How Volcanic Eruptions Modify the Earth’s Climate

Joseph Hollowed
PhD Defense
January 10, 2025

Doctoral Committee:
Prof. Christiane Jablonowski, Prof. Emanuel Gull, Prof. Adriana Raudzens Bailey,
Prof. Robert Deegan, Prof. Mark Flanner

image: US Nat’l Archives NAID 6481524

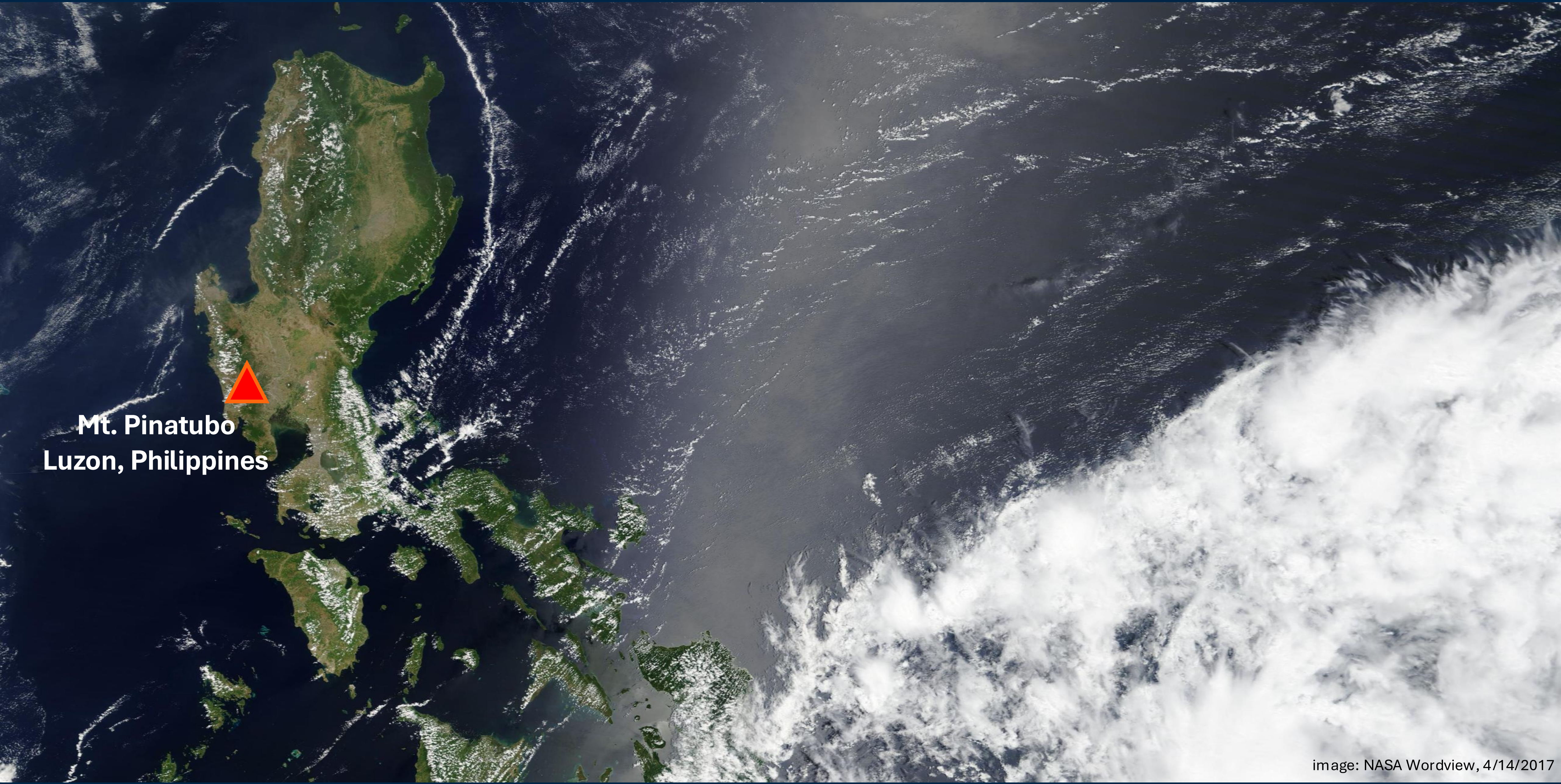

Mt. Pinatubo
Luzon, Philippines
image: NASA Wordview, 4/14/2017

image: NASA Wordview, 4/14/2017

Dec 1990

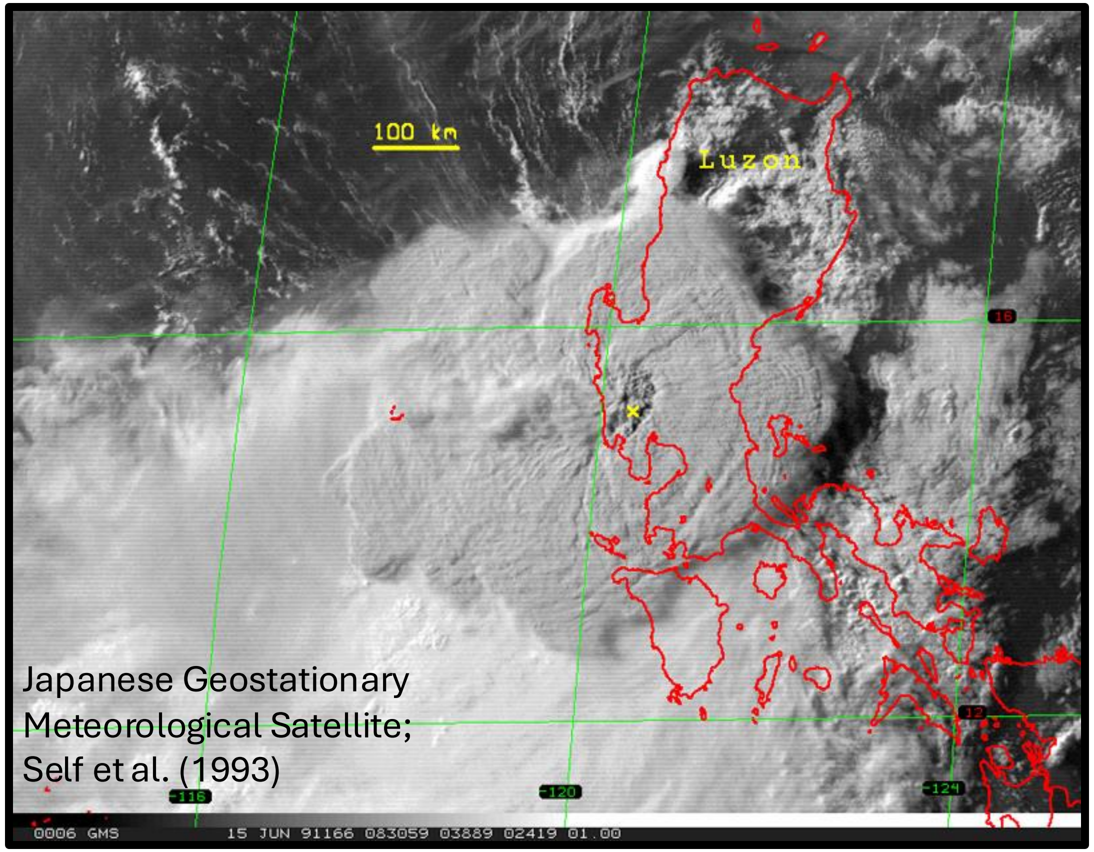
June 1991

image: NASA Wordview, 4/14/2017

image: NASA Wordview, 4/14/2017

image: NASA Wordview, 4/14/2017

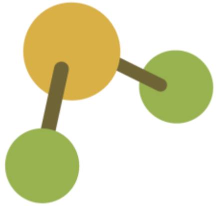
visible plume on day of eruption



Volcanic emissions fuel the production of aerosols:

20 billion kg

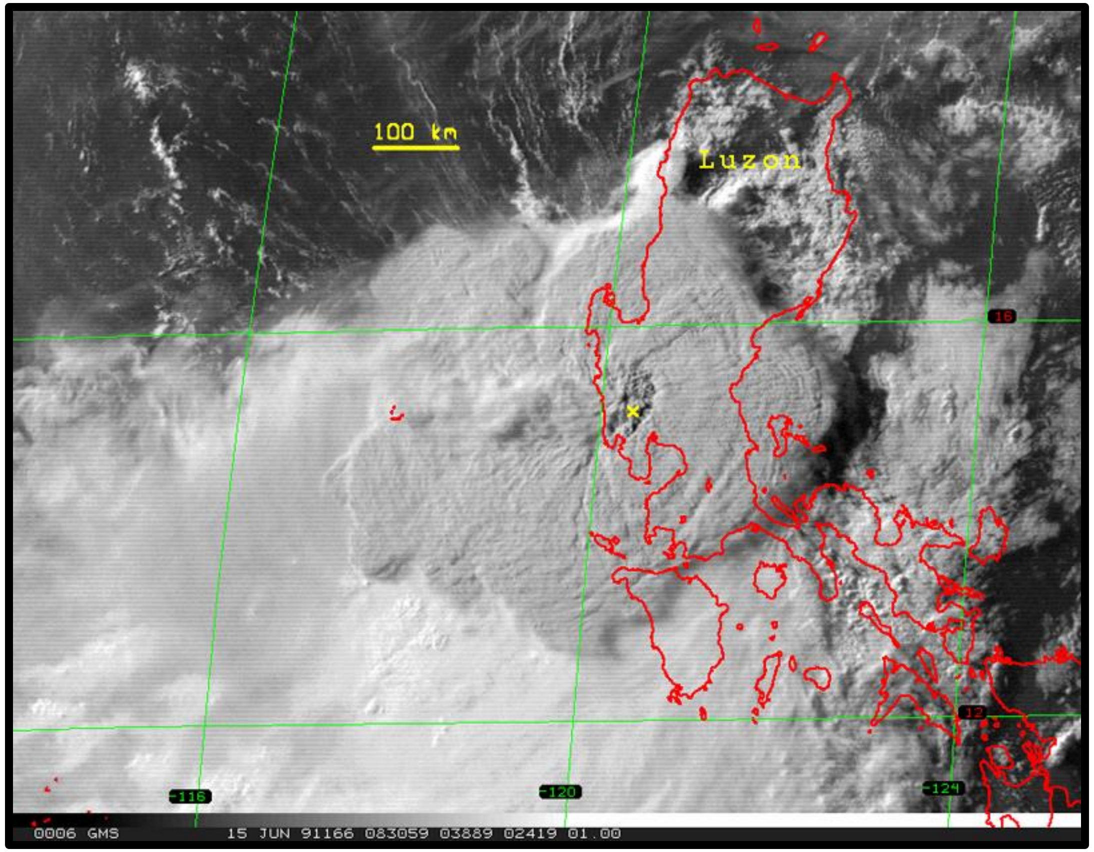
SO_2 → sulfate aerosol



half-life ~20 days

half-life ~300 days

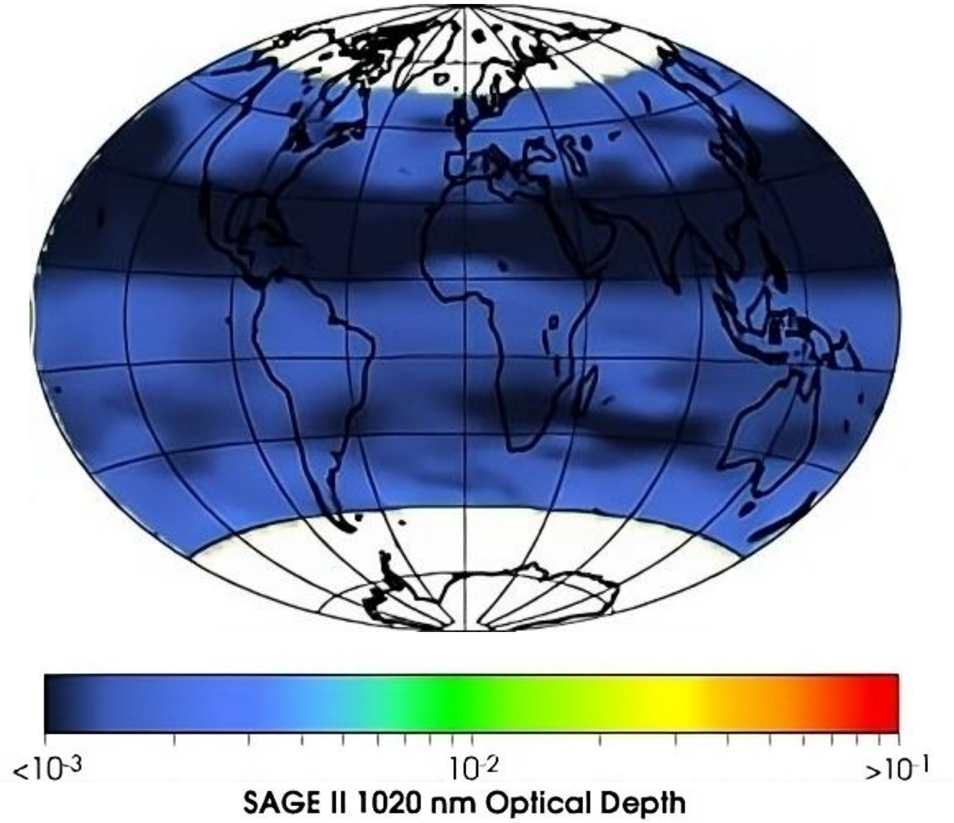
visible plume on day of eruption



Japanese Geostationary Meteorological Satellite;
Self et al. (1993)

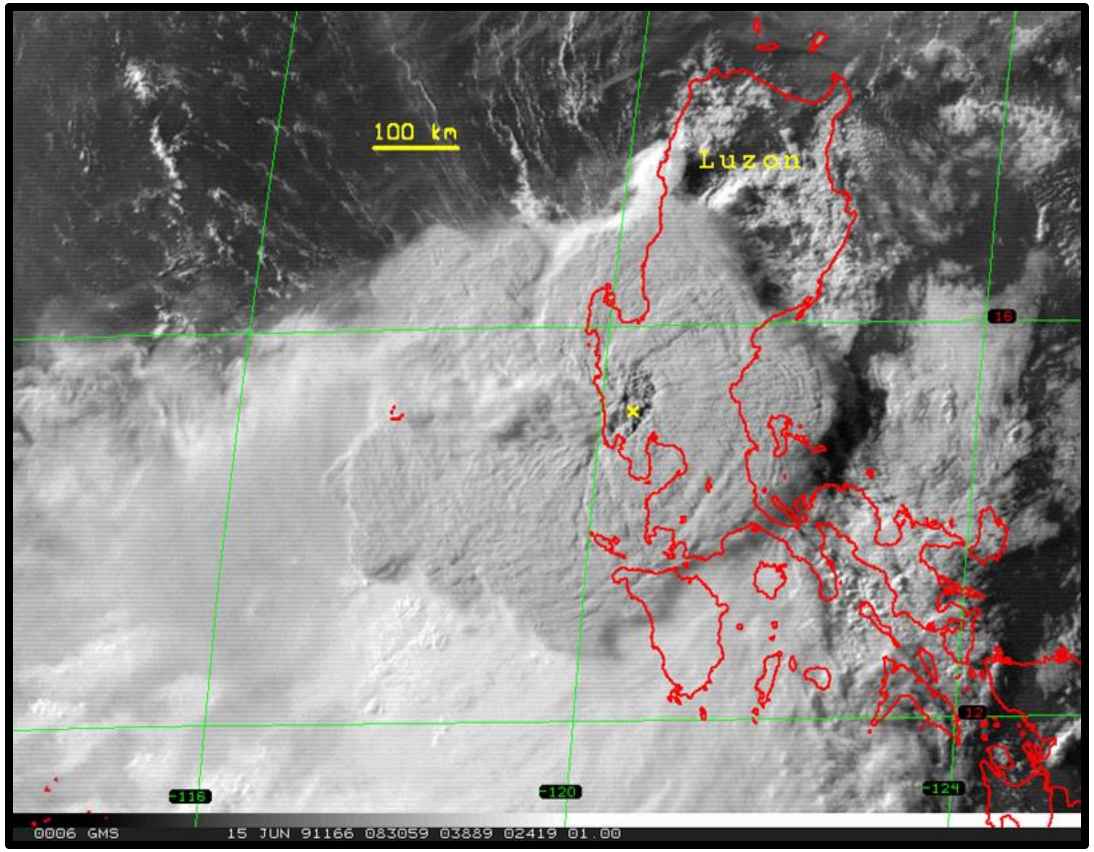
around the globe in ~3 weeks

Apr-May 1991



McCormick at al. (1995)

visible plume on day of eruption



Japanese Geostationary Meteorological Satellite;
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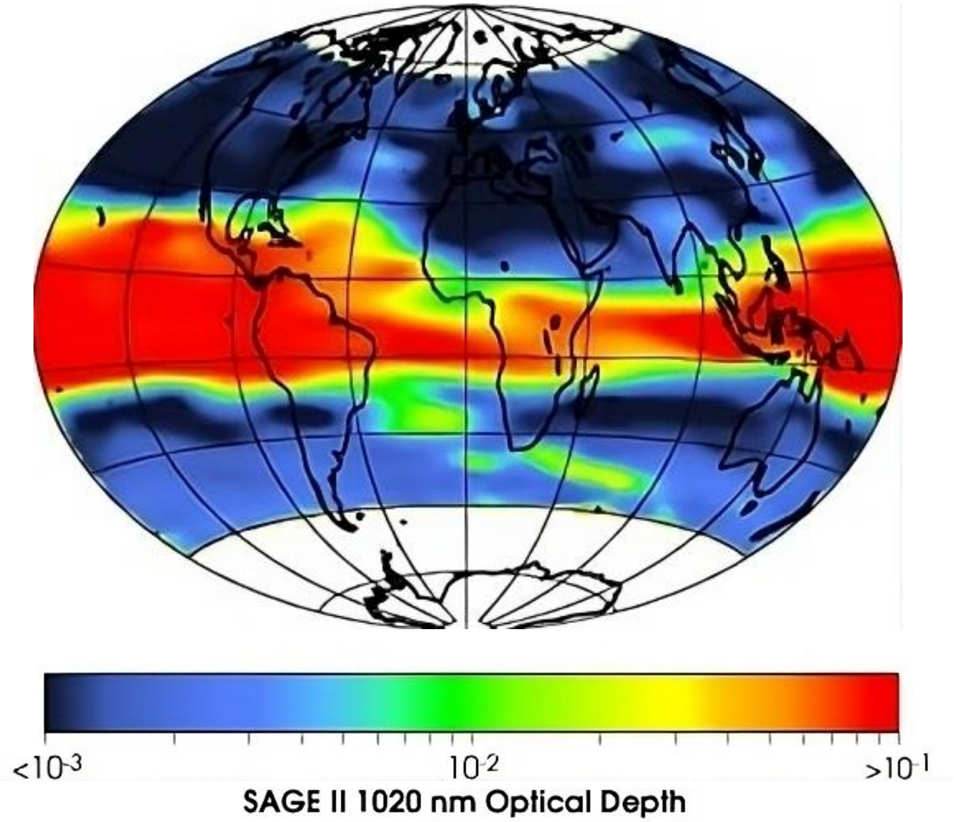
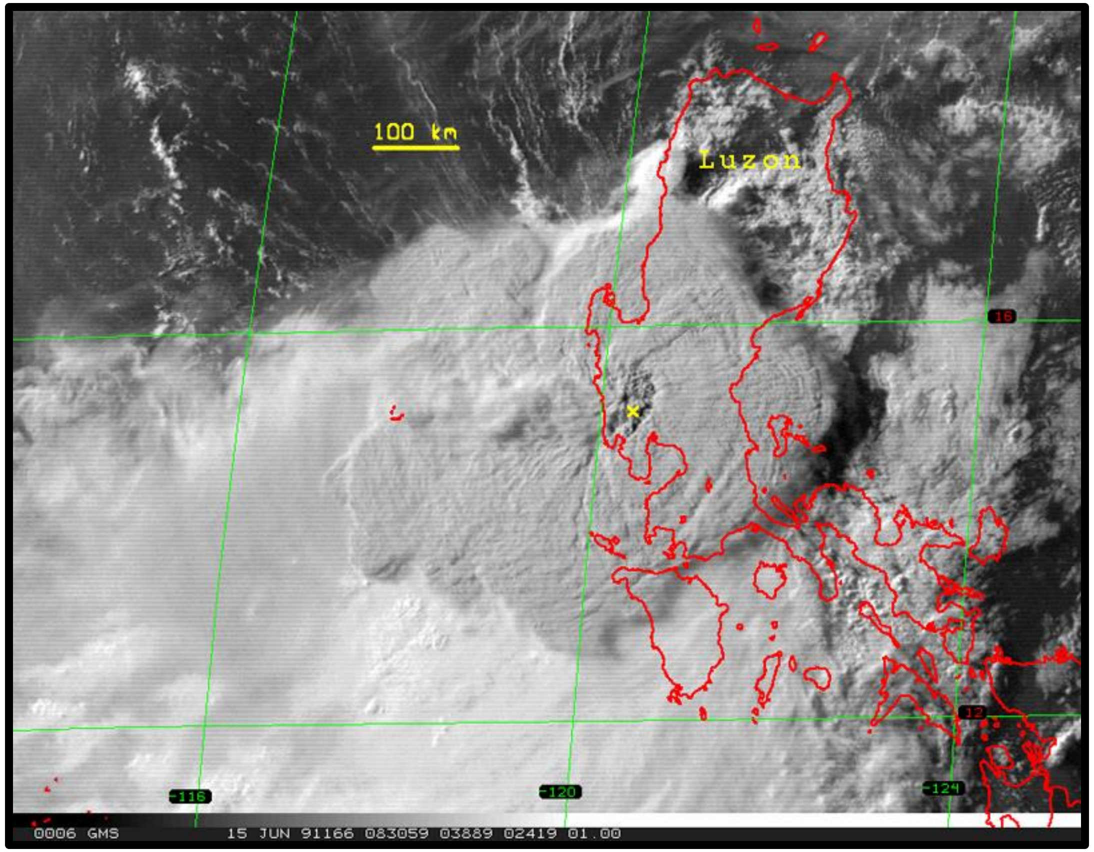
around the globe in ~3 weeks
July 1991



McCormick at al. (1995)

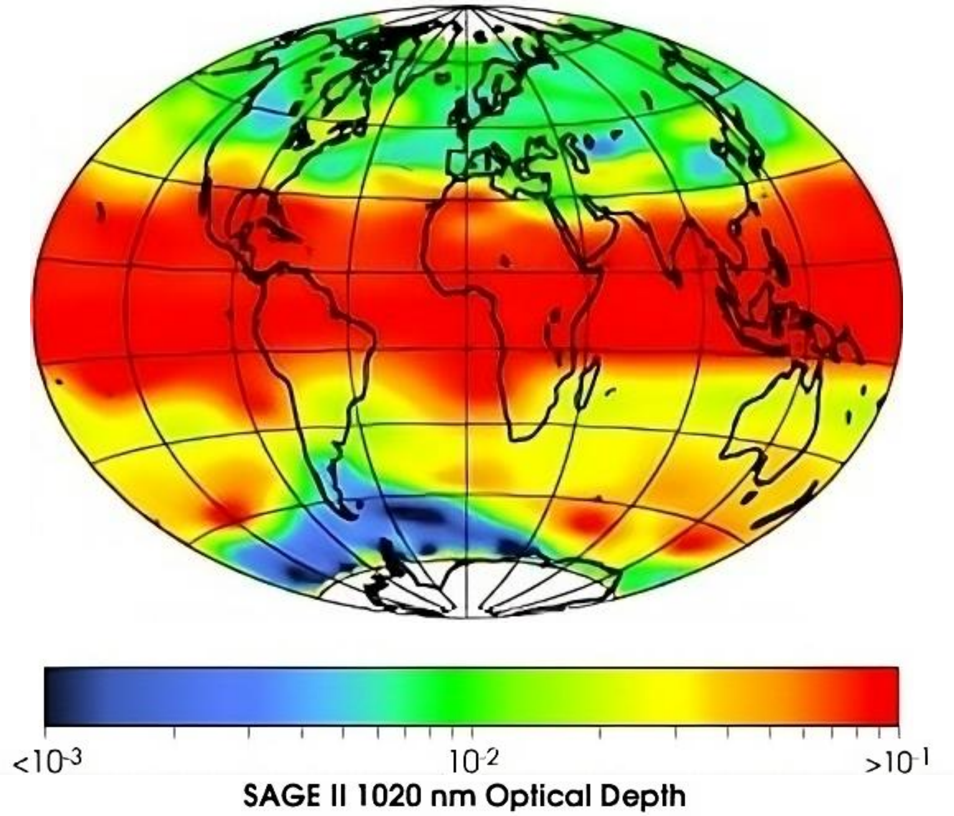
visible plume on day of eruption



Japanese Geostationary Meteorological Satellite;
Self et al. (1993)

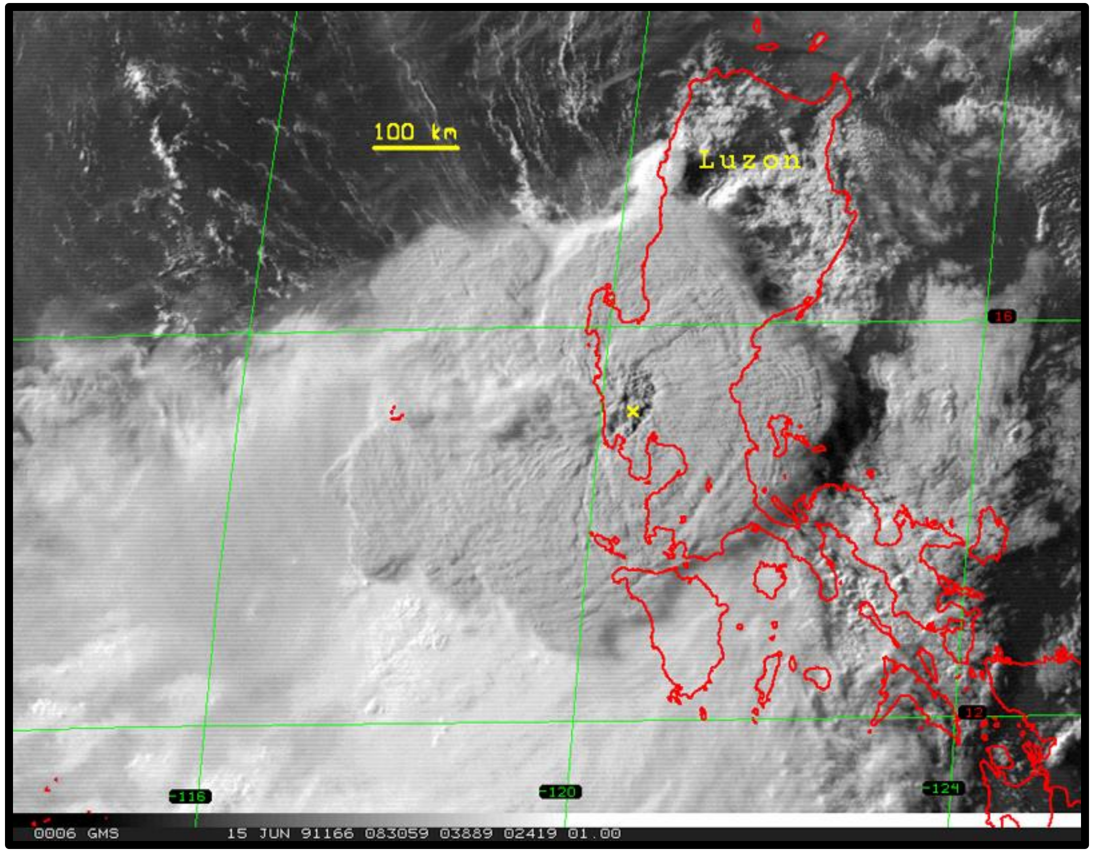
around the globe in ~3 weeks

September 1991



McCormick at al. (1995)

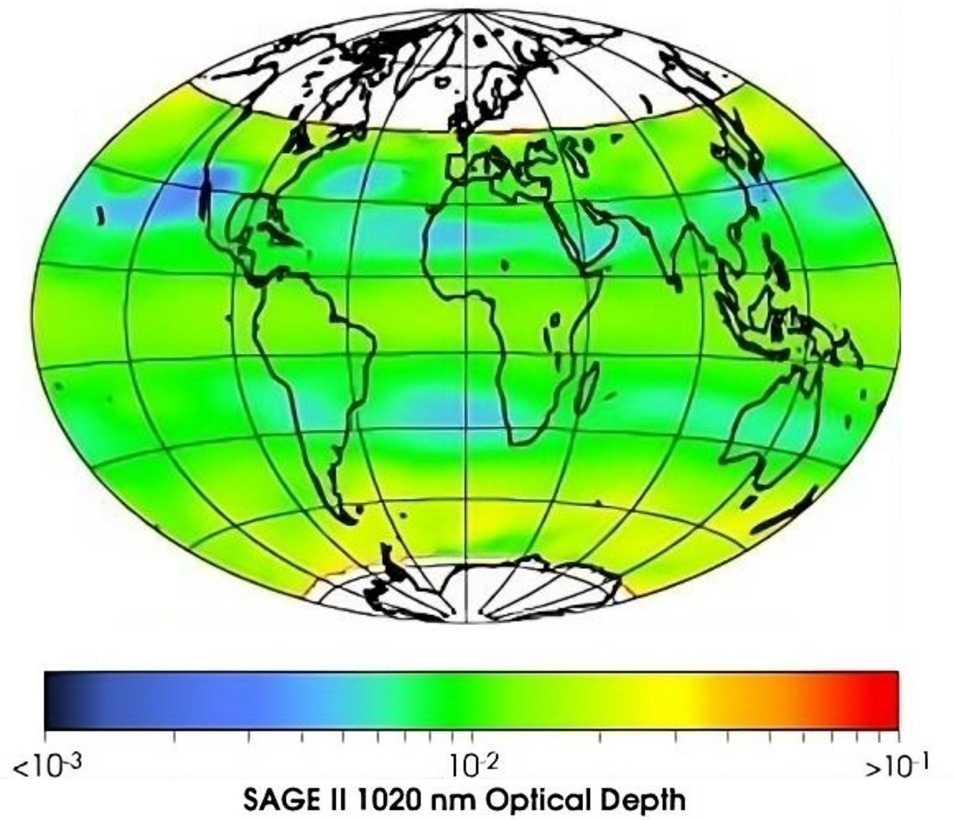
visible plume on day of eruption



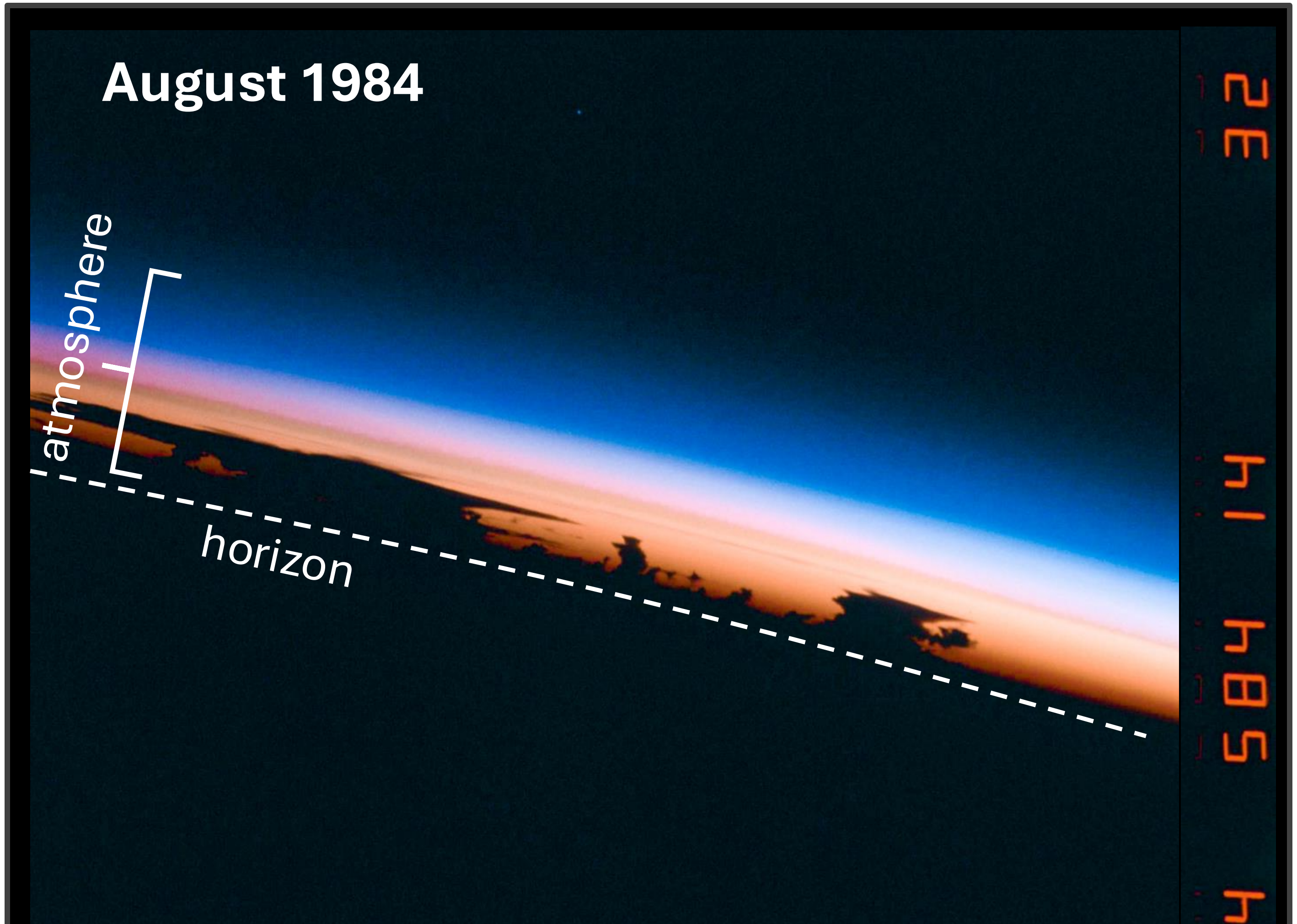
Japanese Geostationary Meteorological Satellite;
Self et al. (1993)

around the globe in ~3 weeks

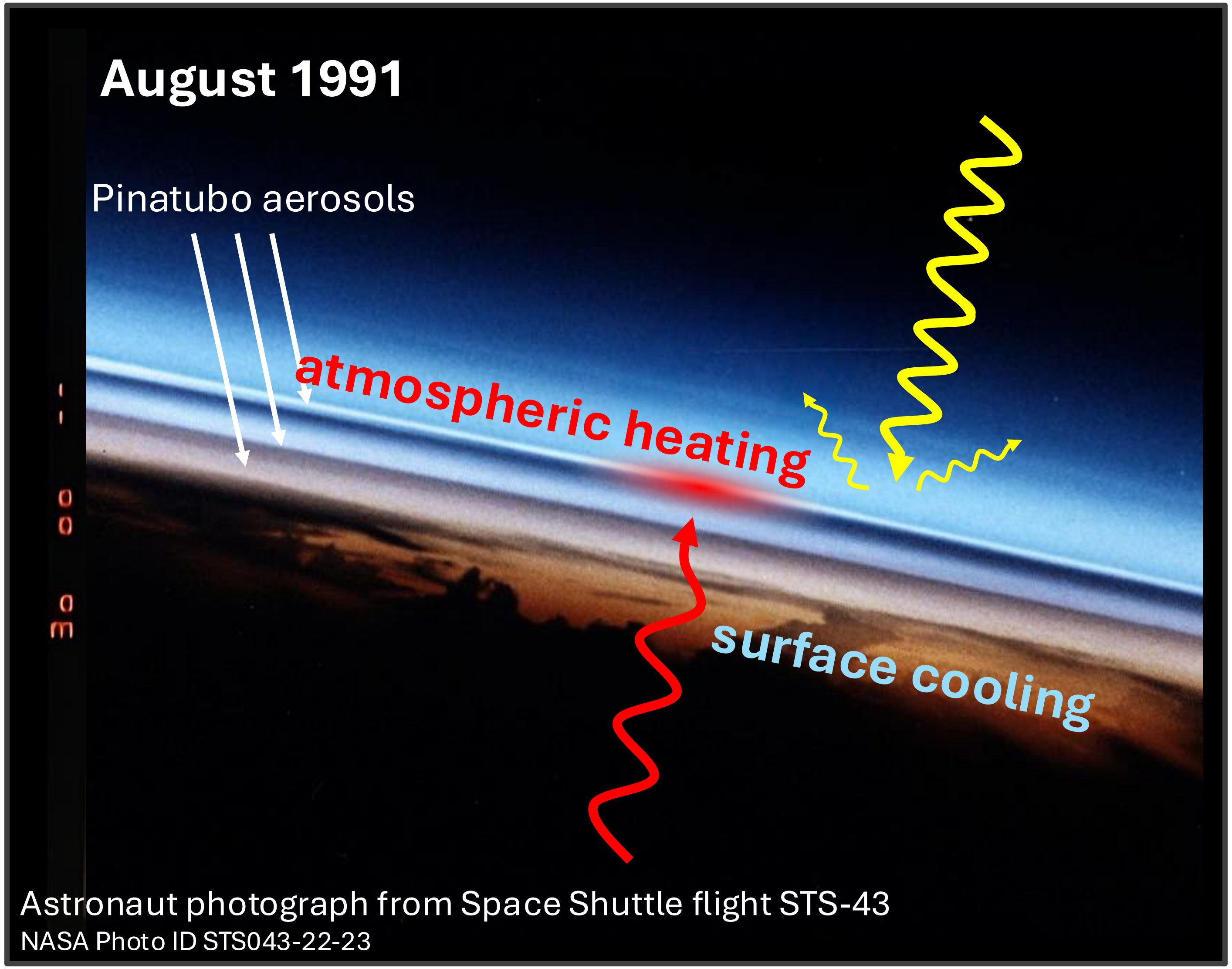
January 1994



McCormick at al. (1995)



Astronaut photograph from Space Shuttle flight STS-41D
NASA Photo ID STS41D-32-14

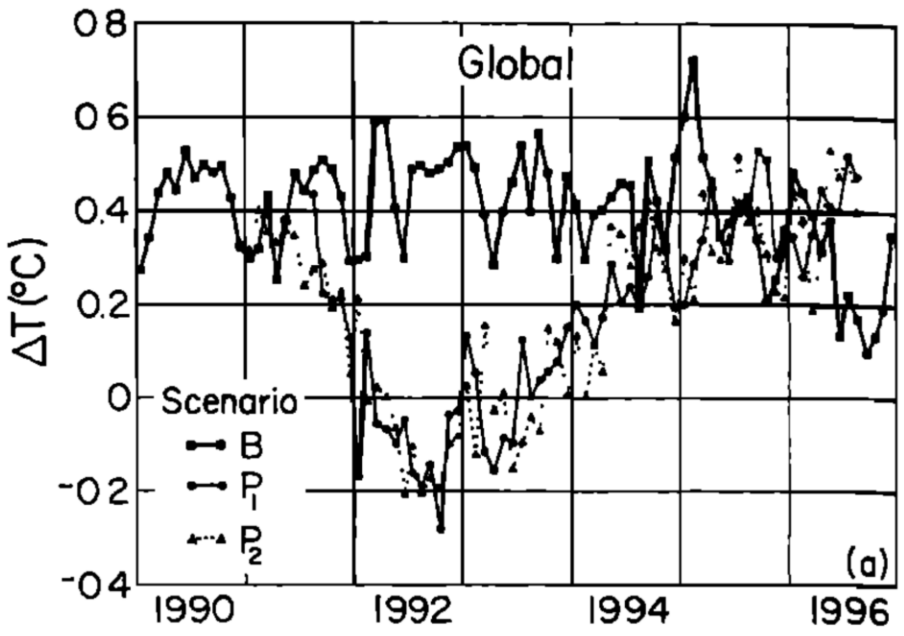


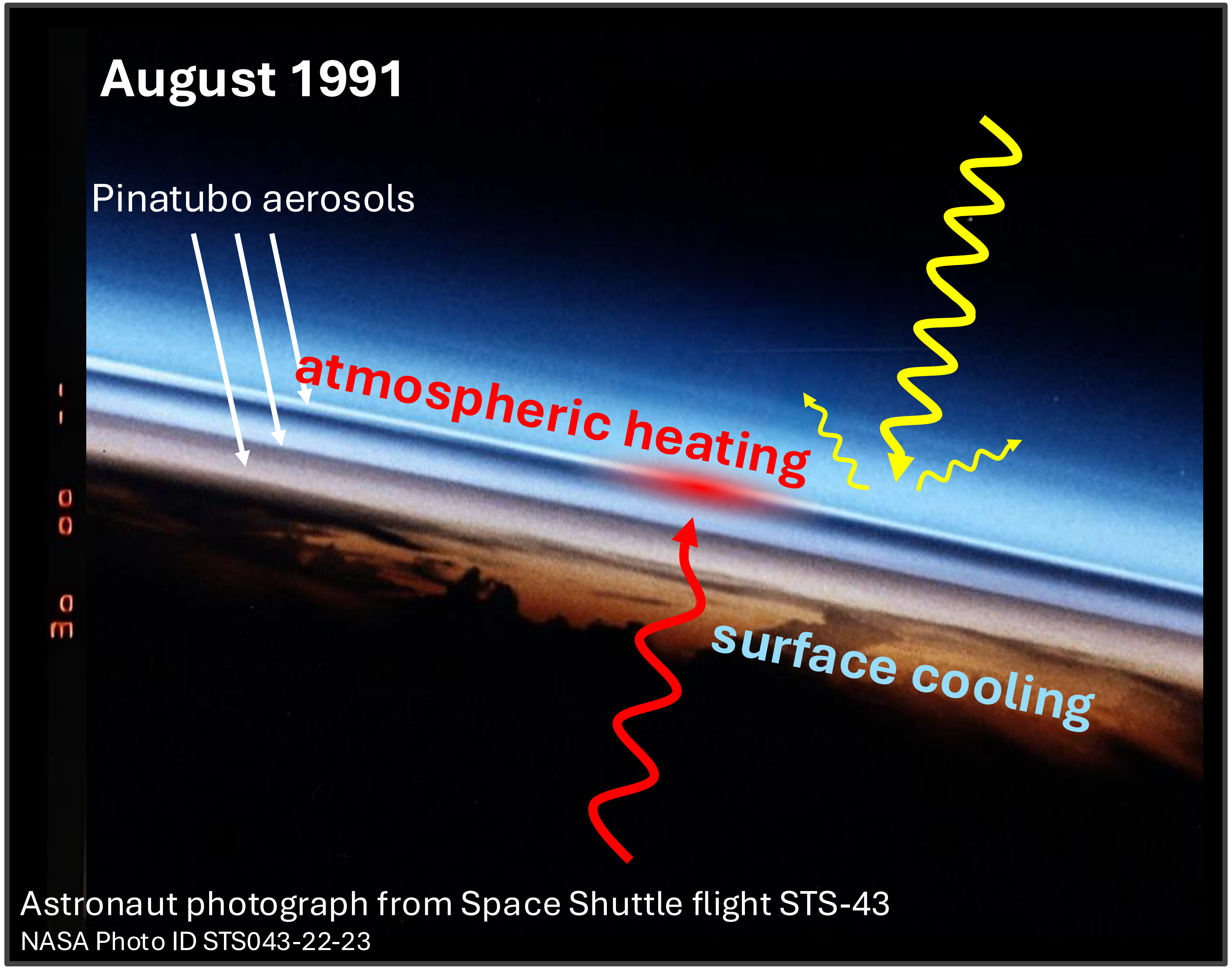
Astronaut photograph from Space Shuttle flight STS-43
NASA Photo ID STS043-22-23

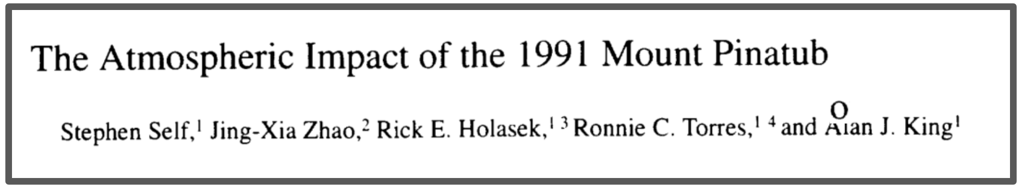
POTENTIAL CLIMATE IMPACT OF MOUNT PINATUBO ERUPTION

James Hansen, Andrew Lacis, Reto Ruedy and Makiko Sato
NASA Goddard Space Flight Center Goddard Institute for Space Studies, New York

1992

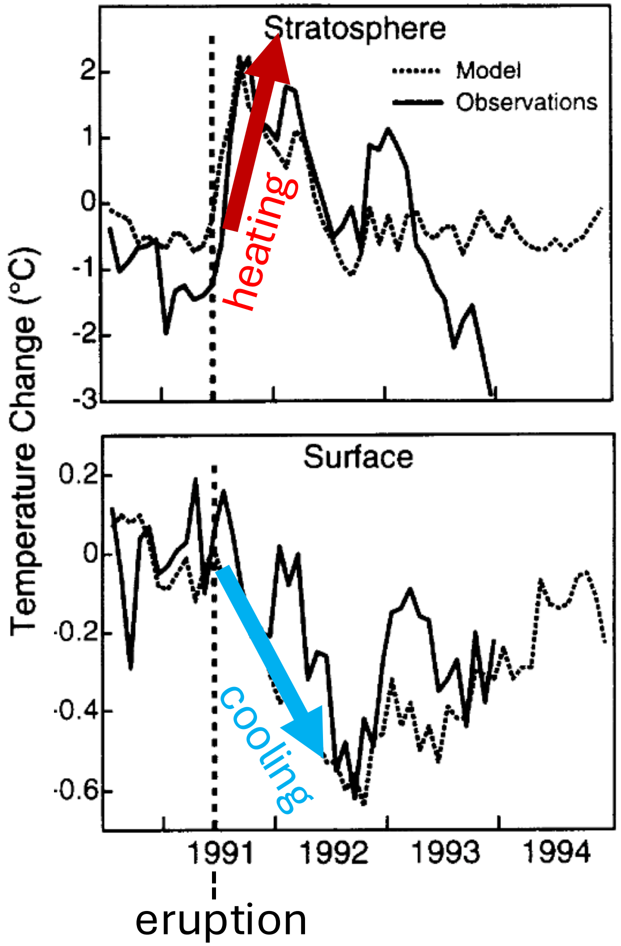


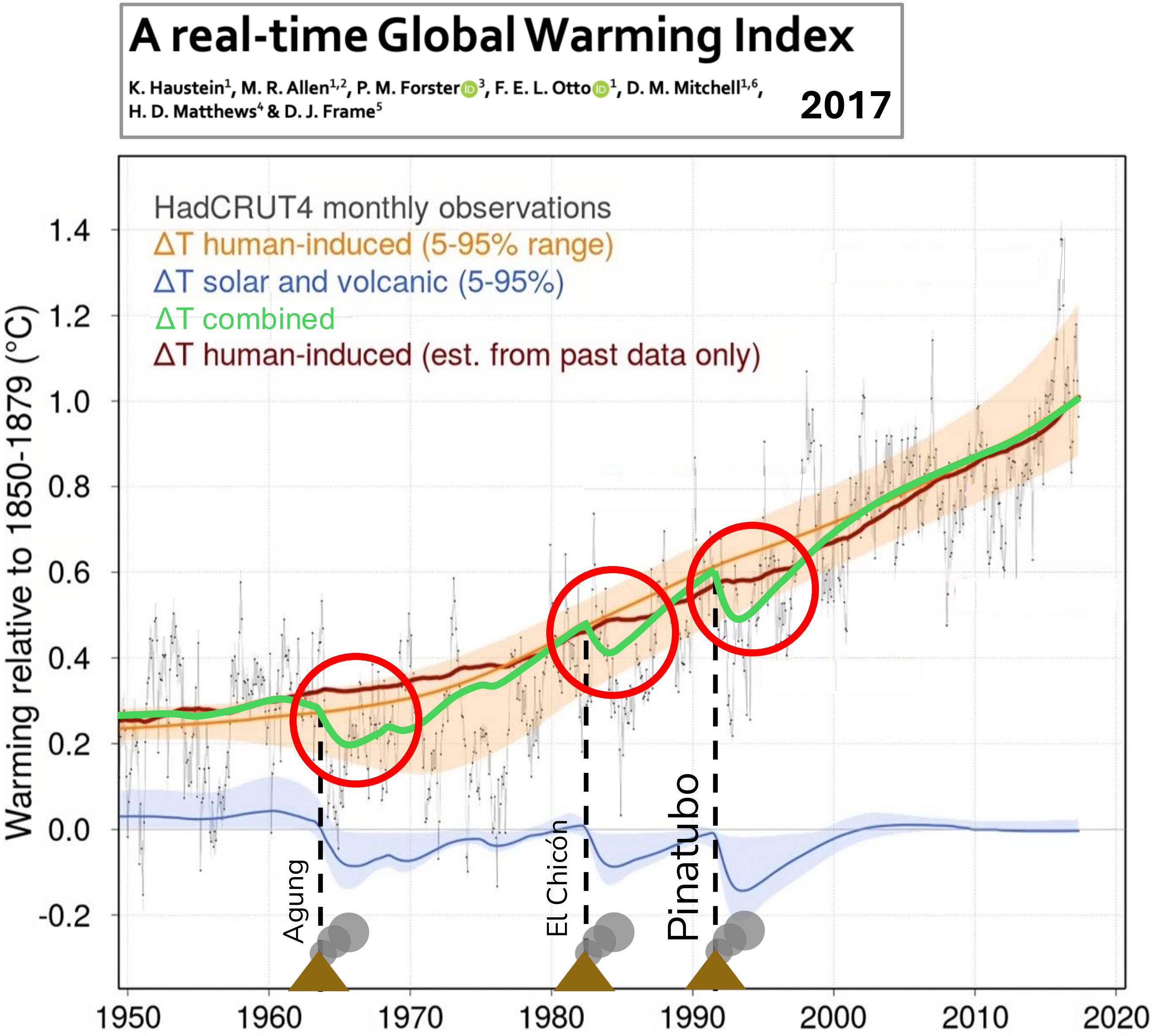



The Atmospheric Impact of the 1991 Mount Pinatub

Stephen Self,[1] Jing-Xia Zhao,[2] Rick E. Holasek,[1 3] Ronnie C. Torres,[1 4] and Alan J. King[1]

1993





Stratospheric Aerosol Injection (SAI)

- a proposed method of geoengineering for climate change mitigation
- human-controlled release of sulfate aerosols, mimicking a continuous volcanic eruption
- active subject of modeling research

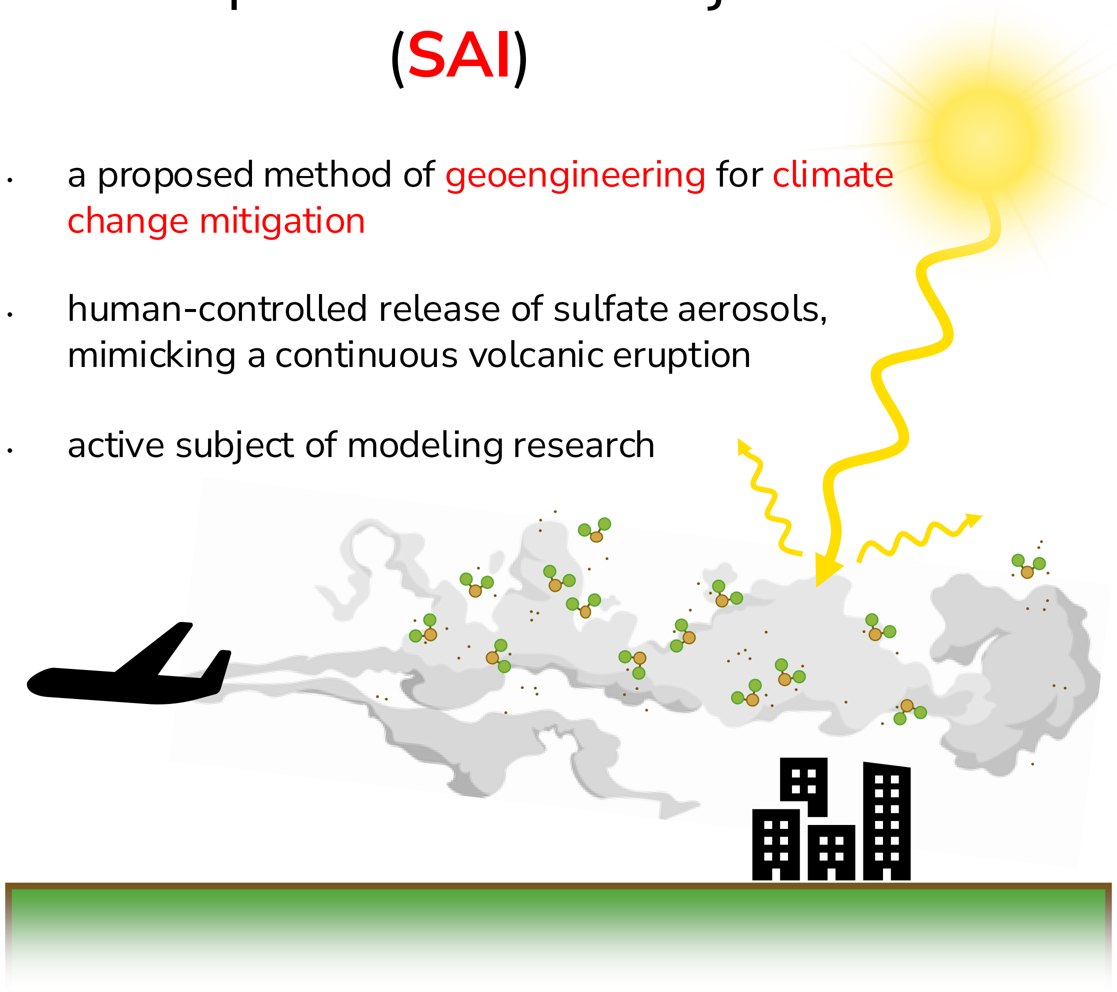


image: Sandia Nat'l Labs

Sandia National Laboratories

CLDERA

- years 3-6 of my PhD
- collaboration based at Sandia National Labs, Albuquerque, New Mexico

CLDERA motivation:

Using the ***1991 Pinatubo eruption*** as an exemplar event: develop methods of ***source–impact attribution***

Hypothesis: methods will generalize to non-volcanic forcing sources, e.g. SAI

Outline

Part 1: volcanic aerosols in a simplified climate model

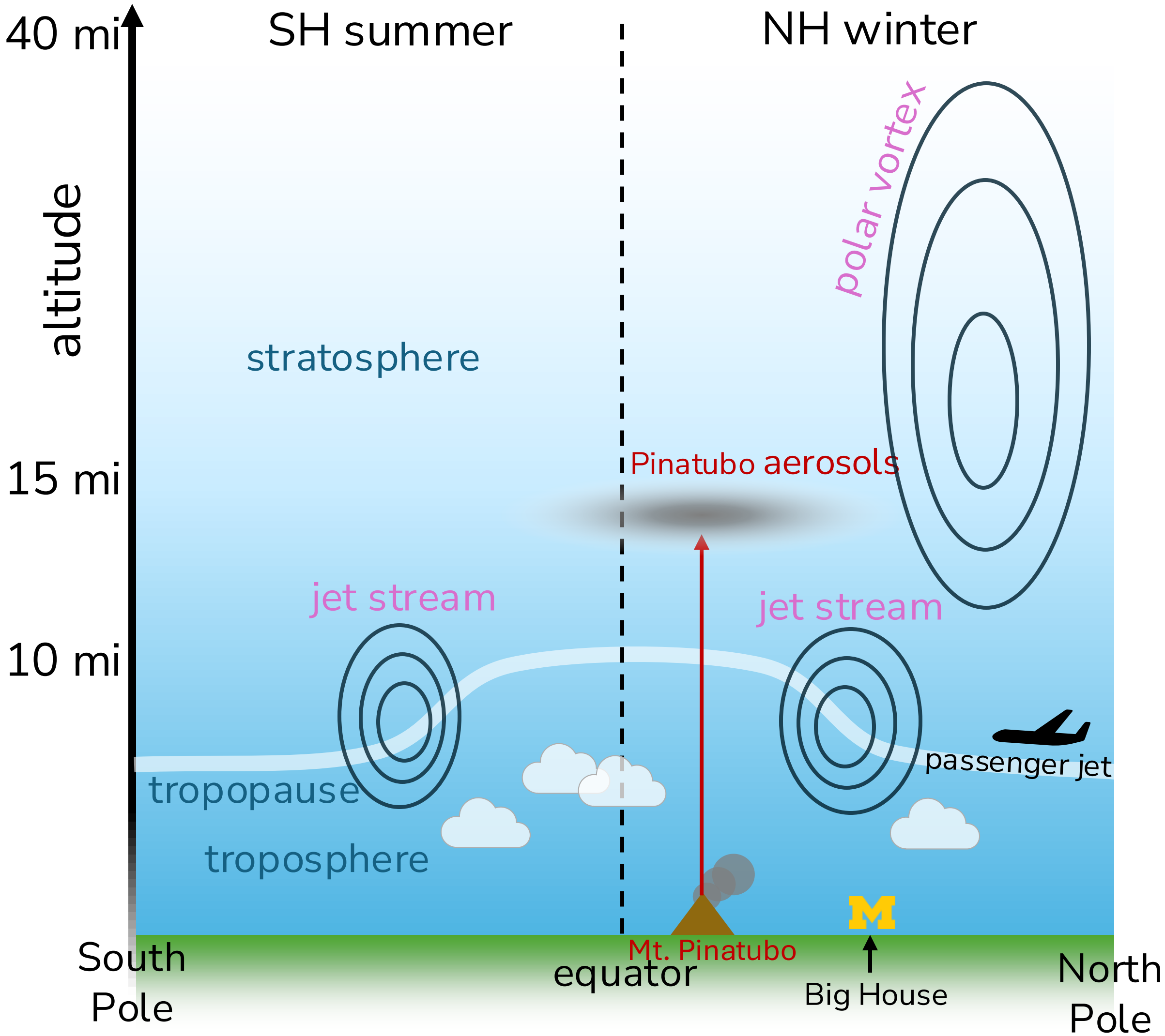
Part 2: volcanic modification of midlatitude winds

Part 3: volcanic effects of the global circulation of mass

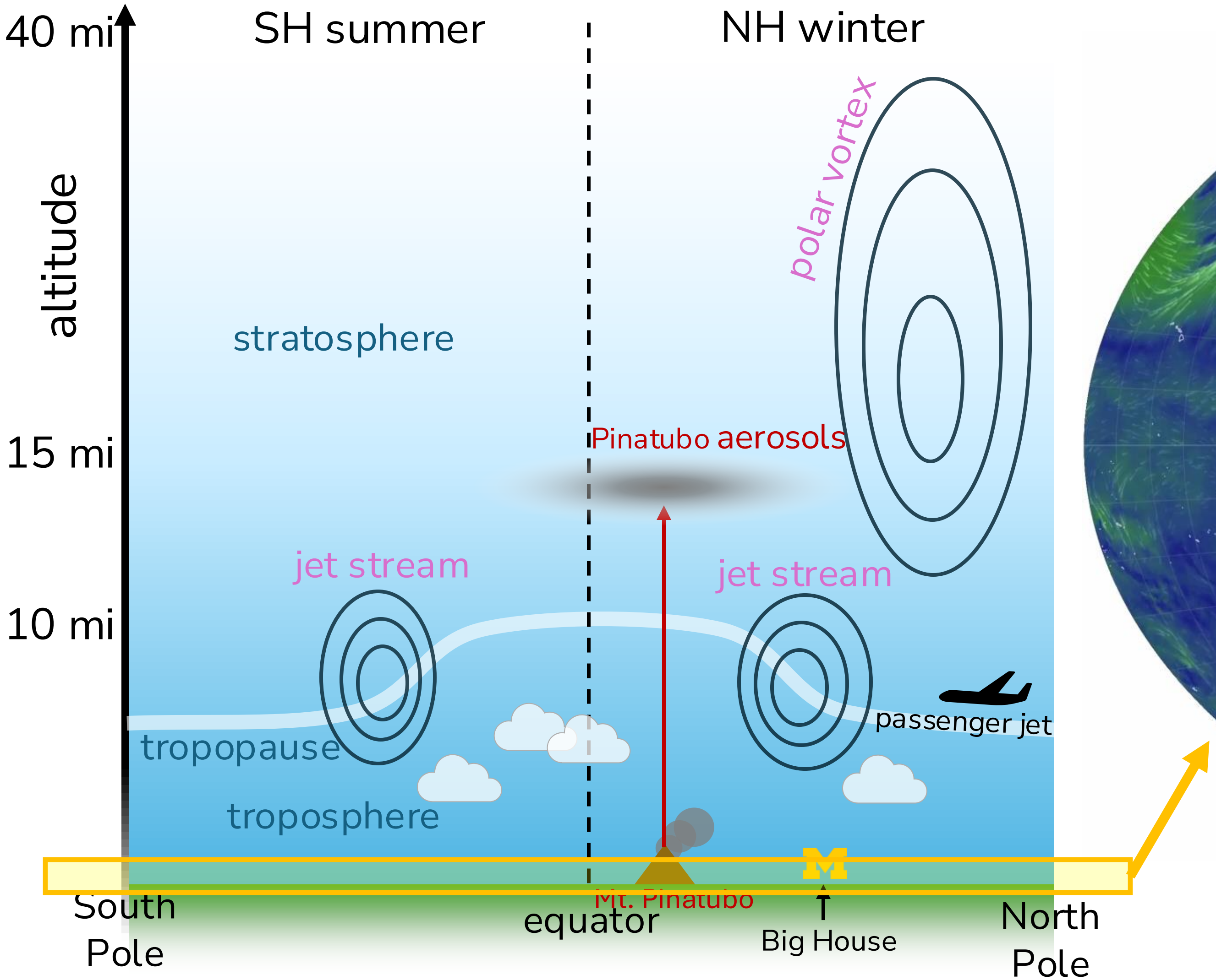
Part 1

volcanic aerosols in a simplified climate model

Vertical structure of the atmosphere

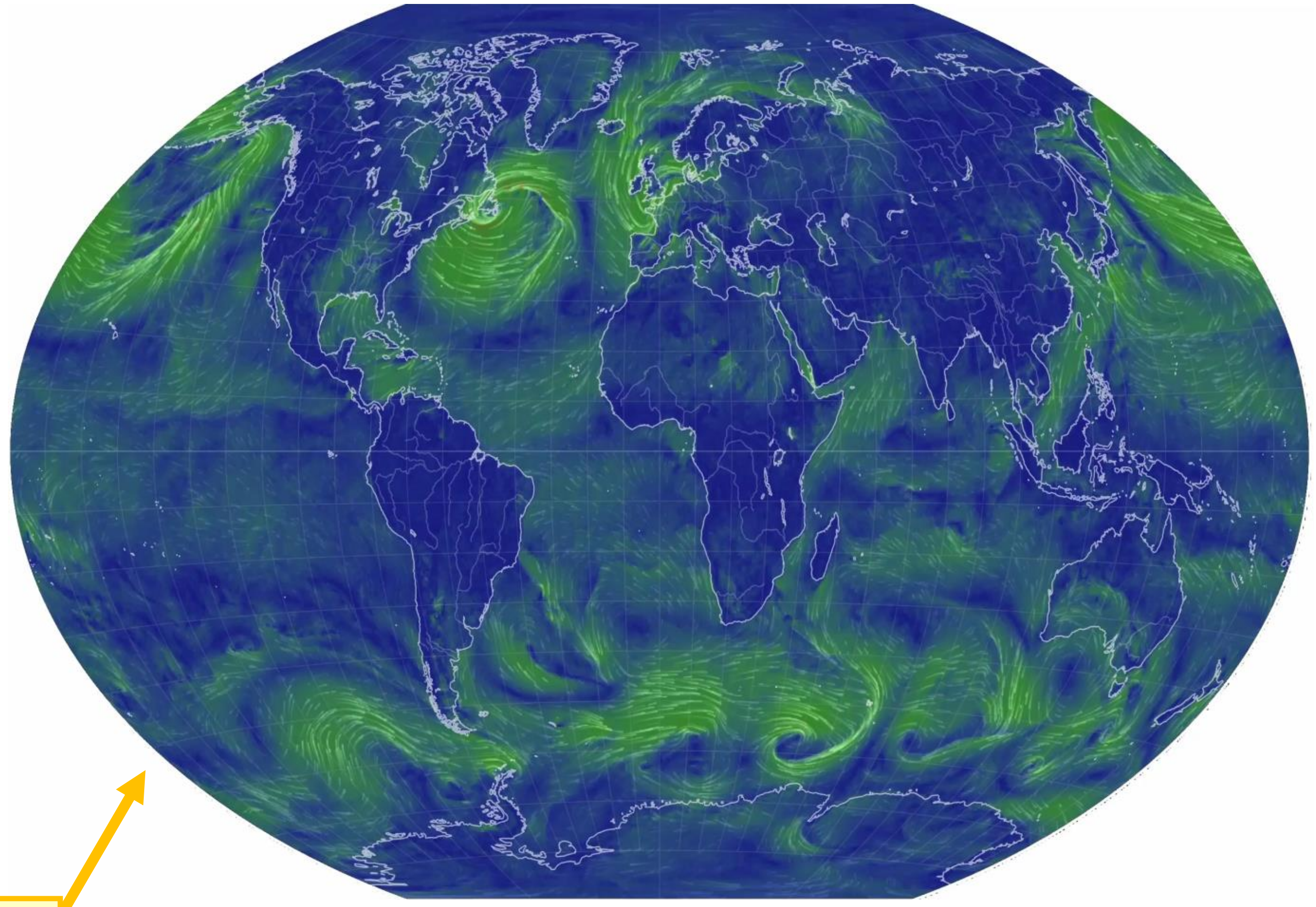


Vertical structure of the atmosphere

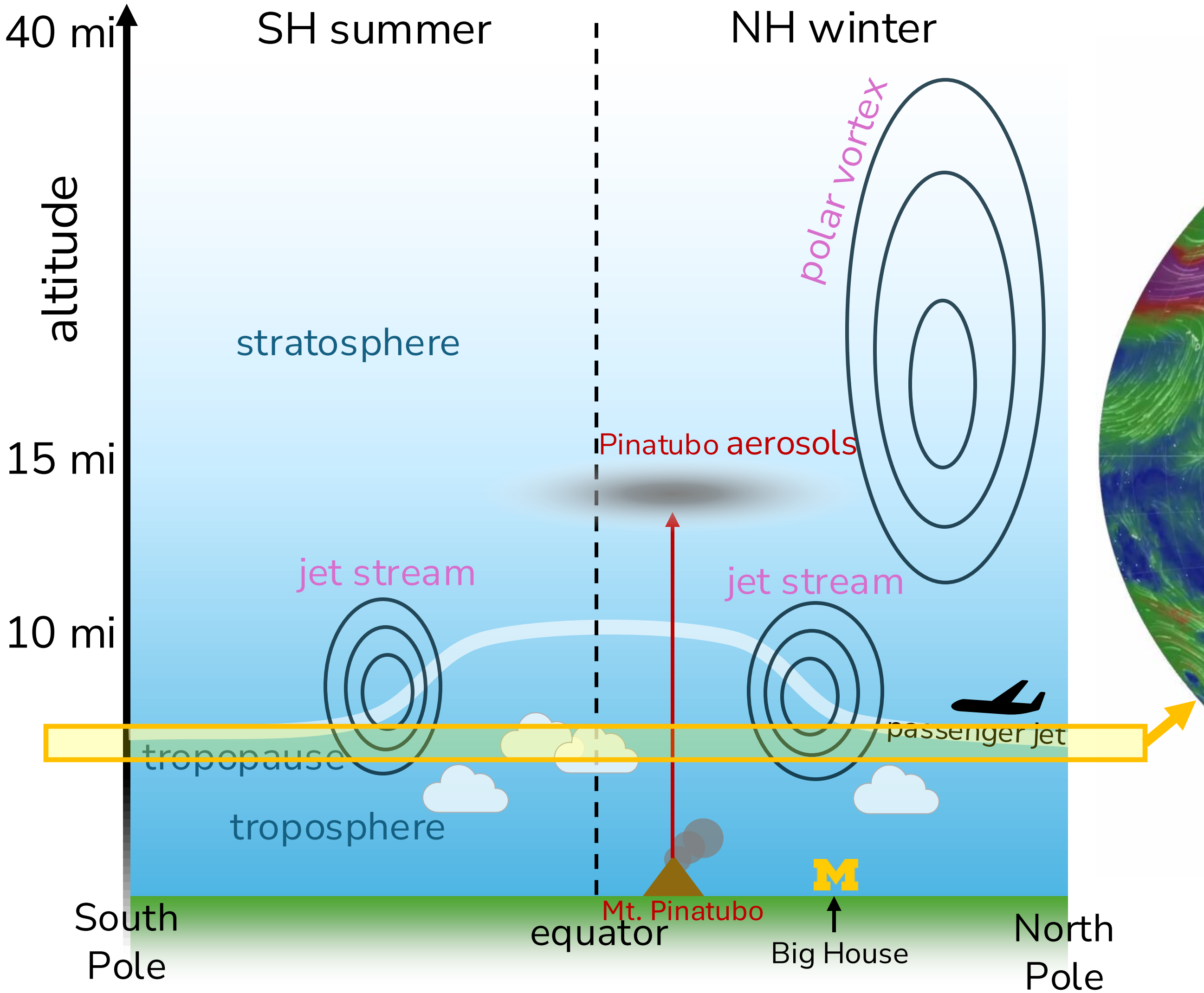


forecasted winds for today 1/10/25

surface

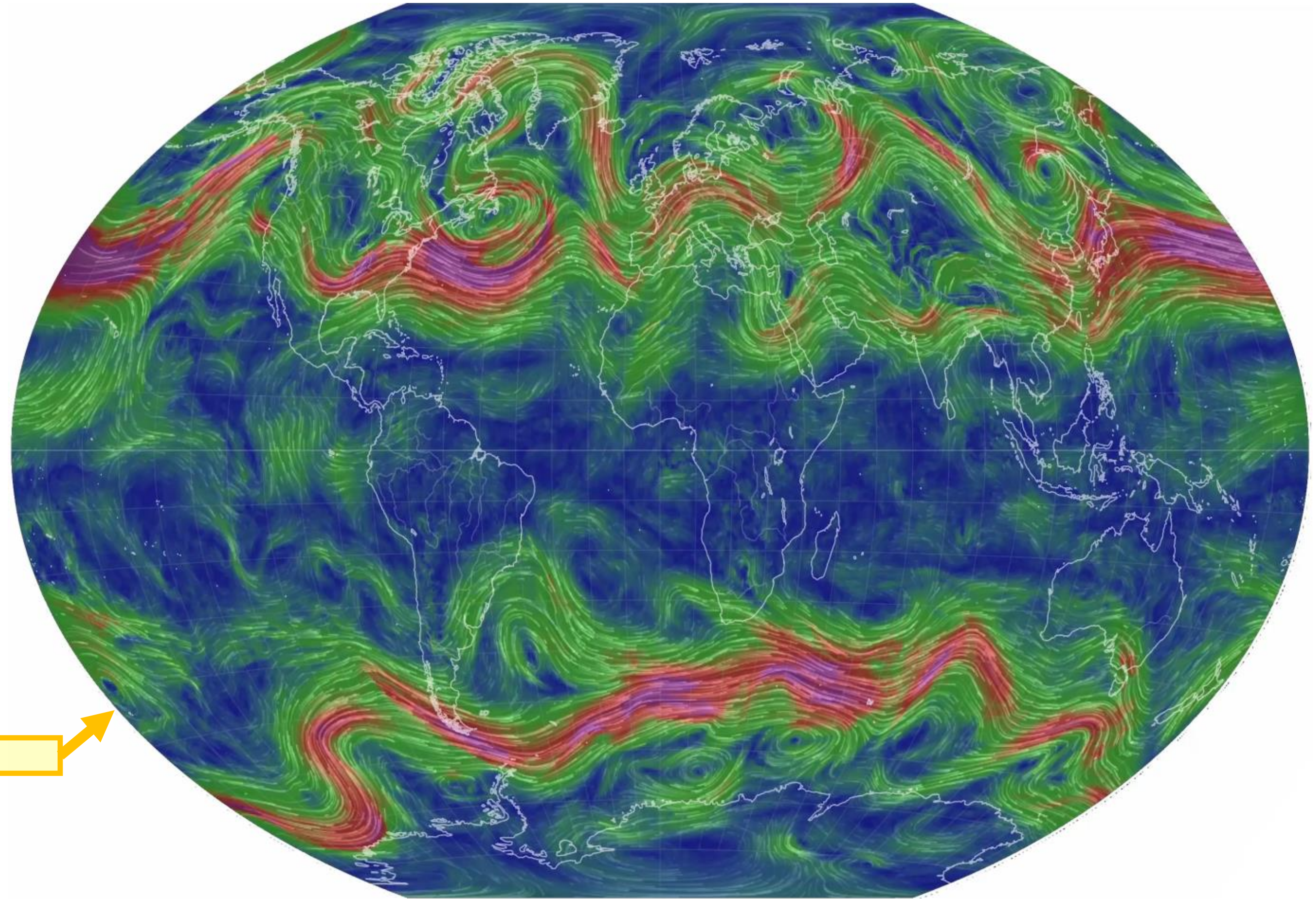


Vertical structure of the atmosphere

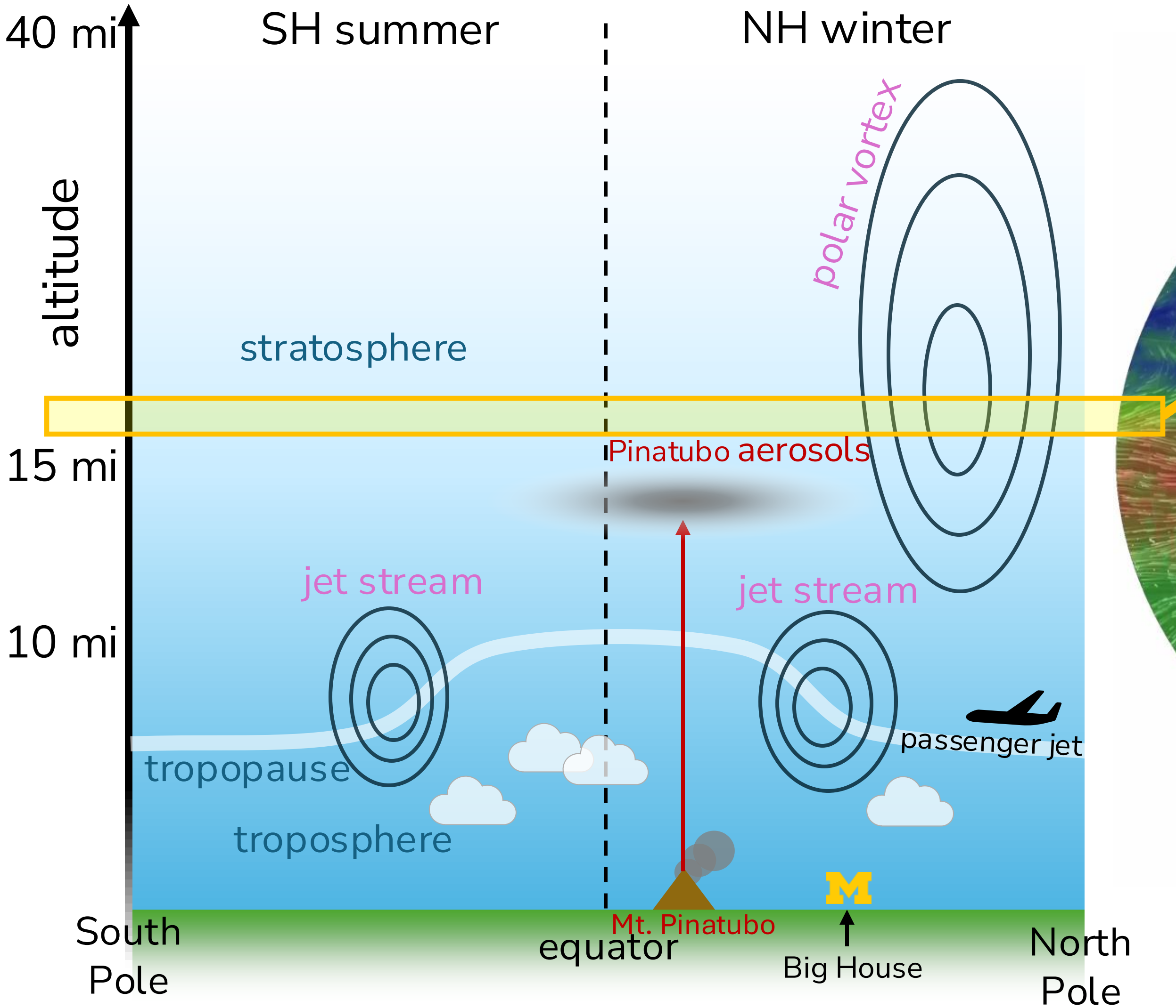


forecasted winds for today 1/10/25

500 hPa

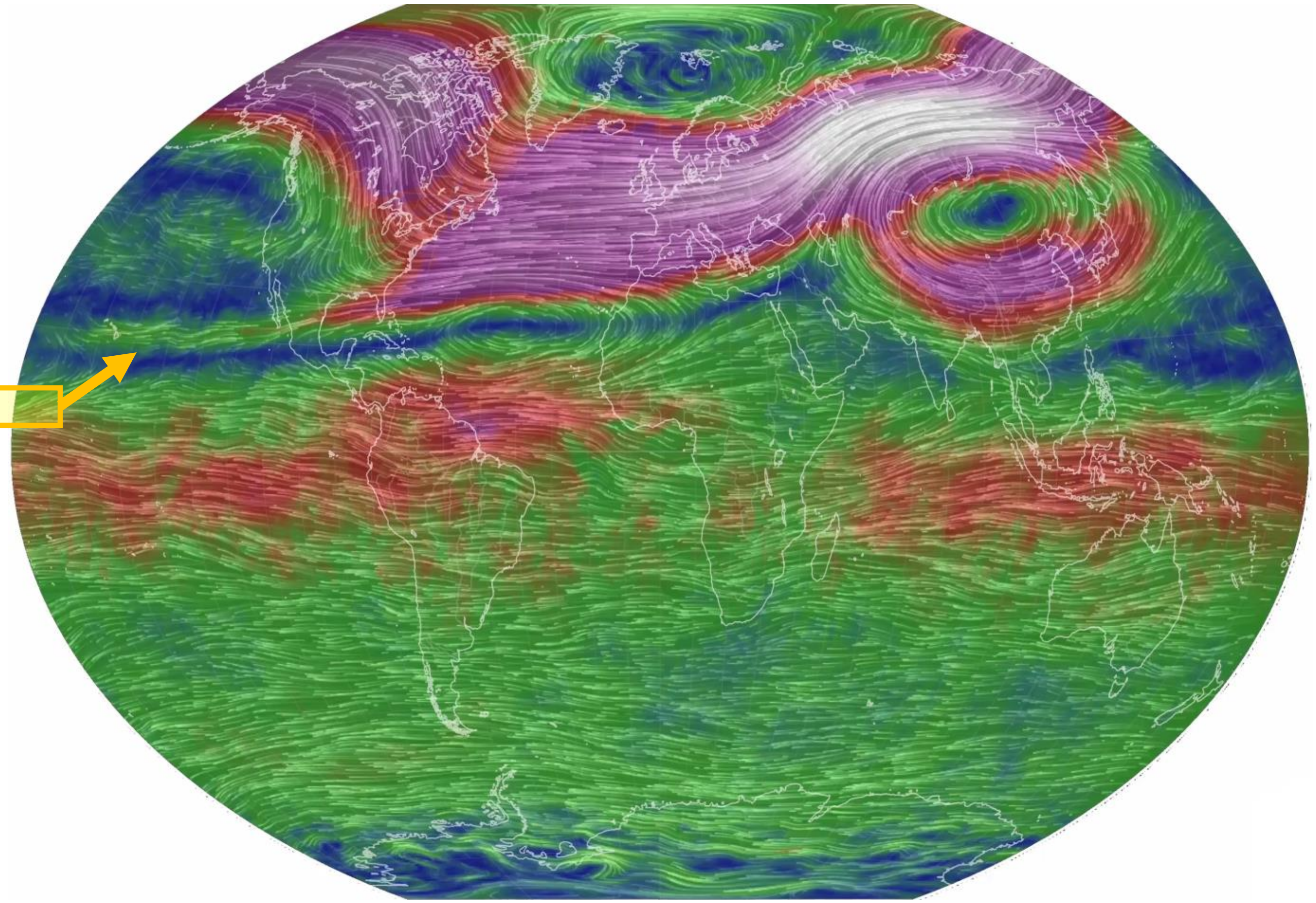


Vertical structure of the atmosphere



forecasted winds for today 1/10/25

10 hPa



Numerical Climate Modeling 101

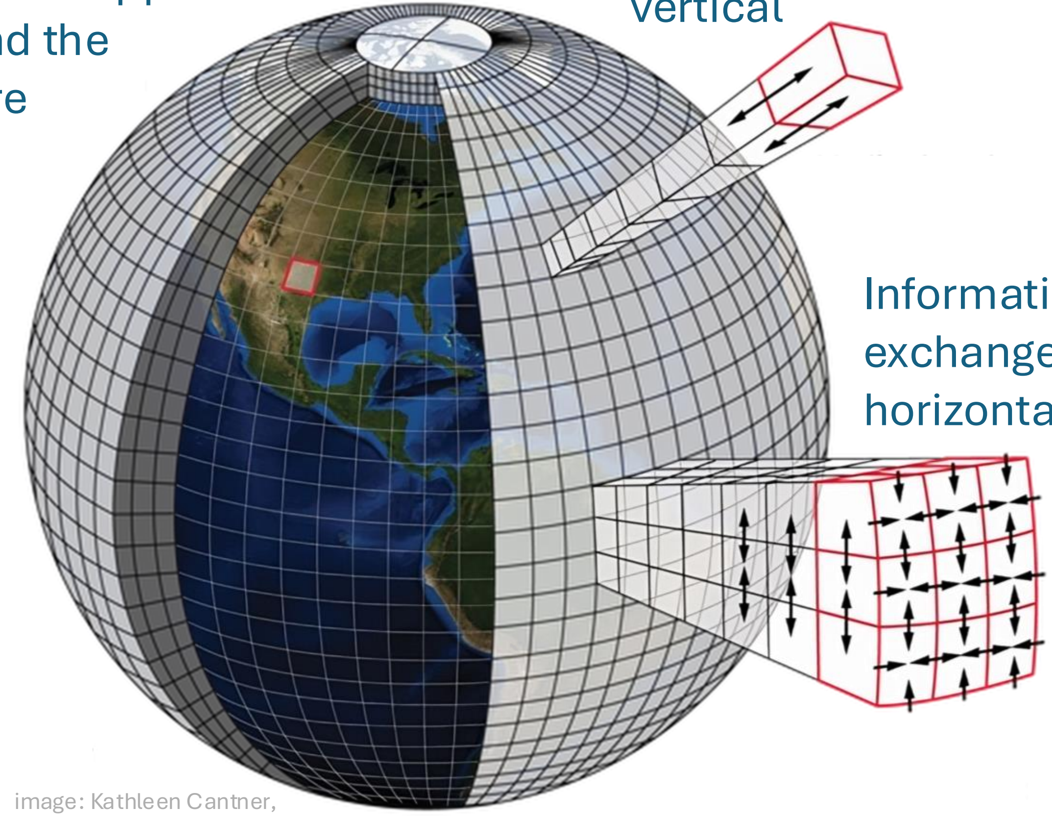


image: Kathleen Cantner, American Geosciences Institute

Wind, temperature, pressure are computed at each point on the grid.

Procedure: Compute, Timestep, Repeat

Equation set with typical approximations:

$\frac{Du}{Dt} =$ zonal (E-W) wind change

$\frac{Dv}{Dt} =$ meridional (N-S) wind change

$\frac{DT}{Dt} =$ temperature change

$\frac{\partial \omega}{\partial p} =$ vertical velocity

$\frac{\partial p}{\partial z} =$ pressure

Numerical Climate Modeling 101

E3SM
Energy Exascale
Earth System Model

fluid solver = “dynamics”

parameterizations = “physics”

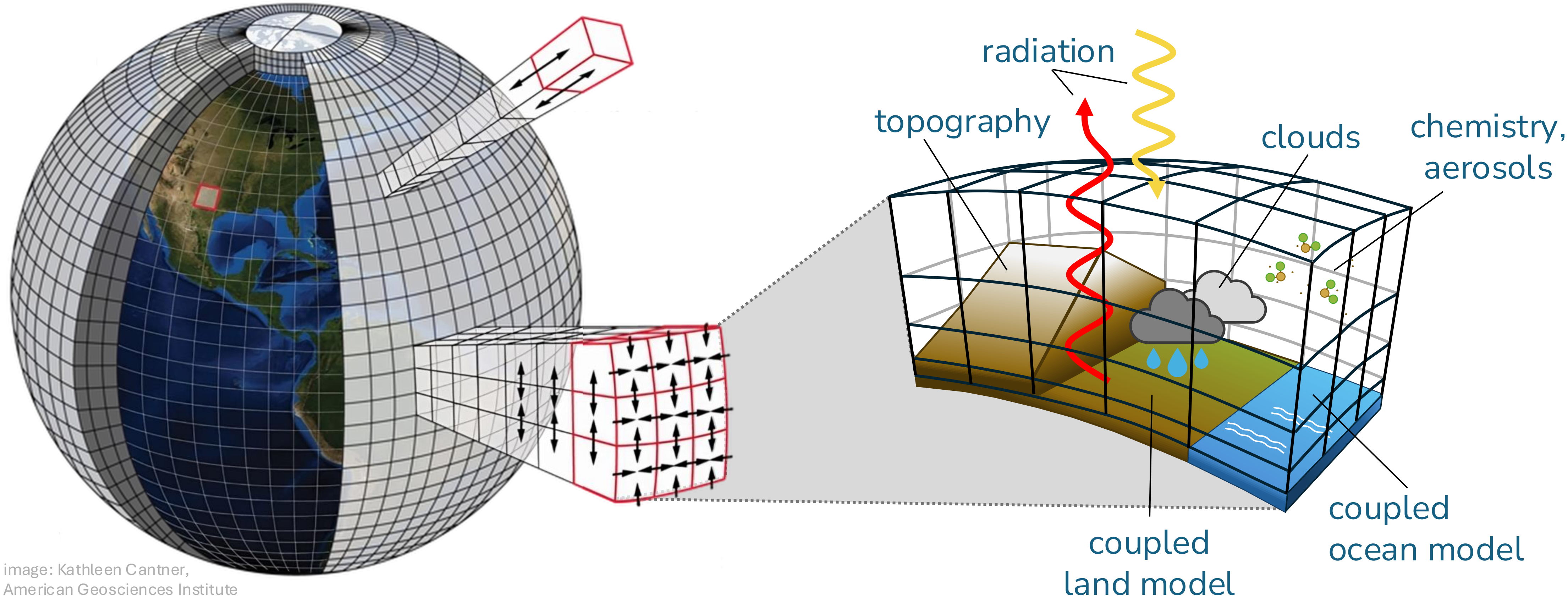


image: Kathleen Cantner,
American Geosciences Institute

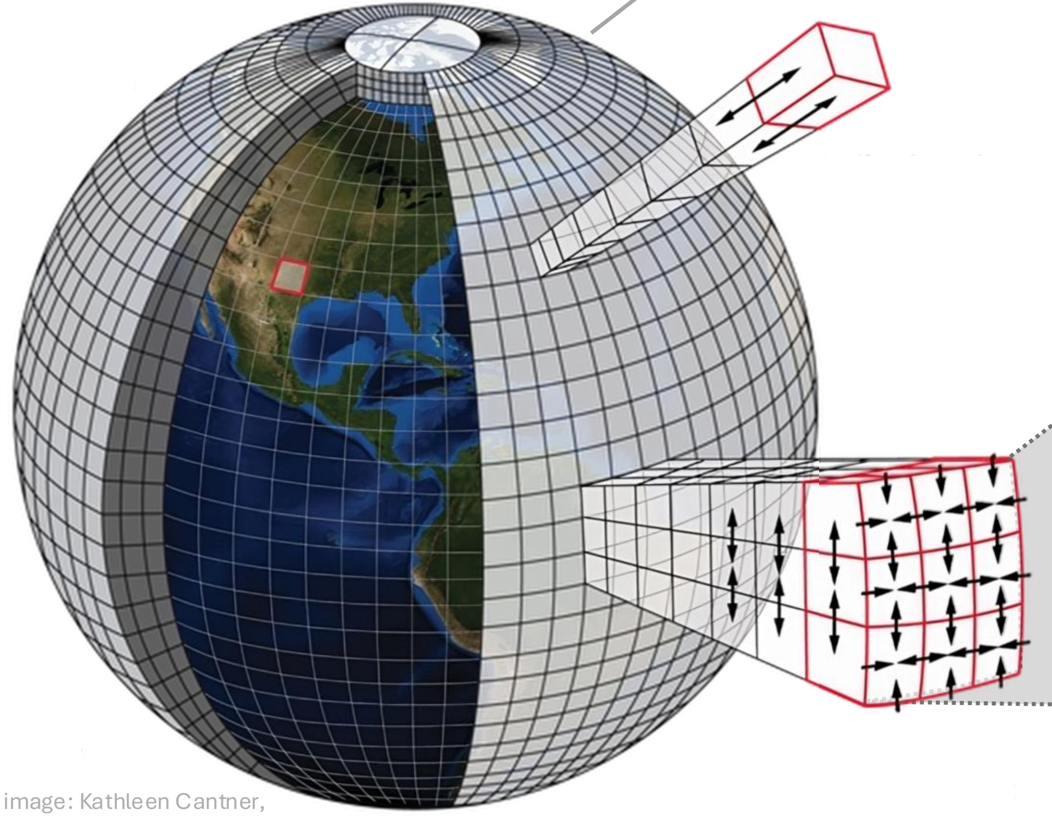
Numerical Climate Modeling 101

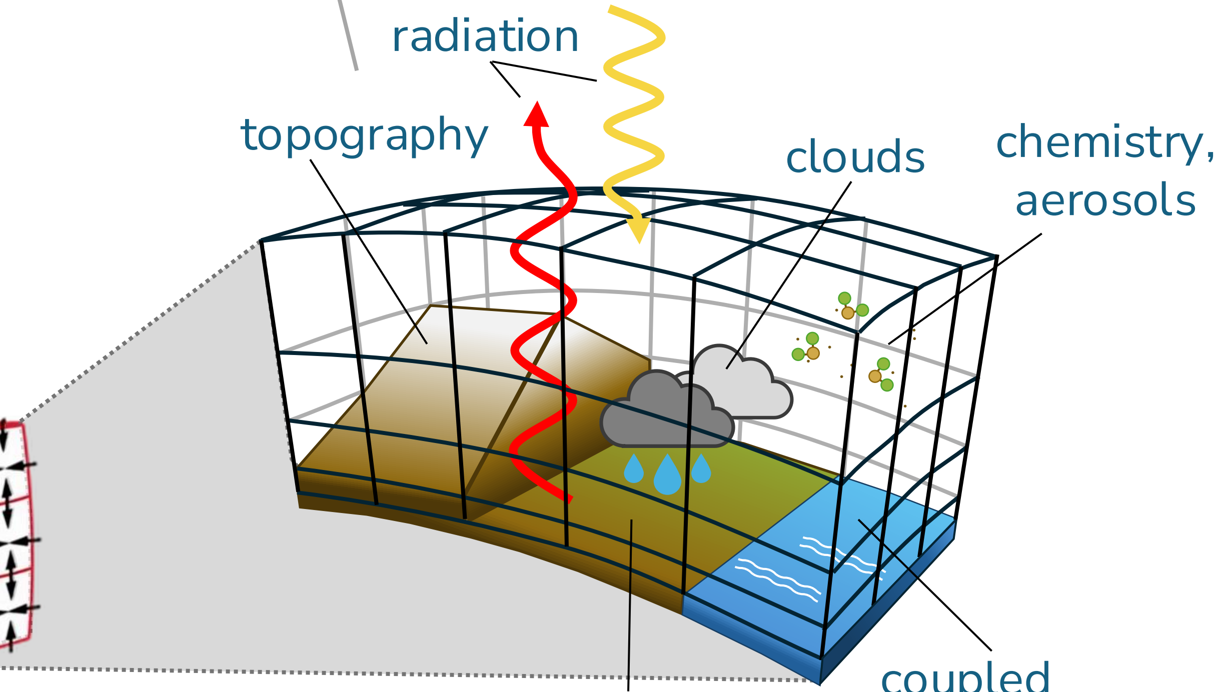
forecasted change in temperature

$$\frac{\mathrm{D}T}{\mathrm{D}t} = \mathrm{dynamics}(T) + \mathrm{physics}(T)$$

Adiabatic fluid flow

unresolved & parameterized physics





Idealized Physics

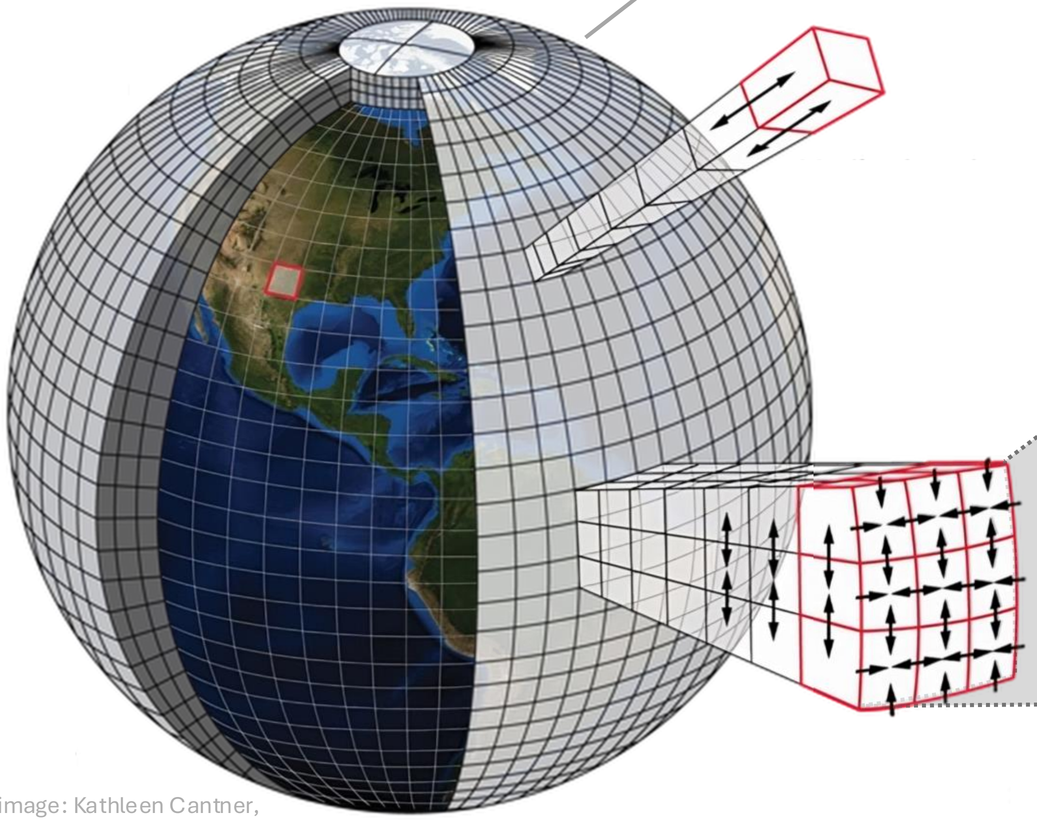
forecasted change in temperature

$$\frac{\mathrm{D}T}{\mathrm{D}t} = \mathrm{dynamics}(T) + \mathrm{physics}(T)$$

Adiabatic fluid flow

"idealized physics" = global relaxation of temperature

- much simpler
- much faster



$T_{\mathrm{reference}} \leftarrow T$

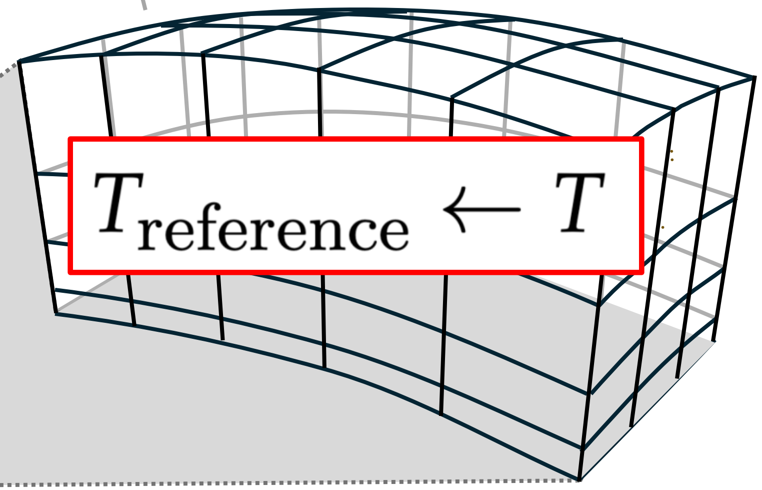


image: Kathleen Cantner, American Geosciences Institute

Idealized Physics

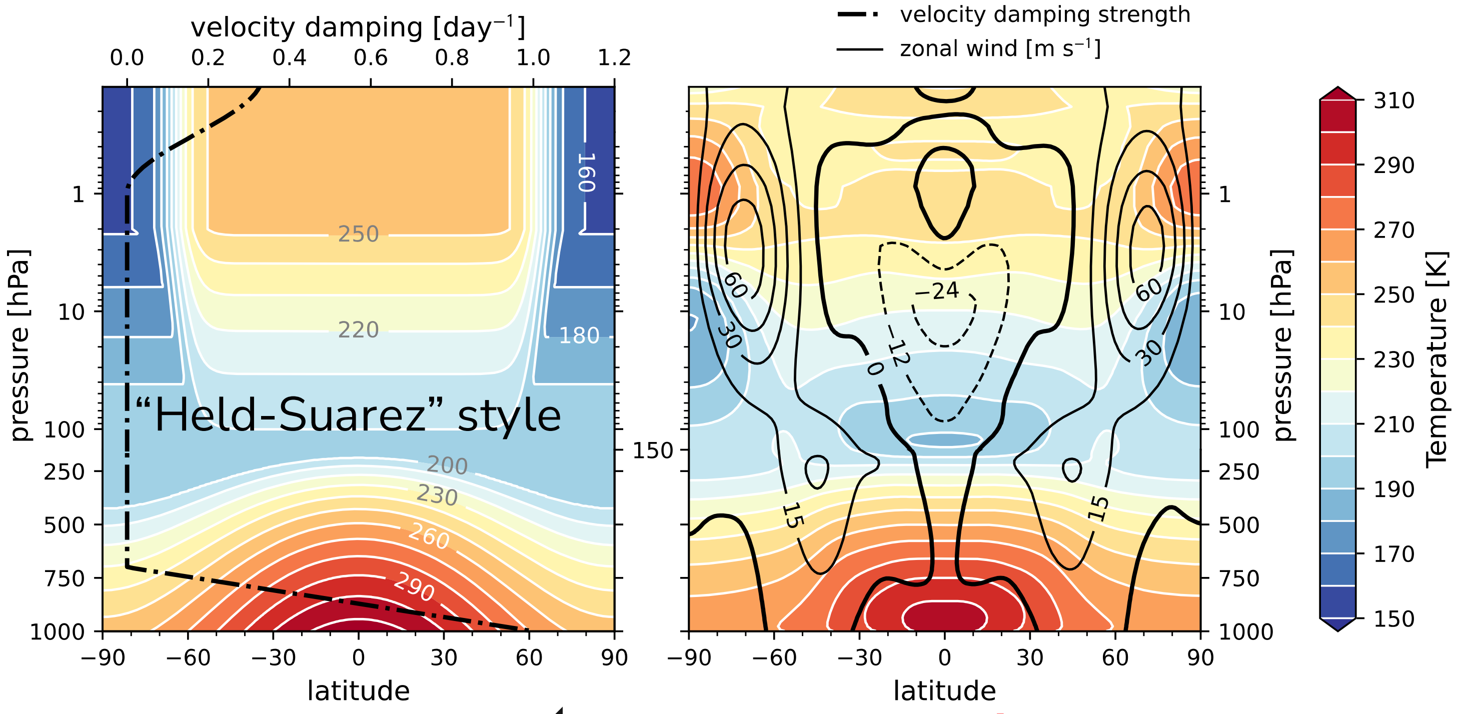
forecasted change in temperature

$$\frac{DT}{Dt} = \text{dynamics}(T) + \text{physics}(T)$$

"idealized physics" = global relaxation of temperature

Goal:

Implement an ability to simulate volcanic eruptions in the idealized atmosphere



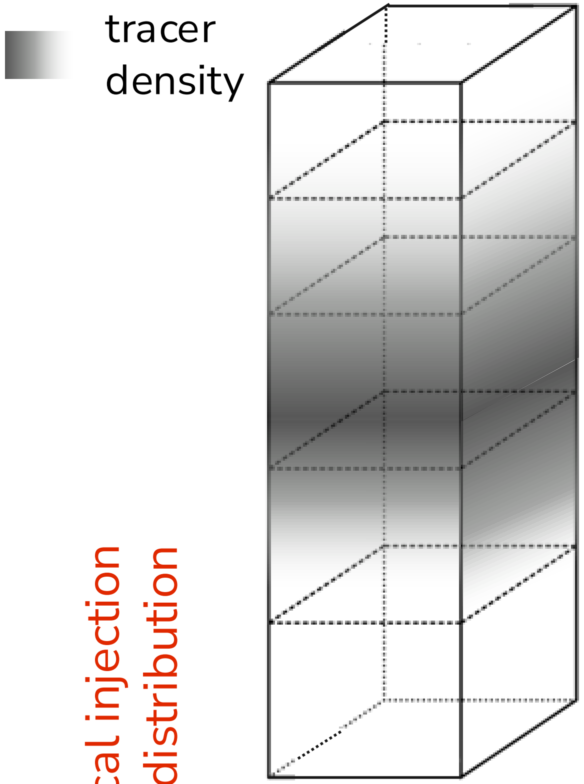
reference temperature ← atmospheric temperature

gently nudge

Step 1: tracer definitions for volcanic substances

Uniform injection over single model column

tracer density



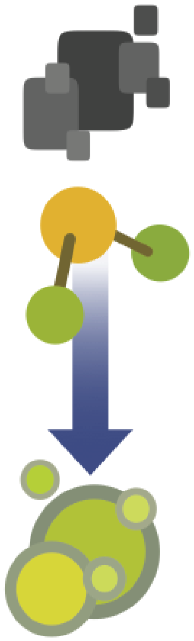
Vertical injection distribution

Ash tracer
50 Tg injected between **11-17 km** over **24 hours**

SO_2 tracer
17 Tg injected between **11-17 km** over **24 hours**

SO_2 → Sulfate conversion with half-life of ~**18 days**

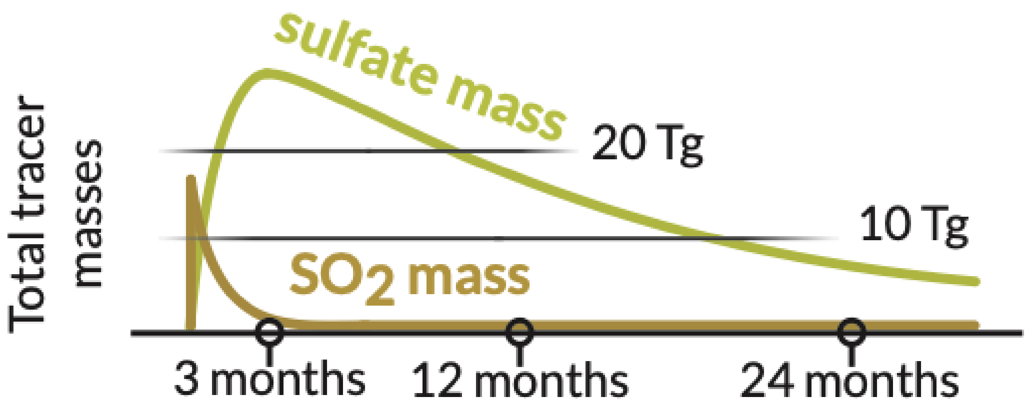
Sulfate tracer
Decays with half-life of ~**265 days**
1:2.4 SO_2:Sulfate mass ratio



evolution of a **tracer** *q*:

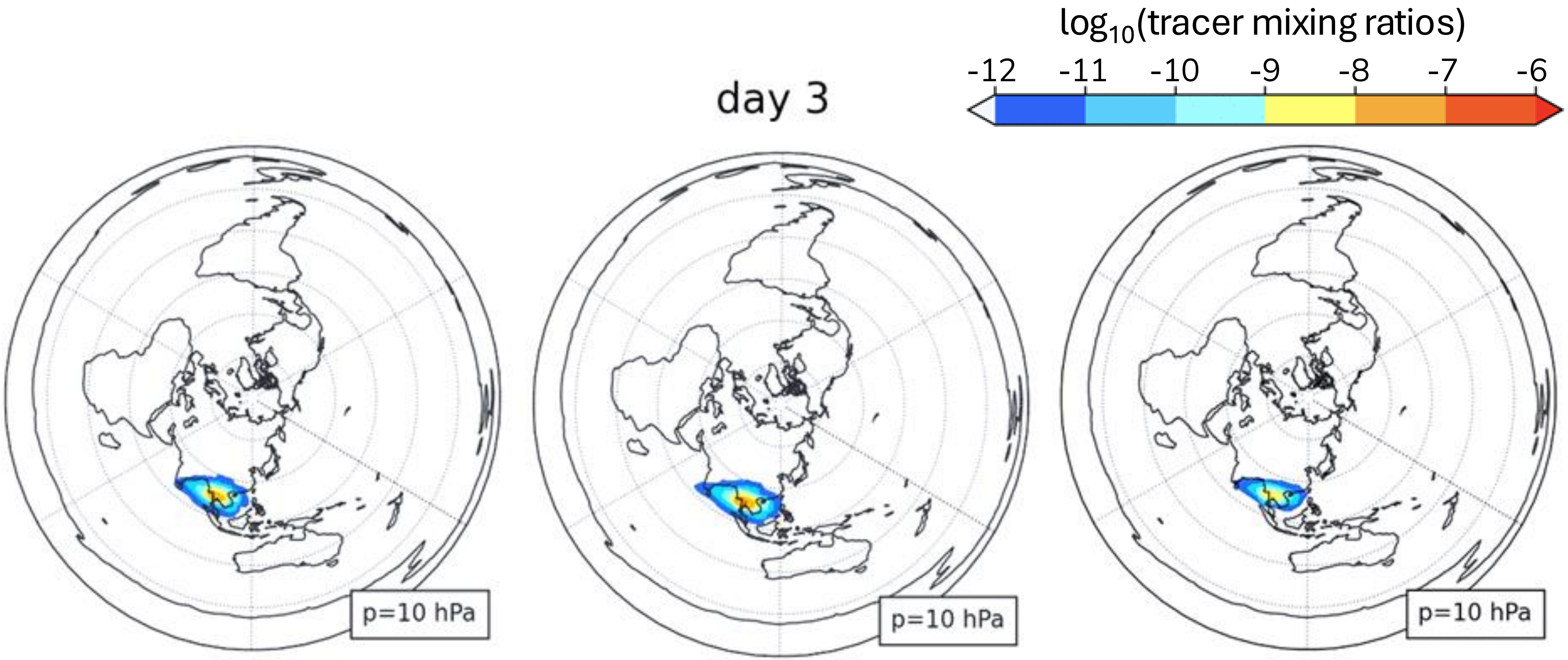
$$\frac{\partial q}{\partial t} = \vec{v}\cdot\nabla q + S$$

change in tracer density = advection + production + decay



Simulated Pinatubo plume circles the globe in **~ 2 weeks**

Aerosol quantities are ~2 order of magnitude higher than SO_2 by **3 months**



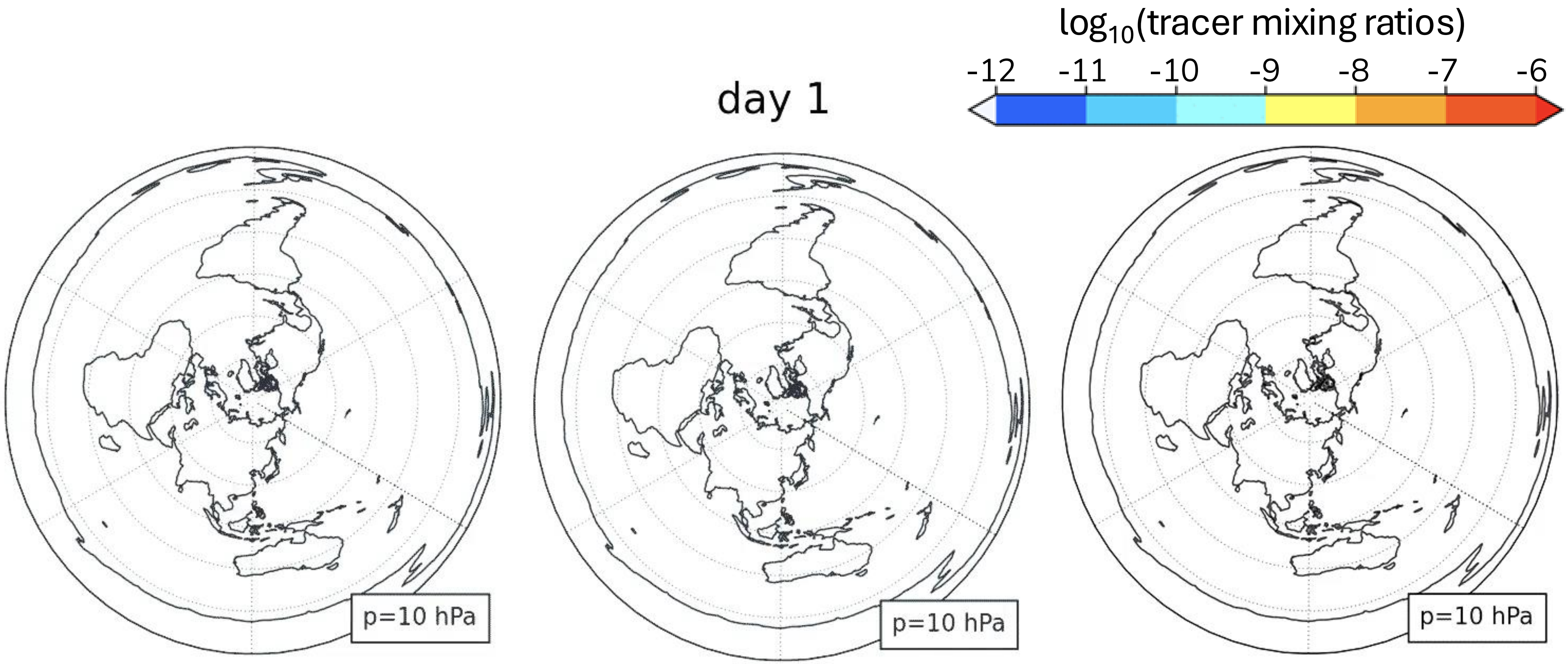
ash
1-day removal

SO2
25-day removal

Sulfate aerosol
360-day removal

Simulated Pinatubo plume circles the globe in **~ 2 weeks**

Aerosol quantities are ~2 order of magnitude higher than SO_2 by **3 months**

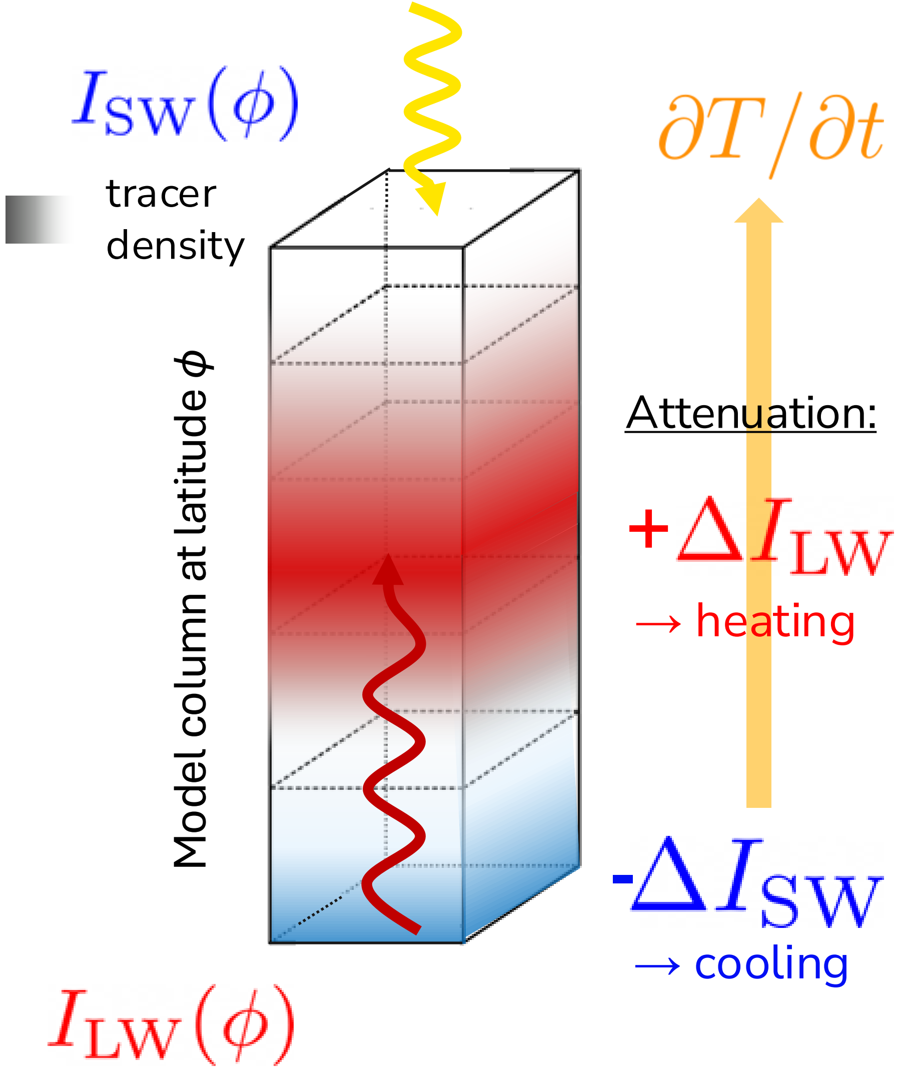


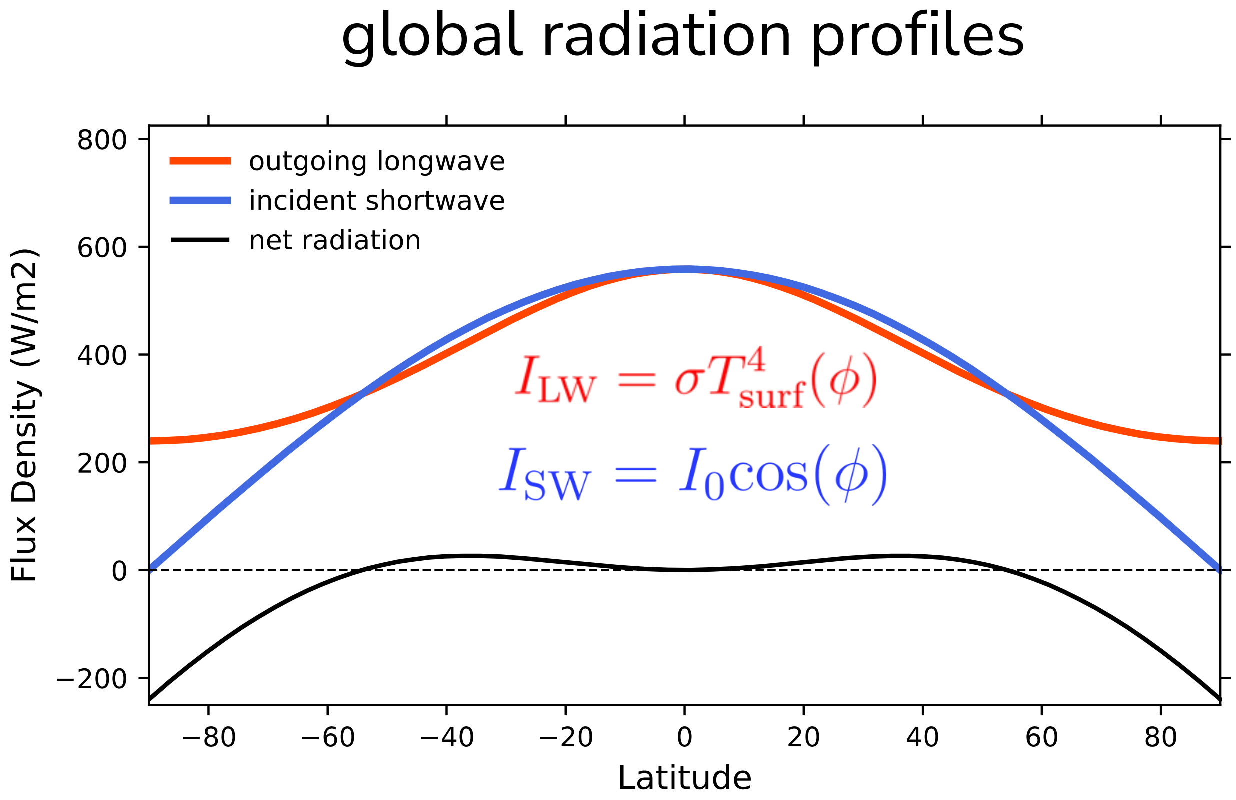
ash
1-day removal

SO2
25-day removal

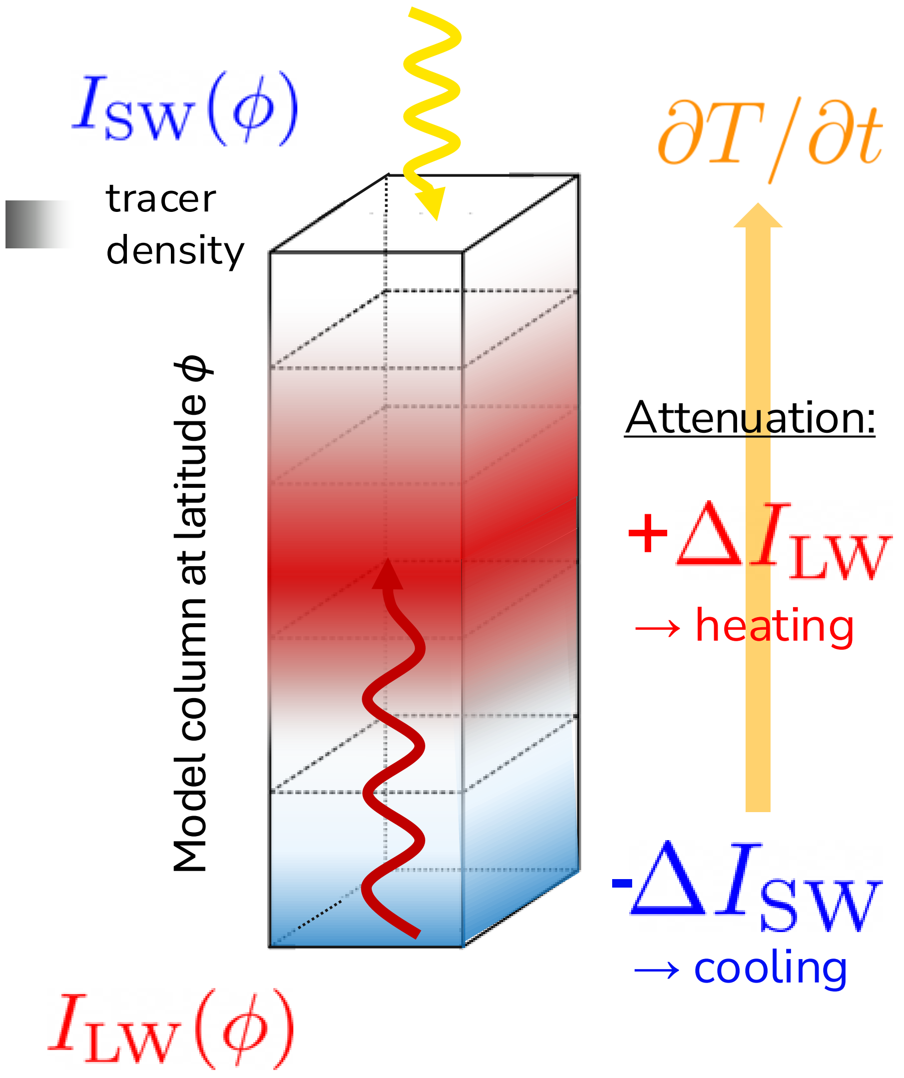
Sulfate aerosol
360-day removal

Step 2: simplified radiative forcing

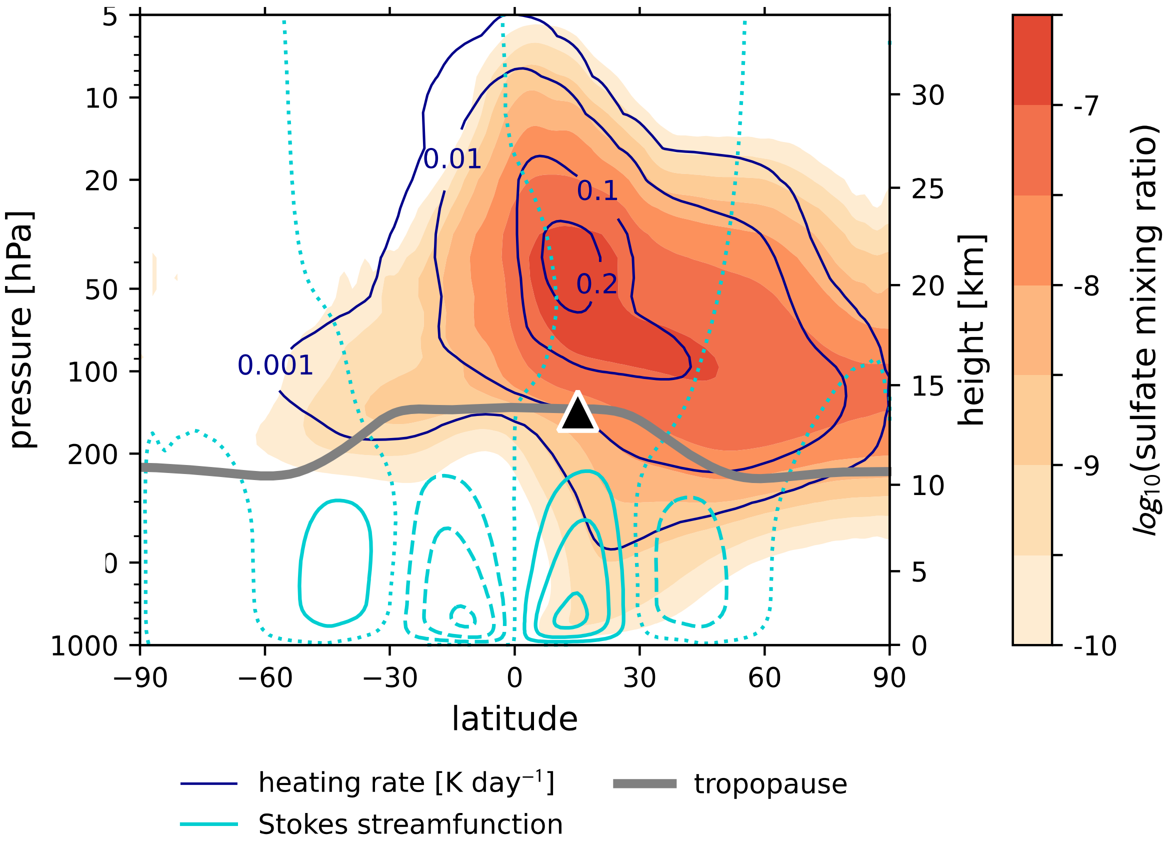




Step 2: simplified radiative forcing



local heating rates
averaged months 2-3 post-eruption

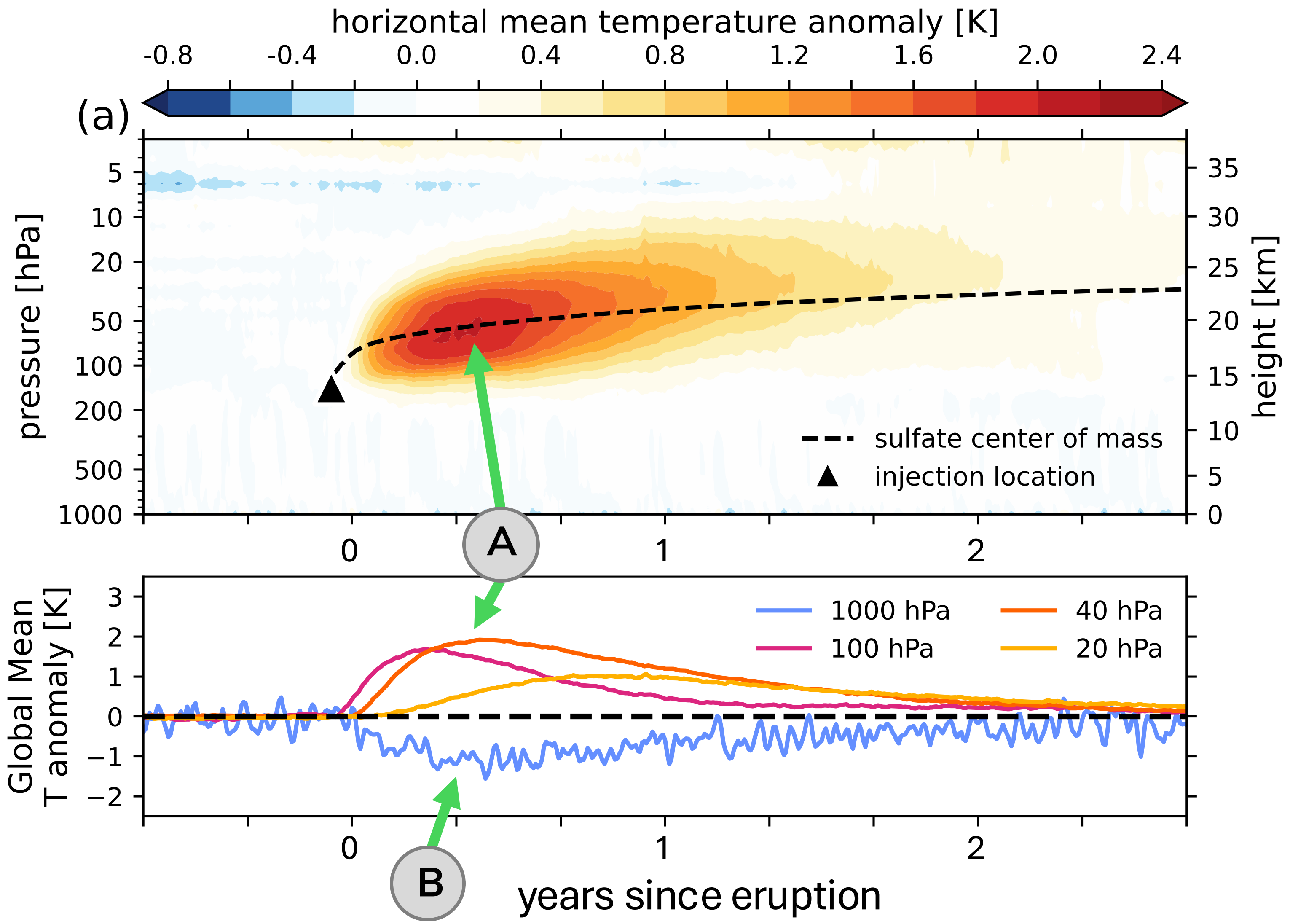


Result:

The forcing + tracer parameters can be **tuned** to produce realistic Pinatubo **temperature anomalies**

Peak forcing at ~3 months:

- A: 2 °C warming near 20 km
- B: -1 °C surface cooling



In summary; our implementation is:

- **tunable** (can mimic historical eruptions)
- **portable** (no reliance on external radiation, aerosol, chemistry codes)
- **publishable!** →
- **usable:**

Geoscientific Model Development
Open Access
EGU

HSW-V v1.0: localized injections of interactive volcanic aerosols and their climate impacts in a simple general circulation model

Joseph P. Hollowed[1], Christiane Jablonowski[1], Hunter Y. Brown[2], Benjamin R. Hillman[2], Diana L. Bull[2], and Joseph L. Hart[2]
[1]Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI, USA
[2]Sandia National Laboratories, Albuquerque, NM, USA

Using feature importance as exploratory data analysis tool on earth system models

Daniel Ries[1], Katherine Goode[1], Kellie McClernon[1], and Benjamin Hillman[1]
[1]Sandia National Laboratories. Albuquerque, NM. United States of America.
Correspondence: Daniel Ries (dries@sandia.gov)

Space-Time Causal Discovery in Climate Science: A Local Stencil Learning Approach

J. Jake Nichol, J Jake Nichol, Michael Weylandt, G Matthew Fricke, Melanie E Moses, Diana Bull, Laura P Swiler

[Submitted on 7 Aug 2024]

In-situ data extraction for pathway analysis in an idealized atmosphere configuration of E3SM

Andrew Steyer, Luca Bertagna, Graham Harper, Jerry Watkins, Irina Tezaur, Diana Bull

A comparison of model validation approaches for echo state networks using climate model replicates

Kellie McClernon*, Katherine Goode, Daniel Ries
Sandia National Laboratories, USA

Part 2

volcanic effects on midlatitude winds

wave-mean flow interaction and the transformed Eulerian mean

Climate Model

E3SM
Energy Exascale
Earth System Model

fluid solver = “dynamics”

parameterizations = “physics”

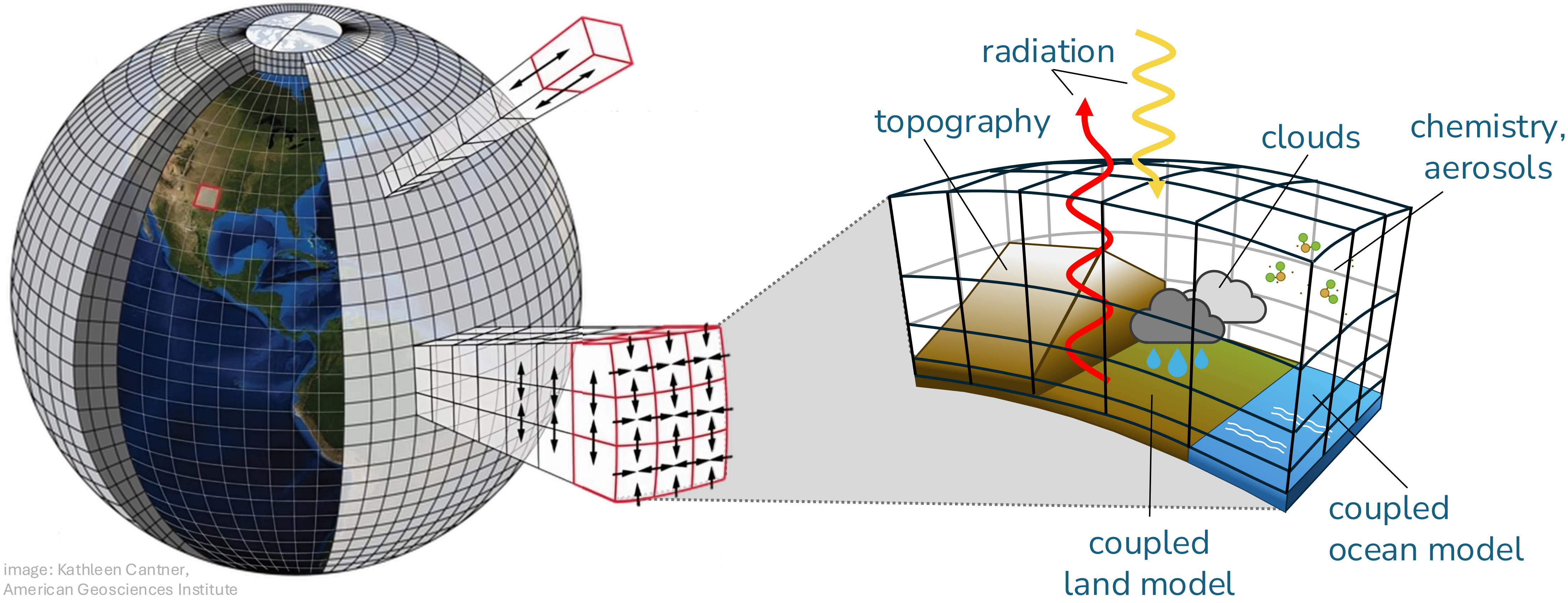
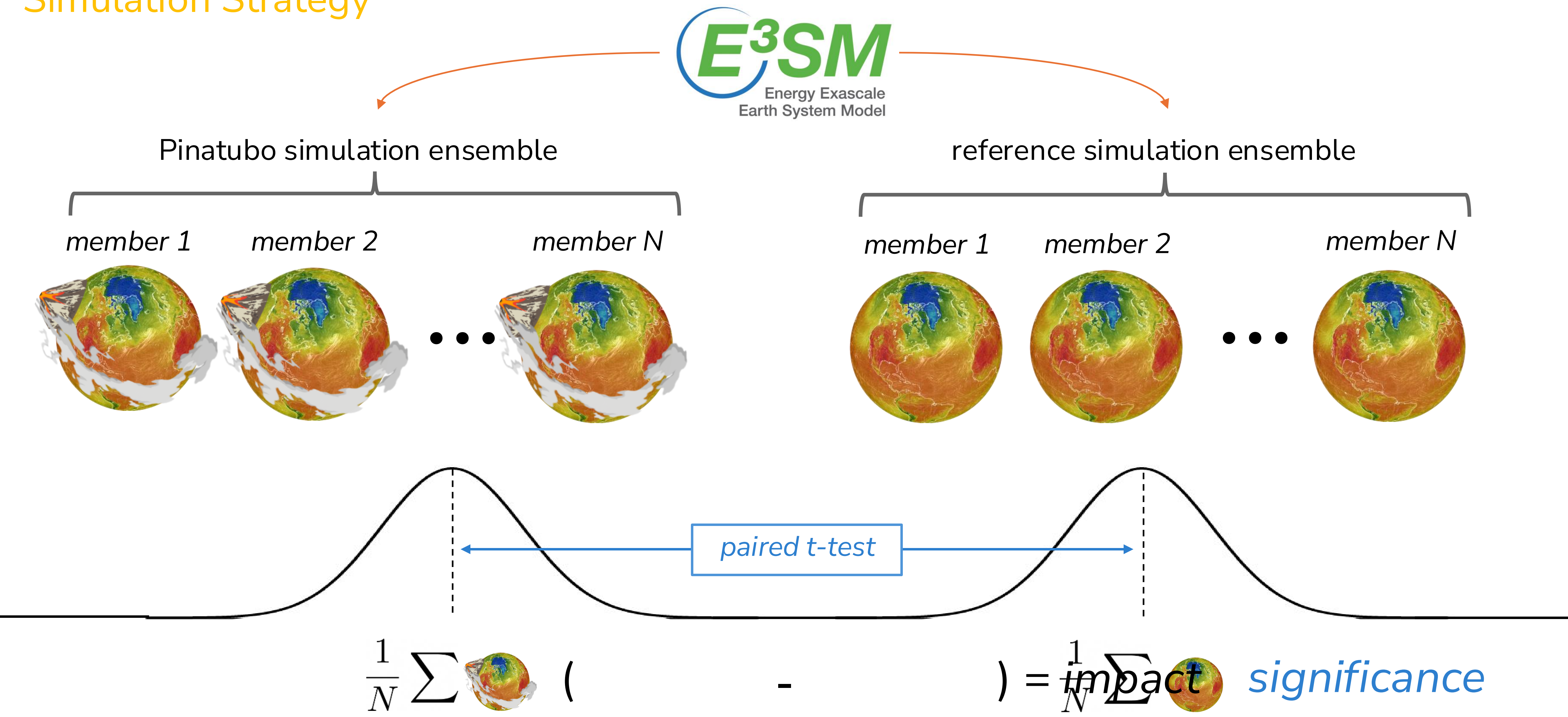


image: Kathleen Cantner,
American Geosciences Institute

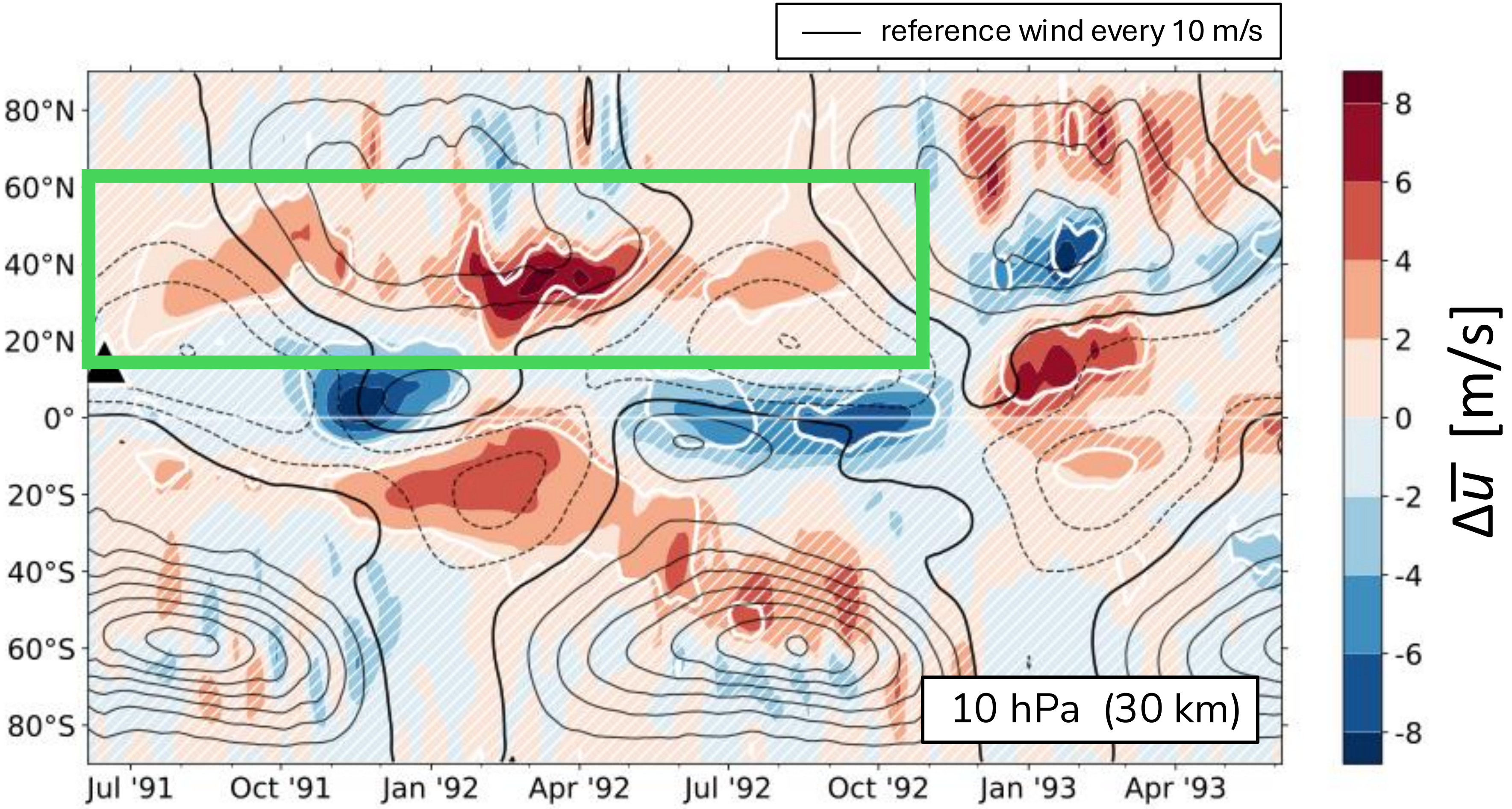
Simulation Strategy



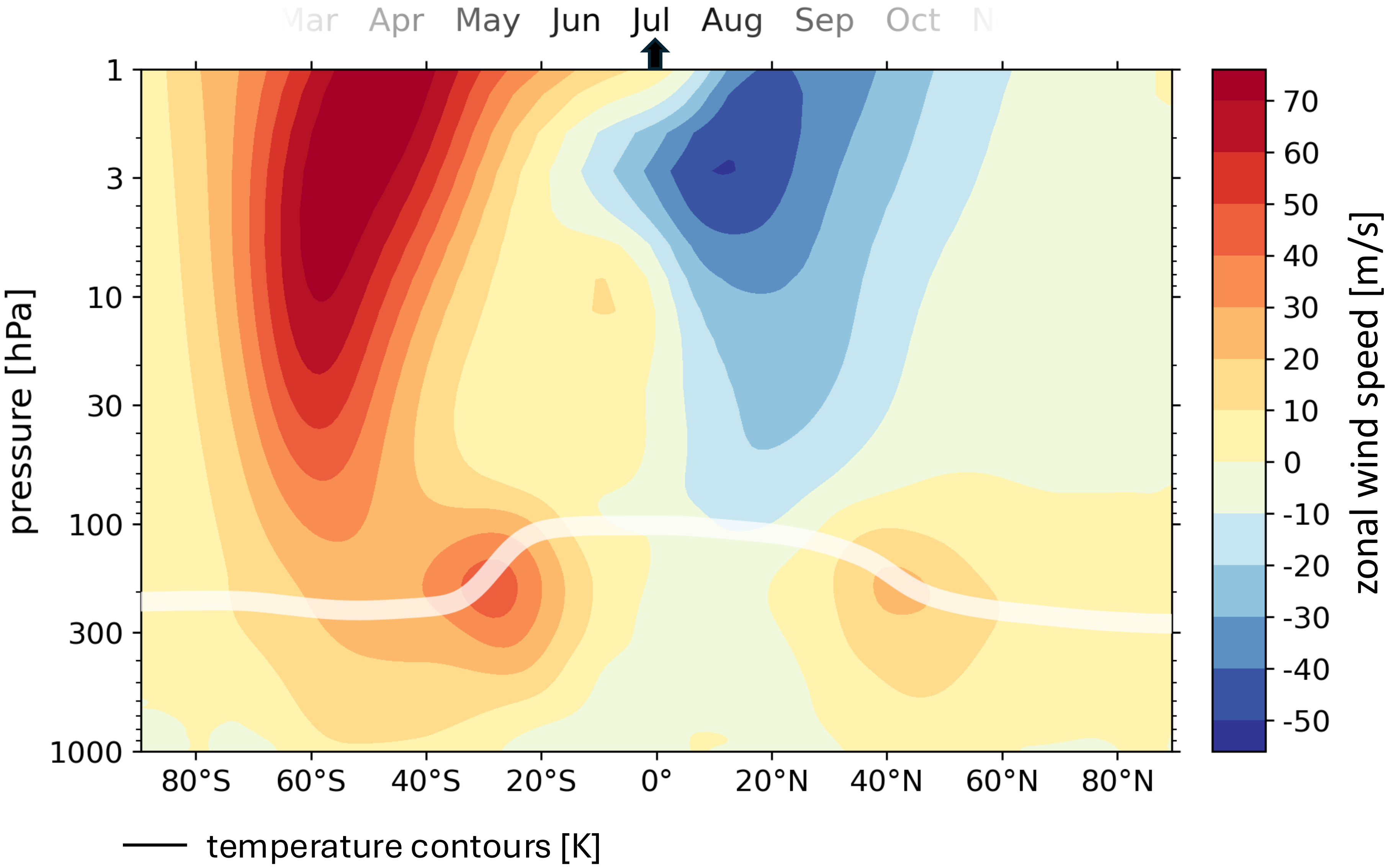
Volcanic impact on zonal wind is localized, but significant

Intermittent accelerations of the NH vortex region

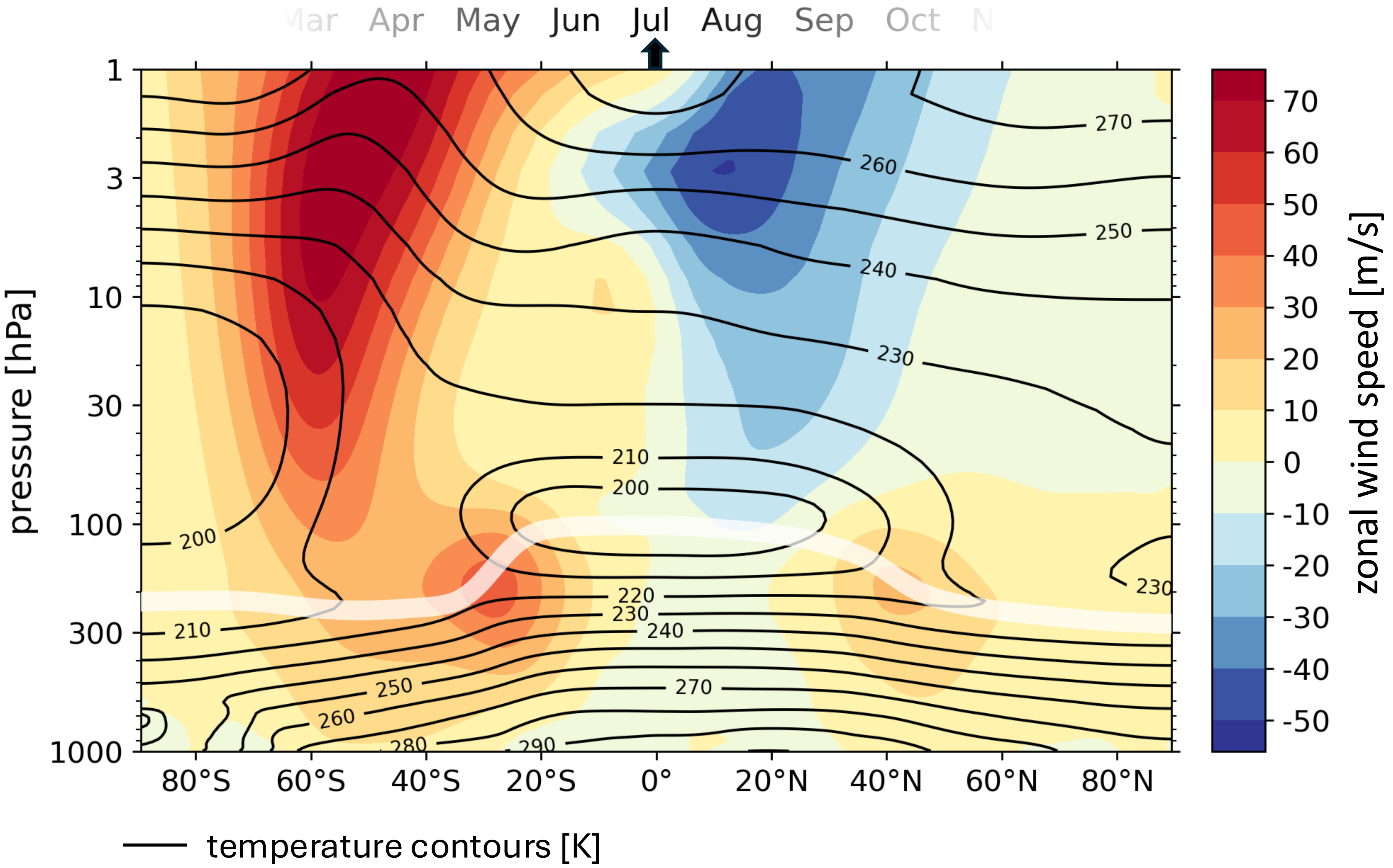
why?



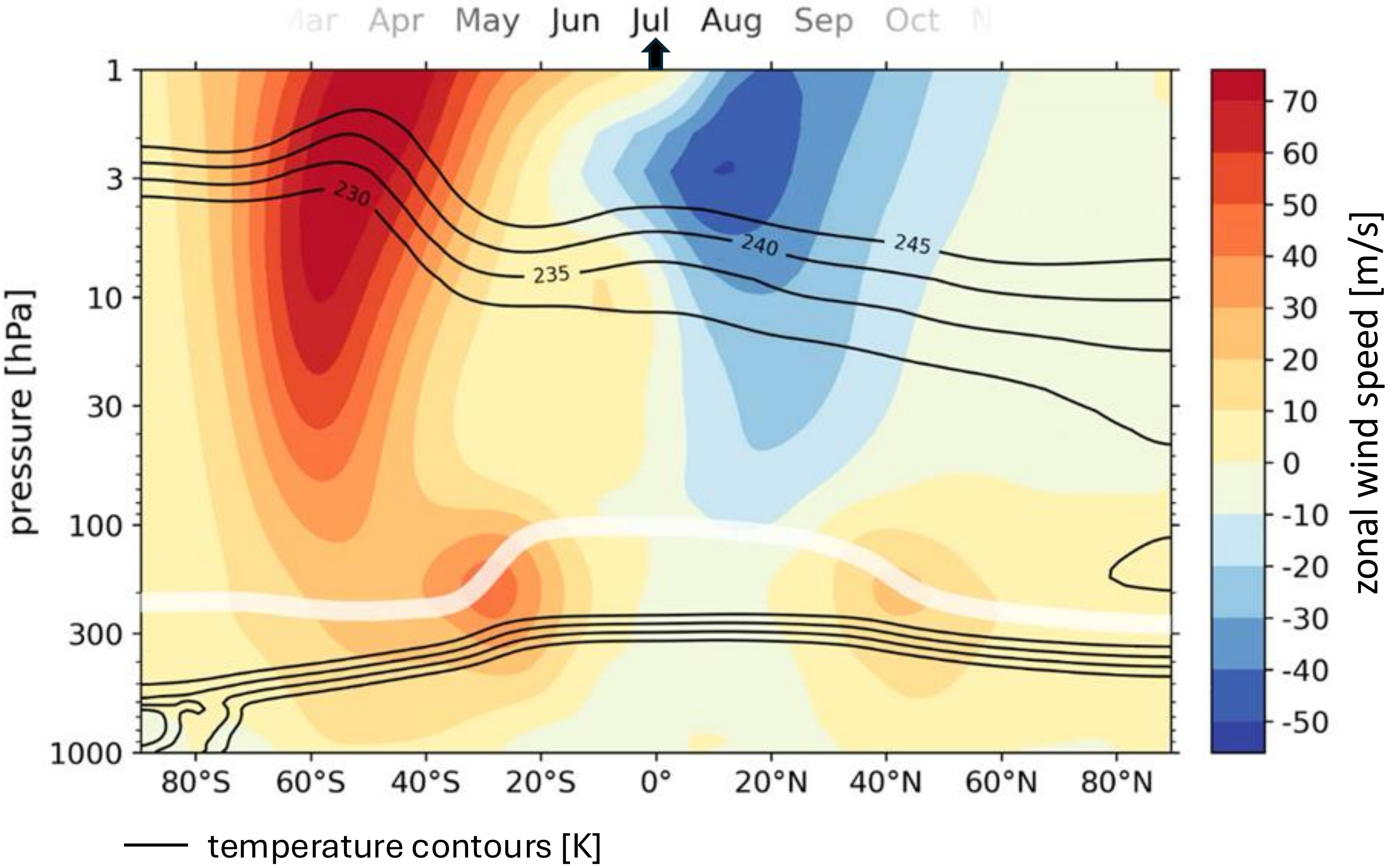
Southern Hemisphere Winter winds



Southern Hemisphere Winter winds, temperature



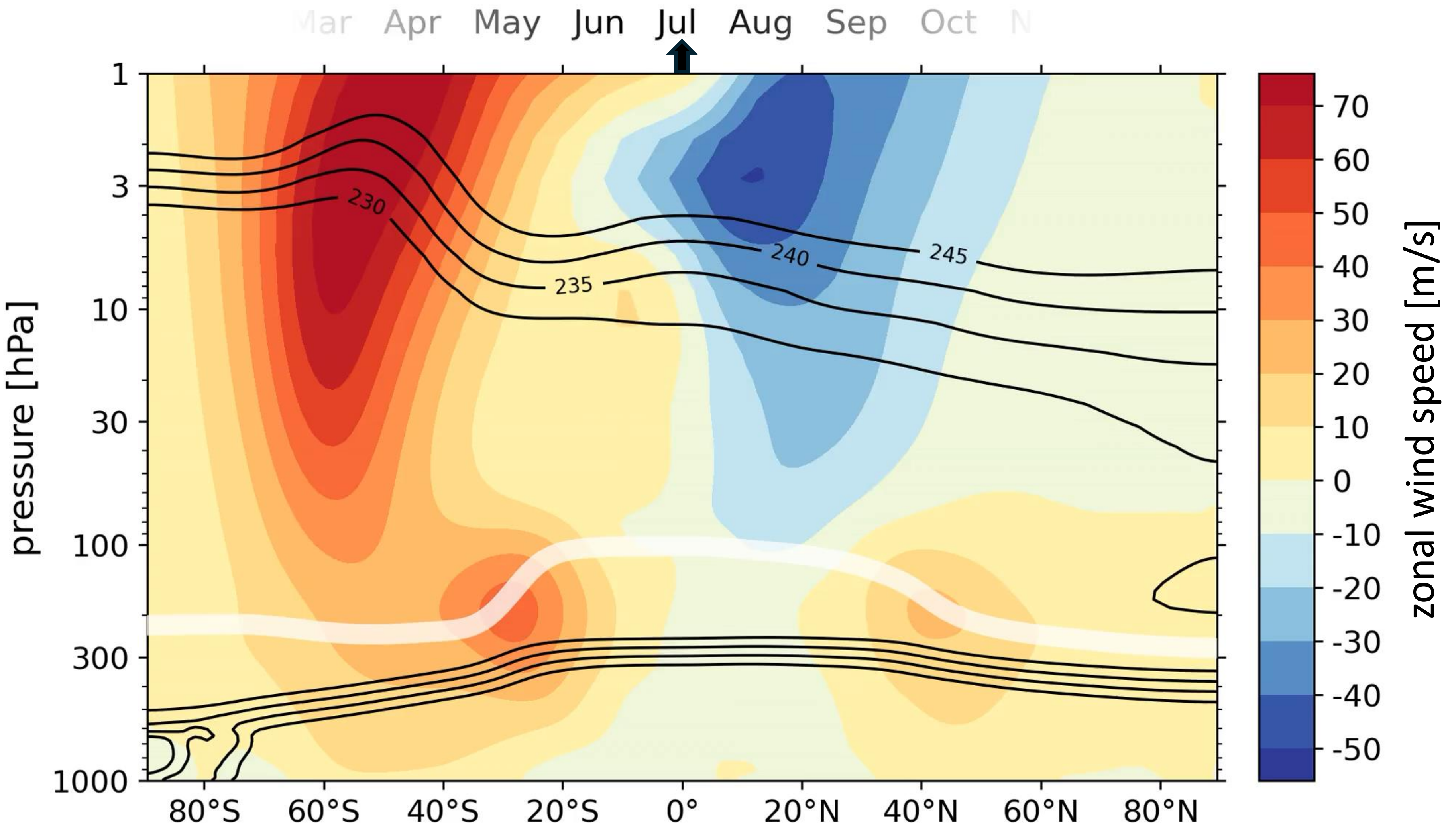
Southern Hemisphere Winter winds, temperature



Thermal Wind Balance:

$$\frac{\partial u}{\partial p} \propto \frac{\partial T}{\partial \phi}$$

"Wind changes in altitude accompany temperature changes in latitude" wind, temperature seasonal cycle



— temperature contours [K]

Thermal Wind Balance:

$$\frac{\partial u}{\partial p} \propto \frac{\partial T}{\partial \phi}$$

"Wind changes in altitude accompany temperature changes in latitude"

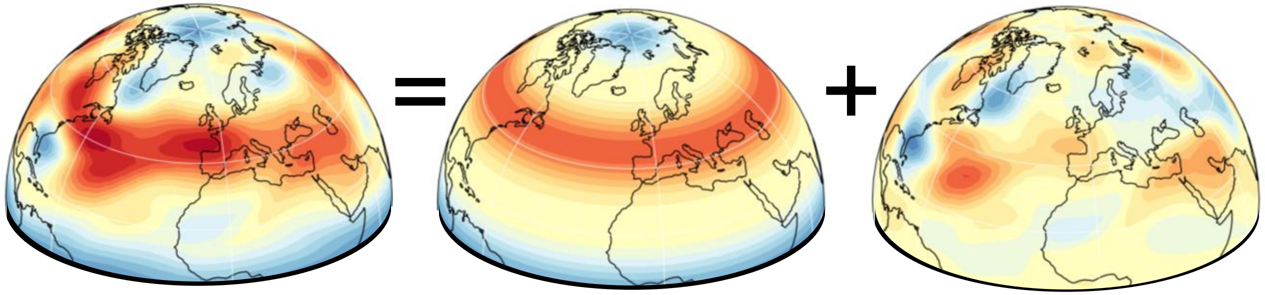
naïve understanding:
stratospheric winds simply respond to temperature changes

...insufficient!

Concept: the Transformed Eulerian Mean (TEM)

$$u = \overline{u} + u'$$

wind speed — zonal mean — eddy



approximate predictive eq. for zonal wind:

$$\frac{\partial u}{\partial t} + v u_y + w u_z = f v + p_x - X$$

split variables like $u = \overline{u} + u'$

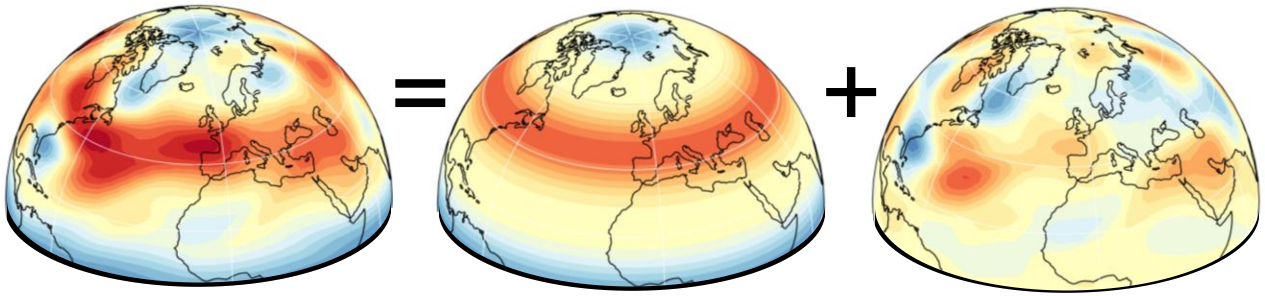
$$\frac{\partial \overline{u}}{\partial t} = \overline{v}^* \left(f - \overline{u}_y\right) - \overline{w}^* \overline{u}_z + \left[\frac{\partial}{\partial y}\left(\overline{u}_z \frac{\overline{v'\theta'}}{\overline{\theta}_z} - \overline{u'v'}\right) + \frac{\partial}{\partial z}\left(\left(f - \overline{u}_y\right)\frac{\overline{v'\theta'}}{\overline{\theta}_z} - \overline{u'w'}\right)\right] - \overline{X}$$

$$\frac{\partial \overline{u}}{\partial t} = \overline{v}^* \left(f - \overline{u}_y\right) - \overline{w}^* \overline{u}_z + \nabla \cdot \mathbf{F} - \overline{X}$$

Concept: the Transformed Eulerian Mean (TEM)

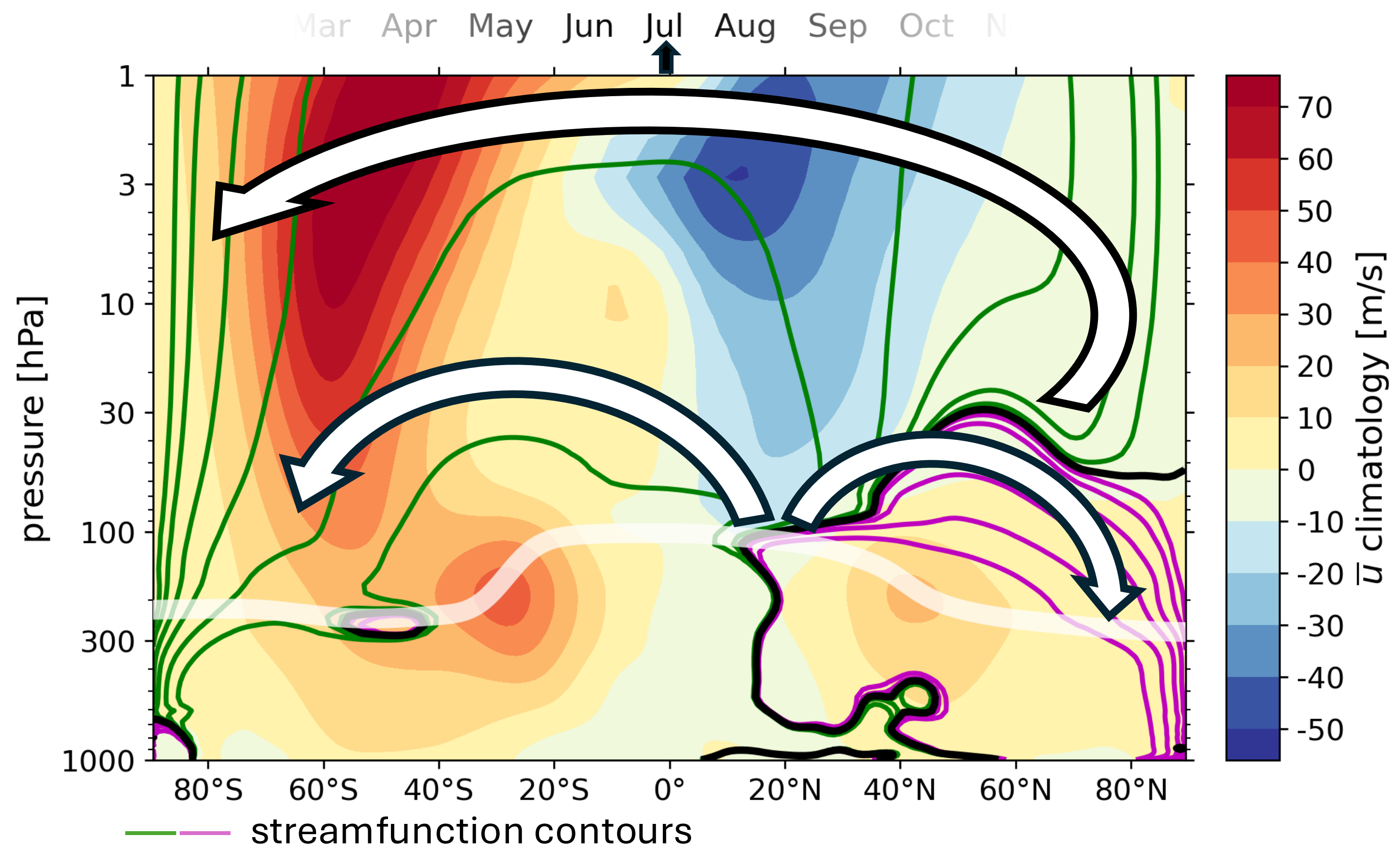
$$u = \overline{u} + u'$$

wind speed | zonal mean | eddy



change in the mean flow = circulation-driven piece + wave-driven piece + diffusive piece

$$\frac{\partial \overline{u}}{\partial t} = \overline{v}^* \left(f - \overline{u}_y\right) - \overline{w}^* \overline{u}_z + \nabla \cdot \mathbf{F} - \overline{X}$$



TEM-inferred movement of mass in the latitude-altitude plane:
the ***Residual Circulation***
green = CCW; purple = CW circulation

Upper stratosphere:
Deep Branch; single pole-to-pole cell, from summer to winter hemisphere

Lower stratosphere:
Shallow Branch; equator-to-pole cells in each hemisphere

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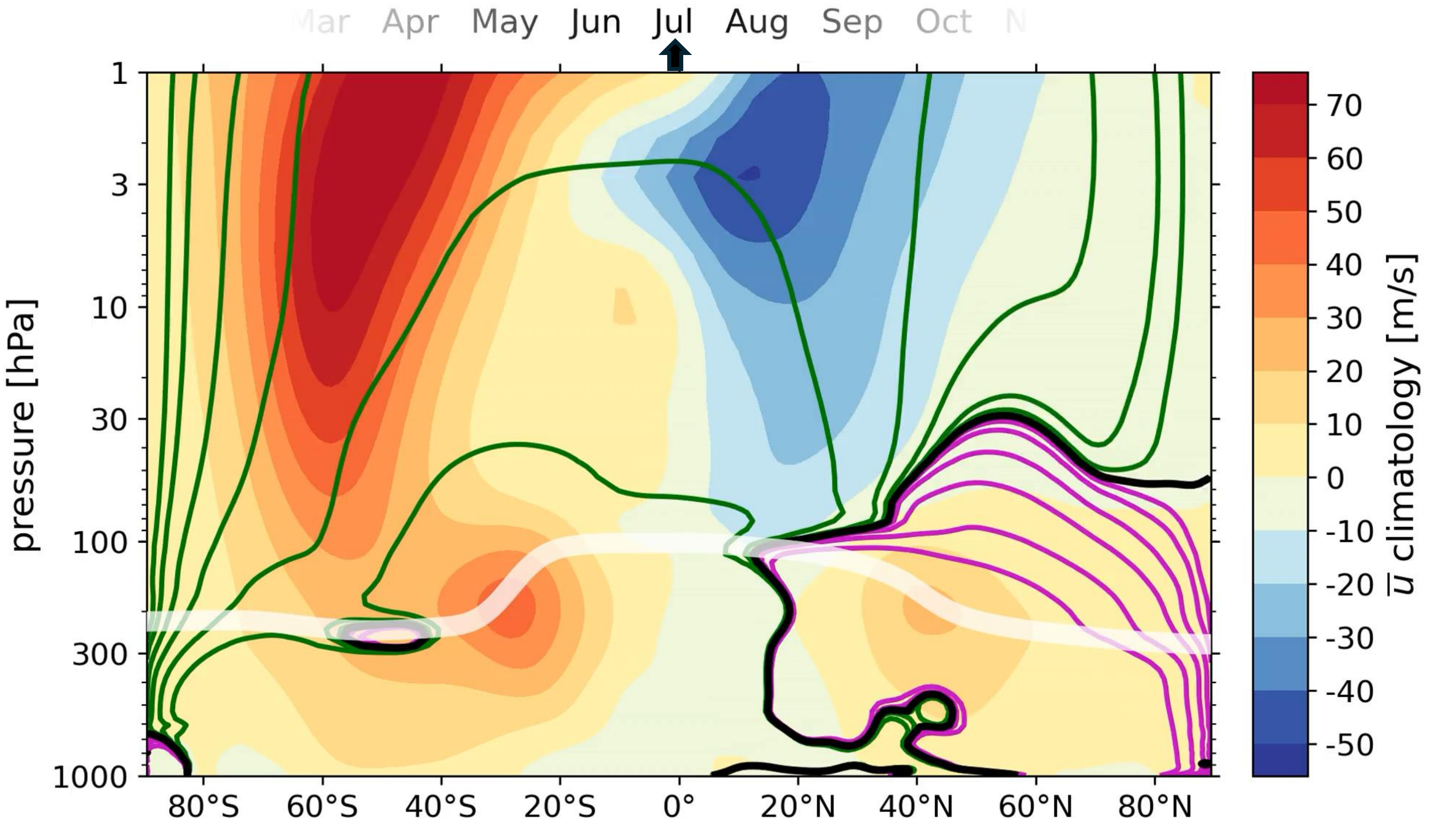

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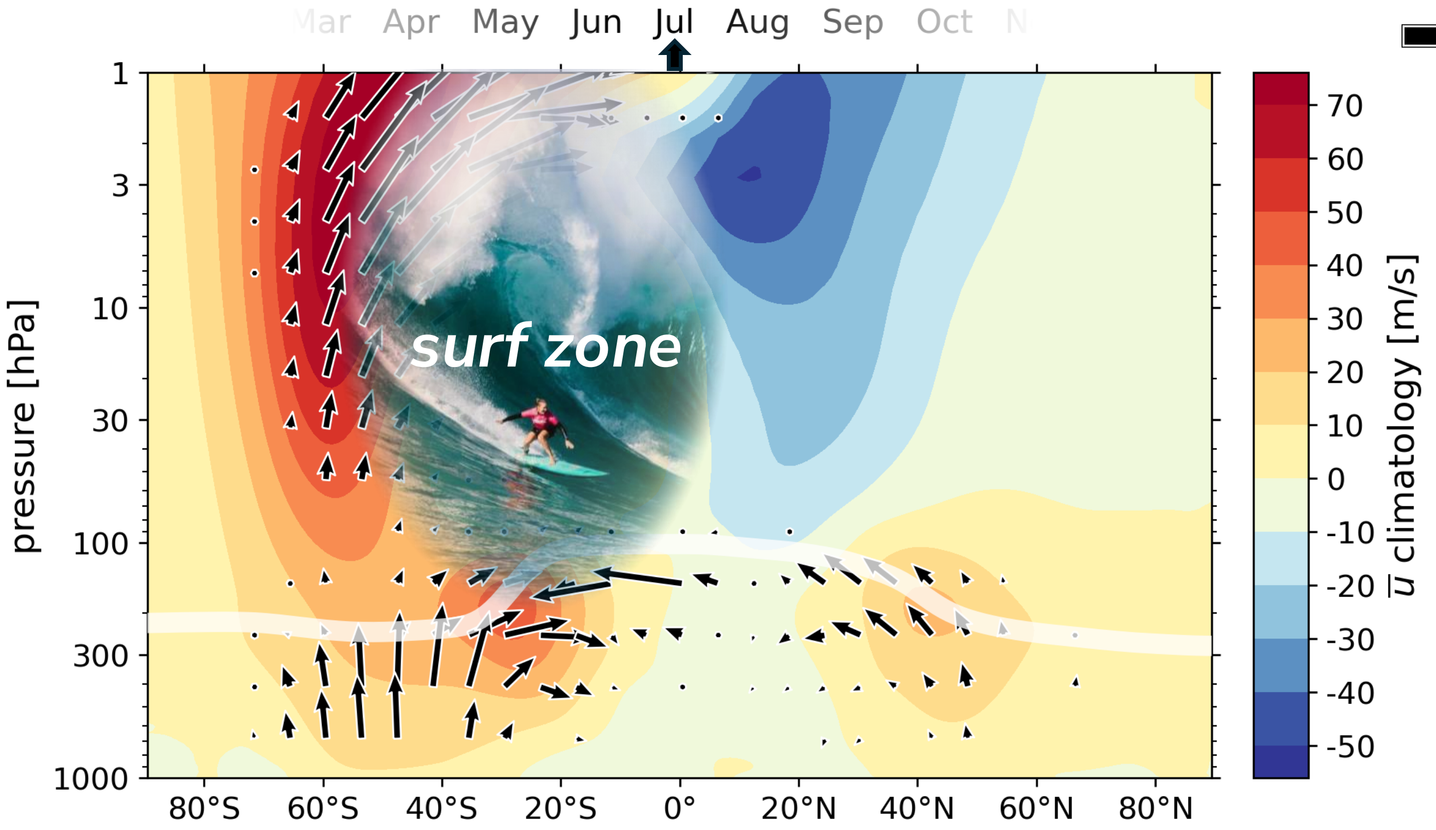
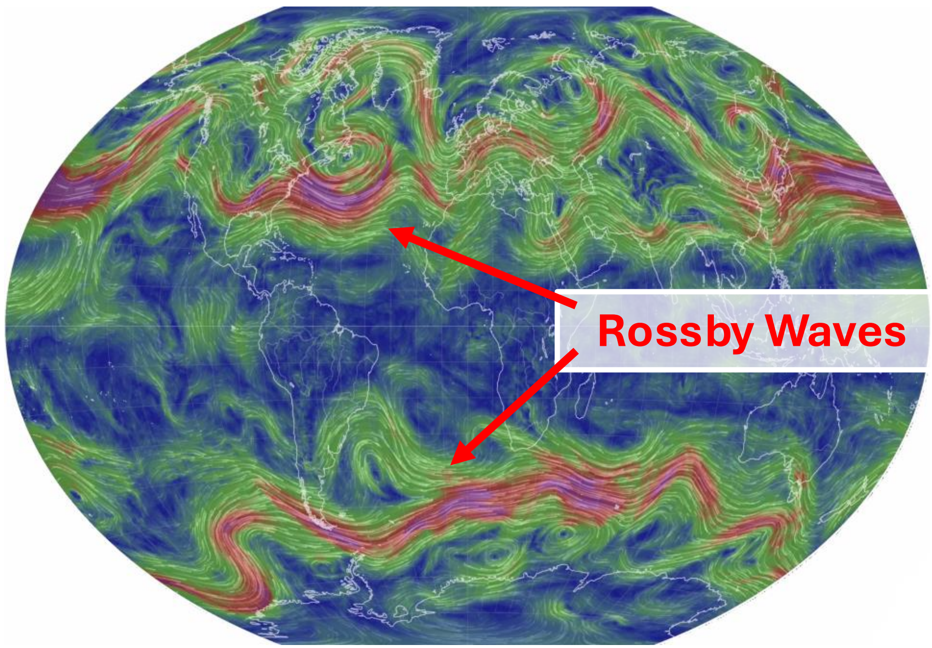


= propagation direction of large-scale atmospheric waves

Forcing: vertical propagation, breaking



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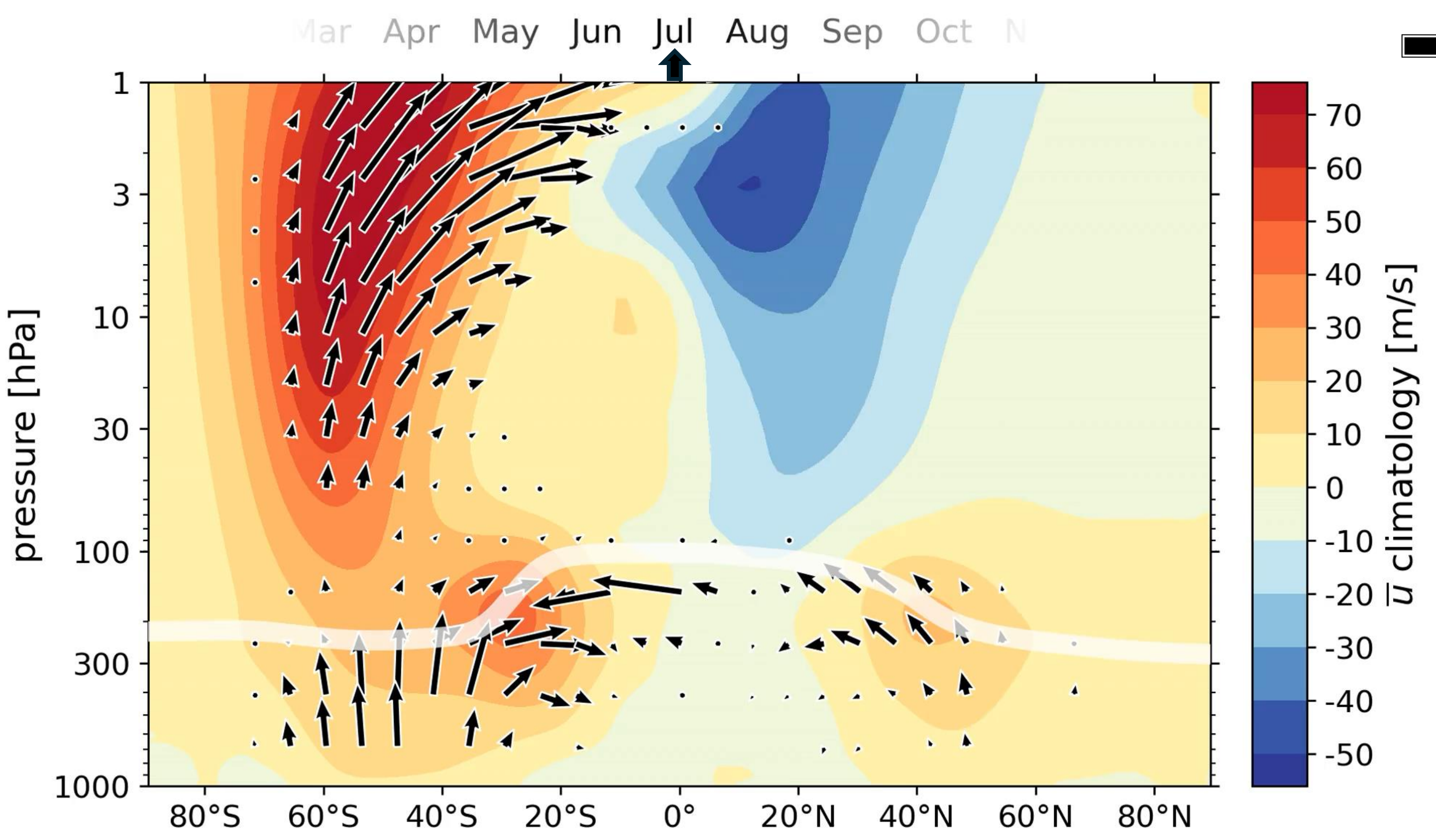
$$\frac{\partial \overline{u}}{\partial t} = \overline{v}^* \left(f - \overline{u}_y\right) - \overline{w}^* \overline{u}_z + \nabla \cdot \mathbf{F} - \overline{X}$$

surf zone photo: Paige Alms, by Christa Funk



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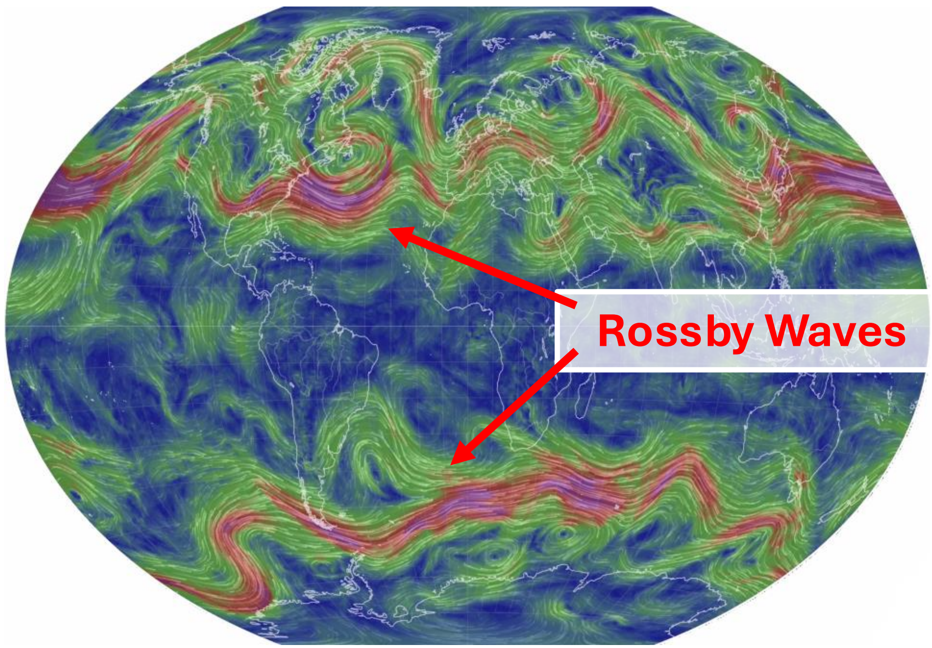
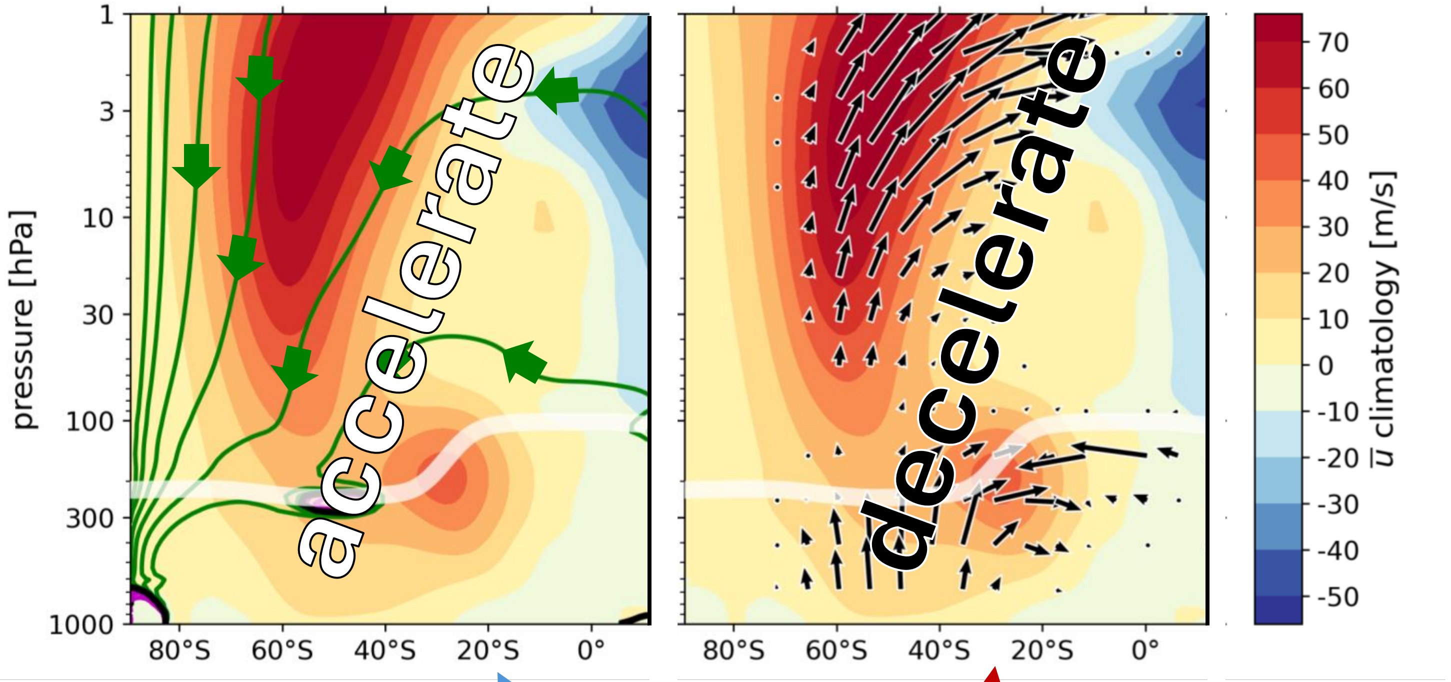


change in the mean flow = circulation-driven piece + **wave-driven piece** + diffusive piece

$$\frac{\partial \overline{u}}{\partial t} = \overline{v}^* \left(f - \overline{u}_y \right) - \overline{w}^* \overline{u}_z + \nabla \cdot \mathbf{F} - \overline{X}$$

Concept: TEM Balance

southern hemisphere winter



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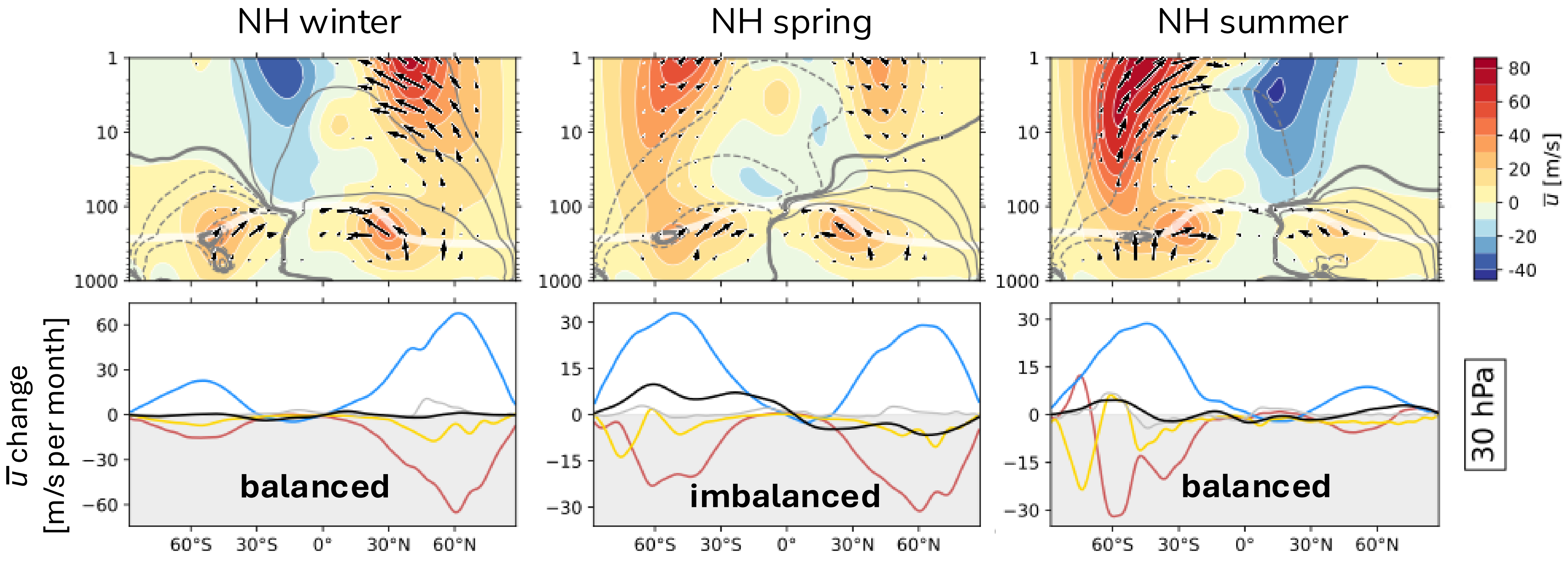
Concept: TEM Balance



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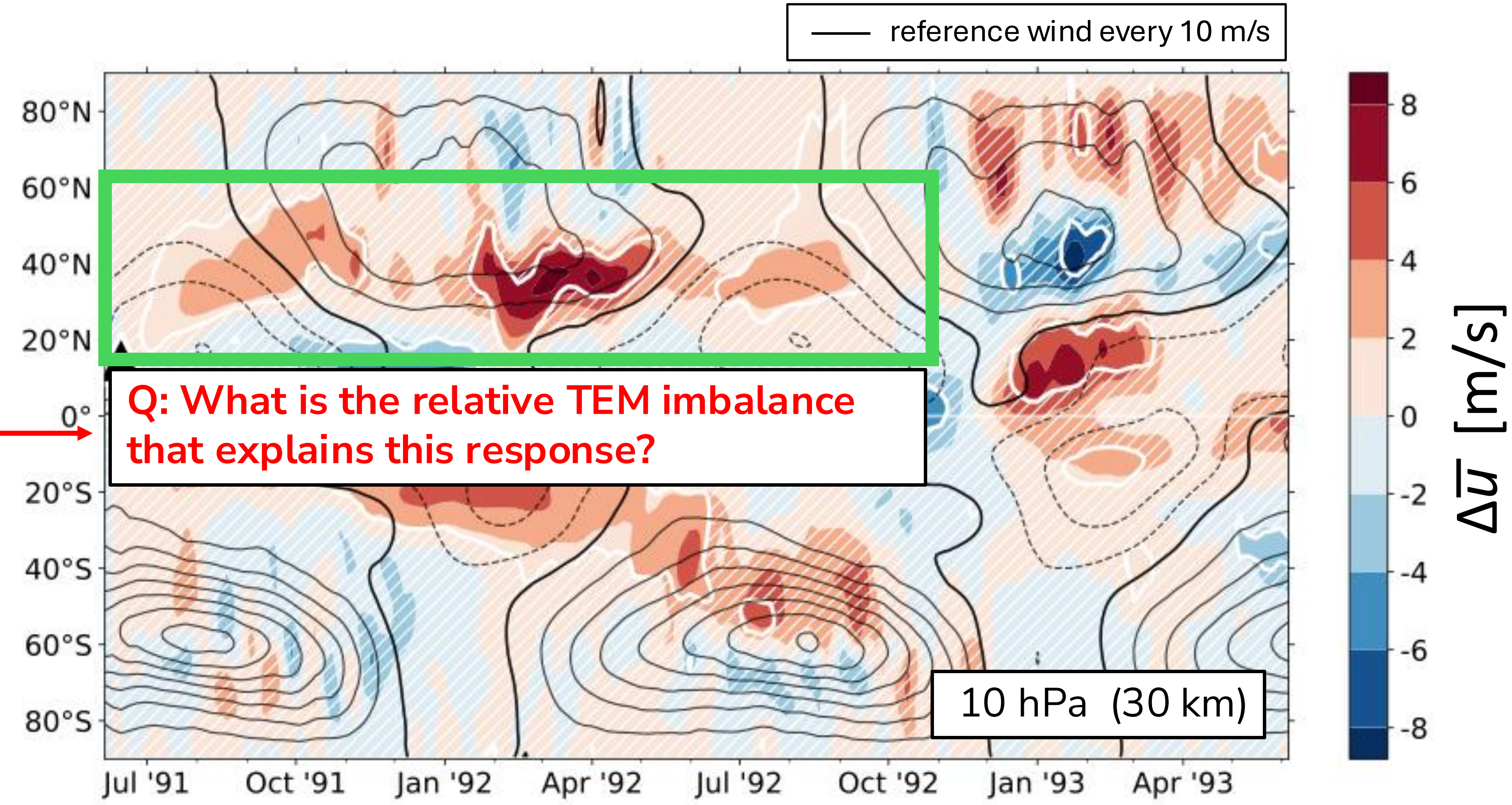
Results: Volcanically-driven TEM imbalance

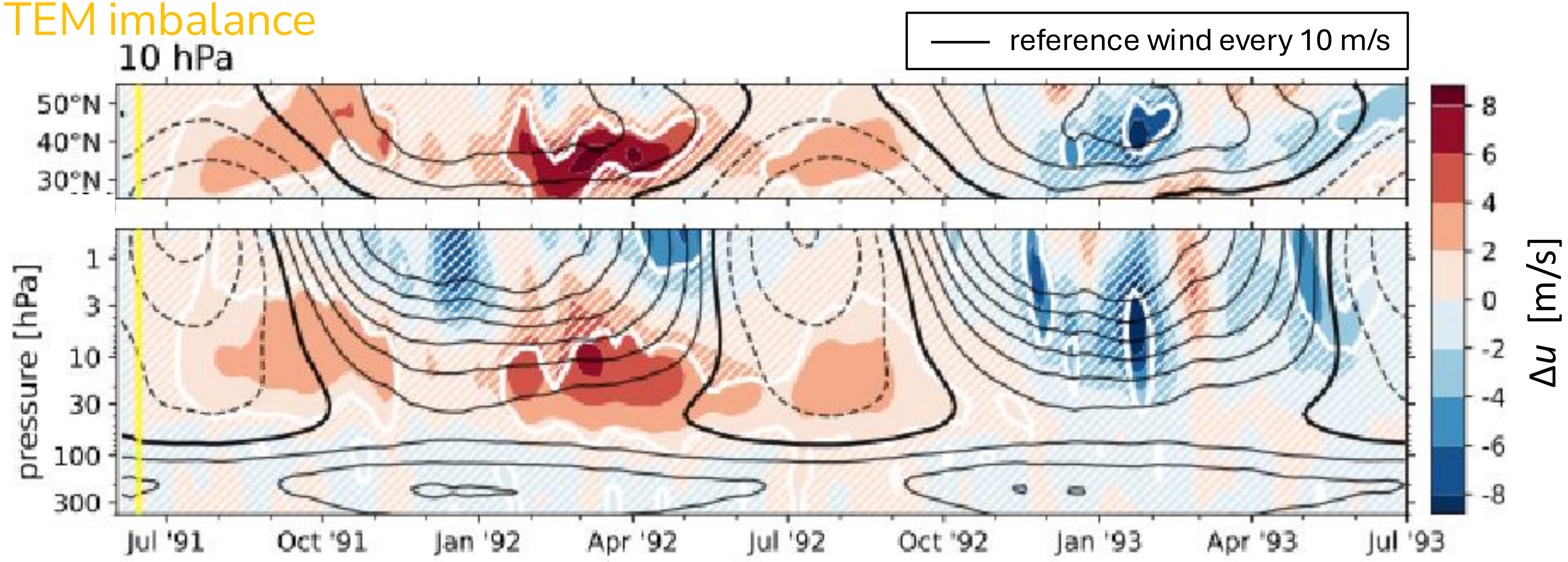
Intermittent accelerations of the NH vortex region

why?



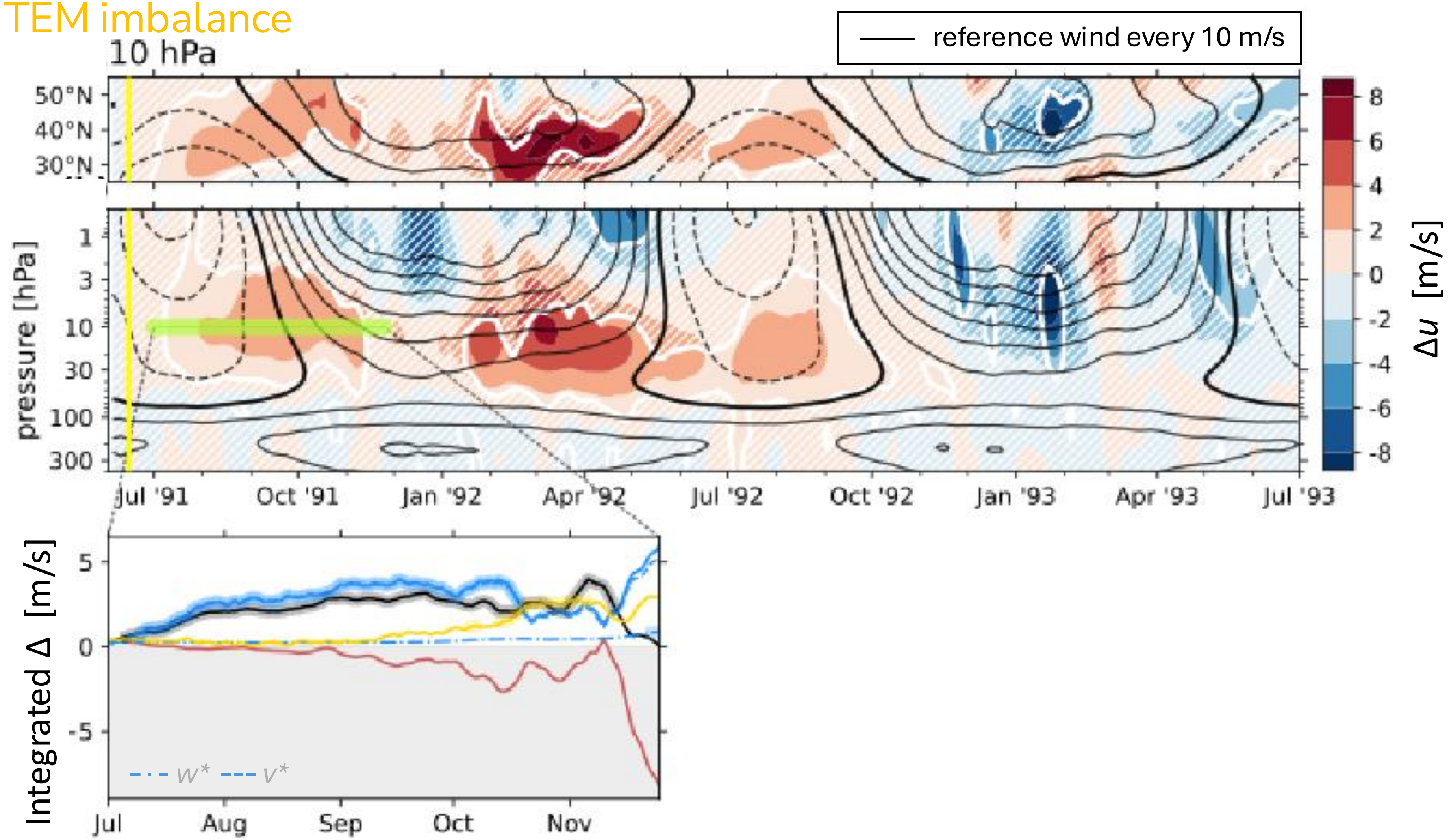
Results: Volcanically-driven TEM imbalance

Identified TEM imbalance:



Identified TEM imbalance:

In summer '91:
Enhanced circulation



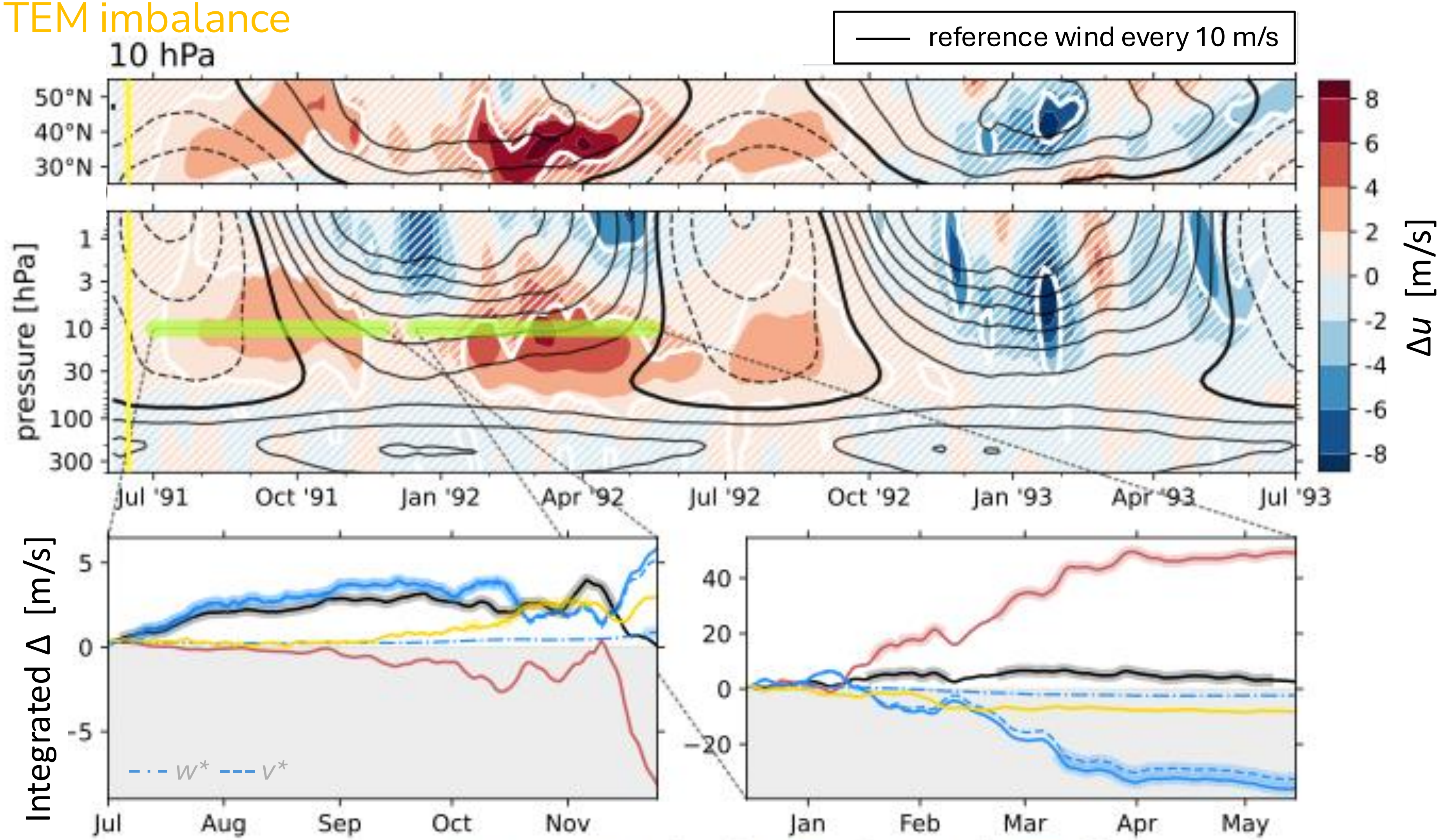
Δ (change in the mean flow) = **Δ(circulation-driven)** + **Δ(wave-driven)** + **Δ(diffusive piece)**

Results: Volcanically-driven TEM imbalance

Identified TEM imbalance:

In summer '91: **Enhanced circulation**

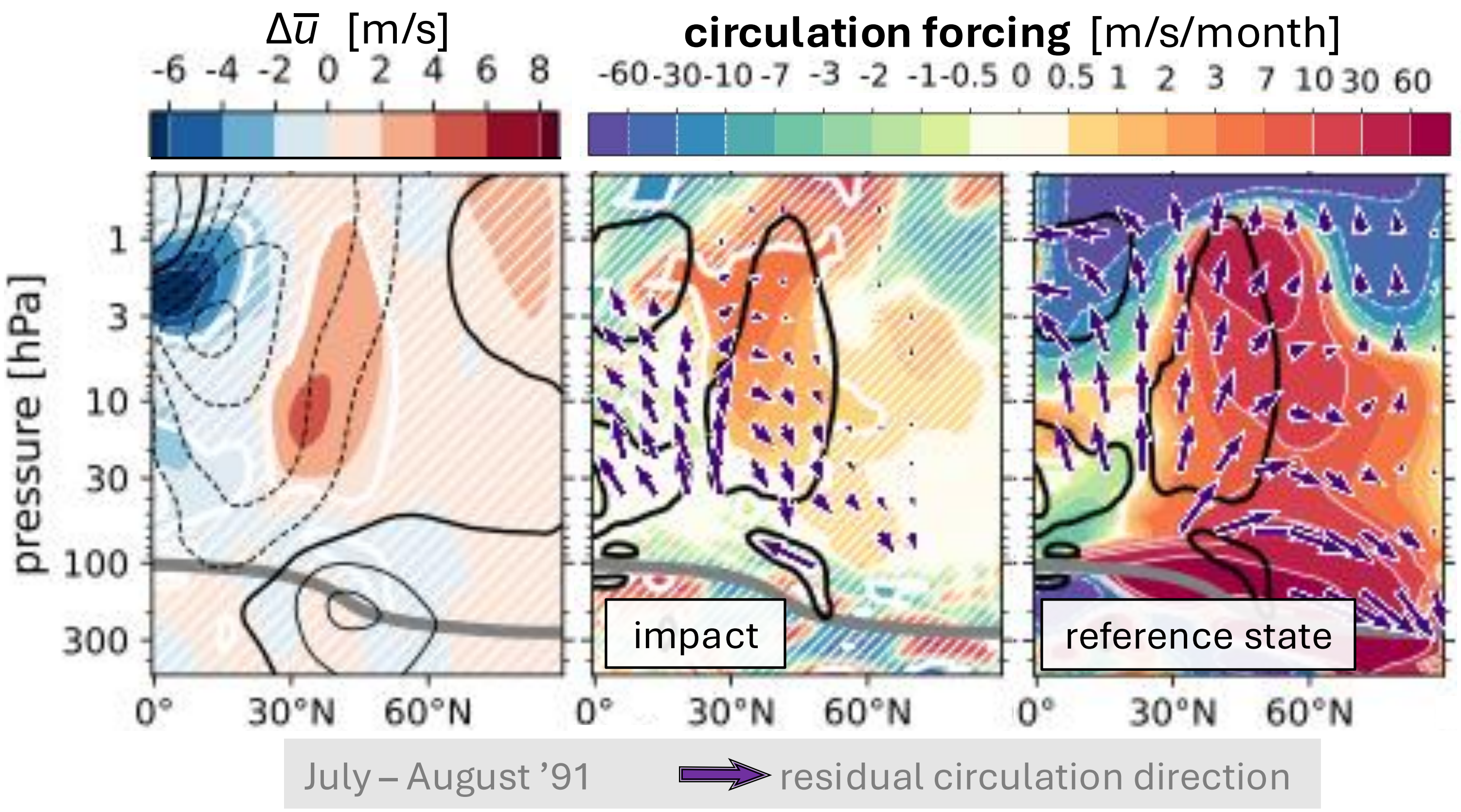
In winter '92: **Diminished wave drag**



Δ (change in the mean flow) = Δ(circulation-driven) + Δ(wave-driven) + Δ(diffusive piece)

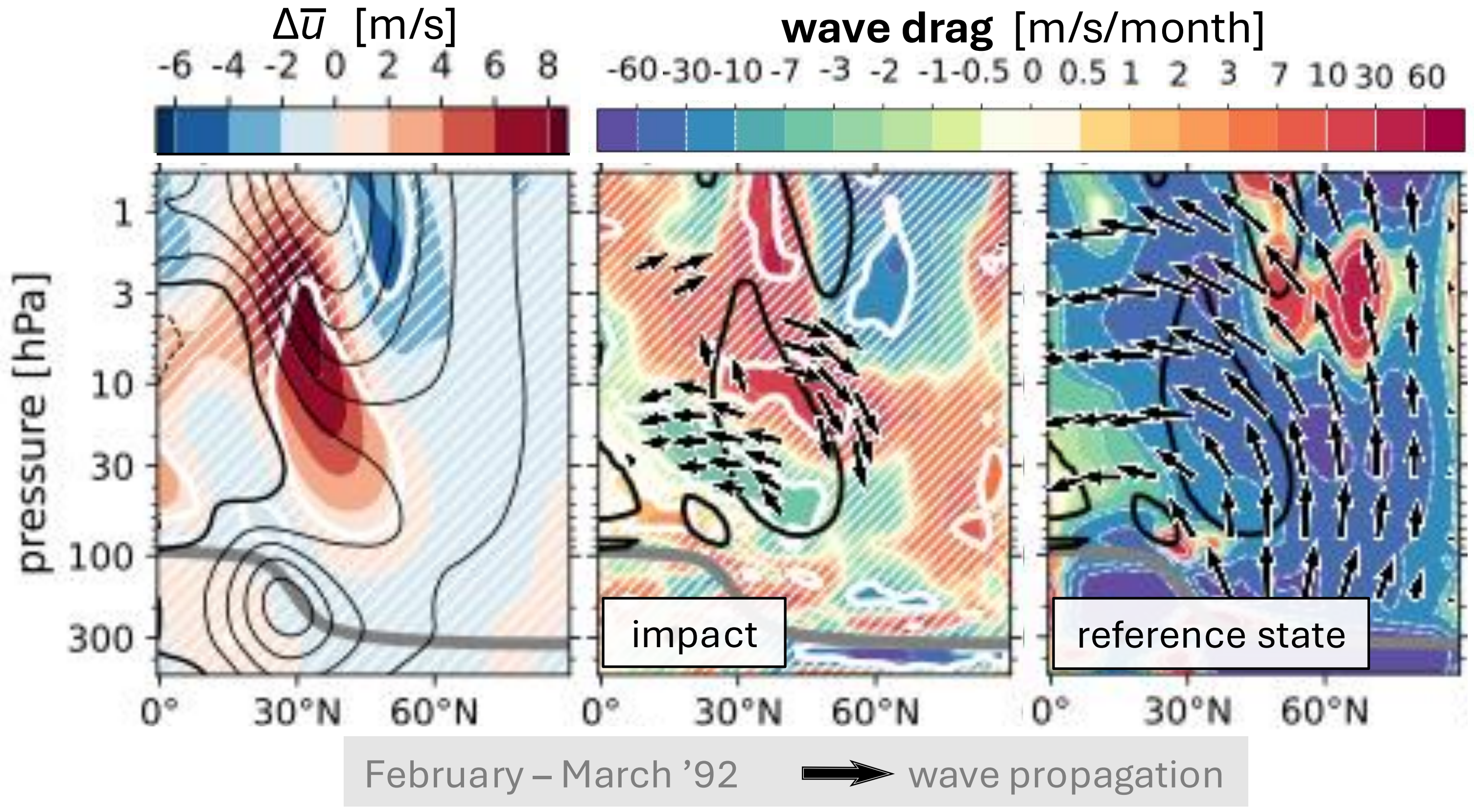
Explanation of summer response:

accelerated residual circulation in its shallow branch
= enhanced Coriolis force near 30°N



Explanation of winter response:

enhanced equatorward wave deflection
= diminished wave drag aloft



Q: What is the relative TEM imbalance that controls the post-Pinatubo wind response?

A: It depends on the background condition

(1) In the quiescent summer stratosphere, advection + Coriolis anomaly in control

(2) In the winter vortex region, Rossby wave deflection anomaly in control

Part 3

volcanic impact on global circulation of mass

diagnostic tracers and the age of stratospheric air

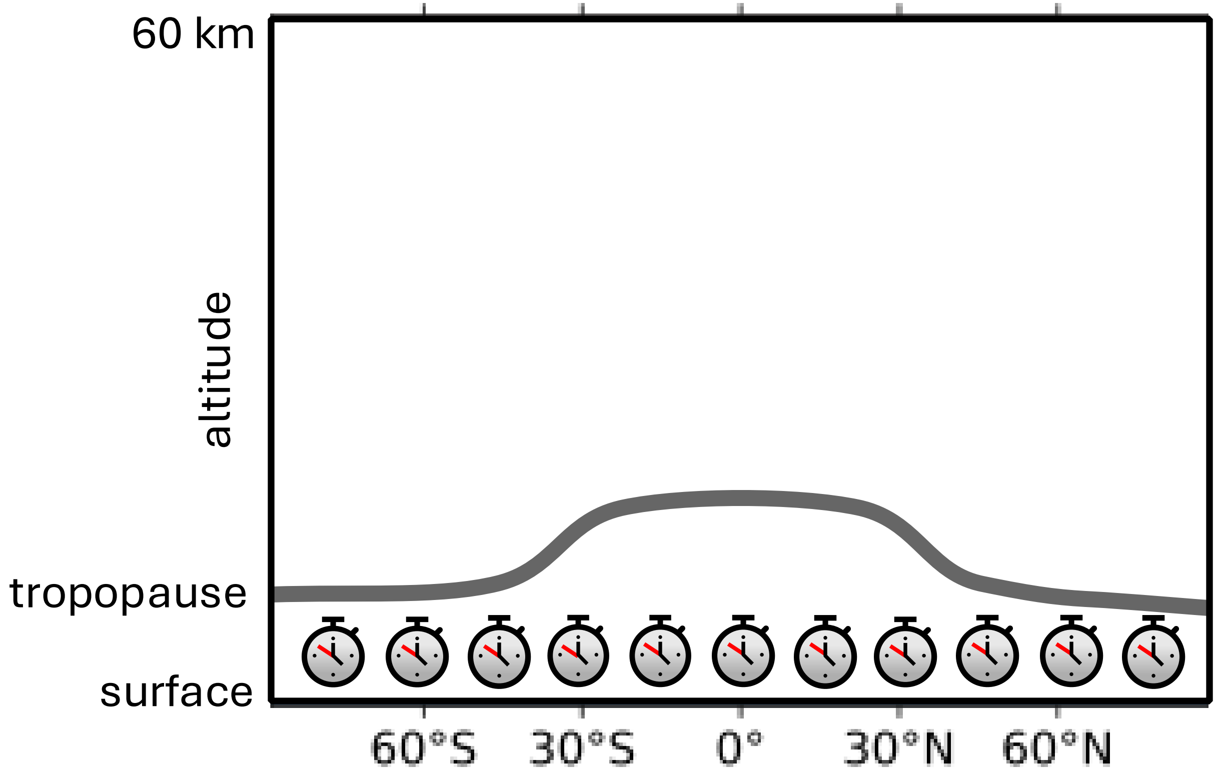
In Part 2, we concluded that the NH summer residual circulation accelerates post-eruption, driving a westerly wind impact

Q: What are the implications on *tracer transport?*

Age of Air (AoA)

a passive tracer for measuring the timescale of global circulation

- constant source at the surface
- no stratospheric sinks



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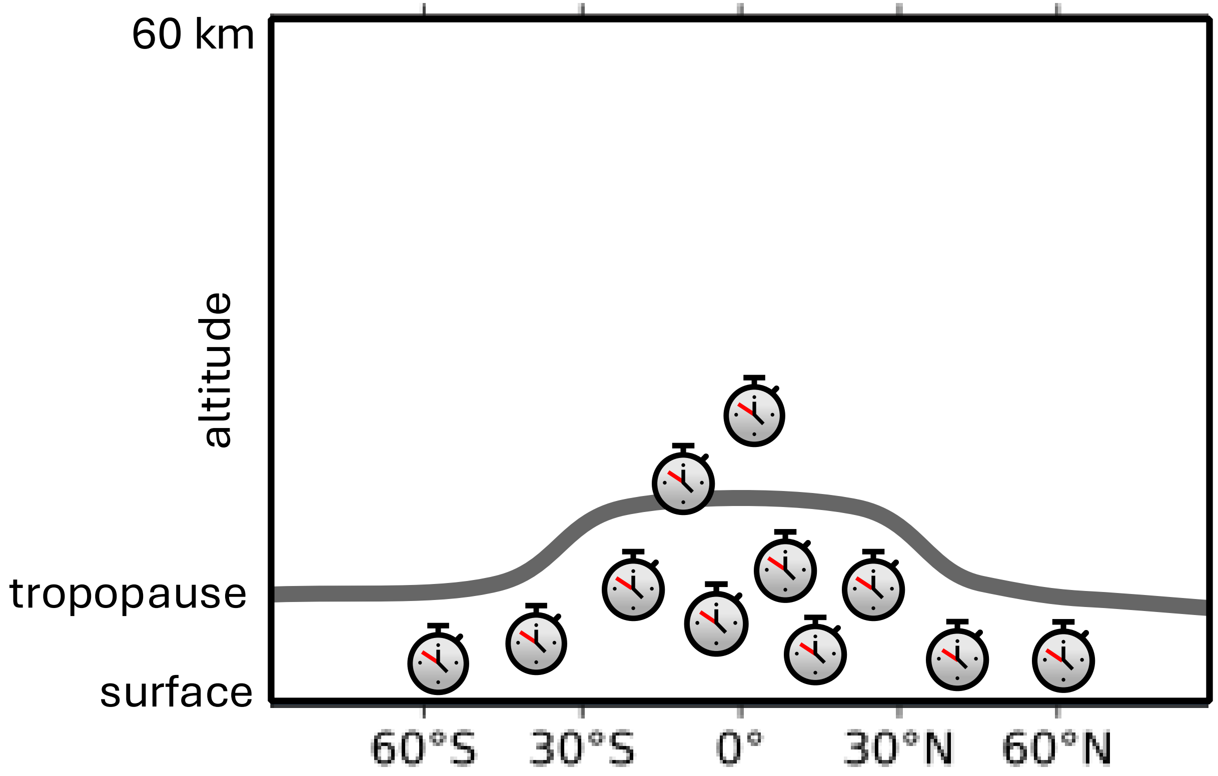

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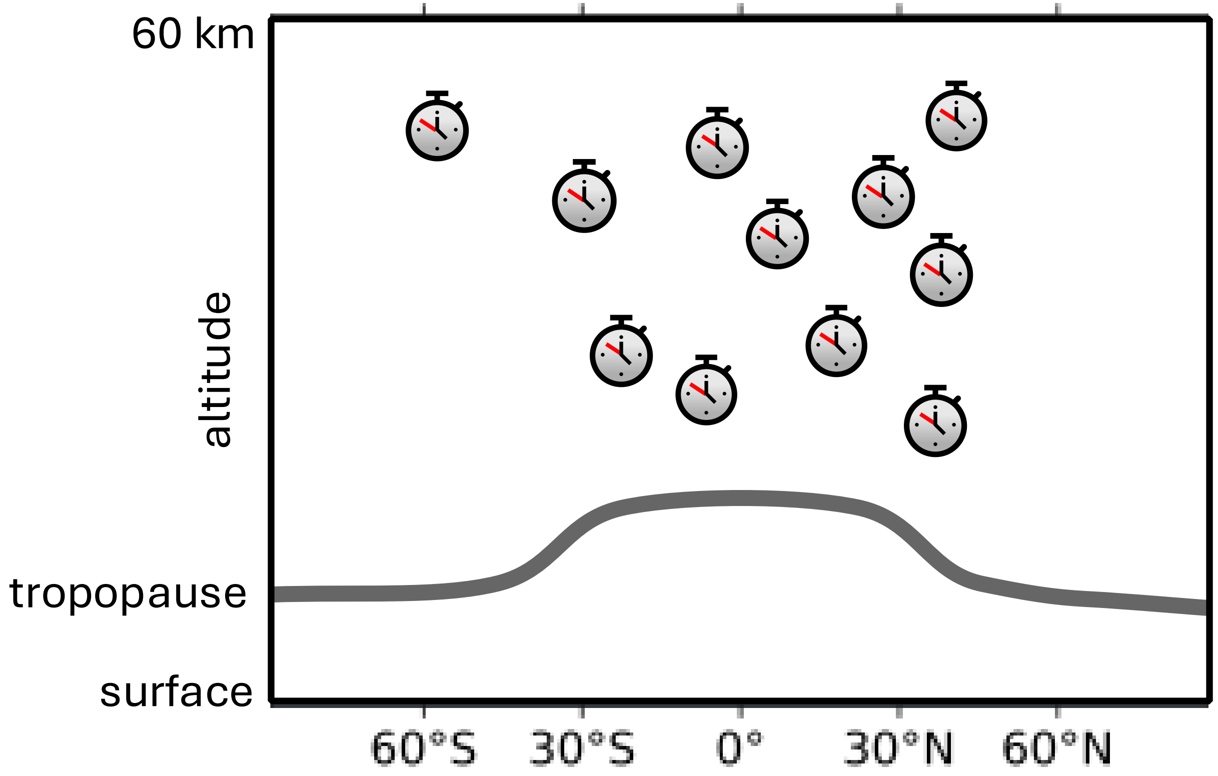

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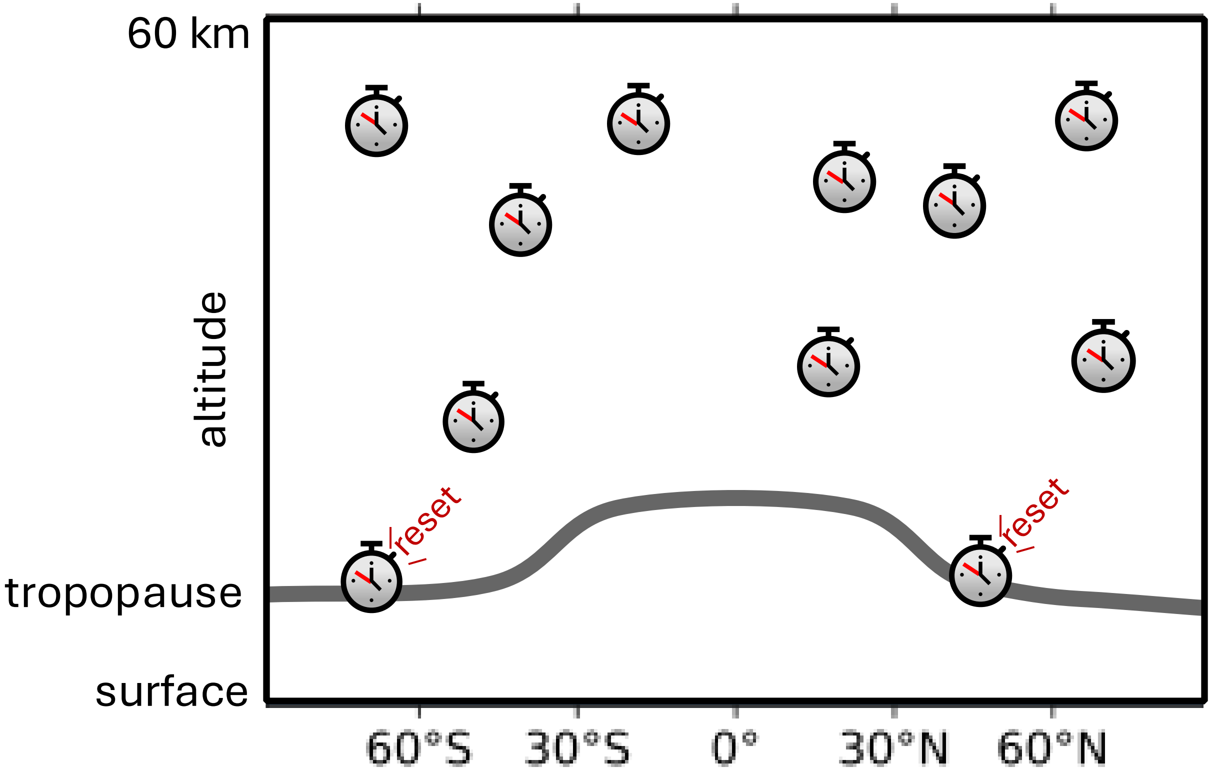


Mean AoA distribution in E3SM

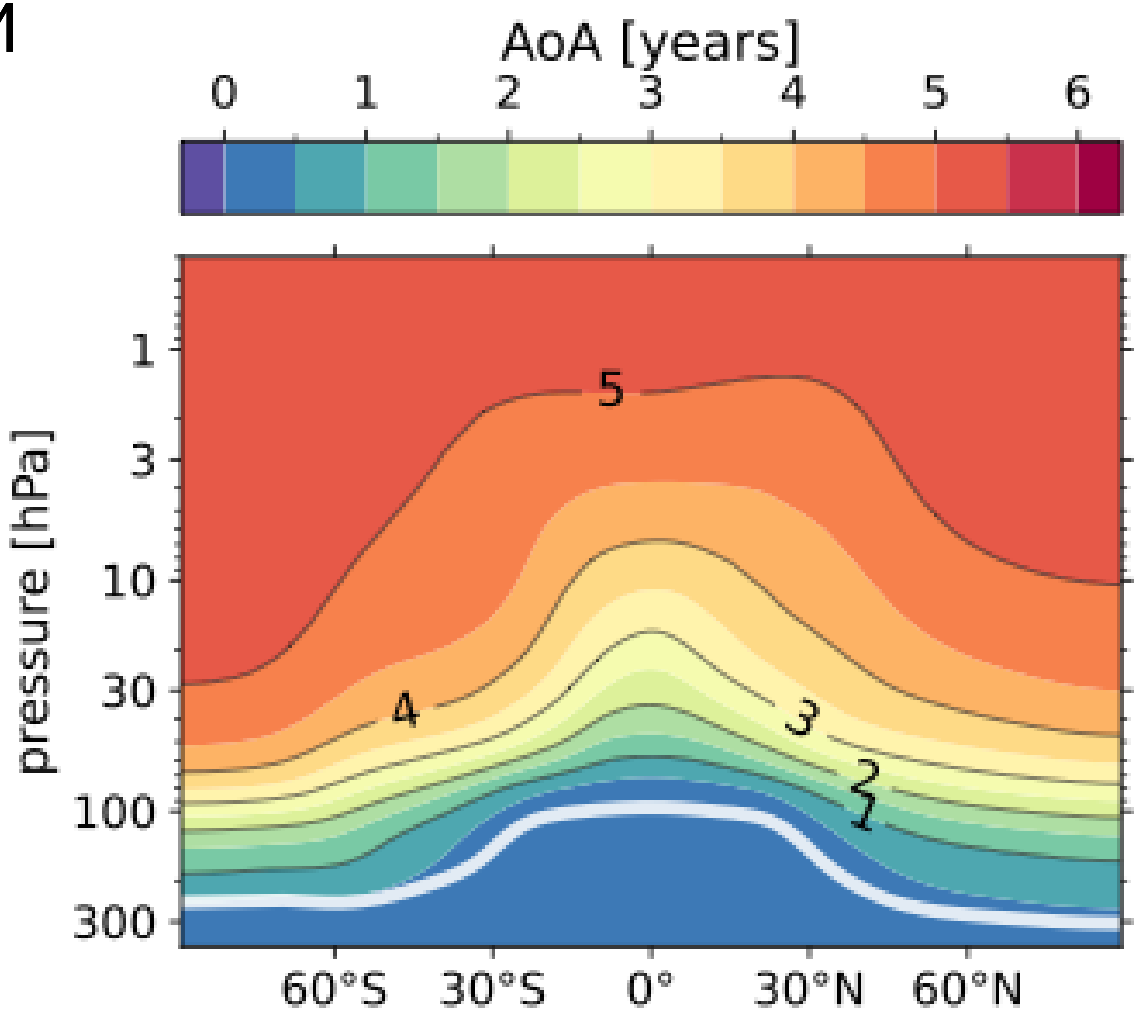
- higher, polar = older
- lower, tropical = younger
- oldest air:
  >5 years since tropospheric contact

meridional transport is **slow**

Why we care:

photochemical rates of greenhouse gases, ozone vary with height and latitude.

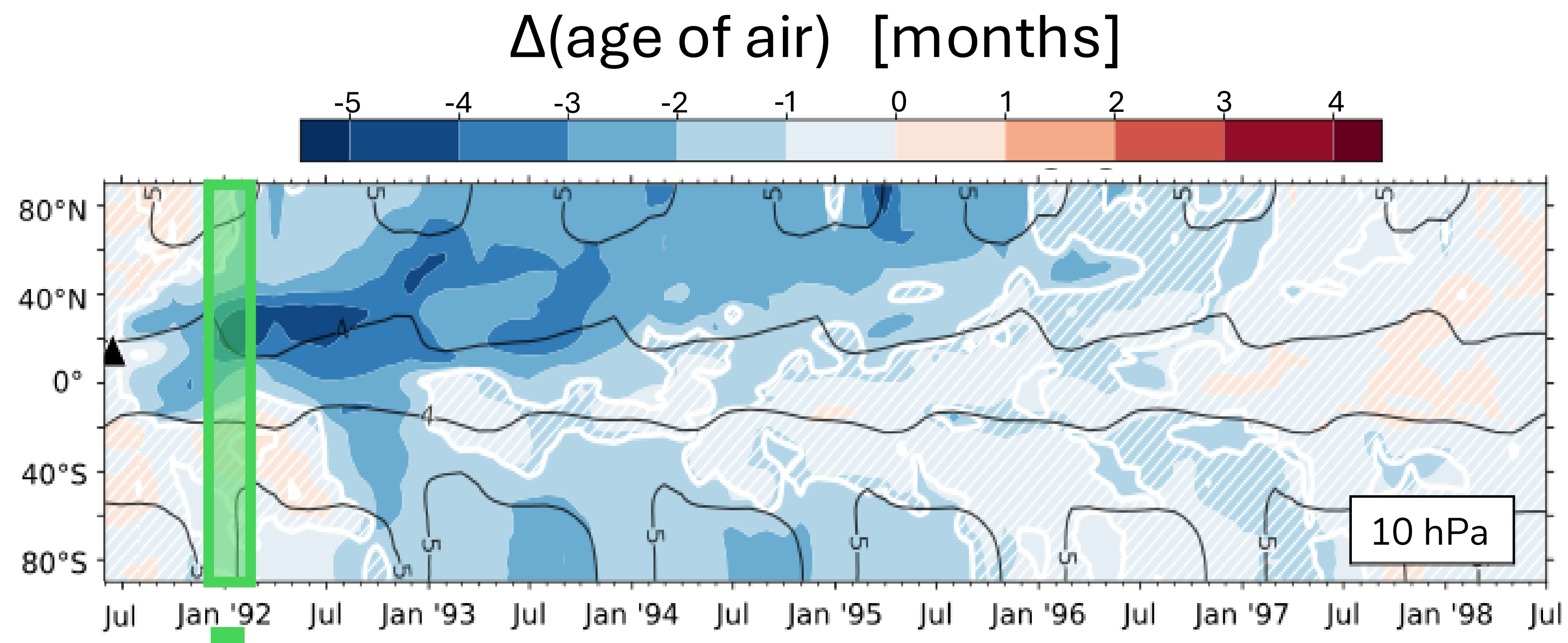
transport is thus determines chemical evolution in the upper atmosphere

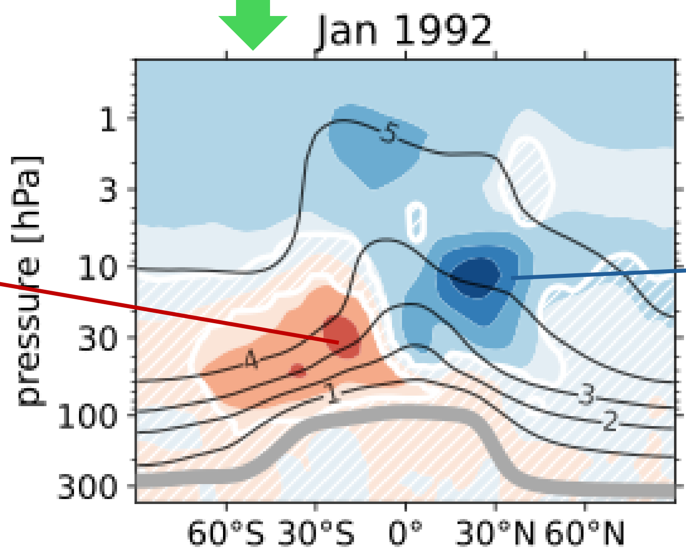


Post-eruption, **age decreases** throughout the stratosphere

Impacts persist at high latitudes for **> 4 years**

Tracers have a much **longer memory** of volcanic forcing than does the wind



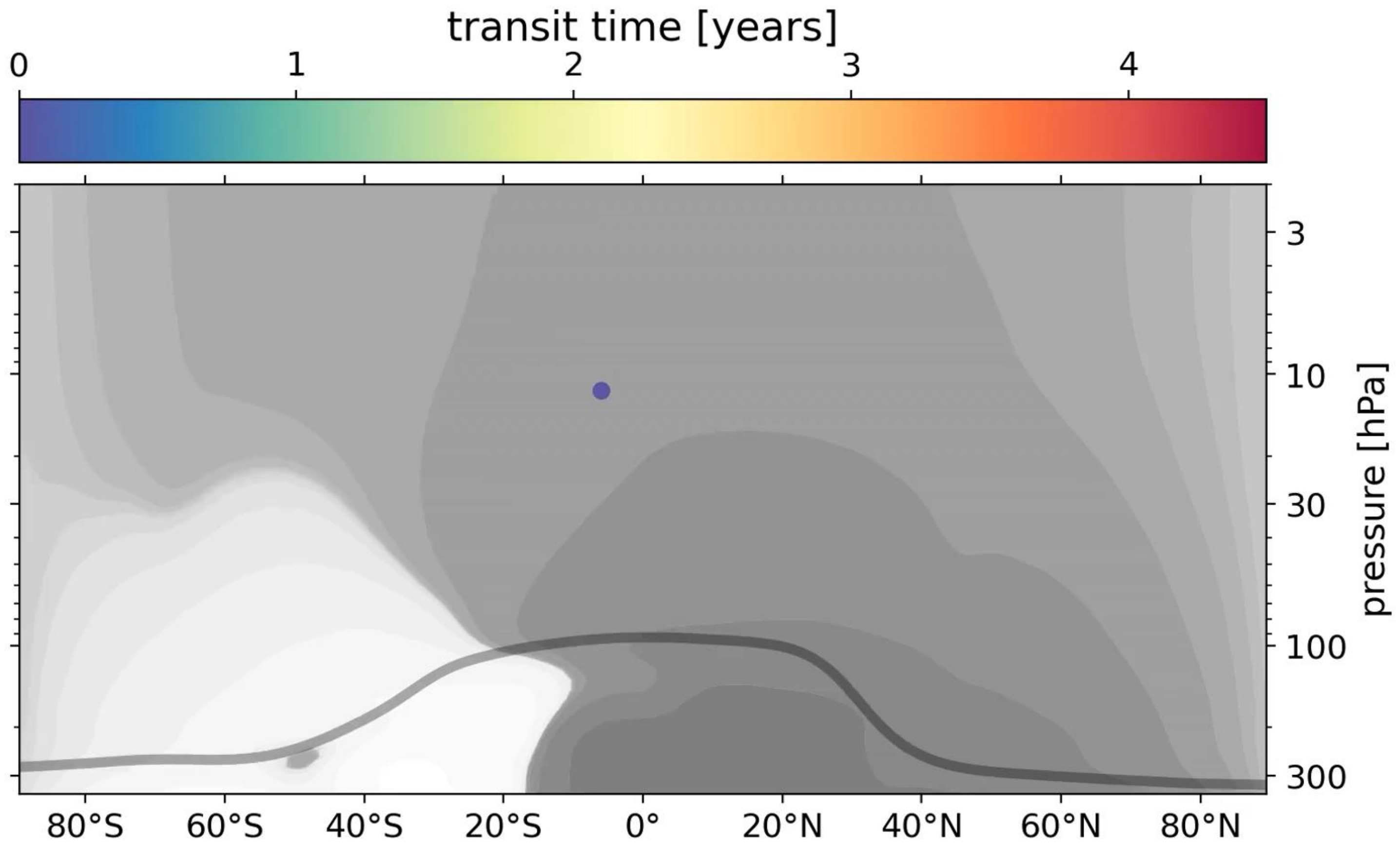


older air = ???

Younger air = consistent with accelerated residual circulation

measurement of the residual circulation transit time (RCTT)

(numerical integration of the time-varying residual-circulation (v^*, w^*))



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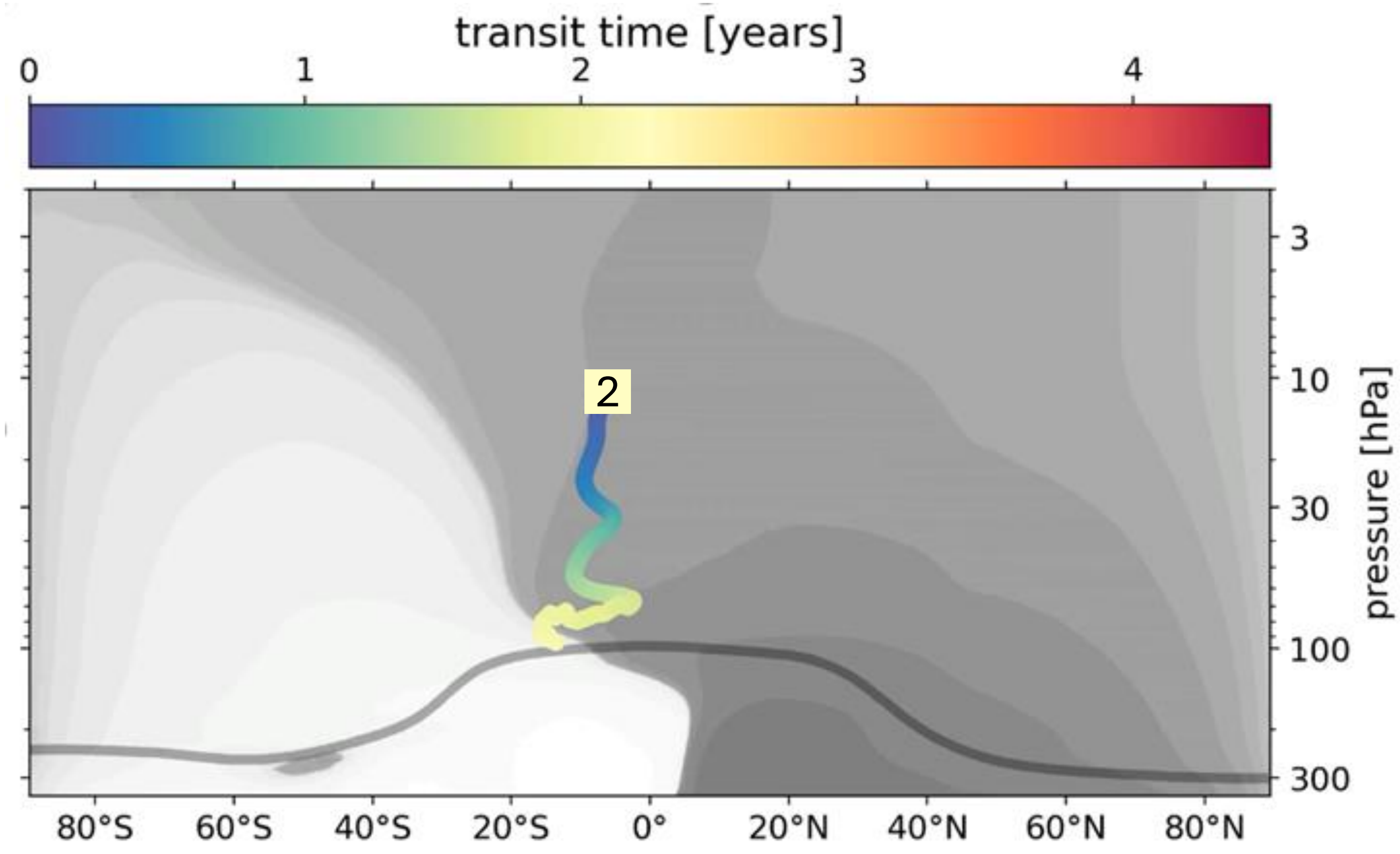

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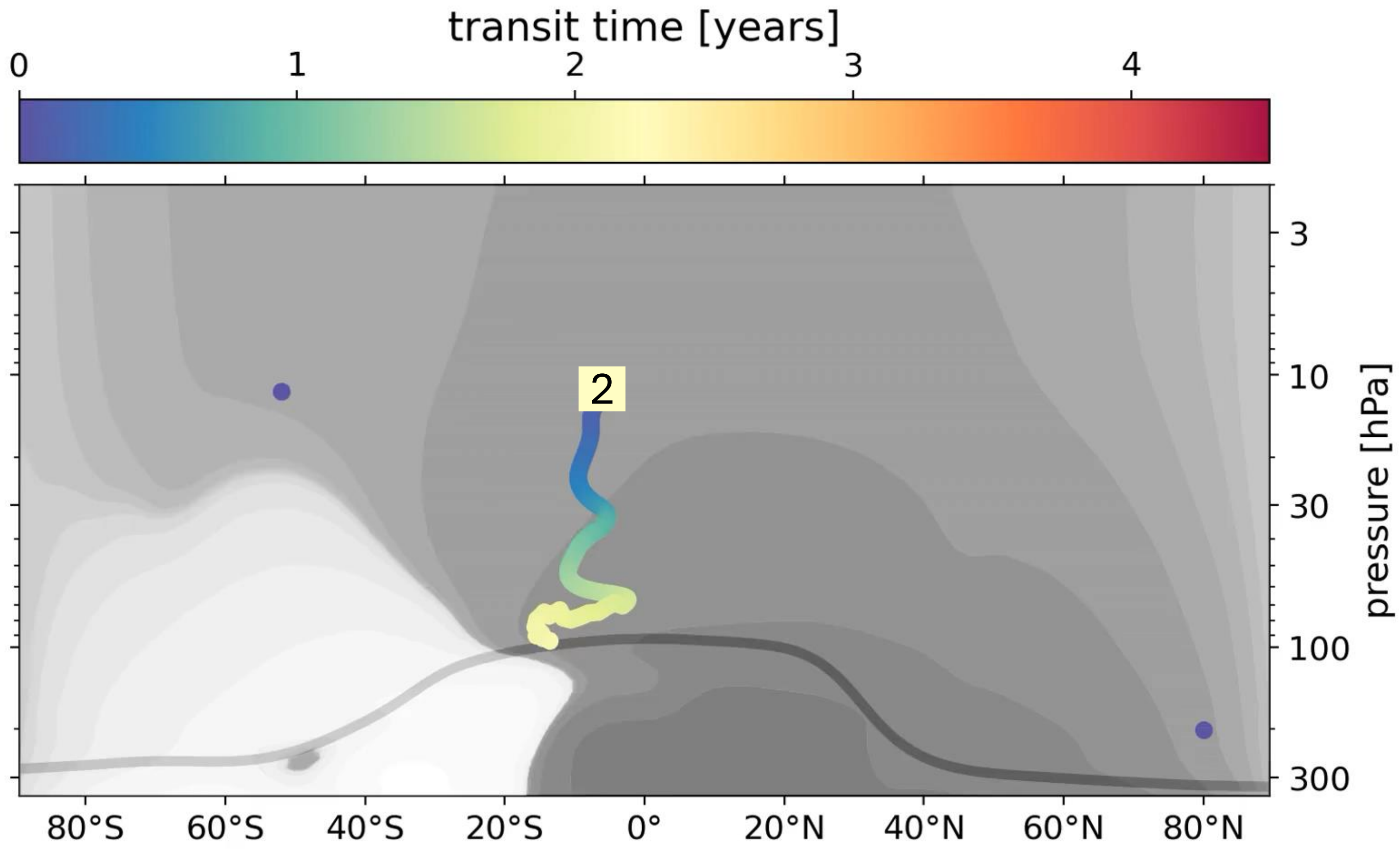

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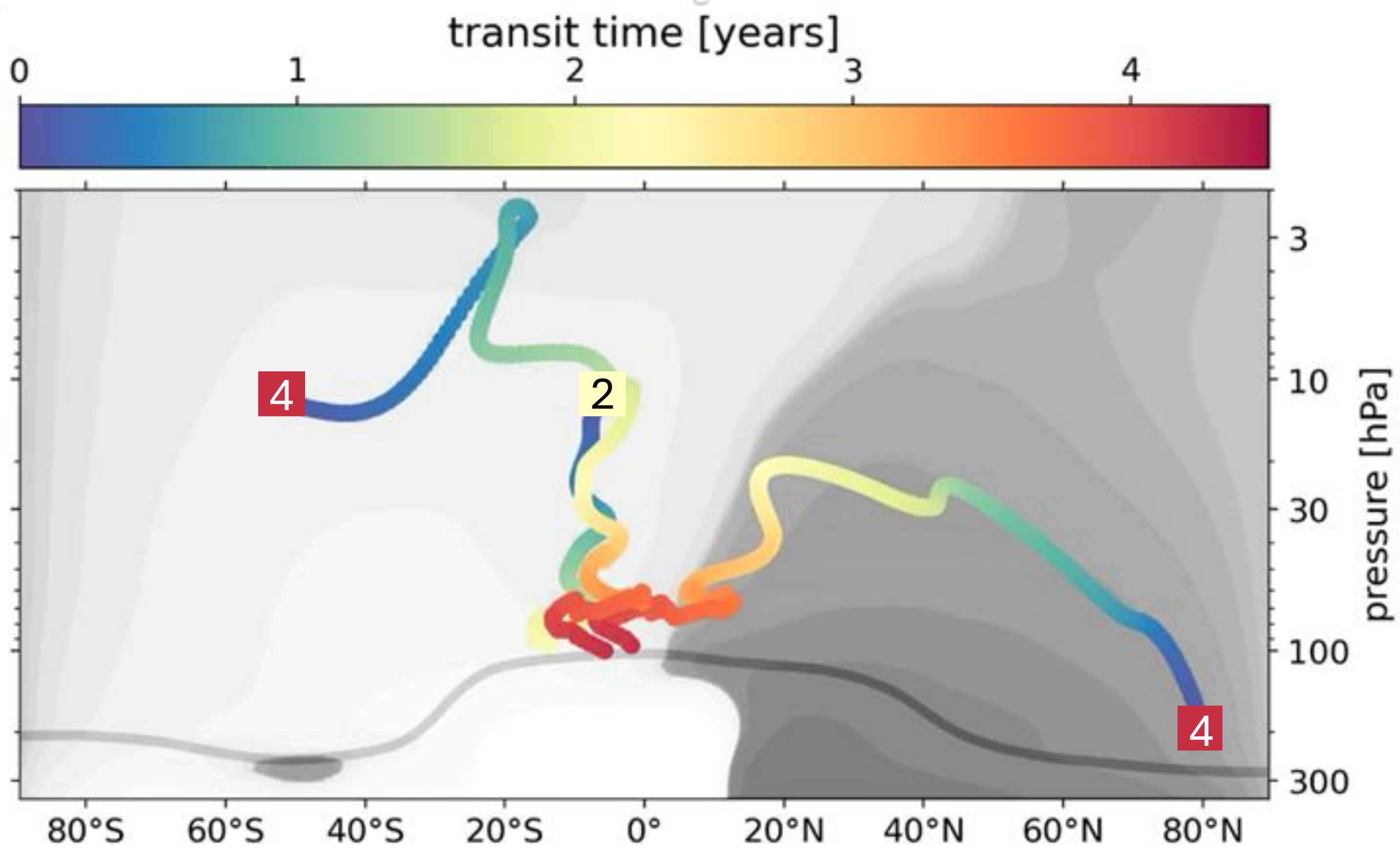
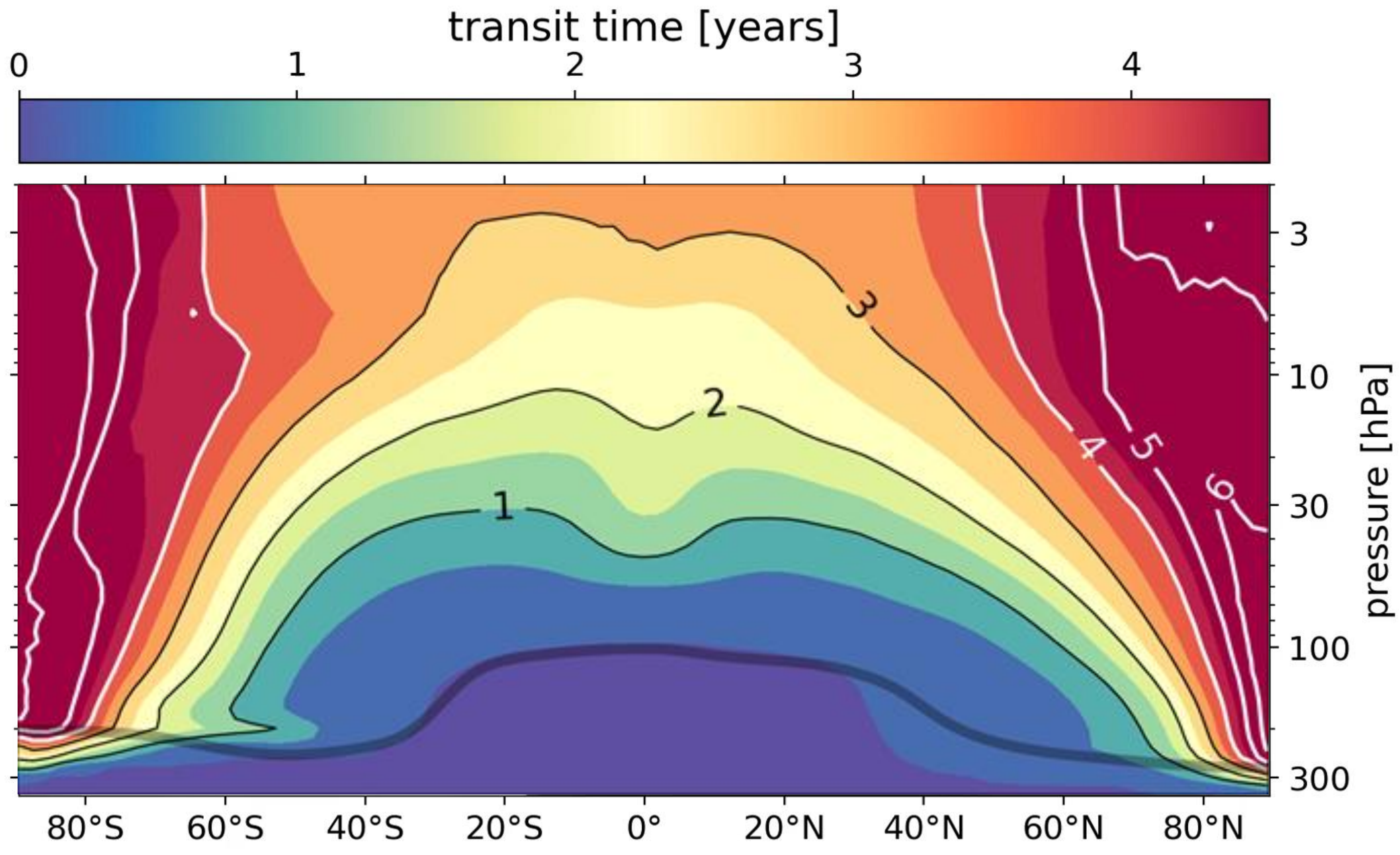
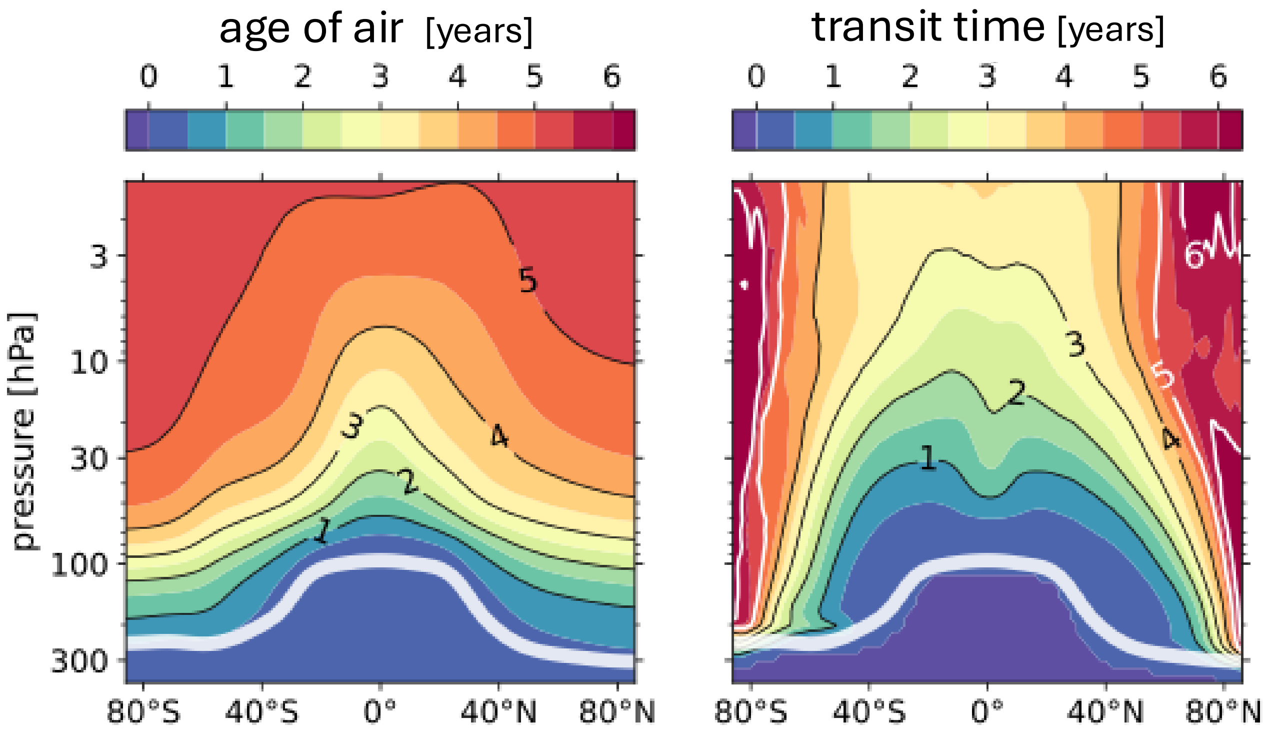


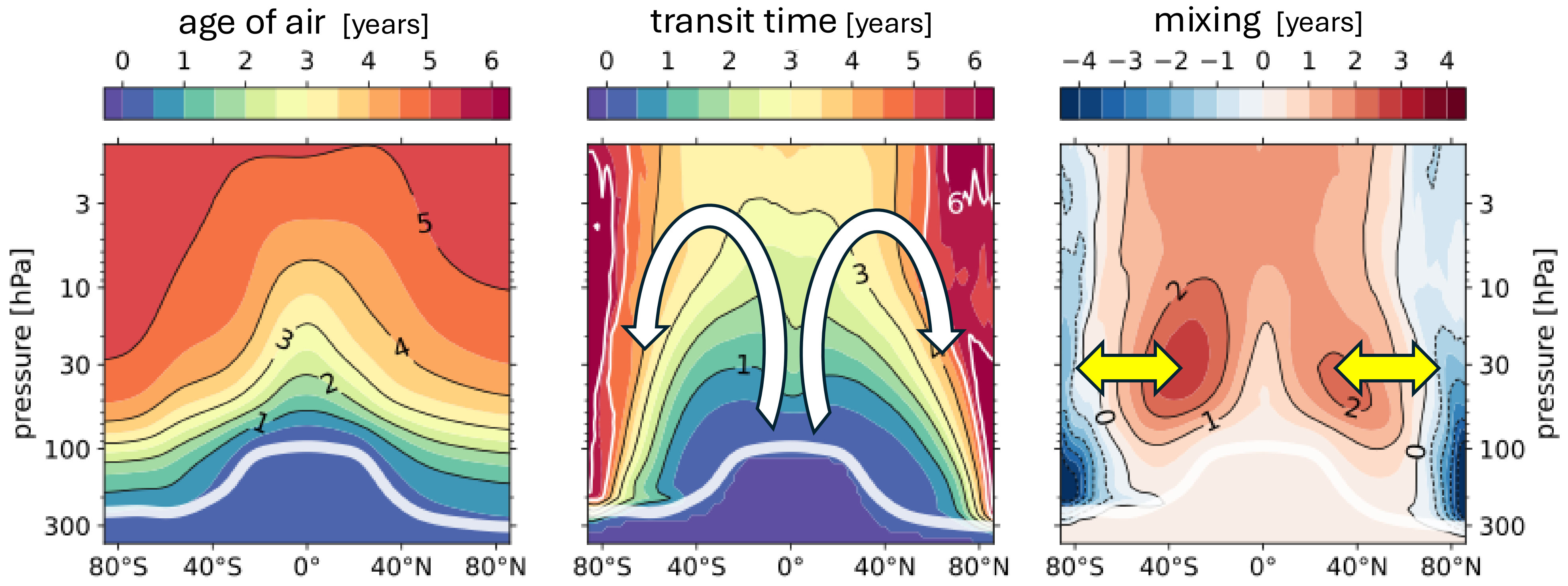
5-year time-mean, ensemble-mean RCTT




age of air [years]
0 1 2 3 4 5 6
transit time [years]
0 1 2 3 4 5 6
pressure [hPa]
3
10
30
100
300
80°S 40°S 0° 40°N 80°N
1
2
3
4
5
6

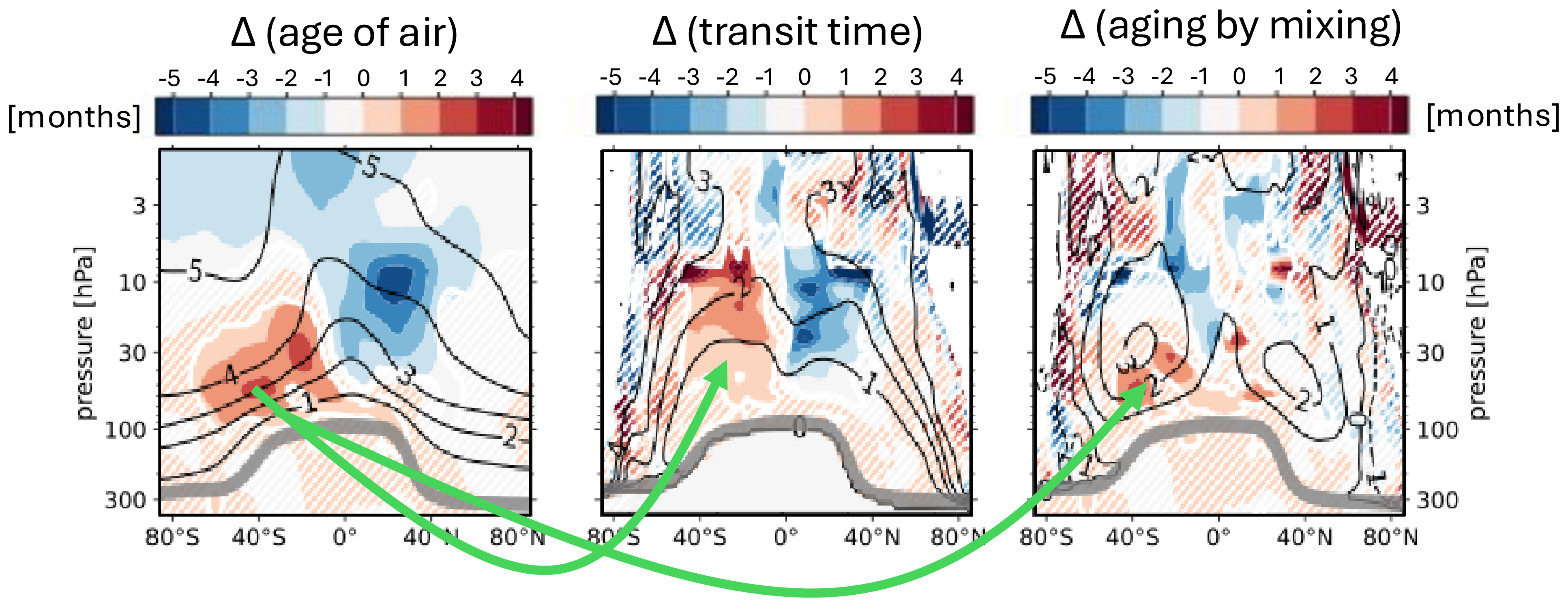
Comparing age to transit time

net aging = aging by pure transport + aging by two-way mixing



Volcanic impact on transport and mixing

southern hemisphere aging feature has transport and mixing contributions



ongoing work; response is associated with the **latitude** and the **season** of the eruption

Low-latitude summertime eruptions seem to reliably produce the positive aging signal

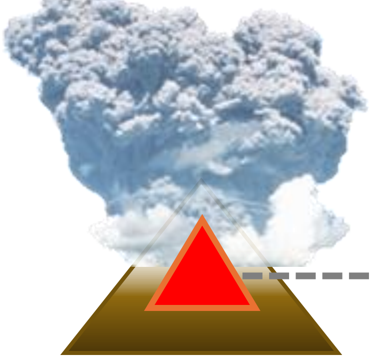
Q: What are the volcanic implications of on tracer transport?

A: Transport speed is affected,
but the sign depends on where we look

(1) In the hemisphere of the eruption (northern), younger air enters the stratosphere and spreads pole-to-pole

(2) In the hemisphere opposite the eruption (southern), older air accumulates in the lower stratosphere

Summary



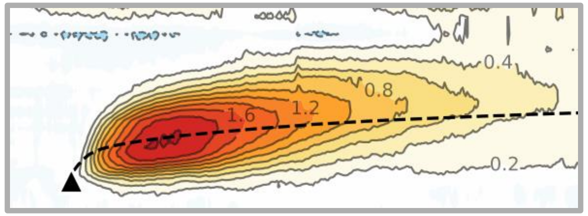
Pinatubo

climate system

observed impacts

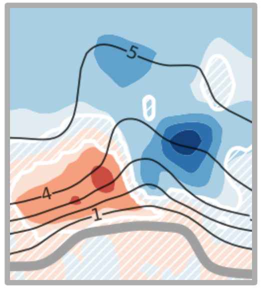
stratospheric heating

surface cooling



winter vortex accelerations

altered stratospheric composition



???

Part 1:
simulation of Pinatubo temperature anomalies in an idealized model

Part 2:
Seasonal mechanisms identified:

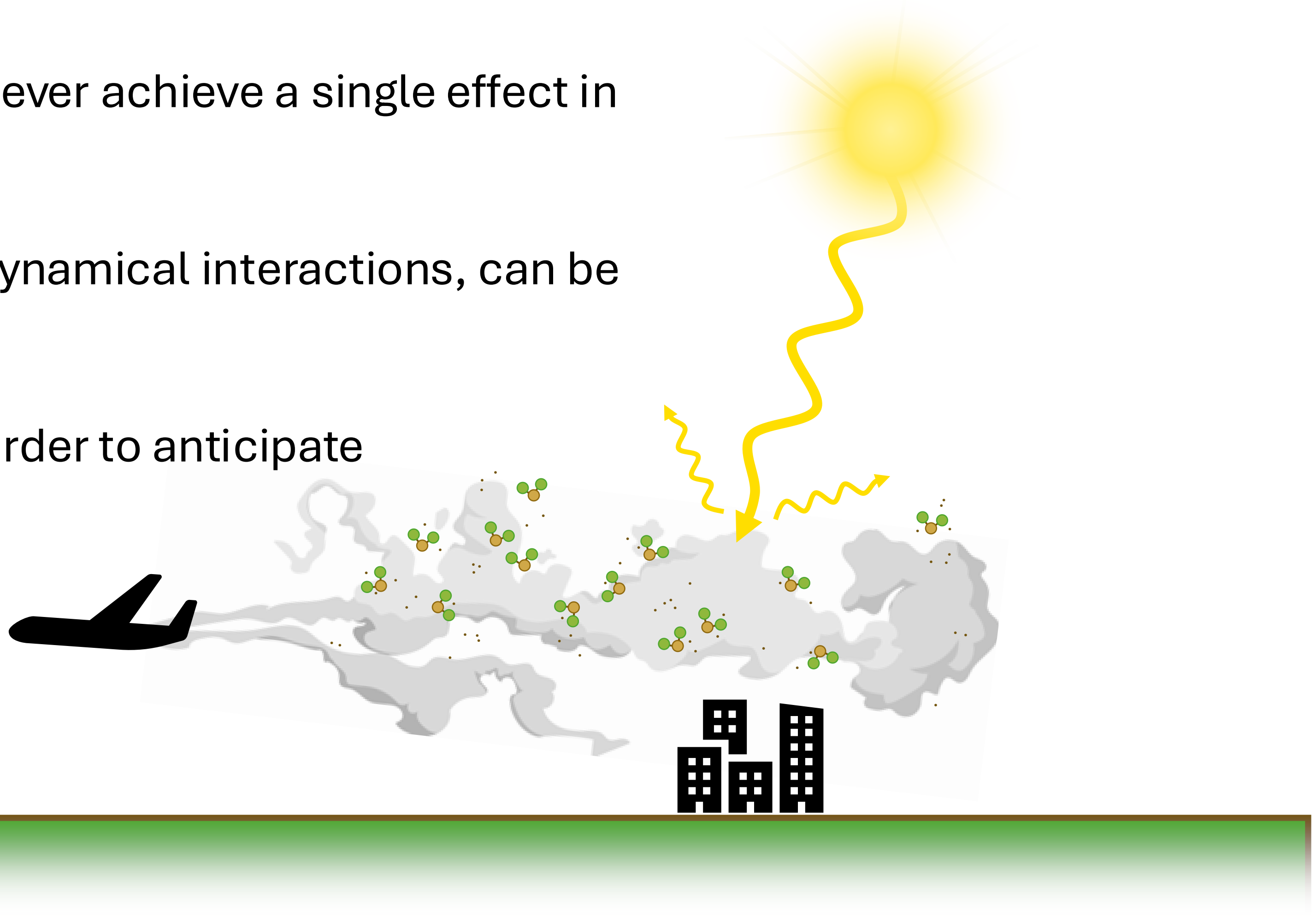
- wintertime wave deflection
- summertime enhanced circulation

Part 3:
changes to global transport inferred from stratospheric age; hemispheric response is asymmetric

Final words:

what this work implies for intentional climate modification (e.g. SAI)

- It is almost certainly not possible to ever achieve a single effect in the climate
- Side effects, governed by complex dynamical interactions, can be indirect, subtle, and unpredictable
- Local effects will always be even harder to anticipate



many thanks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Welco
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The CLDERA Team


Summer in New Mexico
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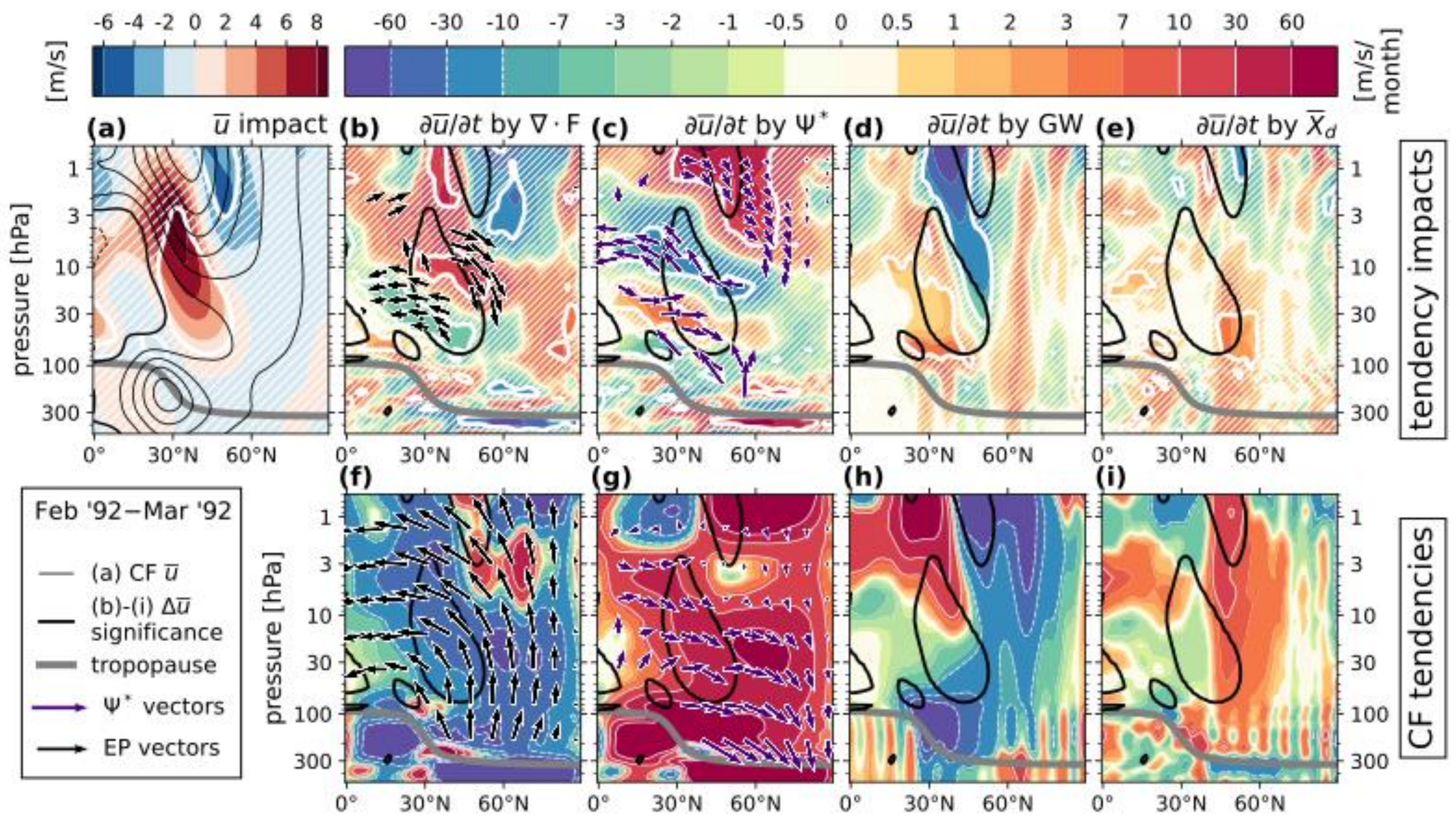
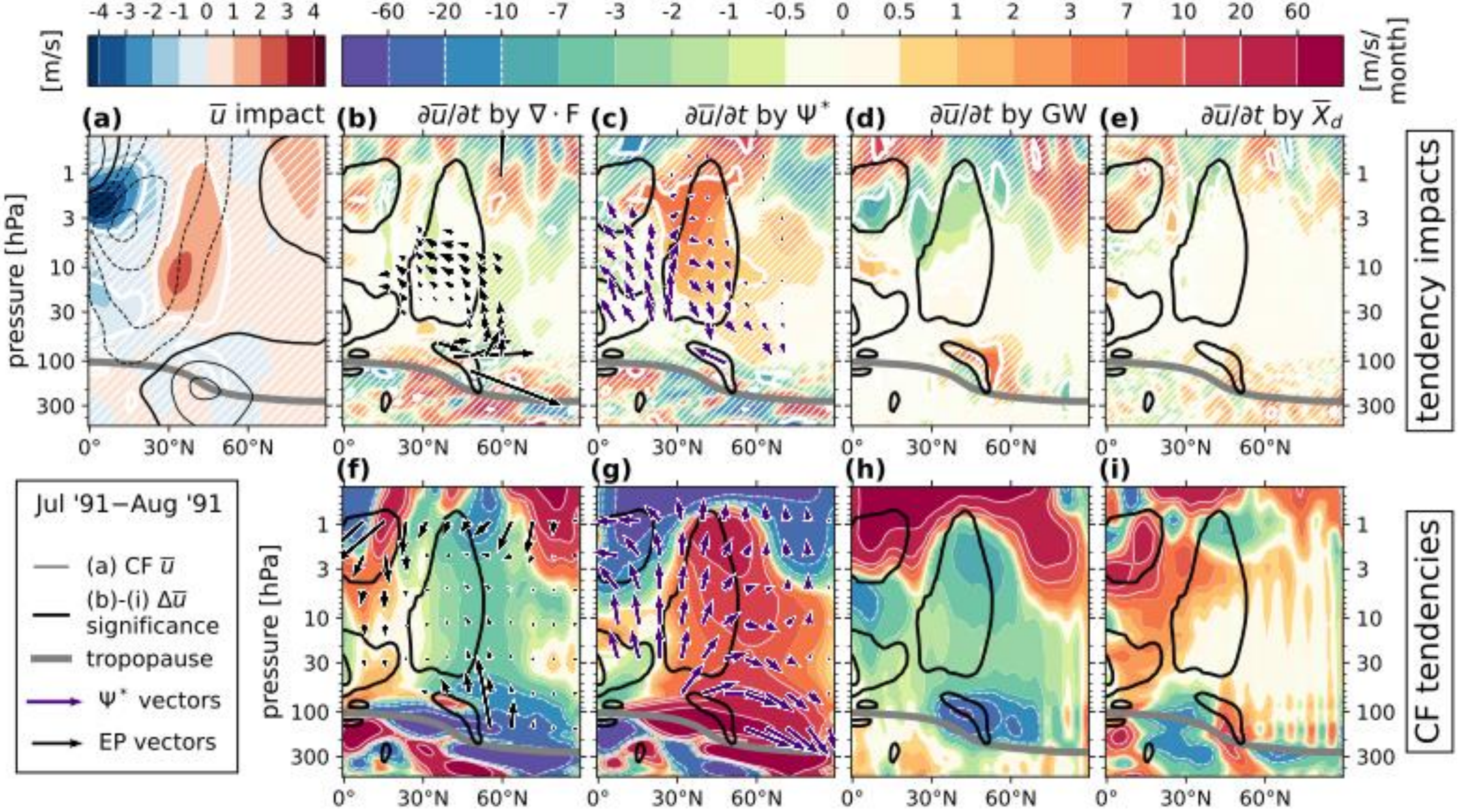
Thank you!

start backup slides



[m/s]
-6 -4 -2 0 2 4 6 8
-60 -30 -10 -7 -3 -2 -1 -0.5 0 0.5 1 2 3 7 10 30 60
[m/s/ month]
(a) $\overline{u}$ impact
(b) $\partial\overline{u}/\partial t$ by $\nabla \cdot F$
(c) $\partial\overline{u}/\partial t$ by Ψ^*
(d) $\partial\overline{u}/\partial t$ by GW
(e) $\partial\overline{u}/\partial t$ by $\overline{X}_d$
tendency impacts
(f)
(g)
(h)
(i)
CF tendencies
pressure [hPa]
1
3
10
30
100
300
0° 30°N 60°N
Feb '92−Mar '92
(a) CF $\overline{u}$
(b)-(i) $\Delta\overline{u}$ significance
tropopause
Ψ^* vectors
EP vectors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(f)
(g)
(h)
(i)
pressure [hPa]
tendency impacts
CF tendencies
Jul '91−Aug '91
(a) CF $\overline{u}$
(b)-(i) $\Delta\overline{u}$ significance
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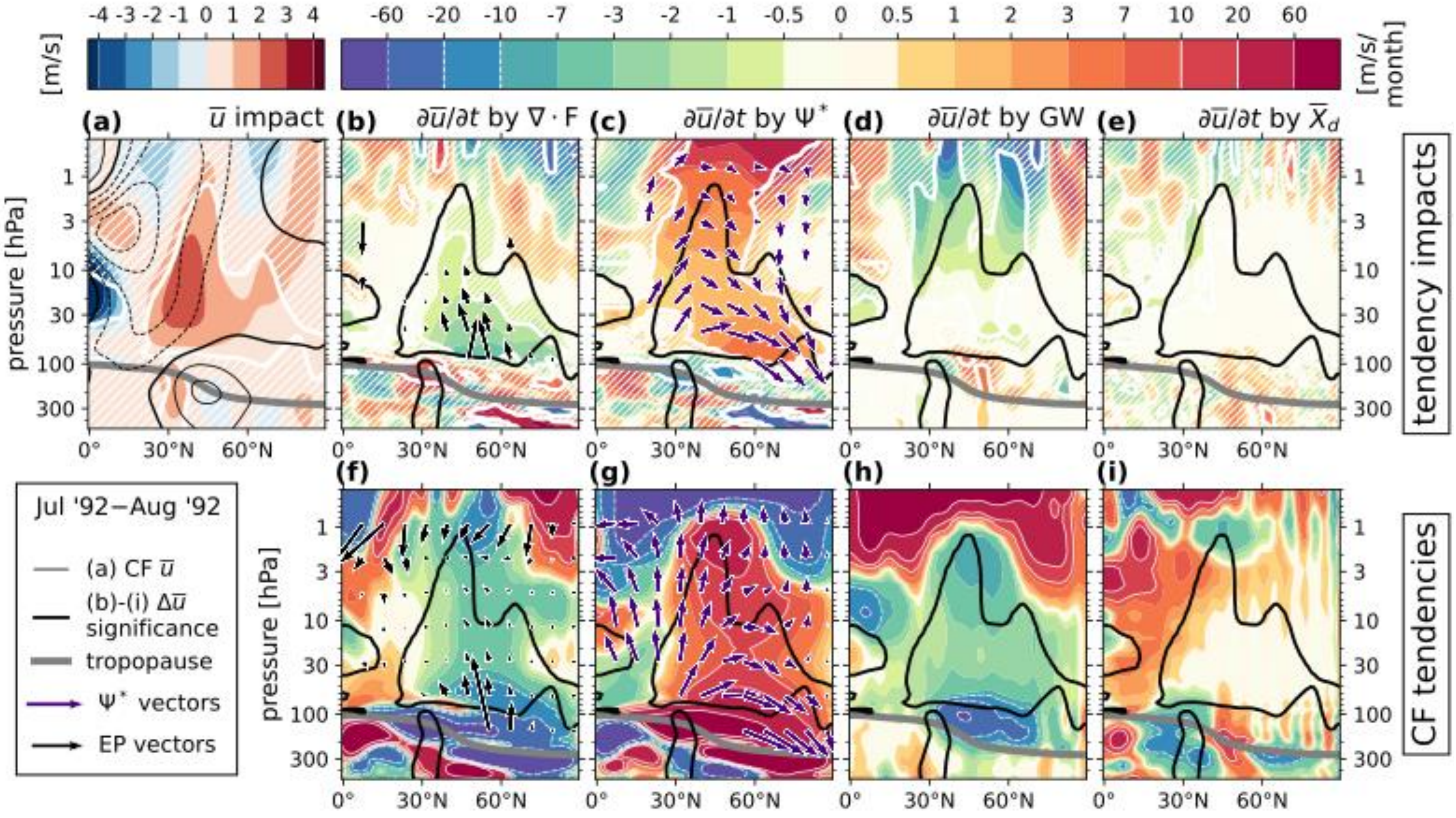
EP vectors



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CF tendencies
pressure [hPa]
Jul '92−Aug '92
(a) CF $\overline{u}$
(b)-(i) $\Delta\overline{u}$ significance
tropopause
Ψ^* vectors
EP vectors

Concept: the Transformed Eulerian Mean (TEM)

$$u = \overline{u} + u'$$

wind speed — zonal mean — eddy

Predictive eq. for zonal wind:

$$\frac{\mathrm{D}u}{\mathrm{D}t} = fv + p_x - \mathrm{X}$$

Predictive eq. for *zonal-mean* zonal wind:
(inefficient for diagnosing wave-mean flow interaction!)

$$\frac{\partial \overline{u}}{\partial t} + \overline{v}\overline{u}_y + \overline{w}\overline{u}_z = f\overline{v} - (\overline{u'v'})_y - (\overline{u'w'})_z - \overline{\mathrm{X}}$$

$$\overline{v}^* = \overline{v} - (\overline{v'\theta'}/\theta_z)_z\,, \quad \overline{w}^* = \overline{w} + (\overline{v'\theta'}/\overline{\theta}_z)_y$$

$$\frac{\partial \overline{u}}{\partial t} = \overline{v}^*\left(f - \overline{u}_y\right) - \overline{w}^*\overline{u}_z + \left[\frac{\partial}{\partial y}\left(\overline{u}_z\frac{\overline{v'\theta'}}{\overline{\theta}_z} - \overline{u'v'}\right) + \frac{\partial}{\partial z}\left(\left(f - \overline{u}_y\right)\frac{\overline{v'\theta'}}{\overline{\theta}_z} - \overline{u'w'}\right)\right] - \overline{\mathrm{X}}$$

$$\frac{\partial \overline{u}}{\partial t} = \overline{v}^*\left(f - \overline{u}_y\right) - \overline{w}^*\overline{u}_z + \nabla \cdot \mathbf{F} - \overline{\mathrm{X}}$$