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Gravity waves in the Middle Atmosphere observed by Rayleigh Lidar

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Introduction

Routine lidar measurements performed at two stations located in the south of France, at the Observatoire de Haute Provence (OHP) (44°N, 6°E) and at Biscarosse (BIS) (44°N, 1°W), during 4 years, from 1986 to 1989, provide a large data base to study the mesoscale variability of the middle atmosphere (defined as the stratosphere and mesosphere). The mesoscale fluctuations are interpreted in the framework of the internal gravity wave theory. Through momentum and energy transport and deposition, gravity waves are thought to play a major role in the large-scale dynamics and thermal budget of the atmosphere. The convergence of the momentum and energy fluxes transported by gravity waves largely induce the mean (zonal and meridional) circulation, and thus the temperature distribution, as well as the turbulent diffusion of heat and constituents in the middle atmosphere. Moreover, large temperature inversions frequently observed in the mesosphere, which could persist several days, are likely to be induced by gravity wave breaking. A climatological description of the gravity wave activity is therefore crucial to the understanding of the large scale dynamic of the middle atmosphere.

Data reduction and processing

The backscattered light from a pulsed laser beam sent vertically into the atmosphere, in the absence of any resonant line, is due to Rayleigh scattering (from neutral molecules) and to Mie scattering (from aerosols). Above 30 km altitude, the Mie contribution is negligible, the backscatterd light is thus proportional to the atmospheric density.

The temperature is estimated by fitting the temperature profile with an atmospheric model at the upper altitude of the measurements, by assuming an hydrostatic equilibrium and by applying the ideal gas law. The sources of errors include:

- The uncertainty on photon counting, proportional to the root mean square of the number of counted photons (Poisson Process).
- The assumed temperature at the top of the profile. This systematical error decreases exponentially with decreasing height.
- The sky noise estimate, evaluated by a linear regression on the signal above 100 km height.
- The non-linearity of the photomultiplier (due to intense signal) can be corrected by collecting the photons in two independent channels (90 and 10 % of the signal respectively)

Regarding to gravity wave motion, it is equivalent to consider the relative temperature or density fluctuations.

$$\frac{\rho\prime}{\bar{\rho}} \sim -\frac{T\prime}{\bar{T}}$$

the relative pressure fluctuations being negligible provided that the vertical scales of the motions are not too large compared to the atmospheric scale height.

From the temperature of density profile one can estimate:

- The Brunt-Väisälä frequency

$$N^2 = -g\frac{\partial}{\partial z}\ln\rho + \frac{g^2}{C_s^2} = \frac{g}{T}\left(\frac{\partial T}{\partial z} - \frac{g}{C_p}\right)$$

- The potential energy per unit mass

$$E_p = \frac{1}{2}N^2 < \xi^2 >= \frac{1}{2}\left(\frac{g}{N}\right)^2 < \left(\frac{\rho\prime}{\bar{\rho}}\right)^2 >\sim \frac{1}{2}\left(\frac{g}{N}\right)^2 < \left(\frac{T\prime}{\bar{T}}\right)^2 >$$

The relative density fluctuations are extracted from a low pass filter applied on the log of the density,

$$\ln(\bar{\rho} + \rho\prime) \sim \ln\bar{\rho} + \frac{\rho\prime}{\bar{\rho}}$$

whereas the temperature perturbations are extracted directly by a low pass filtering.

The power spectral density has been estimated by mean periodigram, averaged on a giver period (a day, a month, a year) from density profiles resulting from 15 mn integration time. The white noise level is estimated on the high wavenumber of the spectrum (where the signal to noise ration is low) before to be subtracted from the raw profile. One have thus access to fluctuations from half an hour to infinity and larger than about one km (depending on the signal to noise ratio). The activity of the wave field is estimated by the potential energy per unit mass, obtained by integrating the mean vertical spectra and subtracting the noise power.

Gravity Waves observed by Rayleigh Lidar

In a single case, we obtained simultaneous wind and temperature measurements from rocketsonde and lidar data. The phase of the temperature and of wind perturbations of the dominant low frequency oscillation are in very good agreement with the gravity wave theory. Such low frequency waves are very frequently observed in the stratosphere and lower mesosphere. and are not observed to be dominant above 60 km altitude. The waves seem thus to have relatively higher frequency in the mesosphere than in the stratosphere, probably due to selective transmission of upward propagating waves.

The power spectral density (PSD) as a function of vertical wavenumber is found to increase from the stratosphere to the mesosphere, reaching a value close to $N^2/2m^3$, in agreement with the hypothesis of a saturated wave field. The saturation processes, (i.e. the instabilities induced by the fluctuations) likely act to limit the amplitude of the waves. The vertical scale of the waves reaching the convective saturation limit is an increasing function of altitude in the mesosphere: the vertical scales of the waves reaching saturation ranges between 2 and 3 km in the lower mesosphere, between 5 and 8 km above 60Œkm altitude.

The amplitude of the fluctuations appears too weak (1.5 to 2.5°K) to produce convective instabilities in the stratosphere. The standard deviation of the temperature fluctuations in the mesosphere ranges between 3 and 5°K, large enough to produce convective instabilities. As a matter of fact, we effectively observe convectively unstable layers in the mesosphere.

The seasonal variability of the wave activity is essentially annual in the high stratosphere and low mesosphere, the maximum of activity occurring during winter and the minimum during summer. A semiannual component is superimposed to the annual cycle above 60 km altitude, two minima of activity occurring during the months of April-May and September, that is to say, when the mean wind intensity is weak.

The wind intensity and the wave energy density are positively correlated in the stratosphere and mesosphere, indicating that the gravity wave activity is partially determined by the background flow.

The energy density per unit mass is larger during winter at OHP than at BIS in the upper stratosphere, whereas no significant difference is observed during summer. As the mountain waves can not propagate during summer due to the stratospheric wind reversal and because the orographic source is likely to be more intense at OHP, the annual variation observed in the stratosphere may thus be due to the vertical transmission of orographic waves.

The potential energy density per unit mass is an increasing function of altitude. The energy scale height is generally larger than 10 km, suggesting an energy and momentum dissipation at all heights.

By filling the gap between the low stratosphere and the high mesosphere, which are accessible by radars, the lidar appears complementary with the atmospheric radar. Because the accessible parameters are different (kinetic and potential energy respectively) comparative studies of the mesoscale variability as observed by lidar and radar are highly desirable in order to better understand the momentum and energy balance of the atmosphere.