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The identification of mesospheric frontal gravity-wave events at a mid-latitude site

Steven M. Smith *

Center for Space Physics, Boston University, Boston, MA 02215, USA

Abstract

Mesospheric frontal-type gravity waves are an uncommon type of wave disturbance that occurs in the mesospheric OH, Na, O_2, and $O(^1S)$ nightglow. They are understood to be the result of gravity waves exhibiting various degrees of non-linear behavior. Despite their similar appearance in all-sky images, careful analysis reveals that there are at least two distinct types of frontal wave disturbances, each with completely different consequences in terms of vertical momentum transport and deposition. Therefore, a correct identification is important in order to characterize their propagation modes. In this report we present the frontal gravity wave activity that occurred during a twelve-month period at Millstone Hill (42.6°N, 172.5°W), a mid-latitude site, to illustrate their range of behaviors.

Keywords: Gravity; Waves; Bores; Walls; Frontal; Mesosphere

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1. Introduction

All-sky imagers record several naturally-occurring night-glow emission layers which serve as dynamical tracers. The four main emissions used in the night-time upper-mesosphere are due to OH, Na, O_2, and $O(^1S)$. The emissions occur as relatively narrow layers – half-maximum brightness (FWHM) of ~8–10 km – and occur at nominal altitudes of 87, 90, 94 and 96 km, respectively. Hence, all-sky imagers can sample the gravity wave field in three dimensions by exploiting the altitude separation of the layers.

Quasi-monochromatic (QM) mesospheric gravity waves are an ubiquitous feature in all-sky images of the mesospheric nightglow. These waves have periods of ~<1-2 h and occur as extensive, long-lasting (~several hours) band-like disturbances that propagate across the sky (e.g., Taylor et al., 1987, 1997; Wu and Killeen, 1996; Swenson et al., 1999; Smith et al., 2000, 2005, 2013; Fechine et al., 2005, 2009; Medeiros et al. 2007). Such waves may exhibit brightness amplitudes ranging from <1% (detector limit) to sometimes over 30%. Two or more wave events can sometimes be observed to occur simultaneously, with each propagating in different directions.

Previous mid-latitude studies have indicated that more than 50% of the mesospheric gravity wave events recorded in all-sky imagers are either evanescent or ducted (Isler et al., 1997; Walterscheid et al., 1999; Smith et al. 2000). However other studies at high-latitudes (e.g. Espy et al. 2004; Suzuki et al., 2009, 2011; Nielsen et al., 2012) have reported that ~80% of the waves recorded were freely propagating and ~20% were ducted or evanescent.

Another type of short-period gravity wave disturbance may also be observed. Frontal gravity waves are characterized by an extensive, stable step-like enhancement or depletion in the nightglow emission radiance (by 5%–20% or more) followed by a series of propagating waves or turbulence.

Frontal wave events were first identified during the ALOHA campaign in the mid-1990’s (Swenson and Espy, 1995; Taylor et al., 1995) and these two reports provide the prototypes of the two distinctive classes of frontal gravity waves: wall events and bores. Since then, there have been several studies of mesospheric “wall” events (Medeiros et al. 2001; Batista et al., 2002, for example)

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* Tel.: +1 6173536658; fax: +1 6173536463.
E-mail address: smsm@bu.edu

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and bores (e.g., Smith et al., 2003, 2005; Brown et al., 2004; She et al., 2004; Fechine et al., 2005, 2009; Nielsen et al., 2006; Shiokawa et al., 2006; Li et al., 2007; Narayanan et al., 2009; Yue et al., 2010; Bageston et al. 2011; Walterscheid et al., 2012).

A complementary pattern of emission brightness between different airglow layers is also commonly observed in frontal wave events. Here, the higher altitude airglow emission usually decreases in brightness in the wake of the disturbance while the lower airglow layer brightens in its wake and creates complementary brightness patterns between the two emissions (the complementarity effect).

The observed stability of the frontal feature, particularly in bores, is the result of non-linear processes that cause steepening of the leading wave-front, which are in balance with dispersive processes that are competing to broaden and dissipate the frontal feature (Lighthill, 1978). The lifetime of the frontal feature ranges from one to several hours.

At mid-latitudes, frontal wave events are relatively uncommon, occurring ~1-2 times per month on average and at a rate <10% the frequency of non-frontal type gravity wave events. However, some low latitude studies (Fechine et al., 2005; Medeiros et al., 2005) have reported higher frequencies of ~1 per week, suggesting an additional or different mechanism for frontal wave generation or their transport characteristics.

Freely propagating gravity wave modes transport momentum and energy both horizontally and vertically. From the dispersion equation, higher frequency waves propagate at steeper angle than lower frequency waves. These modes also possess non-zero vertical fluxes of horizontal momentum and energy which can be transported away from their region of origin and deposited at higher altitudes. Bores and ducted waves, however, are trapped modes and propagate only horizontally. They have zero vertical momentum and energy fluxes and can only transport and deposit their momentum within the horizontal ducting region. A small amount of wave energy may leak vertically from the ducting region in the form of evanescent waves but the deposition of energy and momentum is largely horizontal. Each propagation mode therefore has vastly different potentials with regard to the transport of energy and momentum through the mesosphere and lower thermosphere (MLT) region, so their identification is very important. In this paper, we denote freely propagating gravity waves as vertically propagating waves to distinguish them from ducted and evanescent waves which propagate only horizontally.

In multi-spectral all-sky images, a vertically propagating gravity wave exhibits a vertical phase variation in the wave patterns between the height-separated airglow emissions (OH and O(^{1}S), for example). A horizontally propagating gravity wave, such as a ducted wave, will exhibit either no phase variation or a 180° phase variation between the wave patterns. The phase polarity is determined by the depth of the duct relative to the vertical separation of the emission layers and by the propagation mode of the wave disturbance. A wave disturbance with no detectable vertical phase variation indicates that the vertical wavelength (λ_z) gravity wave is very large or that it is not vertically propagating at all, i.e., the wave is evanescent-like. Evanescent waves, like ducted waves, do not propagate vertically so no vertical phase progression is exhibited in the wave patterns.

The purpose of this study is to illustrate how gravity waves with different propagation modes can exhibit very similar appearances and behaviors in all-sky images. If no additional diagnostic measurements are available (such as vertical lidar temperature profiles or radar wind profiles), one needs to rely on the analysis of the vertical phase structure in order to distinguish between them.

Such an analysis can provide a reasonably conclusive diagnosis of the characteristics of a wave event.

1.1. *Wall events and bores*

Wall events, such as the Swenson and Espy (1995) event, appear to be large upward propagating gravity waves in the process of breaking (Swenson et al., 1998). They typically exhibit non-linear behavior such as large-scale overturning and mixing of the local environment (turbulence).

Bores are a non-linear type of disturbance with distinct properties and characteristics. They have long been known to occur in rivers (e.g., Tricker, 1965; Lighthill, 1978) oceans (e.g., Osborne and Burch, 1980; Apel et al., 1985), and in the lower atmosphere (e.g., Smith, 1988; Mahapatra et al., 1991) but they have only recently been identified in the mesosphere. It was Dewan and Picard (1998) who first suggested that the frontal-type wave event reported by Taylor et al. (1995) was a bore disturbance. Using the analogy of the well-known river bores, they developed a simple theory for an internal mesospheric bore. Smith et al. (2003) presented the first comprehensive case study of a large mesospheric bore. The event occurred over McDonald Obs. in Texas and appeared to have propagated within a temperature inversion over a distance of >1000 km. The bore also exhibited a high degree of non-linearity including soliton-like behavior.

Bores require a ducting region in which to propagate, such as a temperature inversion layer (She et al., 2004) or a wind shear region (Fechine et al., 2009). Co-located OH imaging and Na lidar measurements by She et al. (2004) showed for the first time the existence of a temperature inversion layer associated with a bore disturbance. Narayanan et al. (2009) used imaging and medium-frequency (MF) radar measurements, combined with SABER temperature profiles, to characterize a bore disturbance also associated with a temperature inversion.

Temperature inversions are a common feature in the MLT region (e.g., Hauchecorne et al., 1987; Meriwether and Gardner, 2000; Larsen, 2002). But both of these features can only be detected with a lidar or meteor radar, for example. Ideally, a co-located set of multi-diagnostic