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Atmospheric Gravity Wave Effects on the
Climate, Dynamics and Composition of
The Upper Mesosphere and Lower
Thermosphere (MLT)

Richard Walterscheid
The Aerospace Corporation
Topics

Review of Gravity Waves

Wave-mean-flow interactions

Theory

Wave transports

Nonacceleration theorem

Chemically induced interactions

Phenomena

Cold Summer Mesopause

Pseudotides

Compositional changes
Fig. 8.2  The propagation of a surface gravity wave initiated by a depression at time $t_0$. 
Pl. 199 A stratiform deck of clouds affected by a strong wind that is producing waves similar to those often seen on water. A band of higher clouds shows that the wind effects are widespread.
Believed to consist of ice particles of dimensions less than 0.1 \( \mu \text{m} \), noctilucent clouds offer a splendid summertime light show to northern inhabitants. During the long summer twilights these high-altitude (85 km) clouds are visible by direct solar illumination, while the lower atmosphere is in shadow. The cloud color is generally silvery-blue, primarily due to the Rayleigh-like scattering properties of the tiny particles, and secondarily due to partial removal of red light from absorption in the Chappuis bands of ozone. The characteristic wave forms are probably a result of viewing perspective, a geometrical consequence of the wave undulation of a thin homogeneous cloud layer. However, at times, clouds can sometimes be viewed directly overhead where this effect should not be present, indicating that divergence/convergence of ice particle concentrations may also be partially responsible. This photograph was taken by Pekka Parviainen at Kastavi, Finland (latitude 60.7°N, longitude 21.3°E). It was taken on the night of July 13, 1983, at 2140 UT (about 2300 local time). Camera details: f/2 50-mm lens, Kodachrome K64 film, exposure time unknown.
Atmospheric Internal Gravity Waves

Recall: Tilted surface in a stratified fluid → horizontal pressure gradient

In a continuously stratified fluid a wave disturbance in one layer tilts adjacent layers and excites traveling disturbances which tilt layers adjacent to them and so on

Waves may be external or internal

External: Maximum energy density at a boundary

Evanescent

Internal: Maximum energy density within the fluid

Vertically propagating (usually)

Phase propagation is opposite to vertical group (i.e. energy) propagation

Amplitude $\propto \bar{\rho}^{-1/2}$ for steady conservative waves

Internal waves dominant in MLT because they are vertically propagating and grow in amplitude
Shelton et al. (1990)
Fig. 2A - Track of a Minuteman Missile launched from Vandenberg Air Force Base, Calif. Such condensation trails show the effect of high altitude, shear, and turbulence in the high atmosphere.
Wave Mean State Interactions

Wave Fluxes

Wave Forcing of the Mean State
  Nonacceleration theorem
  Chemically induced forcing

Wave Mean State Interaction Phenomena in the Upper Mesosphere and Lower Thermosphere
  Cold summer mesopause
  Pseudotides
  Compositional changes
Nonacceleration Conditions

Waves

Linear

Conservative

Steady

No critical level ($\bar{u} \neq c$)
Wave Fluxes

Mean state changes induced by wave fluxes

\[ \frac{\partial \psi}{\partial t} = - \frac{1}{\bar{\rho}} \frac{\partial F_z(\psi)}{\partial z} \]

\[ F_z(\psi) = \bar{\rho} \bar{w}' \psi' \]

Wave stress

\[ \psi = u \]

Sensible heat flux

\[ \psi = c_p T \]

Species flux

\[ \psi = r, \psi = n \]
Vertical Wave Fluxes

\[ w' \psi' \]

\[ w' \psi' \]

\[ \pm \]

\[ x \]

\[ z \]
Forcing of Mean Wind by Momentum Flux
Wave Drag Effects on the Mesospheric General Circulation
Fig. 3. Derived radiative equilibrium temperature distribution at solstice. Winter hemisphere on right.

Fig. 4. Observed zonal mean temperature distribution at solstice (after Murgatroyd, 1969). Winter hemisphere on right.
Thermal Wind Relation

In geostrophic balance

\[ f \frac{\partial u}{\partial p} = \frac{R}{p} \left( \frac{\partial T}{\partial y} \right)_p \]

In words:

Westerly shear \(\Rightarrow\) temperature decreases poleward
Fig. 4. As in Fig. 1, but for the June-August period.
Fig. 4. Observed zonal mean temperature distribution at solstice (after Murgatroyd, 1969). Winter hemisphere on right.
Cold Summer Mesopause

Cold summer mesopause is caused by deceleration of summertime easterlies due to wave drag
Drag Mechanisms

Wave breakdown
Viscous dissipation
Wave transience
**Pseudotides**

**Tides**: Periodic response to periodic external forcing by astronomical agency

**Pseudotides**: Tidal frequency oscillations forced internally by tidally modulated gravity wave mean flow interactions

- Viscous absorption near critical levels (Walterscheid, 1981)

- Wave breakdown (Fritts and Vincent, 1987)
Tidally Modulated Gravity Wave Mean Flow Interactions

Fritts and Vincent (1987)

- Observed correlation between momentum fluxes and tidal winds
- Proposed that gravity waves dissipate via wave breakdown

Lu and Fritts (1992)

- Used momentum flux parameterization based on linear saturation theory
- Simulated large wave-induced tidal period oscillation

Forbes et al. (1991)

- Examined nonlocal effects
- Used saturation parameterization in tidal model and inferred deceleration of global tidal modes
Chemical Forcing of Mean-State Minor Constituent Profiles

Vertical flux of constituent mixing ratio is zero when nonacceleration conditions apply and chemical production and loss are nil.

Vertical flux can be induced by chemistry even when nonacceleration conditions apply.


Schoeberl et al. (1983) modified Strobel's parametization to incorporate turbulent mixing (Lindzen, 1981; Garcia and Solomon, 1985; Bjarnason et al., 1987; LeTexier et al., 1987).

Walterscheid and Schubert (1989) used five-reaction model of wave-perturbed $\text{O}_3$ chemistry near the mesopause to calculate chemically induced wave fluxes of minor constituents.
Conclusions

Gravity wave drag is the probable cause of the cold summer mesopause.

Tidal modulation of gravity wave induced winds may generate strong mean winds with tidal frequency in the upper mesosphere and lower thermosphere.

Gravity wave induced fluxes of chemically reacting species can alter concentrations on time scales comparable to chemical lifetimes in the mesopause region, and can be comparable to fluxes attributed to small-scale turbulence.