Towards the implementation of a transient gravity wave drag parameterization in ICON

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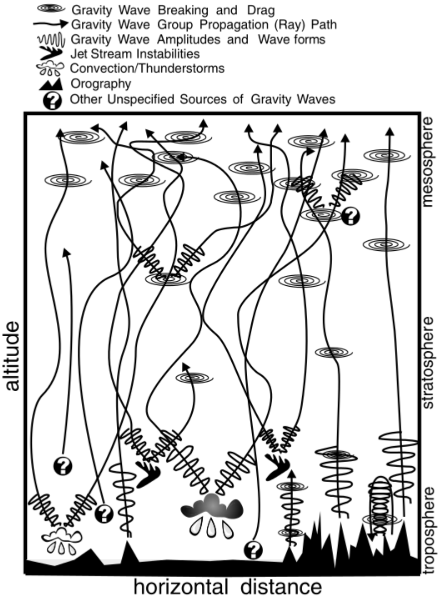
Motivation



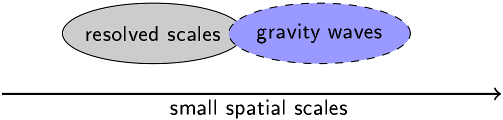
Atmospheric gravity waves (GW)

- main sources: orography, convection, jets/fronts
- mainly vertical energy (momentum) transport with $\vec{c}_g$ $\Rightarrow$ interaction with the large scale flow ("drag")
- wave breaking $\Rightarrow$ turbulence, dissipation, energy transfer to large scale flow ("drag")
- imact: GWs drive high atmosphere (stratosphere & mesosphere) + downward control: e.g. summer cold pole, QBO, NAO

(Kim et al., 2003)

Motivation

Parametrization of atmospheric GWs



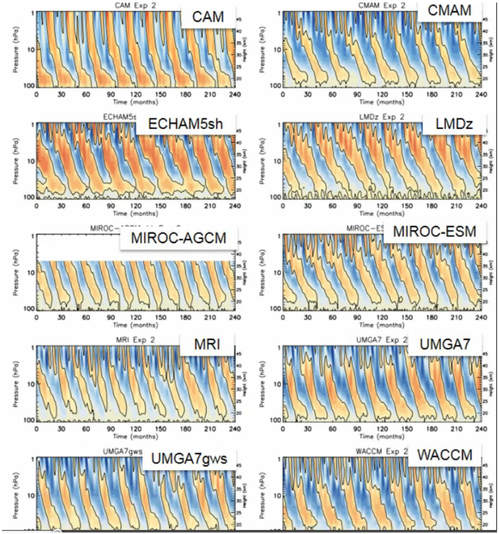
- GWs are not fully resolved by GCMs and NWP models $\Rightarrow$ parametrization
  $\Rightarrow$ (Wentzel–Kramers–Brillouin) WKB theory

- Currently used parametrizations: steady state approximation
  $\Rightarrow$ instantenous propagation through constant resolved flow
  $\Rightarrow$ instantenous drag via wave breaking only!

- Proposal for improvement: weakly-nonlinear coupling between the GW and the resolved flow $\Longleftrightarrow$ transient propagation $\Longleftrightarrow$ continuous drag on the resolved flow during propagation + drag through wave breaking

Motivation for a transient GW scheme

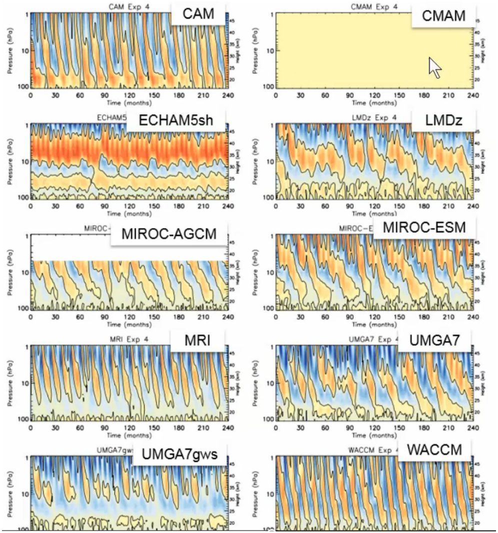
Present climate: QBO quite OK



Richter et al. (2017) (https://ams.confex.com/ams/21Fluid19Middle/webprogram/Paper319481.html)

Motivation for a transient GW scheme

Changing climate: QBO not OK! ⇒ GW parametrizations tuned for present!



Richter et al. (2017) (https://ams.confex.com/ams/21Fluid19Middle/webprogram/Paper319481.html)

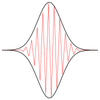
Motivation for a transient GW scheme

Atmospheric governing equations: $\frac{df}{dt} = F(f, \frac{\partial f}{\partial \vec{x}})$

↓

Scaling for <u>gravity waves</u>: $\epsilon =<< 1$

$$f = f_m + f_w \qquad f_w(x,z,t) = \mathrm{Re} F_w(Z,T) e^{i\left[kx + \frac{\phi(Z,T)}{\epsilon}\right]}$$



Order analysis in ϵ (Achatz et al., 2017)

↓

GW parametrization: $\frac{df_m}{dt} = \ldots + \tilde{F}(F_w)$

Motivation for a transient GW scheme

Wave field

WKB theory: transient coupled system

$$\frac{d_g z}{dt} = \mp \frac{Nkm}{(k^2+m^2)^{3/2}} \equiv c_{gz}$$

$$\frac{d_g m}{dt} = \mp \frac{k}{(k^2+m^2)^{1/2}} \frac{dN}{dz} - k\frac{d u_b}{dz} \equiv \dot{m}$$

$$\frac{d_g \mathcal{A}}{dt} = -\mathcal{A}\frac{\partial c_{gz}}{\partial z} \quad \left(\frac{d_g}{dt} = \frac{\partial}{\partial t} + c_{gz}\frac{\partial}{\partial z}\right)$$

Steady state WKB

$$\frac{d_g z}{dt} = \mp \frac{Nkm}{(k^2+m^2)^{3/2}} \equiv c_{gz}$$

$$\frac{\partial m}{\partial t} = 0$$

$$\frac{\partial \mathcal{A}}{\partial t} = 0 \Longleftrightarrow c_{gz}(z)\mathcal{A}(z) = const.$$

Mean flow

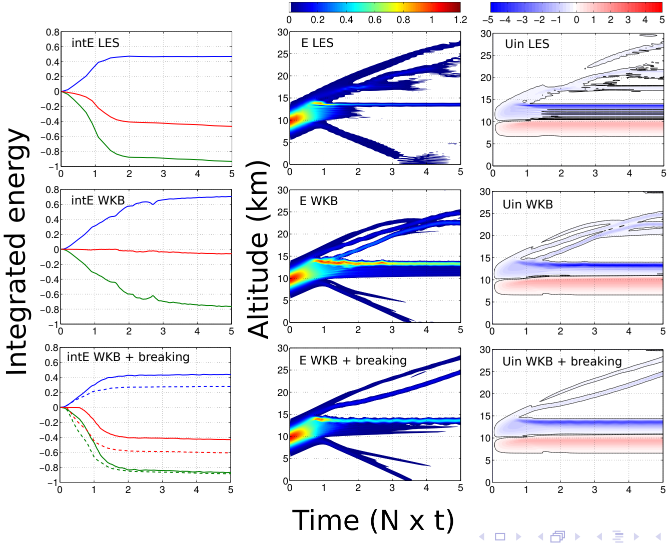
$$\frac{\partial u_b}{\partial t} = -\frac{1}{\bar{\rho}}\frac{\partial}{\partial z}(kc_{gz}\mathcal{A})$$

$$\frac{\partial u_b}{\partial t} = -\frac{1}{\bar{\rho}}\frac{\partial}{\partial z}(kc_{gz}\mathcal{A})$$

$\Rightarrow$ no *wave-mean-flow interaction*! $\Rightarrow$ *wave breaking* (constraining $\mathcal{A}(z)$) is necessary to get an induced wind!

Motivation for a transient GW scheme

Static instability ($\lambda_x = \lambda_z = 1km$) Bölöni et al. (2016)



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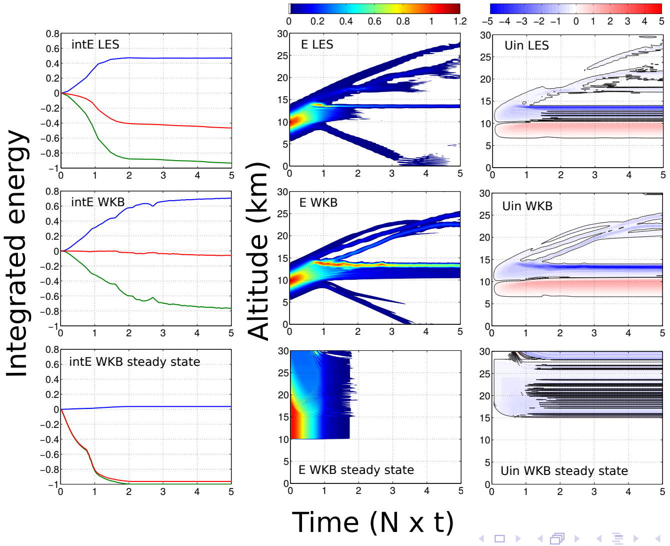


Implementation in ICON: MS-GWaM

Concept

Orographic GWs & direct orographic drag

Lott and Miller (1996)
⇒ untouched

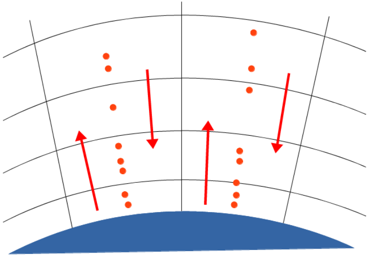
Non-orographic GWs

Warner and McIntyre (1996), Orr et. al (2010), Scinocca (2003) ⇒ WKB (MS-GWaM)

Implementation in ICON: MS-GWaM

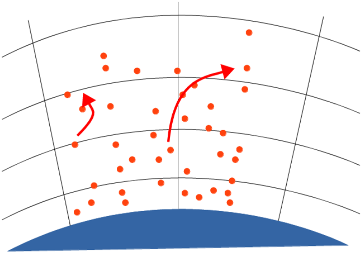
Concept

1D framework



Fits well to the current MPI communicator

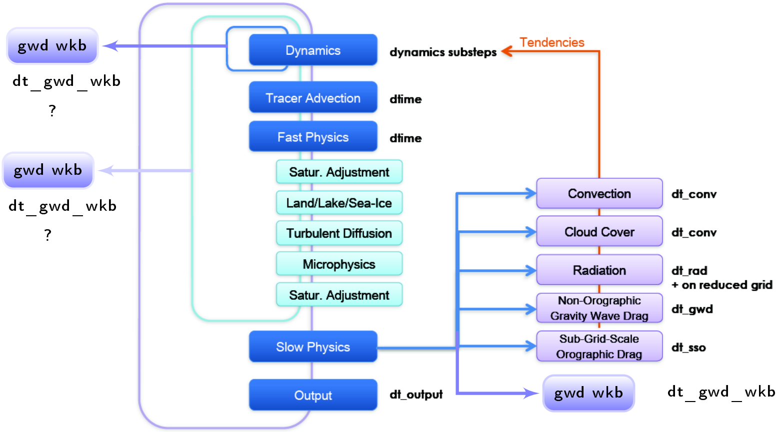
3D framework



Requires new MPI communication style for Lagrangian particles ⇒ later...

Implementation in ICON: MS-GWaM

Concept

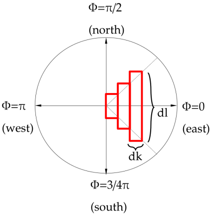


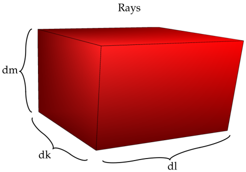
(Original courtesy: DWD, ICON Training 2015)

Implementation in ICON: MS-GWaM

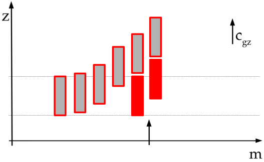
GW source with an effective momentum flux as in Orr et al., (2010)

- **hydrostatic GWs launched:** $\lambda_{lon} \approx \lambda_{lat} >> \lambda_z$
- $N^2 >> \omega^2 >> f^2 \Rightarrow$ **flux:** $F(c_h, \phi)$, $0.25ms^{-1} < c_h < 100ms^{-1}$
- $F(c_h, \phi) \Rightarrow \hat{F}(k, l, m) \Rightarrow$ **wave action density:** $\mathcal{N}(k, l, m)$





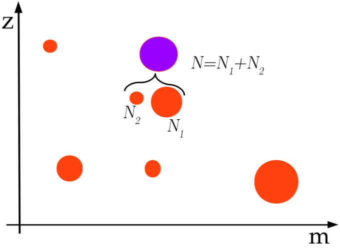
- implement sources as lower boundary condition, i.e. a continuous feeding of the launch spectra $\mathcal{N}(k, l, m)$



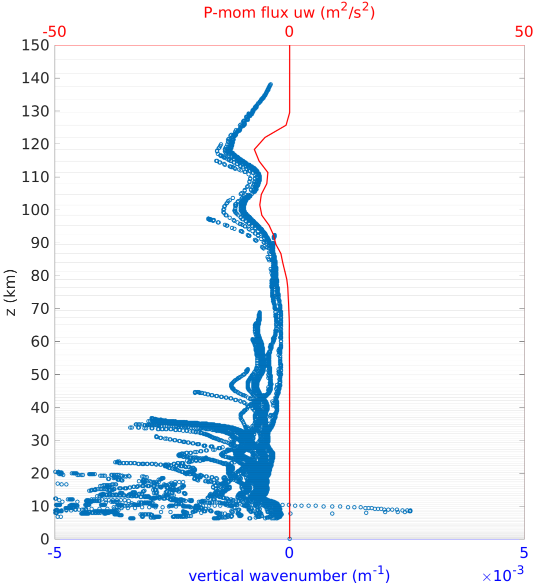
Implementation in ICON: MS-GWaM

Merging rays to avoid continuous increase in CPU

- remove rays getting out of the z domain (model bottom, top)
- merge ray pairs if close in phase space (similar $c_{gz} \Rightarrow$ similar trajectory) iteratively until number of rays decreases to the maximum allowed (user specified)
- merging in an energy conserving way



Implementation in ICON: MS-GWaM



Preliminary evaluation of ICON MS-GWaM

- Winter (2013 nov-dec) simulations with IFS initial conditions

- Experiments:
  noGW: non-orographic GWD parametrizatin switched off
  Orr: state of the art non-orographic GWD parametrization (Orr et al., 2010)
  MS-GWaM: MS-GWaM used as non-orographic GWD parametrization

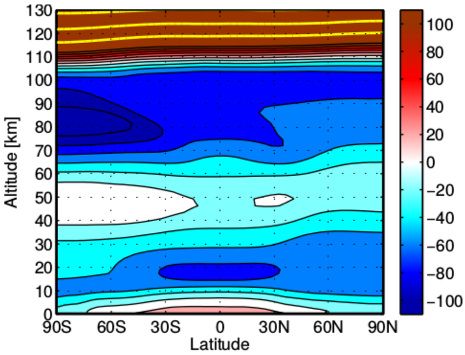
- Domain: Global, $"\Delta x" = 160km$, $z_{top} = 150km$, $\overline{\Delta z} = 1.25km$

- Stability measures: $z_{sponge} = 85km$, GWD limiter $|\frac{du}{dt}, \frac{dv}{dt}| \leq 0.05ms^{-2}$

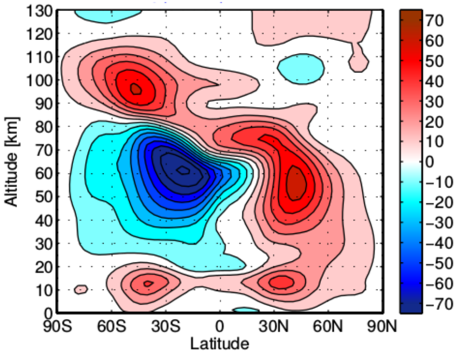
Preliminary evaluation of ICON MS-GWaM

The reference

Hammonia 35 year mean T



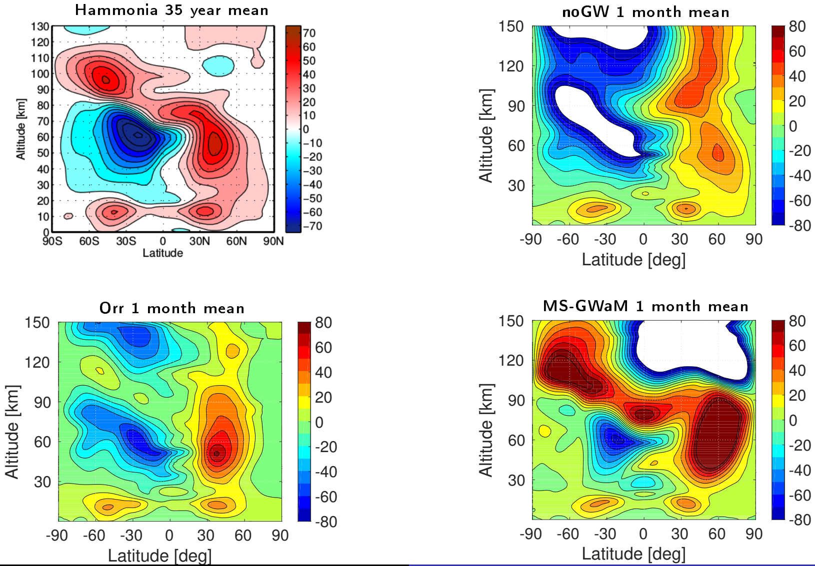
Hammonia 35 year mean u_b



Thermal wind balance: $\frac{\partial u_g}{\partial z} = \frac{g}{fT}\frac{\partial T}{\partial \phi}$

Preliminary evaluation of ICON MS-GWaM

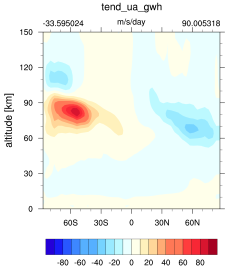
December u_b zonal mean $[ms^{-1}]$



Preliminary evaluation of ICON MS-GWaM

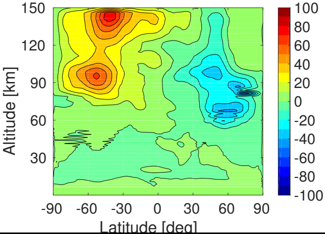
u_b tendency zonal mean $[ms^{-2}]$

Hammonia 35 year Feb mean

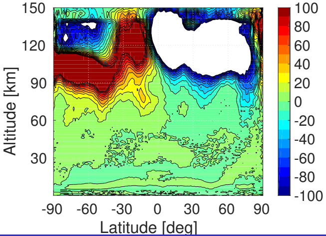


noGW —

Orr single Dec mean

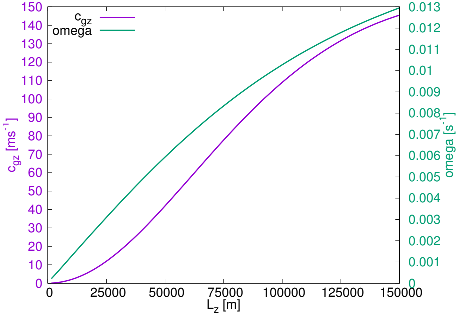


MS-GWaM single Dec mean



Preliminary evaluation of ICON MS-GWaM

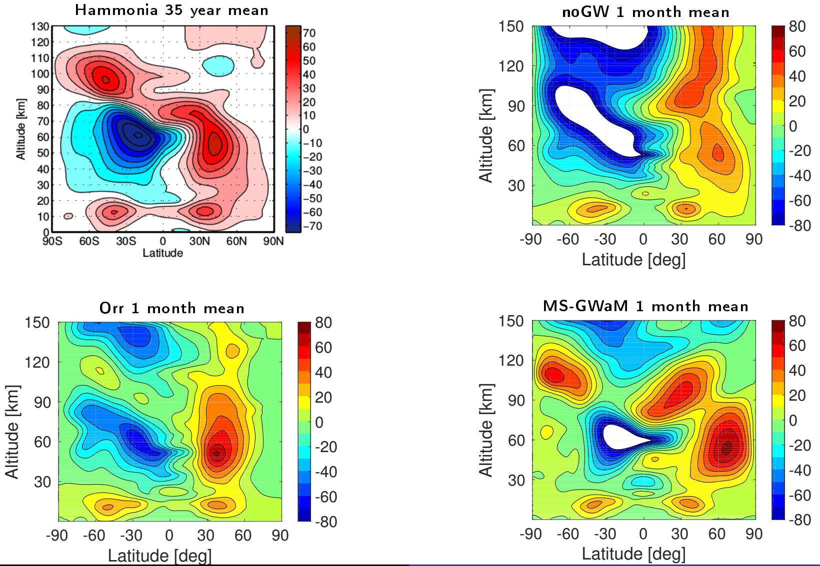
- Too large tendencies: $\frac{\partial u_b}{\partial t} = -\frac{1}{\rho}\frac{\partial}{\partial z}(k c_{gz} \mathcal{A})$
- Dependence of c_{gz} on λ_z (with $\lambda_{lat} = \lambda_{lon} = 200km$)



- Filtering of waves with $\lambda_z > 25km$ above $70km$

Preliminary evaluation of ICON MS-GWaM

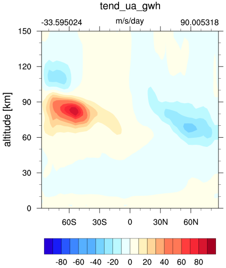
December u_b zonal mean $[ms^{-1}]$



Preliminary evaluation of ICON MS-GWaM

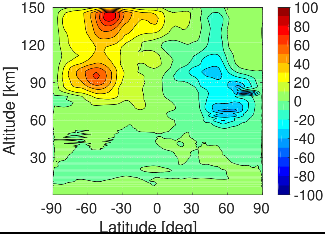
u_b tendency zonal mean $[ms^{-2}]$

Hammonia 35 year Feb mean

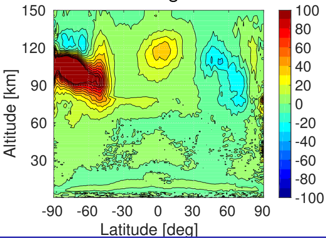


noGW —

Orr single Dec mean



MS-GWaM single Dec mean



Summary

- A new **transient GW drag parametrization proposed (MS-GWAM)**
- Based on idealized MS-GWAM simulations **transient wave-meanflow interactions are more important than wave breaking**. Current GW drag schemes are based only on the latter process.
- A first version of **MS-GWAM** is **implemented** and technically validated **in ICON**. It is to be gradually extended: more realistic sources, 1D $\rightarrow$ 3D, etc.
- Based on "climatological" zonal averages **MS-GWAM is** a **promising** alternative to steady state parametrizations.
- But there is a long way to go... **comparison with observations, understanding**

References

Achatz U., B. Ribstein, F. Senf, R. Klein, 2017: The interaction between synoptic-scale balanced flow and infinite-amplitude mesoscale wave field throughout all atmospheric layers: weak and moderately strong stratification, *Q. J. R. Meteorol. Soc.*, *143*, 342–361, DOI:10.1002/qj.2926

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Scinocca J.F., 2003: An accurate Spectral Nonorographic Gravity Wave Drag Parameterization for General Circulation Models *J. Atmos. Sci.*, *60*, 667–682

Warner C.D., M.E. McIntyre, 1996: On the propagation and dissipation of gravity wave spectra through a realistic middle atmosphere, *J. Atmos. Sci.*, *53*(22), 3213–3235