Unraveling the formation mechanisms of marine heatwaves in the Northeast Pacific

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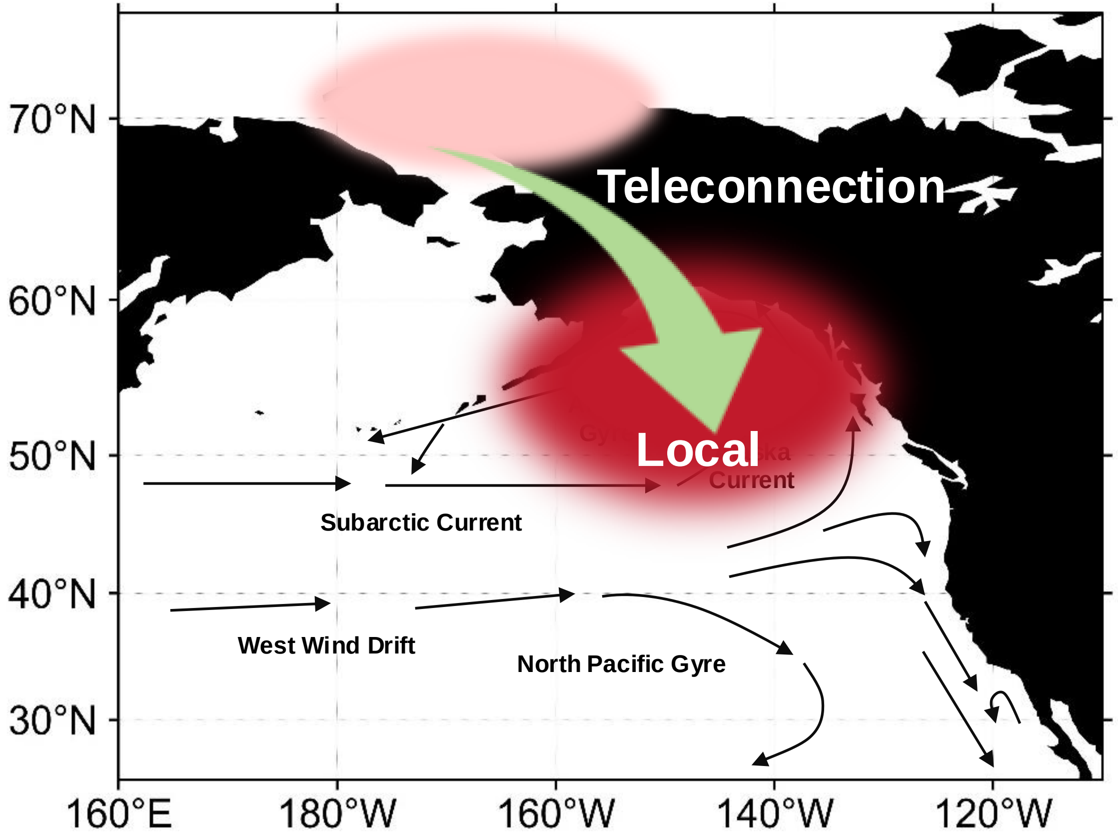
Outline



01 Motivation

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03 Local processes causing the “Blob”

04 Remote drivers of marine heatwaves

05 Brief summary

Chen, Wang, Chai et al. 2023, npj CAS

Chen, Wang, Chai et al. under review, npj CAS

Motivation

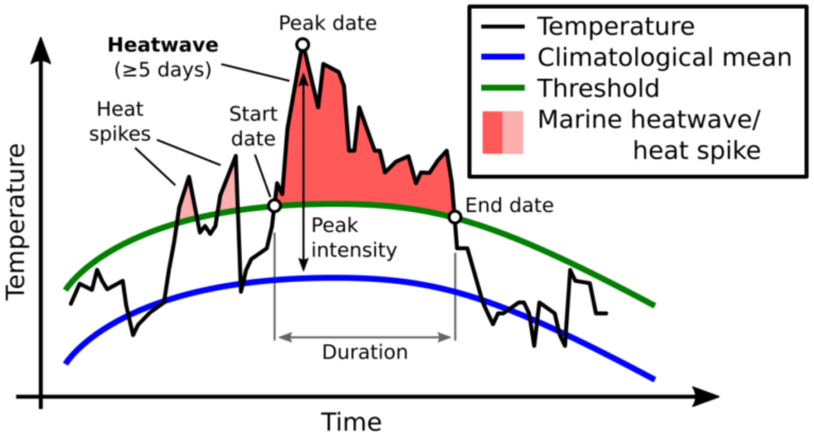
Marine Heatwaves（MHWs）: A discrete prolonged anomalously warm water event

MHWs Definition:

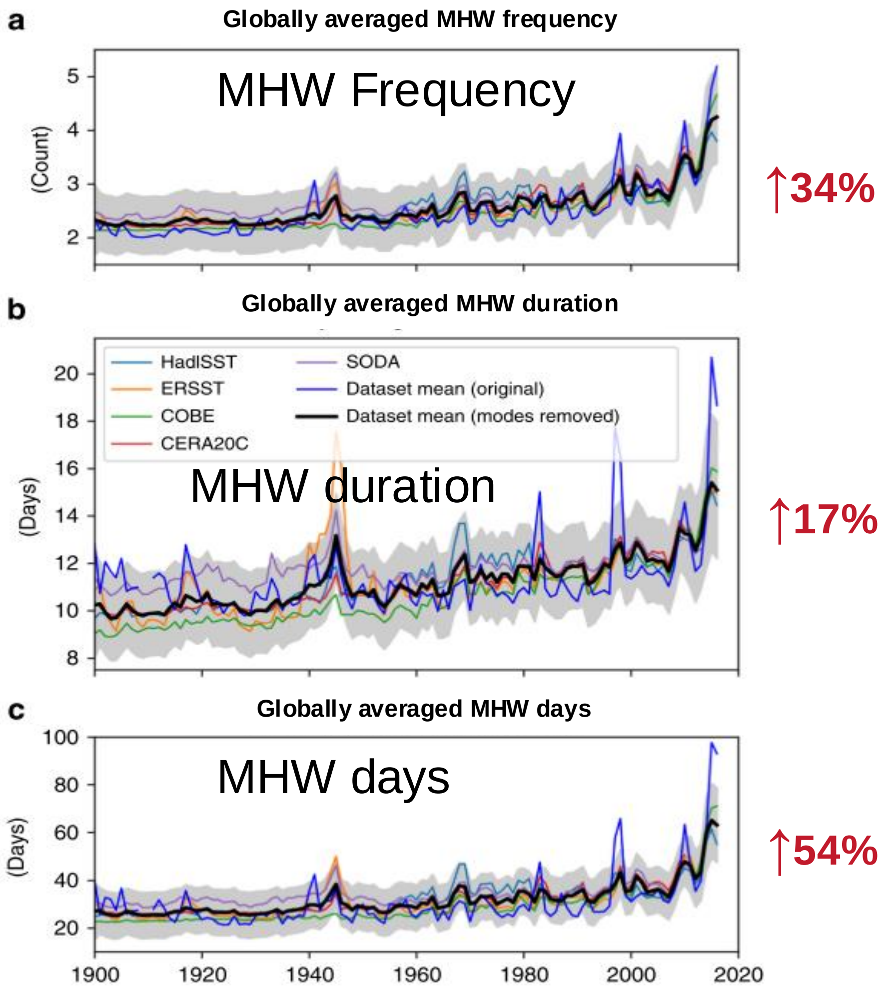
SSTA > 90th percentile

Duration > 5 days

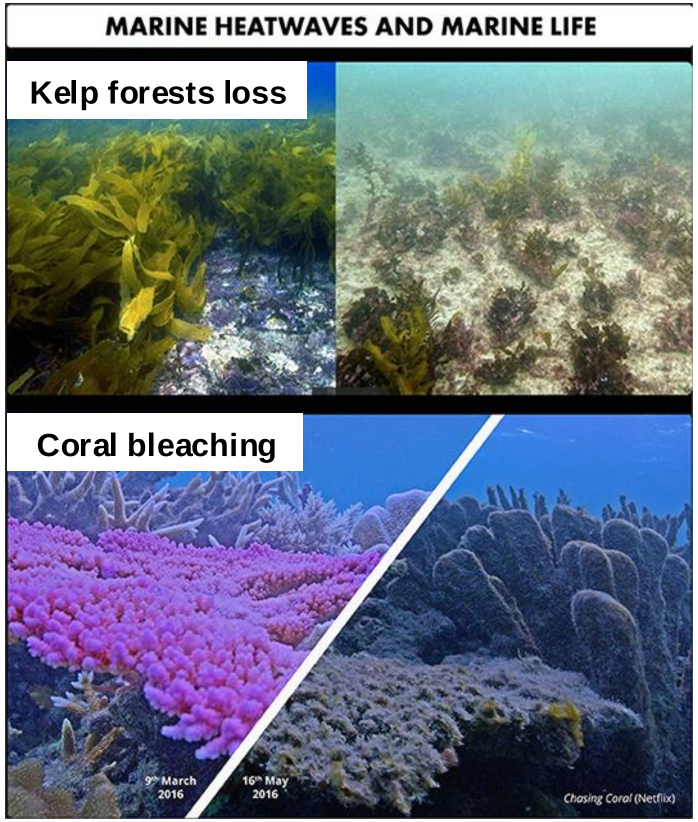
Interval > 3 days



(Hobday et al., 2016)



(Oliver et al., 2018)

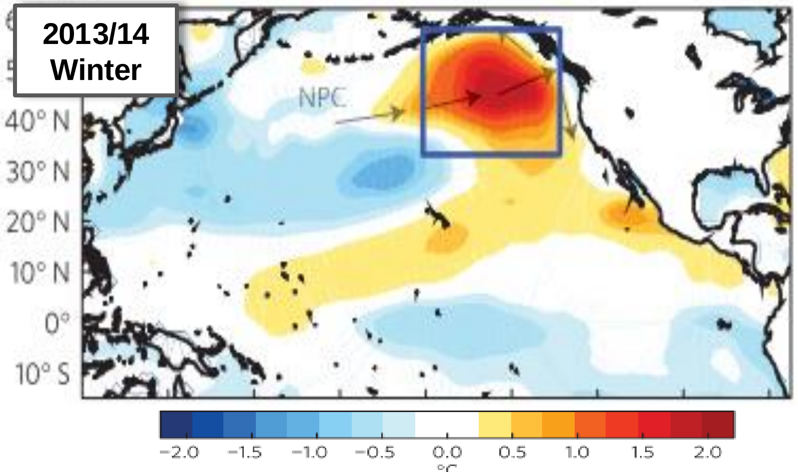


(Beaudin and Bracco, 2022)

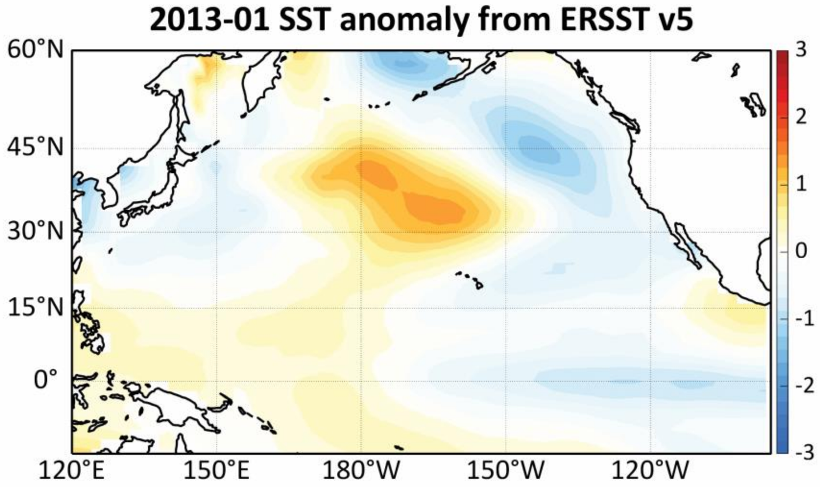
Motivation

The "Blob"

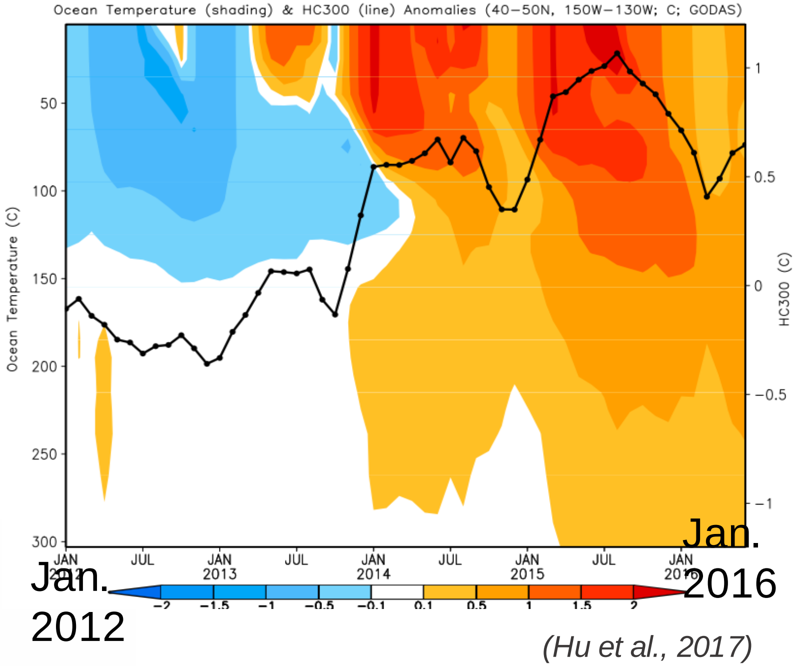
SSTA



(Di Lorenzo and Mantua, 2016)

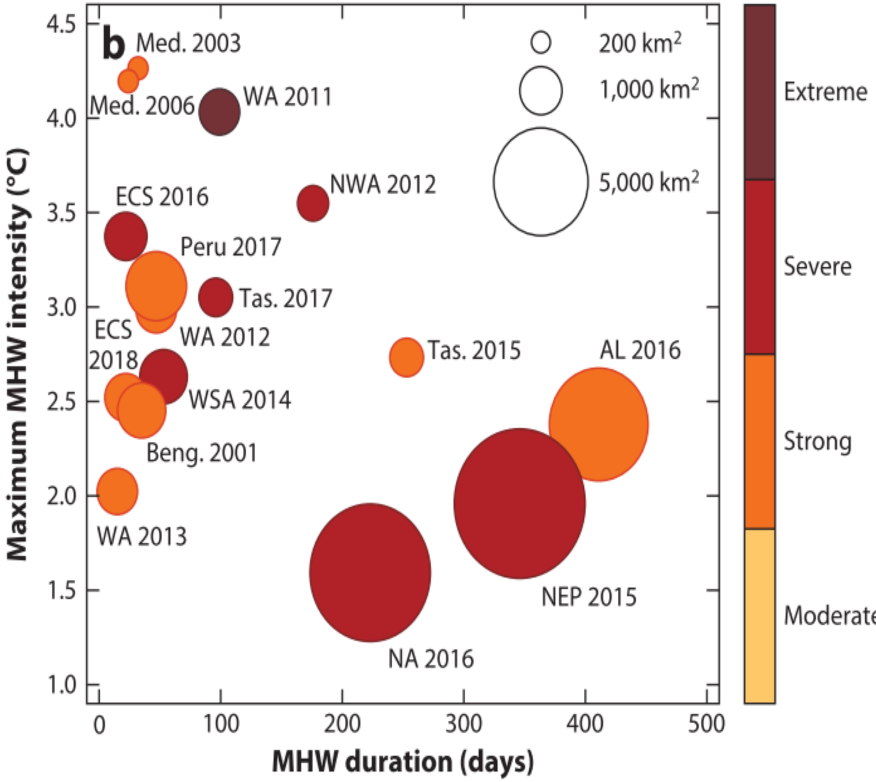


Ocean temperature anomalies



(Hu et al., 2017)

Historical MHWs



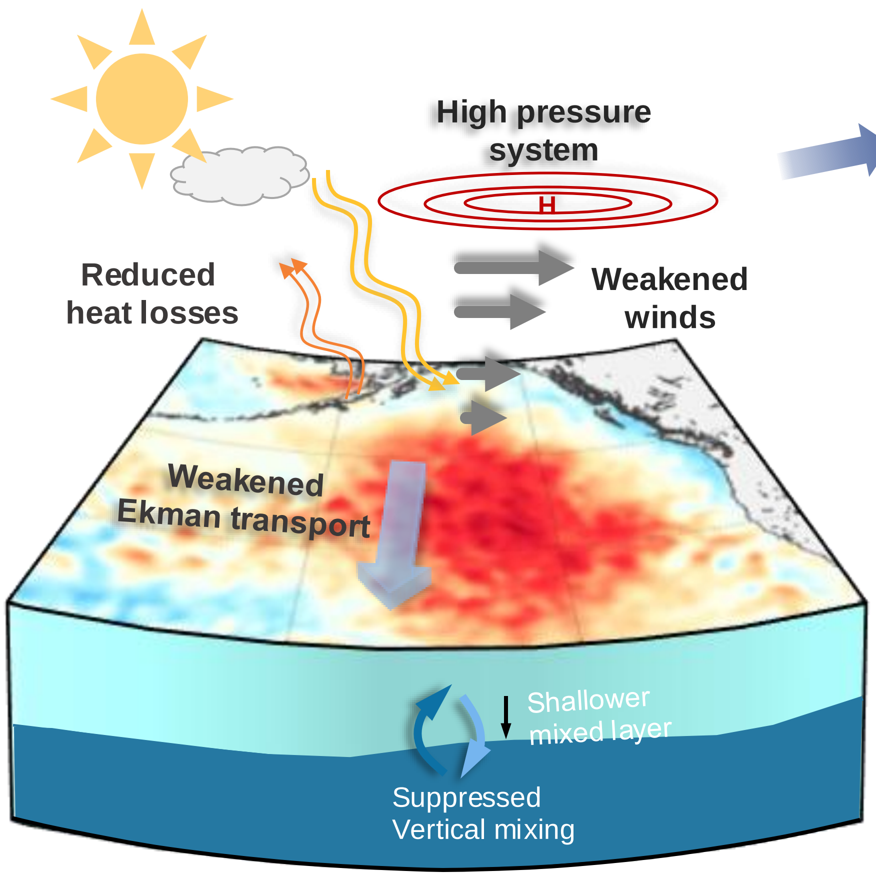
(Oliver et al., 2021)

Characteristics of the Blob

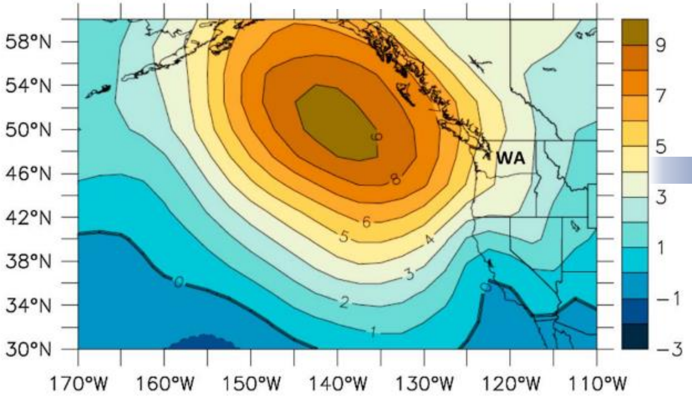
- Monthly SST anomaly can exceed **2.5℃**
- Originated at oceanic surface and propagated downward and reached about **300 m**
- SST anomalies extend from the Gulf of Alaska to the Baja California
- Multi-year persistence from late 2013 to early 2016

Motivation

Mechanisms of the Blob

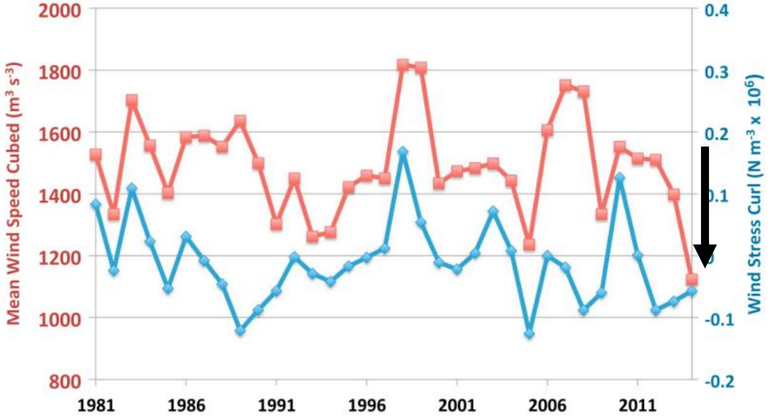


SLPA



(Bond et al., 2015)

Wind speed



(Bond et al., 2015)

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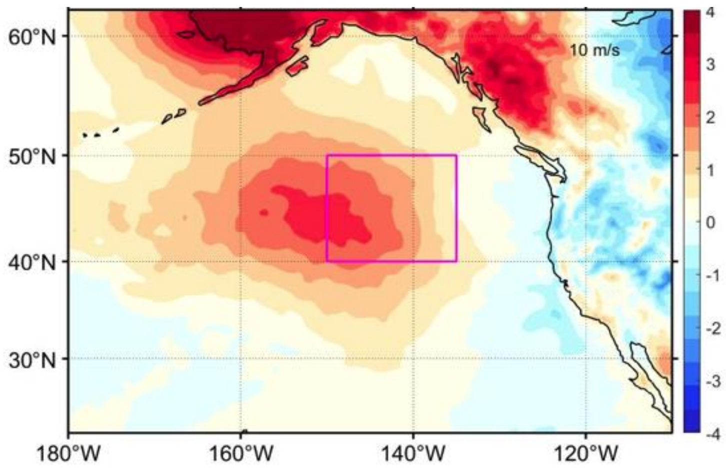
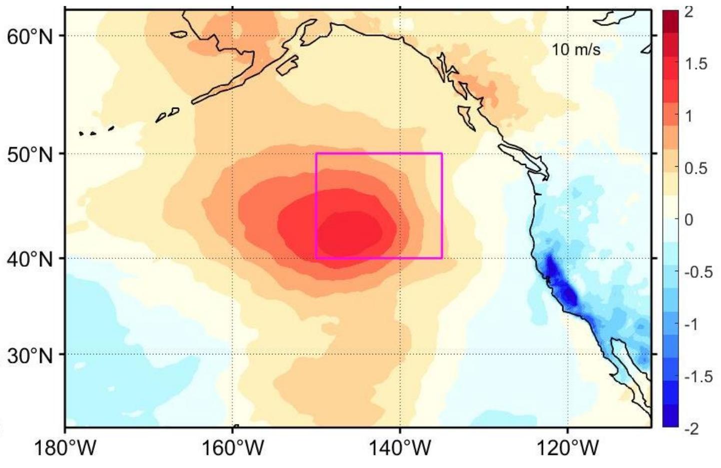
Air temperature anomalies in 2013/14 winter



Specific humidity anomalies in 2013/14 winter



Data and Methods

Data

- **Observation/Reanalysis Data：**
- SST：

  ERA5、HadISST、ERSST V5、OISST V2
- ocean currents and temperature：

  GODAS and SODA
- atmospheric variables：

  ERA5、NCEP/NCAR、OAFlux、HadCRUT5
- **Models:**

  ROMS: Regional Ocean Modeling System

  CAM5: the Community Atmosphere Model, version 5

Methods

- Lanczos filter、regression and correlation analysis
- Mixed layer heat budget

$$\underbrace{\frac{\partial T}{\partial t}}_{\text{Term I}} = \underbrace{\frac{Q}{\rho C_p h}}_{\text{Term II}} \underbrace{- u_a \cdot \nabla T}_{\text{Term III}} \underbrace{- \left(w_h + \frac{dh}{dt}\right)\frac{T - T_h}{h} - \frac{\kappa}{h}\frac{\partial T}{\partial z}\bigg|_{z=h}}_{\text{Term IV: Residual}}$$

(Cronin et al., 2015)

Term I: Mixed layer average temperature tendency

Term II: Net air-sea heat flux

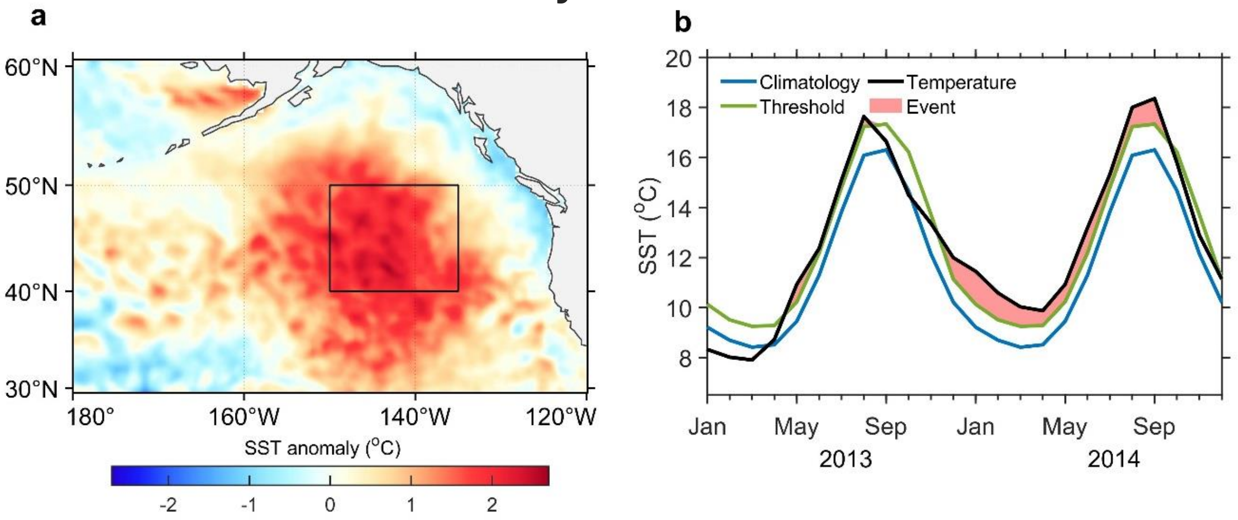
Term III: Horizontal advection

Term IV: Residual

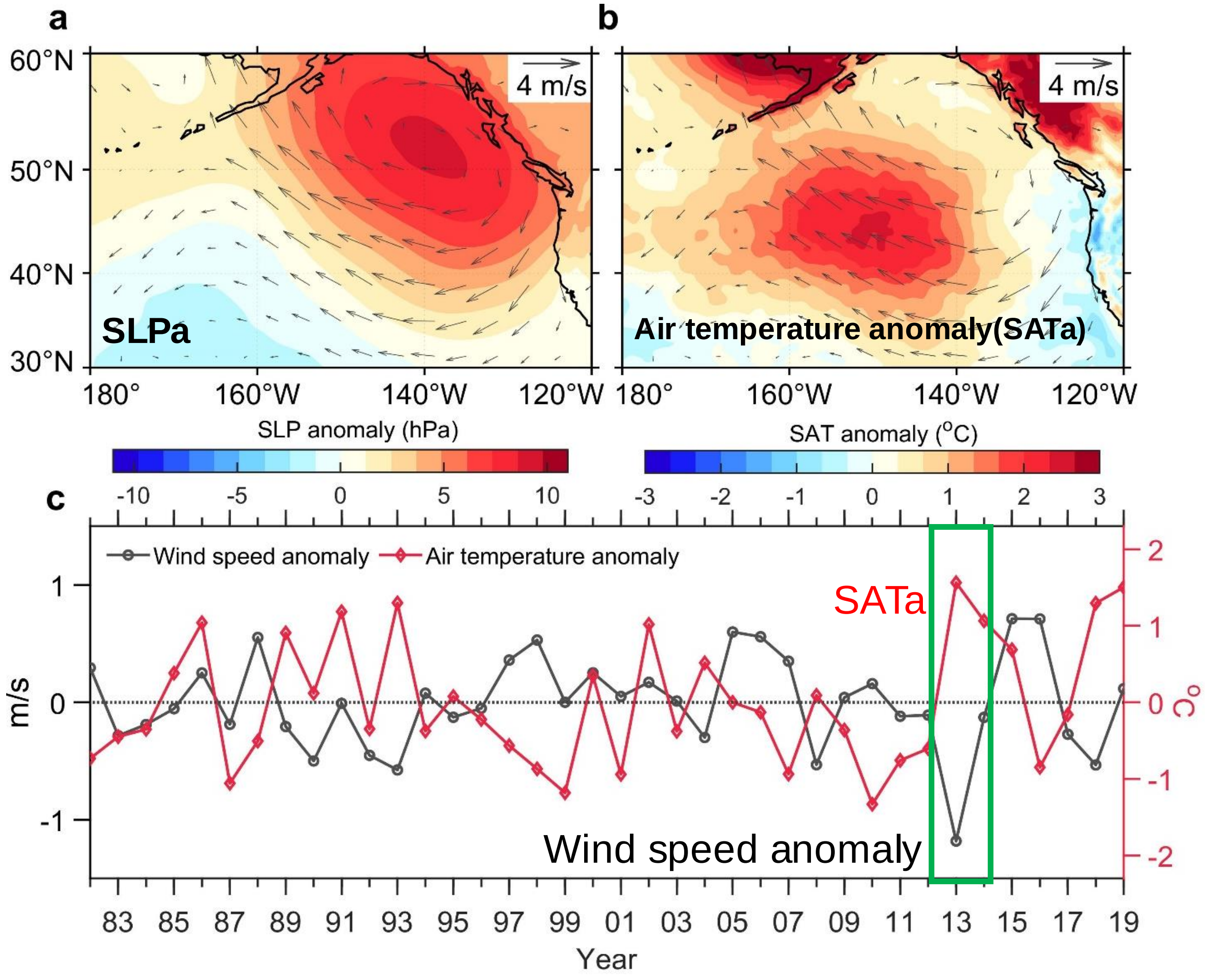
Local processes causing the Blob

Observations and driving mechanisms of the Blob

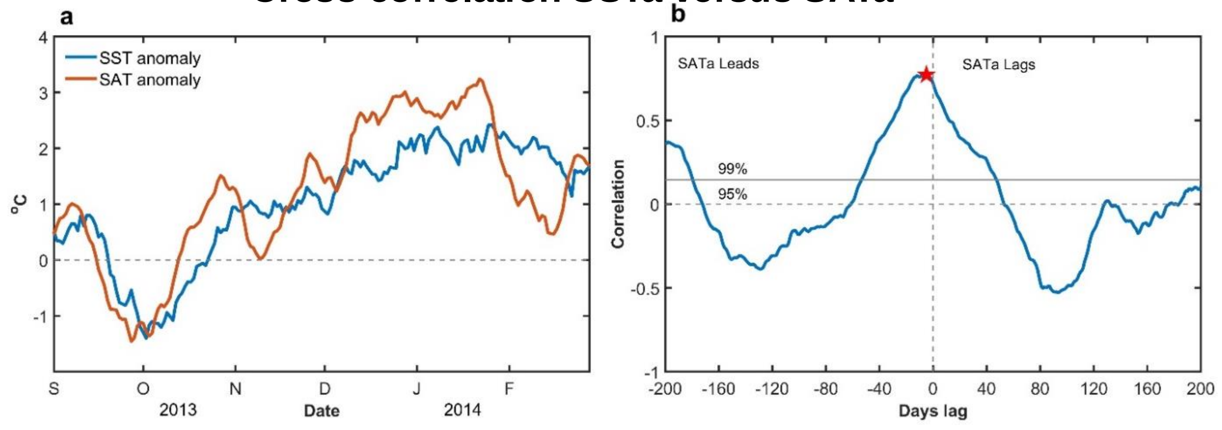
SST anomalies in February 2014



Anomalous atmosphere fields in 2013/14 winter (Oct–Jan)

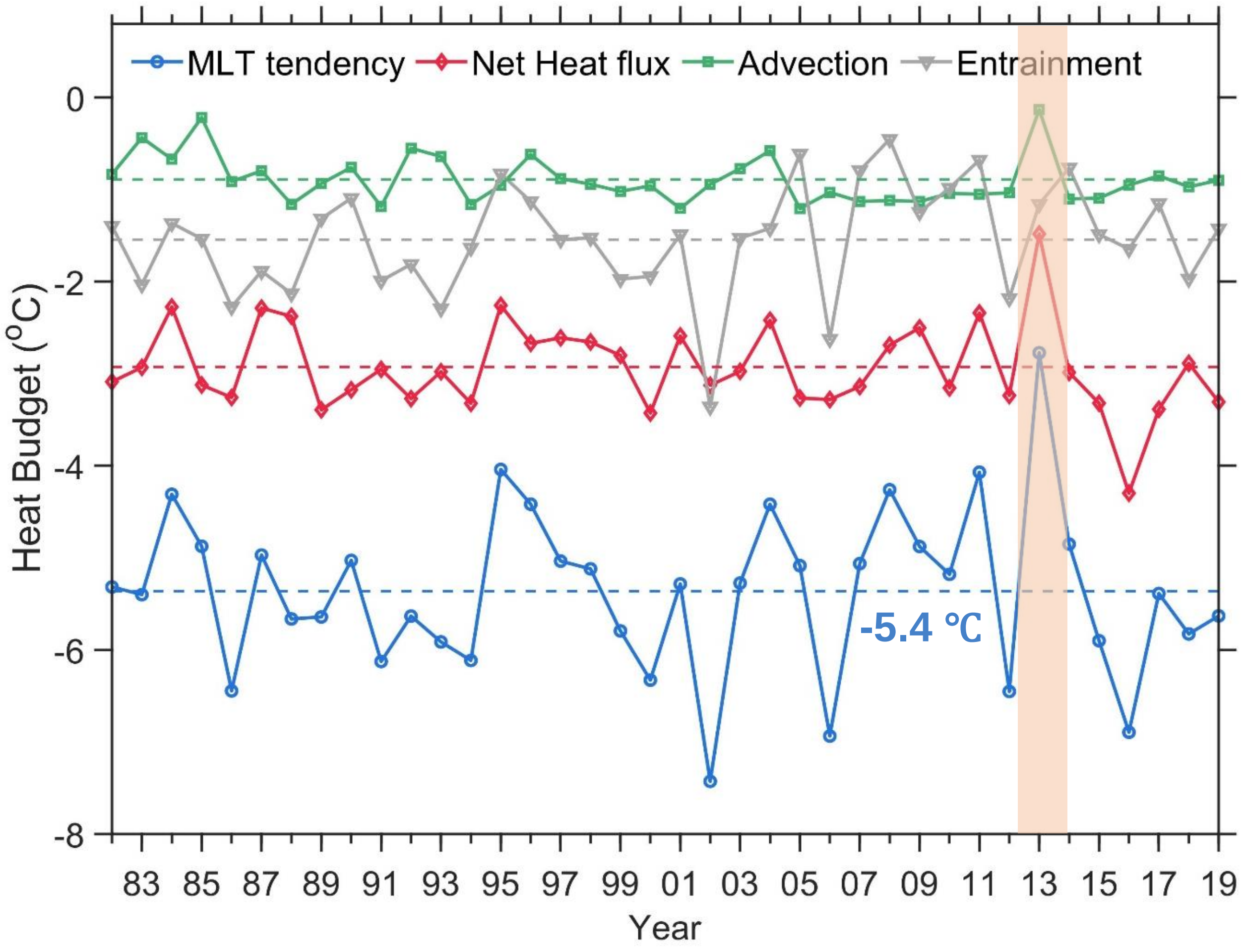


Cross-correlation SSTa versus SATa



- Daily SATa leading SST anomaly~5 days
- The atmosphere forces the SST changes in the NE Pacific

Heat Budget analysis



- In climatological winter (Oct-Jan), MLT change is **-5.4 ℃**
- In 2013/14 winter, MLT change is **-2.8 ℃**, a decrease of approximately **48.2%**

- Heat loss by **advection** was close to zero in 2013/14
- **Entrainment (residual)** was close to average
- **Net air-sea heat Flux loss** was lower than average in 2013/14
- Seasonal values of the **Mixed Layer temperature change** from October to January

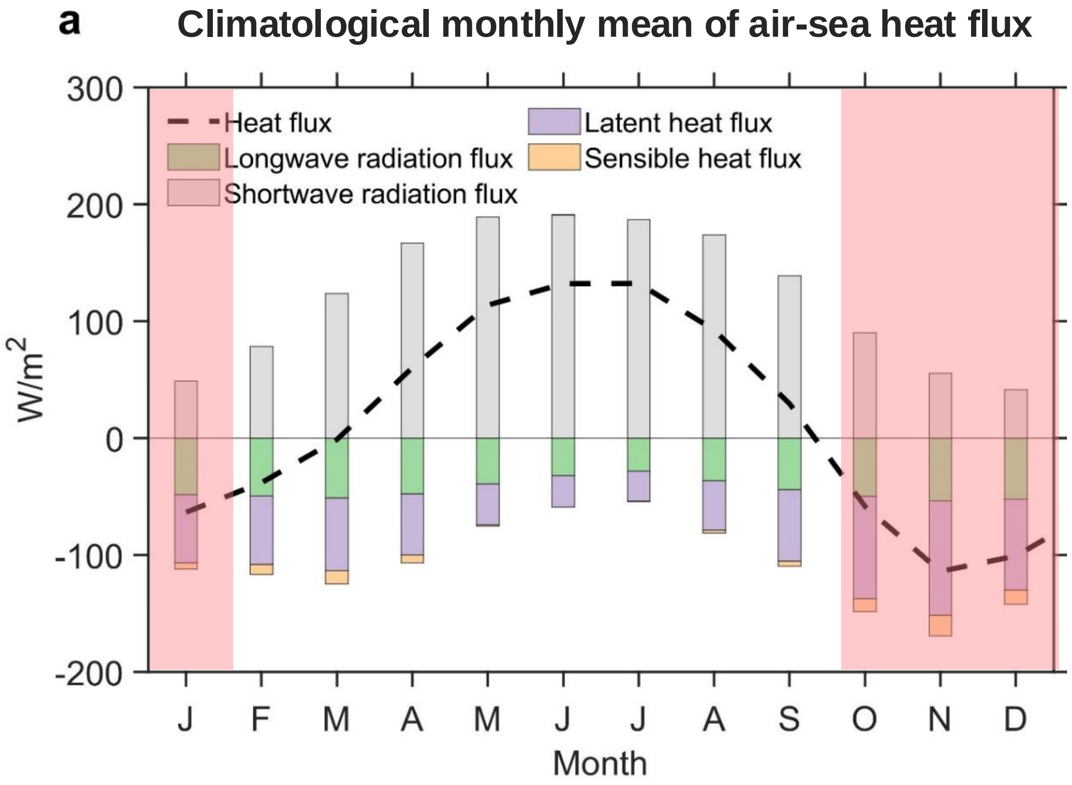
Reduced heat losses by surface fluxes and horizontal advection were the dominant contributors to the Blob

Net air-sea Heat Flux

$$Q = SW + LW + LH + SH$$

Radiative heat flux: Lw: Longwave radiative flux
Sw: Shortwave radiative flux

Turbulent heat flux: LH: Latent heat flux
SH: Sensible heat flux



- In climatological winter, the heat loss from ocean to the atmosphere is **-84.16 w/m²**,
- In 2013/14 winter, net air-sea heat flux is **-42.91 w/m²**, the ocean reduces heat loss by **41.25 w/m²**, approximately **49%**
- Turbulent heat fluxes (LH and SH) dominated the anomalous air-sea heat flux, accounting for approximately **85.5%** **(-35.3 w/m²)**

Decomposed Turbulent Heat Flux

$$LH' = \rho_a L C_E U'_{10}(\overline{q}_s - \overline{q}_a) + \rho_a L C_E \overline{U_{10}}(q'_s - q'_a) + \rho_a L C_E U'_{10}(q'_s - q'_a)$$

$$SH' = \rho_a C_p C_h U'_{10}(\overline{T}_s - \overline{T}_a) + \rho_a C_p C_h \overline{U_{10}}(T'_s - T'_a) + \rho_a C_p C_h U'_{10}(T'_s - T'_a)$$

(Tanimoto et al., 2003)

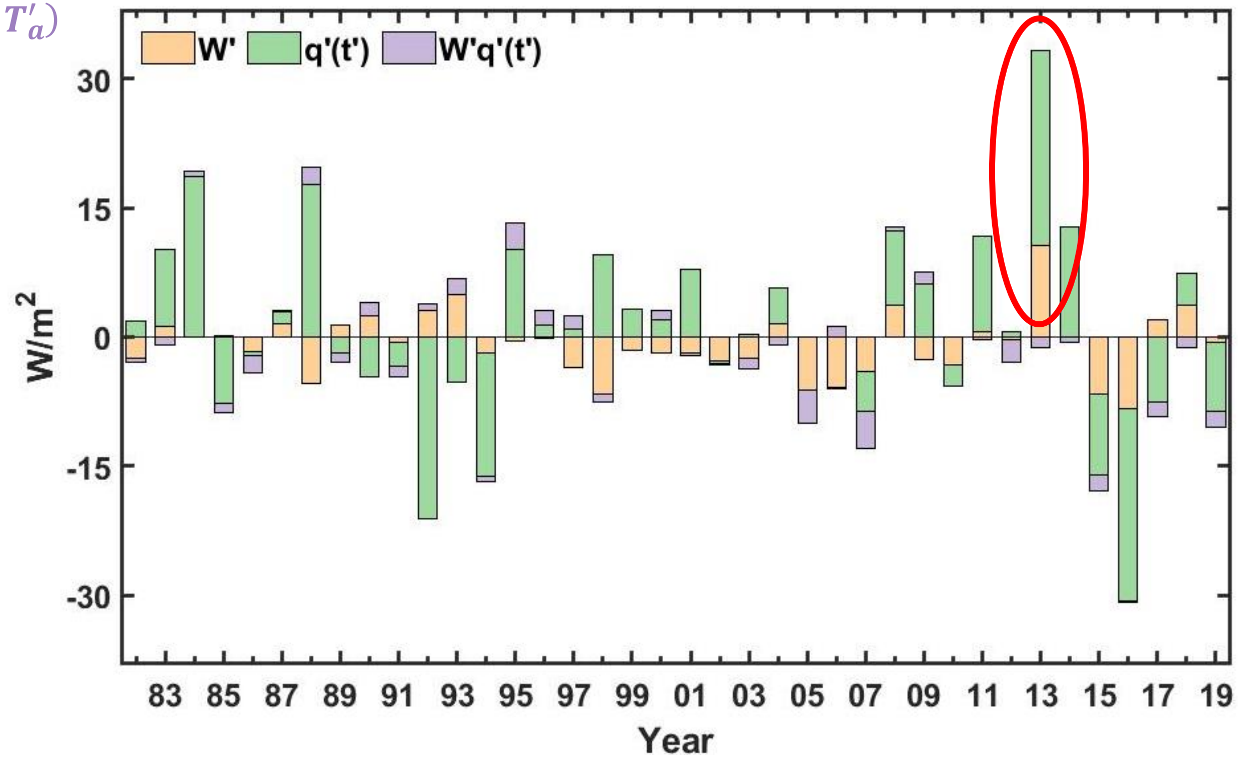
Term I derived from wind speed anomaly

Term II derived from air temperature/moisture anomaly

Term III nonlinear effect

- The turbulent heat flux depends on wind speed and air-sea temperature/humidity difference

Decomposed turbulent heat flux during winter



- In the winter of 2013/14, turbulent heat flux anomalies caused by air temperature anomalies (moisture anomalies) accounted for **69.3**%

Model set-ups and experiments

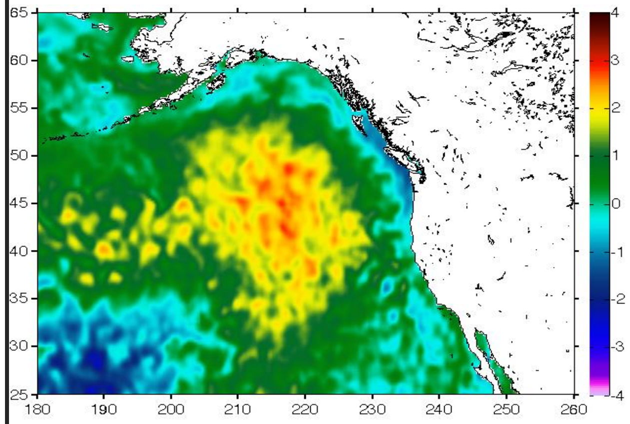
- Model: ROMS
- Vertical level: 30 layers
- Horizontal resolution:1/8°
- Initial: WOA09
- Forcing: NCEP reanalysis;

  NOAA blended winds

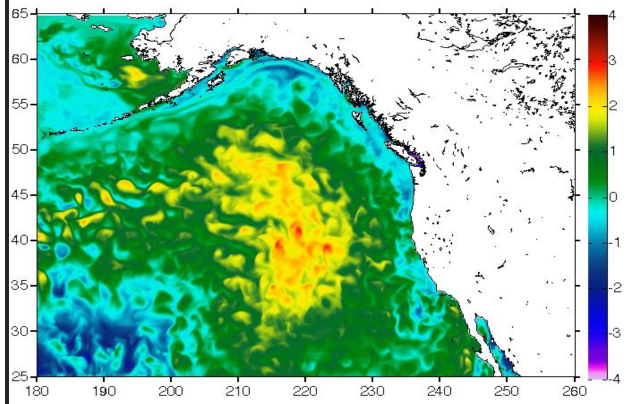
Experiments：

- **Control:** real forcing
- **Case1:** Climatological air temperature
- **Case2:** Climatological winds

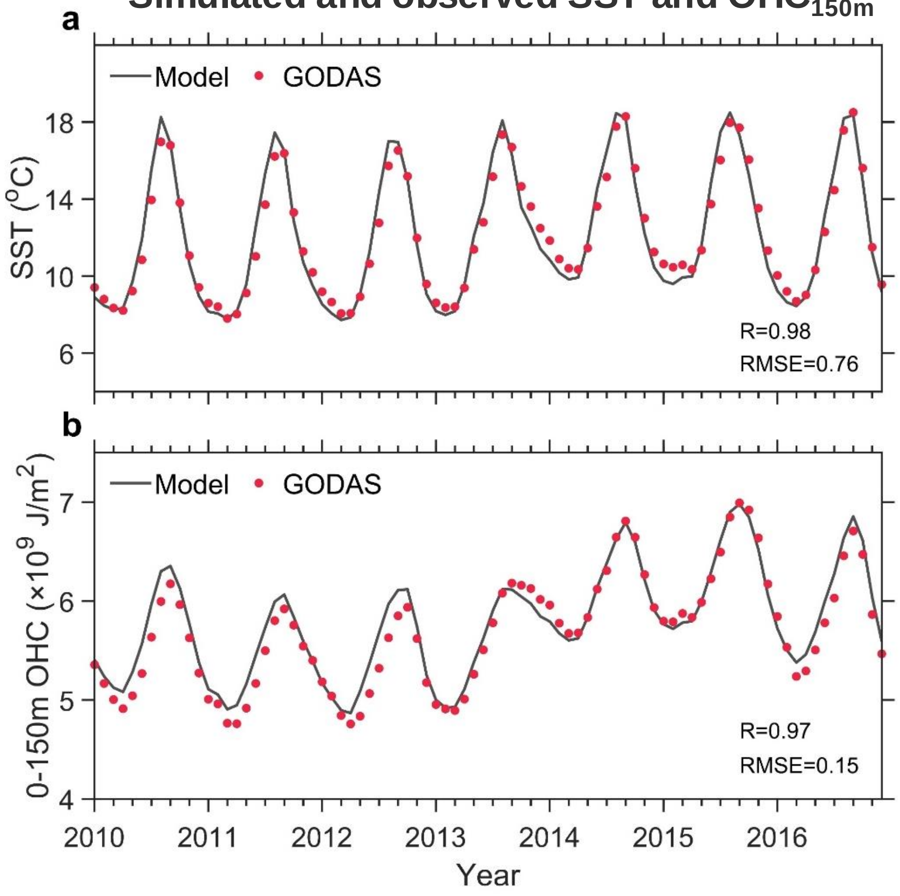
OISST anomalies in Feb 2014



Simulated SSTa in Feb 2014

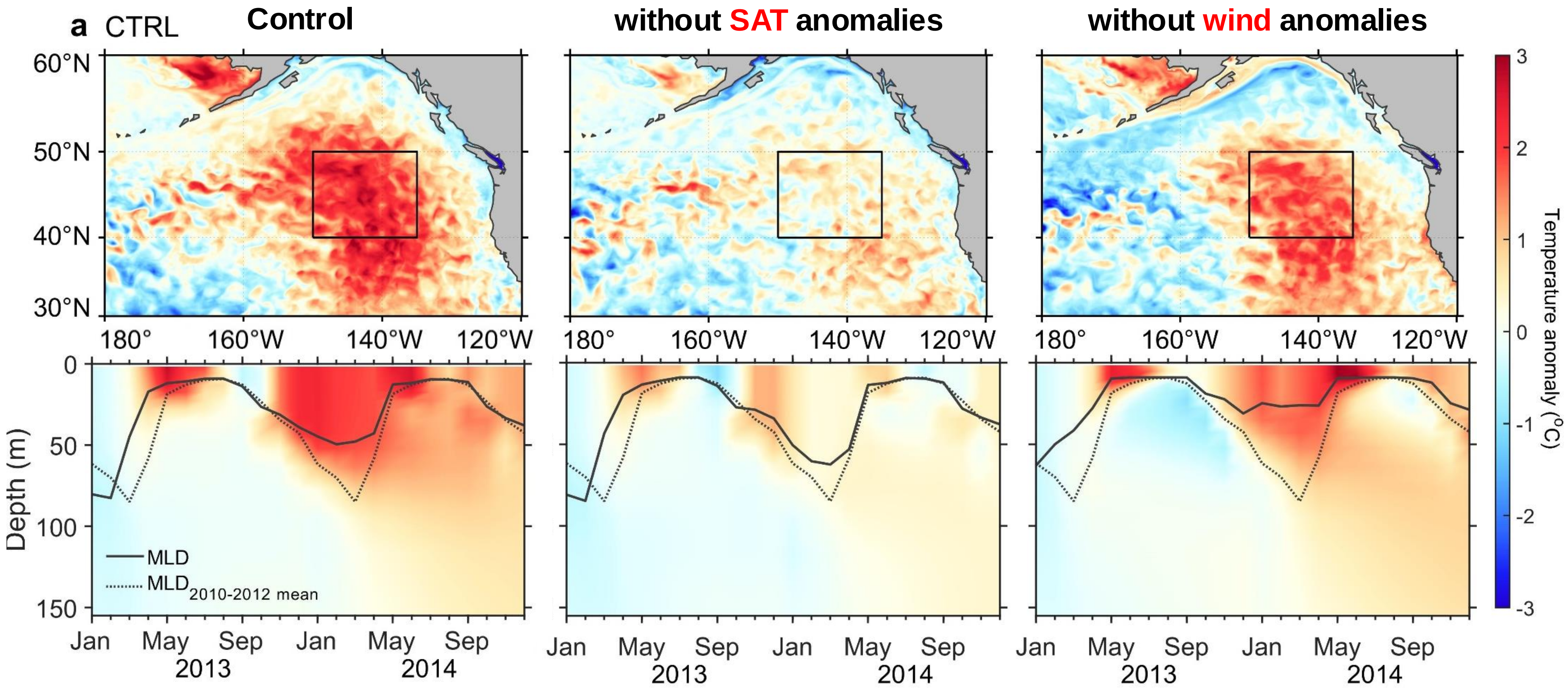


Simulated and observed SST and OHC_{150m}



Mechanisms of The Blob

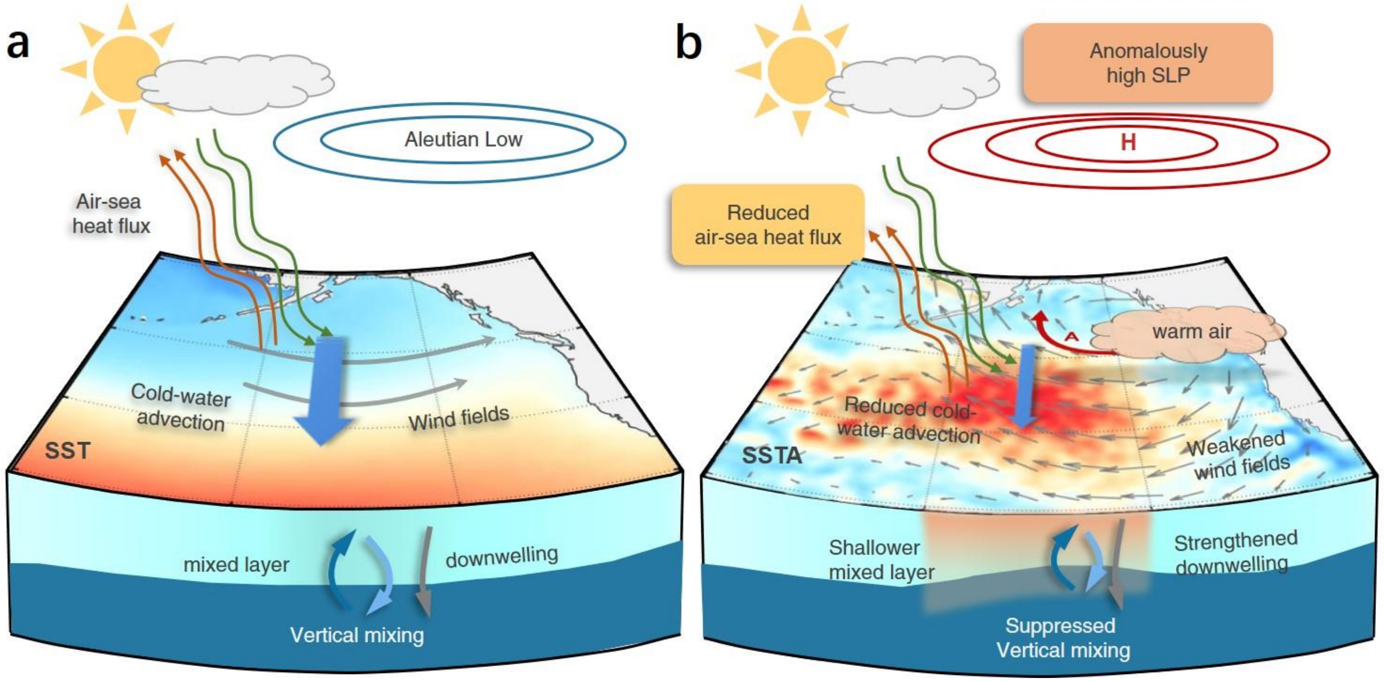
Modeled SST and ocean temperature anomalies in Feb 2014



Poleward winds bring warm and moist air to increase air temperature/humidity

Local Drivers of the Blob

Wind direction change instead of intensity change is more important



Chen, Chai et al. 2023 npj CAS

Mechanisms of The Blob

Weakened Aleutian Low

High SLP

↓

Anomalously wind fields

Wind intensity | Wind direction

Weakened wind speeds + Warm air temperature

↓

Shallowed MLD | Reduced horizontal advection | Reduced heat loss

↓

Lacking of wintertime cooling

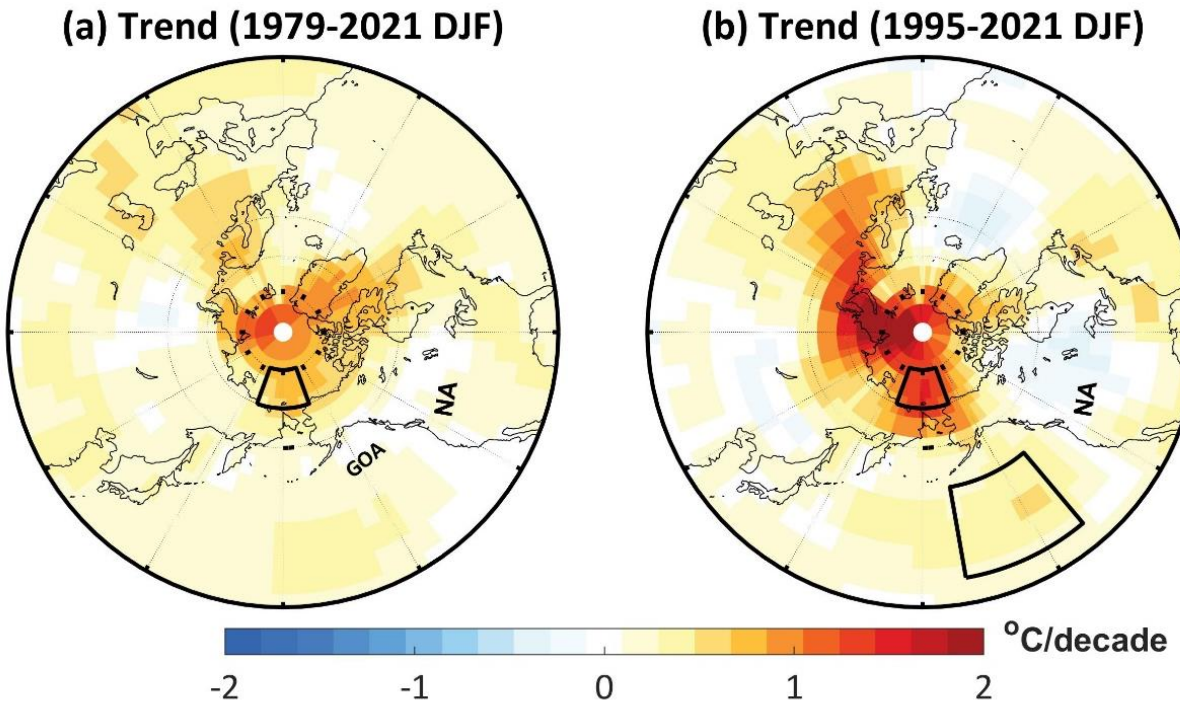
↓

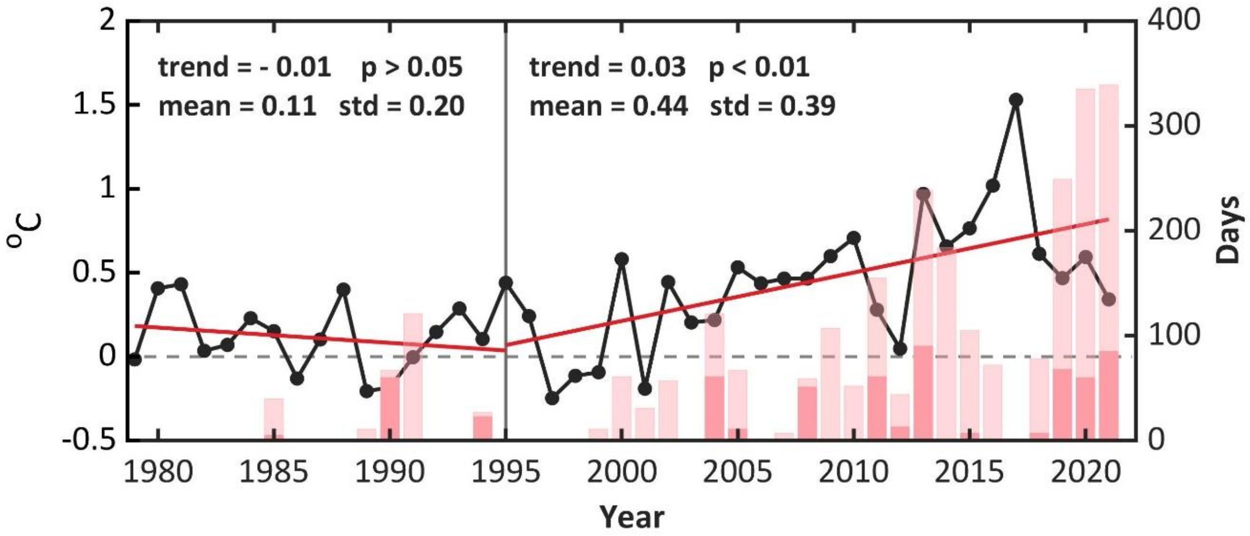
The Blob

Remote drivers of marine heatwaves

Characteristics of Winter SAT and MHWs in the NE Pacific

Linear trend in winter surface air temperature and MHW days from 1979-2021



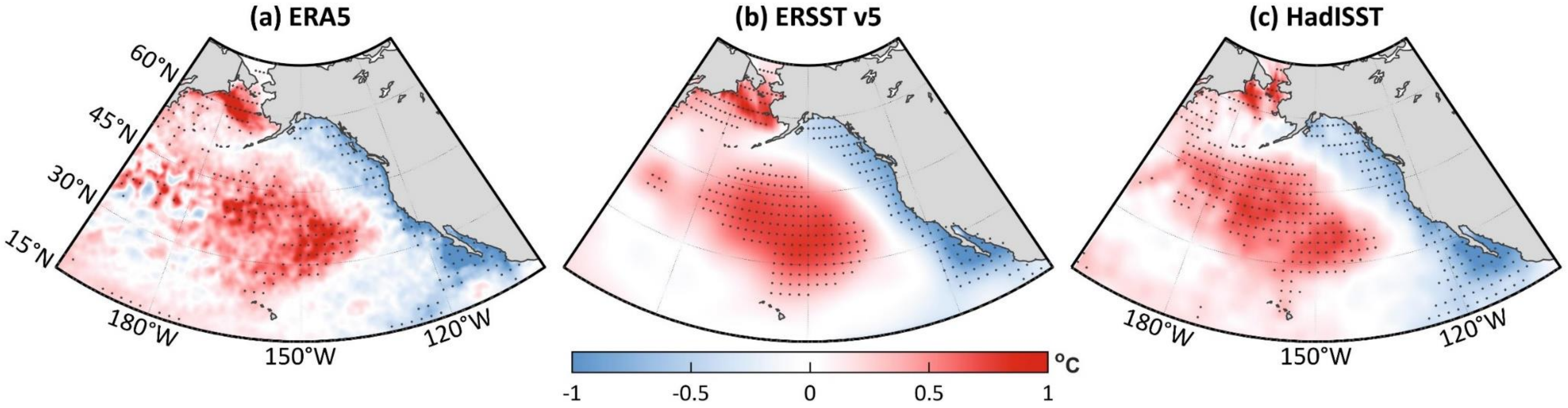


Study region:

- East Siberian-Chukchi Sea (ES-CS, 160° E-160° W, 70-80°N)
- Northeast (NE) Pacific：140-170° W, 30-50° N

- Significant warming in the Arctic during the winter of 1979-2021; The warming trend and oscillations strengthened after mid-1990s
- Annual (pink) and winter (red) MHW days (1979-2021) in the NE Pacific increased at a rate of 4.67 days/yr and 0.97 days/yr, respectively
- Most MHWs (annual: 84%; winter: 87%) mainly occur after mid-1990s

Teleconnection between Arctic warming and NE Pacific SST



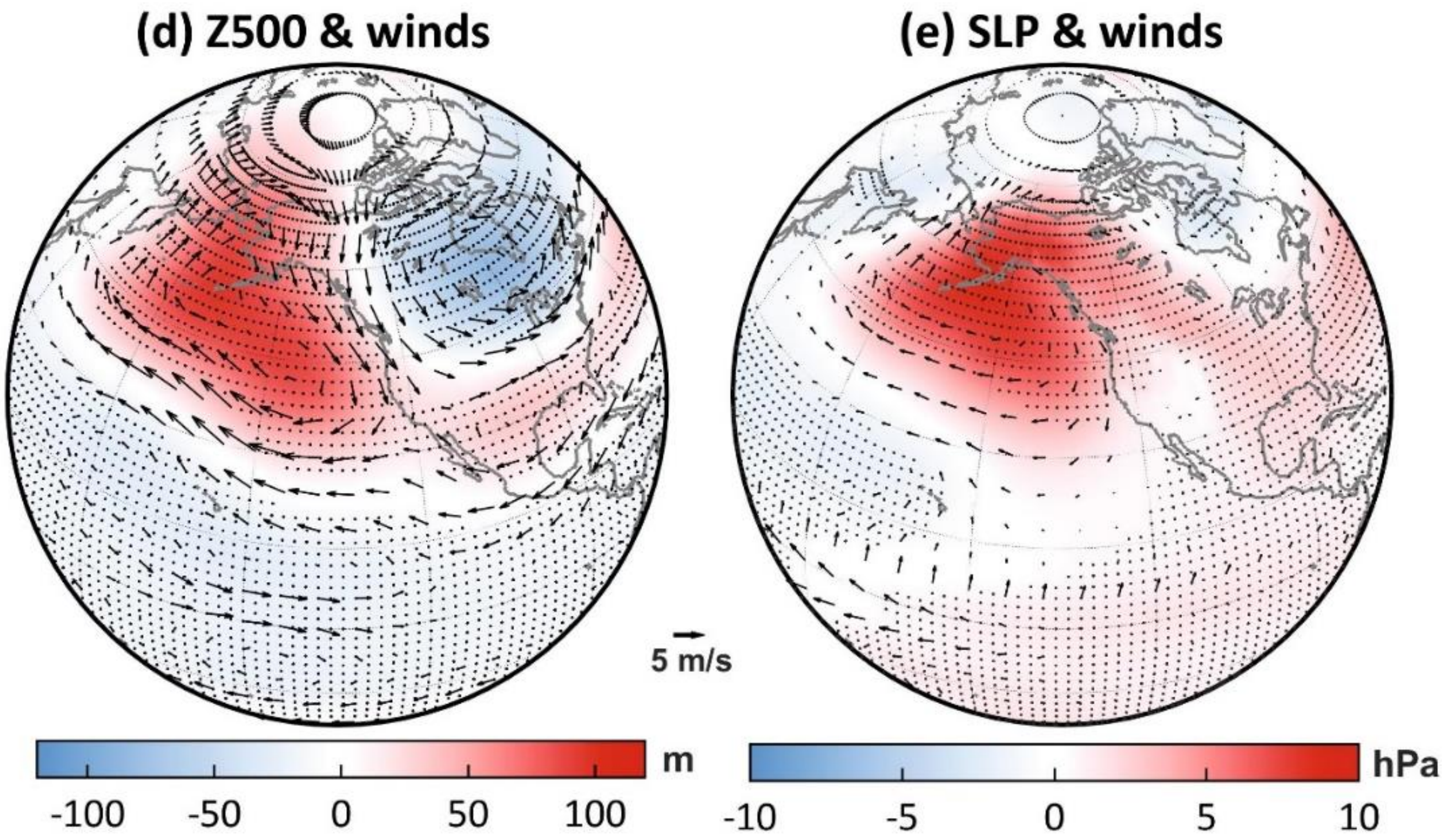
- Winter ES-CS warming can cause positive SSTa in the NE Pacific
- A significant correlation between the winter ES-CS SAT anomaly and the NE Pacific SSTa, the correlation has been strengthened since mid-1990s

Correlation between ES-CS SATa and NEP SSTa

Time span	ERA5	ERSST V5	HadISST
1979~2021	0.36*	0.42**	0.41**
1995~2021	**0.40***	**0.47***	**0.48***
1979~1994	Insignificantly correlated		

**95%, **99% confidence level*

Linear regression of DJF atmospheric variables with ES-CS SAT from 1979 to 2021



- ES-CS warming can form an abnormal high-pressure system over NE Pacific and result in anomalous easterly winds
- This anomalous high-pressure system is a key condition for the formation of MHW in the NE Pacific

Model set-ups and experiments

Hypothesis

Arctic warming

East Siberian-Chukchi sea

↓

Alter the NEP atmospheric circulation

High pressure system anomaly

↓

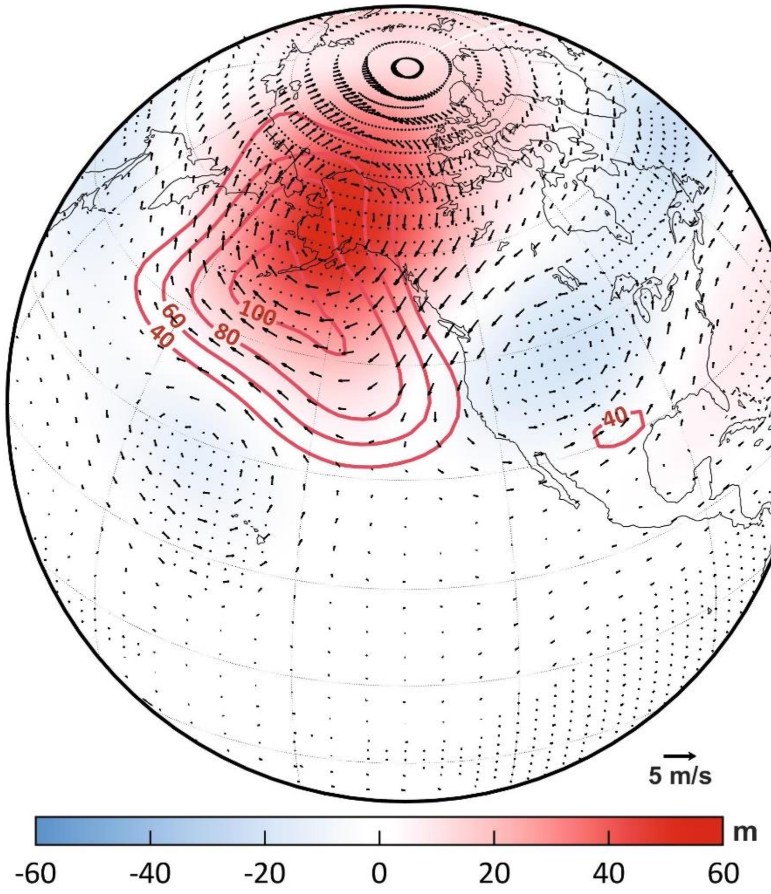
Warm winter SST anomalies in NE Pacific/MHWs

Model set-ups

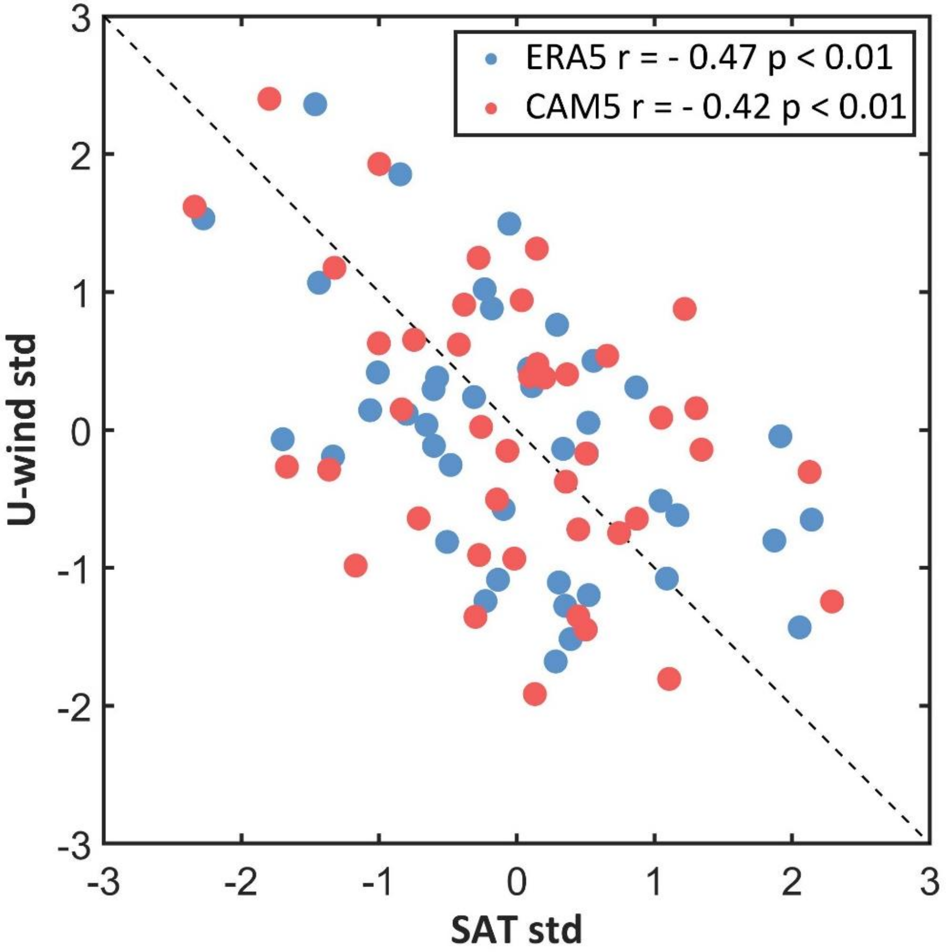
- **Model：** CAM5
- **Vertical level：** 17 layers
- **Spatial resolution：** f19_f19(~2°)
- **Time resolution：** monthly
- **Time span：** 1979.01-2021.12
- **Model runs：** includes 12 ensemble members, each ensemble member is driven by the observed SST over the Arctic region (north of 65°N) with 10° buffer zones on its boundary.
- **Experiment (fn25):** *to test the hypothesis, the SSTs outside Arctic are set to climatological mean state over the period 1981–2010.*

Validation by CAM5 experiment

Simulated winter Z500 and wind responses



Simulated winter U-wind at 850hPa responses



- ES-CS warming indeed alter the NEP atmospheric circulation, with a spatial correlation **0.63** (*p*<0.01) against observations
- ES-CS warming significantly weakens the westerlies over the NE Pacific

Physical processes drive NE Pacific warm events in winter

hypothesis

Arctic warming

East Siberian-Chukchi sea

↓

Alter the NEP atmospheric circulation

High pressure system

↓ HOW？

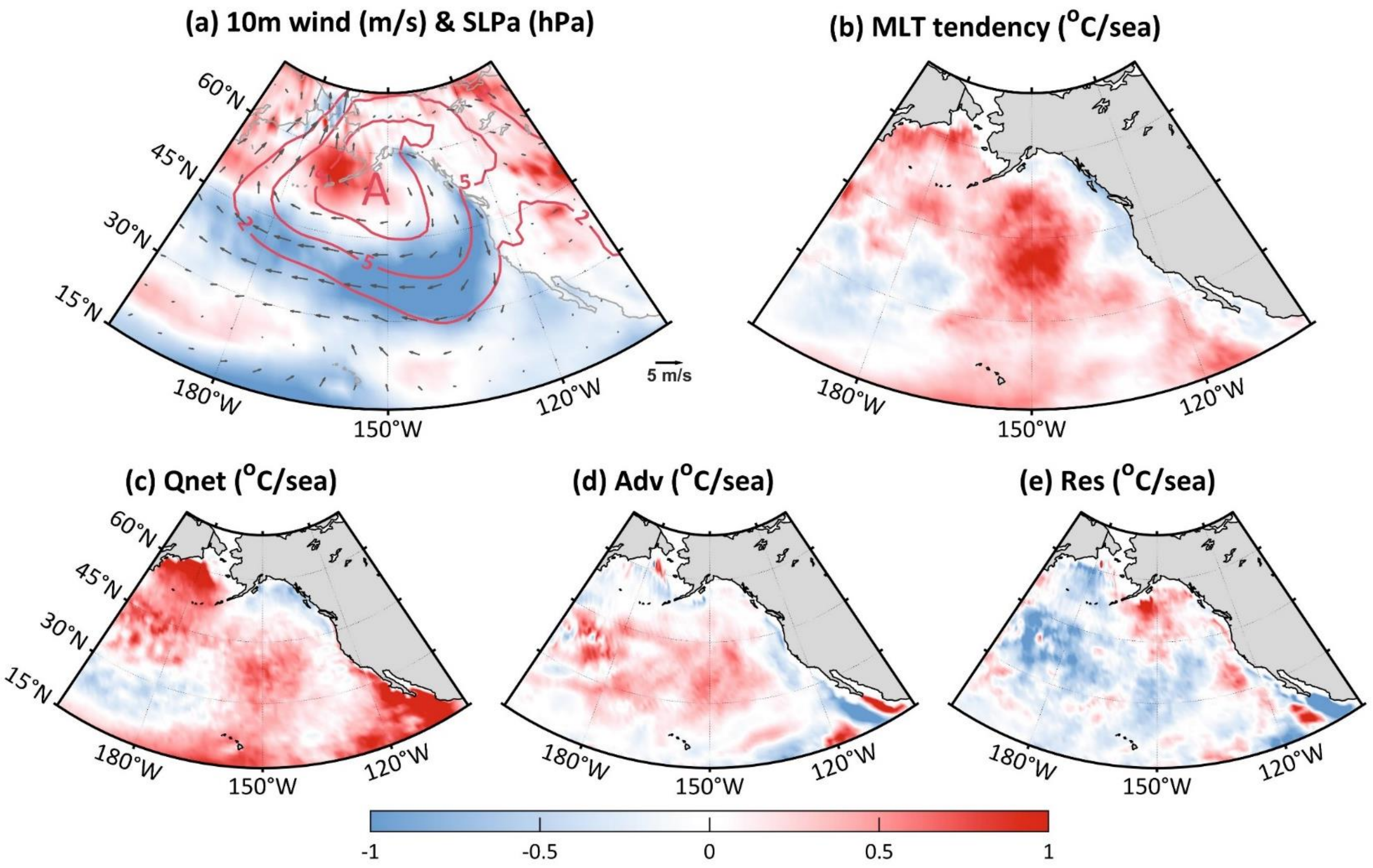
Warm winter SST anomalies in NE Pacific/MHWs

Mixed layer heat budget

$$\frac{\partial T}{\partial t} = \frac{Q}{\rho C_p h} - u_a \cdot \nabla T - \left(w_h + \frac{dh}{dt}\right)\frac{T - T_h}{h} - \frac{\kappa}{h}\frac{\partial T}{\partial z}\bigg|_{z=h}$$

(Cronin et al., 2015)

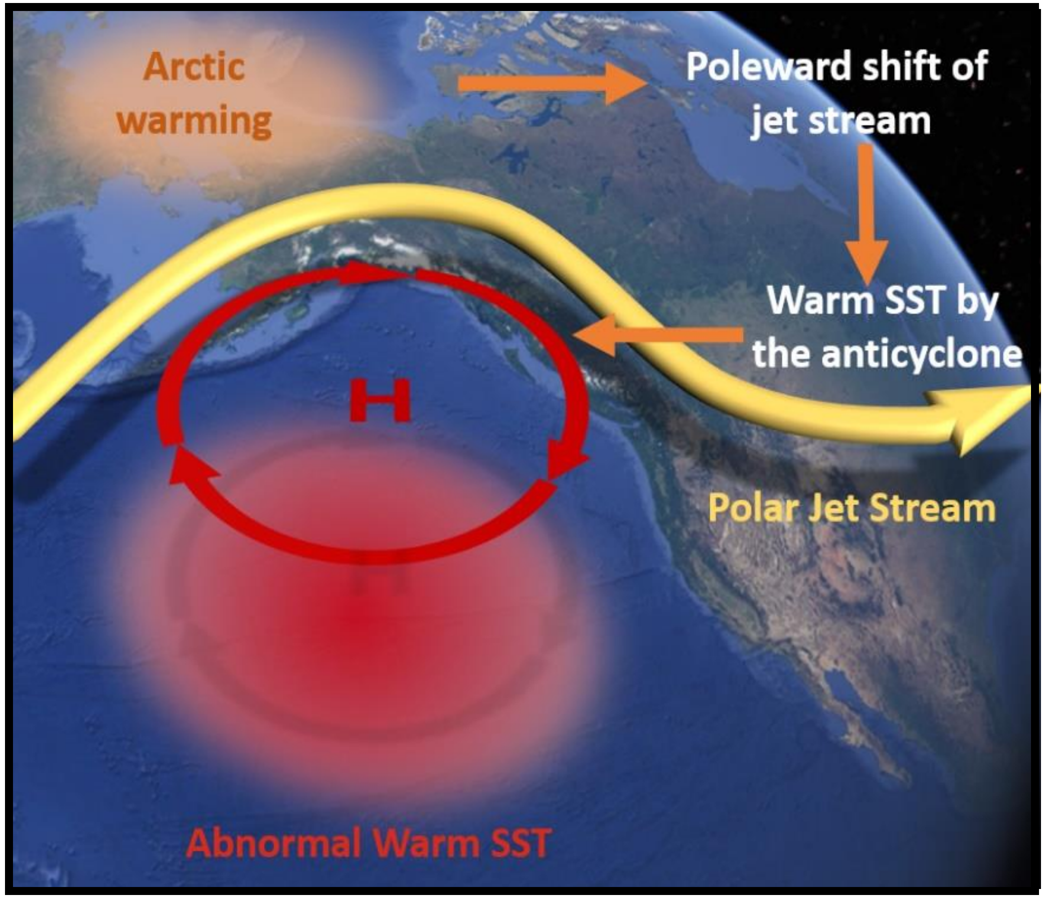
Regression of DJF mixed layer heat budget terms with ES-CS SATa



- **Reduced heat losses by surface fluxes and horizontal advection** were the two dominant processes to the weakened wintertime cooling

Mechanisms of MHWs in the NE Pacific

MHWs caused by Arctic warming



Arctic warming

East Siberian-Chukchi sea

↓

Alter the NEP atmospheric circulation

Anomalous high pressure system

↓

Weakened westerly

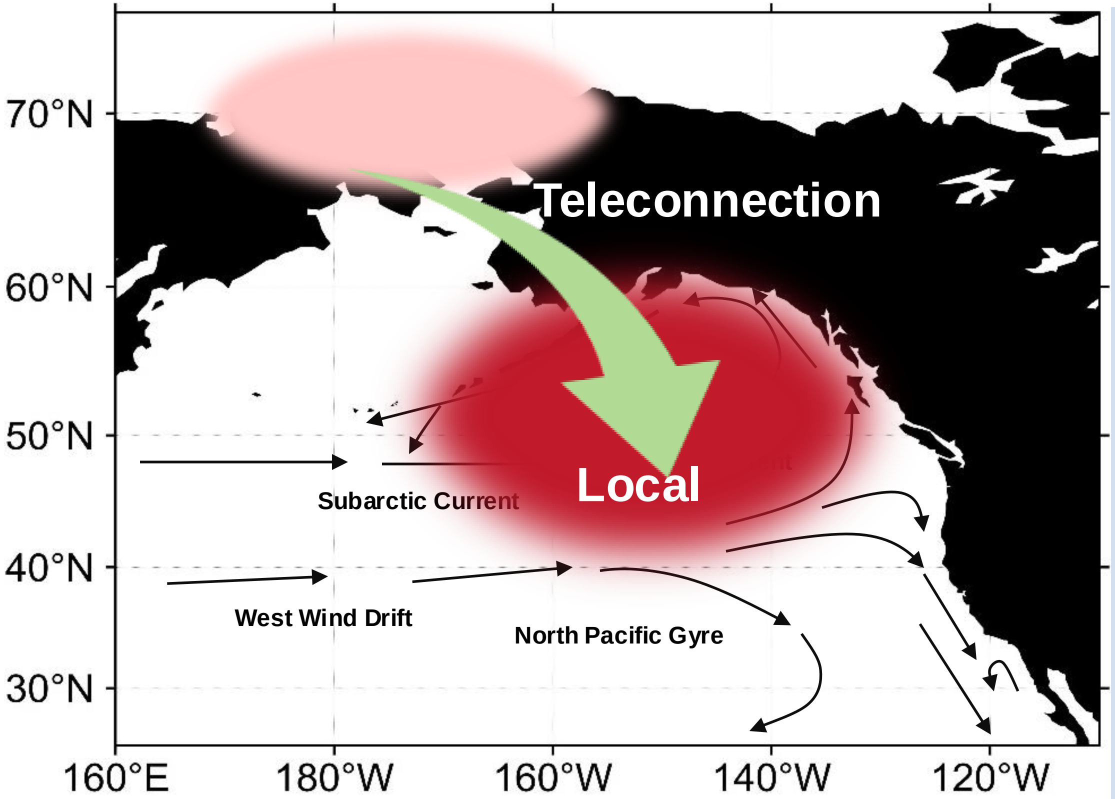
↓

Reduced horizontal advection + Reduced heat loss

↓

Blob-Like SST anomalies

Summary



Take Home Messages

Local processes：

- Reduced heat losses by surface fluxes and horizontal advection were the dominant processes to the Blob
- Wind direction change instead of intensity change is more important *Chen, Wang, Chai et al. 2023, npj CAS*

Teleconnection：

- The ES-CS warming indeed alter NEP atmospheric circulation
- The abnormally high-pressure system weakens the westerlies, thereby reducing the wintertime cooling in the NE Pacific

Chen, Wang, Chai et al. under review, npj CAS

Thank you