Max-Planck-Institut für Meteorologie

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

MS-GWaves / GWING:

Towards UA-ICON – A non-hydrostatic global model for studying gravity waves from troposphere to thermosphere

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2016 SPARC Gravity Wave Symposium

(1) DWD (2) Max-Planck-Institut für Meteorologie (3) GOETHE UNIVERSITÄT FRANKFURT AM MAIN (4) LEIBNIZ-INSTITUT FÜR ATMOSPHÄREN PHYSIK IAP

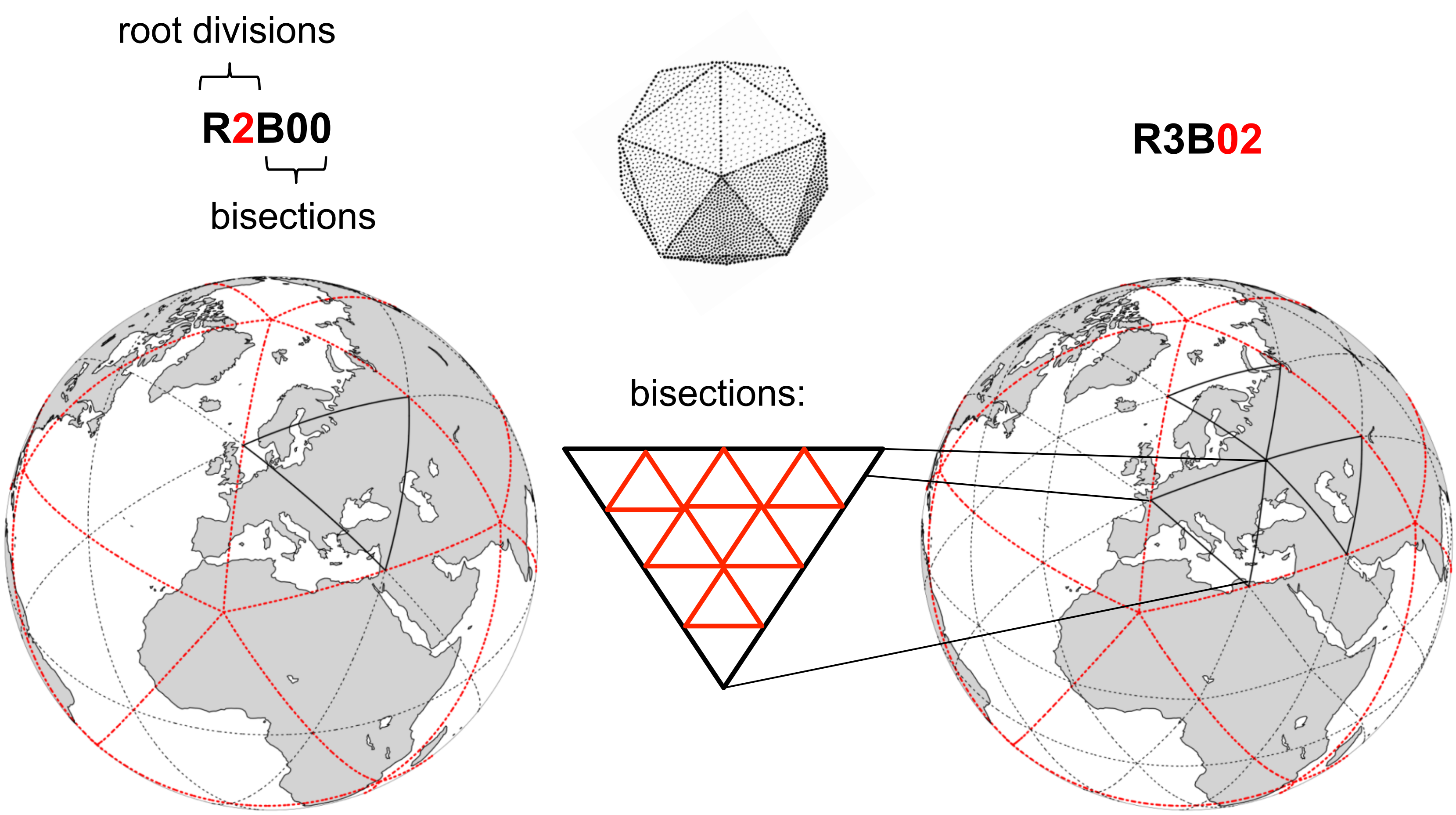
MS-GWaves DFG Deutsche Forschungsgemeinschaft

ICON (ICOsahedral Non-hydrostatic model)

- Joint development of MPI-M and DWD (Zängl et al., 2015) with contributions from KIT (chemistry model ART)
- Primary features:
  - Unified modelling system for NWP and climate projections
  - Non-hydrostatic dynamical core: applicable on wide range of scales
  - Mass conservation (air mass, moisture, trace gases)
  - Grid nesting for local refinement at very high horizontal resolutions
  - Scalability and efficiency on massively parallel computer architectures with $O(10^4+)$ cores
- Global model and EU-nest operational at DWD since 20 Jan. / 21 July 2015

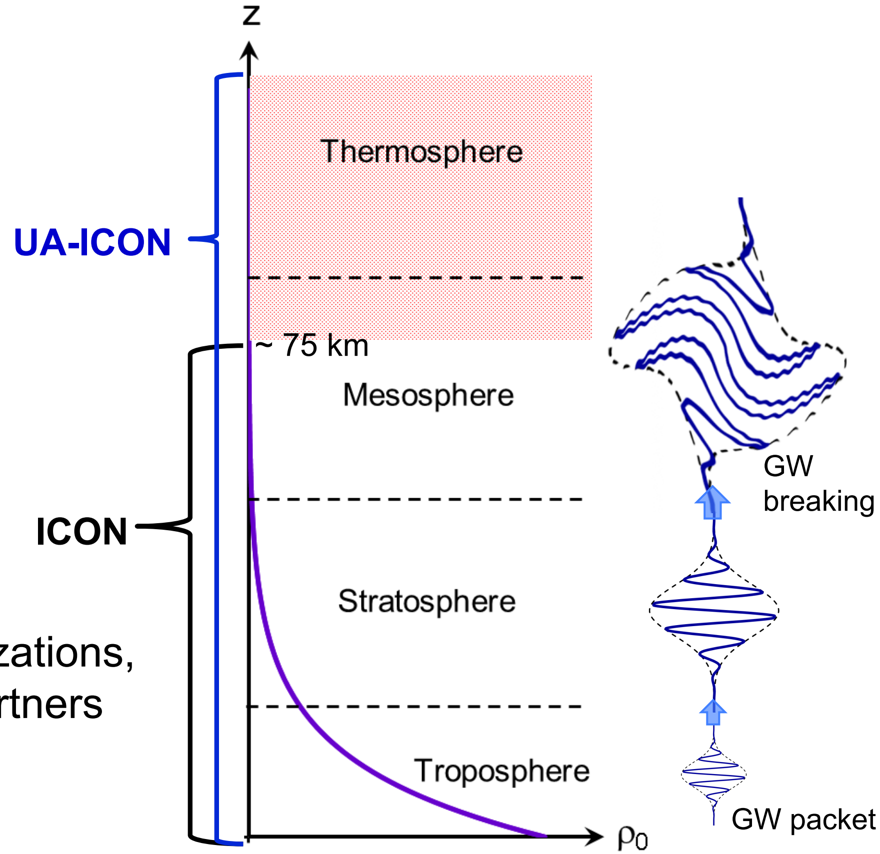
ICON triangle grid with nesting

Numerical discretization on icosahedron-based grid:



Project MS-GWaves/*GWING* (*Gravity Wave Interactions in the Global Atmosphere*)

- **Extend ICON to UA-ICON:**
  - Physics (MPI-M)
  - Dynamical core (DWD)
  - Evaluation with benchmarks: HAMMONIA, ECHAM6 (MPI-M) and KMCM (IAP), reanalysis products, satellite / lidar / radar measurements
- **In close collaboration with other project partners:**
  - Implementation and testing of parameterizations, developed and provided by the project partners
  - Simulation and analysis of case studies to compare with campaign data of gravity waves (GWs) in middle atmosphere

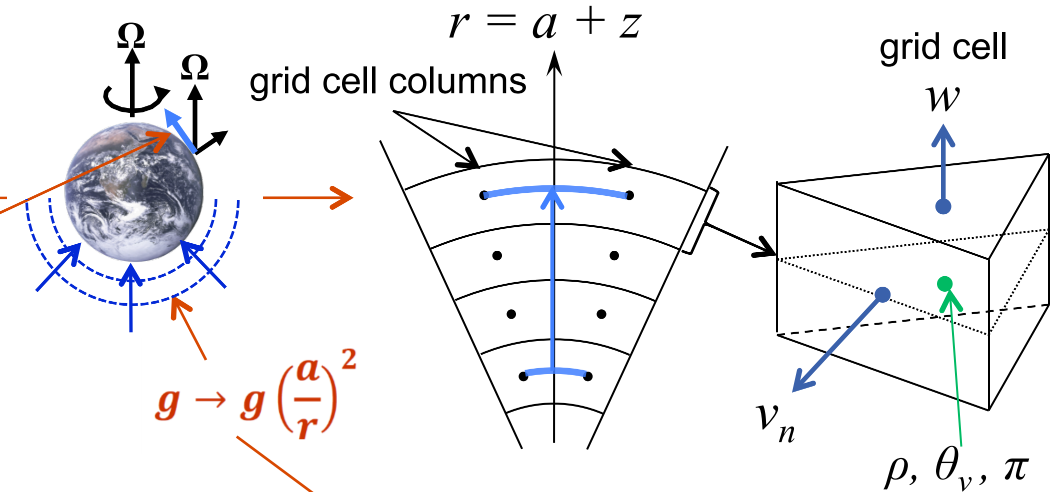


Dynamical core of ICON: New implementations

Deep-atmosphere equations

metrical correction factors

non-traditional terms



$$\frac{\partial v_{\mathrm{n}}}{\partial t} + \left(\frac{a}{r}\right)\frac{\partial K_{\mathrm{h}}}{\partial \mathrm{n}} + (\zeta + f_z)\, v_{\mathrm{t}} + w\left(\frac{\partial v_{\mathrm{n}}}{\partial z} + \frac{v_{\mathrm{n}}}{r} - f_{\mathrm{t}}\right) = -c_{pd}\,(\theta_{v0} + \theta'_v)\left(\frac{a}{r}\right)\frac{\partial \pi'}{\partial \mathrm{n}} + \frac{1}{\rho}F_{\mathrm{n}}$$

$$\frac{\partial w}{\partial t} + v_{\mathrm{n}}\left[\left(\frac{a}{r}\right)\frac{\partial w}{\partial \mathrm{n}} - \frac{v_{\mathrm{n}}}{r} + f_{\mathrm{t}}\right] + v_{\mathrm{t}}\left[\left(\frac{a}{r}\right)\frac{\partial w}{\partial \mathrm{t}} - \frac{v_{\mathrm{t}}}{r} - f_{\mathrm{n}}\right] + w\frac{\partial w}{\partial z} = -c_{pd}\left[(\theta_{v0} + \theta'_v)\frac{\partial \pi'}{\partial z} + \theta'_v\frac{\mathrm{d}\pi_0}{\mathrm{d}z}\right] + \frac{1}{\rho}F_z$$

n $\rightarrow$ direction normal to cell faces
t $\rightarrow$ direction tangential to cell faces
$a \rightarrow$ Earth radius

$K_{\mathrm{h}} = \frac{1}{2}\left(v_{\mathrm{n}}^2 + v_{\mathrm{t}}^2\right)$
$\zeta \rightarrow$ vertical vorticity component
$f_z = 2\Omega\sin(\phi) \quad f_{\mathrm{n,t}} = 2\Omega\cos(\phi)\,\boldsymbol{e}_\phi \cdot \boldsymbol{e}_{\mathrm{n,t}}$

$\pi \rightarrow$ Exner function
$\theta_v \rightarrow$ virtual potential temperature

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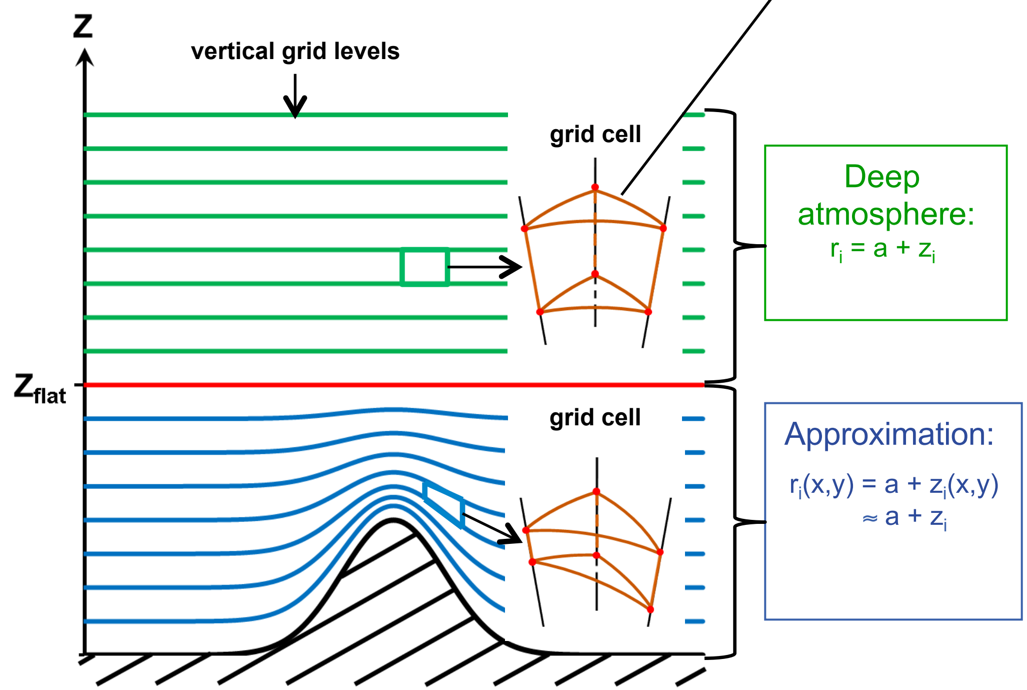
Deep-atmosphere equations

- For efficiency: terms corrected for deep atmosphere by *metrical correction factors* computed once during initialization
- Terrain-following coordinates would require correction factors to depend not only on $\mathbf{z}$, but also on $\mathbf{x}$ and $\mathbf{y}$
  - Considerably higher memory costs
  - Severe, error-prone operation on dynamical core
  - Additional run-time costs have to be minimal: especially important for NWP
- Approximation below $\mathbf{z_{flat}}$: Deep-atmosphere corrections assume flat topography

Flux divergence

$$\frac{1}{V_{\mathrm{cell}}}\int_{V_{\mathrm{cell}}} \nabla \cdot \boldsymbol{F}\,\mathrm{d}V = \frac{1}{V_{\mathrm{cell}}}\oint_{\partial V_{\mathrm{cell}}} \mathrm{d}\boldsymbol{S} \cdot \boldsymbol{F}$$



z_{flat} = 17 km

Current working grid

→ **Horizontal resolution**

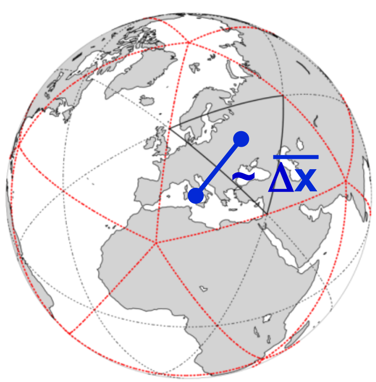
→ *R2B05* → $\overline{\Delta x}$ ~ 80 km*

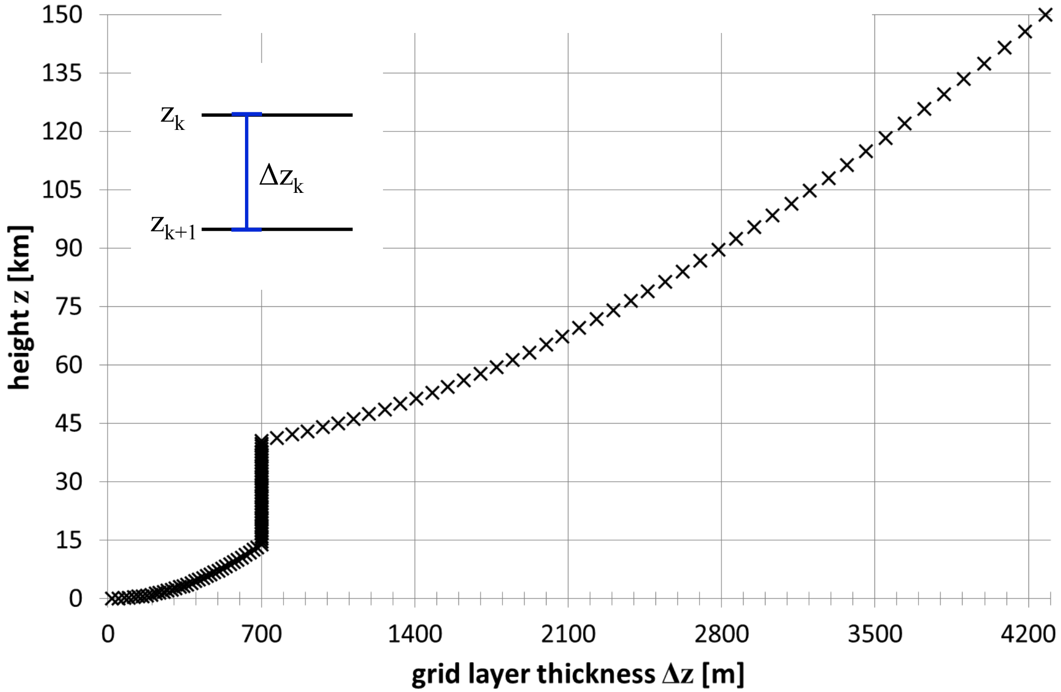
→ *R2B06* → $\overline{\Delta x}$ ~ 40 km

→ **Vertical resolution**

→ Model top at 150 km

→ 120 levels

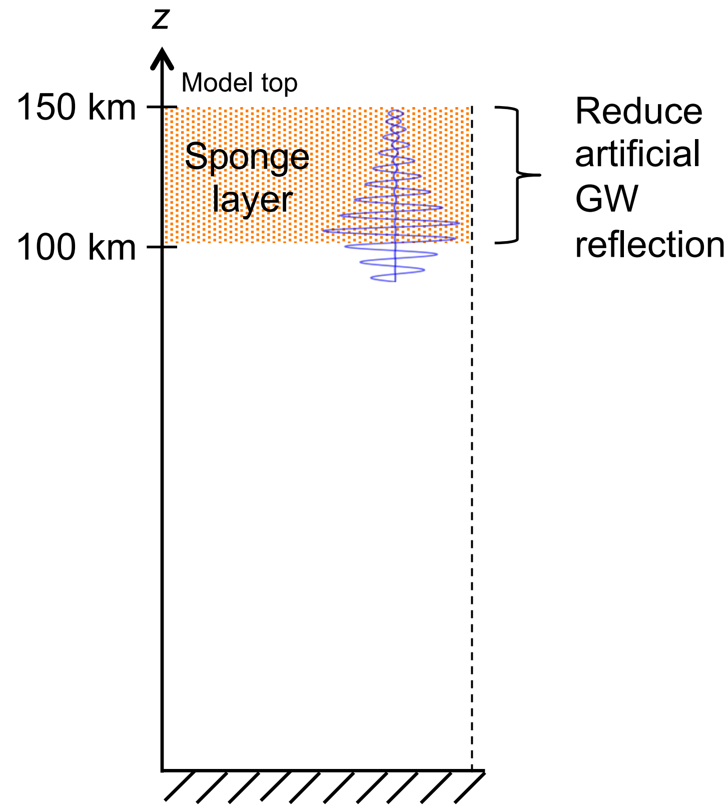




* $\overline{\Delta x} = \sqrt{\bar{a}_{Cell}}$

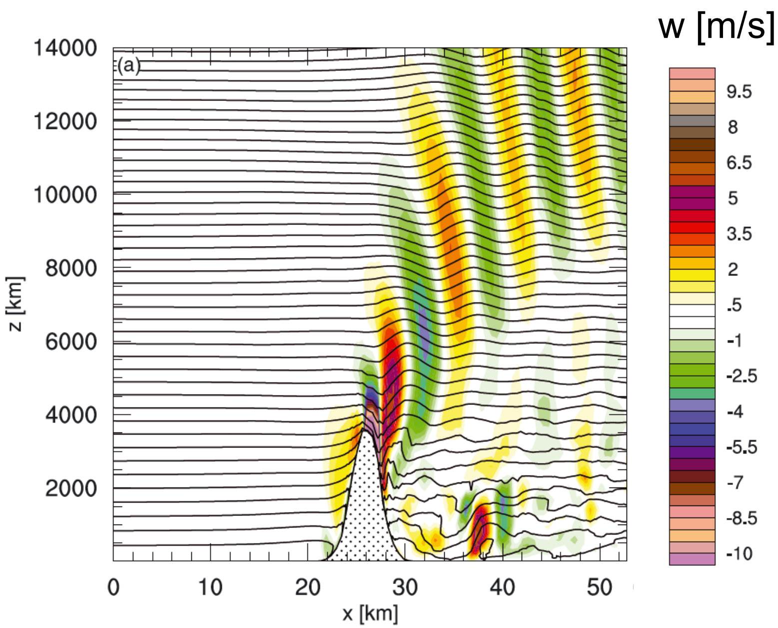
Numerical stability

- **GW reflection at model top can lead to numerical instabilities and model crash: currently prevented by strong (unphysical) Rayleigh damping in sponge layer (after Klemp et al., 2008)**
  - **Simulated state above ~ 100 km not yet reliable**
- **Workaround until upper-atmosphere specific physics with damping effect, such as increased molecular viscosity and ion drag, have been implemented**

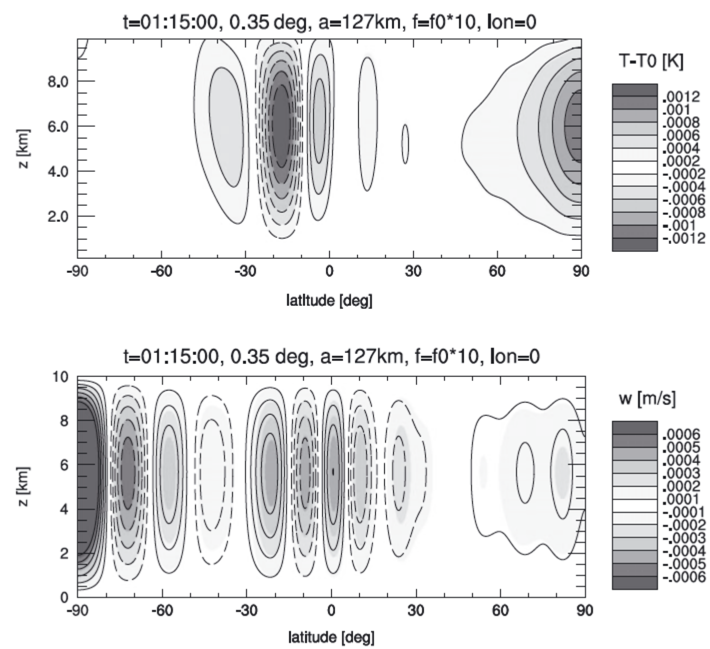


Validation of ICON with focus on GWs

a) Flow over a relatively steep mountain (slope angle ~ 60°) (Zängl et al., 2015)



b) GWs and sound waves from hot bubble: comparison of linear analytical solution (solid/dashed lines) and numerical solution (shaded) (Baldauf et al., 2014)



➔ But analytical(/numerical) benchmark GW-solutions for deep-atmosphere equations unfortunately not yet found in literature

Test case for deep-atmosphere configuration

Modified Jablonowski-Williamson test:
evolution of baroclinic instability on small-Earth (DCMIP test case) (Ullrich et al., 2014)

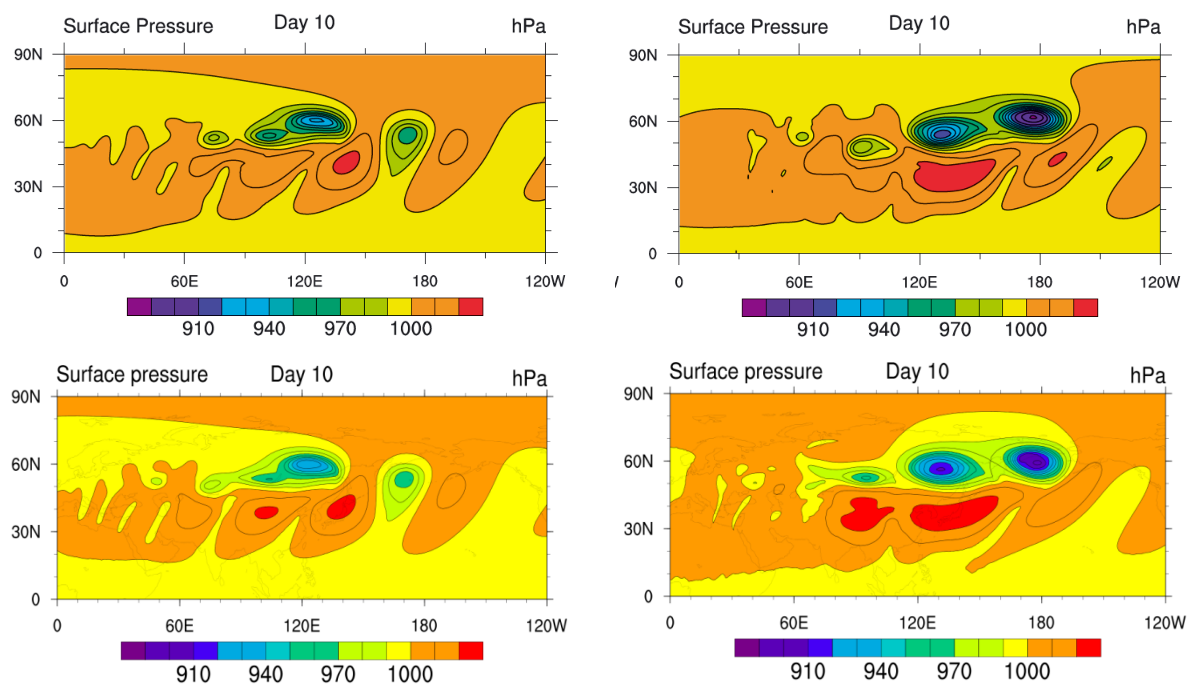
Intensify deep-atmosphere effects by:

- ➔ Radius: $a \rightarrow a/20$
- ➔ Rotation rate: $\Omega \rightarrow 20\Omega$

Shallow atmosphere | **Deep atmosphere**

Benchmark
(numerical solution, Ullrich et al., 2014)

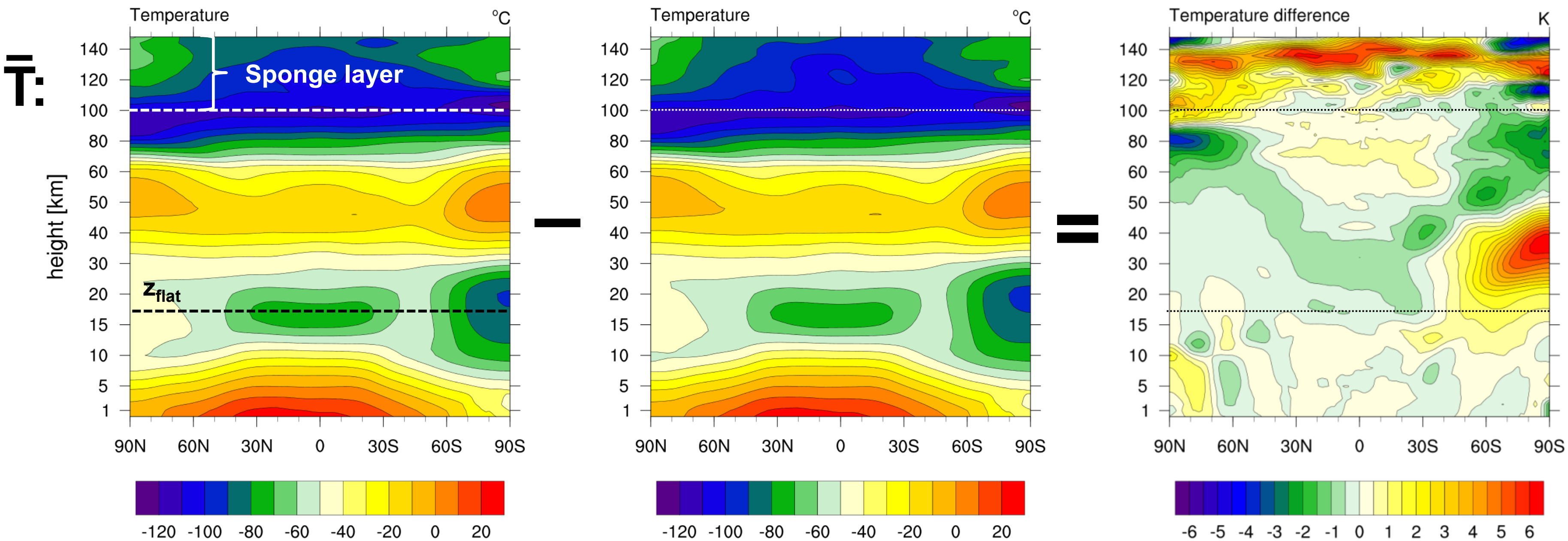
ICON*



*Implementation thanks to Daniel Reinert

First simple attempt to quantify systematic effects of deep atmosphere

➔ Zonal averages from NWP-simulations*
temporally averaged over Aug. + Sep. (6 realizations)



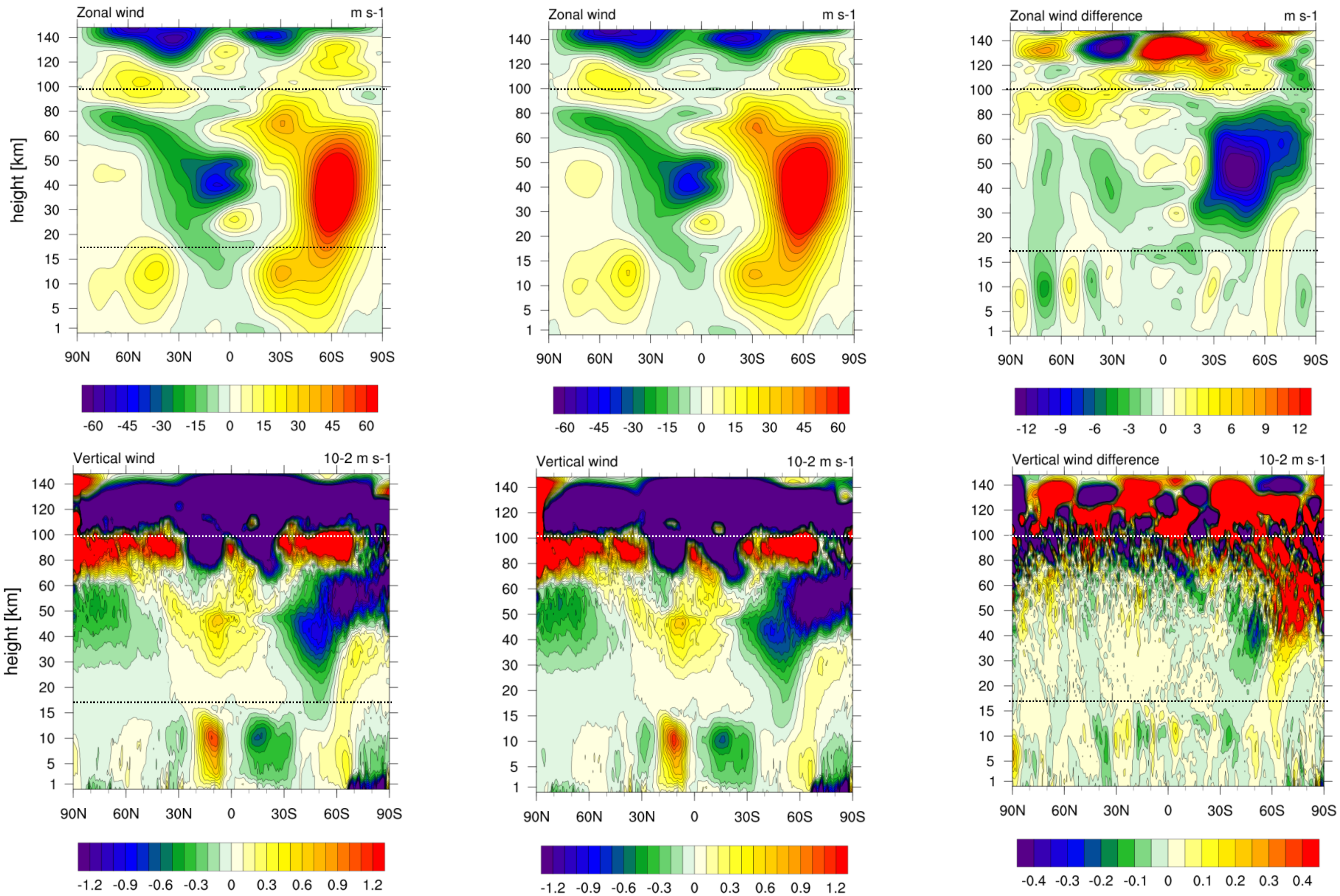
Deep atmosphere | Shallow atmosphere | Difference

*Grid: *R2B06* → Δx ~ 40 km

...

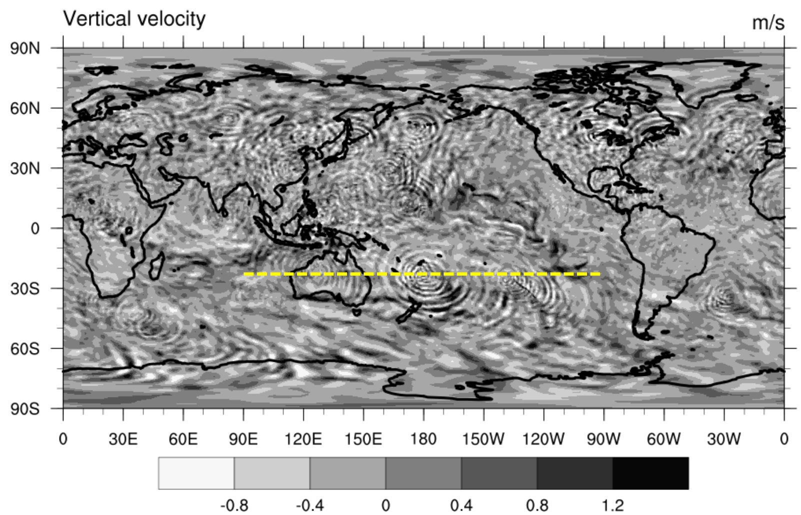
$\bar{u}$:

$\bar{w}$:



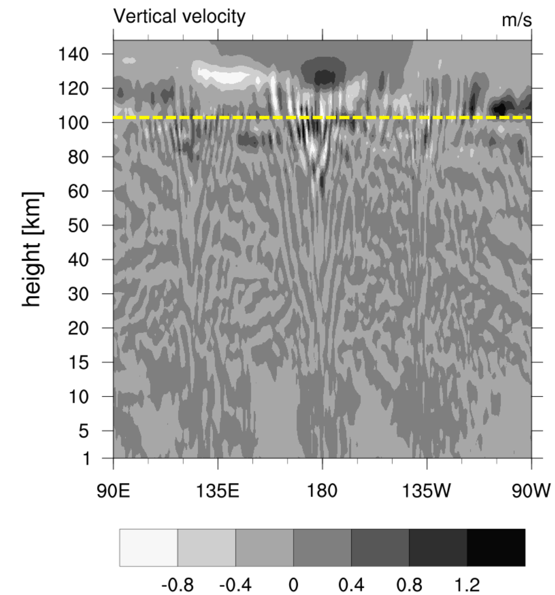
Deep atmosphere | Shallow atmosphere | Difference

Snapshot of GWs in upper atmosphere



$\lambda_h \sim 300$ km

$\lambda_z \sim 15$ km



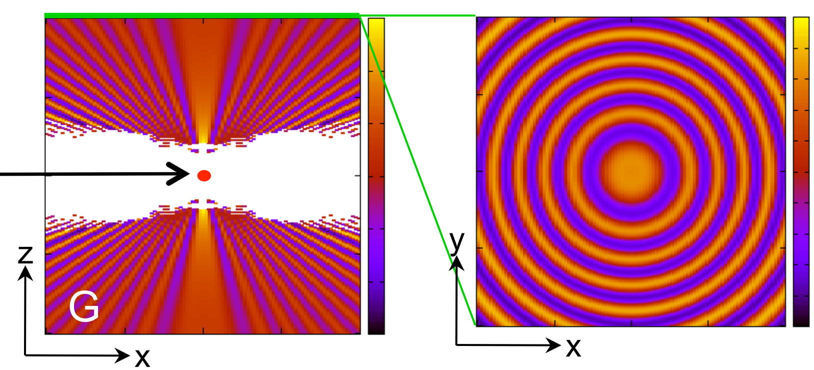
Vertical wind in z = 100 km at 1 September (after 1 simulated month) (following Liu et al., 2014)

Maybe qualitatively (Dickinson, 1969):

$$\frac{\partial}{\partial t}\left[\left(\frac{\partial^2}{\partial t^2}+N^2\right)\nabla_h^2+\left(\frac{\partial^2}{\partial t^2}+f^2\right)\frac{\partial^2}{\partial z^2}\right]G(\mathrm{r},t) = -\alpha\delta(\mathrm{r})\delta(t)$$

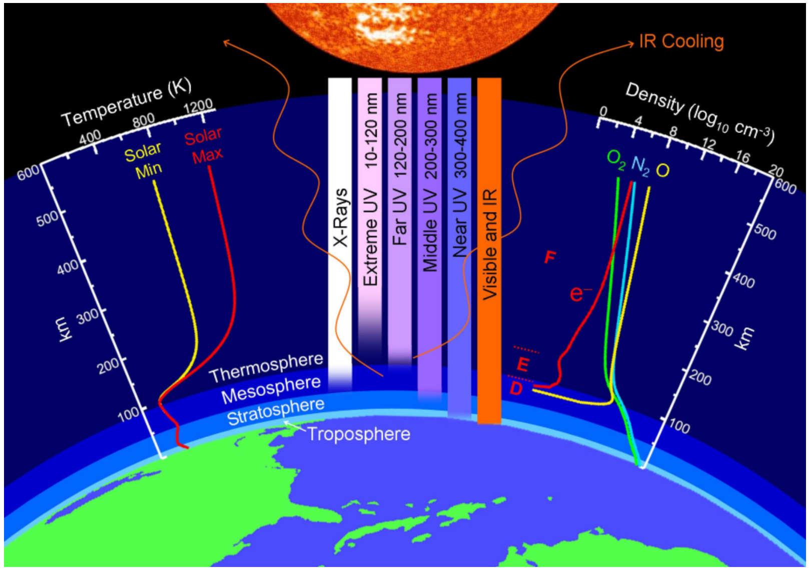
Boussinesq-GW-operator

Approximation of localized GW-emission events (thunderstorms, …)



Physics for UA-ICON (MPI-M*)

- Radiation:
  - Schumann-Runge bands/continuum (O_2)
  - Extreme ultraviolet heating (N_2, O, O_2)
  - Non-LTE infrared heating (CO_2, NO, O_3)
- Molecular diffusion and conduction
- Ion drag/Joule heating
- Chemical heating
- Adjustment of GW parameterization



Source: science.nasa.gov

*by Guidi Zhou, Hauke Schmidt & Elisa Manzini

Outlook

- ➔ ICON contains ECHAM-physics (tailored for climate projections, MPI-M) and NWP-physics (tailored for operational NWP, DWD)
  - ➔ Upper-atmosphere physics are first implemented and tested in ECHAM
  - ➔ Afterwards we transfer them to the NWP-physics (requires thorough testing for additional computational costs/run-time neutrality, since new implementations must not adversely affect operational use)
- ➔ Evaluation of upper-atmosphere physics and dynamics by comparison of large-scale circulation e.g. with HAMMONIA-climatology
- ➔ First comparison with measurements (e.g. lidar and radar)
- ➔ Episodic simulations of campaigns (e.g. DEEPWAVE)

Have a look at poster:
"*Gravity wave momentum flux simulated by the ICON model at gravity wave permitting resolution*"
by Guidi Zhou

Thank you!

References:

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