NOTES AND CORRESPONDENCE

Comments on ‘‘Observations of a Mesoscale Ducted Gravity Wave’’

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ABSTRACT

Recently, a mathematical theory has been developed that proves that there are two main components of the solution of the forced dynamical system that describes a mesoscale storm driven by cooling and heating processes. The component that contains most of the energy of the solution (and is therefore called the dominant component) satisfies a simple nonlinear system devoid of gravity and sound waves. The residual component of the solution satisfies a forced gravity wave equation and essentially does not interact with the dominant component. The mathematical theory also provides information about the amplitude, wavelength, and period of the gravity waves. In the paper entitled ‘‘Comments on ‘Use of ducting theory in an observed case of gravity waves,’ ’’ Dr. F. M. Ralph has claimed that the new gravity wave theory is not consistent with profiler observations of vertical velocity in his earlier paper entitled ‘‘Observations of a mesoscale ducted gravity wave.’’ Here it is shown that the new theory is completely consistent with profilers that have documented error bounds on the vertical velocity measurements. In the case that the new theory is claimed to be inconsistent with observational data, the data were obtained from a profiler with undocumented accuracy of the vertical velocity measurements *in the precipitating case,* and the two components of the solution were not properly separated.

1. Introduction

Recently, Browning and Kreiss (1997) developed a rigorous mathematical theory that proves that there are two components of a mesoscale storm driven by cooling and heating processes. The dominant component contains most of the energy of the solution and satisfies a simple nonlinear (reduced) system devoid of gravity and sound waves. This component can be described accurately by the normal scaling values used for these storms; that is, this component has a timescale $O(3\text{ h})$, a length scale $O(100\text{ km})$, pressure perturbations $O(10^2\text{ kg m}^{-1}\text{ s}^{-2})$, horizontal velocities $O(10\text{ m s}^{-1})$, and vertical velocities $O(1\text{ m s}^{-1})$. After subtracting out the solution of the reduced system from the solution of the full system, the residual component of the solution satisfies a forced linear gravity wave equation. The gravity wave component has a timescale $O(3\text{ h})$, a length scale $O(\gg 100\text{ km})$, pressure perturbations $O(10^2\text{ kg m}^{-1}\text{ s}^{-2})$, horizontal velocities $O(1\text{ m s}^{-1})$, and vertical velocities $O(0.1\text{ m s}^{-1})$ [also see Koch et al. (1993) for an independent evaluation of the size of the vertical velocities of the gravity waves associated with these storms].

The majority of observations of gravity waves have involved time series of the surface pressure; that is, surface pressure oscillations that have a period considerably shorter than for large-scale motions have been designated to be gravity waves (Brunk 1949; Pothecary 1954; Clarke 1962; Wagner 1962; Eom 1975; Stobie et al. 1983; Bosart and Sanders 1986; Uccellini and Koch 1987; Ralph et al. 1993). It is now clear why mesoscale storm-induced gravity waves, which are essentially horizontally propagating, can be observed away from the generating source using surface pressure measurements. The amplitude and period of these long-lived, large-scale gravity waves coincide with those of the high-frequency pressure perturbations that are prevalent in surface pressure observations outside of these storms.

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However, the gravity wave component has the same period as the dominant component, so it is very difficult to distinguish between the two components using bandpass filters on time-dependent data that contains both components. This common property of the two components explains why there has been considerable confusion about the importance of short-period surface pressure oscillations within a storm. In one case the oscillation could be from the dominant component of the solution, and in another it could be from the gravity wave component, with both observations being termed gravity waves because of their period. In the first case the ''gravity wave'' would play a significant role in the evolution of the storm and, in the second it would propagate away from the storm with little effect on that storm [e.g., see statements in section 4b of Bosart and Sanders (1986)]. Because the gravity waves propagate away from the storm, time series of any variable at a nearby observational site should only include information before the storm reaches the observational site if trying to sort out the gravity wave component of the solution. It must also be mentioned that it is possible that the time series information with this approach might contain similar long-lived, large-scale gravity waves from other mesoscale storms.

Earlier, some studies (e.g., Ralph et al. 1993) used profiler measurements of the vertical velocity in an attempt to observe mesoscale storm-induced gravity waves. However, there was no discussion of the impact of the accuracy of the profiler (e.g., Wuertz et al. 1988) on the measurements of the vertical velocities of those waves given their expected size [e.g., see Koch et al. (1993) reference cited by Ralph for a discussion of that size]. Recently, Ralph (Ralph 1997) has claimed that the new mesoscale storm-induced gravity wave theory does not agree with profiler observations of those waves with no additional scientific evidence relative to the above issues: ''They [Browning and Kreiss] also conclude that noise in wind profiler measurements makes observations of gravity waves very difficult with such instruments, a conclusion that runs counter to the results described here and to other wind profiler studies of gravity waves.'' Here it will be shown that this inconsistency arises from the use of observational data with unknown accuracy *in the precipitating case* and from the improper separation of the two components of the solution. To show that profiler observations are completely consistent with the new theory, in section 2 the accuracy of vertical velocities observed by 404- and 50-MHz profilers is reviewed, and the impact of that accuracy on observations of mesoscale storm-induced gravity waves is discussed. Section 3 discusses the problem of trying to compute information about gravity waves when the dominant component of the solution is present in the data. Conclusions are presented in section 4.

2. Accuracy of profiler vertical velocities

Recently, wind profilers have become a popular new instrument to measure the winds [see summary in Strauch et al. (1987)]. One of the major advantages of these instruments is their shorter observational period; for example, the NOAA 404-MHz UHF profiler network observes the winds every 6 min (the density of this information is useful in reducing the impact of random errors; Lu and Browning 1999, manuscript submitted to *J. Atmos. Sci.*). The typical errors in the horizontal and vertical components of the velocity in this network in a nonprecipitating environment are $O(1\ \mathrm{m\ s^{-1}})$ and $O(0.20\ \mathrm{m\ s^{-1}})$, respectively (Strauch et al. 1987). The accuracy of the 404-MHz profiler is very good for the horizontal component of the wind (the profiler wind observations have been compared with rawinsonde observed winds), but the noise level for the vertical component (based on a cross-check between the various beams) is larger than the size of typical large-scale vertical velocities (e.g., Browning and Kreiss 1986) or mesoscale storm-induced gravity waves. In the precipitating case, the errors in the wind are at best 2–4 times larger than the errors in the nonprecipitating case (Wuertz et al. 1988). Given that mesoscale storm-induced gravity waves have vertical velocities that are $O(0.10\ \mathrm{m\ s^{-1}})$ (Koch et al. 1993; Browning and Kreiss 1997), it is clear why they cannot be accurately measured by the 404-MHz profilers in the nonprecipitating or precipitating case.

One of the authors (DvdK) has monitored the output from the 404-MHz profilers every day for over 10 yr. Away from the mountains DvdK has only seen vertical velocity with a 3-h timescale outside the noise range for the nonprecipitating environment ($>0.2\ \mathrm{m\ s^{-1}}$) when there is a front (not under discussion) or precipitating storm over the site. (A typical color plot of the time variation of the vertical velocity in the presence of these features with explanation is available from DvdK on request.) In the latter case the magnitude of the noise in the vertical velocity measurements of a 404-MHz profiler is at best 0.4–0.8 $\mathrm{m\ s^{-1}}$ (Wuertz et al. 1988), that is, as large as the maximum vertical velocity associated with the stratiform rain region of a mesoscale storm (Houze 1989). Thus, in these cases even observations of the vertical velocity of the dominant portion of a mesoscale storm are in question.

VHF (50-MHz) profilers have also been used to measure the winds (e.g., Nastrom et al. 1990). Because there is no reliable basis of comparison (McAfee and Gage 1995), the accuracy of the vertical velocities measured by these instruments is still controversial and not well documented. There are also a number of other issues concerning the accuracy of the vertical velocities observed by VHF profilers. For example, the accuracy of the vertical velocity in a nonprecipitating environment is sensitive to a slight tilt in the vertical beam (Huaman and Balsley 1996), and sloping of the reflectivity surface (Palmer et al. 1991) and lee waves complicate the situation in the presence of topography (VanZandt et al. 1991). For the latter reason, studies have been conducted at sites far away from mountainous areas (e.g., VanZandt et al. 1991). The Flatland profiler shows two distinct levels of activity. Quiescent periods involve random fluctuations of vertical velocity $O(0.10\ \mathrm{m\ s^{-1}})$. Fluctuations of this size (if accurately measured) are consistent with the amplitude of long-lived, large-scale gravity waves produced by mesoscale storms. The active periods were all related to fronts or precipitating mesoscale storms just as with the UHF profilers (Nastrom et al. 1990).

Because VHF profilers have a longer wavelength (approximately 6 m) than that of UHF profilers (approximately 0.74 m), they are claimed to be not as sensitive to the presence of hydrometeors (e.g., McAfee et al. 1995). In a precipitating environment, a technique has been used to remove the hydrometeor fall velocity from the clear air signal for VHF profilers (Wakasugi et al. 1987). However, there is no error analysis of that method and, at present, no way to confirm its validity.

In summary, from the literature it is clear that the accuracy of either type of profiler is different in periods without and with rain. If the data from the profiler is taken from a period when it is raining, as in Ralph et al. (1993), sound scientific references clearly citing the accuracy of the 50-MHz profiler vertical velocities *when it is raining* and that of the Wakasugi algorithm used to separate the clear air signal from that of the hydrometeors must be provided if any scientific results based on the use of the VHF profiler in these circumstances are to be trusted.

3. Separation of solution components

Much of the controversy surrounding the Ralph et al. (1993) paper stems from the use of surface pressure and profiler vertical velocity data during the period when storms passed over the profiler observing site (0900–1500 UTC 19 June 1984). Clearly during this time heating and cooling (see indications of rainfall during this period in Fig. 9 of their paper) had a substantial effect on the surface pressure and vertical velocity as is well known from theory (e.g., Browning and Kreiss 1997) and is evident from the time series of the *raw* values for these variables in the Ralph et al. paper, yet the authors failed to provide an adequate explanation for the impact the presence of the dominant component would have on the accuracy of their results.

It is well known that mesoscale storms contain pressure perturbations $O(10^2\ \mathrm{kg\ m^{-1}\ s^{-2}})$ that are due to both the heating and cooling (dominant component) and gravity wave oscillations. When Ralph et al. use the surface pressure in their computations, they do not distinguish between the two different sources of the pressure. Given that the two components of the solution can have pressure perturbations of the same size, to attribute the pressure perturbations only to gravity waves can lead to considerable error. For example, in the authors' second phase speed computation they state, ‘‘the phase is the time of crossing of zero pressure perturbation as the pressure changes from negative to positive.’’ Certainly the location of zero surface pressure perturbation will be affected by the surface pressure perturbations due to the *translating* dominant component of the solution that has not been removed from the surface pressure data. Also Ralph (2000) includes the following statements about the attempt by Ralph et al. to remove the vertical velocity of the dominant component from the data. ‘‘A threshold of 2 m s^{-1} was used as a criterion to separate the wave and convective motions. This value was based on the fact that vertical air motions within deep convective storms (such as those that crossed the profiler) can greatly exceed this threshold, while mesoscale gravity wave motions should not be that strong.’’ Unfortunately, this argument fails to take into account that the vertical velocity of convective motions follows the heating, so the amplitude of the vertical velocity of the dominant portion varies in the range from the largest value observed in a mesoscale storm driven by heating and cooling to the smallest possible value (0). Thus removing velocities only above 2 m s^{-1} does not correctly remove the vertical velocity due to the dominant component from the data. In fact, after this scientifically questionable alteration of the data, the main signal in the vertical velocity ($\gg 0.2\ \mathrm{m\ s^{-1}}$) occurs only when it is raining [see Fig. 9 in Ralph et al. (1993)], as expected from the argument above.

The authors also claim to show that the vertical velocity and pressure are out of phase (Ralph et al. 1993; their Fig. 11) which is supposedly the signature of a gravity wave. Although the comparison of the phase is shown in the period when there is no rain, note that the large signal during the period with rain has spilled out into the period with no rain, which is typical of the Fourier transform when applied to large isolated signals [compare Figs. 9 and 11 in Ralph et al. (1993).] Also note that the dominant component of the solution satisfies a relationship like [for complete details see the geopotential surface equation (5.3c) in Browning and Kreiss (1997)]

$$\nabla^2\phi = H_{zt} + uH_{xz} + vH_{yz} = w_{zt} + uw_{xz} + vw_{yz}, \tag{3.1}$$

where ϕ is the geopotential, H is the heating (as defined in Browning and Kreiss 1997), and w is the vertical component of the velocity. The pressure is determined from the vertical velocity by computing a sum of products of functions on the right-hand side and then inverting a Laplacian operator; that is, the relationship between the pressure and vertical velocity of the dominant component is not trivial. In fact, the surface pressure and vertical velocity of the dominant component can be out of phase just as in Fig. 11 of Ralph's paper (e.g., see Browning and Kreiss 1997; compare their Figs. 2 and 4). Also the pressure and vertical velocity in the gravity waves are not necessarily any more out of phase than the dominant component (see Browning and Kreiss 1997; compare their Figs. 5 and 8), and the amplitude of the pressure perturbations Ralph et al. observed is consistent with the size of the pressure perturbations of the dominant component of the solution.

The authors claim that the gravity wave is ducted, so that implies it should be able to be seen before the storms reach the site (0400–0900 hours UTC) and after they have passed beyond it (1500–2000 hours UTC). If the profiler is as accurate as Ralph (2000) would have one believe, and the wave Ralph et al. observed was ducted, then the authors should be able to show that the 90-min period is still dominant in both the pressure and vertical velocity spectra using only *raw* data from the two periods mentioned above when the storms are not over the profiler. In those periods there would be none of the troubling issues raised above. We look forward to seeing the results for those periods.

4. Conclusions

It is clear from the new theory of mesoscale storm-induced gravity waves (Browning and Kreiss 1997) why gravity waves can be seen in surface pressure measurements, even far away from the storm. And while wind profilers are providing accurate horizontal wind measurements that are more frequent in time than those provided by the current rawinsonde network, the accuracy of the vertical velocity measurements is still in question, especially in precipitating environments. In this regard the statements by Röttger and Larsen (1990, their section 8.6), ‘‘The vast majority of the studies carried out with VHF/UHF radars have focused on signals from the clear atmosphere. . . . All of the studies cited indicate that great care must be taken in interpretating UHF/VHF radar data when precipitation is present,’’ and by McAfee and Gage (1995, their section 1), ‘‘The resulting velocities are ostensibly the vertical component of the dynamic atmospheric velocity. However, the accuracy of such measurements has not been fully established, and there are a number of observations from various experiments which are not fully explained’’ are apropos. Given the open question of the accuracy of the vertical velocity measurements of wind profilers in a precipitating environment and the possibility that the dominant and gravity wave components can have the same period, it must be concluded that studies that seek to distinguish between the two components using bandpass filters on time-dependent profiler measurements of the instantaneous vertical velocity in a precipitating environment currently are not based on sound scientific evidence. To measure the vertical velocity of the gravity waves away from the cooling/heating source with less than a 10% relative error will require an instrument that has a noise range of less than 0.01 m s^{-1}.

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