\omega \cdot \frac{\partial \mathbf{U}}{\partial p} + 2J(u, v) - \nabla^2\phi. \qquad (9)$$

The term $d\delta/dt$ represents the temporal change in divergence following a parcel, while $\mathbf{U}$ is the total wind vector, ζ the vertical component of the relative vorticity, β the latitudinal variation of the Coriolis parameter, the Jacobian term $J(u, v) = (\partial u/\partial x)(\partial v/\partial y) - (\partial u/\partial y)(\partial v/\partial x)$ and $\nabla^2\phi$ is the Laplacian of the geopotential height. The nonlinear balance equation, an approximate form of the divergence equation applicable to synoptic-scale motions, results from assuming no divergence tendency and a quasi-balance between the four largest terms (Haltiner, 1971):

$$\nabla^2\phi - 2J(u, v) - f\zeta + \beta u = 0. \qquad (10)$$

The Laplacian and Jacobian terms have been shown by Kaplan and Paine (1977) to be large and of the same sign in the diffluent exit region of a jet streak approaching a ridge, leading to a situation where these two terms dominate the other four in Eq. (9), and the assumptions for Eq. (10) can no longer be satisfied. The resulting imbalance among the terms forces a large increase in divergence for parcels exiting the jet and moving toward the ridge axis.

The observations presented in Fig. 1 show that large-amplitude, mesoscale waves are detected consistently within the exit region of a jet streak propagating toward a ridge in the 300-mb height field. Since 1) the upper-level flow regime which characterizes mesoscale gravity wave events is similar to that which has been deemed unbalanced and 2) theoretical and model studies have indicated that gravity–inertia waves are a means to restore the atmosphere back toward a balanced state, there then appears to be excellent reasons to consider the hypothesis that the geostrophic adjustment process contributes to the development of the mesoscale wave events reported here. Our suggestion that these types of waves may be generated by a geostrophic adjustment process and maintained by ducting through a mechanism similar to that proposed by Lindzen and Tung (1976) needs to be confirmed with further observational, theoretical and numerical modeling studies.

6. Summary and suggestions for future research

A review of the large-scale setting for 13 mesoscale wave events reported in the literature reveals that these wave events are associated with a distinct synoptic pattern, while displaying little or no correlation with either the presence or intensity of convective storm cells. This synoptic setting includes the existence of a strong inversion in the lower troposphere (north of a frontal boundary) and the propagation of a jet streak toward a ridge axis in the upper troposphere. The consistent presence of the inversion, as well as other considerations, indicates that the ducting mechanism proposed by Lindzen and Tung (1976) could have played an important role in *maintaining* the wave energy and thus account for the long duration of the gravity wave events. With respect to the *source* mechanisms, the lack of correlation between gravity wave amplitude and the existence of convection would appear to rule out convective systems as a dominant source of wave energy. However, the common presence of the jet streak, with its associated vertical wind shear, may be an important factor in the generation of these mesoscale wave events. In fact, vertical wind shear has been considered as a wave source mechanism for several of these cases. However, theoretical considerations and the consistent nature of the synoptic-scale environment suggest that the geostrophic adjustment process in the exit region of the jet streak should be addressed as an alternative source mechanism for the wave disturbances reviewed in this paper.

Additional research is required to determine whether mesoscale gravity wave activity observed in such cases as those discussed here is an integral part of an adjustment process associated with the propagating jet streak that attempts to restore a balance between the large-scale mass and momentum fields. Moreover, we need to develop a better understanding of how other factors (such as convection and the presence of a low-level inversion) can act to contribute an energy source to the waves, select the wave mode, modulate the response to the synoptic-scale imbalances, or some combination of all three processes [as is also discussed by Stobie et al. (1983)]. Theoretical studies should begin to address the nonlinear processes associated with the configurations of jets, ridges and fronts that characterize these wave events. In particular, investigations need to be made of how alongstream variations in the wind field near the exit region of a jet streak approaching a ridge in the mass field may create an unbalanced state conducive to the generation of gravity and/or gravity-inertia waves. Mesoscale modelers should also begin to address the issues of model initialization and the subsequent simulation of both gravity and solitary wave generation and the interaction between the waves and convective systems.

It is hoped that future field programs can provide high-resolution datasets that, when combined with analytic studies and mesoscale model experiments, can be used to provide insight into the nonlinear aspects of mesoscale wave generation and its interaction with severe convective storms and other mesoscale systems which produce significant precipitation. The isolation of mesoscale wave disturbances requires detailed interpretation of spectral and bandpass filter analyses of numerous microbarograph pressure traces that makes real-time wave detection and subsequent short-term forecasts extremely difficult. However, the simple pattern in the synoptic-scale flow field identified here for previously documented wave events offers a degree of optimism for determining regions with the potential for the occurrence of mesoscale waves which can significantly affect the weather.

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