Towards a transient gravity wave drag parameterization in atmospheric models

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Motivation

- State-of-the-art gravity wave (GW) parameterizations: *steady-state* approximation → resolved flow forcing only via wave breaking and critical layers
- Removing the steady-state approximation → *transient* modeling of GWs: *direct GW-mean-flow interaction*
- Topic #1: relative importance of wave breaking and direct GW-mean-flow interactions with respect to the forcing of the resolved flow in idealized studies
- Topic #2: implementation of a transient GW parameterization in the ICON GCM including direct GW-mean-flow interactions

Phase-space representation

$$\mathcal{N}(z,m,t) = \int_R \mathcal{A}_\alpha(z,t)\delta[m - m_\alpha(z,t)]d\alpha$$

$$\mathcal{A}(z,t) = \int_{-\infty}^{\infty} \mathcal{N}(z,m,t)dm$$

$$\frac{d\mathcal{N}}{dt} = 0 \quad \left(\frac{d}{dt} = \frac{\partial}{\partial t} + c_{gz}\frac{\partial}{\partial z} + \dot{m}\frac{\partial}{\partial m}\right) \quad \textbf{Wave field}$$

$$\frac{\partial u_b}{\partial t} = -\frac{1}{\bar\rho}\frac{\partial}{\partial z}\int_{-\infty}^{\infty} k c_{gz}\mathcal{N}(z,m,t)dm \quad \textbf{Mean-flow}$$

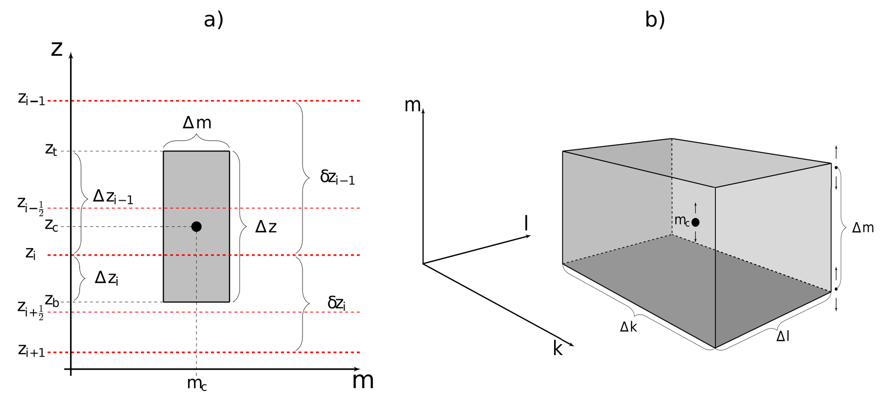

Fig. 1 *GW ray volumes as represented in phase-space*

Direct GW-mean-flow interactions: coupled ray-tracing equations

Theory

- Split up the flow into a mean and a wave part: $f = f_m + f_w$
- Assume scale separation between the two: $H_w/H_m = \epsilon << 1$
- $f_w(x,z,t) = \mathrm{Re}F_w(Z,T)e^{i[kx + \frac{\phi(Z,T)}{\epsilon}]}$ with $X = \epsilon x, Z = \epsilon z$
- Insert the above in the governing eqs. and order terms equal in $\mathcal{O}(\epsilon)$

Wave field

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

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

$$\frac{d\mathcal{A}}{dt} = -\mathcal{A}\frac{\partial c_{gz}}{\partial z}$$

Mean-flow

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

$$\left(\frac{d}{dt} = \frac{\partial}{\partial t} + c_{gz}\frac{\partial}{\partial z}\right)$$

(Grimshaw et al., 1975, Achatz et al., 2017)

Idealized study with a toy model

(Bölöni et al., 2016)

- MS-GWaM: Multi Scale Gravity Wave Model including direct GW-mean-flow interactions (above equations) and wave breaking
- Idealized validation of *transient* vs. the classical *steady-state* GW parameterization against (2D) LES simulations
- Direct GW-mean-flow interaction more important than wave breaking
- Wave breaking adds a second order correction
- Steady-state scheme (including only wave breaking) predicts false induced wind structure

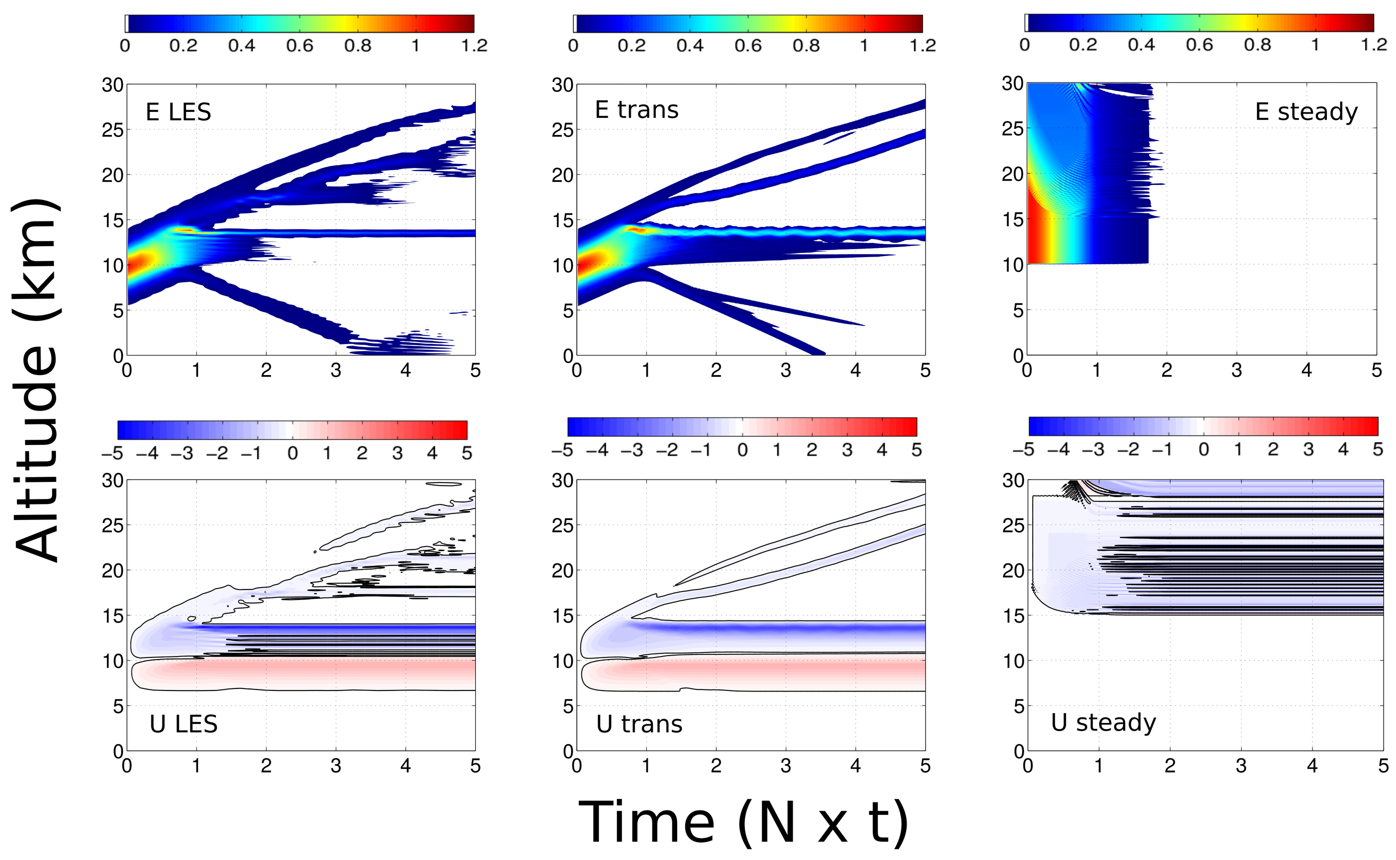

Fig. 2 *idealized Gaussian wave packet, numerical simulations of a reference wave resolving LES (left column), a transient GW parameterization with direct GW-mean-flow interactions (middle column) and a steady-state GW parameterization (right column). 1^{st} row: Hovmöller diagrams for wave energy, 2^{nd} row: Hovmöller diagrams for induced mean-flow.*

Implementation in the ICON Global Circulation Model

- Implementation in the ICON model (Zängl et al., 2015) and its upper-atmosphere version (UA-ICON, Borchert et al., 2018)
- Single-column implementation of MS-GWaM (transient scheme), ST-MS-GWaM (steady-state scheme), STMO-MS-GWaM (steady-state scheme with monochromatic saturation)
- MS-GWaM: $\Delta t \sim 60s$ + RK4 sub-steps for ray volume propagation
- ~ 2500 ray volumes/column (launching, merging, removing)
- Simple non-orographic sources based on the Desaubies spectrum: $\rho \overline{u'w'}(\hat{c},\phi) \to \rho\overline{u'w'}(k,l,m) \to \mathcal{N}(k,l,m)$ (lower boundary condition, see Fig. 3-4)
- Simulations with a model top at $150km$ (sponge above $110km$), with a vertical resolution $\Delta z \approx 700m$ in the stratosphere and coarser above, horizontal resolution "Δx" $\sim 160km$
- 9 months perpetual Dec and June simulations, 1991-1998 Dec, June (URAP period), 2010-2015 Dec, June
- Zonal mean circulation of transient and steady-state schemes rather similar but with some small-magnitude significant differences (see Fig. 5)
- GW momentum flux intermittency is increased by the transient scheme leading to a better match with balloon observations (see Fig. 6)
- Transience might correct for part of the "missing drag" at $\sim 60^oS$ (see Fig. 7)

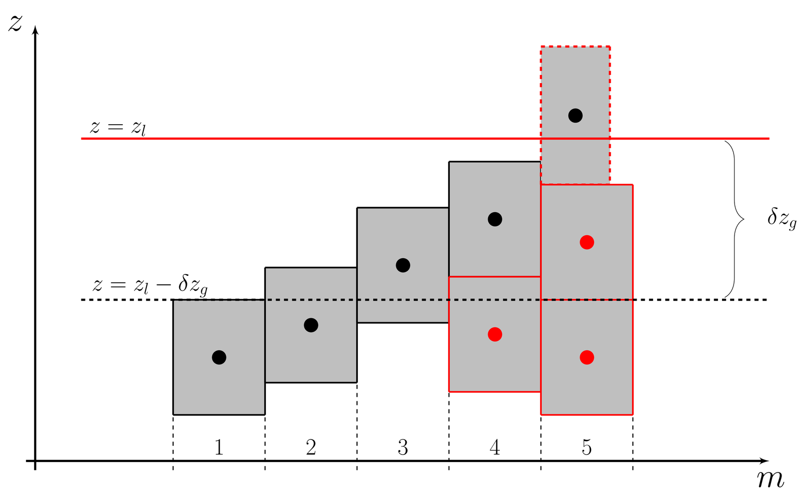

Fig. 3 *GW source implemented as lower boundary condition in MS-GWaM's ray model*

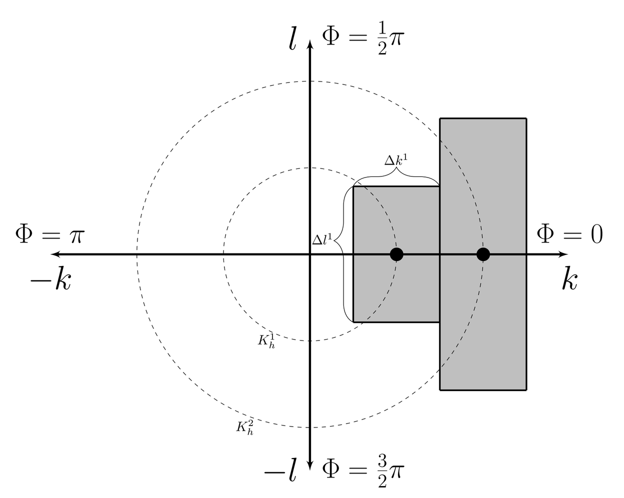

Fig. 4 *Definition of horizontal wavenumbers and the ray volume size in MS-GWaM's ray model*

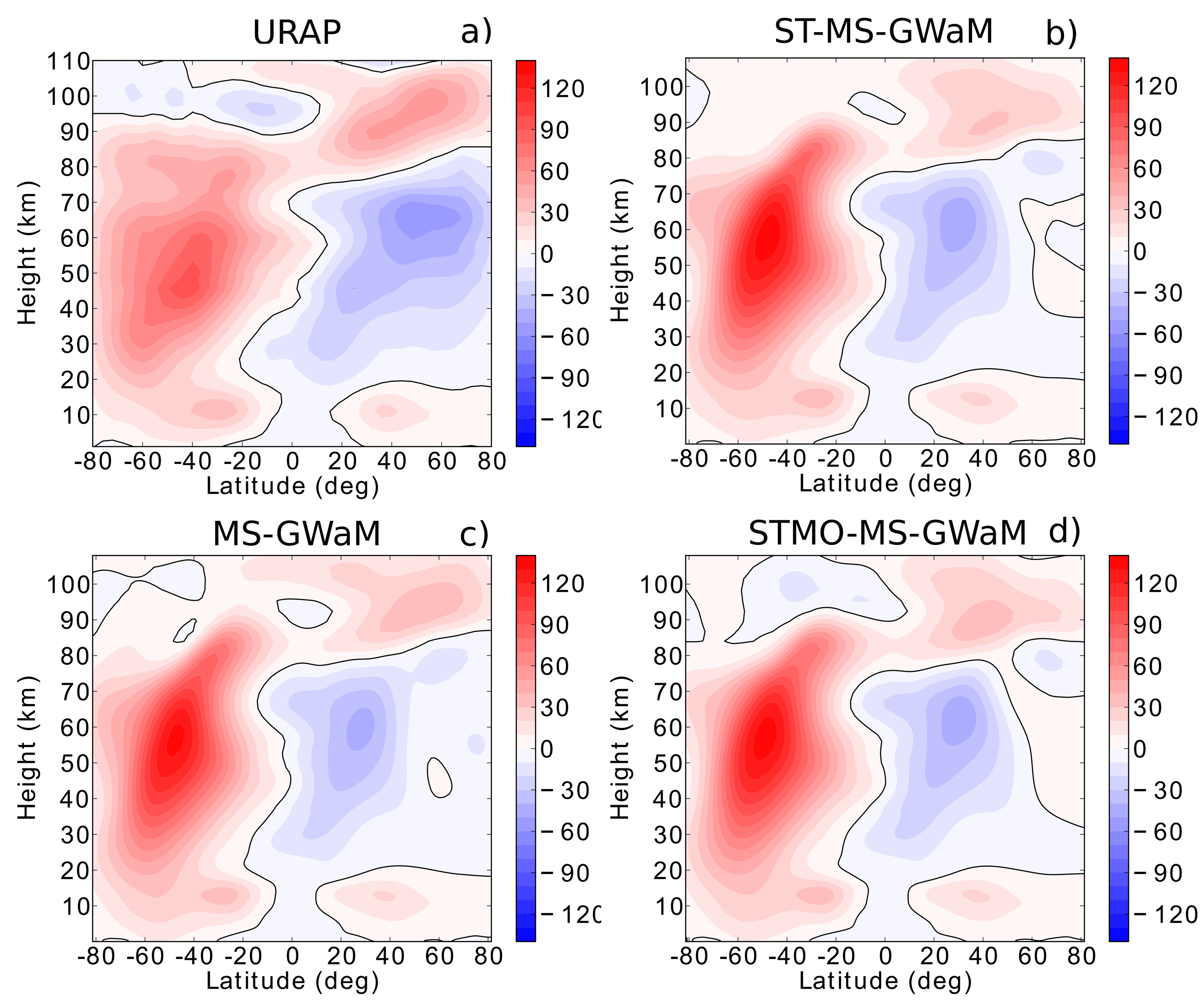

Fig. 5 *Latitude-height cross-section of zonally averaged zonal wind for a) URAP data, b) ICON ST-MS-GWaM (steady-state scheme), c) ICON MS-GWaM (transient scheme), d) ICON STMO-MS-GWaM (steady-state scheme with monochromatic saturation)*

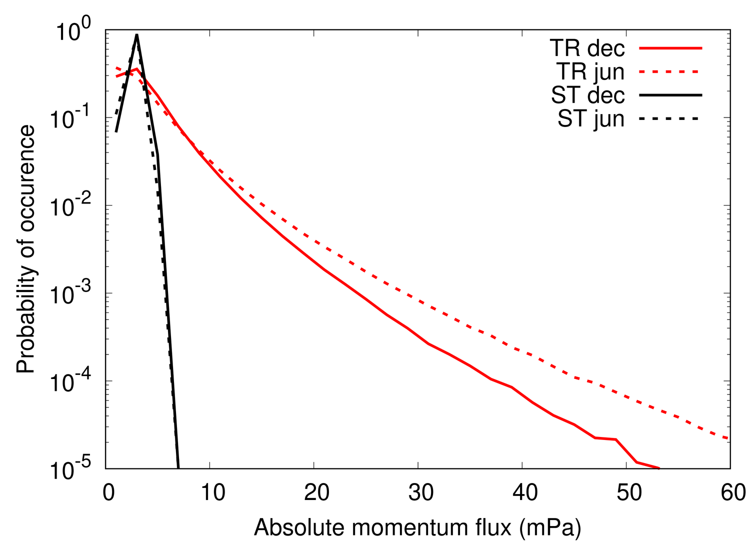

Fig. 6 *Intermittency of GW momentum fluxes at $z \approx 20km$ between $50^oS - 65^oS$*

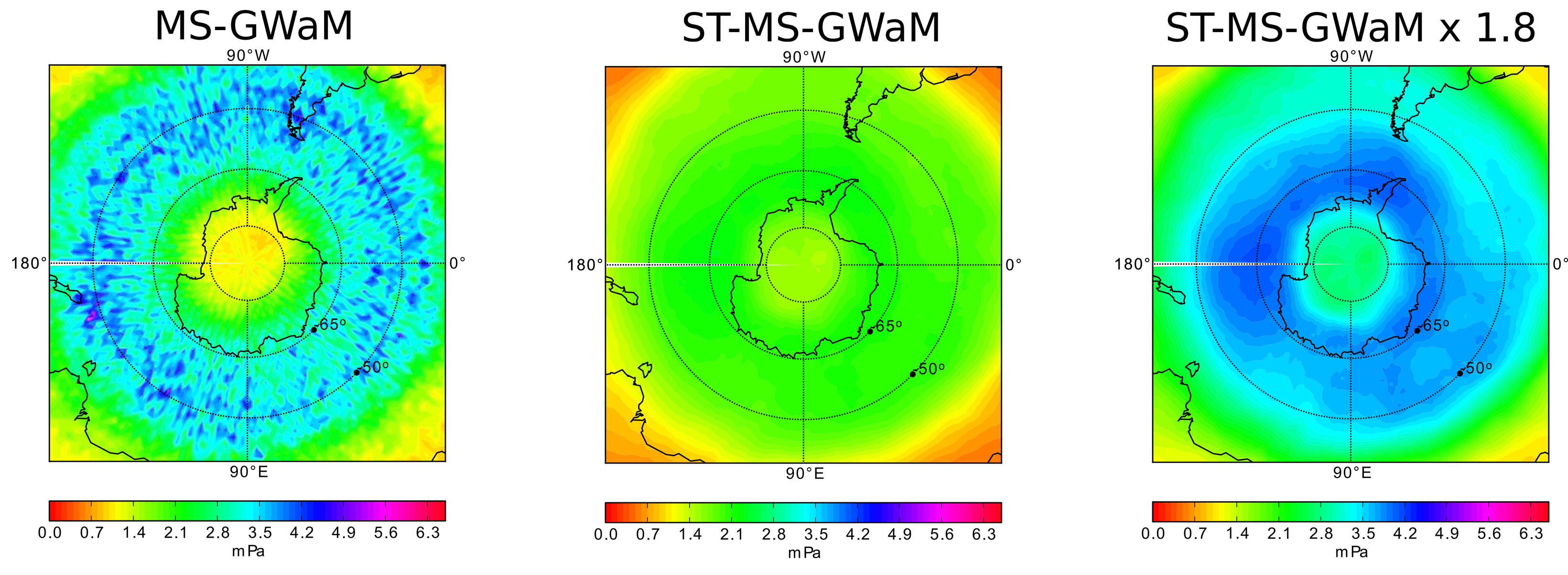

Fig. 7 *Zonal mean GW momentum fluxes over the Southern Hemisphere averaged over 8 individual Junes at $z \approx 40km$ as simulated by MS-GWaM (left), ST-MS-GWaM (middle), ST-MS-GWaM x 1.8 (right)*

Summary & Outlook

- A new transient GW drag parameterization proposed (Multi Scale Gravity Wave Model: MS-GWAM)
- MS-GWAM implementation in ICON: realistic zonal mean circulation, improved GW intermittency
- Missing pieces from the transient modeling puzzle: 1D → 3D propagation, pseudo-momentum flux → momentum fluxes + buoyancy fluxes (Wei et al., 2019), physical GW sources

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