PICES 2022 Annual Meeting at Busan

Stronger decadal variability of the Kuroshio Extension under simulated future climate change

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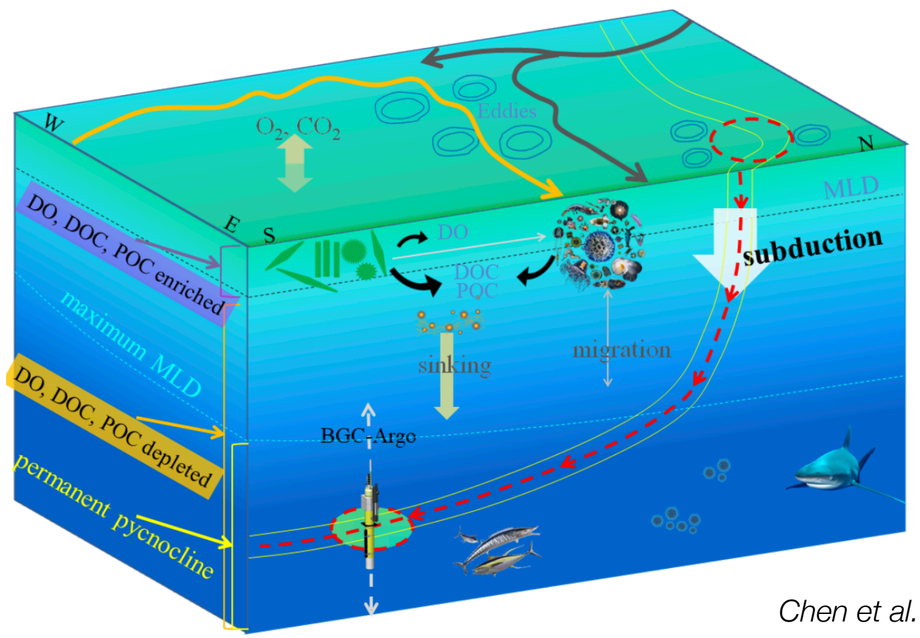
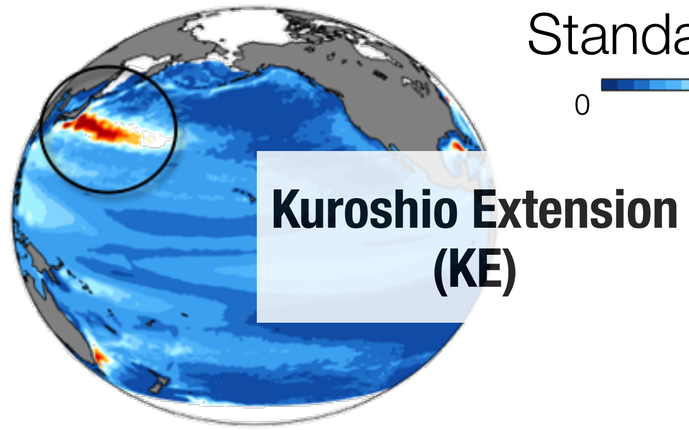
Pacific Western Boundary Currents Extension System

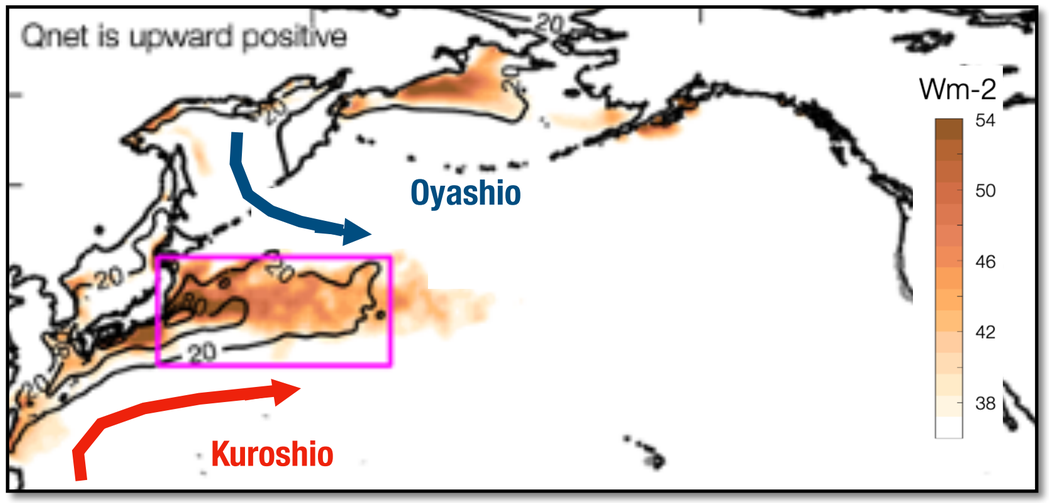
- The strongest sea surface height (SSH) variability associated with eddy activities, oceanic currents, and large-scale gyre circulations
- A greatest ocean heat source to the atmosphere with intensive air-sea heat and moisture exchanges that impact the regional and large-scale weather and climate
- Heat fluxes and oceanic circulations generate the prominent seasonal to decadal time scales of Pacific climate variability
- A crucial role for modulating the upper ocean marine ecosystems in the Northwestern Pacific

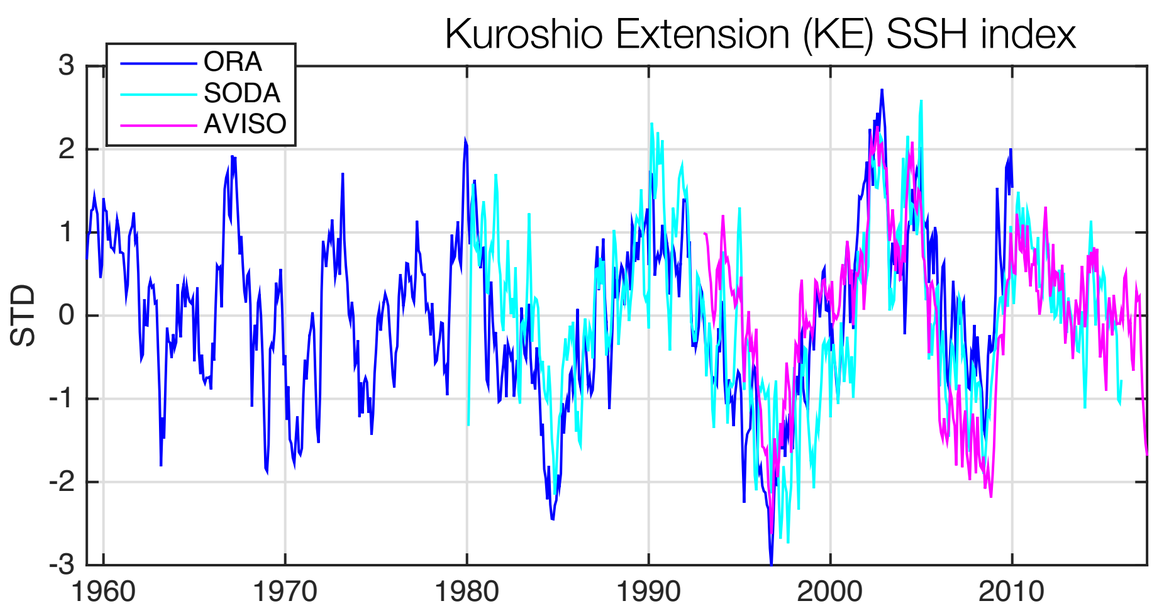


Chen et al. 2021



Net Surface Heat Flux (Qnet) annual mean (contours) & std (shading)





MOTIVATIONS

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“a real dynamical mode”

Future changes in a warming climate?

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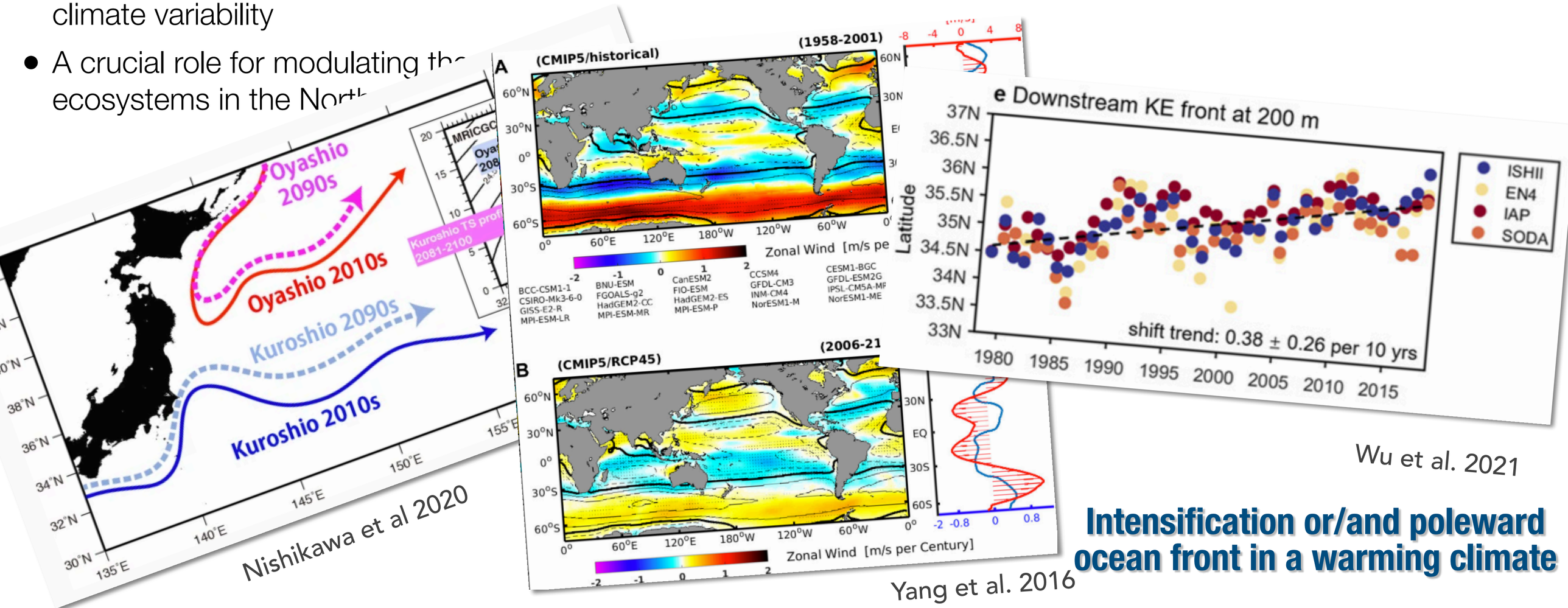
"a real dynamical mode"

Future changes in a warming climate?



Intensification or/and poleward ocean front in a warming climate

MOTIVATIONS

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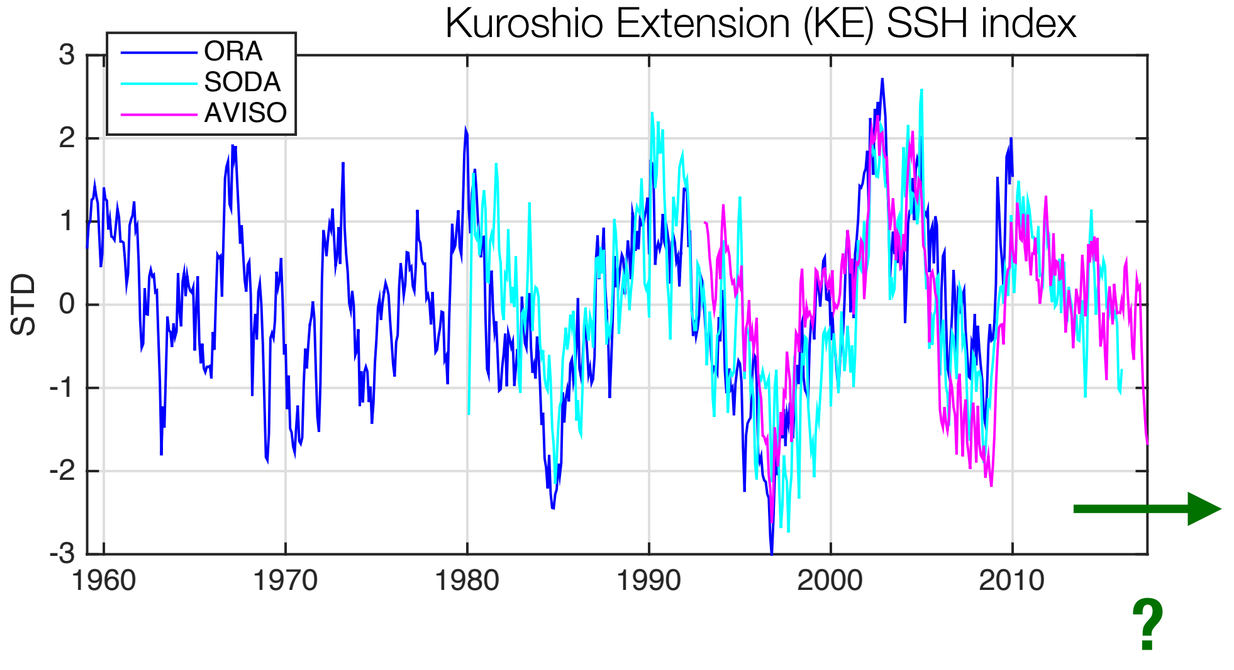
"a real dynamical mode"

Temporal changes in a future climate?

GOAL

To investigate the response of the KE variability and its sensitivity to future climate change scenarios ***with a special focus on the temporal aspects***

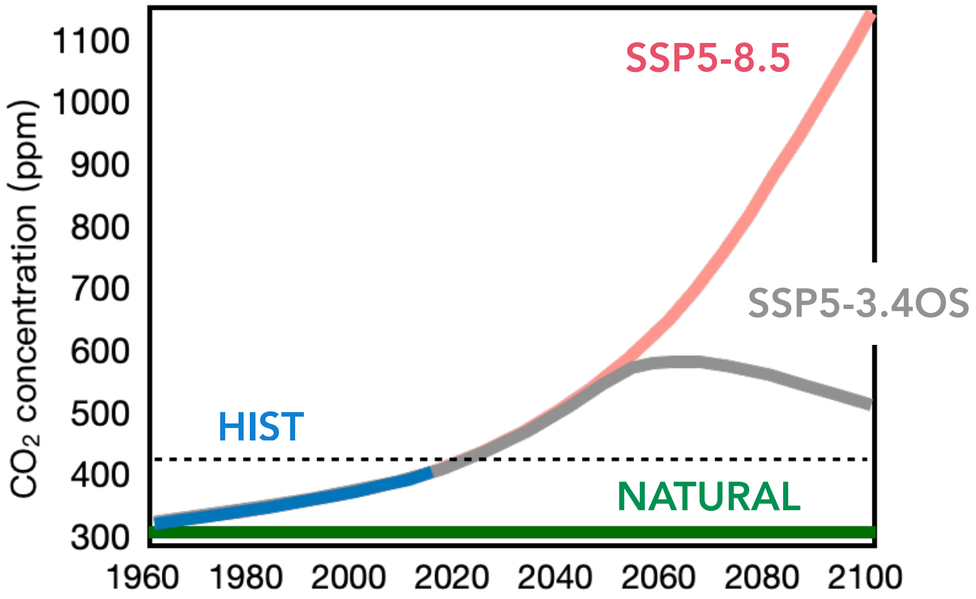


more details in Delworth et al. 2020

SPEAR (Seamless system for Prediction and EArth System Research)

:Next generation modeling system for seasonal to decadal prediction and projection at GFDL
AM4 atmosphere model + MOM6 ocean code + LM4 land model + SIS2 sea ice model

SPEAR_LES Large-Ensemble		SPEAR_LO	SPEAR_MED	SPEAR_HI	SPEAR_HI_25
	atmosphere/land	100km	50km	25km	25km
	ocean/sea ice	approximately 1° (with tropical refinement)			25km



1921-2014

SPEAR_MED_ensemble

2015-2100

HIST

All radiative forcings and land cover from human and natural sources are incorporated. (e.g., greenhouse gases, aerosols, ozone, solar irradiance, and volcanic aerosols)

Natural

Only natural forcing
Solar irradiance and volcanic aerosols vary as projected, but anthropogenic forcing is fixed at the 1921 level.

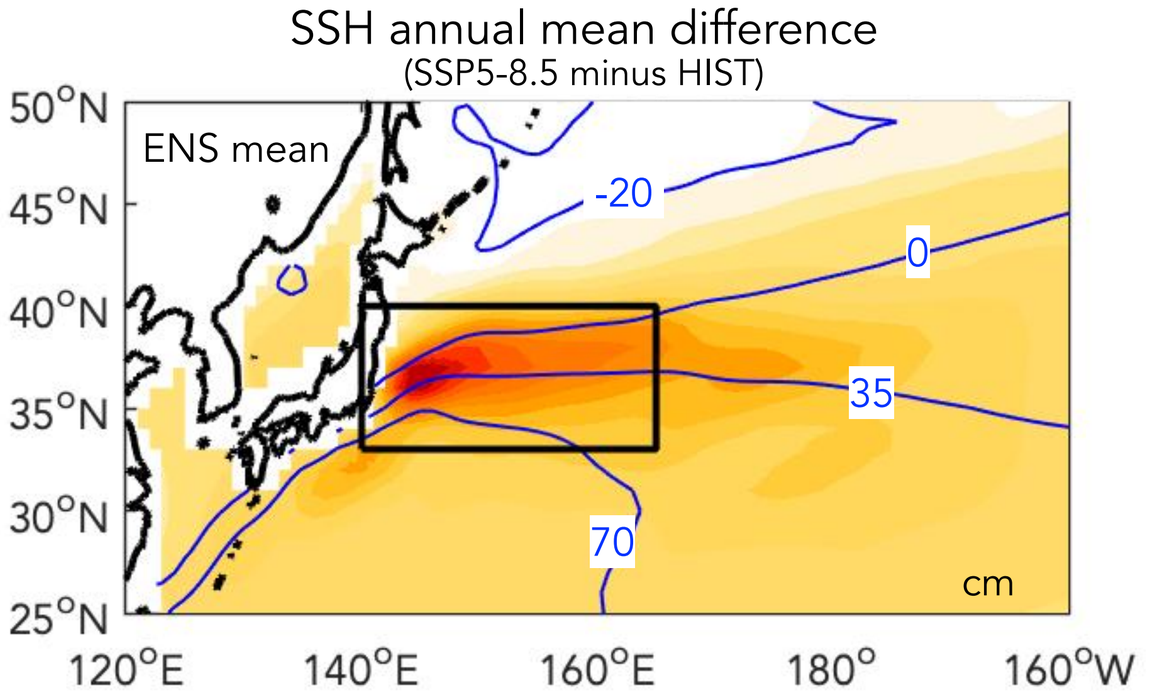
SSP5-8.5

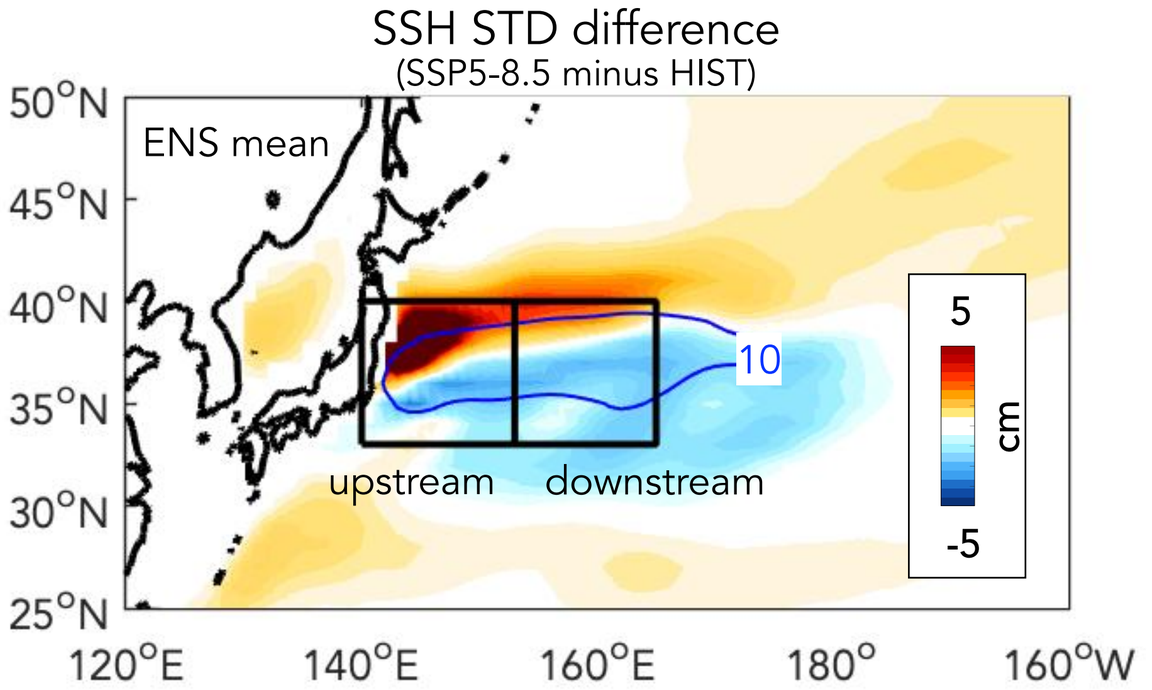
Highest radiative forcing scenario in Shared Socioeconomic Pathway (SSP)
(e.g., future evolution of monthly solar irradiance, global monthly mean concentrations of CO2, CH4, N2O, ozone-depleting substances)

SSP5-3.4OS

Overshoot scenario
The greenhouse gas concentration increases until 2040 following the SSP5-8.5 radiative forcing, and rapidly decreases thereafter.

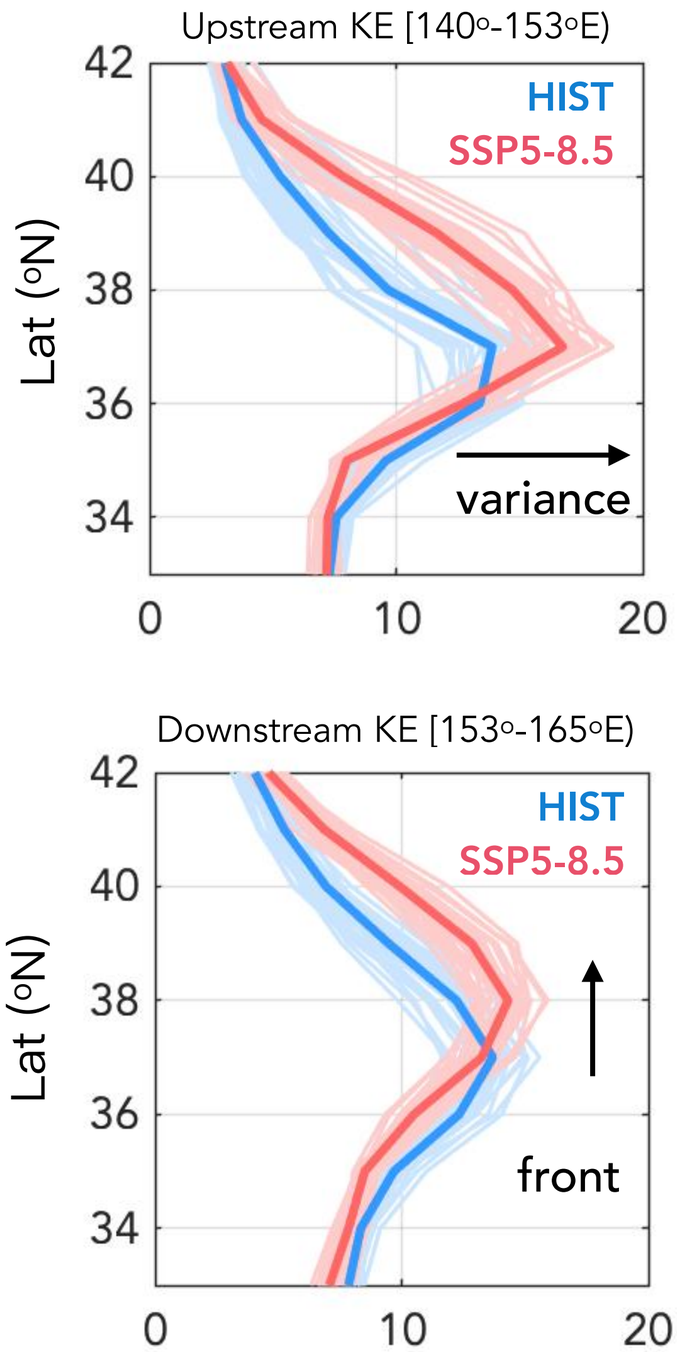
- ✓ Each scenario is a 30-member ensemble.
- ✓ 50 km atmospheric resolution and 1° oceanic resolution
- ✓ Each scenario has prescribed CO_2, CH_4, and other forcing agents.





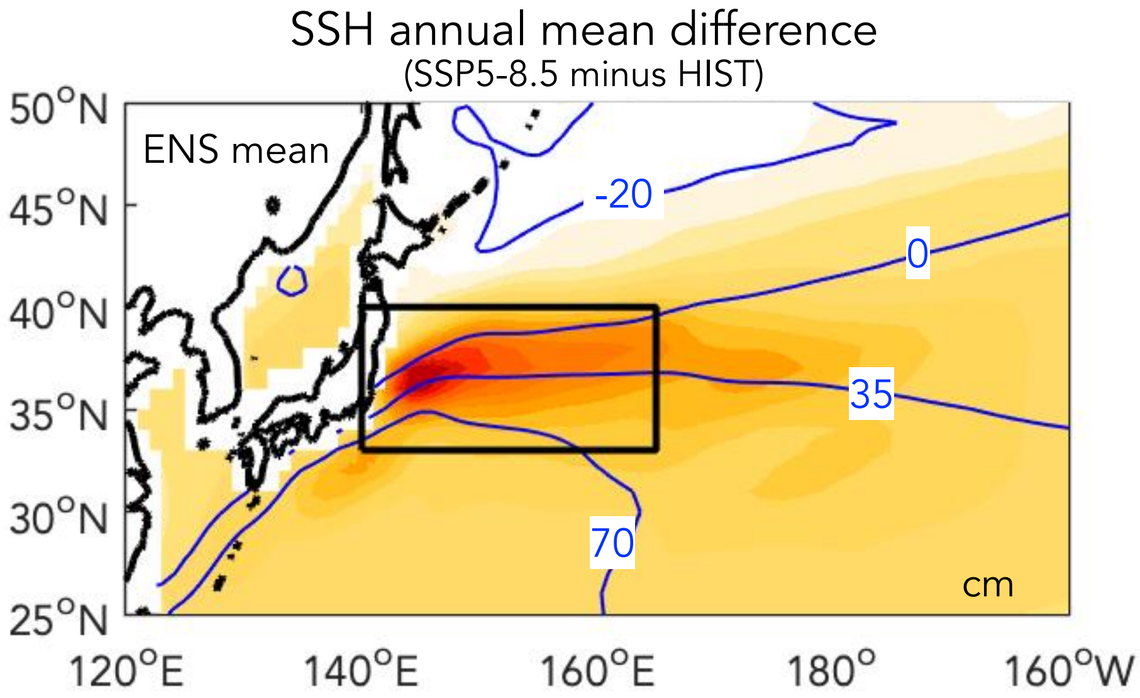
Kuroshio Extension SSH

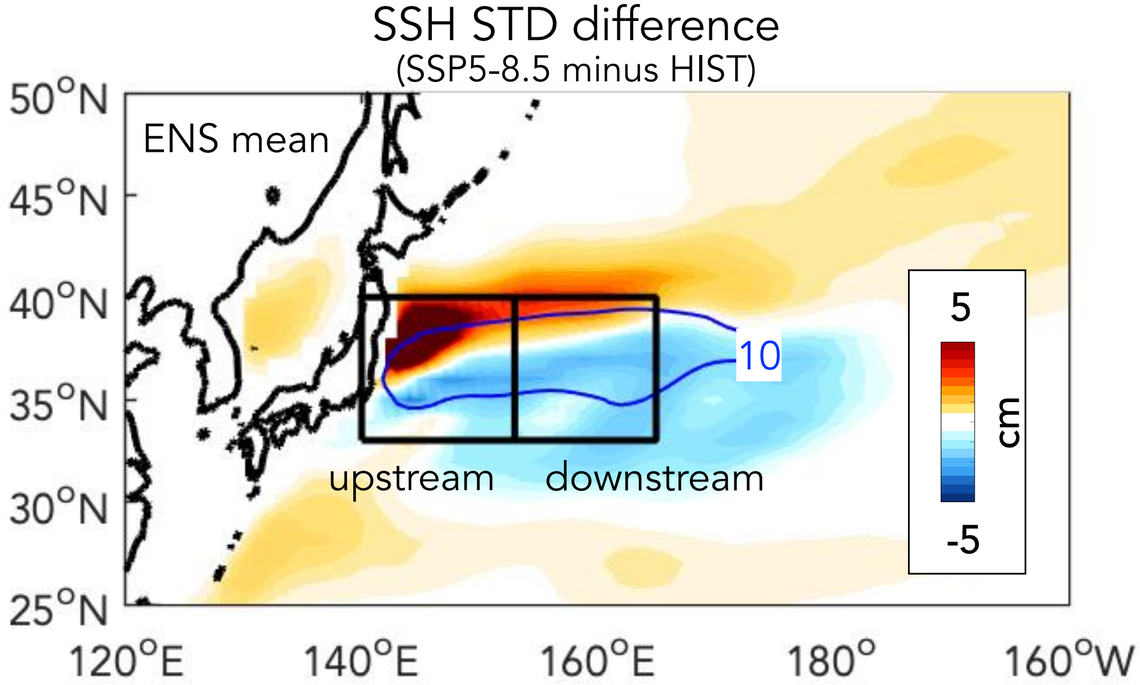
- ✓ **INCREASING** mean
- ✓ **POLEWARD** shifted front
- ✓ **ENHANCED** variance



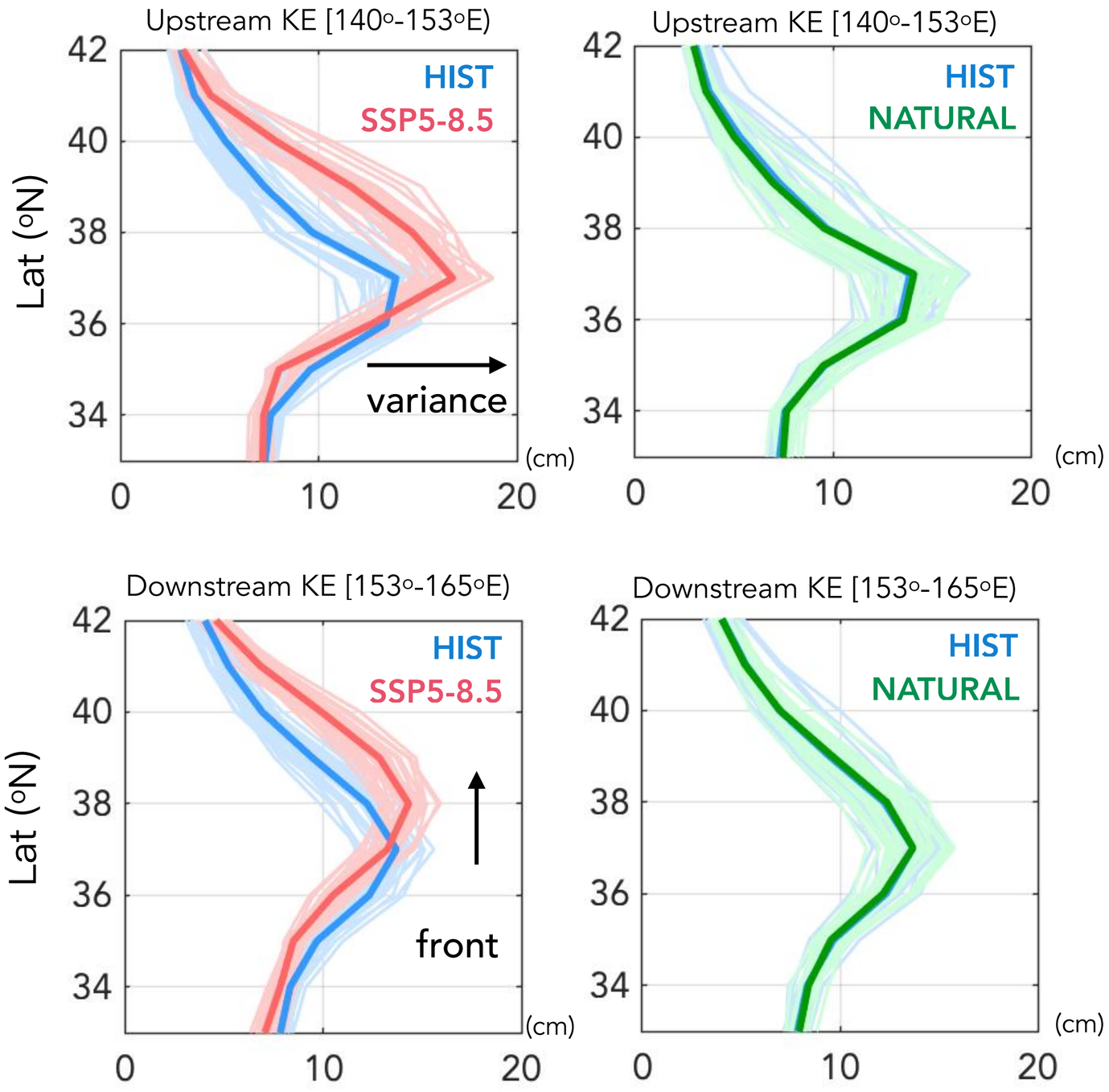
30-member ensemble mean

Individual member



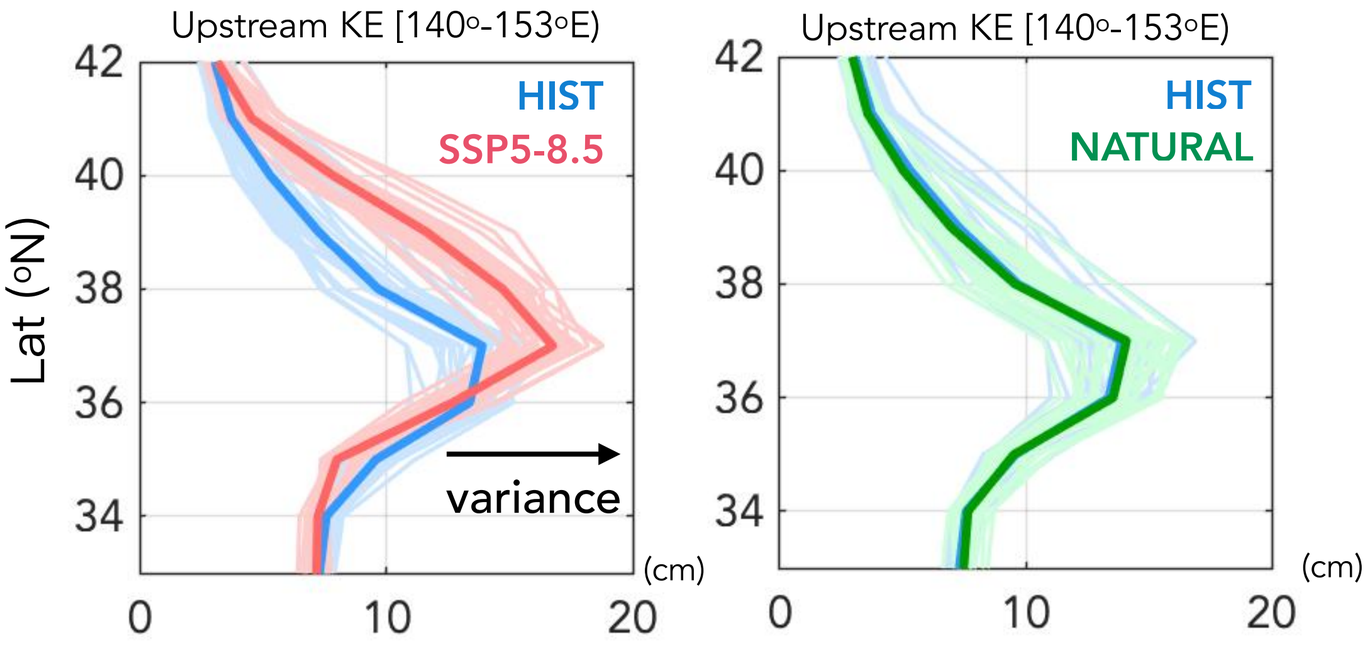


- ✓ **INCREASING** mean SSH
- ✓ **POLEWARD** shifted front in **DOWNSTREAM**
- ✓ **ENHANCED** variance in **UPSTREAM**

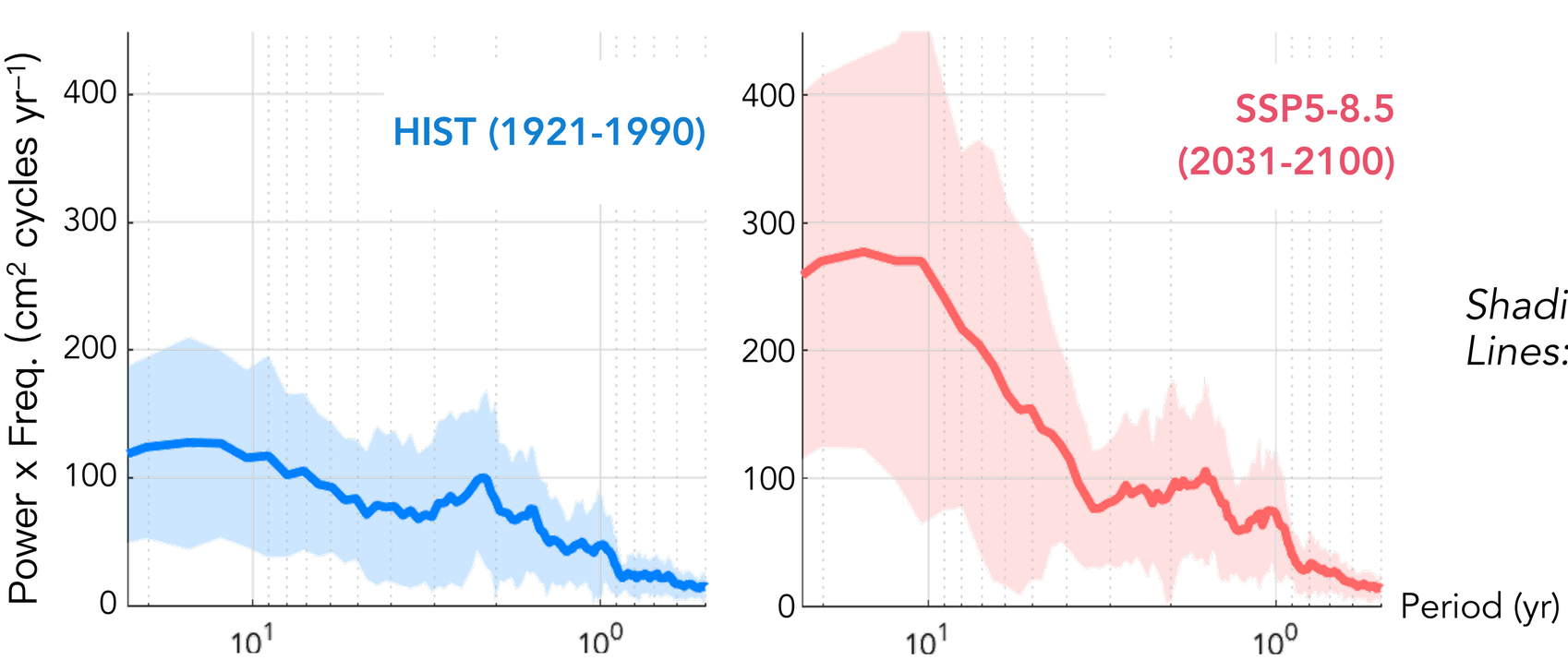


- ✓ **INCREASING** mean SSH
- ✓ **POLEWARD** shifted front in **DOWNSTREAM**
- ✓ **ENHANCED** variance in **UPSTREAM**

by increasing greenhouse gas



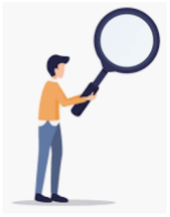
Spectral Analysis of upstream KE SSH



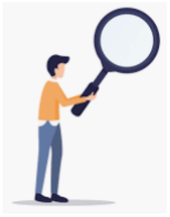
Shading: ensemble spread
Lines: ensemble mean

✓ ***Enhanced decadal variance*** **by increasing greenhouse gas**

-> increasing total KE intensity



What drives the stronger KE decadal variance under anthropogenic forcing?



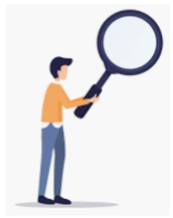
What drives the stronger KE decadal variance under anthropogenic forcing?

H1. Limited or decreasing short-time scale intrinsic variability (e.g., eddy activities)

H2. Enhanced decadal remote atmospheric forcing (e.g., oceanic Rossby waves)

Limited
Short time scale KE

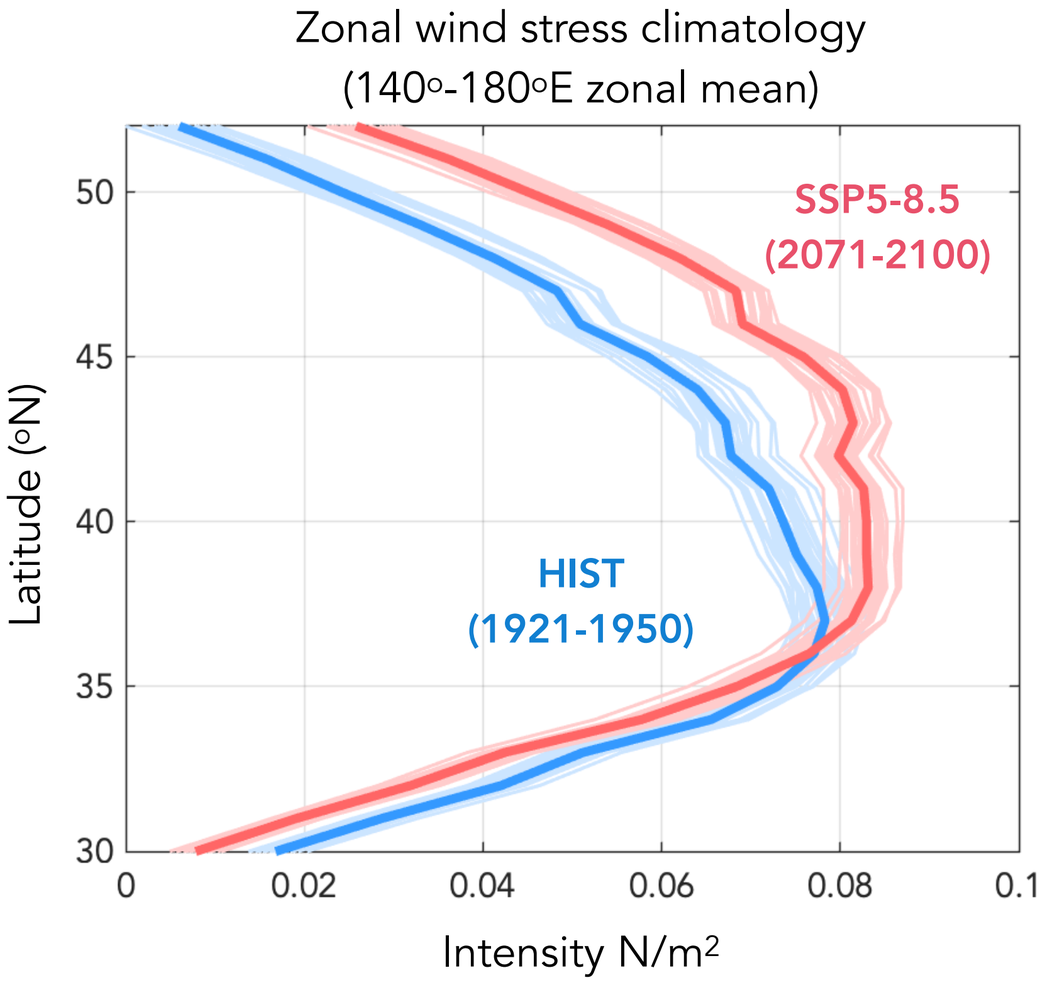
Decadal KE ↑



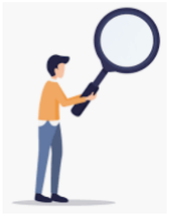
What drives the stronger KE decadal variance under anthropogenic forcing?

Limited Short time scale KE

H1. Changes in midlatitude surface wind climatology & associated impacts to the WBC



An intensification and poleward shift of surface wind forcing



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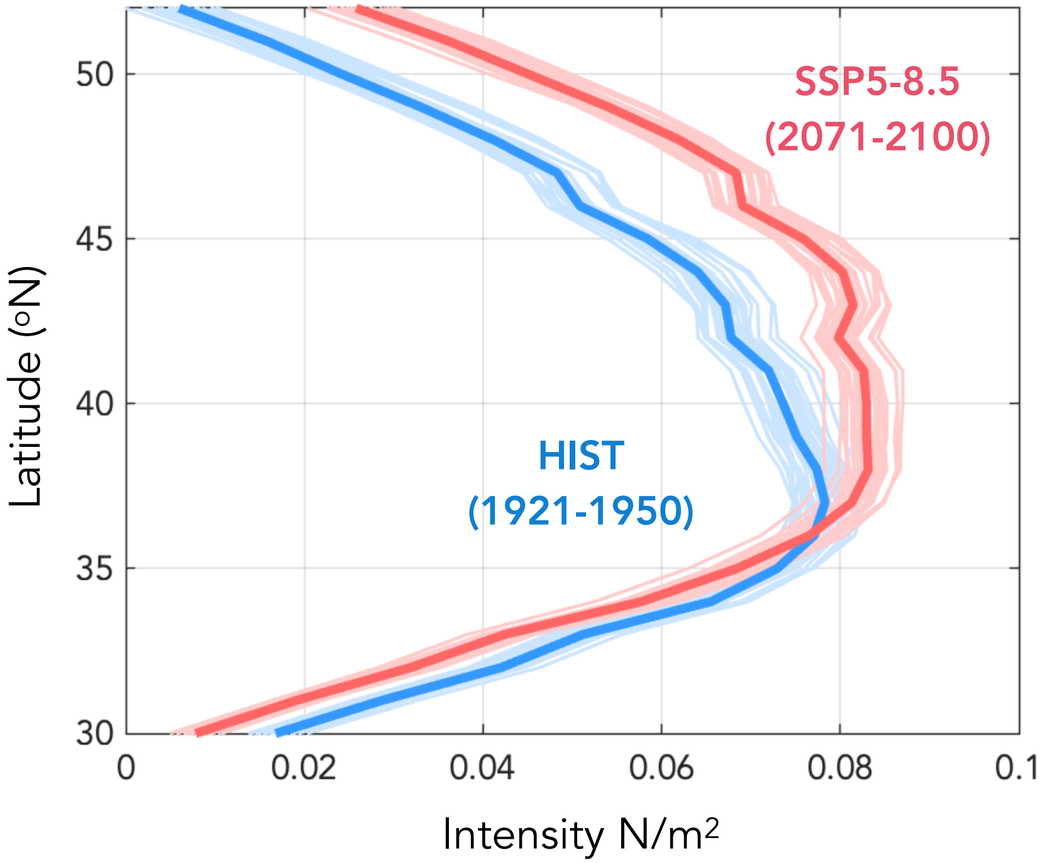
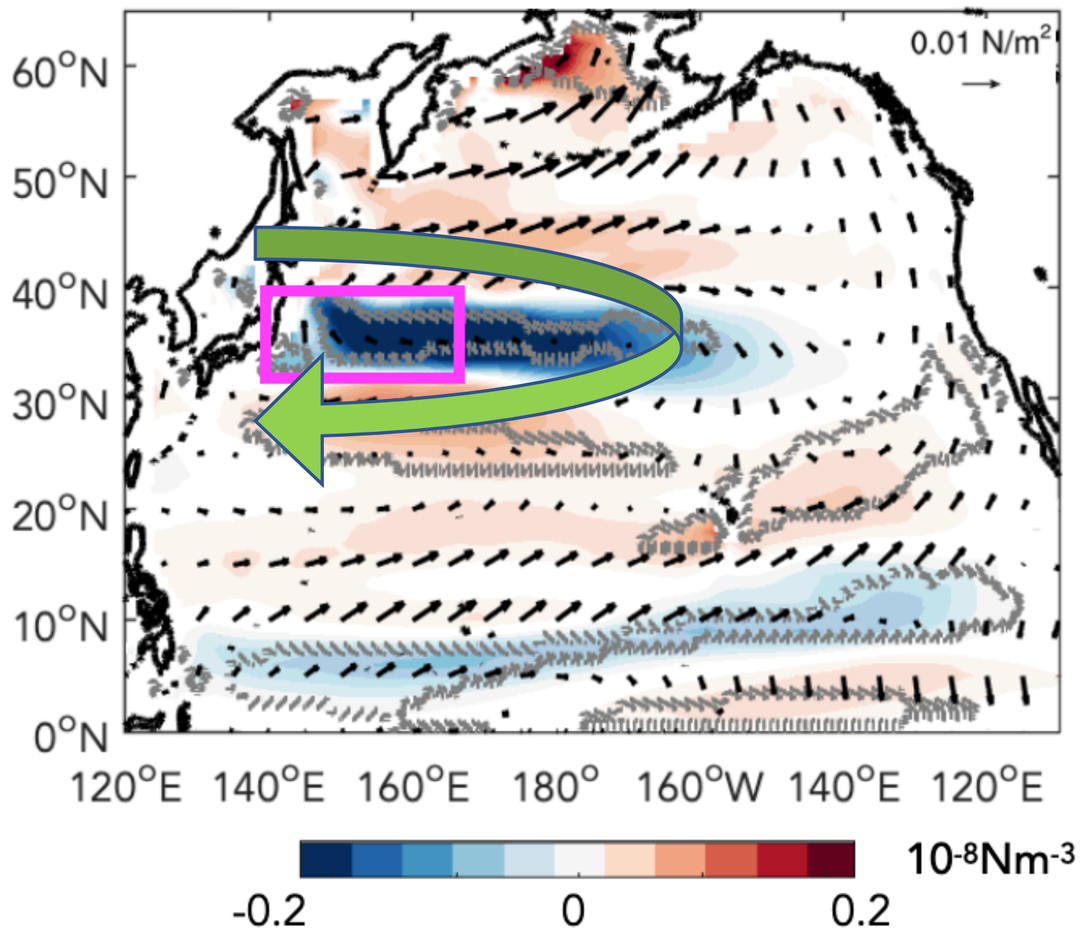
H1. Changes in midlatitude surface wind climatology & associated impacts to the WBC

Zonal wind stress climatology
(140°-180°E zonal mean)



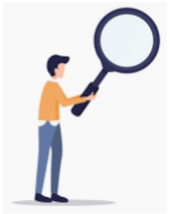
Surface wind stress curl climatology
(SSP585 minus HIST)



An intensification and poleward shift of surface wind forcing

→

- ✓ Spin-up of the Kuroshio recirculation gyre
- ✓ Forcing the KE jet inflow poleward



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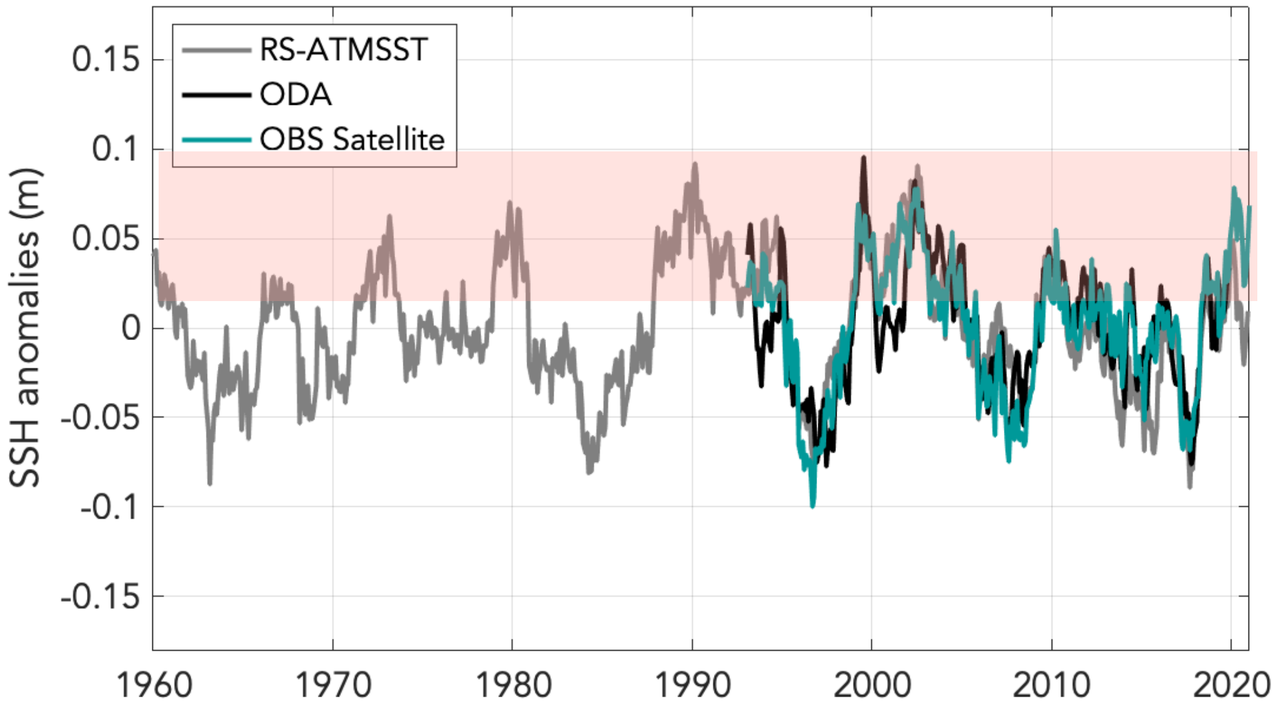
Limited Short time scale KE

KE Sea Surface Height



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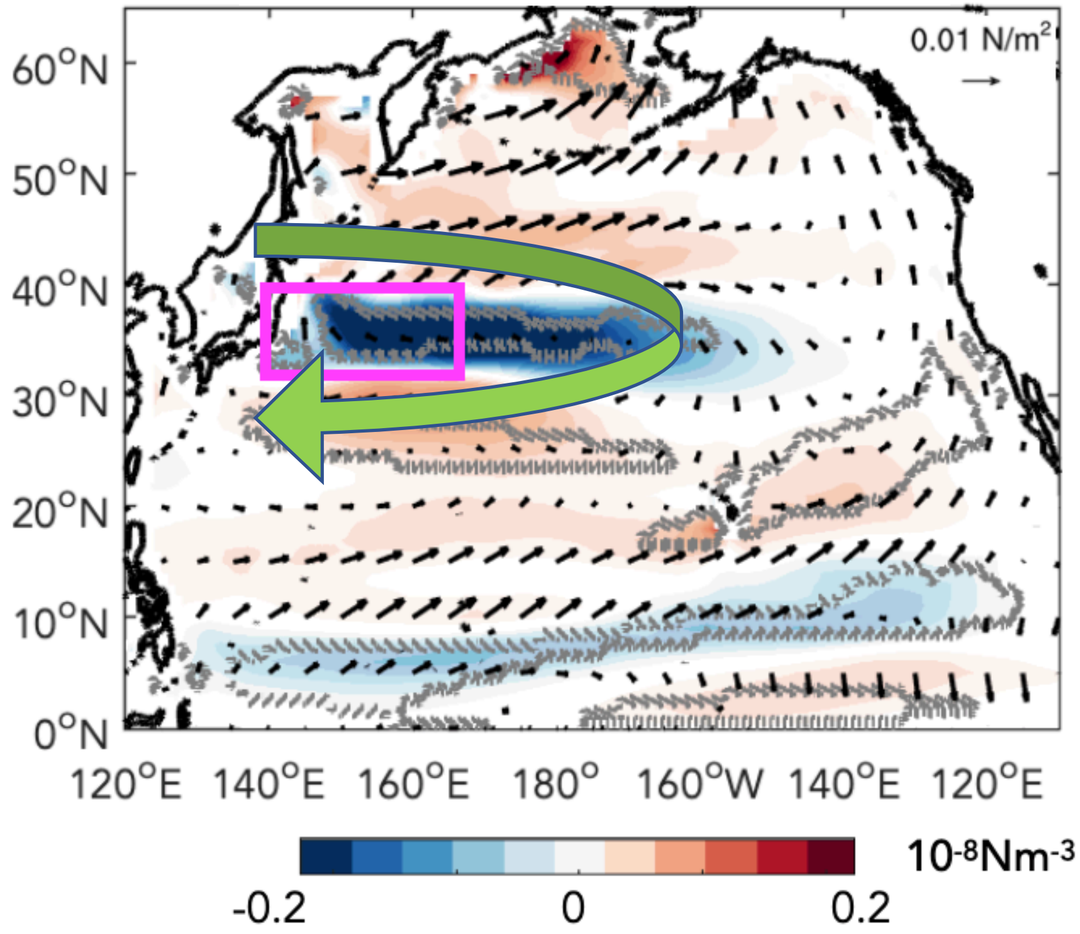


Favored "positive" KE state in warming climate?

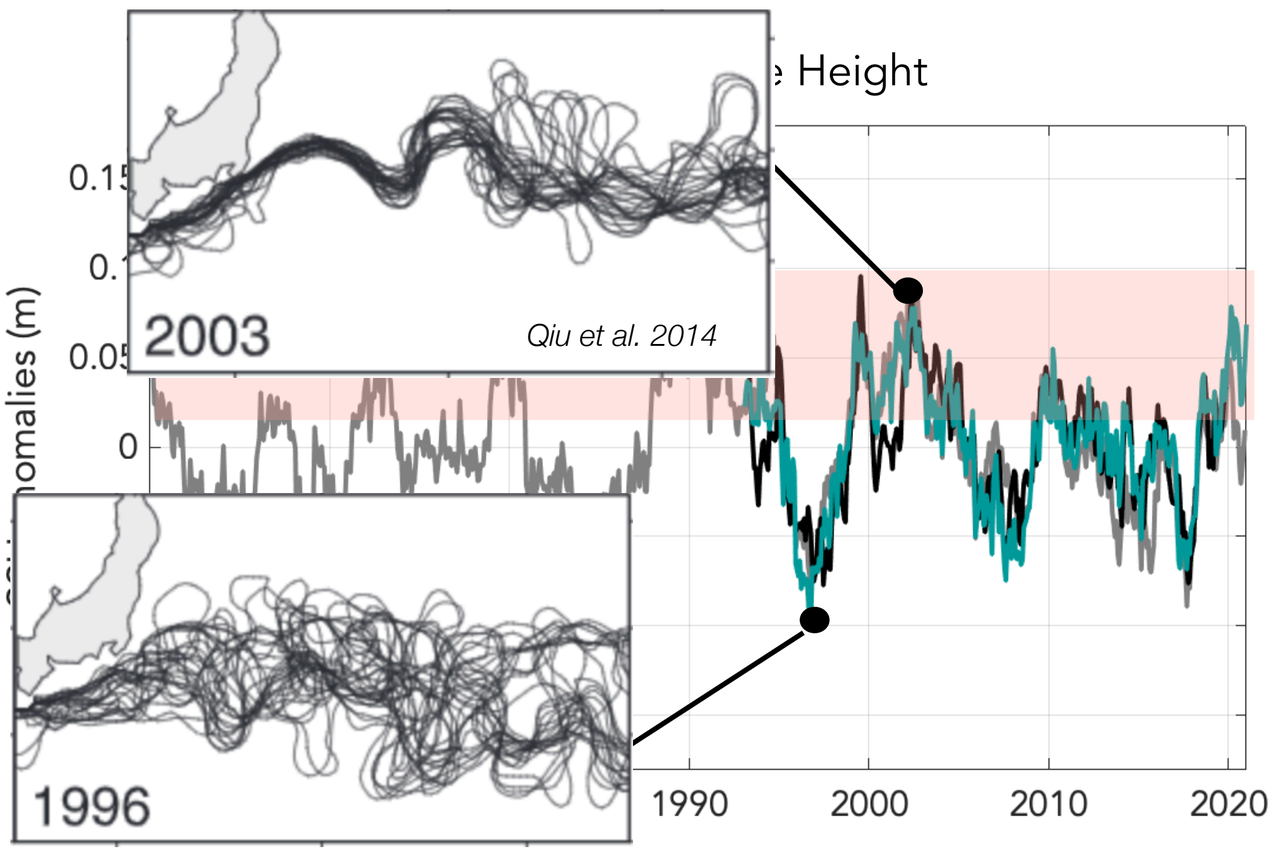
- ✓ Spin-up of the Kuroshio recirculation gyre
- ✓ Forcing the KE jet inflow poleward

What drives the stronger KE decadal variance under anthropogenic forcing?

H1. Changes in midlatitude surface wind climatology & associated impacts to the WBC

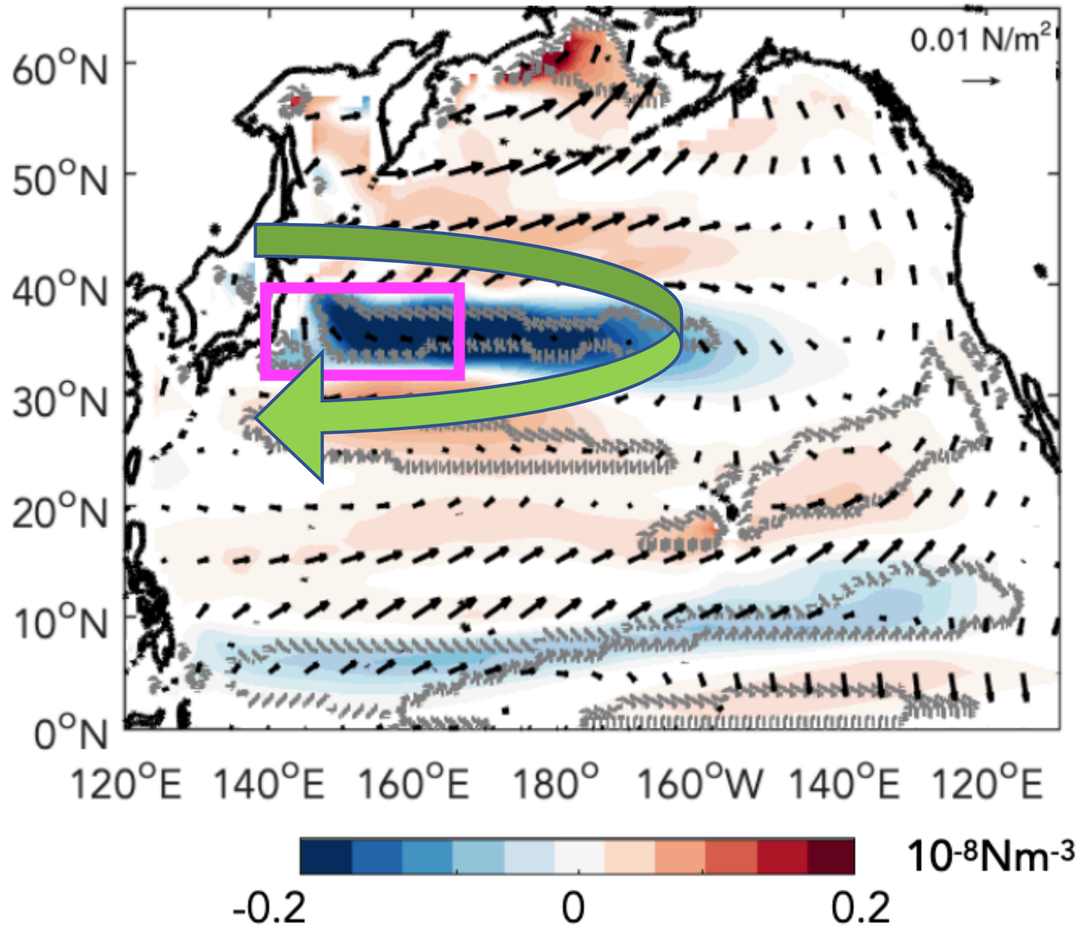
Limited Short time scale KE

Positive KE (EKE level down)



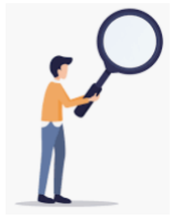
Negative KE (EKE level up)

Surface wind stress curl climatology
(SSP585 minus HIST)



Favored "positive, stable, elongated" KE state in warming climate?

- ✓ Spin-up of the Kuroshio recirculation gyre
- ✓ Forcing the KE jet inflow poleward
- ✓ Limited eddy activities during stable state



What drives the stronger KE decadal variance under anthropogenic forcing?

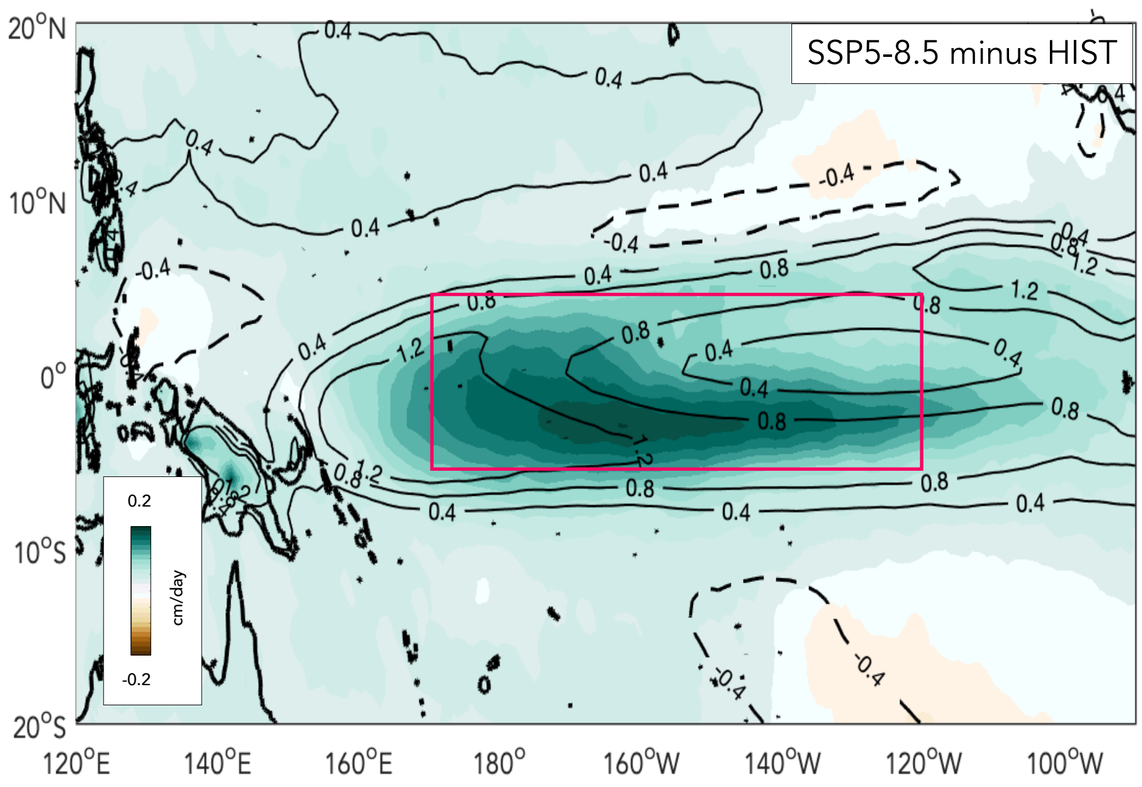
H1. Changes in midlatitude surface wind climatology & associated impacts to the WBC

H2. Stronger atmospheric forcing of oceanic Rossby waves via ENSO teleconnections

Limited Short time scale KE

Decadal KE ↑

Changes in Tropical Precipitation climatology (contours) & STD (shading)



Increasing ENSO amplitude in SPEAR SSP585

↓

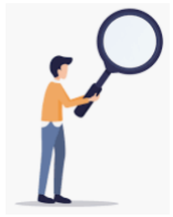
Stronger ENSO teleconnection impacts on the midlatitude air-sea coupled dynamics

↓

Stronger midlatitude atmospheric forcing of Oceanic Rossby waves

↓

KE SSH variability



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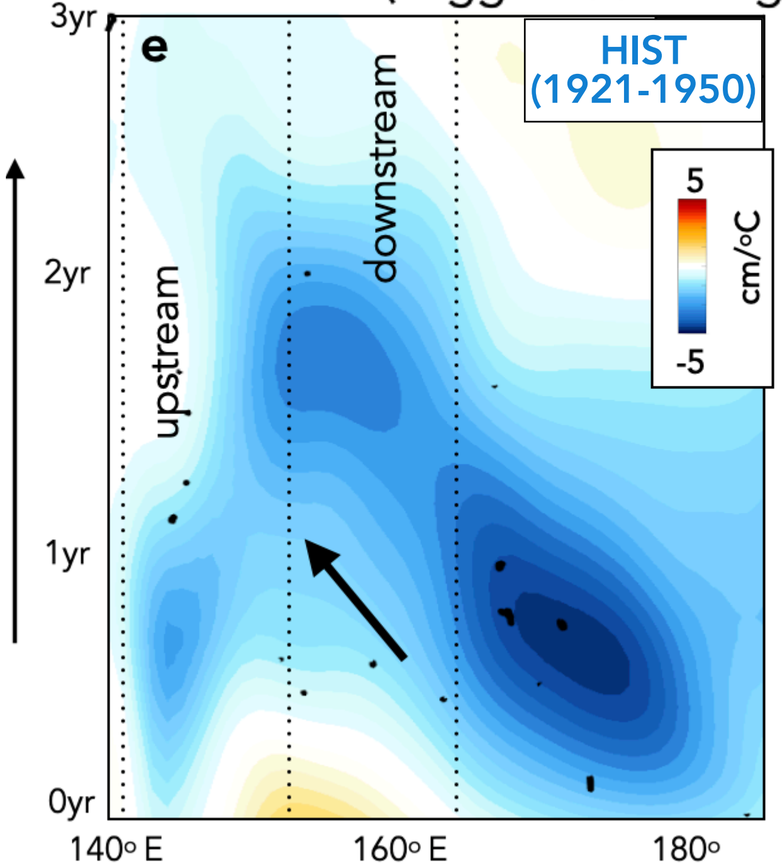
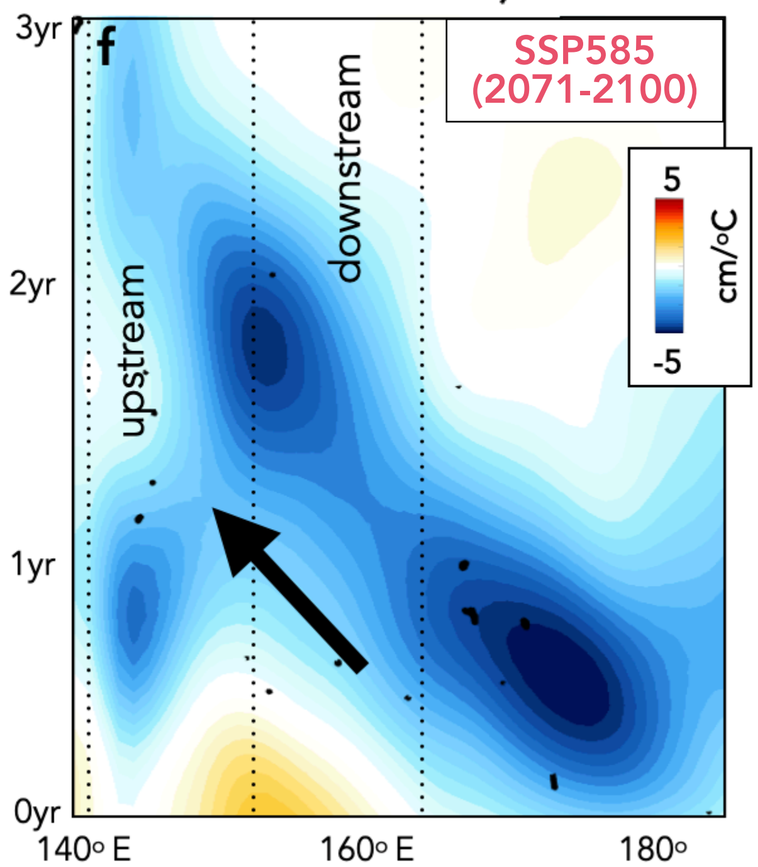
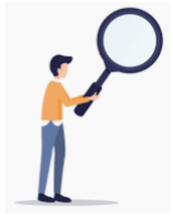
Limited
Short time scale KE

Decadal KE ↑

Progression of westward propagating oceanic forcing of KE
(Lagged SSHa regressed on Nino3.4 index)







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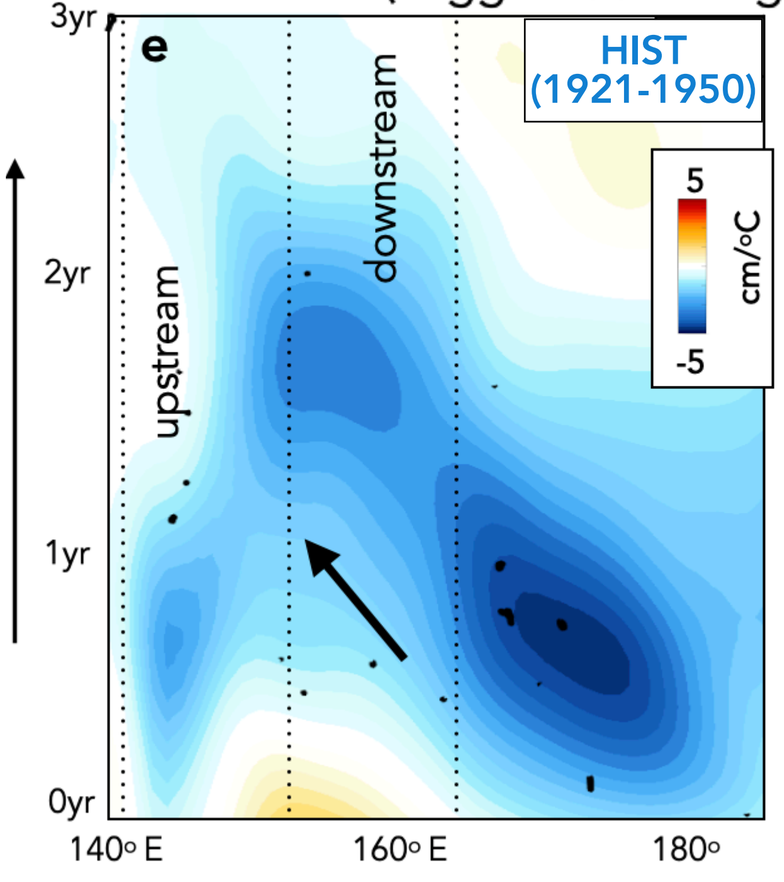
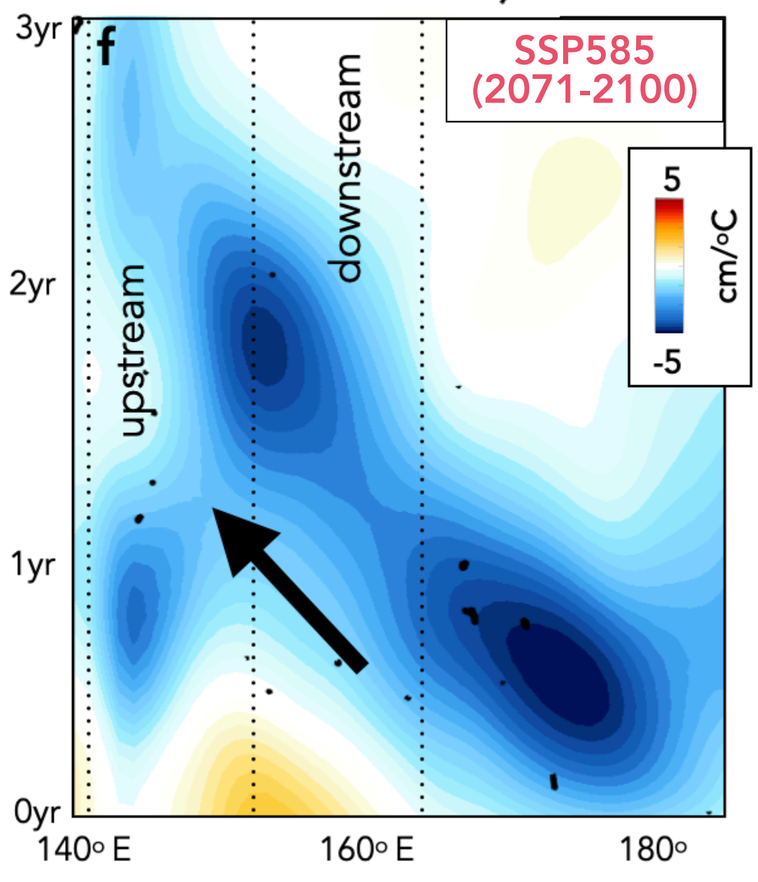
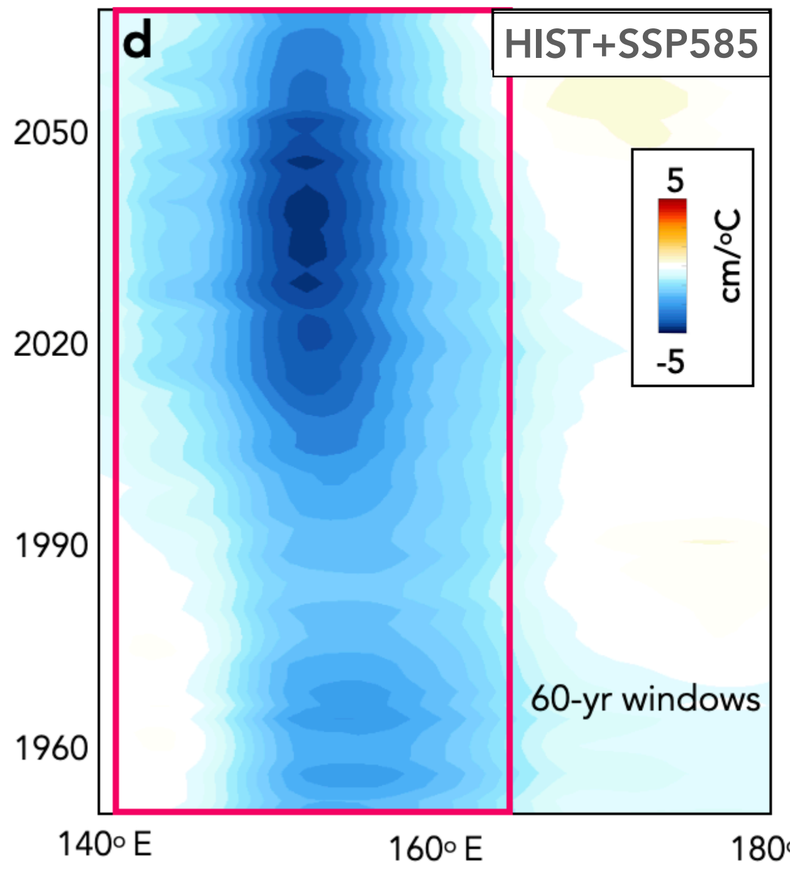




2yr-lagged SSHa regressed by
Nino3.4 index



✓ *As greenhouse gas forcing increases, the ENSO teleconnection impacts on KE SSH is enhancing*

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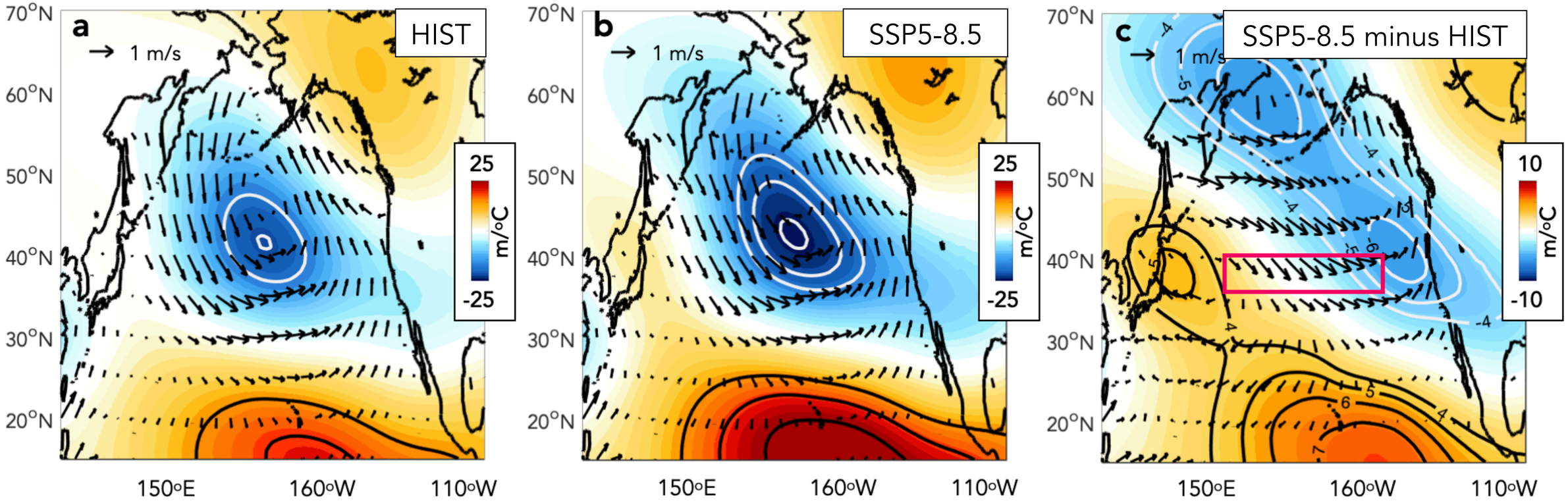
Limited Short time scale KE

Decadal KE ↑

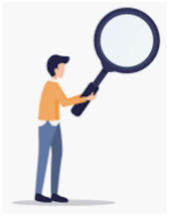
ENSO atmospheric teleconnections

200hPa Geopotential hight (shading) and surface wind vectors (arrows) regressed on Nino3.4 index



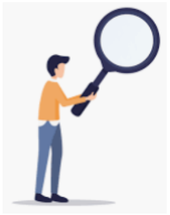
Due to a joint impact of the increasing ENSO amplitude & midlatitude wind migration

✓ *As greenhouse gas forcing increases, the ENSO teleconnection impacts on KE SSH is enhancing*



Temporal changes in KE SSH variability?

$$\textbf{KE variance ratio} = \frac{\text{Decadal KE variance (} > \sim 7\text{yrs)}}{\text{Short-time scale KE variance (} < \sim 7\text{yrs)}}$$



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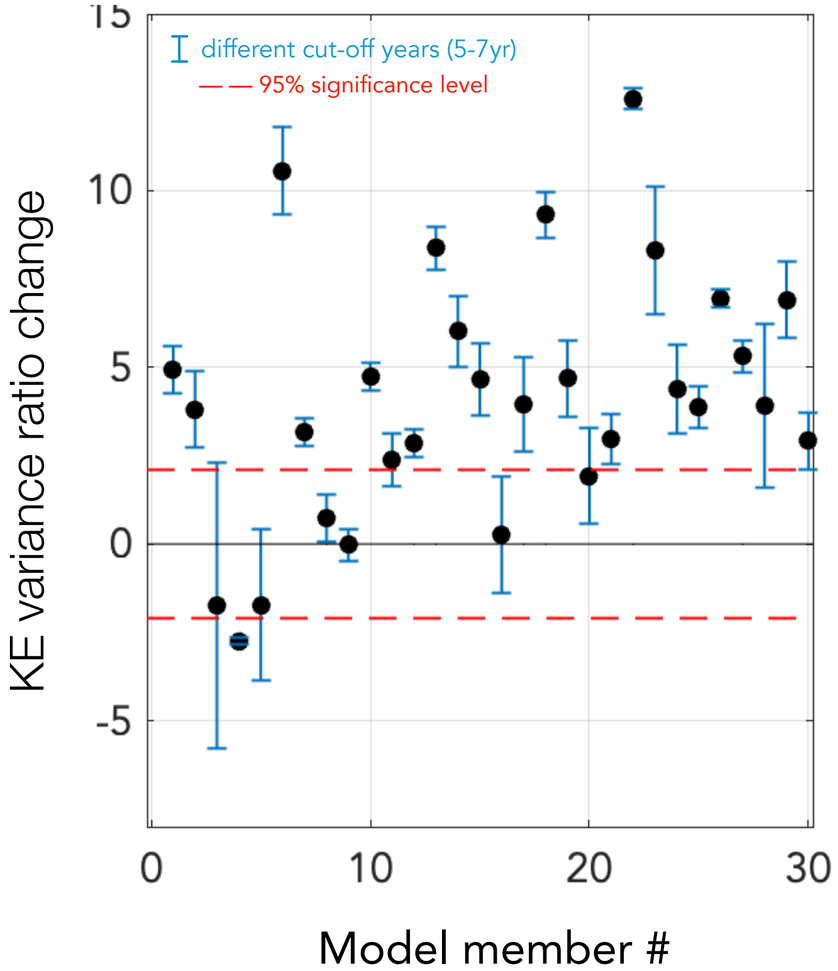
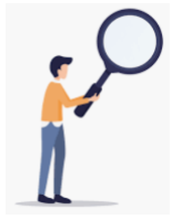
Changes in ratio of KE variance
(SSP5-8.5 minus HIST)



✓ Majority of ensemble members shows the increasing KE decadal variance



Temporal changes in KE SSH variability?

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Changes in ratio of KE variance
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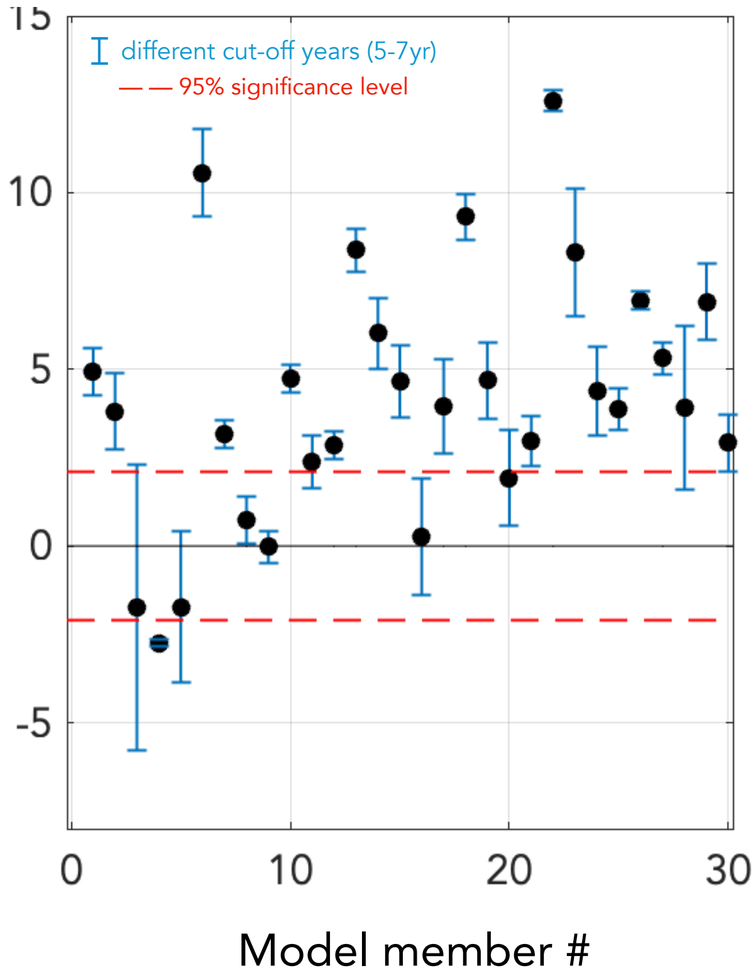
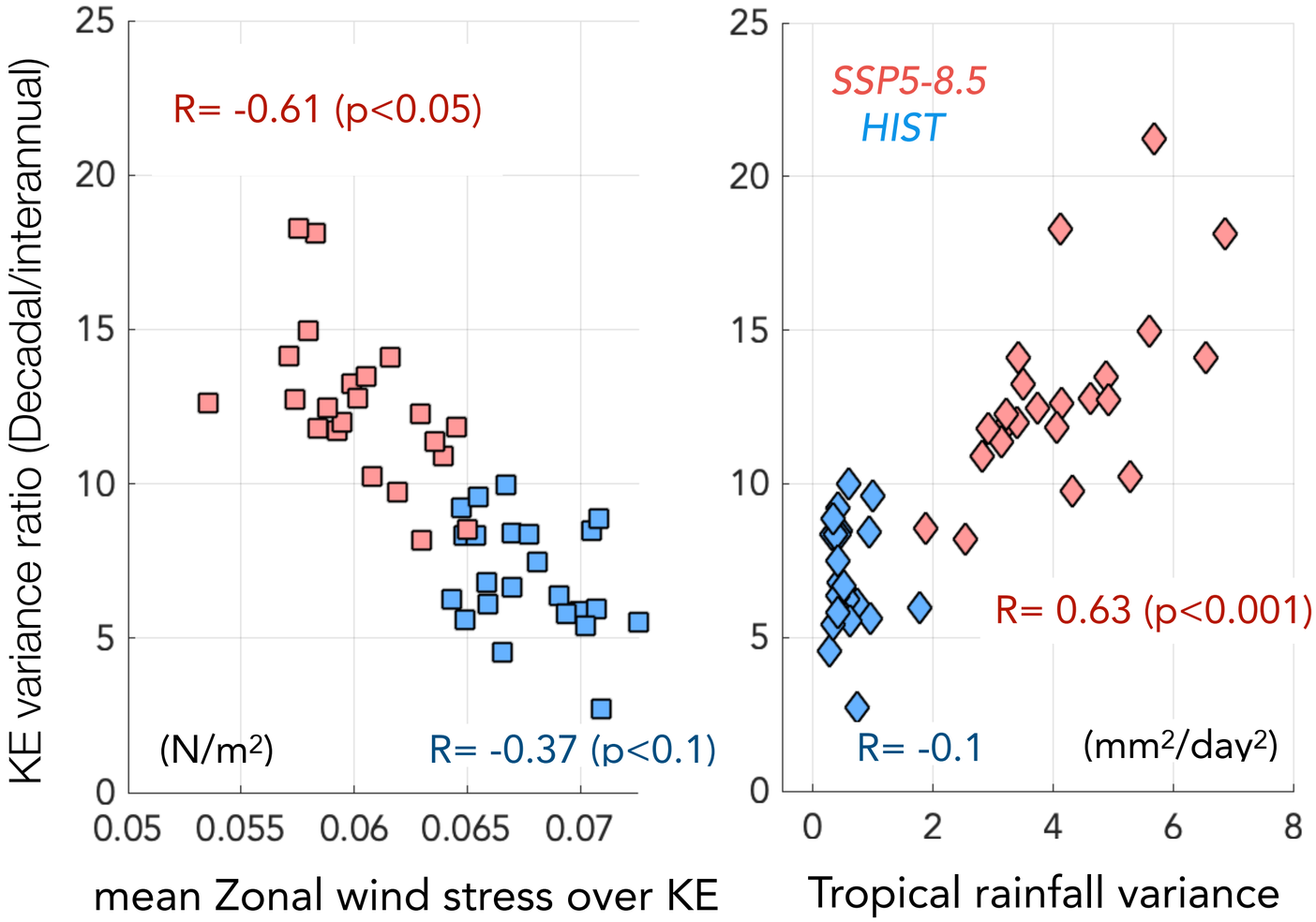
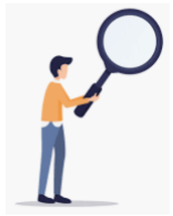


Impacts of anthropogenic-induced climate feedbacks



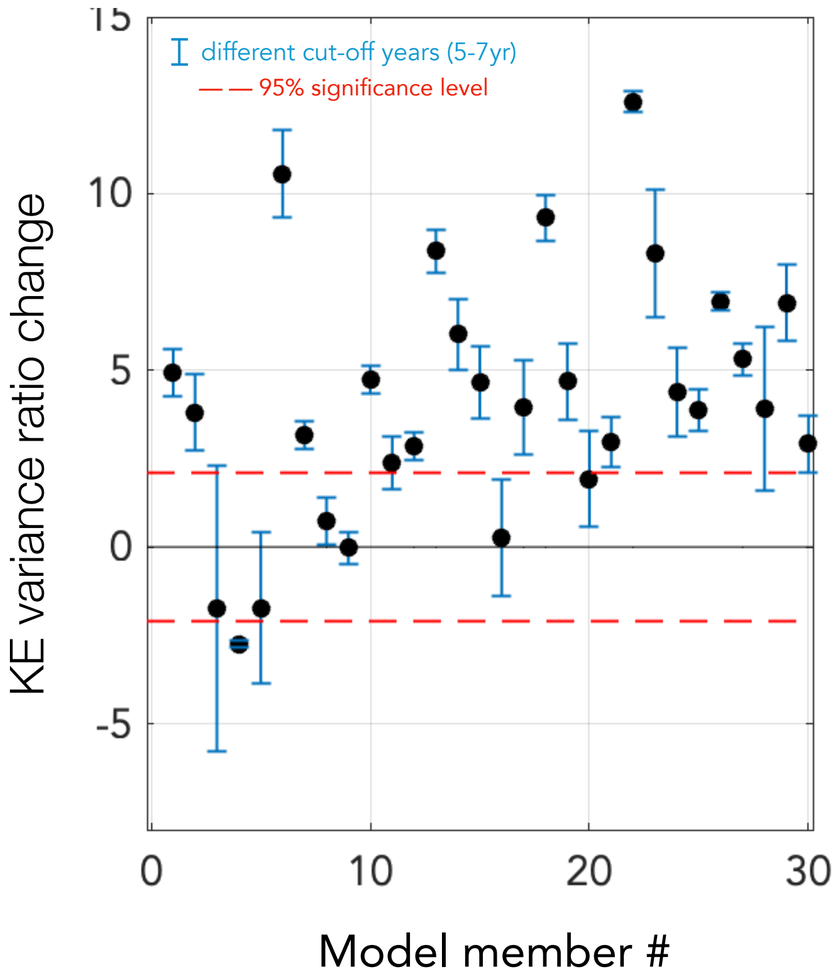
✓ Majority of ensemble members shows the increasing KE decadal variance



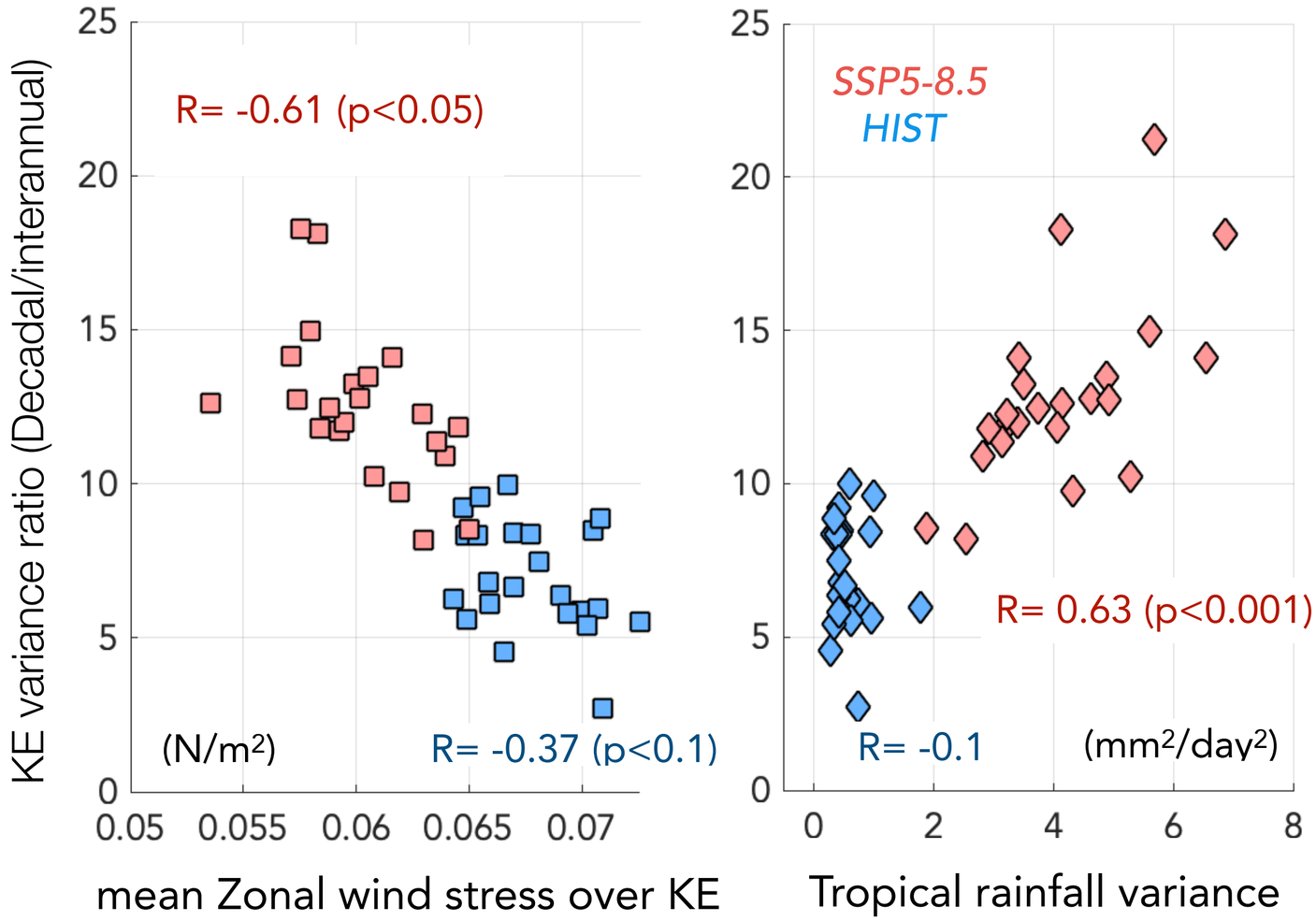
Temporal changes in KE SSH variability?

$$\textbf{KE variance ratio} = \frac{\text{Decadal KE variance (>~7yrs)}}{\text{Short-time scale KE variance (<~7yrs)}}$$

Changes in ratio of KE variance
(SSP5-8.5 minus HIST)

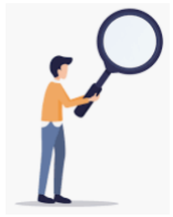


Impacts of anthropogenic-induced climate feedbacks

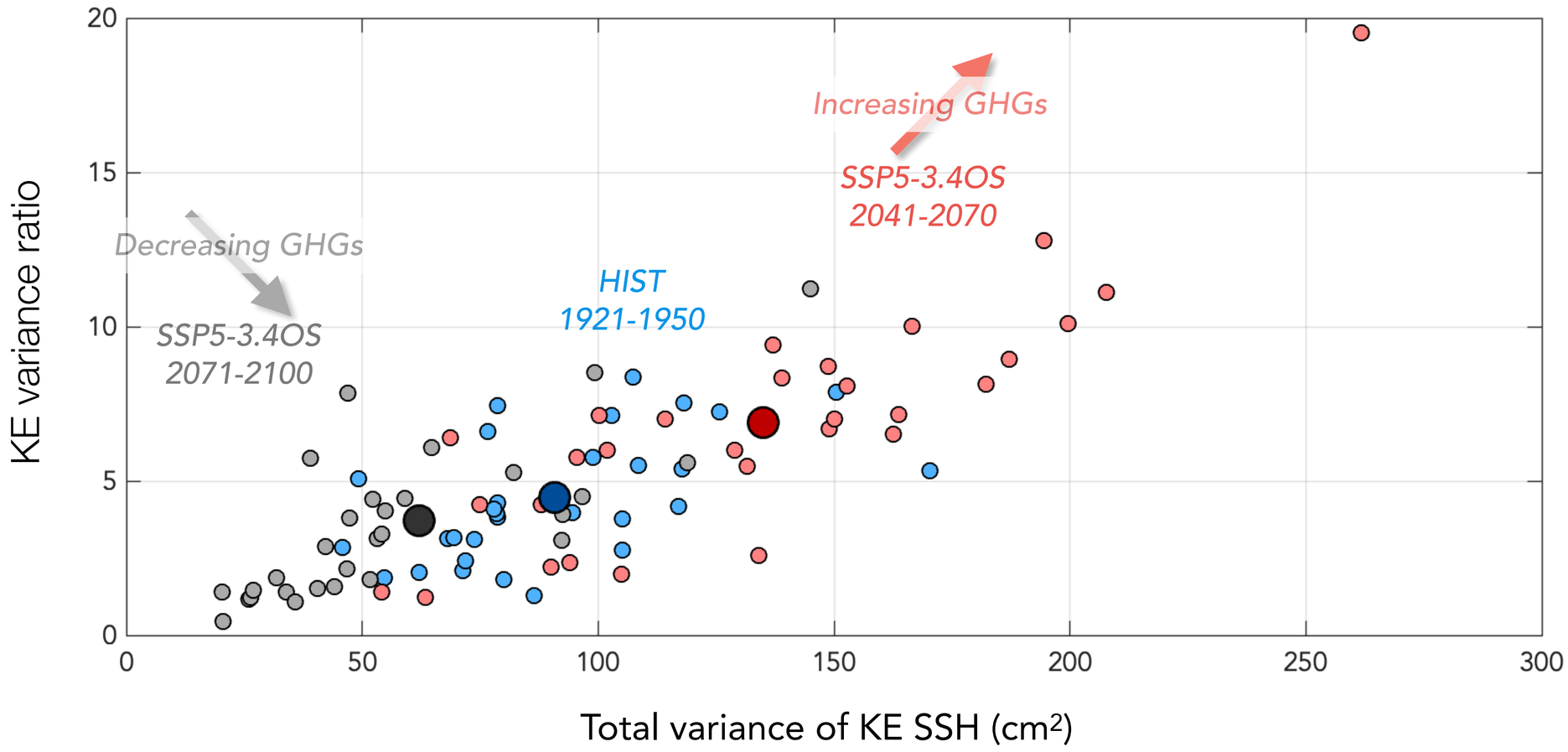


✓ Majority of ensemble members shows the increasing KE decadal variance

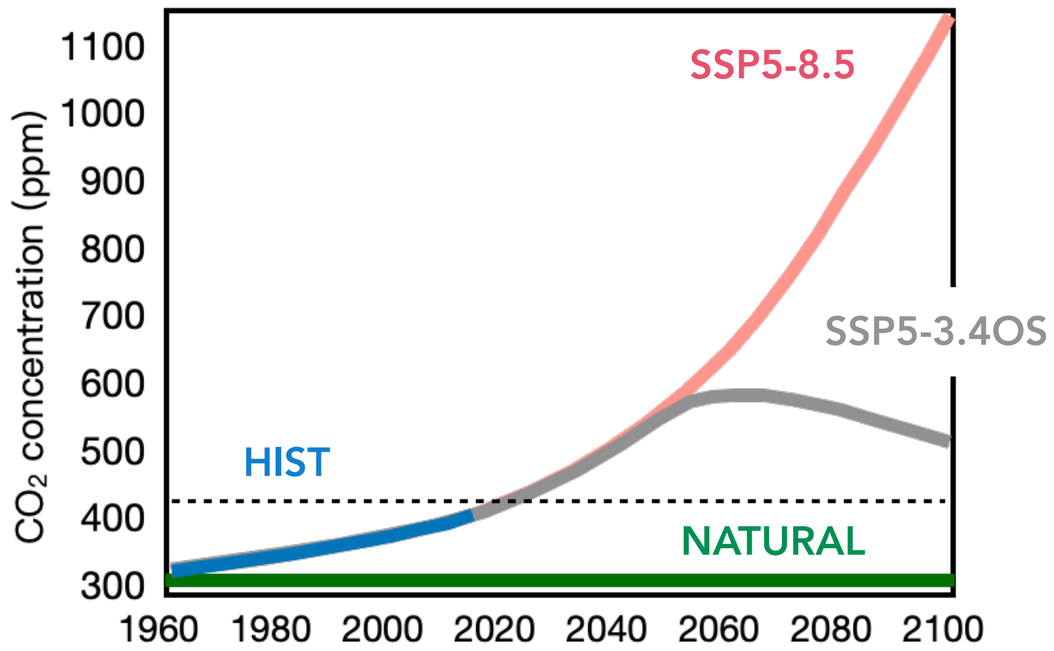
✓ As the negative wind changes and ENSO amplitude increase, the KE variance ratio (decadal KE signal) becomes stronger.

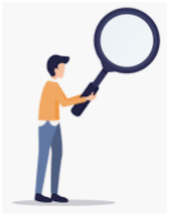


Sensitivity to radiative forcing changes?

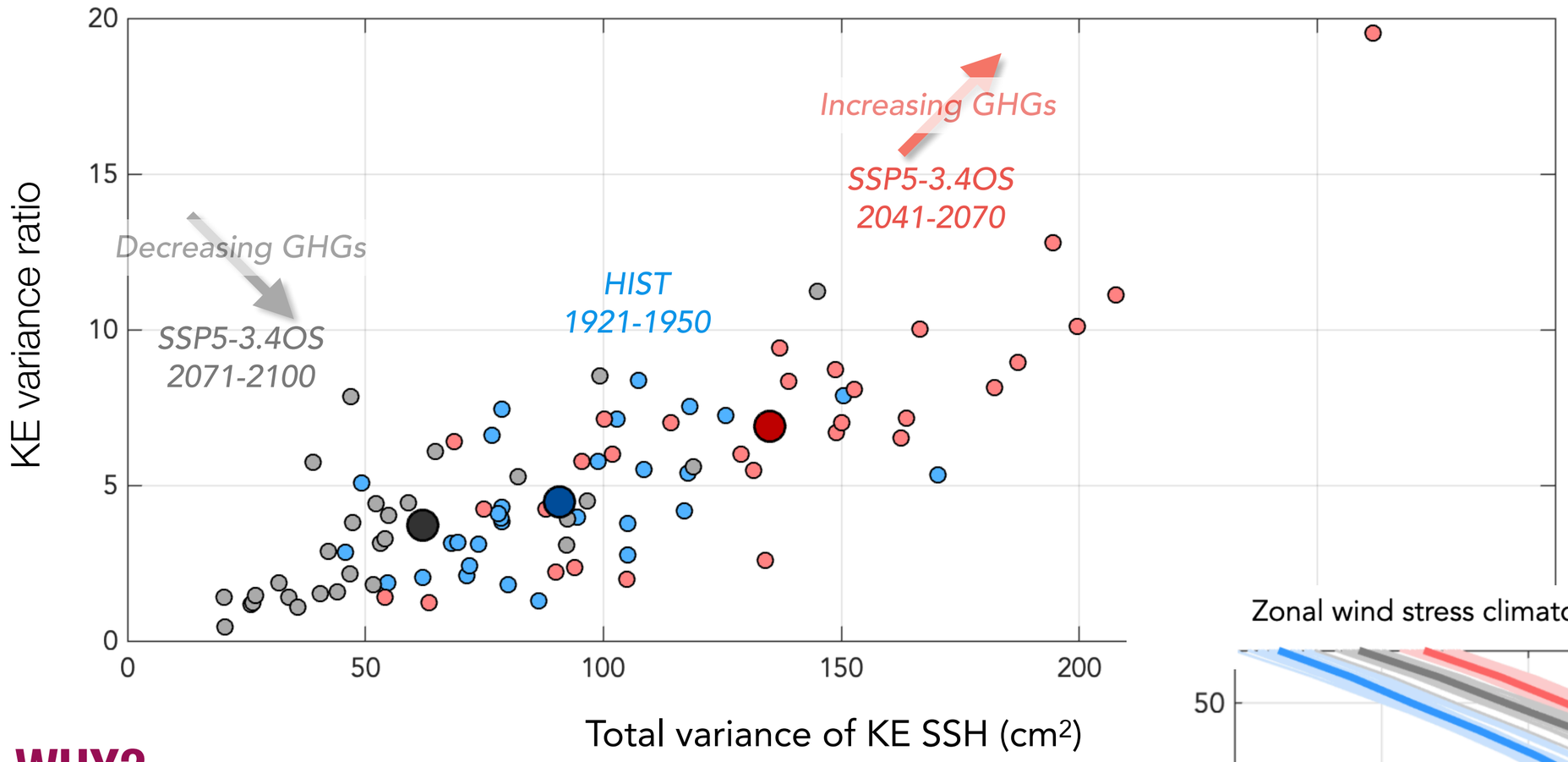


- ✓ The decadal KE variance and total KE intensity are immediately decreasing as a response to reduced greenhouse gas concentration.





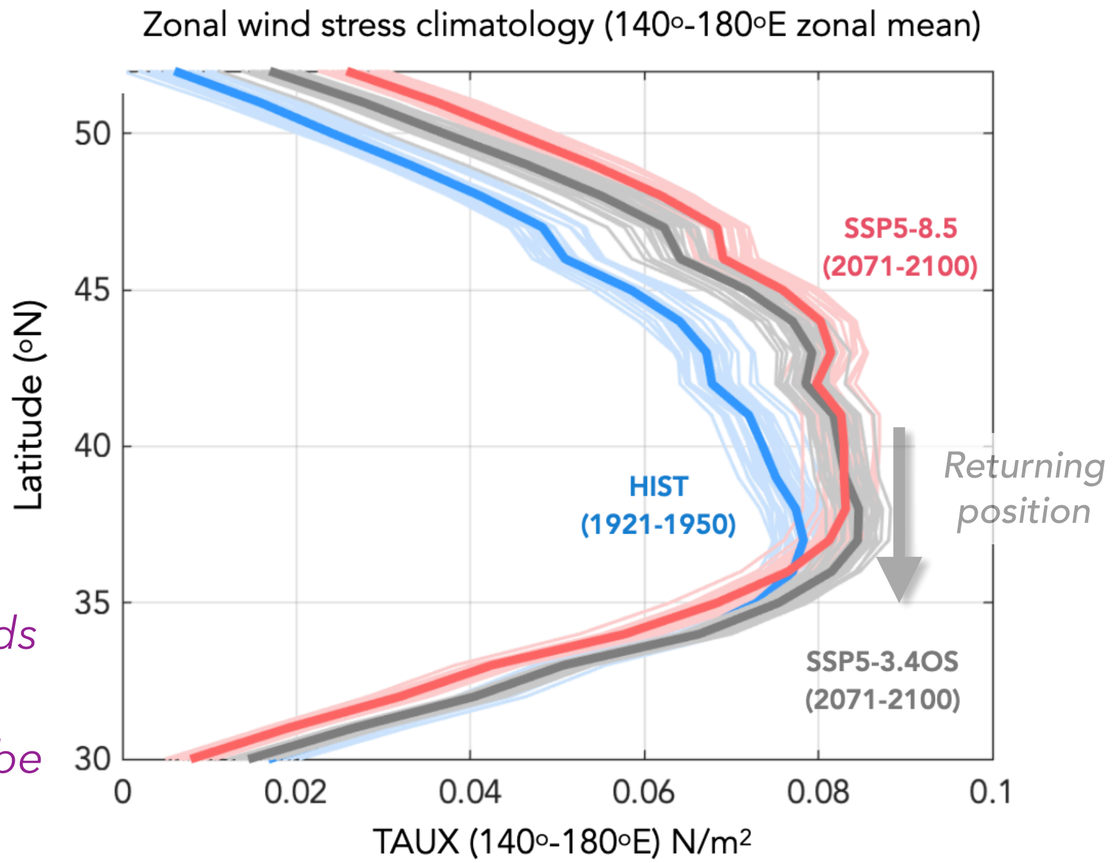
Sensitivity to radiative forcing changes?

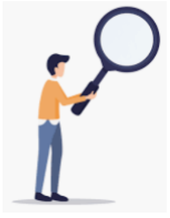


WHY?

✓ The decadal KE variance and total KE intensity are immediately reduced as a response to decreasing greenhouse gas forcing.

The northward-shifted climatological westerly winds move back towards their original position
-> the shifted KE dominant time scale and increased KE intensity may be reversible depending on mitigation situations.





Summary and Key questions

- ✓ Enhanced decadal KE variability due to stronger mid-latitude oceanic Rossby wave atmospheric forcing from a joint effect of the poleward shift of midlatitude surface wind climatology and the stronger ENSO teleconnection impacts on the midlatitude
- ✓ Changing anthropogenic forcing may alter the dominant time scale of the KE SSH variability, as an important factor in KE forecast research.
- ✓ Increasing KE decadal variance -> Amplifying extreme events and threats to ecosystems?
  Lending improved decadal predictability to the Pacific climate?
- ✓ What are other reversible or irreversible components in climate change and mitigation efforts?

Joh et al. 2022
npj climate and atmospheric science

npj | climate and atmospheric science

ARTICLE OPEN

Check for updates

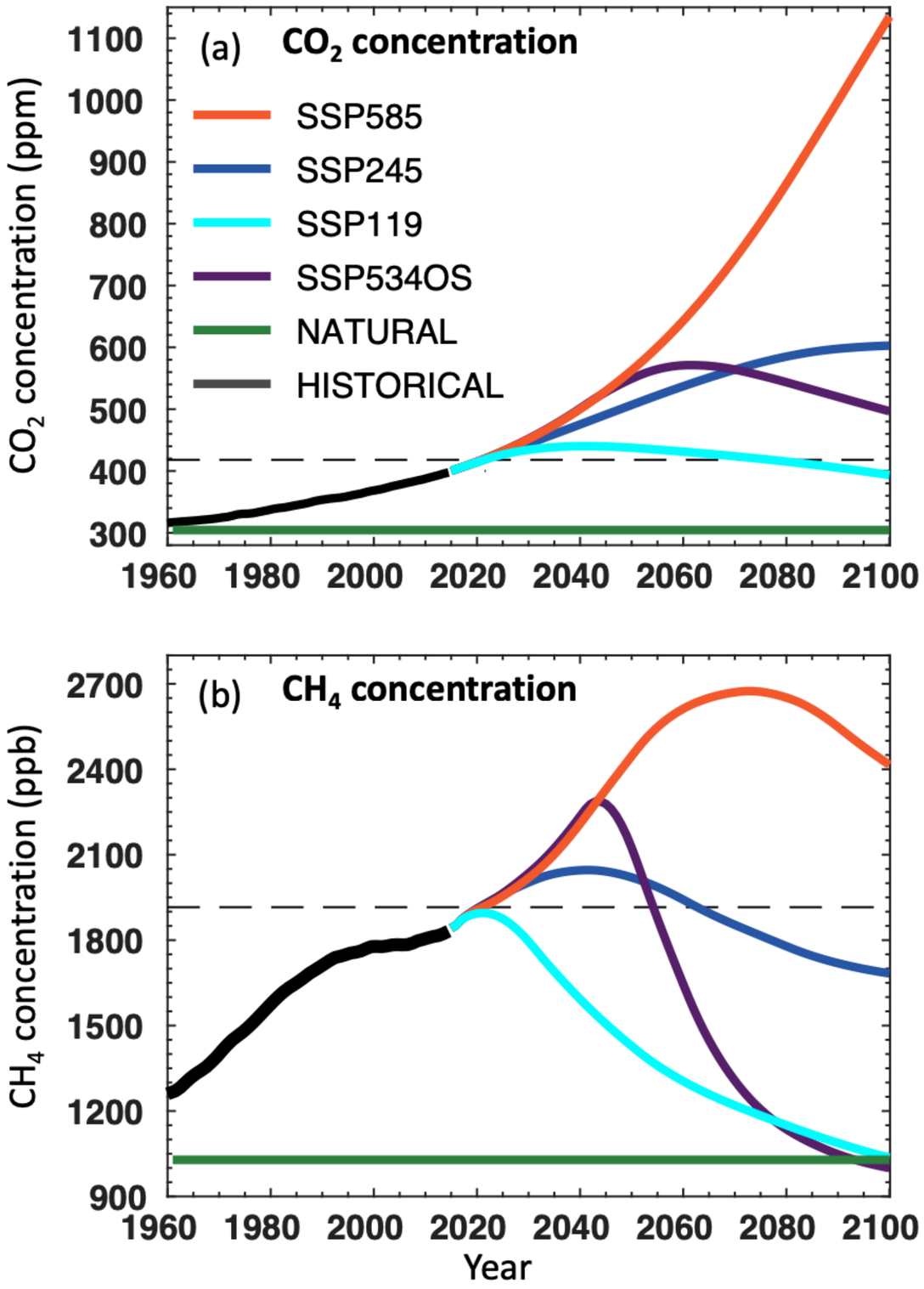
Stronger decadal variability of the Kuroshio Extension under simulated future climate change

Youngji Joh[1,2]✉, Thomas L. Delworth[2], Andrew T. Wittenberg[2], William F. Cooke[2], Anthony J. Rosati[2,3] and Liping Zhang[2,3]

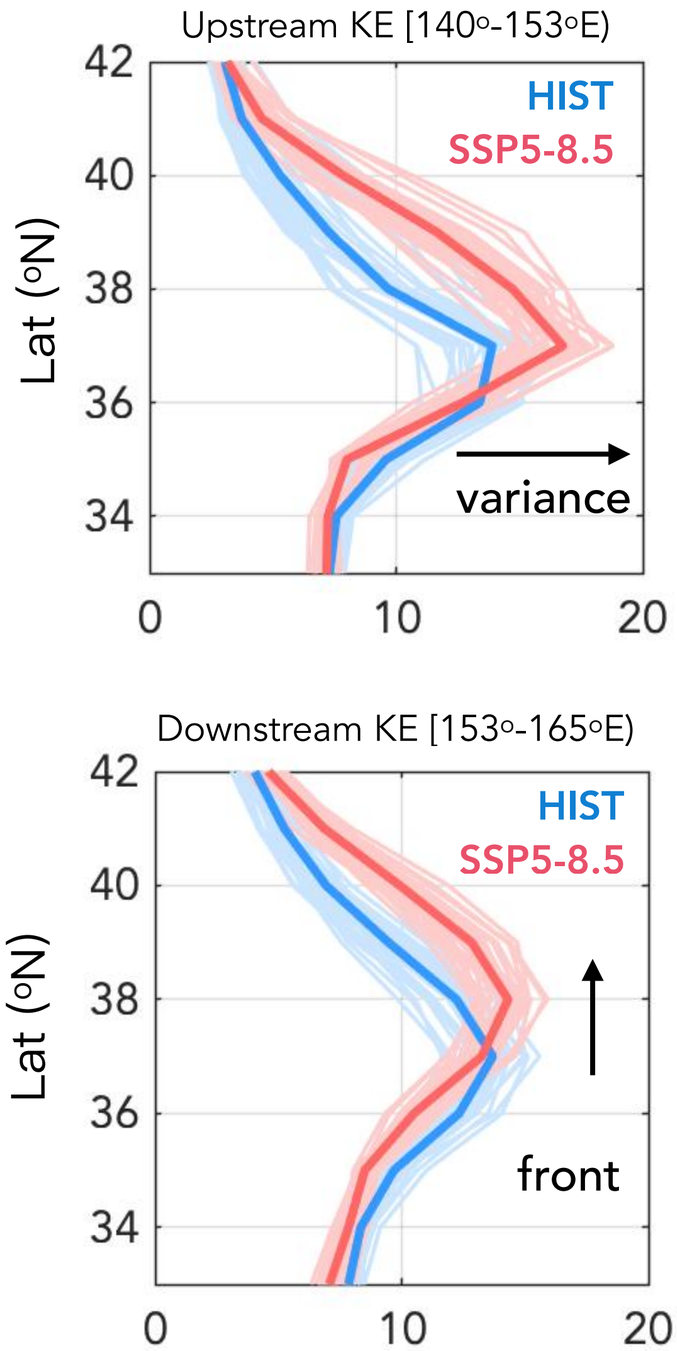
Understanding the behavior of western boundary current systems is crucial for predictions of biogeochemical cycles, fisheries, and basin-scale climate modes over the midlatitude oceans. Studies indicate that anthropogenic climate change induces structural changes in the Kuroshio Extension (KE) system, including a northward migration of its oceanic jet. However, changes in the KE temporal variability remain unclear. Using large ensembles of a global coupled climate model, we show that in response to increasing greenhouse gases, the time scale of KE sea surface height (SSH) shifts from interannual scales toward decadal and longer scales. We attribute this increased low-frequency KE variability to enhanced mid-latitude oceanic Rossby wave activity induced by regional and remote atmospheric forcing, due to a poleward shift of midlatitude surface westerly with climatology and an increase in the tropical precipitation activity, which lead to stronger atmospheric teleconnections from El Niño to the midlatitude Pacific and the KE region. Greenhouse warming leads to both a positive (elongated) KE state that restricts ocean perturbations (e.g., eddy activity) and stronger wind-driven KE fluctuations, which enhances the contributions of decadal KE modulations relative to short-time scale intrinsic oceanic KE variations. Our spectral analyses suggest that anthropogenic forcing may alter the future predictability of the KE system.

npj Climate and Atmospheric Science (2022)5:63 ; https://doi.org/10.1038/s41612-022-00285-z

Q & A slides

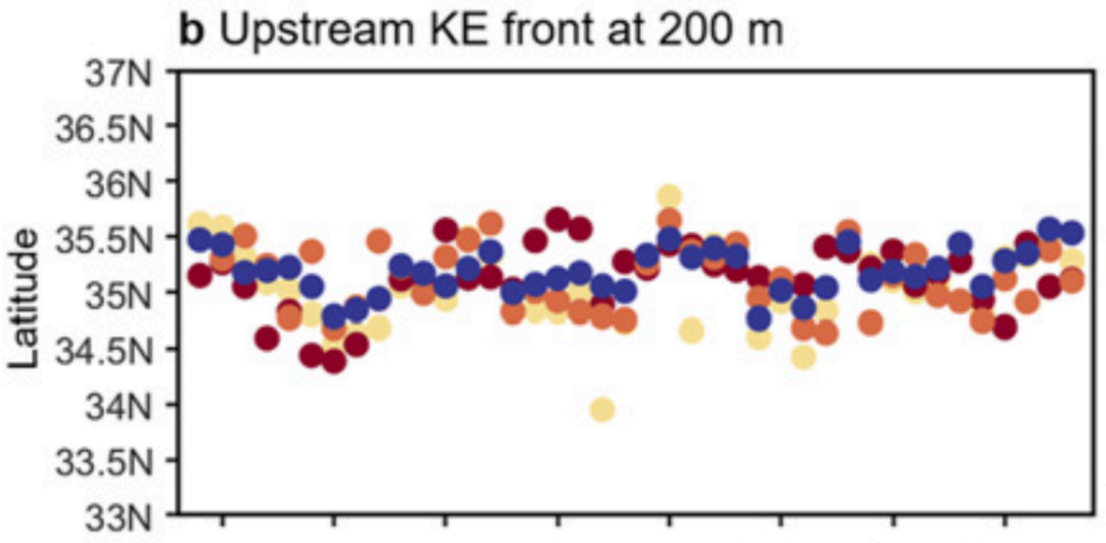

(a) CO2 concentration
SSP585
SSP245
SSP119
SSP534OS
NATURAL
HISTORICAL
CO2 concentration (ppm)
1100
1000
900
800
700
600
500
400
300
(b) CH4 concentration
CH4 concentration (ppb)
2700
2400
2100
1800
1500
1200
900
1960
1980
2000
2020
2040
2060
2080
2100
Year

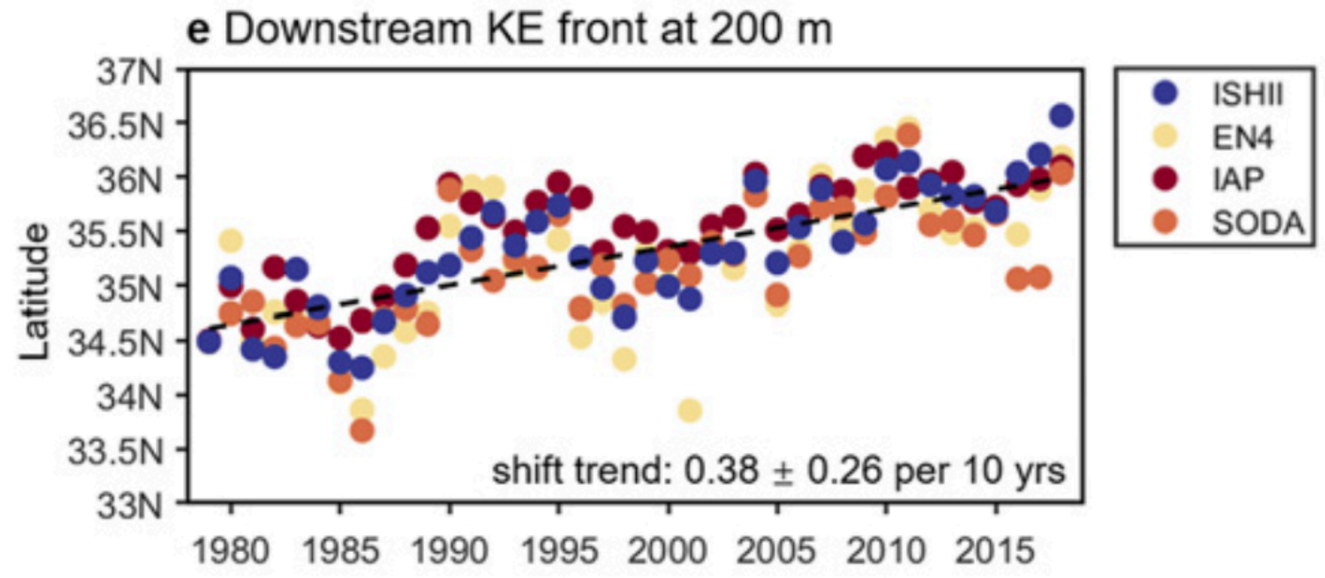
KE front changes in satellite observation



30-member ensemble mean

Individual member



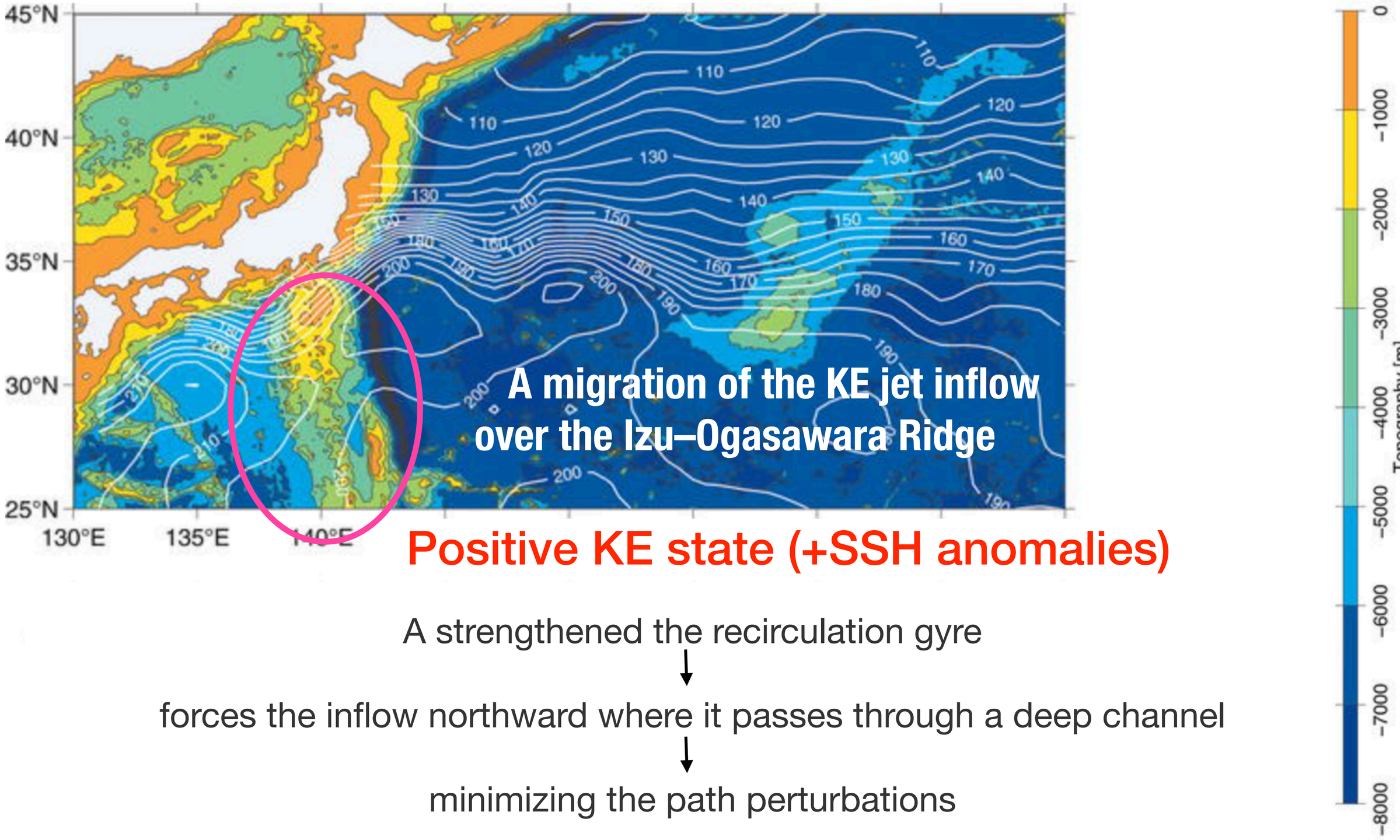


Wu et al. (2021)

- ✓ **INCREASING** mean SSH
- ✓ **POLEWARD** shifted front in **DOWNSTREAM**
- ✓ **ENHANCED** variance in **UPSTREAM**

Q. Why the KE positive state is the elongated state (low EKE level)?

This *negative* correlation between the mean flow intensity and the level of regional eddy kinetic energy is found in both the SSH data and the linear vorticity model (Qiu and Chen, 2005).



Positive KE state (+SSH anomalies)

A strengthened the recirculation gyre

↓

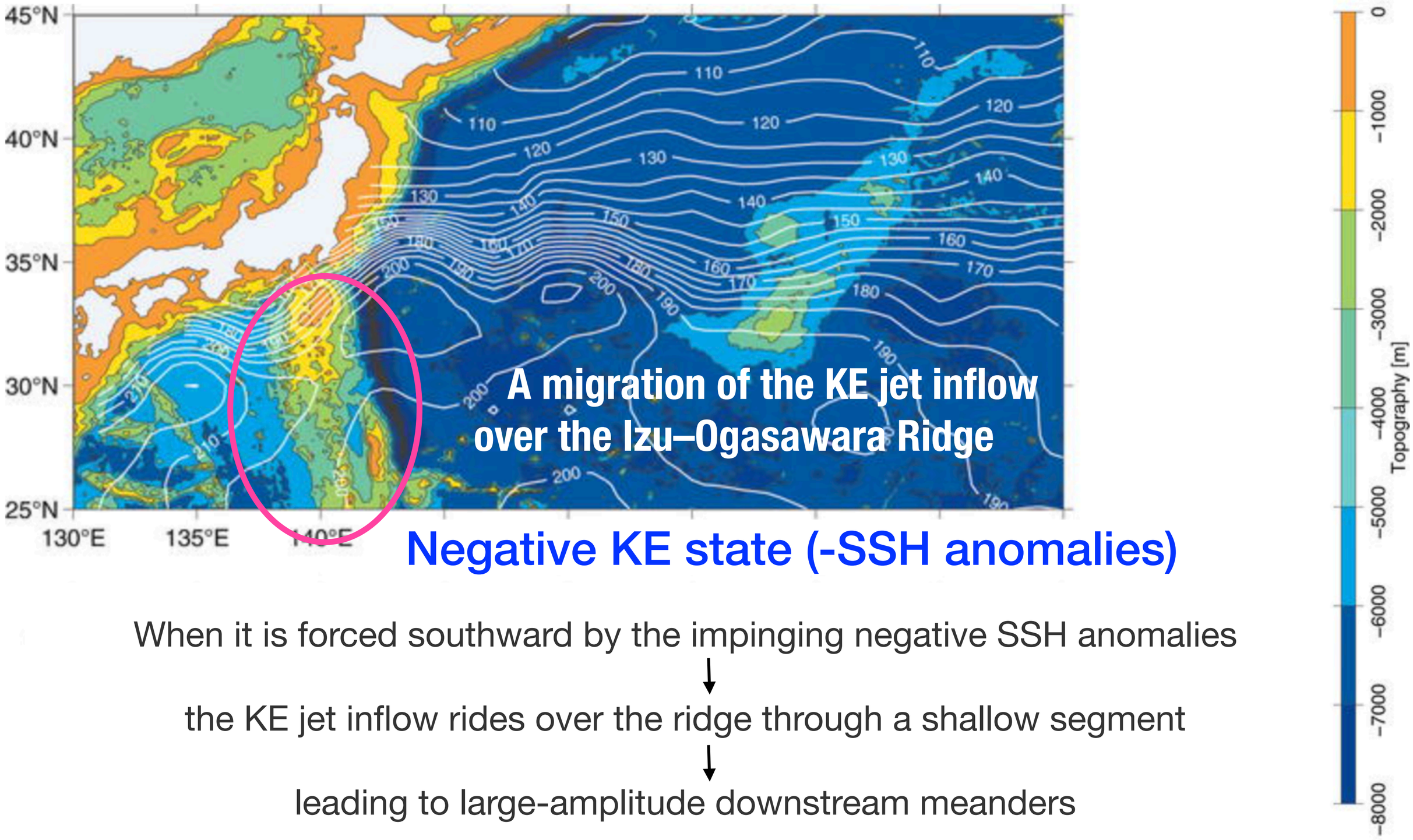
forces the inflow northward where it passes through a deep channel

↓

minimizing the path perturbations

Q. Why the KE positive state is the elongated state (low EKE level)?

This *negative* correlation between the mean flow intensity and the level of regional eddy kinetic energy is found in both the SSH data and the linear vorticity model (Qiu and Chen, 2005).



Negative KE state (-SSH anomalies)

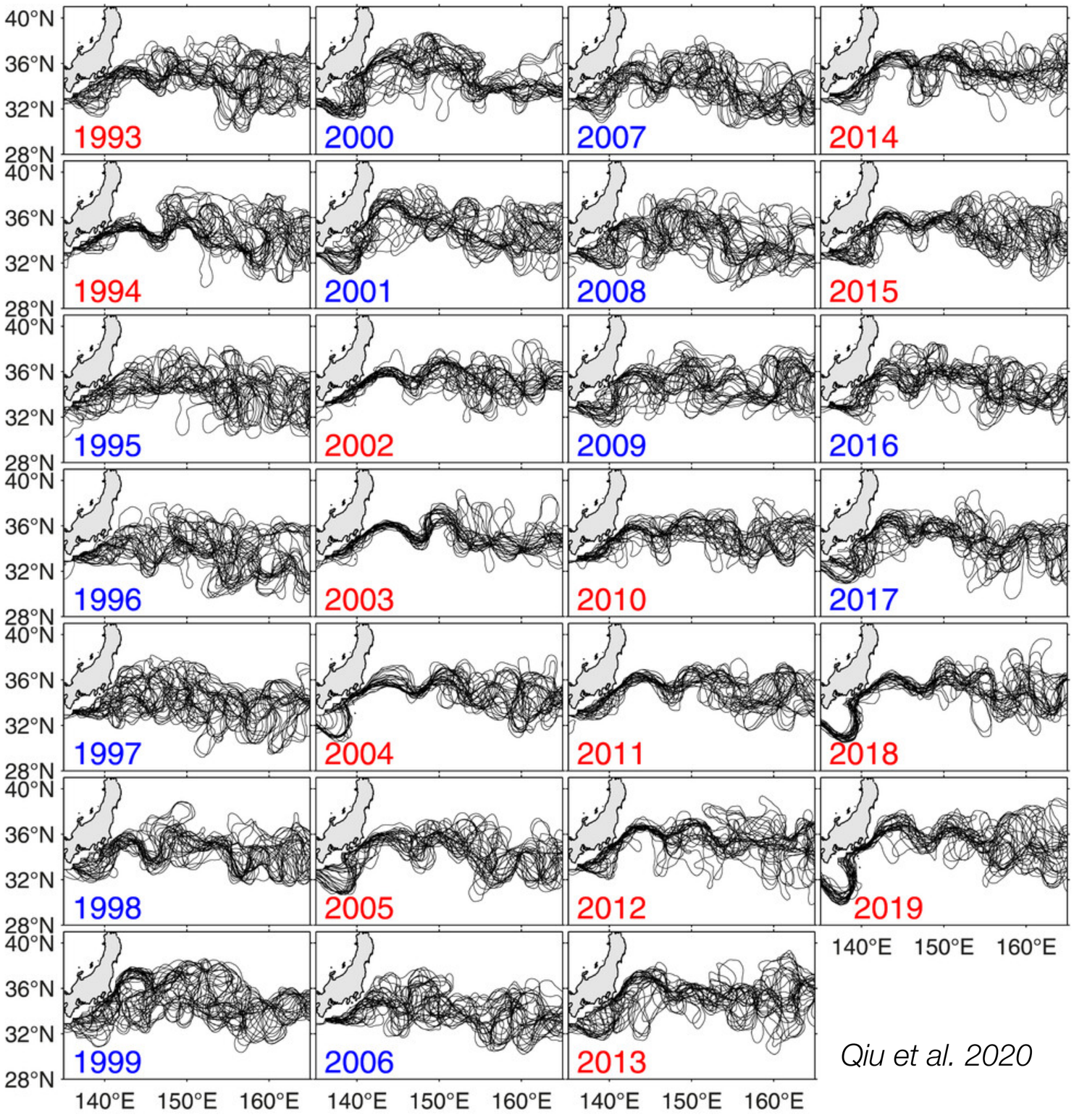
When it is forced southward by the impinging negative SSH anomalies

↓

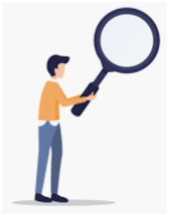
the KE jet inflow rides over the ridge through a shallow segment

↓

leading to large-amplitude downstream meanders



Qiu et al. 2020

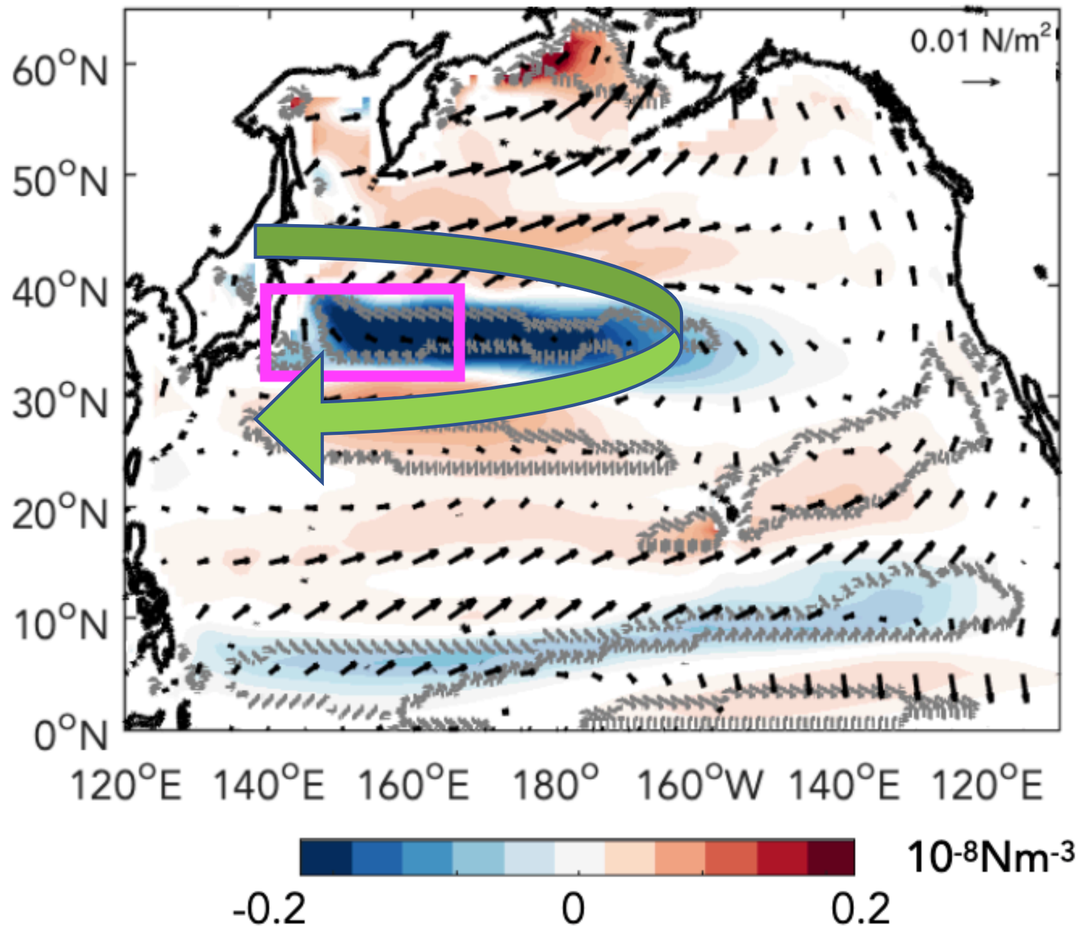


What drives the stronger KE decadal variance under anthropogenic forcing?

H1. Changes in midlatitude surface wind climatology & associated impacts to the WBC

Short time scale KE ↓

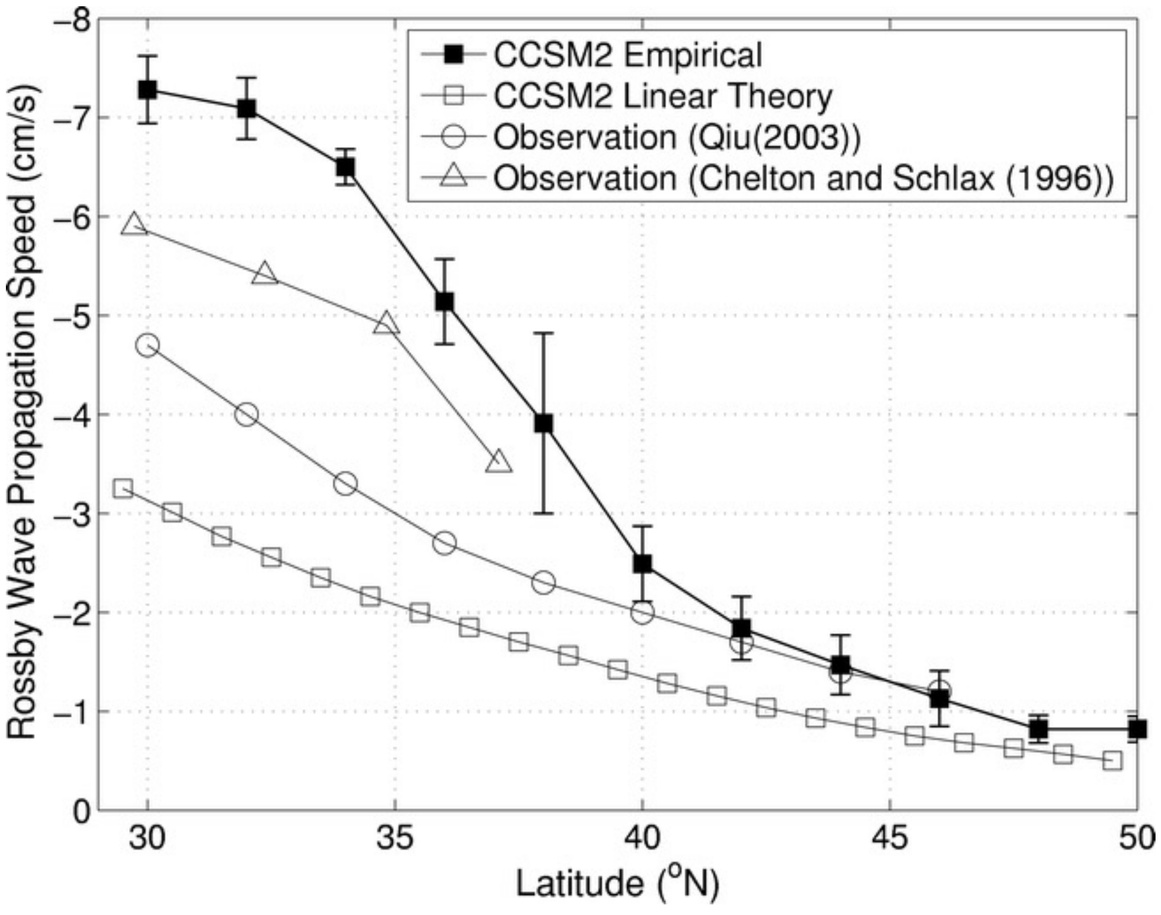
Surface wind stress curl climatology
(SSP585 minus HIST)



Favored "positive, stable, elongated" KE state in warming climate?

- ✓ Spin-up of the Kuroshio recirculation gyre
- ✓ Forcing the KE jet inflow poleward
- ✓ Limited eddy activities during stable state

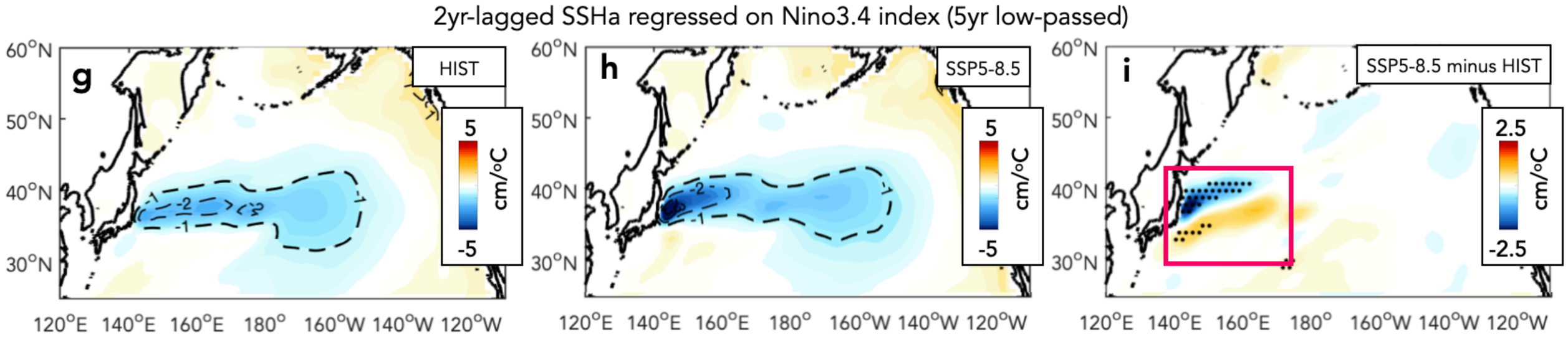
Q. How the lead time of 5 years of significant predictive skill has a longer memory of 3-year memory of oceanic baroclinic Rossby wave adjustment? (where does additional ~2 years of predictive lead time come from?)

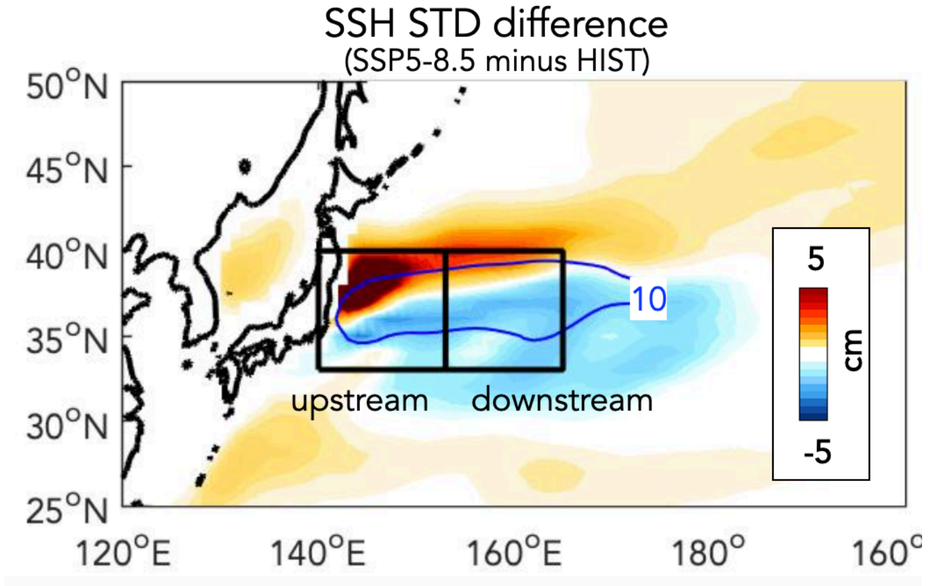


Depending on the scale and location of the mid-latitude wind forcing, the inertial memory of baroclinic Rossby waves could vary (Kwon and Deser, 2007).

When the Rossby waves are excited by strong persistent wind forcing (up to 2-5 years) over the mid-latitude Pacific, the additional multi years of the predictable lead time of KE SSH variability could be provided, thereby allowing that the lead time of significant predictive skill can be longer than general time-scales of the baroclinic Rossby waves (2-5 years)

Q. Decadal ENSO impact on the North Pacific SSH?

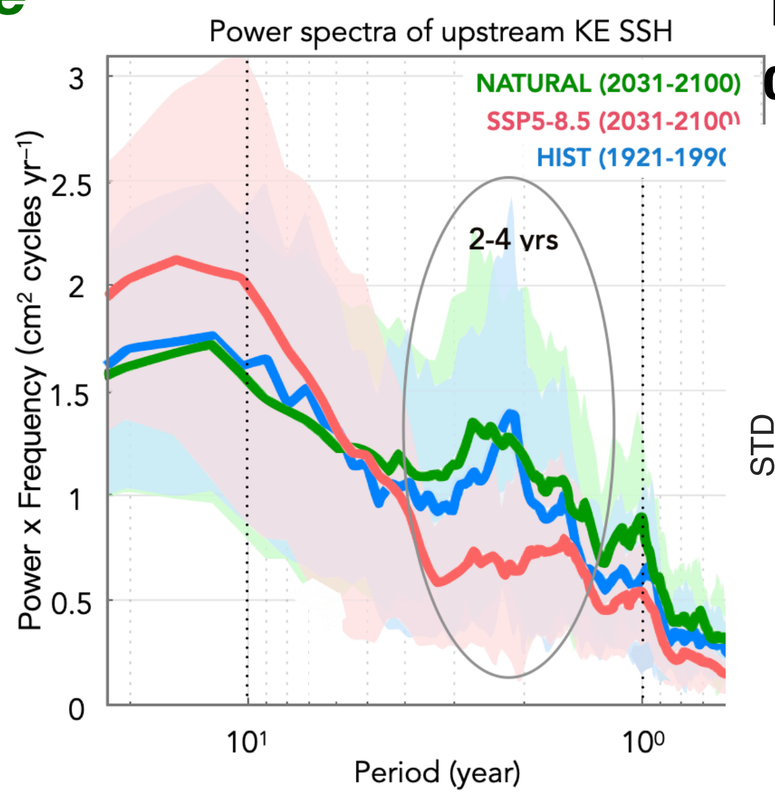




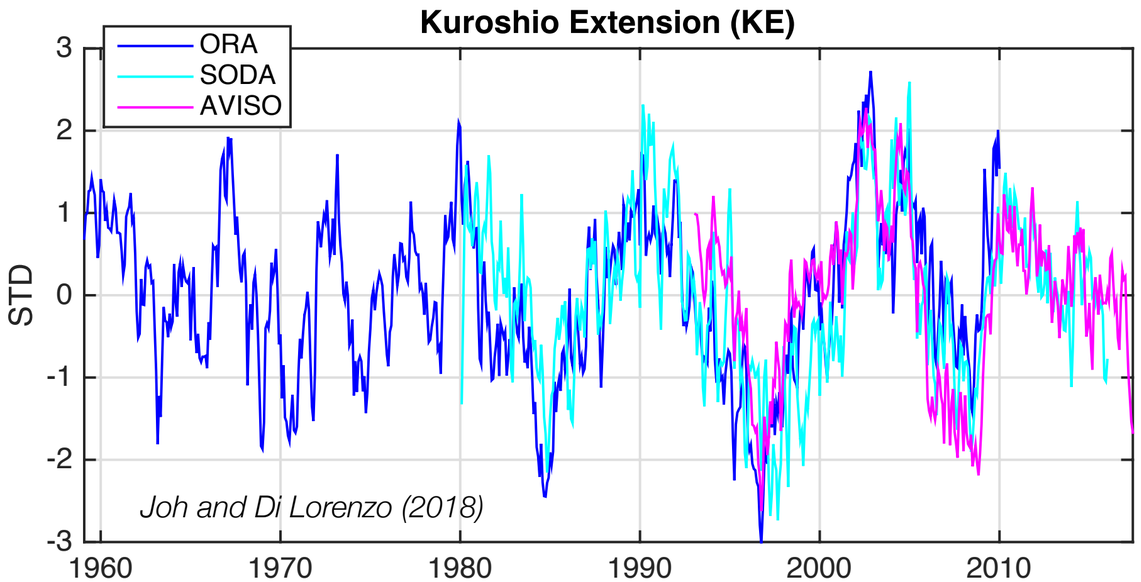
Changes in the ENSO's impacts on the KE resemble the changes in North Pacific SSH variability, with an increase in upstream KE intensity and a northward shift of the KE front.

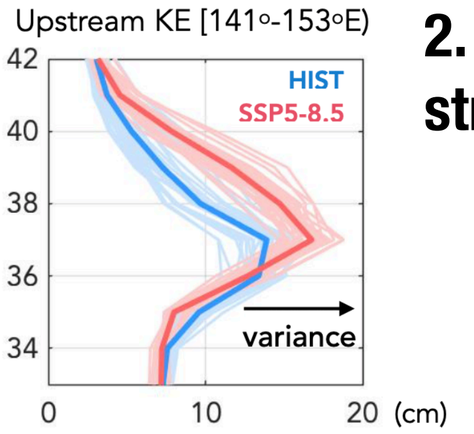
Q & A slides

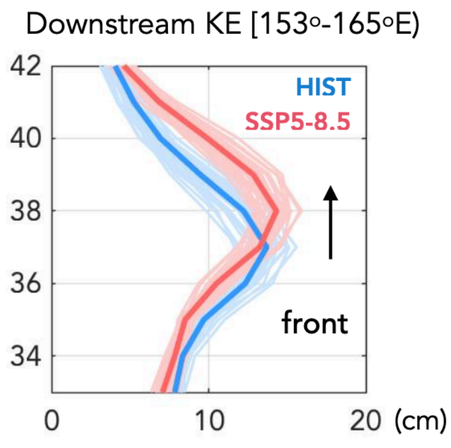
Q. The relatively coarse ocean resolution can resolve the realistic KE dynamics?



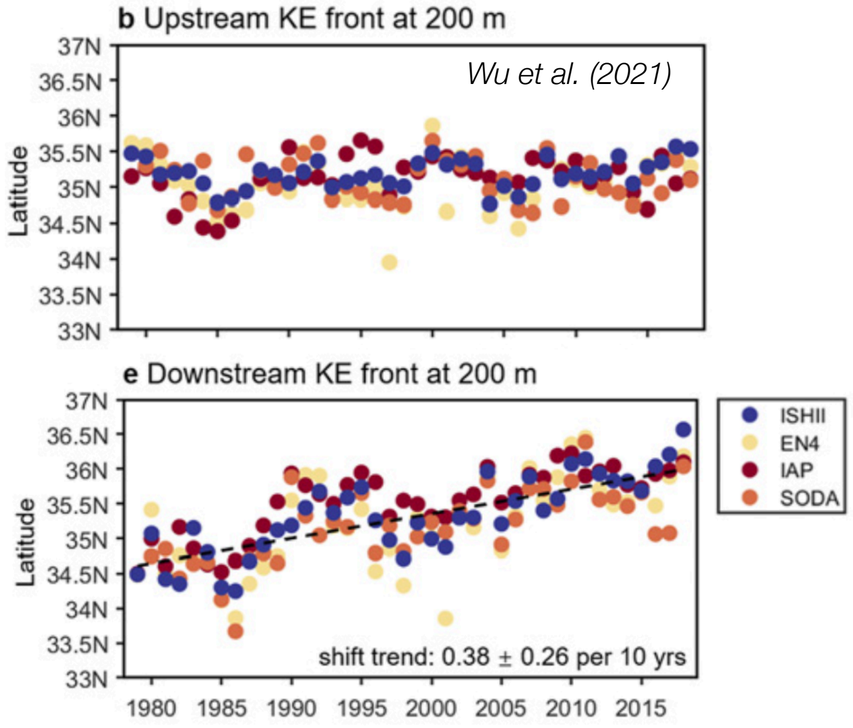
1. Increasing KE decadal fluctuations is being observed in satellite altimeter observation





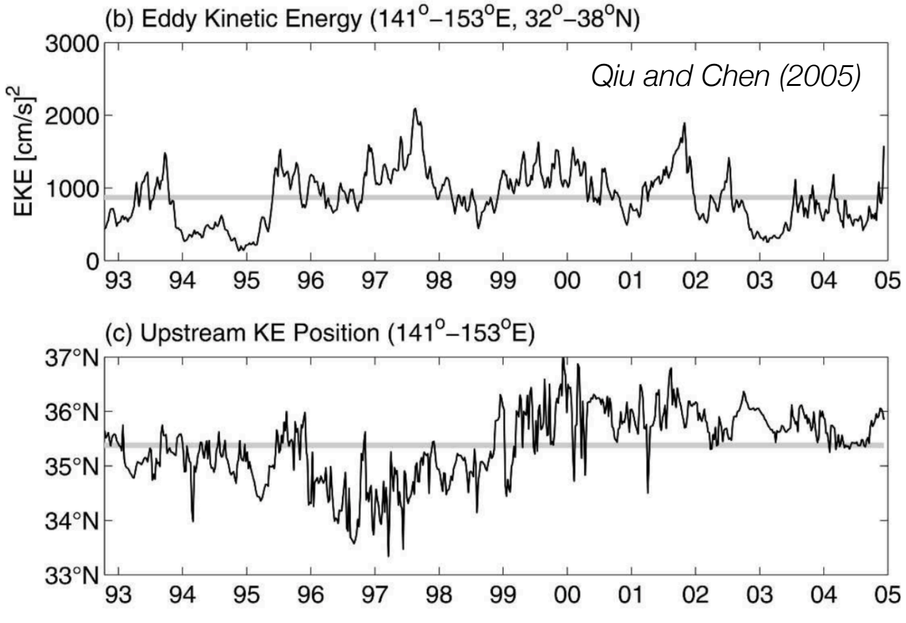


2. Substantial similarity of changes in spatial structure of KE upstream/downstream



3. Based on a robust relationship of KE state and EKE level

-Increasing positive state can indirectly decreased eddy-related short time scale variability

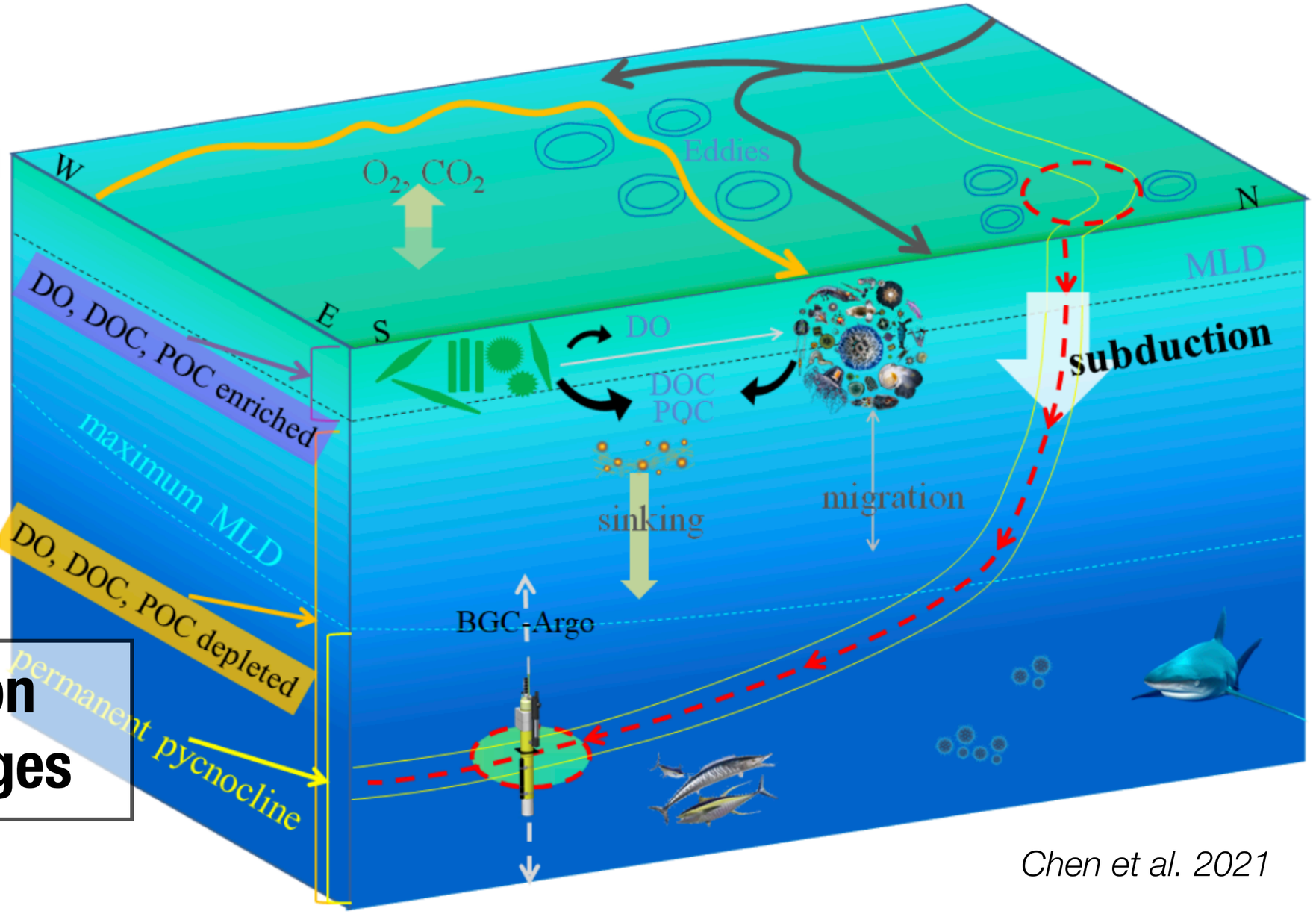


Implications

1. A key to modulate the sig

- Increasing decadal variance
- An essential piece of Pacific [

Skillful KE prediction & Projected KE changes

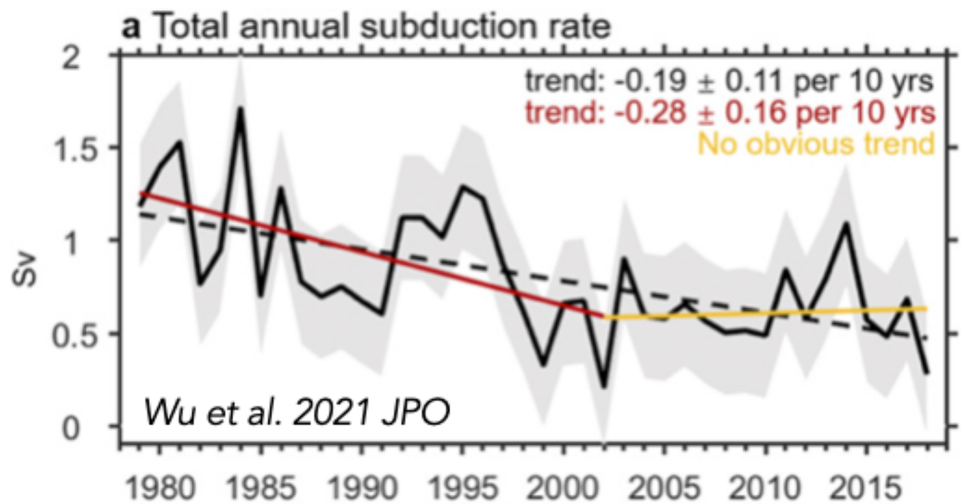


Chen et al. 2021

2. A close relationship between physical condition and subsurface marine ecosystem

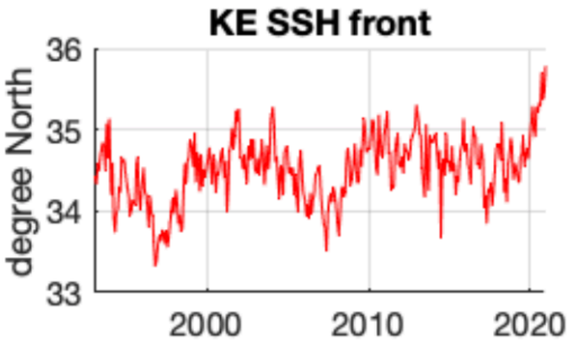
- Potential predictability of biogeochemical environment
- Anthropogenic induced and possible changes in future subsurface WBC ecosystem

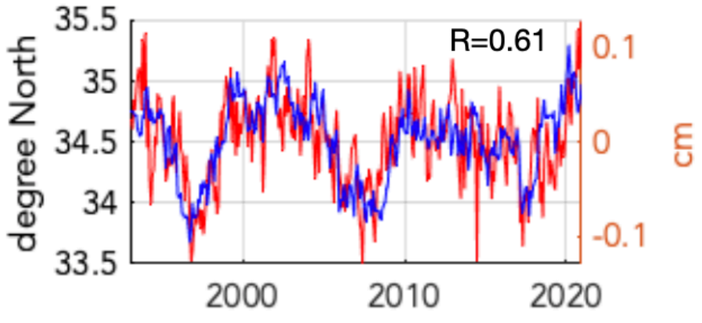
Northward migration of KE → decreasing subduction rate

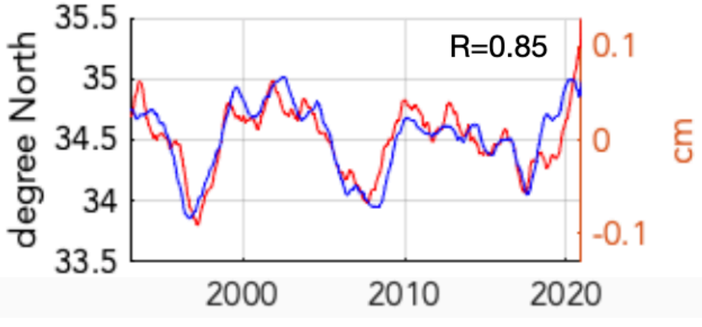


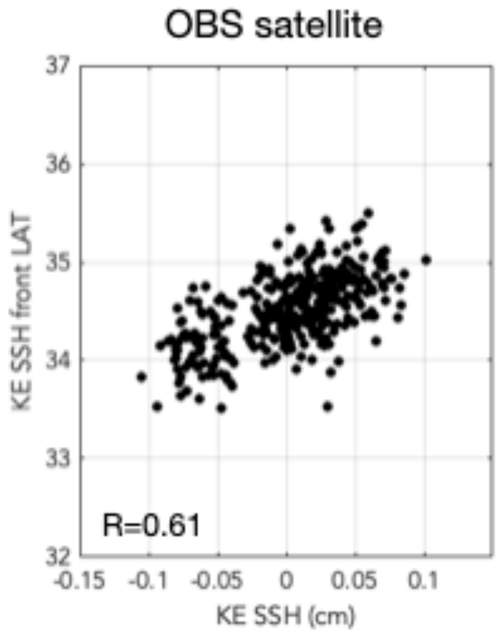
Future work : Potential research directions using SPEAR_HI_25 model

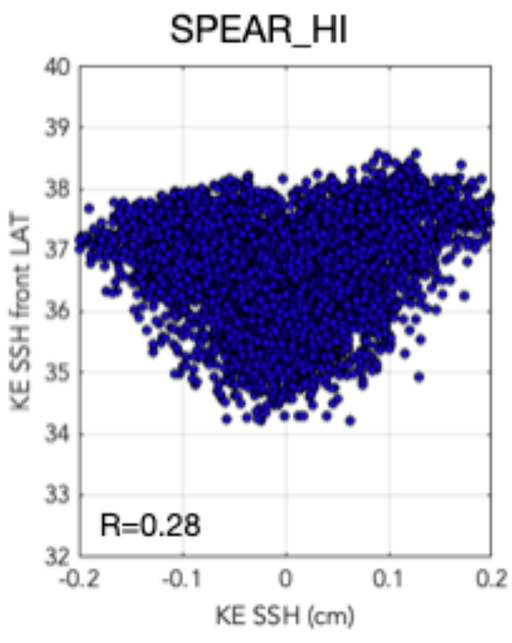
	SPEAR_LO	SPEAR_MED	SPEAR_HI	SPEAR_HI_25
atmosphere/land	100km	50km	25km	25km
ocean/sea ice	approximately 1° (with tropical refinement)			25km

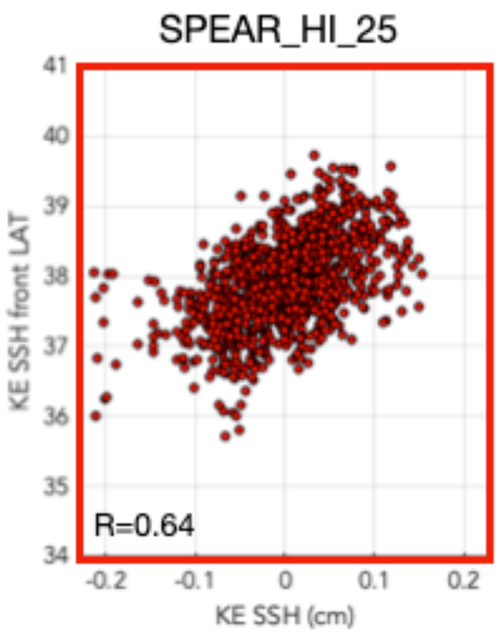












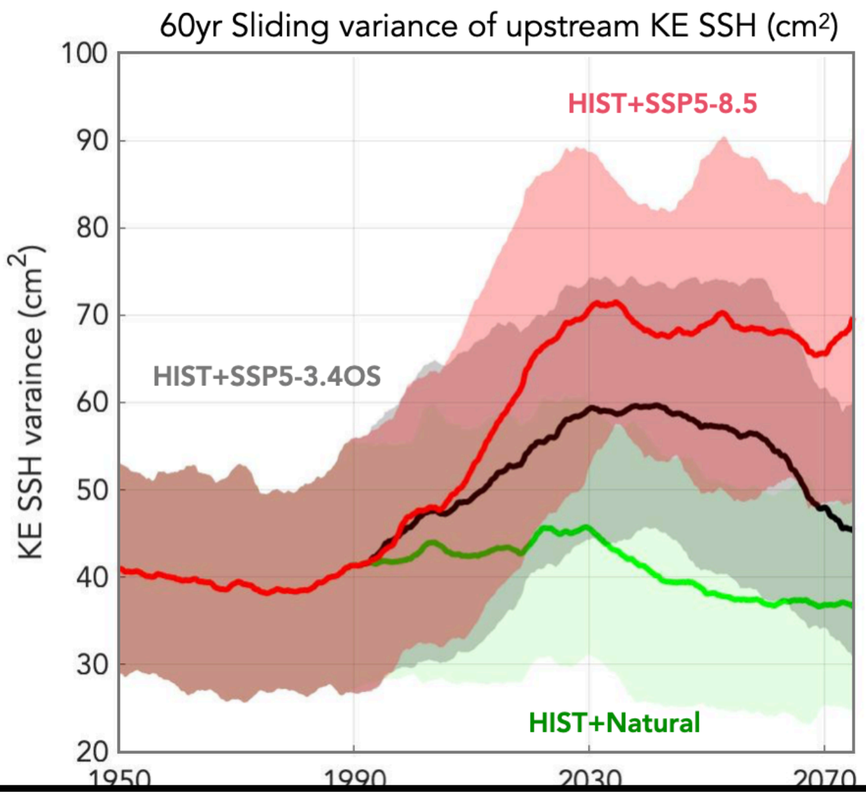
Increasing ocean model resolution

↓

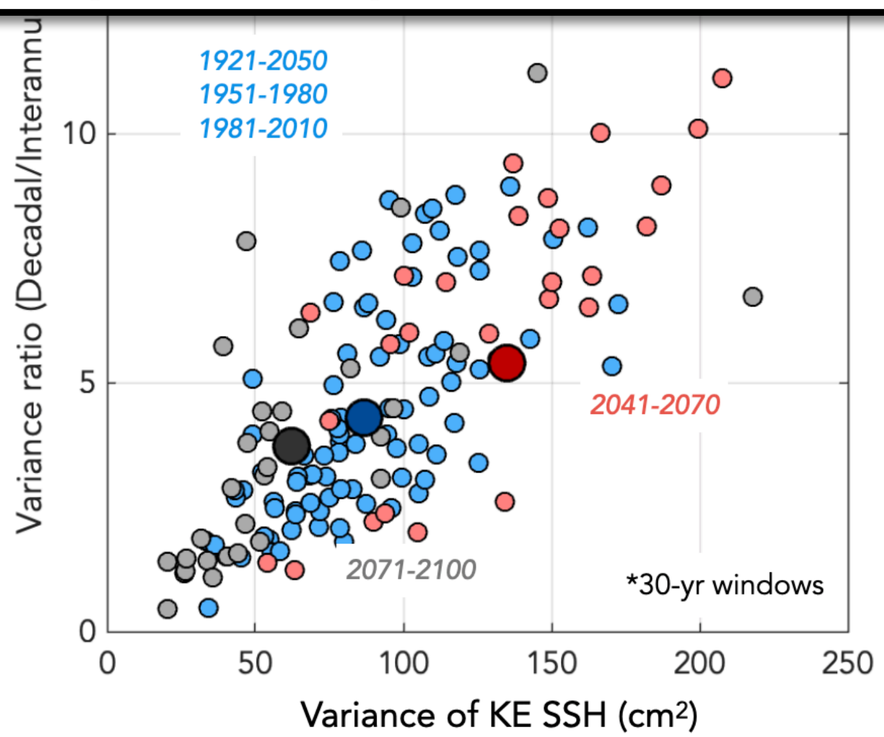
Improved subsurface KE ocean dynamics

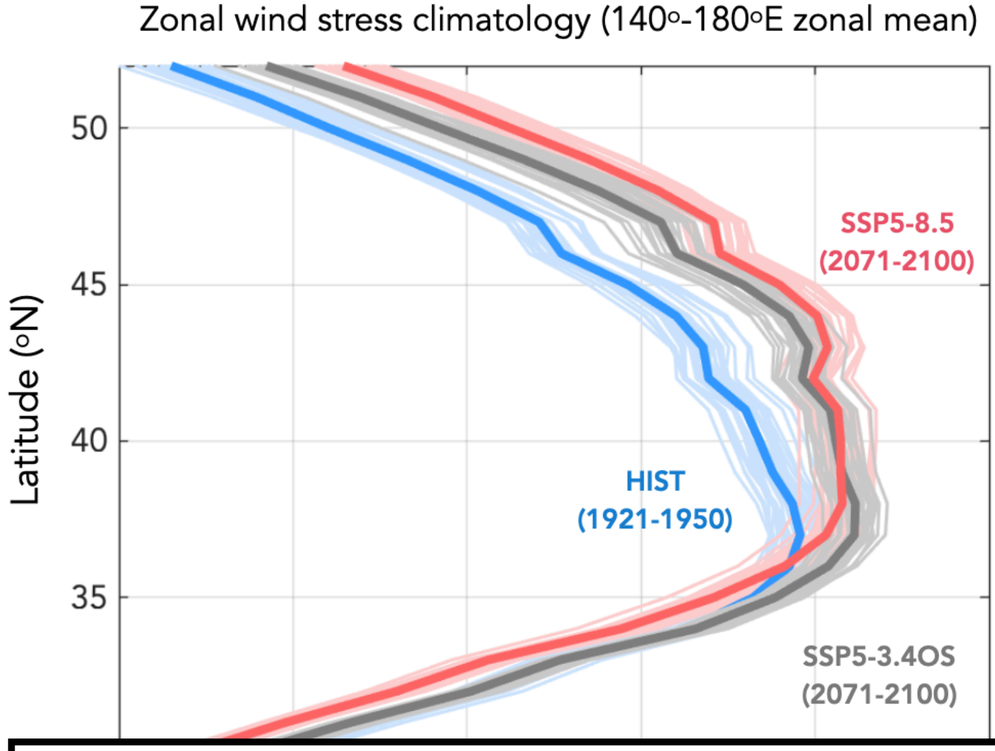
Q. Why KE variability varies with increasing/decreasing greenhouse forcing?

Q & A slides



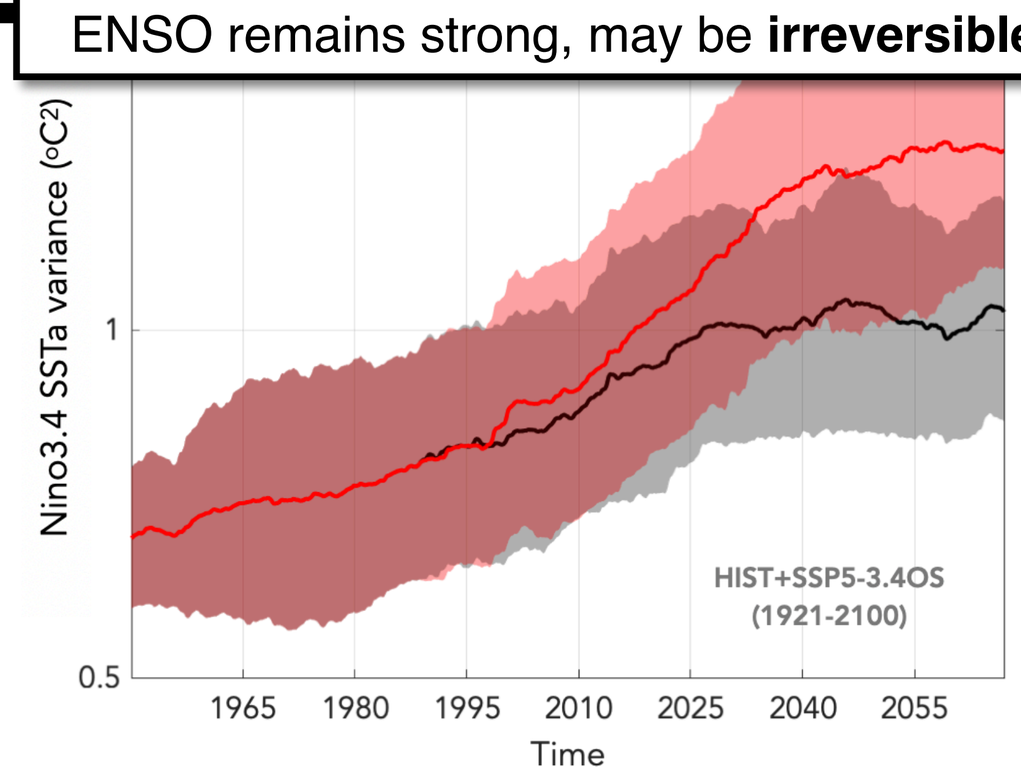
Sensitive response of the KE variance and dominant time scale to changing greenhouse gas concentrations



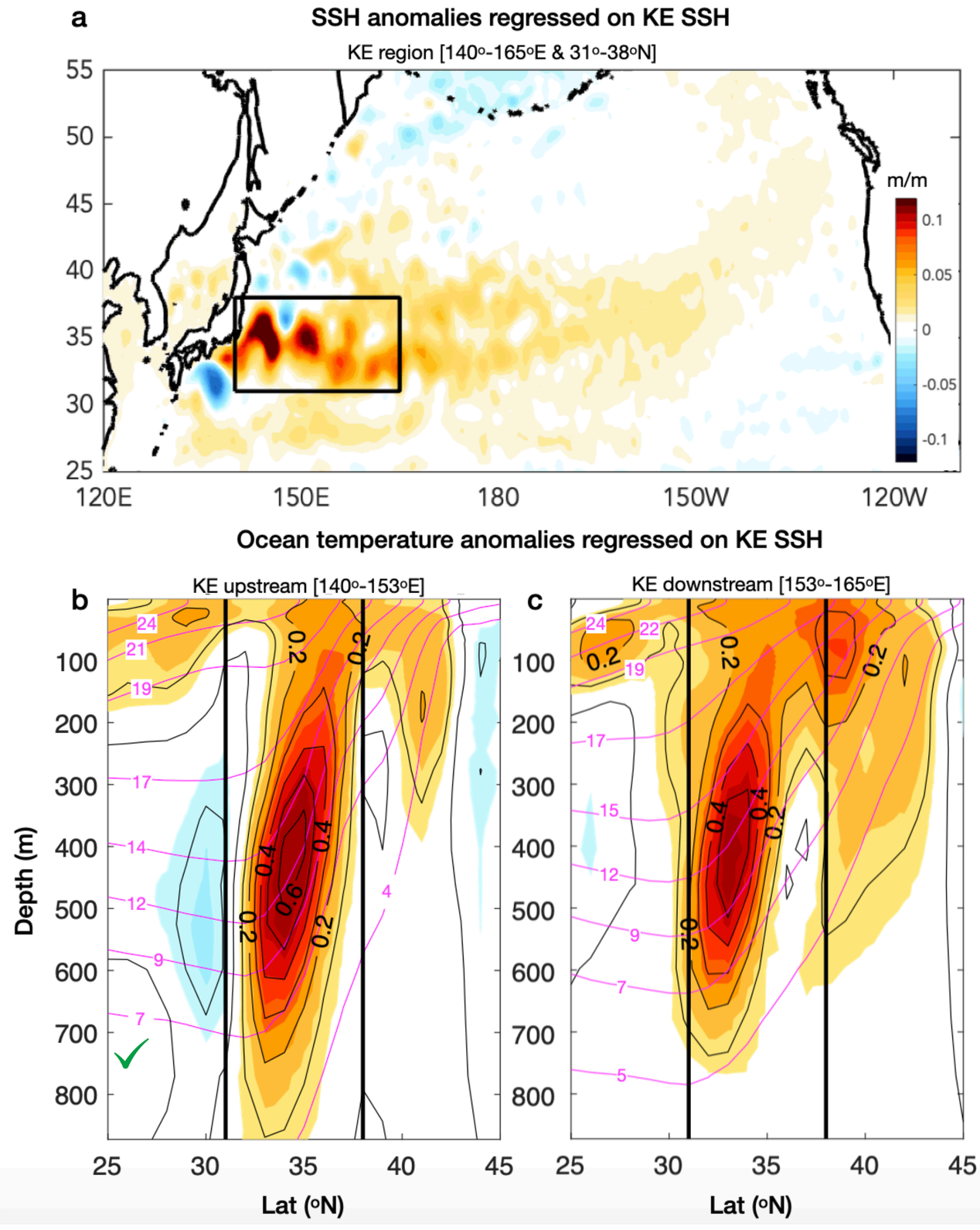


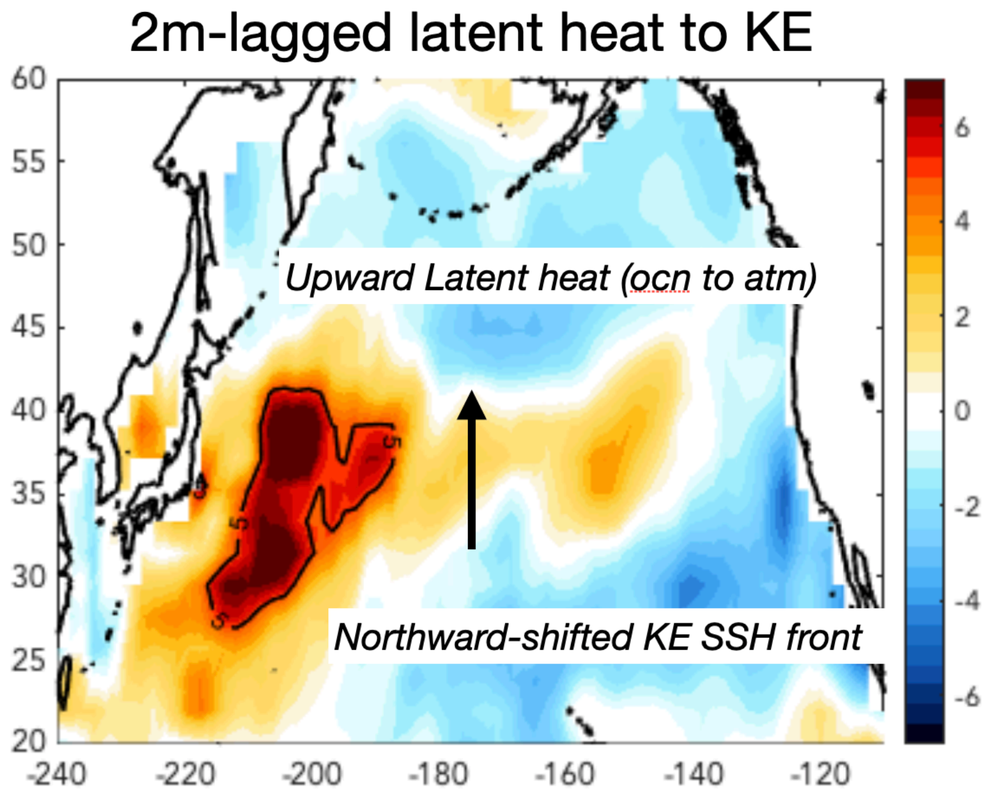
The altered mean position of surface wind climatology may be **reversible**.
(could be a more critical factor)

A variance of both mid-latitude westerlies and ENSO remains strong, may be **irreversible**.



Q. SSH and ocean heat variability over the KE region?





The box region shows persistent (~14m) latent heat flux anomalies.

Future work : Potential research directions using SPEAR_HI_25 model

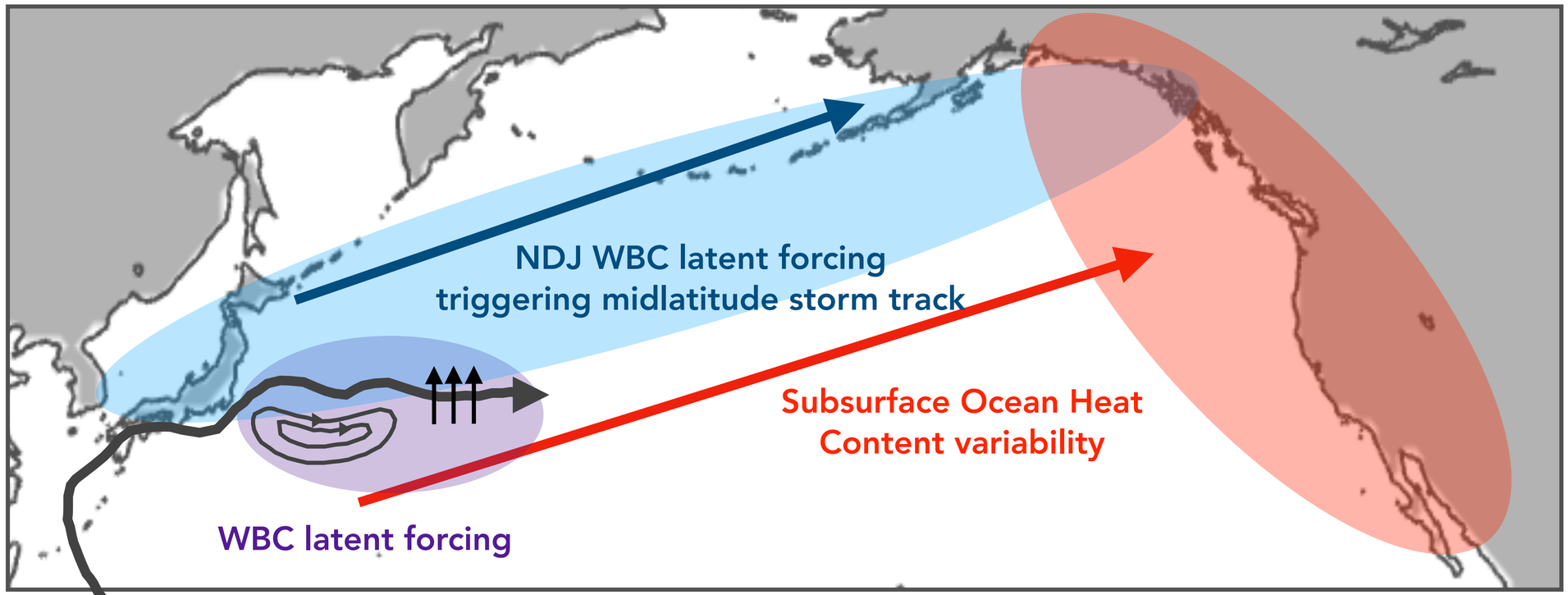
Increasing ocean model resolution

↓

Improved subsurface KE ocean dynamics

Improved ocean dynamics & air-sea coupling

: more realistic subsurface ocean heat content variability & KE downstream feedback on the Pacific Northwest



- Observed winter latent forcing of WBC system on the Pacific Northwest weather (Joh et al. 2022 to be submitted)
- Impact of horizontal resolution on WBC air-sea coupled system in global coupled model

Future work : Potential research directions using SPEAR_HI_25 model

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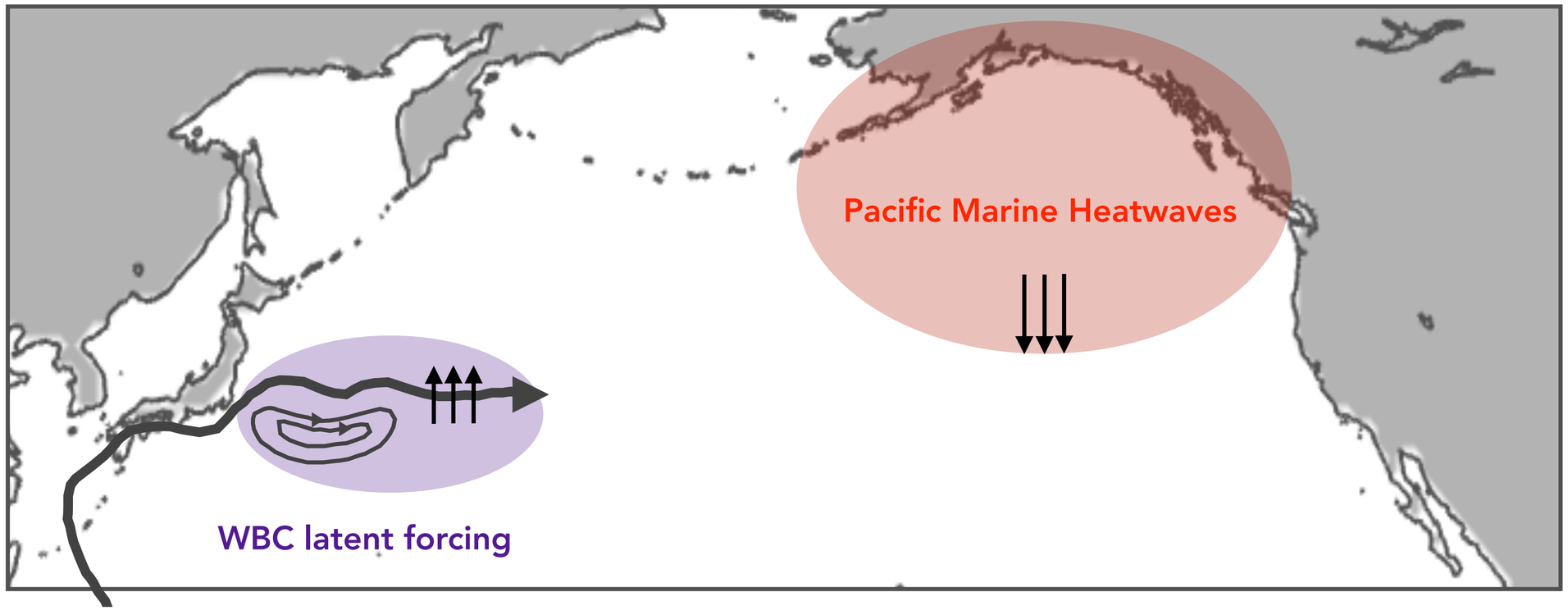
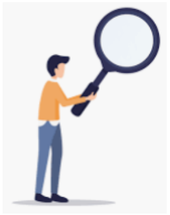


- Observed winter latent forcing of WBC system on the Pacific Northwest weather (Joh et al. 2022 to be submitted)
- Impact of horizontal resolution on WBC air-sea coupled system in global coupled model
- Contribution of WBC impact on Pacific Marine Heatwaves → improving Marine Heatwaves prediction
- A link of Pacific air-sea coupled system to vertical transport and biogeochemistry in the upper ocean

→ **Pacific seasonal to decadal variability and predictability in relation to marine ecosystem prediction**



Sensitivity to radiative forcing changes?