Resolving weather fronts increases the large-scale circulation response to Gulf Stream SST anomalies

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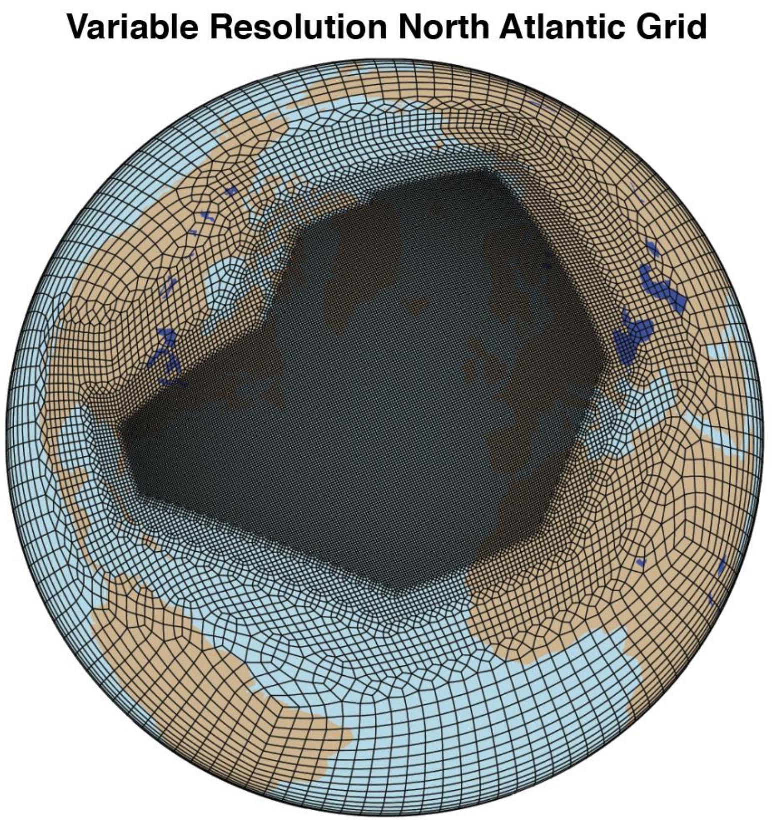
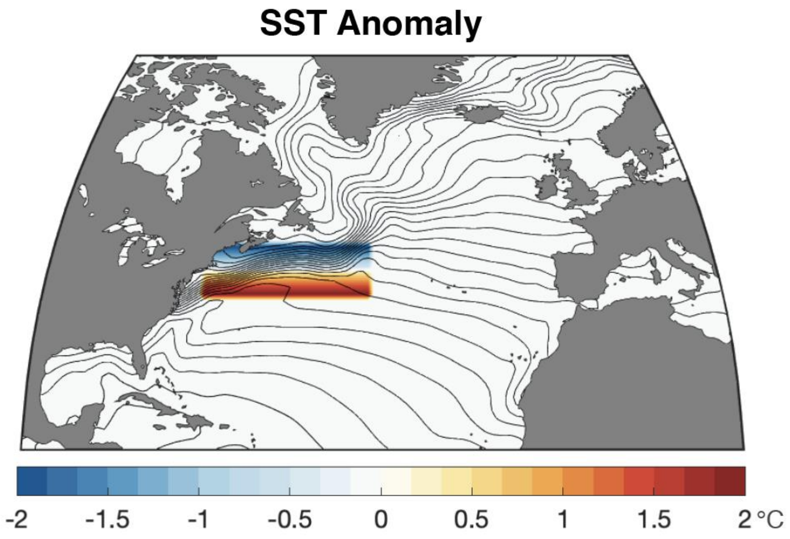
(from April 2023)





CVCWG Meeting
February 21, 2023

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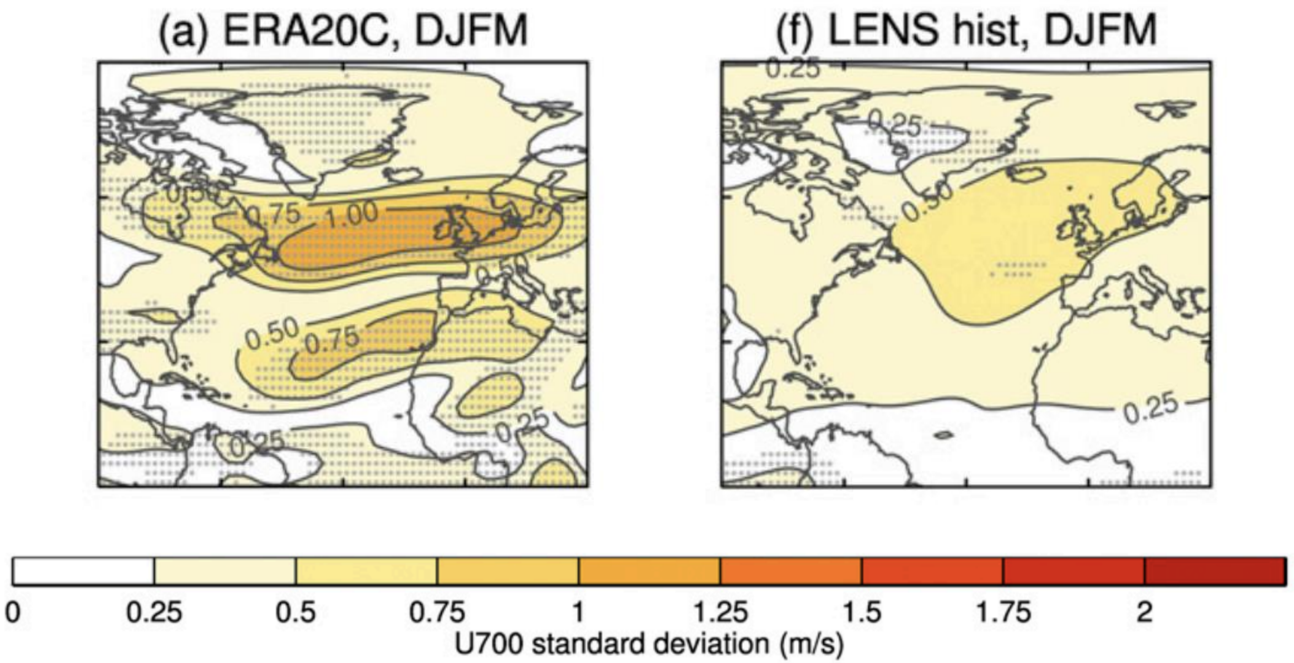
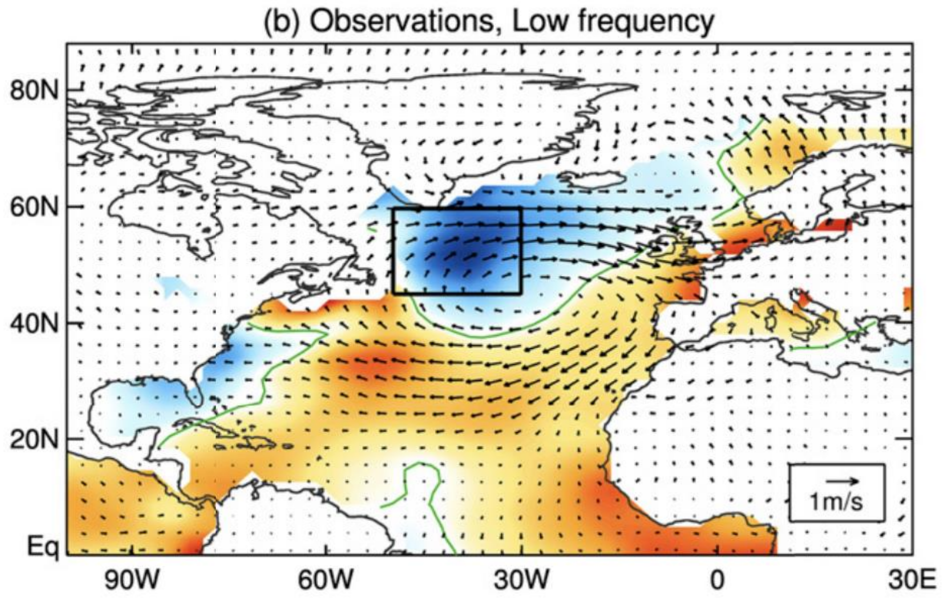
Motivation: Underestimation of multi-decadal atmospheric circulation variability in coupled models





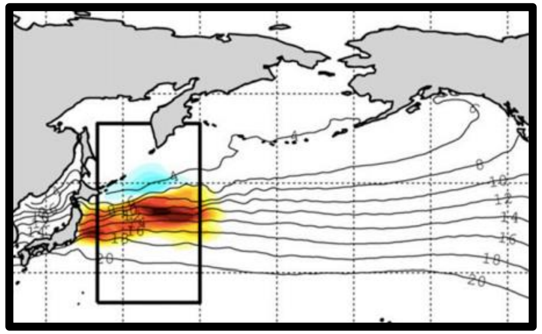
- Wintertime multi-decadal variance in U700 weaker in coupled models than reanalysis
- Also found for multi-decadal variance in sea-level pressure (SLP) *(O'Reilly et al. 2021)*

- Regression of SST anomalies on U700 anomalies shows an apparent relationship

Simpson et al. 2018

Is the weak response of atmospheric circulations to midlatitude SST anomalies an artifact of low resolution?

- The response of the large-scale atmospheric circulation to midlatitude SST anomalies has generally been found to be weak in AGCMs *(Kushnir et al. 2002)*
- However, some studies have found a much larger response at higher resolution *(Smirnov et al. 2015; see also review by Czaja et al. 2019)*

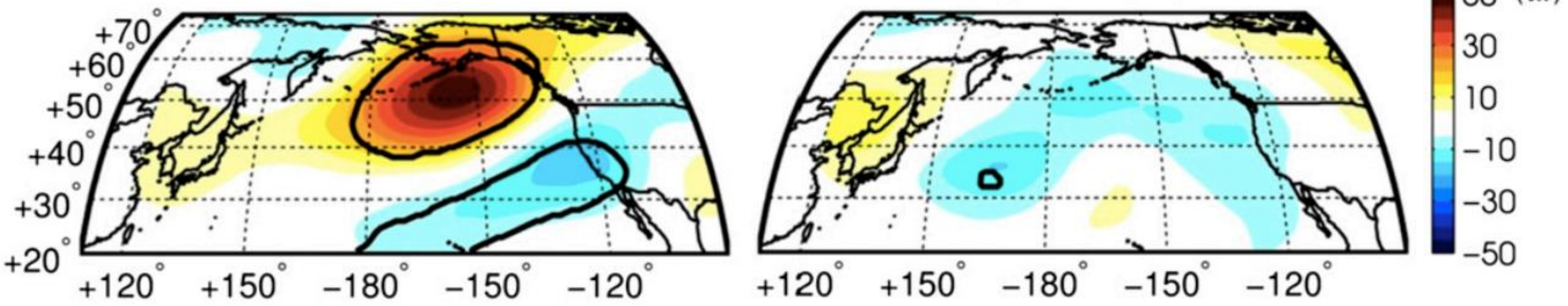


Smirnov et al. 2015

Atmospheric (Z200) response to sharp SST front:

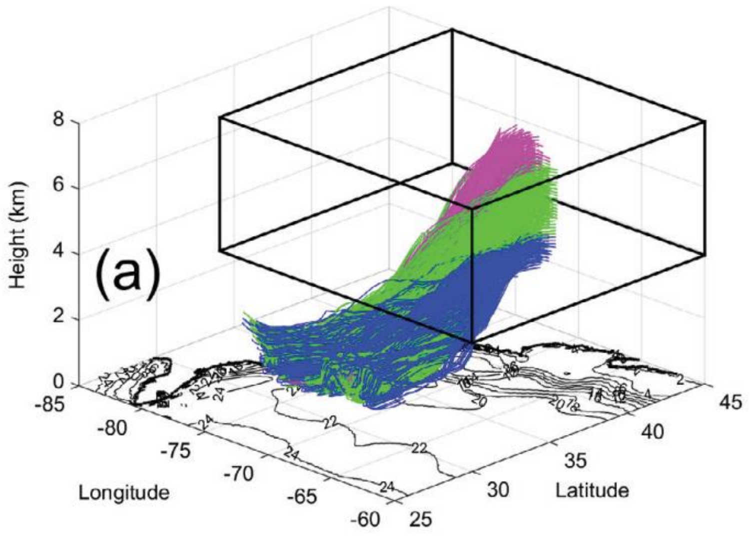
High Atmospheric Resolution (0.25°)

Low Atmospheric Resolution (1°)

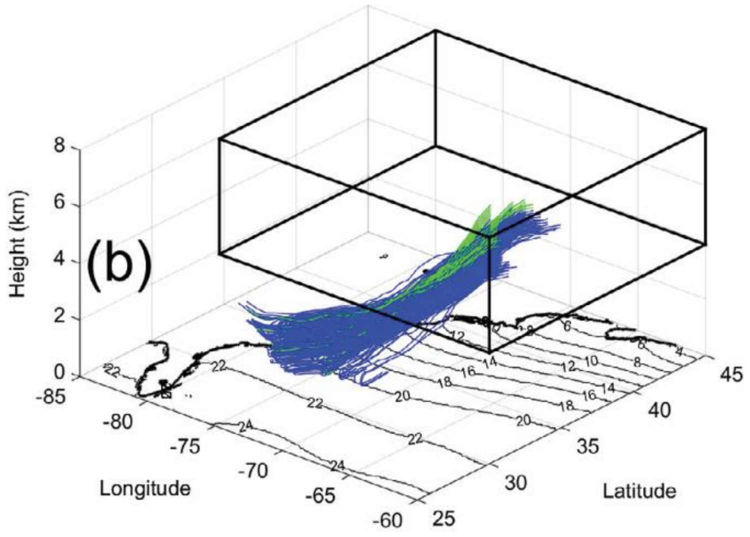


Higher resolution resolves influence of SST front on ascent in frontal bands

Ascent trajectories over Gulf Stream SST front



Ascent trajectories over smoothed SST front



Ascent over SST fronts found to be much larger at 12-km (~1/8°) resolution than 40-km resolution (in a regional model)

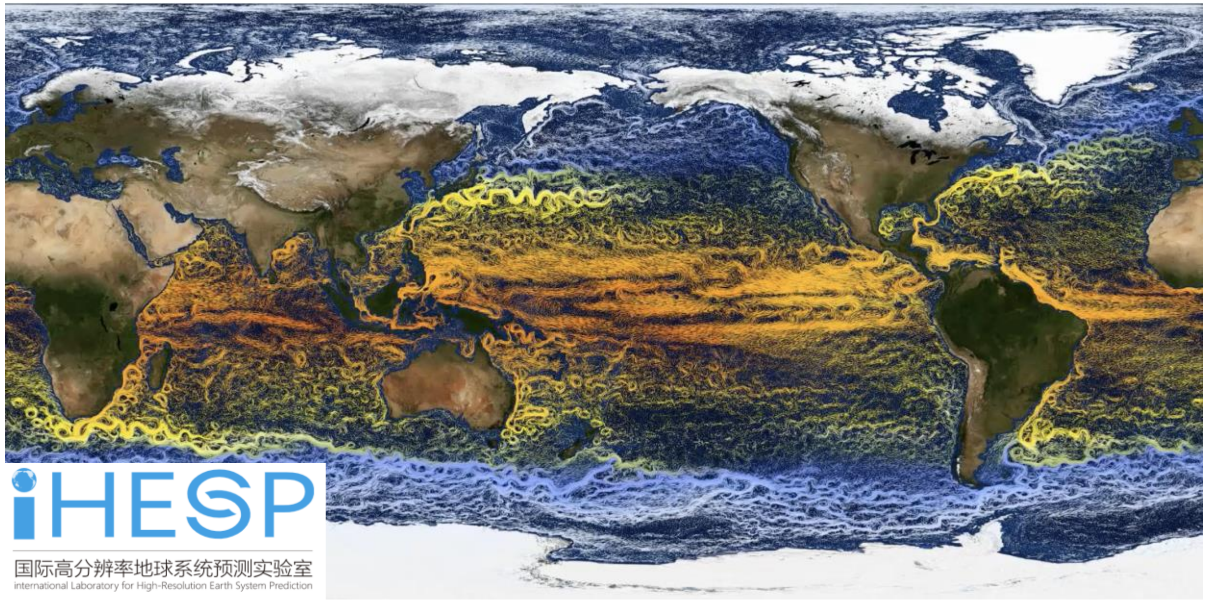
How does this influence the large-scale circulation?

Sheldon et al. (2017)

Most existing high-resolution climate modeling efforts use 1/4° atmospheric resolution

High Resolution Model Intercomparison Project

Model name	Contact institute	Atmosphere resolution (STD/HI) mid-latitude (km)	Ocean resolution (HI)
AWI-CM	Alfred Wegener Institute	T127 (~100 km) T255 (~50 km)	$1–\frac{1}{4}°$ 0.05–1°
BCC-CSM2-HR	Beijing Climate Center	T106 (~110 km) T266 (~45 km)	$\frac{1}{3}–1°$
BESM	INPE	T126 (~100 km) T233 (~60 km)	0.25°
CAM5	Lawrence Berkeley National Laboratory	100 km 25 km	
CAM6	NCAR	100 km 28 km	
CMCC	Centro Euro-Mediterraneo sui Cambiamenti Climatici	100 km 25 km	0.25°
CNRM-CM6	CERFACS	T127 (~100 km) T359 (~35 km)	1° 0.25°
EC-Earth	SMHI, KNMI, BSC, CNR, and 23 other institutes	T255 (~80 km) T511/T799 (~40/25 km)	1° 0.25°
FGOALS	LASG, IAP, CAS	100 km 25 km	0.1–0.25°
GFDL	GFDL	200 km –	
INMCM-5H	Institute of Numerical Mathematics	– 0.3 × 0.4°	0.25 × 0.5° $\frac{1}{6} \times \frac{1}{8}°$
IPSL-CM6	IPSL	0.25°	
MPAS-CAM	Pacific Northwest National Laboratory	– 30–50 km	0.25°
MIROC6-CGCM	AORI, Univ. of Tokyo/JAMSTEC/National Institute for Environmental Studies (NIES)	– T213	0.25°
NICAM	JAMSTEC/AORI/ The Univ. of Tokyo/RIKEN/AICS	56–28 km 14 km (short term)	
MPI-ESM	Max Planck Institute for Meteorology	T127 (~100 km) T255 (~50 km)	0.4°
MRI-AGCM3	Meteorological Research Institute	TL159 (~120 km) TL959 (~20 km)	
NorESM	Norwegian Climate Service Centre	2° 0.25°	0.25°
HadGEM3-GC3	Met Office Hadley Centre	60 km 25 km	0.25°

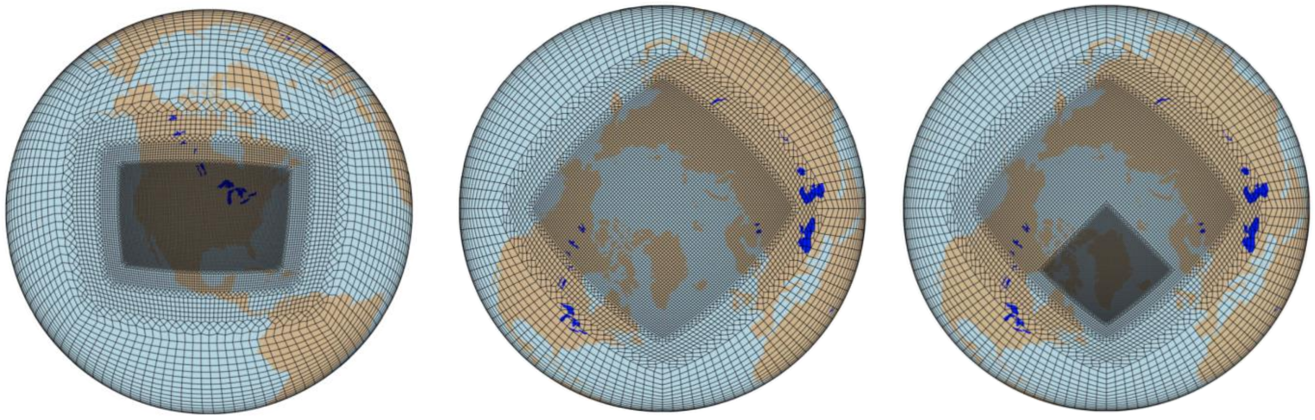


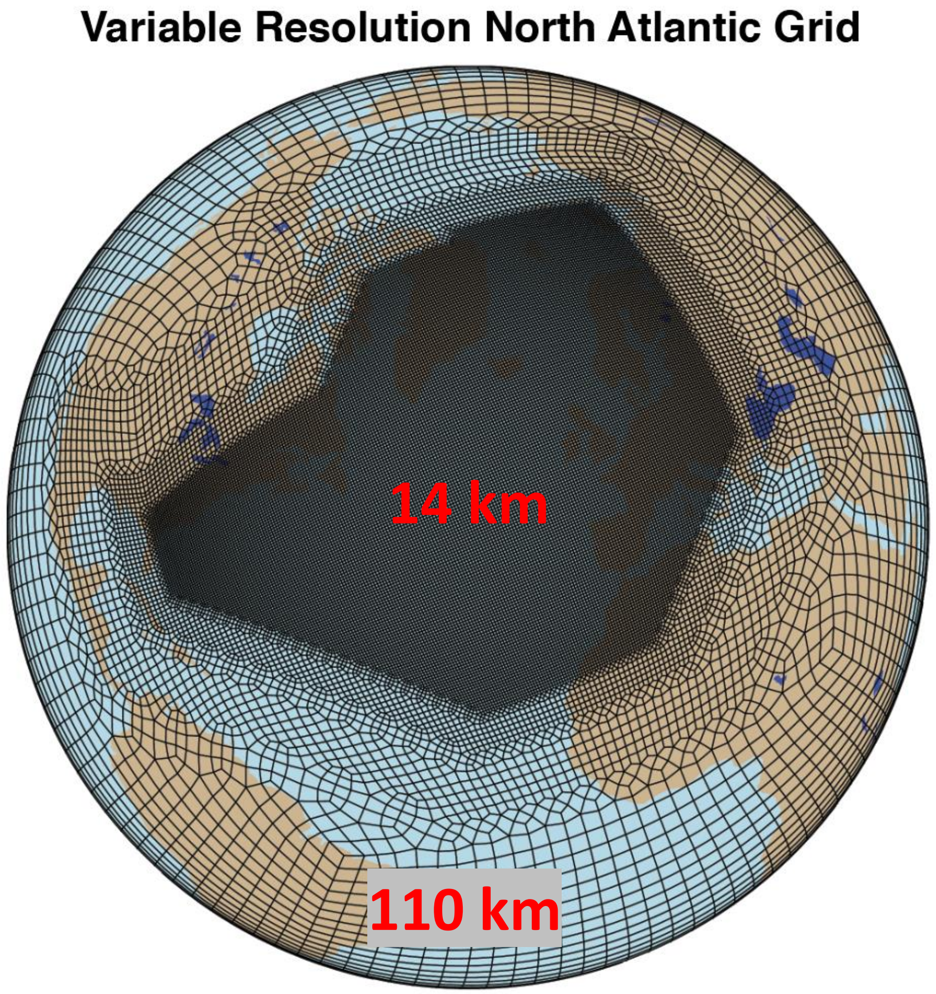
Many efforts underway to resolve mesoscale ocean eddies (e.g., 1/10° iHESP), but the atmosphere is generally still 1/4° (~25 km) and does not fully resolve atmospheric fronts

Haarsma et al. (2016); Chang et al. (2020)

Variable resolution capabilities in CAM6-SE and a new 1/8° (14 km) North Atlantic grid

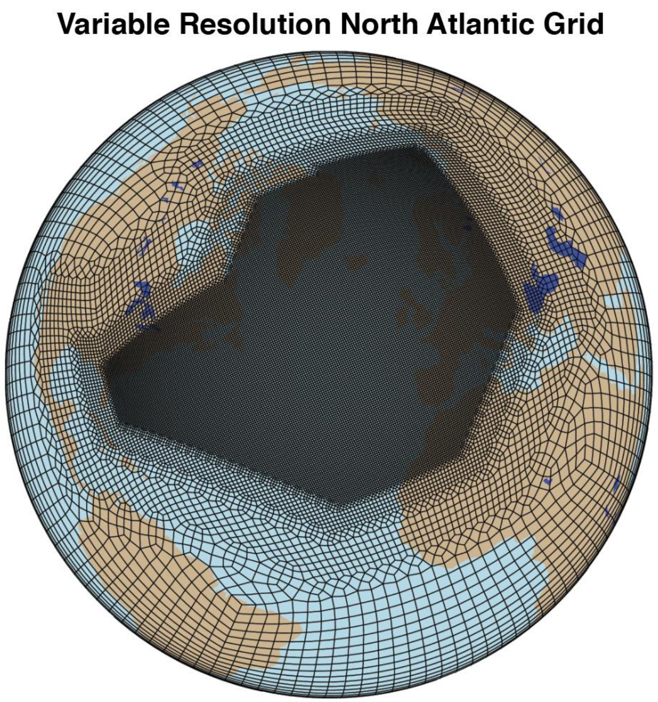
- Community Atmospheric Model Spectral Element Dynamical Core (CAM-SE) has variable resolution capabilities
- Existing grids include CONUS, Arctic, Greenland, and tropical North Atlantic
- We (*much of the heavy lifting by Adam Herrington*) have developed a new grid with 1/8° resolution over the extratropical North Atlantic (NATLx8)



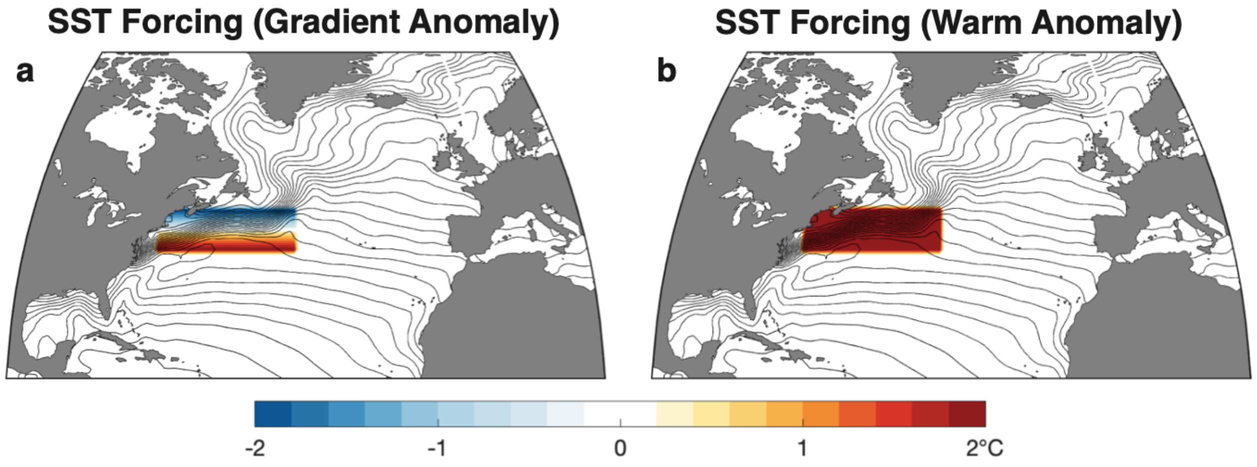


see e.g., Zarzycki et al. 2014; van Kampenhout et al. 2019

Idealized experiments with Gulf Stream SST anomalies

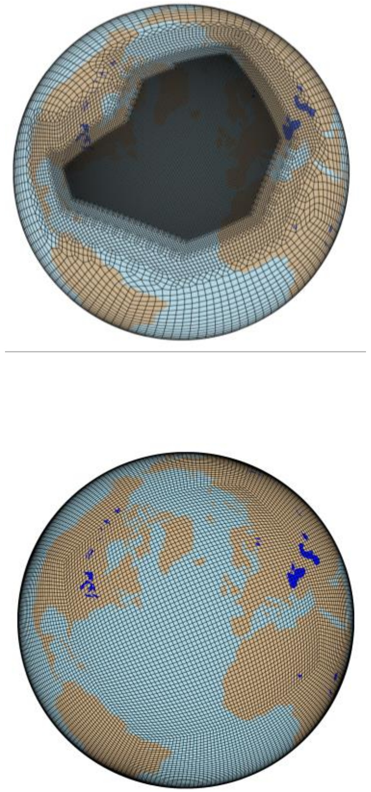


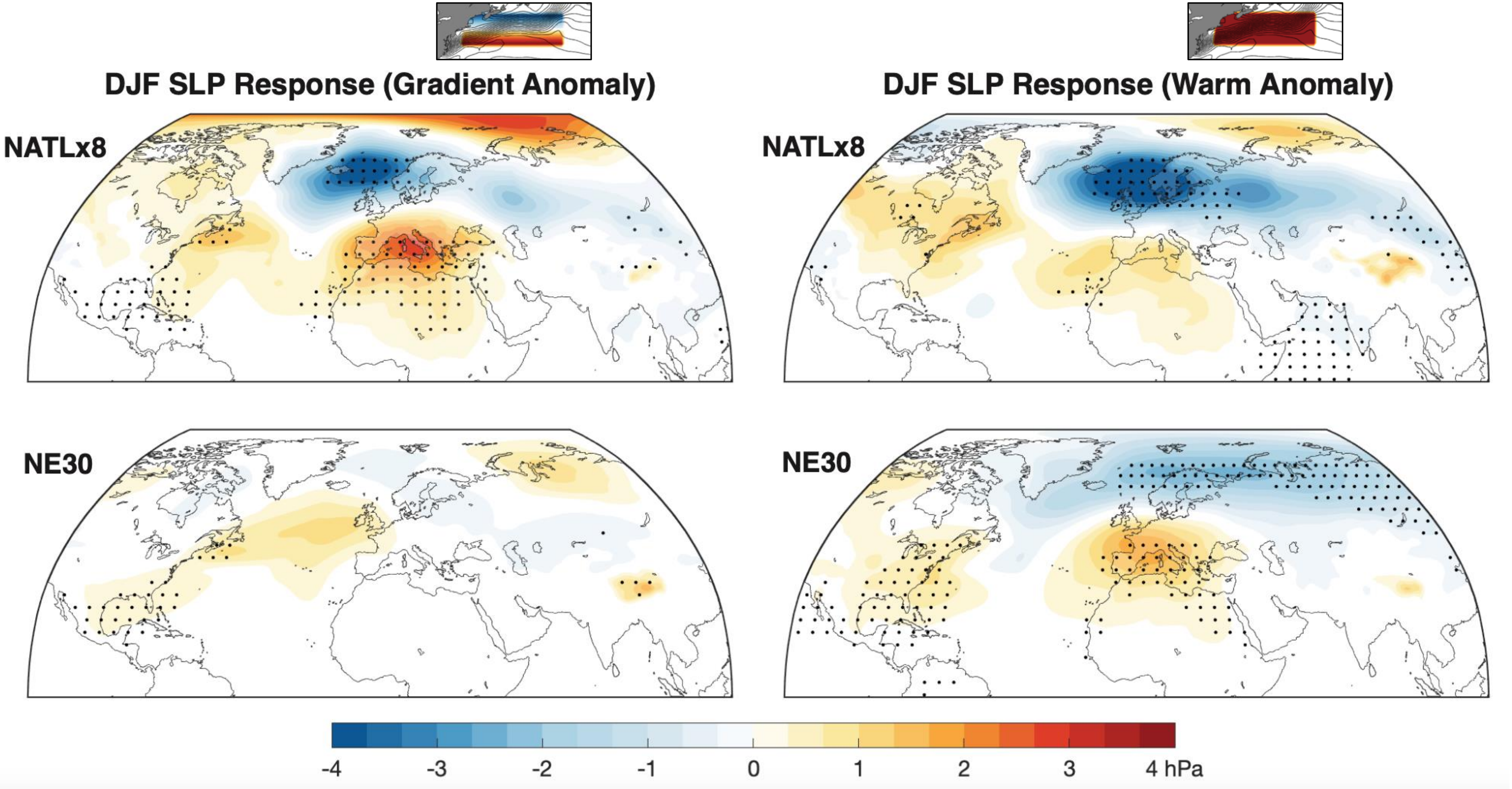
- **Reference:** Atmosphere-only (CAM6-SE) simulations with specified seasonally varying climatological SSTs **(1° resolution)**
- **Experiments:** Two different SST anomaly patterns in the Gulf Stream
- Each simulation run with the VR-NATL grid and with a 1° reference grid (NE30)



- Each simulation spun up for 5 years and averaged over the subsequent 15 years (NATLx8) or 45 years (NE30)
- Cost of NATLx8 is ~35x cost of NE30

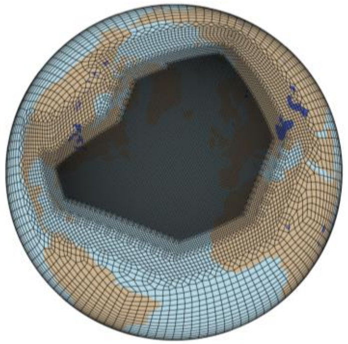
NAO-like large-scale circulation response

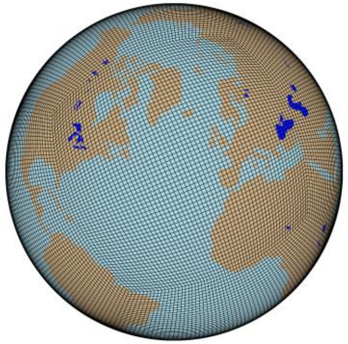


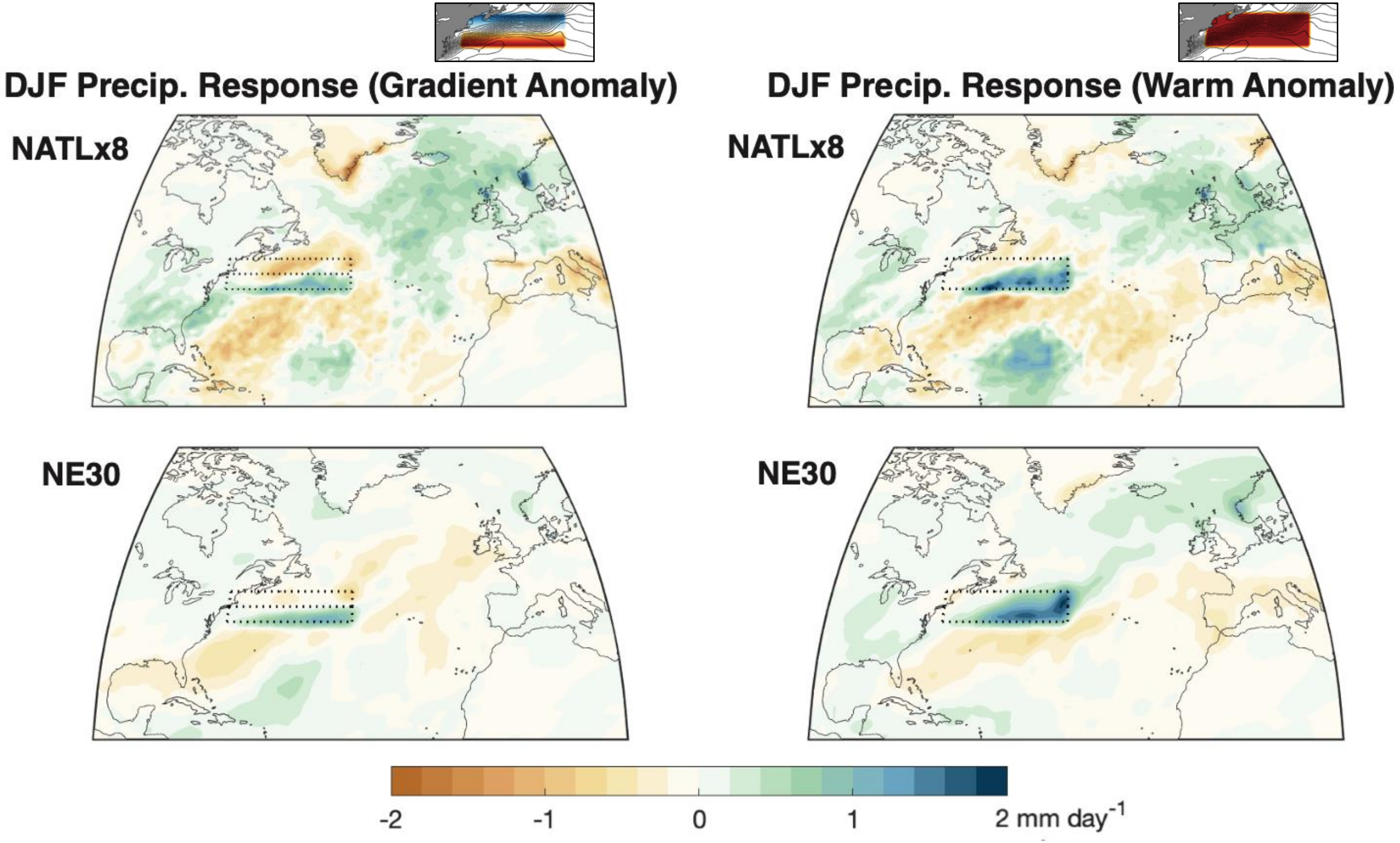


Stippling = significant at 90% confidence level as assessed by bootstrapping of internal variability

Similar precipitation responses in forcing region

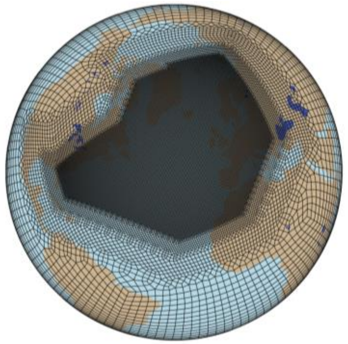


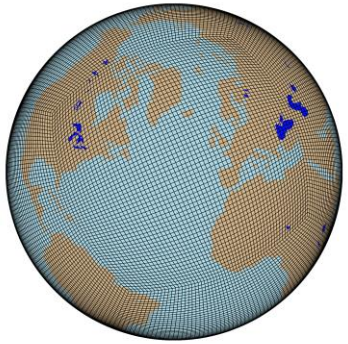


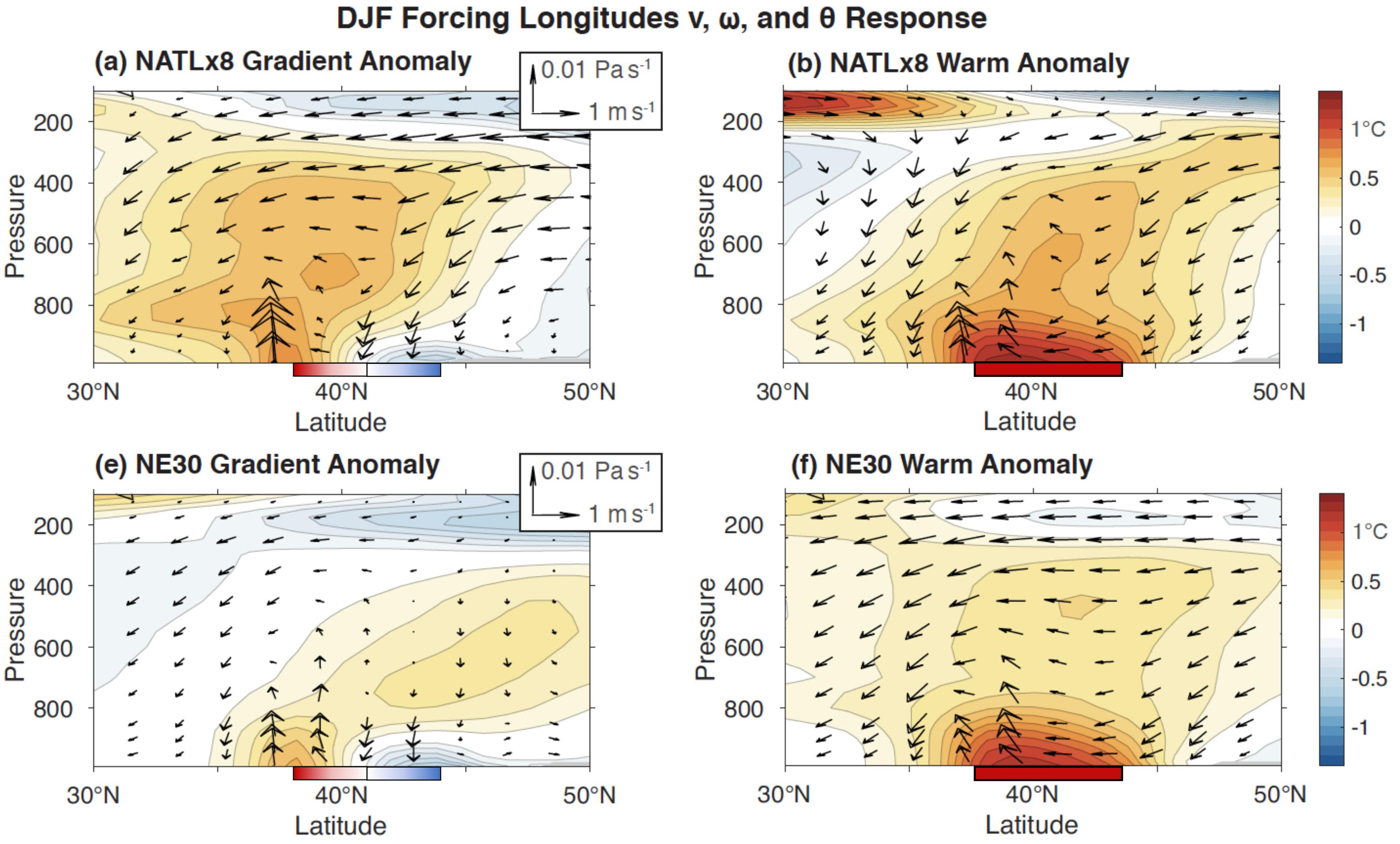


Latent heating is therefore also similar in the forcing region (not shown) and doesn’t explain difference in response

Similar time-mean ascent, but deeper warm anomaly

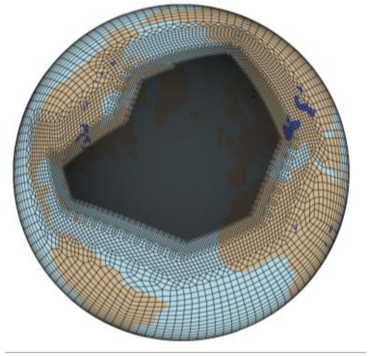


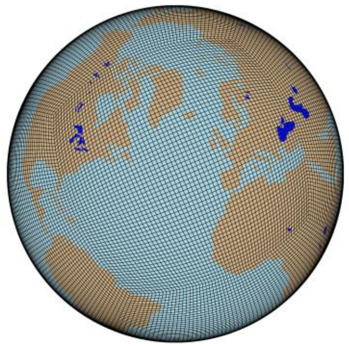


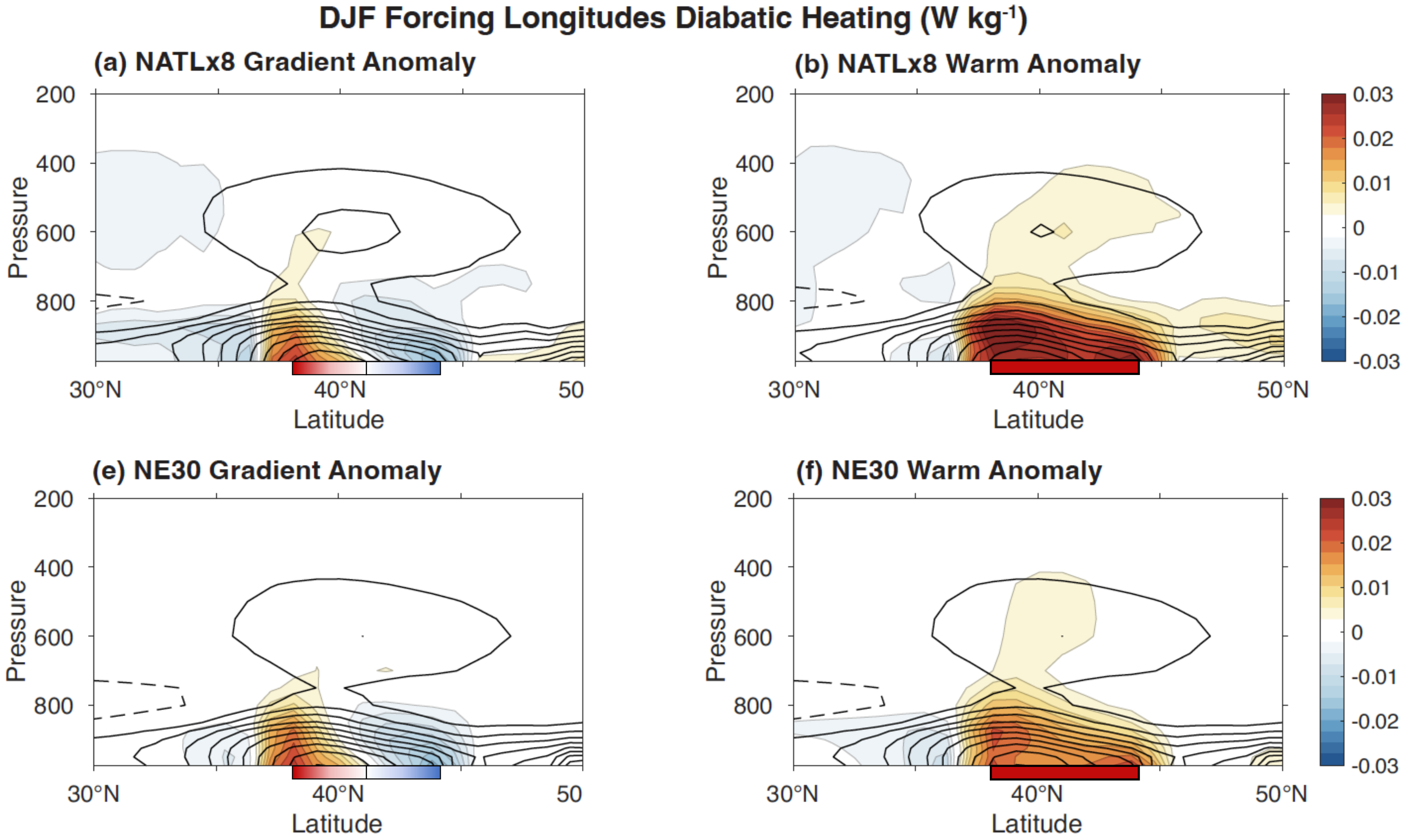


Time-mean ascent is concentrated below 600 hPa and doesn't reach above 400 hPa in any simulation

Similar diabatic heating responses in forcing region

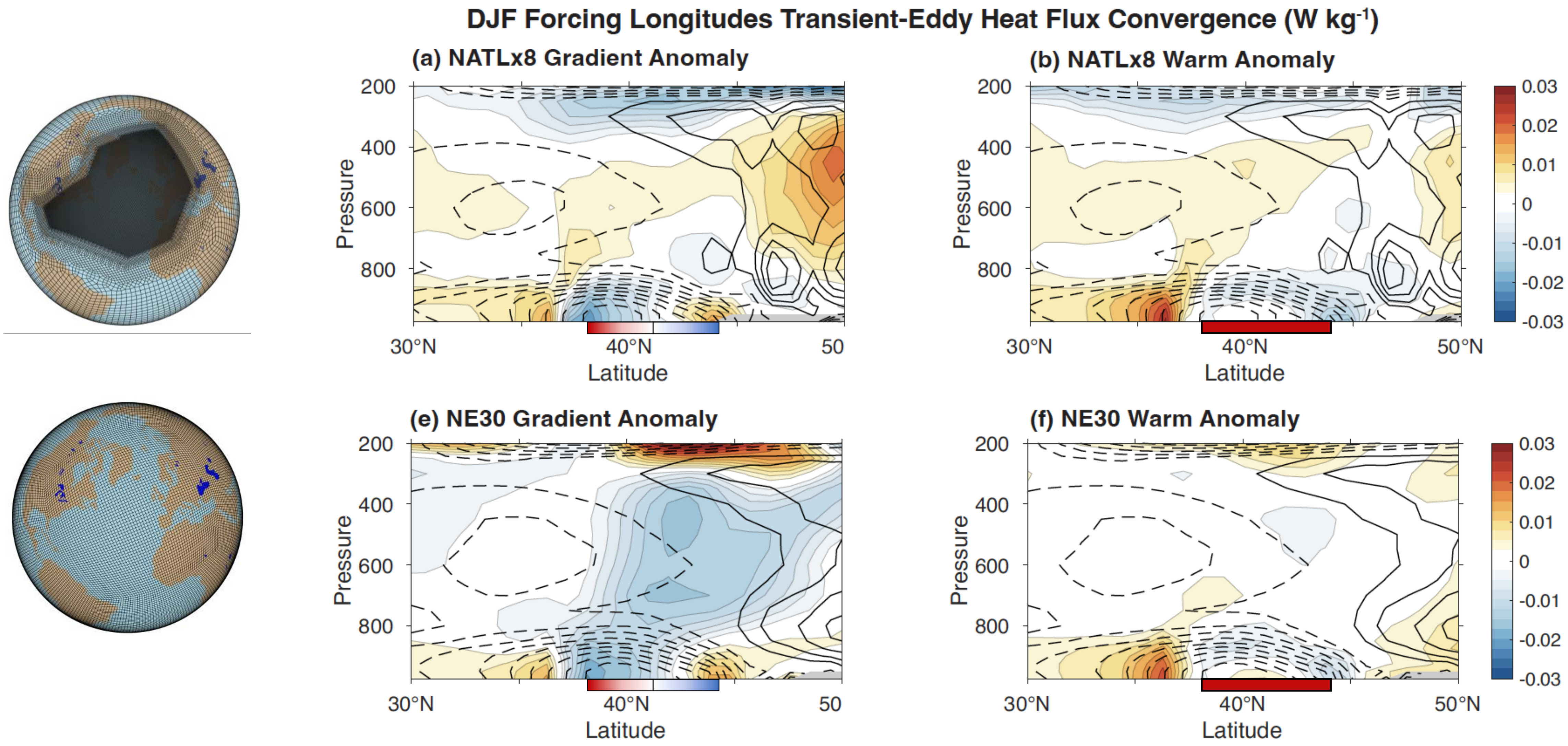






Contours = climatology; shading = response to SST anomalies

Large differences in transient-eddy heating



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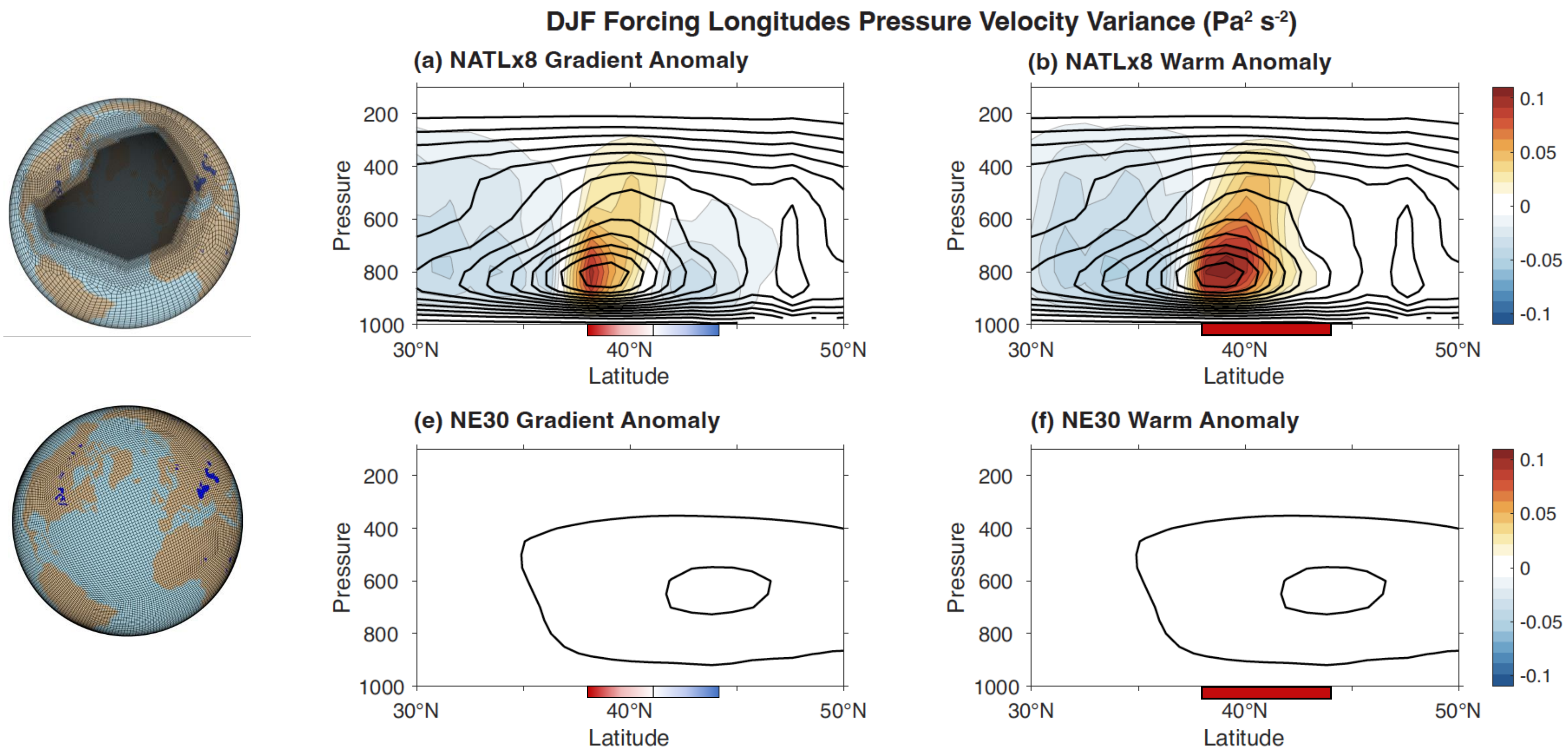
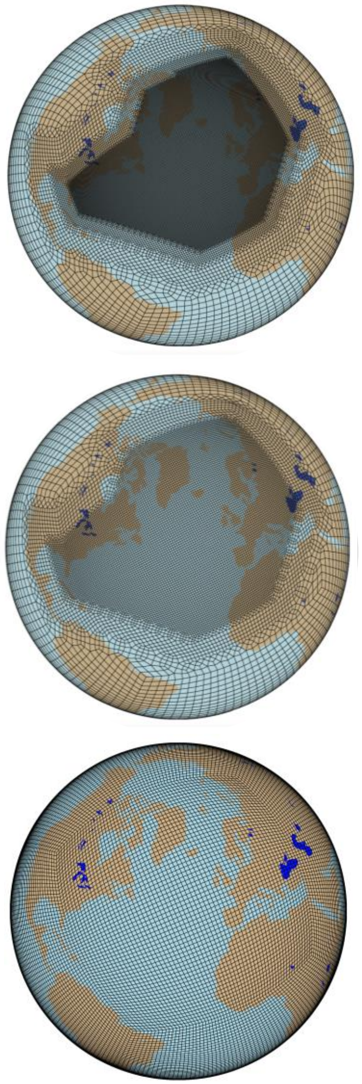
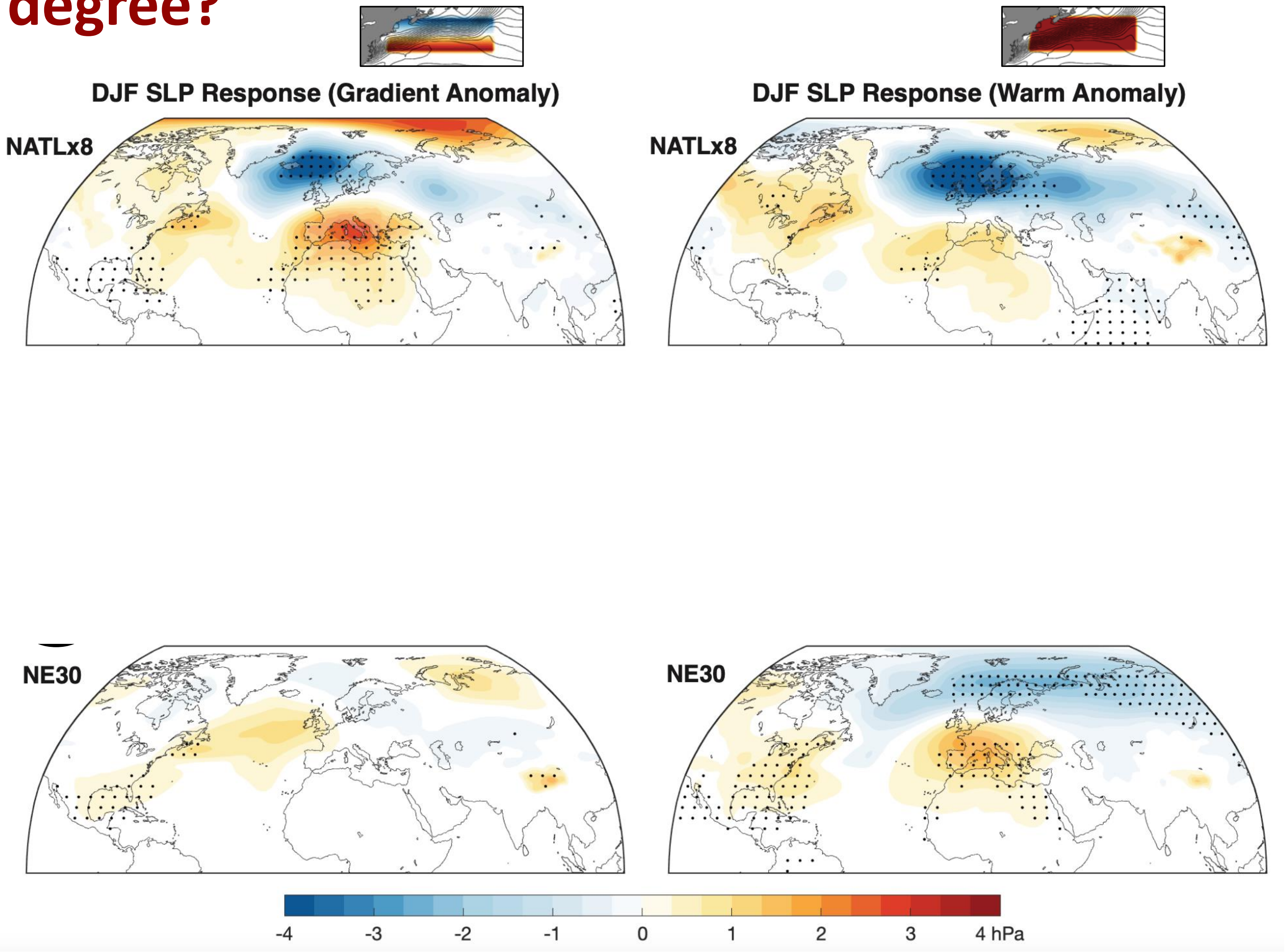
Vertical velocity variance is MUCH stronger at 1/8°



Pressure velocity variance; contours = climatology; shading = response

What about 1/4 degree?





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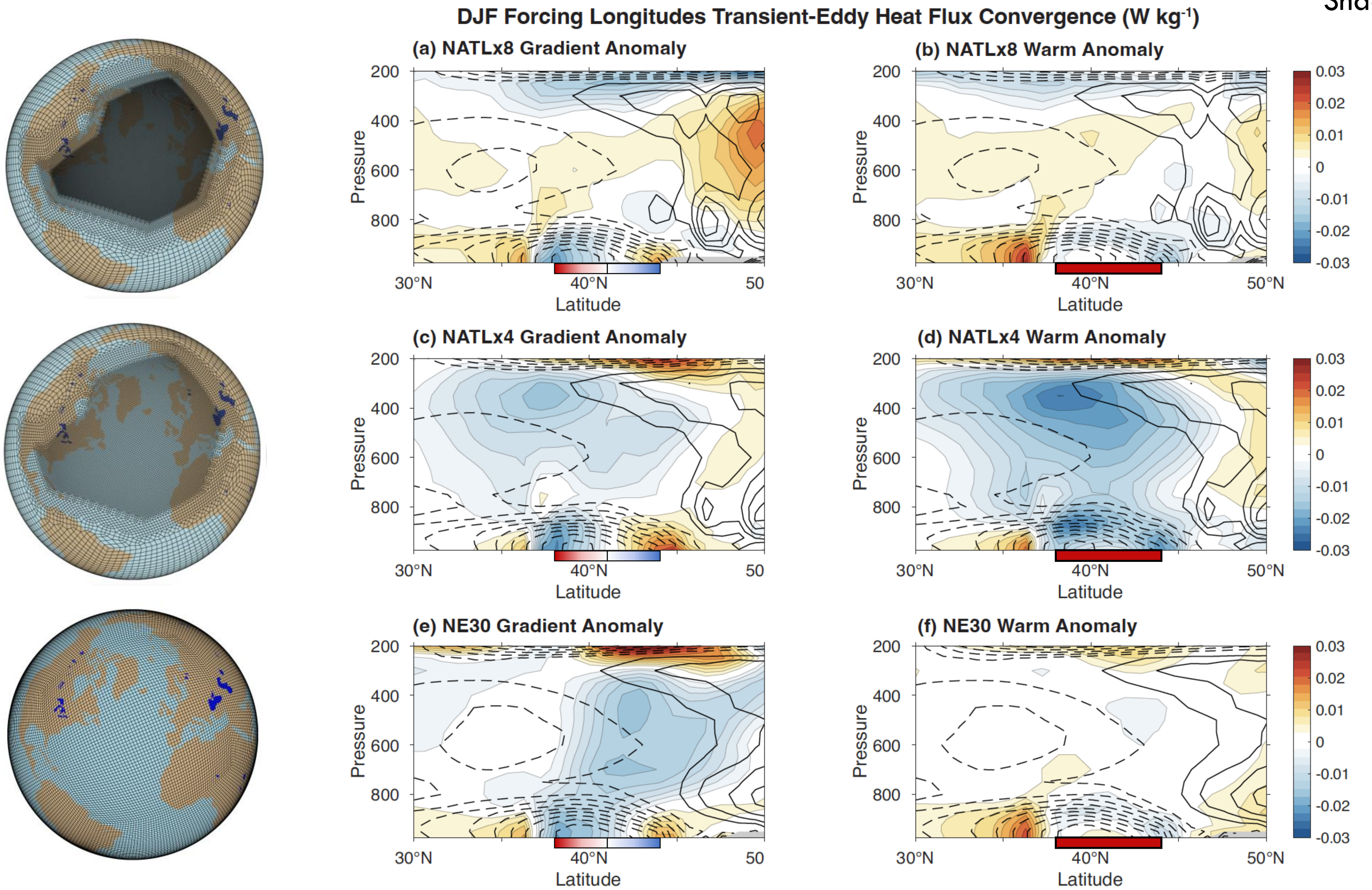
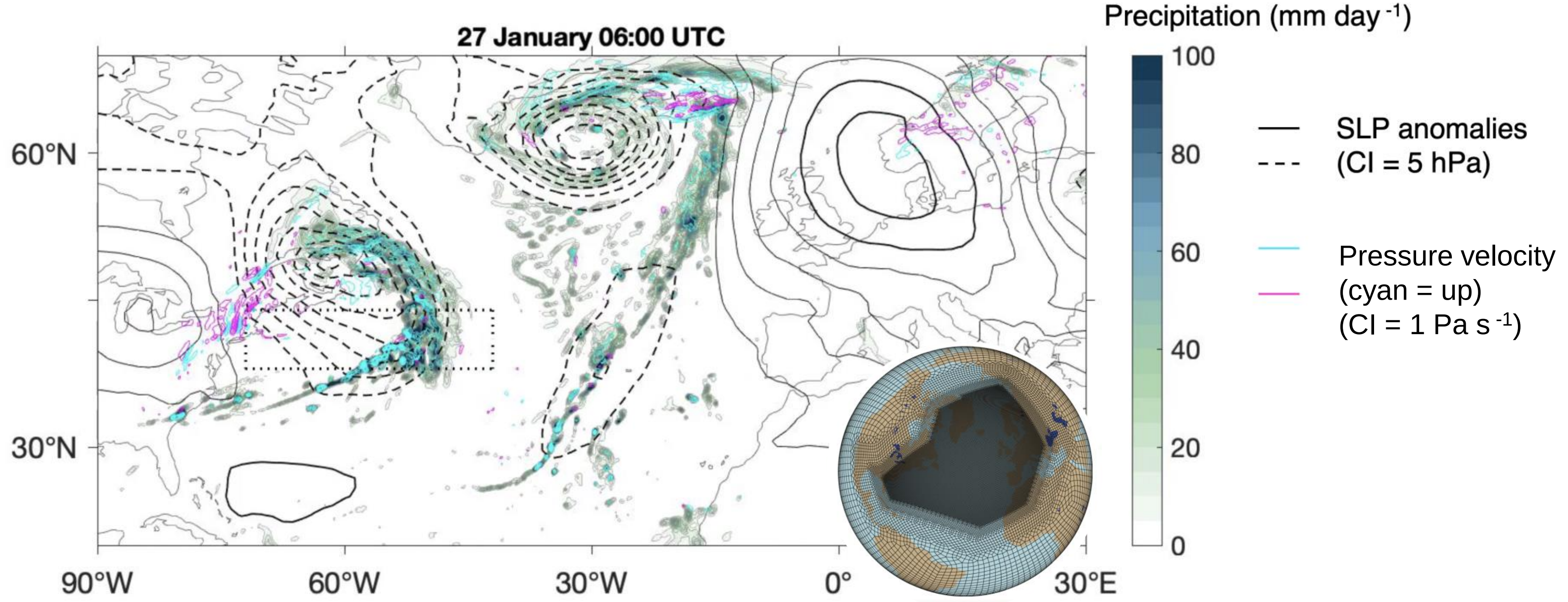
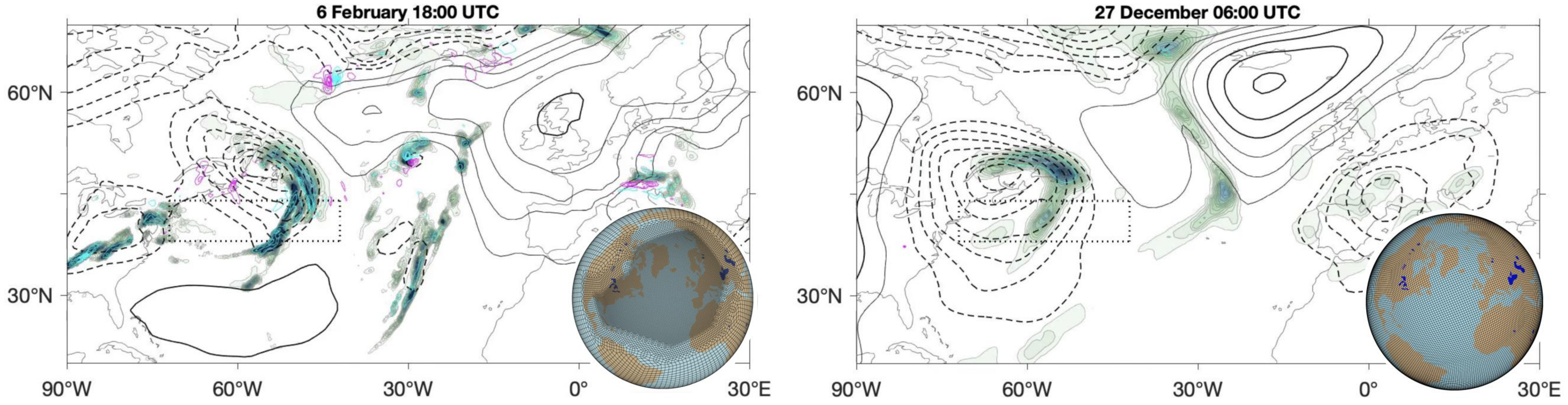
Transient eddies move anomalous heat meridionally instead of vertically in 1/4° simulation

Contours = climatology
Shading = response



Where in cyclones ascent occurs changes eddy statistics





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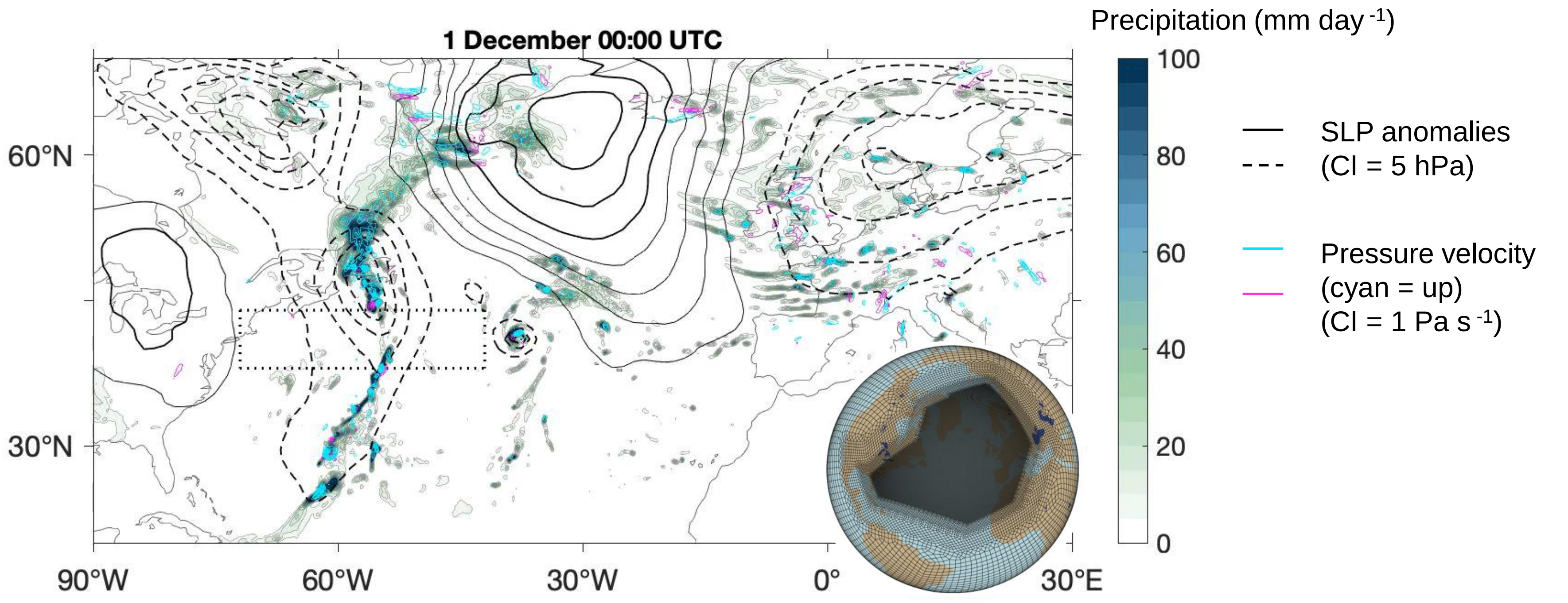
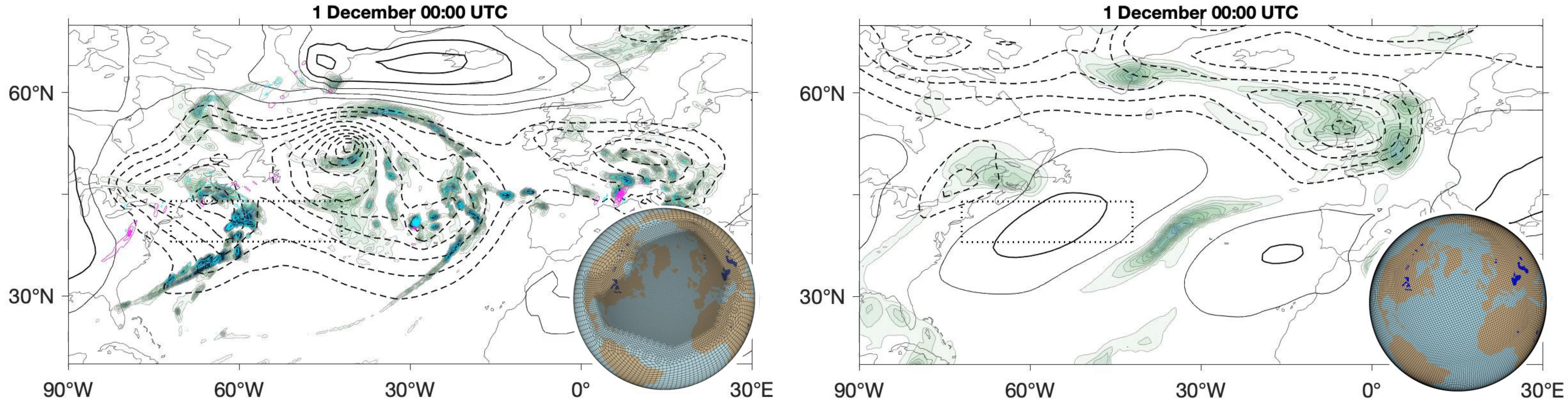




Conclusions

1. 14-km resolution regionally refined CAM6 simulations show a **LARGE** (~2 hPa per °C) positive NAO-like response to warm Gulf Stream SST anomalies that is weaker, absent, or of opposite sign in lower resolution simulations
2. There is a large increase in resolved ascent within midlatitude cyclones, leading to a deeper influence of SST anomalies on transient-eddy fluxes and free-tropospheric temperature
3. Opposite response at 28-km resolution appears to result from preferring warm sector (vs. cold sector) ascent pathway, following less steep isentropic slopes

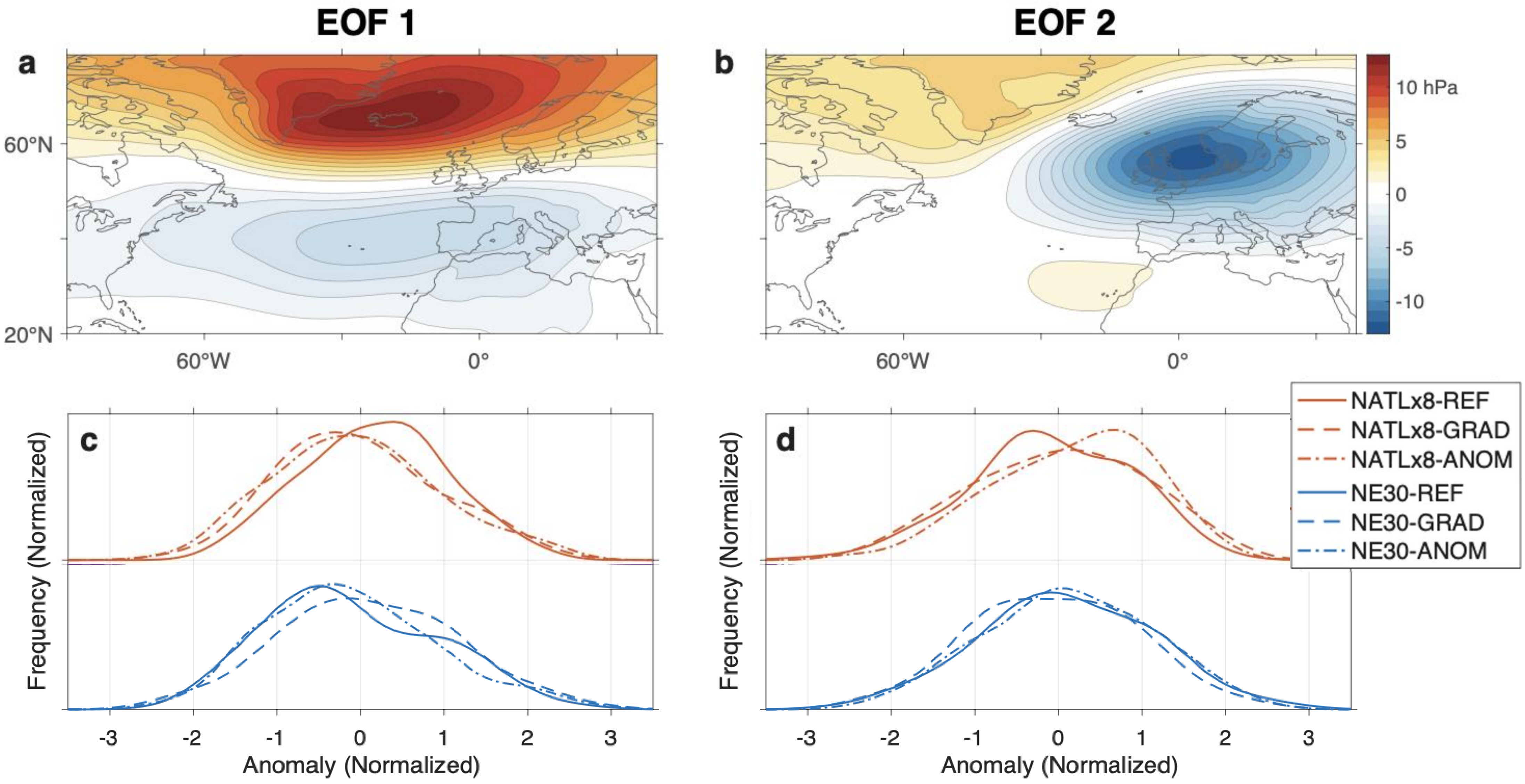
Implications

1. Potential game changer for decadal prediction, due to much bigger influence of predictable SST anomalies on the atmospheric circulation
2. Atmospheric response could influence further evolution of SST anomalies

Open questions

1. Results are potentially very sensitive to the imposed SST anomaly pattern. What aspect of SST pattern matters?
2. Is the response realistic? Can it be reproduced in other models?
3. Much more to learn about mesoscale influences on mean flow

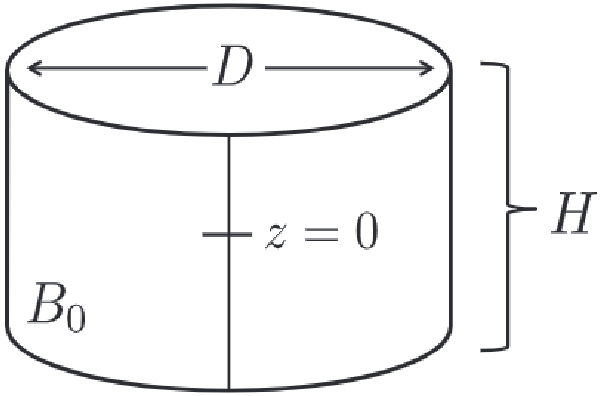
Projection of response onto internal variability



EOFs of 5-day average SLP across all simulations (including climatological differences)

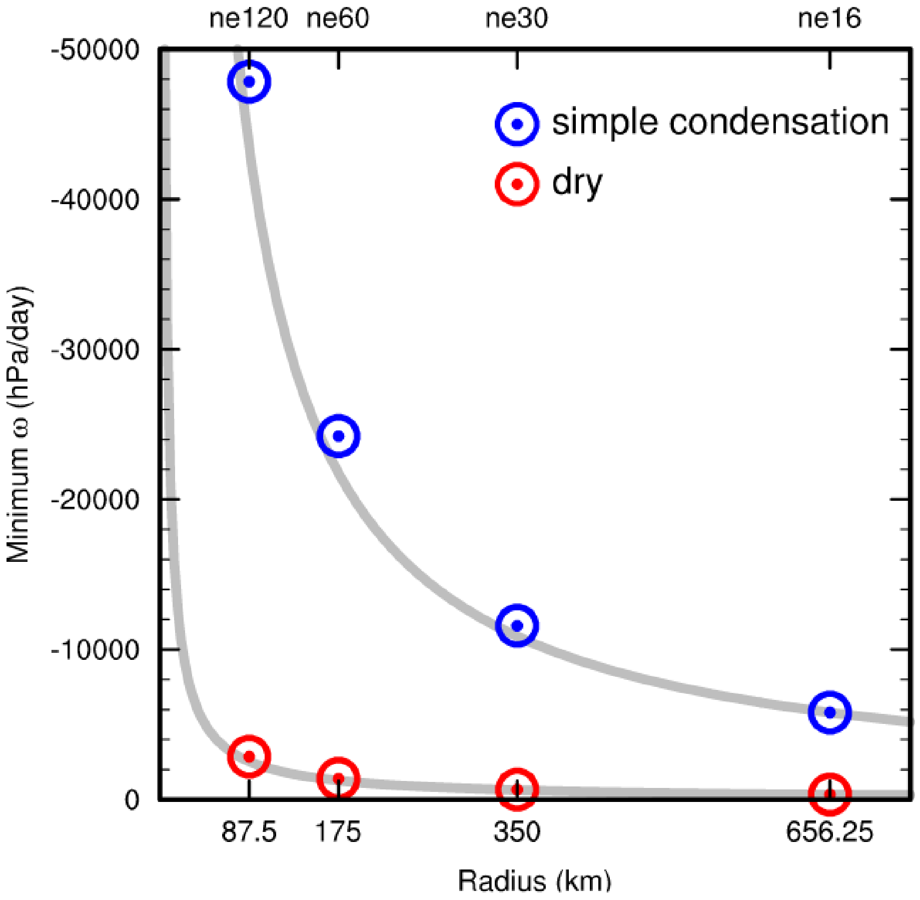
Vertical velocity variance known to increase with resolution (until non-hydrostatic effects lead to saturation)

Buoyant air parcel



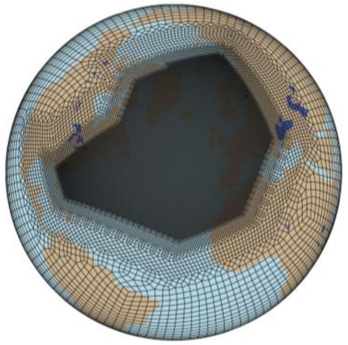
Hydrostatic vertical velocity scaling

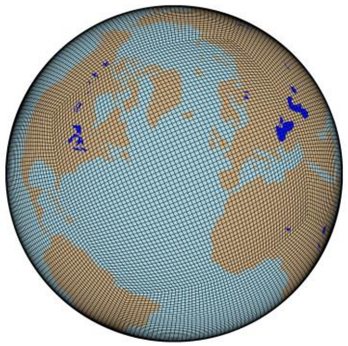
$$W^2 = B_0 \frac{H^3}{D^2}$$

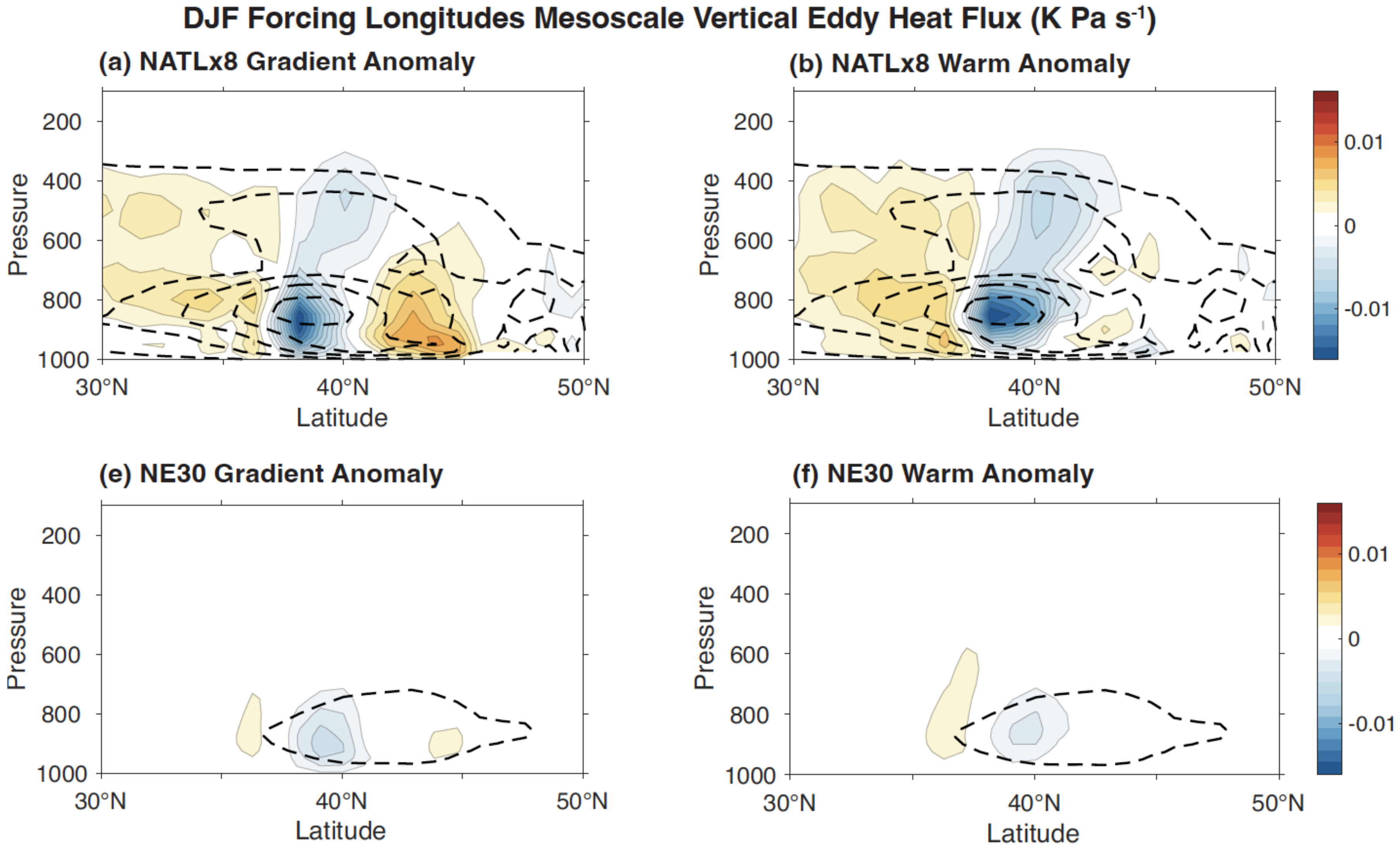


Jeevanjee & Romps 2016; Herrington & Reed 2018

Mesoscale ascent takes heat up

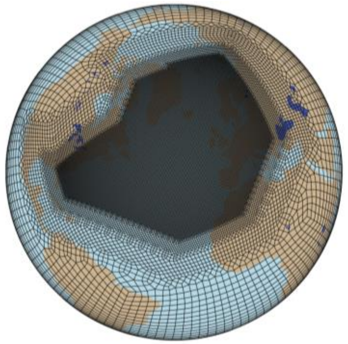


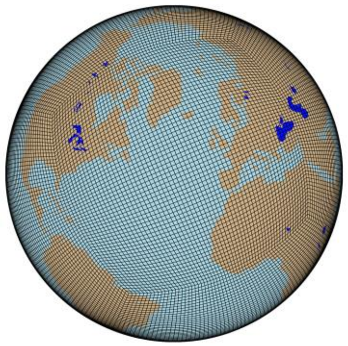


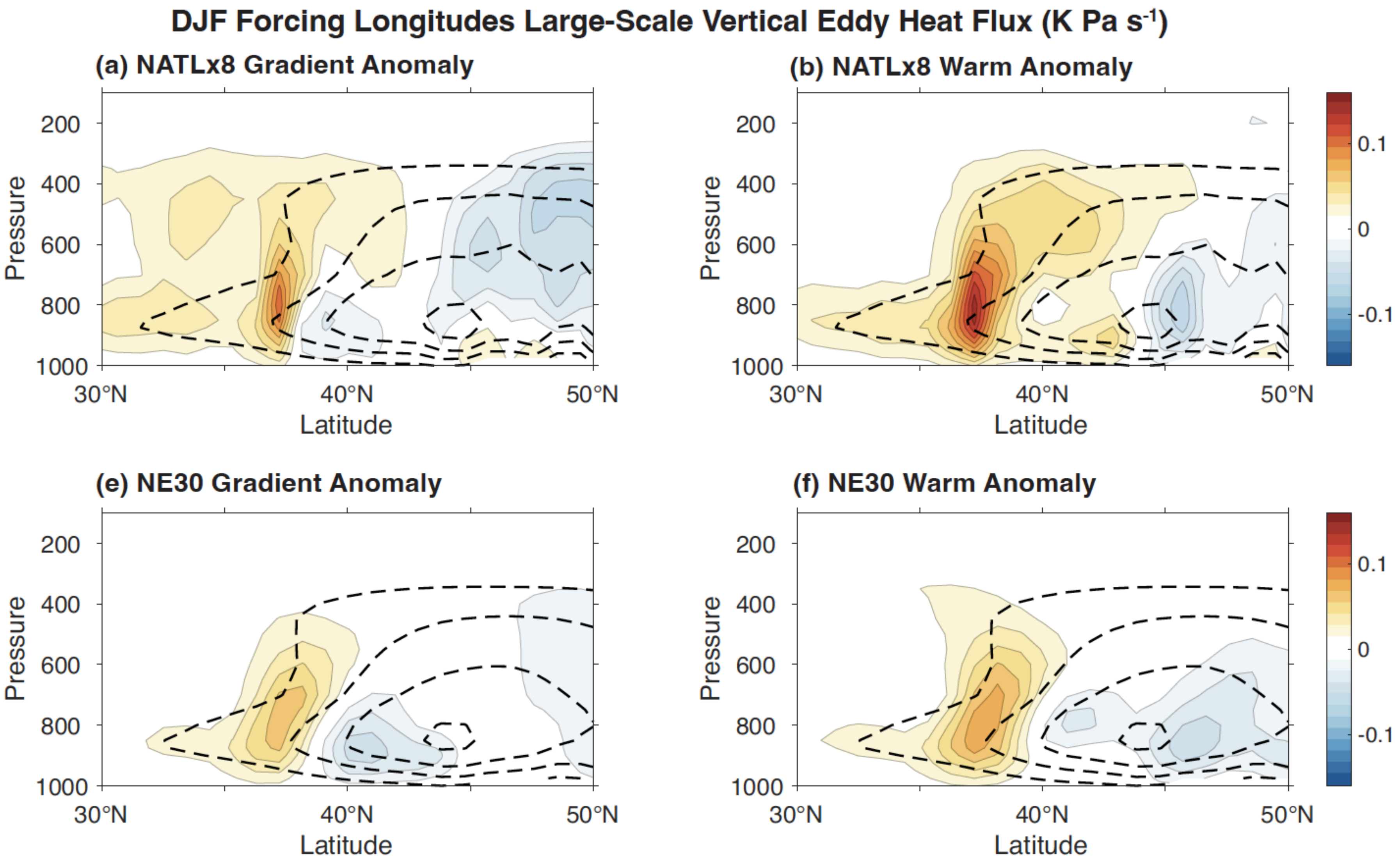


Vertical eddy heat flux (scales smaller than ~150 km); negative upwards; contours = climatology; shading = response

Large-scale descent brings heat back down







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