Pacific Northwest
NATIONAL LABORATORY

Projected Increase in Summer Heat-Dome-Like Stationary Waves over Pacific Northwest (PNW)

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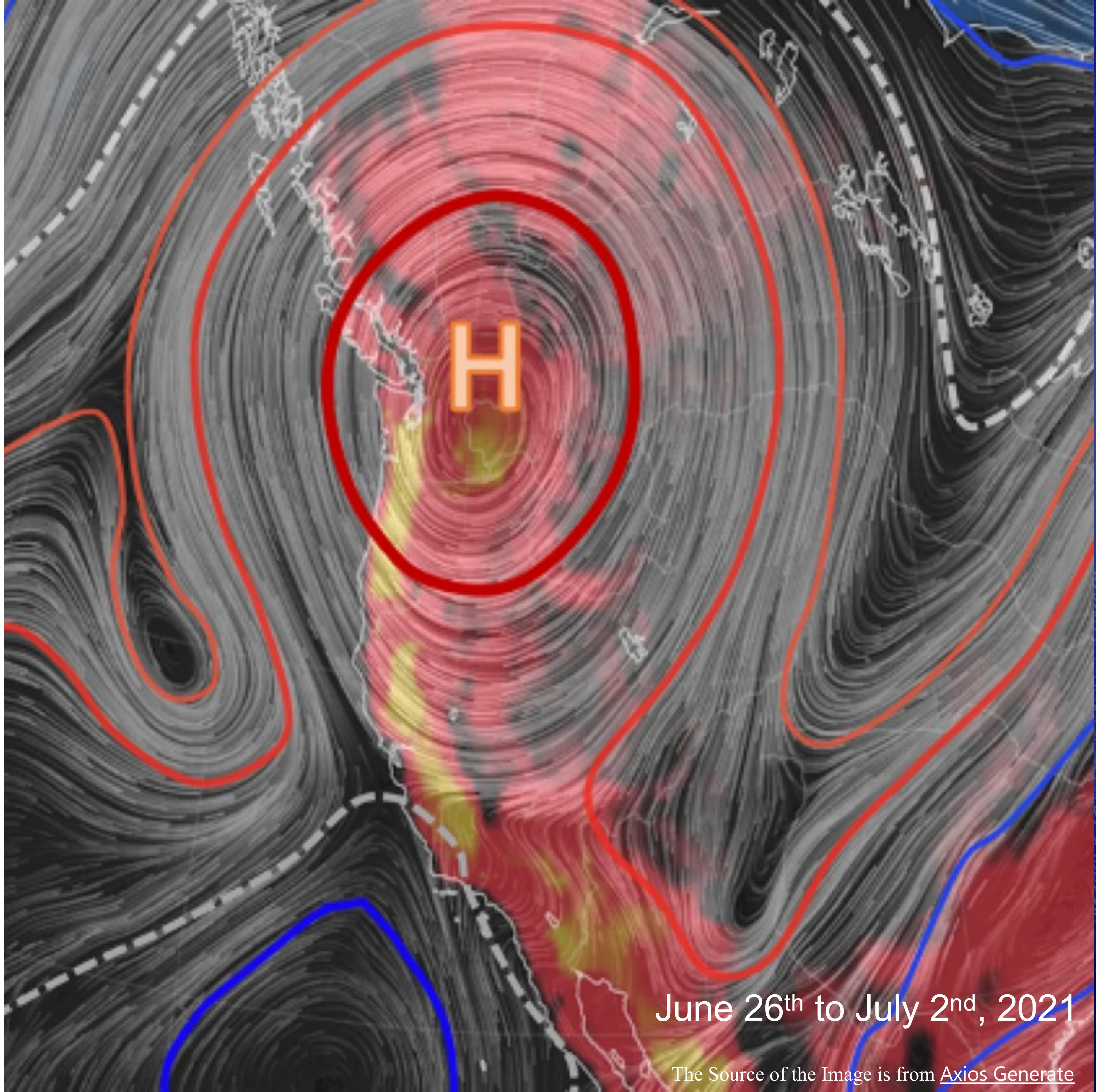

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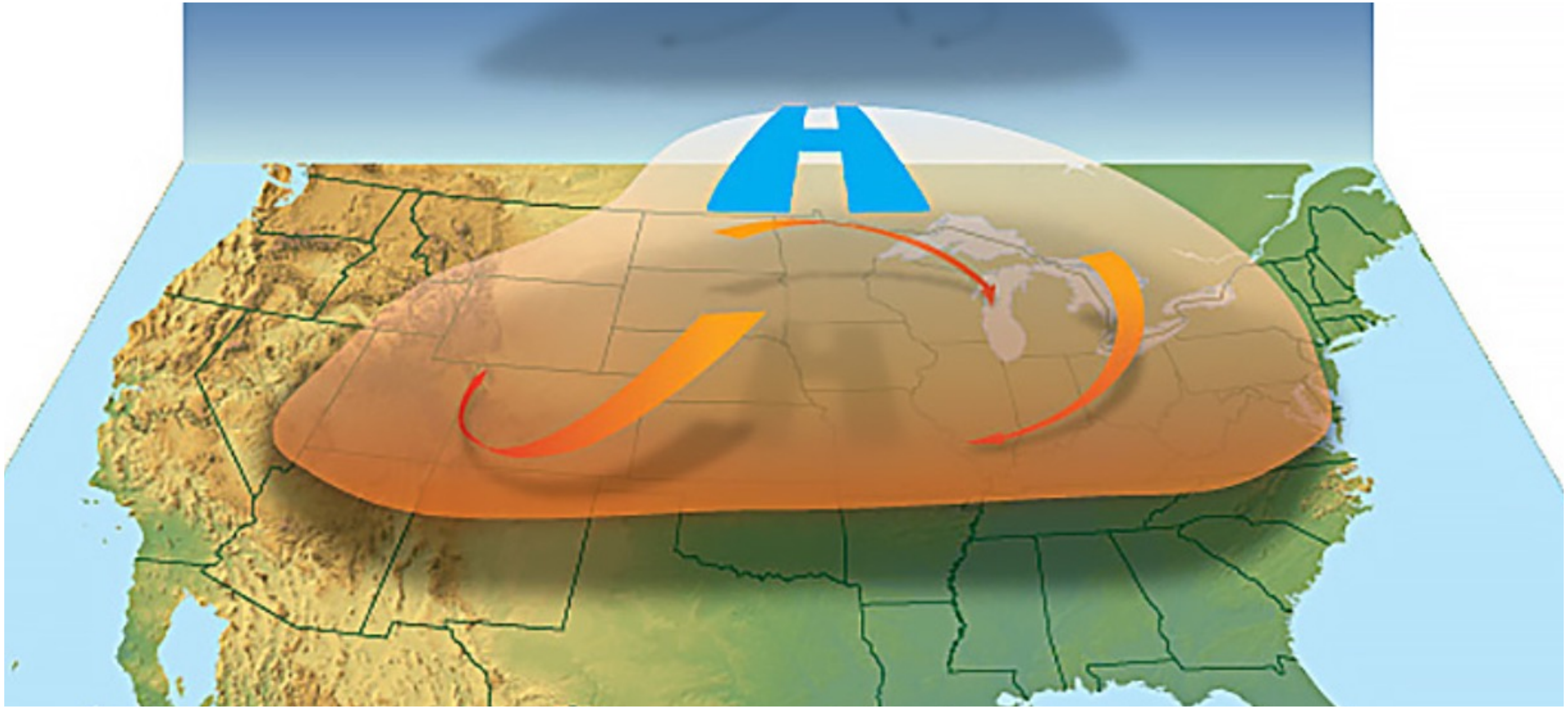
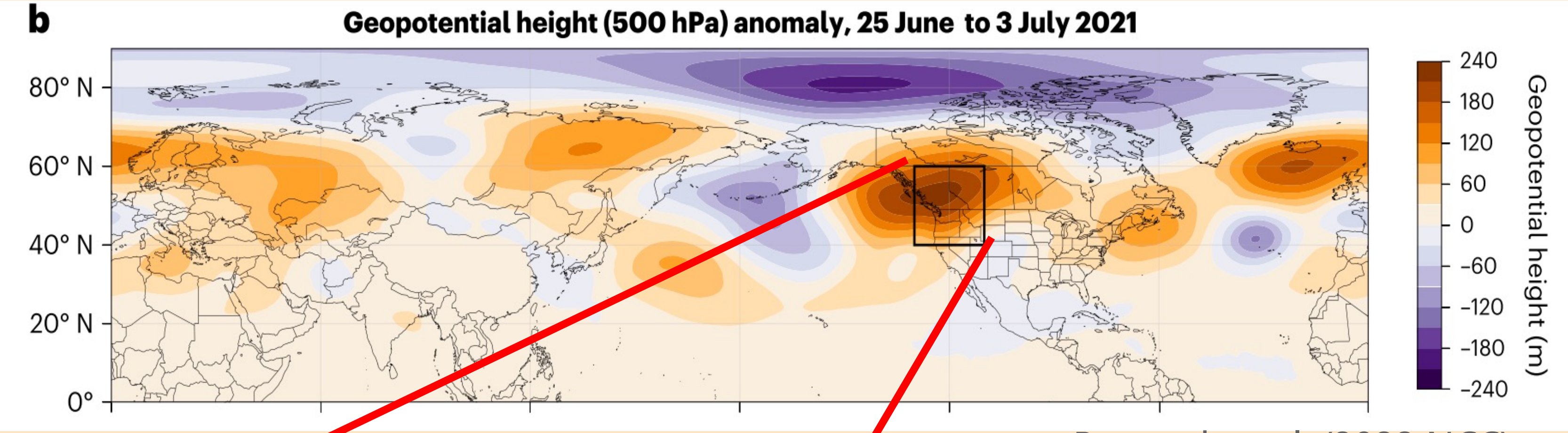
Heat-dome-like stationary wave over Pacific Northwest

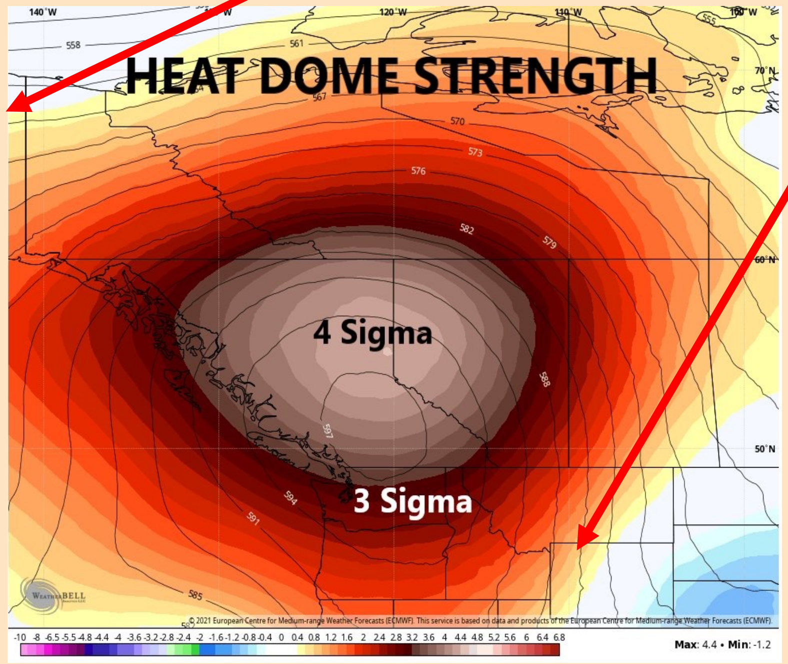


Heat-dome-like stationary wave over Pacific Northwest

Unprecedented Two-week-long Heat Wave in 2021



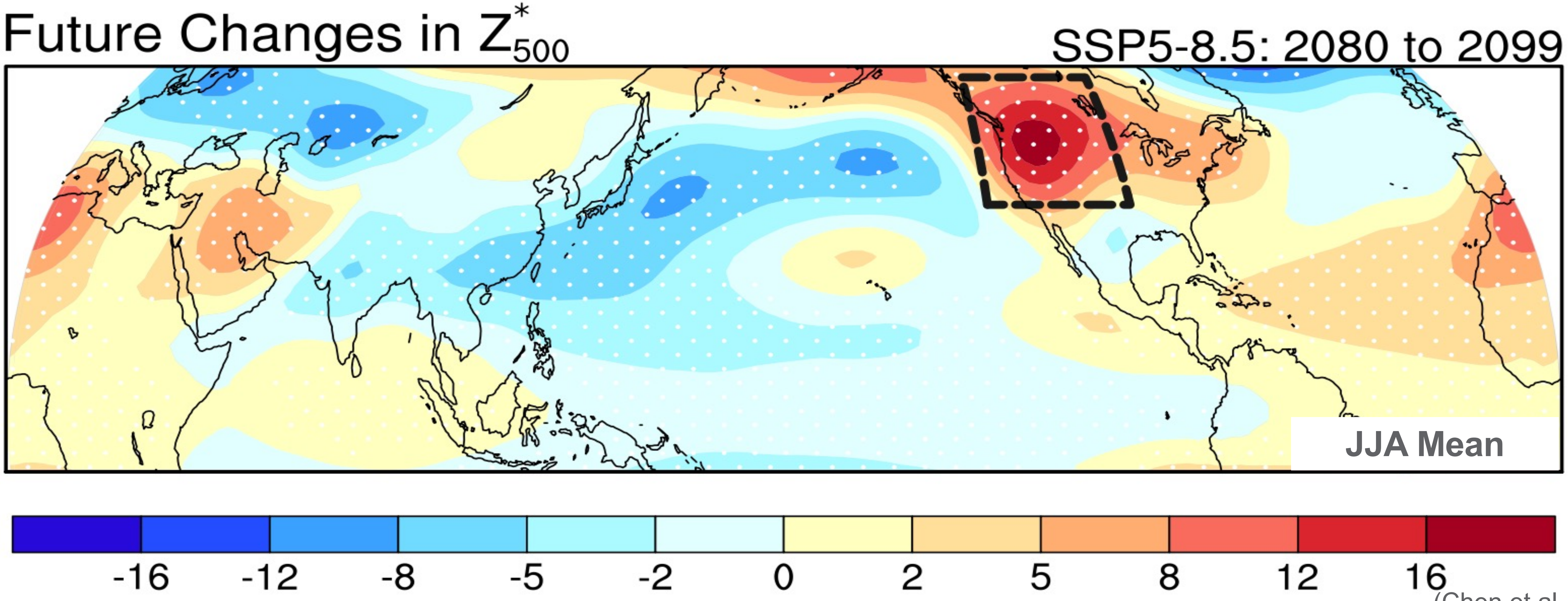
Bartusek et al. (2022 NCC)



(https://twitter.com/WeatherProf/status/1409113893285335041/photo/1)

CBD NEWS

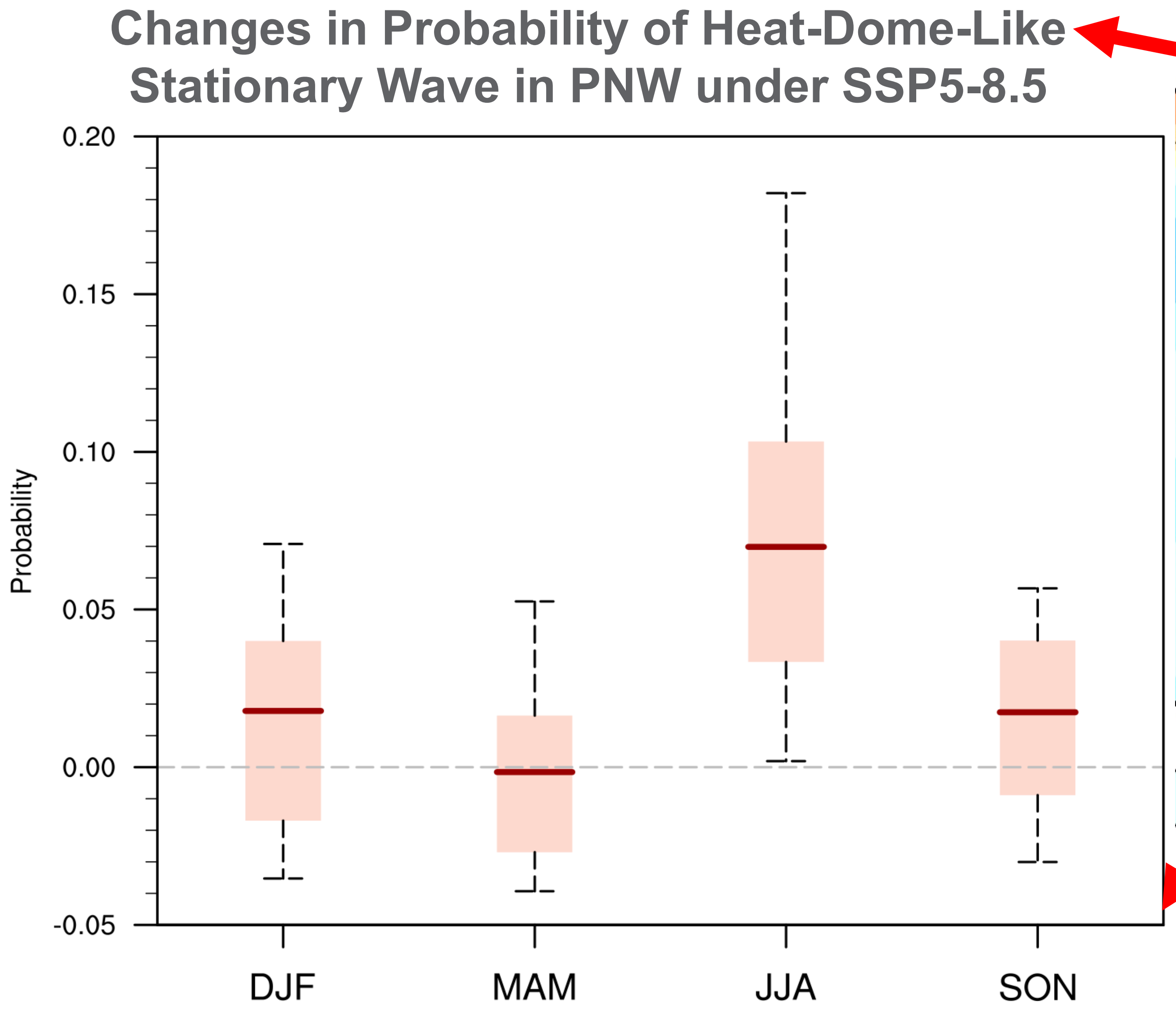
Background: Future Changes of Stationary Wave

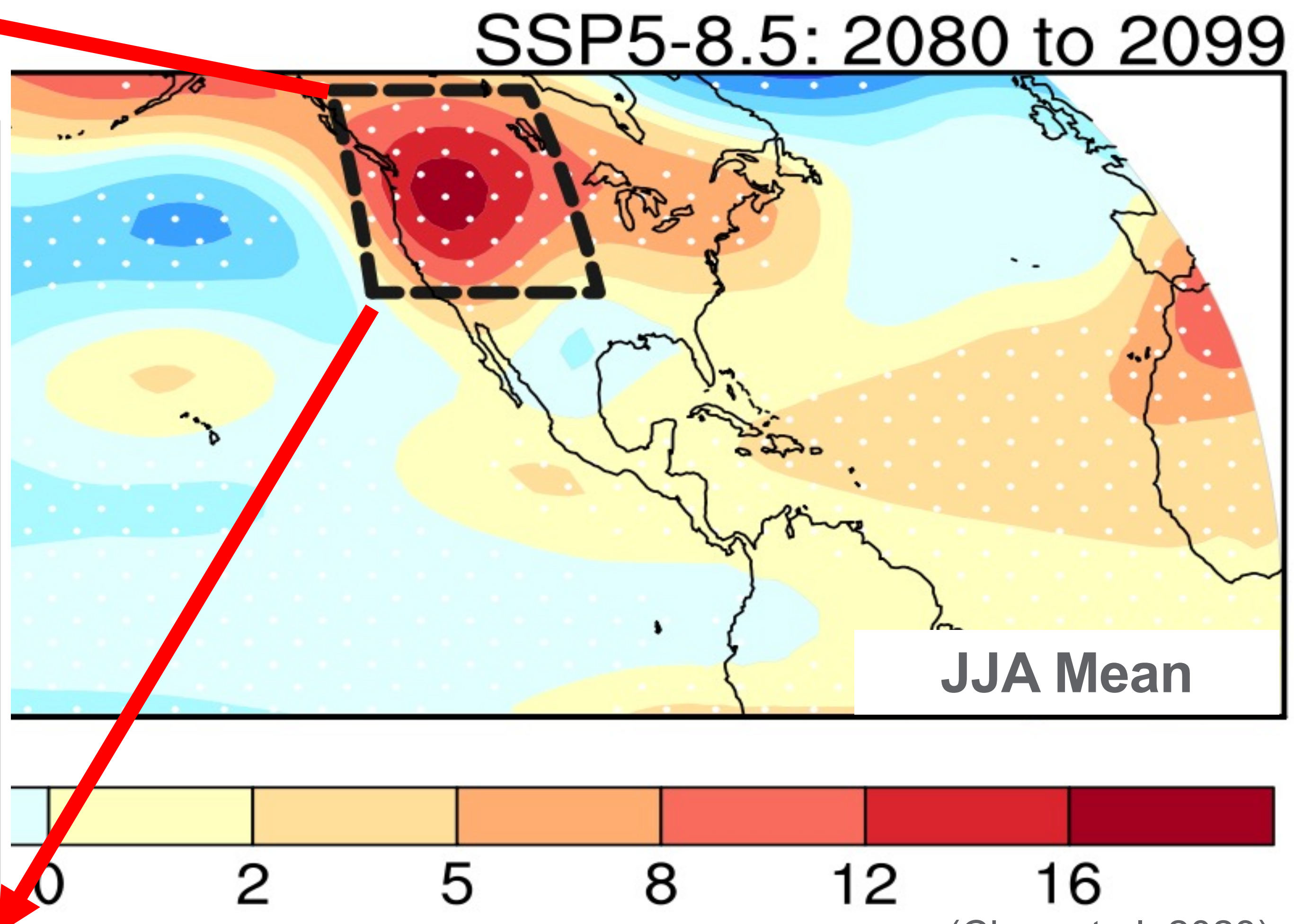


(Chen et al. 2023)

- **Summertime stationary wave circulations under high emission scenario:**
  - **Weaken in the tropics & subtropics (Wills et al. 2019)**
  - **Largest enhancement in PNW region among mid-low latitude (Chen et al. 2023)**

Background: Future Changes of Stationary Wave





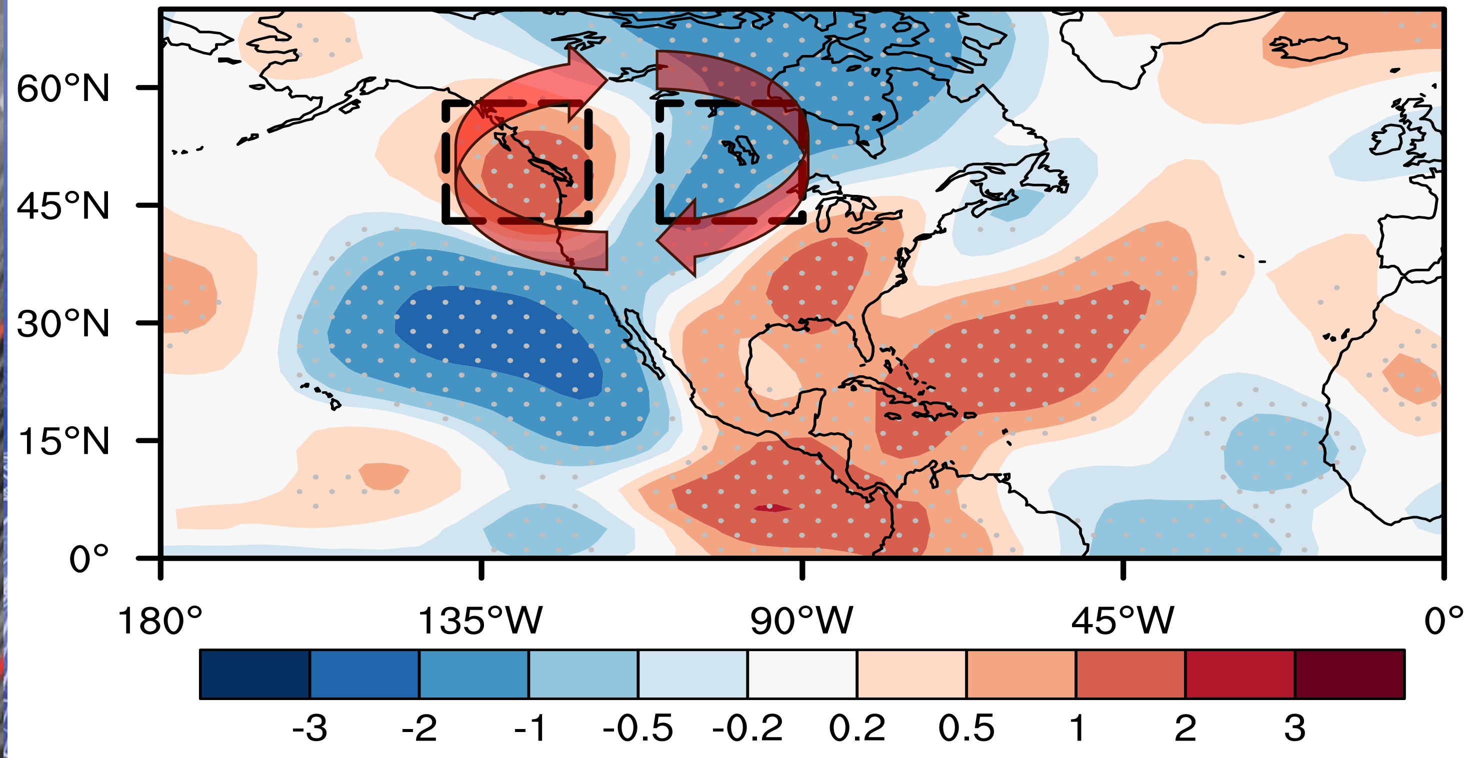
(Chen et al. 2023)

- **Probability and strength of heat-dome-like would increase in PNW region (Chen et al. 2023; Zhang et al. 2023)**

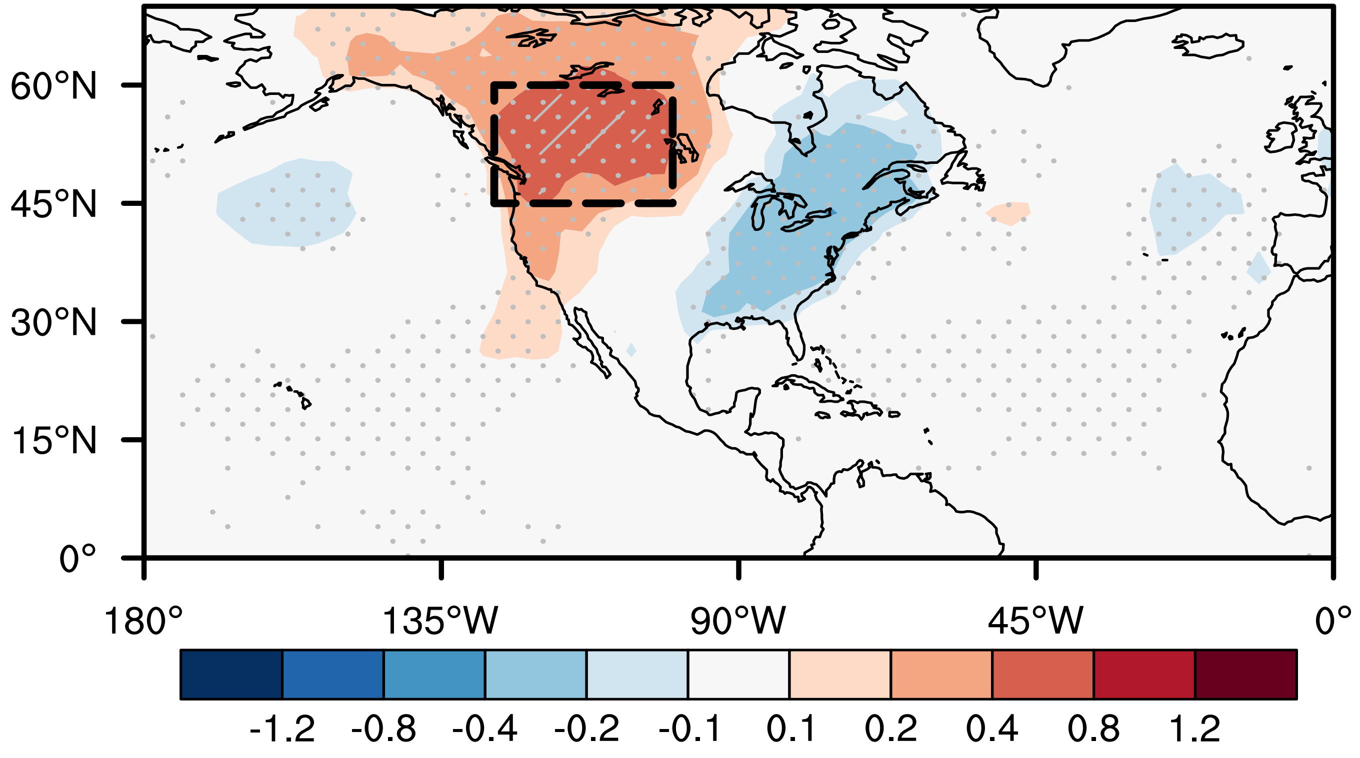
- **What forcings are expected to exert greatest influence on the projected changes in the heat-dome-like anticyclone over PNW?**

Anticyclonic Circulation of Heat-Dome-Like Stationary Waves

Future Changes of Heat-Dome-Like Anticyclonic Stationary Wave Circulation Under SSP5-8.5

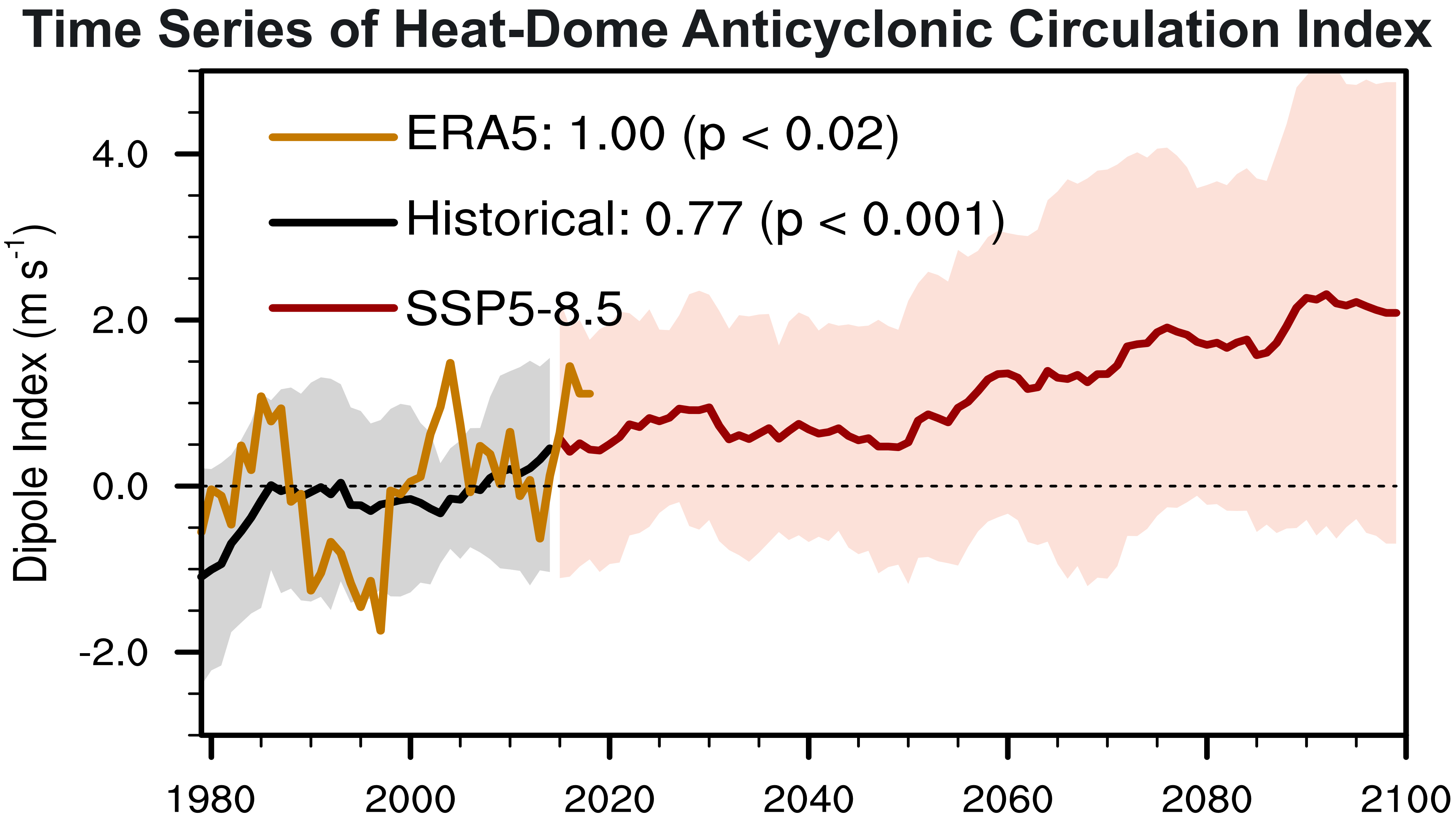


Tmax Warming Related to Heat-Dome-Like Stationary Wave Under SSP5-8.5



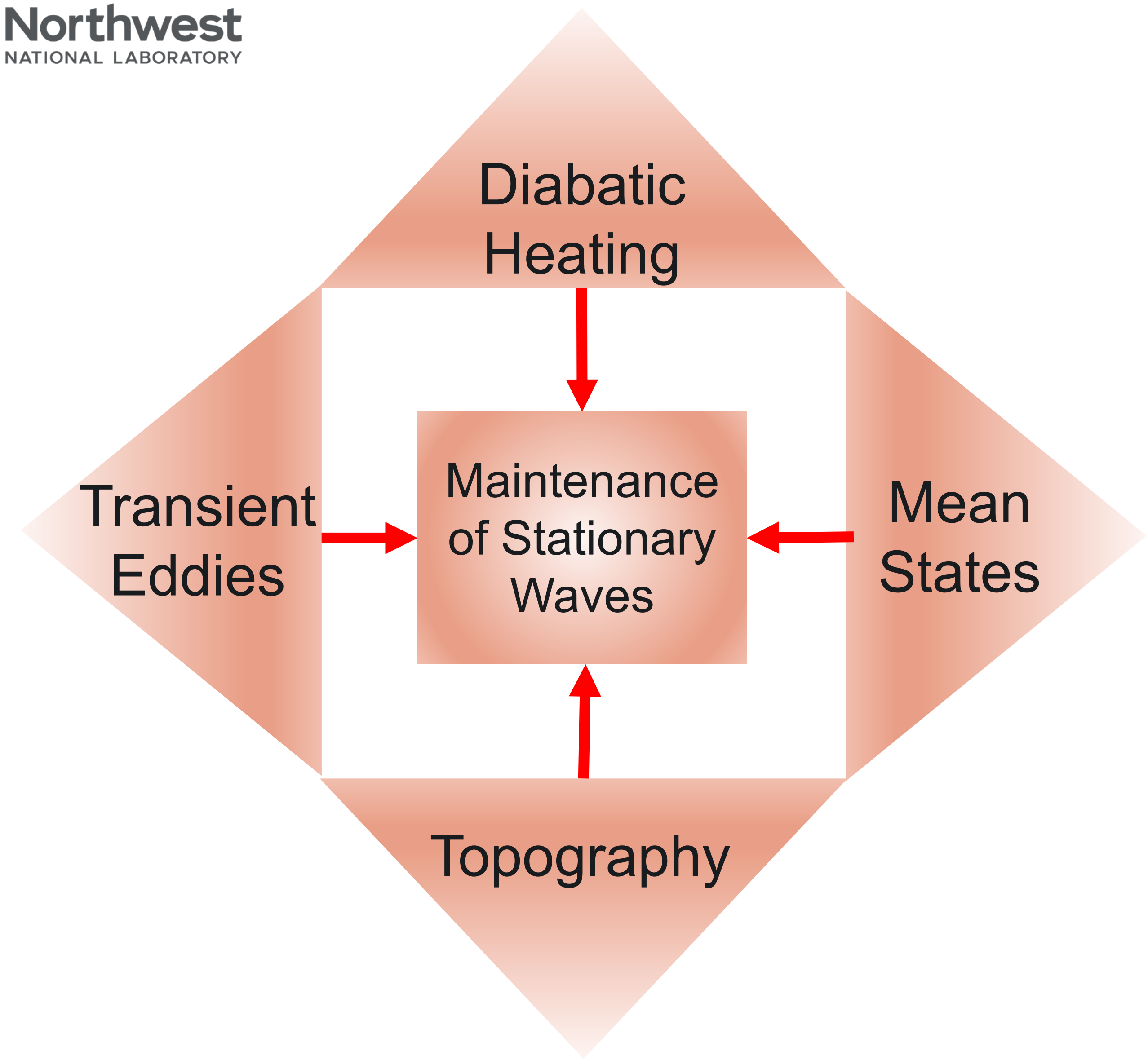
- **Eddy meridional wind (V') dipole index**
  - **Difference in V'_{200} between western and eastern flanks of the anticyclonic circulation**
- **Dynamical control on the heat extremes**
  - **Strengthening of anticyclonic circulation will strongly influence the local extreme heat events**

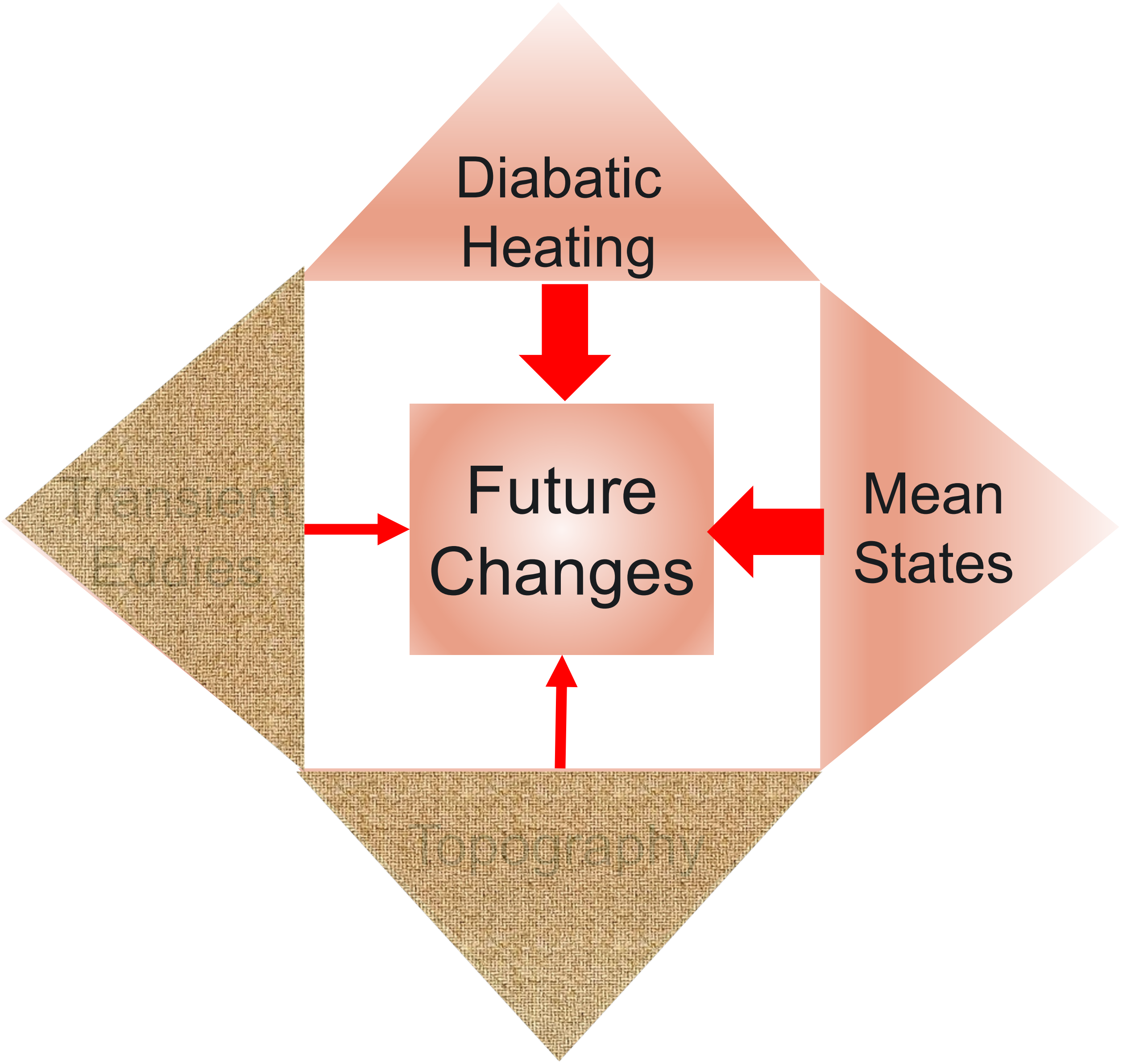
Double in magnitude by the end of the 21st century



- **Anticyclonic circulation would enhance by ~95% under the high-emission scenario**

Maintenance of Stationary Waves





- Diabatic heating and mean state (zonal wind) changes contribute to the stationary wave changes in wintertime (e.g. Stephenson & Held, 1993; Held et al., 2002; Simpson et al., 2016)

Stationary Wave Model Experiments to Diagnose Mechanism

- Stationary wave model (SWM) at R30L24 (Ting & Yu 1998)
- Basic States & Forcings: 14 CMIP6 GCMs
- Run for 100 days with time averages performed over 30~100 days
- Single-forcing Response: the difference between all-forcing run and sensitivity run

Experiments	Basic States	Diabatic heating	Transient Divergence	Transient Vorticity
Control Run	Historical 3D Basic States	Historical	Historical	Historical
Projection Run	Historical 3D Basic States	SSP5-8.5	SSP5-8.5	SSP5-8.5

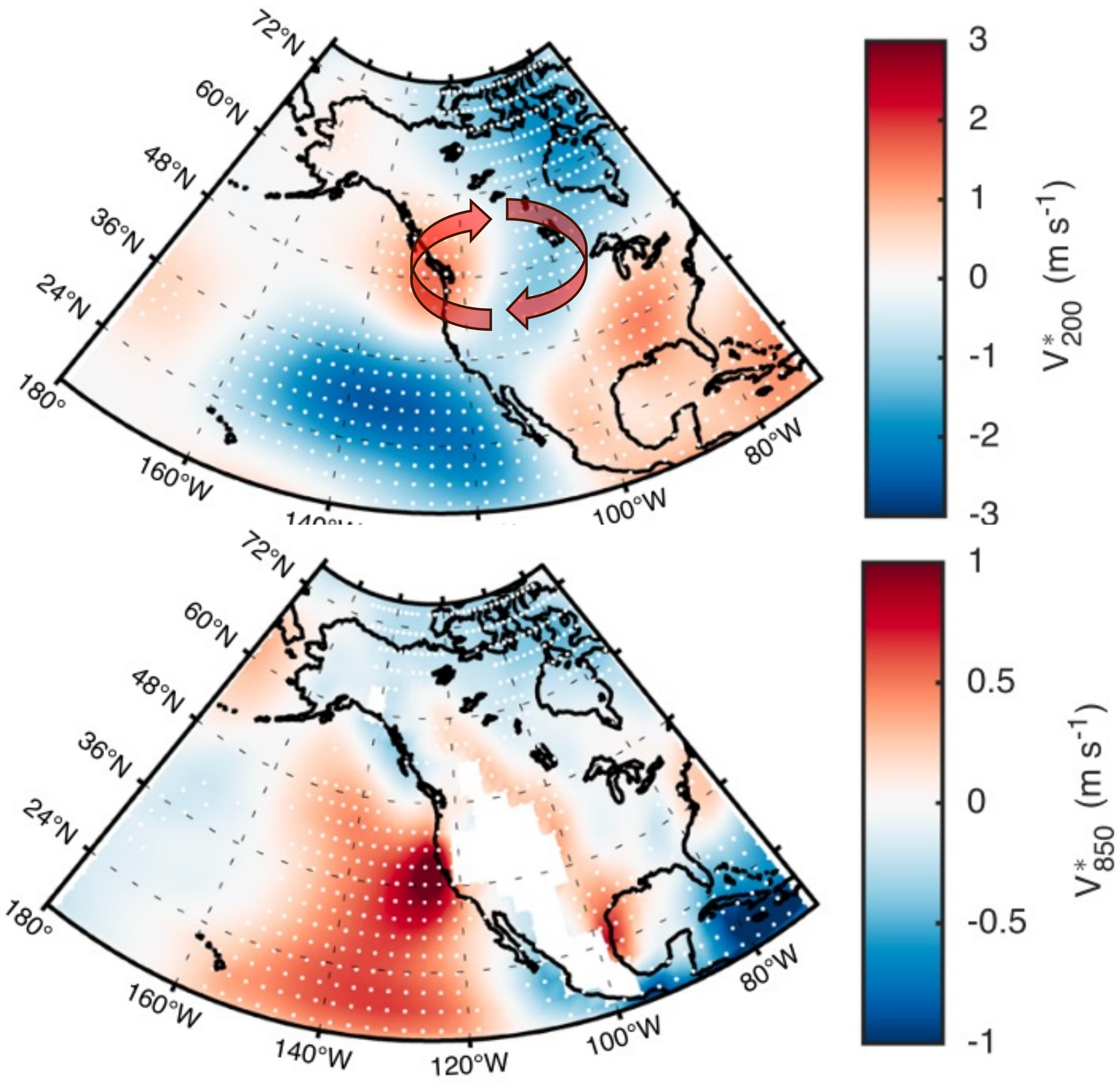
Sensitivity Runs	Diabatic heating	Transient Vorticity	Transient Divergence
Diabatic Heating Run	Historical	SSP5-8.5	SSP5-8.5
Vorticity Run	SSP5-8.5	Historical	SSP5-8.5
Divergence Run	SSP5-8.5	SSP5-8.5	Historical

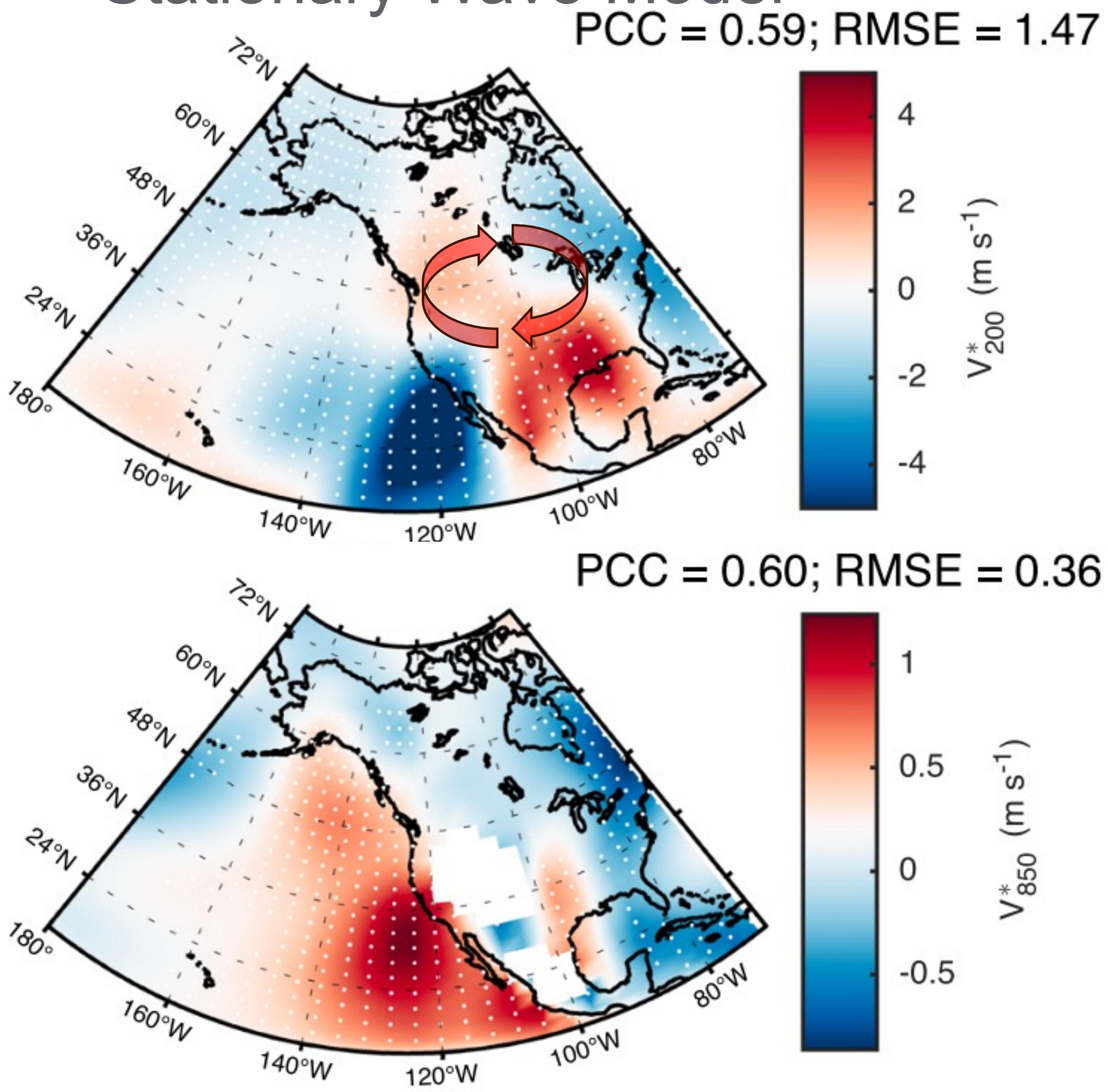
Projected changes can be simulated by SWM: V'_{200} & V'_{850}

CMIP6 MME | Stationary Wave Model

200 hPa

850 hPa





Present-day 3D Basic States Driven by Full Forcings in Projection

White Stippling: Responses exceed twice standard deviation from 30 to 100 days

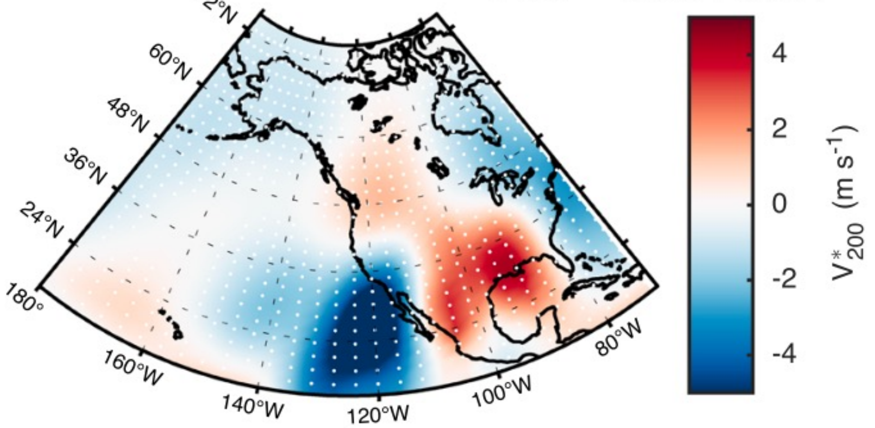
RMSE: Root-mean-square error against CMIP6 MME

PCC: Pattern correlation coefficient against CMIP6 MME

Single Forcing Contribution: Diabatic Heating Plays Dominant Role

V'_{200} Response in SWM Projection Run

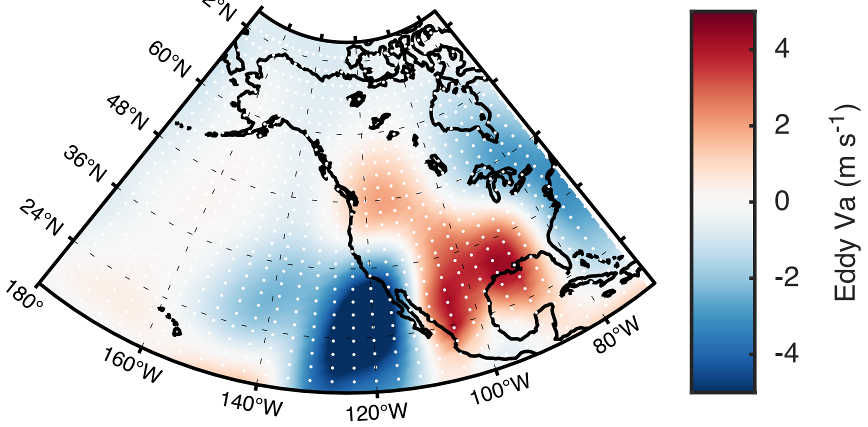
PCC = 0.59; RMSE = 1.47



V'_{200} Response in Single Forcing Runs

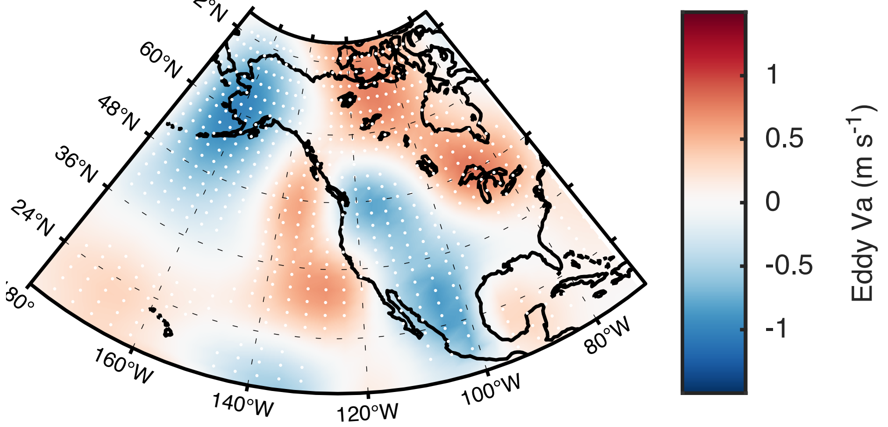
Diabatic Heating Run

PCC = 0.98; RMSE = 0.35



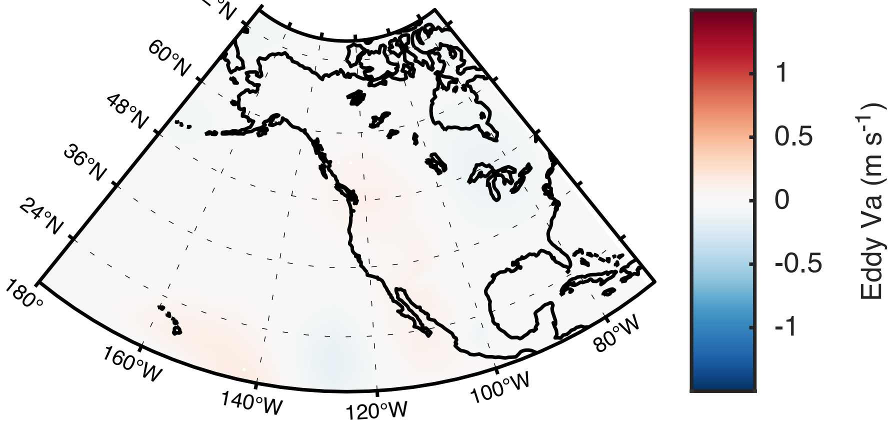
Vorticity Run

PCC = -0.22; RMSE = 1.96



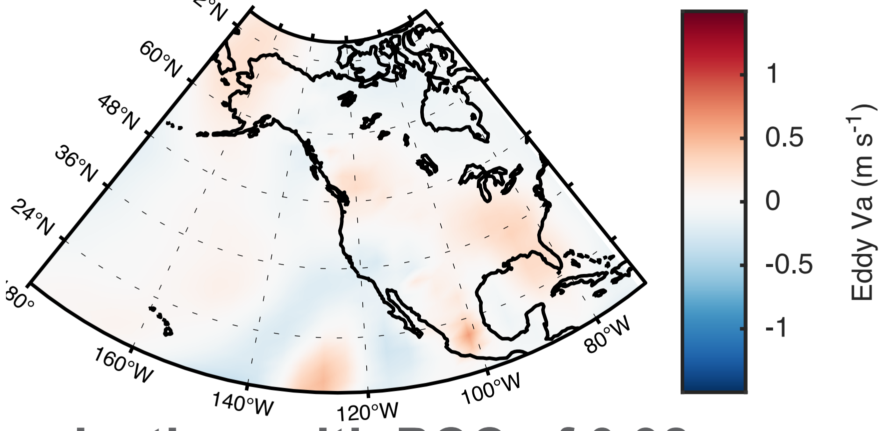
Divergence Run

PCC = 0.27; RMSE = 1.82



Nonlinear Effect

PCC = 0.28; RMSE = 1.81

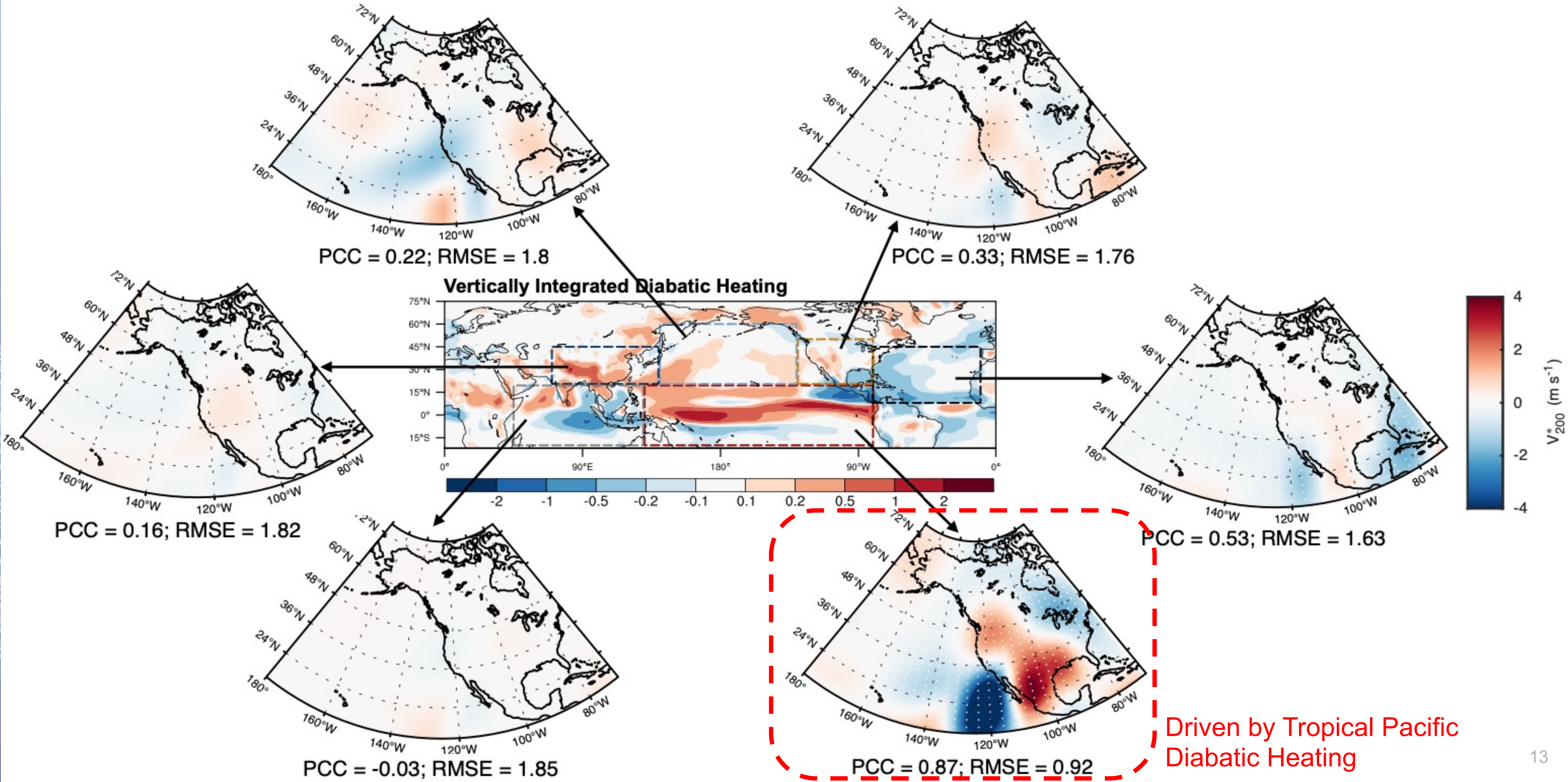


RMSE: Root-mean-square error

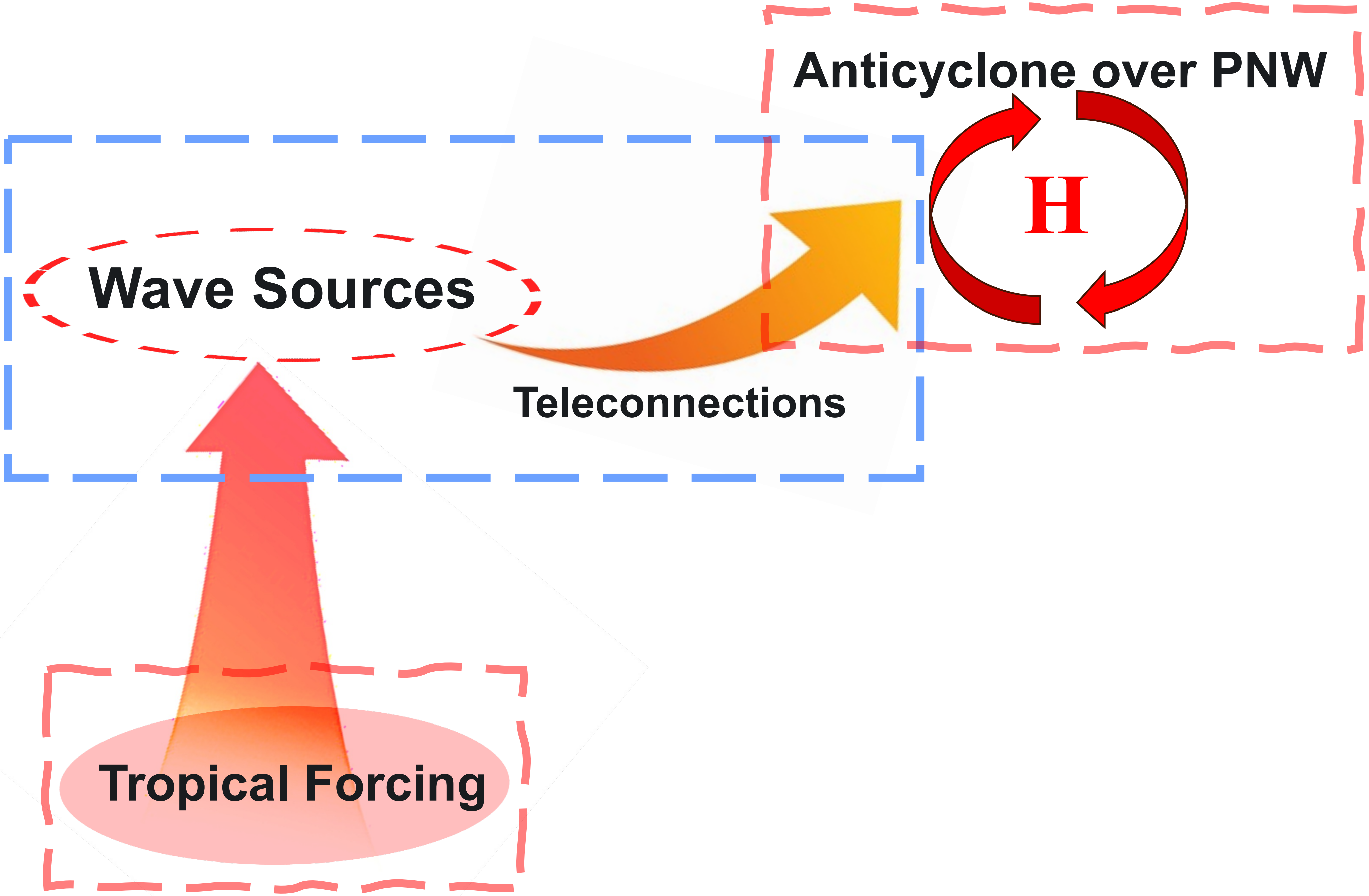
PCC: Pattern correlation coefficient

- **Diabatic heating dominates the response of eddy meridional wind in the projection, with PCC of 0.98**

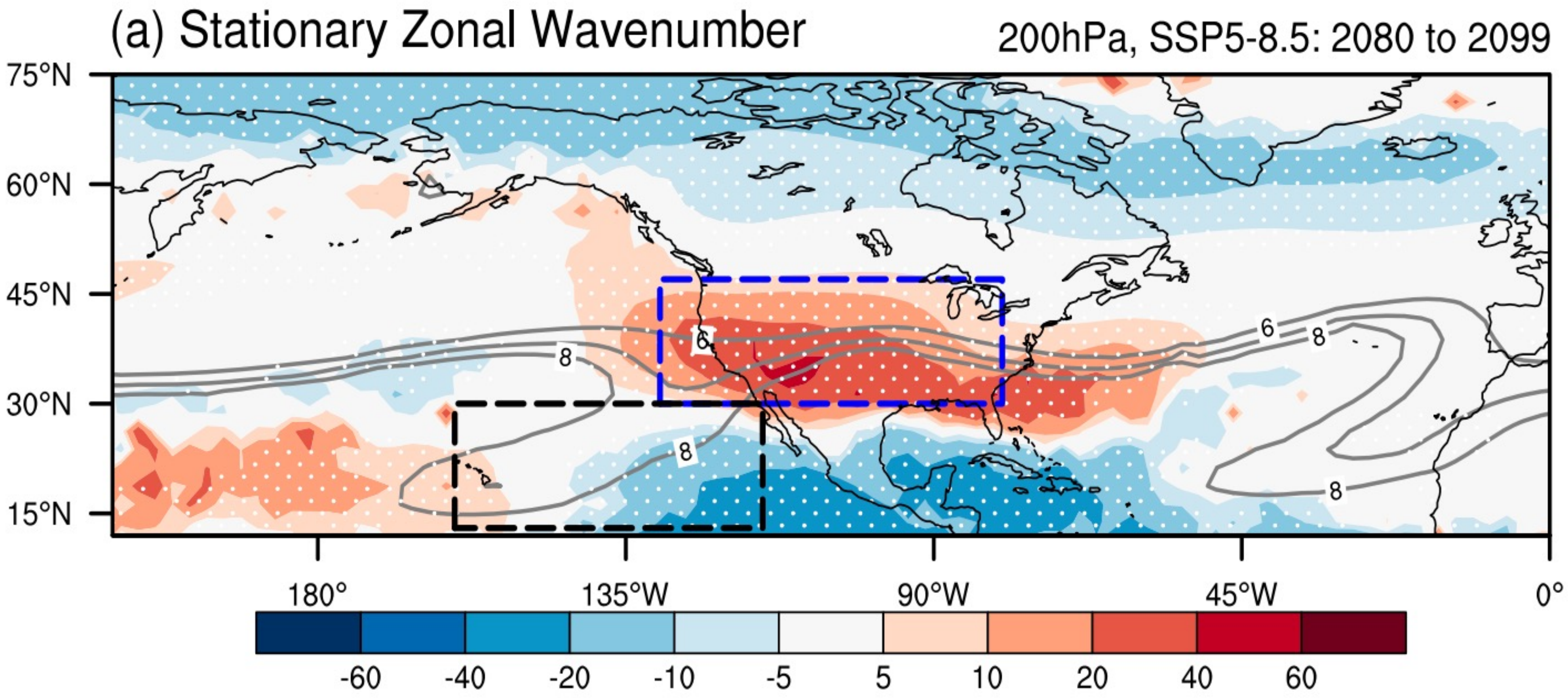
Regional Forcing in Tropical Pacific Dominate Stationary Wave Responses

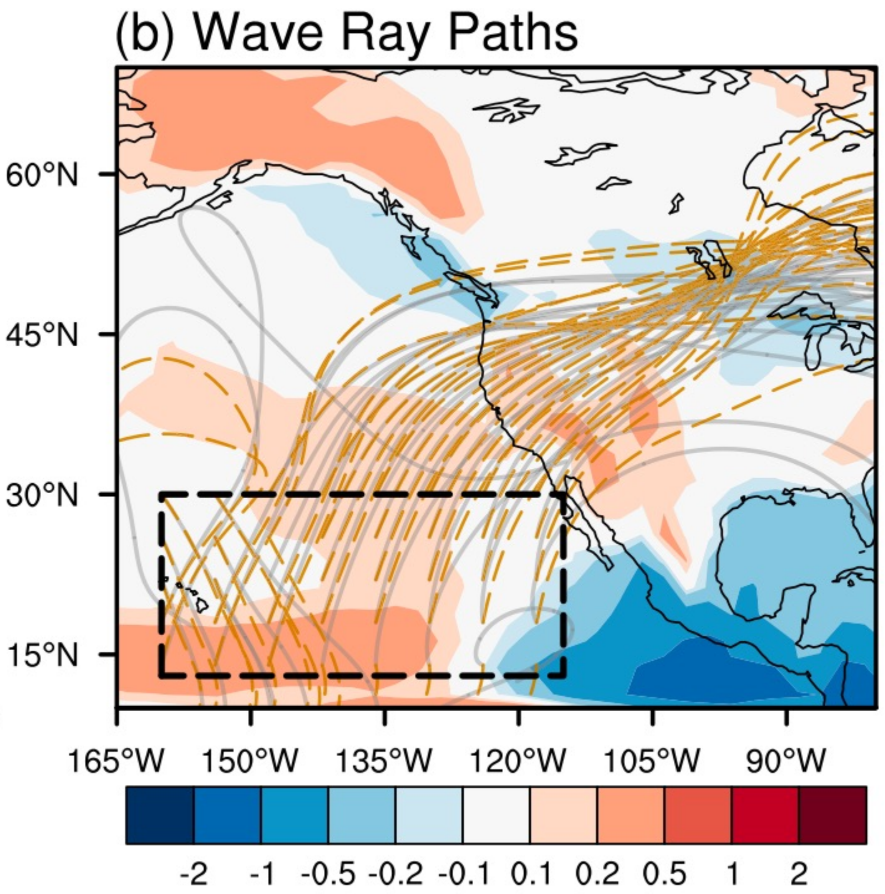


How Pacific diabatic heating enhances anticyclone over PNW



Physical Mechanisms:
Northward Expanded Waveguide → Northward Wave Propagation





Contour: Present-day Waveguide

Shading: Projected Changes of Waveguide

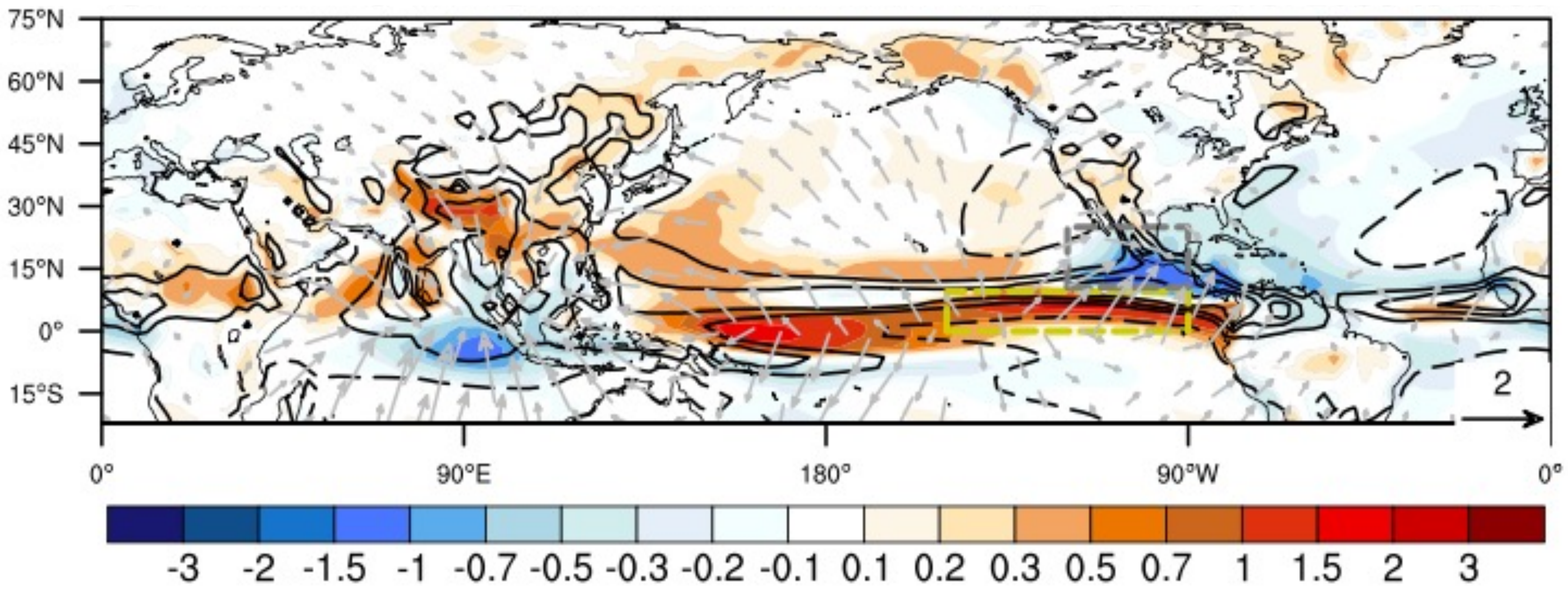
Stippling: > 70% of Model Agreement

Gray Curves: Present-day Ray Tracing

Yellow Curves: Projected Ray Tracing

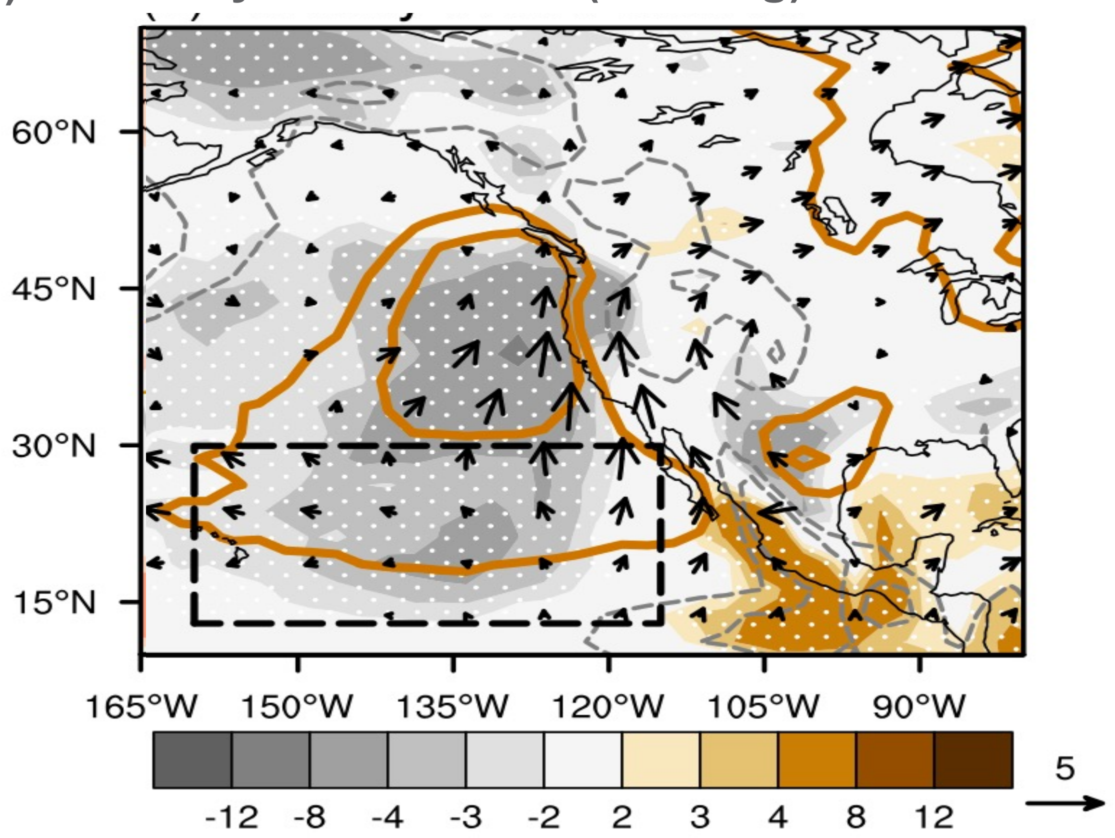
Physical Mechanisms: Enhanced Wave Sources

Projected Diabatic Heating (Shading) & Divergence Wind at 200 hPa(Vectors)



Contours: Diabatic heating at present day

Rossby Wave Source (Shading) at 200 hPa



Arrows: Wave Activity Flux at 200 hPa
Contour: Present-day Wave Source

Dipole Changes of Diabatic Heating

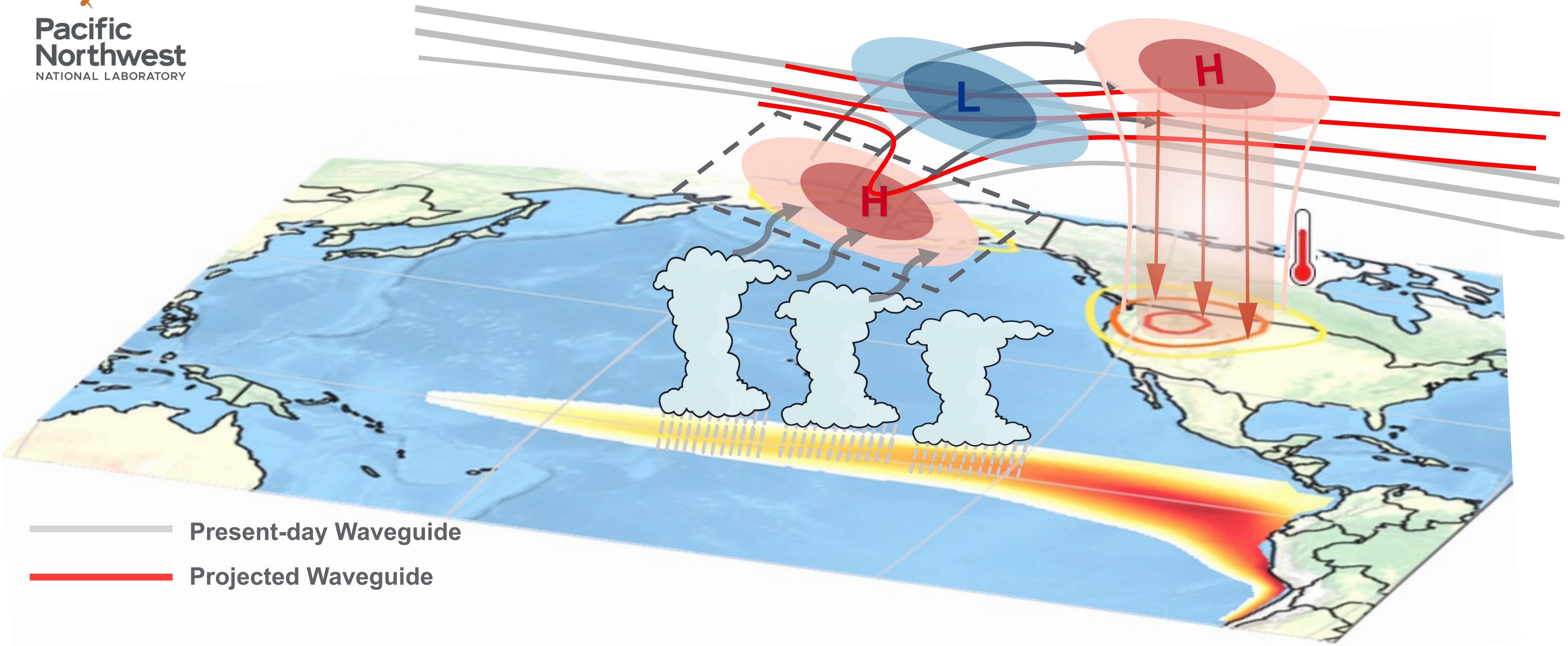
↓

Positive Divergence Anomaly → Wave Source ↑ (Negative Values)

$$S = -\nabla \cdot (\mathbf{v}_\chi \xi)$$

Sardeshmukh & Hoskins (1988 JAS)

Take Home Messages



- Heat-Dome-Like anticyclonic circulation would enhance by ~95% under SSP5-8.5 scenario, driven by
  - diabatic heating changes over the tropical Pacific
  - northward expanded waveguide in North America
- Similar results are found in sensitivity runs of GFDL dry dynamical core driven by diabatic heating

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Chen, Z., Lu, J., Chang, CC. et al. Projected increase in summer heat-dome-like stationary waves over Northwestern North America. *npj Clim Atmos Sci* 6, 194 (2023). https://doi.org/10.1038/s41612-023-00511-2

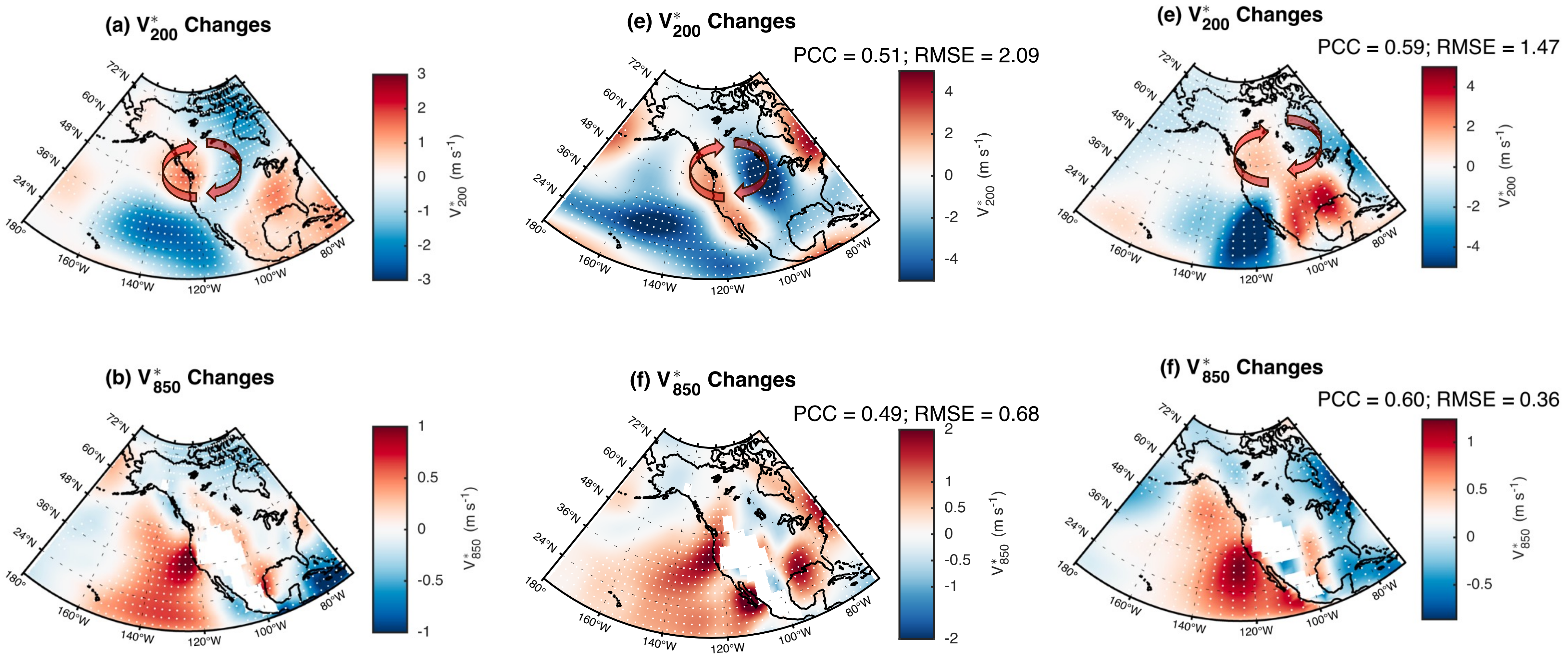
Supporting Information

Projected changes can be simulated by SWM: V'_{200}

CMIP6 MME | GFDL Dycore | Stationary Wave Model

200 hPa

850 hPa



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CMIP6 MME | GFDL Dycore | Stationary Wave Model

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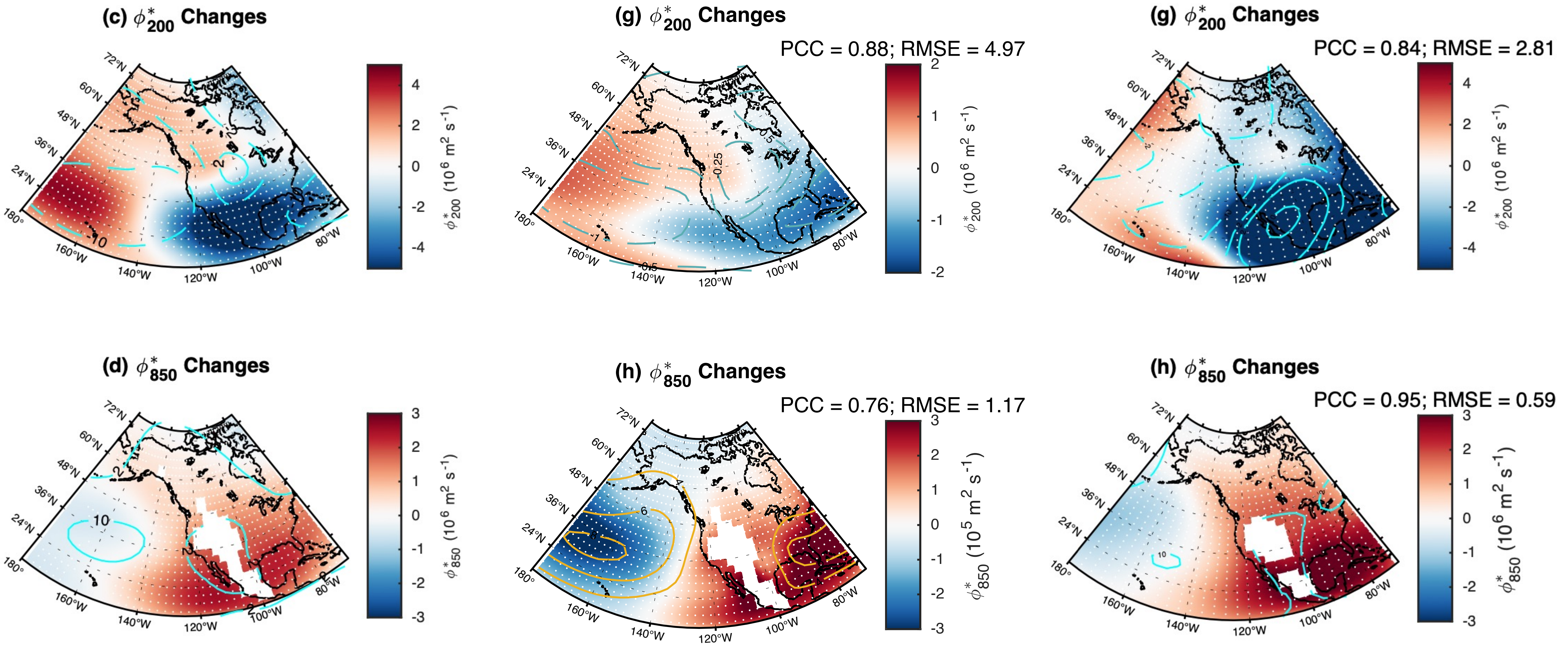

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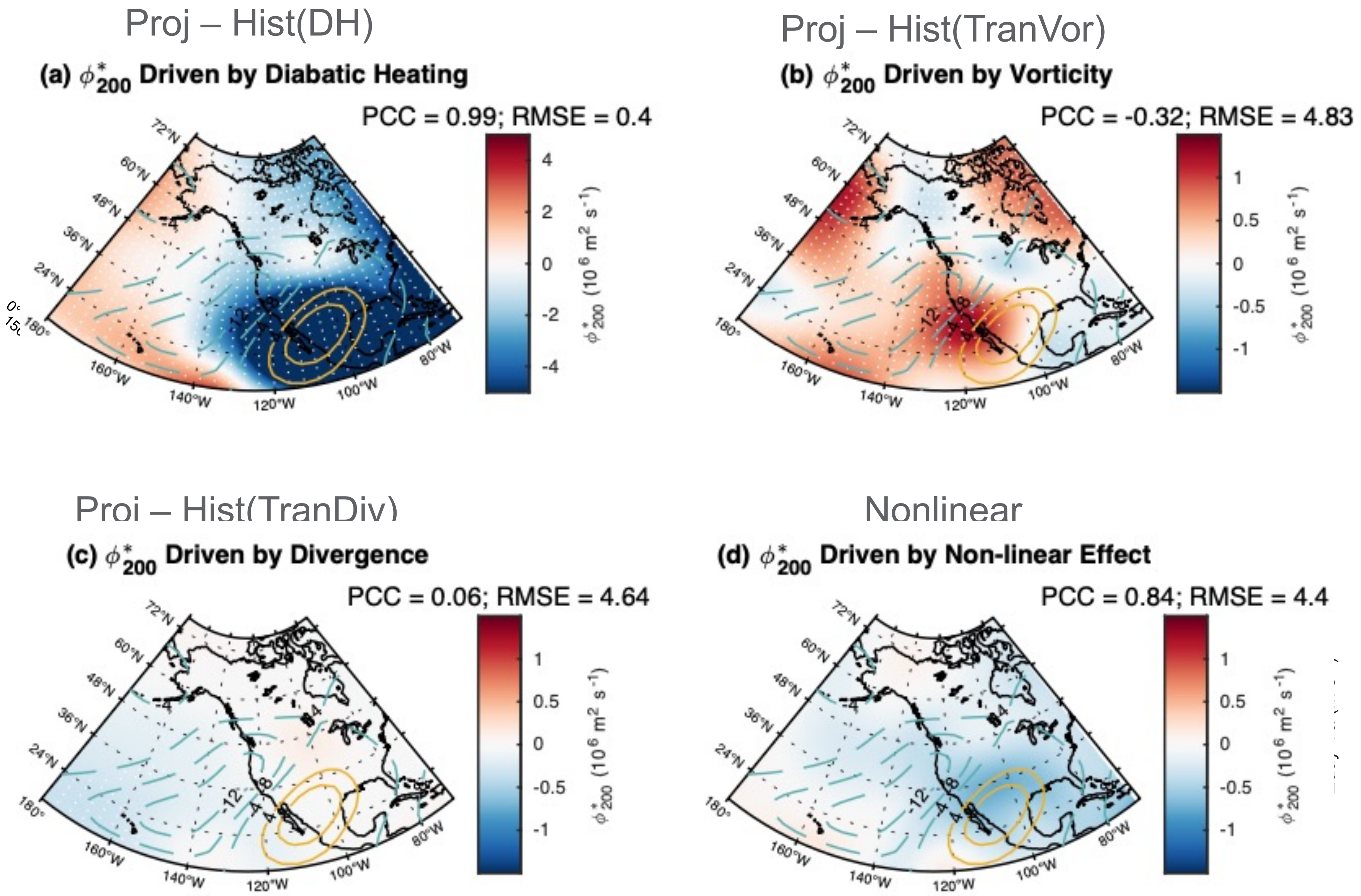

RMSE: Root-mean-square error

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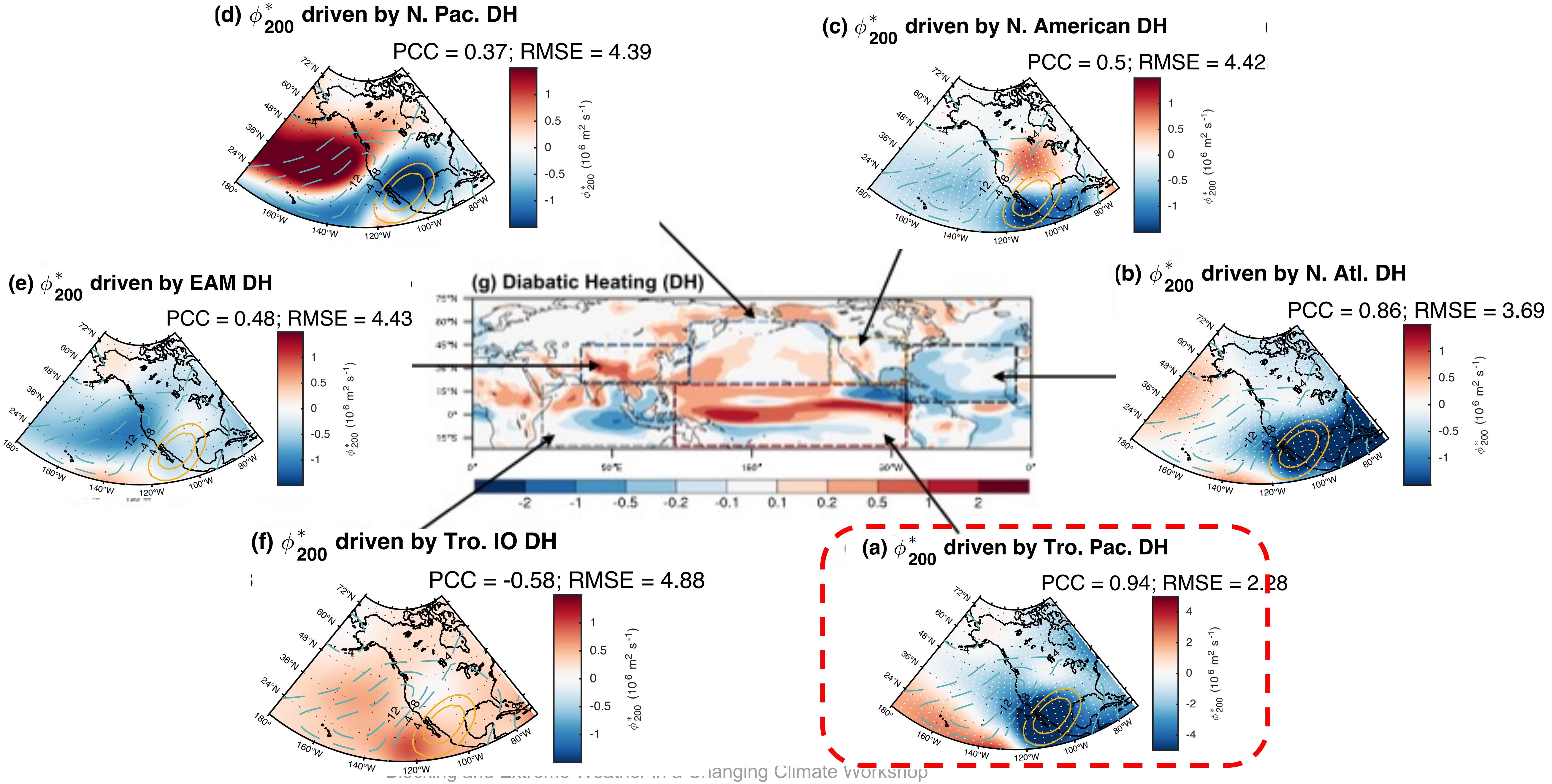
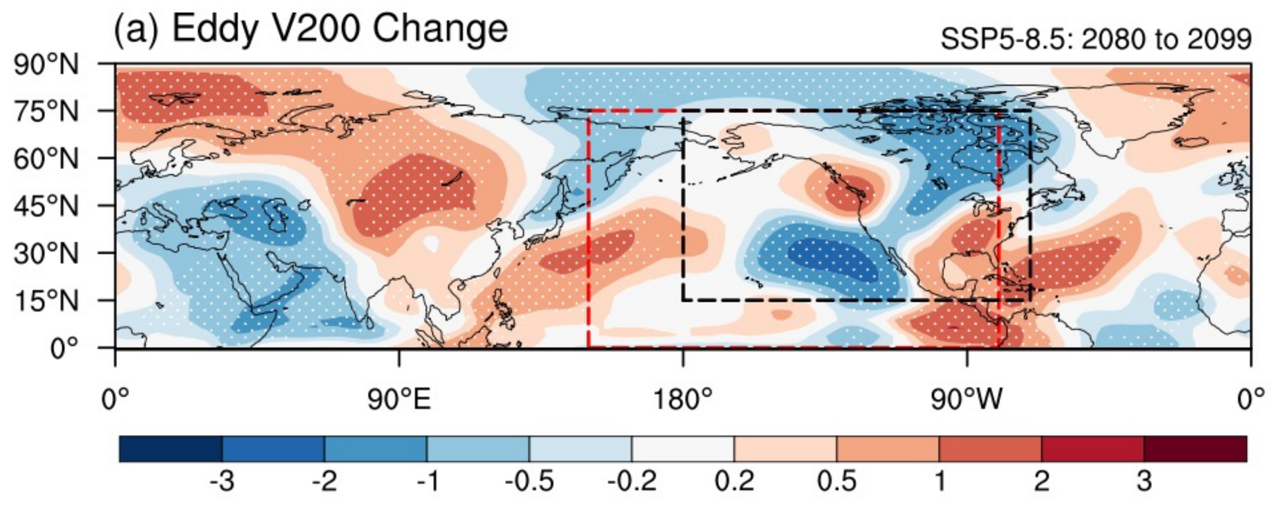
φ^*_{200} Response to Regional Forcings

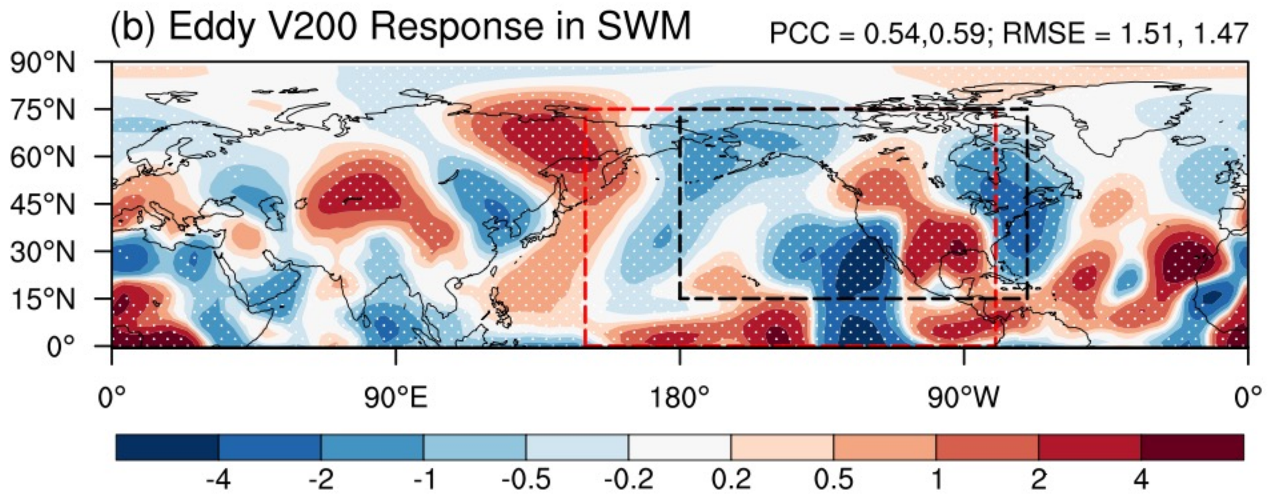


Zonal Mean & 3D Basic States

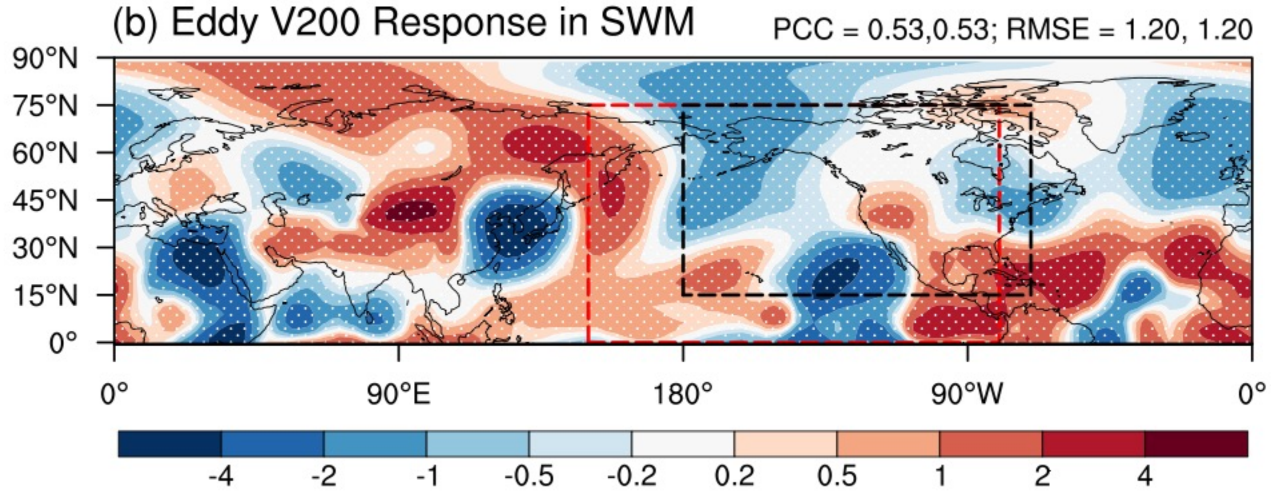
Projected Changes of 26 CMIP6 Model



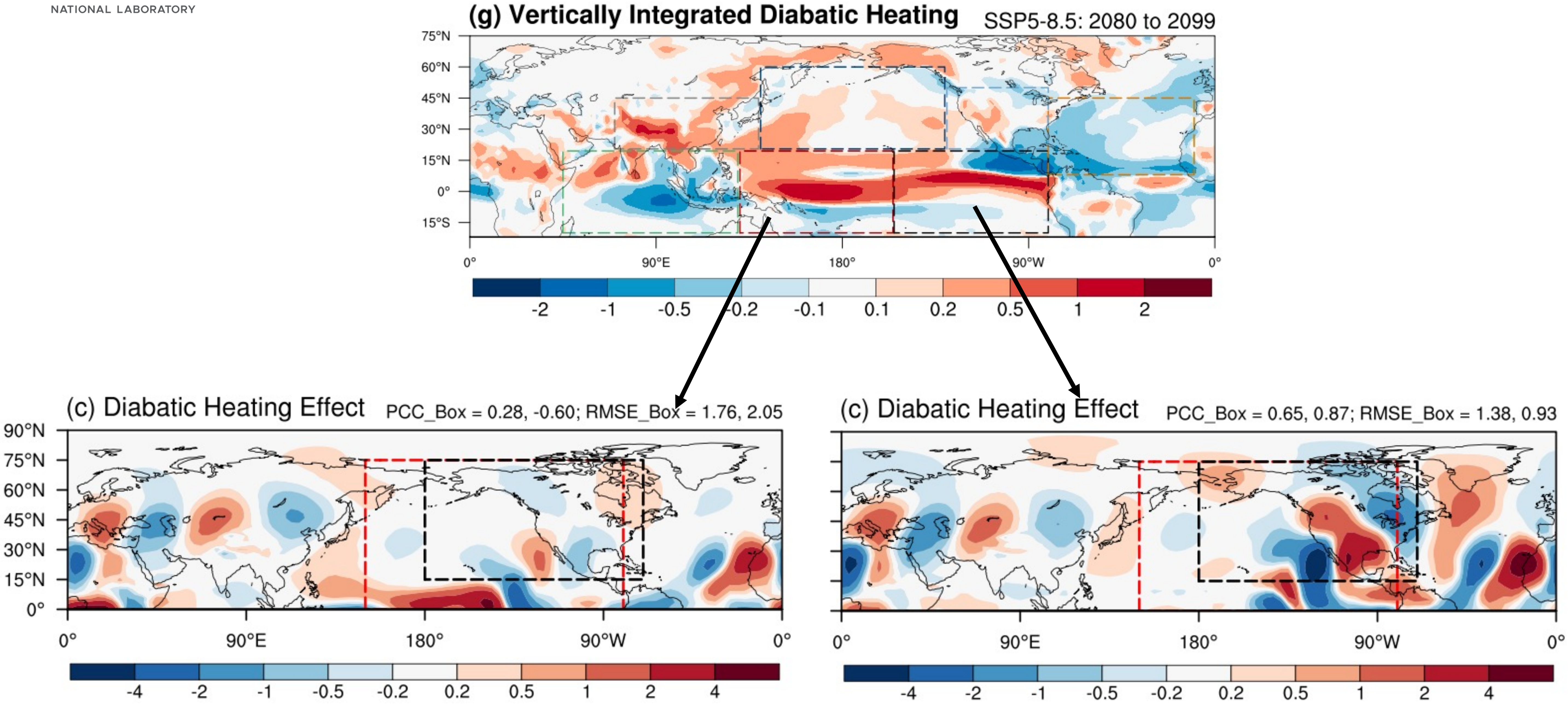
SWM Projection Run by Prescribing 3D Basic States



SWM Projection Run by Prescribing Zonal-mean Basic States

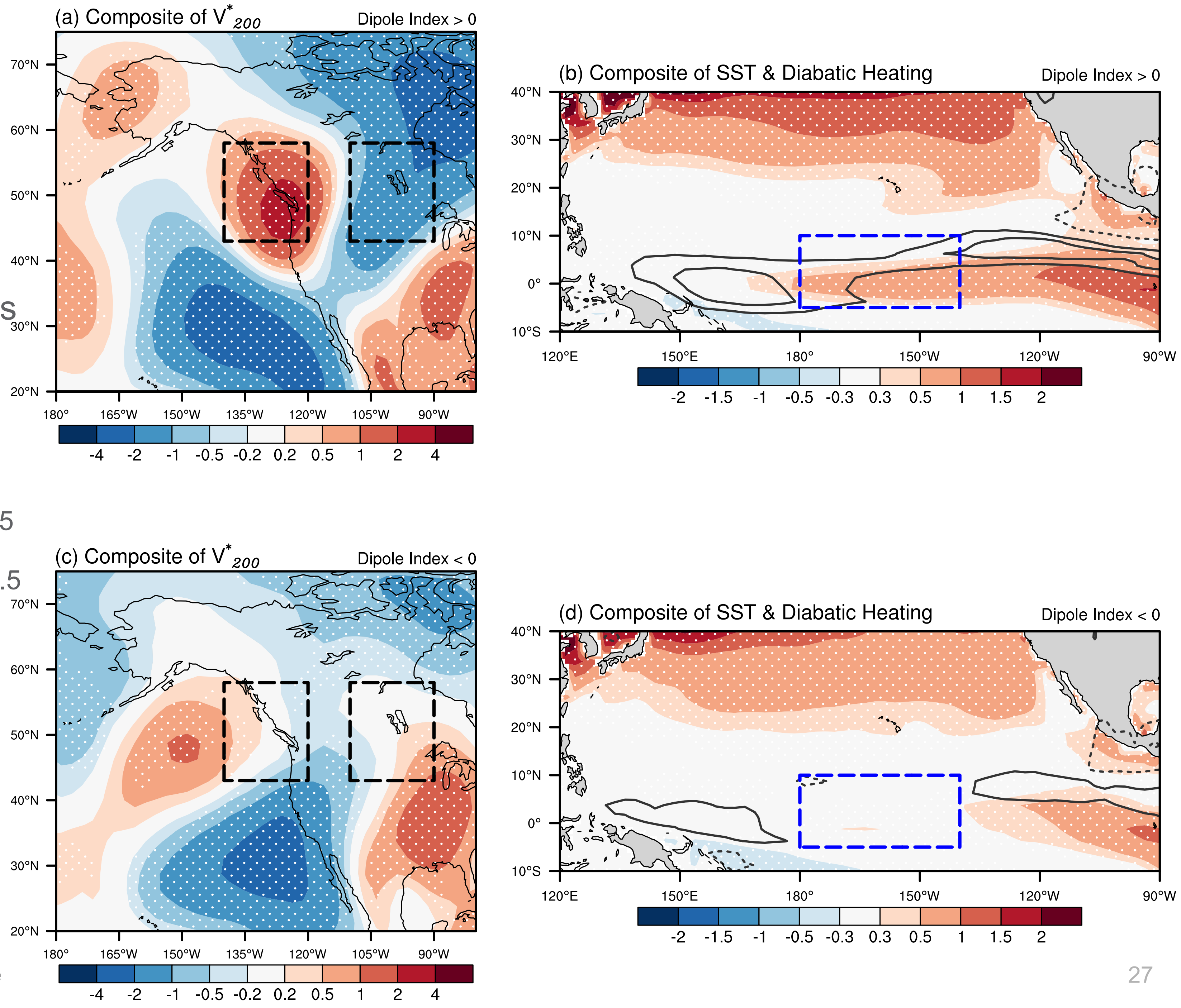


Responses forced by western and eastern Pacific diabatic heating

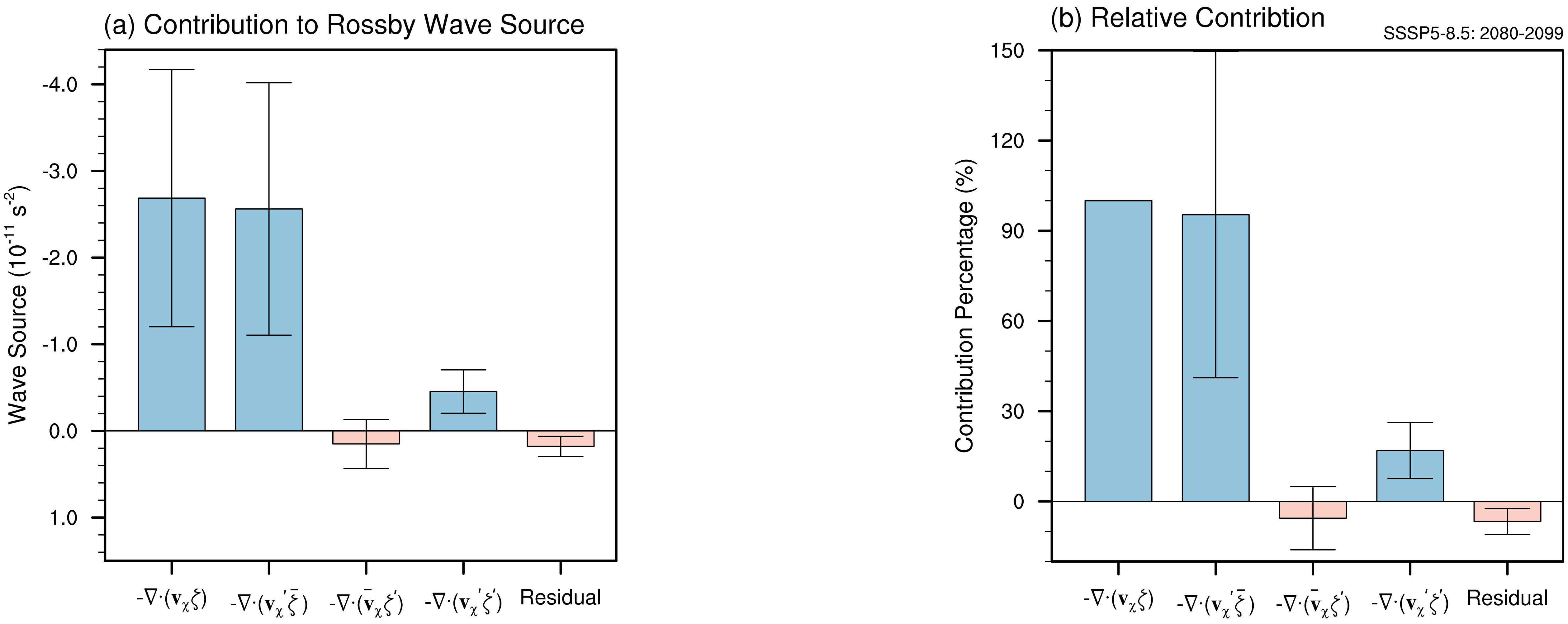


- The dipole changes in diabatic heating over the tropical eastern Pacific dominate the enhancement

- Projected eddy meridional wind (V^*_{200}; a, c),
- Projected relative SST warming (shading in b and d)
- Projected vertically averaged diabatic heating (contours in b and d)
- By the model ensembles which project
  - (a, b) increase in the dipole index in 2080–2099 under SSP5-8.5
  - (c, d) decrease in the dipole index in 2080–2099 under SSP5-8.5



Projected Rossby Wave Source over Northeast Tropical Pacific

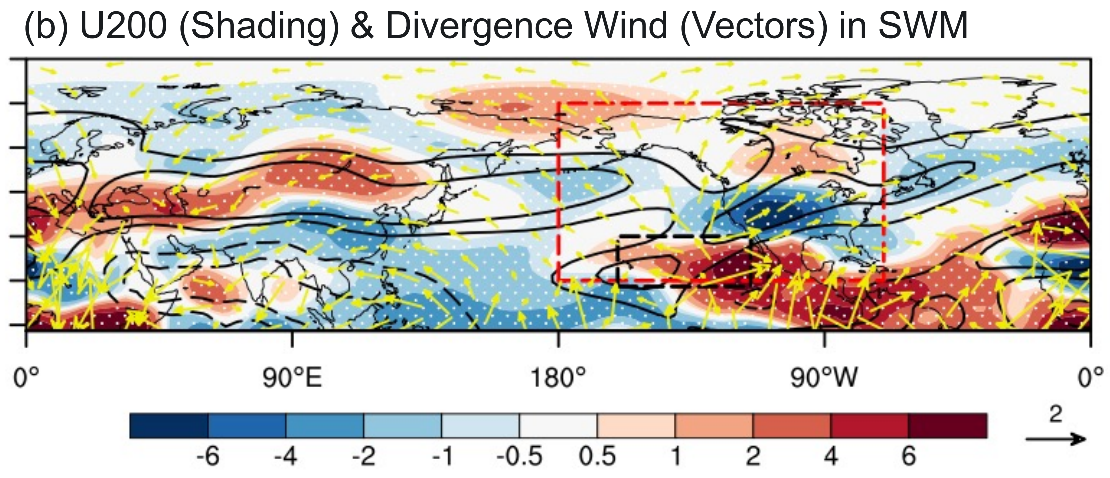


$$S = -\nabla\cdot(v_\chi\xi)$$

$$S' = -\nabla\cdot(v_\chi'\bar{\xi}) - \nabla\cdot(\overline{v_\chi}\xi') - \nabla\cdot(v_\chi'\xi') + \text{Res}$$

Physical Mechanisms: Wave Sources in SWM

Driven by Global Diabatic Heating



Driven by Tropical Pacific Diabatic Heating