U.S. CLIVAR Mesoscale and Frontal-Scale Air-Sea Interactions Workshop, 6 March 2023

An overview of climatic impacts of midlatitude ocean fronts and eddies

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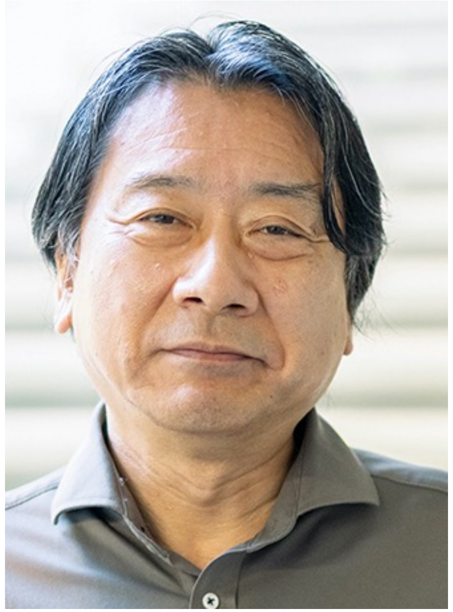

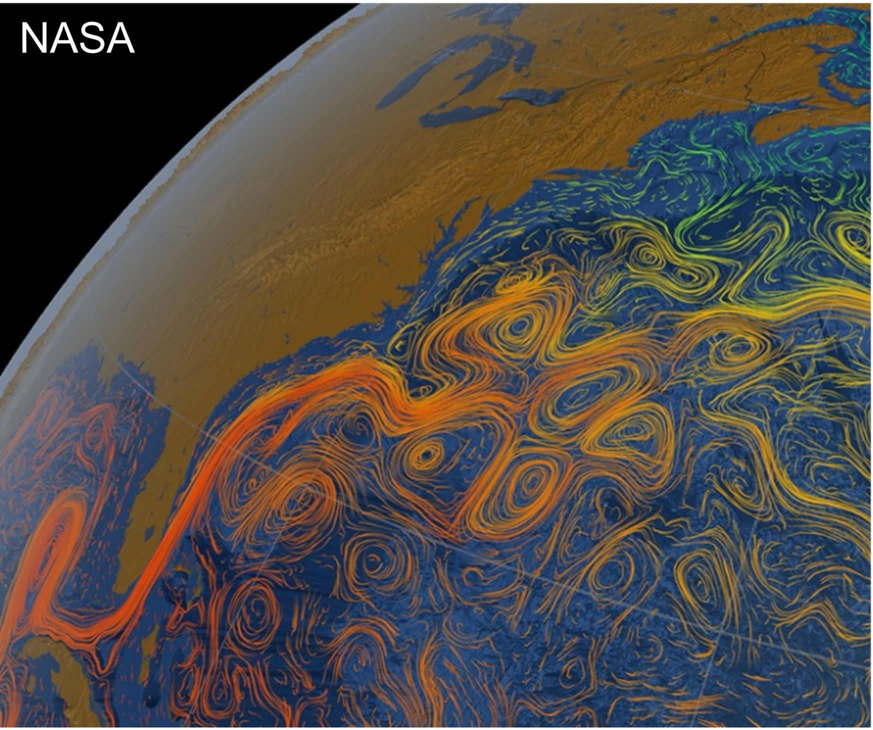
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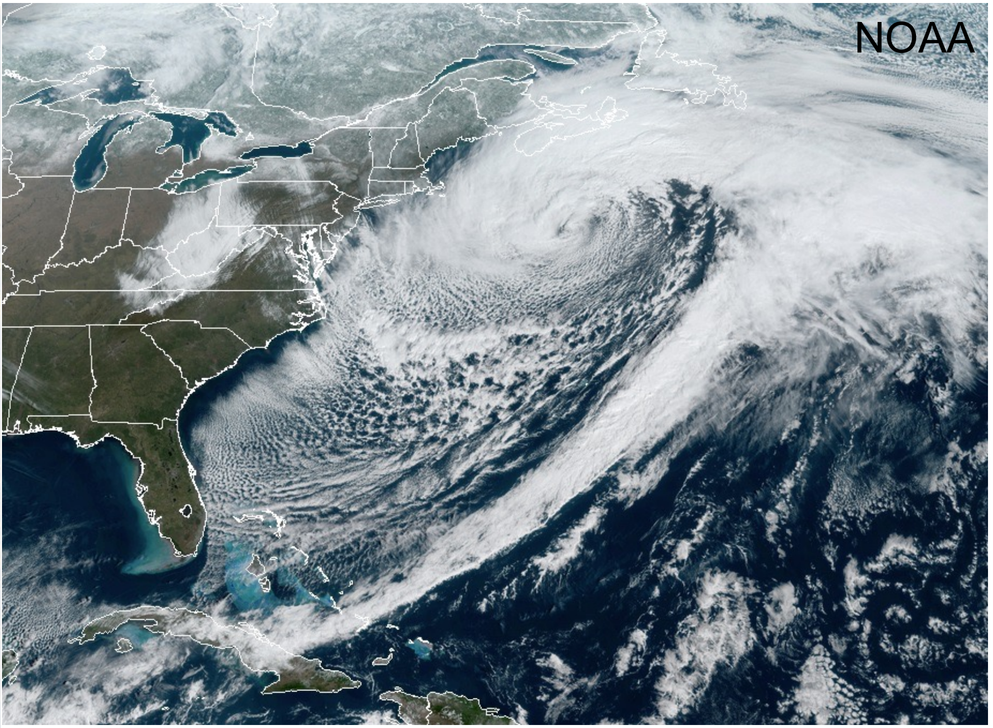
NOAA

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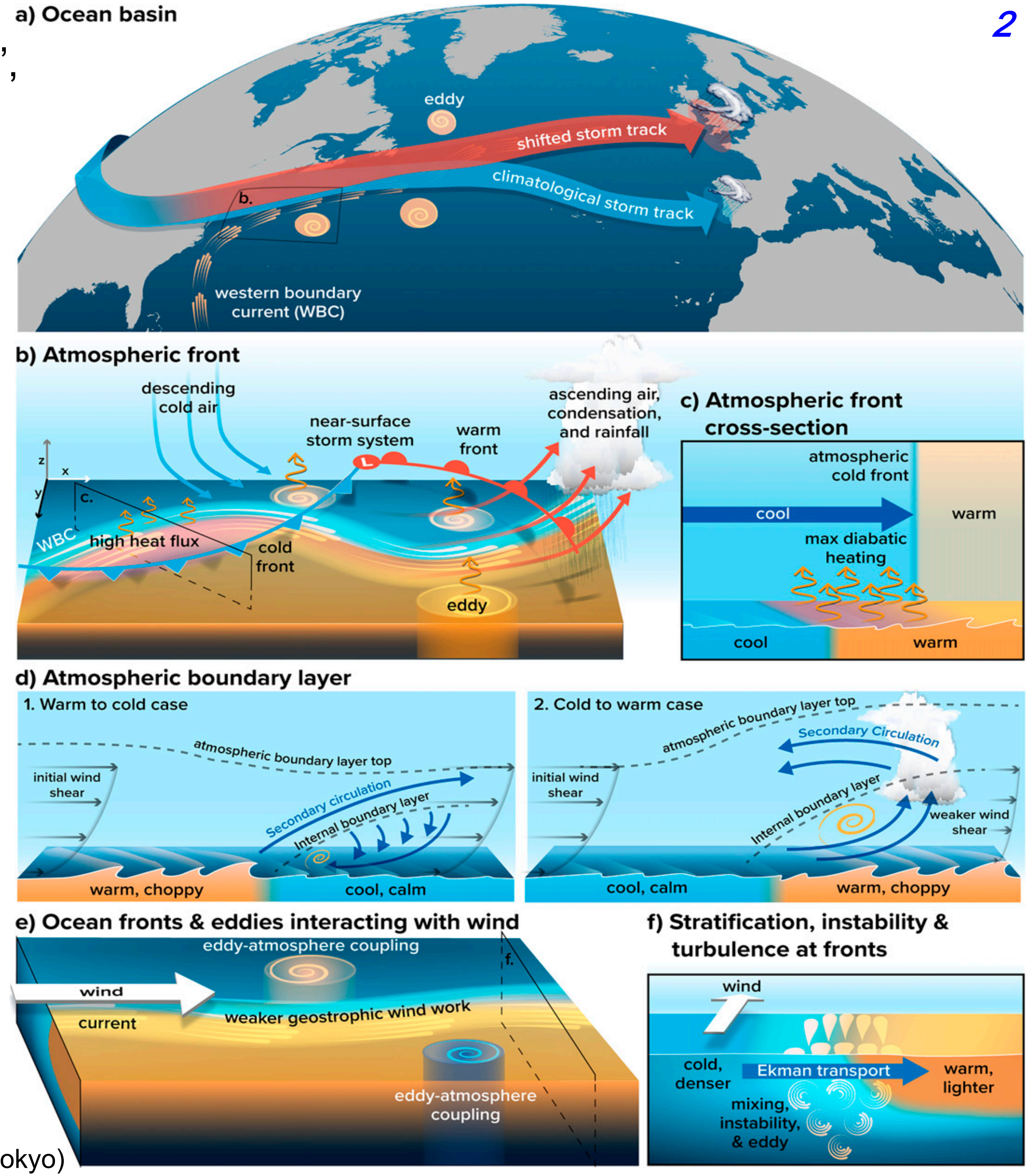
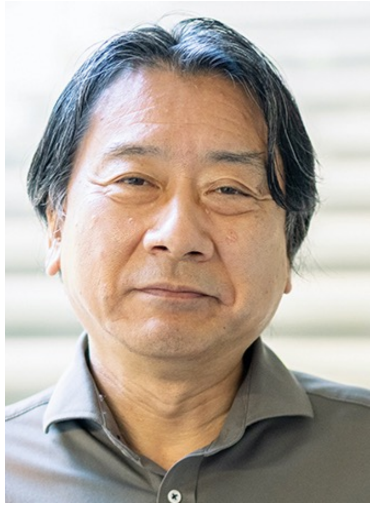
“Ocean Mesoscale and Frontal-Scale Ocean–Atmosphere Interactions and Influence on Large-Scale Climate: A Review”, J. Climate, 2023, U.S. CLIVAR Ocean Mesoscale Air–Sea Interaction WG (Seo et al. 2023)





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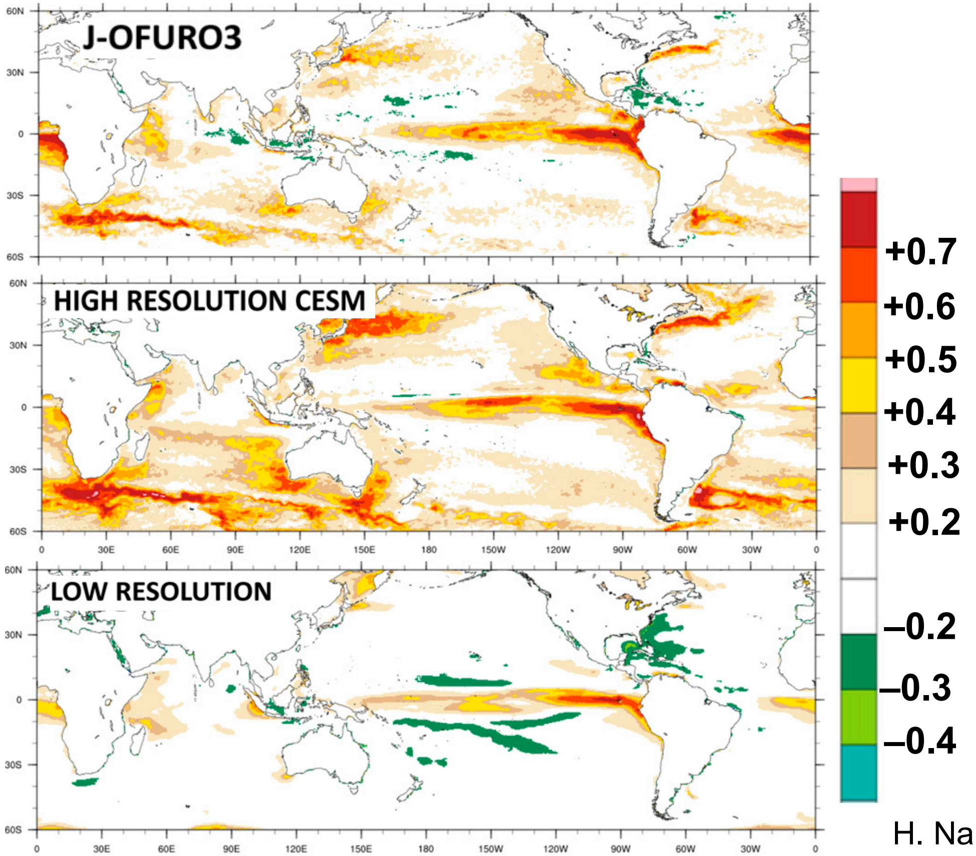
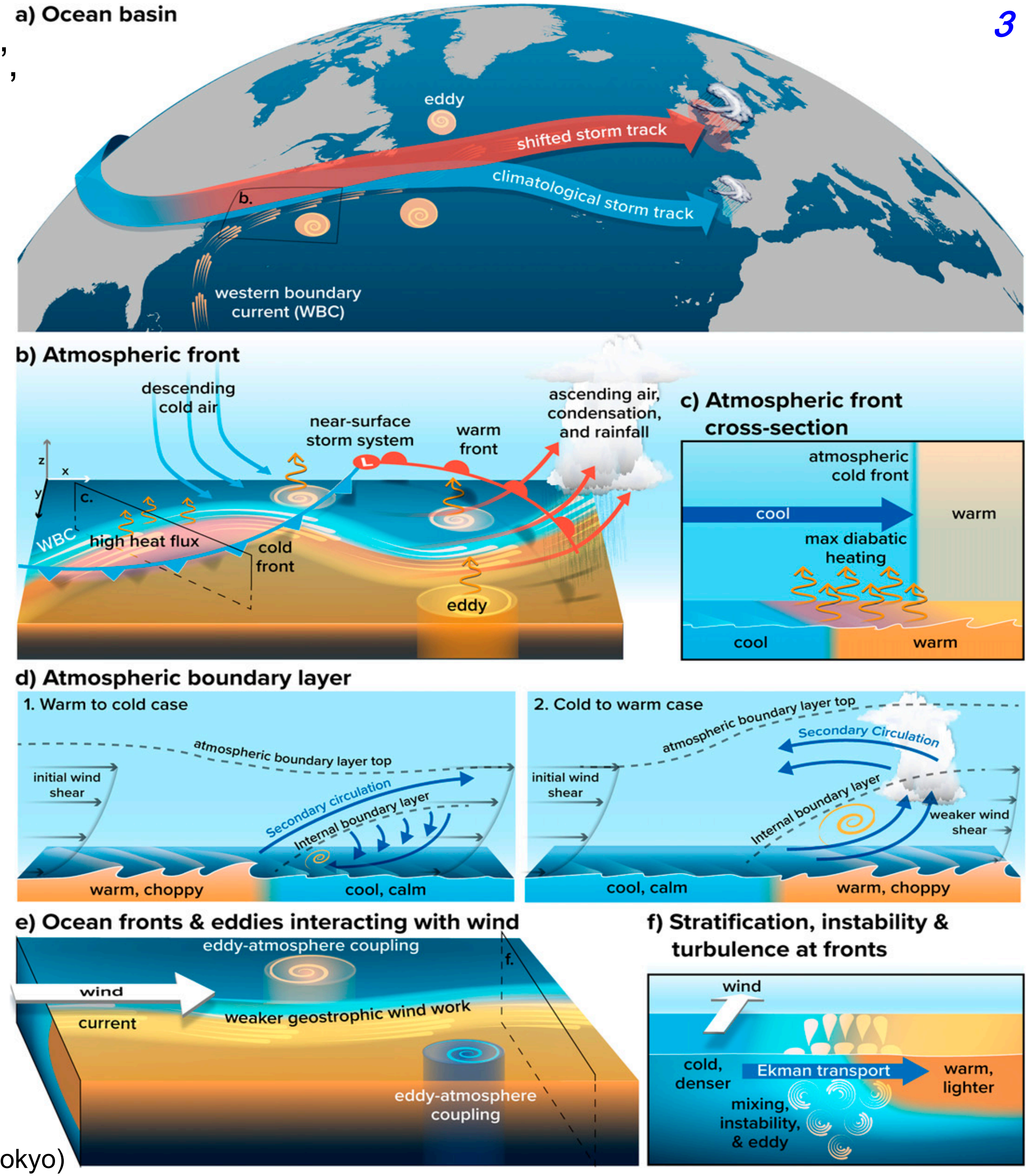
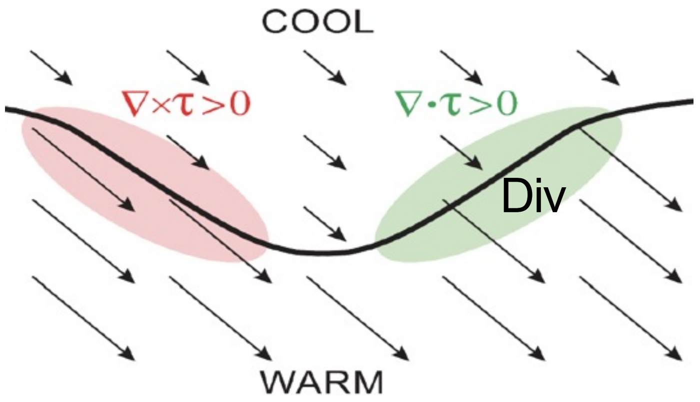
Local correlation between monthly SST and LHF is positive along narrow western-boundary currents and associated SST fronts in the extratropics, suggestive of oceanic thermodynamic forcing on the atmosphere, but low-resolution CGCM fails to reproduce it (Small et al. 2019JC).





Surface wind and pressure response to SST front

surface wind response to a meandering SST front



Chelton et al. (2004)

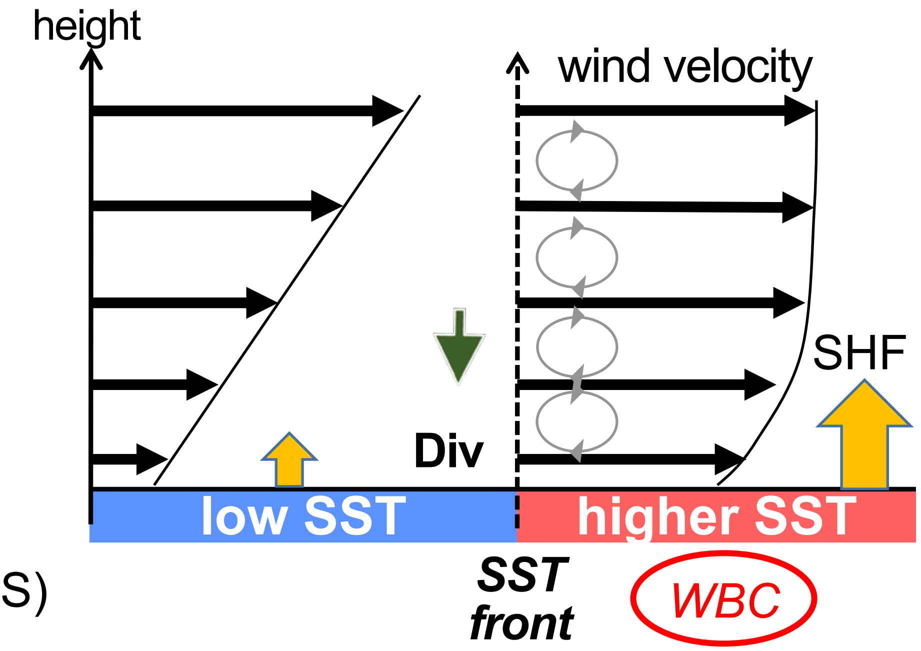
Vertical mixing

(Wallace et al. 1989; Hayes et al. 1989)

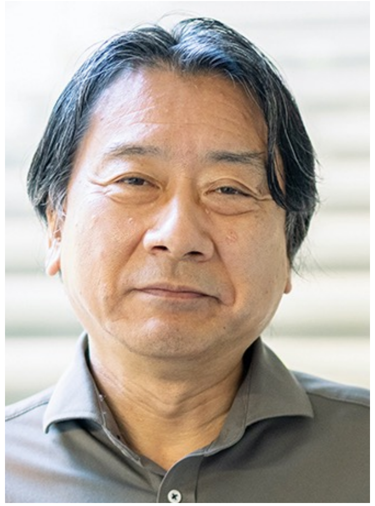
Warm SST destabilizes MABL

→ enhanced downward transport of wind momentum by turbulence

→ surface airflow accelerated in crossing from cool to warm SST



Comprehensive analysis by Schneider & Qiu (2015JAS) and Kilpatrick et al. (2014JC, 2016JAS)



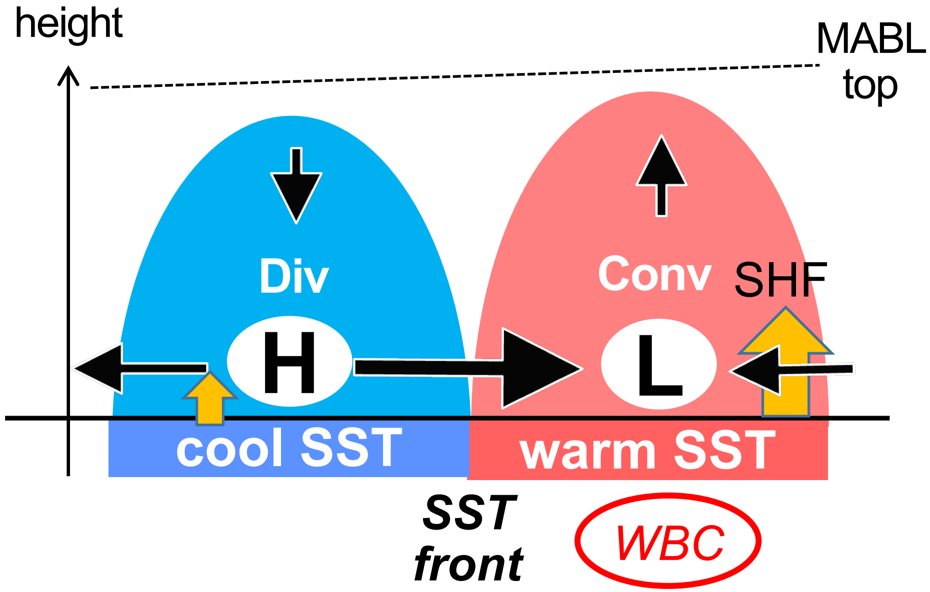
Surface wind and pressure response to SST front

Pressure adjustment
(Lindzen & Nigam 1987)

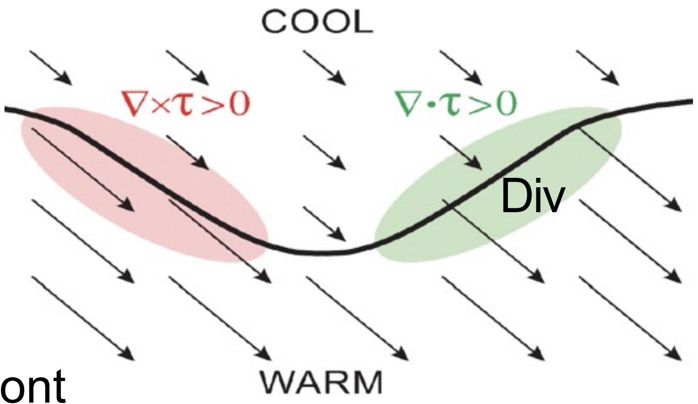
Warm SST heats MABL

→ lowered SLP induces surface wind convergence and ascent aloft

effective for cool airflow parallel to the front



surface wind response to a meandering SST front



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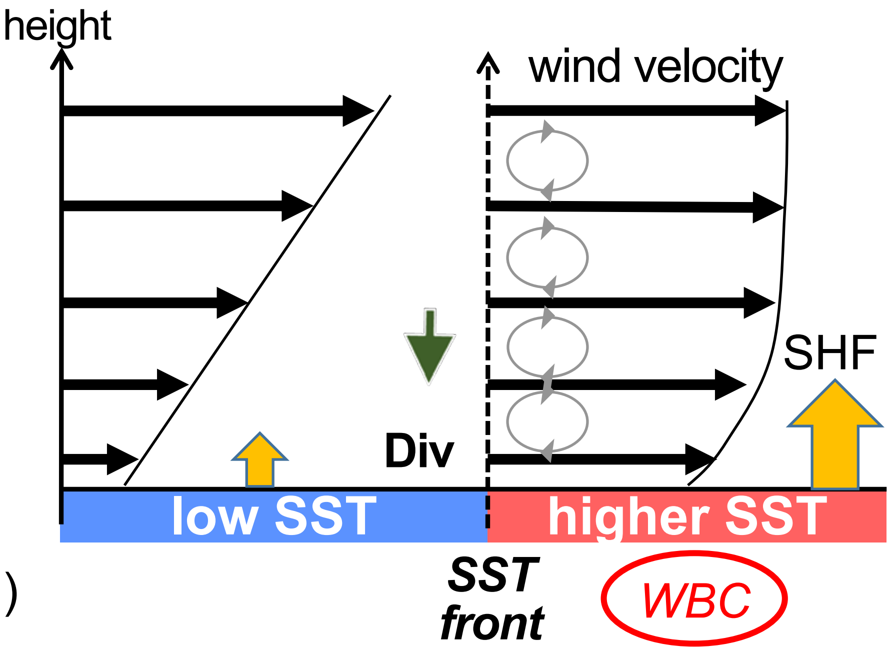
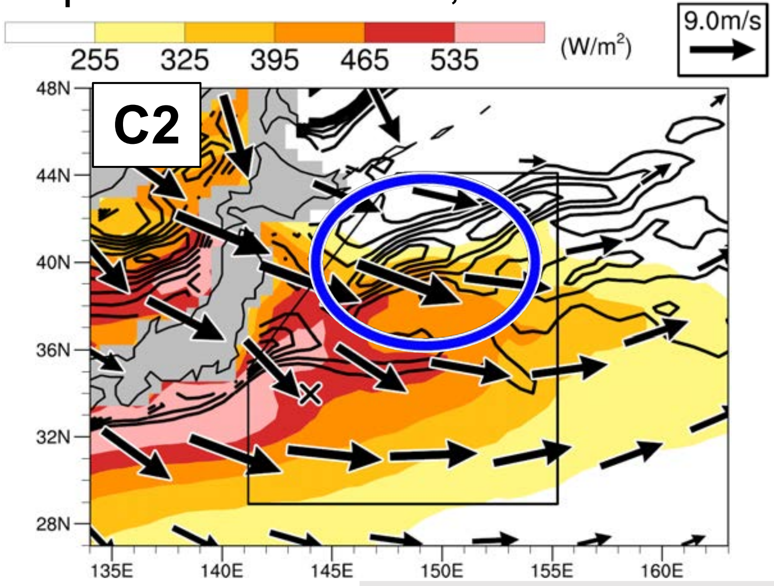
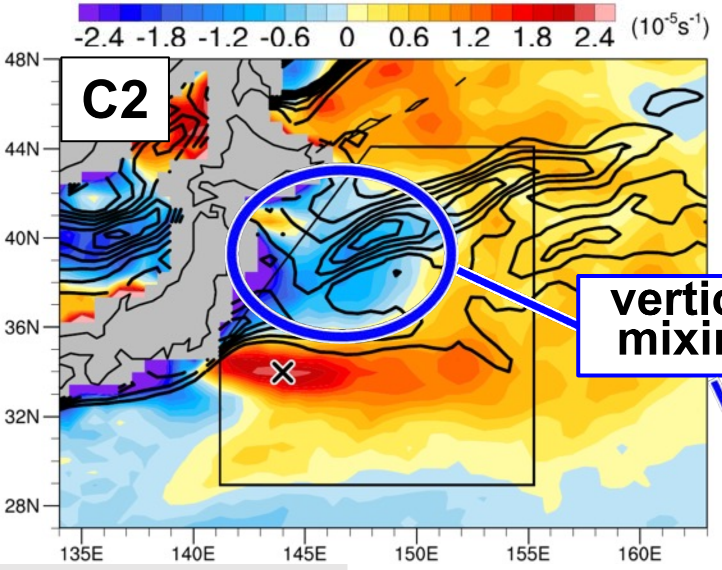


Surface conv./div. in KOE under the enhanced winter monsoon

composited **SHF+LHF**, **surface wind**

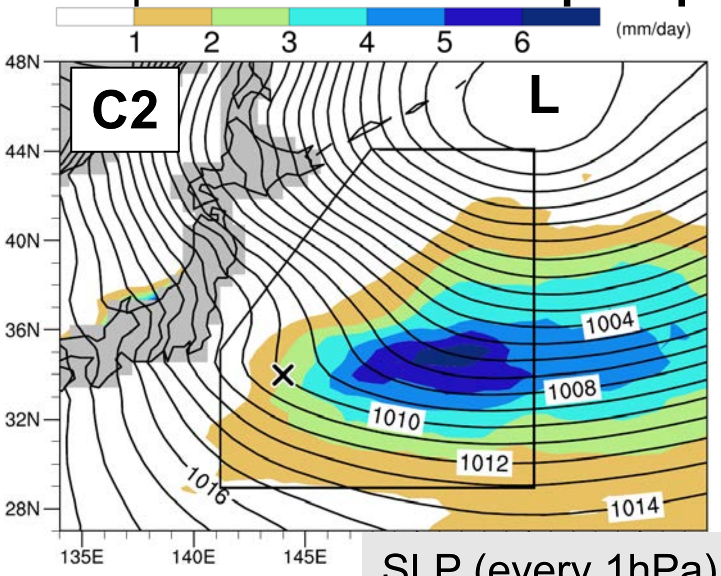


composited surface wind Div./Conv.



contour: SST gradient (0.5, 1., … K/100km)

composited **convective precip.**

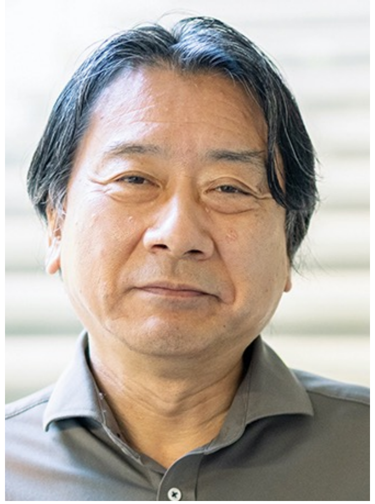


SLP (every 1hPa)

vertical mixing

divergence along the Oyashio front

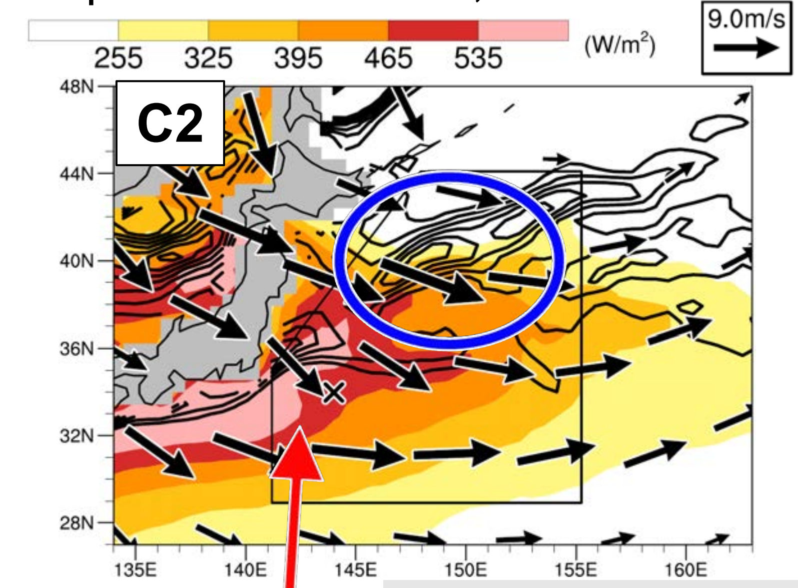
The monsoonal northwesterlies undergo acceleration in crossing the front into the warmer water due to enhanced downward wind momentum transport by turbulence



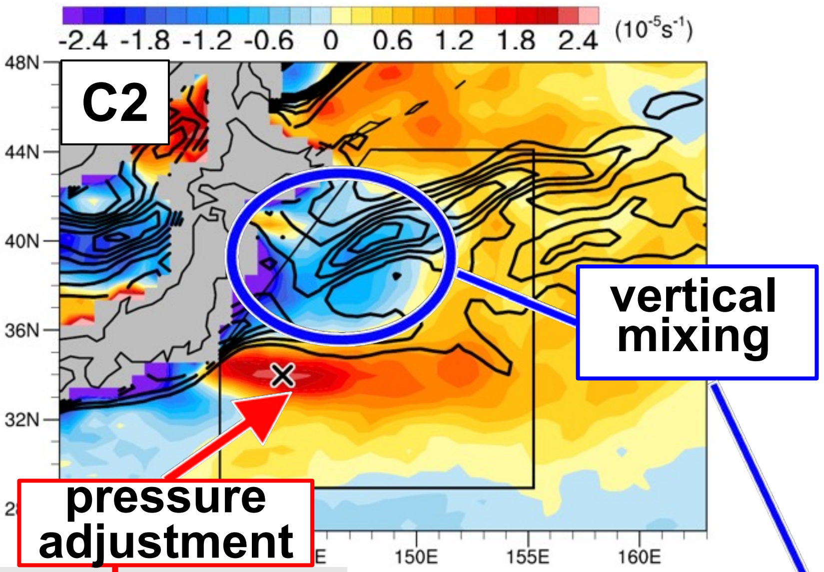
Masunaga et al. (2020a JC)

Surface conv./div. in KOE under the enhanced winter monsoon

composited **SHF+LHF**, **surface wind**



composited surface wind Div./Conv.

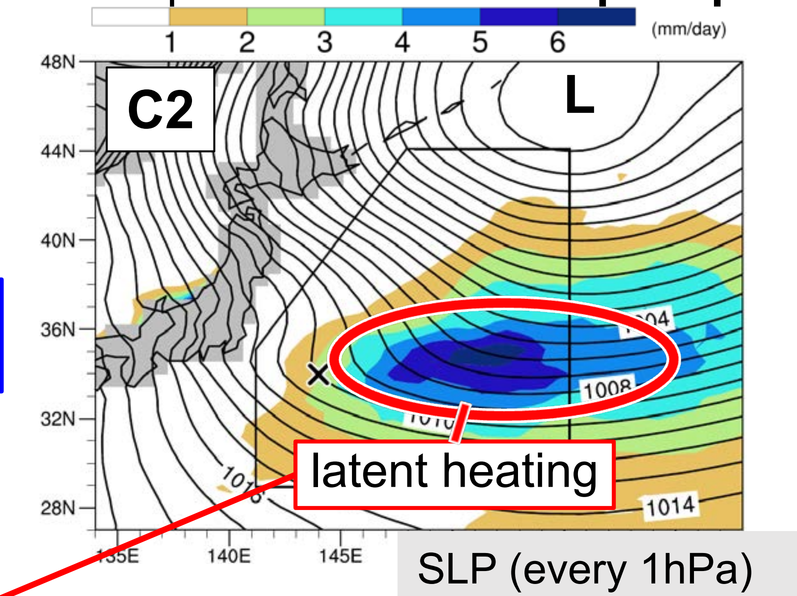


vertical mixing

pressure adjustment

contour: SST gradient (0.5, 1., … K/100km)

composited **convective precip.**



latent heating

SLP (every 1hPa)

convergence along the KE (Kuroshio Extension)

1. The monsoonal airflow is more or less parallel to the KE front and undergoes warming due to **enhanced heat release from the warm KE.**
2. The effective pressure adjustment mechanism leads to surface conv. and ascent, which is reinforced by **shallow convective precipitation** organized along the KE front.
3. These processes are associated with **atmospheric frontogenesis anchored by the KE front**.

divergence along the Oyashio front

The monsoonal northwesterlies undergo acceleration in crossing the front into the warmer water due to enhanced downward wind momentum transport by turbulence

Masunaga et al. (2020a JC)

Time-mean influence of GS front on the boundary layer and free troposphere

Pressure adjustment
(Lindzen & Nigam 1987)

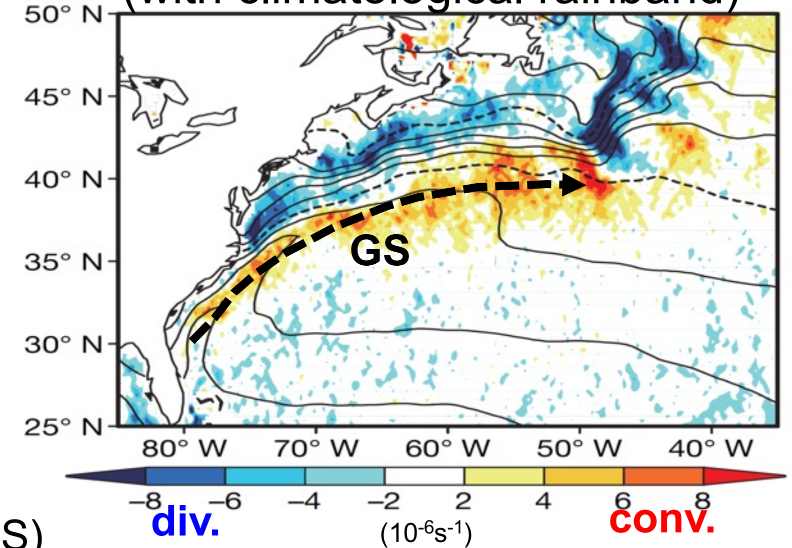
Warm SST heats MABL

→ Lowered SLP induces surface wind convergence and ascent aloft as boundary-layer response

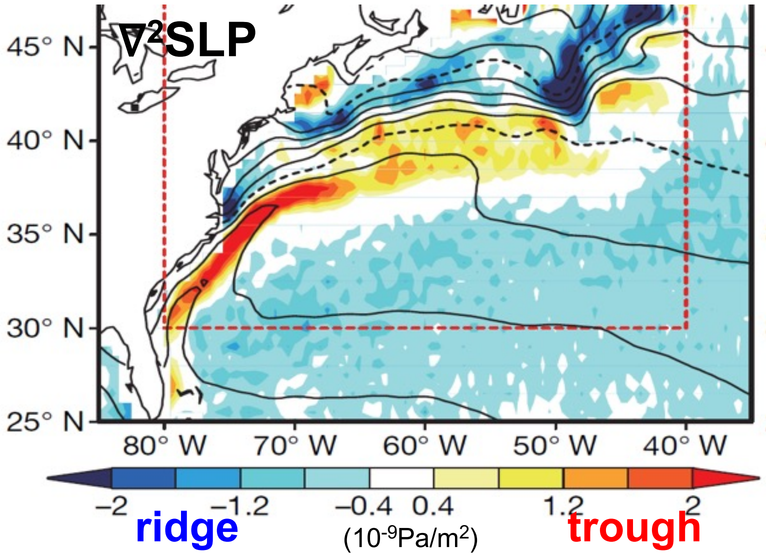
→ favorable for organizing convective precipitation systems as free-tropospheric response

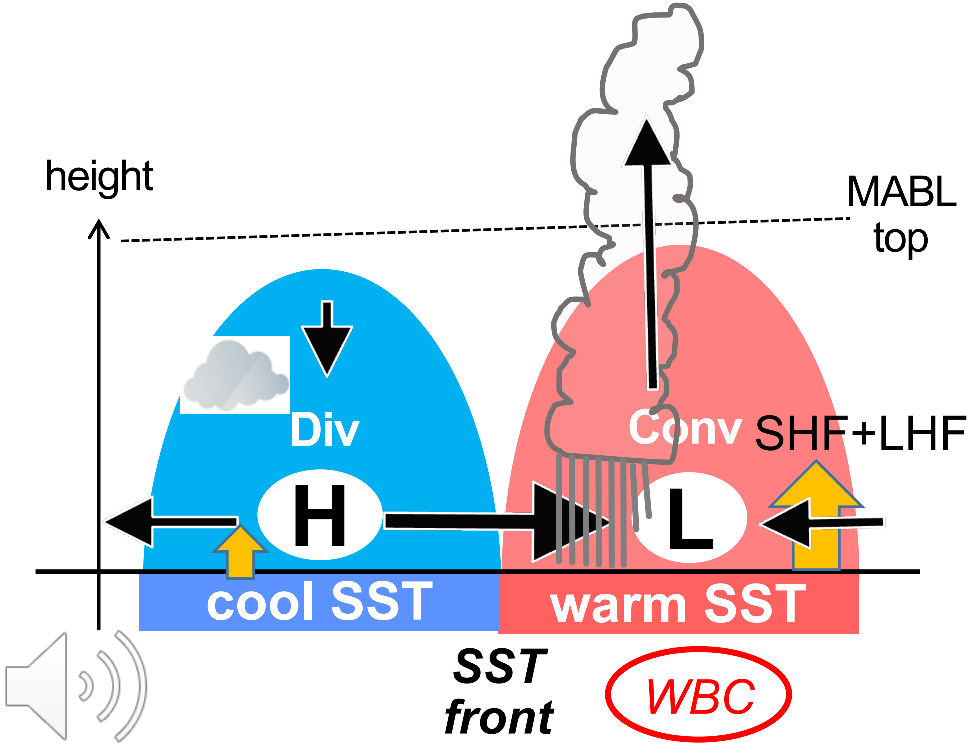
→ Diabatic heating reinforces ascent and surface convergence; also can influence storm activity and large-scale circulation

surface wind conv. along GS
(with climatological rainband)

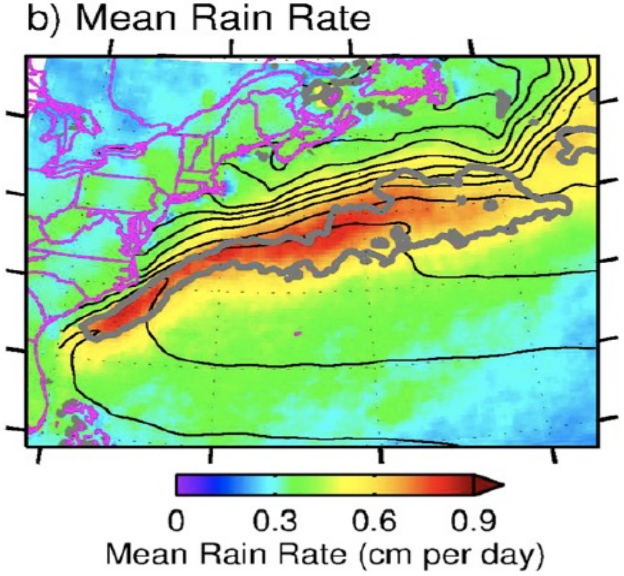


Minobe et al. (2008 Nature), Kuwano-Yoshida et al





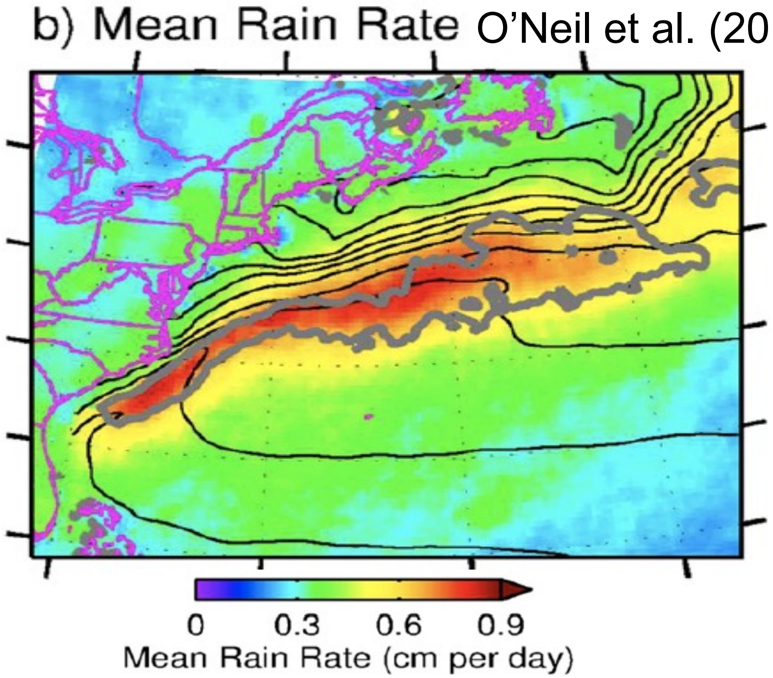
O'Neill et al. (2017 JAS)



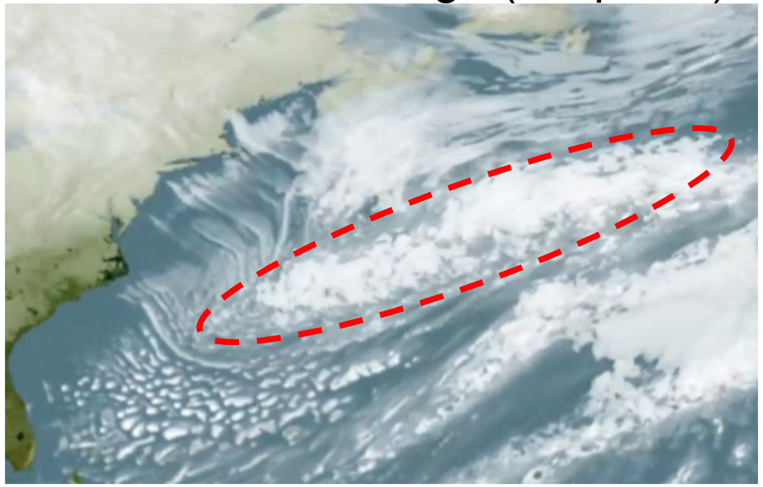
Role of transient eddies in shaping mean surface conv./div.

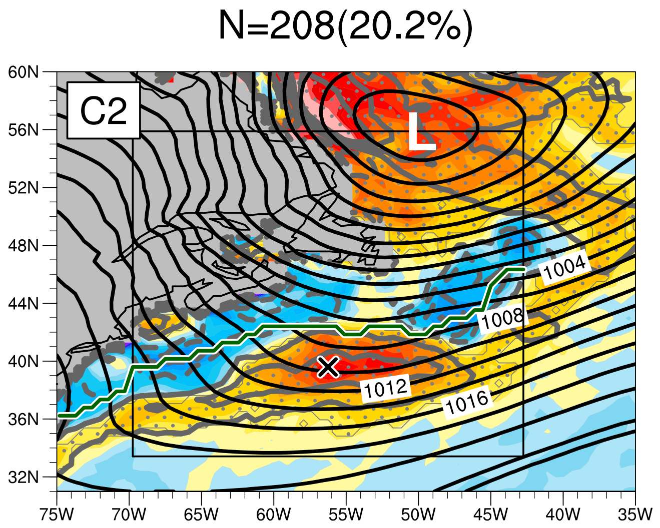
annual-mean climatology (satellite)

O'Neil et al. (2017 JAS)



Satellite image (snapshot)





Cluster #2 for moderate surface convergence (red) events (Masunaga et al. 2020b JC)

- **Climatological surface convergence and ascent as well as precipitation band along the GS cannot be interpreted without considering contributions of transient disturbances**, i.e., cyclones and fronts (Parfitt & Czaja 2016QJ; O'Neill et al. 2017JAS; Plougonven et al. 2018; Rousseau et al. 2021JC)
- Enhanced heat and moisture supply from the GS behind a cyclone and main cold front are important (Vanniere et al. 2017QJ; Masunaga et al. 2020b JC)
- Frontal SST gradient associated with the GS is favorable for atmospheric fronts to be enhanced or stagnated (Parfitt et al. 2015, 2017GRL; Masunaga et al. 2020b JC; c.f., Reeder et al. 2021JAS)

Stormtracks and eddy-driven surface westerlies along oceanic frontal zones in the wintertime Northern Hemisphere

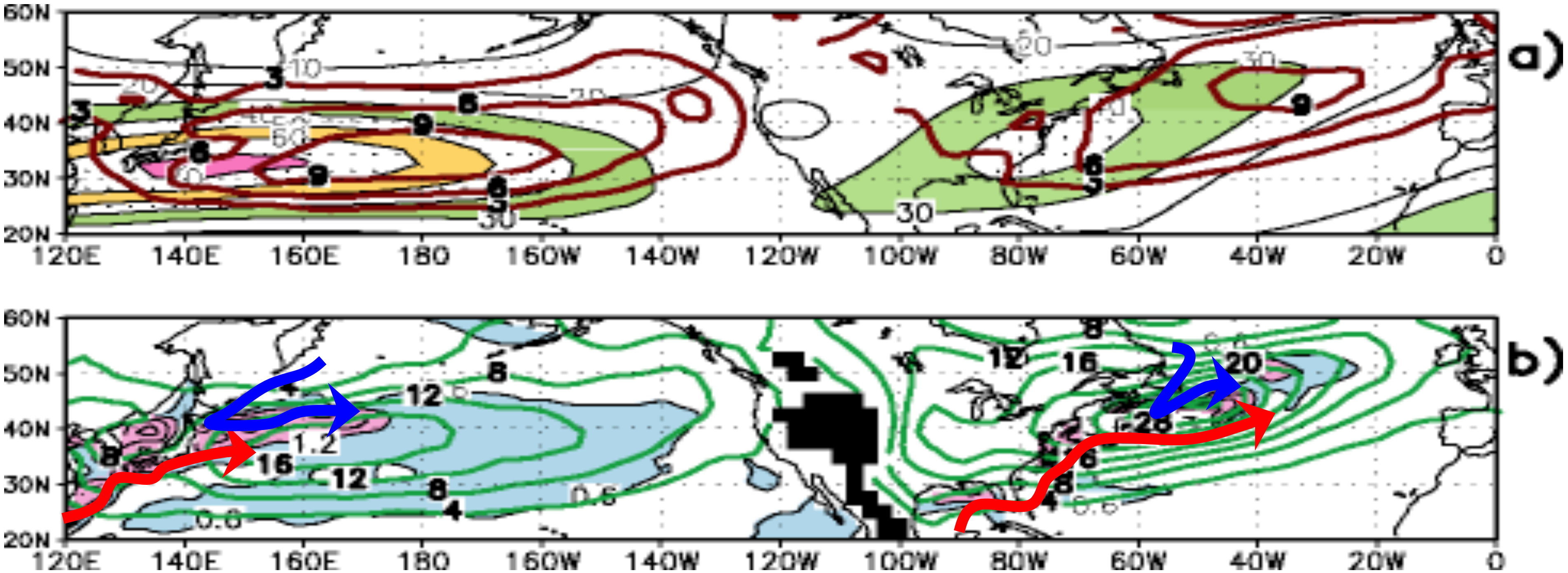
Nakamura et al. (2004, AGU Geophys. Monogr.)

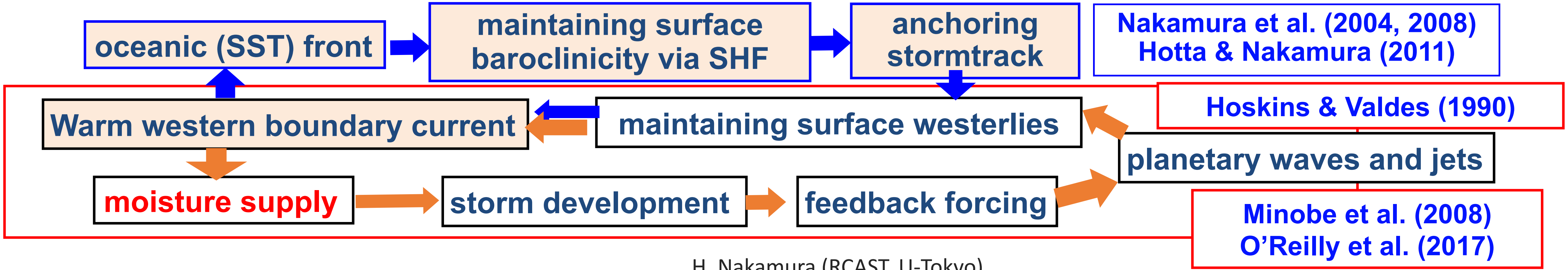
250-hPa *U*

925-hPa *U*

850-hPs *v' T'*

SST front





oceanic (SST) front → maintaining surface baroclinicity via SHF → anchoring stormtrack

Nakamura et al. (2004, 2008)
Hotta & Nakamura (2011)

Warm western boundary current ← maintaining surface westerlies

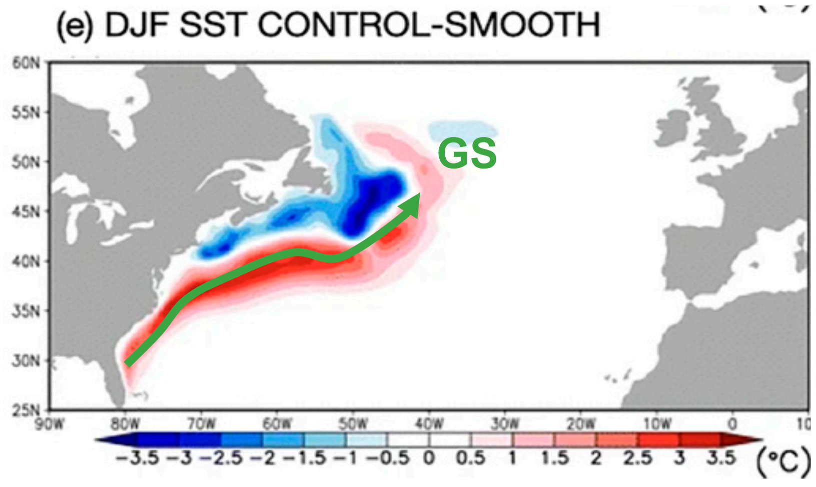
Hoskins & Valdes (1990)

planetary waves and jets

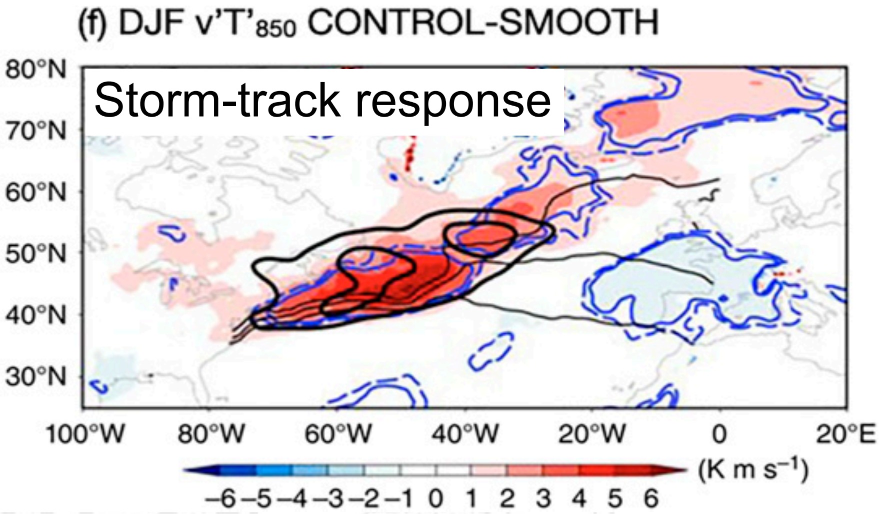
moisture supply → storm development → feedback forcing

Minobe et al. (2008)
O'Reilly et al. (2017)

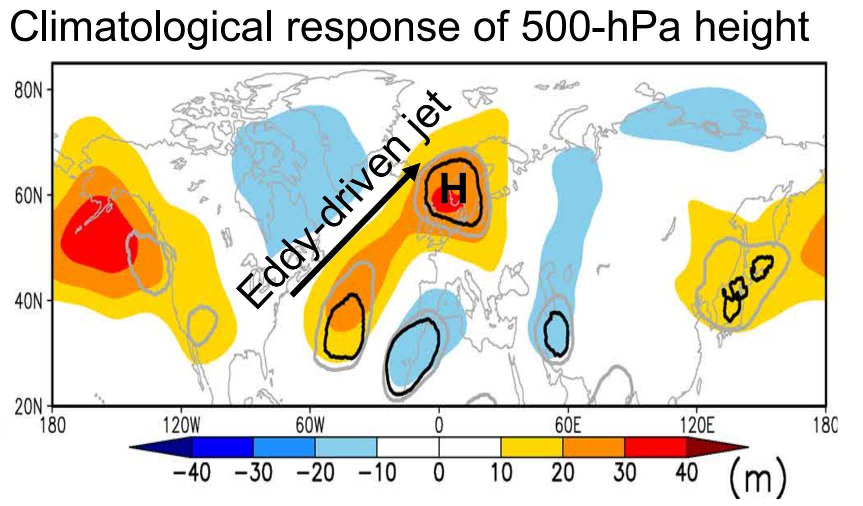
Storm-track and large-scale circulation response to SST front along the GS



(e) DJF SST CONTROL-SMOOTH



(f) DJF v'T'850 CONTROL-SMOOTH

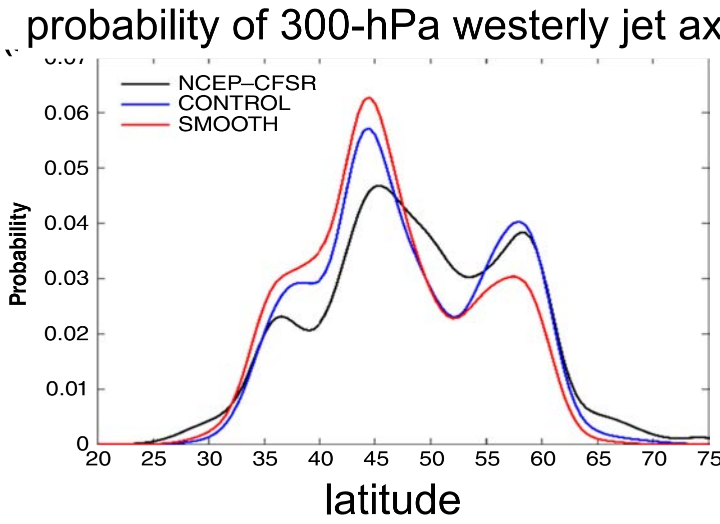


Climatological response of 500-hPa height

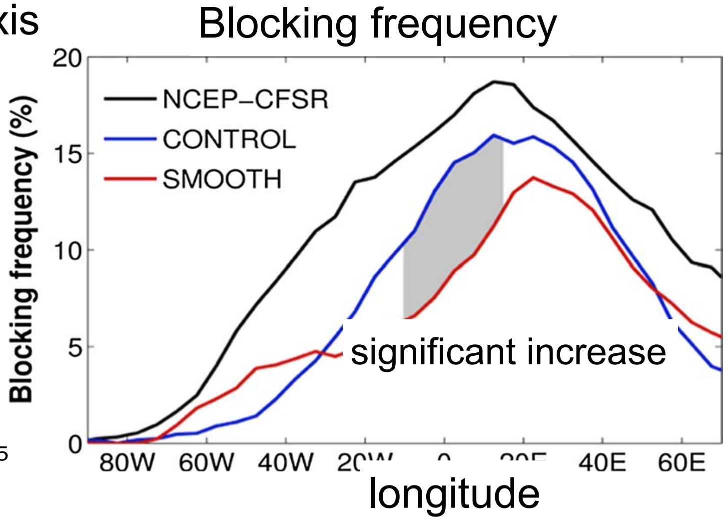
O'Reilly et al. (2016CD; 2017QJ)

AGCM (~50km) experiments with realistic GS front (CNTL) and smoothed SST gradient (SMTH)

- SST front along the GS climatologically enhances storm-track activity.
- Energized transient eddies maintain eddy-driven North Atlantic jet via momentum flux convergence, to increase likelihood of its northeastward deflection as in positive NAO.



probability of 300-hPa westerly jet axis



Blocking frequency

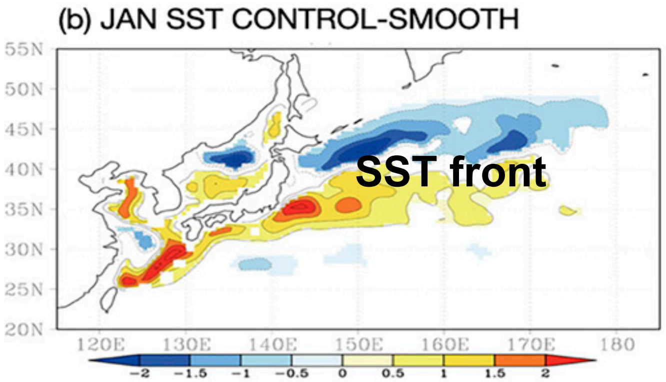
- Enhanced storm-track activity also maintains a planetary-wave pressure ridge over Europe, leading to significant increase in blocking-high formation closer to its observed frequency.

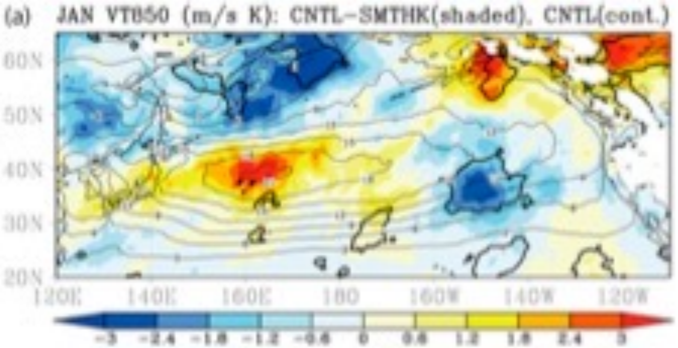
➔ Realistic GS representation in high-resolution climate models leads to better reproduction of atmospheric mean state and variability, as confirmed by PRIMAVREA/HighResMIP project (Athanasiadis et al. 2022JC)

Storm-track and large-scale circulation response to western Pacific SST front

- As in the North Atlantic, AGCM simulations extract impact of frontal SST gradient in the KOE region on storm-track activity and westerlies (Kuwano-Yoshida & Minobe 2017JC; Omrani et al. 2019SRep.)
- KOE SST front climatologically enhances storm-track activity in winter, and energized transient eddies act to reinforce the eddy-driven jet through momentum flux convergence and increase likelihood of its northeastward deflection downstream.

50km AGCM simulations by Kuwano-Yoshida & Minobe (2017JC)

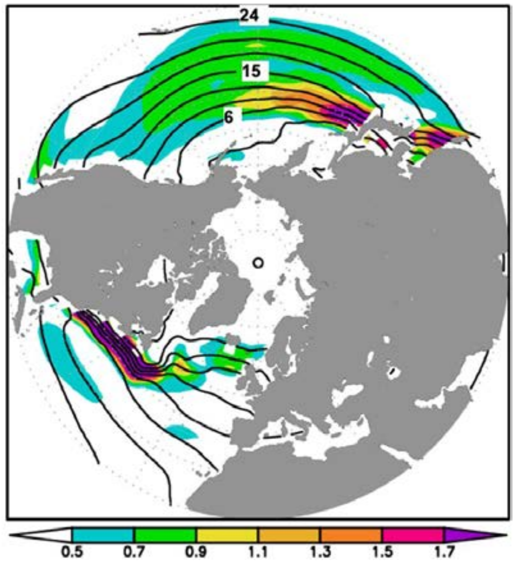




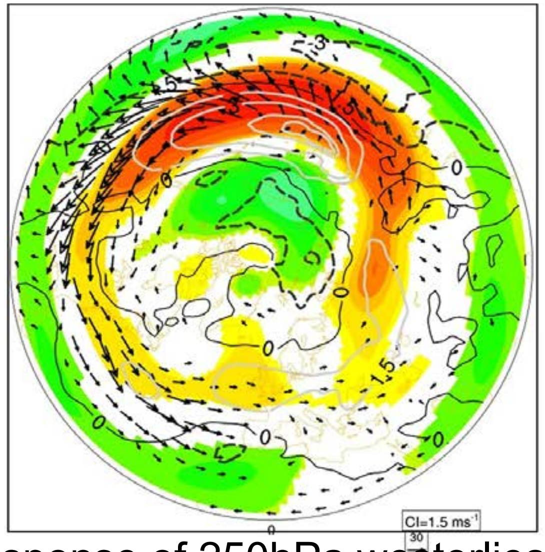
850hPa poleward eddy heat flux (contour) and its response (color)

- Tropospheric response to N. Pacific SST front enhances upward propagation of planetary waves, acting to weaken the polar-night jet and cold polar vortex in the Arctic stratosphere (Omrani et al. 2019SRep.).

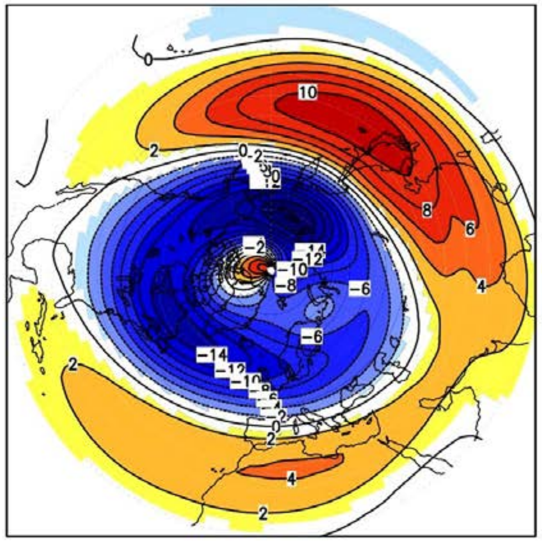
high-top AGCM simulations by Omrani et al. (2019 S.Rep.)



SST (contour) and its gradient (red: SST front)



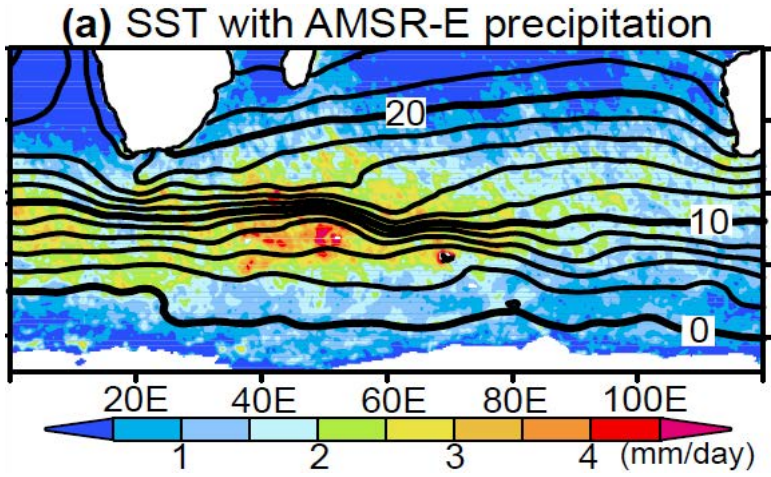
Response of 250hPa westerlies (red: enhanced) and storm-track activity (E-vectors) to Pacific SST front



Response of 50hPa westerlies (blue: weakened) to Pacific SST front

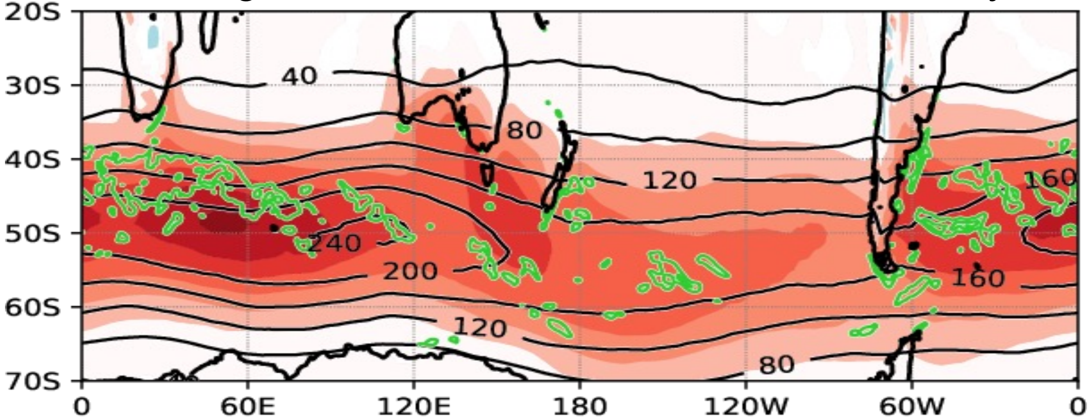
Storm-track and large-scale circulation response to SH SST fronts

- Compared to its NH counterpart, midlatitude SST front is more zonally extended over SH, with its core region along the Agulhas Return Current in the S. Indian Ocean, collocated with the storm-track core and rainband (Nakamura & Shimpo 2004JC, Nakamura et al. 2008GRL).
- AGCM simulations suggest that the SST front acts to enhance storm-track activity and thereby maintain deep eddy-driven westerly jet around 50ºS, making the southern ocean stormy (Nakamura et al. 2008GRL;.Miyamoto et al. 2022JC).
- AGCM simulations also suggest that the SST front may be essential for reproducing SAM, wobbling of the eddy-driven jet (Nakamura et al. 2008GRL; Sampe et al. 2010JC; Ogawa et al. 2015GRL, 2016JC) as well as BAM, hemispheric pulsing of storm-track activity (Nakayama et al. 2021, 2023JC).
- Ocean-atmosphere coupling may be important for BAM periodicity (Xue et al. 2021JGR) as well as for future poleward shift of summertime SH storm-track (Chemke 2022 NatureCom).



Nakamura et al. (2008GRL)

Climatological summertime SH storm-track activity and **SST front axis**



300-hPa EKE (contour, m^2/s^2)

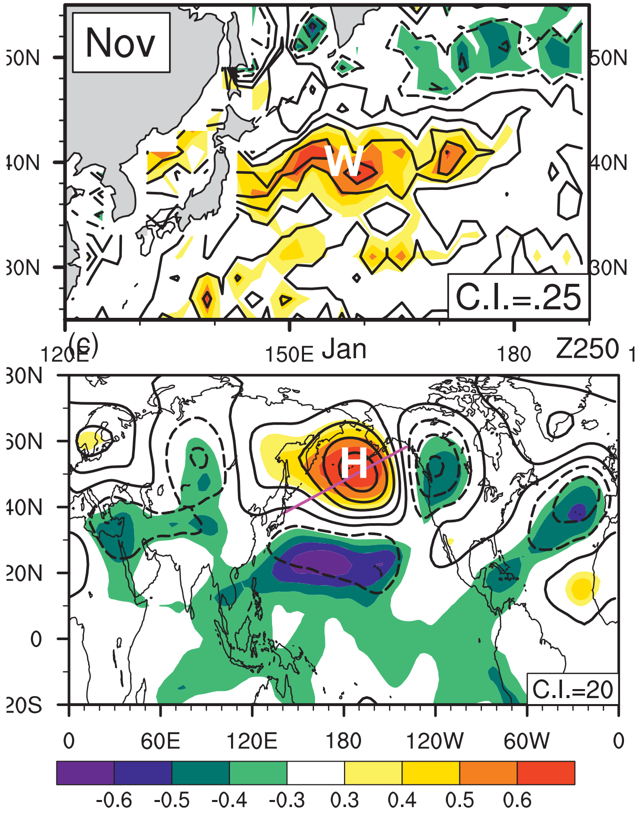
850-hPa poleward heat flux (color)

Nakayama et al. (2023JC)

Storm-track and large-scale circulation response to SST-front variability in KOE

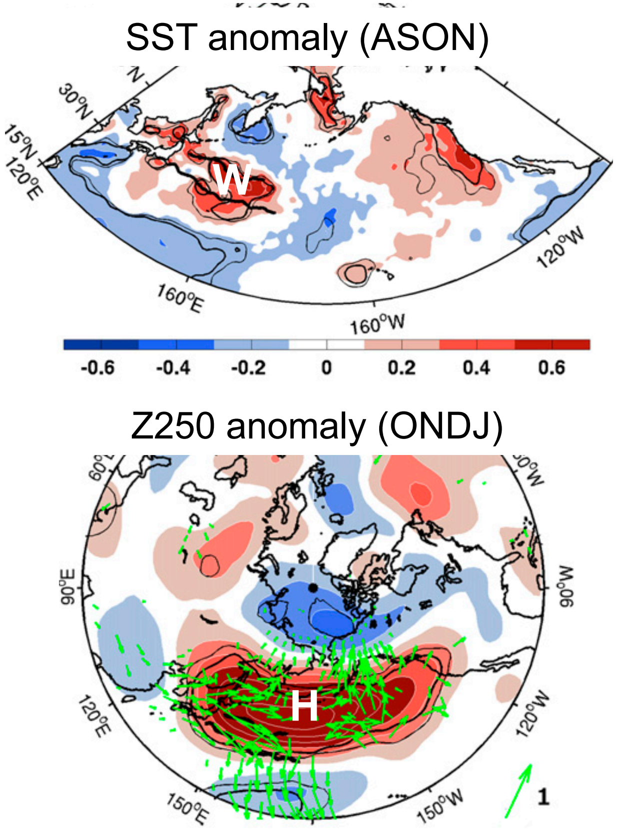
- Atmospheric response to persistent SST anomalies due to ocean front variability may be a key for PDO (Newman et al. 2016JC). Warm SST anomalies due to poleward-shifted Subarctic or KE front with enhanced heat and moisture supply tend to induce anticyclonic response downstream by modulating storm-track activity (Taguchi et al. 2012JC; Revelard et al. 2016JC).

Poleward-shifted subarctic front
→ PNA-like anticyclone response



Regression/correlation analysis by Taguchi et al. (2012JC)

Poleward-shifted KE front
→ NPO-like anticyclone response



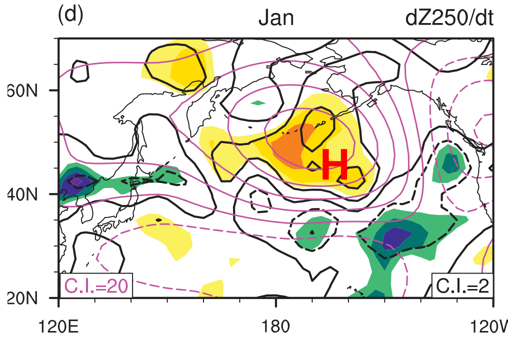
Composite analysis by Revelard et al. (2016JC)

- Tropospheric response to North Pacific SST anomalies can modulate upward propagation of planetary waves, to influence Arctic stratosphere (Hurwitz et al. 2012JGR; Revelard et al 2016JC).
- Tropospheric response to cool SST anomalies due to equatorward shift of KE front is weaker and not symmetric to that to warm SSTA (Revelard et al 2016JC).
- Similar nonlinear features are also found in the atmospheric response to the meridional shift of the GS (Seo et a.l 2017JC).

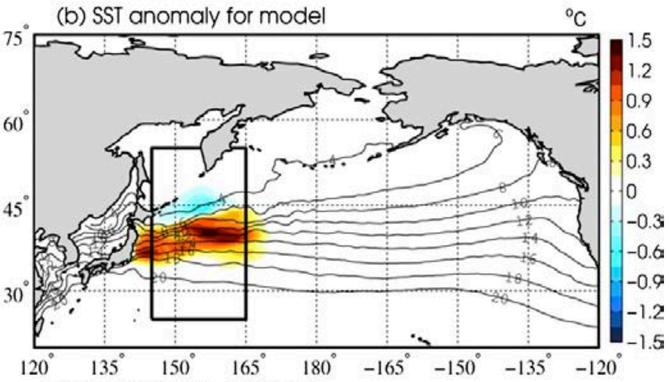
Model-resolution sensitivity of atmospheric response to frontal SST anomalies

- Decadal-scale poleward shift of the subarctic SST front in the KOE region tends to be observed with a PNA-like anticyclonic response in midwinter with poleward-shifted storm-track activity (Taguchi et al. 2012JC).
- A high-resolution (0.25º) AGCM can reproduce this response because of realistic representation of transient eddies along poleward shifted storm-track, but its lower-resolution (1º) version cannot because near-surface heating anomaly is balanced unrealistically with cold advection by anomalous northerlies (Smirnov et al. 2015JC).
- Consistent with recent studies showing importance of a high-resolution model in reproducing moist processes in cyclones (Booth et al. 2012MWR, Willison et al. 2013JAS).

observed Jan Z250 and eddy feedback response to poleward-shifted KOE subarctic SST front (Taguchi et al. 2012JC)

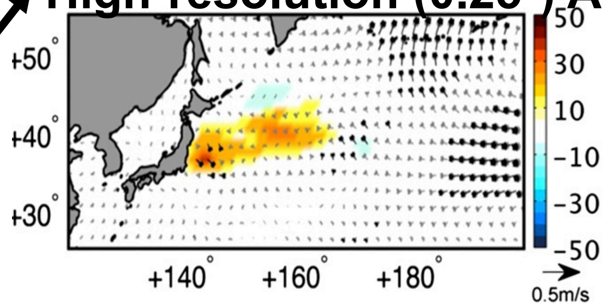


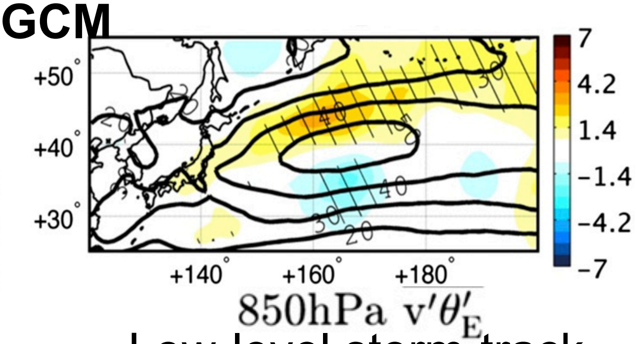
warm SST anomalies for (CAM5) AGCM experiments

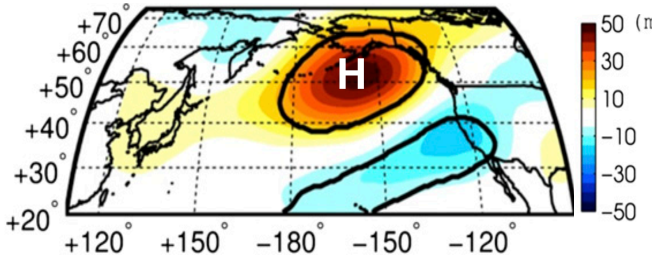


Smirnov et al.(2015JC)

High-resolution (0.25º) AGCM



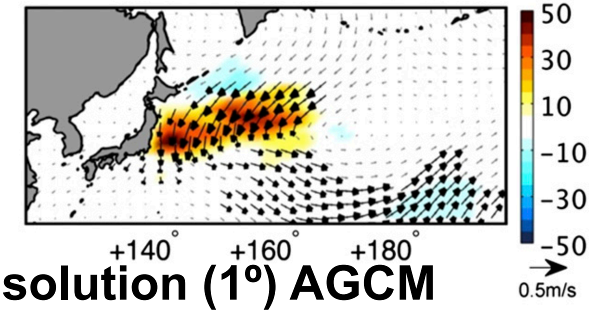


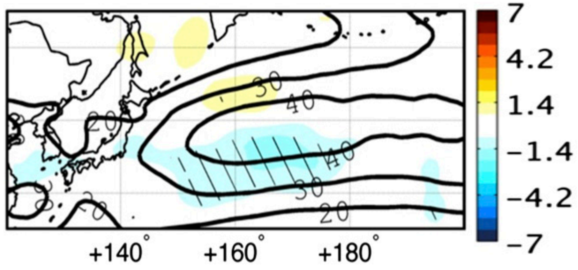


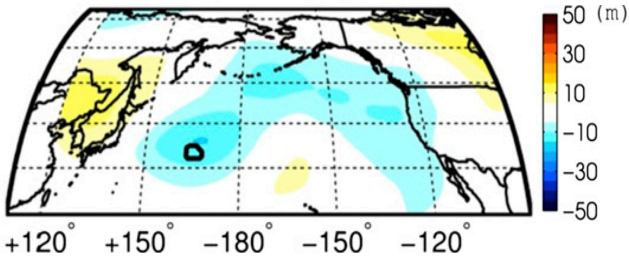
Anomalous SHF+LHF ‘color) winter-mean 925-hPa wind anomaly

Low-level storm-track response (color), mean

winter-mean 300-hPa height response (bold: 95% confidence)



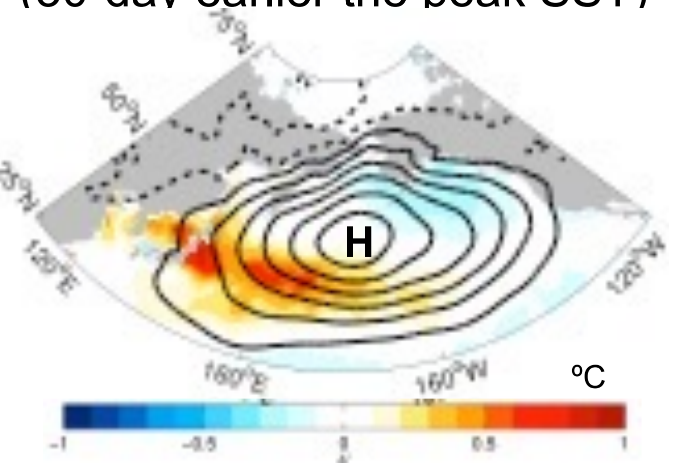




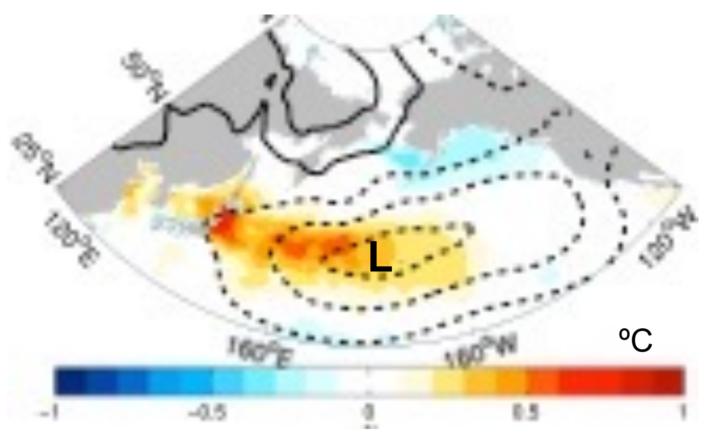
Lower-resolution (1º) AGCM

Atmospheric response to time-varying SST anomalies in the KOE

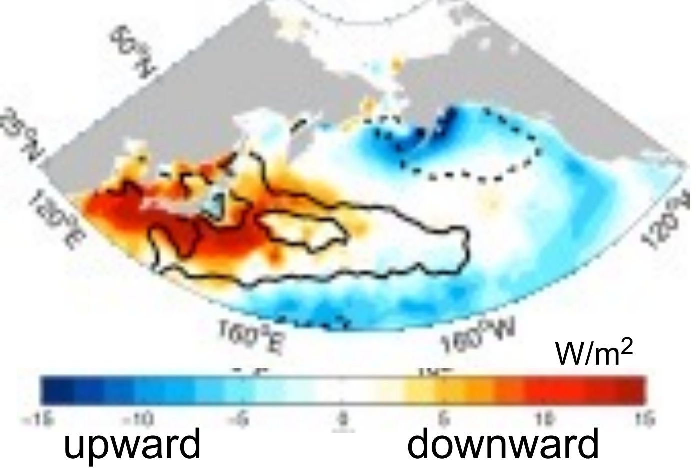
SLP anomalies with high significance **forcing** warm SST anomalies (color) in KOE (30-day earlier the peak SST)



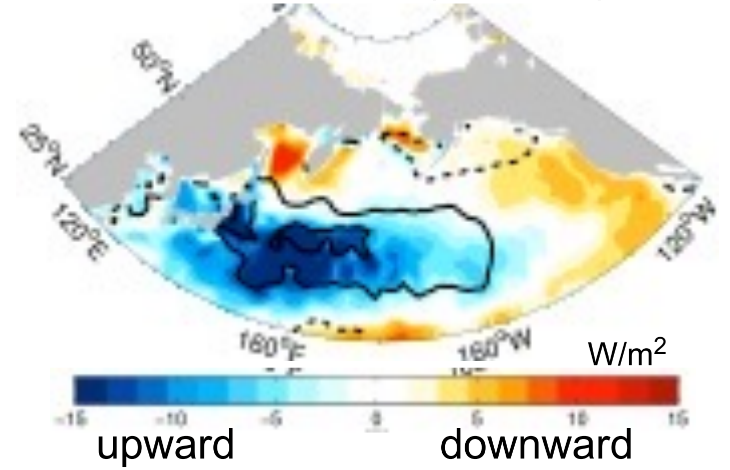
SLP anomalies with lower significance regarded as a **response** to warm SST anomalies (30-day later the peak SST)



associated anomalous surface heat flux (downward)



associated anomalous surface heat flux (upward)

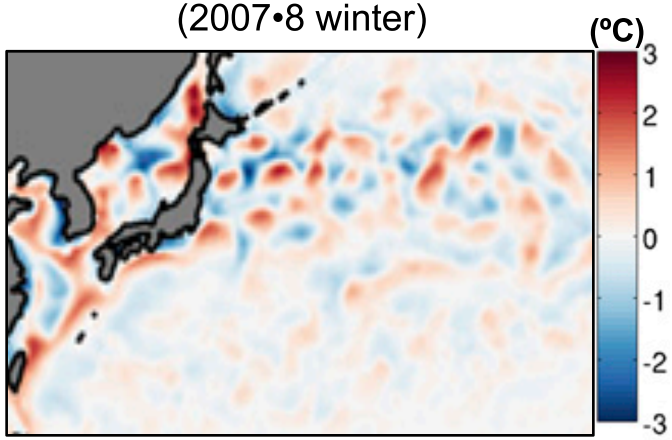


- Atmospheric anomalies in ERA-Interim regarded as response to time-varying SSTA in KOE fundamentally differ from those that forced the SSTA (Wills & Thompson 2018JC).
- The forcing atmospheric pattern is highly significant, but the atmospheric “response” is less significant and similar to the low-resolution model response by Smirnov et al. (2015).
- Essentially the same results are obtained from CGCM simulations, including the one in which KOE SSTA is restored to observations (Yook et al. 2022JC).
- Time-varying SSTA may not necessarily be associated with SST front variability caused by oceanic processes, leading to response different from Taguchi et al. (2012JC) and Revelard et al. (2016JC).

Similar atmospheric response is found to time-varying SSTA along GS (Wills et al 2016JC).

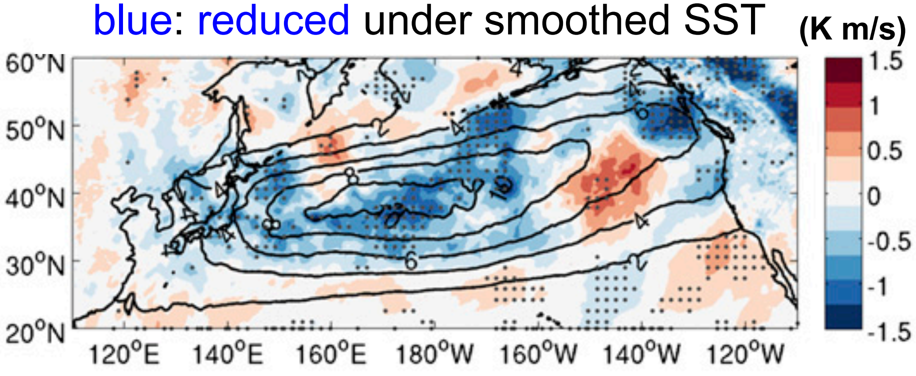
Wintertime atmospheric response to meso-scale SST pattern in the North Pacific

Meso/frontal-scale SST pattern
(2007•8 winter)

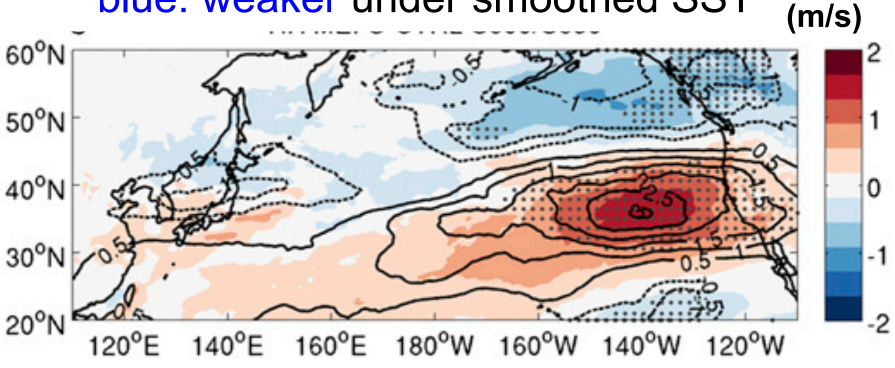


Difference between 0.1º SST smoothed SST

storm-track response (850hPa *v'T'*)
blue: reduced under smoothed SST



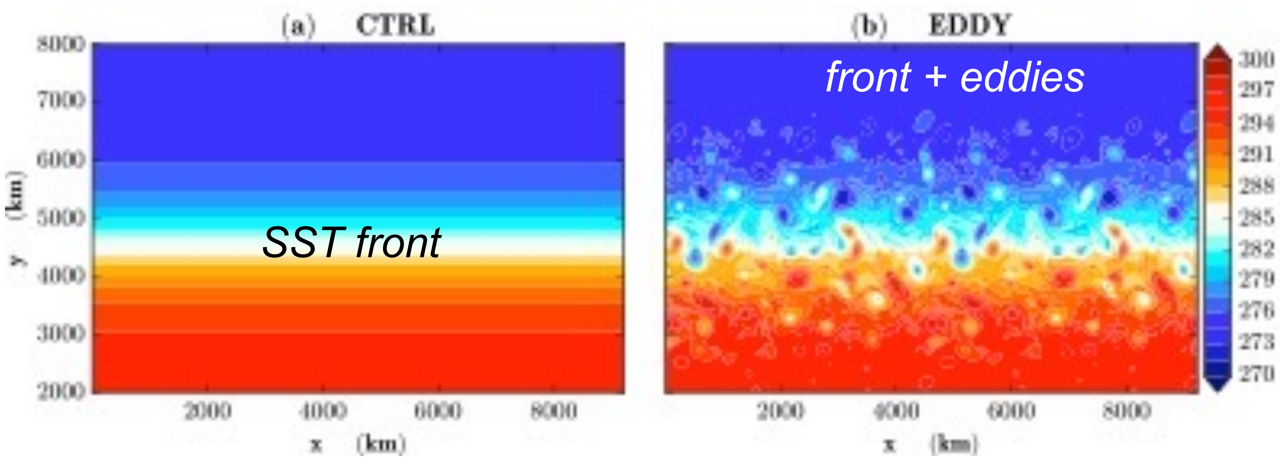
zonal-wind response (300hPa)
blue: weaker under smoothed SST



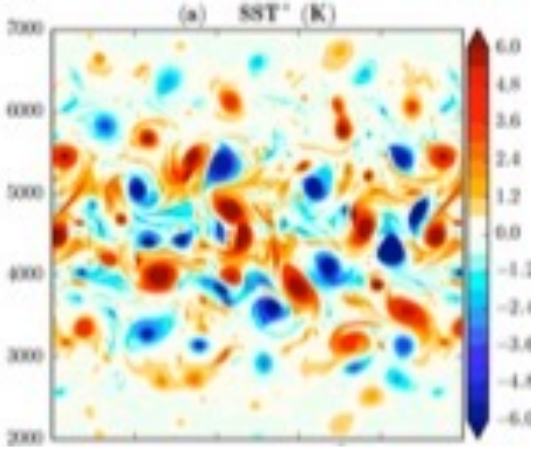
27-km WRF simulations by Ma et al. (2017JC)

- Time-slice simulation for 2007•08 cold season (Nov-Feb) with 27-km WRF with high-resolution SST is compared to its counterpart with spatially smoothed SST, to extract atmospheric response to meso/frontal-scale SST pattern (Ma et al. 2017JC).
- Warm meso-scale eddies tend to augment heat and moisture supply into the atmosphere, which acts as thermal damping for the eddies but thermodynamic forcing on the atmosphere.
- Enhanced heat and moisture supply from warm core eddies contributes to cyclone development (Zhang et al. 2019JGR, 2023GRL), thereby intensifying storm-track activity across the basin and thus acting to displace the eddy-driven westerly jet poleward over the eastern North Pacific (Ma et al. 2017JC).
- Lower-resolution (162 km) WRF cannot reproduce the overall response.

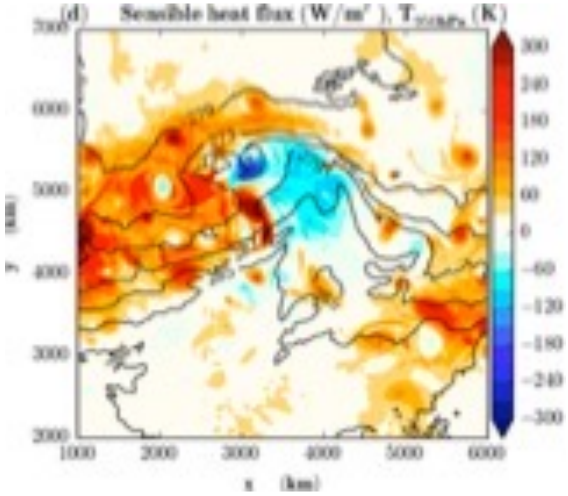
Idealized simulation of atmospheric response to meso-scale ocean eddies (I)



Eddy SST pattern

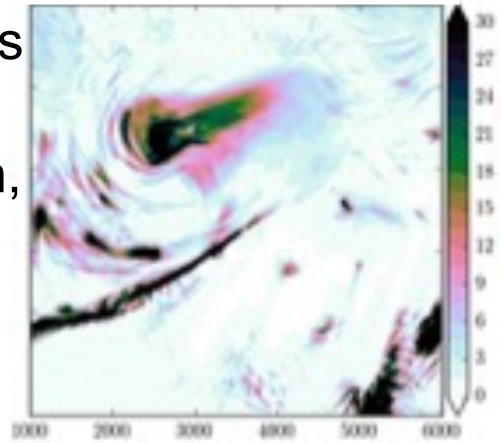


SHF (color), 925-hPa Temp.



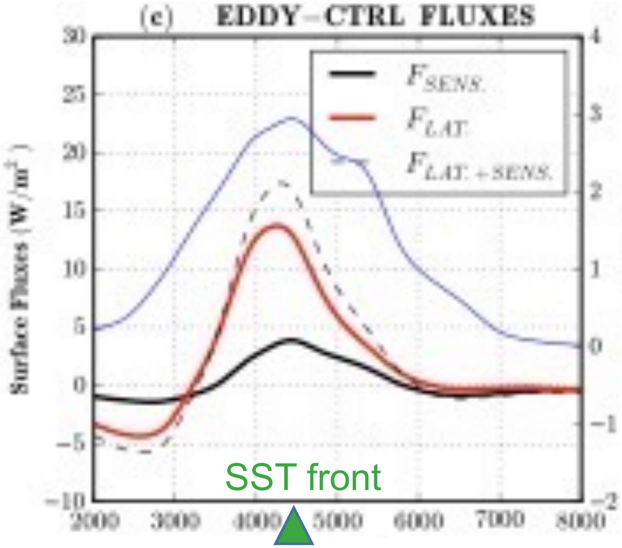
- . Idealized model experiment by Foussard et al. (2019JC) is instrumental in understanding the dynamics and thermodynamics involved in atmospheric responses to meso-scale SST patterns.
- 18-km WRF model is configured into a midlatitude *ß*-plane channel of 9216-km width, with zonally-symmetric SST with SST "front" prescribed for CTRL simulation and 100~500-km "eddies" randomly added for EDDY simulation.
- In the EDDY simulation, heat supply is locally enhanced from warm eddies and so is precipitation under cold airflow behind a cyclone.

precipitation (mm/d)

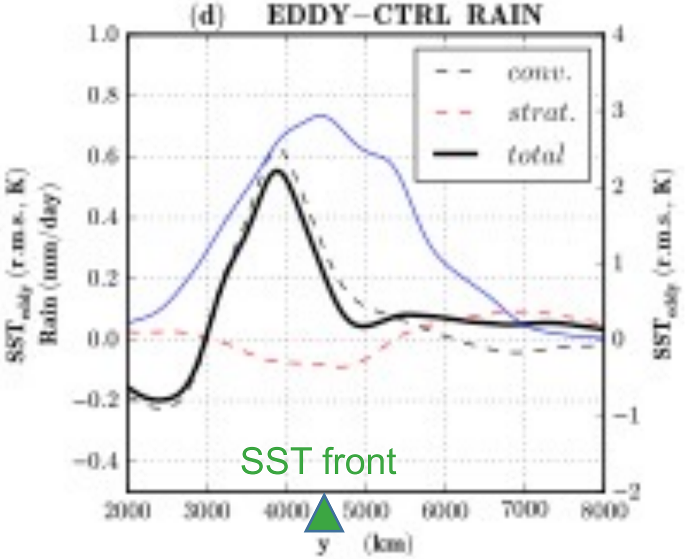


Idealized simulation of atmospheric response to meso-scale ocean eddies (II)

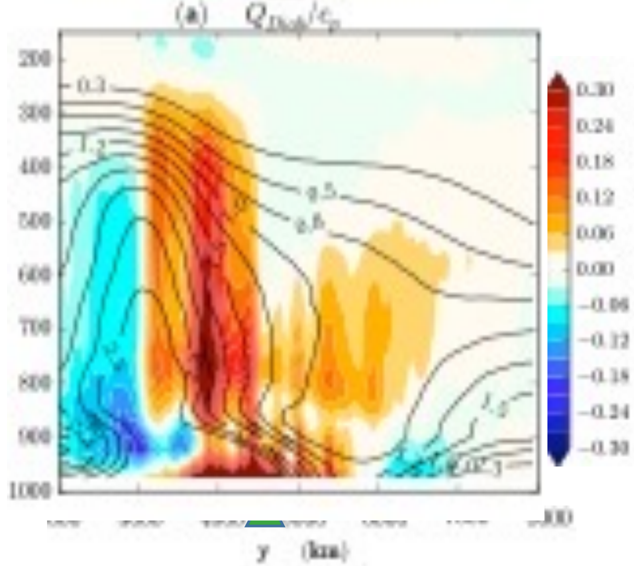
Zonally-averaged eddy impact on SHF, LHF with **eddy SST magnitude**



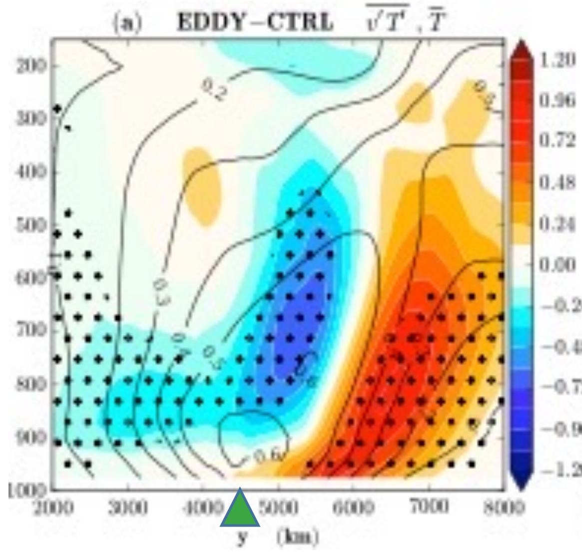
Eddy impact on convective rain, stratiform rain with **eddy SST magnitude**



Eddy impact on diabatic heating (color, ∂T/∂t) with CTRL exp. (contour)

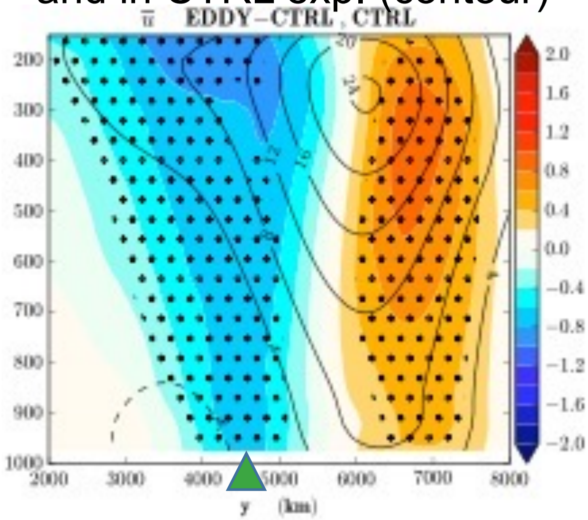


Eddy impact on poleward eddy heat flux (color) and zonal-mean temp. (contour)



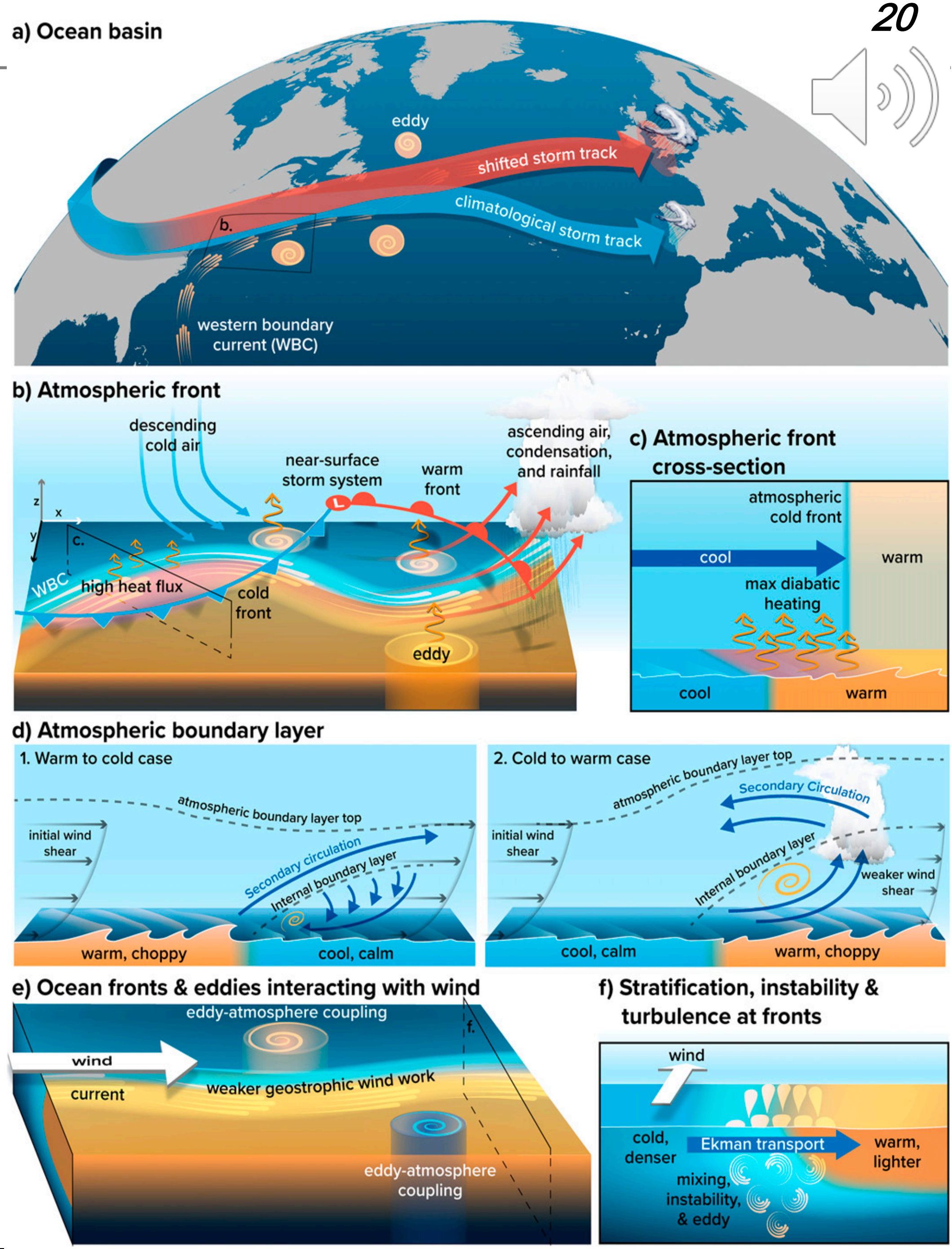
- **Warm eddies augment heat and moisture supply**, which maximizes on the warmer flank of the SST front, where eddy SST magnitude is set particularly high and storm-track activity is climatologically high. **Increase in convective rainfall** peaks farther south (Foussard et al. 2019JC).
- Modulated mean-meridional circulation by increased convective rainfall and increased stratiform rainfall both act to warm up on the cooler flank of the SST front, leading to **poleward shift of the storm-track and eddy-driven westerly jet**, in agreement with Ma et al. (2016JC).
- In more realistic cases, however, separation of ocean eddies from SST front is not simple.

Eddy impact on zonal-mean zonal wind (color) and in CTRL exp. (contour)



More aspects to be discussed

- Specific air-sea interaction processes involved in extra-tropical cyclone development, such as WCB (e.g., Booth et al. 2012 MWR; Binder et al. 2016JAS; Sheldon et al. 2017 Tellus) and CCB (e.g., Hirata et al. 2016MWR, 2019GRL).
- Ocean contribution to moist processes in blocking formation (e.g., Steinfield & Pfahl 2019CD; Yamamoto et al. 2021WCD).
- Dependence of model reproducibility of atmospheric response to frontal SST anomalies on model biases via preferred modes of variability (e.g., Peng et al. 1997JC; Okajima et al. 2018JC), and its model resolution dependence.
- Dependence of atmospheric response to frontal SST anomalies on how they have formed (ocean processes or atmospheric forcing). → Better interpretation?
- GS-KE co-variability (Kohyama et al. 2021 Science)
- Influence of rapidly warming WBCs and marginal seas (Wu et al. 2012NCC) on extreme rainfall events (e.g., Manda et al. 2014 SRep; Kawase et al. 2020BAMS) through attribution.
- Role of midlatitude air-sea interaction in climate projection (e.g., Woollings et al. 2012 NGEO; Chemke 2022 NatureCom; Schemm et al 2023WCD).
- Relative contributions between ocean eddies and SST fronts to their impact on the atmosphere (c.f., Foussard et al. 2019JC) in realistic situations. Their separation in SST fields may be possible by focusing on flow curvature (Okajima et al. 2021SRep).



Relevant review papers

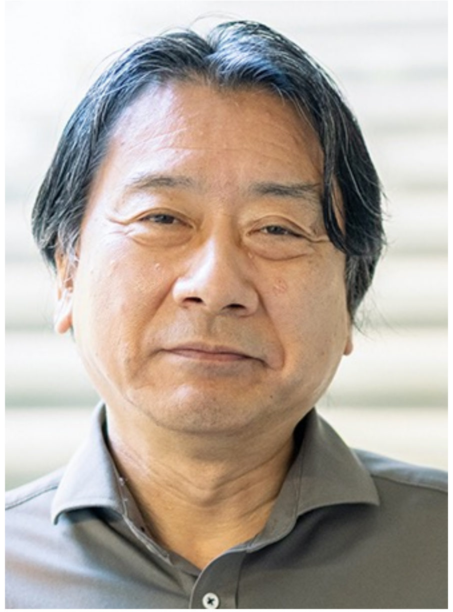
"Ocean Mesoscale and Frontal-Scale Ocean–Atmosphere Interactions and Influence on Large-Scale Climate: A Review", J. Climate, 2023
by the U.S. CLIVAR Ocean Mesoscale Air–Sea Interaction WG (Seo et al. 2023)

Role of the Gulf Stream and Kuroshio-Oyashio systems in large-scale atmosphere–ocean interaction: A review.
by the U.S. CLIVAR Western Boundary Current WG, Kwon et al. J. Climate 2010

Western boundary currents and frontal air–sea interaction: Gulf Stream and Kuroshio Extension.
by the U.S. CLIVAR Western Boundary Current WG, Kelly et al. J. Climate 2010

Air–sea interaction over ocean fronts and eddies.
Small et al. Dyn. Atmos. Oceans 2008

Satellite observations of cool ocean–atmosphere interaction.
Xie, BAMS 2004



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