Lateral Gravity Wave Propagation in the Extratropical Stratosphere from 44 Years of ERA5

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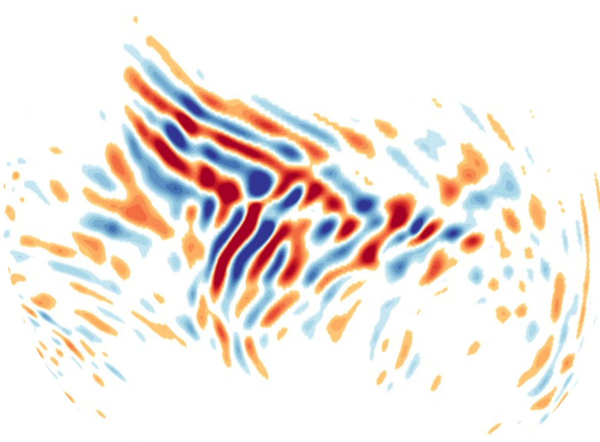
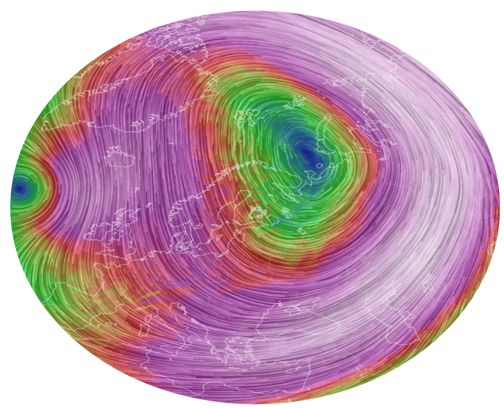
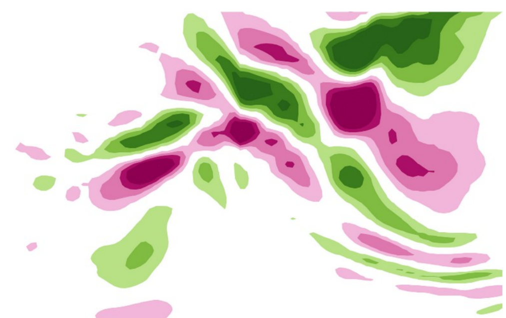
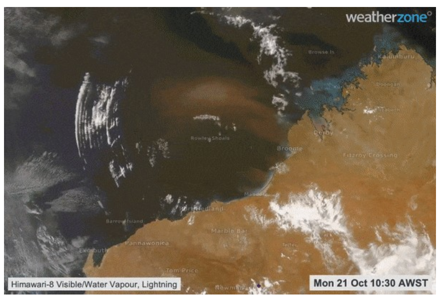
Deutsches Zentrum für Luft-und-Raumfahrt (DLR), Oberpfaffenhofen, Bavaria, Germany
17th May 2024

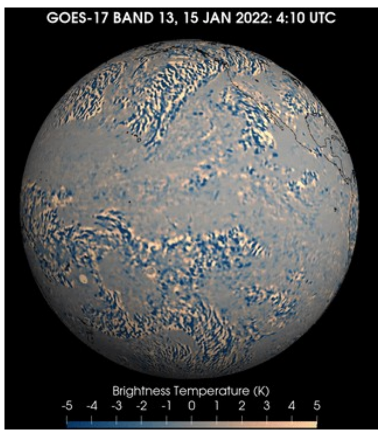
Images: Gravity wave packets converging over Drake Passage, polar vortex over Scandinavia (earth.nullschool.net), wave refraction into the polar night jet

An Introduction to Gravity Waves (GWs)

Menlo Park, CA



Convective GW
JAXA Himawari satellite



Hunga-Tonga eruption

GW over mountains

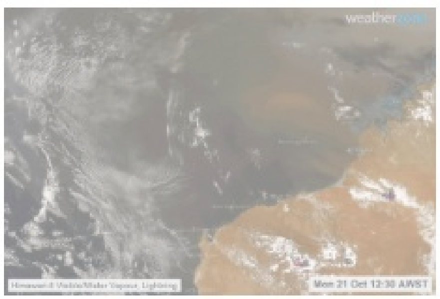
GWs traced by
Noctilucent clouds

- Fast response to a perturbation in a stably stratified fluid.
  - Jet imbalance
  - Geostrophic adjustment
  - Convective activity
  - Flow over mountain
  - Secondary generation from breaking GWs

- Evolve over 100 m - 1000 km horizontally, from over minutes to couple of days.

- **Spectrum of gravity waves!**

Menlo Park, CA



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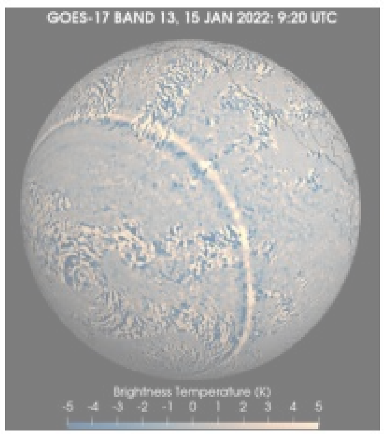

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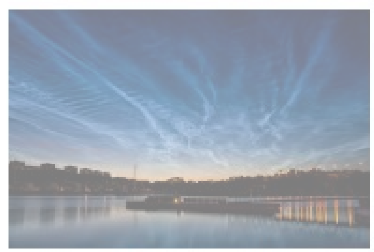
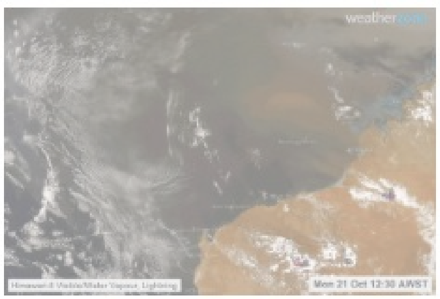


GWs traced by
Noctilucent clouds

Where's this?

????

Menlo Park, CA



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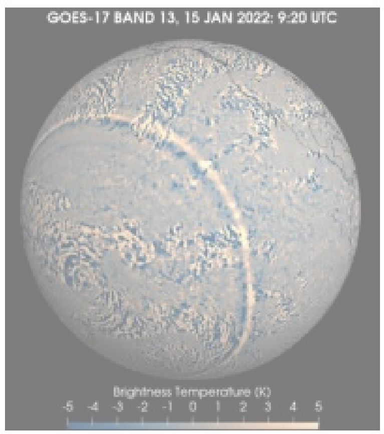

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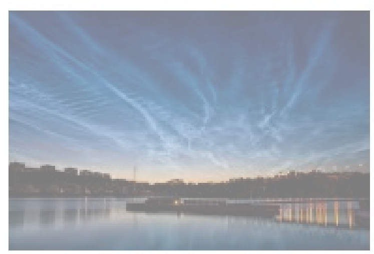
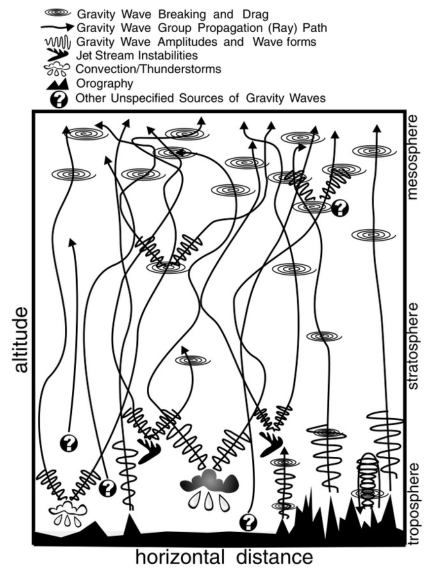


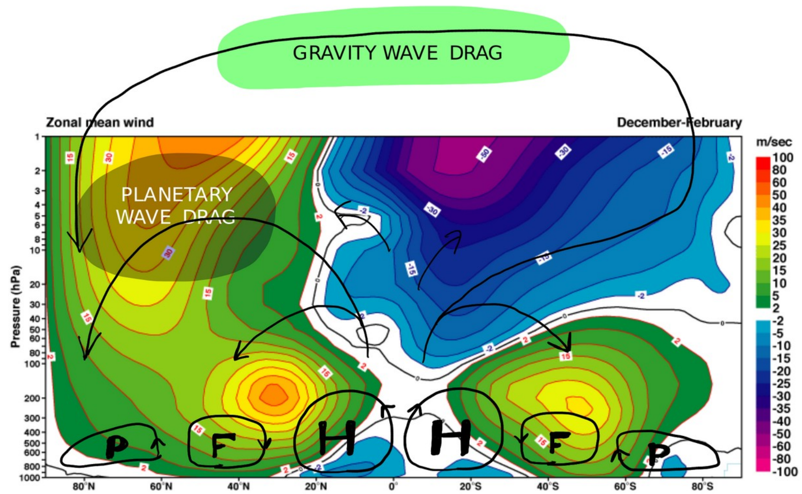
GWs traced by
Noctilucent clouds

Where’s this?

Mars!

GWs: Key Drivers of Upper Atmospheric Overturning Circulation





- Carry near surface momentum to upper atmosphere: vertical coupling

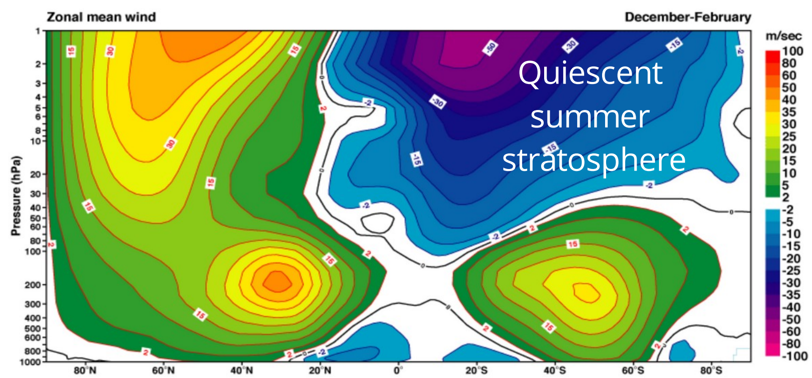
GWs drive the pole-to-pole meridional overturning circulation in the mesosphere.

Tertiary → Secondary → Primary

troposphere stratosphere mesosphere

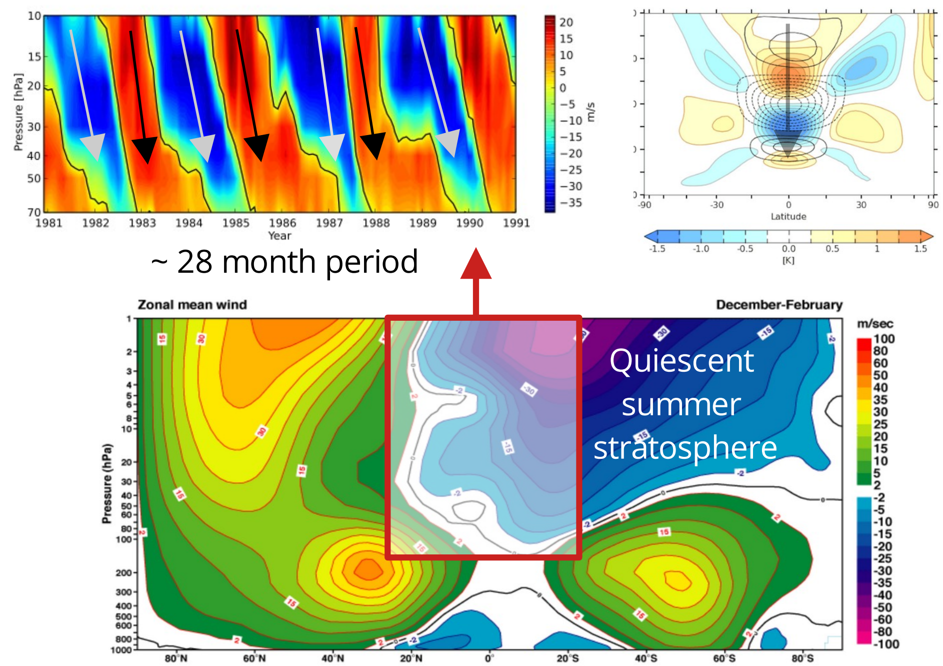
GW schematic: Kim et al. (2003), Atmos-Ocean

GWs: Key Contributors to Stratospheric Variability



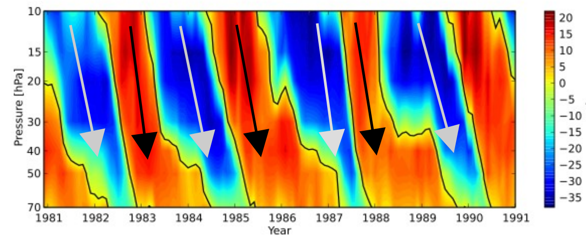
GWs: Key Contributors to Stratospheric Variability

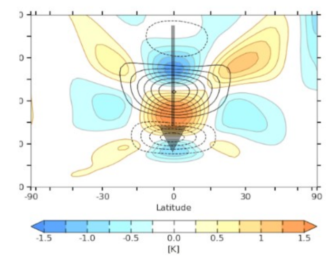
Tropical Quasi-Bienniel Oscillation (QBO)

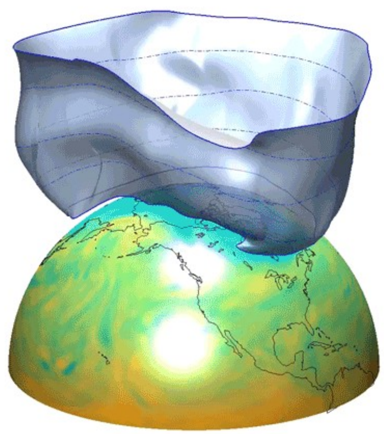


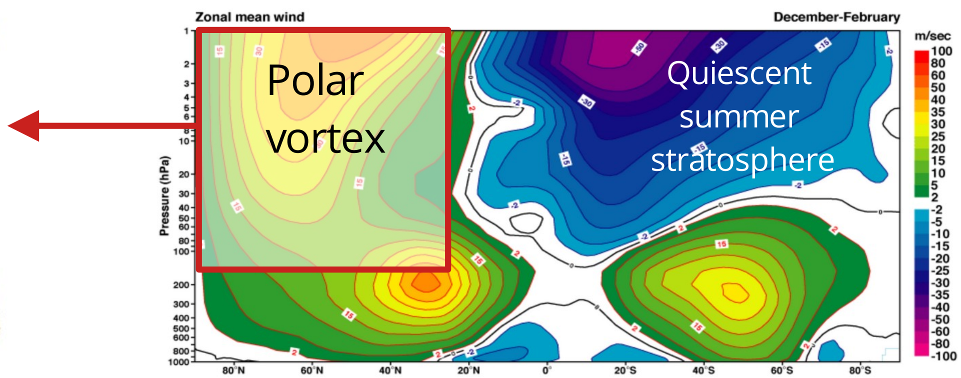
QBO animation credits: Hamid Pahlavan

GWs: Key Contributors to Stratospheric Variability





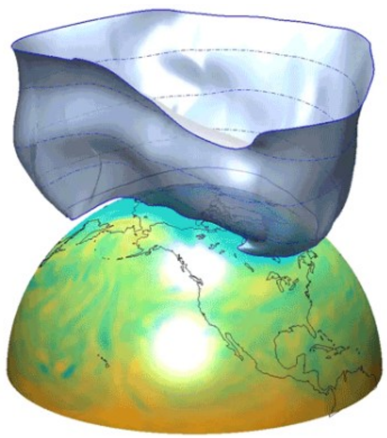


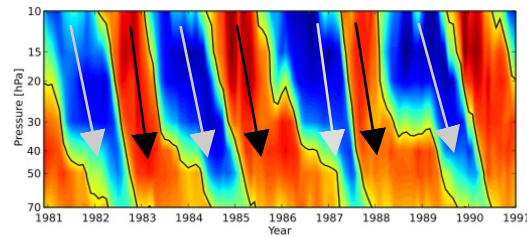


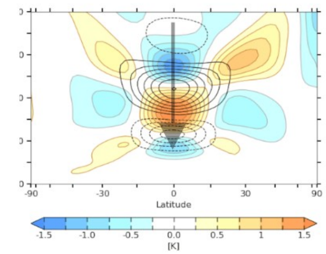
Polar vortex animations: Mattia Serra and George Haller (ETH Zurich)

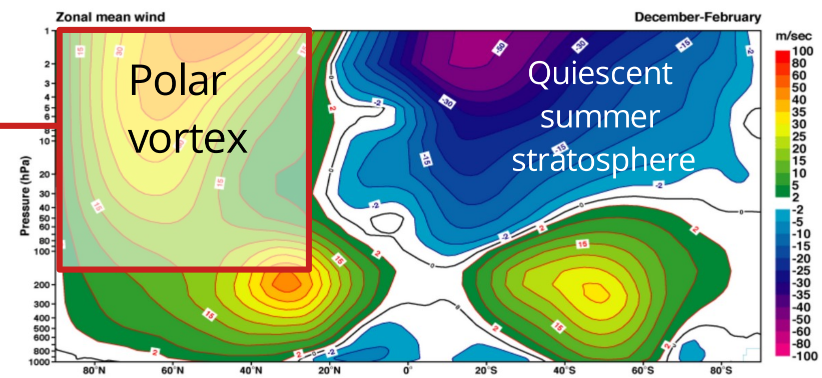
GWs: Key Contributors to Stratospheric Variability

Occasional sudden warming and breakdown of the vortex (**SSWs**)



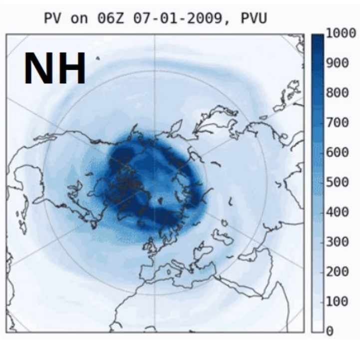






Polar vortex animations: Aditi Sheshadri

GWs: Key Contributors to Stratospheric Variability



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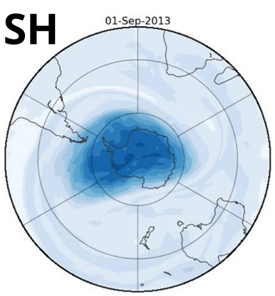
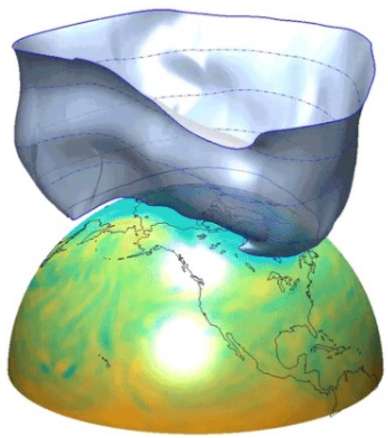
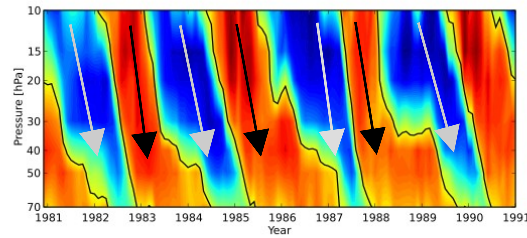
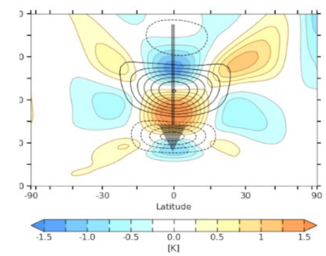
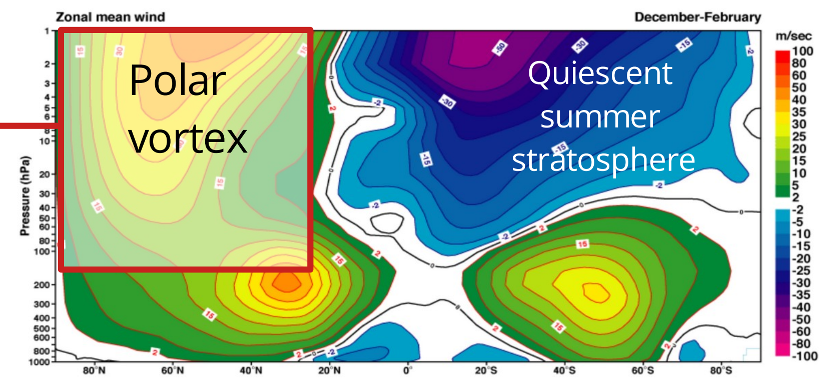


Gradual springtime erosion (**final warming**)



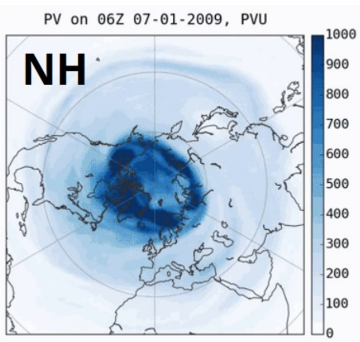






Polar vortex animations: Aditi Sheshadri

GWs: Key Contributors to Stratospheric Variability



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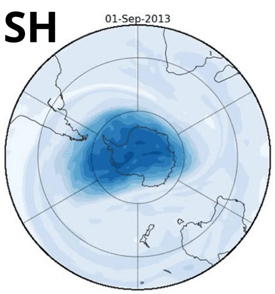

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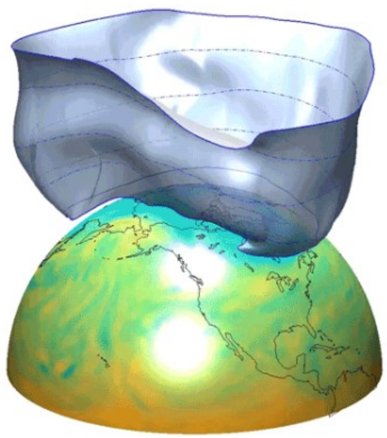
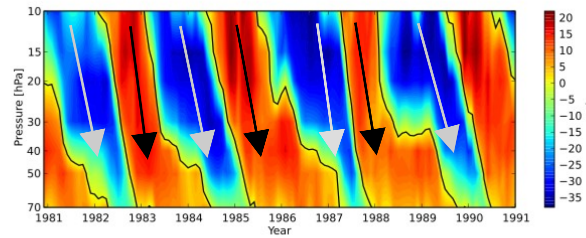
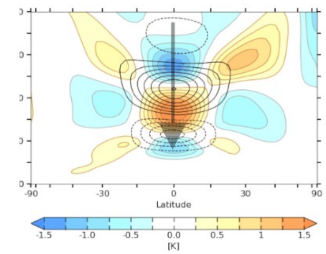
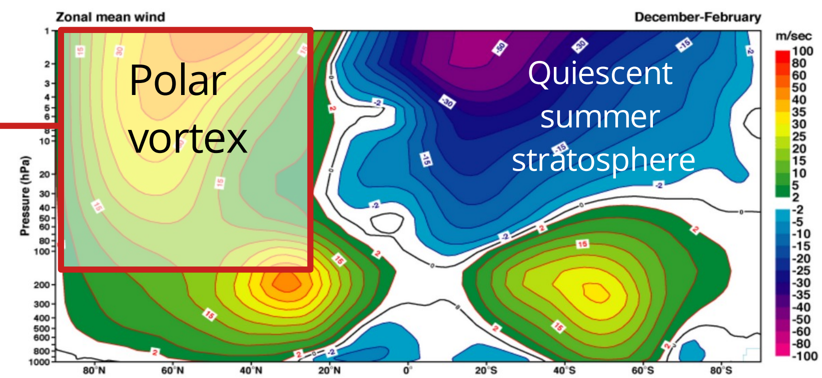
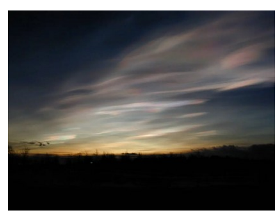










Chemically, GWs trigger creation of polar stratospheric clouds that are crucial to ozone destruction
(Doernbrack et al. (2002), JGR-A)

Polar vortex animations: Aditi Sheshadri

GWs: Limited Obs. and Inadequate Model Representation

Horizontal mapping

Strateole-2/Concordiasi/Google Loon

Vertical profiling

LiDARs Radiosondes

Limited channels satellites

HIRDLS/AIRS/Aeolus

GWs: Limited Obs. and Inadequate Model Representation

Horizontal mapping

Strateole-2/Concordiasi/Google Loon

Vertical profiling

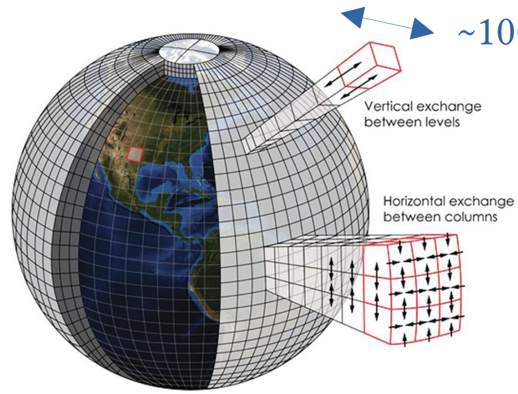
LiDARs

Radiosondes

Limited channels satellites

HIRDLS/AIRS/Aeolus

~100-300 km



Climate models too coarse to resolve most GWs and their sources

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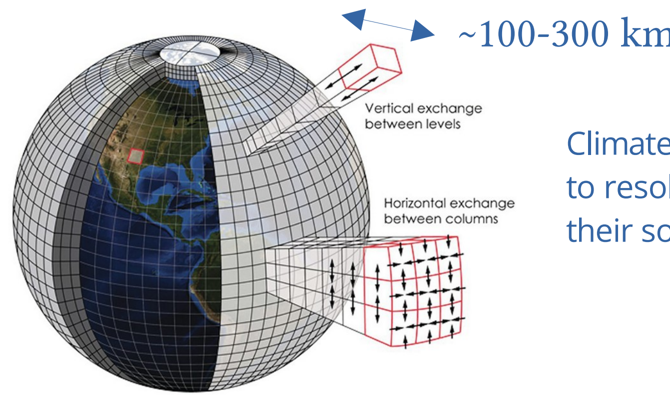
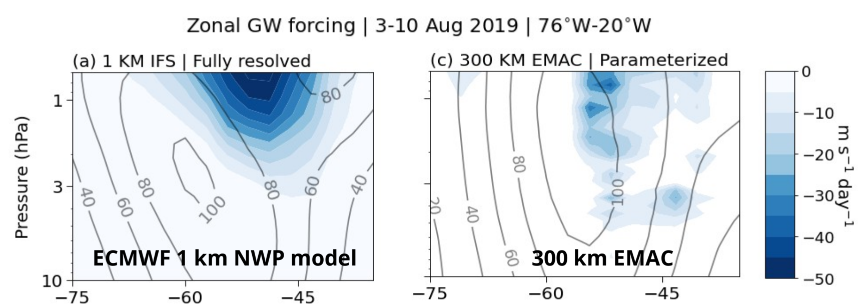


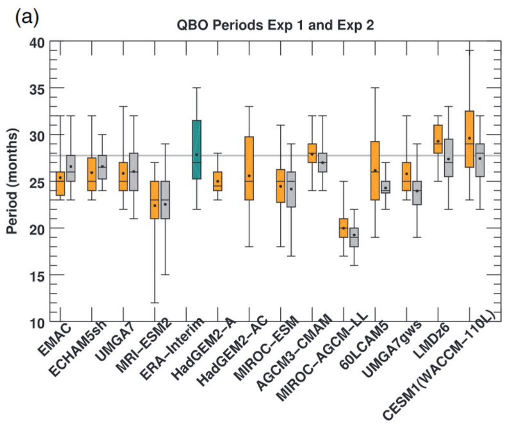
Climate models too coarse to resolve most GWs and their sources

Resolved and parameterized GW forcings are worlds apart

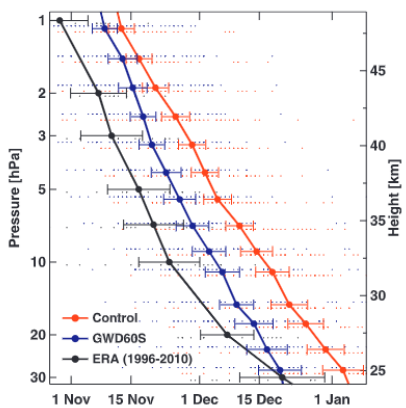


Gupta et al. (2024), JAS

Inaccurate GW Forcing in Models leads to Circulation Biases



Tropics: Model uncertainty in QBO period and amplitude
(Bushell et al. (2020), QJRMS)



Extratropics: “Cold-pole bias” in models due to missing GWs near 60^{O}S. Seasonal transitions of polar vortex delayed by up to 2-4 weeks.
(McLandress et al. (2012), JAS)

No GWD Imposed GWD ERA-I

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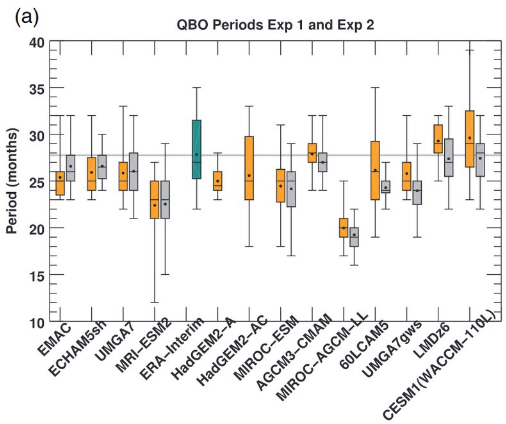

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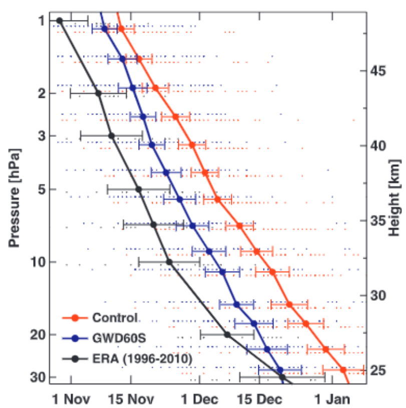

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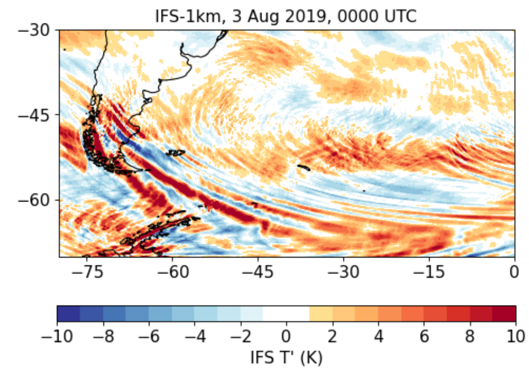
Parameterizations miss key GW physics



- Lateral Propagation
- Refraction
- Transience
- Missing sources

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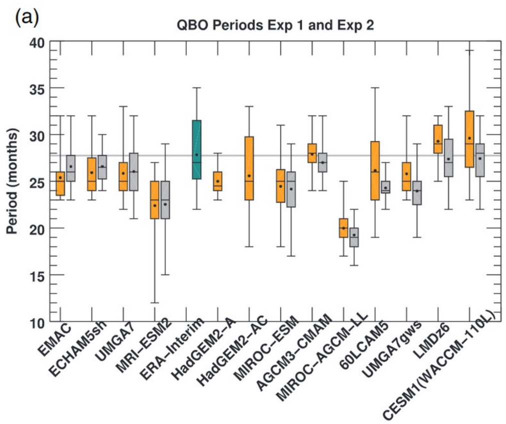

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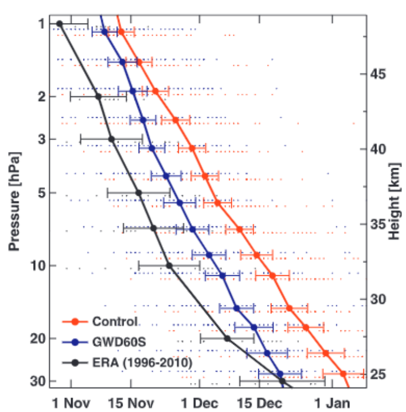

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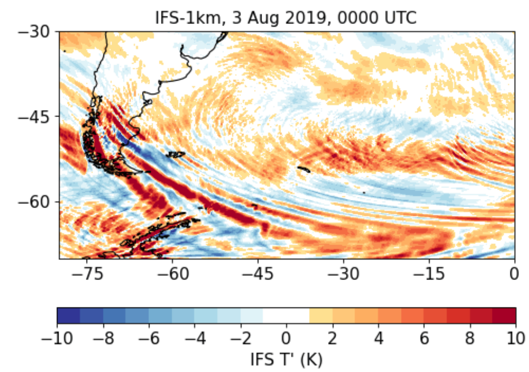

- Lateral Propagation
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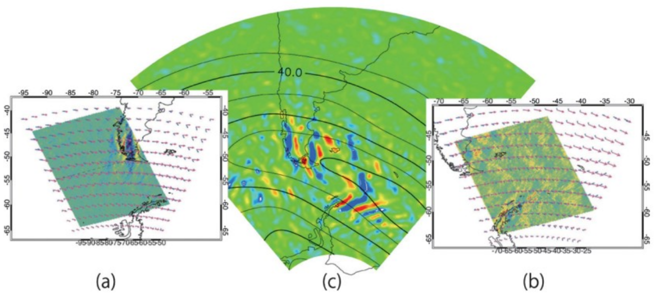
Obs. and High-Res models show GW lateral propagation

Southeastward extension of phase lines associated with GW packet excited over the Andes.



Sato et al. (2011), JAS

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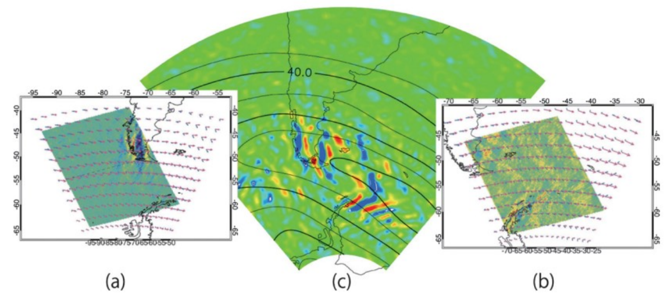
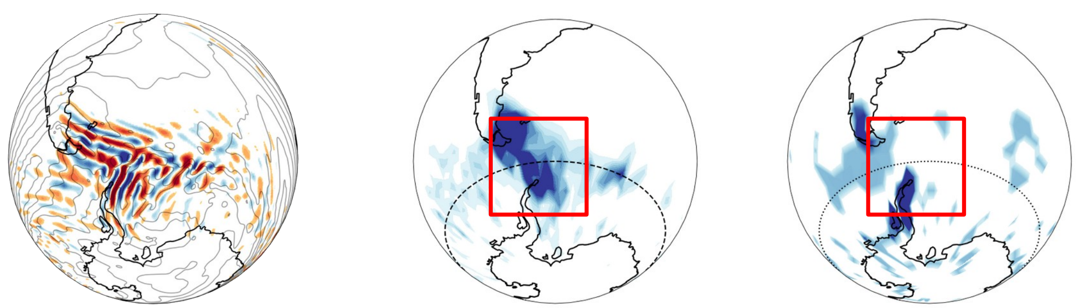


Sato et al. (2011), JAS

Simulated GW (ERA5) | Resolved forcing | Parameterized forcing



Fluxes not propagated to over the ocean

Evidence of GW lateral propagation, but parameterizations assume pure vertical propagation

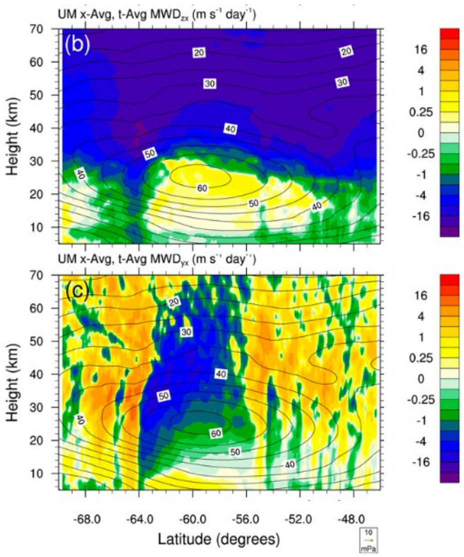
Lateral Flux Forcing Sensitive to Wave Type

$$\mathbf{MF}_x = \langle \mathrm{MF}_{xx} = \overline{\rho u'^2}, \mathrm{MF}_{yx} = \overline{\rho}\, \overline{u'v'}, \mathrm{MF}_{zx} = \overline{\rho u'w'} \rangle,$$

$$\mathrm{GWD}_{xx} = -\frac{1}{\overline{\rho}} \frac{\partial \mathrm{MF}_{xx}}{\partial x}, \quad \mathrm{GWD}_{yx} = -\frac{1}{\overline{\rho}} \frac{\partial \mathrm{MF}_{yx}}{\partial y}, \quad \mathrm{GWD}_{zx} = -\frac{1}{\overline{\rho}} \frac{\partial \mathrm{MF}_{zx}}{\partial z},$$

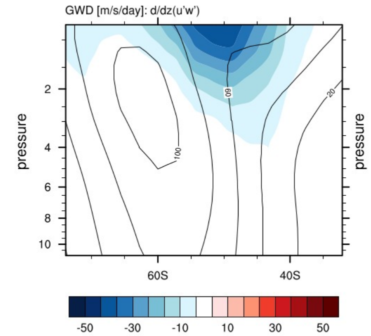
Forcing from vertical flux

Forcing from lateral flux

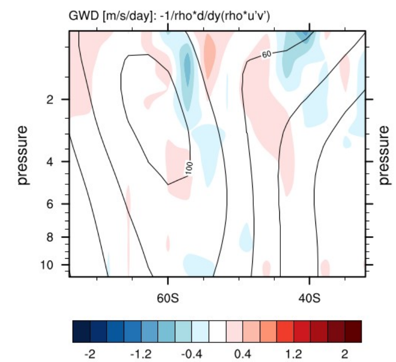


Lateral flux contributions **similar to** vertical flux for mountain waves in October 2010 in UM.
(Kruse et al. (2022), *JAS*)

Forcing from vertical flux



Forcing from lateral flux



Lateral flux contributions **much weaker** for mountain waves in August 2019 in IFS-1km.
(Gupta et al. (2024), *JAS*)

Do lateral propagation effects matter on climatological timescales?

- What is the mean wintertime forcing due to lateral fluxes on the zonal flow?
- What is the global distribution of lateral GW fluxes?
- How does this forcing evolve during the SSW and final warming period?

Insights on Lateral Gravity Wave Propagation in the Extratropical Stratosphere from 44 Years of ERA5 Data

Aman Gupta[1], Aditi Sheshadri[1], M. Joan Alexander[2], and Thomas Birner[3,4]

Submitted to GRL

Computing Resolved GW Forcing

TEM Equations for zonal mean zonal flow

$$\overline{u}_t = \left(f - \frac{1}{R\cos\phi}(\overline{u}\cos\phi)_\phi \right) \overline{v}^* - \overline{u}_p \overline{\omega}^* + \underbrace{\frac{1}{R\cos\phi} \vec{\nabla} \cdot \vec{F}}_{\text{EPFD}} + \overline{X}$$

mean meridional circulation

Resolved + unresolved wave-driving

Computing Resolved GW Forcing

$$\underbrace{\frac{1}{R\cos\phi}\vec{\nabla}\cdot\vec{F}}_{\text{EPFD}}$$

Resolved
wave-driving

Computing Resolved GW Forcing

$$\underbrace{\frac{1}{R\cos\phi}\vec{\nabla}\cdot\underline{\vec{F}}}_{\text{EPFD}} \qquad \vec{F} = \left(F^{(\phi)}, F^{(p)}\right) = R\cos\phi\left(-\overline{u'v'} + \overline{u}_p\frac{\overline{v'\theta'}}{\overline{\theta}_p}, \left(f - \frac{1}{R\cos\phi}(\overline{u}\cos\phi)_\phi\right)\frac{\overline{v'\theta'}}{\overline{\theta}_p} - \overline{u'\omega'}\right)$$

Computing Resolved GW Forcing

$$\underbrace{\frac{1}{R\cos\phi}\vec{\nabla}\cdot\vec{F}}_{\text{EPFD}}$$

$$\frac{1}{R\cos\phi}\vec{\nabla}\cdot\vec{F} = \frac{1}{R\cos\phi}\left(\frac{1}{R\cos\phi}\left(F^{(\phi)}\cos\phi\right)_{\phi} + F_p^{(p)}\right)$$

Meridional Momentum Flux Convergence

$$\frac{-1}{R\cos^2\phi}\left(\overline{u'v'}\cos^2\phi\right)_{\phi}$$

Vertical Momentum Flux Convergence

$$-\overline{u'\omega'}_p$$

Meridional Heat Flux Convergence

$$\frac{1}{R\cos^2\phi}\left(\overline{u}_p\frac{\overline{v'\theta'}}{\overline{\theta}_p}\cos^2\phi\right)_{\phi}$$

Vertical Heat Flux Convergence

$$\left(\left[f - \frac{(\overline{u}\cos\phi)_{\phi}}{R\cos\phi}\right]\frac{\overline{v'\theta'}}{\overline{\theta}_p}\right)_p$$

Dataset:

44 Yrs of ERA5 output:

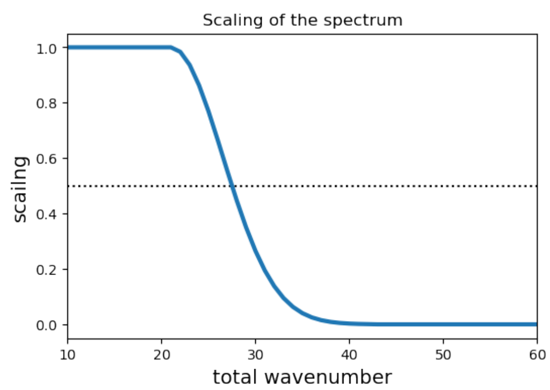
- ~30 km horizontal resolution, 137 model levels, interpolated to a 25 km grid and 37 pressure levels
- 0.25 km vertical resolution in UTLS, 2.5 km near stratopause
- Resolves GWs ~150 km and above

- ✘ Limited vertical and horizontal resolution
- ✘ All waves model generated, none assimilated
- ✘ Stratospheric sponge above 10 hPa, mesospheric sponge above 1 hPa

Methodology to compute fluxes:

Extract small-scale wave fluxes (EP-Fluxes) using Gaussian tapering of spectral harmonics:

$$(u, v, \omega, \theta) \rightarrow$$



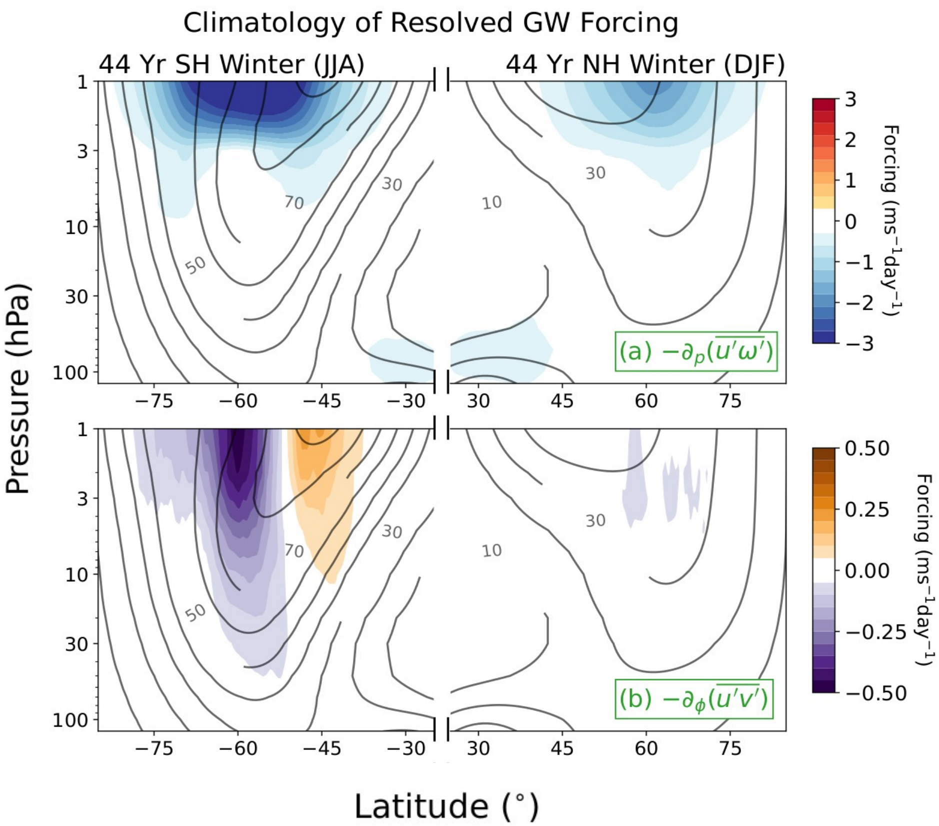
$$\rightarrow (u', v', \omega', \theta')$$

$$\downarrow$$

$$(\overline{u'\omega'}, \overline{u'v'}, \overline{v'\theta'})$$

- Damping over scales 500-1000 km in the midlatitudes
- Coefficients damped by a factor of ~2 for wavenumber 30.

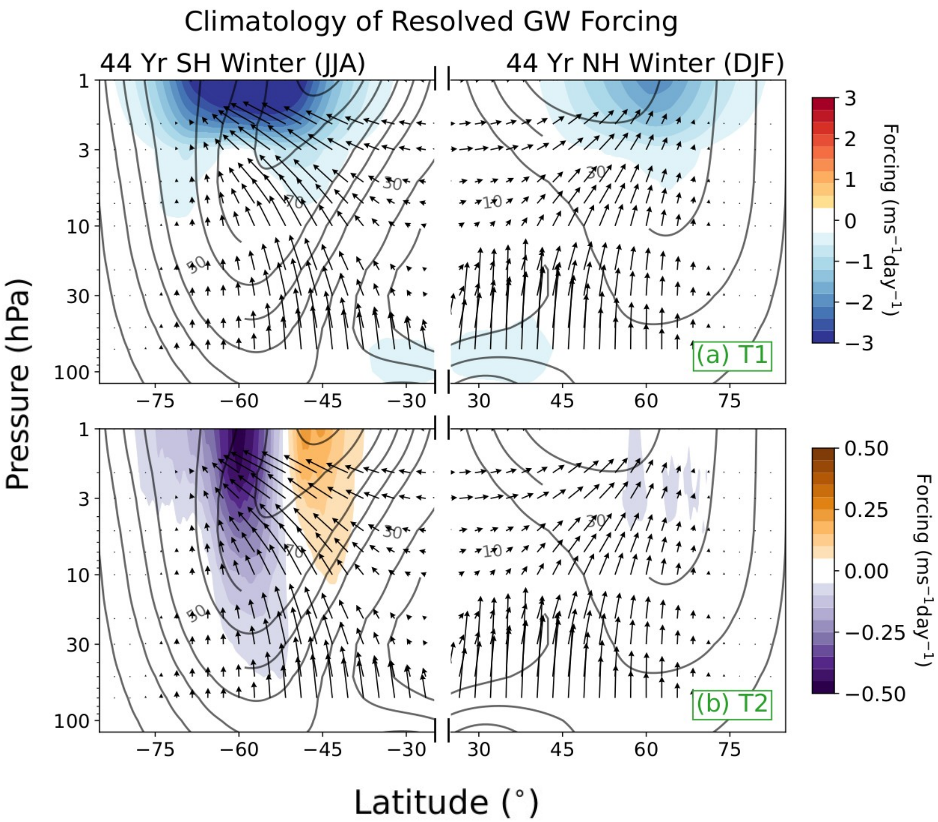
How Much Forcing to Resolved Gravity Waves Provide?



Strongest contribution towards net resolved forcing provided by vertical momentum flux convergence

Yet, contribution from lateral flux convergence same order-of-magnitude

How Much Forcing do Resolved Gravity Waves Provide?

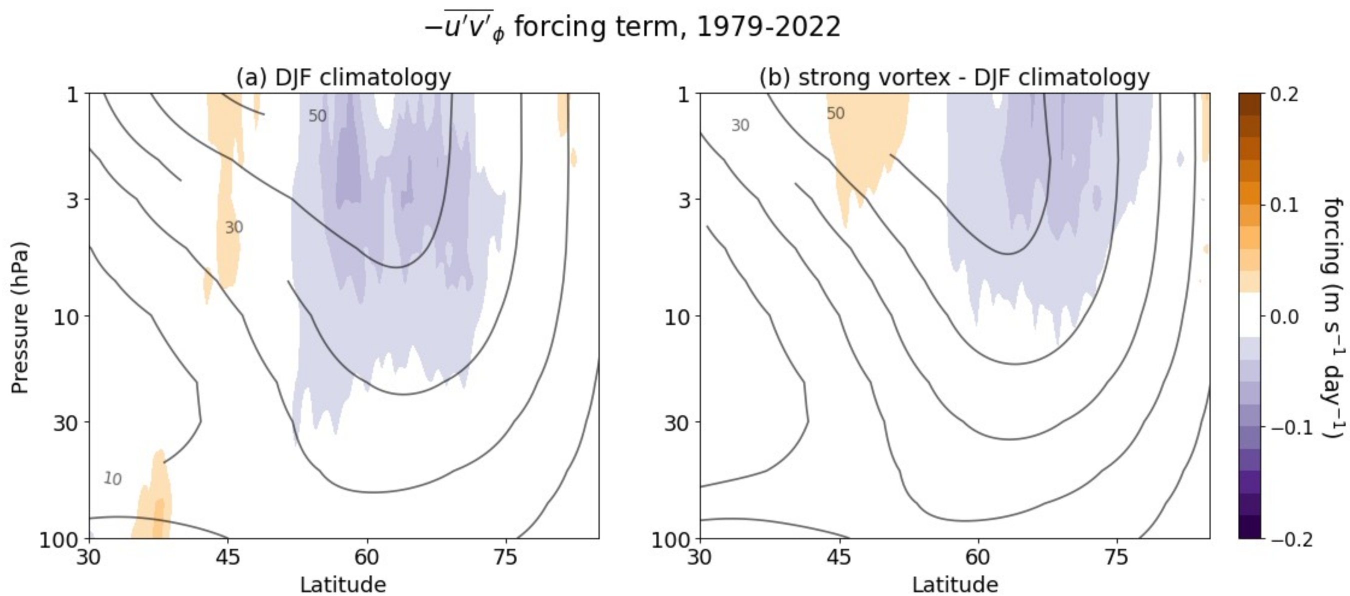


arrows: small-scale EP-Flux vectors

Strongest contribution towards net resolved forcing provided by vertical momentum flux convergence

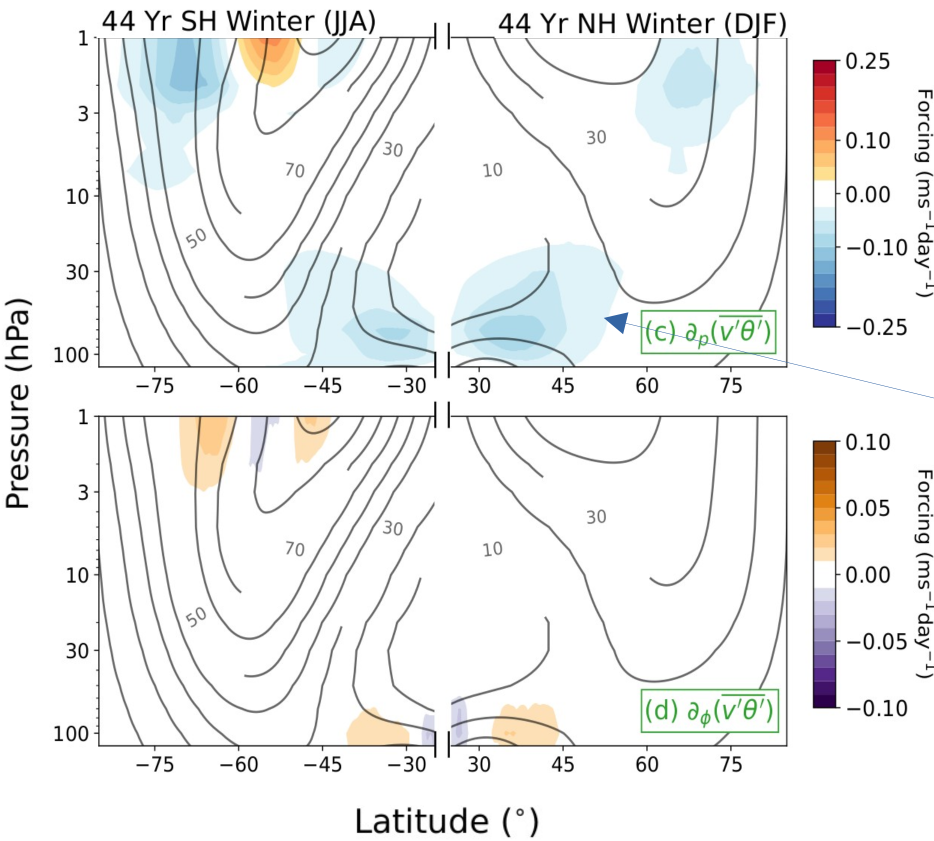
Yet, contribution from lateral flux convergence same order-of-magnitude

How Much Forcing do Resolved Gravity Waves Provide?



For strong vortex days, DJF forcing in the Northern Hemisphere is nearly identical to the JJA forcing in the Southern Hemisphere, highlighting the role of shear

How Much Forcing do Resolved Gravity Waves Provide?

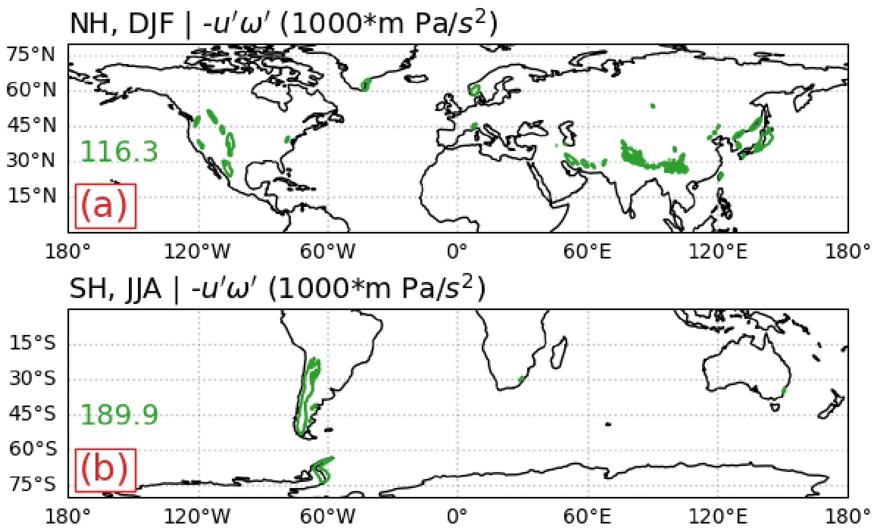


Weak contributions from the heat flux convergence terms in the upper stratosphere.

Notable contributions in the midlatitude UTLS region, comparable to vertical momentum flux convergence.

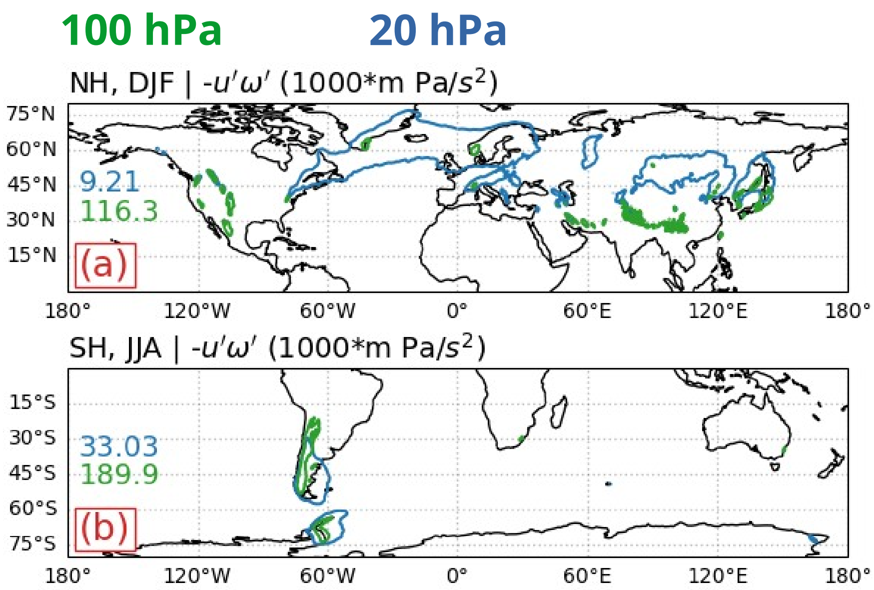
Peak-Winter Vertical Flux Distribution $\boxed{-u'\omega'}$

100 hPa



Vertical fluxes in the lower stratosphere mostly concentrated over orographic regions

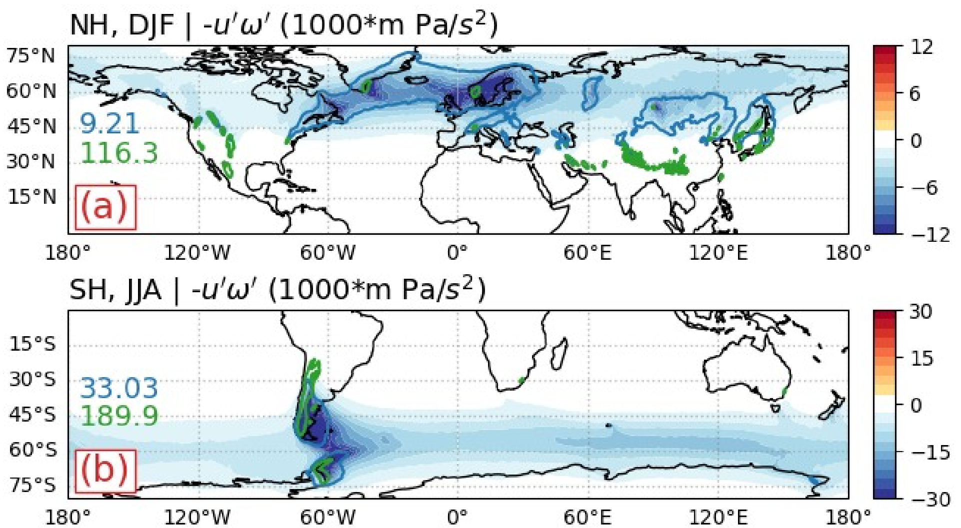
Peak-Winter Vertical Flux Distribution $\boxed{-u'\omega'}$



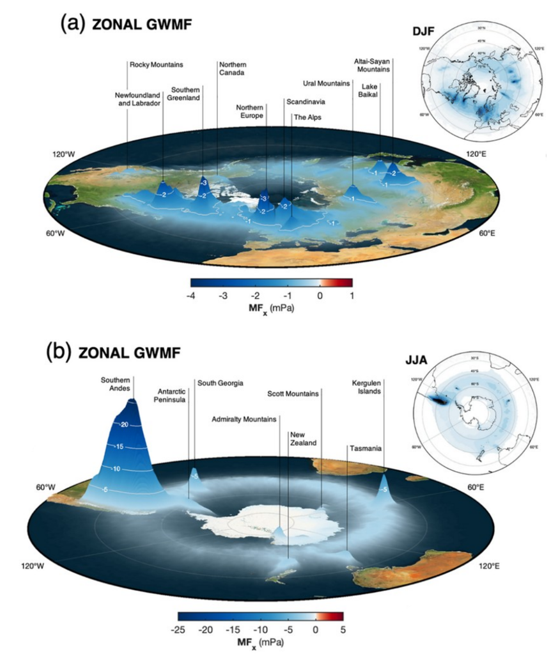
Higher up, at 20 hPa, fluxes spread over a wider expanse.

Peak-Winter Vertical Flux Distribution $-u'\omega'$

100 hPa **20 hPa** **Color: 2 hPa**



In the upper stratosphere (color), fluxes spread to form a belt of GW activity.

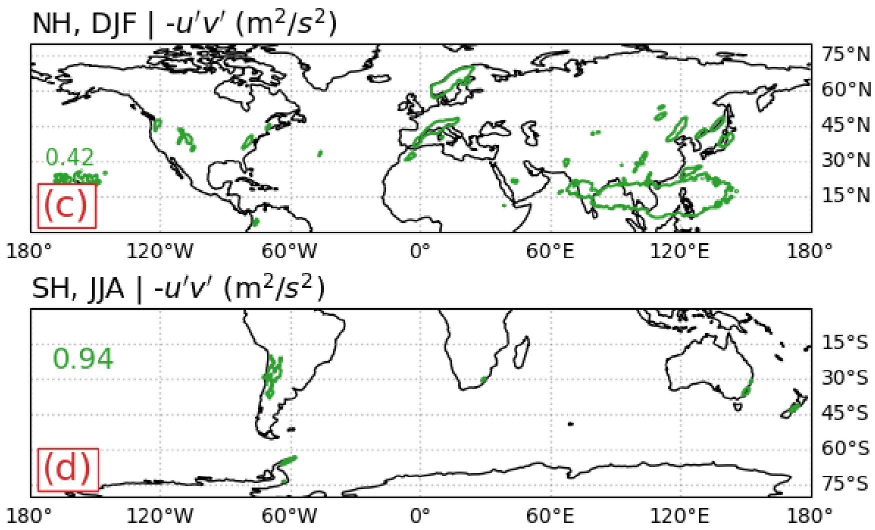


Agreement with AIRS climatology using temperature variance.
Hindley et al. (2020), GRL

Fluxes in ERA5 a factor 2 stronger.

Peak-Winter Lateral Flux Distribution $\boxed{-u'v'}$

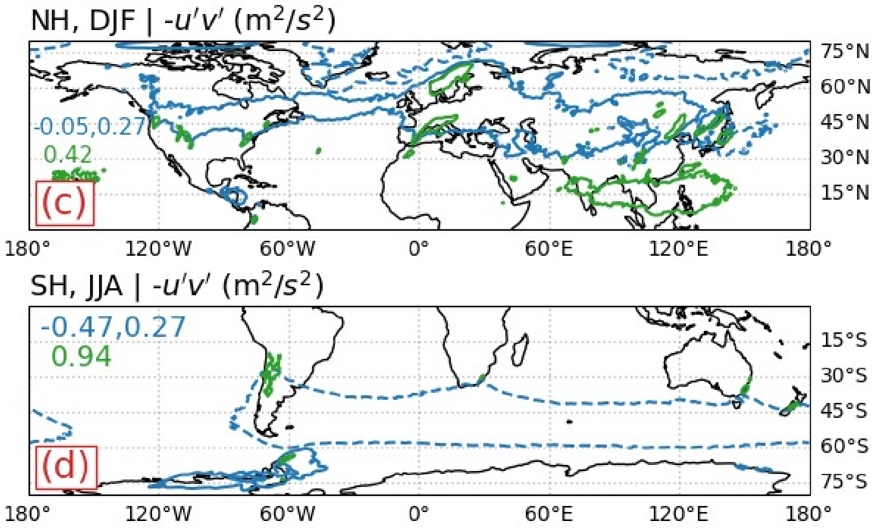
100 hPa



Lateral fluxes in the lower midlatitude stratosphere
too concentrated over orographic regions

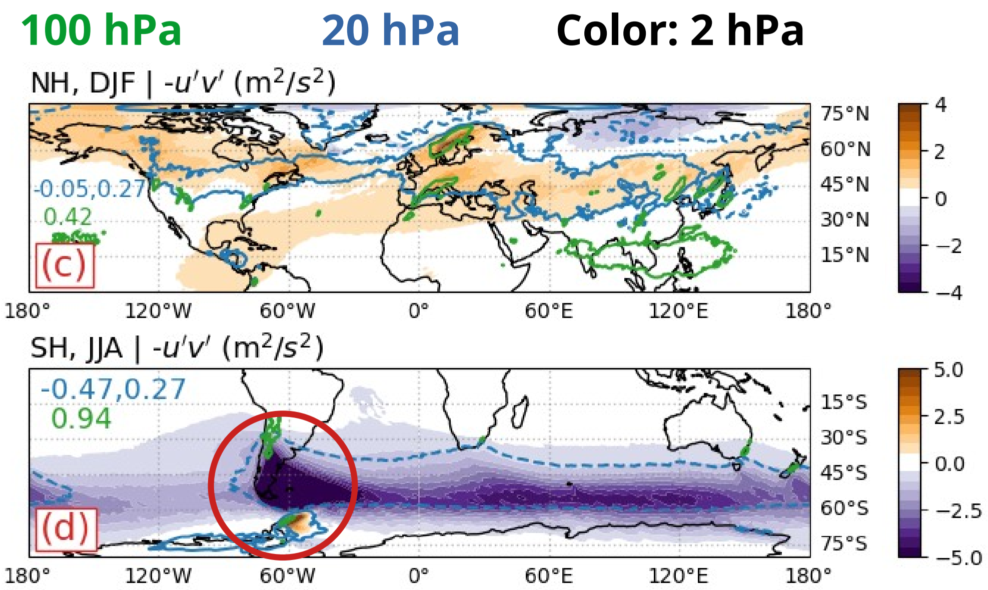
Peak-Winter Lateral Flux Distribution $\boxed{-u'v'}$

100 hPa **20 hPa**



Higher up, at 20 hPa, lateral fluxes not strongly correlated with topography, but spread over the whole latitude circle.

Peak-Winter Lateral Flux Distribution $\boxed{-u'v'}$

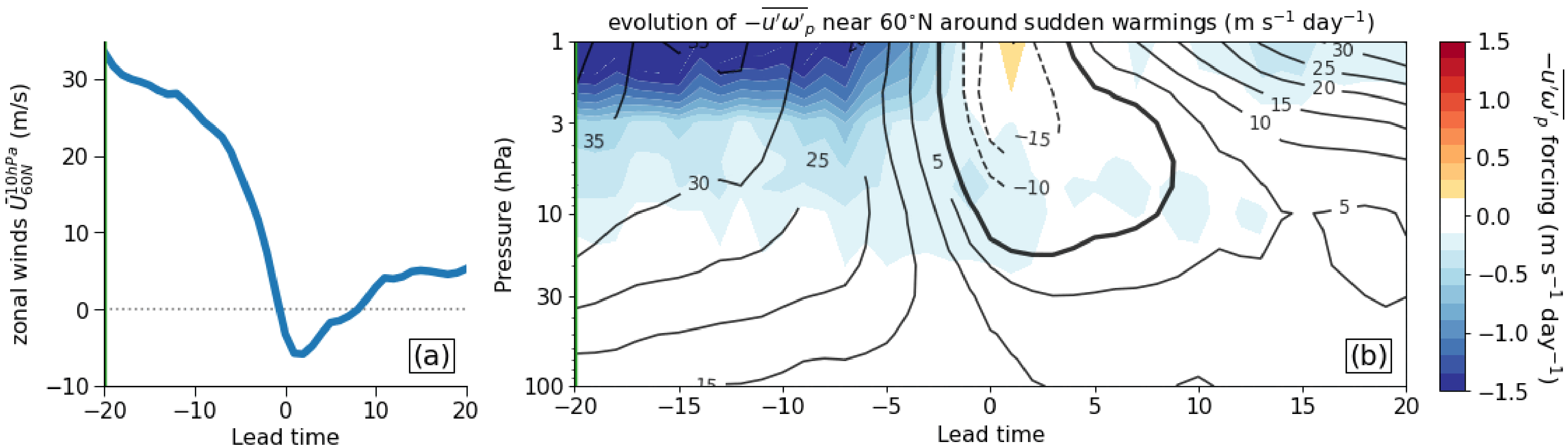


Poleward shift in the lateral flux belt in the middle-to-upper stratosphere. Lateral flux notable over the whole Southern Ocean, not just over the Drake passage.

Could be nice to validate these with Ray tracing experiments?

Evolution of GW Fluxes around Sudden Warmings

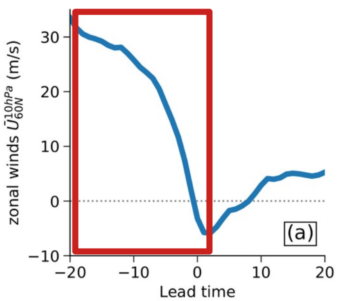
How do vertical and lateral fluxes evolve around abrupt changes in the stratospheric mean flow?

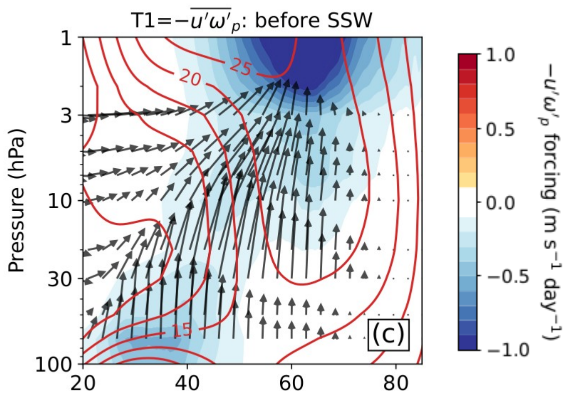


Downward migration of GW vertical momentum flux in response to changing background winds

GW forcing does not fully recover, despite vortex recovery

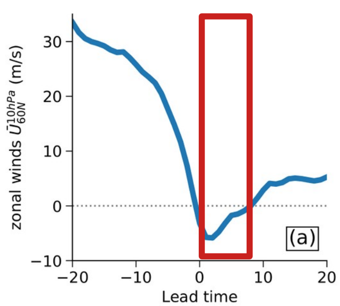
Evolution of GW Fluxes around Sudden Warmings



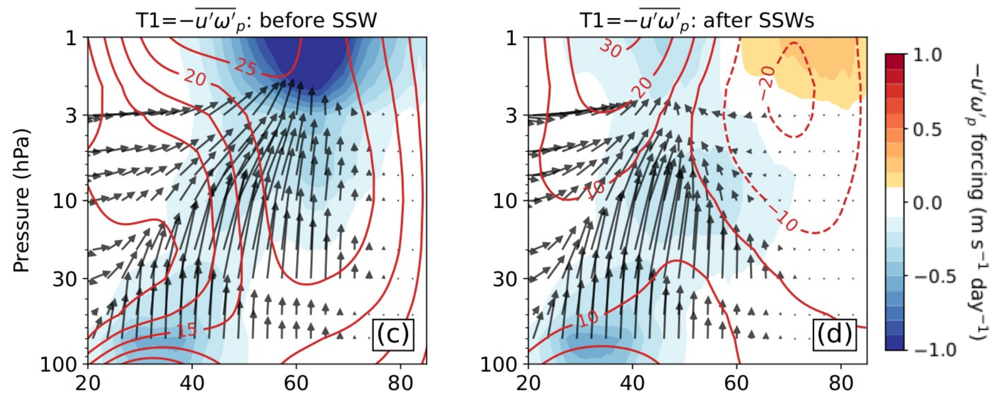


Forcing before SSWs

Evolution of GW Fluxes around Sudden Warmings

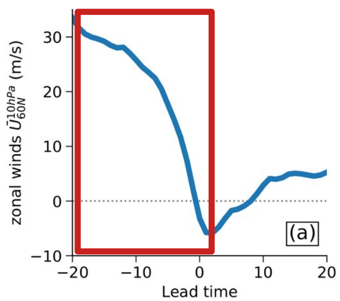


Forcing after SSWs

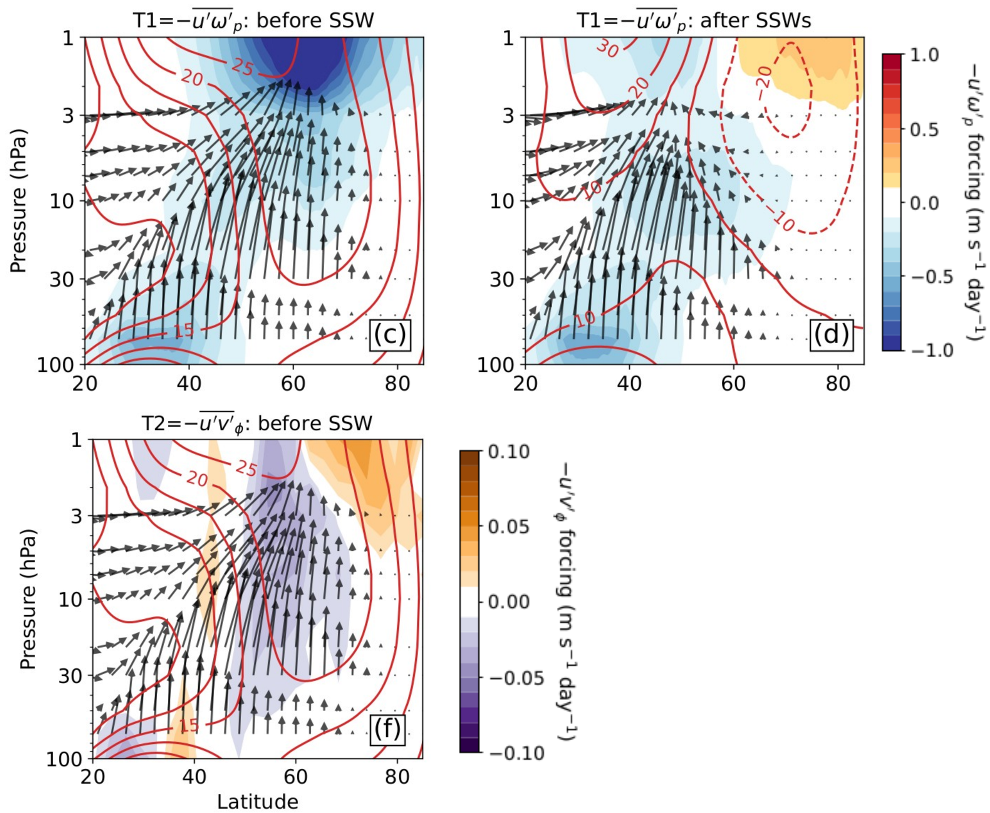


Dramatic reduction in vertical flux convergence in the upper stratosphere following SSWs

Evolution of GW Fluxes around Sudden Warmings



Forcing before SSWs



Dramatic reduction in vertical flux convergence in the upper stratosphere following SSWs

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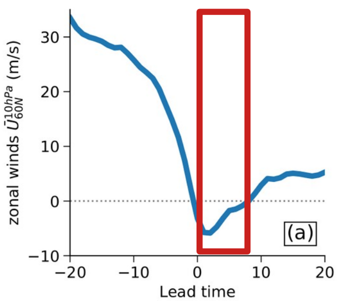
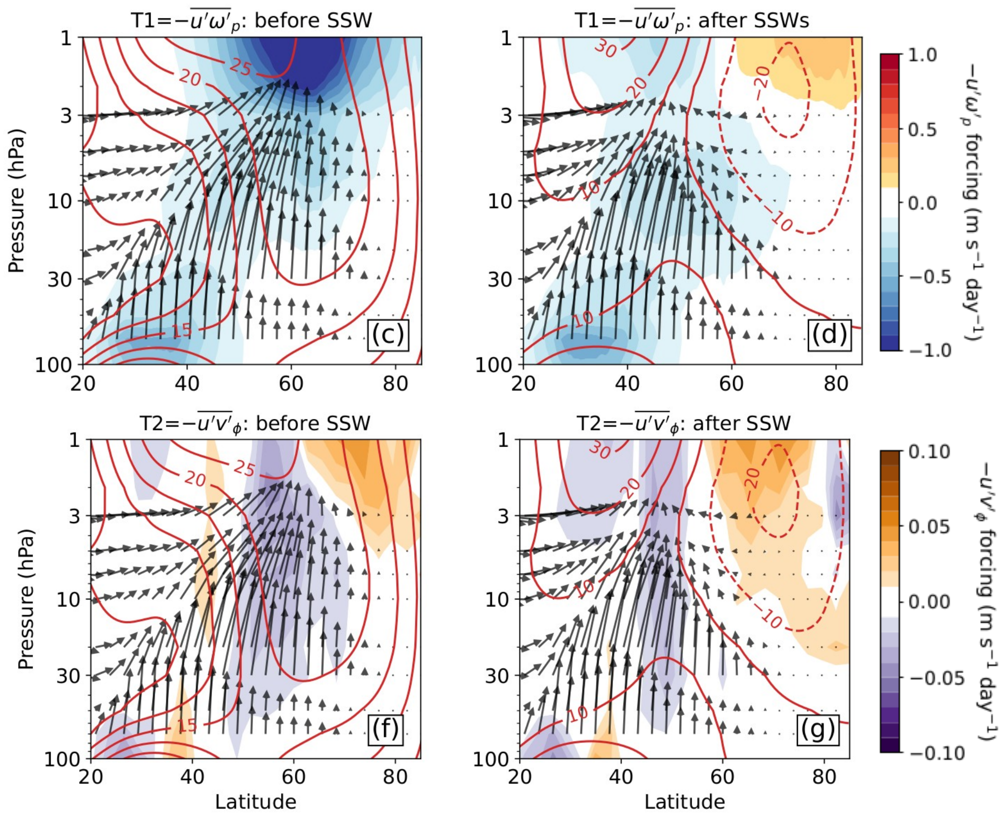


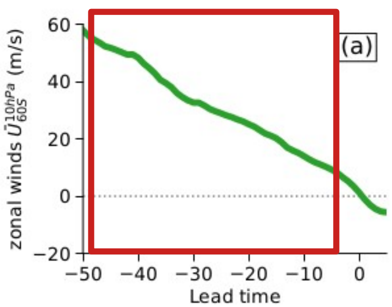
Forcing after SSWs

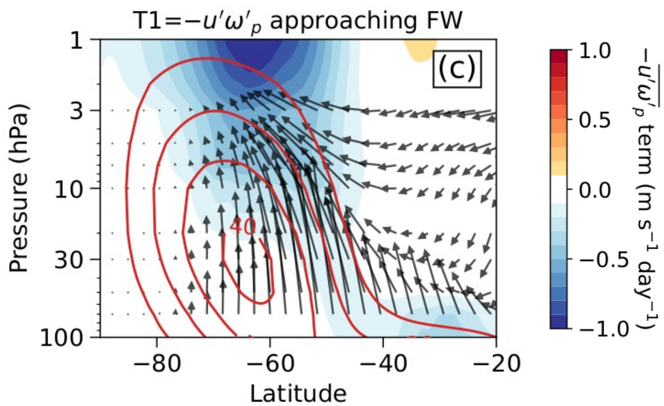


Dramatic reduction in vertical flux convergence in the upper stratosphere following SSWs

Lateral fluxes converge much equatorward following SSWs

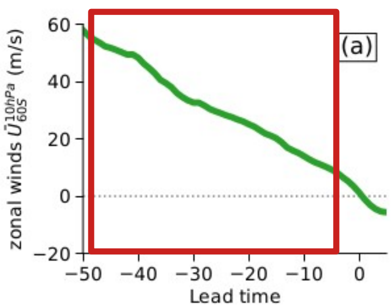
Evolution of GW Fluxes around Antarctic Final Warmings



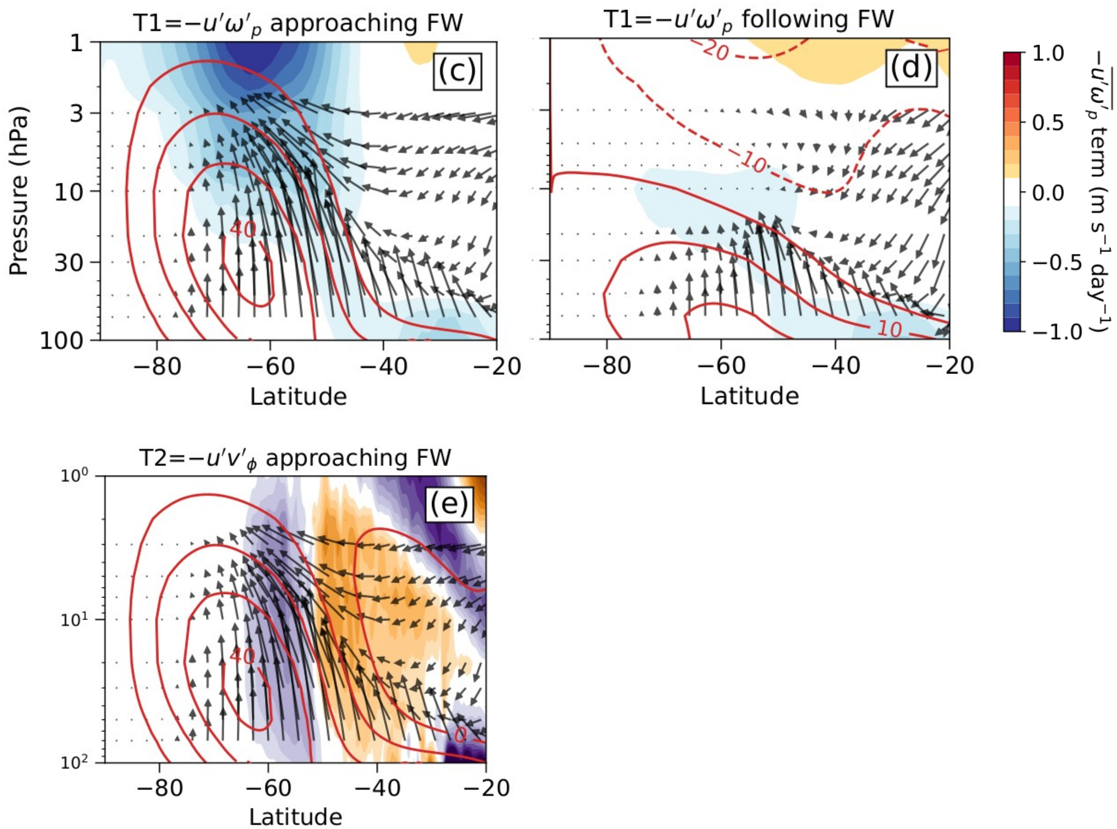


Forcing before
final warming

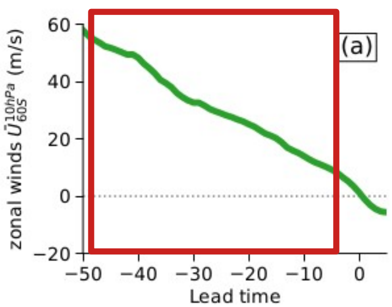
Evolution of GW Fluxes around Antarctic Final Warmings

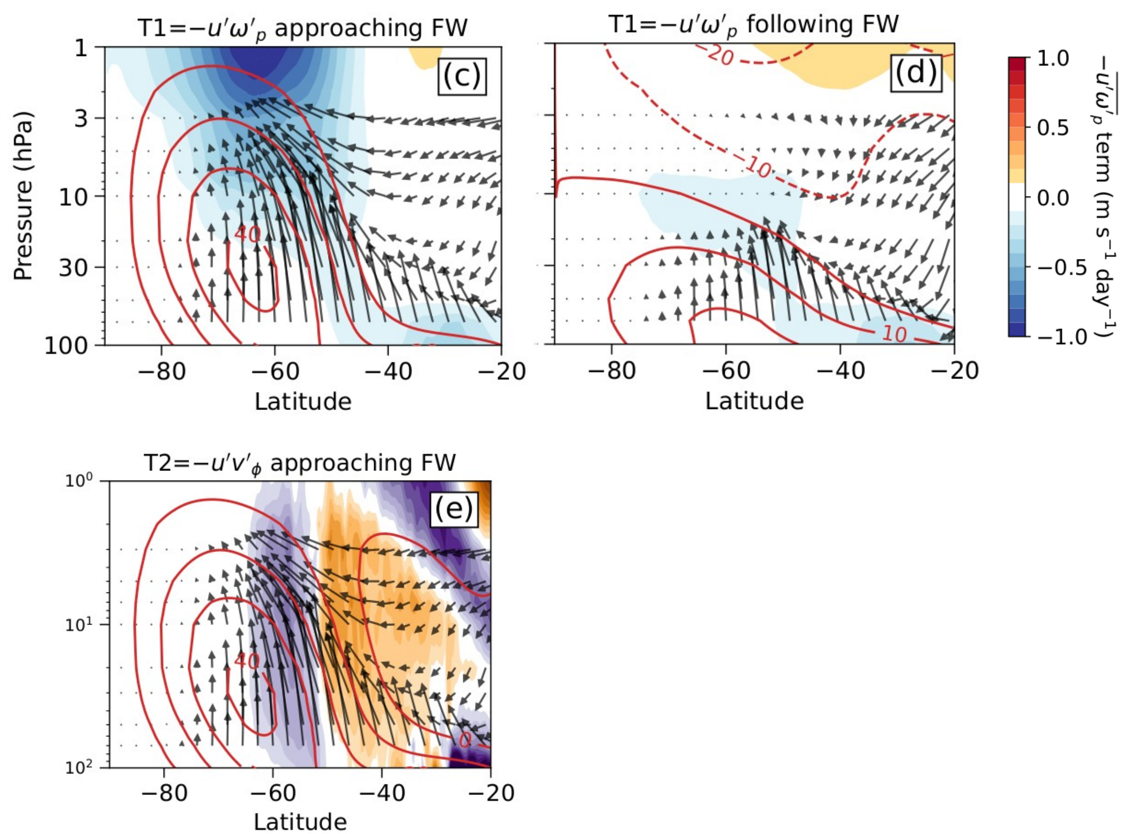


Forcing before final warming



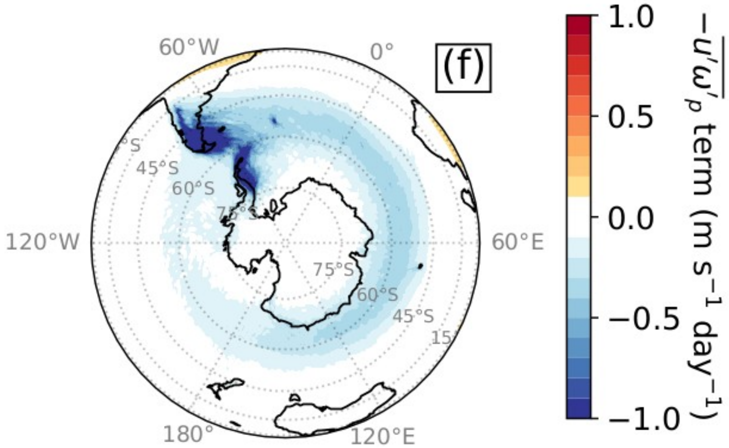
Evolution of GW Fluxes around Antarctic Final Warmings



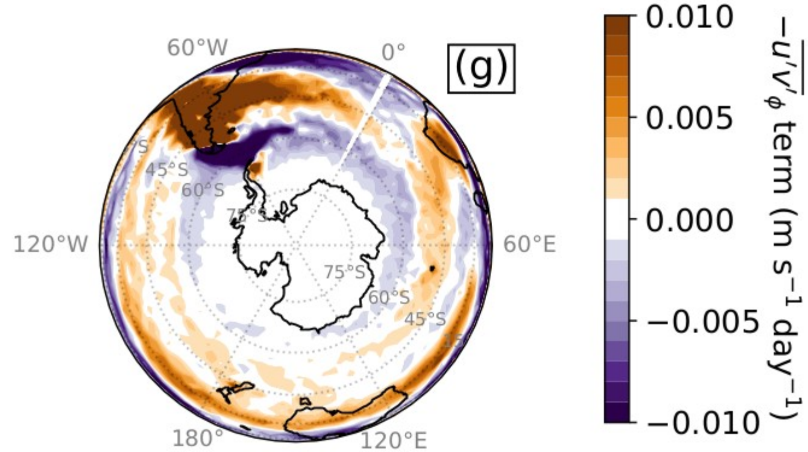


Forcing before
final warming

Lateral Propagation Weak During Final Warming

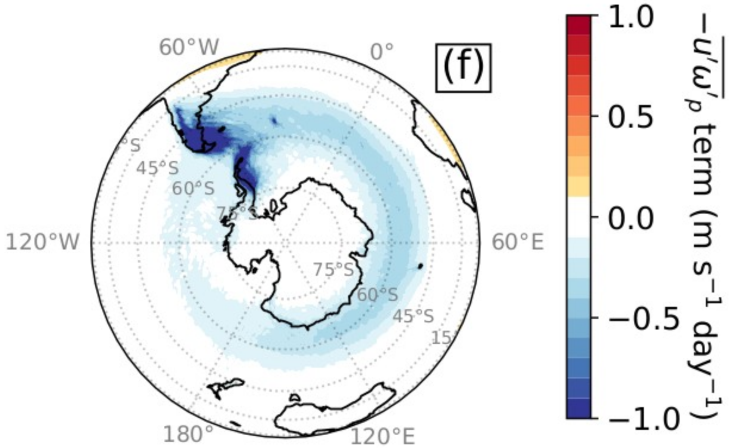


A belt of westward flux dissipation surrounds Antarctica with maxima over the Andes, Antarctic Peninsula, and small island



Lateral flux dissipation is weak and more localized leeward of the topography

Lateral Propagation Weak During Final Warming



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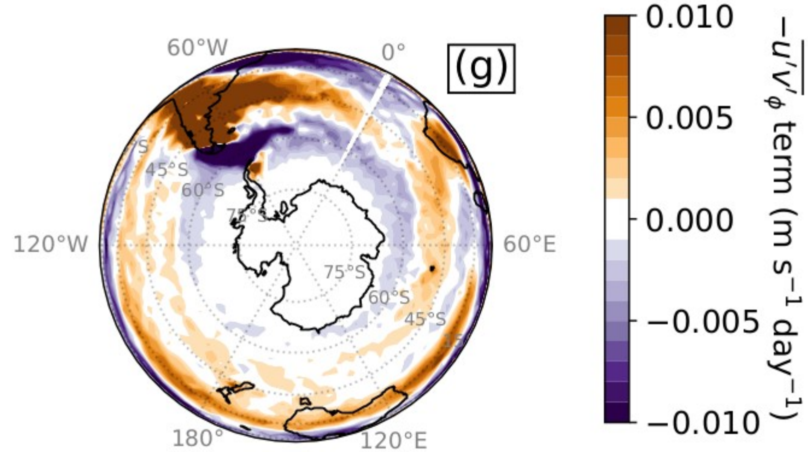


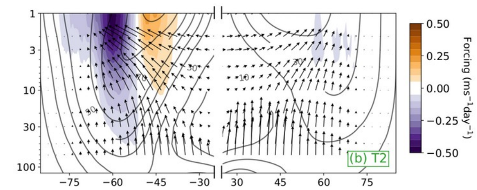
Lateral flux dissipation is weak and more localized leeward of the topography

Is Missing Orographic Gravity Wave Drag near 60°S the Cause of the Stratospheric Zonal Wind Biases in Chemistry–Climate Models?

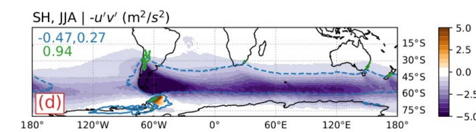
McLandress et al. (2012), JAS

Key Takeaways

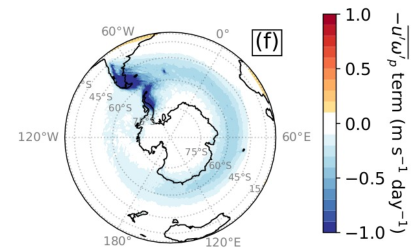
1 **GWs are one of the key drivers** of the middle atmospheric overturning circulation and variability. GW excitation is local but has global impacts which are not accurately represented even in state-of-the-art climate models.



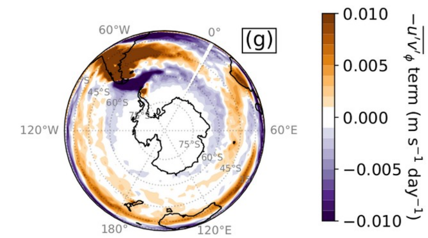
2 **First-ever quantification** of peak winter resolved GW forcing over climatological timescales reveals that forcing from lateral flux convergence is the same order-of-magnitude as that from vertical flux convergence.



3 **GW activity belt:** prominent belts of both vertical and lateral fluxes in the midlatitude upper stratosphere noted in climatology. Sources not fully known.



4 **Abrupt changes** in stratospheric GW forcing around SSWs. Causality remains to be explored.



5 **Lateral effects relatively weaker around Antarctic final warmings** – likely due to weakening shear.

Thank You!