Unravelling climate impacts of atmospheric internal gravity waves.

Petr Šácha (+ Aleš Kuchař, Zuzana Procházková, Dominika Hájková, Roland Eichinger, Petr Pišoft, Harald Rieder, Christoph Jacobi, Nadja Samtleben, Friederike Lilienthal..)

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Charles University

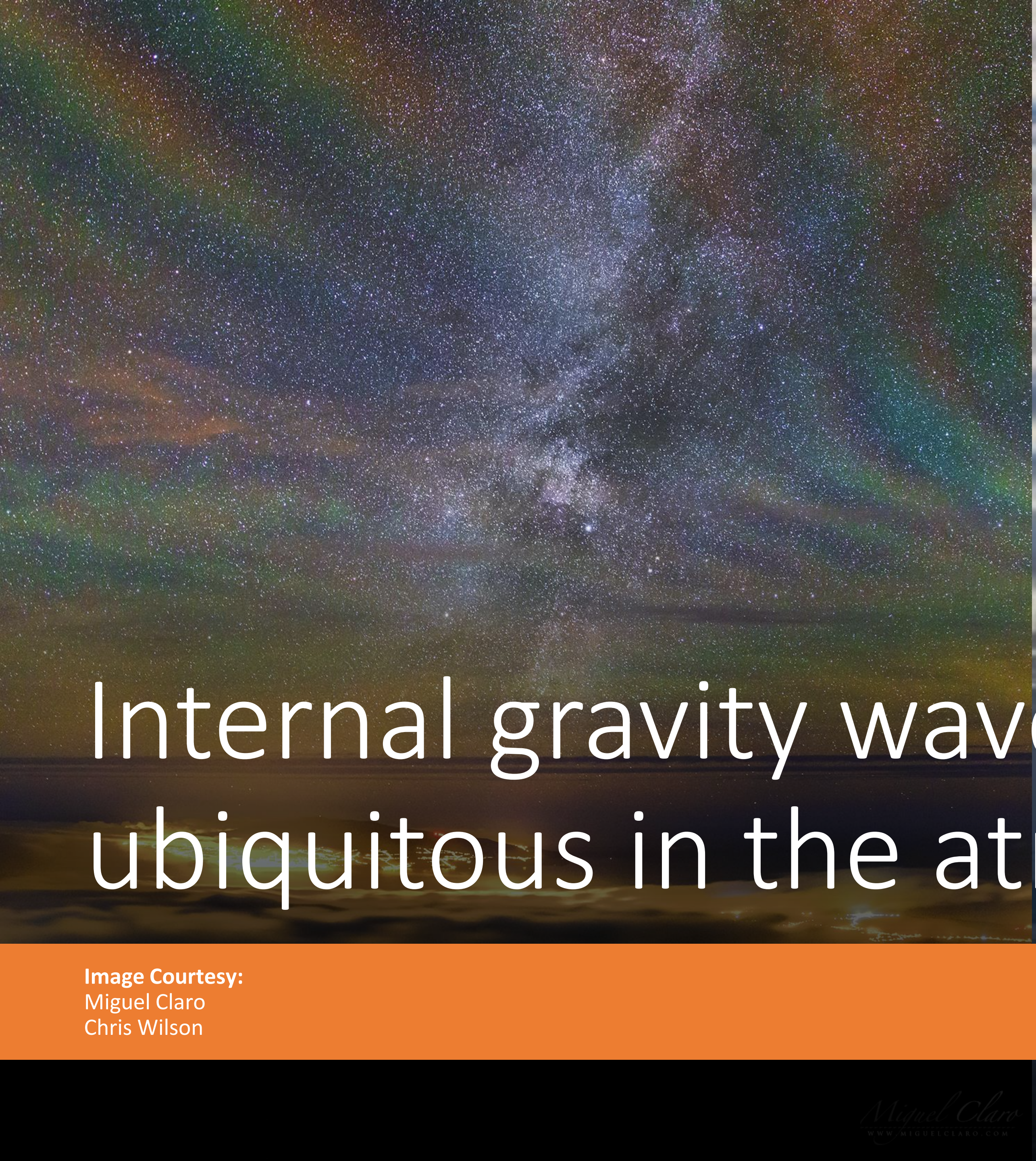
- Established in 1348 (ranked 200-300 in the world)
- Flagship - Faculty of Mathematics and Physics (ranks regularly among the 20 best European institutions concerning both, physics and mathematics).
- Around 60 best students in Czech (+ Slovaks and other eastern Europeans) enroll each year to study general physics.
- Department of Atmospheric physics – starting from the MSc degree (around 4 students each year).

Department of atmospheric physics

- Variety of research topics:
- Regional and urban climate modeling
- Air quality
- Atmospheric chemistry
- Turbulence
- Chaos and nonlinear processes
- Middle atmosphere
- Gravity waves and atmospheric dynamics

Outline

- Selected features of internal gravity waves (GWs) in the atmosphere known from observations.
- Chemistry-climate models (CCMs).
- The role of parameterized OGWD for the large-scale dynamics and transport in CCMs.
- Role for Brewer-Dobson circulation?

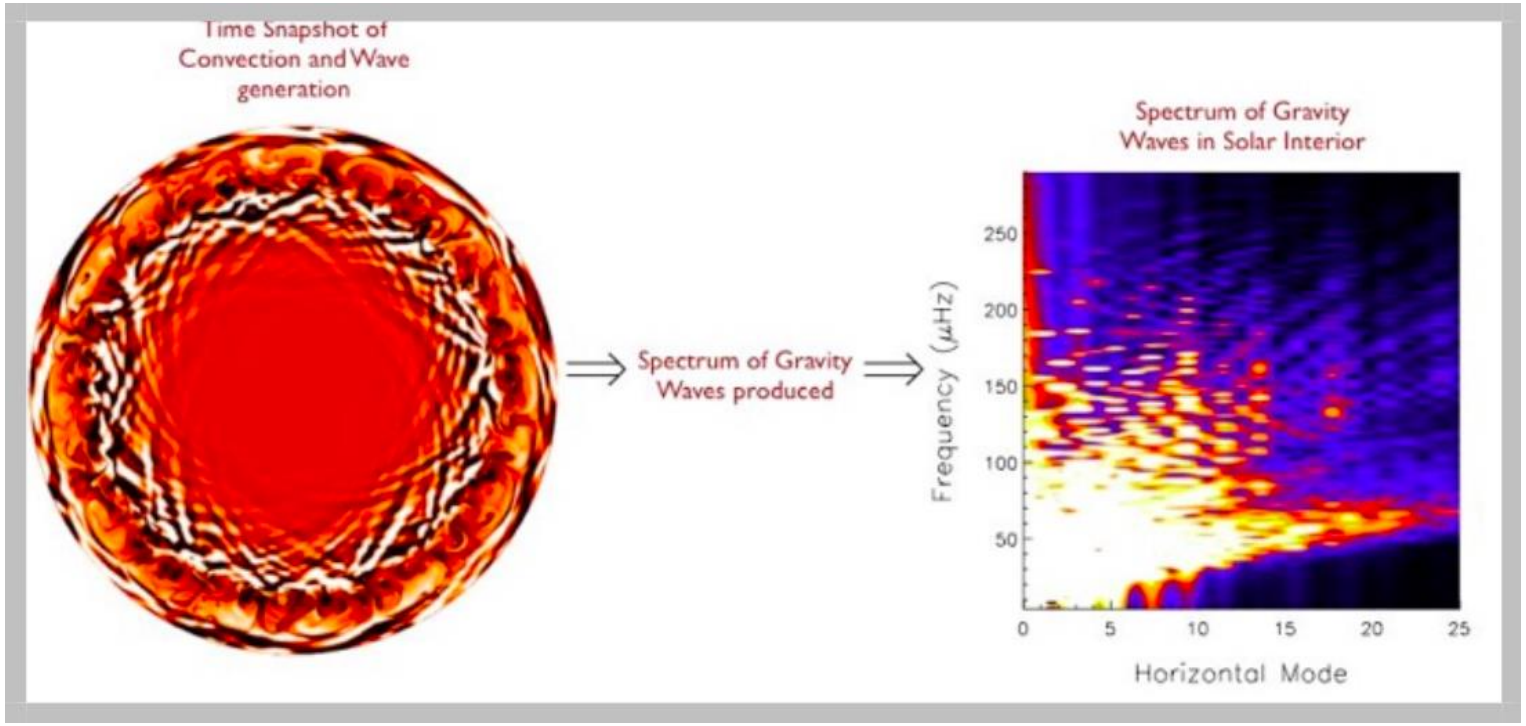


Internal gravity waves are ubiquitous in the atmosphere.

Image Courtesy:
Miguel Claro
Chris Wilson

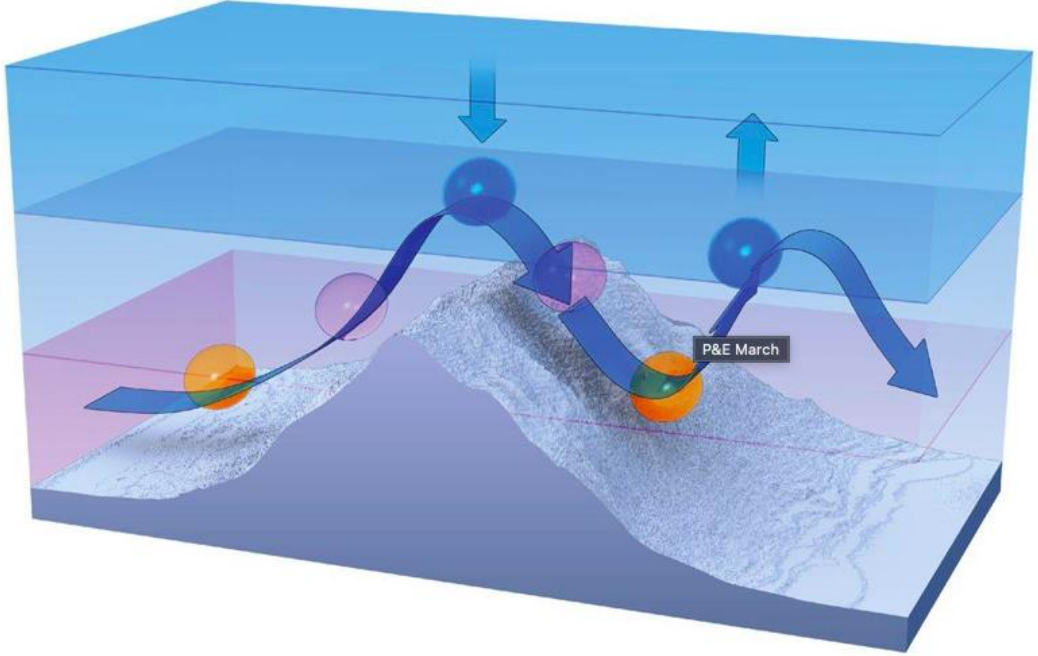
Gravity waves in the Solar interior.

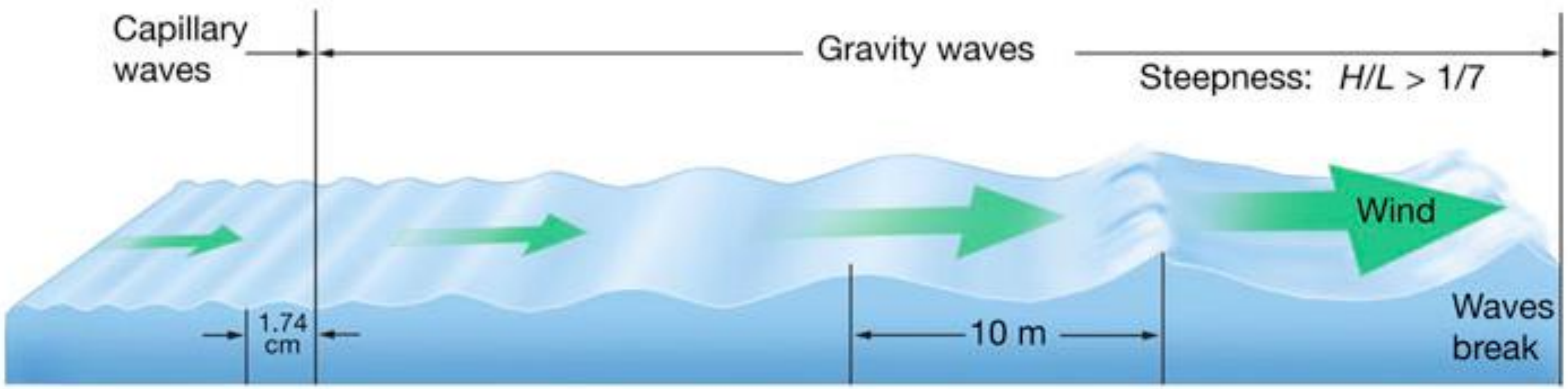
Adapted from T. Rogers.



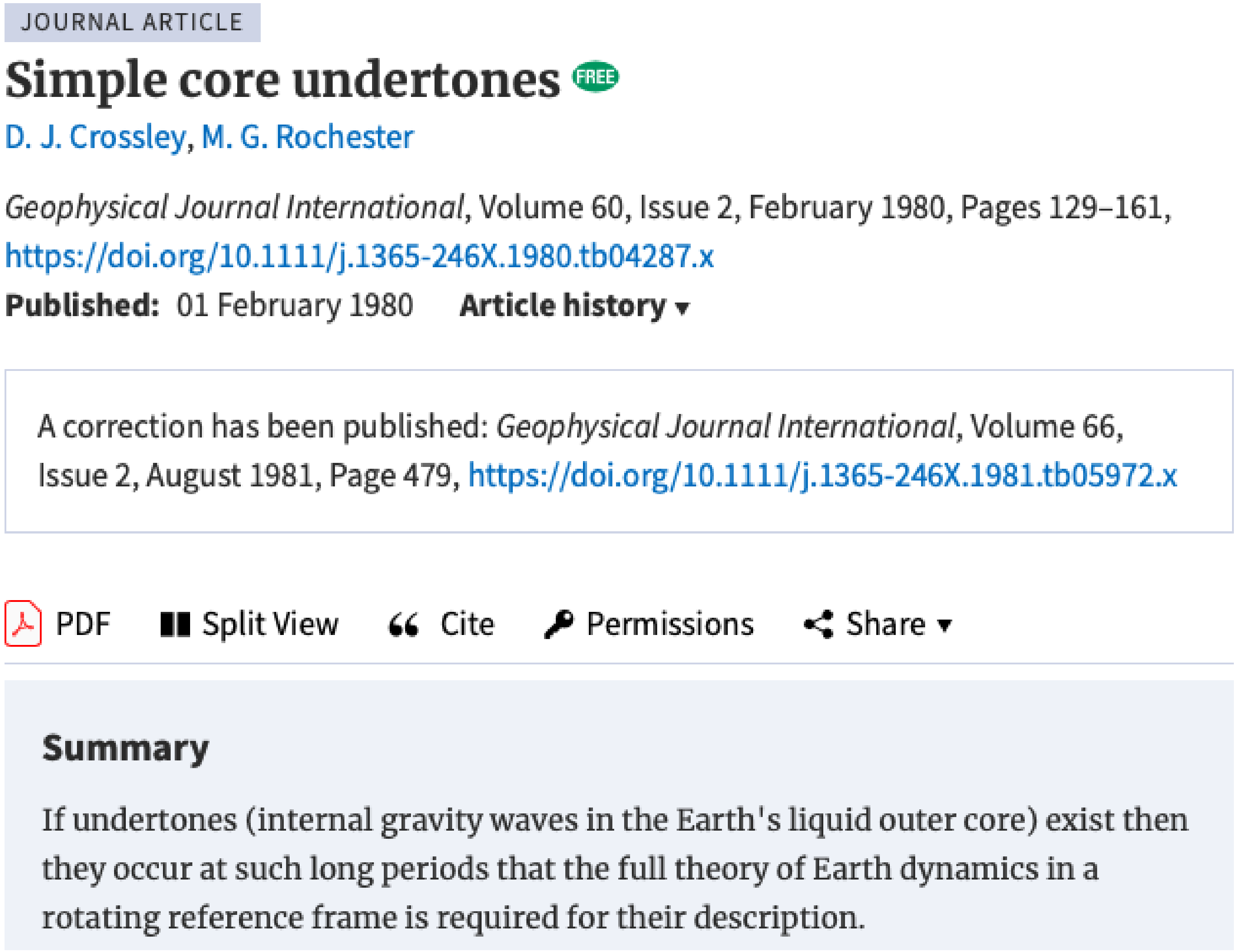
Gravity waves in ocean.

Adapted from aopa.org





Gravity waves in the Earth's core.



JOURNAL ARTICLE

Simple core undertones

D. J. Crossley, M. G. Rochester

Geophysical Journal International, Volume 60, Issue 2, February 1980, Pages 129–161, https://doi.org/10.1111/j.1365-246X.1980.tb04287.x

Published: 01 February 1980 **Article history** ▾

A correction has been published: *Geophysical Journal International*, Volume 66, Issue 2, August 1981, Page 479, https://doi.org/10.1111/j.1365-246X.1981.tb05972.x

Summary

If undertones (internal gravity waves in the Earth's liquid outer core) exist then they occur at such long periods that the full theory of Earth dynamics in a rotating reference frame is required for their description.

Internal gravity waves

- Dispersive buoyancy waves that propagate to all cardinal directions.
- Restoring force is the gravity.
- Horizontally and vertically transport energy and momentum from disturbances.
- Induce turbulent mixing.

$$\hat{\omega}^2 = \frac{N^2(k^2 + l^2) + f^2\left(m^2 + \frac{1}{4H^2}\right)}{k^2 + l^2 + m^2 + \frac{1}{4H^2}}.$$

$$m^2 = \frac{(k^2 + l^2)(N^2 - \hat{\omega}^2)}{\hat{\omega}^2 - f^2} - \frac{1}{4H^2}.$$

$$\tilde{u} = \left(\frac{i\hat{\omega}k - fl}{i\hat{\omega}l + fk}\right)\tilde{v},$$

$$\tilde{p} = \left(\frac{\hat{\omega}^2 - f^2}{\hat{\omega}k + ifl}\right)\tilde{u} = \left(\frac{\hat{\omega}^2 - f^2}{\hat{\omega}l - ifk}\right)\tilde{v},$$

$$\tilde{w} = \frac{\left(m - \frac{i}{2H}\right)\hat{\omega}}{N^2 - \hat{\omega}^2}\tilde{p}.$$

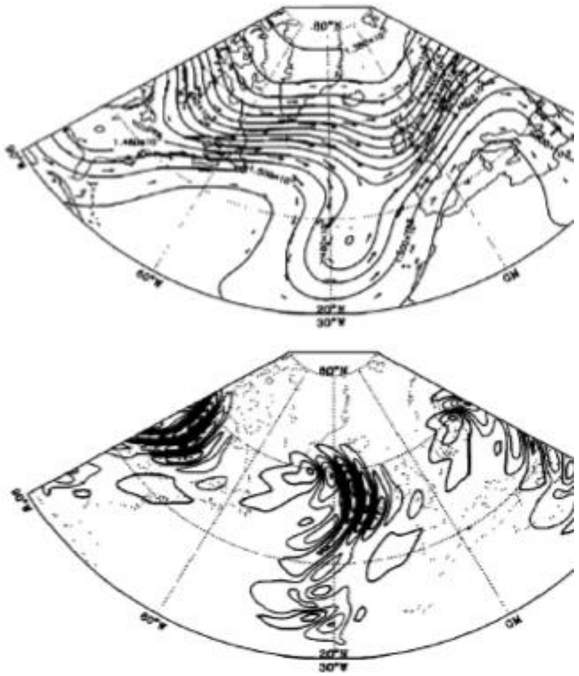
Multiscale phenomenon – need to be paramterized even in current high-resolution global simulations of O(3 km)!!!

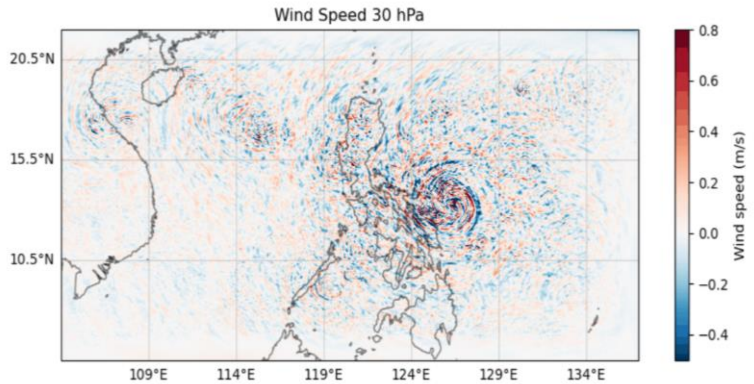
Internal gravity waves

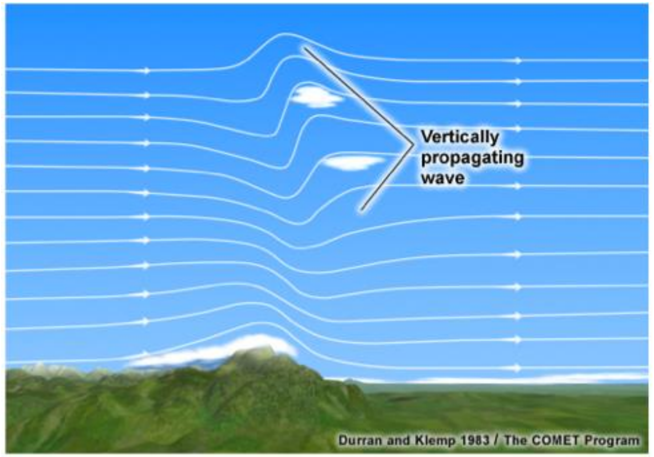
Ubiquitous but also intermittent, multi-scale phenomenon in the atmosphere.

Sources: Orography, convection, jets and fronts, imbalances in the flow..

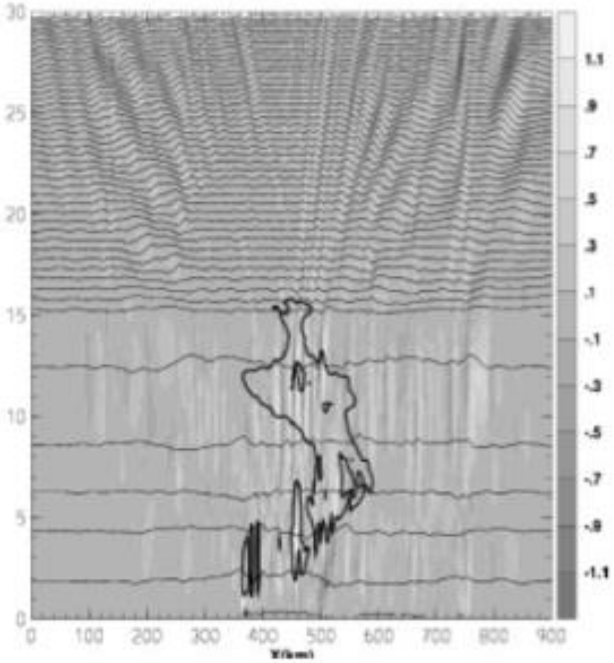
Dissipation at all atmospheric levels – from near surface to the upper atmosphere (secondary, terciary generation completely neglected process in the parameterizations)



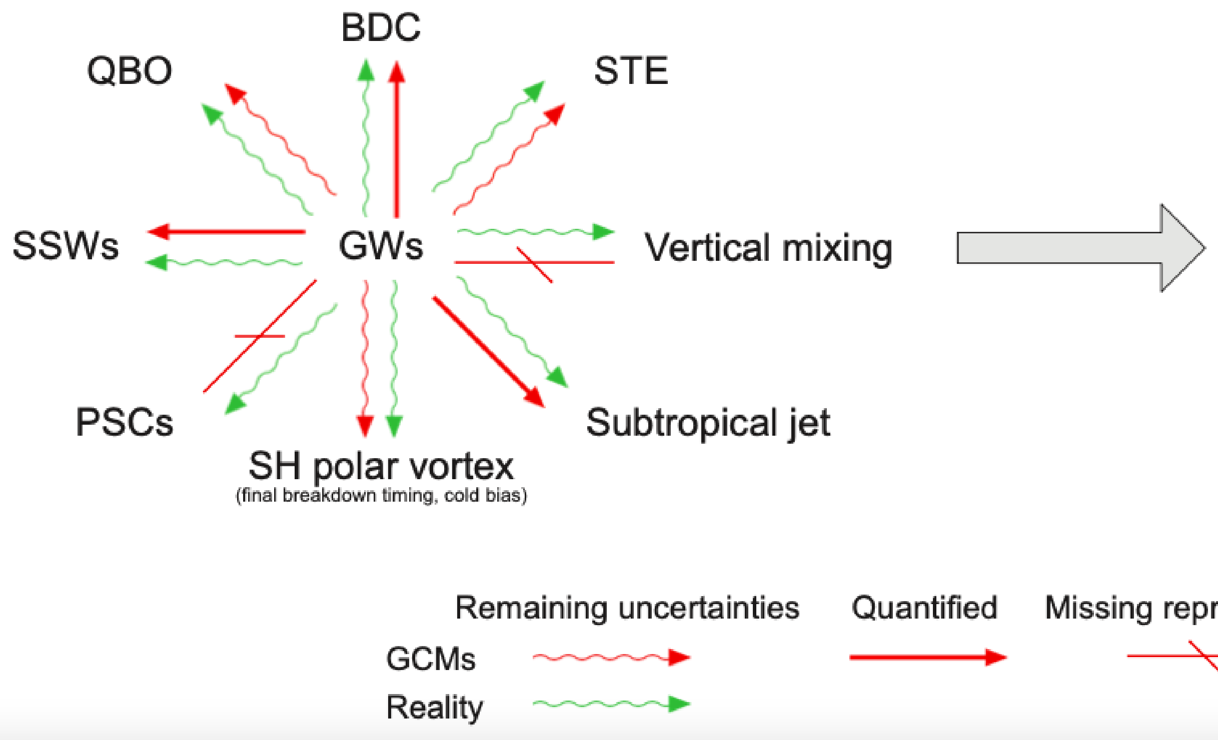




Durran and Klemp 1983 / The COMET Program



Gravity wave importance – an open question



Chemical composition of the atmosphere

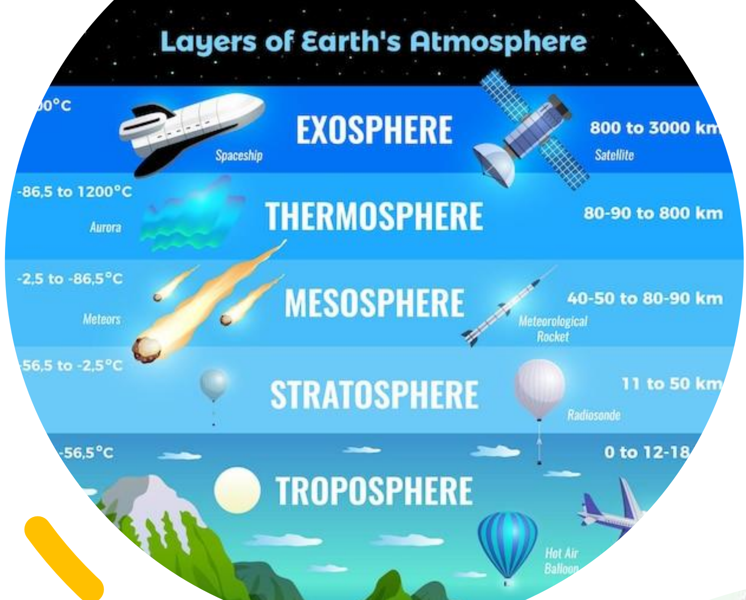
Regional climate projections

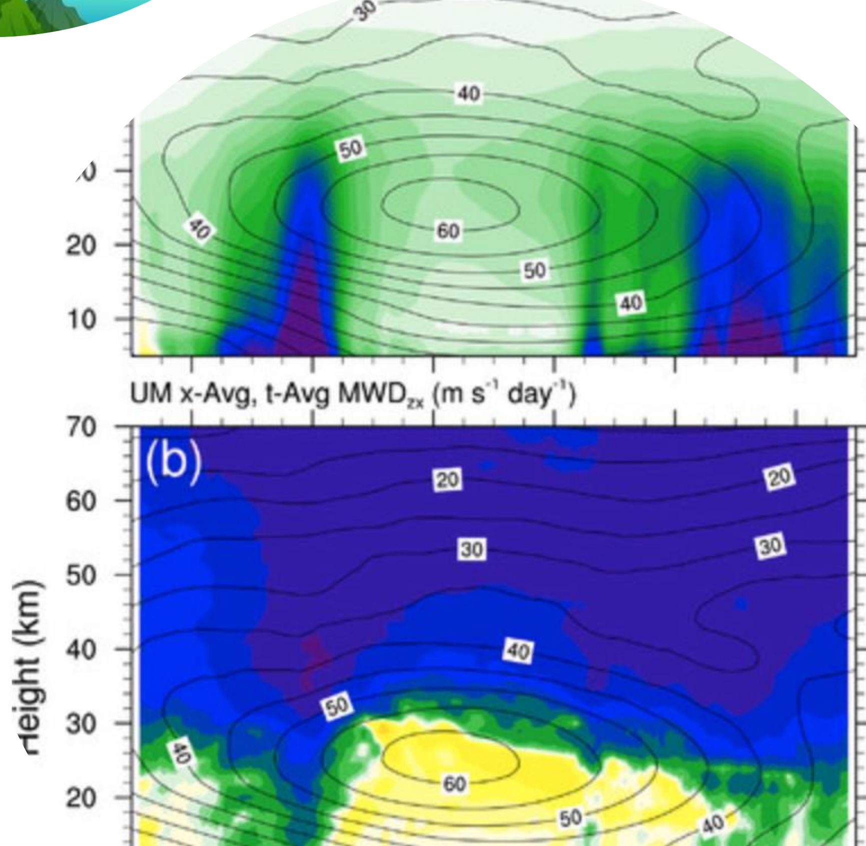
Extreme weather events

Enhanced predictability from weeks to decades

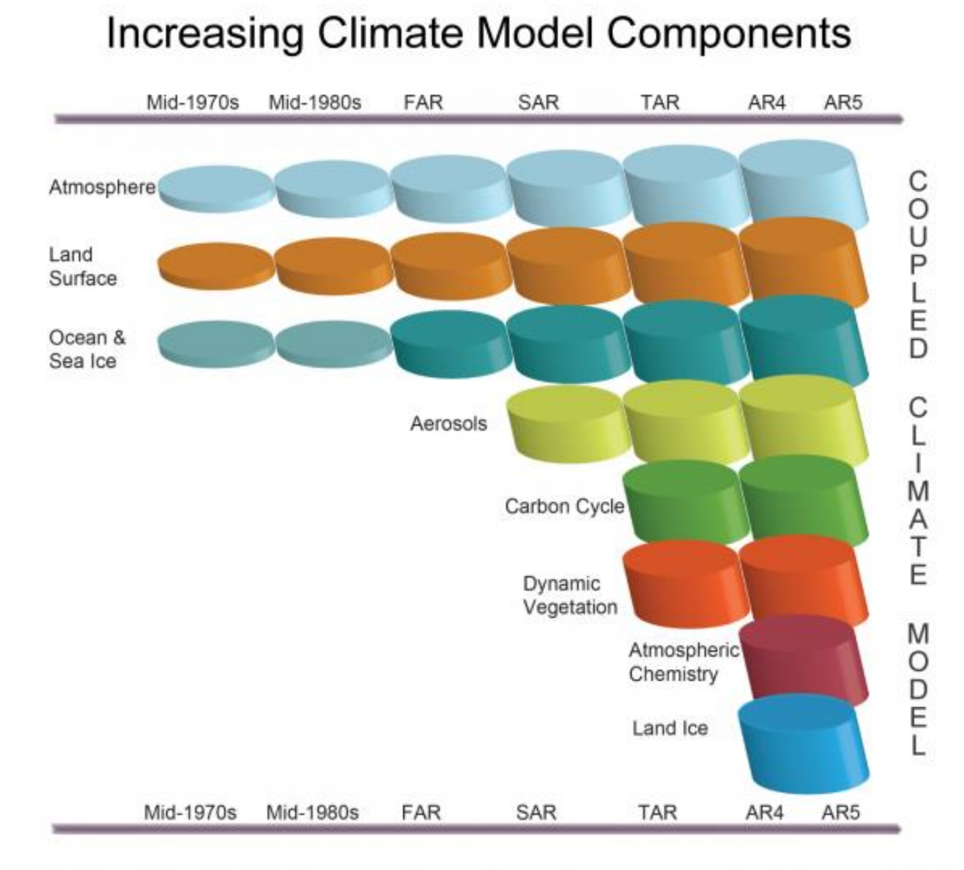
Gravity wave importance – an open question

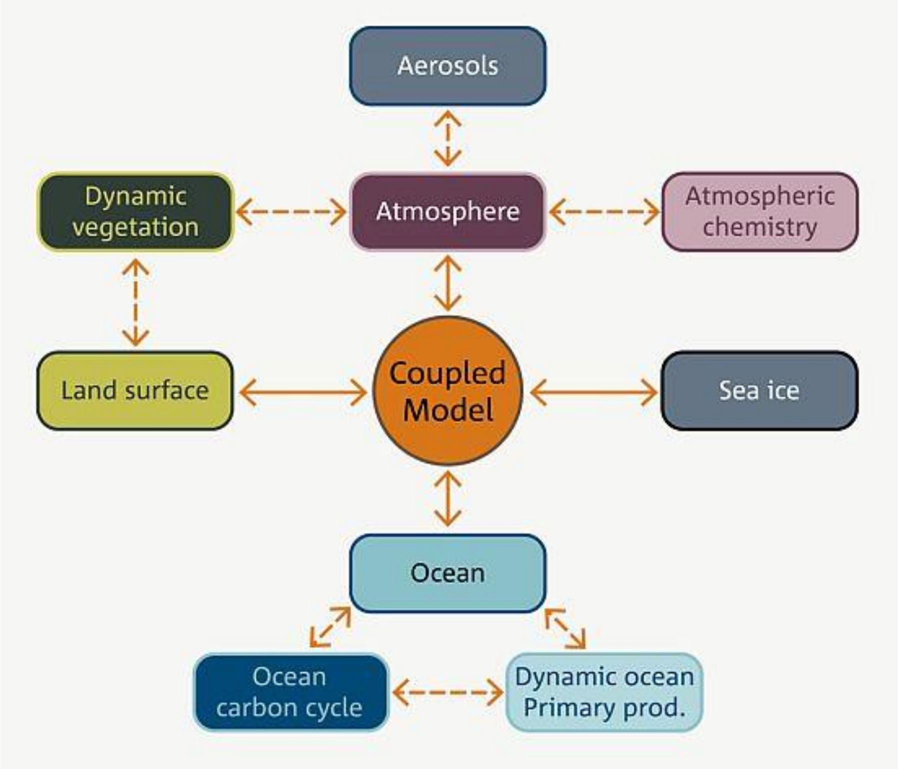
- For illustration – around 460m/s is the speed of rotation of the surface near equator, 350 m/s in midlatitudes.
- The angular momentum of the atmosphere is incredibly efficiently coupled with the solid Earth (turbulence, waves, molecular diffusion).





Chemistry-climate models

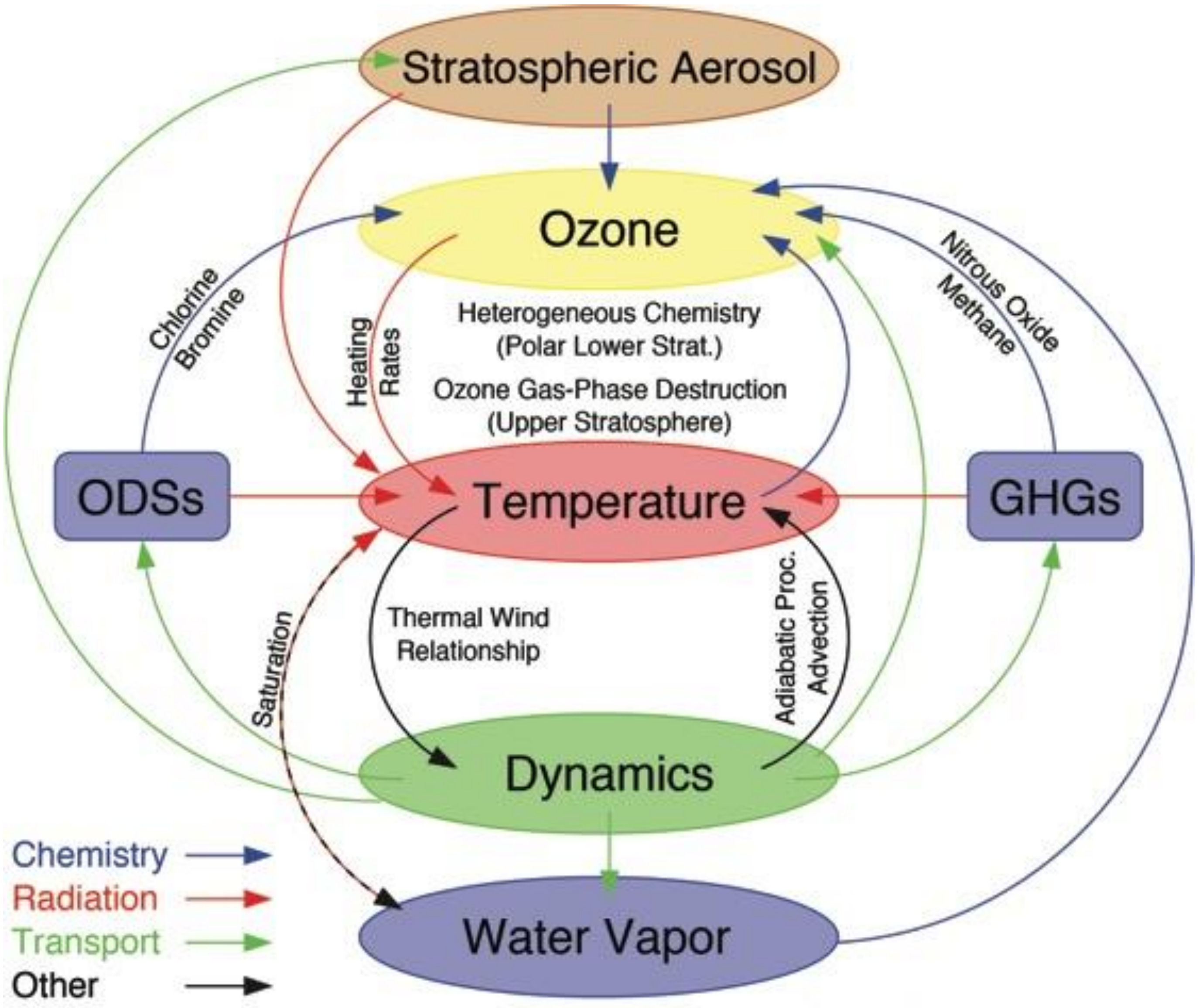




But increasing complexity does not mean improvement…

Chemistry-climate models

- Capturing the chemistry-dynamics-radiation-circulation and transport interactions is essential for reliable future climate projections.
- The atmospheric model is coupled with the interactive chemistry model via model winds and temperature in the one way and concentrations in the other.



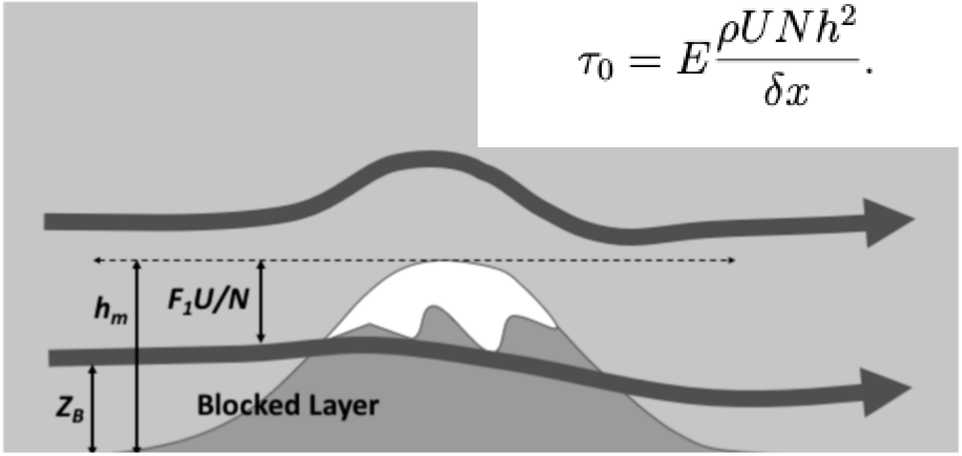
From Chapter 3 of *Scientific Assessment of Ozone Depletion: 2010* (WMO, 2011).

Global circulation models (atmospheric models)

- Dynamical core that solves the equations of motion and parameterization schemes.
- Parameterization in a weather or climate model is a method of replacing processes that are too small-scale or complex by a simplified process.
- Parameterizations for -
- -turbulence
- -convection
- -orographic drag and gravity waves
- -non-orographic gravity waves
- -radiation
- -microphysics and clouds.

Orographic gravity wave parameterizations and simplifications used – sourcing.

- Model



$$\tau_0 = E\frac{\rho U N h^2}{\delta x}.$$

h is a measure of a standard deviation of the subgrid orography.

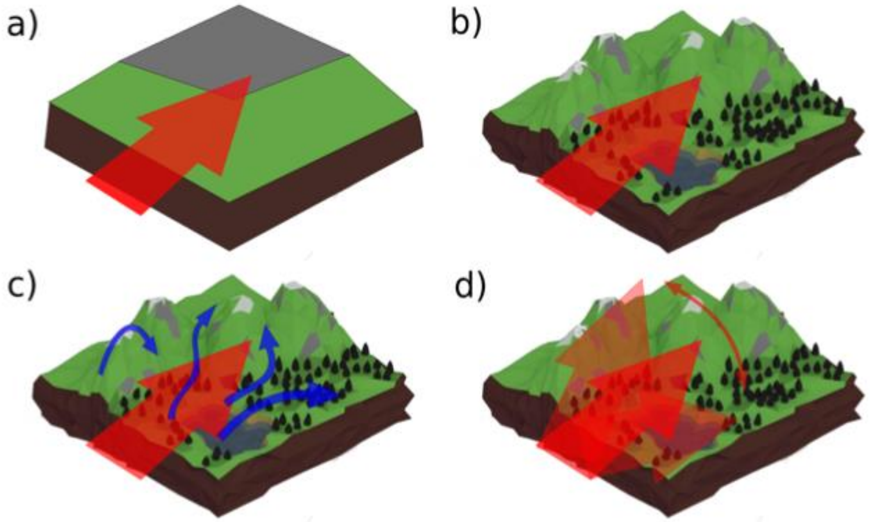
Elliptical mountain is assumed, one or two monochromatic modes launched.

Novel approaches include Fourier transform of SSO, however not yet operational.

- Reality

A spectrum of GWs is launched, high spatial and time variability.

Our modification: Add the variability to the resolved wind field.



Orographic gravity wave parameterizations and simplifications used – propagation.

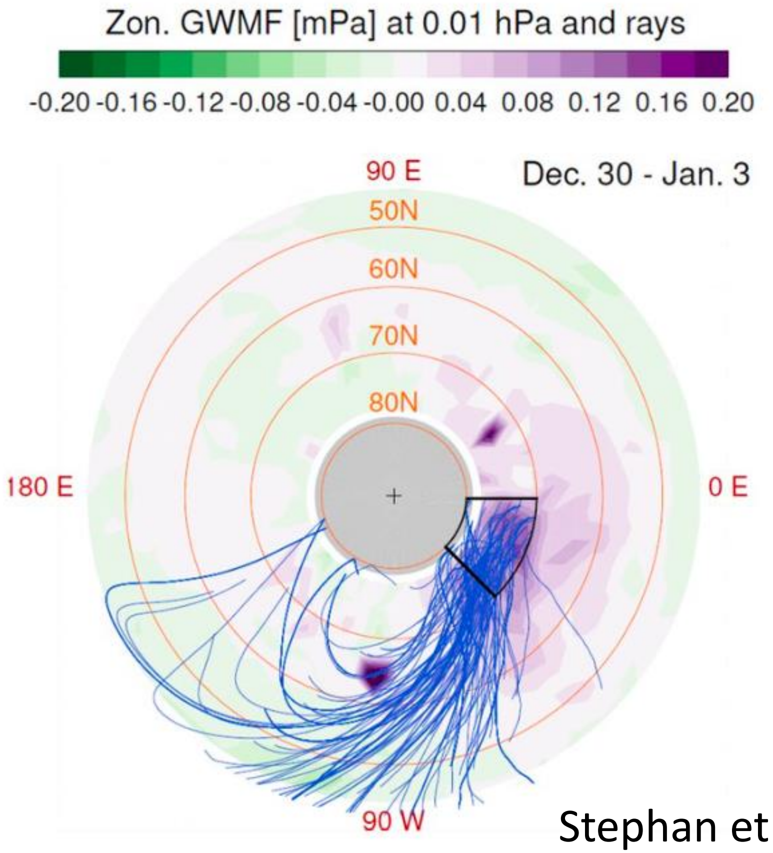
- Model

- Strictly vertical
- Instantaneous (infinite speed of propagation) up to the dissipation level, which is diagnosed from the saturation hypothesis

$$\tau_s = \frac{\rho U^3 \alpha}{N}.$$

- No consideration of non-dissipative effects.

- “Reality”



Stephan et al. 2020

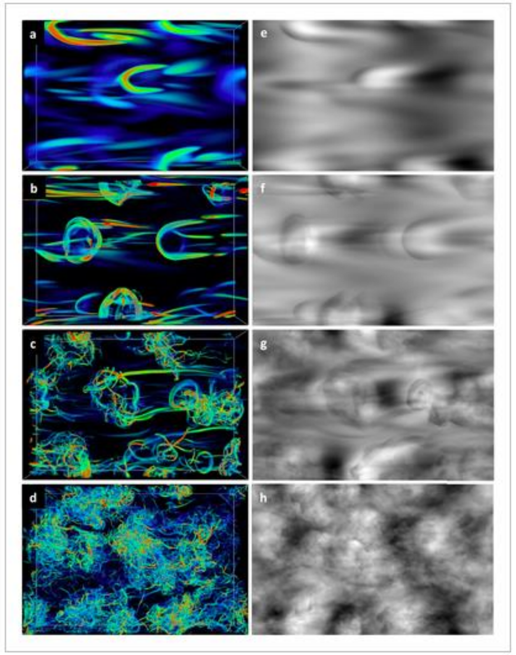
Orographic gravity wave parameterizations and simplifications used – dissipation.

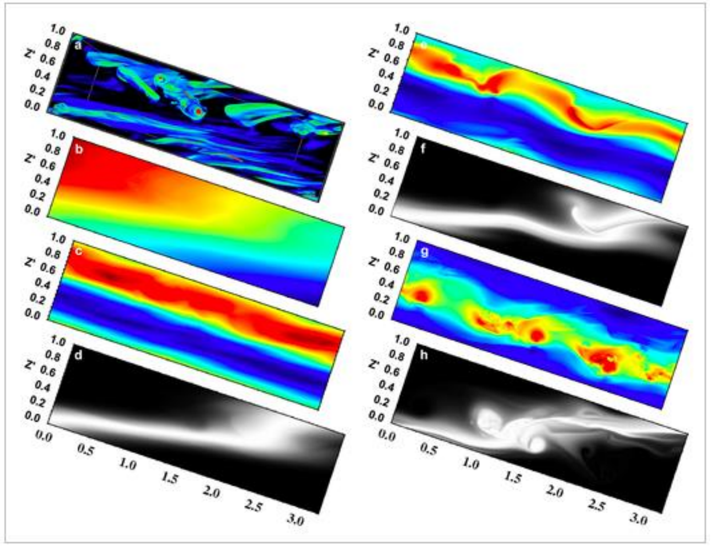
- Model

- Convective instability:
  The portion of momentum flux exceeding the saturation value is deposited.
- Critical level filtering is also included.
- How close to instability we allow the waves to "grow" is controlled by a tuneable parameter (f(Fi))
- Deceleration resulting from the dissipation is communicated to the dynamical core.

- Reality

- Overturning across a wide range of scales, depositio of momentum intimately tied with mixing of particle (not only vertical) and turbulence

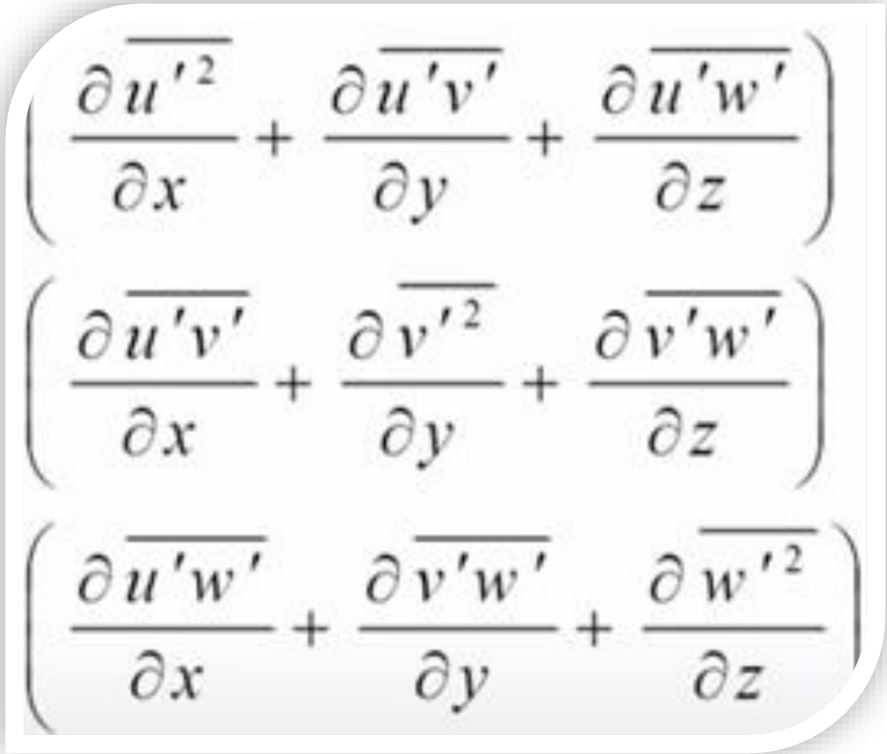




Vortex tubes and knots dynamics.
Fritts et al. (2019)

Parameterized GW effects

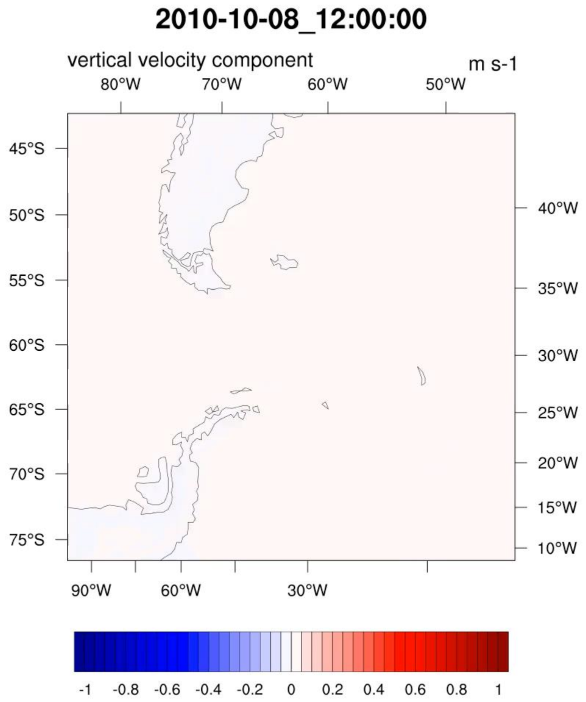
- Mostly only the drag in x and y direction is parameterized (sometimes also heating, but never mixing).
- Traditionally only two terms from the Reynolds stress tensor are taken into account.

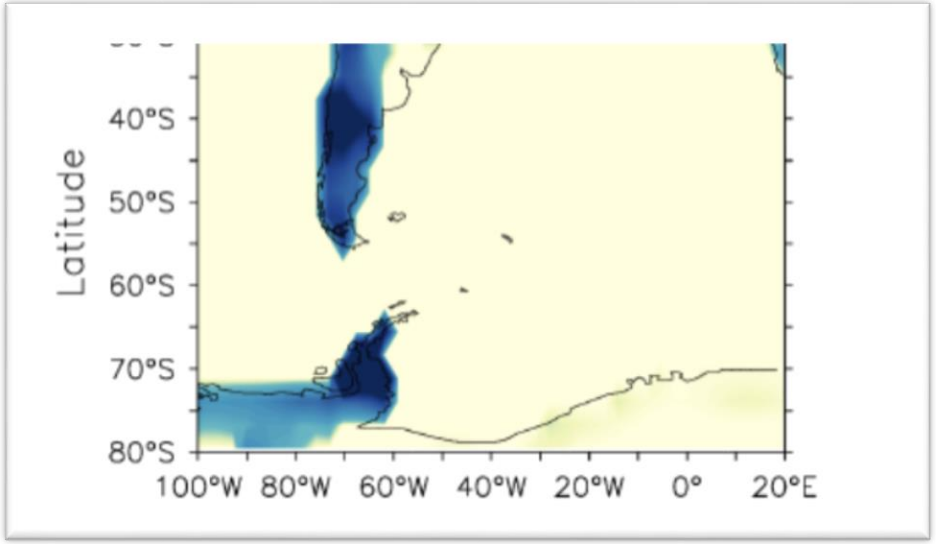


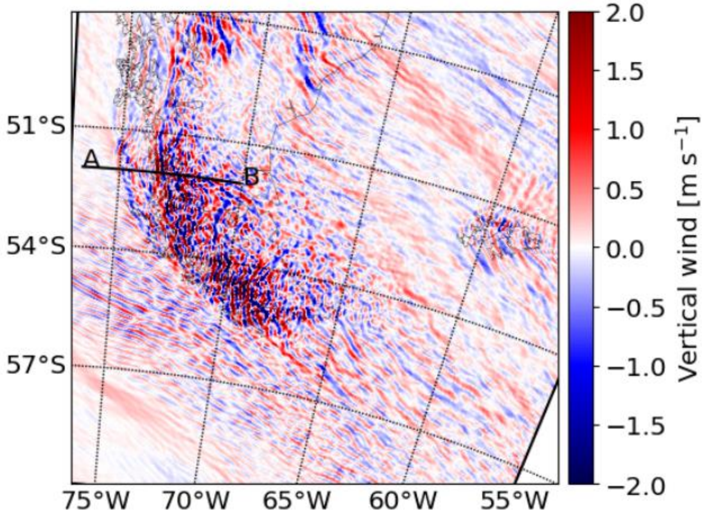
$$\left(\frac{\partial \overline{u'^2}}{\partial x} + \frac{\partial \overline{u'v'}}{\partial y} + \frac{\partial \overline{u'w'}}{\partial z}\right)$$

$$\left(\frac{\partial \overline{u'v'}}{\partial x} + \frac{\partial \overline{v'^2}}{\partial y} + \frac{\partial \overline{v'w'}}{\partial z}\right)$$

$$\left(\frac{\partial \overline{u'w'}}{\partial x} + \frac{\partial \overline{v'w'}}{\partial y} + \frac{\partial \overline{w'^2}}{\partial z}\right)$$







Resulting parameterized drag is overly homogeneous

- Parameterized orographic GW drag in the middle (NH), and visualization of the resolved GW field on the left and right for SH.

Emerging methodological issue

- The dissipative drag deposition (the single parameterized GW effect) is extremely hard to constrain from observations or GW resolving simulations, because there is no optimal methodology for computing it from complex datasets in the Eulerian framework

First issue – decompose the field (no optimal method exists to date).

$$\partial_t(\langle u\rangle + u') + \partial_x\left((\langle u\rangle + u')^2\right) + \partial_y\left((\langle u\rangle + u')(\langle v\rangle + v')\right) + \frac{1}{\hat{\rho}}\partial_z\left(\hat{\rho}(\langle u\rangle + u')w'\right) = -\frac{1}{\hat{\rho}}\partial_x p + f(\langle v\rangle + v')$$

For the sensitivity of the resulting GW drag estimates on the decomposition method please refer to the recent paper Procházková et al. (2023, JAS).

Second issue – the dissipative GW effects emerge in an “average” sense only. But how to define optimal averaging operator?

$$\overline{u'} = 0.$$

versus

$$\overline{\langle\cdot\rangle(\cdot)'} = 0$$

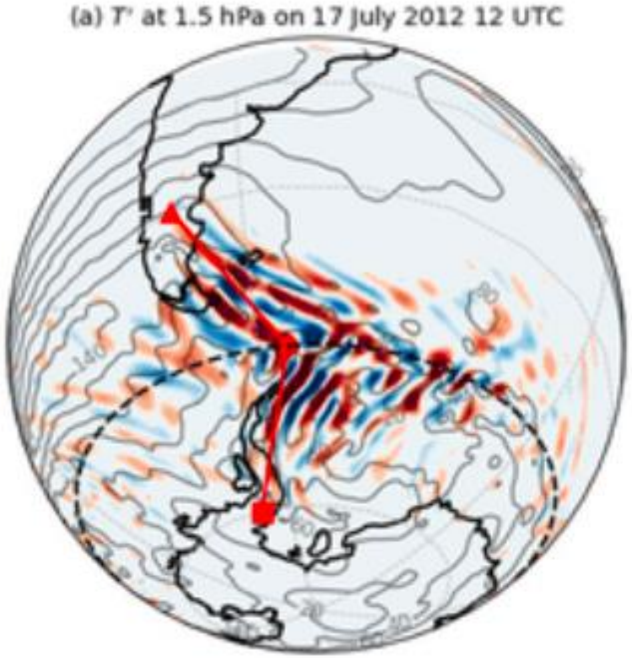
For spatial averaging:

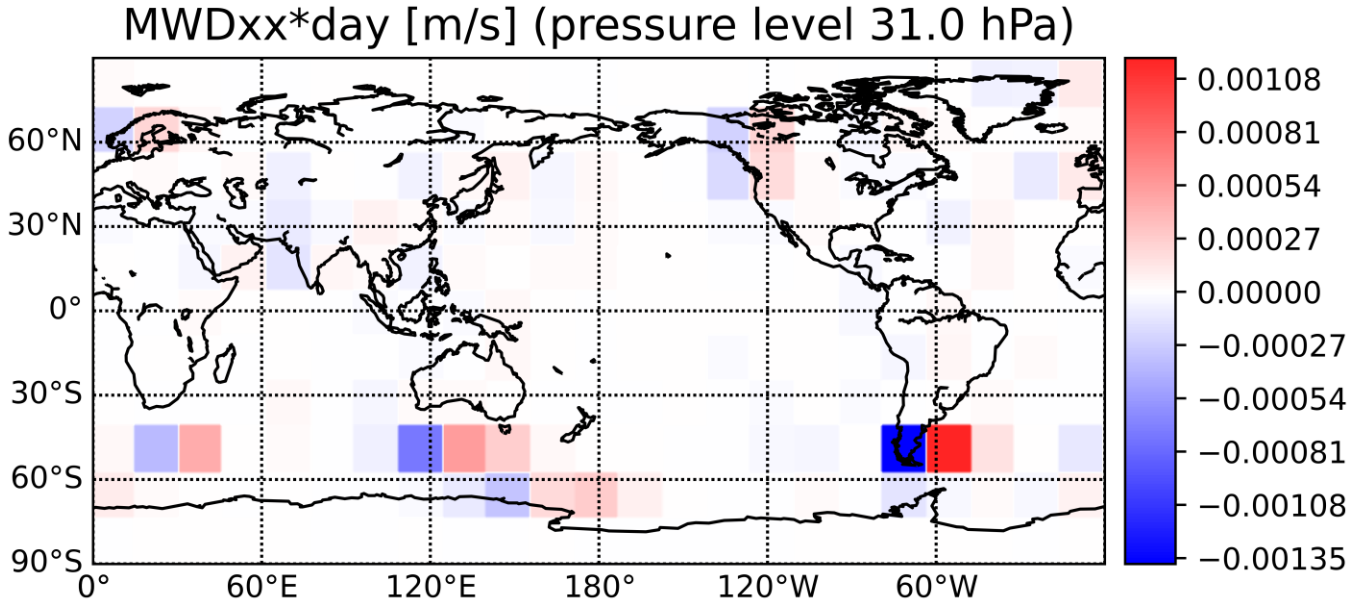
$$MWD_{xx} = -\frac{1}{A}\left[\int (u')^2\,\mathrm{d}y\right]_{x_1}^{x_2},$$

$$MWD_{yx} = -\frac{1}{A}\left[\int u'v'\,\mathrm{d}x\right]_{y_1}^{y_2},$$

$$MWD_{zx} = -\frac{1}{A}\frac{1}{\hat{\rho}}\partial_z\iint \hat{\rho}u'w'\,\mathrm{d}x\,\mathrm{d}y.$$

Emerging methodological issue





$$MWD_{xx} = -\frac{1}{A}\left[\int (u')^2 \,\mathrm{d}y\right]_{x_1}^{x_2},$$

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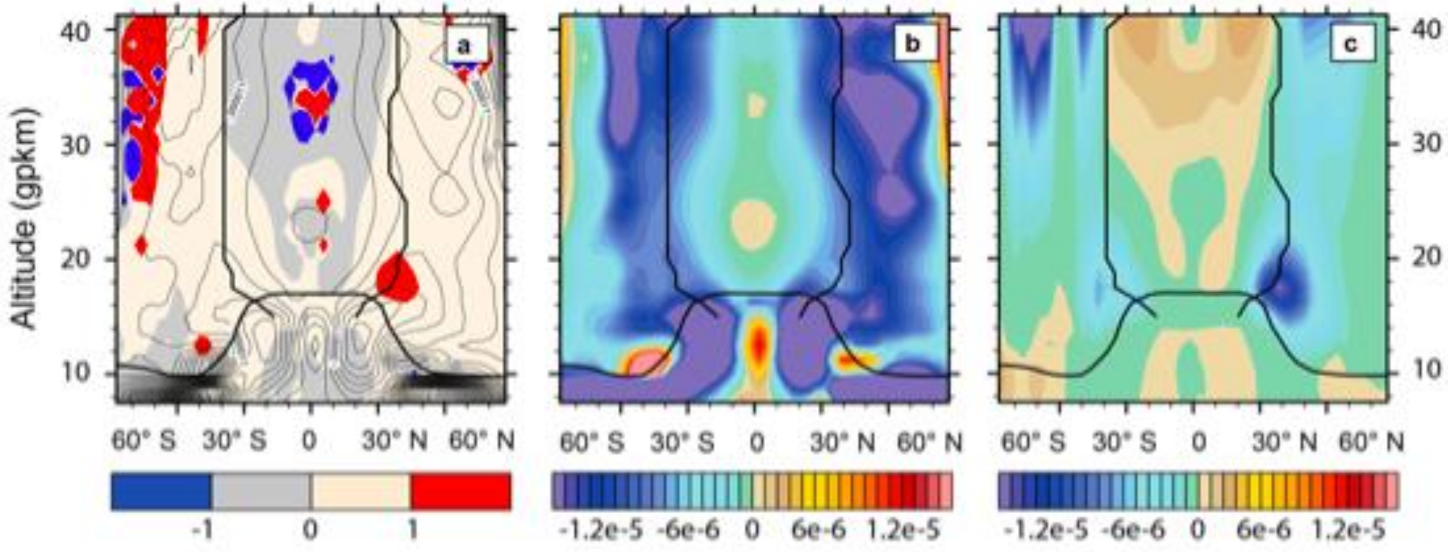
$$MWD_{zx} = -\frac{1}{A}\frac{1}{\hat{\rho}}\partial_z \iint \hat{\rho} u'w' \,\mathrm{d}x\,\mathrm{d}y.$$

Complexity reduction due to averaging

Vertical distribution of the wave drag in climate models (CMAM).

- A) Ratio between parameterized OGWD and resolved wave drag, B) resolved wave drag, C) OGWD.



How to compute the resolved wave drag? (Resolved waves≈Rossby waves)

- Primitive equations - decomposition into zonal averages and corresponding perturbations.
- Modification of the zonal mean meridional and vertical velocities:

$$\overline{v}^* = \overline{v} - \rho_0^{-1}\frac{\partial}{\partial z}\left(\frac{\rho_0\overline{v'\theta'}}{\overline{\theta}_z}\right) \qquad \overline{w}^* = \overline{w} + \frac{1}{a\cos\phi}\frac{\partial}{\partial\phi}\left(\frac{\cos\phi\,\overline{v'\theta'}}{\overline{\theta}_z}\right)$$

- The resulting TEM zonal-mean momentum equation:

$$\nabla\cdot\mathbf{F} \equiv (a\cos\phi)^{-1}\frac{\partial}{\partial\phi}(F^{(\phi)}\cos\phi) + \frac{\partial F^{(z)}}{\partial z}$$

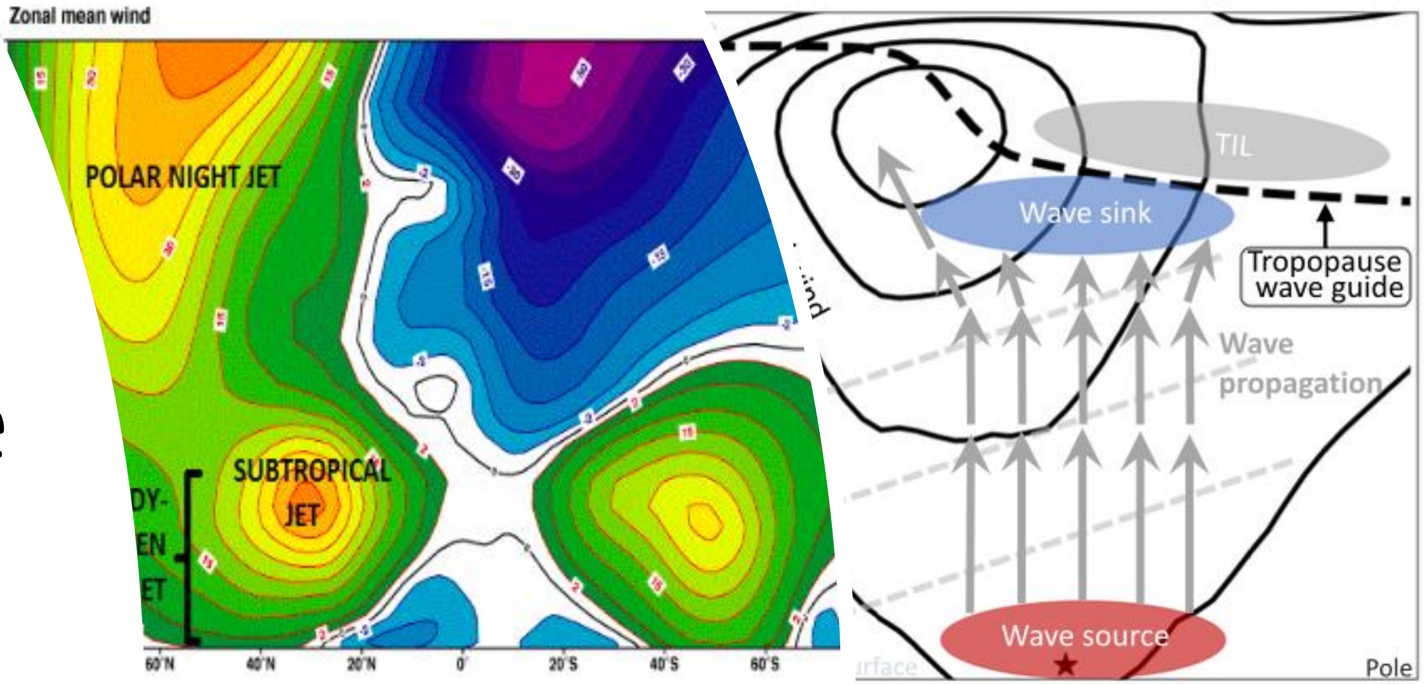
$$\overline{u}_t + \overline{v}^*\left[\frac{(\overline{u}\cos\phi)_{,\phi}}{a\cos\phi} - f\right] + \overline{w}^*\overline{u}_{,Z} = \frac{\nabla\cdot\mathbf{F}}{\rho_0 a\cos\phi} + \overline{G}_\lambda,$$

- **F** is the Elliassen-Palm flux and its divergence quantifies the resolved wave drag.

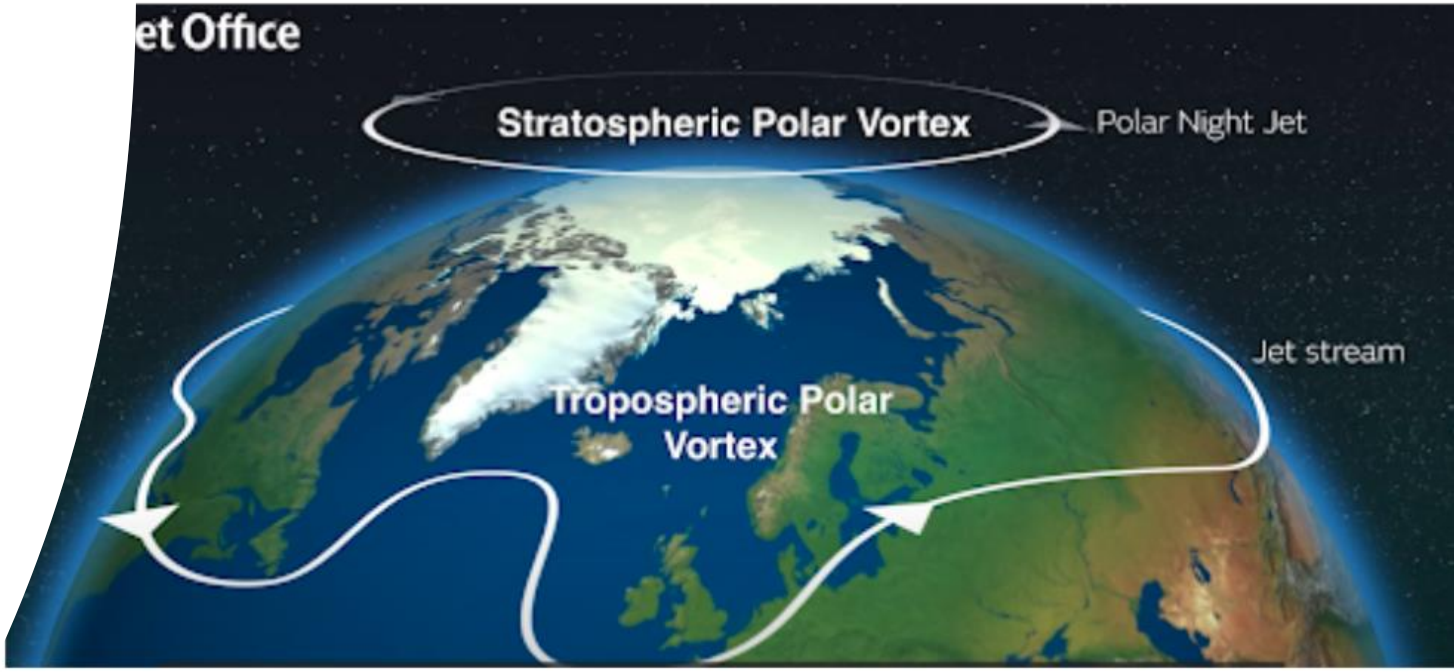
$$F^{(\phi)} \equiv \rho_0 a\cos\phi(\bar{u}_z\,\overline{v'\theta'}/\bar{\theta}_z - \overline{v'u'}),$$

$$F^{(z)} \equiv \rho_0 a\cos\phi\{[f - (a\cos\phi)^{-1}(\bar{u}\cos\phi)_\phi]\overline{v'\theta'}/\theta_z - \overline{w'u'}\};$$

Internal gravity wave importance for climate model dynamics

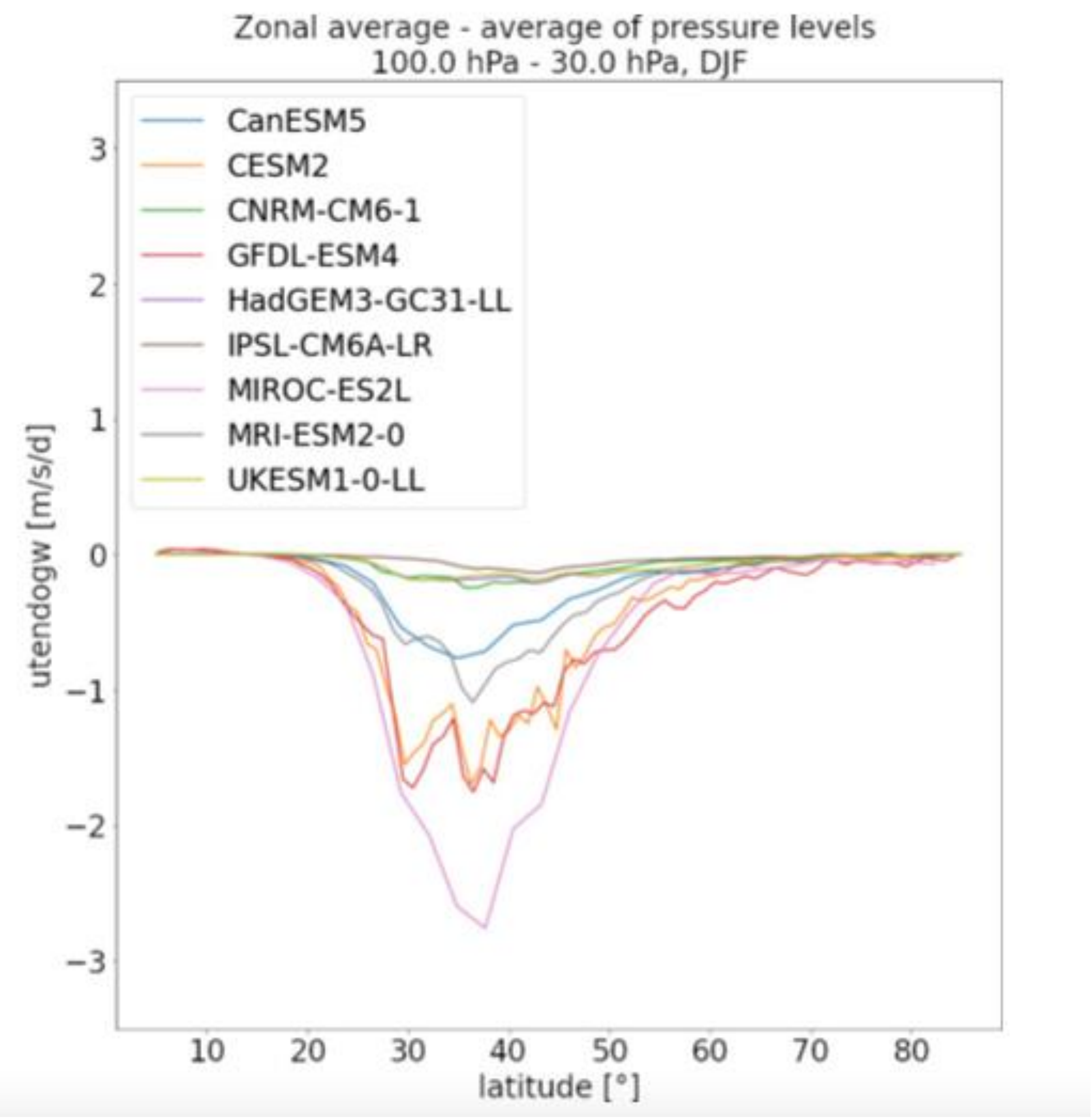


Adapted from Boljka and Birner (2022) and Met Office.

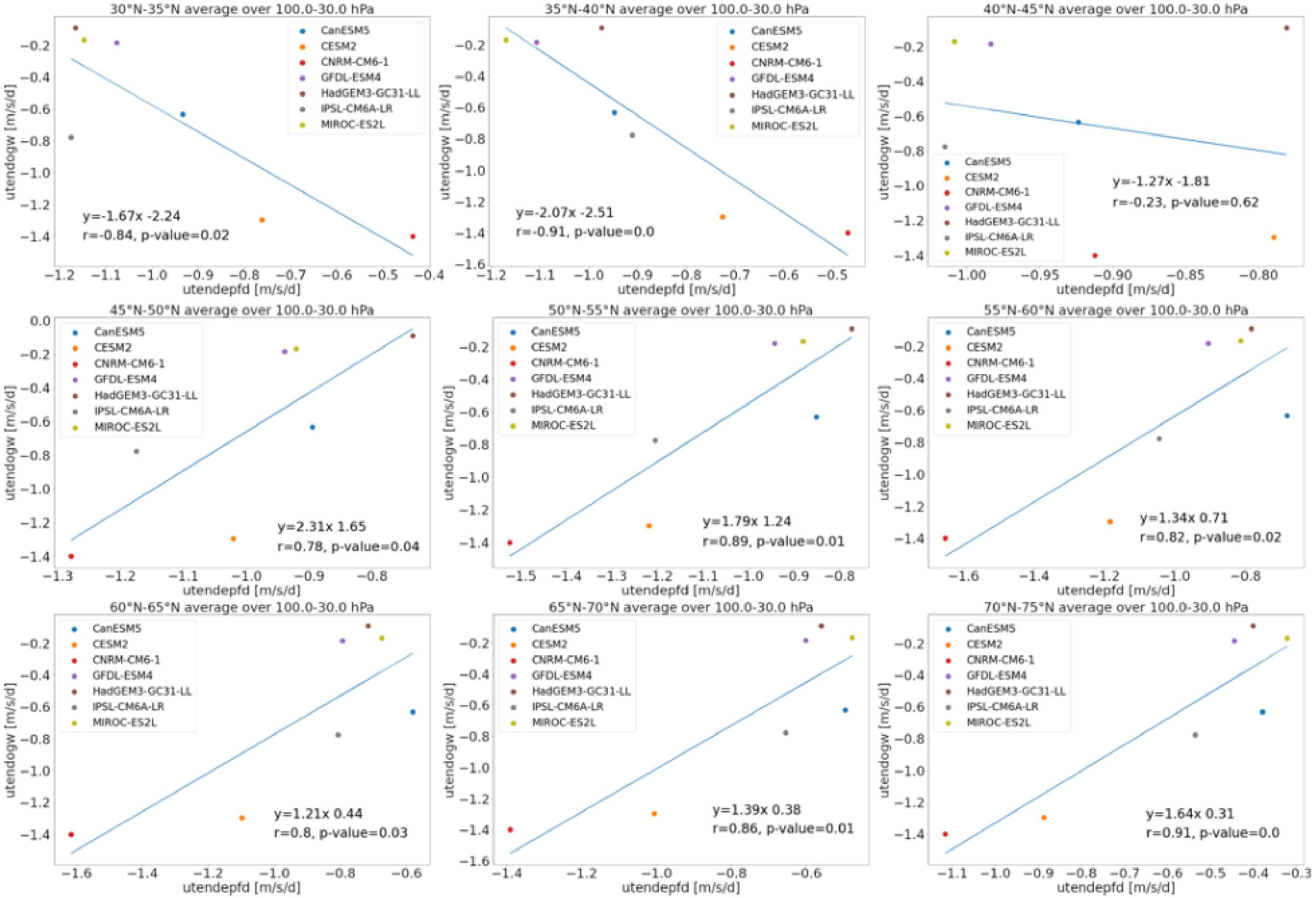


Climate Model Intercomparison Project Phase 6 (CMIP6)

- Differences caused by a large part by the modeler’s subjective choice of the inverse Froude number in the parameterization for their simulations.



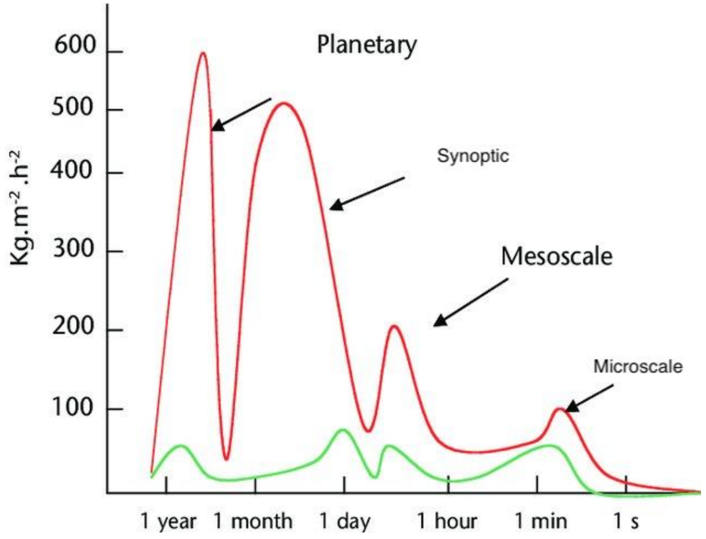
Parameterized OGW drag controls the resolved dynamics in the stratosphere in CMIP6

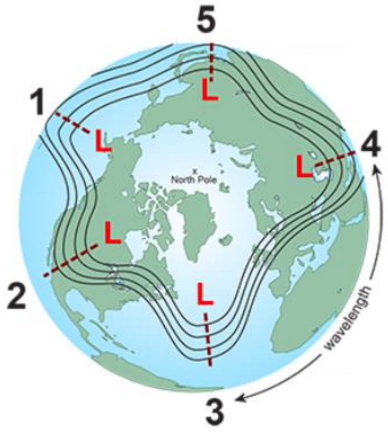


Hájková and Šácha, CliDyn, in review.

Leading hypothesis

- The influence of the parameterized OGW drag in the models is to a large extent artificial.
- We must revisit our understanding of climate GW effects.
- Informed by the previous step, we must modify the parameterizations to mitigate the uncertainty of future climate projections.





An example of a five planetary-wave pattern.

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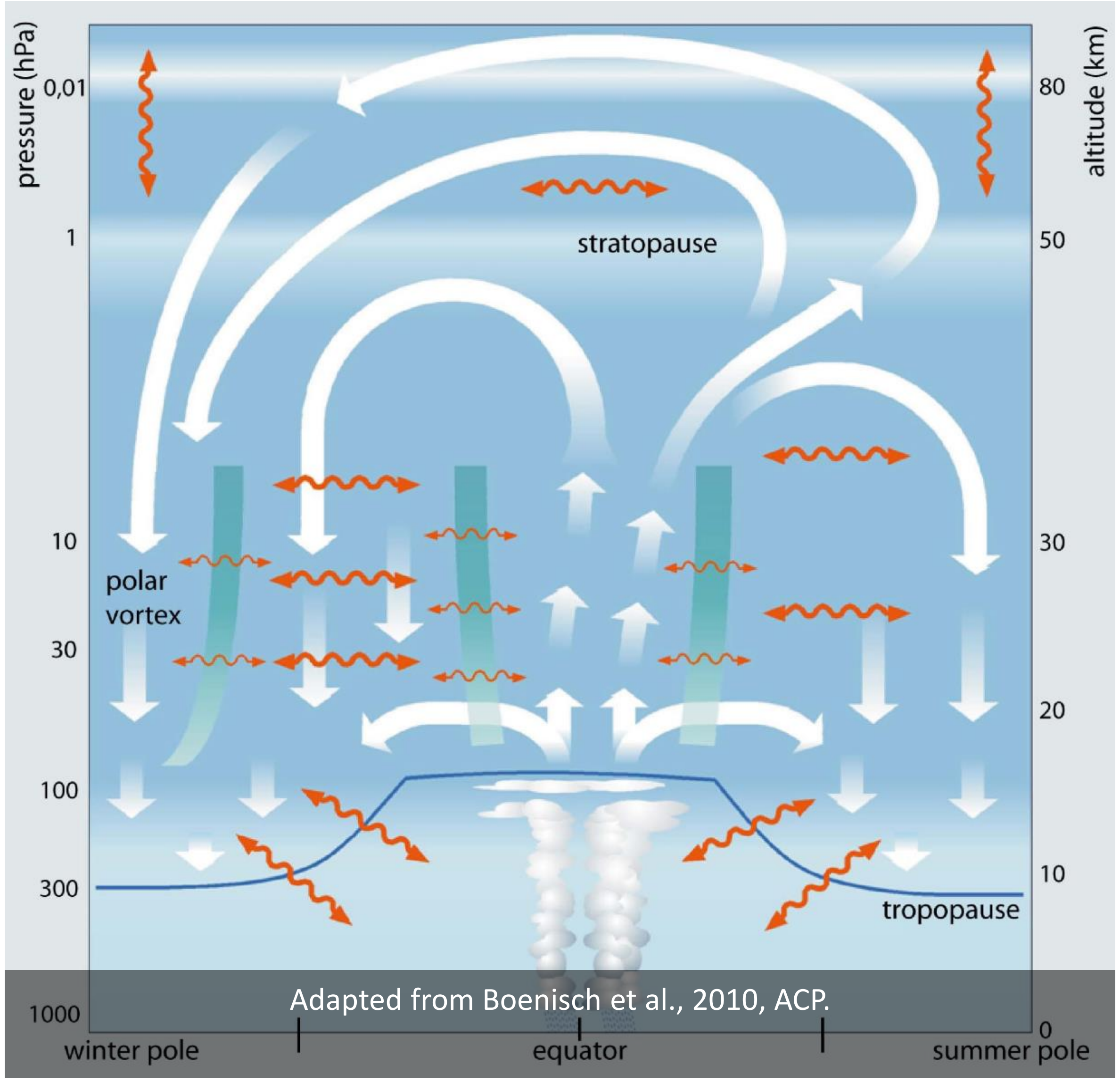
Unravelling climate impacts of atmospheric internal gravity waves (23-04921M)

- GW research group at KFA (2023-2027).
- https://kfa.mff.cuni.cz/?page_id=2134&lang=en
- Aims at revisiting the climate GW effects based on the analysis of high-resolution simulations and use this understanding to constrain and modify GW parameterizations.

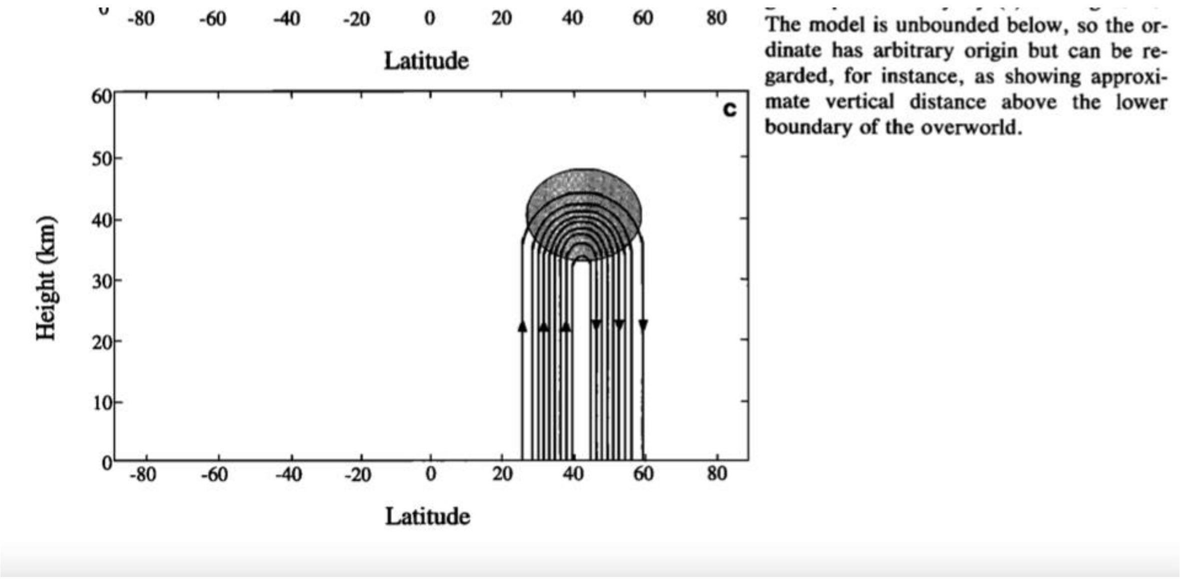
- *Keep your fingers crossed for us over the next 5 years!*

Brewer-Dobson circulation

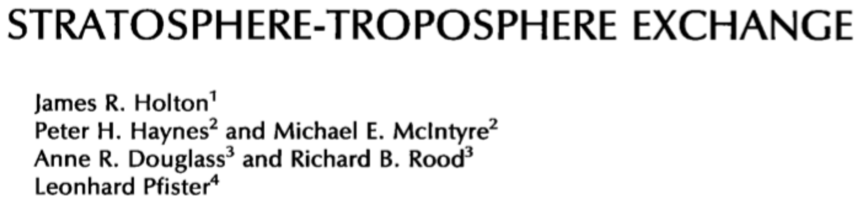
Interhemispheric meridional overturning circulation influencing the middle atmospheric composition.



Adapted from Boenisch et al., 2010, ACP.



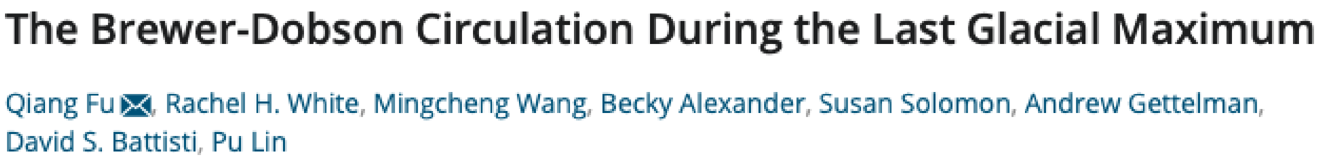
The model is unbounded below, so the ordinate has arbitrary origin but can be regarded, for instance, as showing approximate vertical distance above the lower boundary of the overworld.



STRATOSPHERE-TROPOSPHERE EXCHANGE

James R. Holton[1]
Peter H. Haynes[2] and Michael E. McIntyre[2]
Anne R. Douglass[3] and Richard B. Rood[3]
Leonhard Pfister[4]

Wave driving paradigm

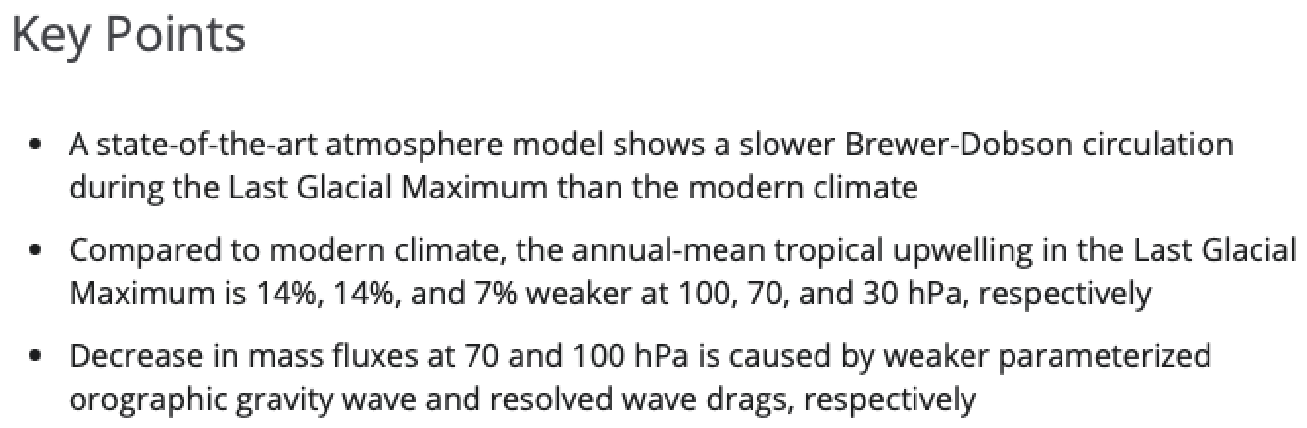


The Brewer-Dobson Circulation During the Last Glacial Maximum

Qiang Fu ✉, Rachel H. White, Mingcheng Wang, Becky Alexander, Susan Solomon, Andrew Gettelman, David S. Battisti, Pu Lin

Many papers overinterpret the role of waves:

One recent striking example from GRL (attracted already 13 citations).



Key Points

- A state-of-the-art atmosphere model shows a slower Brewer-Dobson circulation during the Last Glacial Maximum than the modern climate
- Compared to modern climate, the annual-mean tropical upwelling in the Last Glacial Maximum is 14%, 14%, and 7% weaker at 100, 70, and 30 hPa, respectively
- Decrease in mass fluxes at 70 and 100 hPa is caused by weaker parameterized orographic gravity wave and resolved wave drags, respectively

Many papers overinterpret the role of waves:

One recent striking example from GRL (attracted already 13 citations).

Outstanding issue regarding long-term BDC changes:

- Modeled BDC trends cannot be fully matched with observations.
- Besides the uncertainty in driving of the circulation, drivers of the trend are also uncertain.
- Namely, there was a question how the BDC trends overlap with structural changes of the atmosphere.

Geophysical Research Letters

Research Letter | Free Access

Is the Brewer-Dobson circulation increasing or moving upward?

Sophie Oberländer-Hayn, Edwin P. Gerber, Janna Abalichin, Hideharu Akiyoshi, Andreas Kerschbaumer, Anne Kubin, Markus Kunze, Ulrike Langematz ... See all authors

First published: 06 February 2016 | https://doi.org/10.1002/2015GL067545 | Citations: 38

Tropical upwelling

- Useful scalar proxy for the BDC strength, given by (Rosenlof, 1995):

$$U_{ver.} = 2\pi a^2 \int_{\varphi_1}^{\varphi_2} \rho \overline{w}^* \cos\varphi \, \mathrm{d}\varphi$$

- Our new approach including meridional transport:

$$U = 2\pi a \int_{\varphi_1}^{\varphi_2} \rho \left(\overline{v}^*, \overline{w}^*\right) \cdot \mathrm{d}\vec{l}$$

- Transport across two pressure levels (100 and 70 hPa) and the tropopause is analyzed

What influences time changes in *U*?

- Not only changes in the residual circulation!

$$U = 2\pi a \int_{\varphi_1}^{\varphi_2} \rho \left(\overline{v}^*, \overline{w}^* \right) \cdot \mathrm{d}\vec{l}$$

- Our idea is to split time changes in transport into individual kinematic terms:

$$\frac{\mathrm{d}U}{\mathrm{d}t} = \ldots + \ldots + \ldots + \ldots + \ldots + \ldots$$

This is disentangled in Šácha et al.(GRL, in review) using a methodology of decomposition to individual kinematic factors influencing the change.

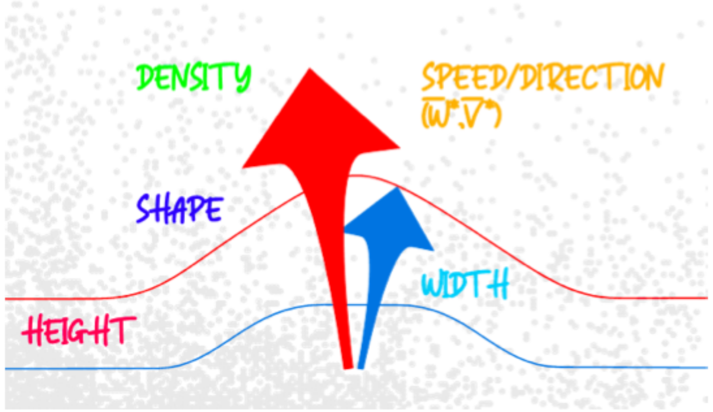


Figure S1. Schematic illustration of the contributions to the change of net upwelling across a material line A (blue line) and B (red line). The net change consists of contributions from changes of the speed (size of the arrow) and direction (inclination of the arrow) of the circulation, the width of the upwelling region, the vertical shift (height changes) of the material line, changes in the shape of the material line controlling the effectivity of meridional transport and of changing density of air that is connected with the spatially variable temperature trends (stippled background).

$$
\begin{aligned}
\delta U = {} & \overbrace{\int_{\varphi_2(t)}^{\varphi_2(t+\delta t)} \mathrm{d}T(\overline{z}(t^*,\varphi),t^*,\varphi) - \int_{\varphi_1(t)}^{\varphi_1(t+\delta t)} \mathrm{d}T(\overline{z}(t^*,\varphi),t^*,\varphi)}^{\text{width term}} + \\
& + \overbrace{2\pi a^2 \int_{\varphi_1}^{\varphi_2} \frac{\partial \overline{z}_{str}}{\partial t} \frac{\partial \overline{\rho}(\overline{w}^* + \overline{v}^* \tan\alpha)}{\partial z} \cos\varphi \, \mathrm{d}\varphi \cdot \delta t}^{\text{z term}} + \\
& + \overbrace{2\pi a^2 \int_{\varphi_1}^{\varphi_2} \overline{\rho} \frac{\partial \overline{w}^*}{\partial t} \cos\varphi \, \mathrm{d}\varphi \cdot \delta t}^{\overline{w}^* \text{ term}} + \overbrace{2\pi a^2 \int_{\varphi_1}^{\varphi_2} \tan\alpha \overline{\rho} \frac{\partial \overline{v}^*}{\partial t} \cos\varphi \, \mathrm{d}\varphi \cdot \delta t}^{\overline{v}^* \text{ term}} + \\
& + \overbrace{2\pi a^2 \int_{\varphi_1}^{\varphi_2} \overline{w}^* \frac{\partial \overline{\rho}}{\partial t} \cos\varphi \, \mathrm{d}\varphi \cdot \delta t + 2\pi a^2 \int_{\varphi_1}^{\varphi_2} \tan\alpha \overline{v}^* \frac{\partial \overline{\rho}}{\partial t} \cos\varphi \, \mathrm{d}\varphi \cdot \delta t}^{\varrho \text{ term}} + \\
& + \overbrace{2\pi a^2 \int_{\varphi_1}^{\varphi_2} \frac{\overline{\rho}\overline{v}^*}{\cos^2\alpha} \frac{\partial \alpha}{\partial t} \cos\varphi \, \mathrm{d}\varphi \cdot \delta t}^{\text{shape term}} .
\end{aligned}
\tag{4}
$$

Is the decomposition accurate?

- For pressure levels almost perfectly, for the tropopause there is a small error

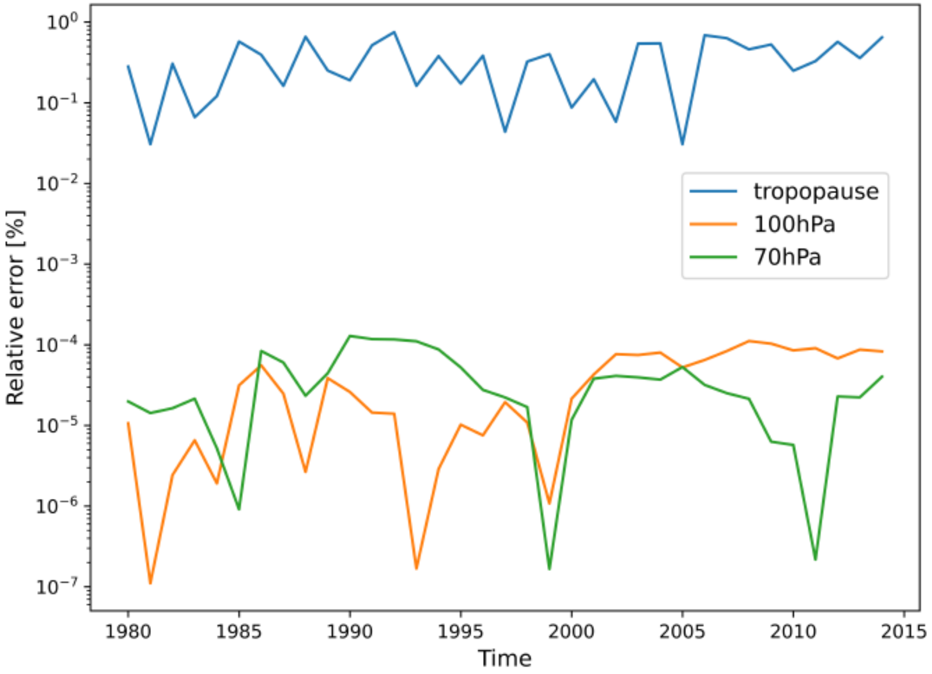
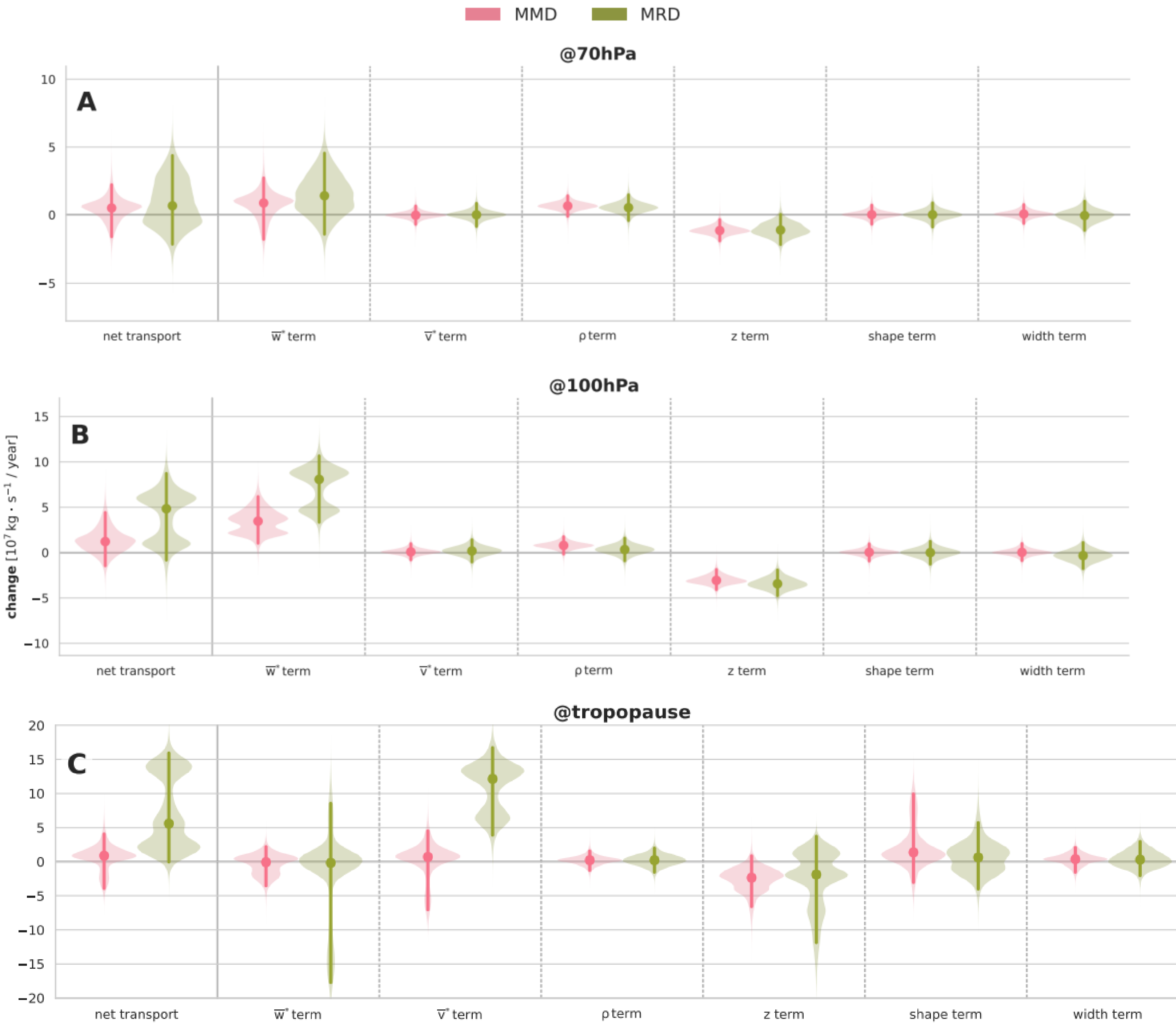


Figure 3.2: Time evolution of the relative error of the decomposition method applied to the ERA5 annual mean data for 1980-2014 at three material lines (70 hPa, 100 hPa, and tropopause).

MMD vs MRD: (1979 – 2014)



Conclusions

1. New methodology was successfully derived and implemented
2. Results underline that the net tropical upwelling is sensitive to all detailed mechanisms connected to climate change (troposheric warming and stratospheric cooling), but to different amounts at different material lines
3. Larger spread is found among the reanalyses than models regarding the net upwelling and individual contribution changes

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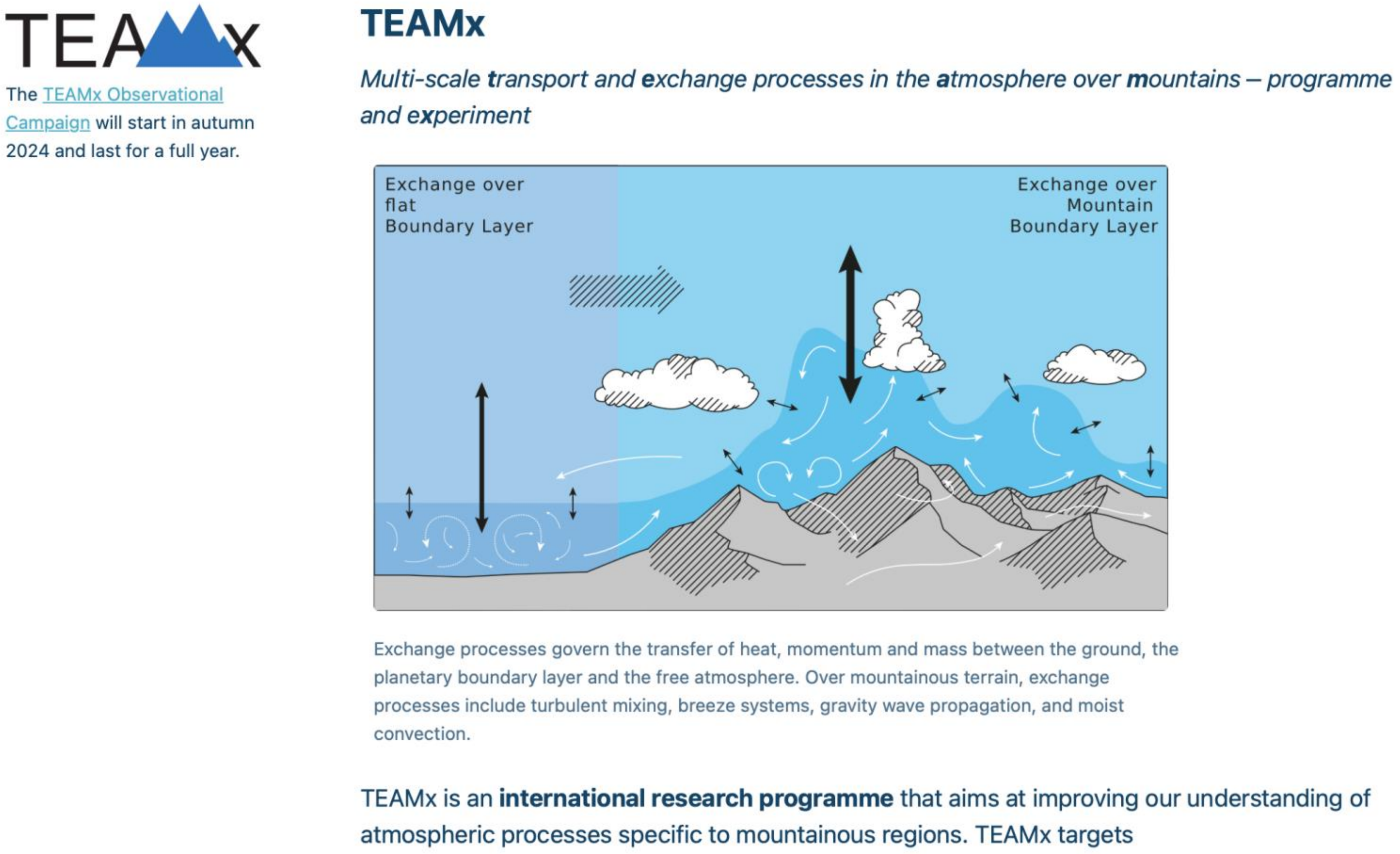

The [TEAMx Observational Campaign] will start in autumn 2024 and last for a full year.

TEAMx

*Multi-scale **t**ransport and **e**xchange processes in the **a**tmosphere over **m**ountains – programme and e**x**periment*

Exchange processes govern the transfer of heat, momentum and mass between the ground, the planetary boundary layer and the free atmosphere. Over mountainous terrain, exchange processes include turbulent mixing, breeze systems, gravity wave propagation, and moist convection.

TEAMx is an **international research programme** that aims at improving our understanding of atmospheric processes specific to mountainous regions. TEAMx targets