Atmospheric gravity waves and their influence on weather and climate: Challenges and new approaches

U. Achatz, G.S. Völker, Y.-H. Kim, G. Bölöni, J. Muraschko, M. Fruman (all GU Frankfurt),
R. Klein (FU Berlin) & …

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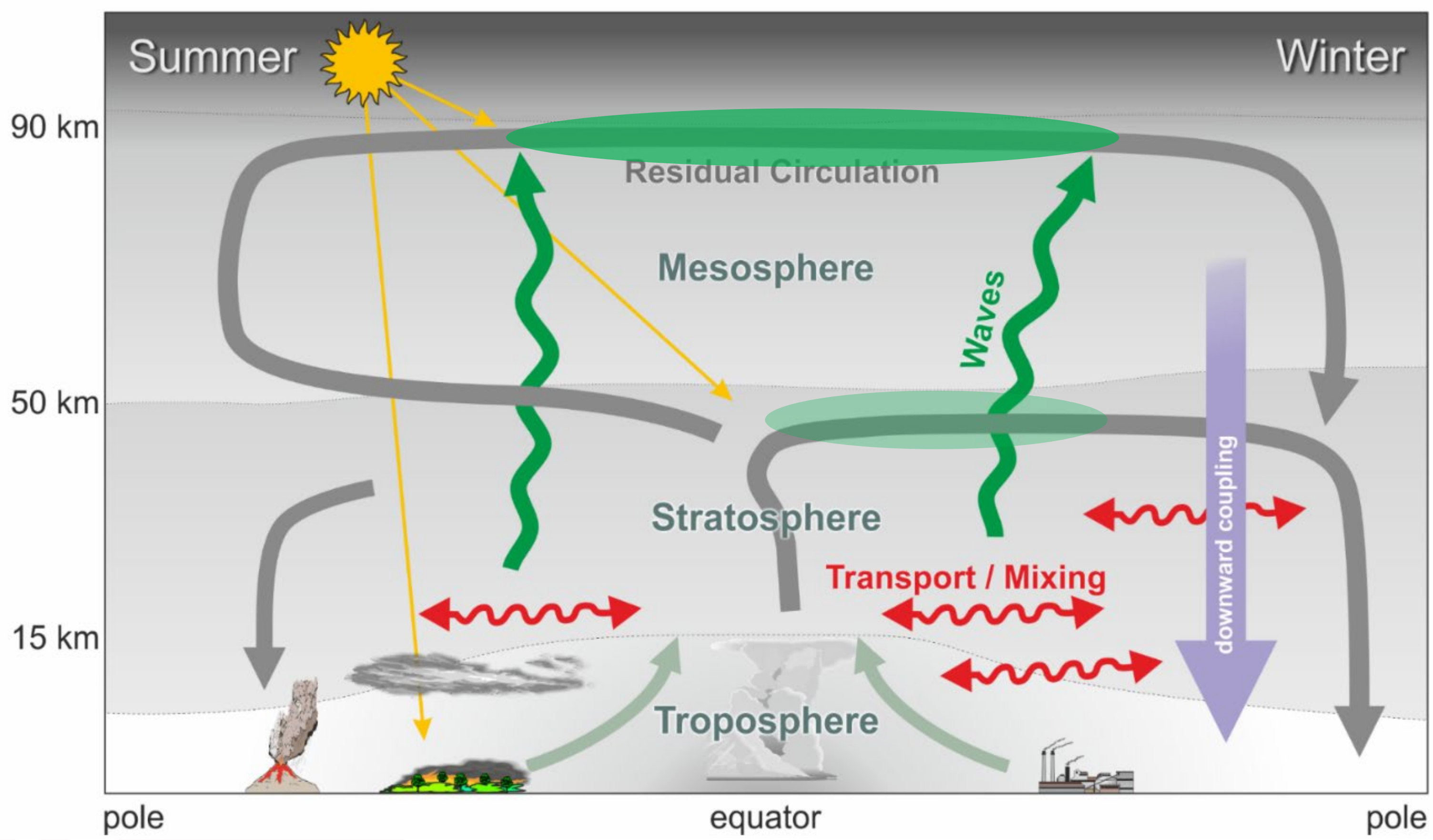
Atmospheric Gravity Waves: Impacts & Issues

Atmospheric GWs:
Impacts and issues

- Rossby-wave and **GW breaking** force the **Brewer-Dobson circulation**



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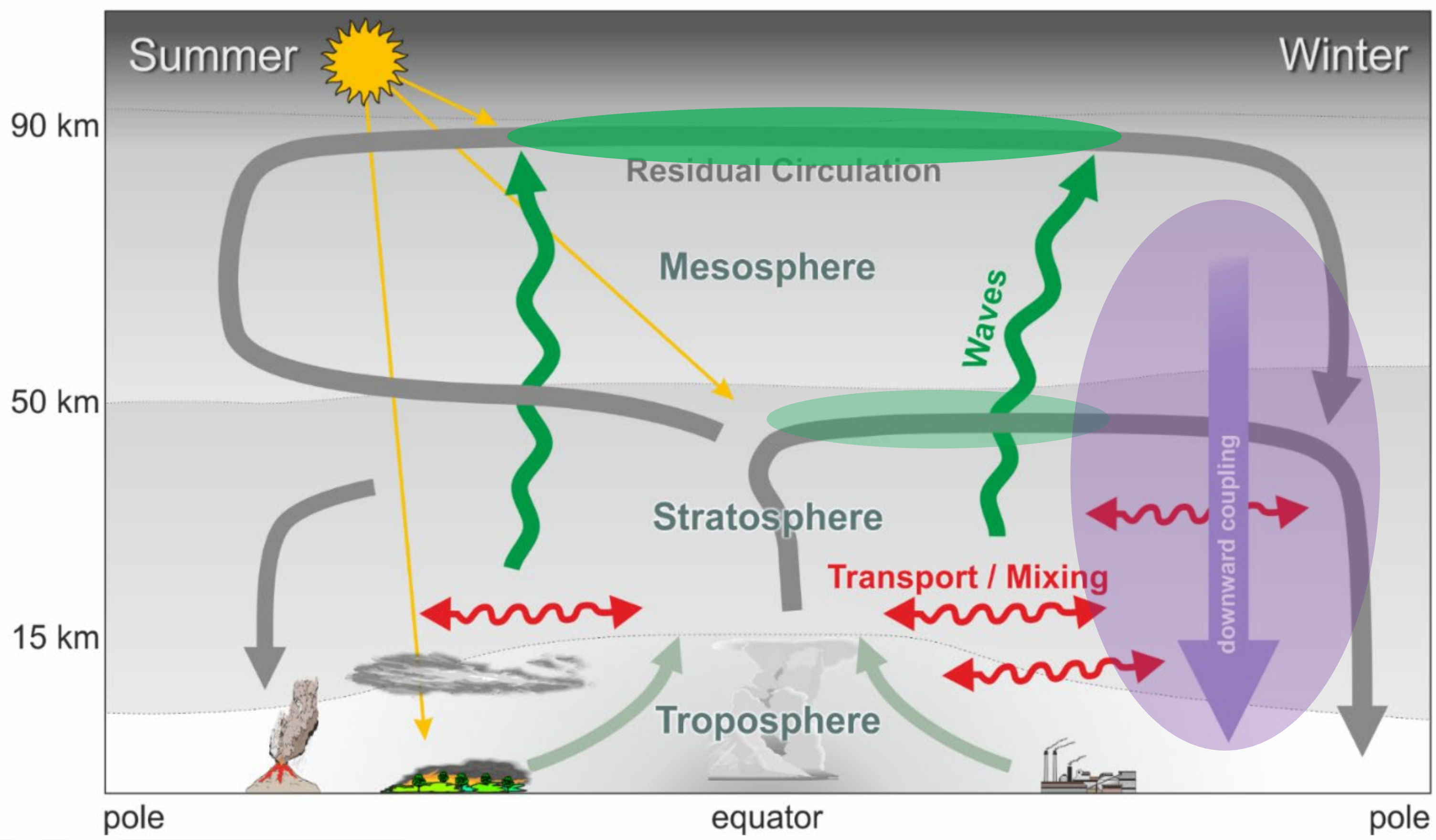
- **Downward control:** Middle atmosphere influences tropospheric climate (Haynes et al 1991)



Atmospheric GWs:
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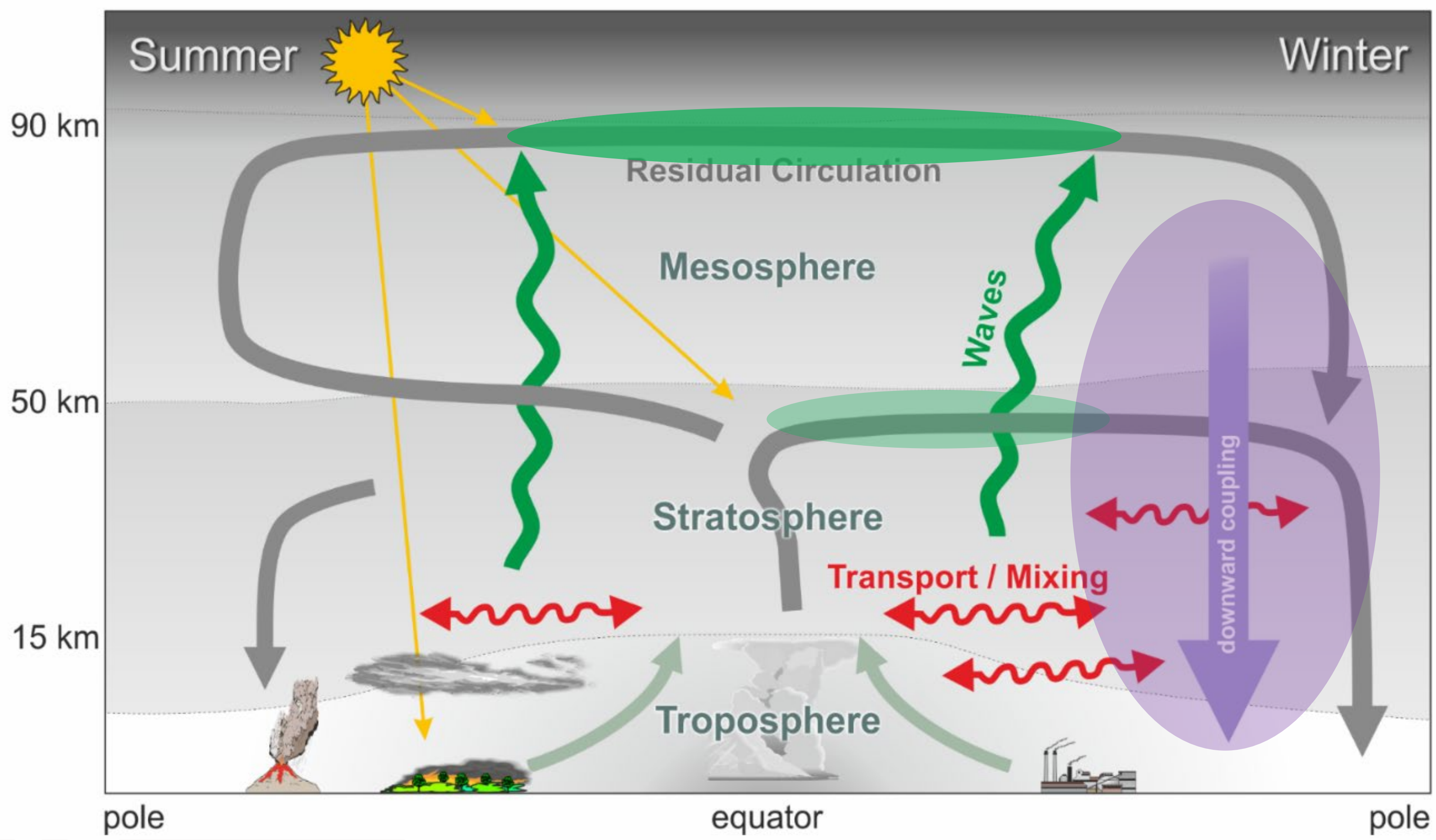
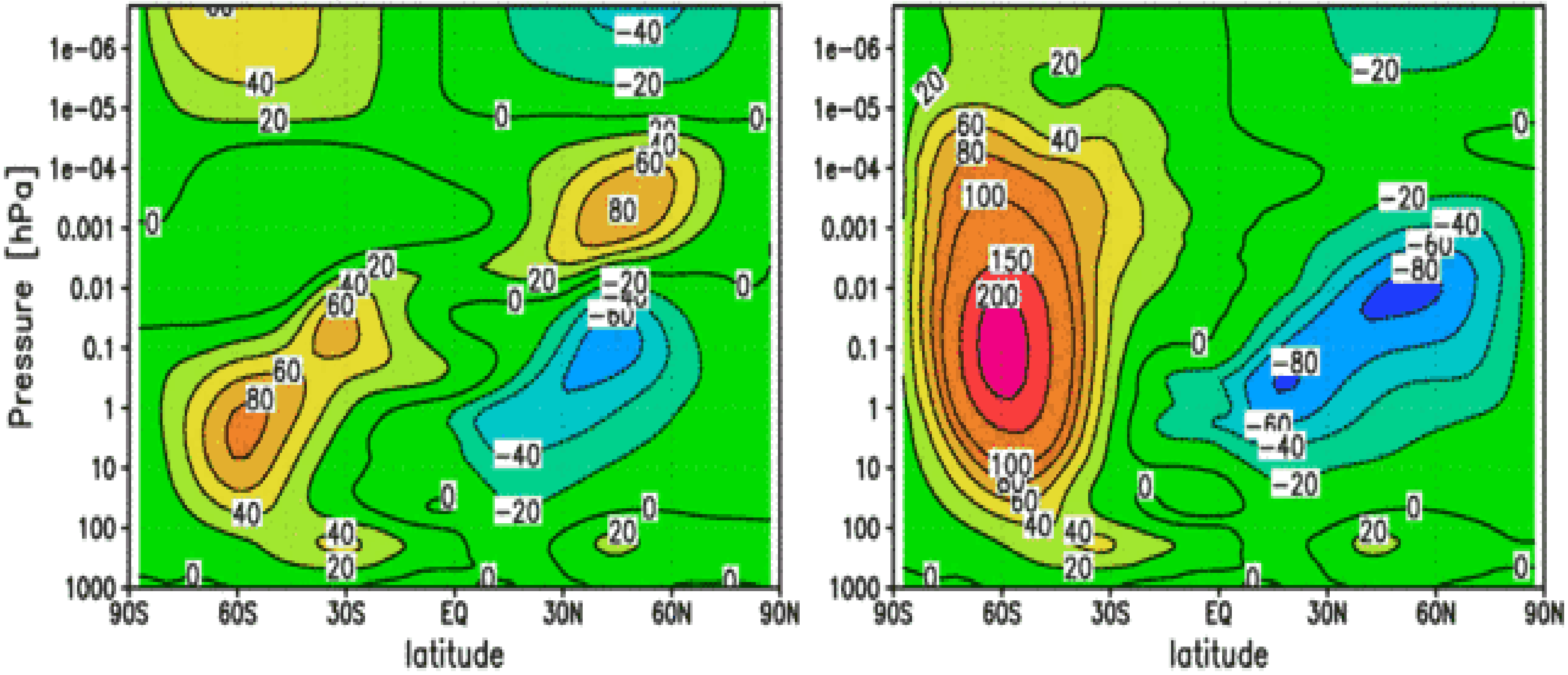
- Rossby-wave and **GW breaking** force the **Brewer-Dobson circulation**
- **Downward control:** Middle atmosphere influences tropospheric climate (Haynes et al 1991)
- BDC under **climate change**: Impact from GWs (Butchard 2014)



Atmospheric GWs:
Impacts and issues

Zonal-mean zonal winds (westerlies)



With GW parameterization

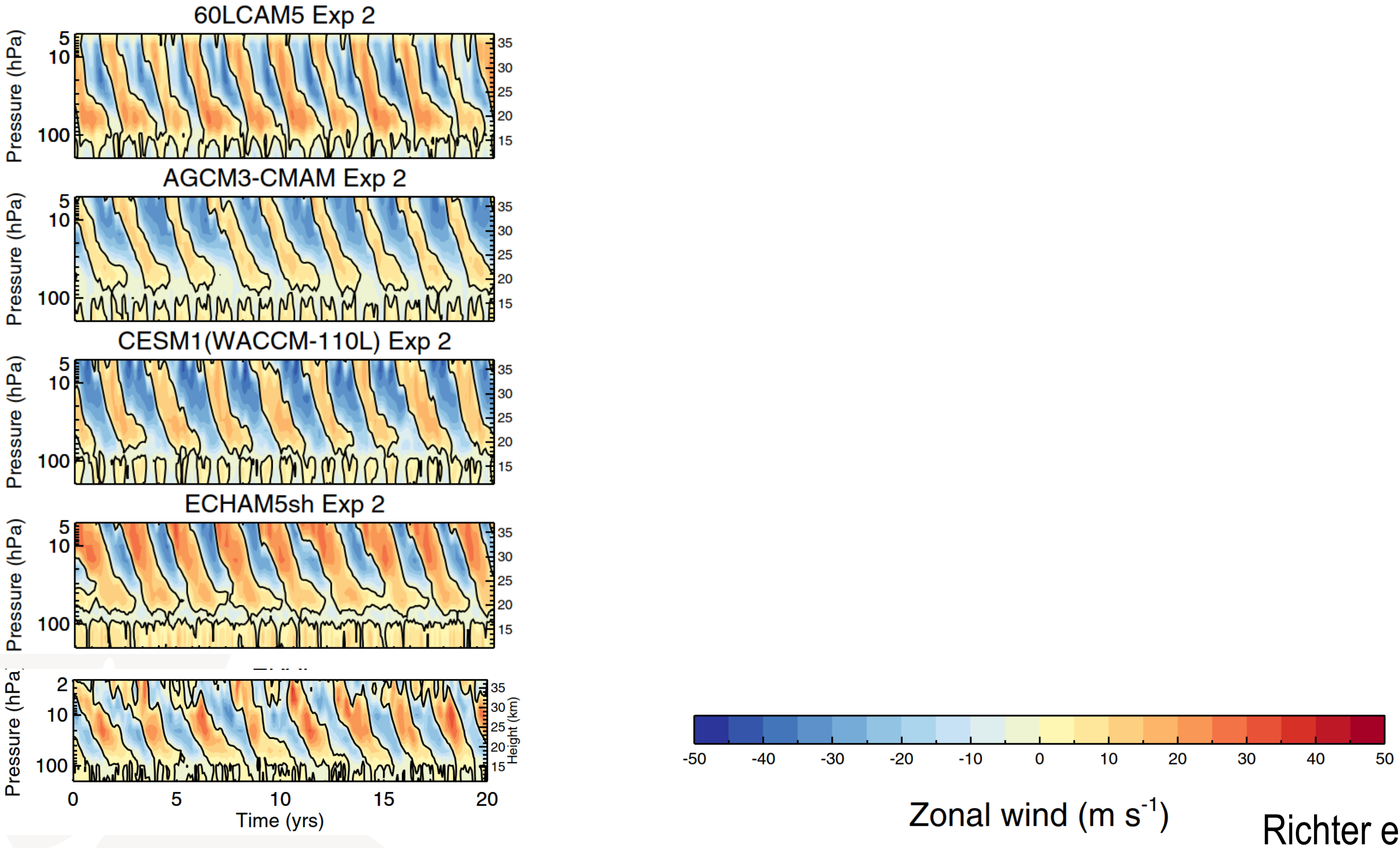
Without GW parameterization

Schmidt et al (2006)

Atmospheric GWs:
Impacts and issues

Quasi-Biennial Oscillation (QBO) of zonal-mean zonal wind over the equator:

Unperturbed climate



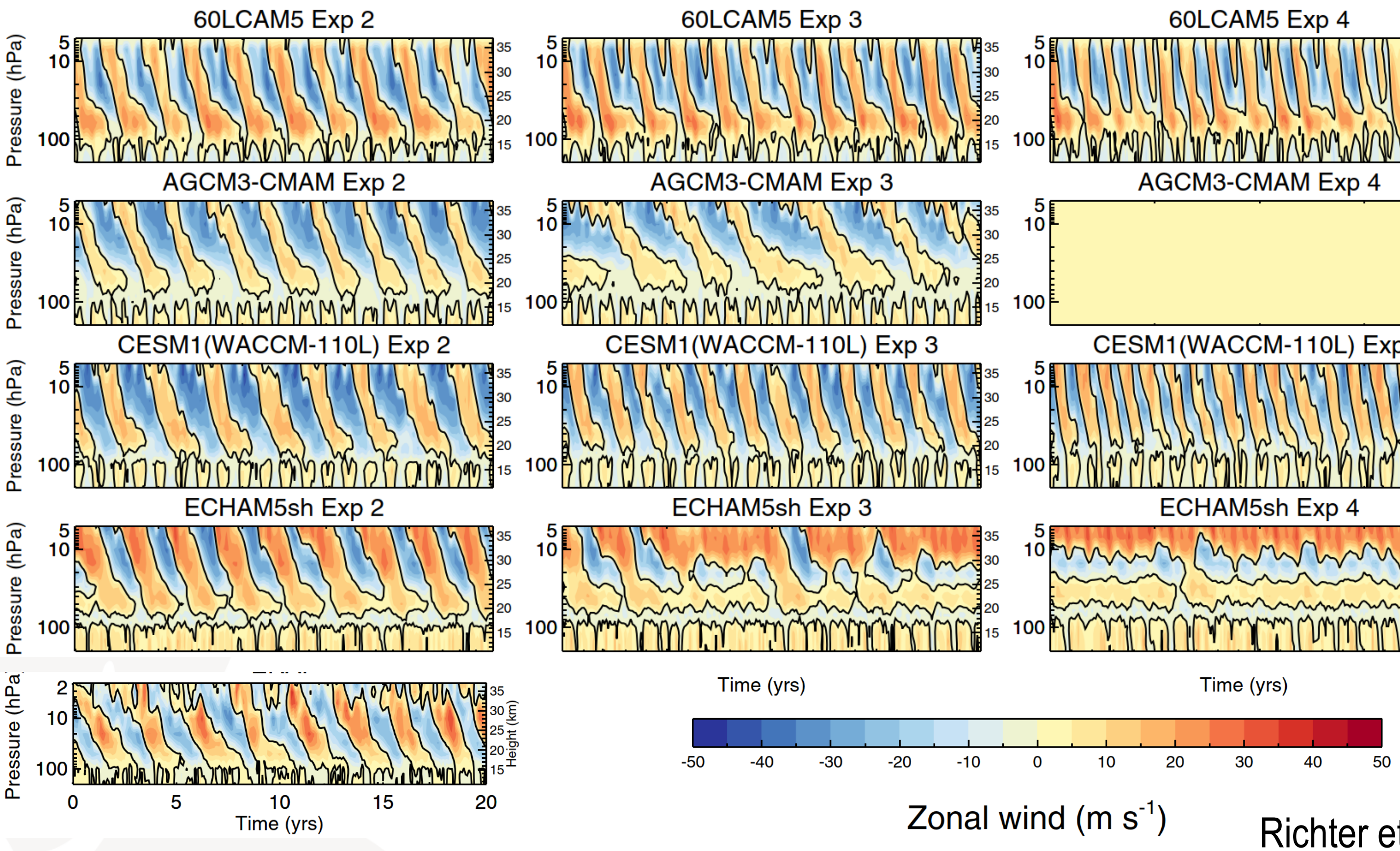
Richter et al (2020)

Atmospheric GWs:
Impacts and issues

Quasi-Biennial Oscillation (QBO) of zonal-mean zonal wind over the equator:

Model predictions for QBO under **climate change** (Schirber et al 2014, Richter et al 2020)

Unperturbed climate | 2 x CO_2 | 4 x CO_2



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Atmospheric GWs: Impacts and issues

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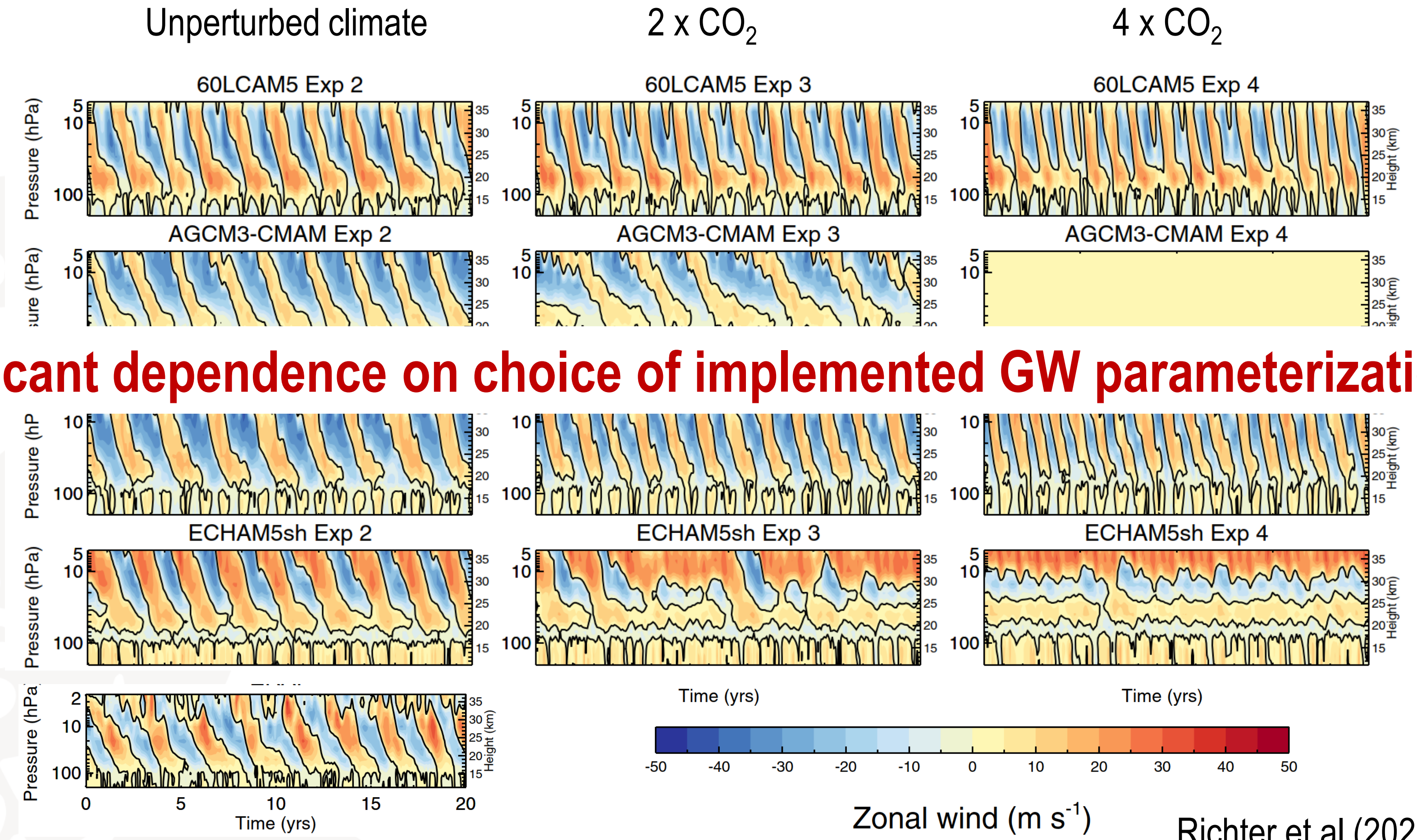


Unperturbed climate

2 x CO_2

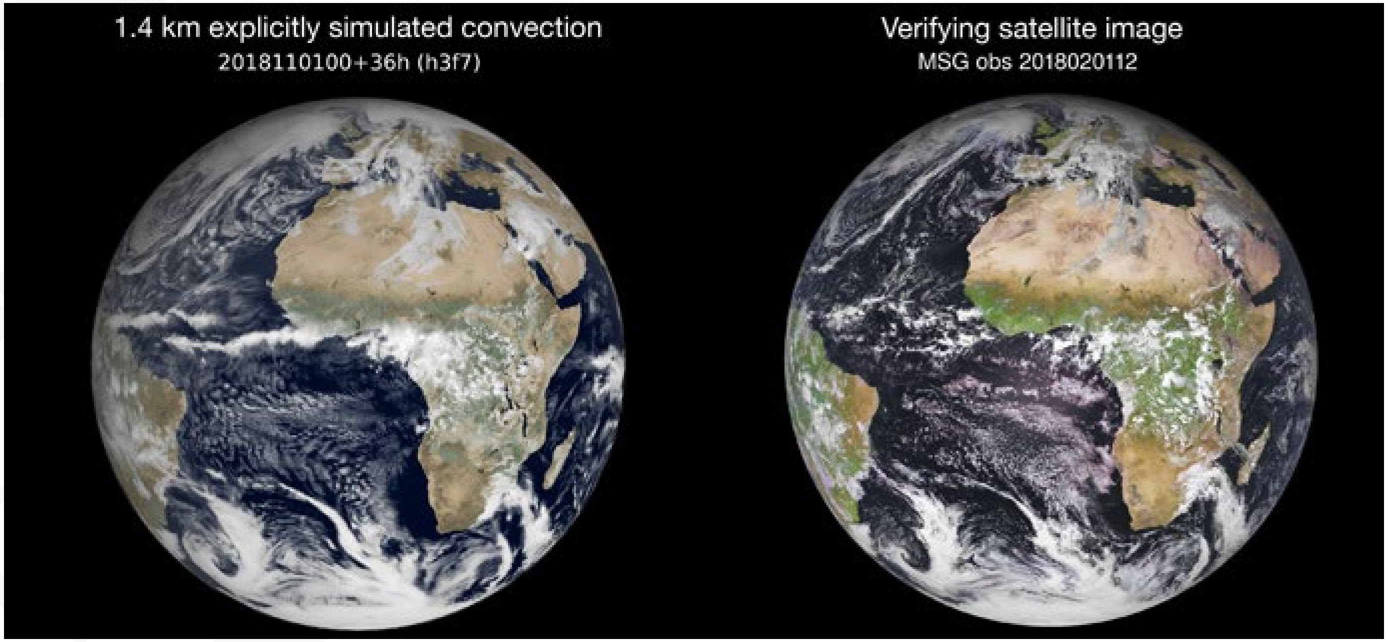
4 x CO_2

Significant dependence on choice of implemented GW parameterization

Richter et al (2020)

Atmospheric GWs:
Impacts and issues

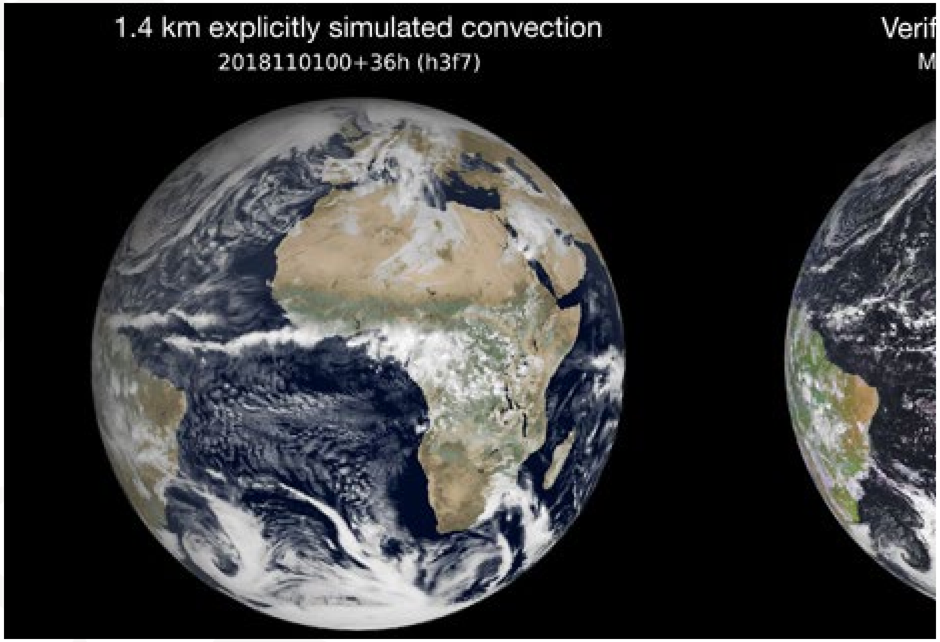
Try and resolve everything?



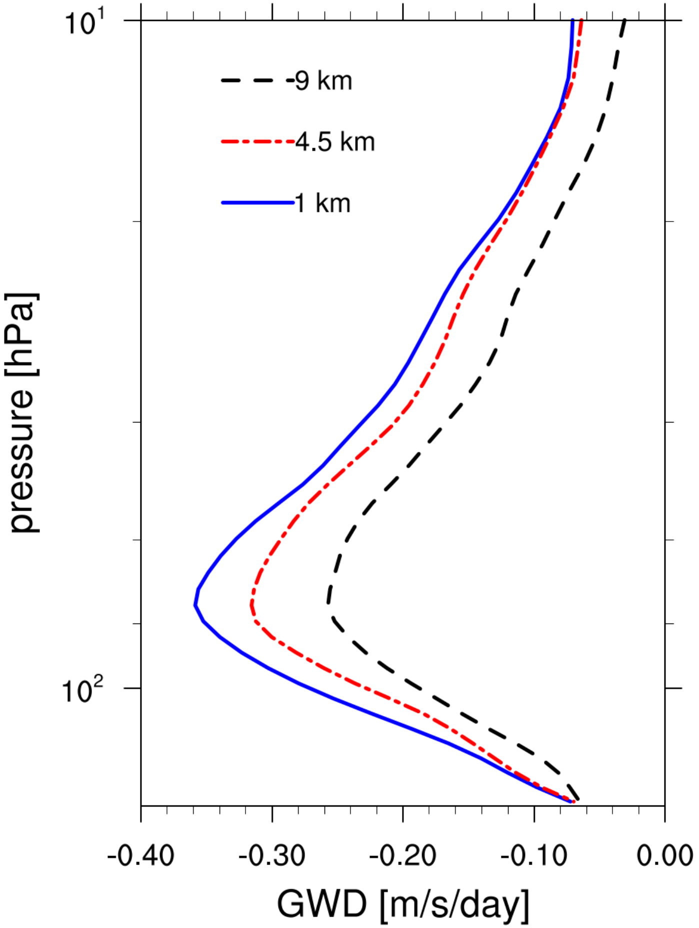
Atmospheric GWs:
Impacts and issues

Try and resolve everything?

- **No convergence** at accessible resolutions (e.g. Polichtchouk et al 2022)



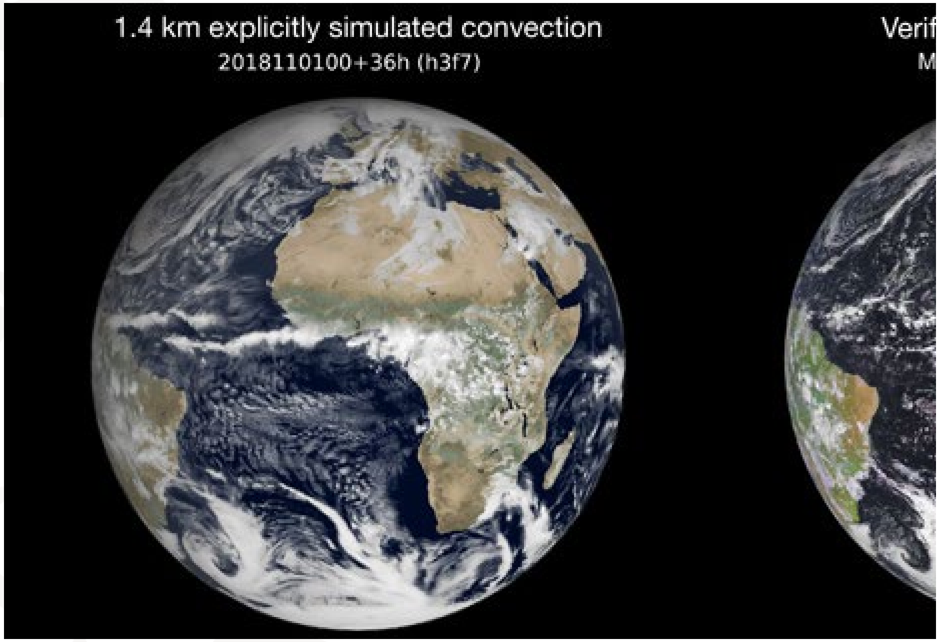
GWD 20°N – 80°N (Polichtchouk et al 2022)



Atmospheric GWs:
Impacts and issues

Try and resolve everything?

- **No convergence** at accessible resolutions (e.g. Polichtchouk et al 2022)
- **Model hierarchy** needed for conceptual understanding (Held 2005)



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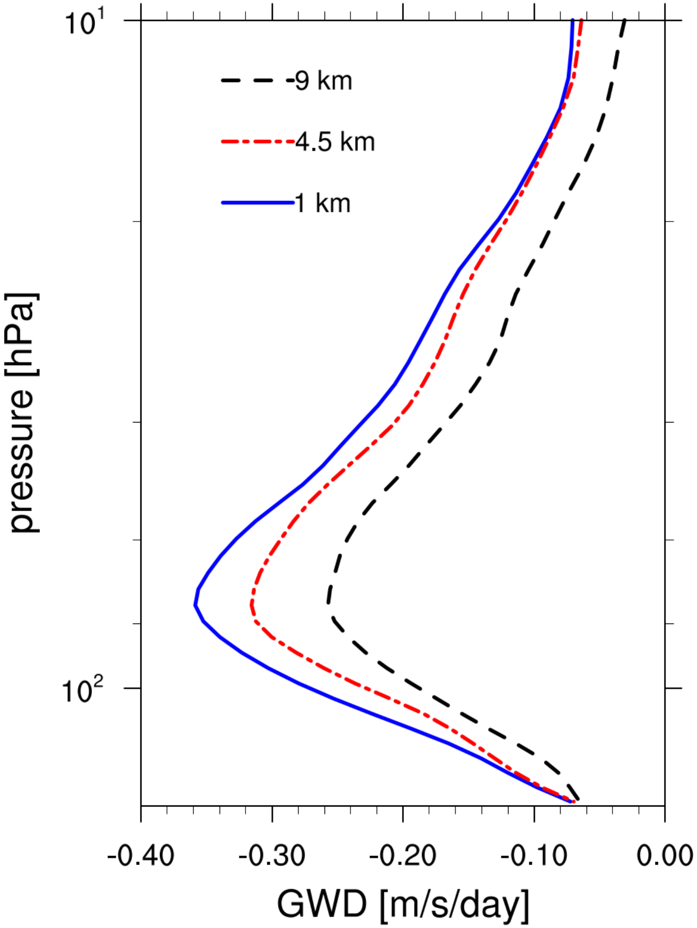
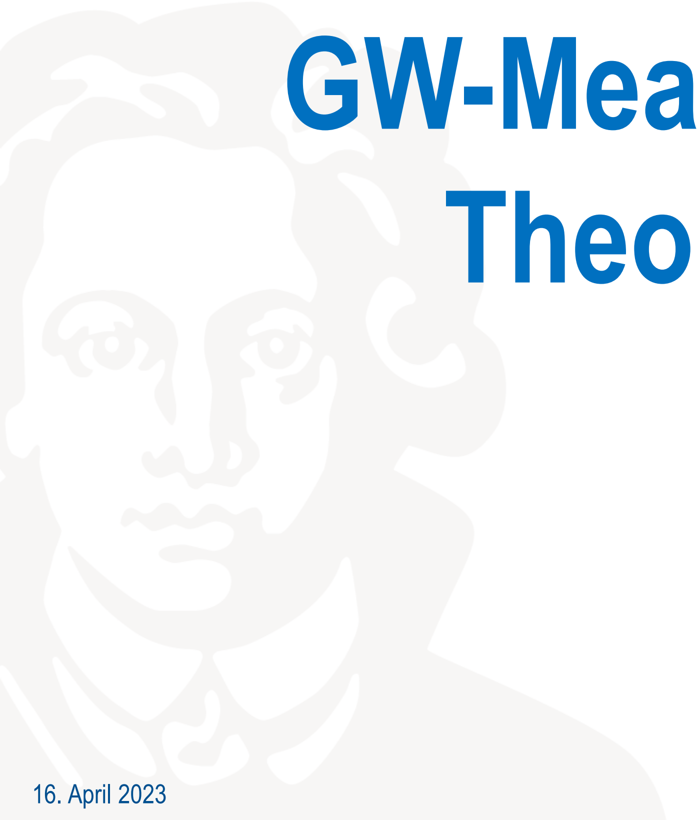
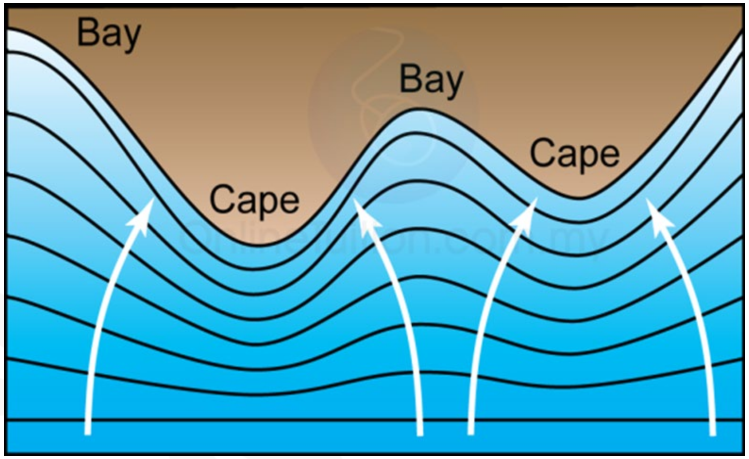




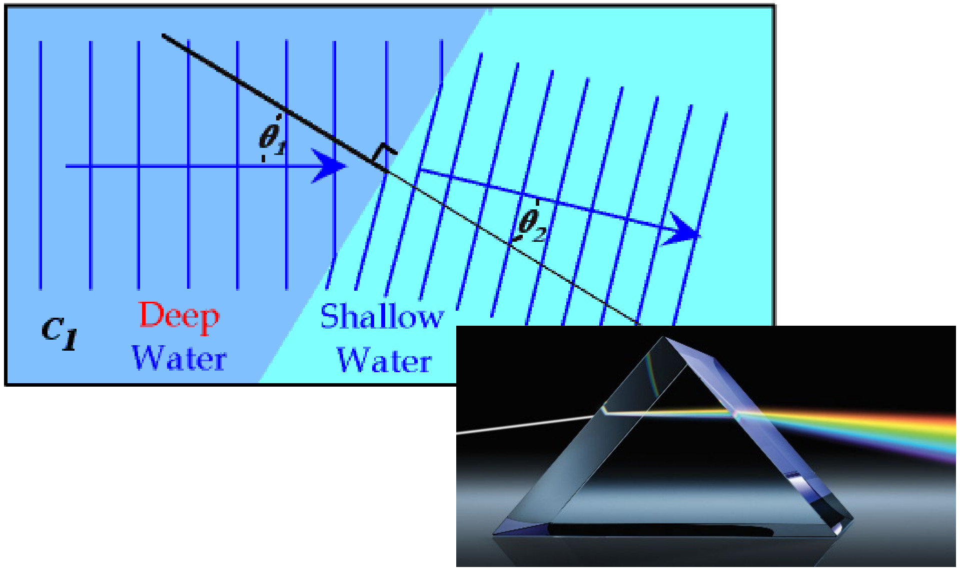
GW-Mean-Flow Interaction: Theory in a Nutshell

Theory:
GW-mean-flow interaction



Short-wavelength GWs in the **atmosphere** related to **geometric optics**:

- **Atmosphere = medium with refractive properties**
- **GWs** modify the **medium**
- Two-way interaction described using **WKB theory**



Theory:
GW-mean-flow interaction

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WKB theory for

- GWs (locally monochromatic or weak amplitude)
- on a slowly varying stratified mean flow $\boldsymbol{u}(\boldsymbol{x}, \boldsymbol{t})$

(e.g. Bretherton 1966, Grimshaw 1975, Achatz et al 2017, Achatz 2022):

- frequency and wave number connected by **dispersion relation**

$$\omega = \Omega(\boldsymbol{x}, \boldsymbol{k}, t) = \boldsymbol{k} \cdot \boldsymbol{u}(\boldsymbol{x}, \boldsymbol{t}) \underbrace{\pm \sqrt{\frac{N^2(z) k_h^2 + f^2(\phi) k_z^2}{k_h^2 + k_z^2}}}_{\widehat{\omega}\ \text{(intrinsic frequency)}}$$

- GW amplitudes connected by **polarization relations**, e.g. ($\hat{b} = g\,\hat{\theta}/\bar{\theta}$)

$$\widehat{\boldsymbol{u}} = -\frac{i}{mN} \frac{N^2 - \widehat{\omega}^2}{\widehat{\omega}^2 - f^2} \left(\boldsymbol{k}_h \widehat{\omega} - i f \boldsymbol{e}_z \times \boldsymbol{k}_h\right) \hat{b}$$

$$\widehat{w} = \frac{i\widehat{\omega}}{N^2} \hat{b}$$

Theory:
GW-mean-flow interaction

Prognostic equations for weak-amplitude GWs:

Spectral wave-action linked to spectral energy density via

$$\mathcal{N}(\boldsymbol{x},\boldsymbol{k},t) = \mathcal{E}(\boldsymbol{x},\boldsymbol{k},t)/\widehat{\omega}$$

and satisfies

$$(\partial_t + \boldsymbol{c_g} \cdot \nabla_{\boldsymbol{x}} + \dot{\boldsymbol{k}} \cdot \boldsymbol{\nabla_k})\mathcal{N} = D + S \qquad \boldsymbol{c_g} = \nabla_{\boldsymbol{k}}\Omega \qquad \dot{\boldsymbol{k}} = -\nabla_{\boldsymbol{x}}\Omega$$

D = GW sources and sinks (e.g. wave breaking)

S = scattering due to GW-GW interactions or interactions with mesoscale balanced motion

- theory from oceanography (Hasselmann 1966, Eden et al 2019) asumes weak mean flows
- neglected in the atmosphere

If $D = S = 0$ then $\mathcal{N}$ is conserved along rays $(\boldsymbol{x},\boldsymbol{k})(t)$ satisfying

$$d_t\boldsymbol{x} = \boldsymbol{c_g} \qquad d_t\boldsymbol{k} = \dot{\boldsymbol{k}}$$

Theory:
GW-mean-flow interaction

GW impact on (phase averaged)mean flow, with fluxes from polarization relations:

Horizontal momentum

$$D_t \boldsymbol{u} = \cdots - \frac{1}{\bar{\rho}} \nabla_x \cdot \langle \bar{\rho}\, \boldsymbol{v}' \boldsymbol{u}' \rangle \qquad \langle \bar{\rho}\, \boldsymbol{v}' \boldsymbol{u}' \rangle = \bar{\rho} \int d^3k\, \overleftrightarrow{\boldsymbol{M}}(\boldsymbol{k})\, \mathcal{N}$$

Entropy

$$D_t \theta = \cdots - \nabla_x \cdot \langle \boldsymbol{u}' \theta' \rangle \qquad \langle \boldsymbol{u}' \theta' \rangle = \int d^3k\, \boldsymbol{\Theta}(\boldsymbol{k})\, \mathcal{N}$$

More conventional (pseudomomentum) approach is

$$D_t \boldsymbol{u} = \cdots - \frac{1}{\bar{\rho}} \nabla_x \cdot \int d^3k\, \boldsymbol{c}_g \boldsymbol{k}_h\, \mathcal{N} \qquad D_t \theta = \cdots - 0$$

but this can lead to errors (Wei et al 2019)

Non-acceleration theorem (Charney & Drazin 1961, Andrews & McIntyre 1978, Achatz 2022):
GWs have no impact on a synoptic-scale mean flow if

- they are steady,
- their spatial distribution is horizontally homogeneous, and
- there are no GW sources and sinks (and no wave-wave interactions)

Numerical Approach: Lagrangian Ray Tracing MS-GWaM

Numerics:
MS-GWaM vs conventional GWP

Non-acceleration theorem (Charney & Drazin 1961, Andrews & McIntyre 1978, Achatz 2022):
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Conventional GW parameterizations:

- Steady state (no transience)
  Equilibrium profiles assumed, i.e. instantaneous propgation from source to model top
- Single column (1D):
  no horizontal GW propagation, no horizontal variations of GW energy taken into account
- Rely exclusively on GW breaking

MS-GWaM (Multi-Scale Gravity-Wave Model):

All three processes taken into account

Numerics:
Conservative Lagrangian Numerics

Without sources and sinks:

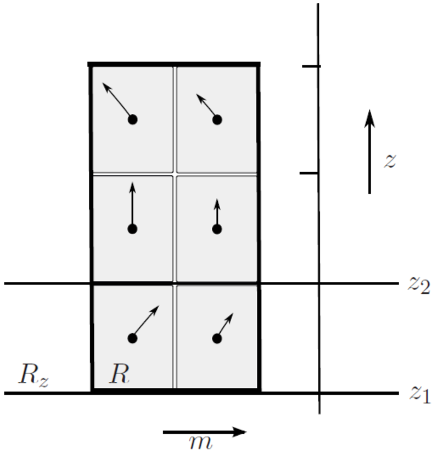
$$(\partial_t + \boldsymbol{c}_{\boldsymbol{g}} \cdot \nabla_{\boldsymbol{x}} + \dot{\boldsymbol{k}} \cdot \boldsymbol{\nabla}_{\boldsymbol{k}})\mathcal{N} = 0$$

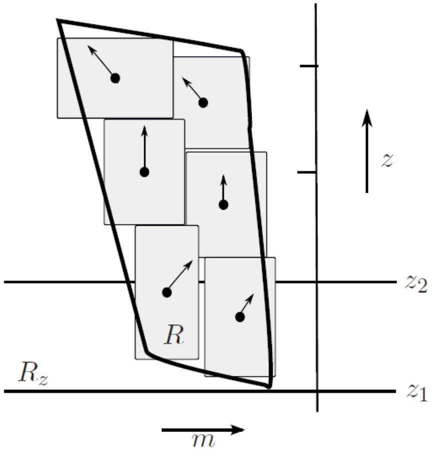
Phase-space velocity nondivergent ($\nabla_X \cdot \boldsymbol{c}_{\boldsymbol{g}} + \nabla_k \cdot \dot{\boldsymbol{k}} = 0$)

$\Longrightarrow$ flow is **volume preserving**

Region of nonzero $\mathcal{N}$ approximated by **rectangular ray volumes**

- Ray volumes move with **central ray**
- Ray volumes **change spatial and wavenumber extent** in area-preserving manner

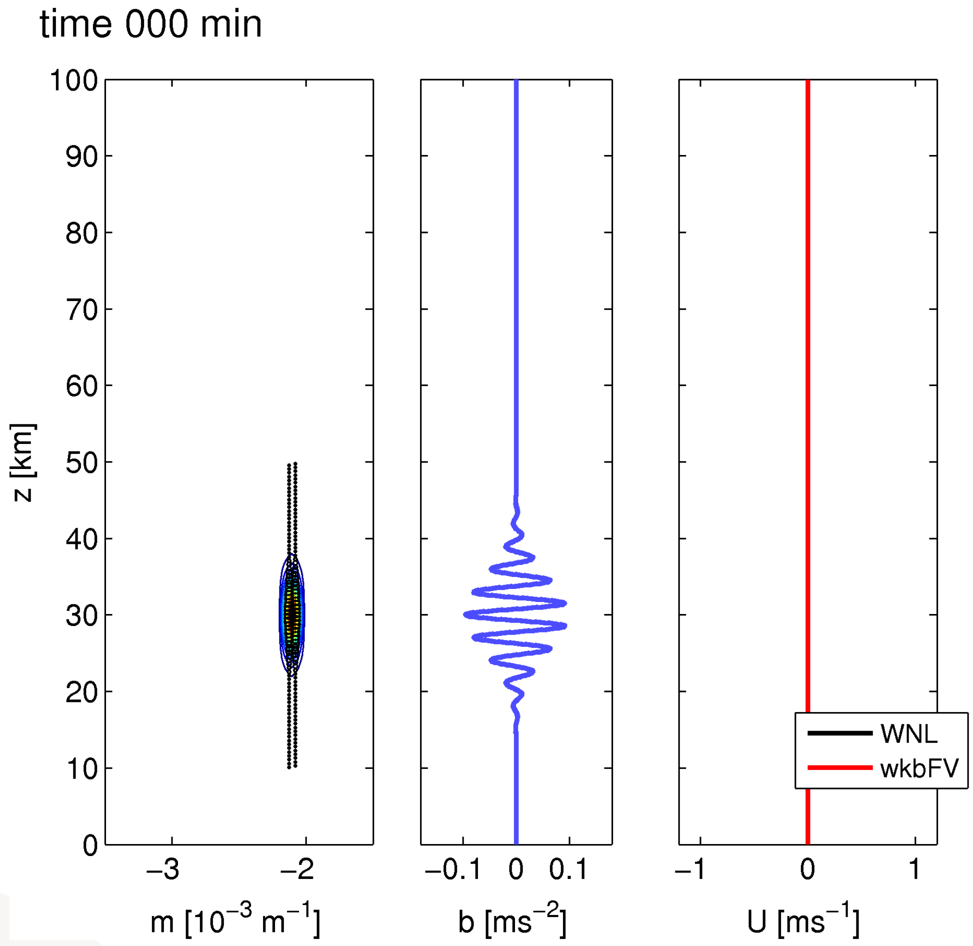




Numerics:
Conservative Lagrangian Numerics

GW packet in Boussinesq flow:

1D, i.e. GW energy and mean flow horizontally homogeneous



Numerics:
MS-GWaM in UA-ICON

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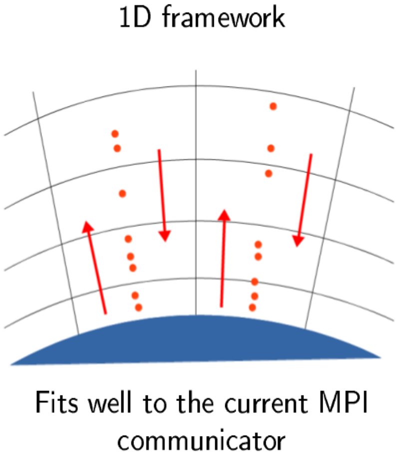
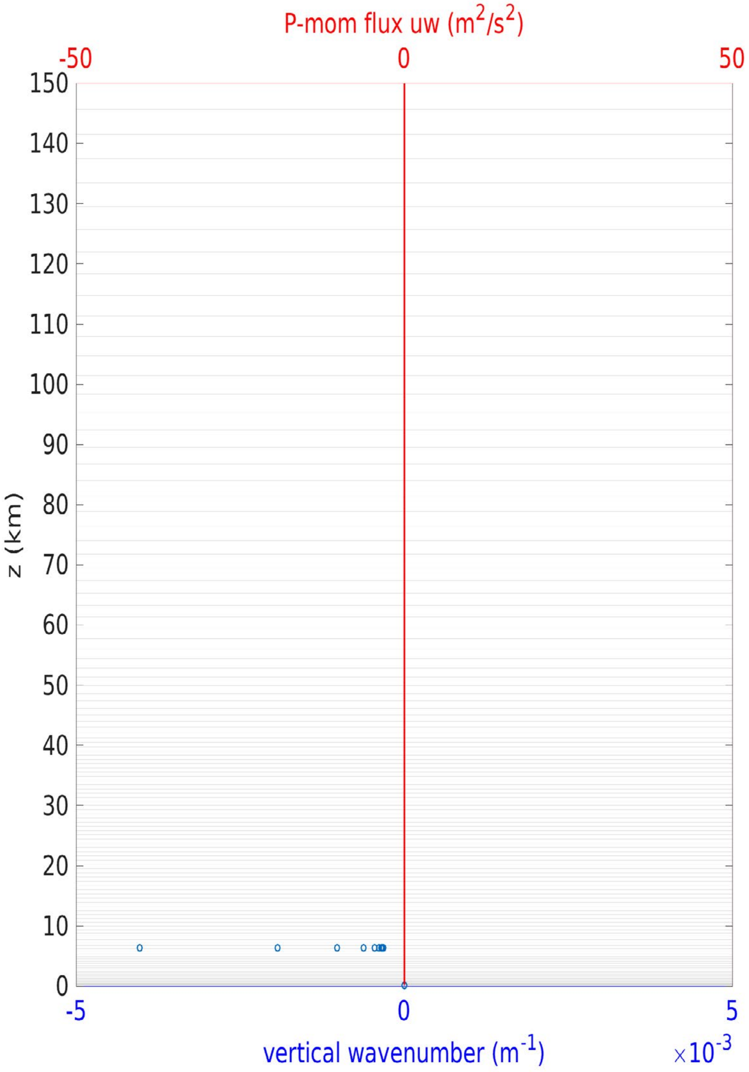
MS-GWaM in the
Upper-**A**tmosphere extension of ICON (DWD/MPI)

$\Delta x \sim$160 km (R2B4), $\Delta z \sim$ 1km, $z_{top} =$ 150km

UA-ICON
(Borchert et al 2019)



Fits well to the current MPI communicator



Numerics:
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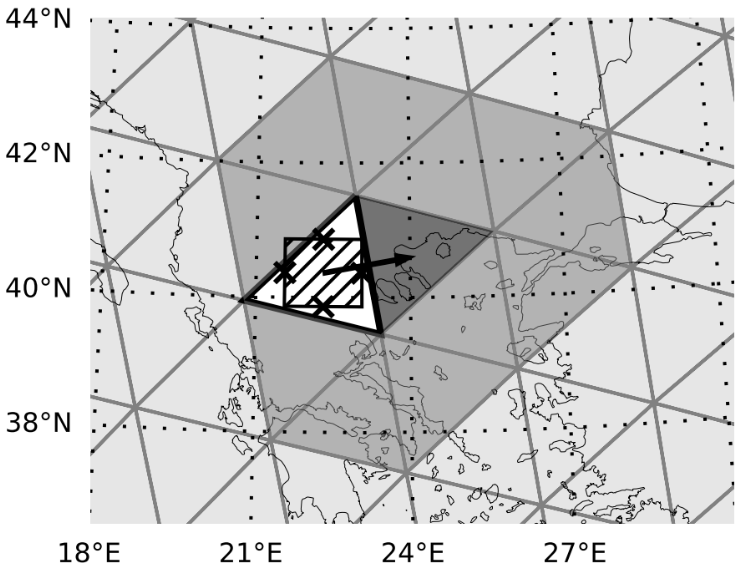
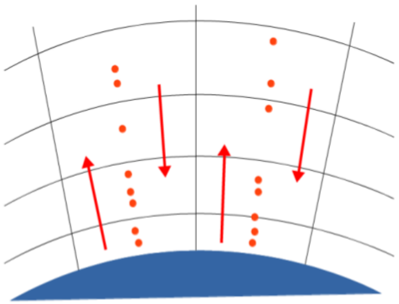
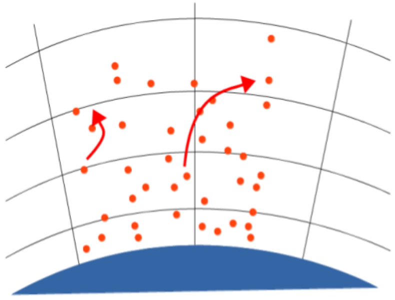


1D framework



Fits well to the current MPI communicator

3D framework



Requires new MPI communication style for Lagrangian particles

Implementation 3D

- Cell-based ray-volume handling
- Handover from cell to cell
- MPI parallelization

Numerics:
MS-GWaM in UA-ICON

Sources:

- GWs from convection (based on Choi et al 2011)
  - using latent heat release
  - small-scale waves from convective cells
  - larger-scale waves from mesoscale convective systems
- Background GW source based on Orr et al (2010)
  - Seasonal dependence
  - In each hemisphere horizontally homogeneous
- Orographic GWs parameterized outside MS-GWaM (Lott and Miller 1997)

Sink:

Wave breaking due to static instability, using saturation approach
(Lindzen 1981, Bölöni et al 2016)

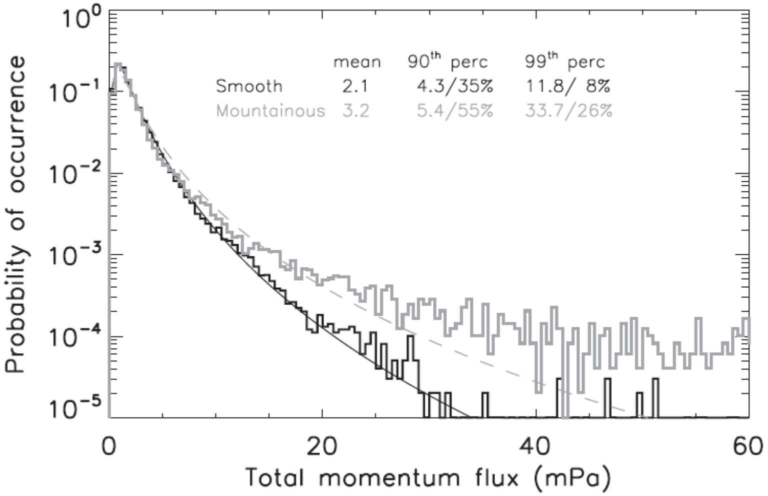
Effects of GW Transience on Momentum-Flux Intermittency

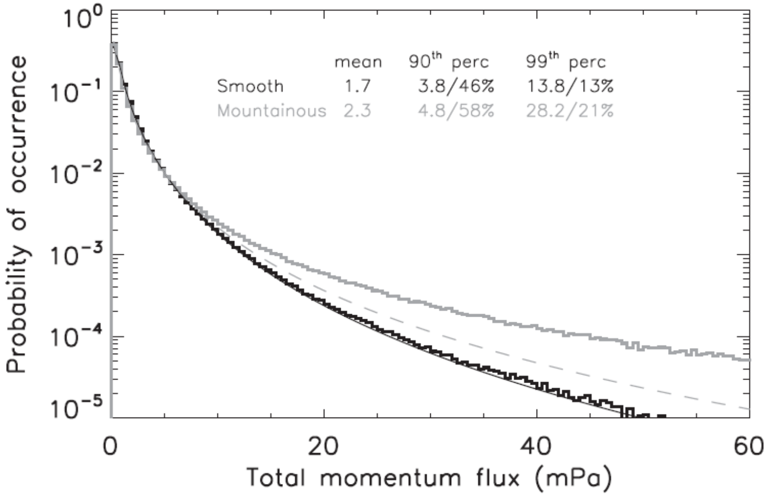
16. April 2023

Effects of GW transience:
GW momentum-flux intermittency

Hertzog et al (2012): Vorcore measurements

WRF





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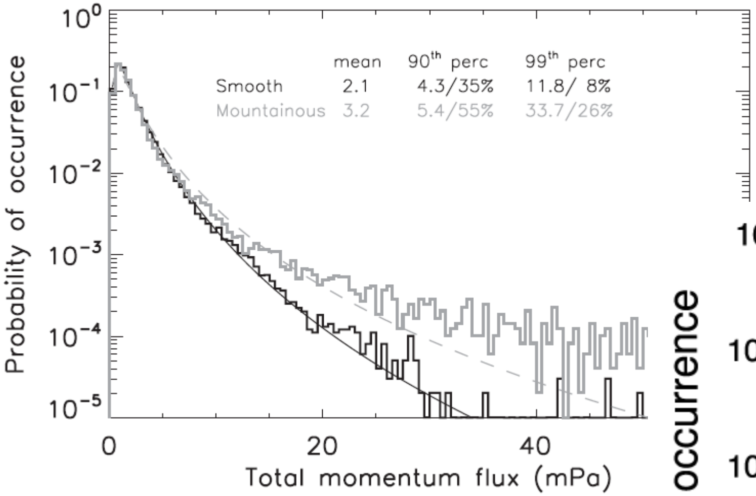

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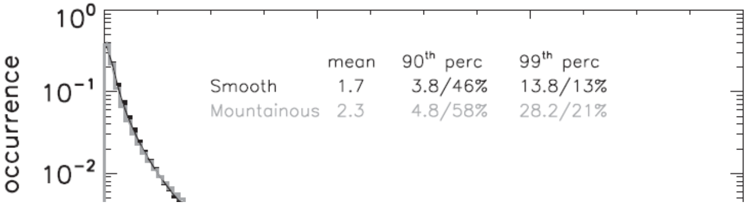
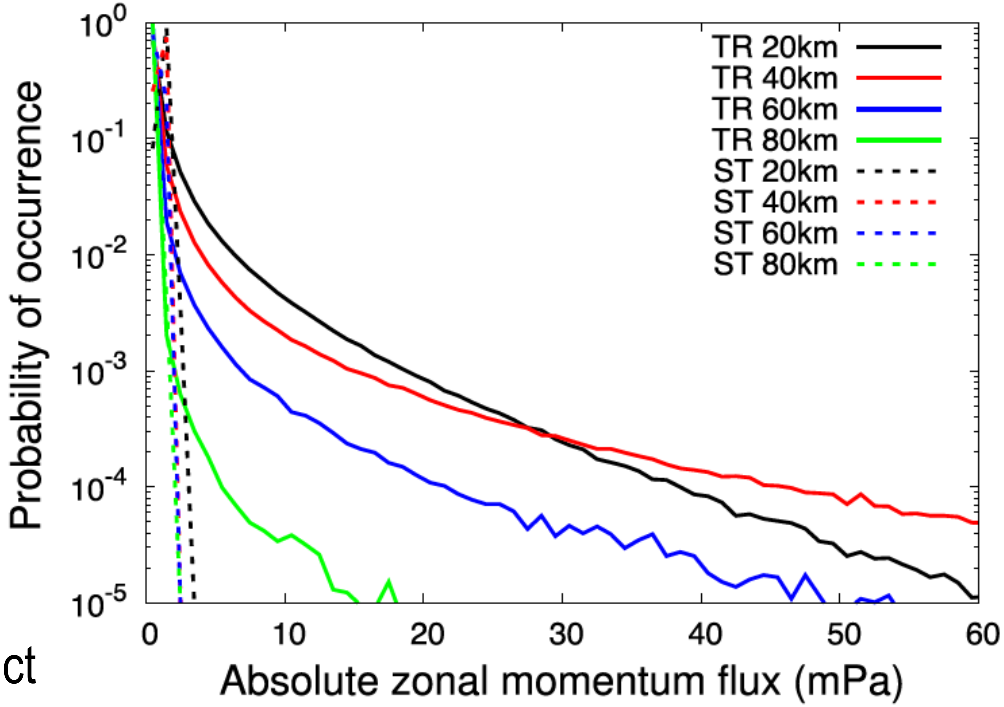
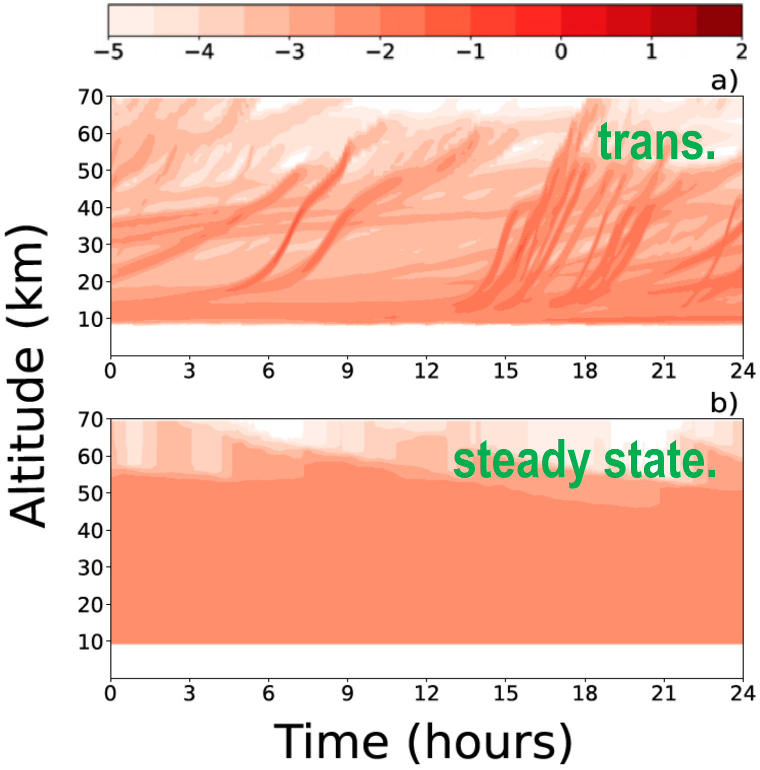




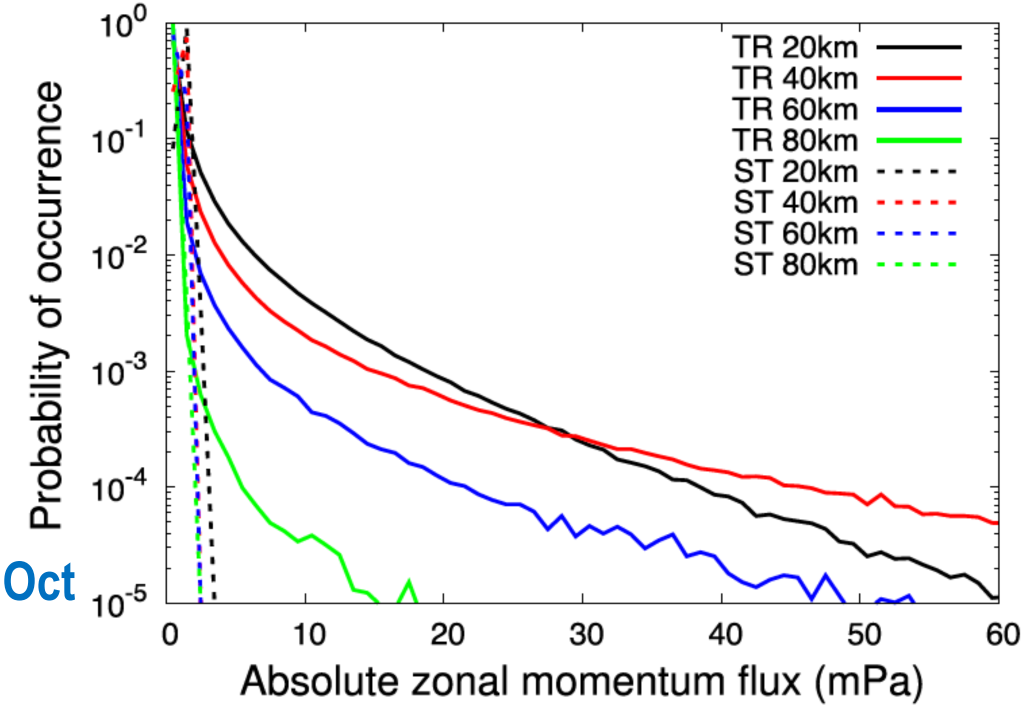
Bölöni et al (2021): 65°S – 50°S in Oct

Effects of GW transience:
GW momentum-flux intermittency



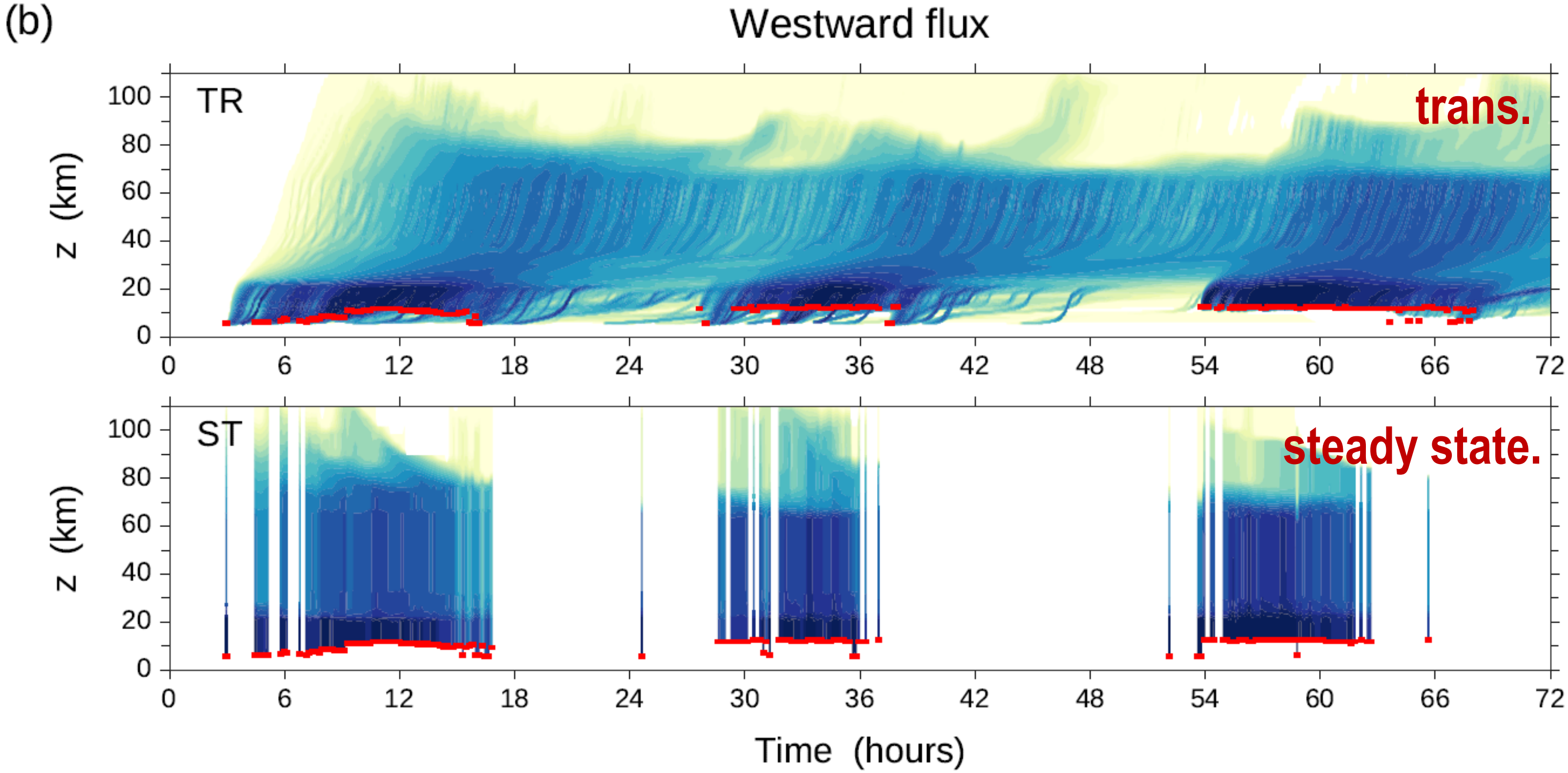
Bölöni et al (2021): 65°S – 50°S in Oct

(150°W,60°S) on Jun 1st 1998



Effects of GW transience
on GW momentum-flux intermittency

Kim et al (2021): 116°E, 3.5°N in May 1998

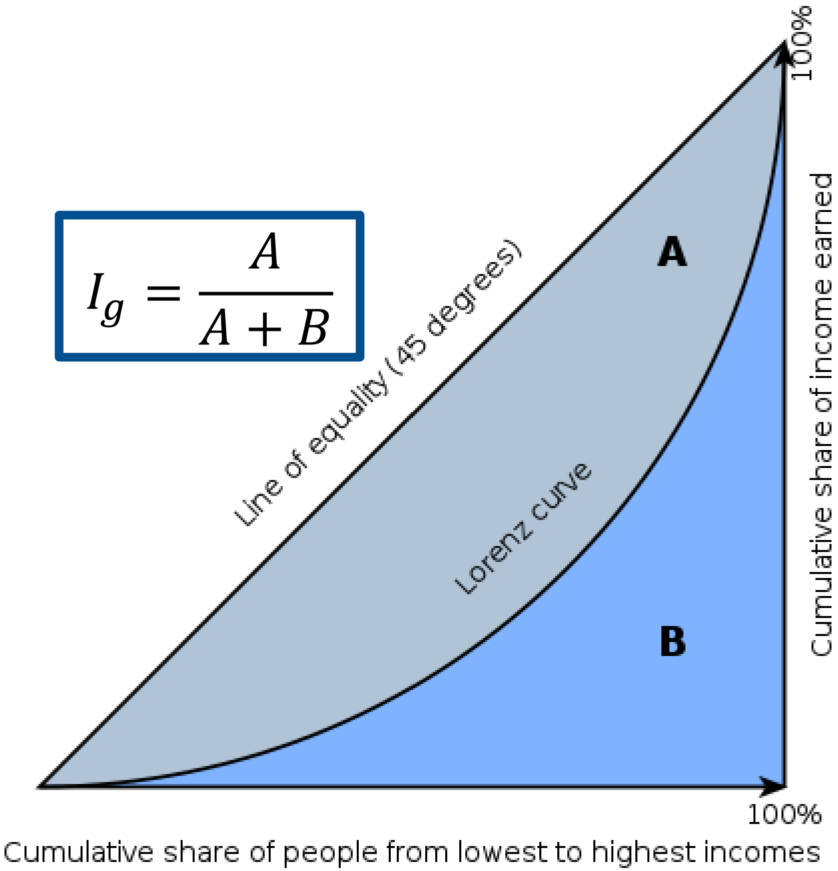


GW source from convection (Son & Chun 2005, Choi & Chun 2011)

Effects of GW transience
on GW momentum-flux intermittency

Gini coefficient: Index for unbalance in distribution

$$I_g = \frac{A}{A+B}$$



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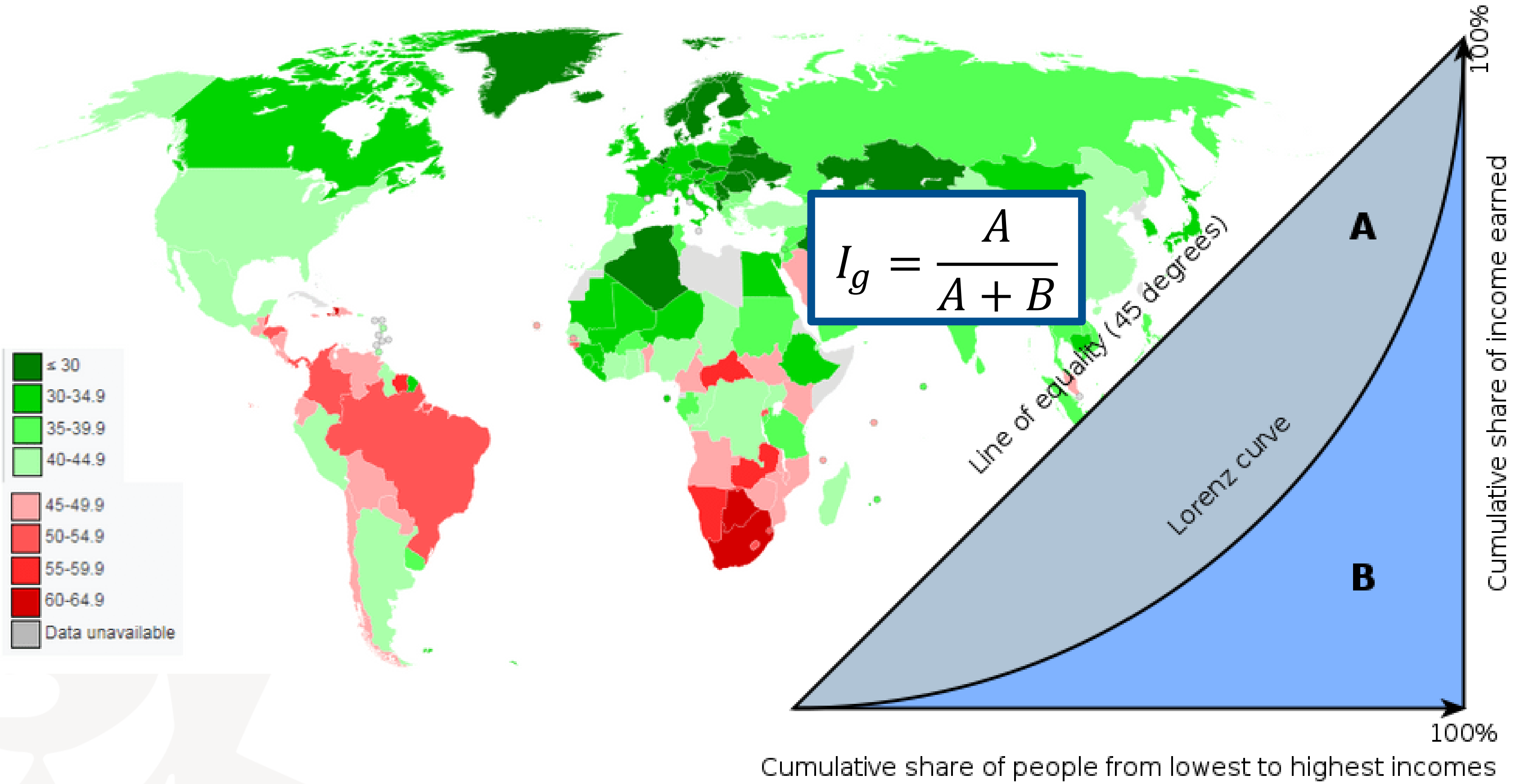
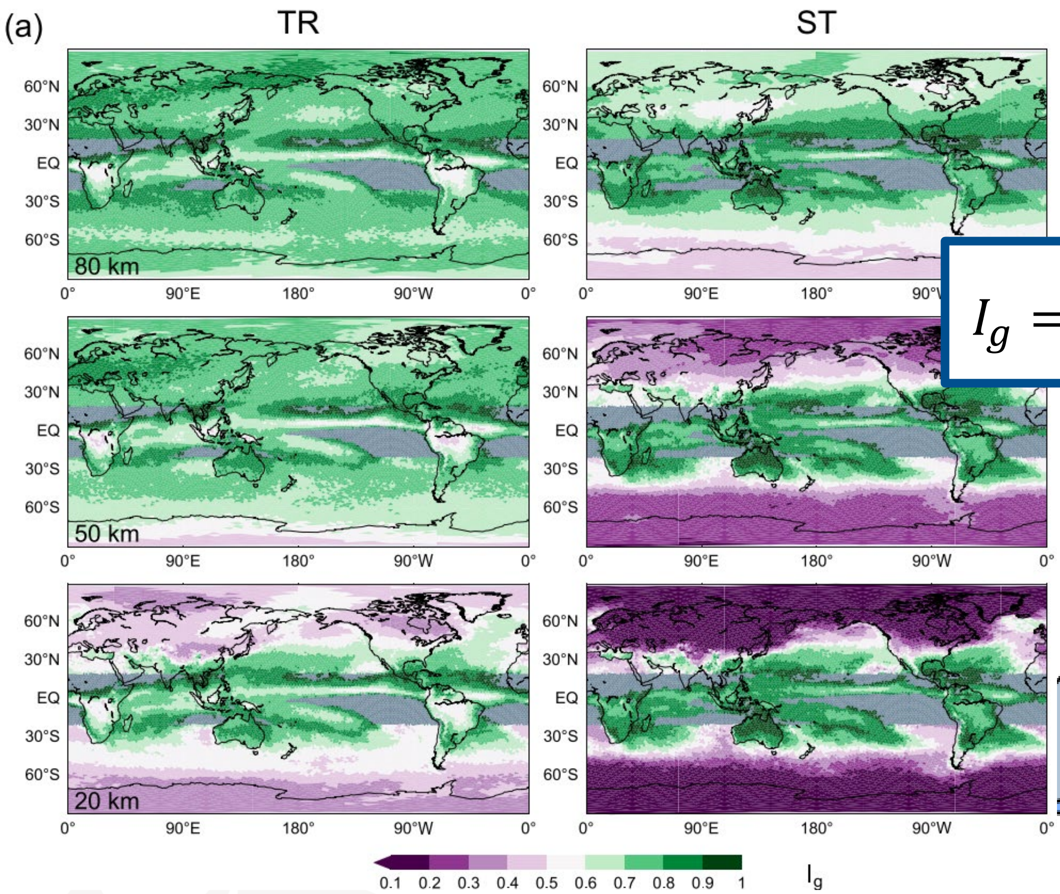


$$I_g = \frac{A}{A+B}$$

Effects of GW transience
on GW momentum-flux intermittency

Kim et al (2021): Gini coefficient for GWMF



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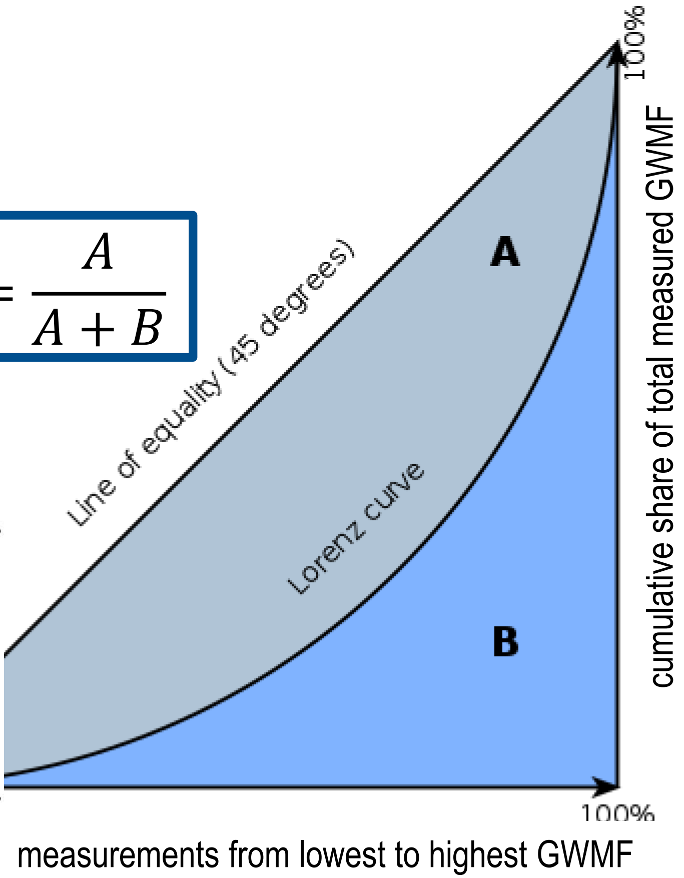
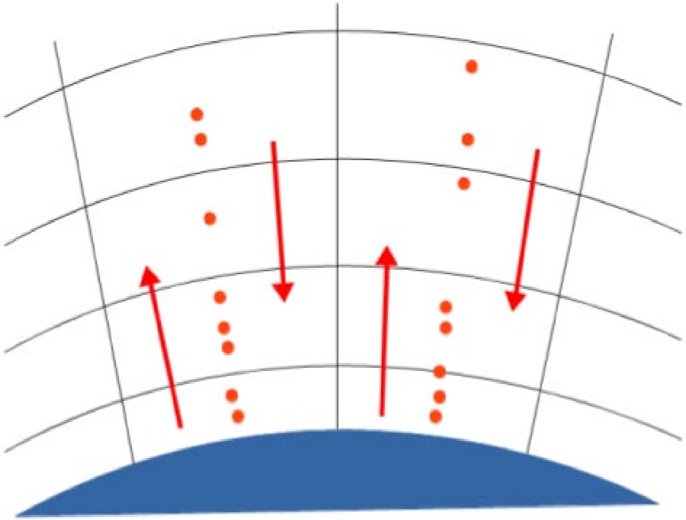
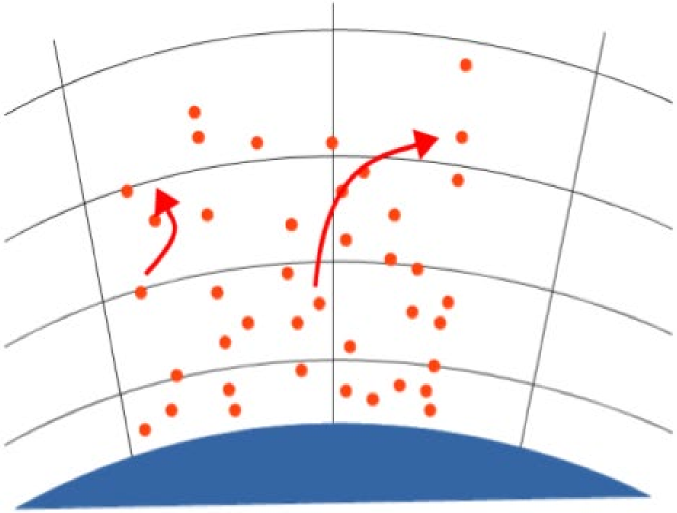


Effects of Horizontal Propagation

1D framework



3D framework



Effects of horizontal propagation: Wave-action budget

Spatial wave-action density $\mathcal{A} = \int d^3k\, \mathcal{N}$ satisfies

$$\partial_t \mathcal{A} = -\nabla_h \cdot \left(\boldsymbol{c}_{gh}\, \mathcal{A}\right) - \partial_z\left(c_{gz}\, \mathcal{A}\right) + D$$

with e.g. $\boldsymbol{c}_{gh}\, \mathcal{A} = \int d^3k\, \boldsymbol{c}_{gh}\, \mathcal{N}$

Time mean

$$0 \approx \frac{\Delta\mathcal{A}}{\Delta t} = -\nabla_h \cdot \langle \boldsymbol{c}_{gh}\, \mathcal{A}\rangle - \partial_z \langle c_{gz}\, \mathcal{A}\rangle + \langle D\rangle$$

Effects of horizontal propagation:
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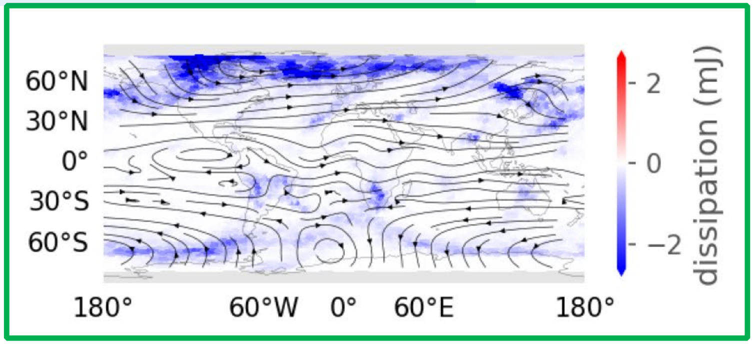
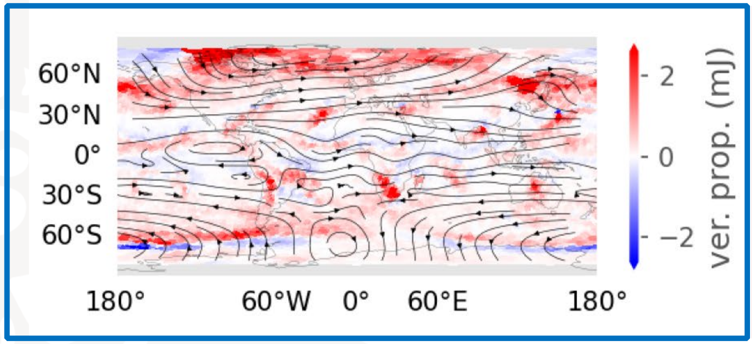
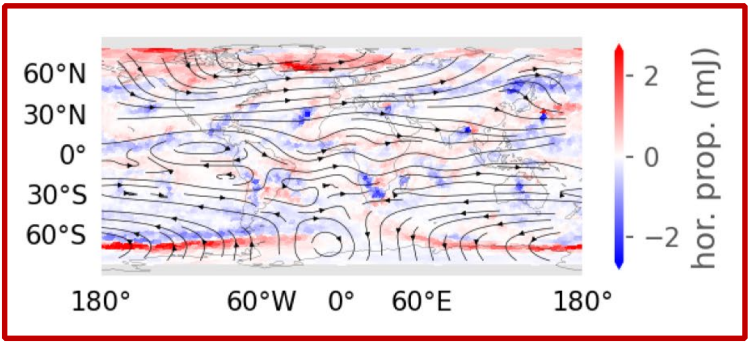
June
$z \approx$ 40km
(Völker et al 2023, in prep.)

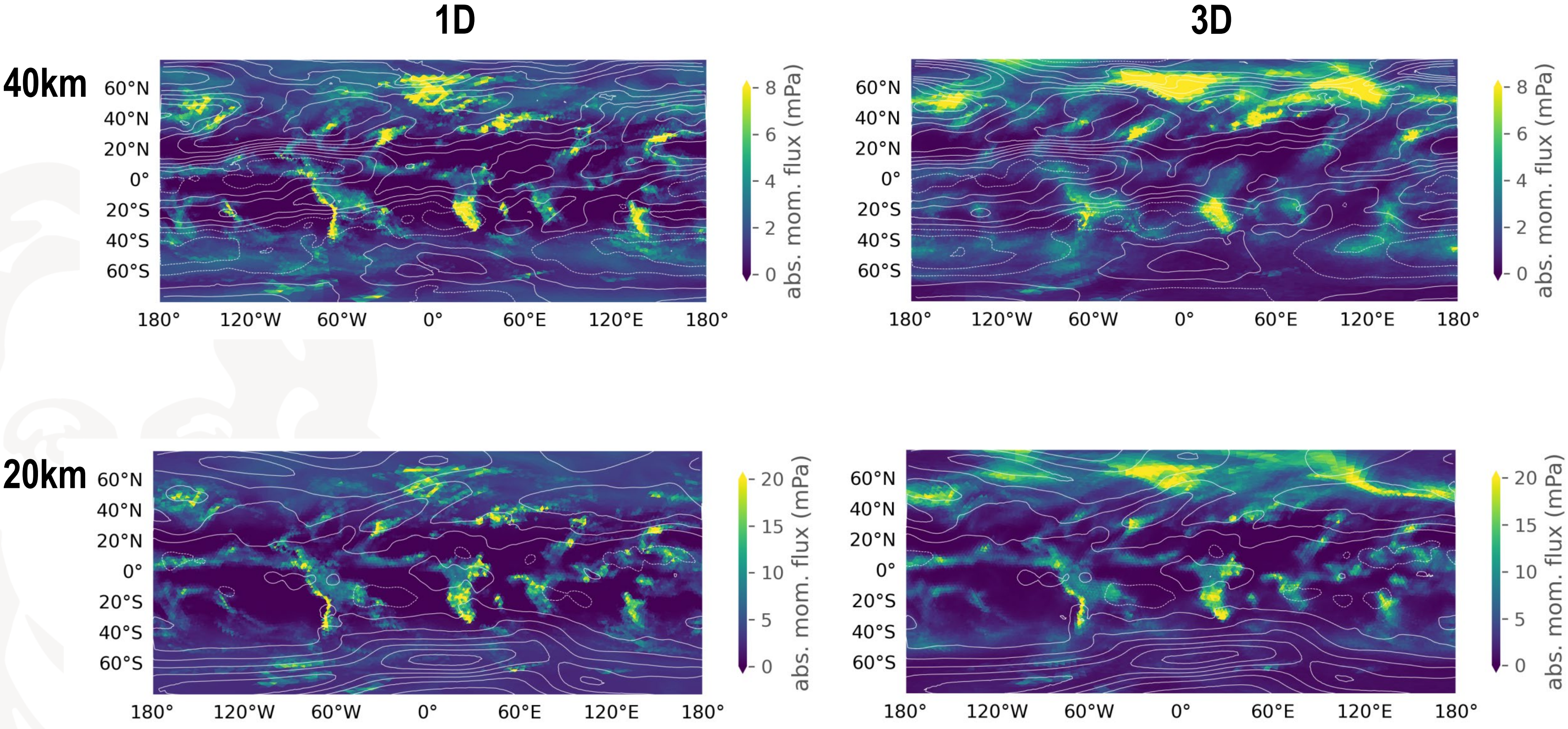






Effects of horizontal propagation:
Horizontal distribution GW mom.flux

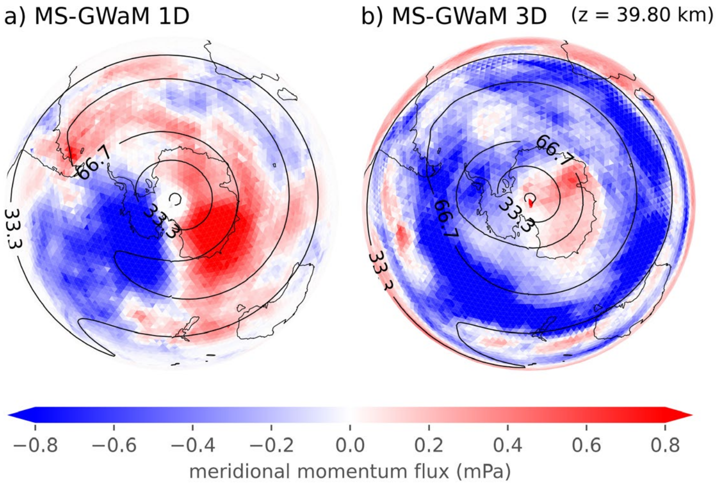
GW **momentum flux** November (snapshot) at two altitudes
(Völker et al 2023, in prep.)



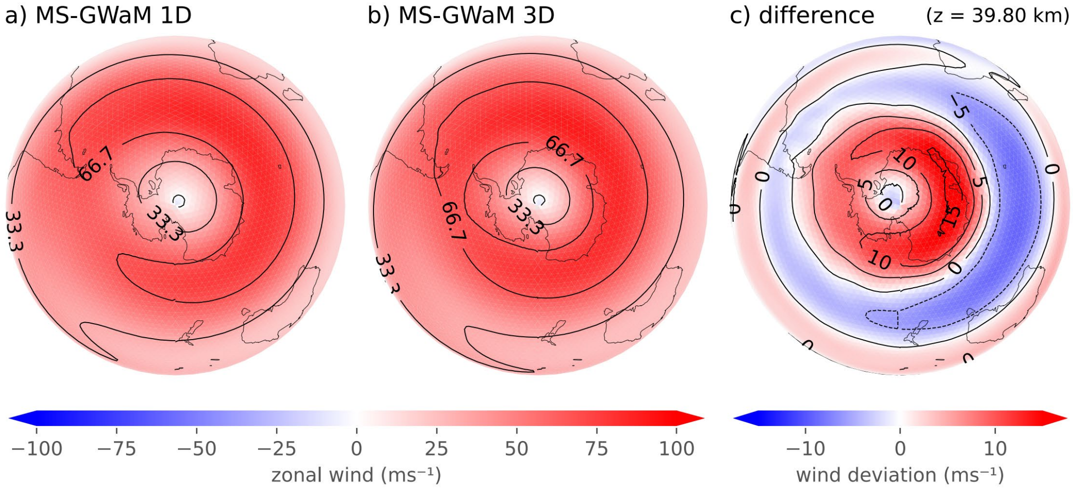
Effects of horizontal propagation:
GW mom.flux & mean winds

June 1994 Southern Hemisphere **GW meridional momentum flux & mean zonal wind**
(Völker et al 2023, in prep.)

$\bar{\rho}\langle\overline{w'v'}\rangle$



$\langle\bar{u}\rangle$



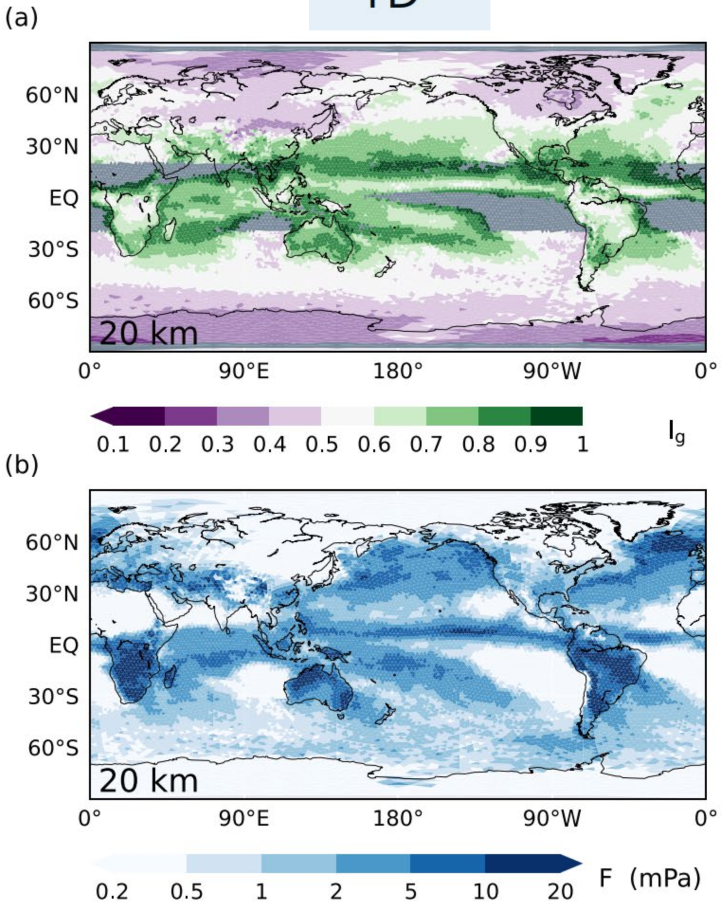
Effects of horizontal propagation: GWMF intermittency

Kim et al (2023, in prep.)

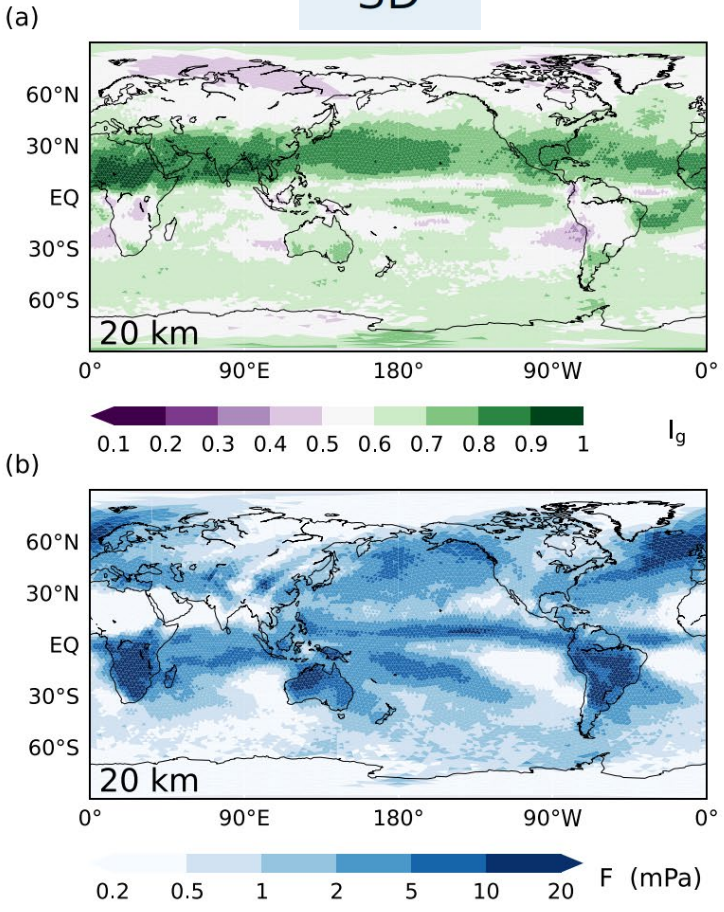
Gini

GWMF

1D

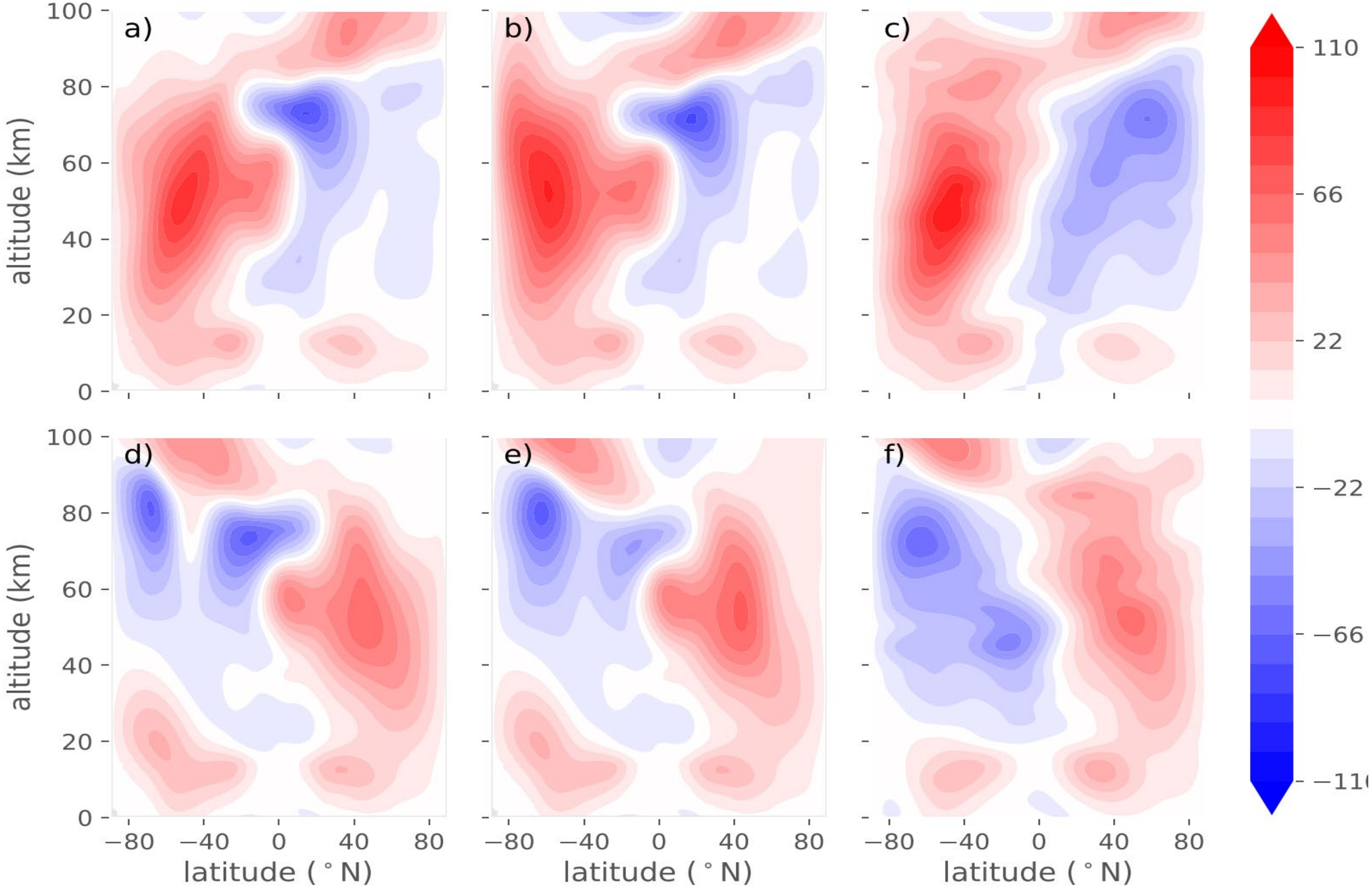


3D



Effects of horizontal propagation:
Zonal-mean zonal wind

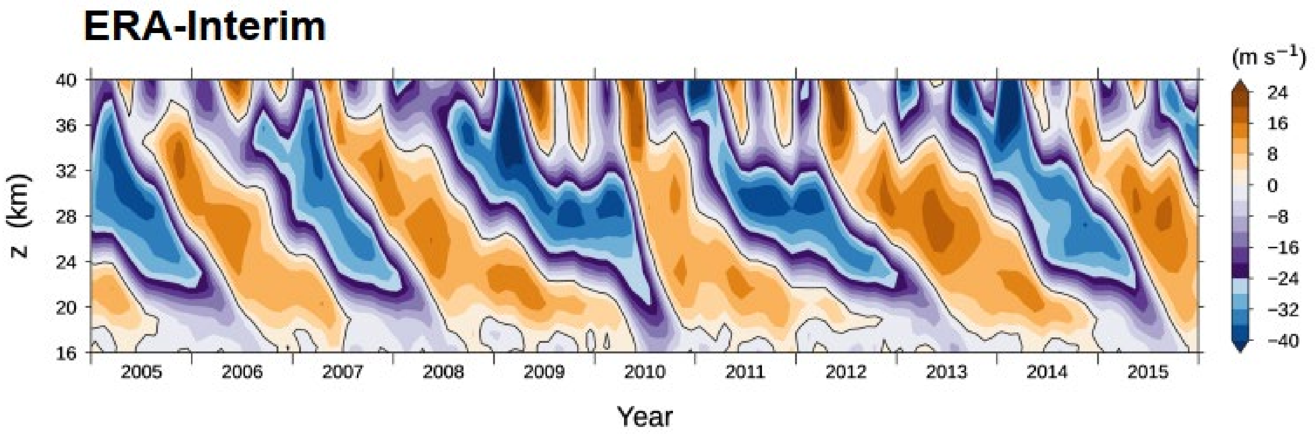
Völker et al (2023, in prep.)



MS-GWaM 1D **MS-GWaM 3D** **Obs (HWM2014)**

Effects of horizontal propagation:
QBO

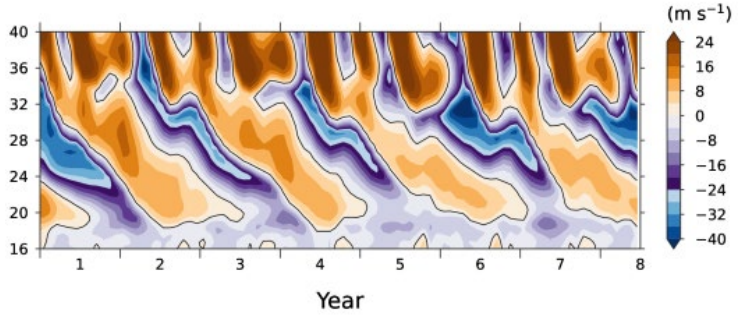
Quasi-Biennial Oscillation: zonal-mean zonal wind 5°S – 5°N
(Kim et al 2023, in prep.)

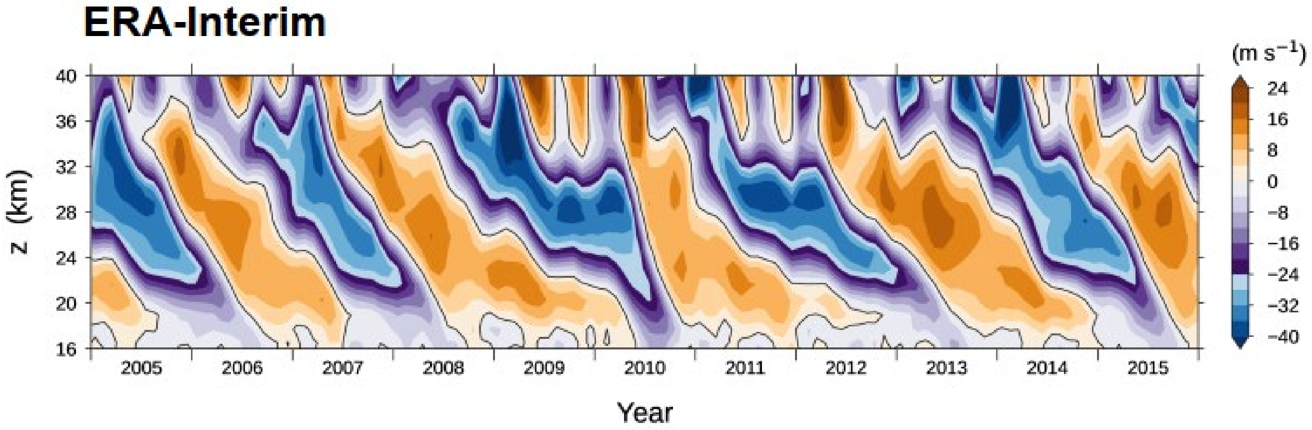


Effects of horizontal propagation: QBO

Quasi-Biennial Oscillation: zonal-mean zonal wind 5°S – 5°N
(Kim et al 2023, in prep.)

transient 3D

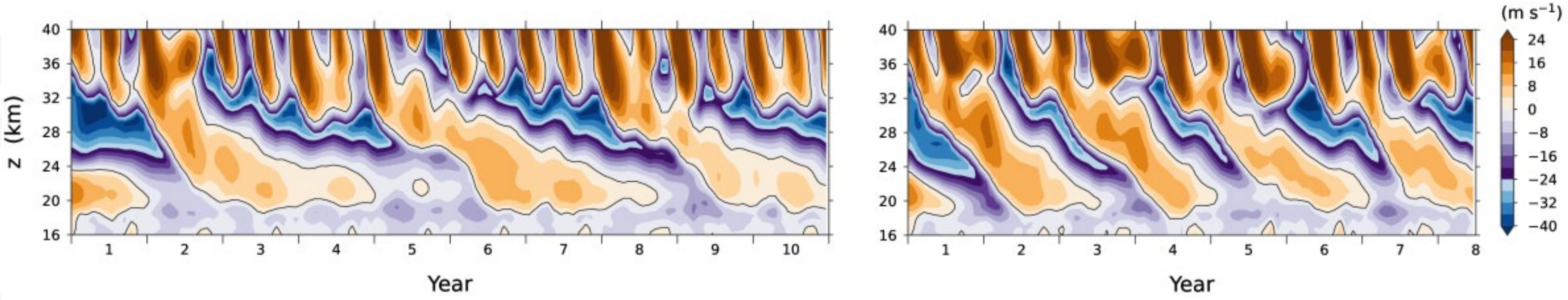


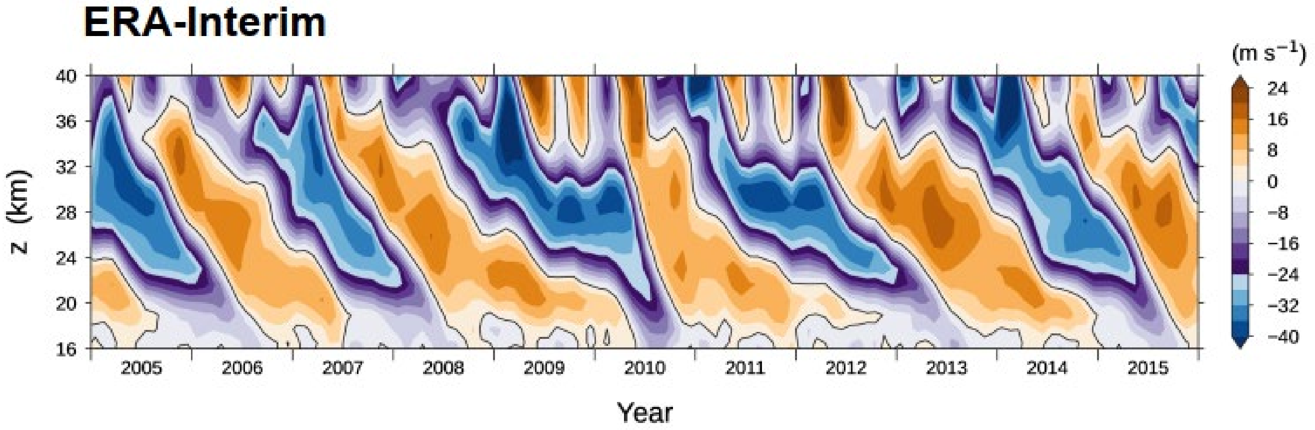


Effects of horizontal propagation:
QBO

Quasi-Biennial Oscillation: zonal-mean zonal wind 5°S – 5°N
(Kim et al 2023, in prep.)

Steady state 1D **transient 3D**





Effects of horizontal propagation: QBO

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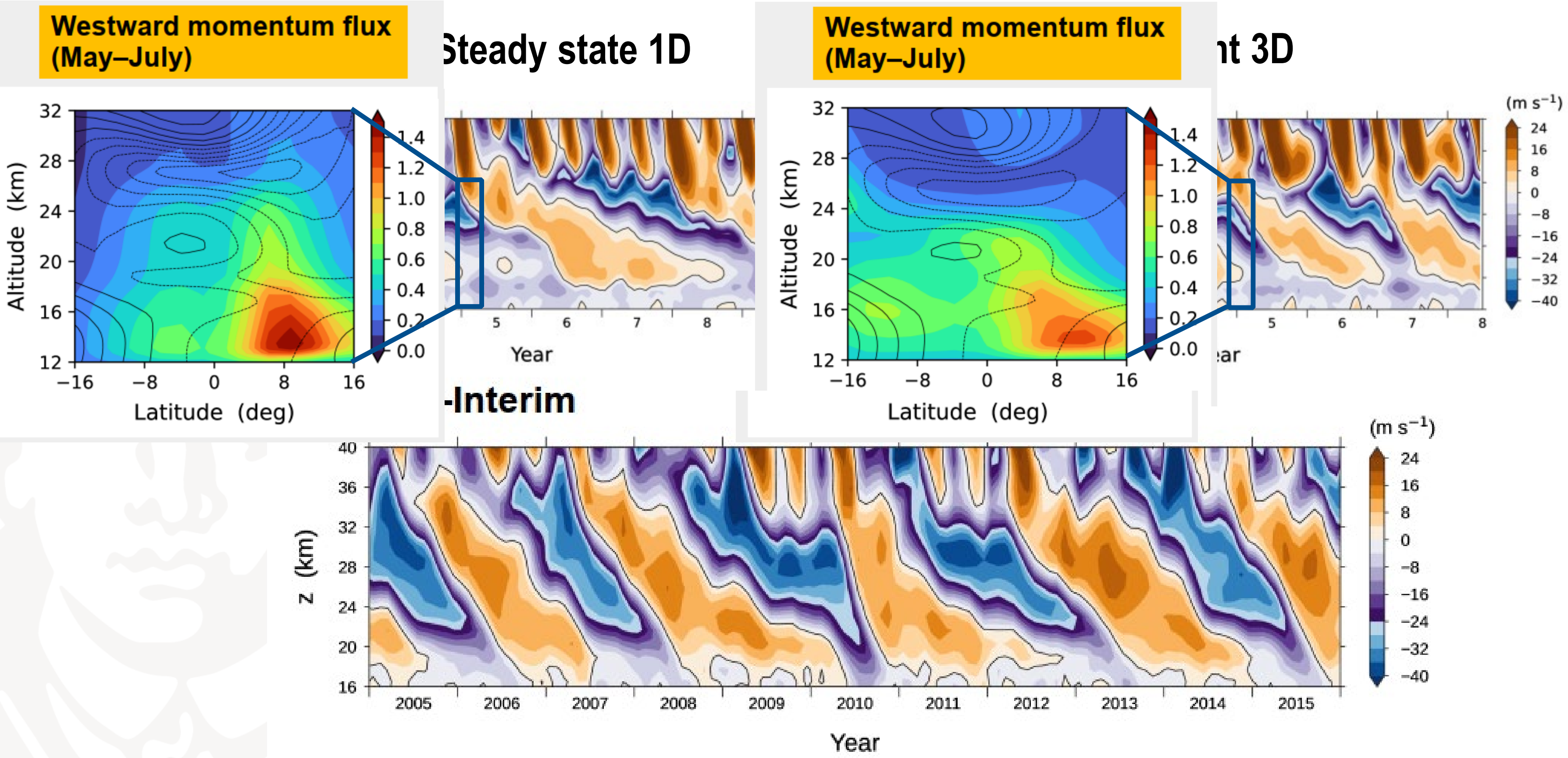
Quasi-Biennial Oscillation: zonal-mean zonal wind 5°S – 5°N
(Kim et al 2023, in prep.)



Is it affordable?

MS-GWaM in UA-ICON

computational effort

	UA-ICON / MS-GWaM (3D)
Δx/km	160
Δz/km	0.02 (BL) – 0.7 (ST) – 4.5 (top)
relative increase comp. time (compared to ICON with classic GWP - Orr et al 2010)	**10-40**

UA-ICON / MS-GWaM is

- **more expensive** than UA-ICON with **classic GW parameterization**, but

MS-GWaM in UA-ICON
computational effort

	UA-ICON / MS-GWaM (3D)	UA-ICON GW resolving
Δx/km	160	5
Δz/km	0.02 (BL) – 0.7 (ST) – 4.5 (top)	0.02 (BL) – 0.2 (ST) – 0.2 (top)
relative increase comp. time (compared to ICON with classic GWP - Orr et al 2010)	**10-40**	**240000**

UA-ICON / MS-GWaM is

- **more expensive** than UA-ICON with **classic GW parameterization**, but
- **considerably cheaper** than **a wave-resolving set-up of UA-ICON**

Summary & Discussion

- **Subgrid-scale processes** still present major challenges to the **reliability of climate simulations**
- **Gravity waves (GW)** are a corresponding phenomenon
- Both **transient dynamics** and **horizontal propagation** not represented in present-day parameterizations
- **MS-GWaM in UA-ICON** is 1st prognostic GW model to simulate these effects
- Corresponding **differences are leading order**, e.g.
  - Intermittency
  - Horizontal distributions
  - QBO
- MS-GWaM is more expensive than classic GW parameterizations but much **cheaper than wave-resolving simulations**
- Even when we will be able to resolve all processes even in climate simulations, **conceptional models with a solid theoretical basis** will remain essential for our gain of **understanding**

Literature

Book:

Achatz, U., 2022: Atmospheric Dynamics. Springer, Berlin

Journal Papers:

Achatz, U., Ribstein, B., Senf, F., and R. Klein, 2017: 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. R. Met. Soc.,* **143**, 342–361

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

Bölöni, G., Kim, Y.-H., Borchert, S., and U. Achatz, 2021: Toward transient subgrid-scale gravity wave representation in atmospheric models. Part I: Propagation model including nondissipative wave–mean-flow interactions. *J. Atmos. Sci.* **78**, 1317-1338

Kim, Y.-H., G. Bölöni, S. Borchert, H.-Y. Chun, and U. Achatz, 2021: Toward transient subgrid-scale gravity wave representation in atmospheric models. Part II: Wave intermittency simulated with convective sources. *J. Atmos. Sci.*, **78**, 1339–1357

Muraschko J, Fruman M, Achatz U, Hickel S, Toledo Y. 2015: On the application of WKB theory for the simulation of the weakly nonlinear dynamics of gravity waves. *Quart. J. R. Met. Soc.* **141,** 676–697.

Wei, J., Bölöni, G., and U. Achatz 2019: Efficient modeling of the interaction of mesoscale gravity waves with unbalanced large-scale flows: Pseudomomentum-flux convergence versus direct approach, *J. Atmos. Sci.*, **76**, 2715–2738

Wilhelm, J., Akylas, T.A., Bölöni, G., Wei, J., Ribstein, B., Klein, R., and U. Achatz, 2018: The interaction between meso- and sub-mesoscale gravity waves. *J. Atmos. Sci.,* **75**, 2257-2280

MS-GWaves: https://ms-gwaves.iau.uni-frankfurt.de/