

How Volcanic Eruptions Modify the Earth's Climate

Joseph Hollowed
PhD Defense
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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



A satellite image of the Philippines, showing the main island of Luzon and the Visayas. A red triangle marks the location of Mt. Pinatubo on Luzon. The surrounding ocean is dark blue, and the land is green with some white clouds. A large, bright white cloud formation is visible on the right side of the image.

Mt. Pinatubo
Luzon, Philippines

image: NASA Wordview, 4/14/2017



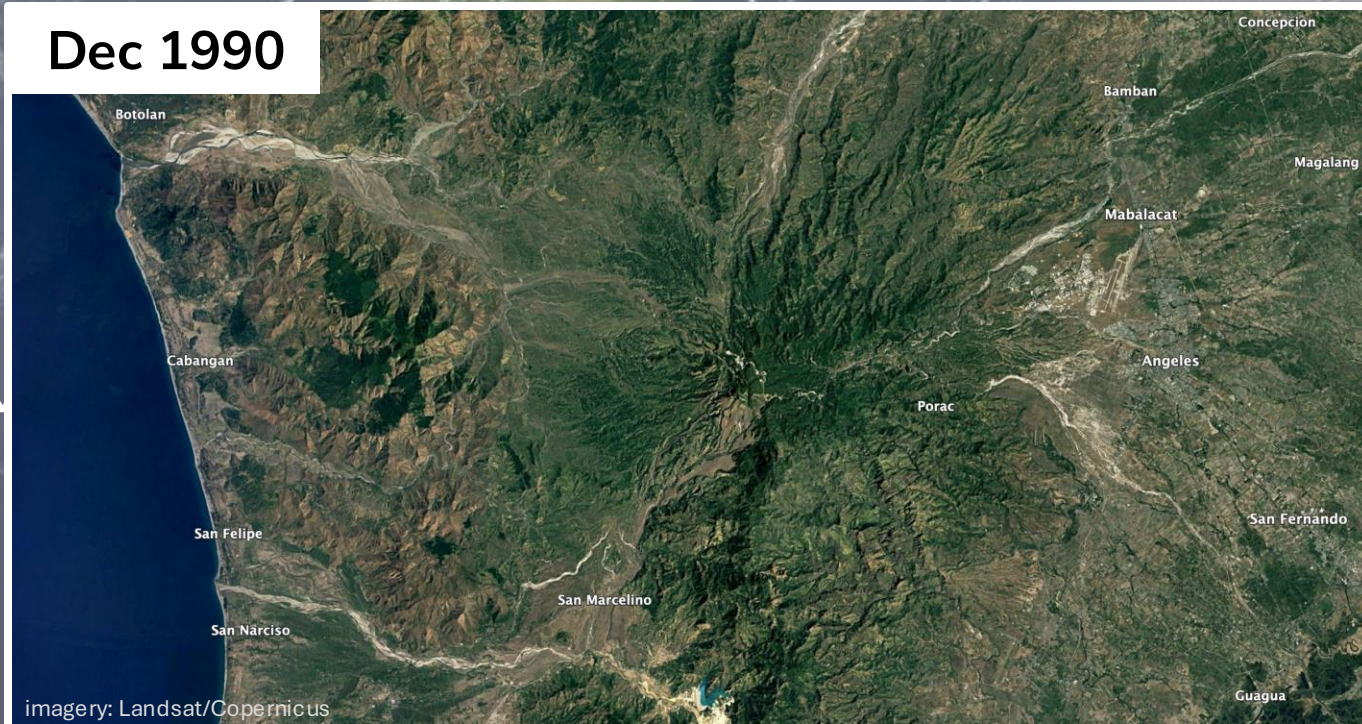
Mt. Pinatubo
Luzon, Philippines

June 1991



image: NASA Wordview, 4/14/2017

Dec 1990

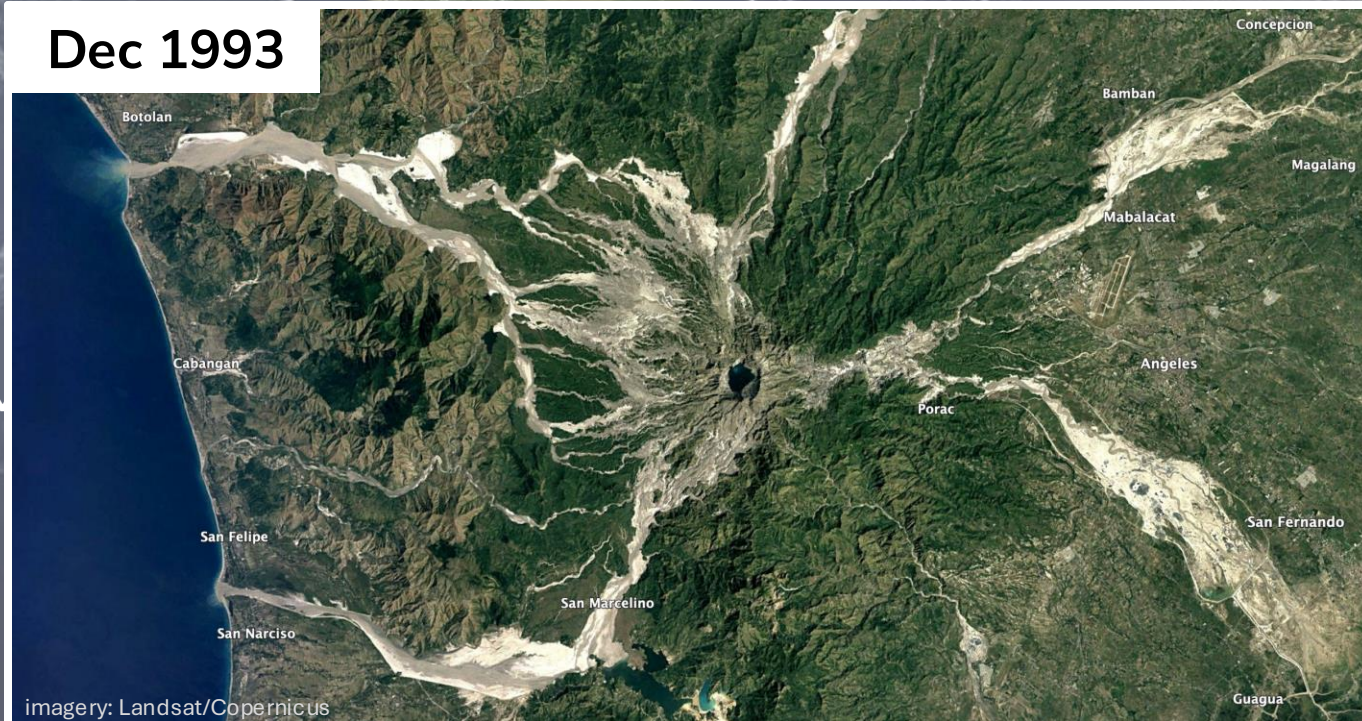


June 1991



image: NASA Wordview, 4/14/2017

Dec 1993

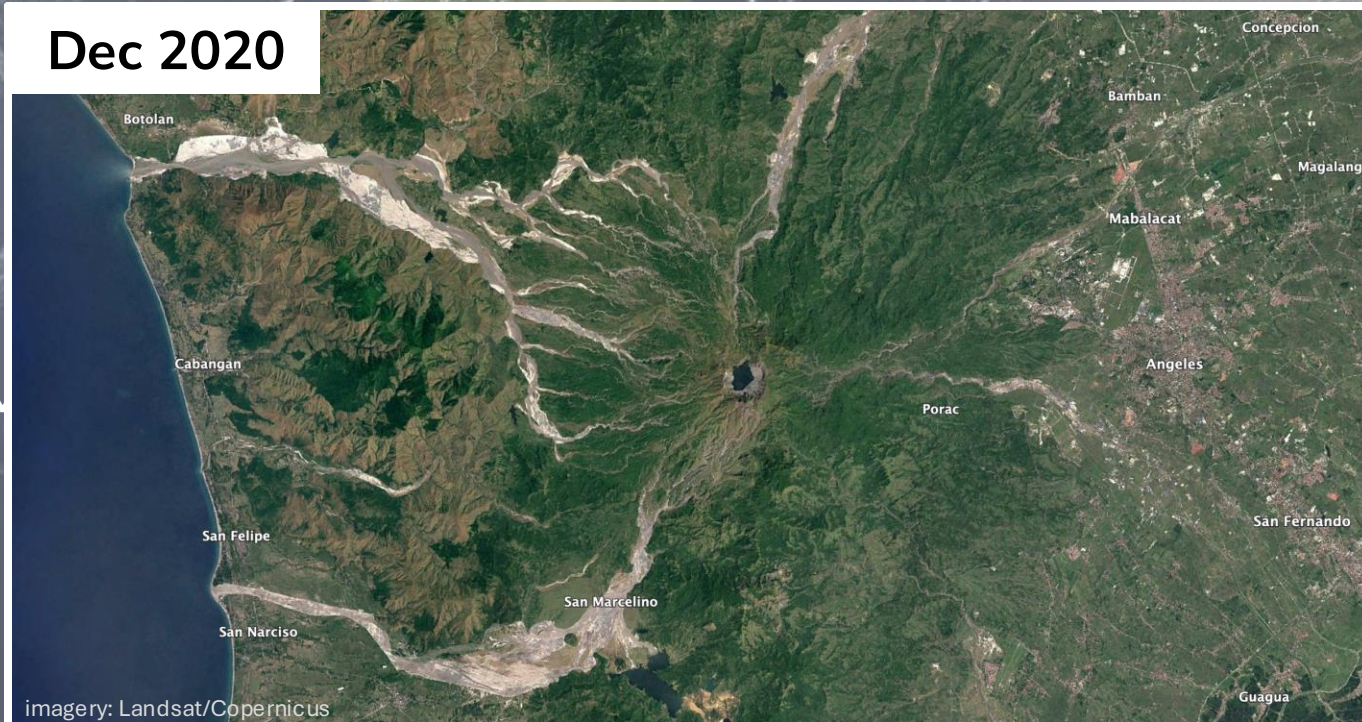


June 1991



image: NASA Wordview, 4/14/2017

Dec 2020



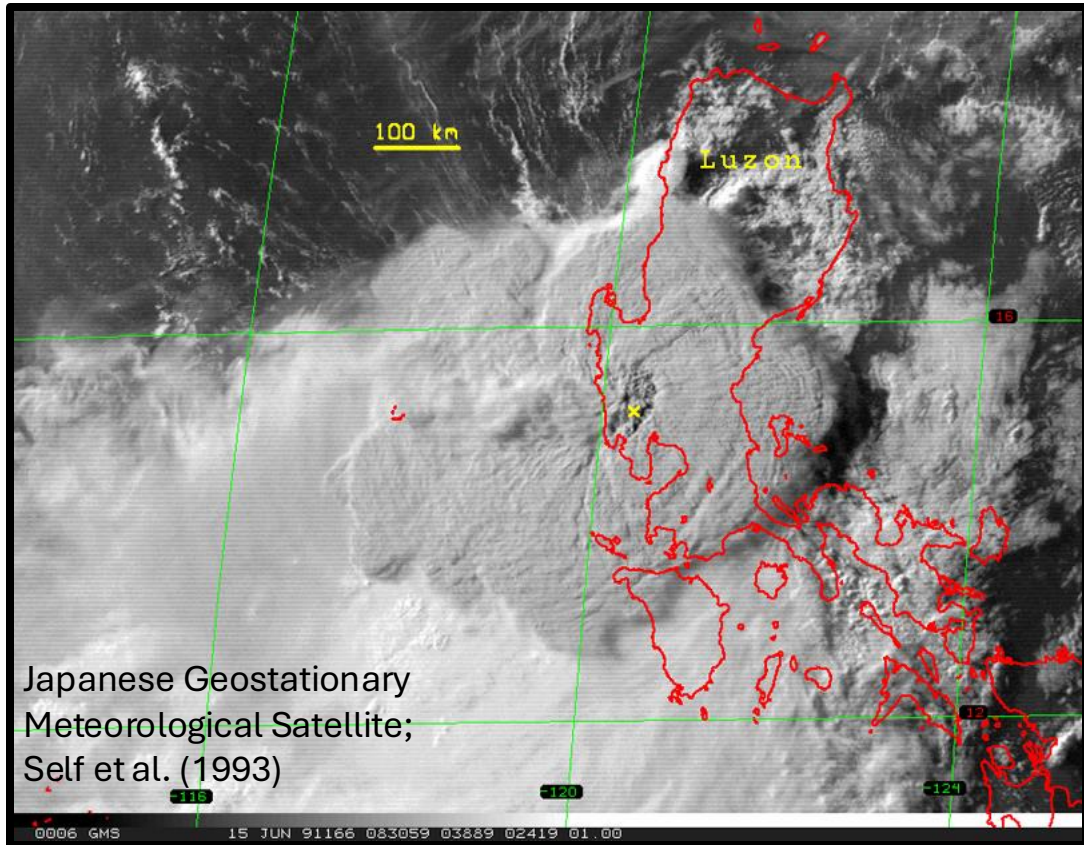
June 1991



US Nat'l Archives NAID 6471952

image: NASA Wordview, 4/14/2017

visible plume on day of eruption



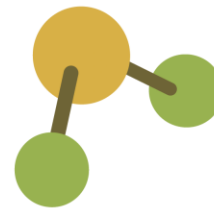
Volcanic emissions fuel the production of aerosols:

20 billion kg

SO_2



sulfate aerosol

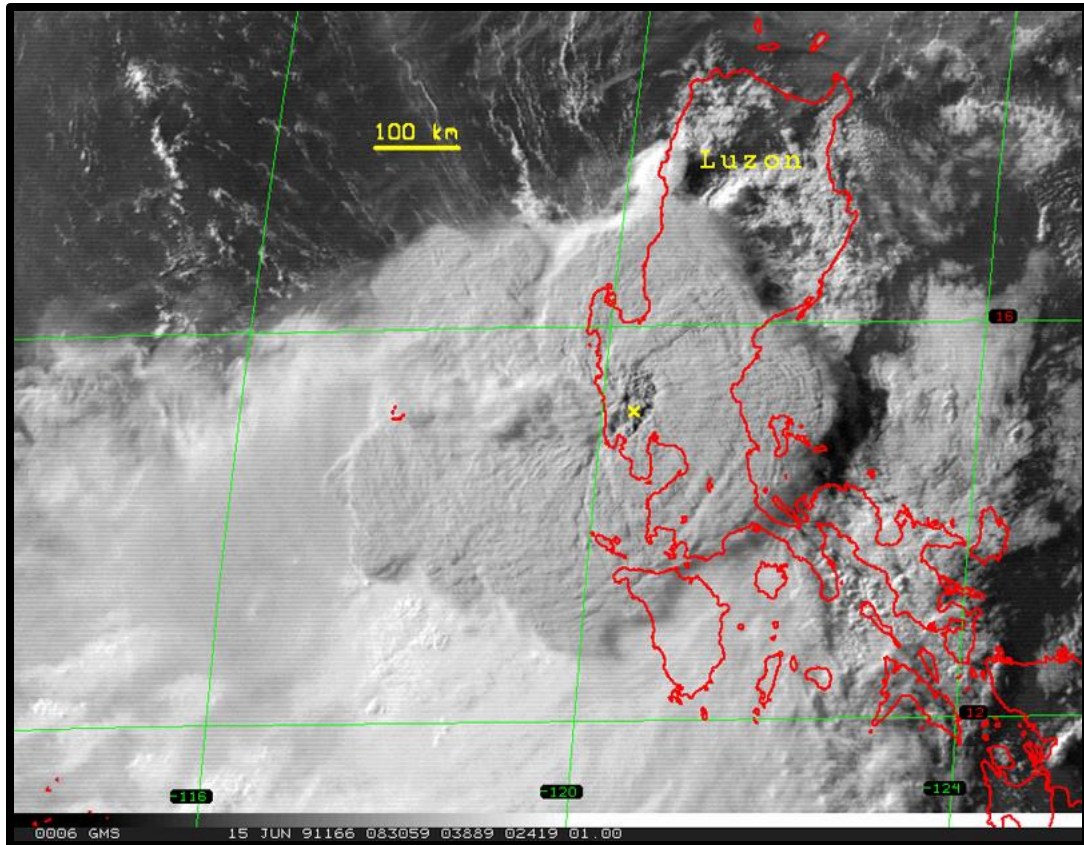


half-life ~20 days



half-life ~300 days

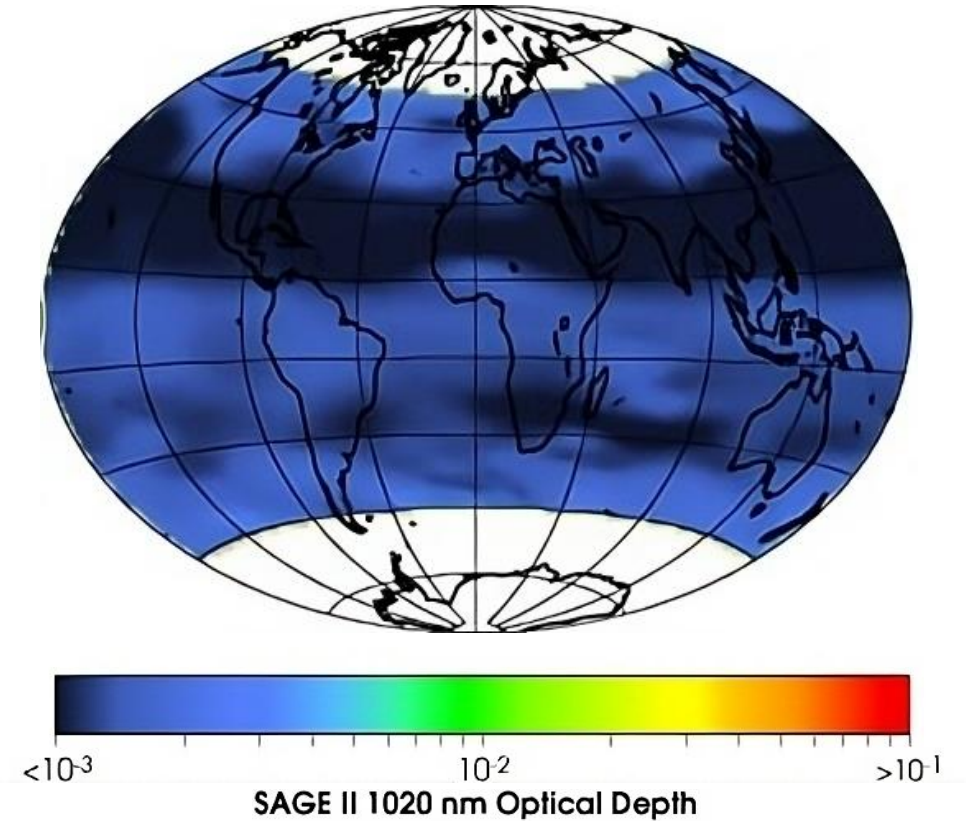
visible plume on day of eruption



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

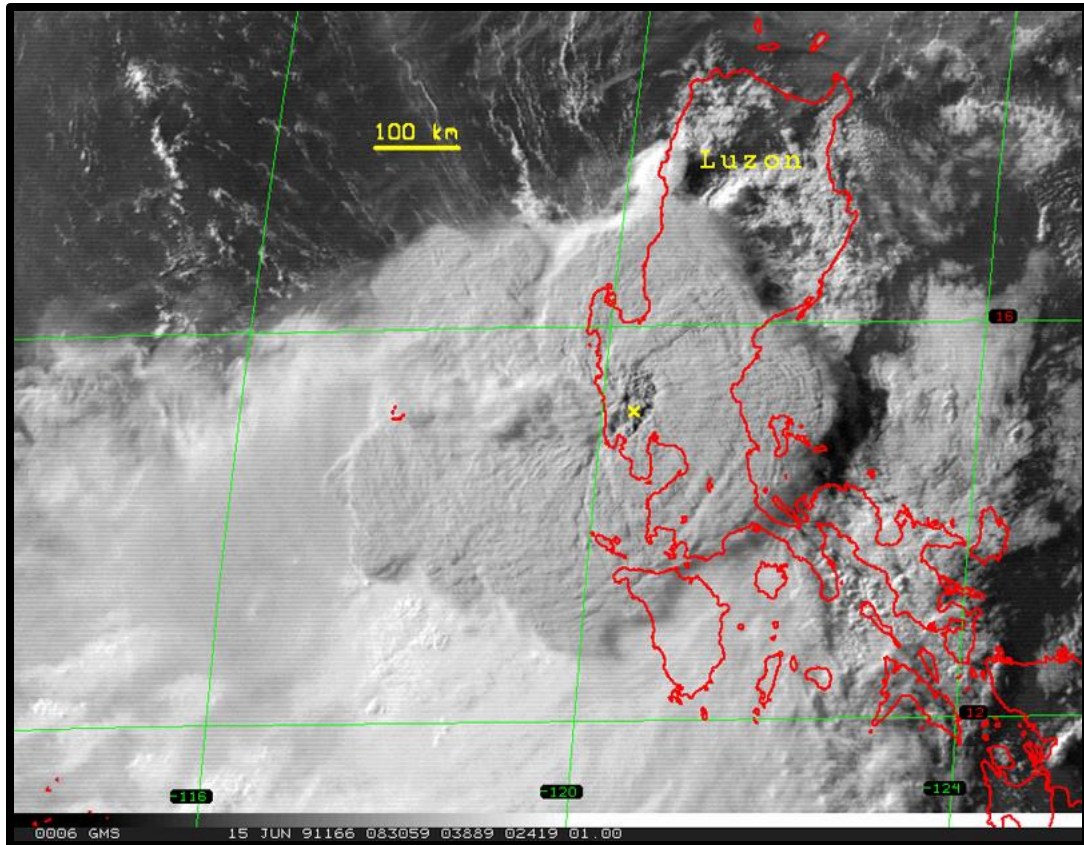
around the globe in ~3 weeks

Apr-May 1991



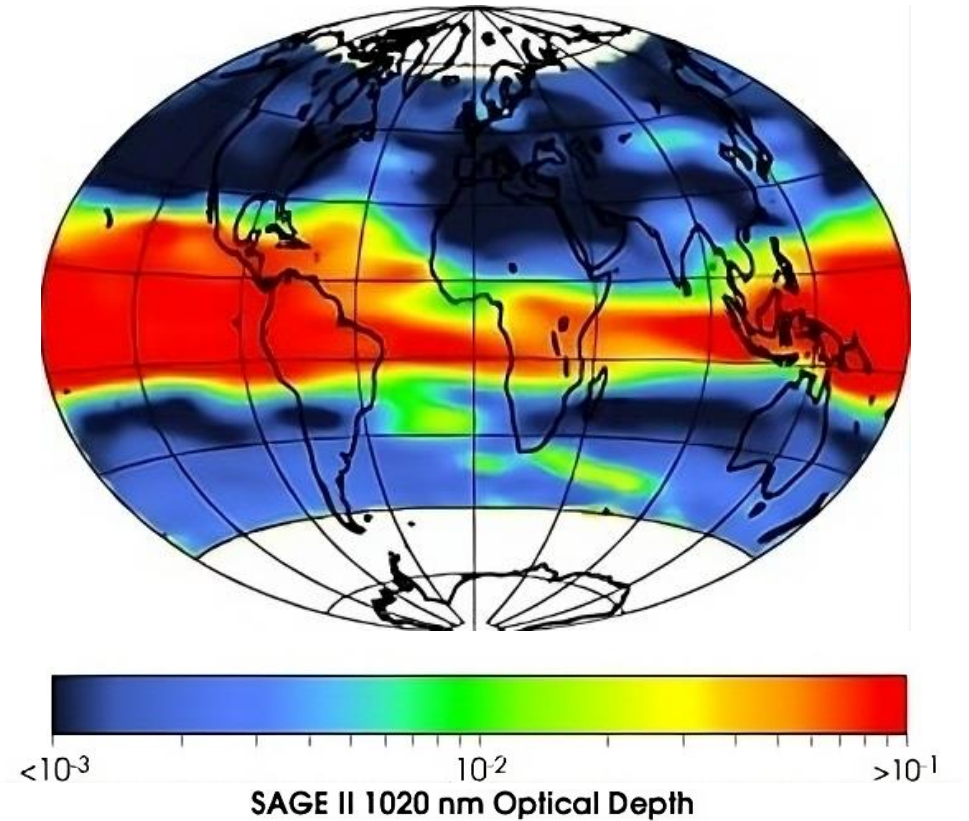
McCormick et al. (1995)

visible plume on day of eruption



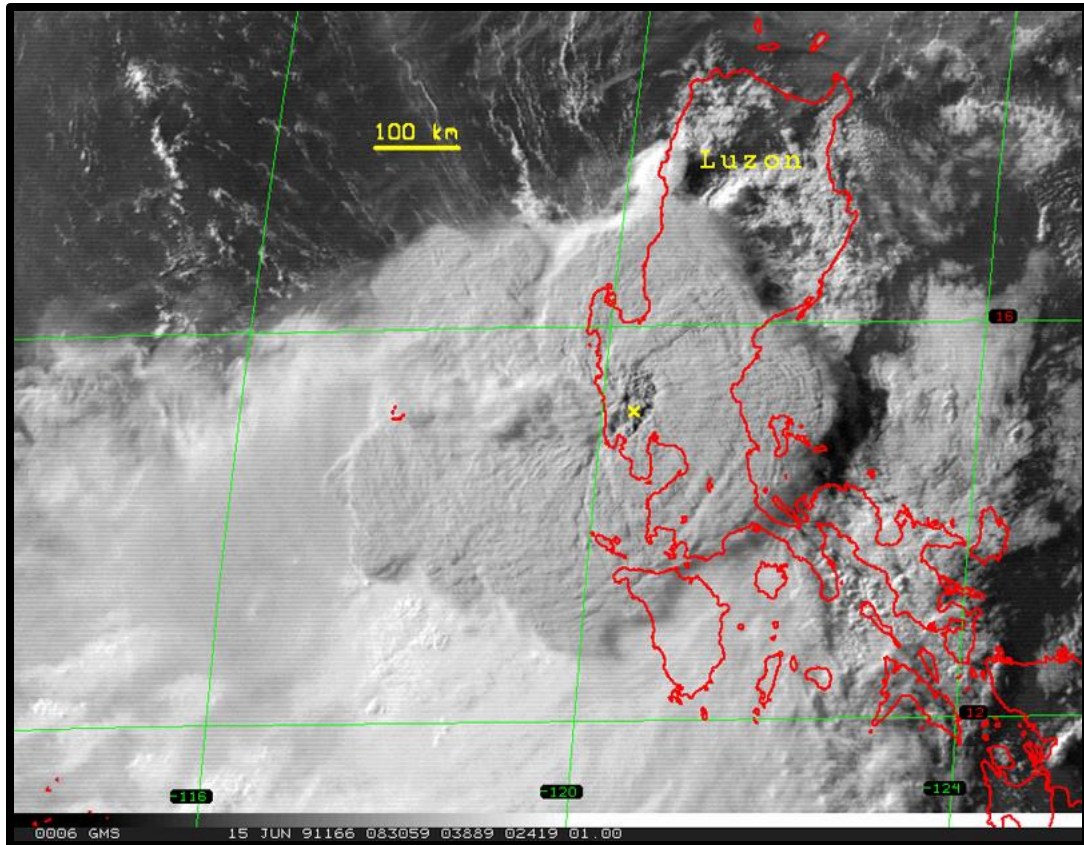
Japanese Geostationary Meteorological Satellite;
Self et al. (1993)

around the globe in ~3 weeks
July 1991



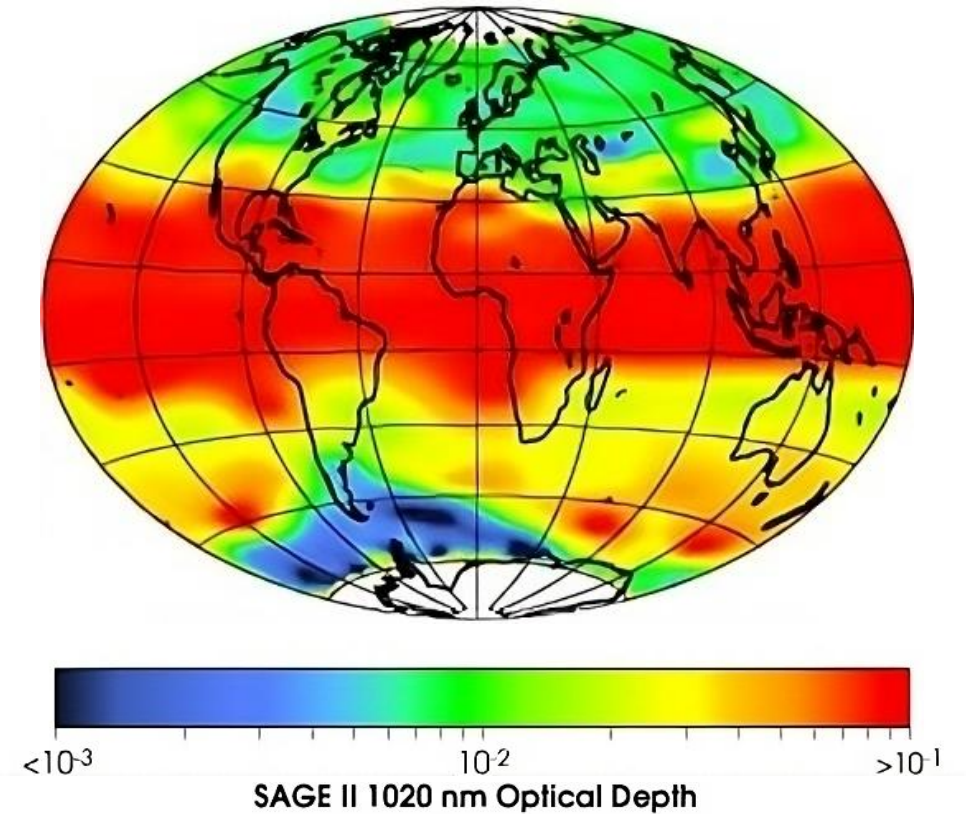
McCormick et al. (1995)

visible plume on day of eruption



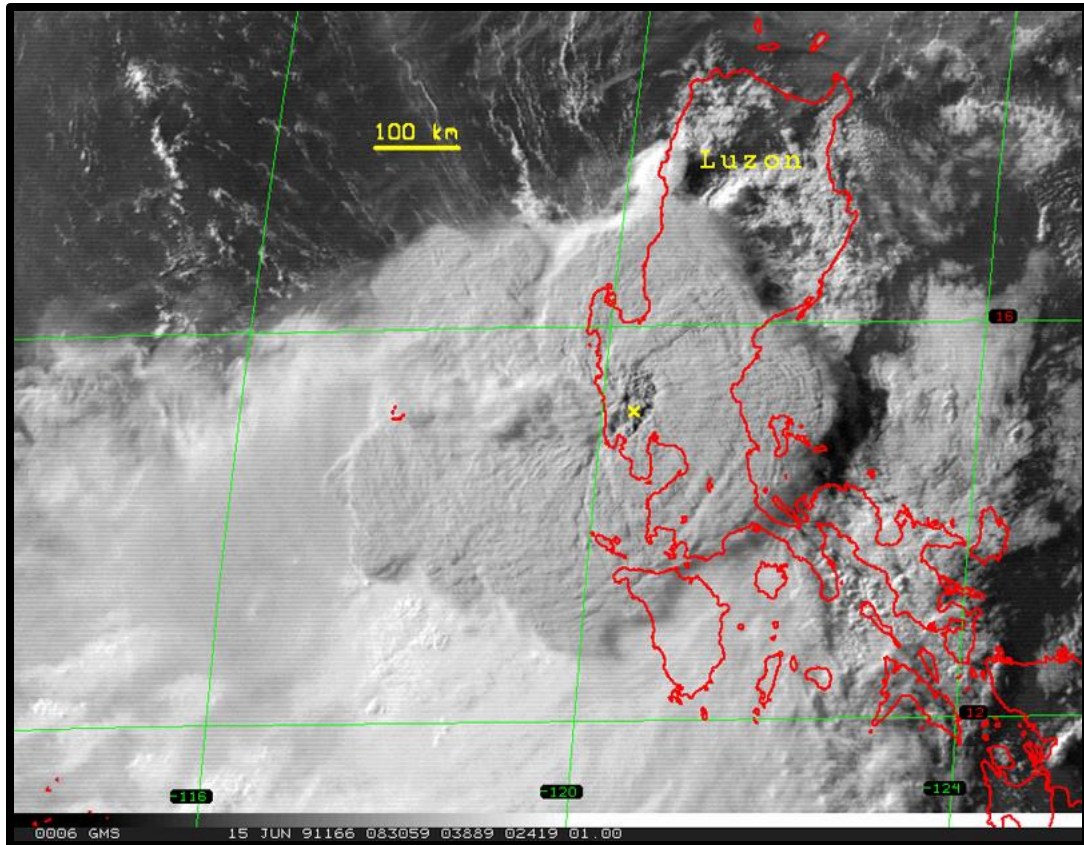
Japanese Geostationary Meteorological Satellite;
Self et al. (1993)

around the globe in ~3 weeks
September 1991



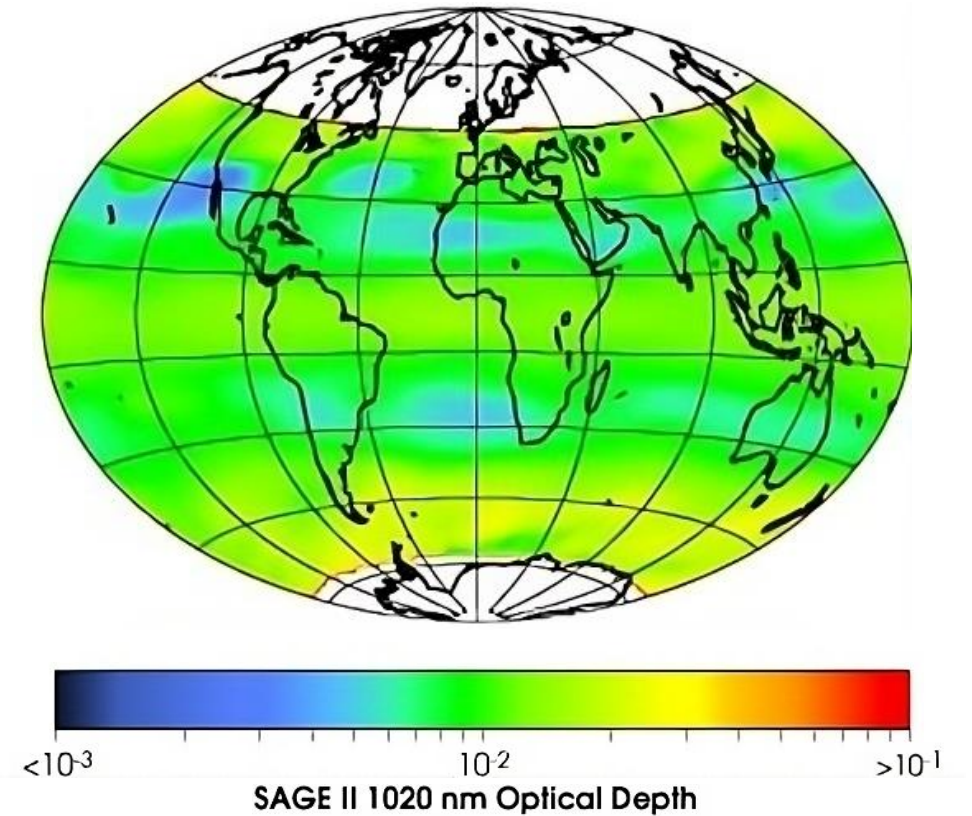
McCormick et al. (1995)

visible plume on day of eruption



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

around the globe in ~3 weeks
January 1994



McCormick et al. (1995)

August 1984

atmosphere

horizon

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

August 1991

Pinatubo aerosols

atmospheric heating

surface cooling

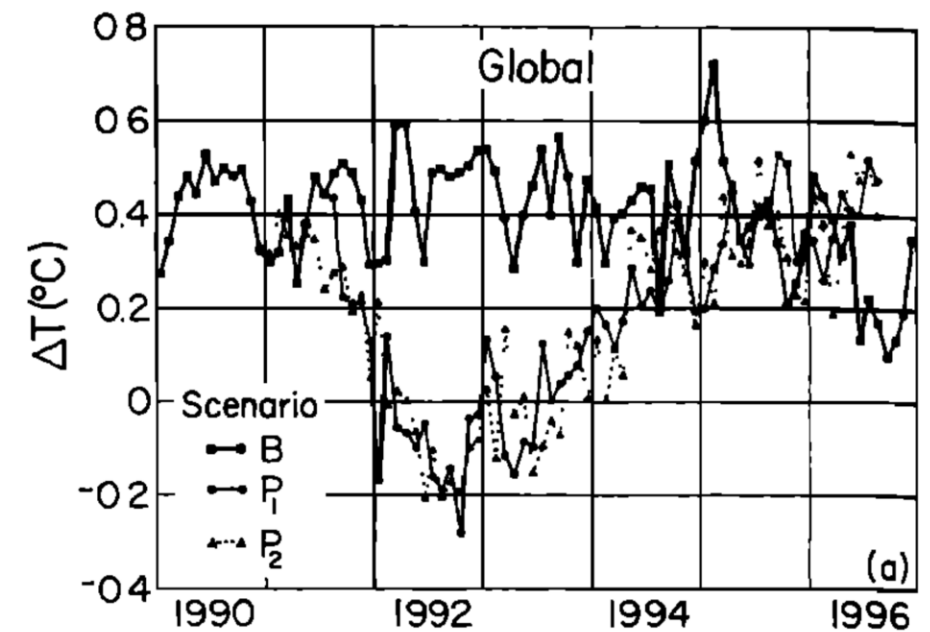
Astronaut photograph from Space Shuttle flight STS-43
NASA Photo ID STS043-22-23

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



August 1991

Pinatubo aerosols

atmospheric heating

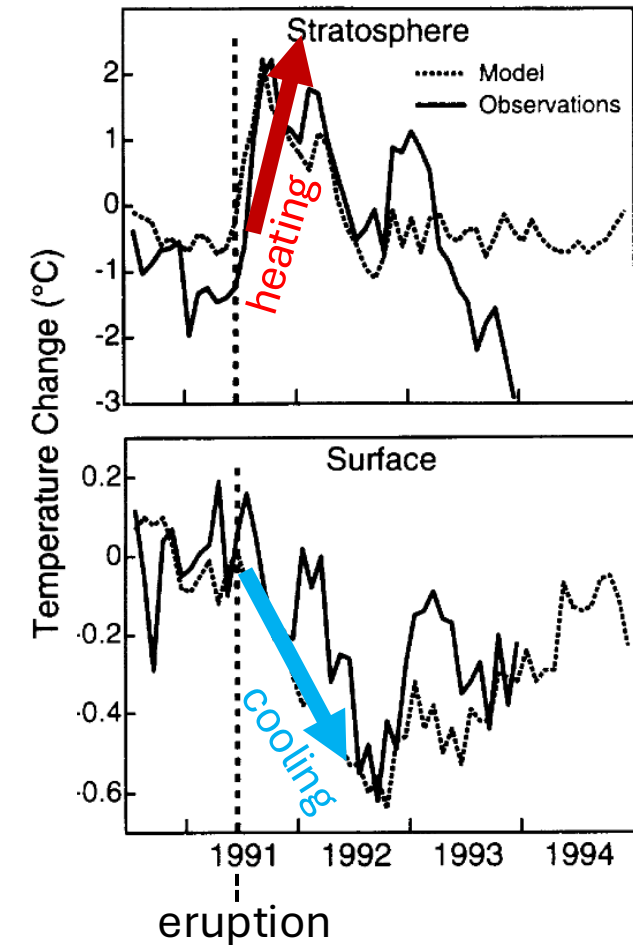
surface cooling

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

The Atmospheric Impact of the 1991 Mount Pinatubo

Stephen Self,¹ Jing-Xia Zhao,² Rick E. Holasek,^{1,3} Ronnie C. Torres,^{1,4} and Alan J. King¹

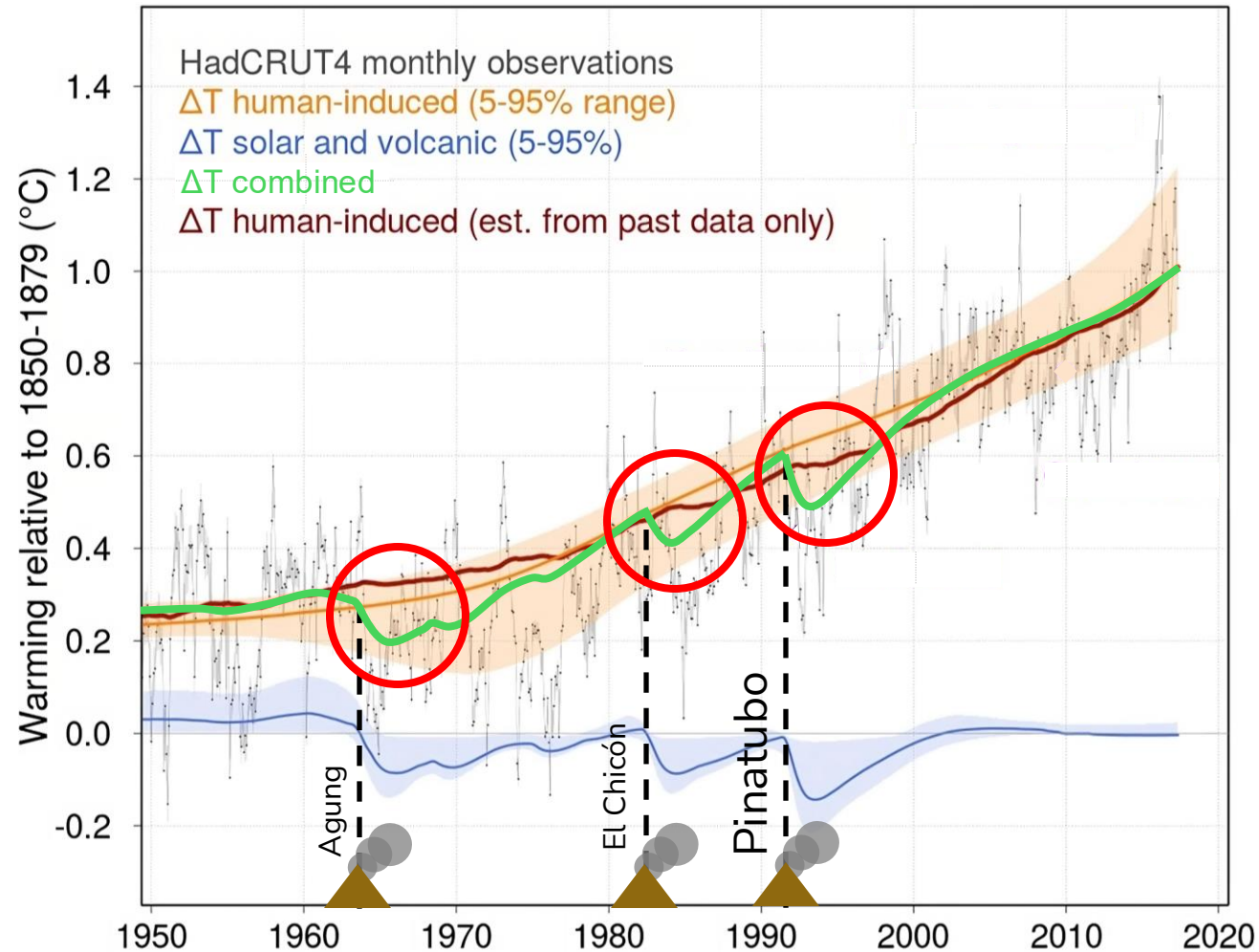
1993



A real-time Global Warming Index

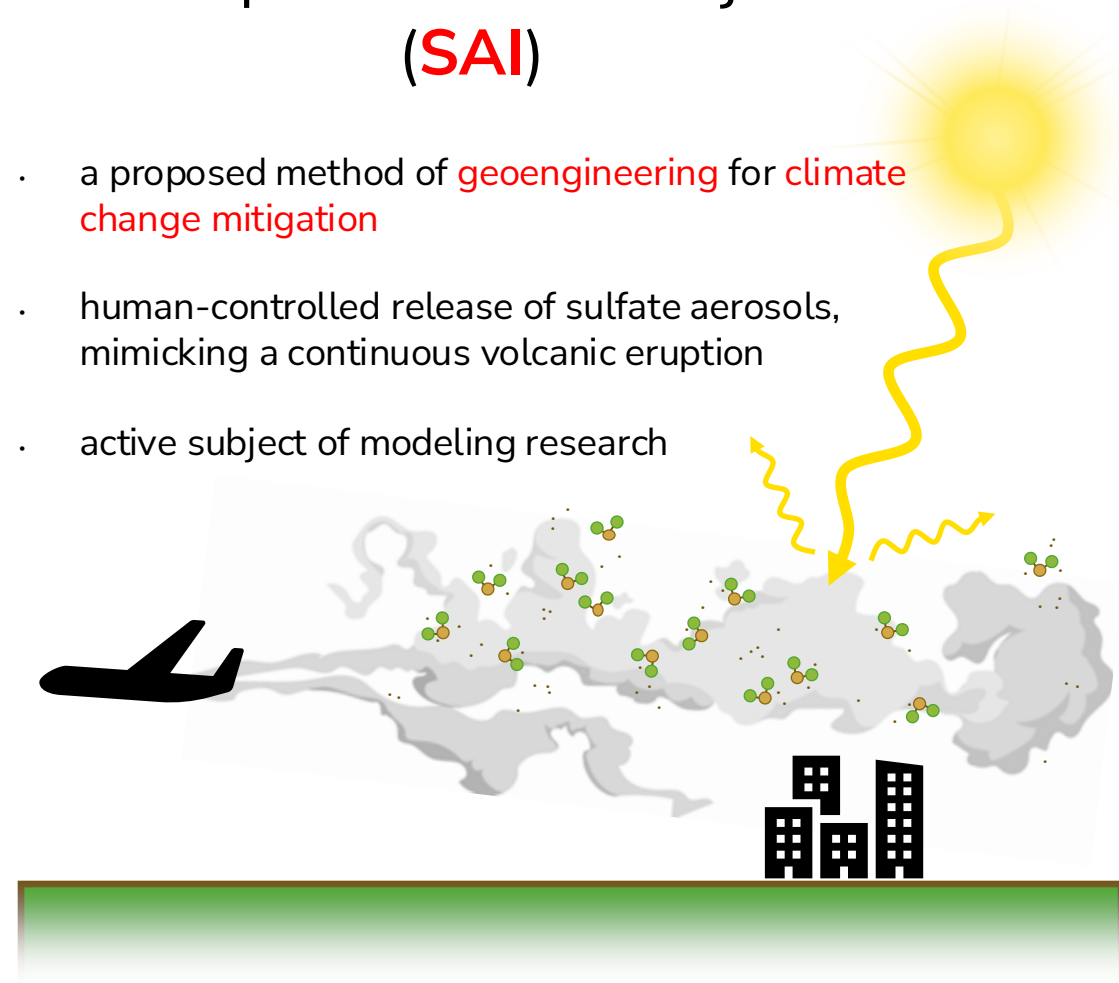
K. Haustein¹, M. R. Allen^{1,2}, P. M. Forster³, F. E. L. Otto¹, D. M. Mitchell^{1,6},
H. D. Matthews⁴ & D. J. Frame⁵

2017



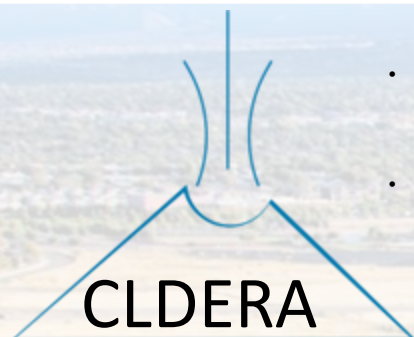
Stratospheric Aerosol Injection (SAI)

- 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





Sandia
National
Laboratories



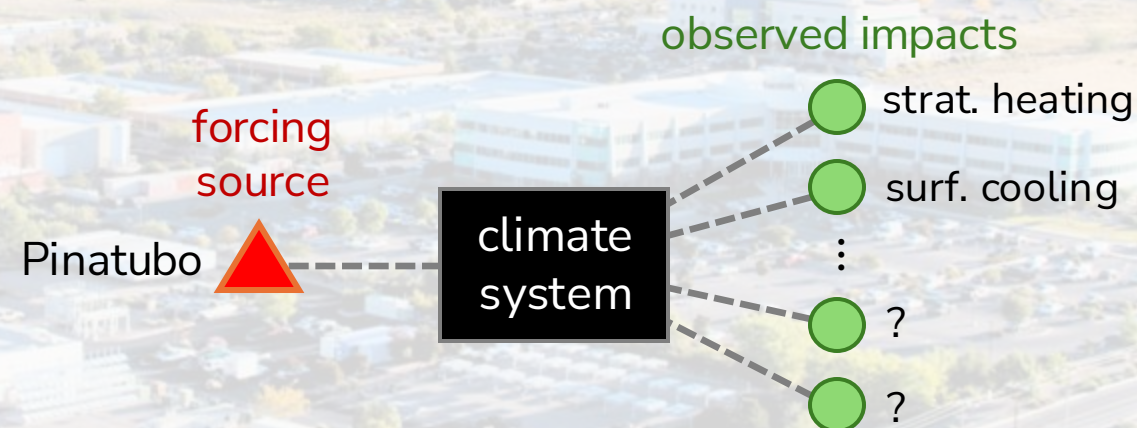
- years 3-6 of my PhD
- collaboration based at Sandia National Labs, Albuquerque, New Mexico



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

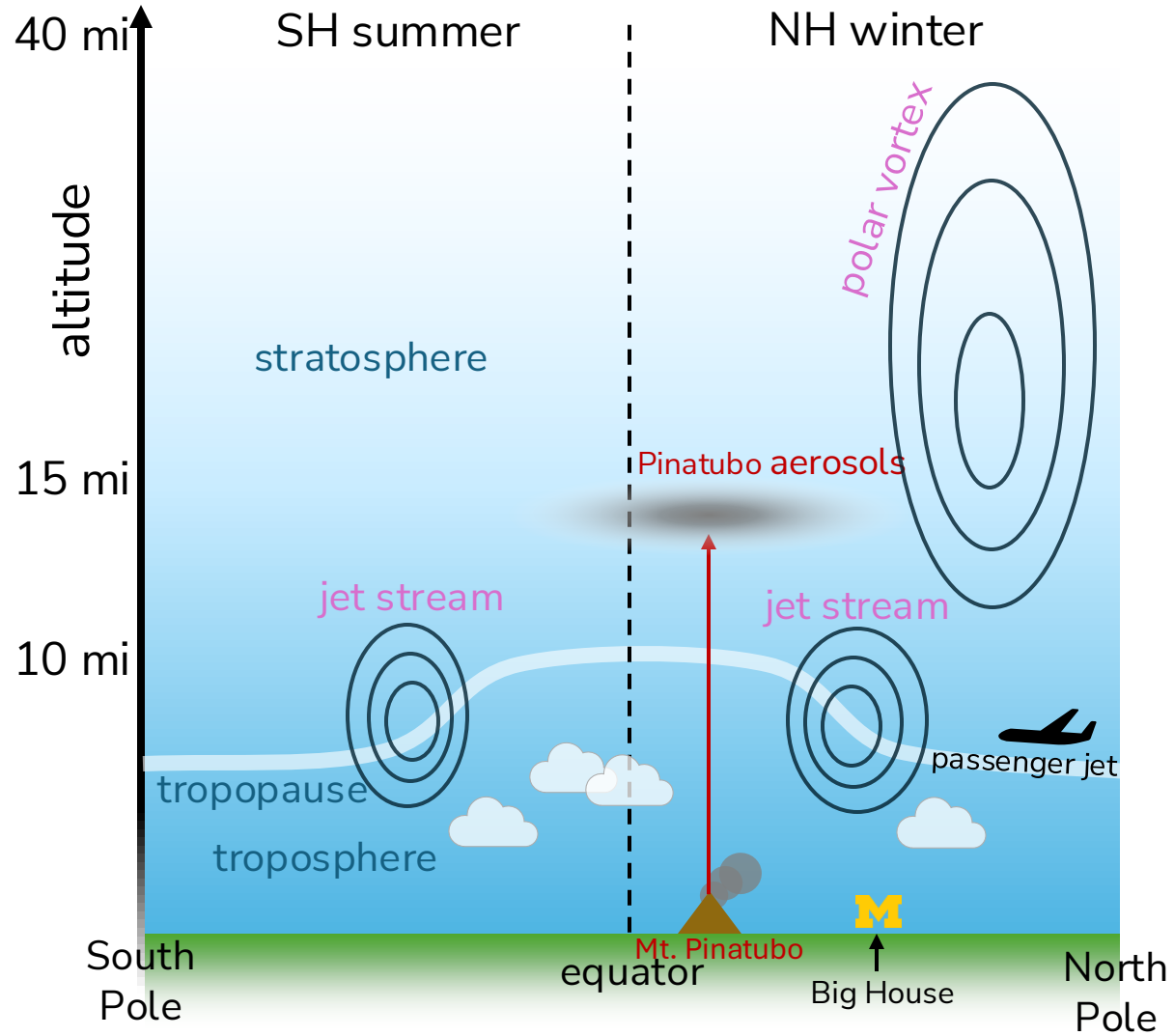
Part 2: volcanic modification of midlatitude winds

Part 3: volcanic effects of the global circulation of mass

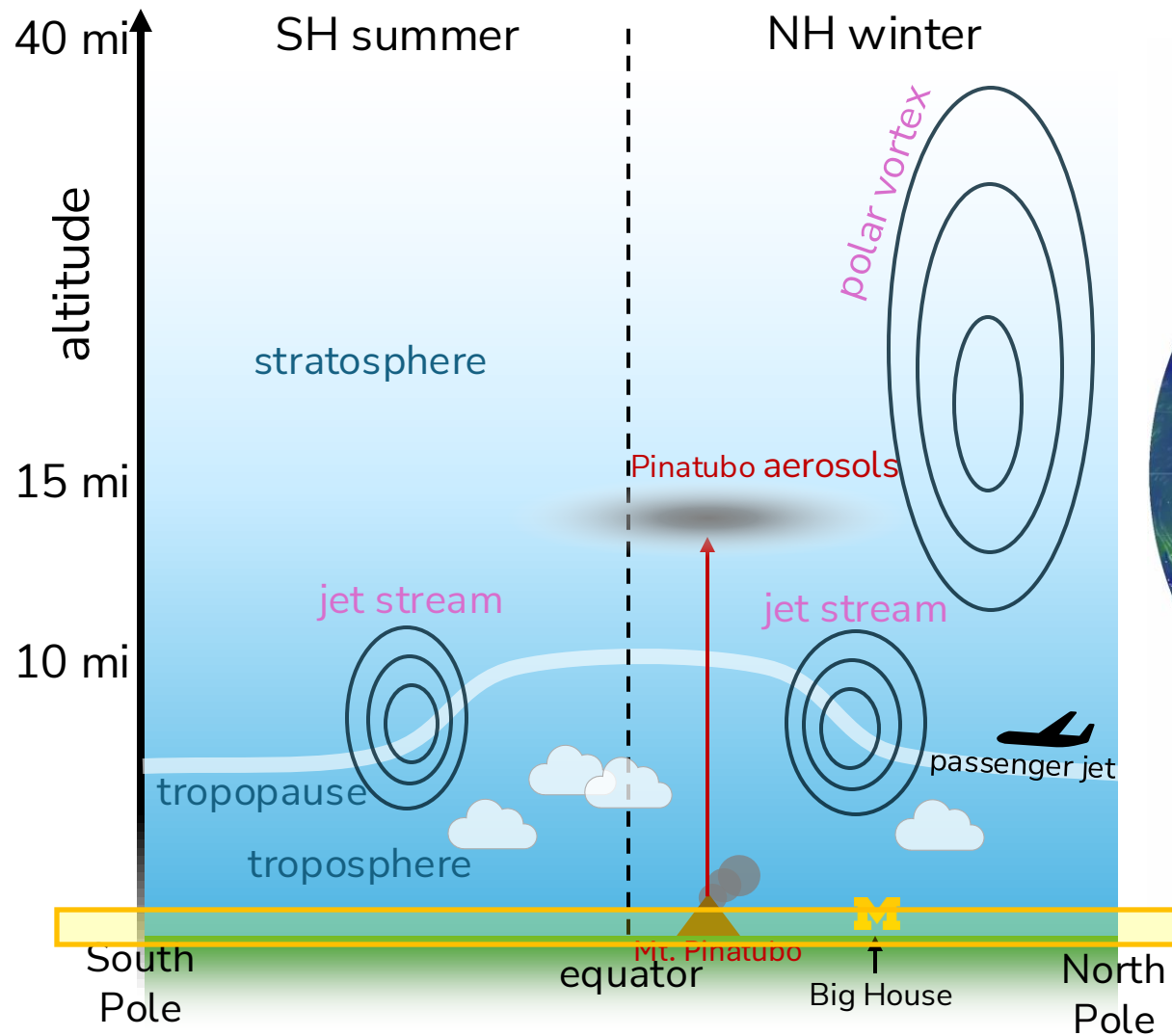
Part 1

volcanic aerosols in a simplified climate model

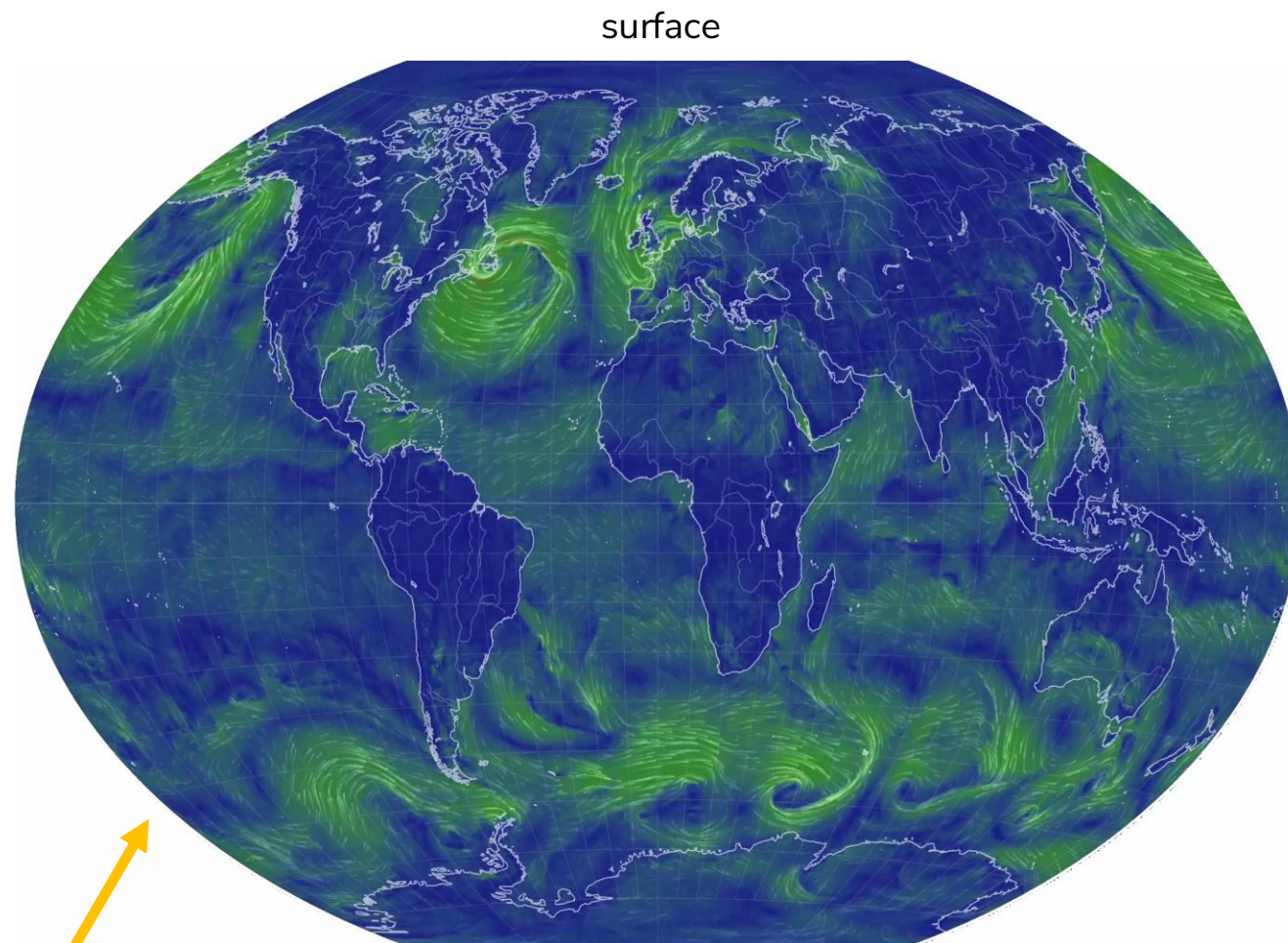
Vertical structure of the atmosphere



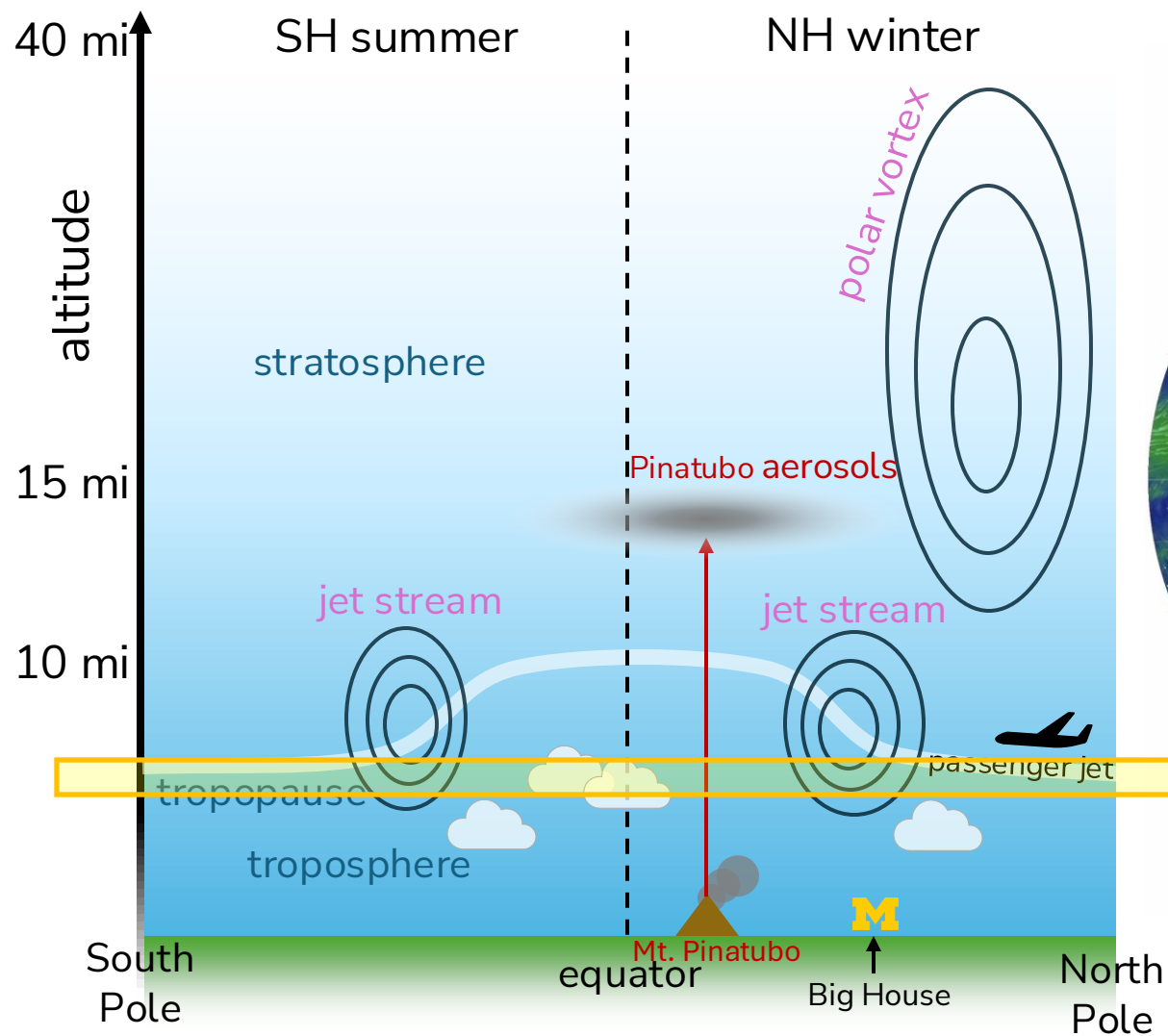
Vertical structure of the atmosphere



forecasted winds for today 1/10/25

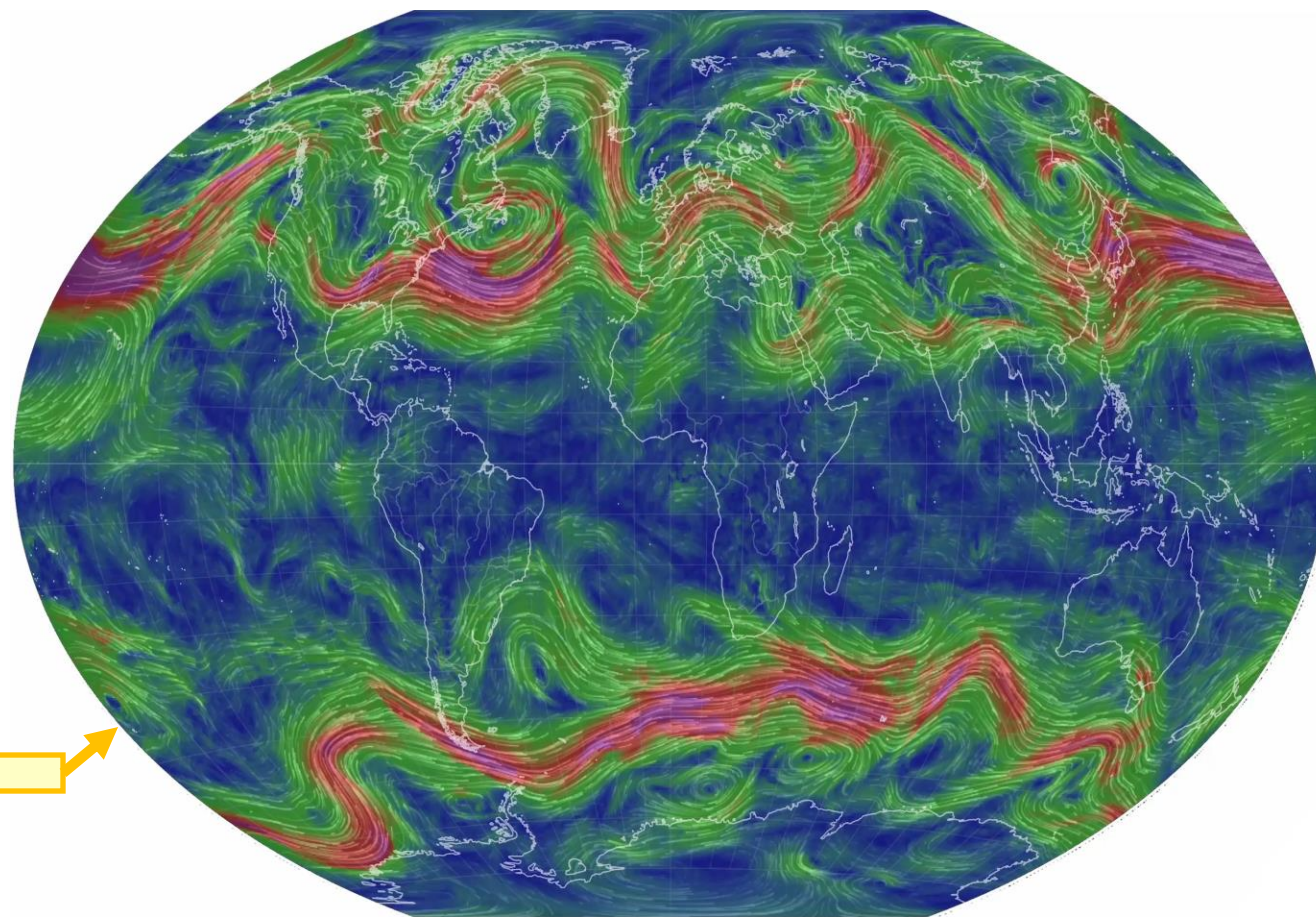


Vertical structure of the atmosphere

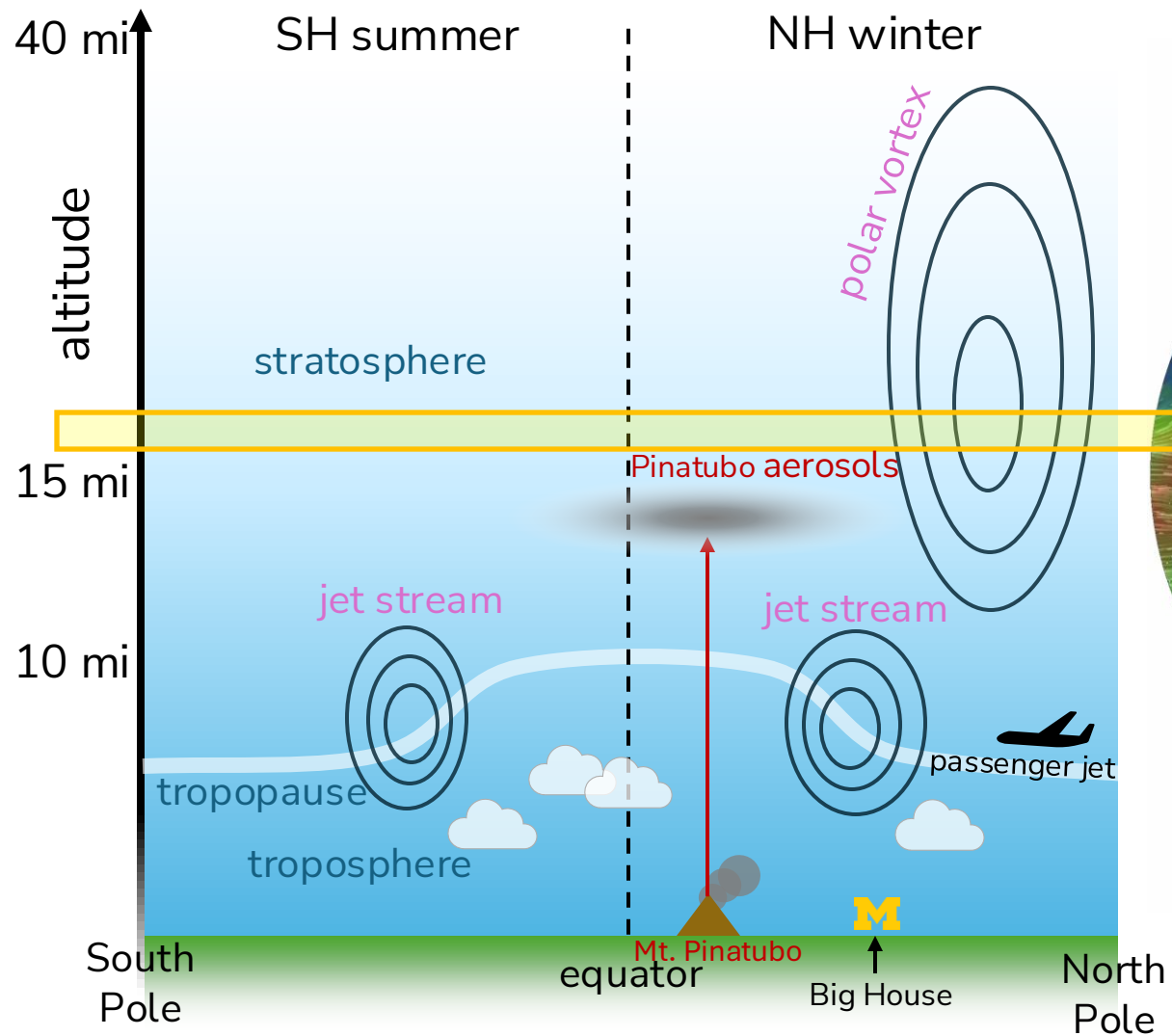


forecasted winds for today 1/10/25

500 hPa

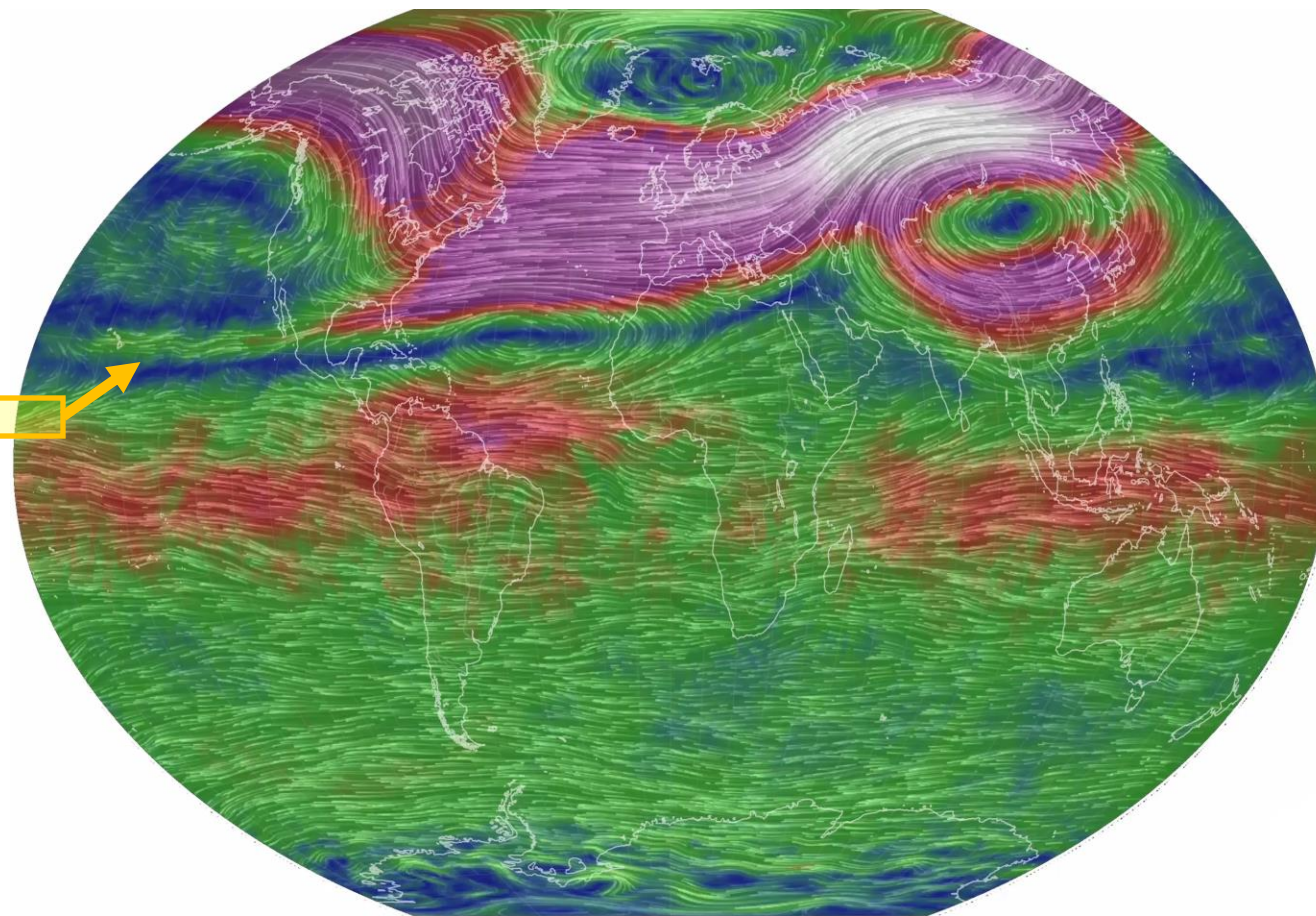


Vertical structure of the atmosphere



forecasted winds for today 1/10/25

10 hPa



Numerical Climate Modeling 101

3D grid wrapped around the sphere

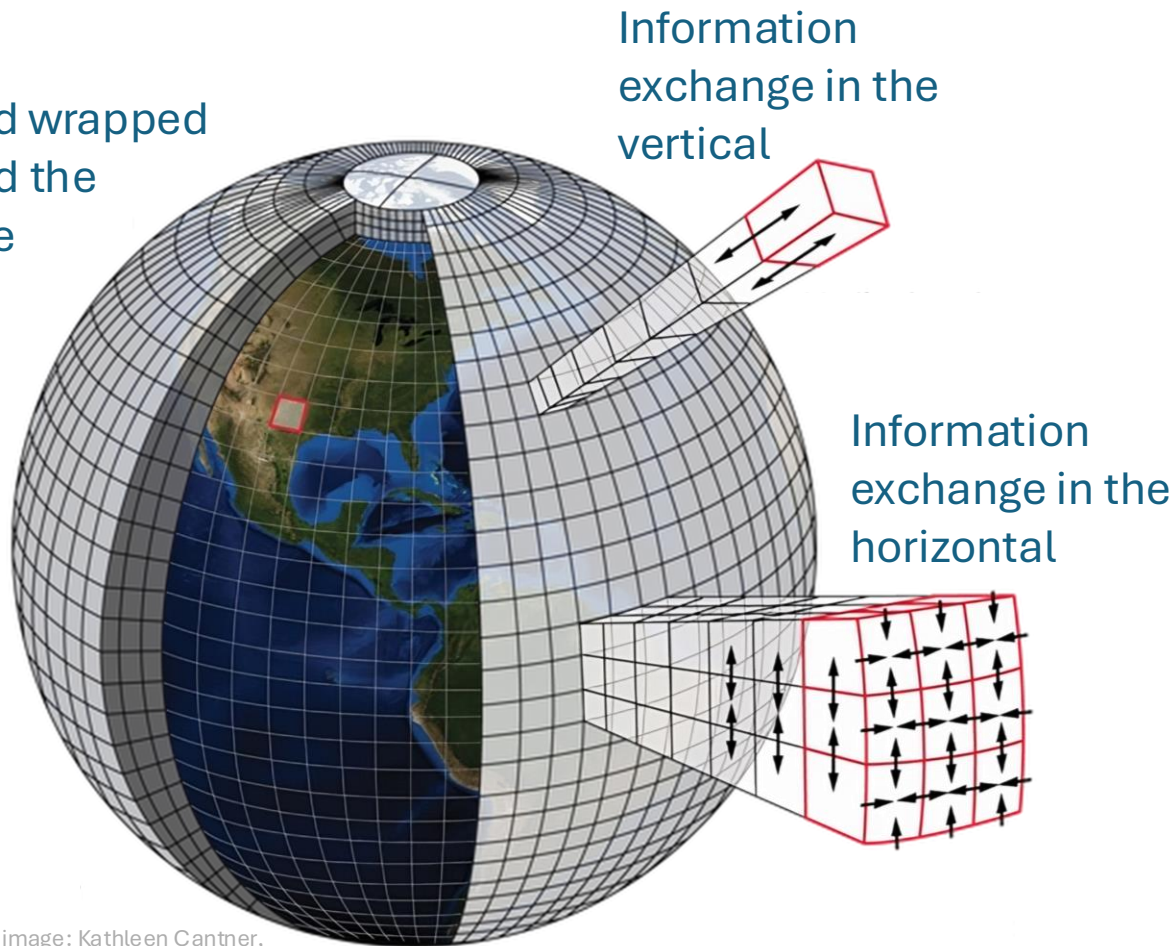


image: Kathleen Cantner,
American Geosciences Institute

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

Procedure: Compute, Timestep, Repeat

Equation set with typical approximations:

$\frac{Du}{Dt}$	$\frac{1}{\rho a \cos \phi} \frac{\partial p}{\partial \lambda}$	zonal (E-W) wind change
$\frac{Dv}{Dt}$	$\frac{1}{\rho a \cos \phi} \frac{\partial p}{\partial \phi}$	meridional (N-S) wind change
$\frac{DT}{Dt}$	$\frac{RT}{pc_p} \omega + \frac{Q}{c_p}$	temperature change
$\frac{\partial \omega}{\partial p}$	$-\frac{1}{a \cos \phi} \left[\frac{\partial u}{\partial \lambda} \frac{\partial v \cos \phi}{\partial \phi} \right]_p$	vertical velocity
$\frac{\partial p}{\partial z}$	$-\frac{RT}{gp}$	pressure

Numerical Climate Modeling 101



fluid solver = “dynamics”

parameterizations = “physics”

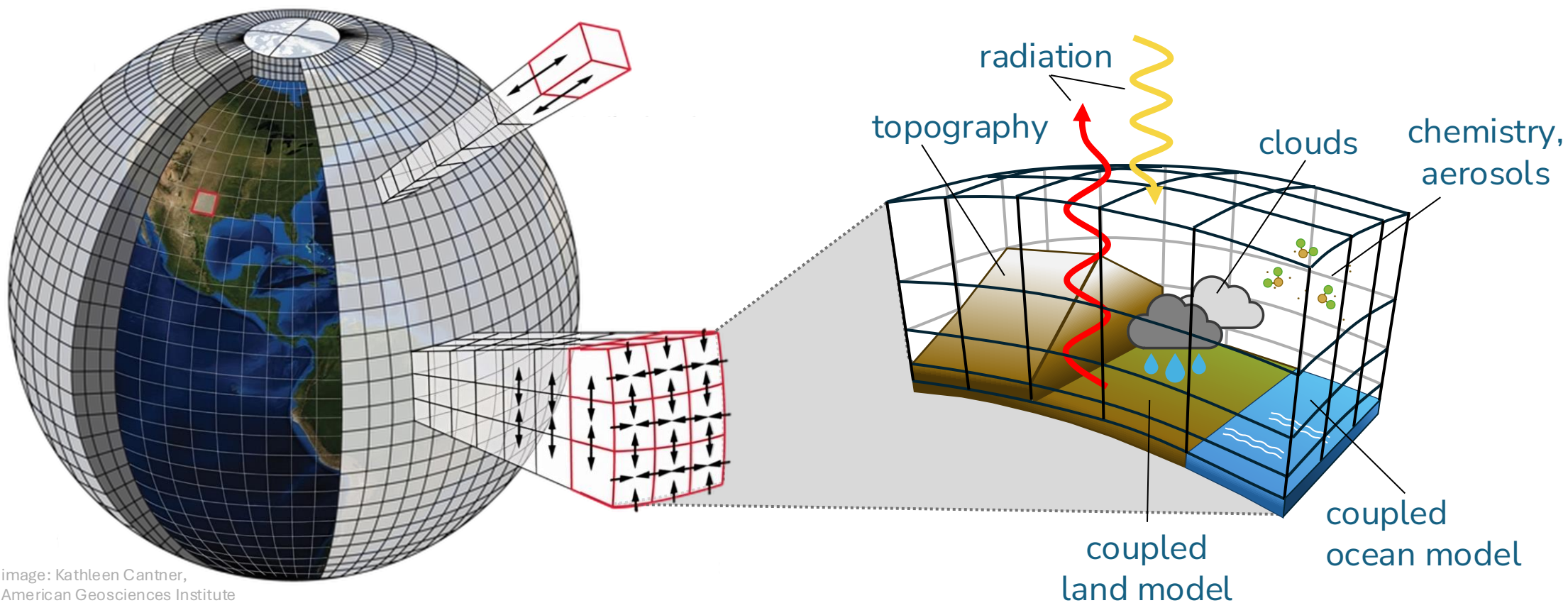
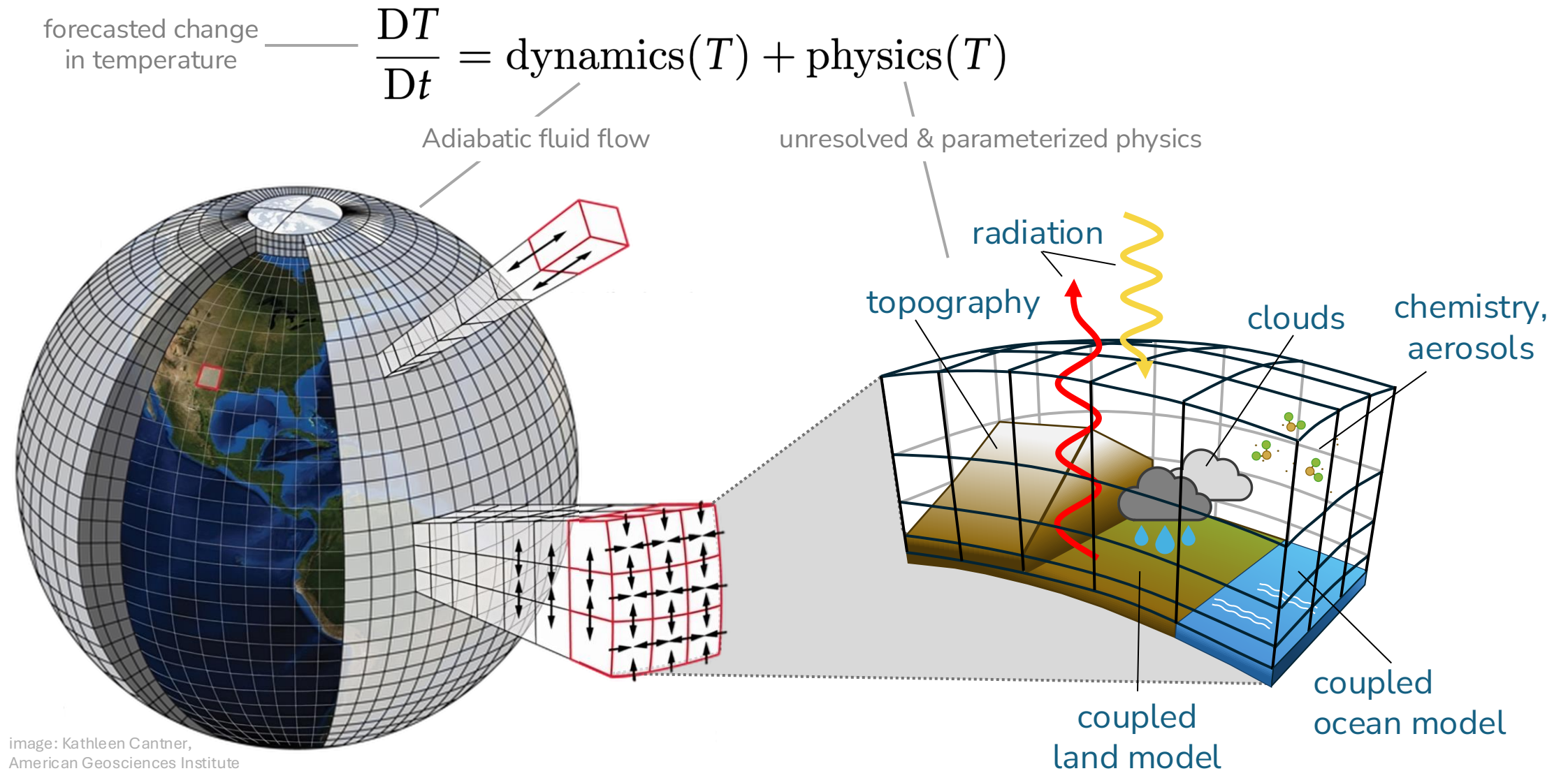


image: Kathleen Cantner,
American Geosciences Institute

Numerical Climate Modeling 101



Idealized Physics

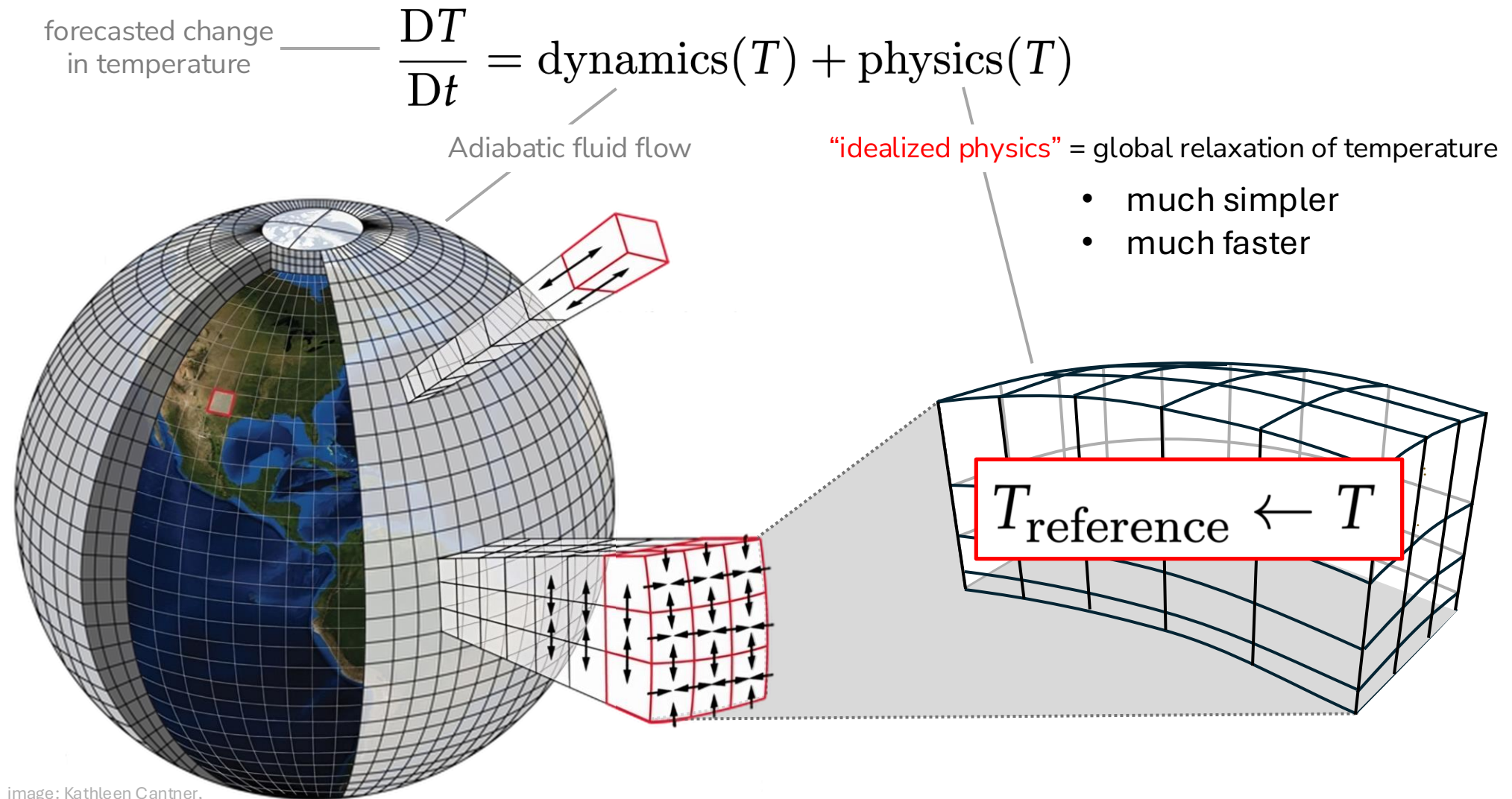


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American Geosciences Institute

Idealized Physics

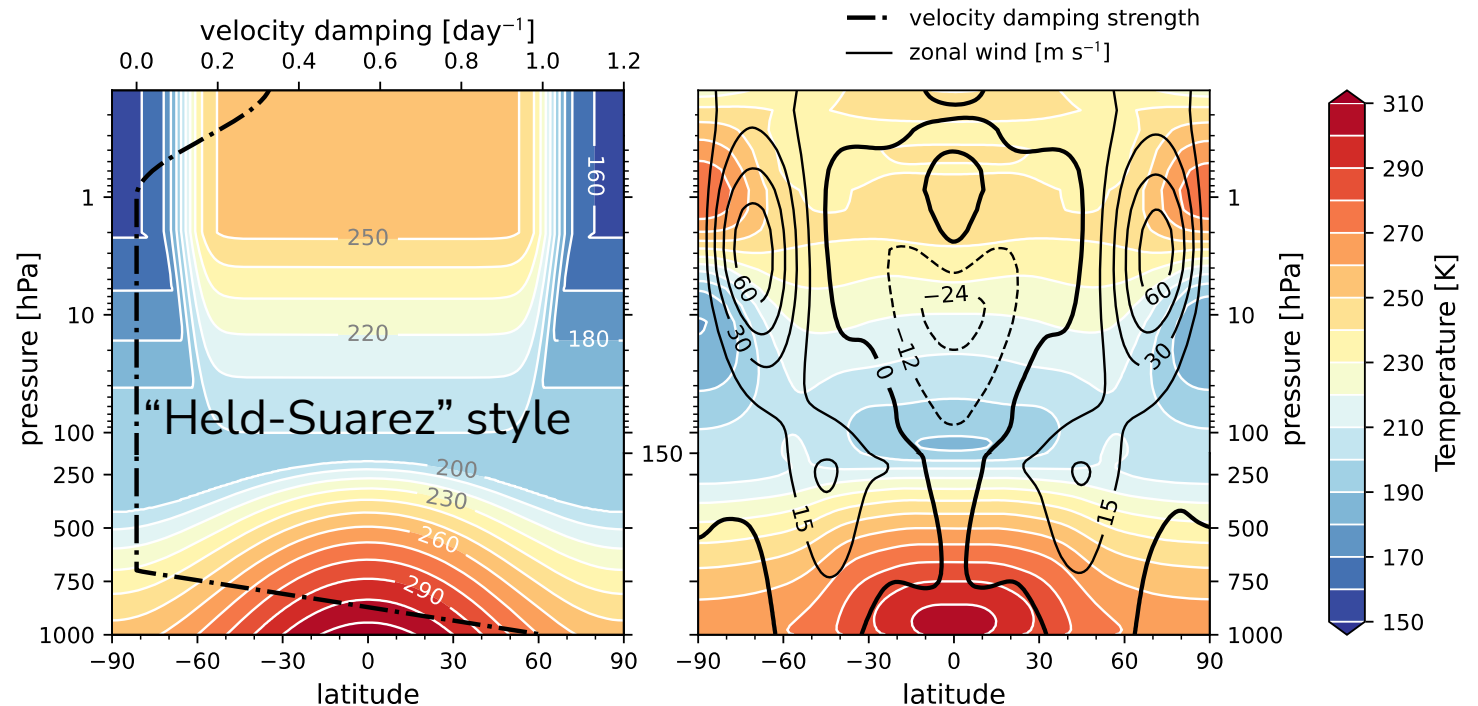
forecasted change
in temperature

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

“idealized physics” = global relaxation of temperature

Goal:

Implement an ability to
**simulate volcanic
eruptions** in the
idealized atmosphere

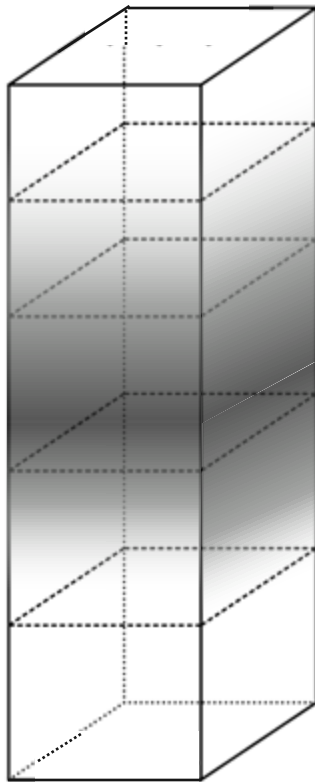


reference temperature ← atmospheric temperature
gently nudge

Step 1: tracer definitions for volcanic substances

Uniform injection over
single model column

tracer
density



Ash tracer

50 Tg injected between
11-17 km over 24 hours



SO₂ tracer

17 Tg injected between
11-17 km over 24 hours



SO₂ → Sulfate conversion
with half-life of ~18 days

Sulfate tracer

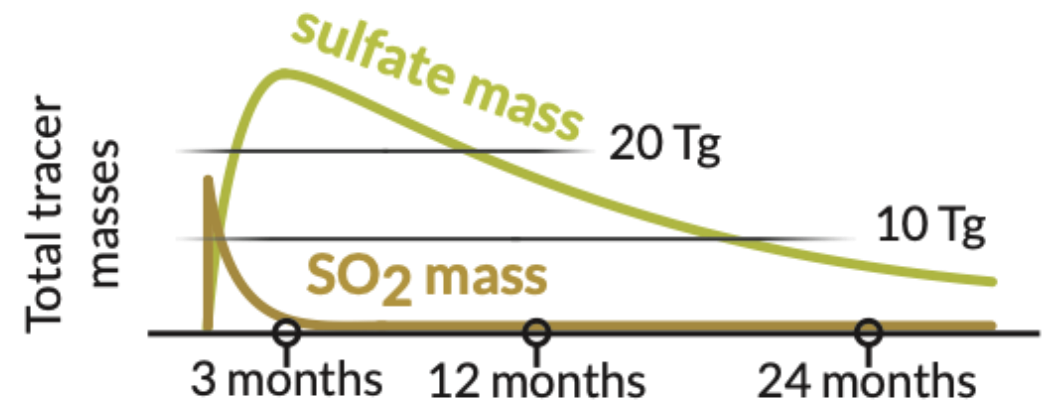
Decays with half-life of ~265 days
1:2.4 SO₂:Sulfate mass ratio



evolution of a **tracer** q :

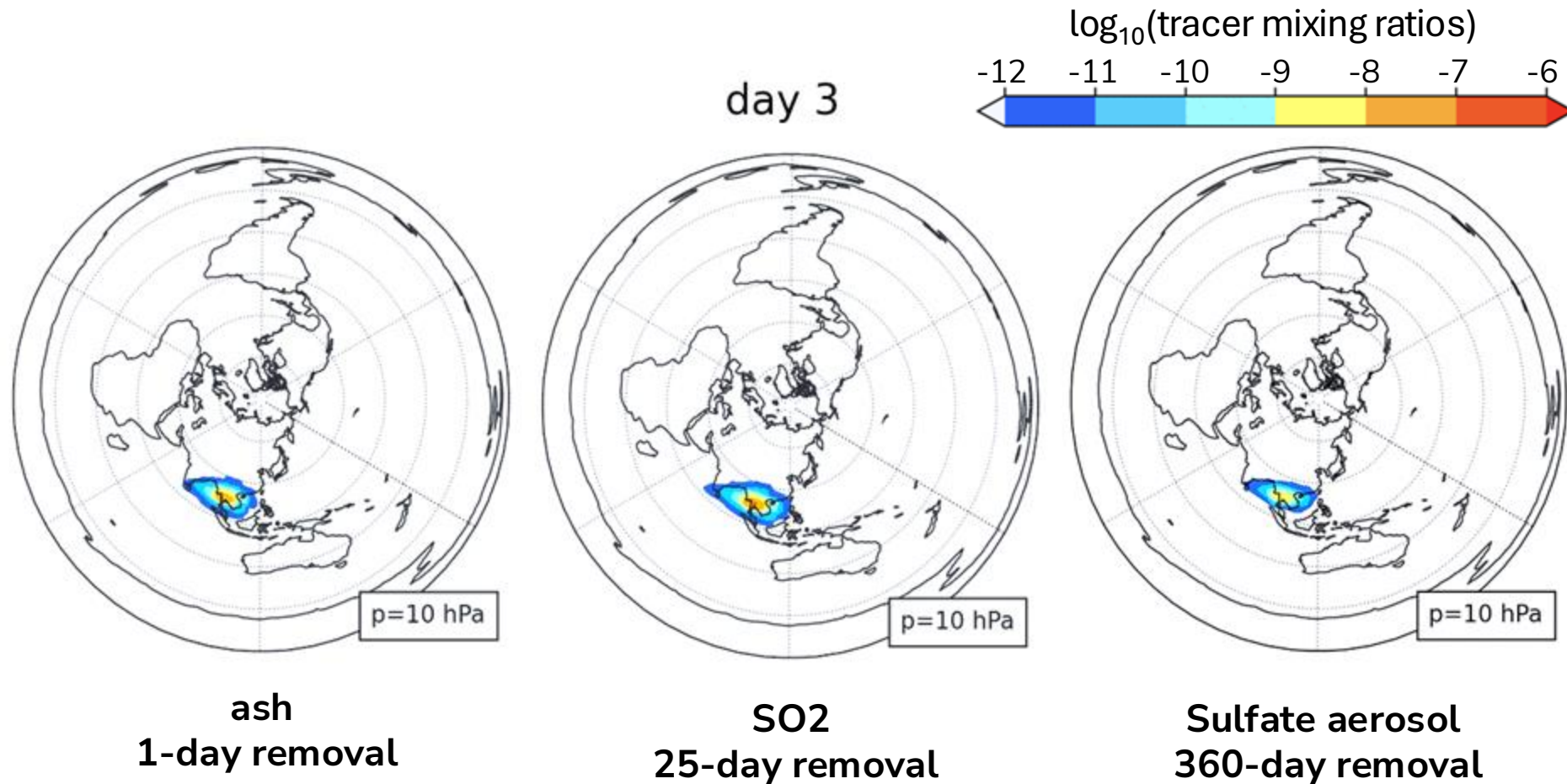
$$\frac{\partial q}{\partial t} = \vec{v} \cdot \nabla q + S$$

change in
tracer density = advection + production + decay



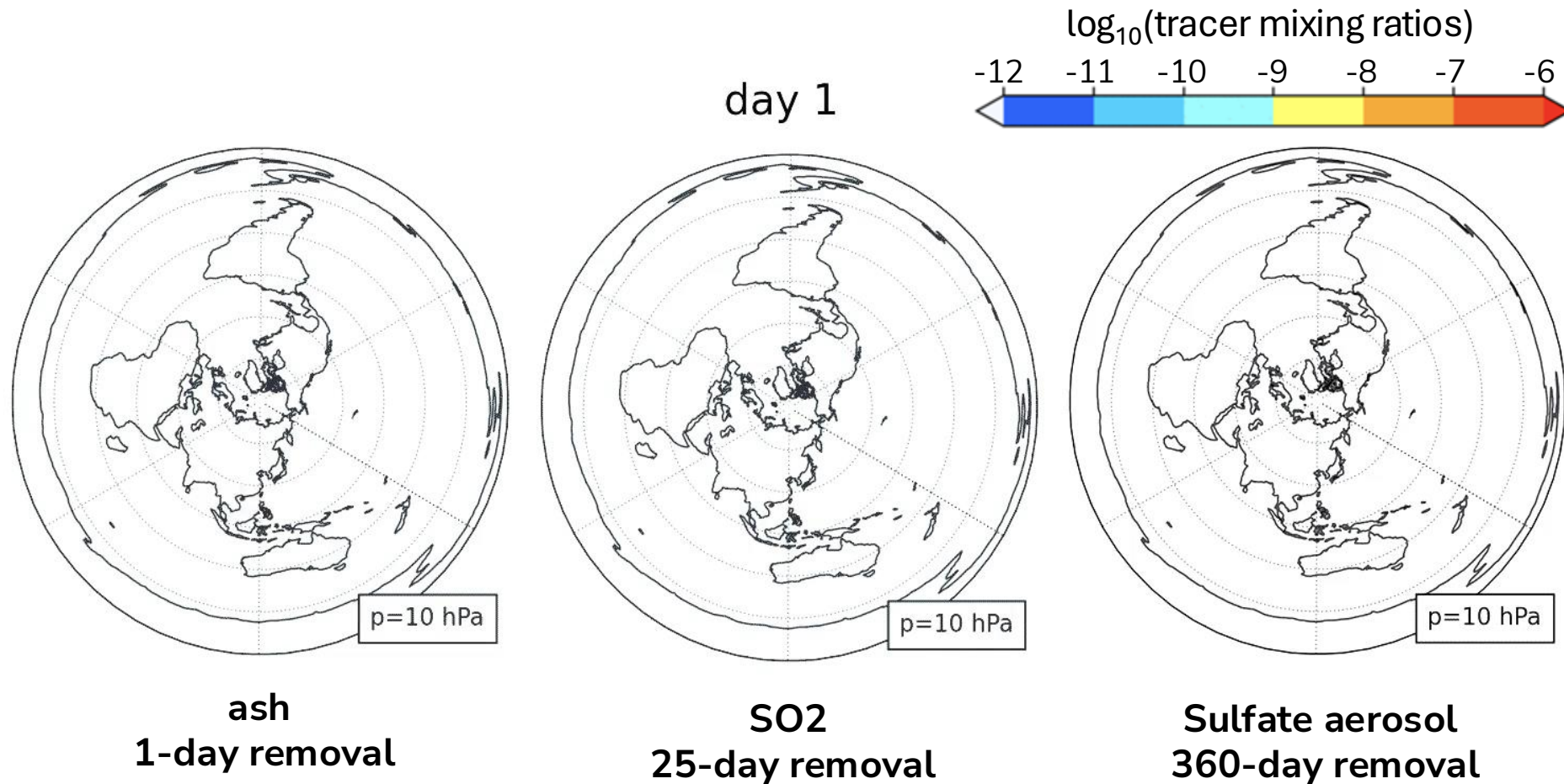
Simulated Pinatubo plume circles the globe in **~ 2 weeks**

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

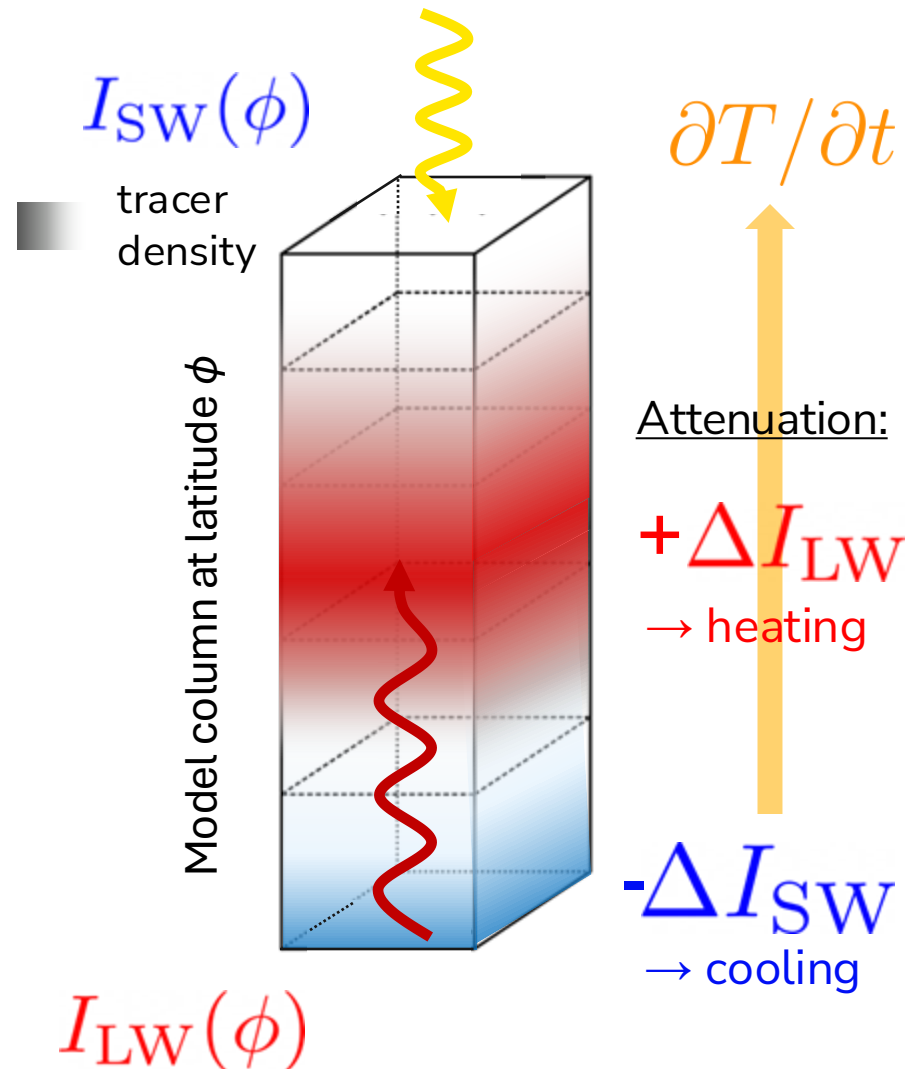


Simulated Pinatubo plume circles the globe in **~ 2 weeks**

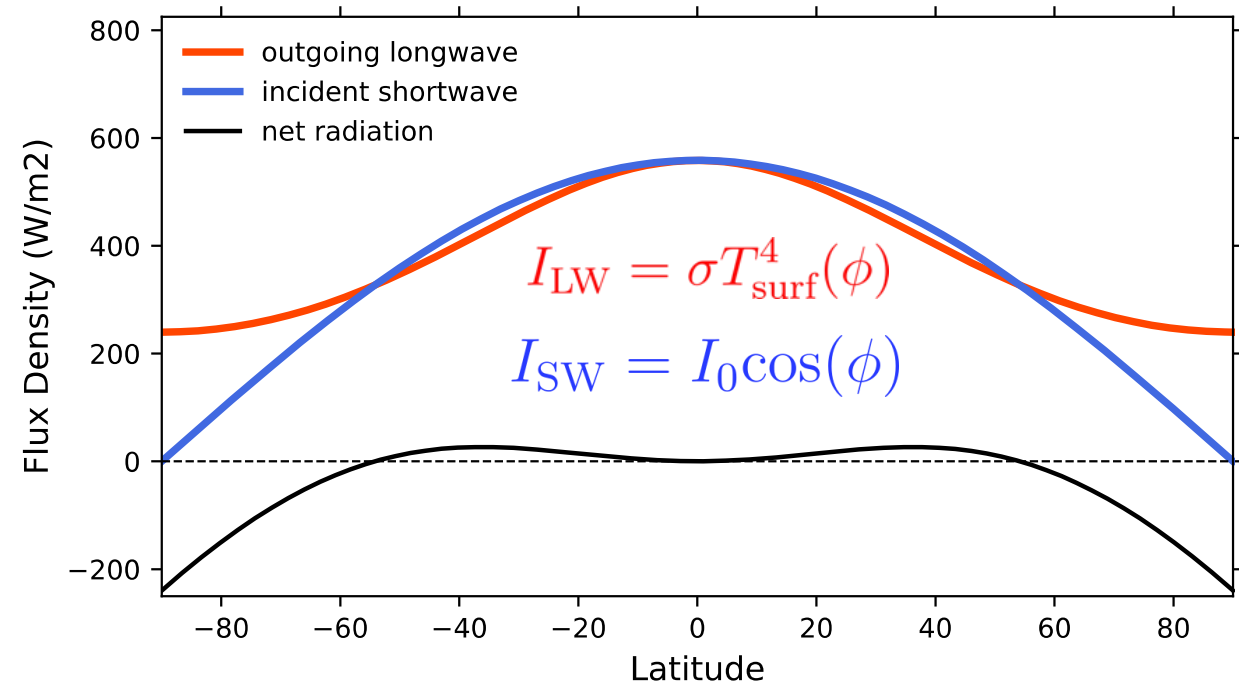
Aerosol quantities are ~2 order of magnitude higher than SO_2 by **3 months**



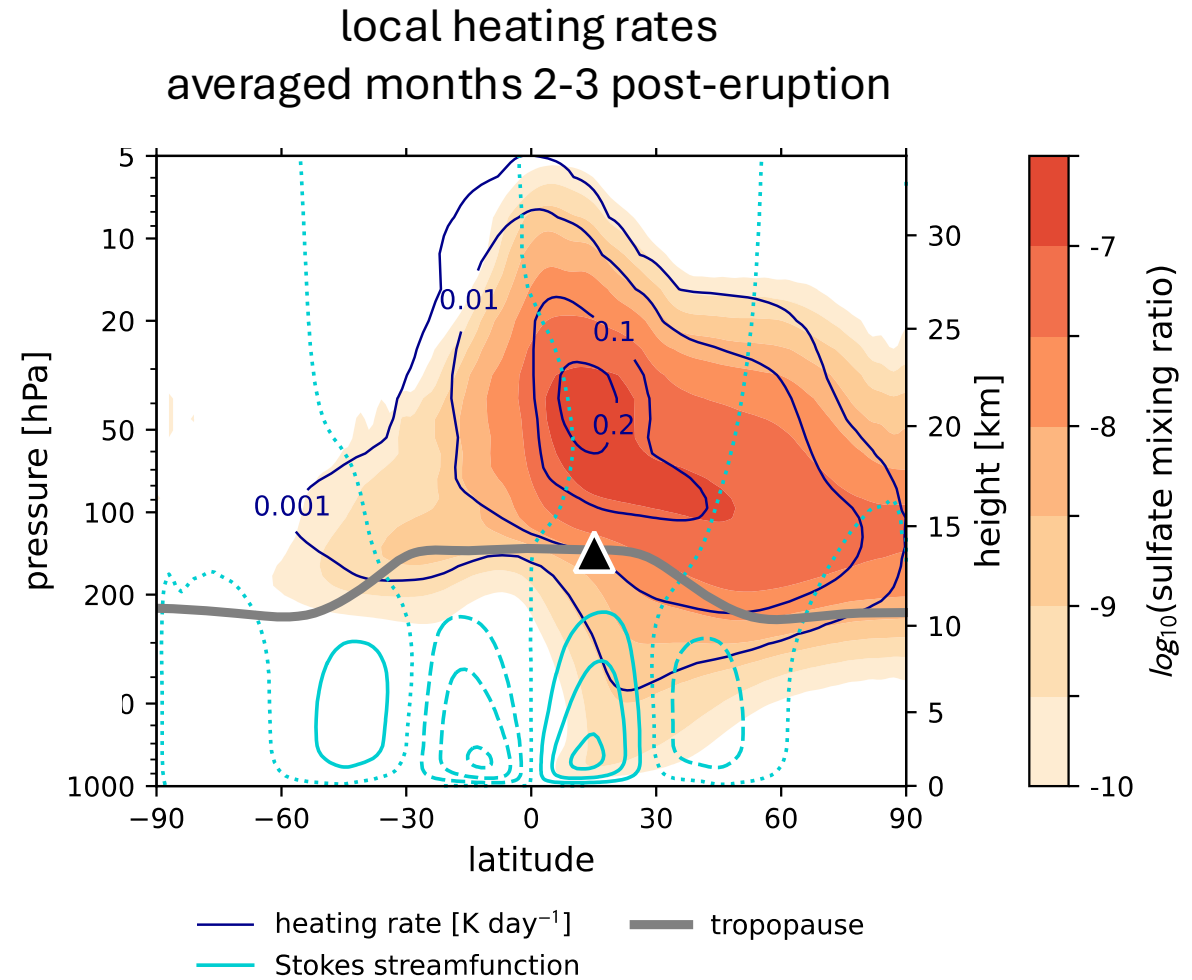
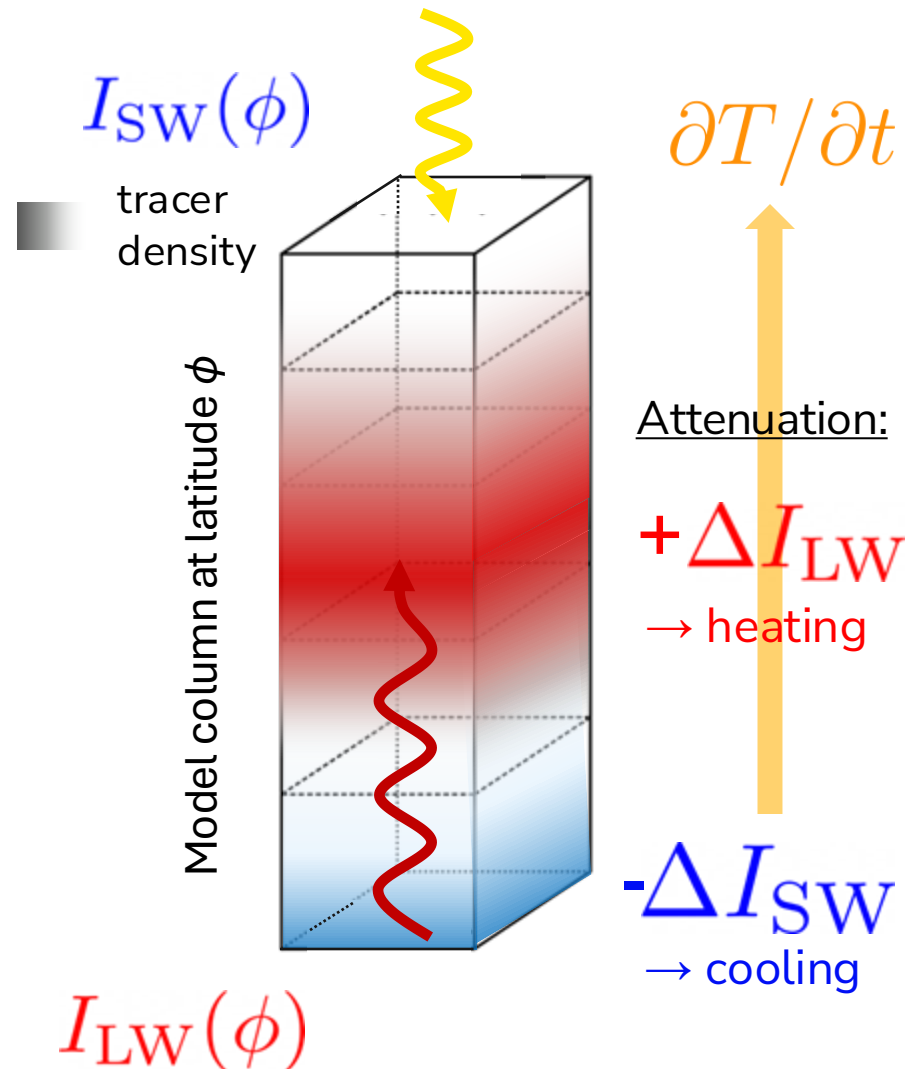
Step 2: simplified radiative forcing



global radiation profiles



Step 2: simplified radiative forcing



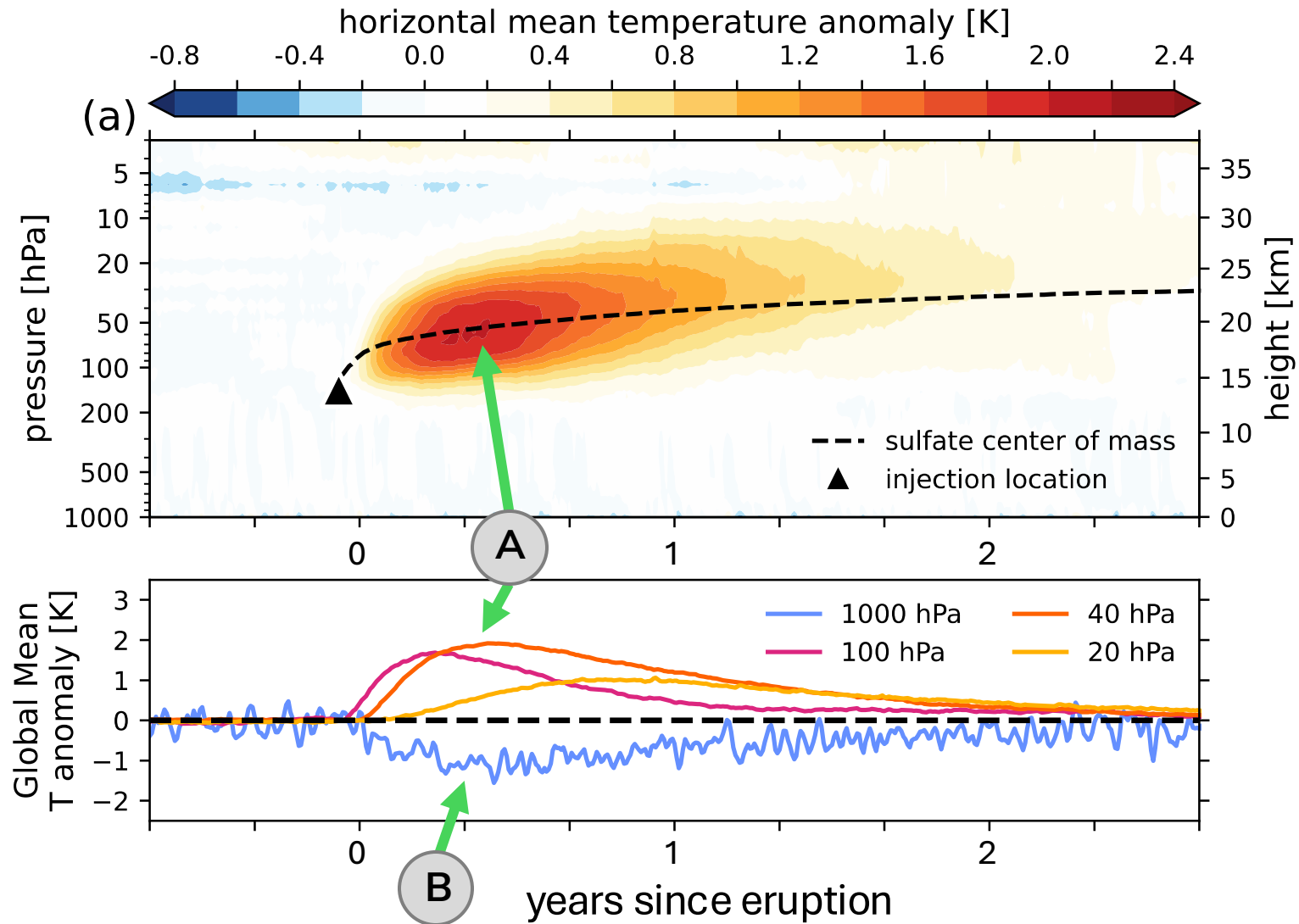
Result:

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:**

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

Joseph P. Hollowed¹, Christiane Jablonowski¹, Hunter Y. Brown², Benjamin R. Hillman², Diana L. Bull², and Joseph L. Hart²

¹Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI, USA

²Sandia National Laboratories, Albuquerque, NM, USA


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

Daniel Ries¹, Katherine Goode¹, Kellie McClernon¹, and Benjamin Hillman¹

¹Sandia 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

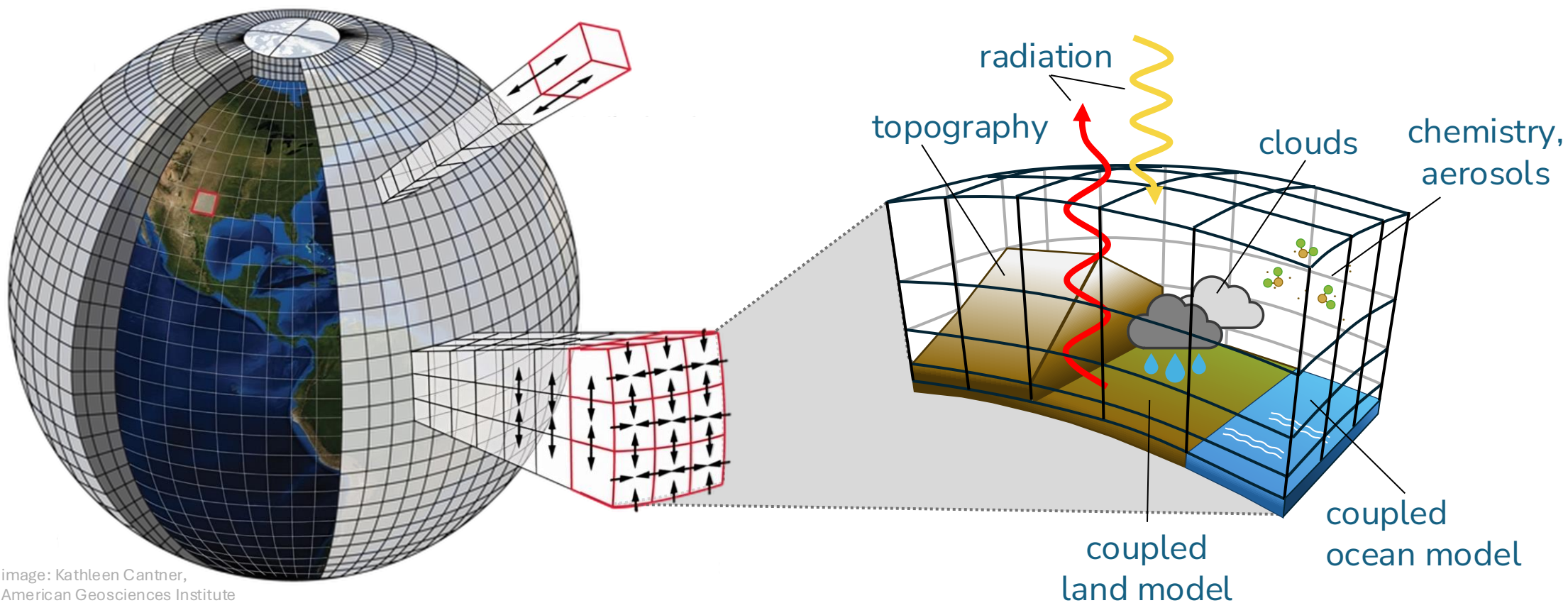
volcanic effects on midlatitude winds
wave-mean flow interaction and the transformed Eulerian mean

Climate Model



fluid solver = “dynamics”

parameterizations = “physics”



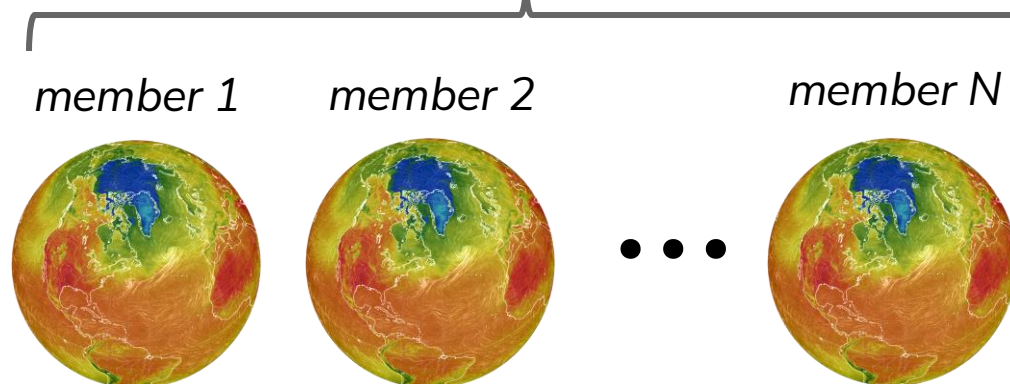
Simulation Strategy



Pinatubo simulation ensemble



reference simulation ensemble



paired t-test

$$\frac{1}{N} \sum \text{ (globe icon) }$$

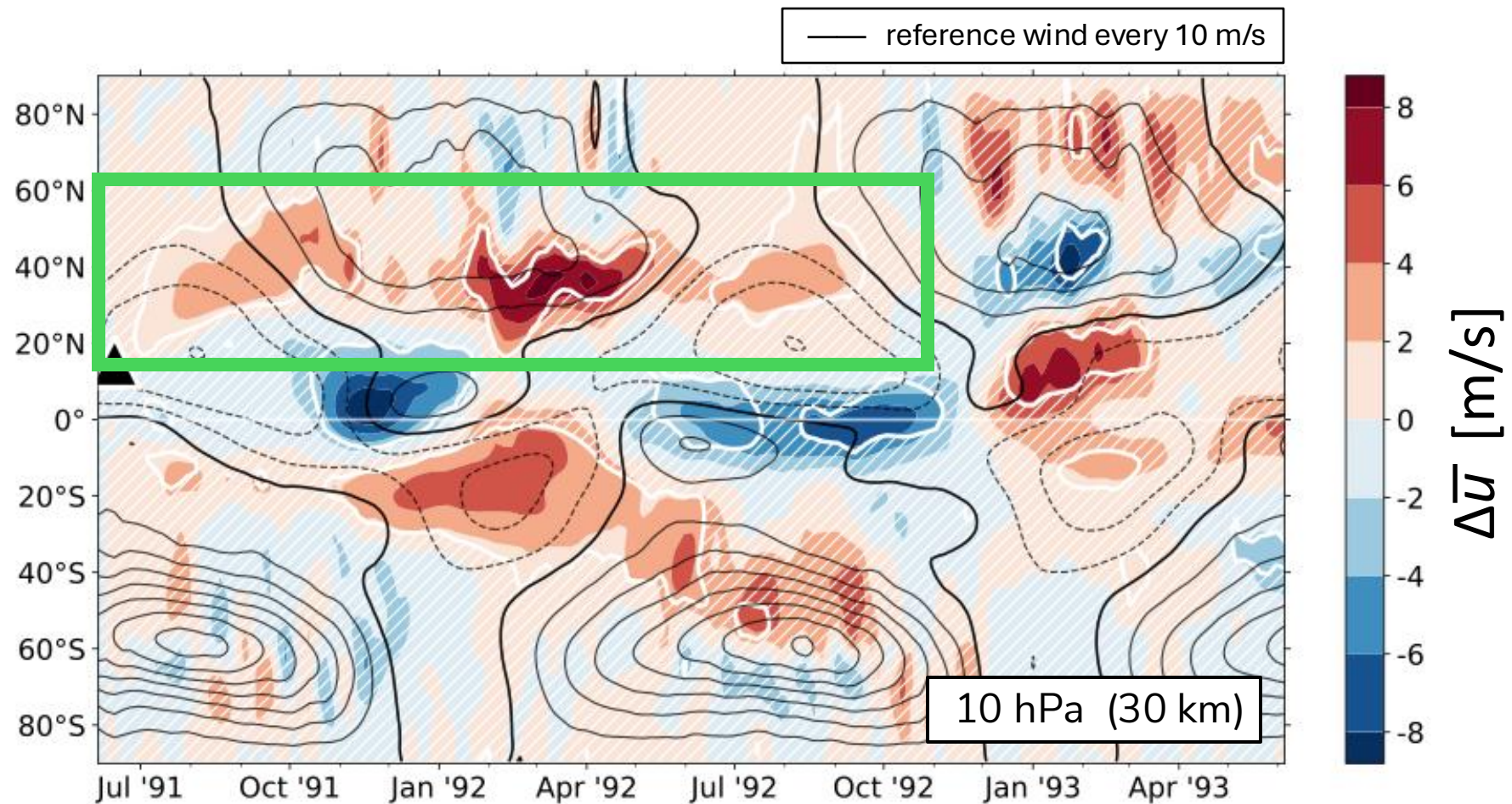
-

$$\frac{1}{N} \sum \text{ (globe icon) } = \text{impact significance}$$

Volcanic impact on zonal wind is localized, but significant

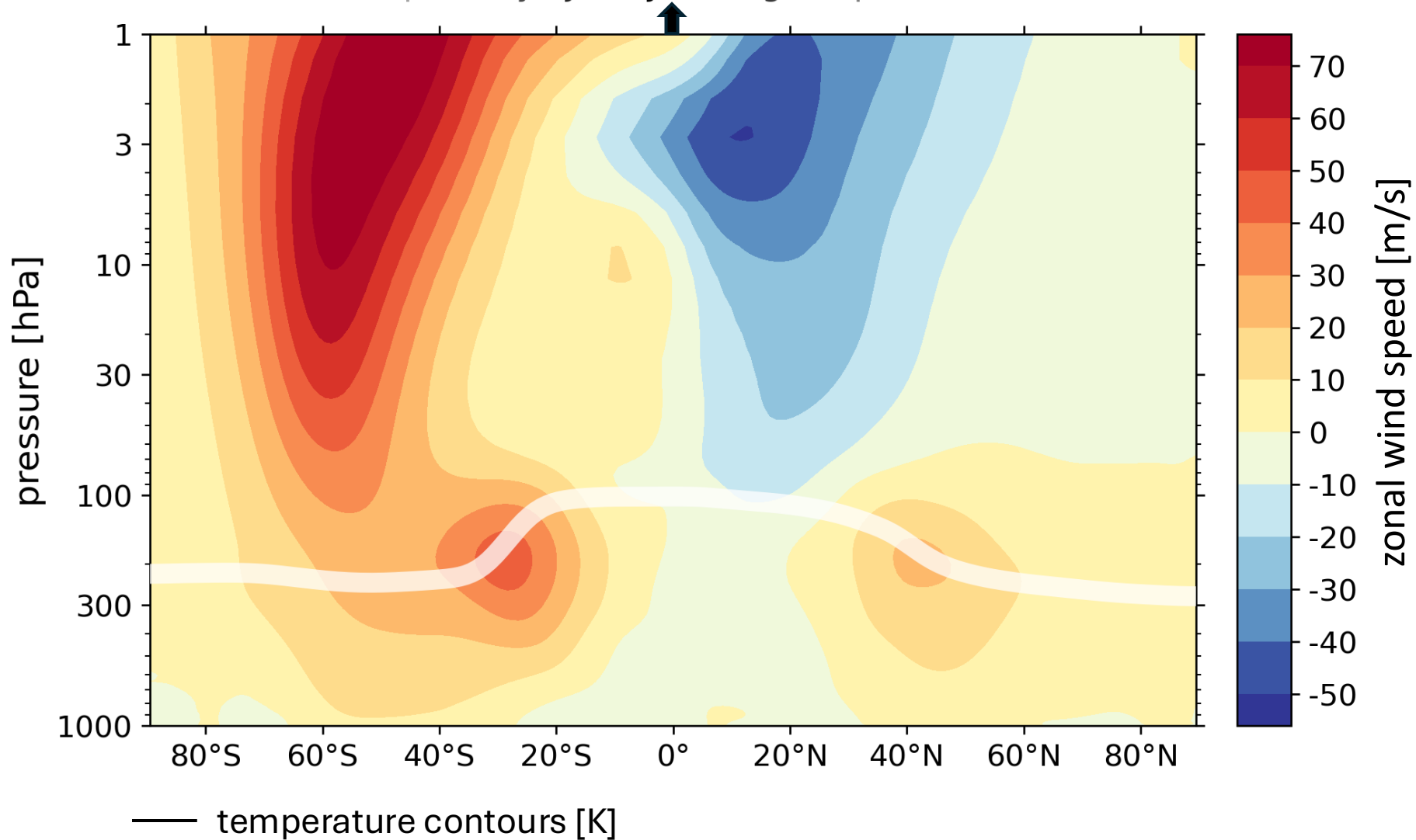
Intermittent
accelerations
of the NH
vortex region

why?



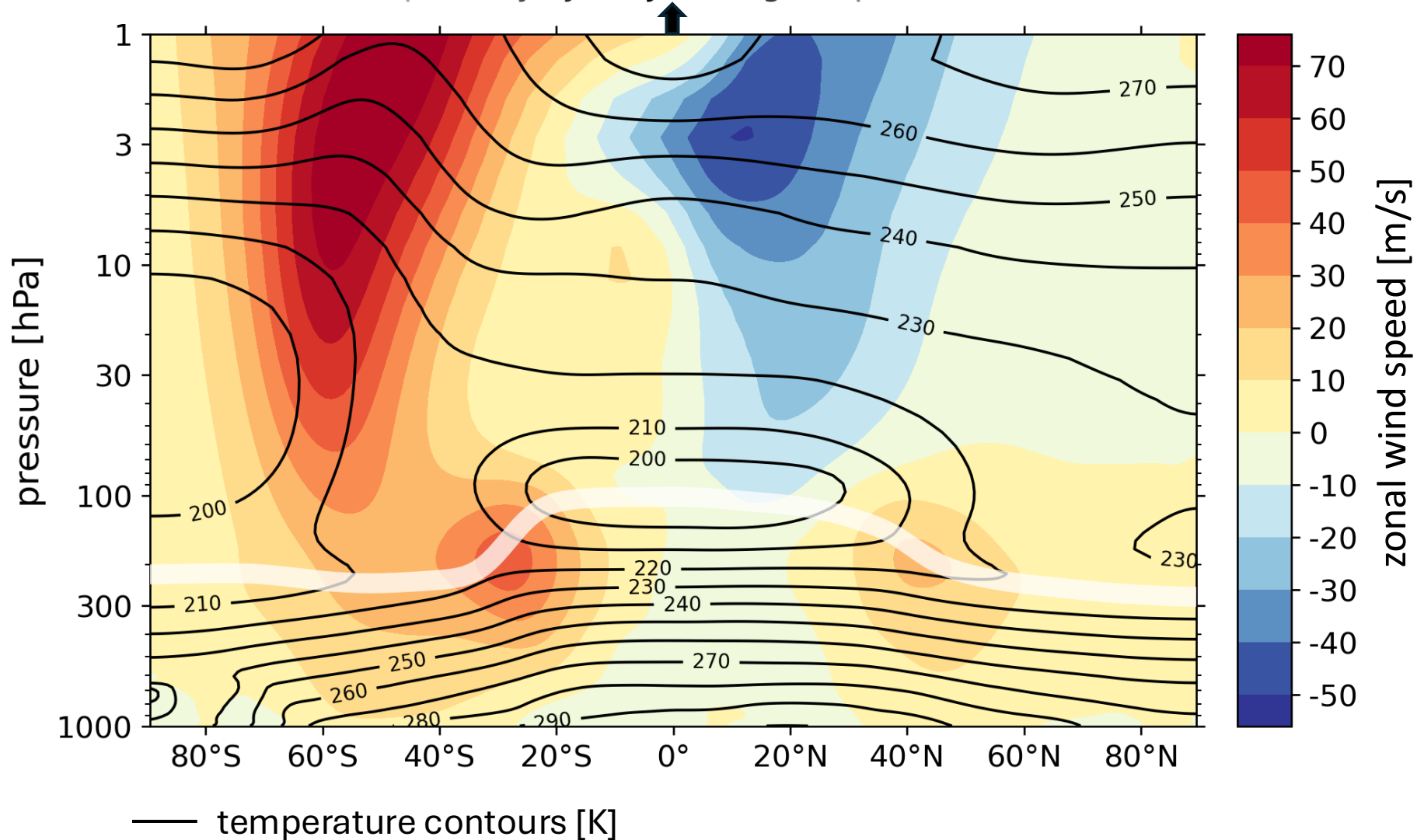
Southern Hemisphere Winter winds

Mar Apr May Jun Jul Aug Sep Oct N

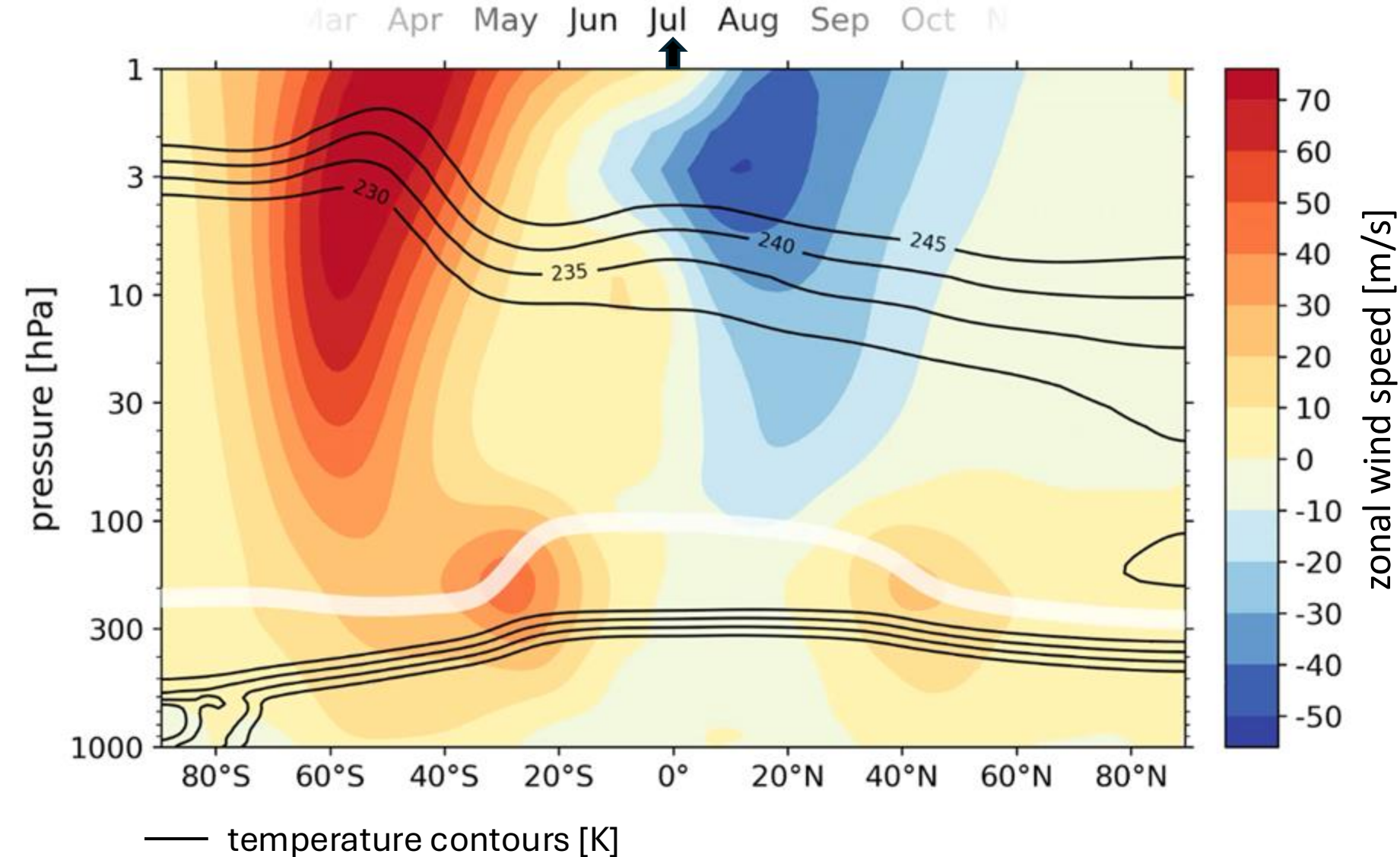


Southern Hemisphere Winter winds, temperature

Mar Apr May Jun Jul Aug Sep Oct N



Southern Hemisphere Winter winds, temperature



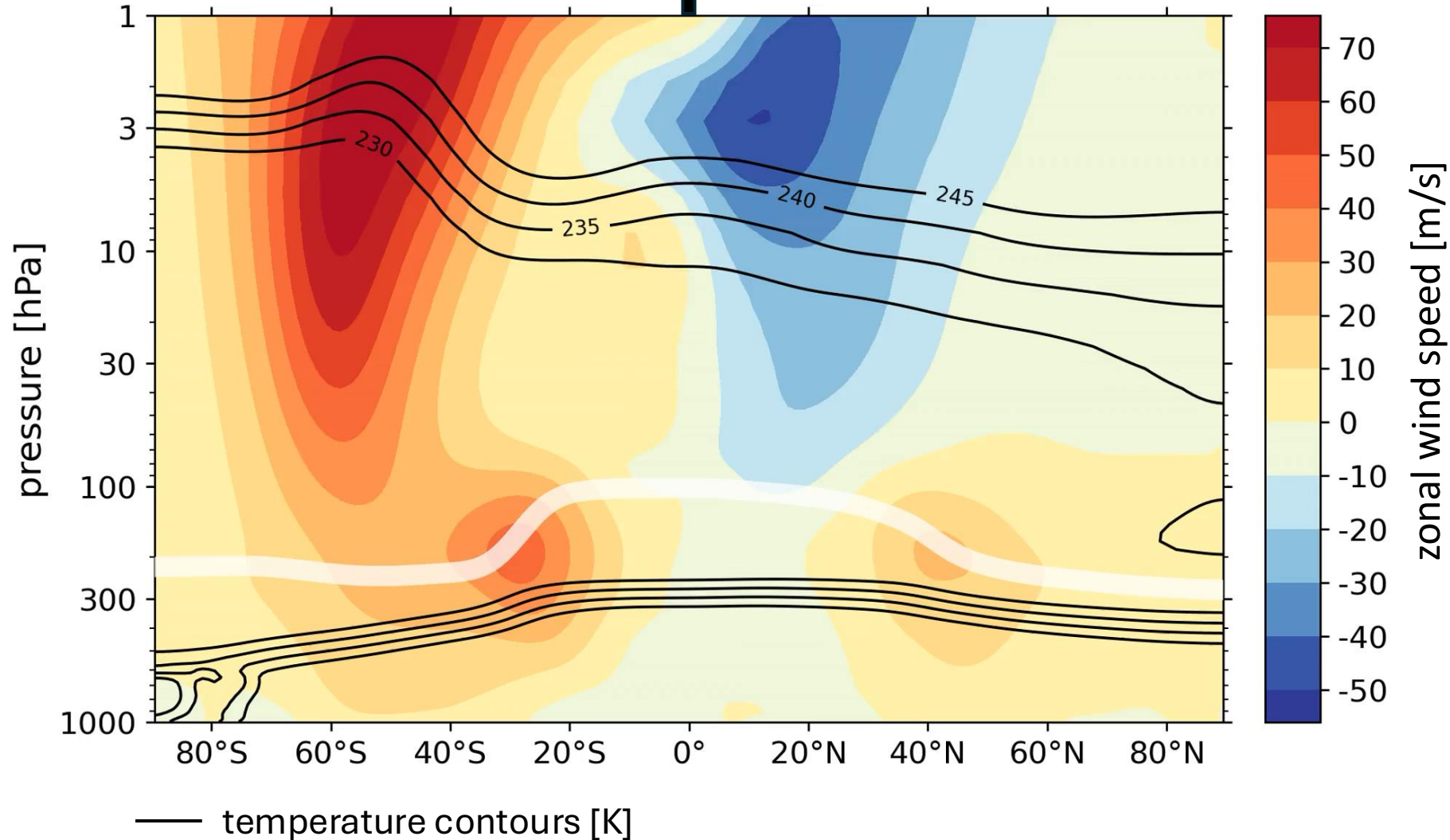
Thermal Wind Balance:

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

“Wind changes in altitude
accompany temperature
changes in latitude”

wind, temperature seasonal cycle

Mar Apr May Jun Jul Aug Sep Oct N



Thermal Wind Balance:

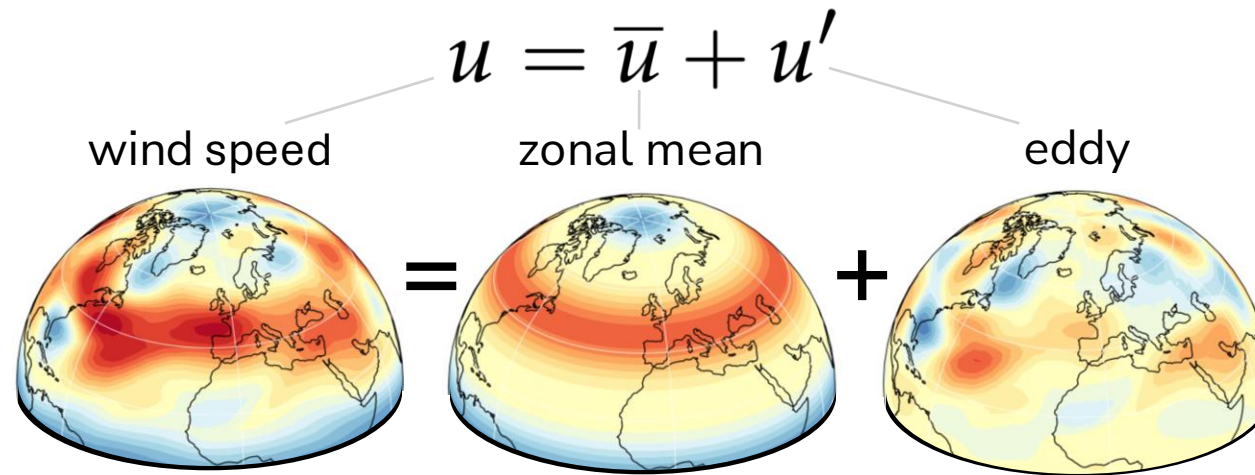
$$\frac{\partial u}{\partial p} \propto \frac{\partial T}{\partial \phi}$$

“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)



approximate predictive eq. for zonal wind:

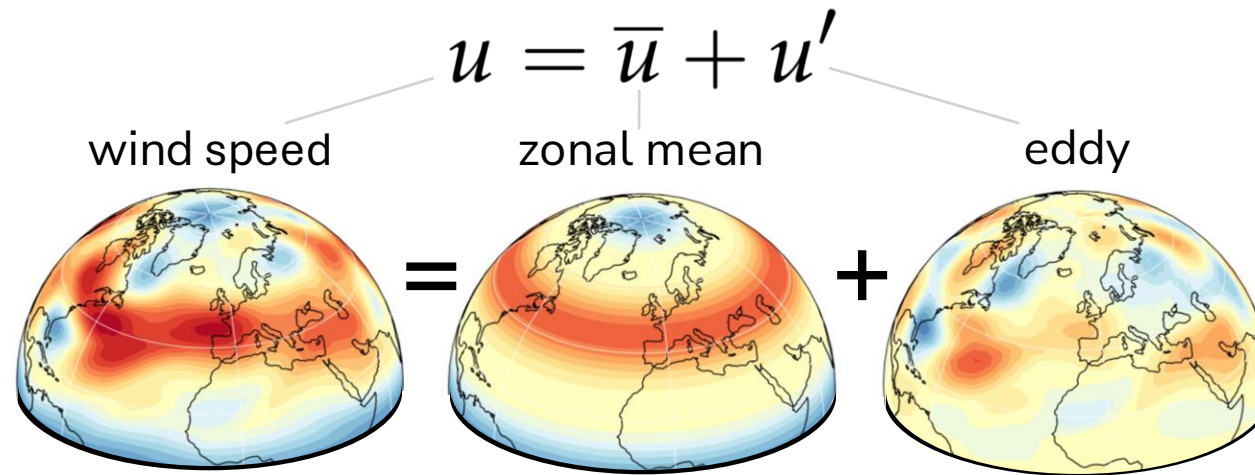
$$\frac{\partial u}{\partial t} + v u_y + w u_z = f v + p_x - X$$

↓ split variables like $u = \bar{u} + u'$

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

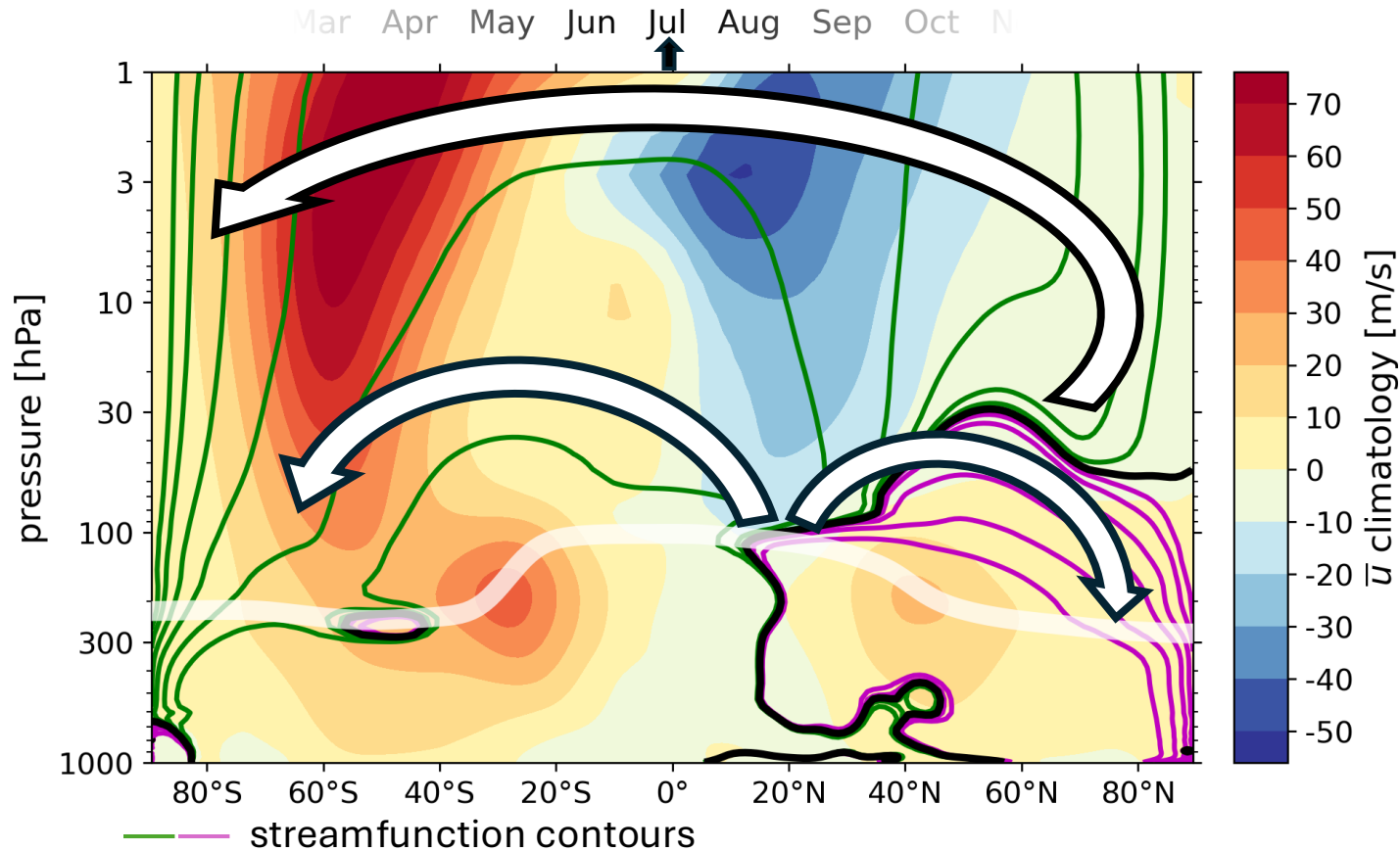
$$\frac{\partial \bar{u}}{\partial t} = \bar{v}^* (f - \bar{u}_y) - \bar{w}^* \bar{u}_z + \nabla \cdot \mathbf{F} - \bar{X}$$

Concept: the Transformed Eulerian Mean (TEM)



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

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



TEM-inferred movement of mass in the latitude-altitude plane:

the **Residual Circulation**

green = CCW; purple = CW circulation

Upper stratosphere:

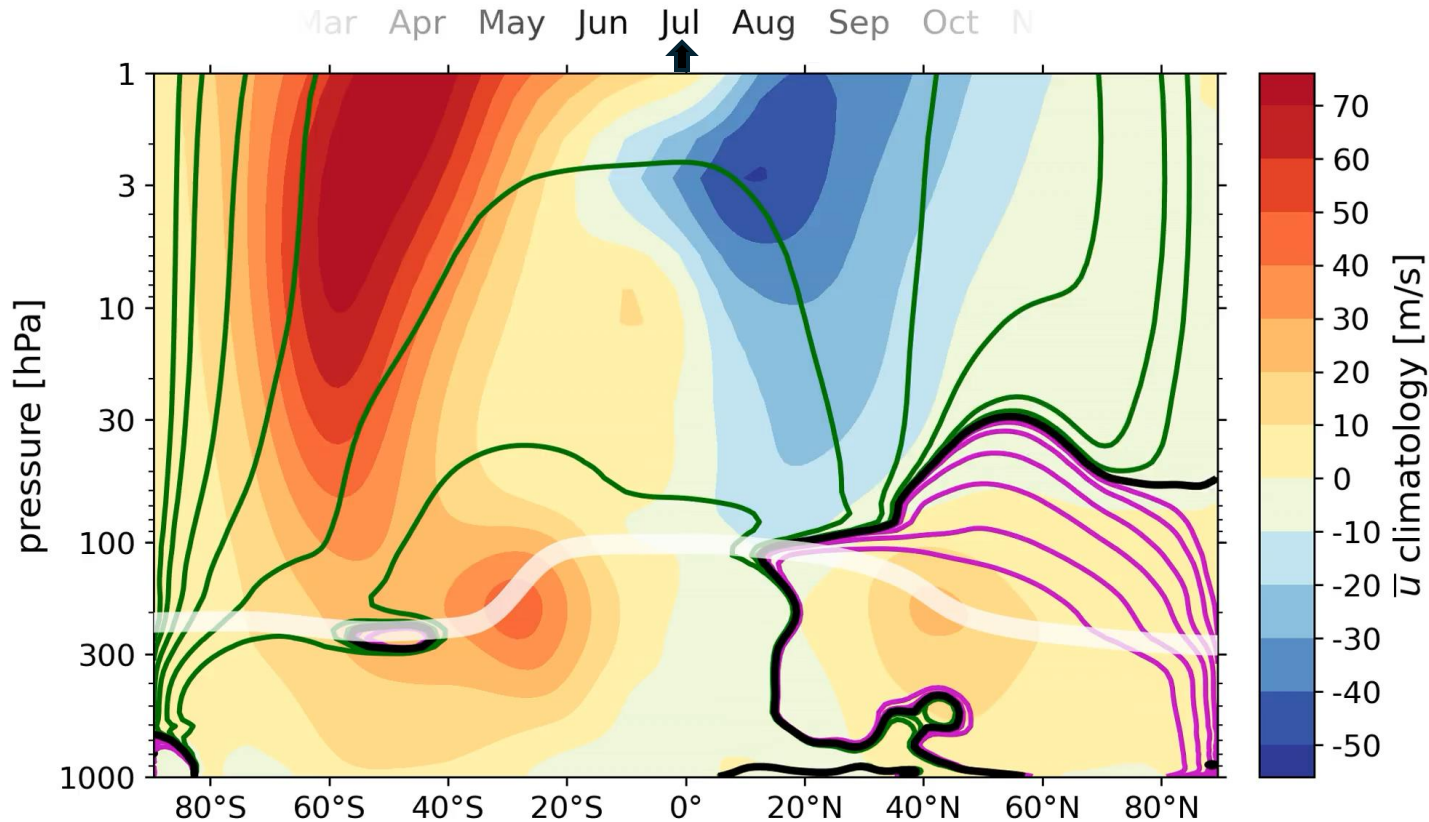
Deep Branch; single pole-to-pole cell, from summer to winter hemisphere

Lower stratosphere:

Shallow Branch; equator-to-pole cells in each hemisphere

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

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



TEM-inferred movement of mass in the latitude-altitude plane:

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green = CCW; purple = CW circulation

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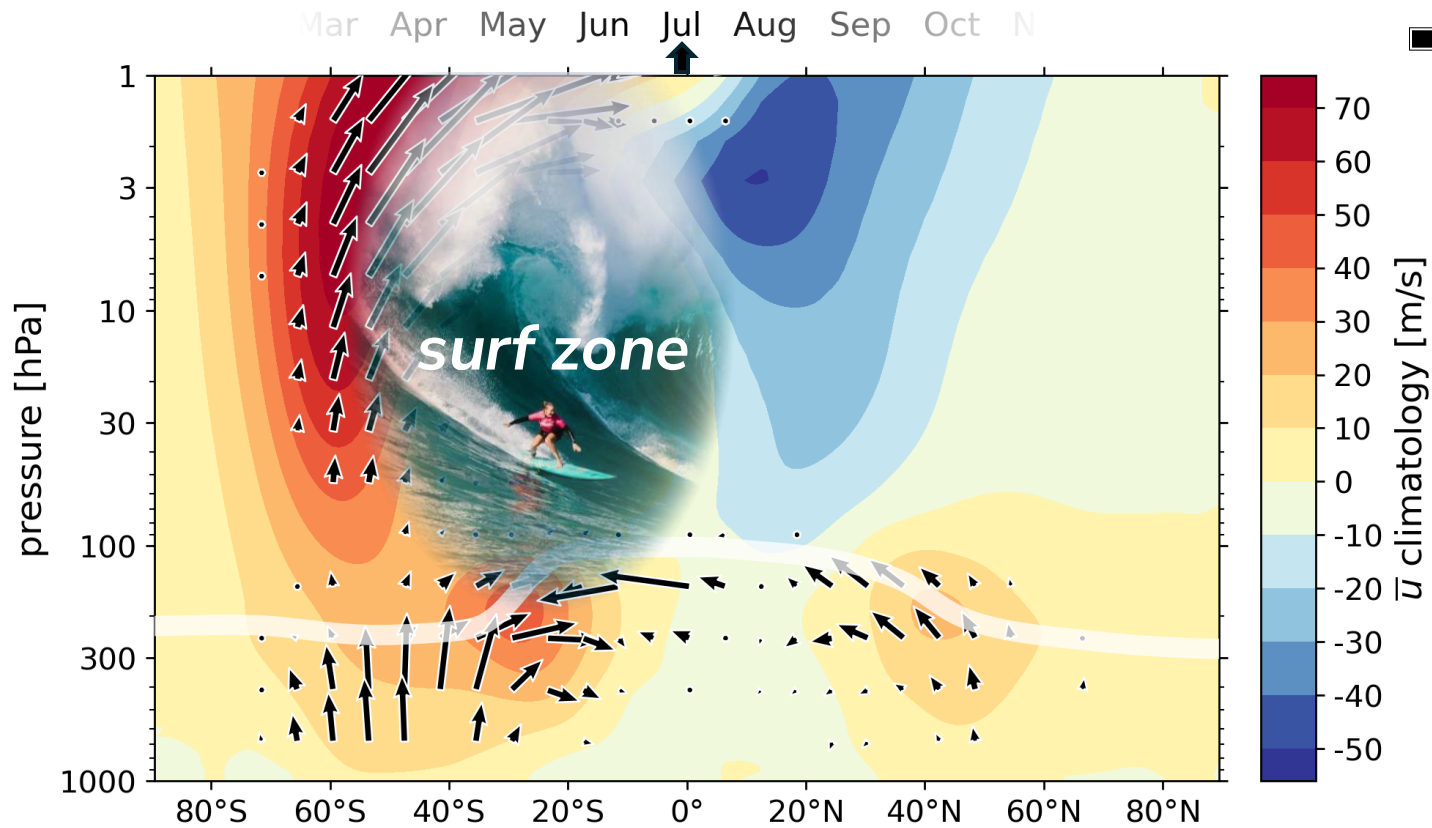
Deep Branch; single pole-to-pole cell, from summer to winter hemisphere

Lower stratosphere:

Shallow Branch; equator-to-pole cells in each hemisphere

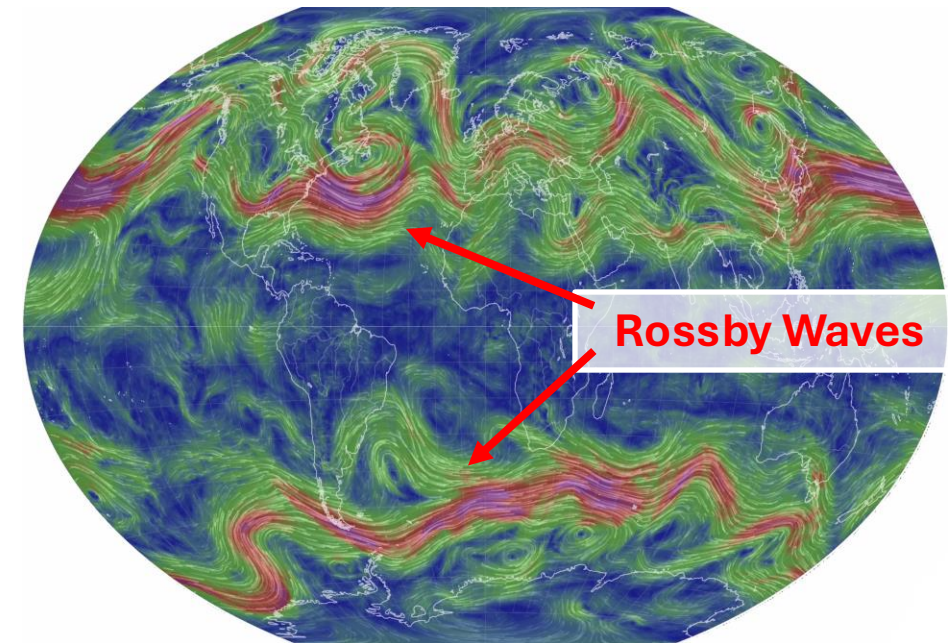
change in the mean flow = **circulation-driven piece** + **wave-driven piece** + **diffusive piece**

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



→ = propagation direction of large-scale atmospheric waves

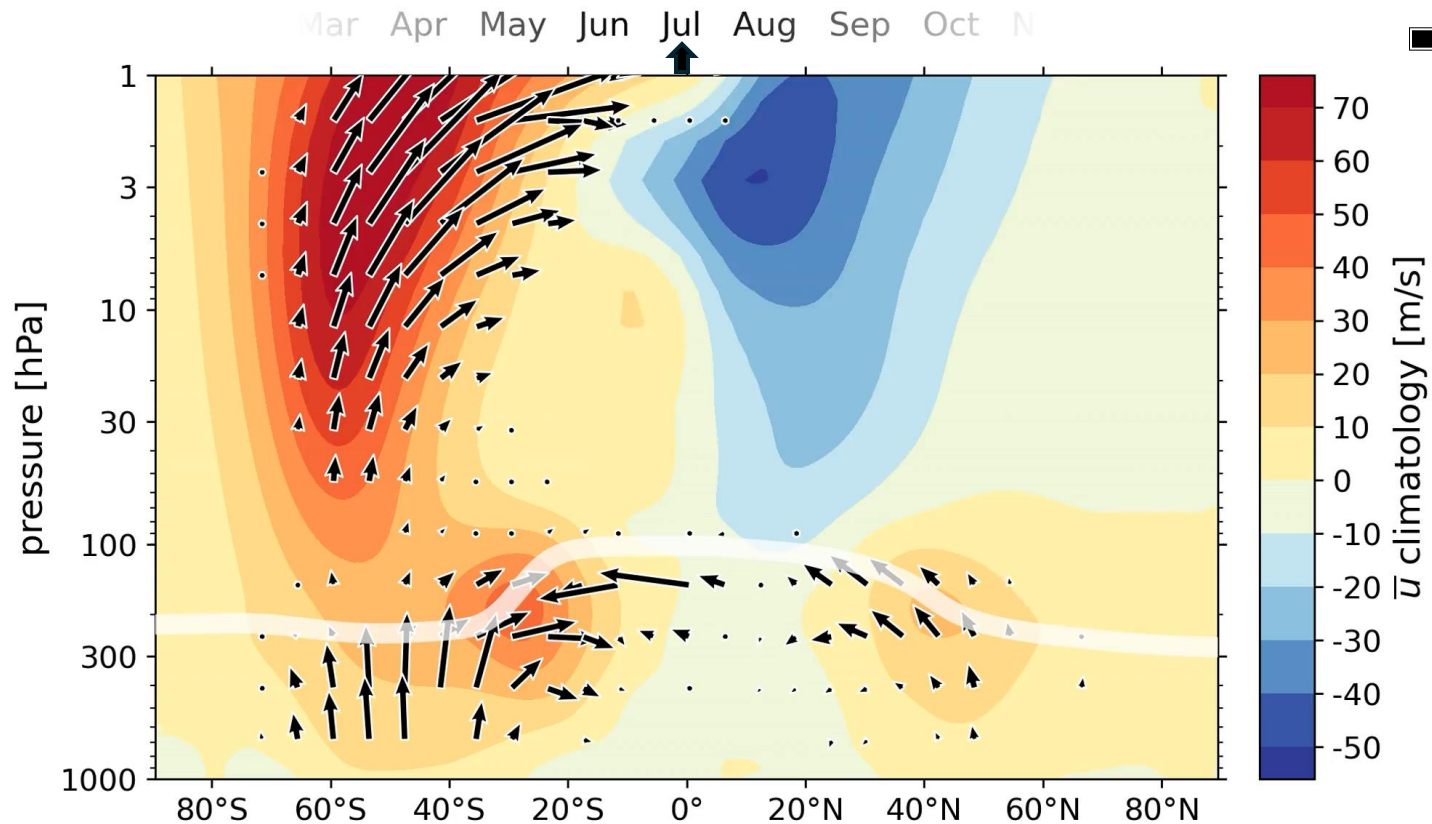
Forcing: vertical propagation, breaking



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

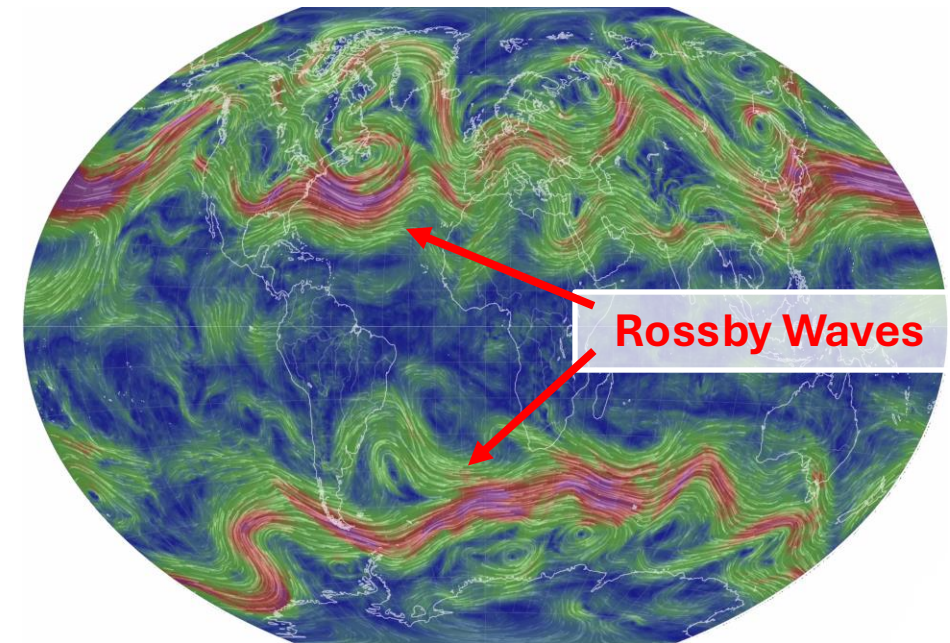
$$\left[\frac{\partial \bar{u}}{\partial t} \right] = \left[\bar{v}^* (f - \bar{u}_y) - \bar{w}^* \bar{u}_z \right] + \left[\nabla \cdot \mathbf{F} \right] - \left[\bar{X} \right]$$

surf zone photo: Paige Alms, by Christa Funk



→ = propagation direction of large-scale atmospheric waves

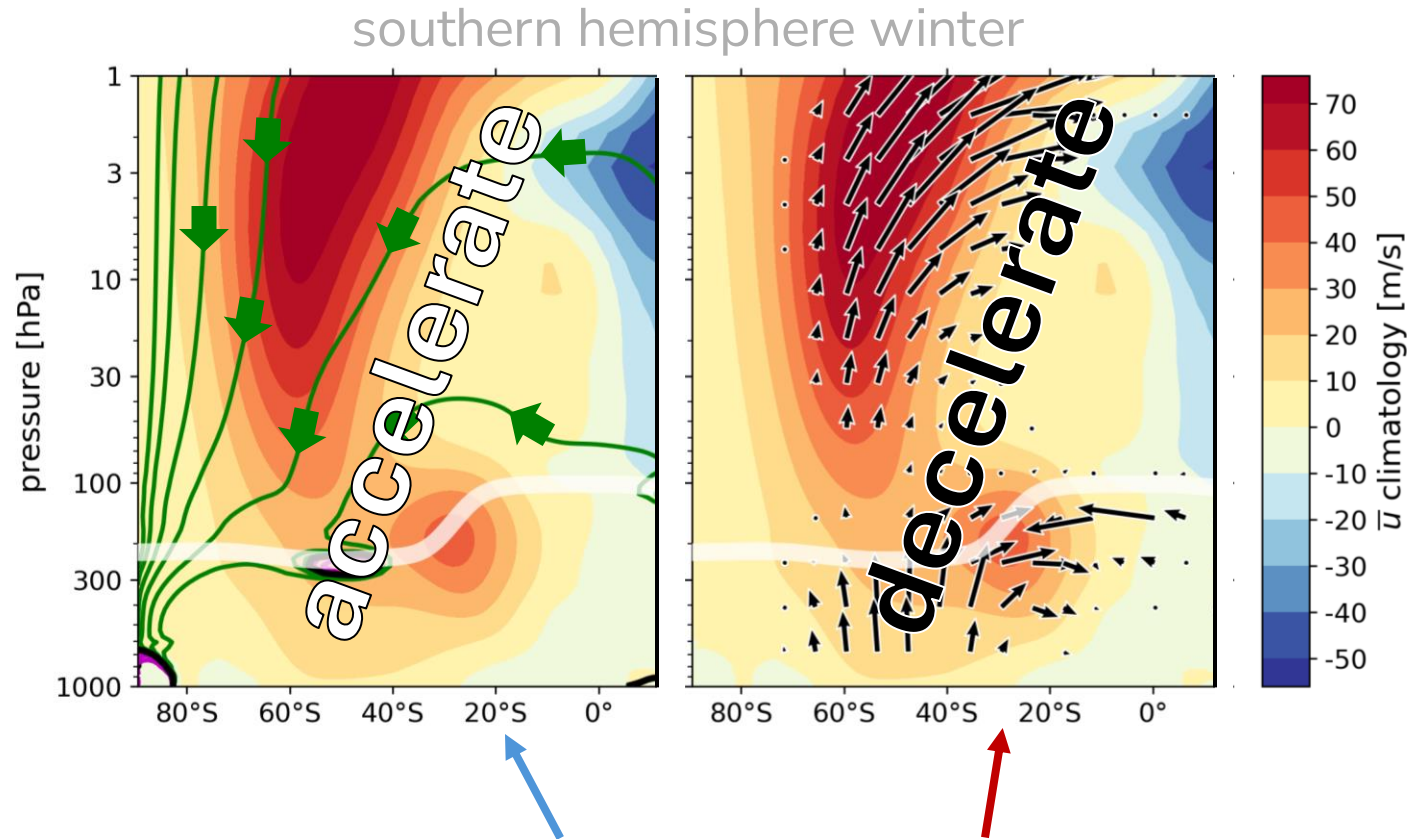
Forcing: vertical propagation, breaking



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

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

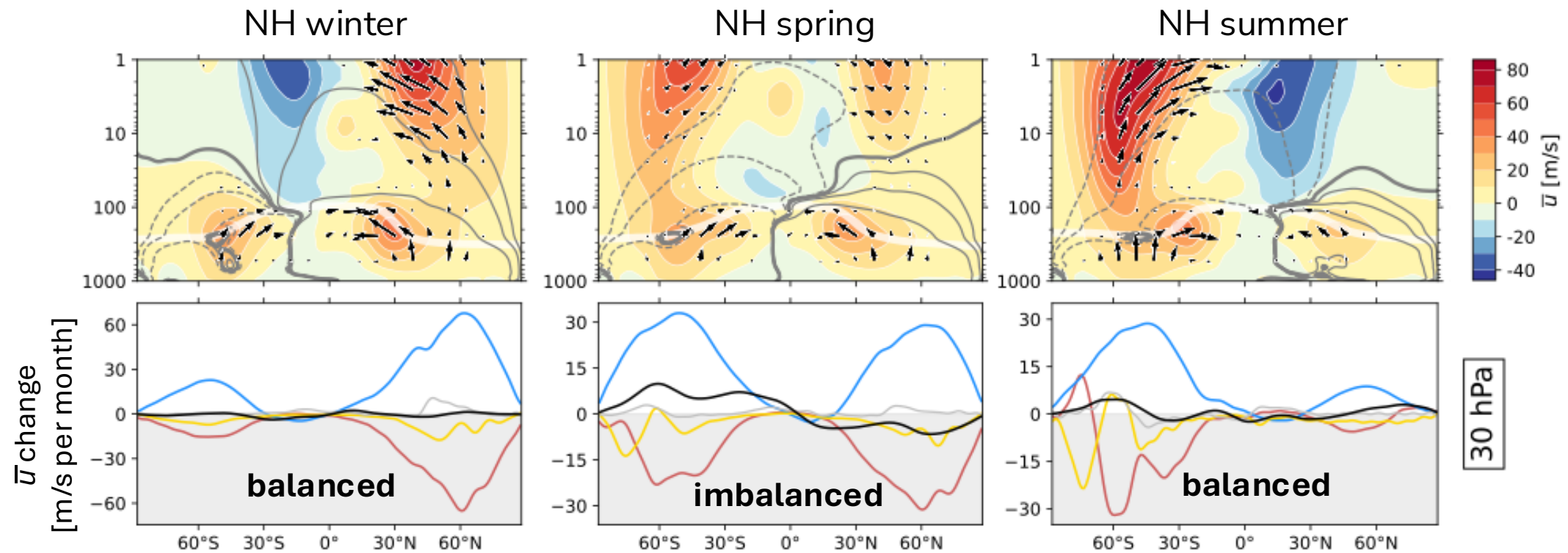
Concept: TEM Balance



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

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

Concept: TEM Balance



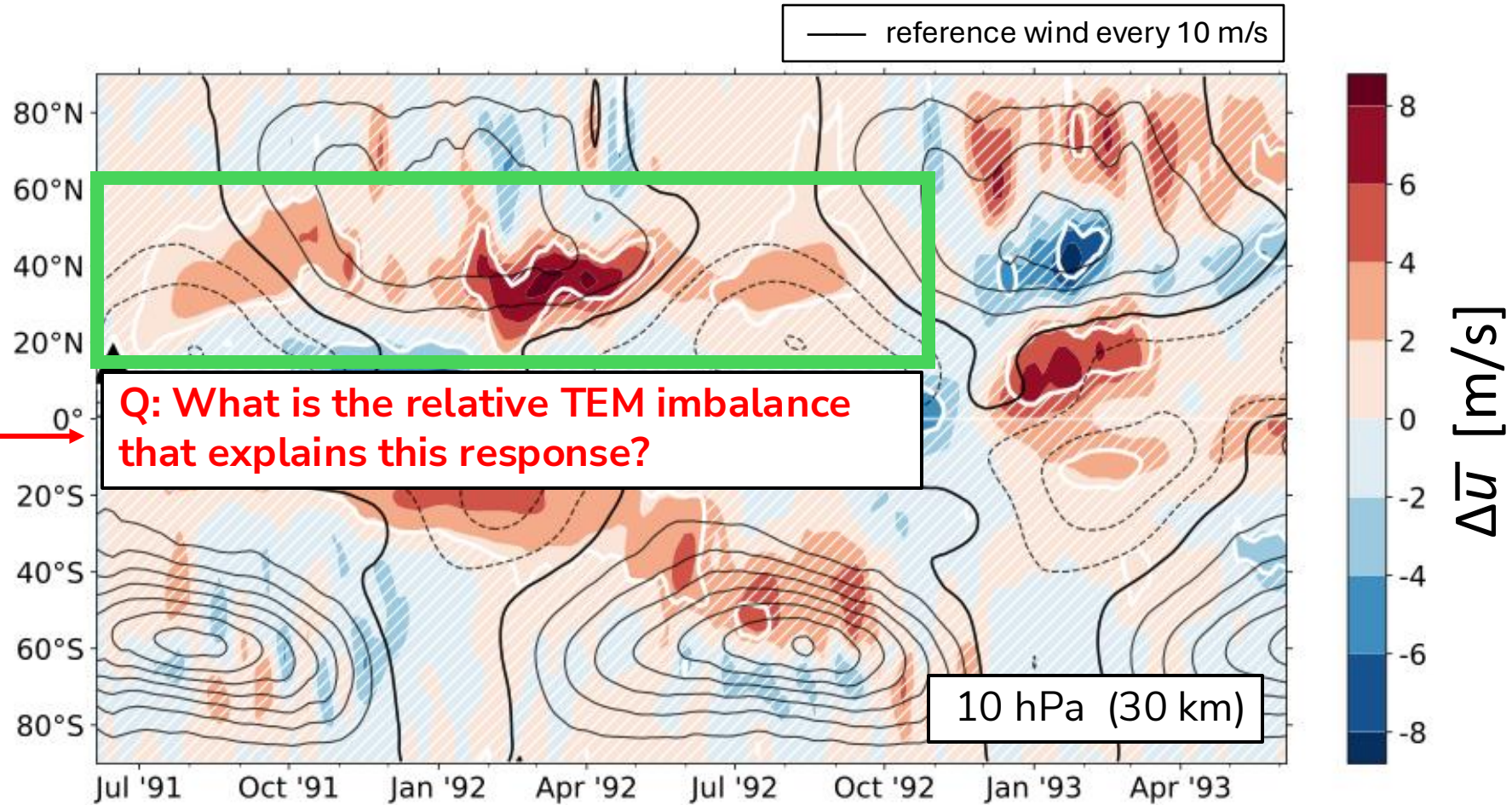
change in the mean flow = **circulation-driven piece** + **wave-driven piece** + **diffusive piece**

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

Results: Volcanically-driven TEM imbalance

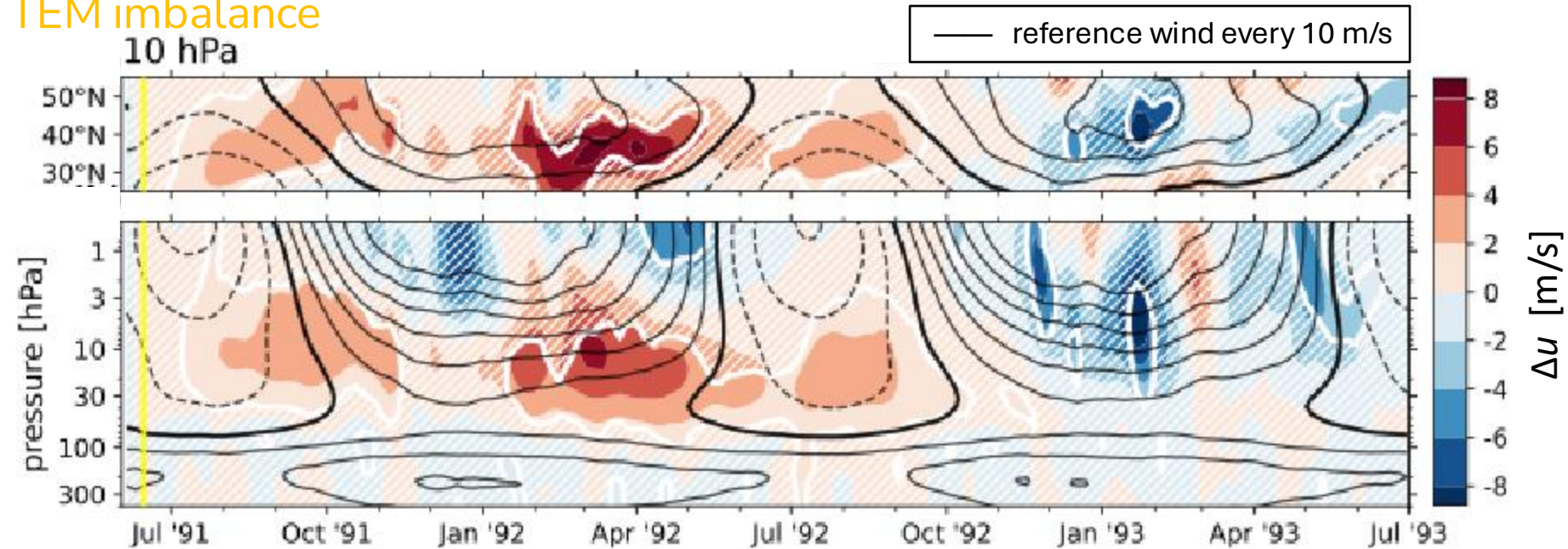
Intermittent
accelerations
of the NH
vortex region

why? →



Results: Volcanically-driven TEM imbalance

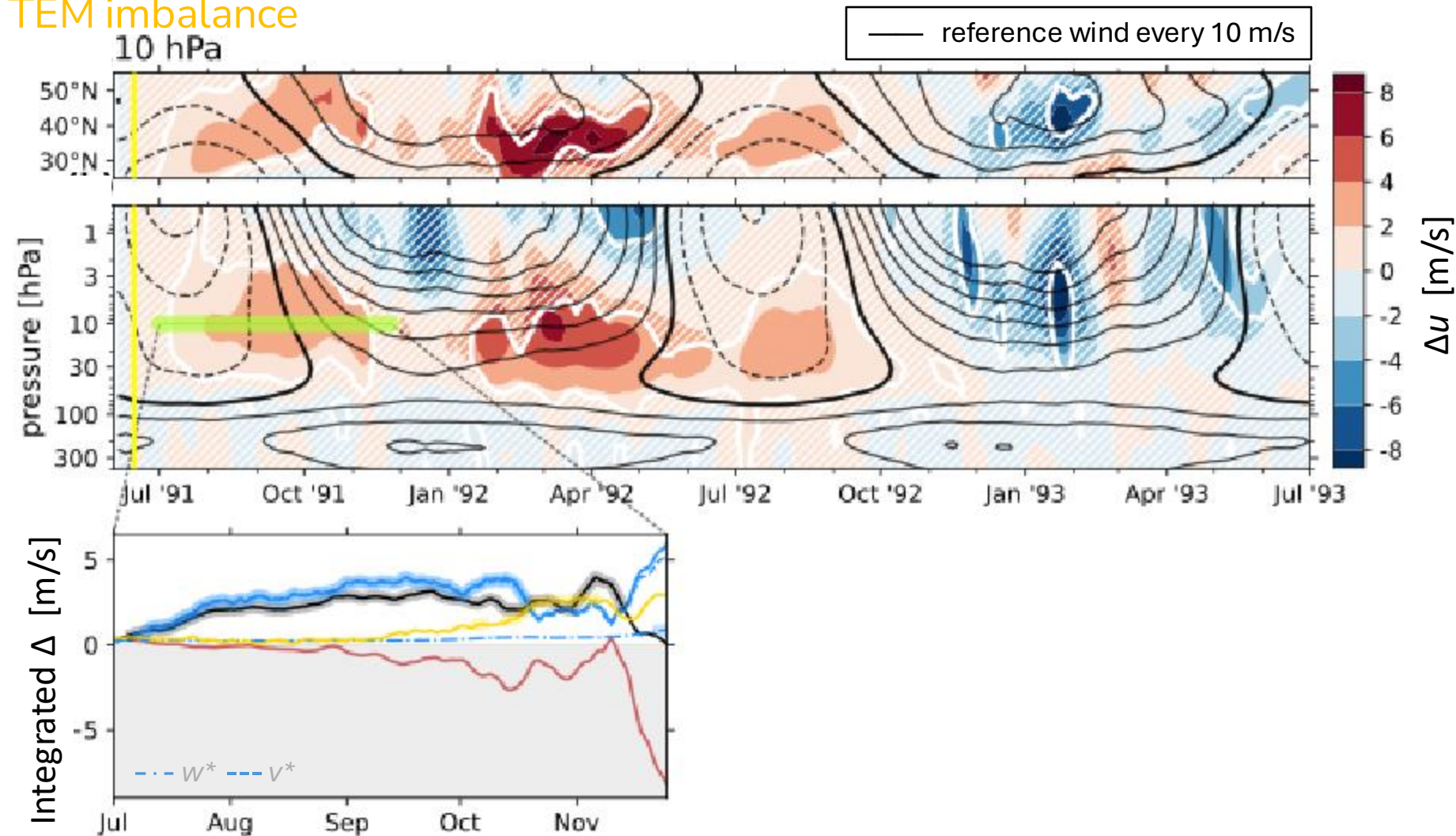
Identified TEM
imbalance:



Results: Volcanically-driven TEM imbalance

Identified TEM
imbalance:

In summer '91:
**Enhanced
circulation**



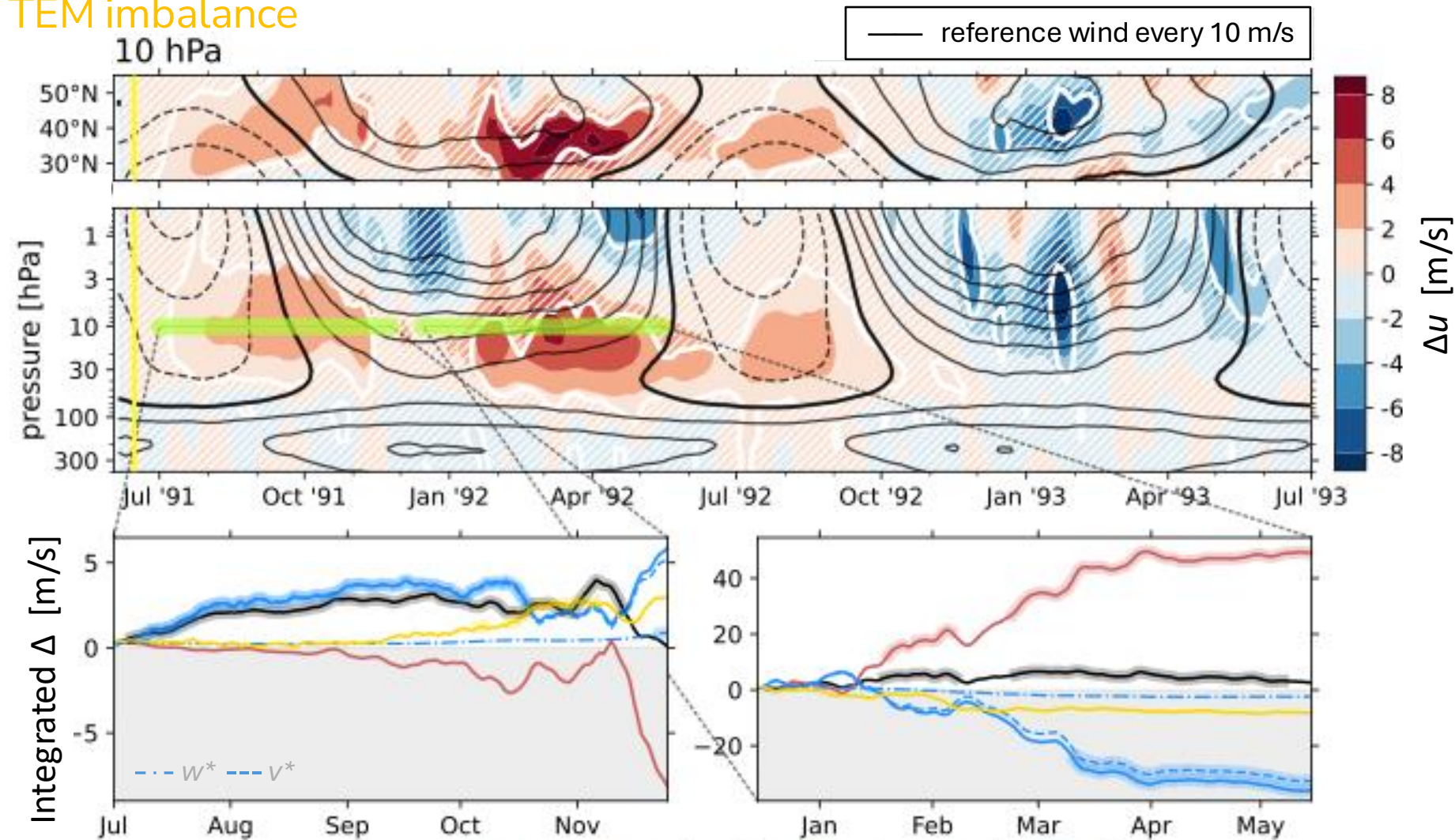
$$\Delta (\text{change in the mean flow}) = \Delta(\text{circulation-driven}) + \Delta(\text{wave-driven}) + \Delta(\text{diffusive piece})$$

Results: Volcanically-driven TEM imbalance

Identified TEM
imbalance:

In summer '91:
**Enhanced
circulation**

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

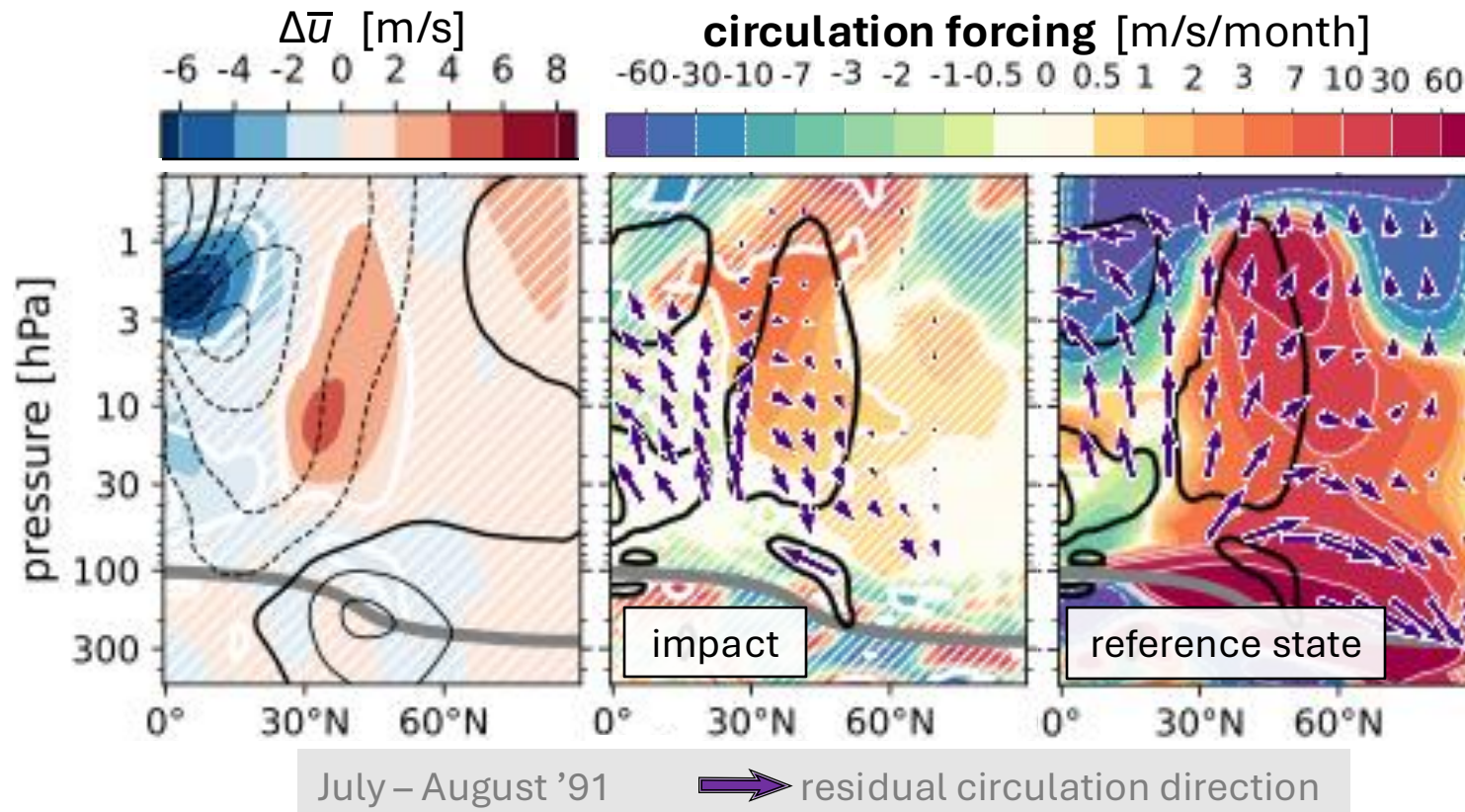


$$\Delta (\text{change in the mean flow}) = \Delta(\text{circulation-driven}) + \Delta(\text{wave-driven}) + \Delta(\text{diffusive piece})$$

Results: Volcanically-driven TEM imbalance

Explanation of summer response:

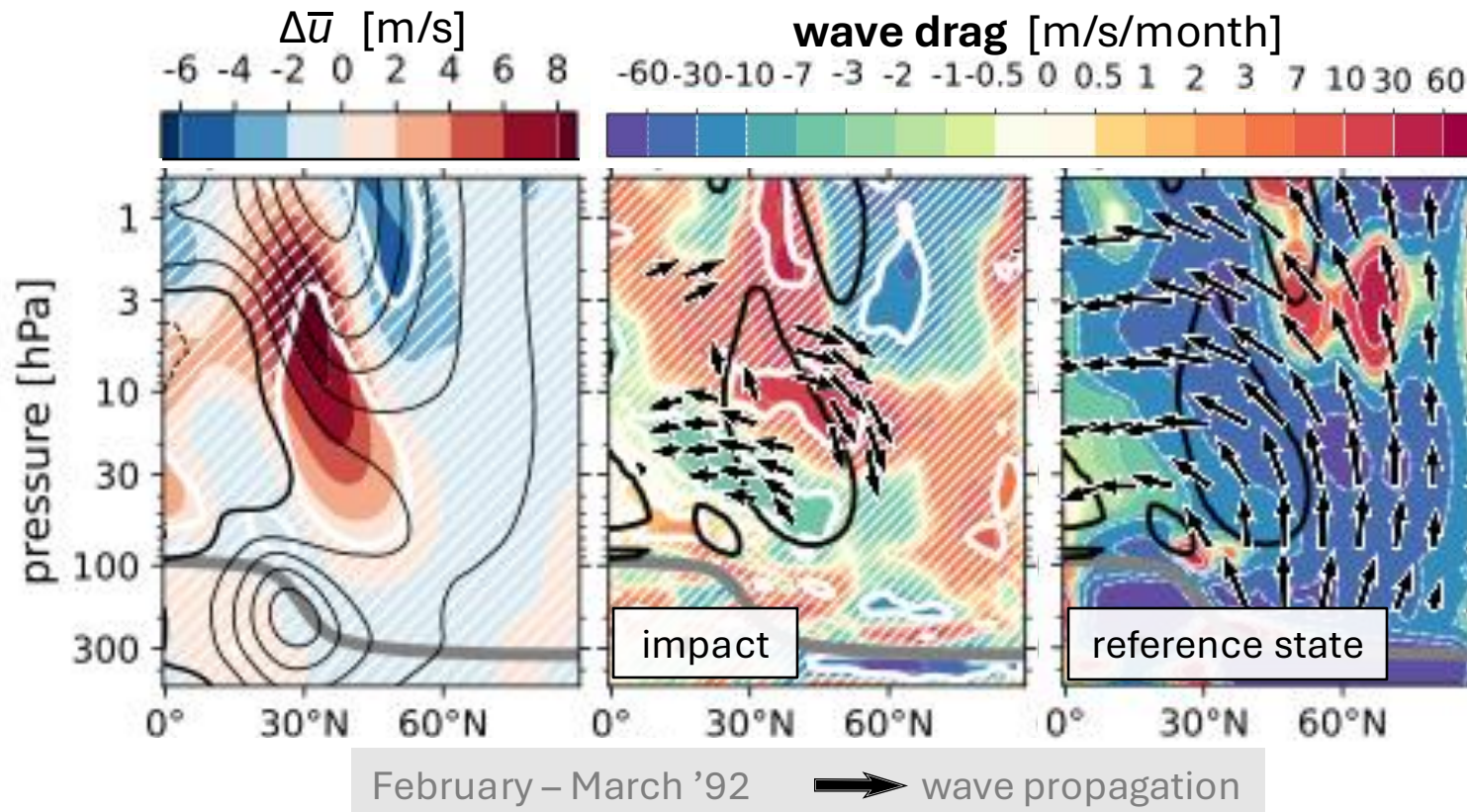
accelerated residual circulation in its shallow branch
= enhanced **Coriolis force** near 30°N



Results: Volcanically-driven TEM imbalance

Explanation of winter response:

enhanced equatorward wave deflection
= diminished wave drag aloft



Results: Volcanically-driven TEM imbalance

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

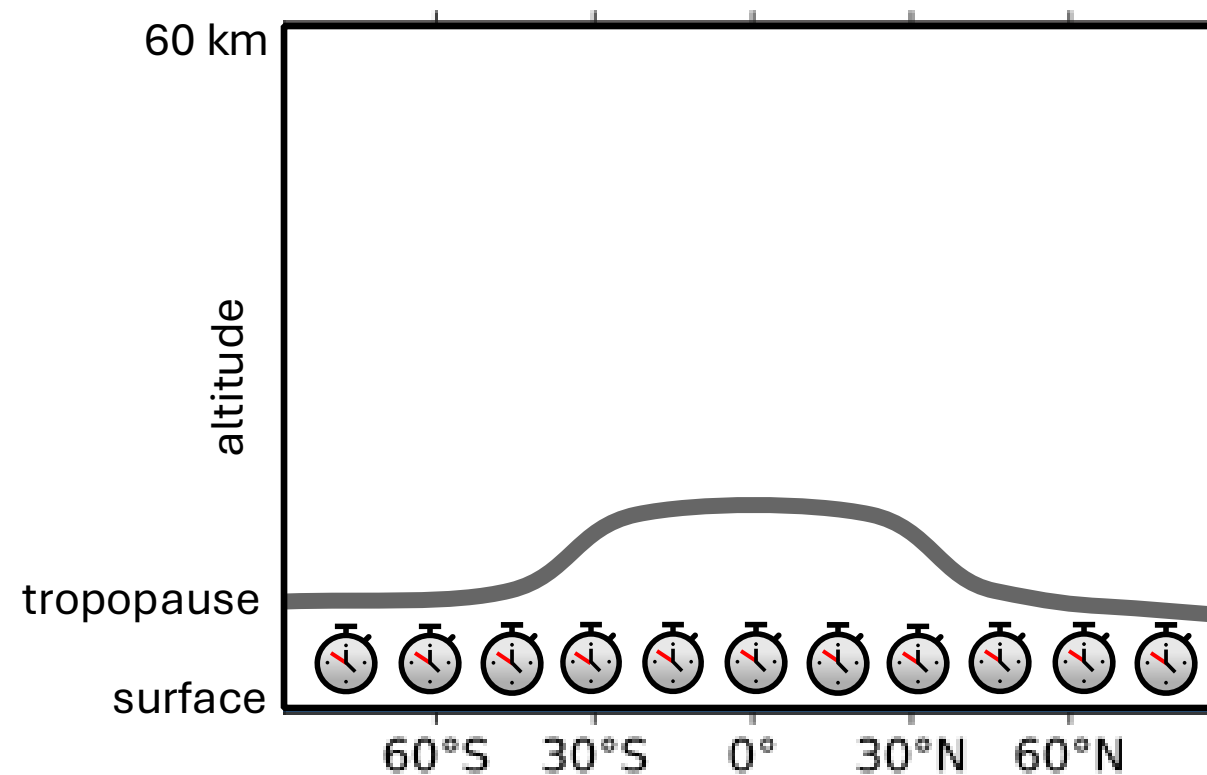
In Part 2, we concluded that the NH summer residual circulation accelerates post-eruption, driving a westerly wind impact

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

Age of Air (AoA)

a passive tracer for measuring the timescale of global circulation

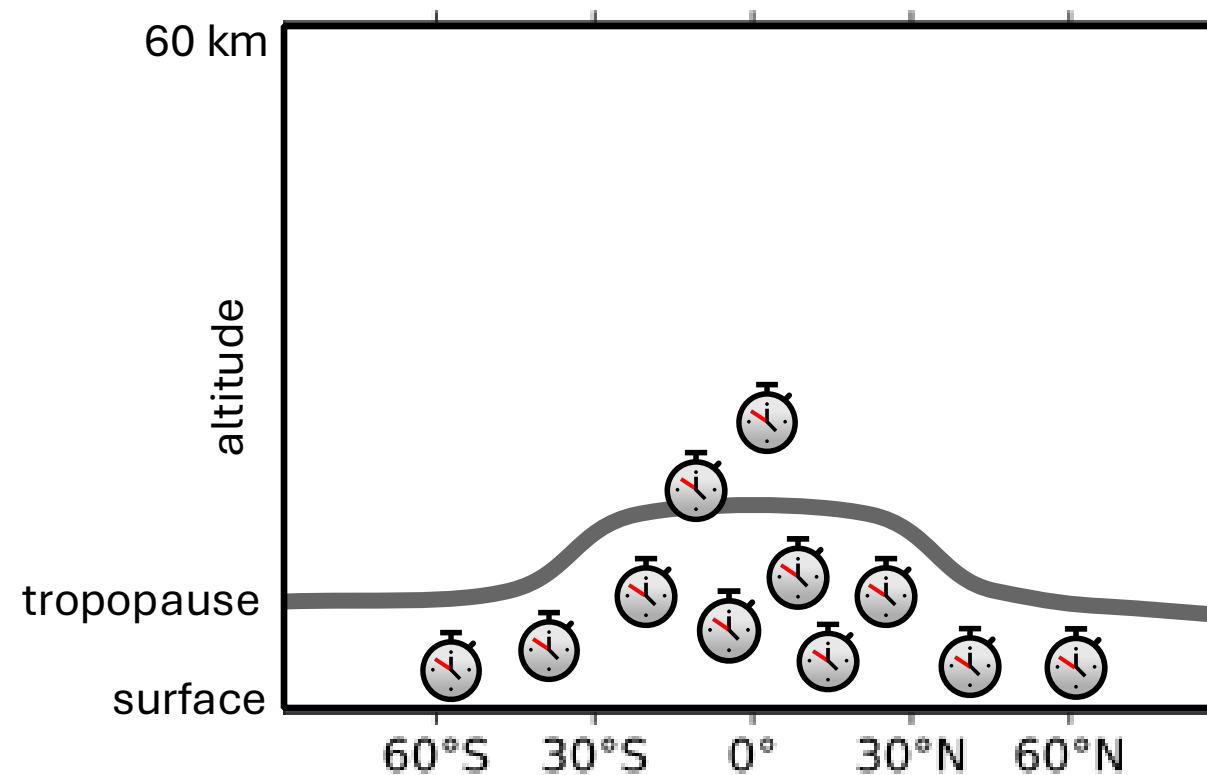
- constant source at the surface
- no stratospheric sinks



Age of Air (AoA)

a passive tracer for measuring the timescale of global circulation

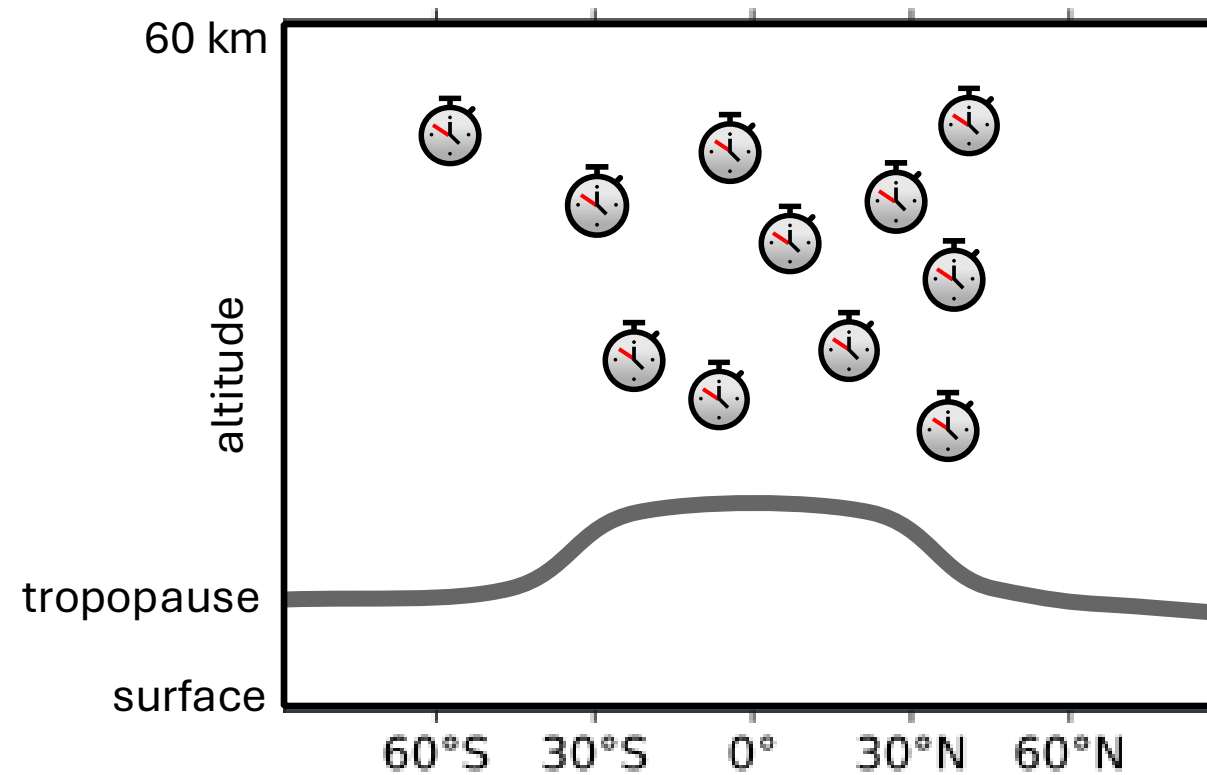
- constant source at the surface
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Age of Air (AoA)

a passive tracer for measuring the timescale of global circulation

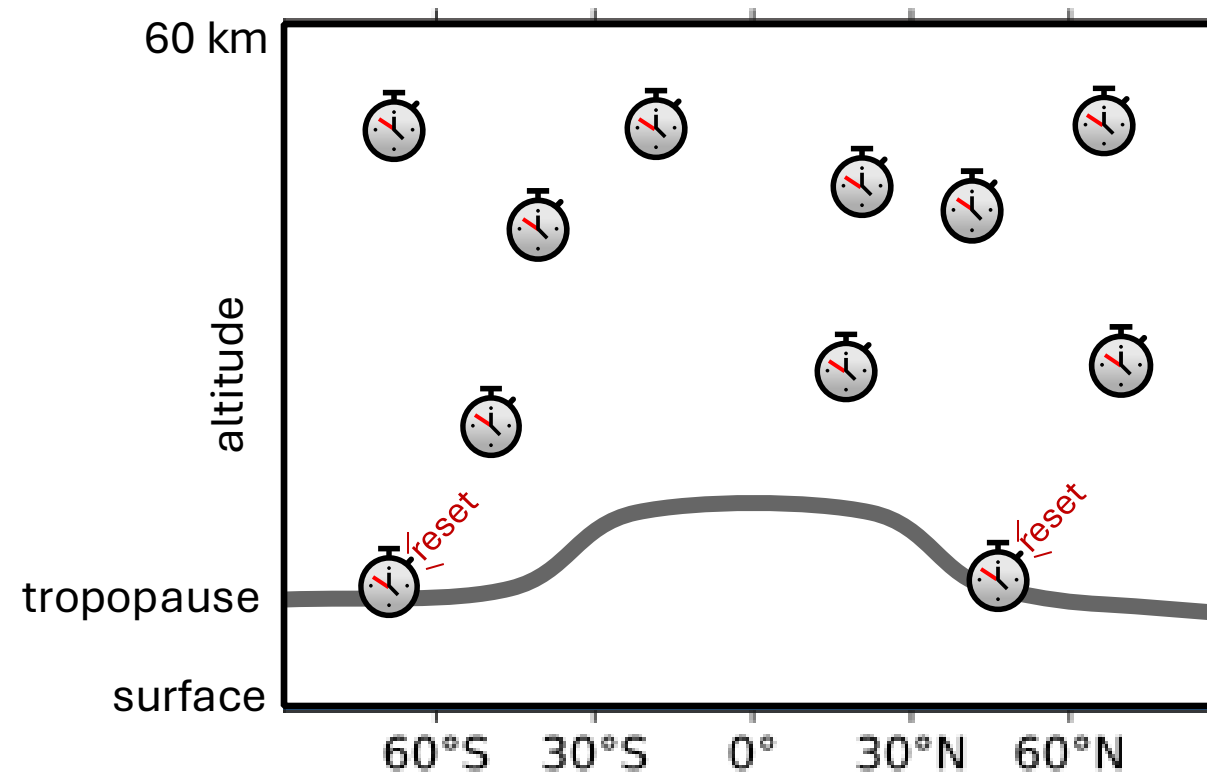
- constant source at the surface
- no stratospheric sinks



Age of Air (AoA)

a passive tracer for measuring the timescale of global circulation

- constant source at the surface
- no stratospheric sinks



Mean AoA distribution in E3SM

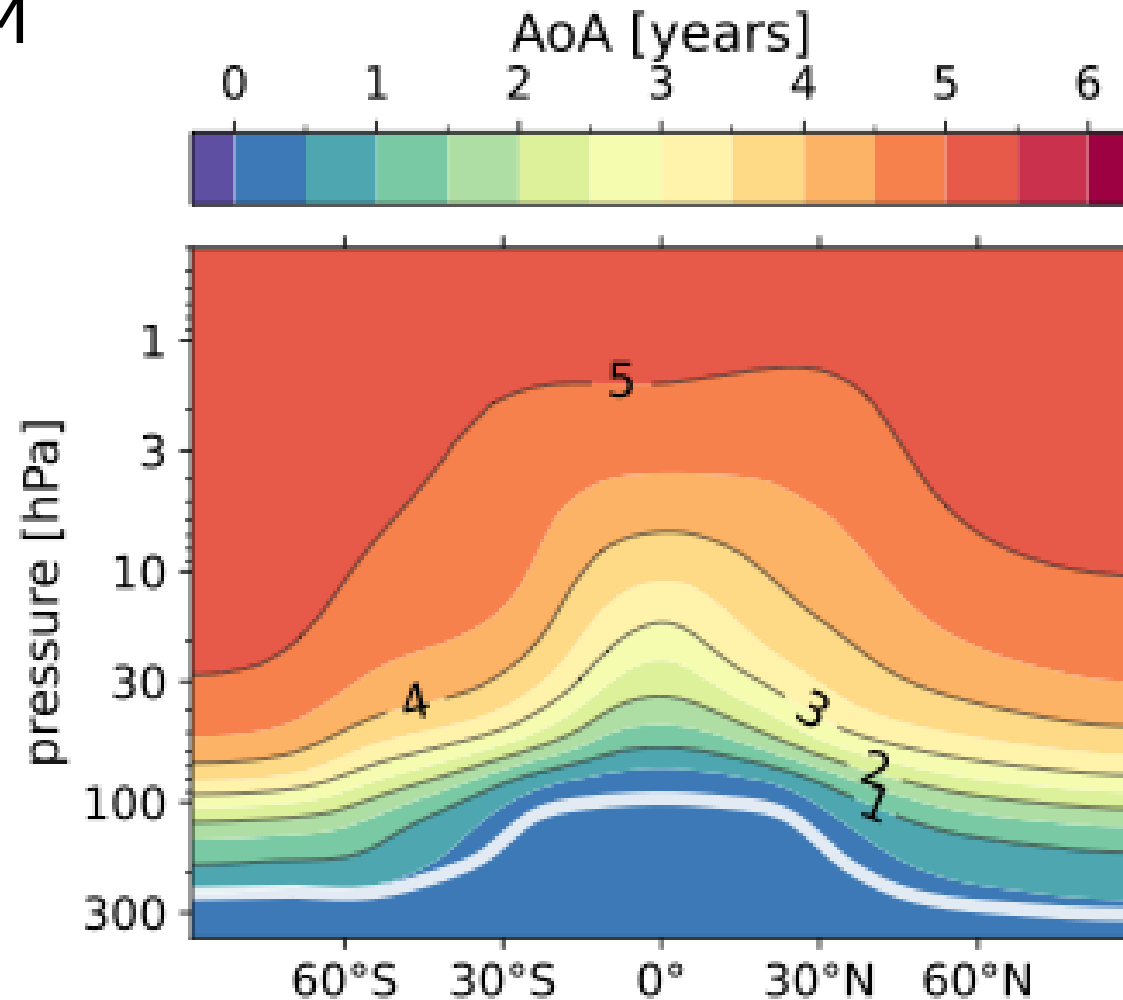
- higher, polar = older
- lower, tropical = younger
- oldest air:
>5 years since tropospheric contact

meridional transport is **slow**

Why we care:

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

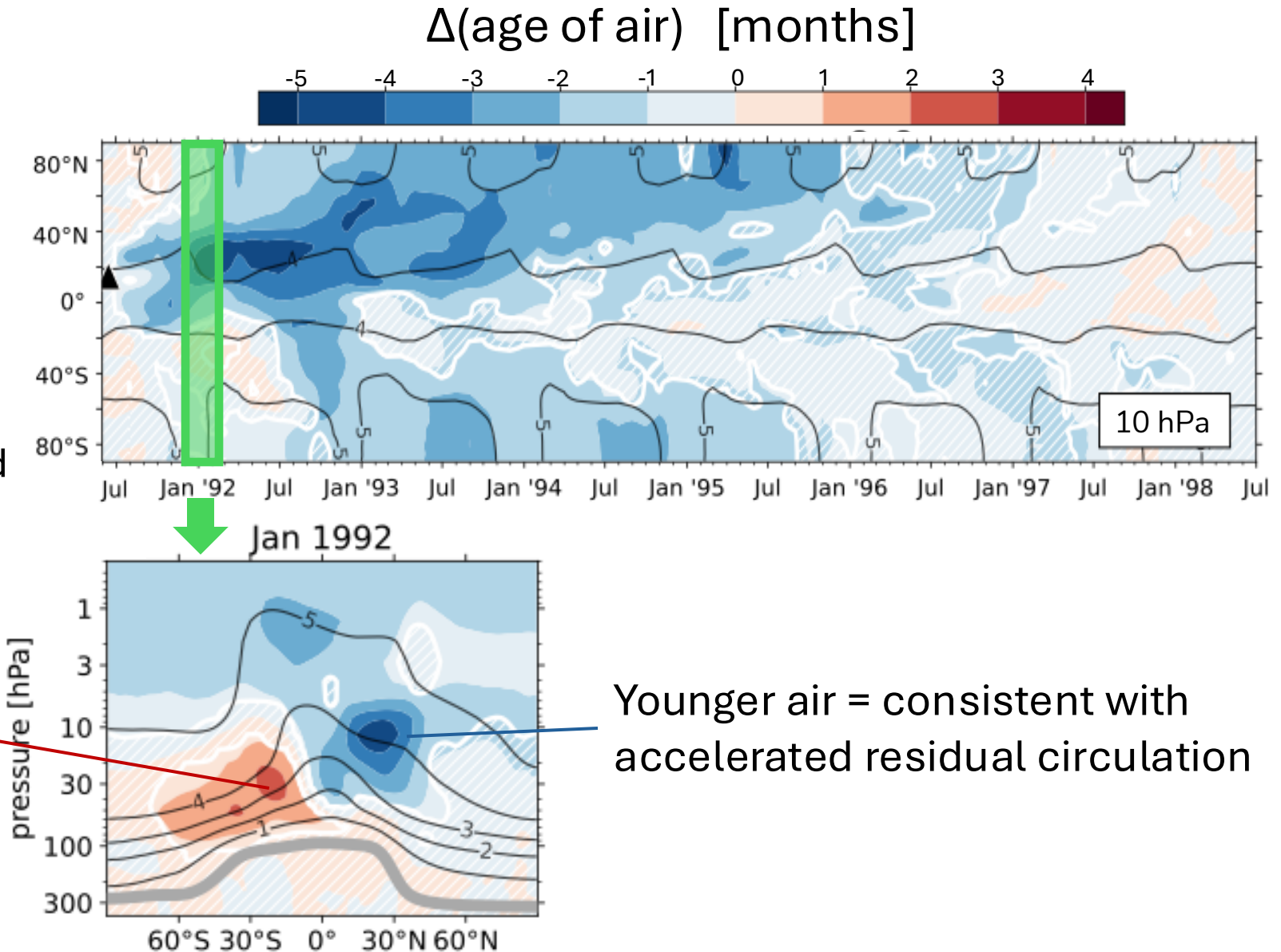
transport is thus **determines chemical evolution** in the upper atmosphere



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

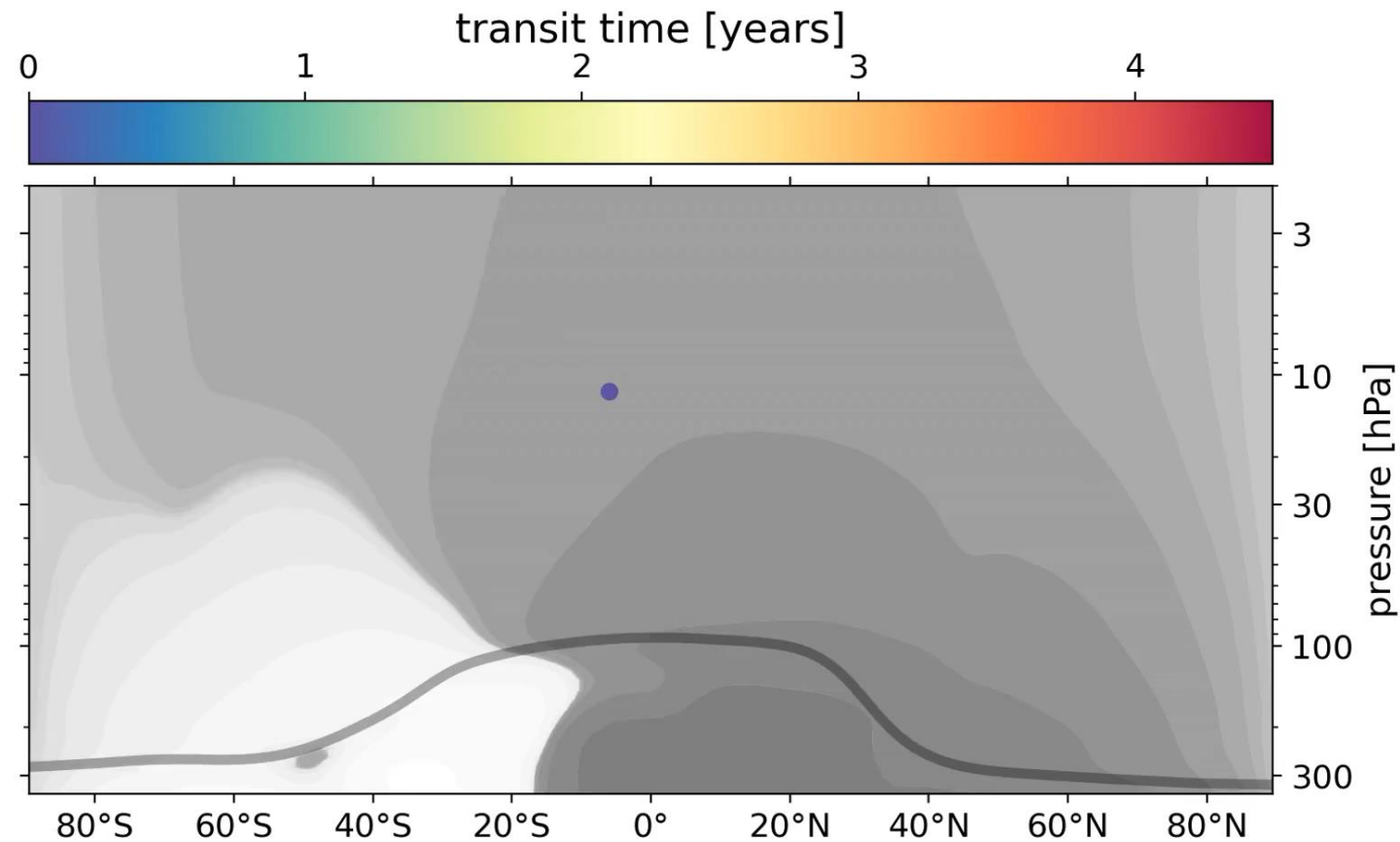
Impacts persist at high latitudes for
> 4 years

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

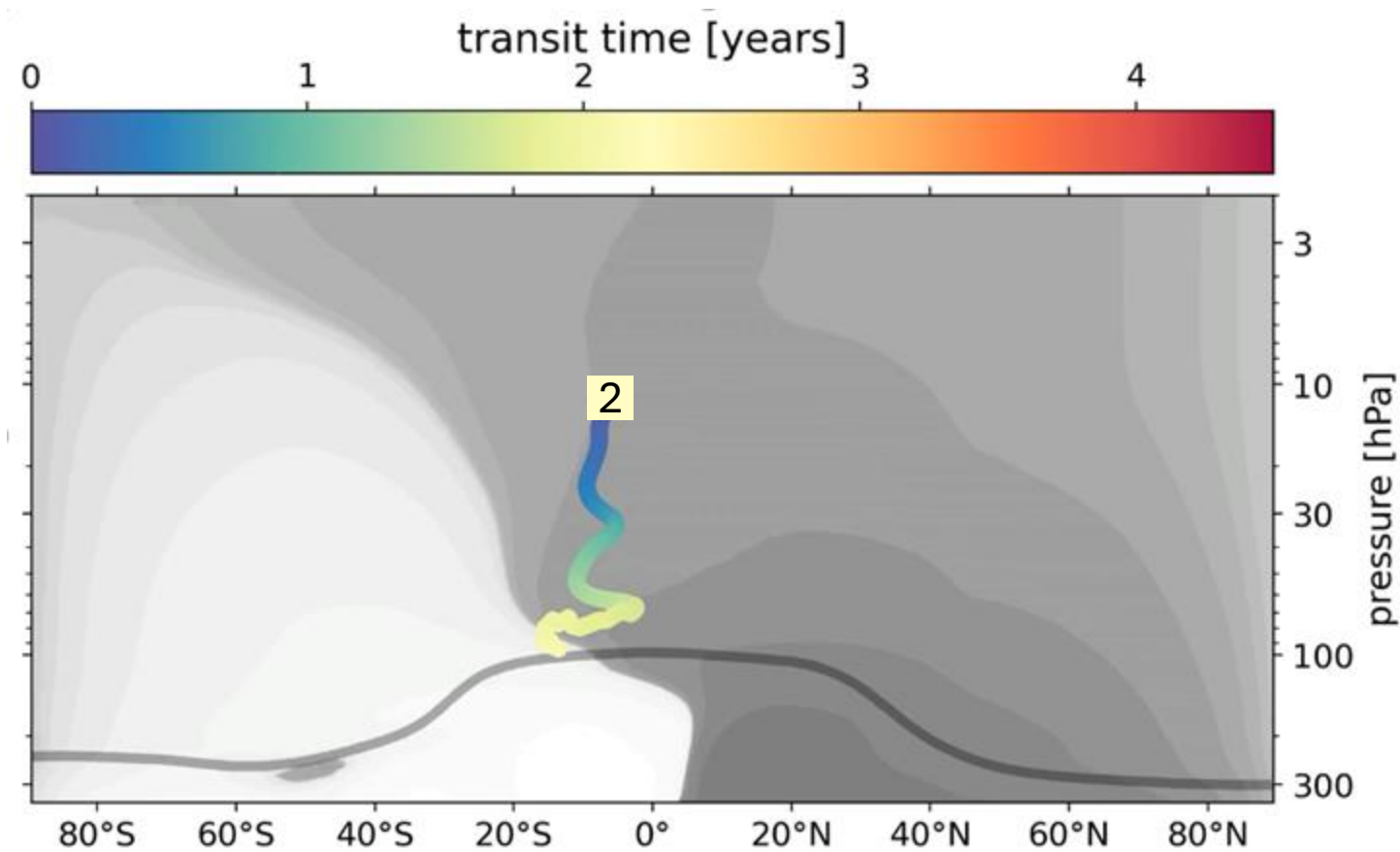


measurement of the residual circulation transit time (RCTT)

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

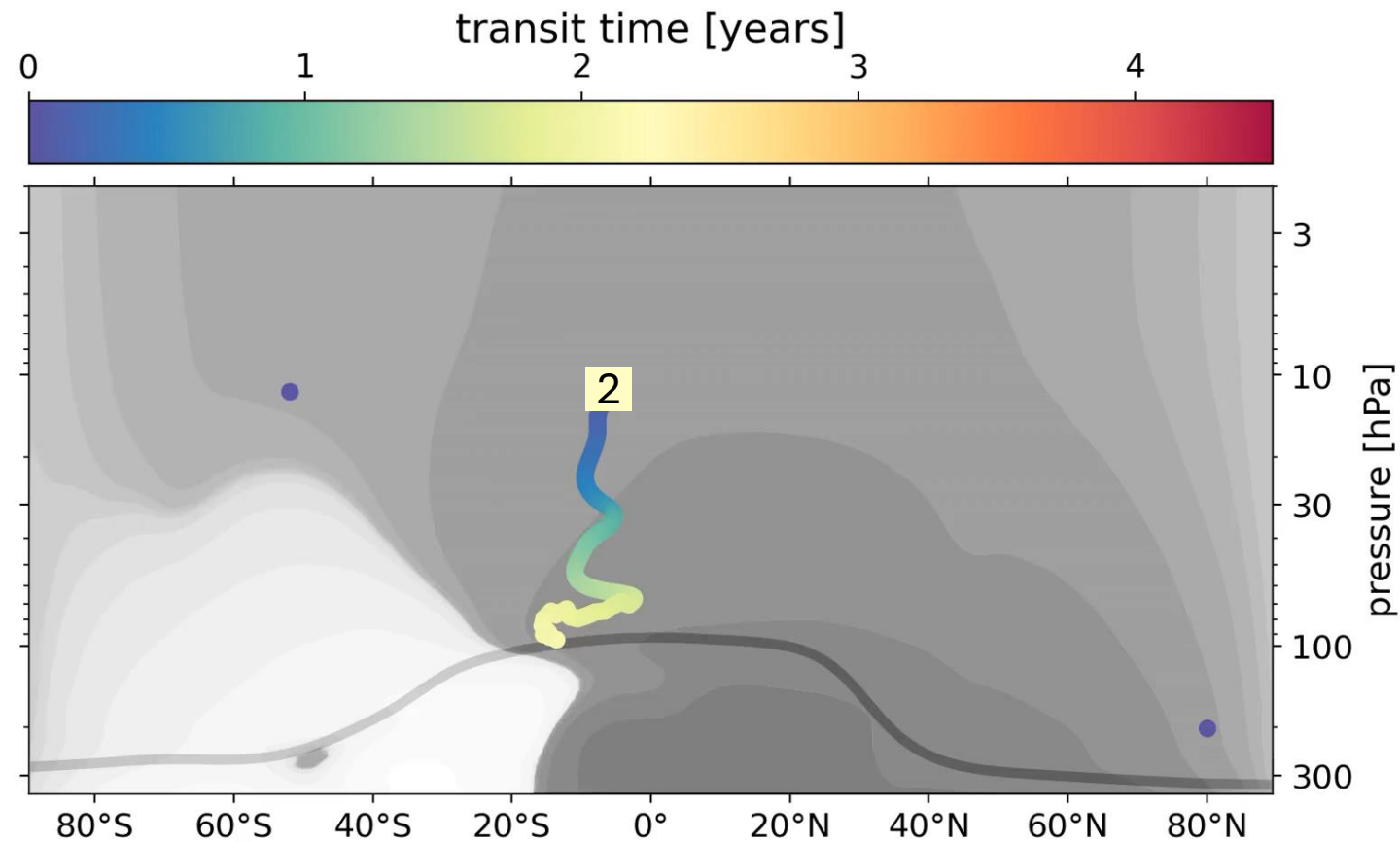


measurement of the residual circulation transit time (**RCTT**)
(numerical integration of the time-varying residual-circulation (v^* , w^*))



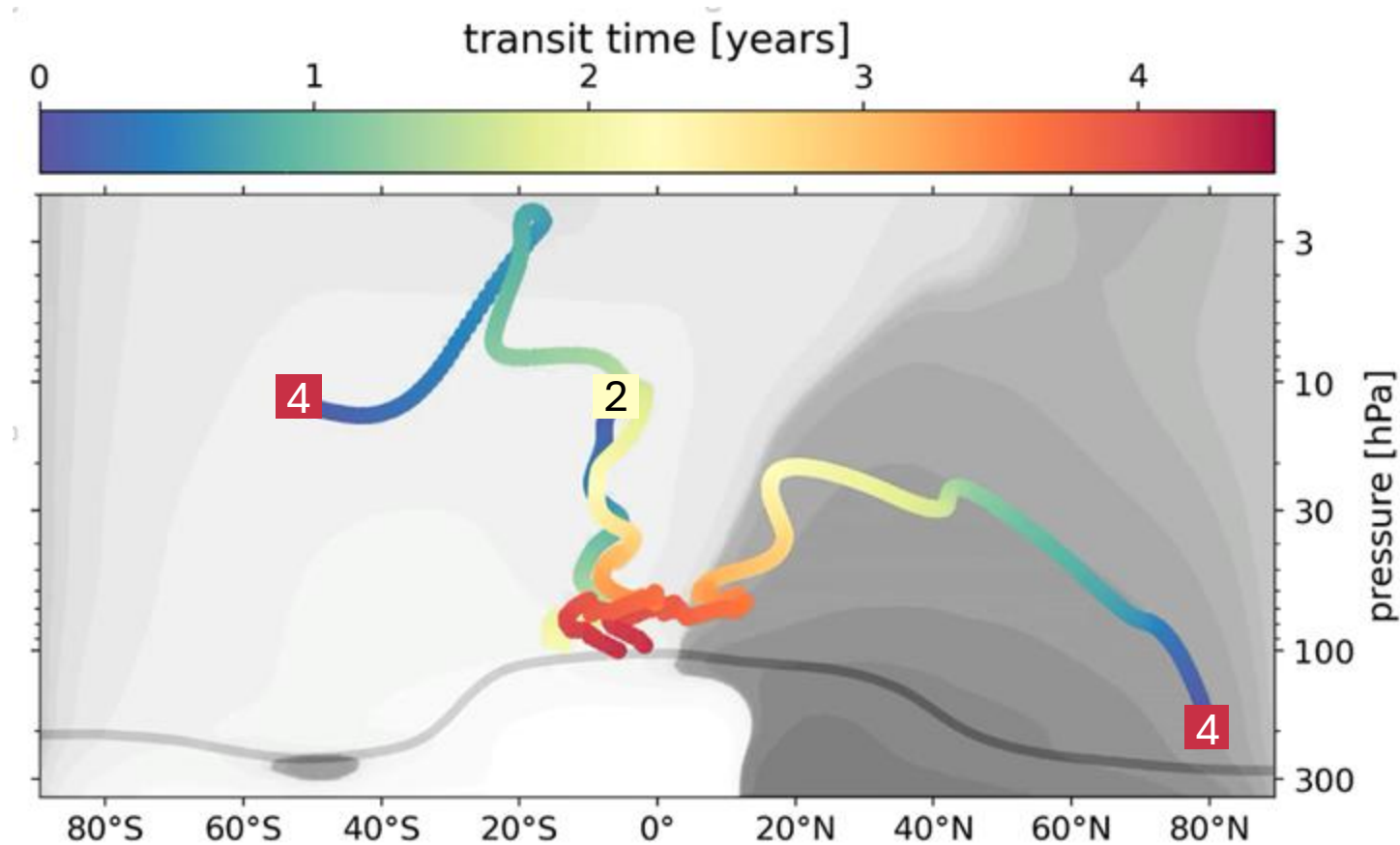
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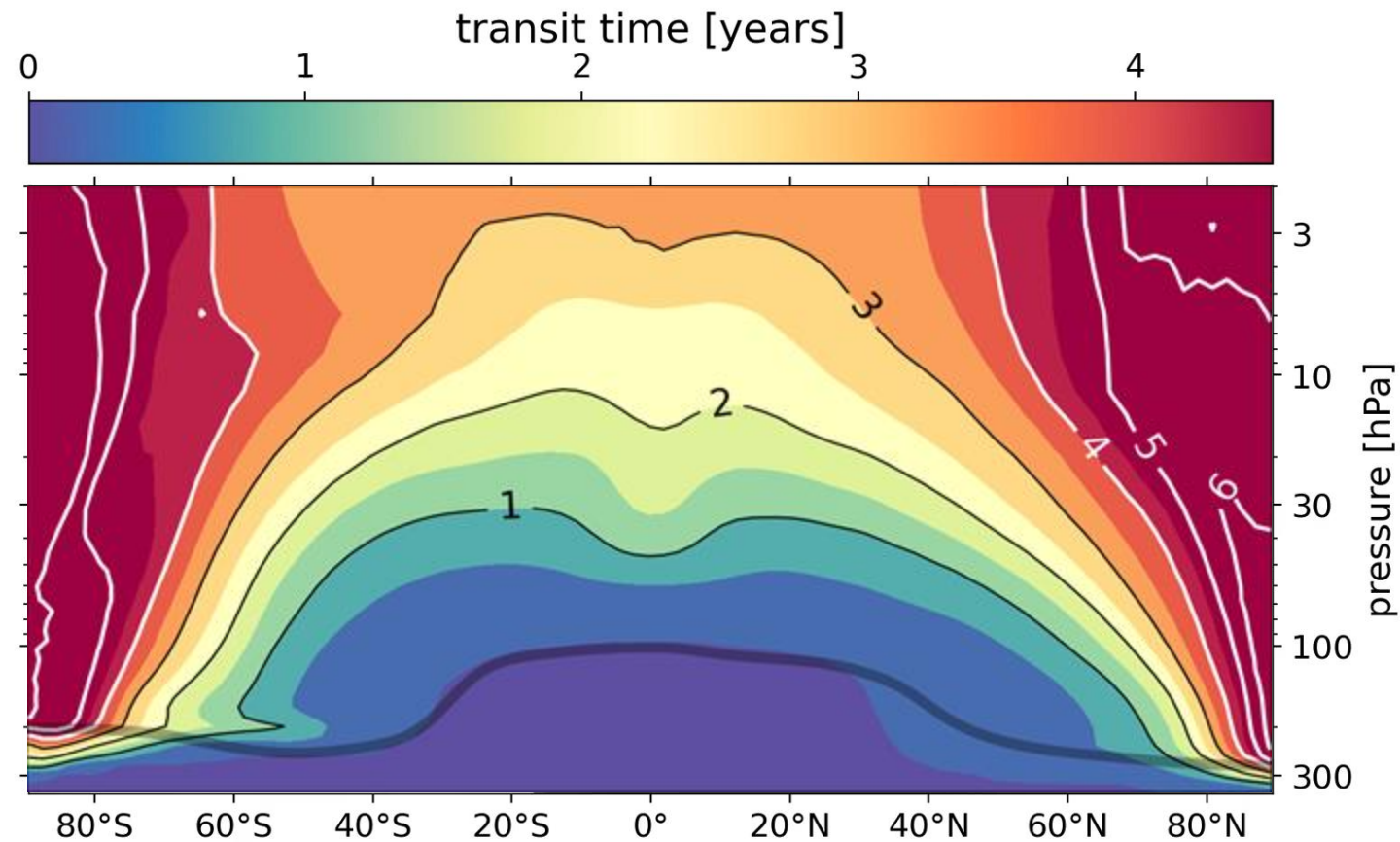


measurement of the residual circulation transit time (RCTT)

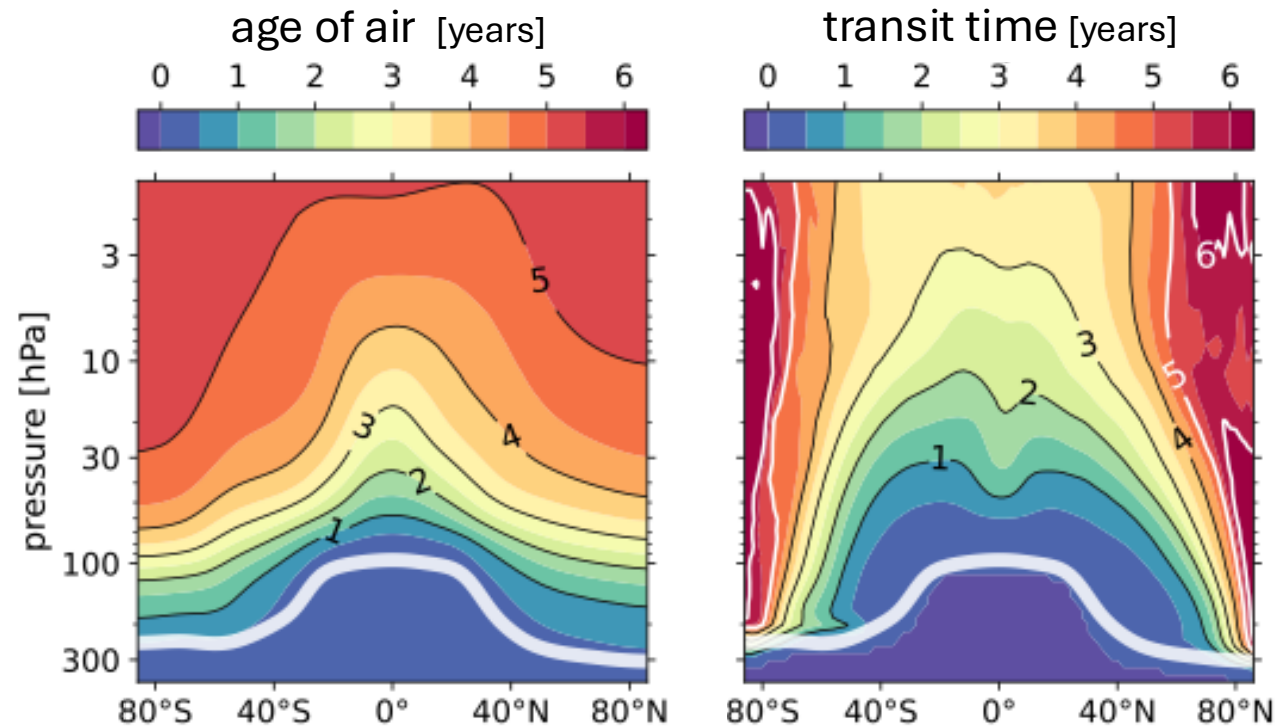
(numerical integration of the time-varying residual-circulation (v^* , w^*))



5-year time-mean, ensemble-mean RCTT

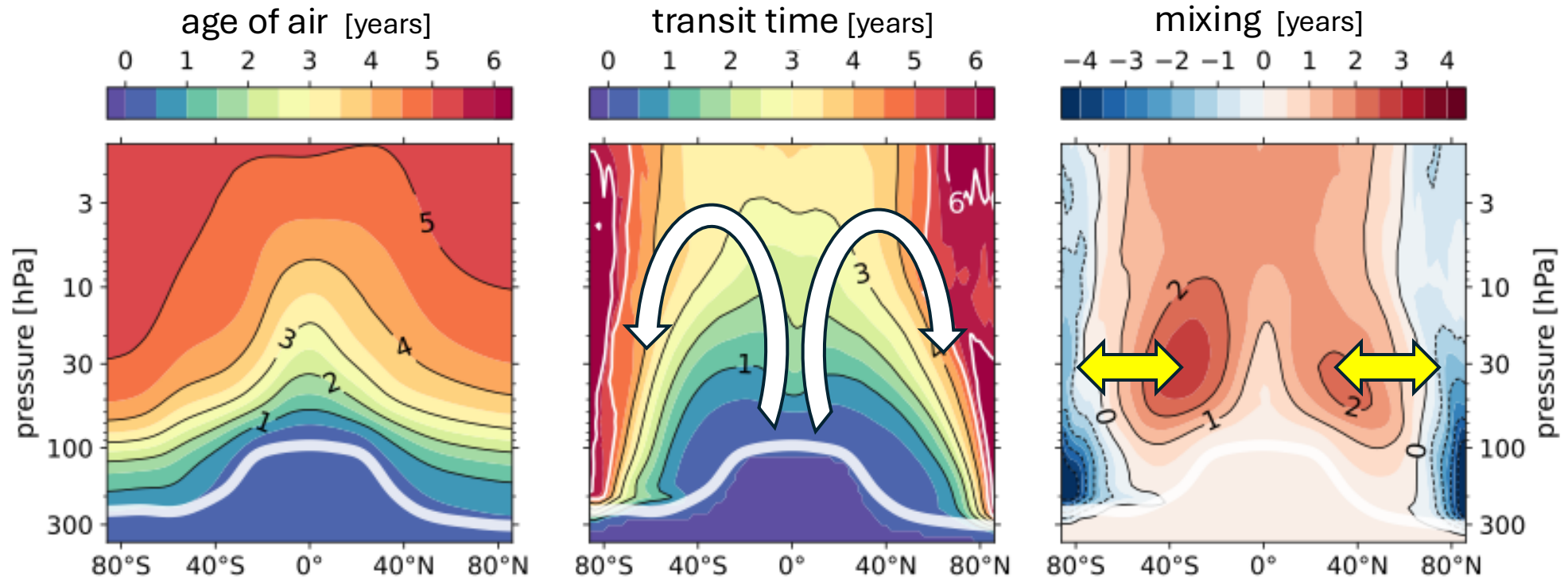


Comparing age to transit time



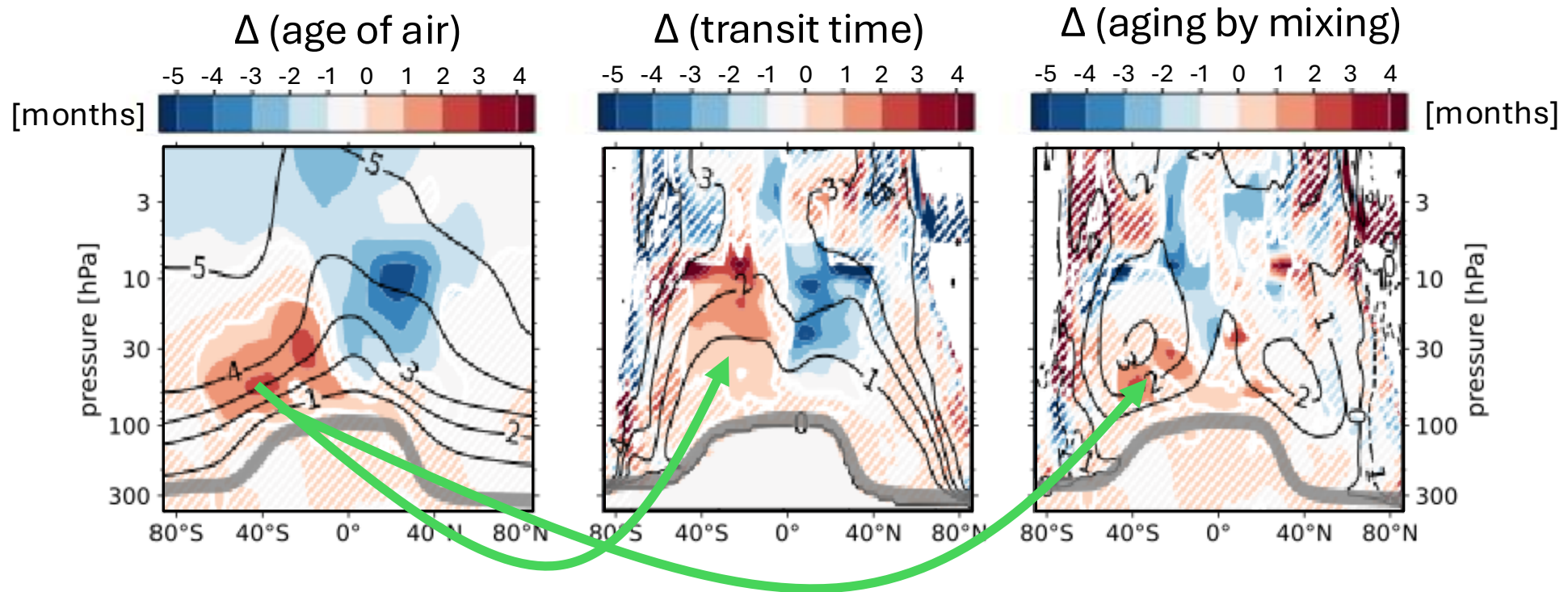
Comparing age to transit time

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

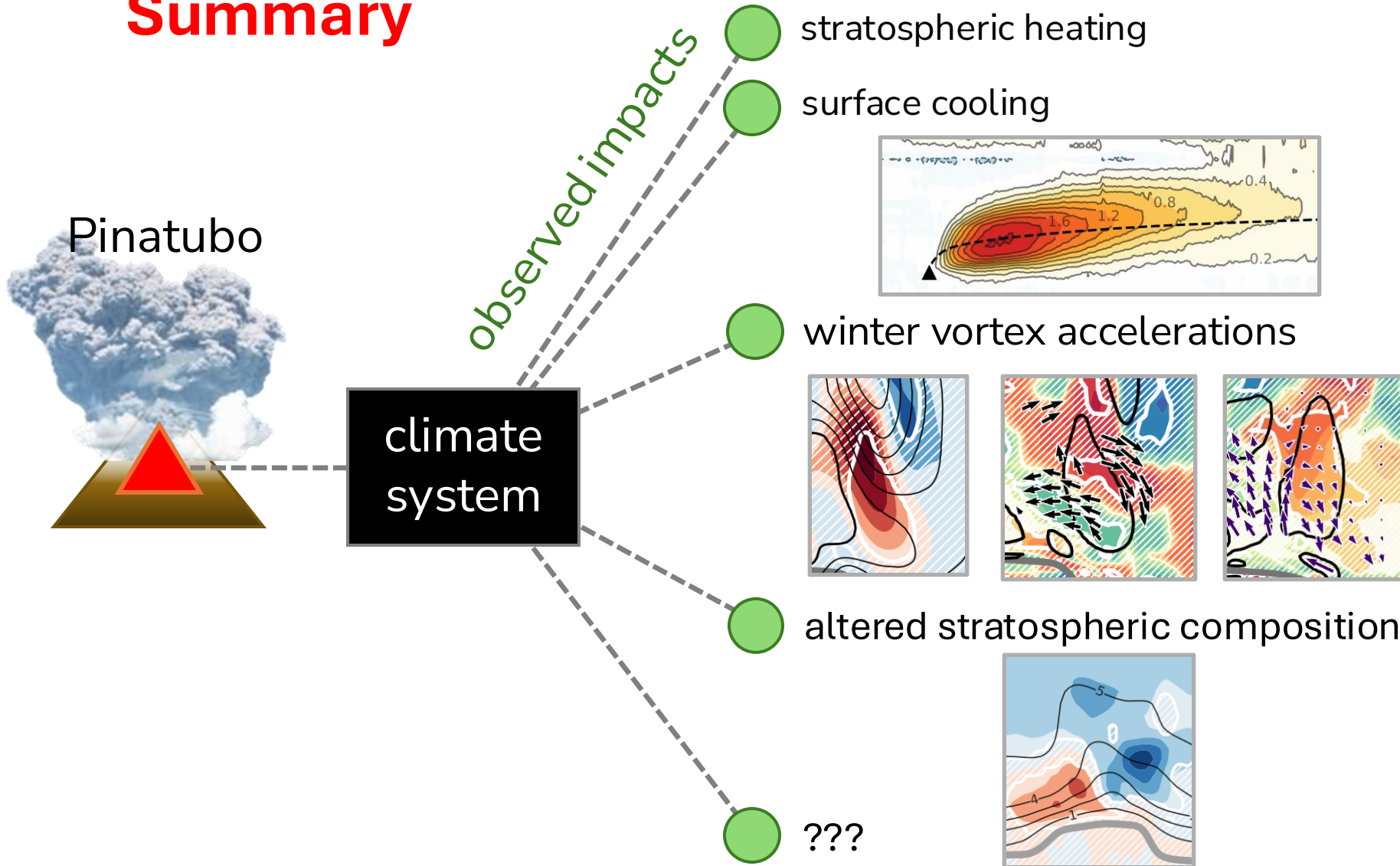
Low-latitude summertime eruptions seem to reliably produce the positive aging signal

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



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

Part 2:
Seasonal mechanisms
identified:

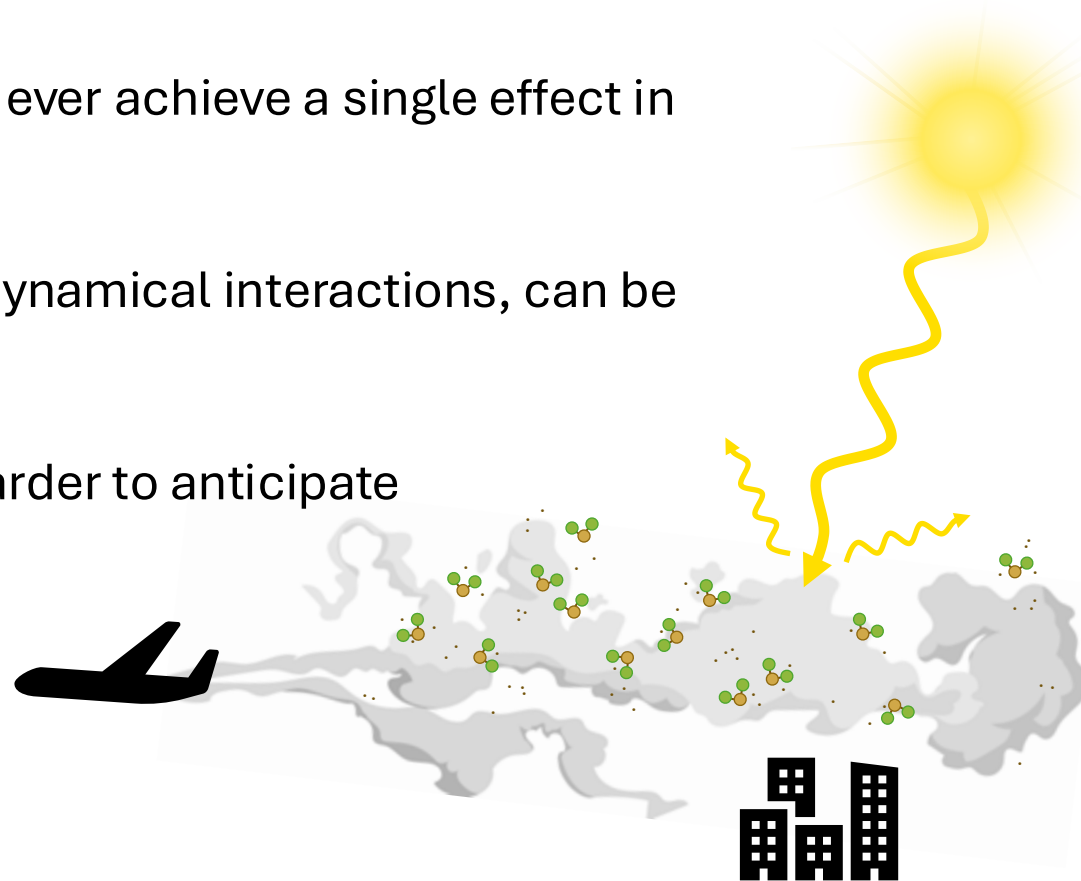
- wintertime **wave deflection**
- summertime **enhanced circulation**

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



EGU in Vienna



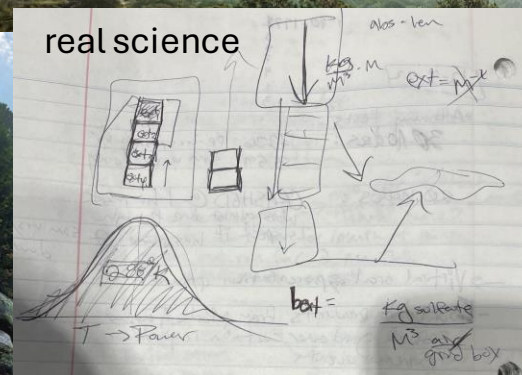
The CLDERA Team



our research group



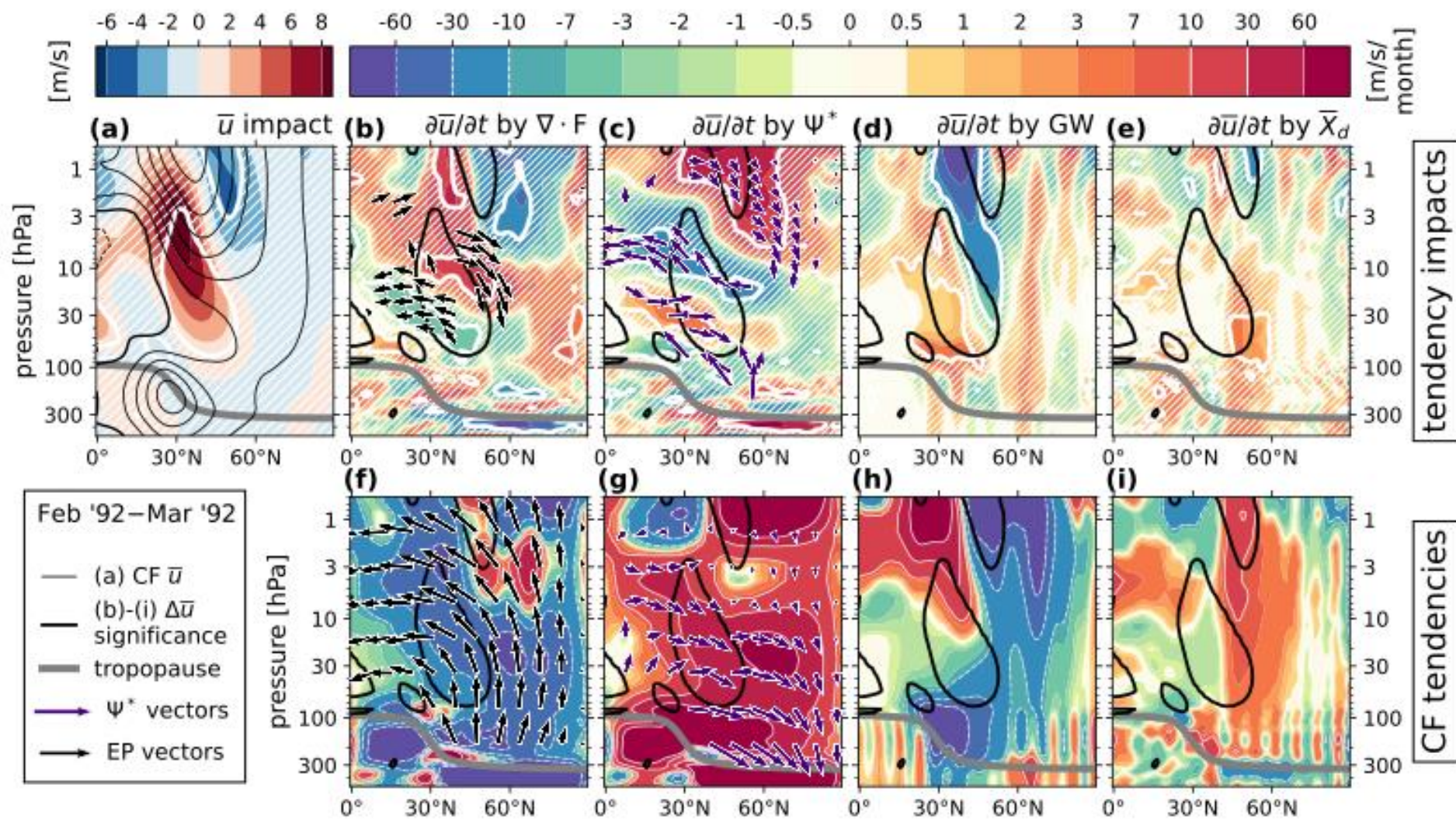
Summer in New Mexico

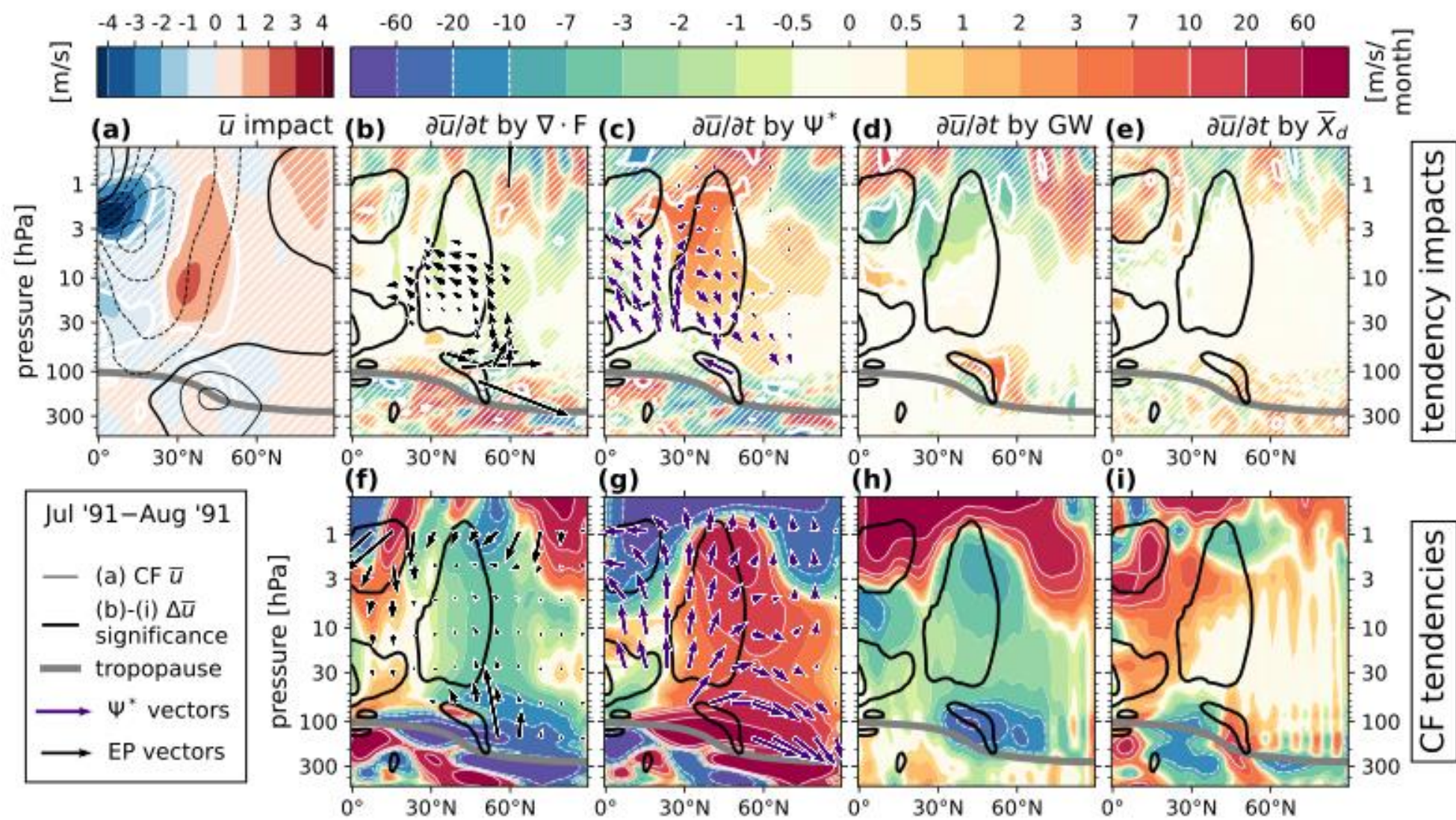


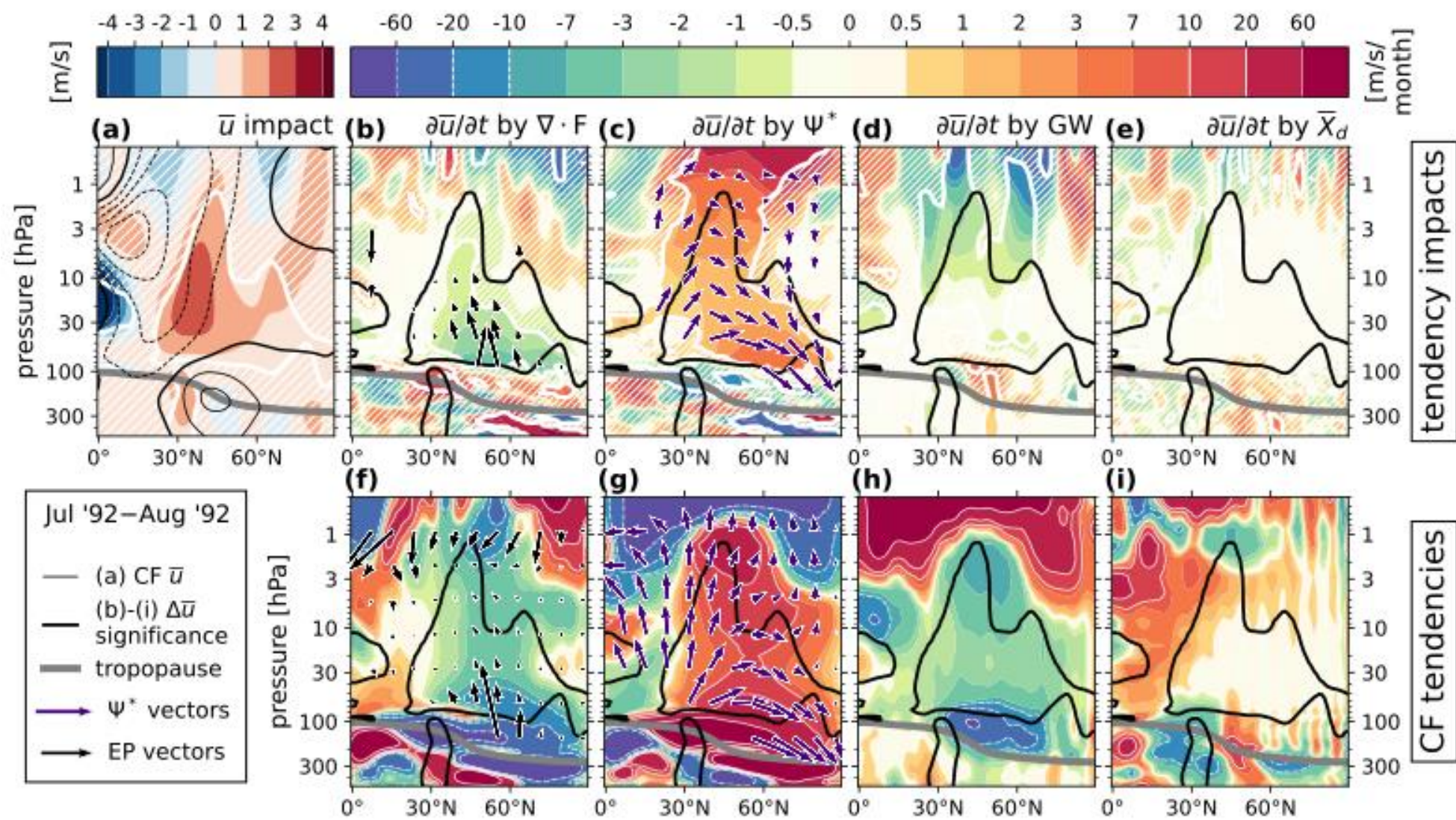


Thank you!

start backup slides







Concept: the Transformed Eulerian Mean (TEM)

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

wind speed
zonal mean
eddy

Predictive eq. for zonal wind:

$$\frac{Du}{Dt} = fv + p_x - X \quad \longrightarrow \quad \frac{\partial \bar{u}}{\partial t} + \bar{v}\bar{u}_y + \bar{w}\bar{u}_z = f\bar{v} - (\overline{u'v'})_y - (\overline{u'w'})_z - \bar{X}$$

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

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

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

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

