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

Ray-tracing model ; Linear Tidal model

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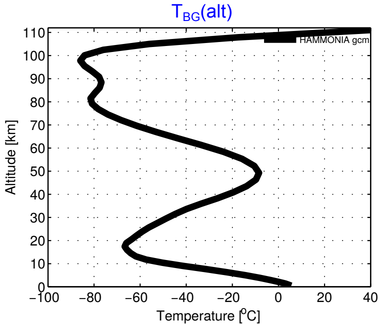
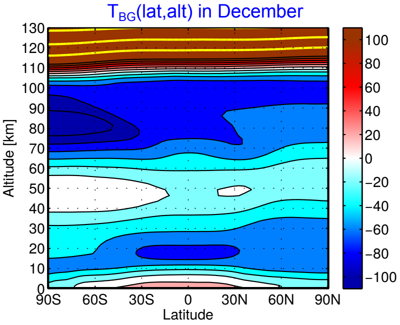
Middle Atmosphere mean circulation

Climatology-temperature in the HAMMONIA model

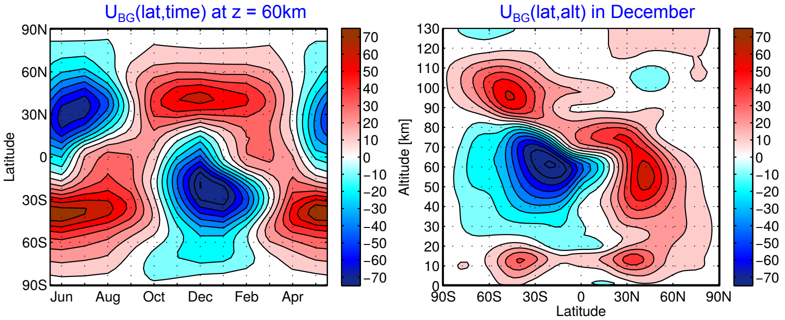




Stratosphere, mesosphere and lower thermosphere :

Homogeneous and neutral composition

Climatological-zonal-wind, in the HAMMONIA model



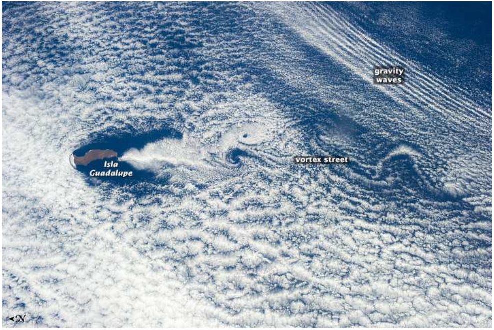
Circulation is balanced due to waves-mean flow interactions !

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

References : *Alexander, Buhler, Chun, Fritts, Grimshaw, Holton, Lindzen . . .*

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 mesopheric 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)]

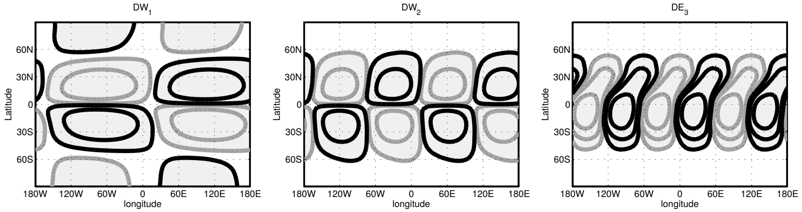
Interaction between the GW and the wave-induced mean-flow, known as self-acceleration, can strongly modified GW propagation [e.g. *Sutherland* (2001) ; *Murashko et al.* (2015) ; *Bölöni et al.* (submitted, 2016)]

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-dirunal. . . tides, propagating east(west)ward
Tides propagating with apparent sun motion : migrating tides



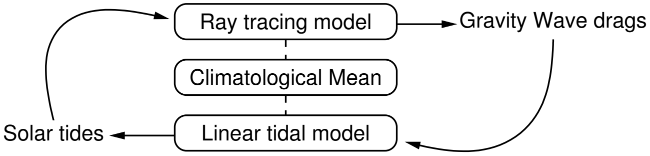
Transport momentum and buoyancy from lower to middle atmosphere,
often dominating *Mesosphere lower-Thermosphere* dynamics

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.



B. Ribstein, U. Achatz and F. Senf. *"The interaction between gravity waves and solar tides : results from 4-D ray tracing coupled to a linear tidal model"*. JGR : Space physics (2015)

Ray-tracing model

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

- Rays propagate along characteristics : ($d_t\mathbf{x} = \mathbf{c_g}$, $d_t\mathbf{k} = -\nabla_\mathbf{x}\Omega$)
- Phase-space Wave-Action density $\mathcal{N}$ is conserved along ray-propagation

$$\partial_t\mathcal{N} + \mathbf{c_g} \cdot \nabla_\mathbf{x}\mathcal{N} + d_t\mathbf{k} \cdot \nabla_\mathbf{k}\mathcal{N} = 0$$

[*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

$$f_x = -\frac{1}{\rho}\nabla_\mathbf{x} \cdot < \rho\mathbf{v}'u' > \approx < f_x > -\gamma^\mathcal{R} U_{ST} - \frac{\gamma^I}{\Omega_T}\partial_t U_{ST}$$

Convergence-fluxes (f_x ; f_y ; f_b)

Rayleigh-friction and *Newtonian-relaxation* coefficients : ($\gamma^\mathcal{R}$; γ^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-dirunal ($n = 3$) ...tides

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

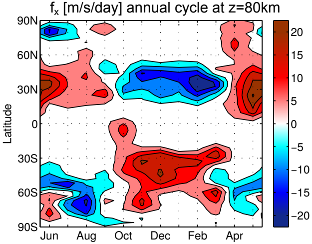
- Tidal model is a linearization $\mathcal{L}_0 Y$ of *KMCM* $-$ *gcm* around *climatology* Y_0
  - *HAMMONIA* $-$ *gcm* provides state-vector Y_0 and heating-rates $\mathcal{Q}$
  - $\mathcal{L}_0 Y$ include linear terms of the dynamical system and the nonlinearities between Y_0 and Y
- ***Iterative* approach :** $\left(1 + \frac{\gamma^{\mathcal{I}}}{\Omega_T}\right) \partial_t Y = \left(\mathcal{L}_0 - \gamma^{\mathcal{R}}\right) Y + \mathcal{Q}$

  Rayleigh-friction and *Newtonian-relaxation* coefficients : $(\gamma^{\mathcal{R}} ; \gamma^{\mathcal{I}})$
- ***Fully coupled* approach :** $\partial_t Y = \mathcal{L}_0 Y + f_{GW} + \mathcal{Q}$

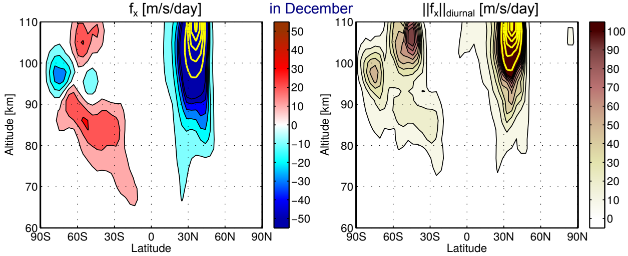
  Convergence-fluxes : f_{GW}

Ray-tracing results (1/2) : *directly coupled* approach

``*Full*'' experiment with diurnal forcing



Consistent with *Iterative* approach

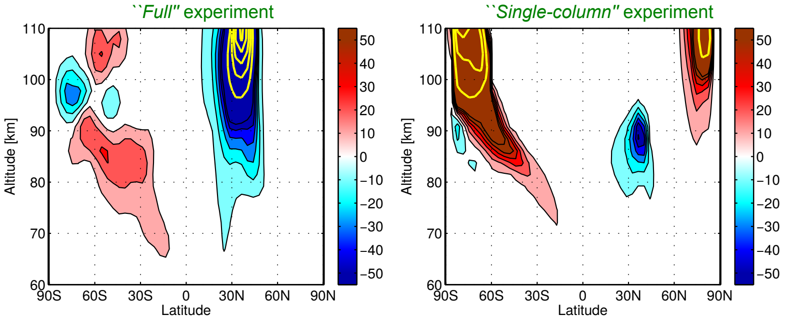


$f_{x,y,b} > 0$ GW-forcing impose an acceleration on climatology and on STs

Ray-tracing results (2/2) : *directly coupled* approach

"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 [m/s/day] in December with diurnal forcing

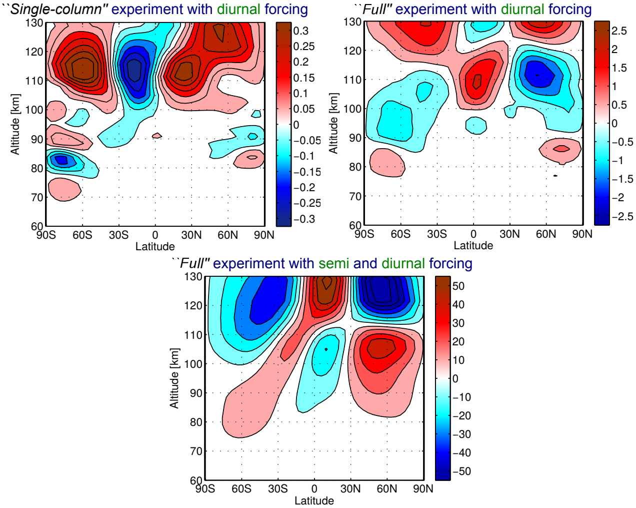


Consistent with *Iterative* approach

GW deposition DIFFERS between the *"single-column"* and the *"full"* experiments !

Linear tidal results (1/2) : *iterative* approach

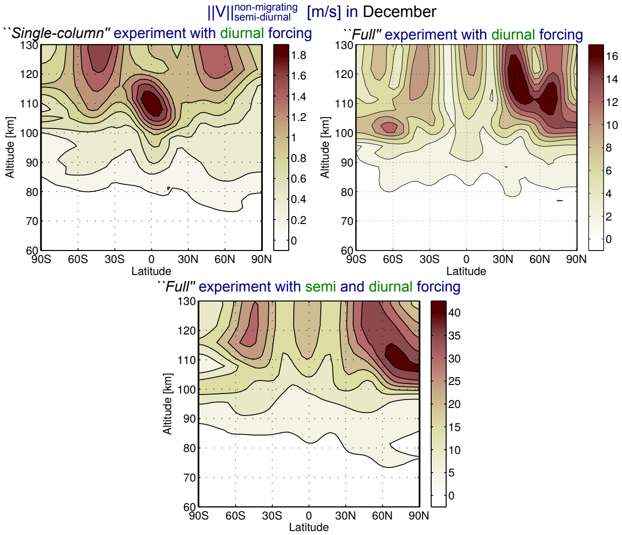
Im(V)$_{SW2}$ [m/s] in May



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

Summary

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

Publications

1. **B. Ribstein**, U. Achatz and F. Senf. *The interaction between gravity waves and solar tides : results from 4-D ray tracing coupled to a linear tidal model*. J. Geophys. Res. : Space physics, 10.1002/2015JA021349 (2015, 23 pp.)

2. G. Bölöni, **B. Ribstein**, U. Achatz, J. Muraschko, C. Sgoff and J. Wei. *The interaction between atmospheric gravity waves and large-scale flows : an efficient description beyond the non-acceleration theorem*. J. Atmos Sci., submitted (2016)

3. **B. Ribstein**, U. Achatz *The interaction between gravity waves and solar tides : results from 4-D ray tracing* directly *coupled to a linear tidal model*. J. Geophys. Res. : Space physics, submitted (2016)