Interaction between Middle-Atmosphere Solar-Tides and Gravity-Waves

Ray-tracing model ; Linear Tidal model

B. Ribstein, U. Achatz

Theory of Atmospheric Dynamics and Climate,
Goethe-Universität, Frankfurt/Main, Germany
Middle Atmosphere mean circulation

Climatology-temperature in the HAMMONIA model

Stratosphere, mesosphere and lower thermosphere:
Homogeneous and neutral composition
Climatological-zonal-wind, in the HAMMONIA model

Circulation is balanced due to waves-mean flow interactions!

1. Closure of mesospheric jets
2. Cold (warm) polar summer (winter) mesopause
3. Quasi-biennial oscillation (stratosphere)

Additional imbalance and forcing solved by emission of waves, e.g. gravity waves and solar tides
Internal Gravity-waves

Short-scale free waves excited in lower-atmosphere, e.g. by topography and convection
Wave-amplitude increases with altitude (density decreases)

Transport momentum and buoyancy from lower to middle atmosphere, shaping middle atmosphere circulation

Gravity Waves (small scales) dynamics needs to be parameterized because explicitly resolve the whole GW spectrum is computationally impossible.

Major GW effects came from wave-mean flow interaction, contributing e.g. to the closure of thermohaline circulation or mesospheric jets.

Gravity waves and Solar tides (global scale) are important for the dynamical coupling between lower and middle atmosphere (from source to breaking level).

Time and horizontal variations of large-scale flows as the horizontal propagation of GWs are neglected in usual GW parameterization [e.g. Vanderhoff et al. (2008, 2010); Senf and Achatz (2011); Ribstein et al. (2015)].

Interaction between the GW and the wave-induced mean-flow, known as self-acceleration, can strongly modified GW propagation [e.g. Sutherland (2001); Murashko et al. (2015); Bölöni et al. (submitted, 2016)].

How to include those effects in a GW parameterization?
Solar Tides

Global-scale forced waves, thermally driven by absorption of solar radiation
Wave-amplitude increases with altitude (density decreases)

Existence of diurnal, semi-diurnal, ter-diurnal… tides, propagating east(west)ward
Tides propagating with apparent sun motion: migrating tides

Transport momentum and buoyancy from lower to middle atmosphere, often dominating Mesosphere lower-Thermosphere dynamics

References: Forbes, Hagan, Lindzen, Walterscheid…
GWs - STs interaction: *directly coupled* approach

**Gravity Waves** (small scales) and **Solar Tides** (global scale) are important constituents of dynamical coupling between lower and middle atmosphere, that still need to be model!

1. Temporal and spatial variations of background flow are not neglected, allowing **GWs** horizontal propagation in ray-tracing model.
2. **GWs** propagate on a “realistic” *climatology* + **STs** as large-scale flow.
3. **STs** propagate on a “realistic” *climatology* flow. **STs** are described in a linear global tidal model, partly forced by **GWs**.
4. Ray-tracer and linear tidal model are run simultaneously.

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Ray-tracing model

Small-scale wave propagating in a large-scale flow (W.K.B. ansatz)

- Rays propagate along characteristics: \( d_t x = c_g, \quad d_t k = -\nabla_x \Omega \)
- Phase-space Wave-Action density \( \mathcal{N} \) is conserved along ray-propagation
  \[
  \partial_t \mathcal{N} + c_g \cdot \nabla_x \mathcal{N} + d_t k \cdot \nabla_k \mathcal{N} = 0
  \]
  
  \[\text{[Buhler et al. 1999, Hertzog et al. 2002, Muraschko et al. 2015]}\]
- GWs propagate in 6D location-wavenumber phase-space
- Solve impossibility of Rays to cross each other
- Simplified, homogeneous and continuous GW emission source
- Evaluation of momentum and buoyancy deposition
  \[
  f_x = -\frac{1}{\rho} \nabla_x \cdot \langle \rho v' u' \rangle \approx \langle f_x \rangle - \frac{\gamma^R}{\Omega_T} U_{ST} - \frac{\gamma^I}{\Omega_T} \partial_t U_{ST}
  \]

Convergence-fluxes \( (f_x; f_y; f_b) \)

Rayleigh-friction and Newtonian-relaxation coefficients: \( (\gamma^R; \gamma^I) \)
Linear *global* tidal model

- Migrating \((s = n)\) and non-migrating \((s \neq n)\) STs state-vector \(Y\).
- Diurnal \((n = 1)\), semi-diurnal \((n = 2)\), ter-diurnal \((n = 3)\) ... tides

\[
\sum_{n=1}^{\infty} \sum_{s \in \mathbb{Z}} \left( Y_{ST}(n, s) e^{i(n\Omega_T t + s\lambda)} + Y_{ST}(n, s)^* e^{-i(n\Omega_T t + s\lambda)} \right)
\]

- Tidal model is a linearization \(L_0 Y\) of KMCM \(-\) gcm around climatology \(Y_0\)
  - *HAMMONIA* \(-\) gcm provides state-vector \(Y_0\) and heating-rates \(Q\)
  - \(L_0 Y\) include linear terms of the dynamical system and the nonlinearities between \(Y_0\) and \(Y\)

- **Iterative approach** : 
  \[
  \left(1 + \frac{\gamma_I}{\Omega_T}\right) \partial_t Y = \left(L_0 - \gamma_R\right) Y + Q
  \]
  *Rayleigh-friction* and *Newtonian-relaxation* coefficients : \((\gamma_R; \gamma_I)\)

- **Fully coupled approach** : 
  \[
  \partial_t Y = L_0 Y + f_{GW} + Q
  \]
  *Convergence-fluxes* : \(f_{GW}\)
Ray-tracing results (1/2) : *directly coupled* approach

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"Full" experiment with diurnal forcing

f_x [m/s/day] annual cycle at z=80km

Consistent with *Iterative* approach

f_{x,y,b} > 0 GW-forcing impose an acceleration on climatology and on STs
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Ray-tracing results (2/2) : \textit{directly coupled} approach

\textit{``single-column''} experiment : no horizontal GW propagation ($d_t \lambda = d_t \theta = 0$), no horizontal variation of background flow ($d_t k = d_t l = 0$), no curvature contribution

\[ f_x \text{ [m/s/day] in December with diurnal forcing} \]

Consistent with \textit{iterative} approach

GW deposition \textbf{DIFFERS} between the \textit{``single-column''} and the \textit{``full''} experiments !
Linear tidal results (1/2) : iterative approach

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Im( V )_{SW2} [m/s] in May

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- **Single-column** experiment with diurnal forcing
- **Full** experiment with diurnal forcing

Diurnal tides in the “full” experiment similar to both HAMMONIA model and observations

GW deposition influence (non)diurnal ST phases
Linear tidal results (2/2) : *directly coupled* approach

In the "full" experiment:
- Important part of tidal signal is forced directly by GW forcing.
By implementing a GW 4-dimensional ray-tracer in a linear-global-tidal model, we analyzed the STs - GWs interaction.

- Temporal and spatial variations of the large-scale flow show major GW dynamical effects.
- Horizontal propagation of GWs contribute importantly to GW drags, leading to strong GW influence on STs phase-structures and amplitudes.
- Important part of tidal signal is forced directly by GW forcing.
