Gravity Waves in the Middle Atmosphere (a modeler's perspective)

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Outline of Lecture

- Part 1 (Theory and Modelling)
  1. Importance of small-scale gravity waves
  2. Basic theory (simple)
  3. Parameterization in GCMs
  4. Results from the CMAM

- Part 2 (Observations)
  1. Measurement techniques
  2. Sampling issues
  3. What modelers need

- Summary

Importance of small-scale GWs

1. **GWs keep the mesosphere far from radiative equilibrium.**
    - radiative equilibrium:

      ⇒ temperature highest where heating strongest & vice versa.

      ⇒ summer pole should be warm, winter pole should be cold.

    - observations show the opposite:

      → summer pole is cold

      → winter pole is warm.

Figure 1

- Why?

  → GWs deposit zonal momentum in the mesosphere.

  → this GW force (or drag) is negative in the winter hemisphere and positive in the summer hemisphere.

  → drag must be balanced by Coriolis force ($f\bar{v}$) ⇒ flow from summer pole to winter pole.

  → meridional wind ($\bar{v}$) generates a vertical wind ($\bar{w}$) by mass continuity.

  → downwelling ($\bar{w} < 0$) ⇒ adiabatic compression ⇒ warming (winter pole).

  → upwelling ($\bar{w} > 0$) ⇒ adiabatic expansion ⇒ cooling (summer pole).

  → this is dynamical heating and cooling.

- zonal winds computed from radiative-equilibrium temperature:

  → are much stronger than observed winds

  → do not reverse in mesosphere.

Figure 2

- strong radiative-equilibrium wind is understood from thermal wind equation:

$$\frac{\partial \bar{U}_r}{\partial z} \propto -\frac{1}{f}\frac{\partial \bar{T}_r}{\partial \phi}$$

  → in NH winter $\partial \bar{T}_r/\partial \phi < 0$ and $f > 0$

  ⇒ U_r increases with height.

2. **GWs warm winter polar stratosphere.**

- downwelling ($\bar{w}^*$) produced by breaking GWs in the mesophere extends into the stratosphere.
  - downwelling ⇒ adiabatic compression ⇒ warming.
  - polar winter stratosphere is cold and dark.

    ⇒ long radiative relaxation time scale ($1/\alpha$).

  $\therefore$ $\bar{w}^* < 0$ and small α ⇒ large departure from radiative equilibrium, since from thermodynamic equation have that

$$(\bar{T} - \bar{T}_{rad}) \approx -\alpha^{-1} N^2 \bar{w}^* \ .$$

Figure 3

- “downward-control” impact of GWs is stronger in SH winter stratosphere since planetary wave drag is weaker.
- absence of drag in GCMs in SH winter is referred to as the “cold-pole problem.”
  - → alleviated using GW drag parameterizations
  - → or higher horizontal resolution.

Figure 4

3. **GWs help drive the equatorial QBO.**

Figure 5

- in the presence of tropical upwelling, planetary waves are unable to drive QBO.

  → small-scale GWs provide the required extra drag (Dunkerton, 1997).

Figure 6

- most GCMs do not naturally produce a QBO from resolved waves ⇒ and must use parameterized GWs to get one.

Figure 7

Basic theory (simple)

1. **Hydrostatic GWs without rotation**
   (see Andrews et al., 1982)

   - use hydrostatic approximation ⇒ pressure gradient equals gravitational force.
   - neglect the rotation of the Earth.
   - assume background atmosphere with constant zonal wind (U) and buoyancy frequency (N); allow only density (ρ_o) to vary with height.
   - consider small-amplitude case
     ⇒ governing equations can be linearized.
   - assume wavelike perturbations proportional to exp$[i(kx + mz - \omega t)]$, where
     k is the horizontal wavenumber
     (i.e., only east-west propagation),
     m is the vertical wavenumber,
     ω is the (ground-based) frequency.

- *dispersion relation* for the resulting set of equations* is

$$m^2 = \frac{N^2 k^2}{\widehat{\omega}^2}.$$

- $\widehat{\omega} \equiv \omega - kU$ is the *intrinsic frequency* .

  → It is the frequency of the wave measured in a reference frame moving with the background wind (or *Doppler-shifted* frequency).

- *vertical propagation:*
  - since m^2 is positive, m is real and the wave is vertically propagating.
  - for upward energy propagation (i.e., upward group velocity) phase lines tilt:

    → eastward with height for $\widehat{\omega} > 0$,

    → westward with height for $\widehat{\omega} < 0$.

*It has been assumed that the vertical scale of the wave is much less than the density scale height, i.e., the Boussinesq approximation.

- *amplitude growth with height:*
  - to conserve energy the amplitude of a vertically propagating wave increases exponentially with height[†].

- *momentum flux:*
  - a vertically propagating wave transports horizontal momentum upward.
  - this can be seen by computing the momentum flux (τ).

    → it is easy to show that for our simple example $\tau = \rho_o \overline{u'w'}$ is constant.
  - It is important to note that the sign of the momentum flux depends on the direction of horizontal propagation:[‡]

    $$\Rightarrow \tau > 0 \text{ for } \widehat{\omega} > 0,$$
    $$\tau < 0 \text{ for } \widehat{\omega} < 0.$$

[†] This follows from the exponential decrease of background density.

[‡] The continuity equation in pressure coordinates indicates that u' and w' are approximately in phase for $\widehat{\omega} > 0$ and out of phase for $\widehat{\omega} < 0$.

2. **Rotation and nonhydrostatic effects** (see Gill, 1982)

- the previous example was for hydrostatic GWs and did not include the effects of the Earth's rotation.

- when these effects are included, the dispersion relation becomes

  $$m^2 = \frac{(N^2 - \widehat{\omega}^2)k^2}{\widehat{\omega}^2 - f^2}$$

  where f is the Coriolis parameter.

- whether a wave is vertically propagating now depends on the intrinsic frequency, since $m^2 > 0$ requires

  $$|f| < |\widehat{\omega}| < N.$$

- for $m^2 < 0$, the wave is vertically trapped.

  → amplitude decreases exponentially with height.

  → momentum flux is zero.

- example: mountain waves ($\omega = 0$) propagate vertically into the stratosphere only if $\lambda > (2\pi U)/N \approx$ 10 km for typical values of U and N.

  $\Rightarrow$ small-scale mountain waves, where $\lambda < (2\pi U)/N$, are vertically trapped (lee waves).

Figure 8

3. **Gravity wave drag**

- in the above examples (where the waves are steady, linear, and undamped), the momentum flux is independent of height.

- since the flux divergence is zero, such waves do not alter the background flow:

$$\frac{\partial U}{\partial t} + ... = -\frac{1}{\rho_o}\frac{\partial \tau}{\partial z} = 0.$$

- when the GWs are damped they deposit their momentum, which exerts a force on the background flow.

  → This is called *gravity wave drag*.

- wave dissipation occurs when:

  (1) $\hat{\omega} \to 0$ (a *critical line*), where the vertical wavelength gets very small, or

  (2) amplitude gets large enough that the wave breaks (like a wave on a beach).

Parameterization of GWs in GCMs

1. **Resolved vs unresolved GWs**

- a GCM cannot resolve horizontal scales smaller than a model grid box.

  → ∼ 300-500 km for most GCMs.

- neglecting unresolved GWs leads to erroneous results as seen in Figure 4.

- simulations using high-resolution GCMs show that the momentum flux spectrum in the mesosphere is very shallow.

  Figure 9

  ⇒ extremely high resolution is required to resolve most of the wave momentum flux → this is not currently possible.

  ⇒ these GWs must be parameterized.

2. **GWD parameterizations**

- GW quantities are expressed in terms of the background (i.e., resolved) winds and temperatures.

- simplifying assumptions are made to make the problem computationally feasible.

- features common to all parameterizations:
  - GW propagation is governed by a linear dispersion relation and conservation of (pseudo-) momentum.

  - only vertical propagation of energy is allowed ⇒ a GW is assumed to remain in a grid box.

  - background quantities are assumed to vary only in height, and to vary more slowly in height than wave quantities.

  - a GW is removed at a critical level (i.e., *critical level filtering*).

  - a *GW source* is specified in the troposphere for a discrete or continous spectrum of waves:

    → momentum flux as a function of horizontal wavenumber and frequency.

- features which differentiate all parameterizations:
  - dissipation mechanism when wave amplitudes are large (*saturation criterion*).
  - specific details of source spectrum (i.e., momentum flux distribution).

3. **Summary of GWD parameterizations**

- Lindzen (1981):
  - saturation criterion: when the amplitude of a GW is large enough that the total (i.e., background plus GW) temperature lapse rate is convectively unstable.

    → above the 'breaking height', turbulence damps the GW so as to maintain neutral stability ⇒ momentum is deposited over a range of heights.

- Hines (1997):
  - saturation criterion: when a GW meets a critical level induced by the combination of the background wind and the wind induced by the entire spectrum of GWs.

    → at this height, the GW is obliterated ⇒ all the wave's momentum is deposited at once.

- Warner-McIntyre (1996):
  - saturation criterion: when a GW exceeds a prescribed amplitude threshold that is based empirically on the observed GW spectrum in the middle atmosphere.

    → above this height, the wave amplitude is constrained to remain at the prescribed saturated value.

- Alexander-Dunkerton (1999):
  - saturation criterion: when a GW exceeds convective instability threshold.

    → at this height, the GW is obliterated, and all of its momentum is deposited.

Results from the CMAM

1. **Description of the CMAM:**

   - a middle atmosphere GCM, which extends from the ground to $\sim$ 100 km.

   - a whole slew of physical processes (radiation, chemistry, clouds, hydrologic cycle, etc.).

   - details in Beagley et al. (1997).

   - T32 horizontal resolution $\Rightarrow \sim$ 600 km.

   - 65 vertical levels $\Rightarrow \Delta z \sim$ 1.5 km above troposphere.

2. **Orographic GWD experiments:**

- momentum deposition by unresolved GWs generated by flow over topography → parameterization of McFarlane (1987).

- spatial pattern of the GW source is well known → it's the topography.

- separate Earth's topography into resolved ($\lambda_x > 600$ km) and unresolved ($\lambda_x < 600$ km) parts ⇒ for a T32 model.

  → use standard deviation of unresolved topography to specify the amplitude of the GW.

- single GW, with zero frequency and propagation direction opposite to horizontal wind vector at each GCM grid point.

- saturation criterion of Lindzen (1981).

Figure 10

Figure 11

- summary of orographic GWD experiments:
  - no impact in the summer stratosphere or mesosphere. Why?

    → because of critical-level filtering of the stationary GW by the stratospheric easterlies (i.e., where $U = 0$).

  - greater impact in NH winter than in SH winter.

    → because there are more mountains in the NH.

  - no reversal of the zonal mean zonal wind in the mesosphere.

    → because a stationary GW can only decelerate winds to zero, not reverse them.

3. **Non-orographic GWD experiments:**

- non-orographic GWs are generated by mechanisms other than topography:

  → convection, wind shear, etc.

- sources are difficult to characterize:

  → highly variable in space and time.

  → generation mechanisms poorly understood.

- because of these uncertainties, modellers assume the simplest form:

  → a source that is uniform in space and time.

- we will examine 2 non-orographic GWD parameterizations described earlier:

  (1) Hines (1997)

  (2) Warner-McIntyre (1996).

- the GW source for both is identical:

  → “isotropic” in intrinsic frequency

  (momentum flux is distributed symmetrically about $\widehat{\omega} = 0$).

- aspects we will examine:

  (1) saturation mechanism

  Figure 12

  (2) GW launch level

  Figure 13

  Figure 14

- summary of non-oro GWD experiments:
  - details of saturation mechanism not important to the time mean flow. Why?

    → because by rescaling the saturation criteria, different parameterizations can produce similar results.

    → the simulation using only critical-level filtering makes this point most clearly.
  - this means that the heated debate over "whose parameterization is right?" is irrelevant to modellers.
  - what is important is:

    (1) the height at which the GWs deposit their momentum,

    (2) the momentum flux distribution at the source height.

4. **Resolved GWs in GCMs:**

- GCMs generate a broad spectrum of resolved GWs as a result of tropospheric processes like convection, flow over (resolved) topography.

- these disturbances can propagate vertically, grow in amplitude, dissipate, and deposit their momentum.

- we have seen evidence of resolved waves in the CMAM simulation with only critical-level filtering (Figure 12).

  → Are they GWs?

- to answer this a more quantitative analysis is required:

Figure 15

Figure 16

Figure 17

⇒ Koshyk et al. (1999) paper demonstrates that GCMs with upper boundaries above $\sim$ 80 km have enhanced KE spectra in mesosphere:

→ divergent (i.e., gravity wave) component of KE as large as rotational.

→ power at wide range of spatial scales.

→ CMAM is the most energetic model.

- Which of the GCMs is most realistic?

  → We don' know → no global observations of these horizontal scales.

- *resolved GWs in the tropics:*
  - deep convection in the tropics causes condensation of water ⇒ release of latent heat.

    → heating generates waves with a wide range of spatial and temporal scales.
  - more waves are able to propagate vertically since the Coriolis force is small. → see dispersion relation.
  - waves generated by convective heating propagate upward and interact with the zonal mean flow.

    → dissipating waves drive zonal wind oscillations like the QBO in the lower stratosphere and the SAO in the stratosphere and mesosphere.

- deep convection cannot be resolved in GCMs ⇒ must be parameterized.

- there are various convective parameterizations used in models: moist convective adjustment, mass-flux schemes, etc. (details unimportant here).

- the ability of GCMs to simulate the QBO and SAO depend crucially on these resolved equatorial waves and consequently on the convection parameterizations.

- a careful GCM intercomparison of convective parameterizations and corresponding wave spectra was performed by Horinouchi et al. (2003).

Figure 18

- their results explain why a GCM like SKYHI can generate a QBO-like oscillation without parameterized GWs, while the CMAM cannot:

  → SHYHI uses a convection scheme which is very "active" and generates a broad spectrum of frequencies.

  → CMAM uses a parameterization that does not.

- unclear which is more realistic:

  → lack of global measurements.

  → uncertainty in interpreting satellite-derived proxies of tropical latent heating (Horinouchi, 2002).

Part 2 (Observations)

1. Measurement techniques

2. Sampling issues

3. What modelers need

1. **Measurement techniques**

- overview of several techniques:
  - *airglow imagers:*

    → measure emission from photo-chemically excited species in the upper mesosphere and lower thermosphere.

    → sensitive only to GWs with long λ_z and relatively short λ_x ⇒ nonhydrostatic GWs → often vertically trapped or ducted waves.

    Figure 19

  - *lidars:*

    → measure backscattered laser radiation ⇒ air density ($\sim$ 30-60 km).

    → ideal gas law and hydrostatic equilibrium ⇒ temperature profile.

    → high vertical resolution.

    Figure 20

- *radars:*

  → winds in middle atmosphere.

  → high temporal frequency.

  → comparison of MF radar to CMAM:

  Figure 21

  → CMAM has a much steeper KE spectrum than does radar.

  → due to numerical damping of high frequency waves in CMAM.

- *pressurized balloons:*

  → drift along in prevailing wind.

  → measure horizontal and vertical wind components, temperature, etc.

  ⇒ able to measure momentum fluxes and intrinsic frequency → very important.

  Figure 22

– *satellites:*

→ optically thick limb radiances from Microwave Limb Sounder on UARS ⇒ proxy for temperature along satellite track.

→ high horizontal resolution.

→ technique sensitive to long λ_z.

→ also sensitive to direction of GW propagation (orientation of wave phase lines with instrument line of sight).

→ global information about convective sources in tropics:

Figure 23

2. **Sampling issues**

- each measurement technique is sensitive to a portion of the GW spectrum.

  ⇒ no one technique can measure the entire spectrum!

  → in order to compare observations and model results, must first apply an "observational filter" to the simulated spectrum. → this mimics the instrument sensitivity (Alexander, 1998).

- Alexander (1998) also explains that GW intermittency complicates the interpretation of the measurements:

  → intermittent sources will generate wave packets.

  → packets with long λ_z will propagate rapidly upward through the atmosphere.

  ⇒ these waves will be difficult to see.

  → packets with short λ_z propagate slowly upward and so are much more likely to be observed.

3. What modelers need

- observational constraints on the source spectra for GWD parameterizations.
- observational constraints on the resolved GWs in the mesosphere.