DFG

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

MS-GWaves

Multi-Scale Dynamics of Gravity Waves

U. Achatz

Goethe Universität Frankfurt

and many others:

https://ms-gwaves.iau.uni-frankfurt.de/index.php

Leibniz-Institut für Atmosphären Physik IAP

Freie Universität Berlin

Max-Planck-Institut für Meteorologie

Deutscher Wetterdienst – Wetter und Klima aus einer Hand

Johannes Gutenberg Universität Mainz

b-tu Brandenburg University of Technology Cottbus - Senftenberg

DLR

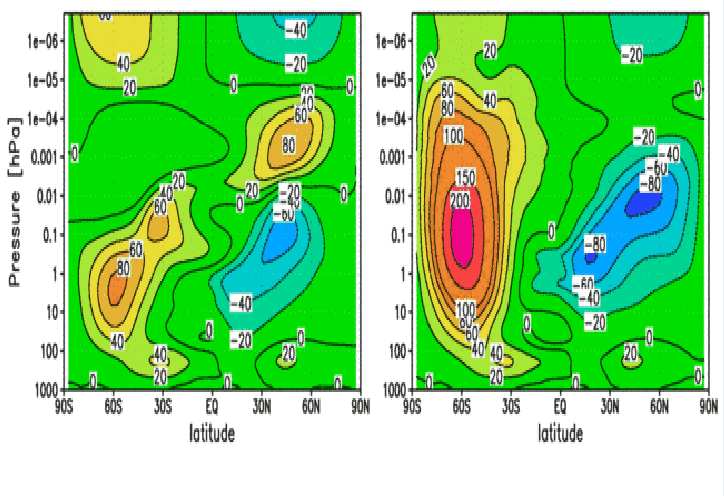
Jülich Forschungszentrum

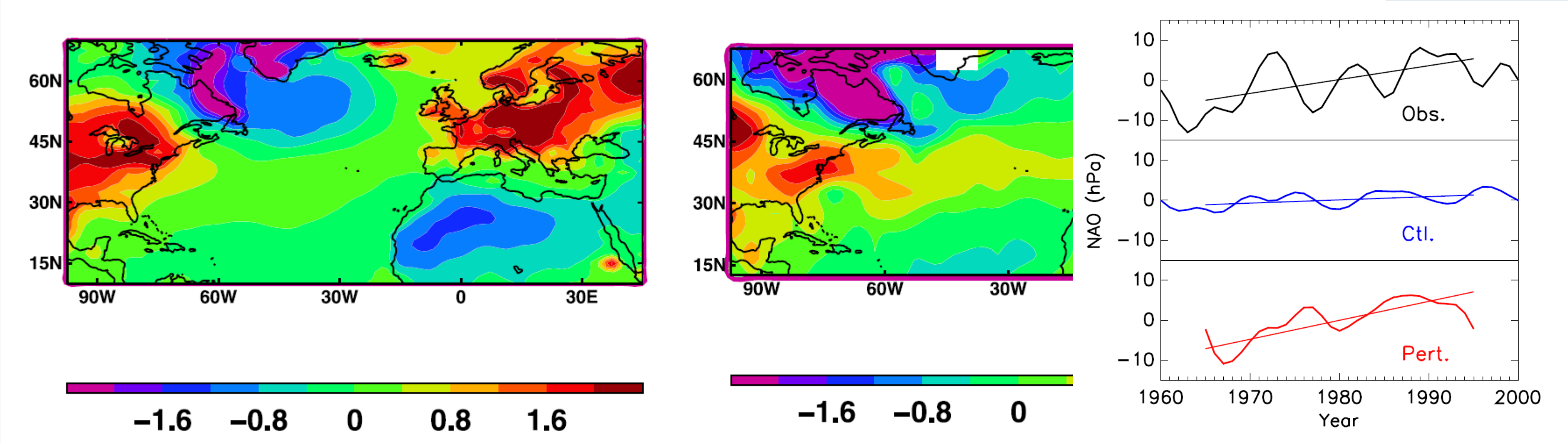
State of the Art: GW Impacts

MS-GWaves

Gravity-wave effects numerous, e.g.

- Clear-air turbulence (e.g. Koch et al 2005)
- **Clouds** (e.g. Zhang et al 2001, 2003, Joos et al 2009)
- **Middle-atmosphere waves** (QBO, solar tides, PWs)
- **residual circulation**
  - GW impact in stratosphere (e.g. Palmer et al 1986)
  - GW control in mesosphere (e.g. Lindzen 1981)
- **Indirectly: Impact middle atmosphere on troposphere (downward control)**





Scaife et al (2005)

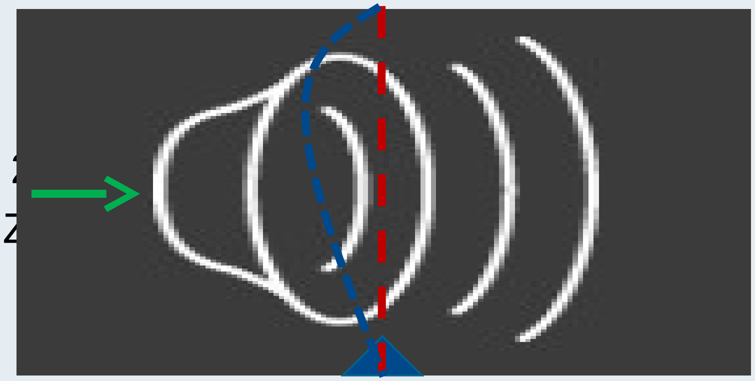
State of the Art: Parameterization of GW Processes

MS-GWaves

Sources:

- **Orographic GWs best understood** (Palmer et al 1986, Jiang et al 2002)
- **Convective GWs** (Chun & Baik 1998, Beres et al 2005, Song & Chun 2005, …)
- **Spontaneous GW emission** (e.g. Plougonven & Zhang 2014)
- **2ndary waves, …**

State of the Art:
Parameterization of GW Processes



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GW propagation

- **Simplifications** of WKB Theory (Grimshaw 1975, Achatz et al 2017) for efficiency: **Single-column** and **steady state** limit validity (e.g. Bühler & McIntyre 2003, Ribstein & Achatz 2016, Bölöni et al 2016)
- **Synoptic-scale balanced background assumed**
  But NWP models resolve some GWs!
- **GW propagation through sharp gradients: Tropopause**

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MS-GWaves

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- **Synoptic-scale balanced background assumed**
  But NWP models resolve some GWs!
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GW disipation:

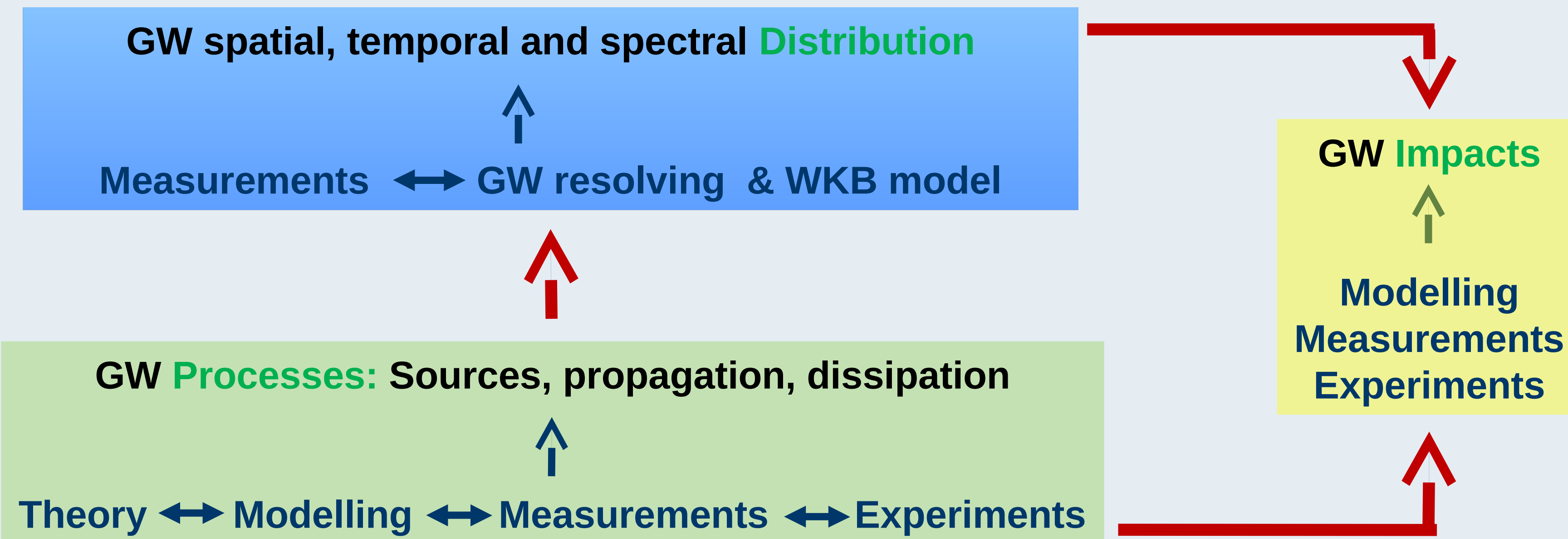
- **Saturation** (Lindzen 1981, …)
  not in agreement with DNS
- **Wave-mean flow interaction** (Dosser & Sutherland 2011, **Bölöni et al 2016**)

Objectives:
Central Goals & Key Research Areas

Goals

1. **Efficient parameterization based on understanding and computational representation of GW processes**
2. **A prognostic model for SGS GWs & implementation into NWP and climate model.**

Key Research Areas



Progress & Results: GW Distribution

Distribution

Impacts

Processes

MS-GWaves

D1: **Analysis of measurements and weather-service data of the GW distribution**

Some examples: Overlap DEEPWAVE & field campaign

- Refraction of GWs into the polar night jet **(Ehard et al 2017)**
- Mountain waves New Zealand **(Portele et al 2017, subm.)**
- **Field campaign** northern Scandinavia winter 2015/16

Progress & Results: GW Distribution

Distribution

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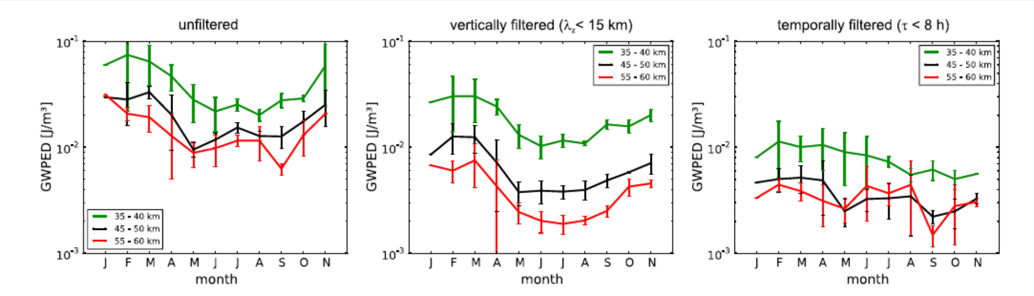
MS-GWaves

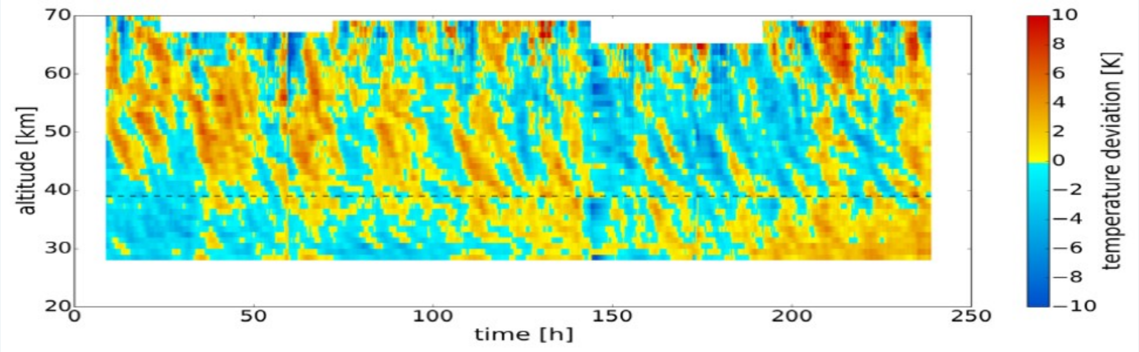
D1: Analysis of measurements and weather-service data of the GW distribution

Some examples: RMR lidar Kühlungsborn

- Climatology T variances **(K. Baumgarten et al 2017)**



- Unprecedented long data set (4-13 May 2016) **(K. Baumgarten et al 2017, subm.)**



Progress & Results: GW Distribution

Distribution

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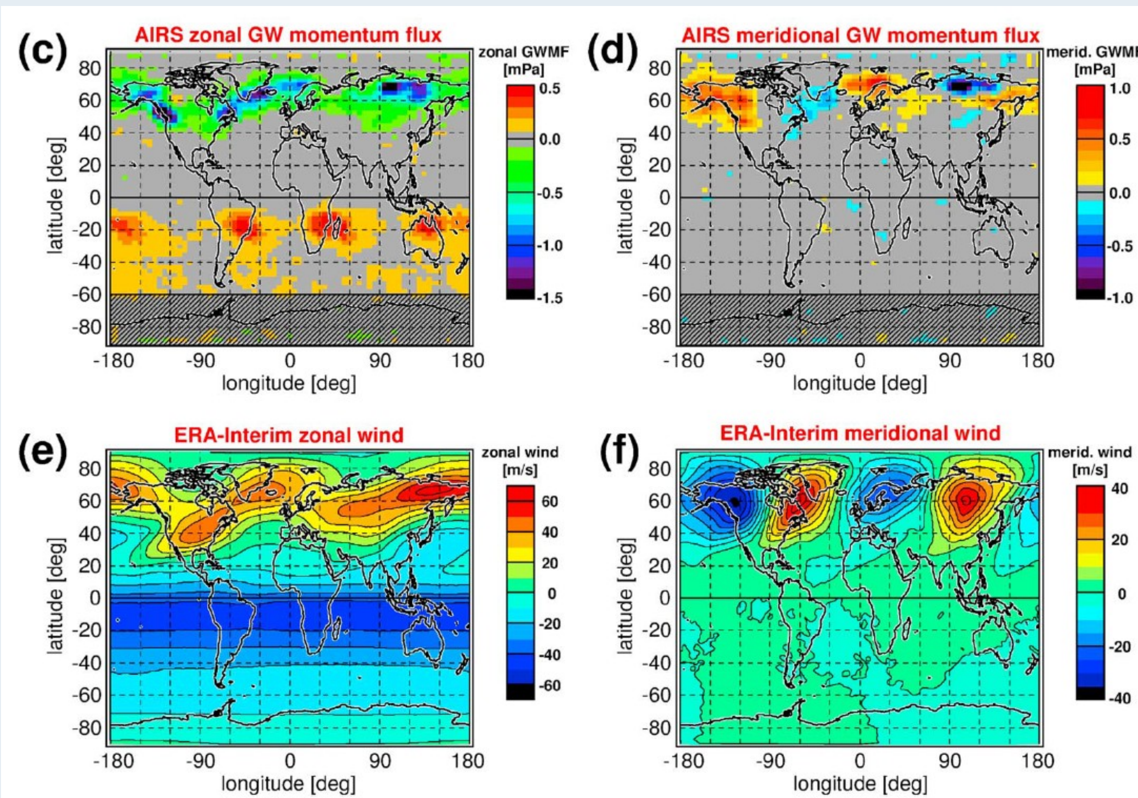
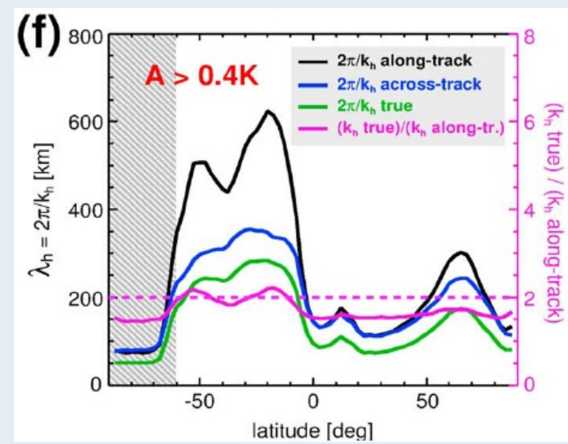
D1: **Analysis of measurements and weather-service data of the GW distribution**

Some examples: Satellite data

- Global GW momentum fluxes from AIRS data **(Ern et al 2016)**





Progress & Results: GW Distribution

Distribution

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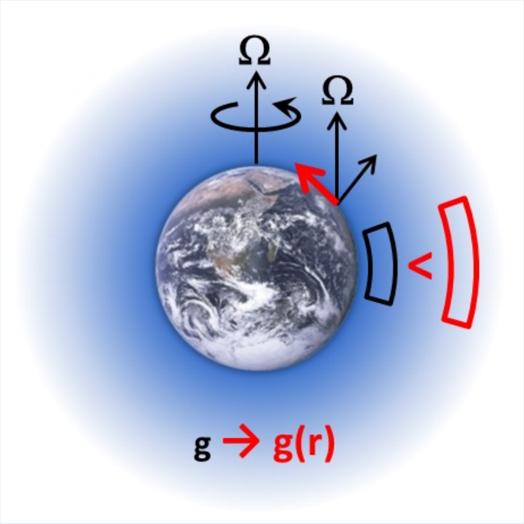
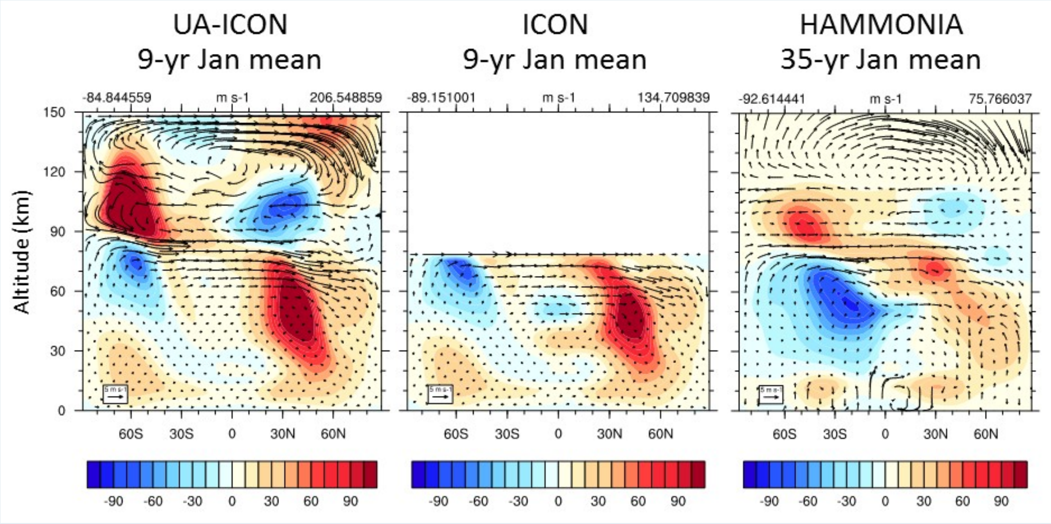
D2: Non-hydrostatic GW permitting/resolving global model (UA-ICON with MS-GWaM)

Upper-Atmosphere-ICON with standard GW parameterizations **(Borchert et al 2017, in prep.)**

- height dependence of g
- Coriolis acceleration for all spatial directions
- sphericity changes grid volumes with height
- Development completed (test case and NWP-scores show good results)





Progress & Results:
GW Distribution

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- Development completed (test case and NWP-scores show good results)

Multi-Scale-Gravity-Wave Model (WKB model)

- implemented (1D, interactive)
- validation in planning (Bölöni et al 2017, in prep.)

Progress & Results: GW Distribution

Distribution

Processes

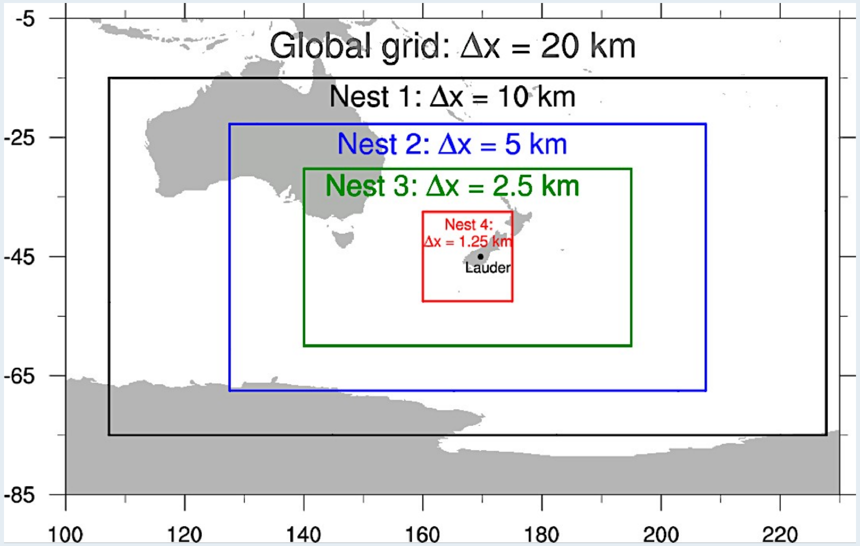
Impacts

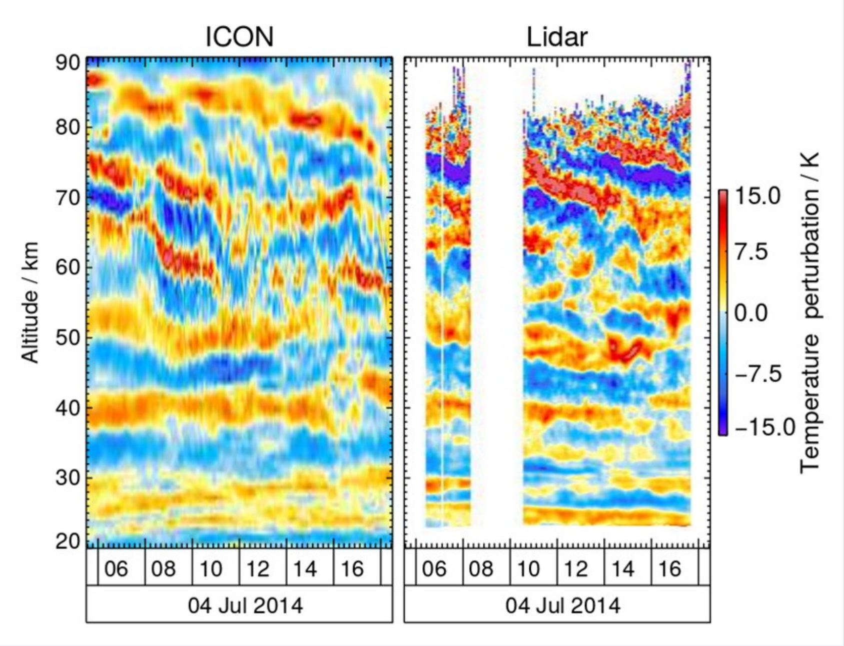
MS-GWaves

D3: Validation of the GWs simulated by UA-ICON

Activities so far:

- Implementation of **observational filter** for comparisons against satellite data
- ICON simulations of **campaign episodes**
  (DEEPWAVE, northern Scandinavia Jan 2016)





Progress & Results:
GW Processes

Distribution

Processes

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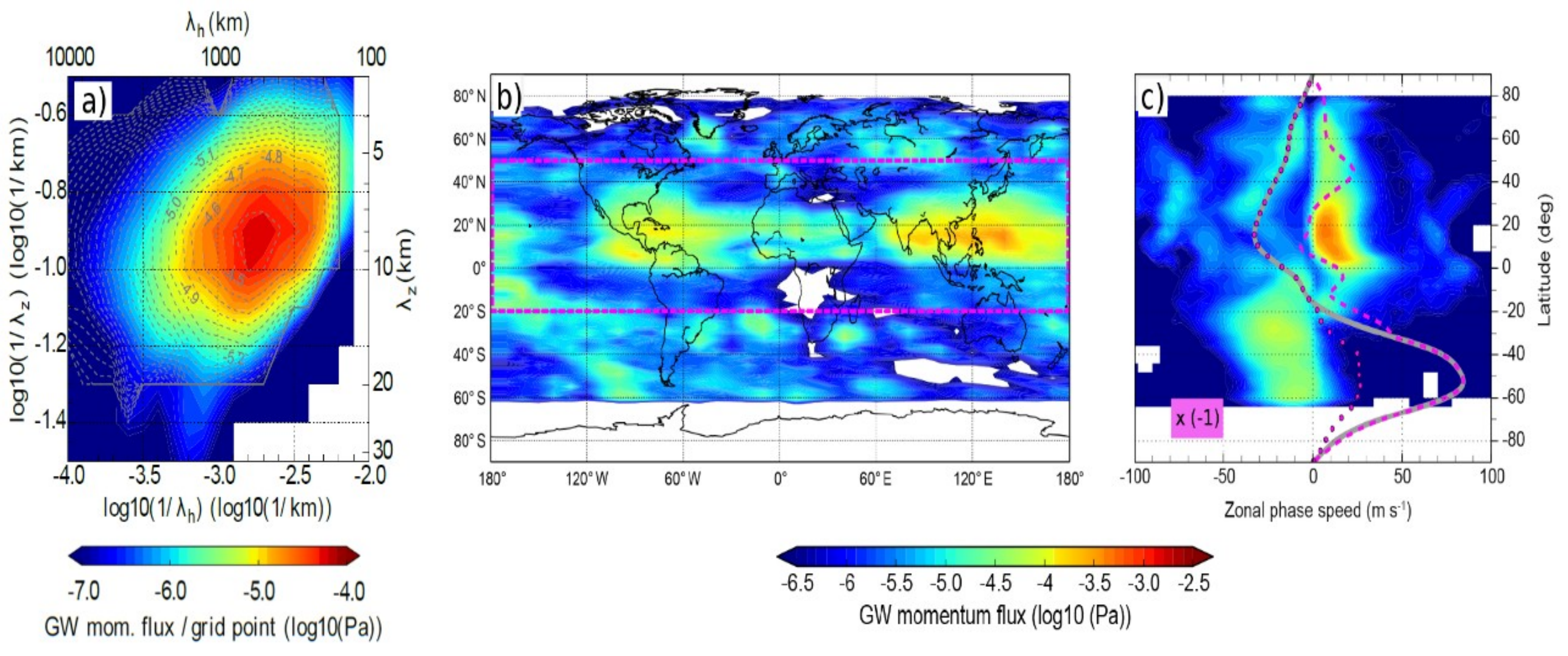
P1: GW source processes and their efficient parameterization

Results so far:

- Tuning of convective GW-source parameterization **(Thrinh et al 2016)**



Progress & Results:
GW Processes

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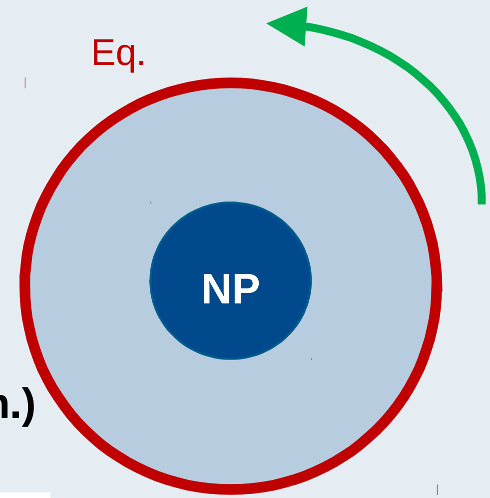
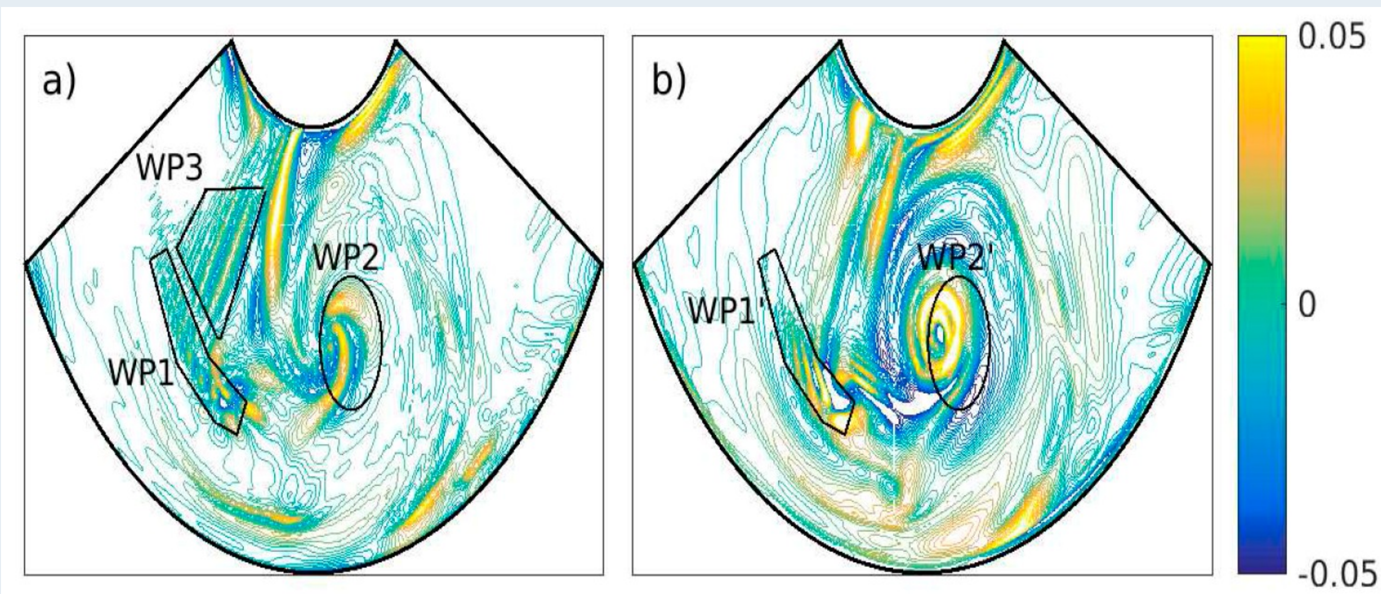
MS-GWaves

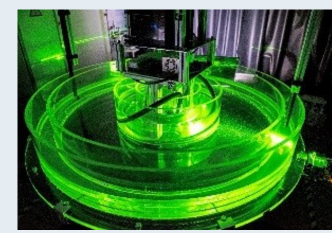


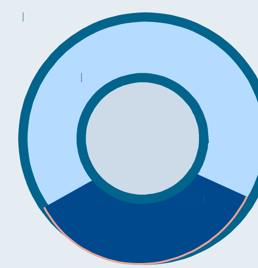
P1: GW source processes and their efficient parameterization

Results so far:

- Demonstration/analysis of spontaneous imb. in differentially heated rotating annulus **(Hien et al 2017, revised)**
- … uses wave analysis tool UWADI **(Schoon & Zülicke 2017, subm.)**







Progress & Results: GW Processes

Distribution

Processes

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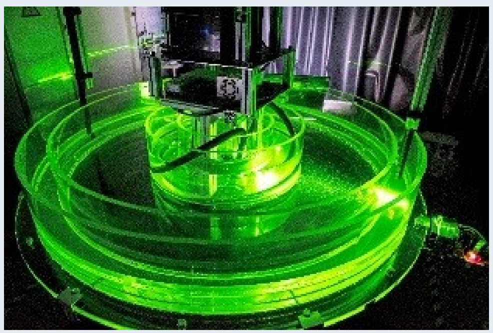
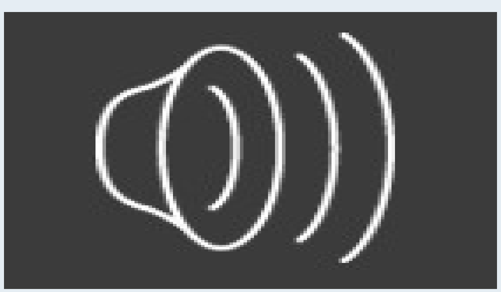
MS-GWaves

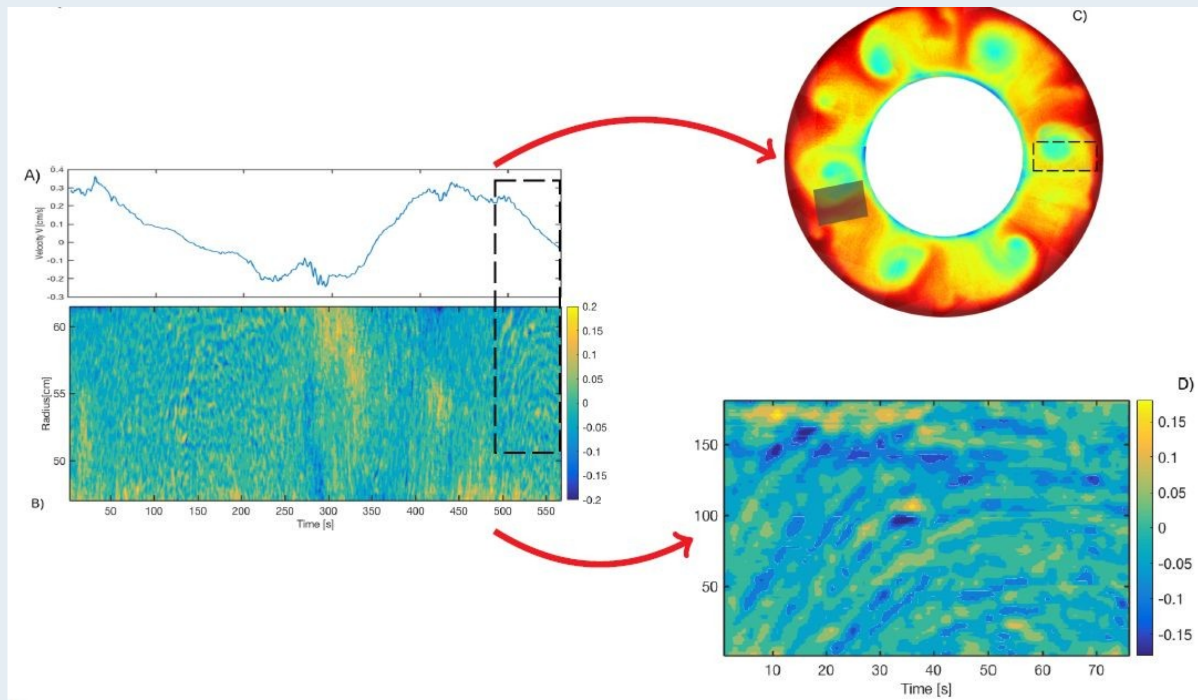
P1: GW source processes and their efficient parameterization

Results so far:

- GWs in the differentially heated annulus **(Rodda et al 2017, subm.)**







Progress & Results: GW Processes

Distribution

Processes

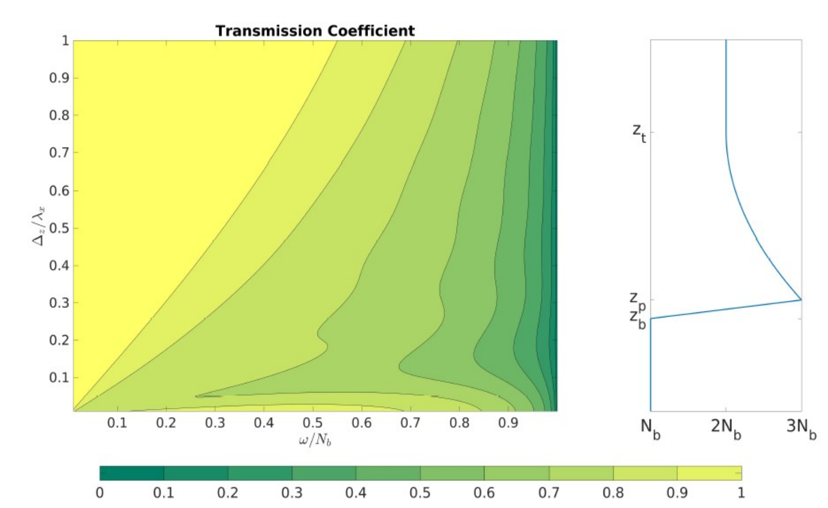
Impacts

MS-GWaves

P2: GW-mean-flow interactions & Multi-Scale Gravity-WAve Model (MS-GWaM)

Some Results:

- Generalized theory: all stratifications, nonlinear, GMs **(Achatz et al 2017)**
- Comparsion role direct GW-mean-flow interaction with turbulence **(Bölöni et al 2016)**
- Impact lateral propagation on tides **(Ribstein et al 2015, Ribstein & Achatz 2016)**
- Interaction sub-mesoscale waves with mesoscale flow **(Wilhelm et al 2017, in prep.)**
- GW-tropopause interactions (**Gisinger et al 2017, subm., Pütz et al 2017, subm.**)



Progress & Results: GW Processes

Distribution

Processes

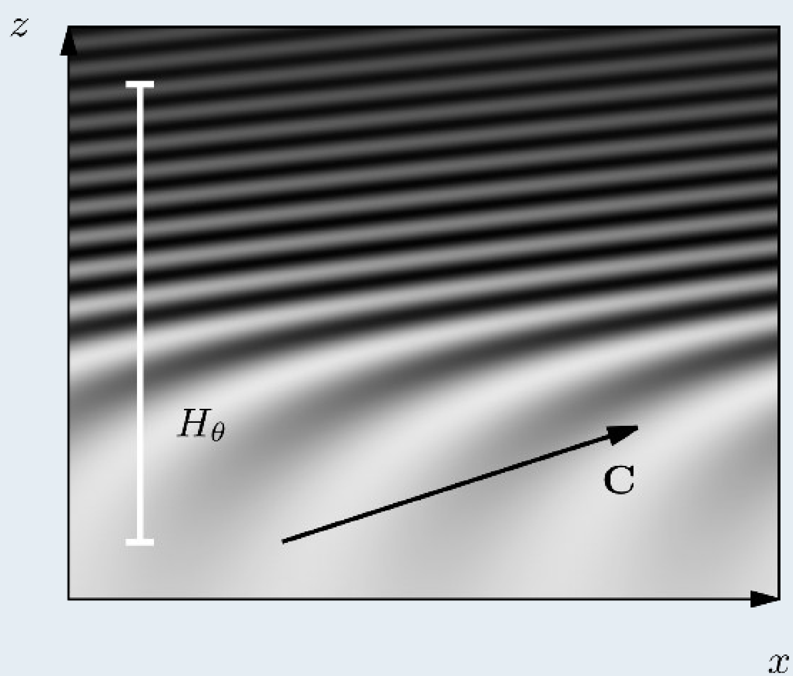
Impacts

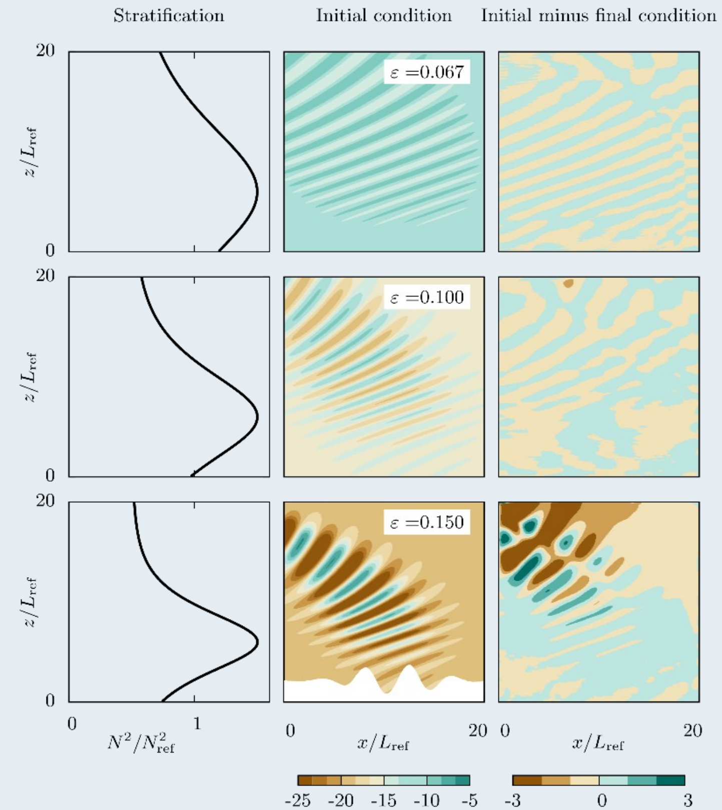
MS-GWaves

P3: GW Dissipation

Results:

- Travelling-wave solutions to modulational equations **(Schlutow et al 2017)**
- Stability analysis





MS-GWaves

Focus:

Wave-mean-flow Interaction beyond traditional parameterization approaches

Ray tracing with caustics: Numerics for fully coupled WKB

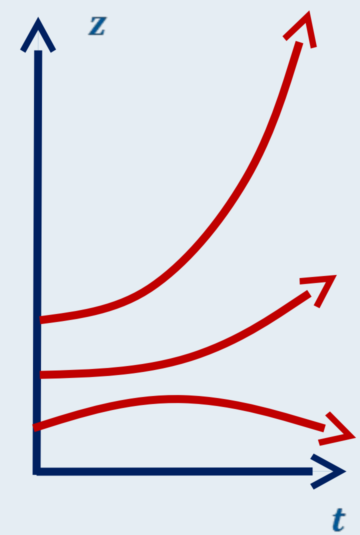
Classic WKB (Grimshaw 1975, ...) for illustration 1D:
Classic WKB (Grimshaw 1975, ...) for illustration 1D:

Locally monochromatic fields of the form $b'(\boldsymbol{x},t) = \Re\, B(z,t) e^{i\phi(\boldsymbol{x},t)}$
Locally monochromatic fields of the form

local wavenumber and frequency: $\boldsymbol{k}(z,t) = k\boldsymbol{e_x} + m\boldsymbol{e_z} = \nabla\phi, \quad \omega(z,t) = -\partial\phi/\partial t$
local wavenumber and frequency: ,

wave-action density $\boldsymbol{A(z,t)}$ so that (e.g.)
wave-action density so that (e.g.)

$$\boldsymbol{E_{GW}(z,t) = A(z,t)\,\hat{\omega}(m)}$$



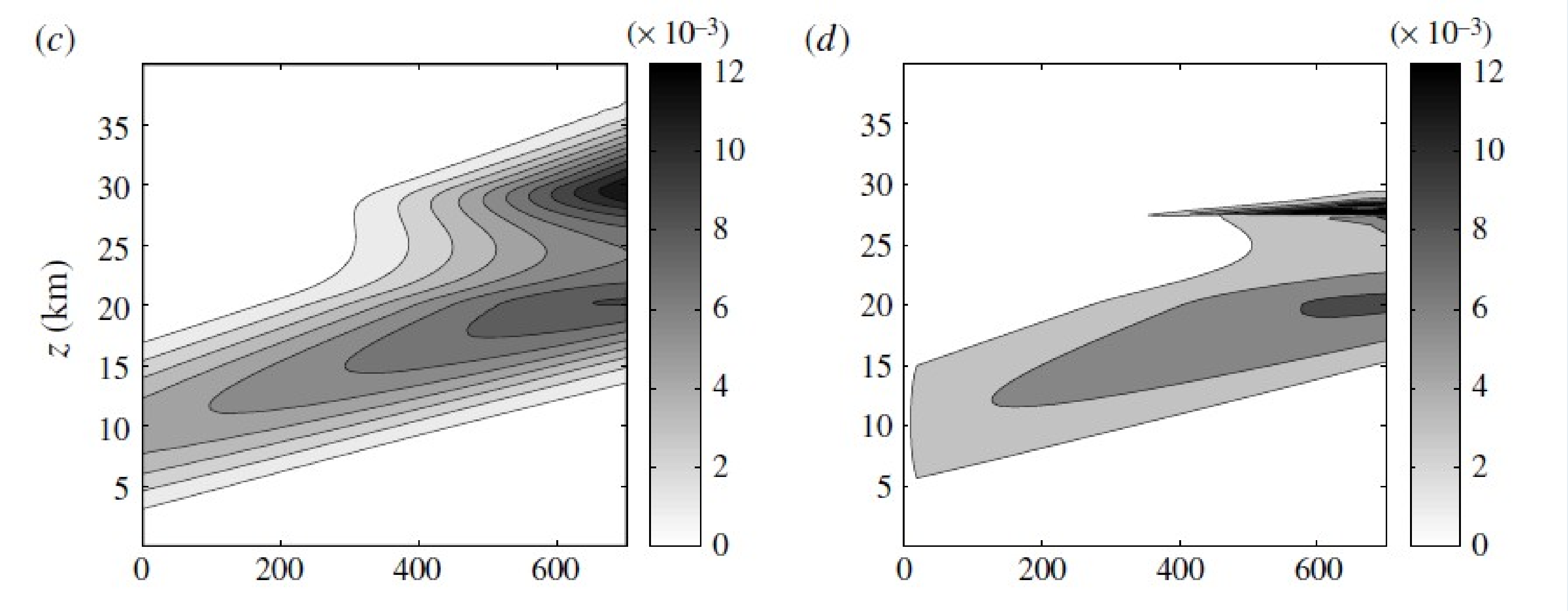
Along **rays**, defined by $\boldsymbol{dz/dt = c_g}$
Along rays, defined by

$$\boldsymbol{\frac{dm}{dt} = -k\frac{\partial U}{\partial z}}, \qquad \boldsymbol{\frac{dA}{dt} = -A\frac{\partial c_g}{\partial z}}$$

Mean flow: $$\frac{\partial \boldsymbol{U}}{\partial t} = -\frac{1}{\bar\rho}\frac{\partial}{\partial z}\left(\bar\rho\,\overline{u'w'}\right) = -\frac{1}{\bar\rho}\frac{\partial}{\partial z}\left(\boldsymbol{c_g k A}\right)$$

Ray tracing with caustics: Stability Problem

GW packet refracted by a jet



time

LES **WKB**

Rieper et al (2013)

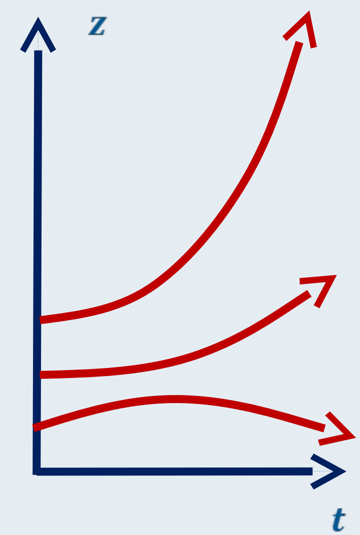
Ray tracing with caustics: Uniqueness Problem

Locally monochromatic fields
Locally monochromatic fields

wave-action density so that (e.g.)
wave-action density $A(z,t)$ so that (e.g.)

$$E_{GW}(z,t) = A(z,t)\,\hat{\omega}(m)$$

Along rays, defined by
Along **rays**, defined by $dz/dt = c_g$



$$\frac{dm}{dt} = -k\frac{\partial U}{\partial z}, \qquad \frac{dA}{dt} = -A\frac{\partial c_g}{\partial z}$$

Mean flow: $$\frac{\partial U}{\partial t} = -\frac{1}{\bar{\rho}}\frac{\partial}{\partial z}(\bar{\rho}\,\overline{u'w'}) = -\frac{1}{\bar{\rho}}\frac{\partial}{\partial z}(c_g k\, A)$$

Ray tracing with caustics: Uniqueness Problem

MS-GWaves

Locally monochromatic fields
Locally monochromatic fields

wave-action density $A(z,t)$ so that (e.g.)
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$$E_{GW}(z,t) = A(z,t)\,\hat{\omega}(m)$$

Along **rays**, defined by $dz/dt = c_g$
Along rays, defined by

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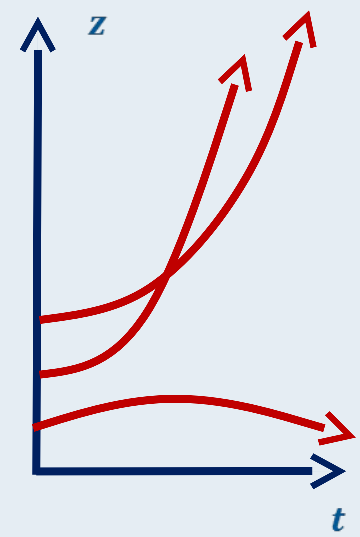
Mean flow: $\frac{\partial U}{\partial t} = -\frac{1}{\bar{\rho}}\frac{\partial}{\partial z}\left(\bar{\rho}\,\overline{u'w'}\right) = -\frac{1}{\bar{\rho}}\frac{\partial}{\partial z}\left(c_g k A\right)$

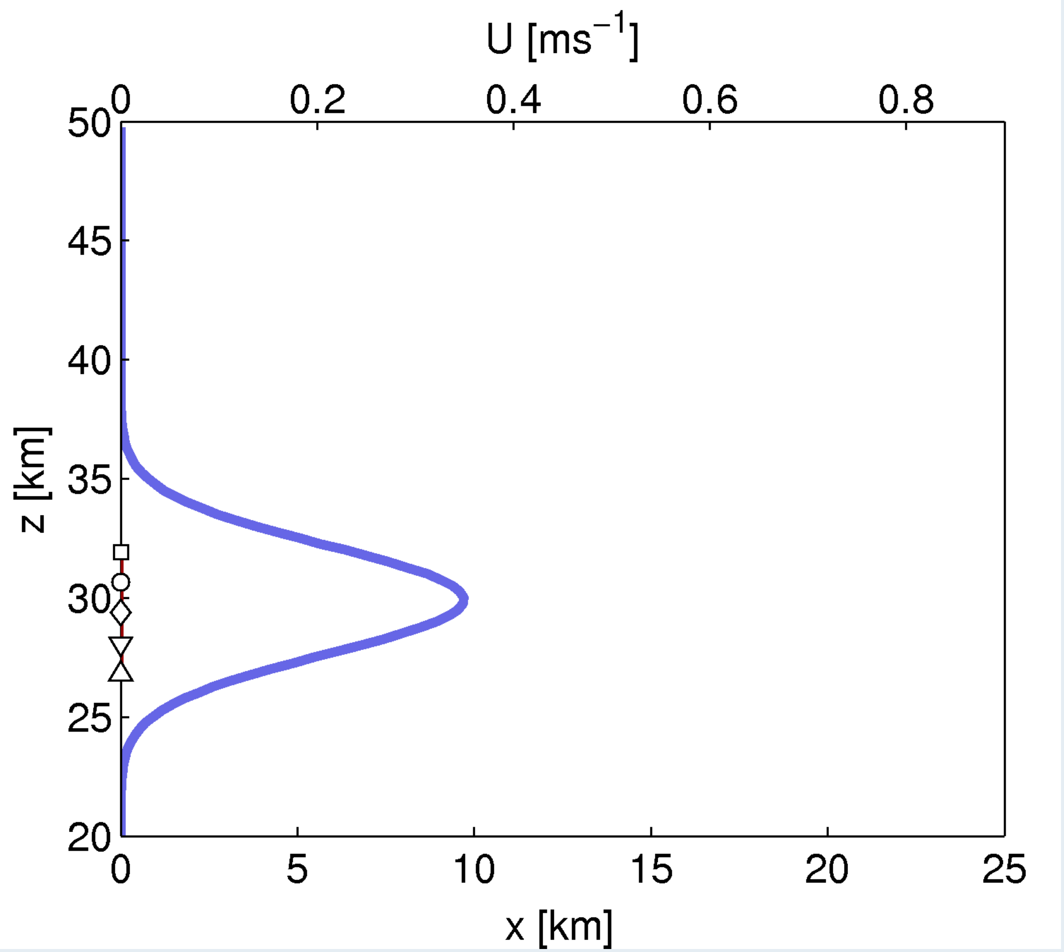
Crossing rays (caustics): uniqueness problem for A and m!
Crossing rays (caustics): uniqueness problem for and !



Ray tracing with caustics: examples for caustic situations

Nonuniqueness of wave number and wave-action density arises easily:

e.g. by
wave-induced mean flow



Ray tracing with caustics: spectral approach

MS-GWaves

linear limit: wave field can be **decomposed** into fields with singlevalued wavenumbers

spectral description in phase space (Dewar 1970, Dubrulle & Nazarenko 1997, Bühler & McIntyre 1999, Hertzog et al 2000, Muraschko et al 2015) does this automatically

phase-space wave-action density

$$\mathcal{N}(m,z,t) = \int d\alpha\, A_\alpha(z,t)\;\; \delta[m - m_\alpha(z,t)] \qquad \Leftrightarrow \qquad A(z,t) = \int dm\, \mathcal{N}(m,z,t)$$

satisfies conservation equation

$$\frac{\partial \mathcal{N}}{\partial t} + \frac{\partial}{\partial z}\left(c_g\, \mathcal{N}\right) + \frac{\partial}{\partial m}\left(\dot{m}\, \mathcal{N}\right) = 0 \qquad\qquad \dot{m} = -k\frac{\partial U}{\partial z}$$

Mean flow: $$\frac{\partial U}{\partial t} = -\frac{1}{\bar\rho}\frac{\partial}{\partial z}\left(\bar\rho\, \overline{u'w'}\right) = -\frac{1}{\bar\rho}\frac{\partial}{\partial z}\left(\int dm\, c_g k\, \mathcal{N}\right)$$

generalization to 3D straightforward

generalization to 3D straightforward

Ray tracing with caustics: efficient numerics (Muraschko et al 2015)

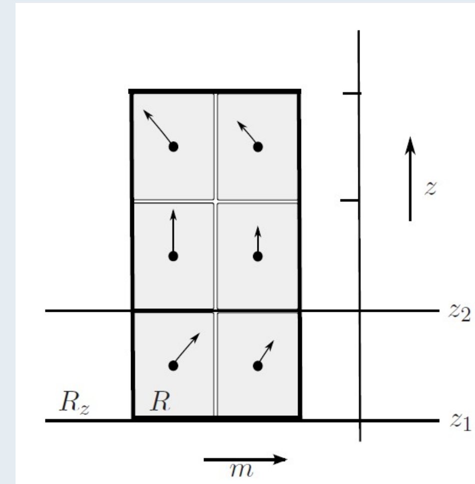
phase-space velocity is non-divergent

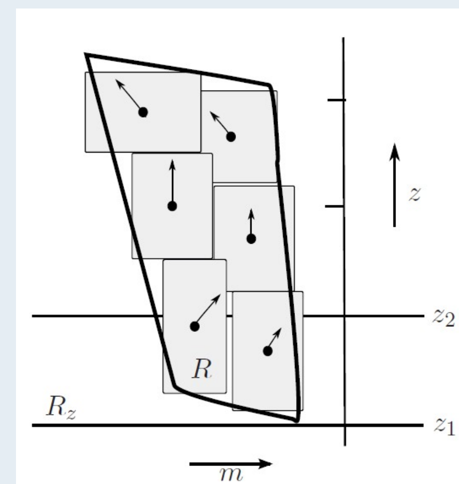
hence
$$\frac{\partial c_g}{\partial z} + \frac{\partial \dot{m}}{\partial m} = \frac{\partial}{\partial z}\frac{\partial \Omega}{\partial m} + \frac{\partial}{\partial m}\left(-\frac{\partial \Omega}{\partial z}\right) = 0$$

- flow is volume preserving
- rays cannot cross
- Wave-action density conserved on rays

$$\frac{D\mathcal{N}}{Dt} = \frac{\partial \mathcal{N}}{\partial t} + c_g \frac{\partial \mathcal{N}}{\partial z} + \dot{m}\frac{\partial \mathcal{N}}{\partial m} = 0$$

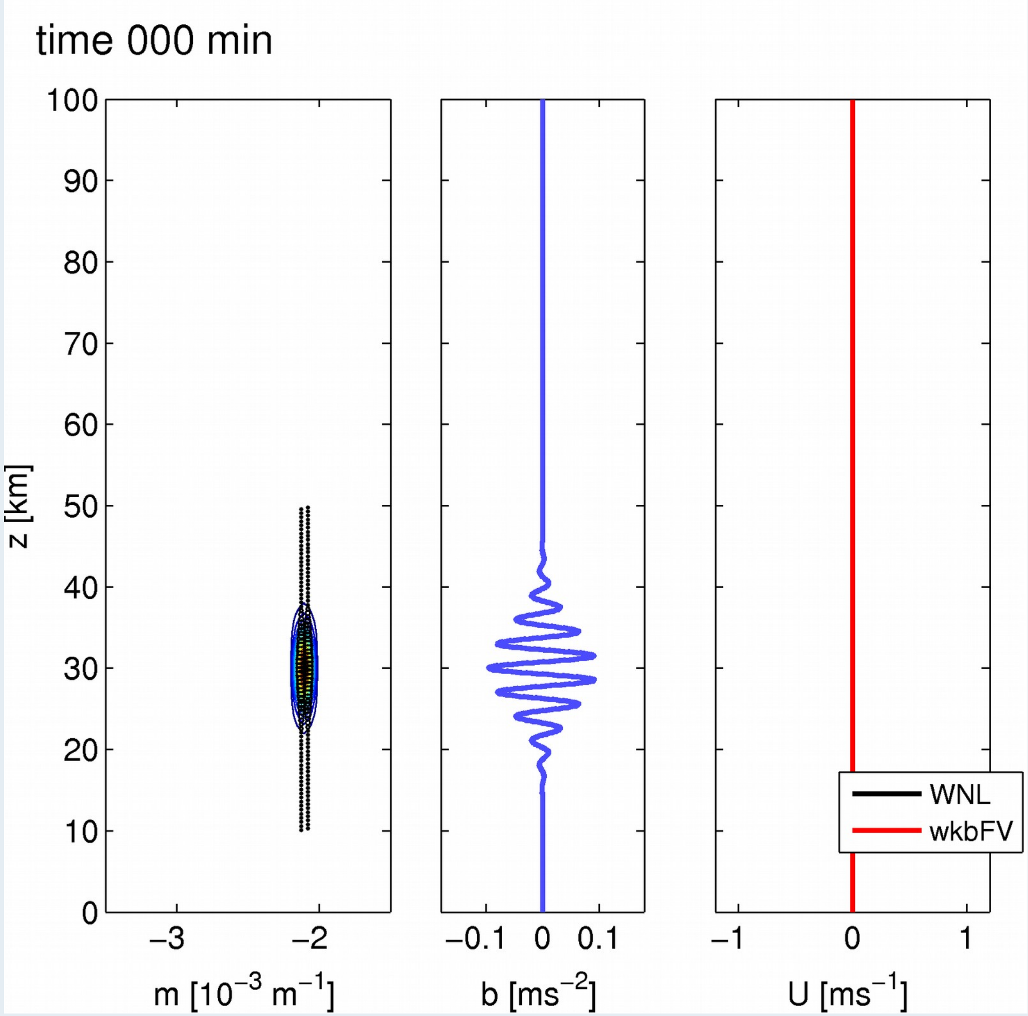
- region of nonzero $\mathcal{N}$ approximated by rectangular ray volumes
- ray volumes move with central ray
- ray volumes change height (Δz) and width (Δm) in area-preserving manner





Ray tracing with caustics: efficient numerics (Muraschko et al 2015)

hydrostatic wave packet (Boussinesq)

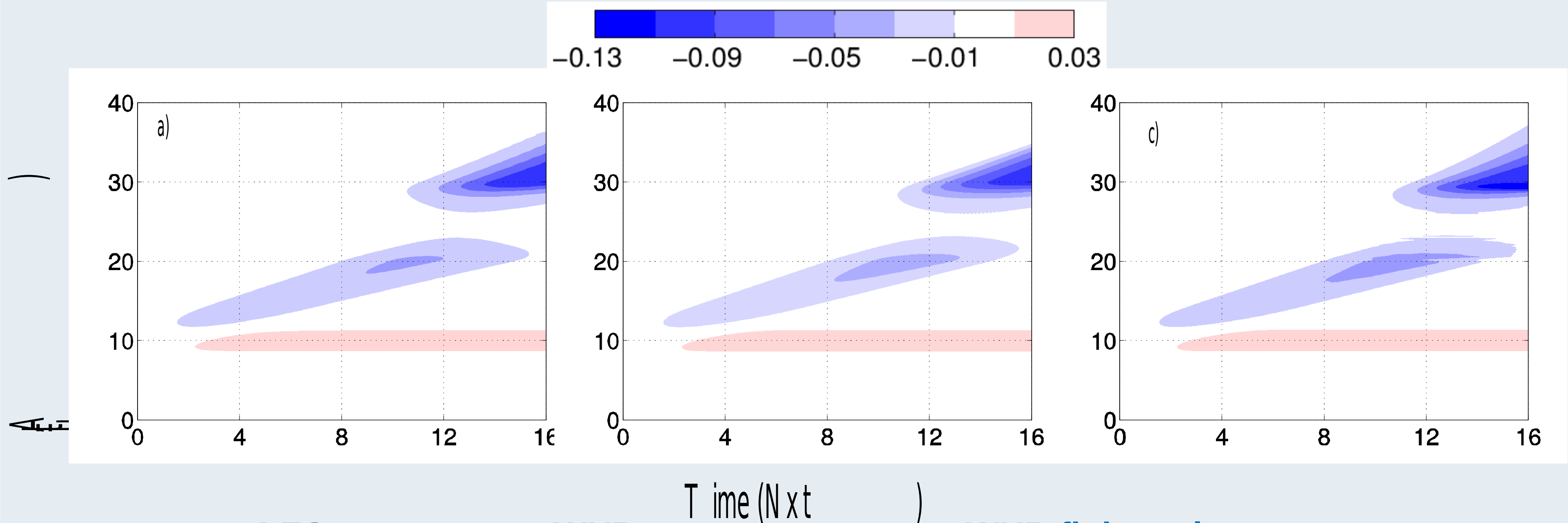


Rays are no wavepackets

No turbulence taken into account!

Ray tracing with caustics: no numerical instabilities (Bölöni et al 2016)

GW packet refracted by a jet



LES WKB ray tracer WKB finite volume

Direct wave-mean-flow interaction: comparsion with role of wave breaking

MS-GWaves

- **transient GWs** can interact with the mean flow without the onset of turbulence (eg Dosser & Sutherland 2011)
- GW parameterizations (steady-state approximation) only rely on **wave breaking**

comparative role of wave transience (direct interaction) vs wave breaking?

direct wave-mean-flow interaction vs wave breaking (Bölöni et al 2016)

horizontally infinite GW packets in interaction with mean flow

- **1D**: $U(z,t), A(z,t), m(z,t)$
- direct GW-mean-flow interaction always active
- WKB: $\boldsymbol{E_{mean} + E_{wave} = const}$.

tools:

- wave resolving **LES** (reference data)
- fully coupled **WKB**
- **turbulence** onset
  - once static instability threshold can be surpassed

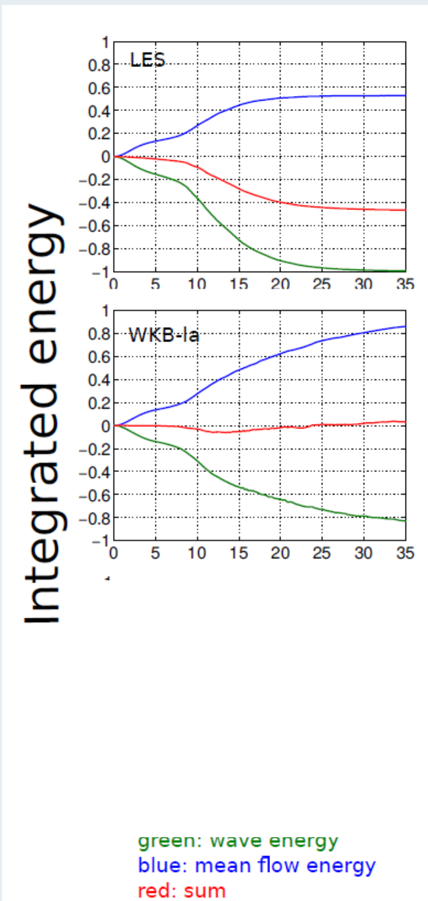
$$\int dm\; m^2 \frac{d|B|^2}{dm} = \int dm\; \mathcal{N} f(m) > \alpha N^2$$

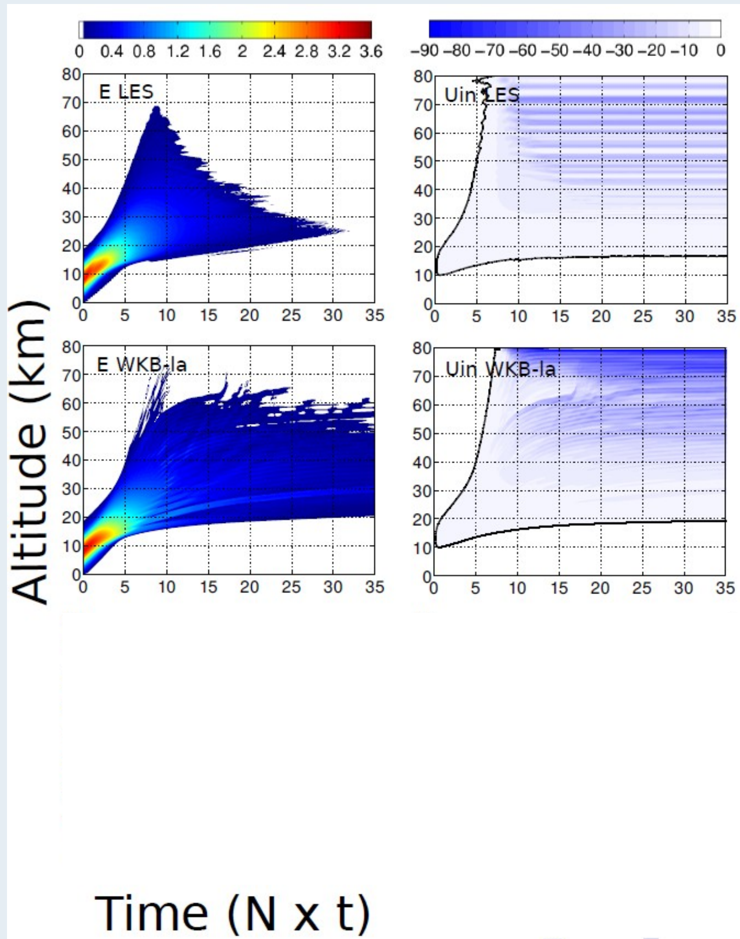
  - parameter $\alpha \in [1,2]$ accounting for phase cancellations between spectral components
  - (scale selective) **eddy viscosity/diffusivity** reduces wave amplitude to inst. threshold

direct wave-mean-flow interaction vs wave breaking (Bölöni et al 2016)

MS-GWaves

static instability hydrostatic wave packet





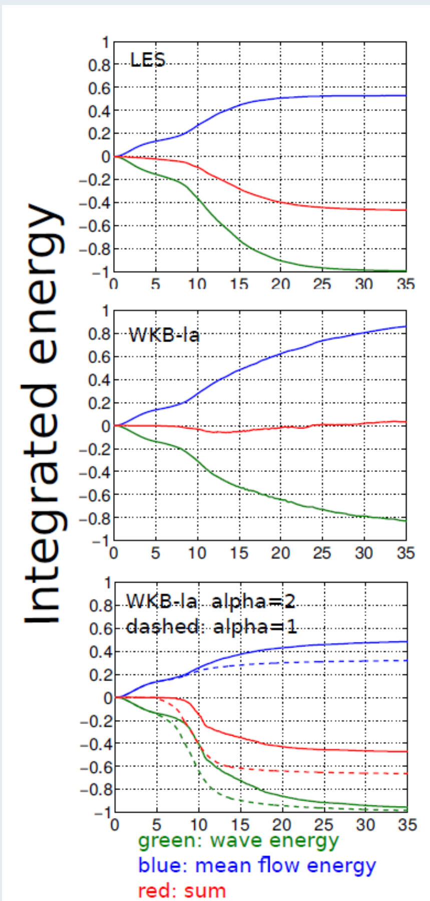
LES (wave-resolving)

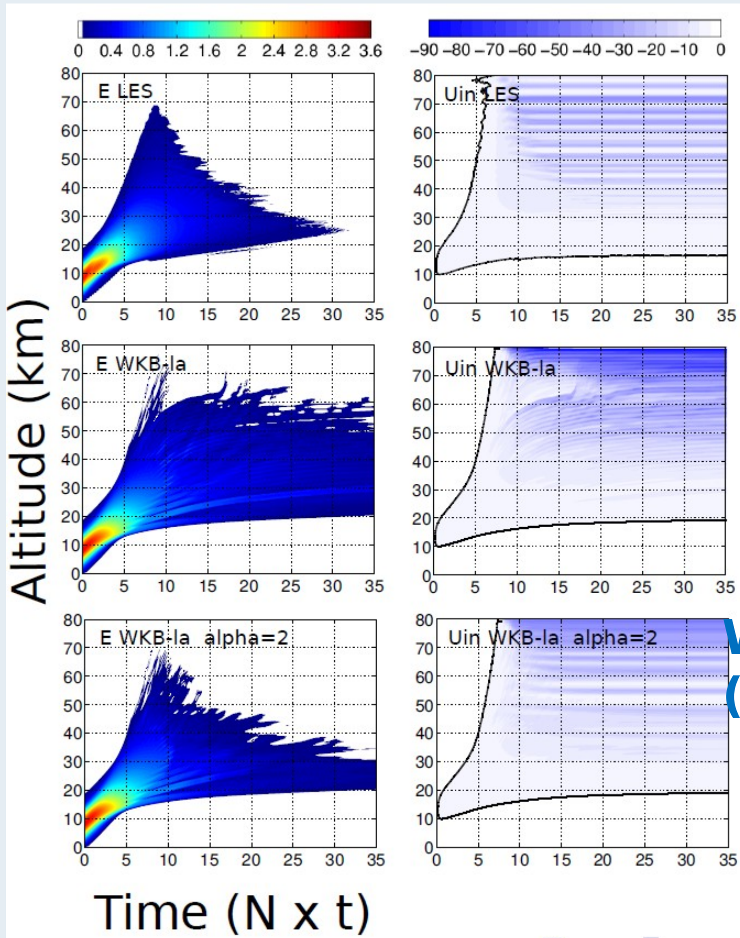
WKB

direct wave-mean-flow interaction vs wave breaking (Bölöni et al 2016)

MS-GWaves

static instability hydrostatic wave packet





LES (wave-resolving)

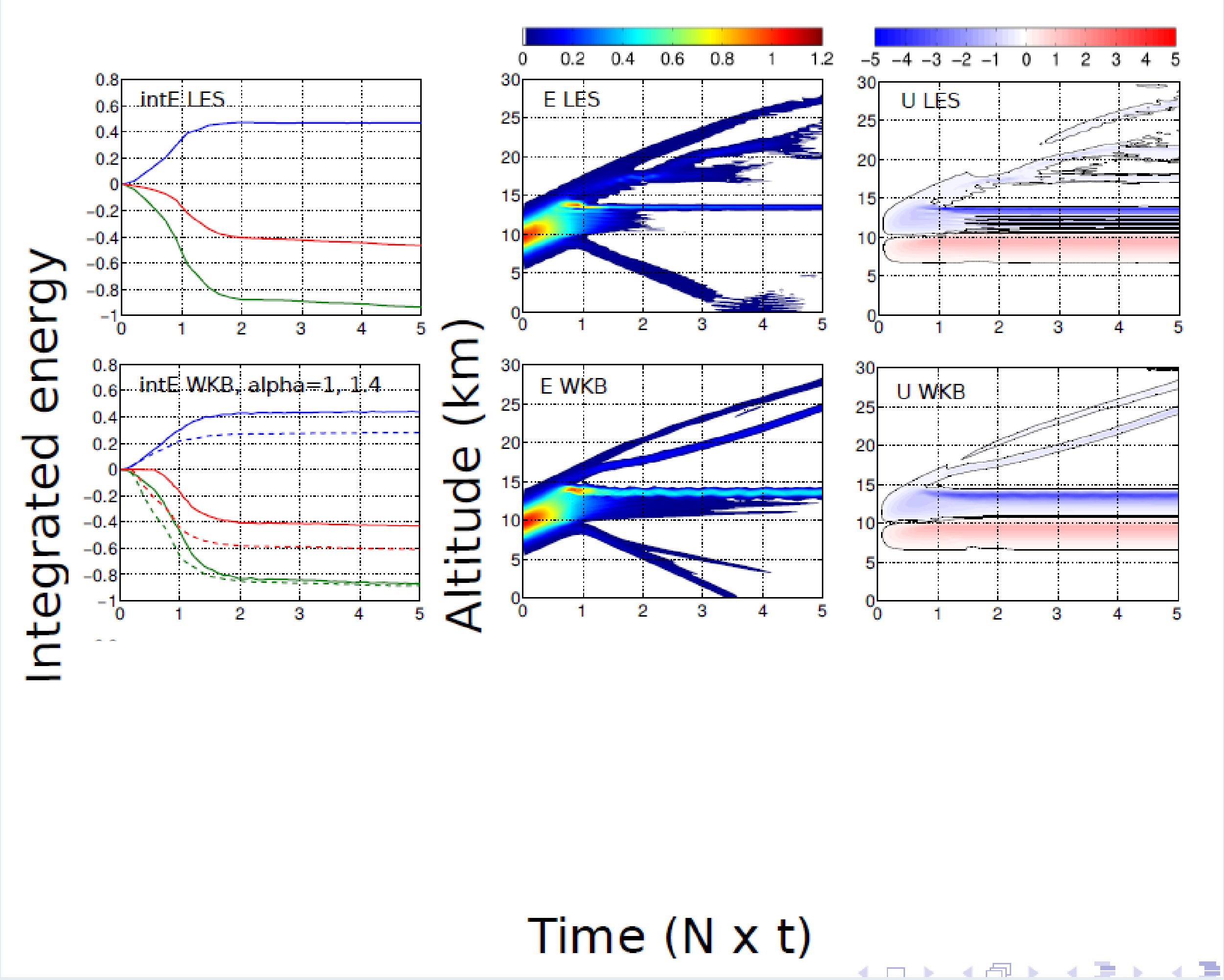
WKB

WKB with saturation (turbulence param.)

direct wave-mean-flow interaction vs wave breaking (Bölöni et al 2016)

MS-GWaves

static instability non-hydrostatic wave packet

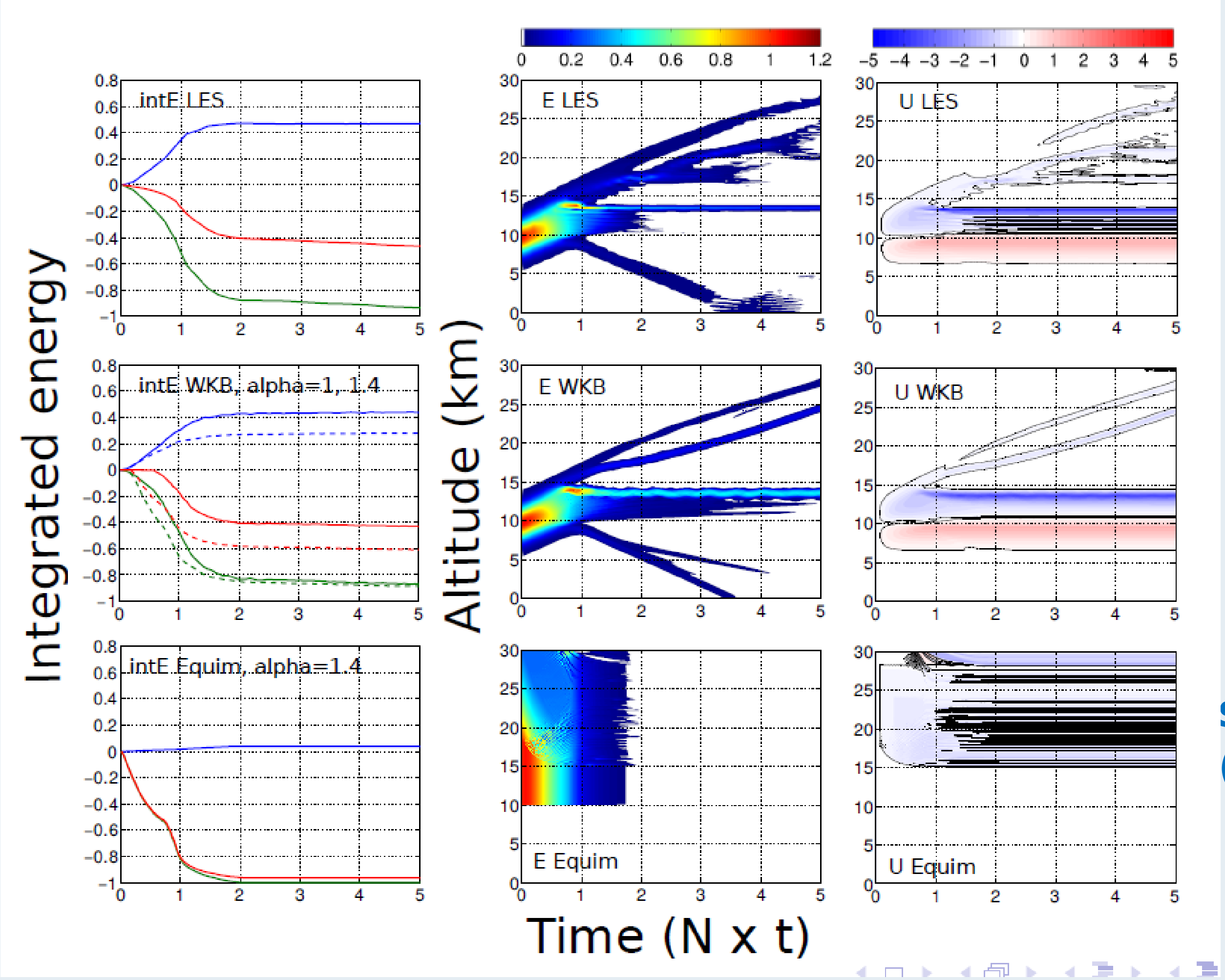


LES (wave-resolving)

WKB with saturation (turbulence param.)

direct wave-mean-flow interaction vs wave breaking (Bölöni et al 2016)

static instability non-hydrostatic wave packet



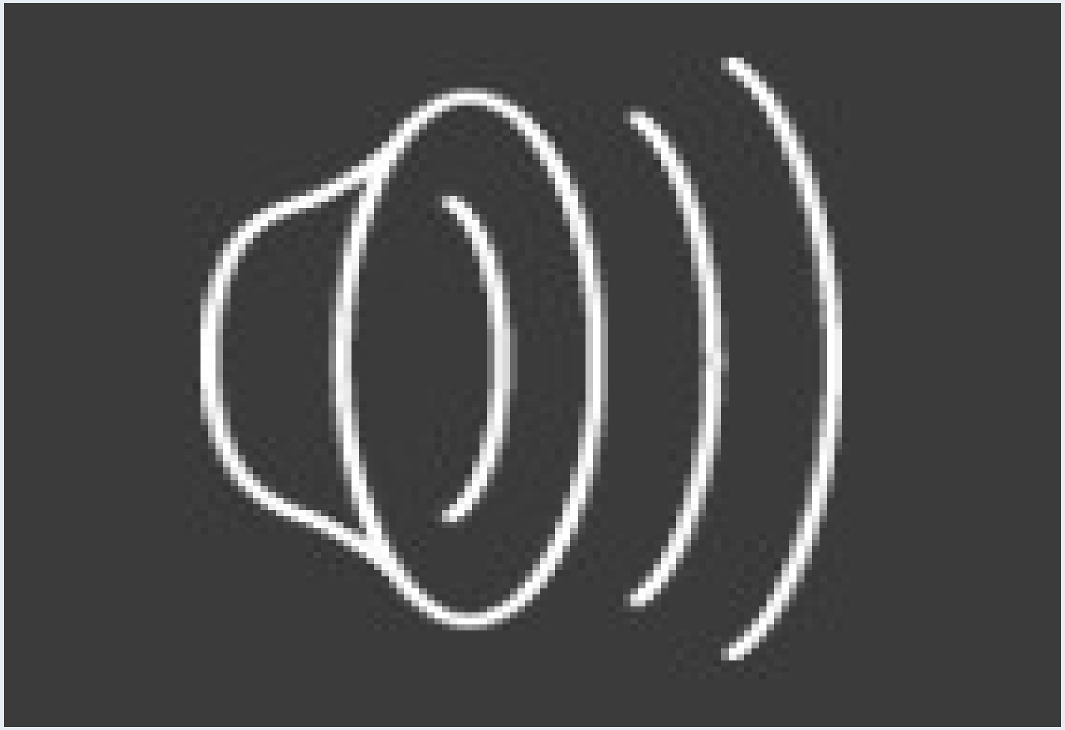
LES (wave-resolving)

WKB with saturation (turbulence param.)

steady-state (GW parameterization

Solar tides: An example of 3D GW-mean-flow interaction

Large-scale waves forced by the diurnal cycle of solar heating

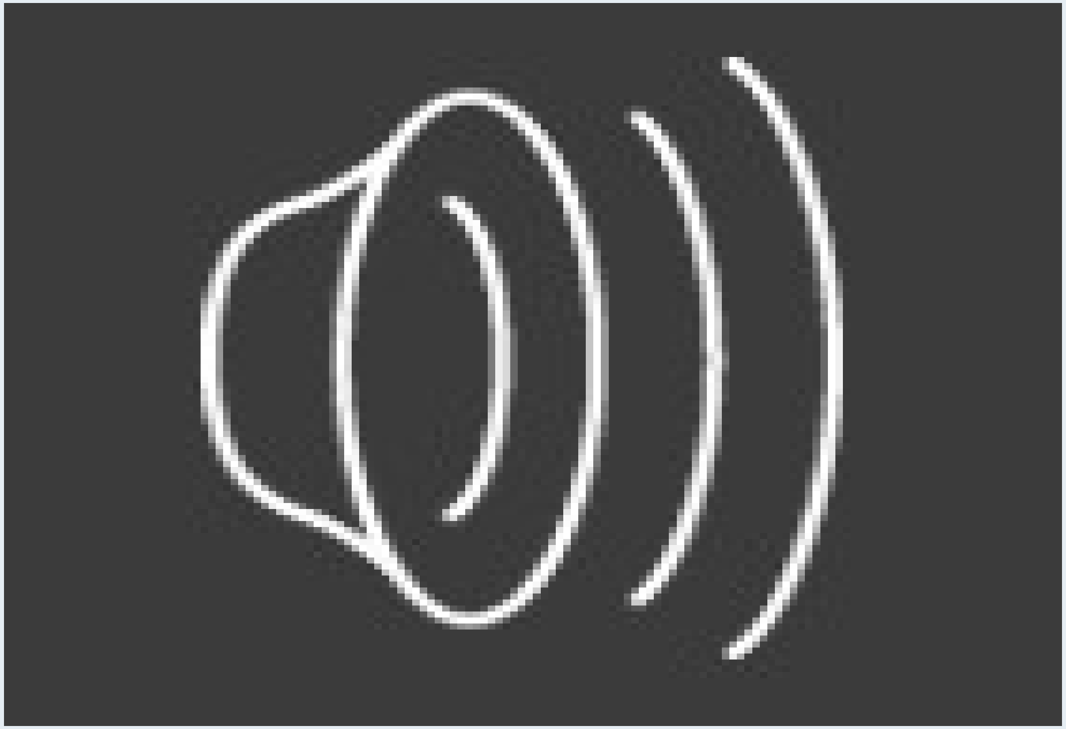


Solar tides

Large-scale waves forced by the diurnal cycle of solar heating

Two components:

- **Migrating tides**
  follow solar movement

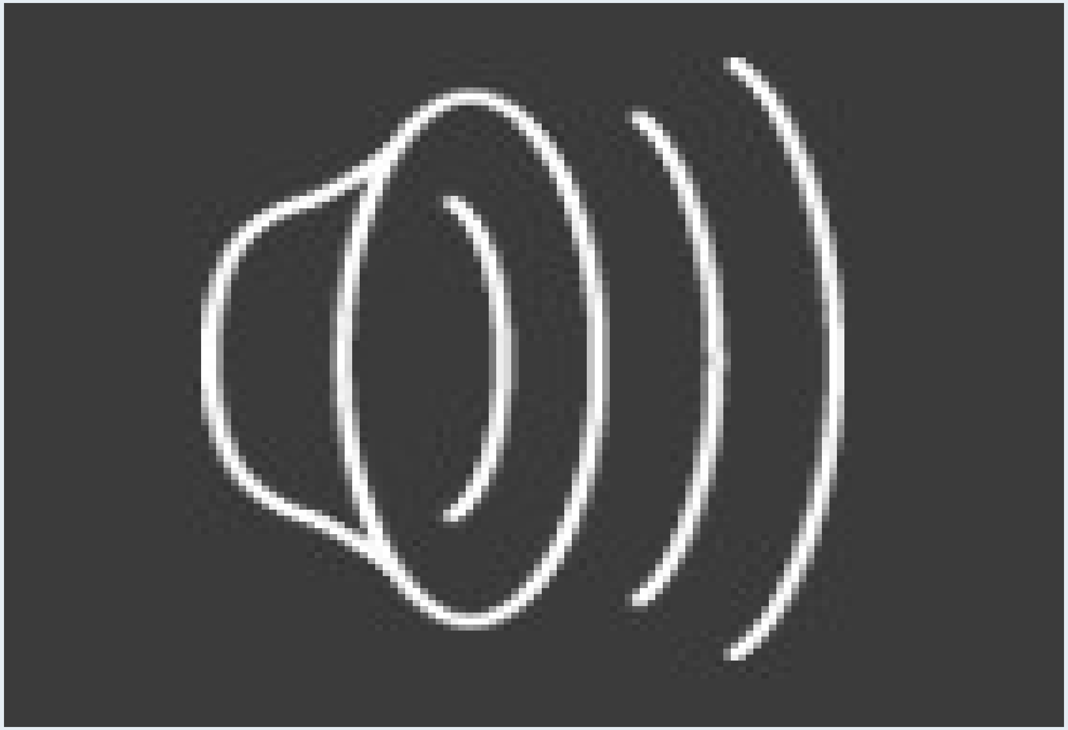


Solar tides

Large-scale waves **forced by the diurnal cycle of solar heating**

Two components:

- **Migrating tides**
  follow solar movement
- **Nonmigrating tides**:
  all the rest



Solar tides

Large-scale waves forced by the diurnal cycle of solar heating

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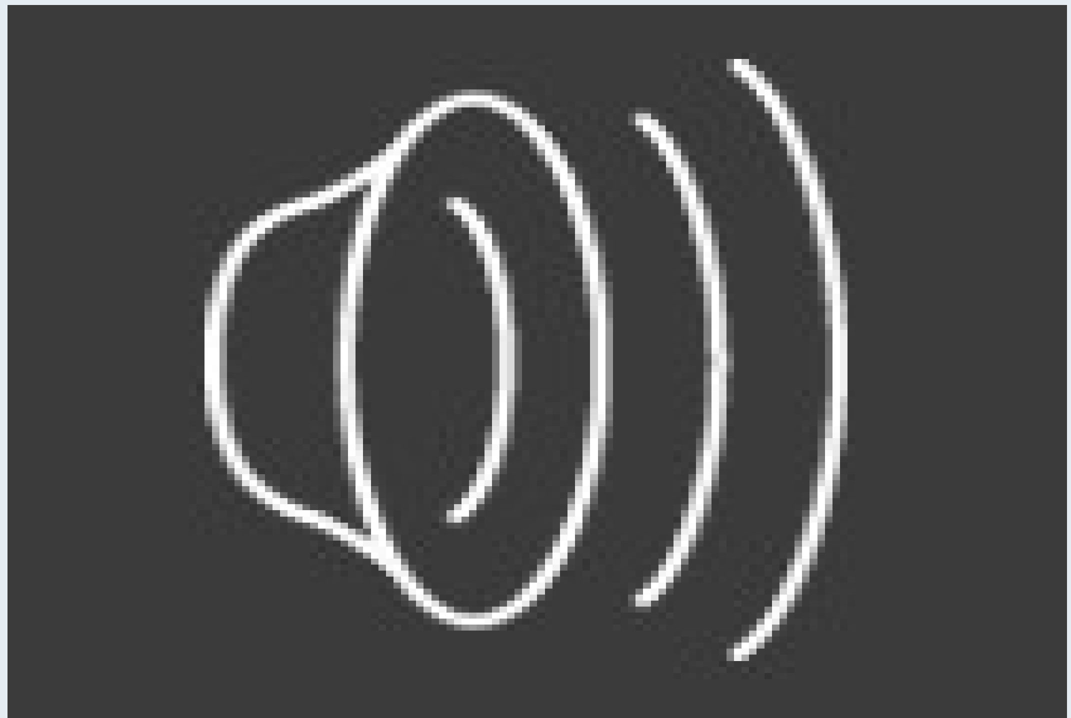


Interaction with GWs:

- STs influence **GW propagation and amplitude development**
- GW impact on STs by **GW momentum and buoyancy deposition**

Tidal model in interaction with GWs (Ribstein et al 2015, Ribstein & Achatz 2016)

From **GCM data** (HAMMONIA, Schmidt et al 2006):

- Seasonally dependent reference climatology $\overline{\boldsymbol{u}}(\lambda,\phi,z),\ \overline{T}(\lambda,\phi,z)$
- Diurnal heating cycle $\Re \sum_n Q_n(\lambda,\phi,z)\, e^{in\Omega t}$

Linear model (Achatz et al 2008, based on KMCM, Becker and Schmitz 2003)

$$\boldsymbol{u} = \overline{\boldsymbol{u}} + \boldsymbol{u}'(\lambda,\phi,z,t)$$
$$T = \overline{T} + T'(\lambda,\phi,z,t)$$

$$\left(\frac{\partial}{\partial t} + \overline{\boldsymbol{u}} \cdot \nabla_h\right)\boldsymbol{u}' + \cdots = -\frac{1}{\bar{\rho}}\,\nabla\cdot\left(\bar{\rho}\ \overline{\boldsymbol{v}_{GW}\boldsymbol{u}_{GW}}\right)$$

$$\left(\frac{\partial}{\partial t} + \overline{\boldsymbol{u}} \cdot \nabla_h\right)T' + \boldsymbol{v}'\cdot\nabla\overline{T} + \cdots = \Re\sum_n Q_n(\lambda,\phi,z)\, e^{in\Omega t} - \nabla_h\cdot\left(\overline{\boldsymbol{u}_{GW}T_{GW}}\right)$$

GW fluxes from **4D WKB model with rays** propagating on $(\overline{\boldsymbol{u}} + \boldsymbol{u}', \overline{\boldsymbol{T}} + \boldsymbol{T}')$

First implementation of a fully coupled transient ray tracer into a global model

Tidal model in interaction with GWs (Ribstein et al 2015, Ribstein & Achatz 2016)

3D effects (beyond single column)

- **Horizontal GW propagation**

$$\frac{d\boldsymbol{x}_h}{dt} = \boldsymbol{c}_{gh}, \qquad \frac{dz}{dt} = c_{gz}$$

- **Horizontal gradients in reference climatology and tides**

$$\frac{d\boldsymbol{k}_h}{dt} = -k\,\nabla_h(\bar{u}+u') - l\,\nabla_h(\bar{v}+v'), \qquad \frac{dm}{dt} = -k\frac{d}{dz}(\bar{u}+u') - l\frac{d}{dz}(\bar{v}+v')$$

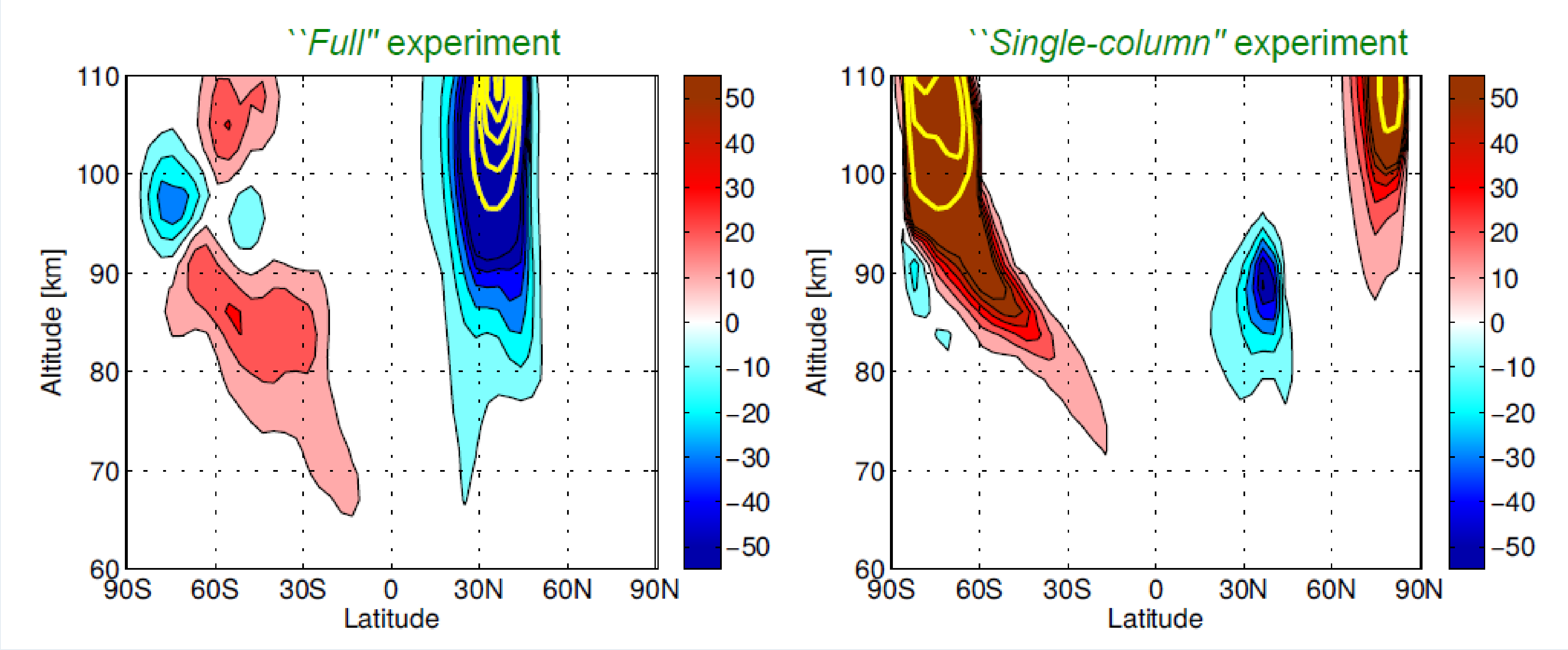
- **Horizontal GW flux convergence**

$$\left(\frac{\partial}{\partial t} + \bar{\boldsymbol{u}}\cdot\nabla_h\right)\boldsymbol{u}' + \cdots = -\frac{1}{\bar{\rho}}\frac{\partial}{\partial z}\left(\bar{\rho}\;\overline{\boldsymbol{w}_{GW}\boldsymbol{u}_{GW}}\right) - \frac{1}{\bar{\rho}}\nabla_h\cdot\left(\bar{\rho}\;\overline{\boldsymbol{u}_{GW}\boldsymbol{u}_{GW}}\right)$$

$$\left(\frac{\partial}{\partial t} + \bar{\boldsymbol{u}}\cdot\nabla_h\right)T' + \boldsymbol{v}'\cdot\nabla\bar{T} + \cdots = \Re\sum_n Q_n(\lambda,\phi,z)\,e^{in\Omega t} - \nabla_h\cdot\left(\overline{\boldsymbol{u}_{GW}\,T_{GW}}\right)$$

Tidal model in interaction with GWs (Ribstein et al 2015, Ribstein & Achatz 2016)

3D effects (beyond single column)

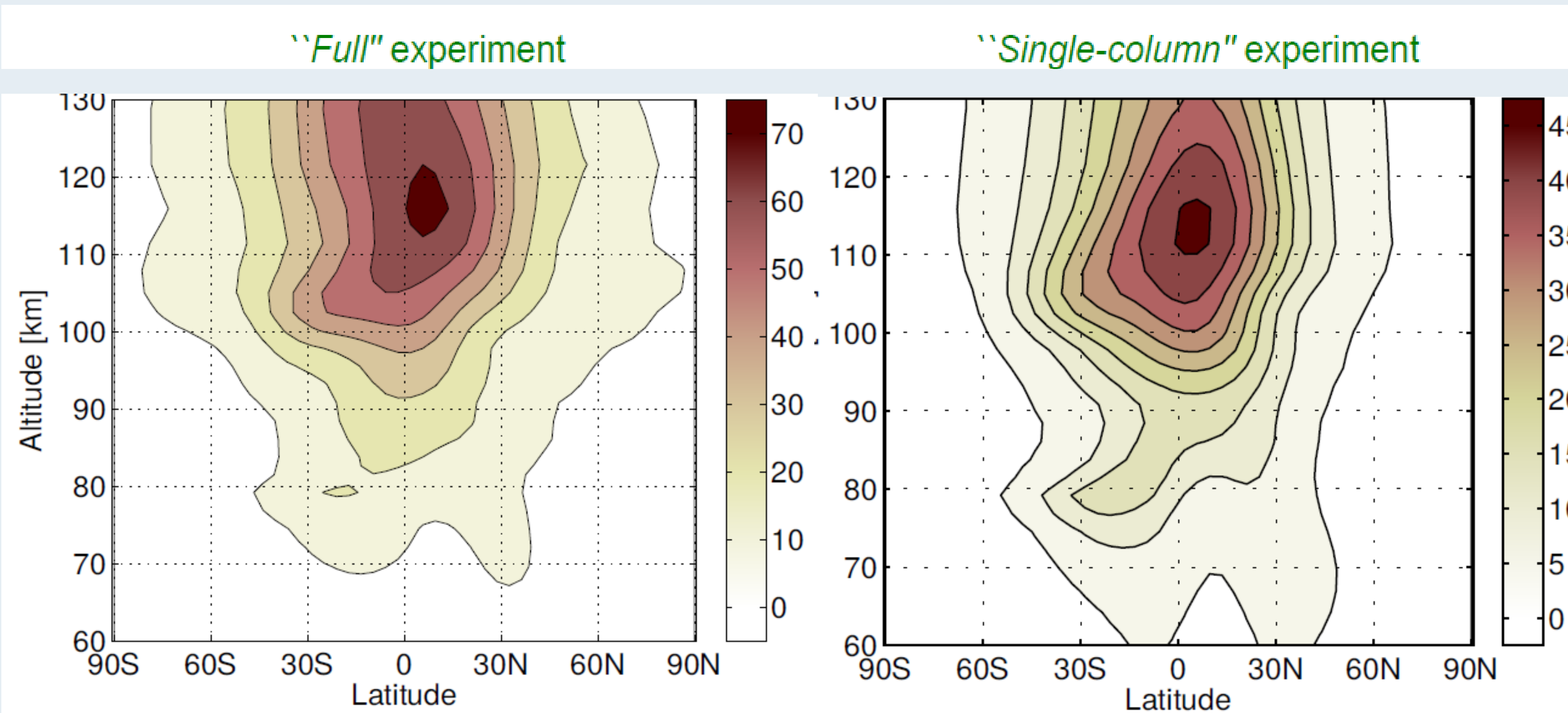


zonal-mean daily-mean GW forcing (December)

Tidal model in interaction with GWs (Ribstein et al 2015, Ribstein & Achatz 2016)

MS-GWaves

3D effects (beyond single column)



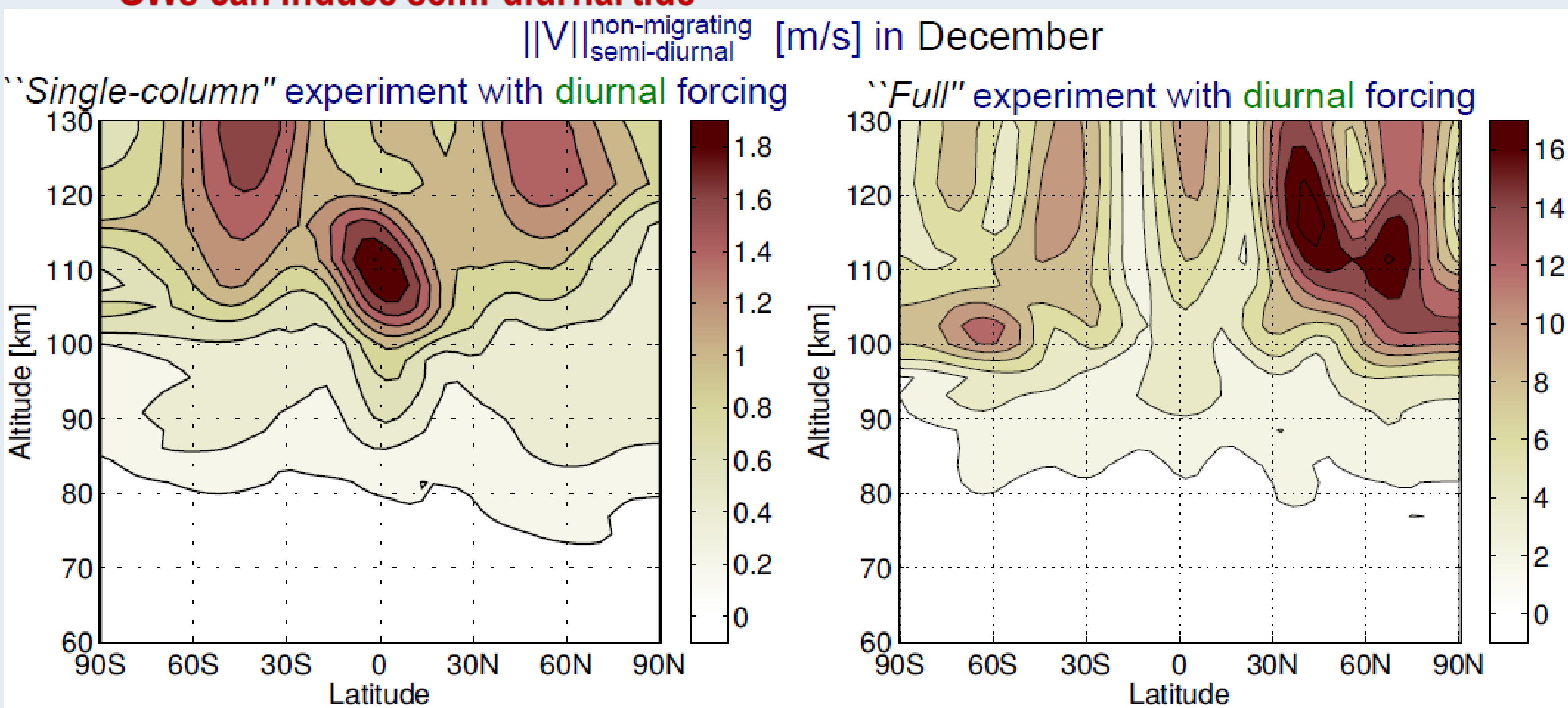
Tidal model in interaction with GWs (Ribstein et al 2015, Ribstein & Achatz 2016)

3D effects (beyond single column):

- **Tidal model**
  - Diurnal forcing only induces diurnal tide
  - **GWs can induce semi-diurnal tide**

3D effects (beyond single column):

- Tidal model $dY'/dt = L(\bar{u},\bar{T})Y' + \Re\sum_n Q_n e^{-in\Omega t} + F_{GW}(t)$
  - Diurnal forcing only induces diurnal tide
  - GWs can induce semi-diurnal tide



Tidal model in interaction with GWs (Ribstein et al 2015, Ribstein & Achatz 2016)

MS-GWaves

3D effects (beyond single column):

- **Tidal model** $dY'/dt = L(\bar{u},\bar{T})Y' + \Re\sum_n Q_n e^{-in\Omega t} + F_{GW}(t)$
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  - **GWs can induce semi-diurnal tide** (40% effect)

3D effects (beyond single column):
- Tidal model
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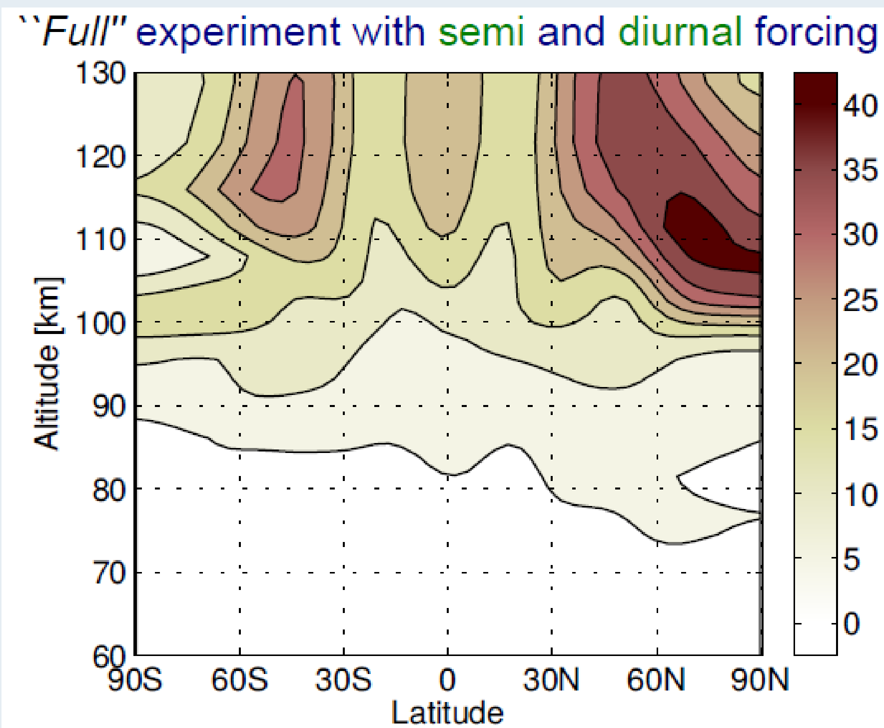
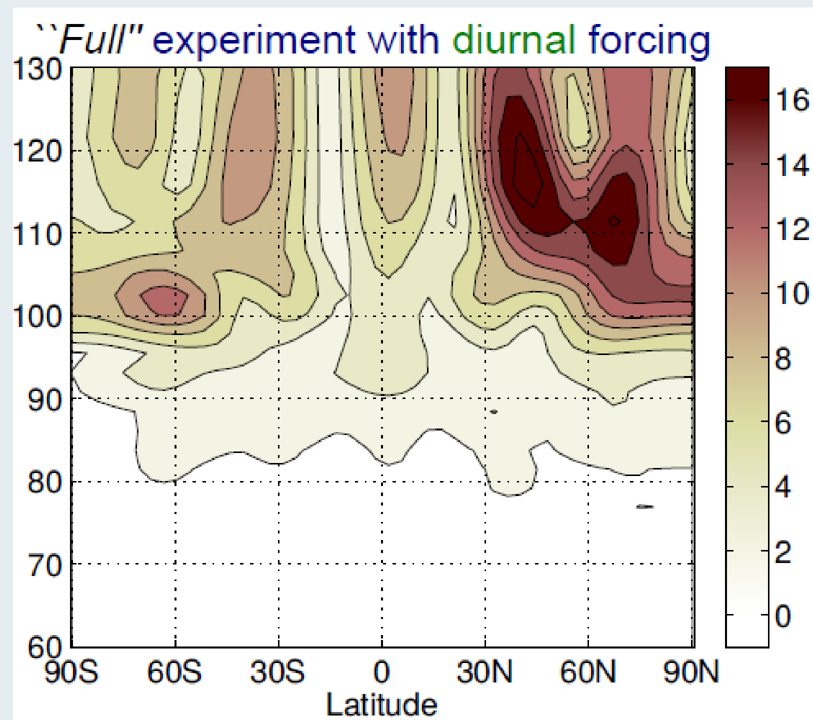




Summary

- **Approximations in present-day GW parameterizations critically limit their validity**
  - **Single-column**
  - **Steady state**
- **First implemention of a generalized approach into a global model**
- **Significant impact:**
  - **Zonal-mean forcing**
  - **Solar tides**

Achatz, U., Ribstein, B., Senf, F., and R. Klein 2016: The interaction between synoptic-scale balanced flow and a finite-amplitude mesoscale wave field throughout all atmospheric layers: Weak and moderately strong stratification. *Quart. J. Roy. Met. Soc.,* **143**, 342–361

Ribstein, B., Achatz, U. und F. Senf, 2015: The interaction between gravity waves and solar tides: Results from 4D ray tracing coupled to a linear tidal model, *J. Geophys. Res.*, **120**, doi:10.1002/2015JA021349

Bölöni, G., Ribstein, S., Achatz, U., Muraschko, J., Sgoff, C. und J. Wei, 2016: The interaction between atmospheric gravity waves and large-scale flows: an efficient description beyond the non-acceleration theorem. *J. Atmos. Sci.*, **73**, 4833-4852

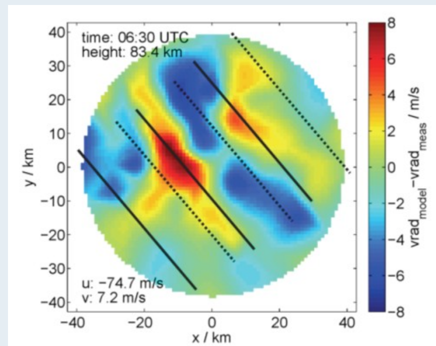
Ribstein, B. und U. Achatz, 2016: Gravity wave propagation and impacts on a diurnal middle atmosphere : results from 4D ray tracing directly coupled to a linear tidal model. *J. Geophys. Res.,* doi:10.1002/2016JA022478

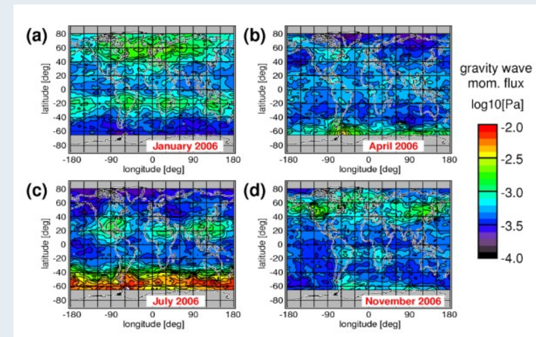
GWaves

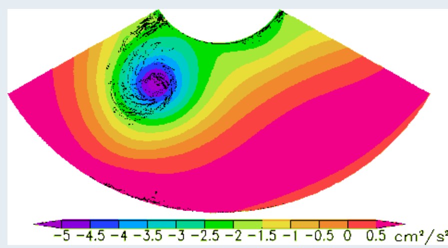
https://ms-gwaves.iau.uni-frankfurt.de/index.php

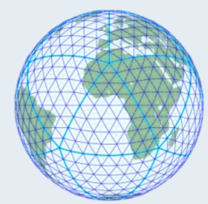
MS-GWaves

- Investigation multi-scale dynamics of GWs in 6 projects
- prognostic WKB GW parameterization to be developed for NWP and climate model
- To be addressed:
  - Sources
  - Propagation
  - dissipation
- Combined effort:
  - Theory,
  - modelling,
  - measurements,
  - laboratory experiments









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