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A Review on Remote Sensing of Atmospheric Gravity Waves and their Role in the Vertical Coupling of Atmosphere

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The atmospheric gravity waves, by carrying energy and momentum, play a pivotal role in coupling the Earth's atmosphere right from the troposphere to thermosphere. Being a sub-grid process, the representation of gravity waves in global circulation models is one of the greatest challenges. Their accurate representation in models is essential for simulating and forecasting the state of the middle and upper atmosphere. These waves take the middle atmosphere away from the radiative equilibrium by adding additional energy to the system. This is one of the driving forces for numerous investigations on these ubiquitous waves since its discovery by Hines [1]. Most of the early studies focused on characterizing the gravity in the troposphere, stratosphere and mesosphere in terms of their time-period, amplitude, phase speed, vertical and horizontal wavelengths. Later, many of the studies attempted to retrieve the momentum fluxes and wave drag in order to quantify the momentum budget of these waves [2]. Among others, atmospheric convection, topography, wind shears, frontal systems are identified as the sources for triggering of the primary gravity waves in the lower atmosphere. Earlier studies also reported the generation of secondary gravity waves in the upper mesosphere and lower thermosphere excited by the dissipating primary gravity waves. Once generated in the lower atmosphere these waves undergo breaking, dissipation, ducting and saturation. Investigations on these waves for the past six decades have resulted in much needed parameterization schemes to represent them in numerical models. However, there have been attempts to improve these schemes based on more comprehensive observations from various platforms.

Among many observational platforms radar and lidar remote sensing techniques have been wealth of information on the atmospheric gravity wave structure and dynamics. Especially, Mesosphere-Stratosphere-Troposphere radar observations are employed to measure gravity wave momentum fluxes using dual beam techniques as well as direct measurements of u′w′ and v′w′, representing zonal and meridional momentum fluxes, respectively. The high-temporal and height resolution along with direct vertical velocity measurements from radar have been providing detailed information on gravity wave dynamics. The dual-beam technique can also be generalized using multi-beam approach from the active-aperture radar. The clear-air radars are the only instruments that can provide real-time observations of convection generated gravity waves especially during thunderstorm events. Recently, meteor radars operating at VHF also providing gravity wave momentum fluxes in mesosphere and lower thermosphere. One more important remote sensing tool, which has been providing gravity wave observation, is Rayleigh lidar. The lidar by measuring temperature profiles in ~30-75 km altitude at ~5 minute intervals provides unprecedented information on gravity propagation in the middle atmosphere, which is inaccessible for many ground based experiments. The temperature perturbations measured by lidar can be employed to measure gravity wave momentum flux through the following relation,

$$F = \left\langle \overline{u'w'} \right\rangle = \frac{k}{m}\left(\frac{g}{N}\right)^2 \left\langle \frac{T'}{\overline{T}} \right\rangle^2 \approx \frac{\omega}{N}\left(\frac{g}{N}\right)^2 \left\langle \frac{T'}{\overline{T}} \right\rangle^2$$

Here the assumption made is $N \gg \omega \gg f$, where ω is frequency of the gravity wave, N is the Brunt Vaisala frequency, f is the Coriolis parameter, g is acceleration due to gravity, $\overline{T}$ and T' are the mean and perturbation of temperature from lidar measurements.

In the present review, radar and lidar contributions for investigating atmospheric gravity waves will be discussed in details along with space based remote sensing techniques in obtaining the global scale gravity wave activity right from upper troposphere to lower thermosphere.

1. C.O. Hines, "Internal atmospheric gravity waves at ionospheric heights", *Can. J. Phys.,* 38, 1441–148, 1960

2. D. C Fritts and M. J. Alexander, "Gravity wave dynamics and effects in the middle Atmosphere", *Rev. Geophys.,* 41(1), 1003, 2003, doi: 10.1029/2001RG000106.