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

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with contributions from:
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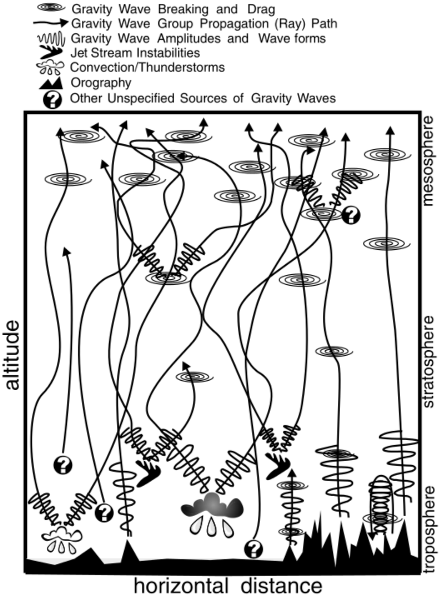
MS-GWaves

Deutsche Forschungsgemeinschaft

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Motivation



Atmospheric gravity waves (GW)

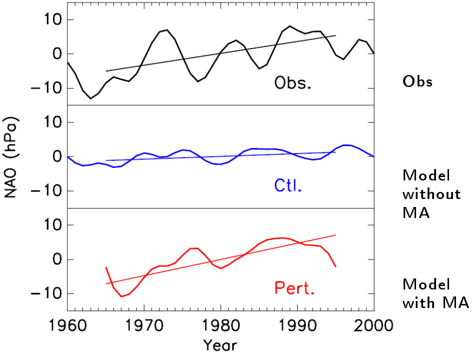
- main sources: orography, convection, jets/fronts
- mainly vertical energy (momentum) transport with $\vec{c}_g \Rightarrow$ interaction with the large scale flow ("drag")
- wave breaking $\Rightarrow$ turbulence, dissipation, energy transfer to large scale flow ("drag")

(*Kim et al.*, 2003)

Motivation

Importance of atmospheric GWs in weather & climate

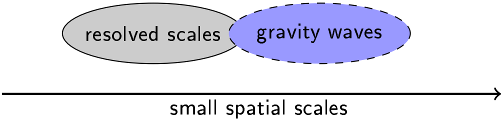
- Mesospheric jet reversal, summer cold pole (*Holton*, 1983)
- Strong effect of GWs on North Atlantic Oscillation (NAO) (*Scaife et al.*, 2005)
- Models with middle atmosphere (MA) allow for more accurate GW dynamics ⇒ better NAO patterns



Scaife et al. (2005)

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

WKB theory

Wave resolving system (2-D Euler equations, no rotation):

$$\begin{aligned}\frac{Du}{Dt} + c_p\theta\frac{\partial\pi}{\partial x} &= 0\\ \frac{Dw}{Dt} + c_p\theta\frac{\partial\pi}{\partial z} + g &= 0\\ \frac{D\theta}{Dt} &= 0\\ \frac{D\pi}{Dt} + \frac{\kappa}{1-\kappa}\pi\left(\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z}\right) &= 0\end{aligned}$$

with $\frac{D}{Dt} = \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + w\frac{\partial}{\partial z}$

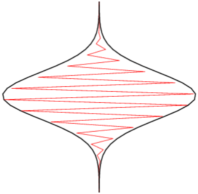
Exner pressure $\pi = (p/p_0)^\kappa$

Pot. temperature $\theta = T(p_0/p)^\kappa = T/\pi$

$\kappa = R/c_p$

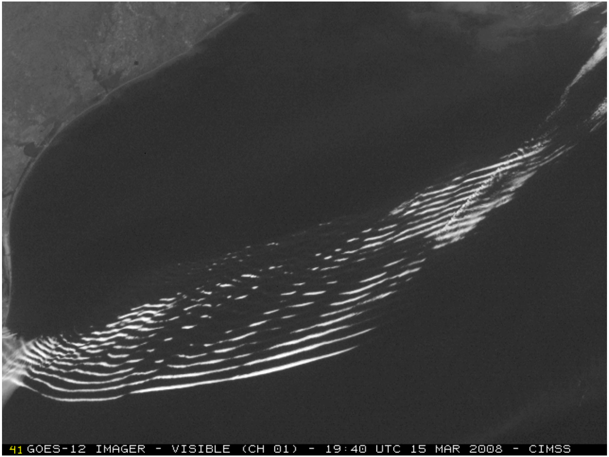
Simplification ingredients:

- Decomposition of the fields: $f = f_b + f_w$
- WKB ansatz: $f_w(x,z,t) = \mathrm{Re} F_w(Z,T)e^{i\left[kx + \frac{\phi(Z,T)}{\epsilon}\right]}$
  with $Z = \epsilon z, T = \epsilon t$, $m = \partial\phi/\partial Z$ and $\omega = -\partial\phi/\partial T$
- Scaling for the gravity waves: $\epsilon = \lambda_{wave}/\lambda_{background} << 1$



WKB theory

WKB ansatz in nature:



(cimss.ssec.wisc.edu)

WKB theory

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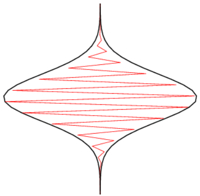

WKB theory

Order analysis in $\epsilon \Rightarrow$ GW parametrization

Wave field | Mean flow

WKB theory: transient coupled system

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

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

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

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

Steady state WKB theory: instantenous decoupled system

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

$$\frac{d_g m}{dt} = 0$$

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

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

$\Rightarrow$ no *wave-mean-flow interaction*! $\Rightarrow$
Drag sources: *ONLY! wave breaking* (constraining $\mathcal{A}(z)$)

WKB theory

Order analysis in $\epsilon \Rightarrow$ GW parametrization

<u>Wave field</u>

<u>Mean flow</u>

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

<u>Drag sources</u>: *wave-mean-flow interaction*
+ *wave breaking*

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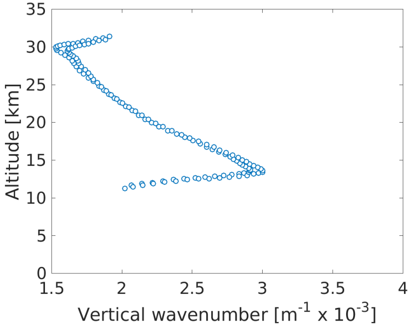
Numerical implementation: toymodel

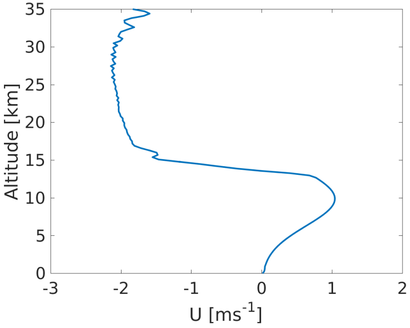
GW field

Ray positions in phase space



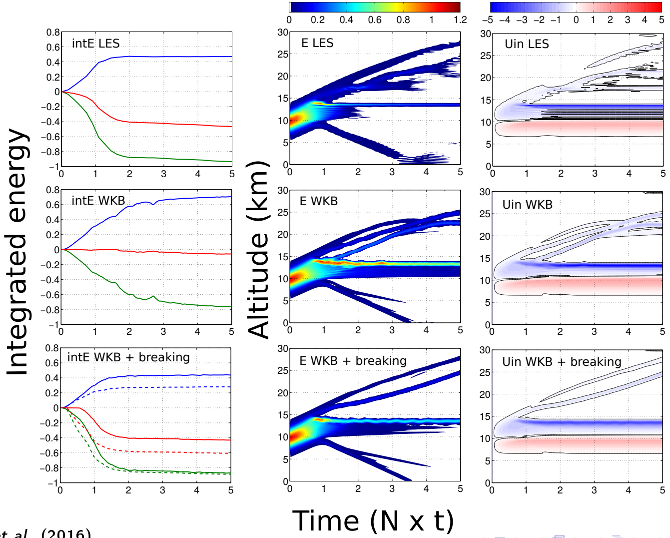
Meanflow

Induced large scale wind



Numerical implementation: toymodel

Static instability $(\lambda_x = \lambda_z = 1km)$



Bölöni et al. (2016)

Numerical implementation: toymodel

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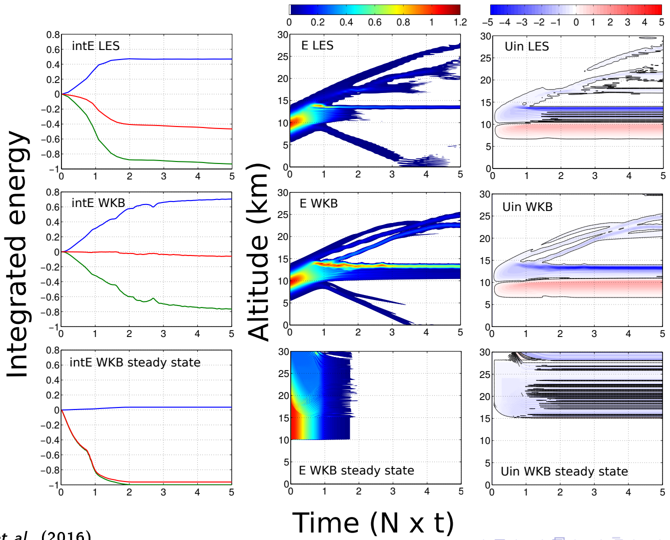
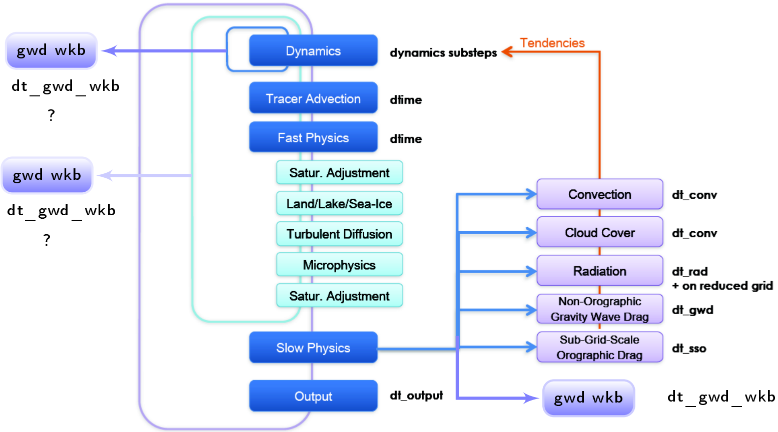


Bölöni et al. (2016)

Numerical implementation: ICON

Concept

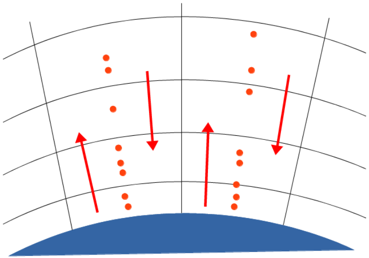


(Original courtesy: DWD, ICON Training 2015)

Numerical implementation: ICON

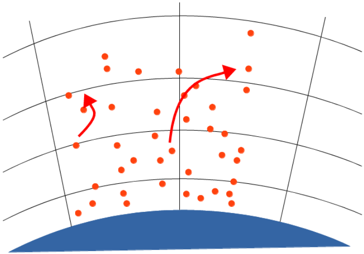
Concept

1D framework



Fits well to the current MPI communicator

3D framework



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

Numerical implementation: ICON

Primary code validation

WKB in ICON ⟷ WKB in toymodel

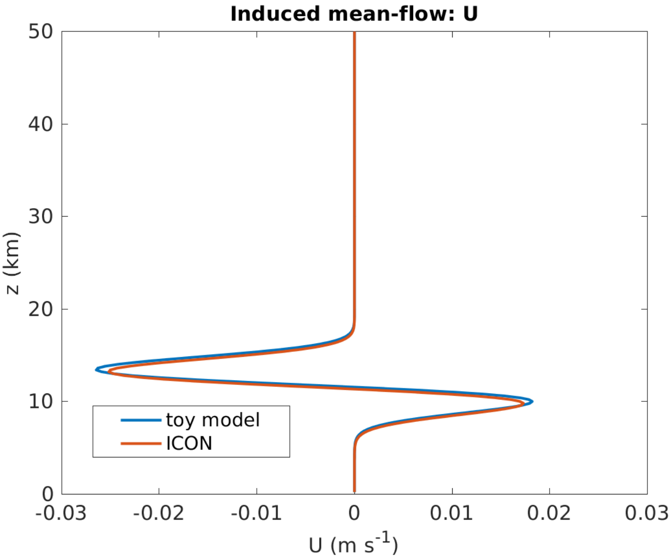
- low resolution: $dx \approx 1250km$ (R02B01), $dz \approx 200m$
- no orography, simple stratification, steady state initial meanflow
- dynamical core off (ldynamics=.F.), no rotation (lcoriolis=.F.)
- all other physical parametrizations switched off
- known cases, uniform source over the Globe $\Rightarrow$ "single column"

Moving towards realism...

WKB in ICON ⟷ OPER ICON / OBS

- $dx \approx 160km$ (R02B04), $dx \approx 80km$ (R02B05), $dz \approx 50 - 350m$
- switch on dynamical core (ldynamics=.T.) and rotation (lcoriolis=.T.)
  $\Rightarrow$ interaction of GWs and inertial waves
- real orography, same GW sources as in OPER ICON NWP (*Orr et al., 2010*)
- comparison of zonal means, etc.

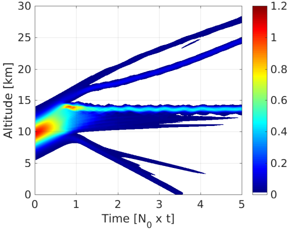
Numerical implementation: ICON



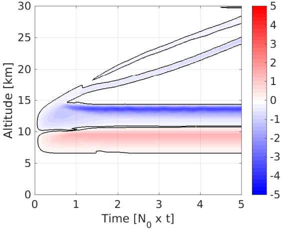
Numerical implementation: ICON

Static instability ($\lambda_x = \lambda_z = 1km$)

Energy (toymodel)



Induced U (toymodel)



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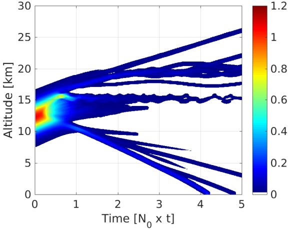

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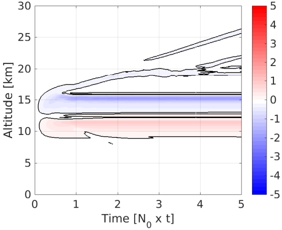
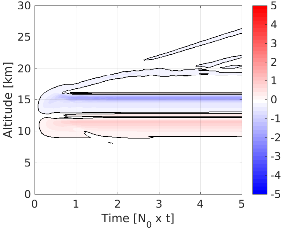


Induced V (ICON)



Numerical implementation: ICON

Static instability ($\lambda_x = \lambda_z = 1km$)

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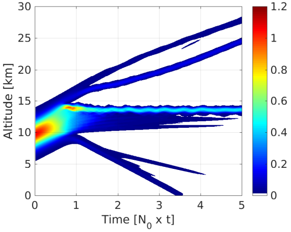

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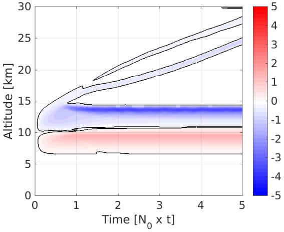
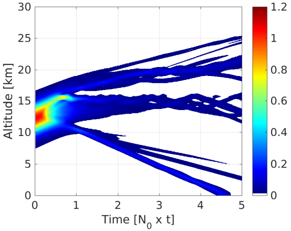
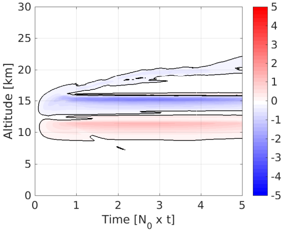


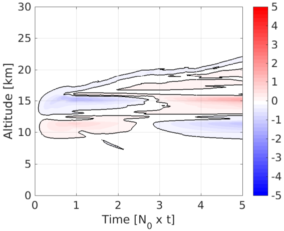
Energy (ICON rotation)



Induced U (ICON rotation)



Induced V (ICON rotation)



Numerical implementation: ICON

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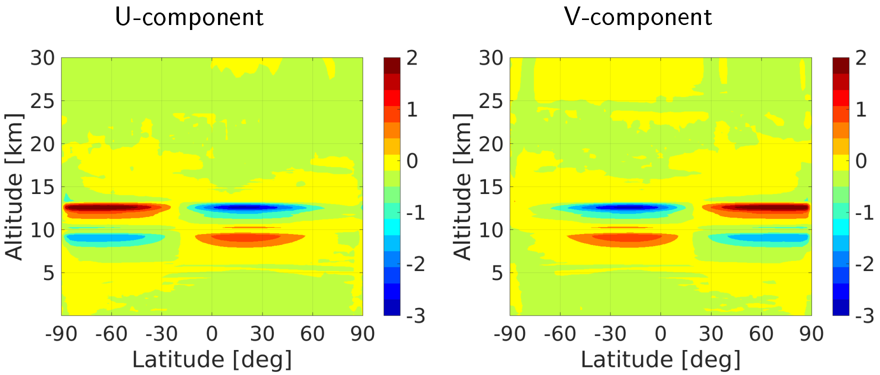

Conclusions

- A **new GW drag parametrization** proposed (**MS-GWAM**[1]): *full* WKB theory $\Longleftrightarrow$ *steady state* WKB theory.
- 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.
- An **MS-GWAM 1.0** is **implemented** and technically validated **in ICON (NWP)**. It is to be gradually extended: more realistic sources, 1D $\rightarrow$ 3D, etc.

[1] Multi Scale Gravity Wave Model

References

Achatz, U., R. Klein, F. Senf (2010), Gravity waves, scale asymptotics, and the pseudo-incompressible equations. *J. Fluid Mech.*, *141*(663), 120–147, DOI:10.1017/S0022112010003411

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Scaife, A. A., J. R. Knight, G. K. Vallis, and C. K. Folland (2005), A stratospheric influence on the winter NAO and North Atlantic surface climate, *Geophys. Res. Lett.*, *32, L18715*, DOI:10.1029/2005GL023226.