Mode Water's Climate Impact and the Role of Meso- and Submesoscale Processes

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Prof. Bo Qiu, Angelic White, David Karl (University of Hawaii)

Prof. Hideharu Sasaki (JAMSTEC) et al.

Outline

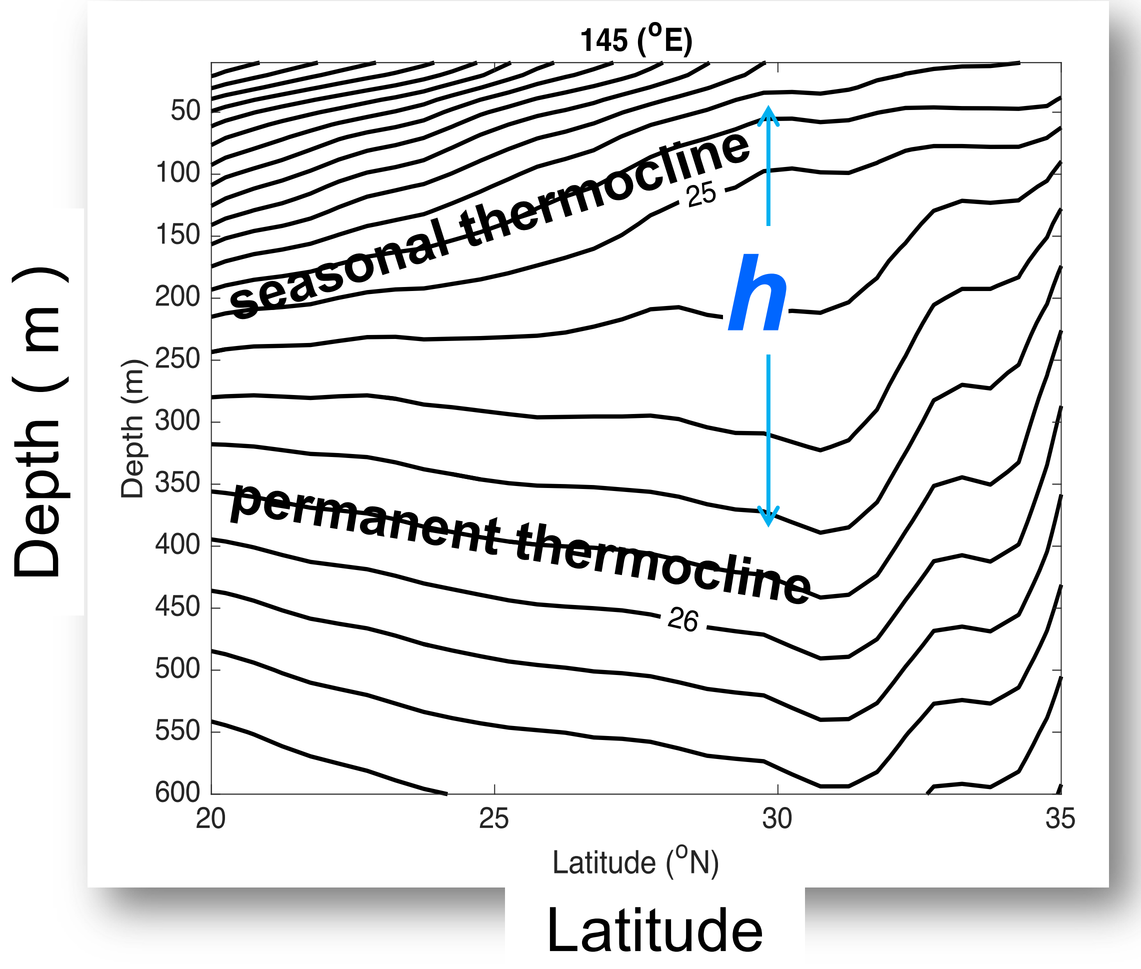
- Climate impacts
- Role of mesoscale eddies
- Role of submesoscales
- Summary with discussion

backgrounds

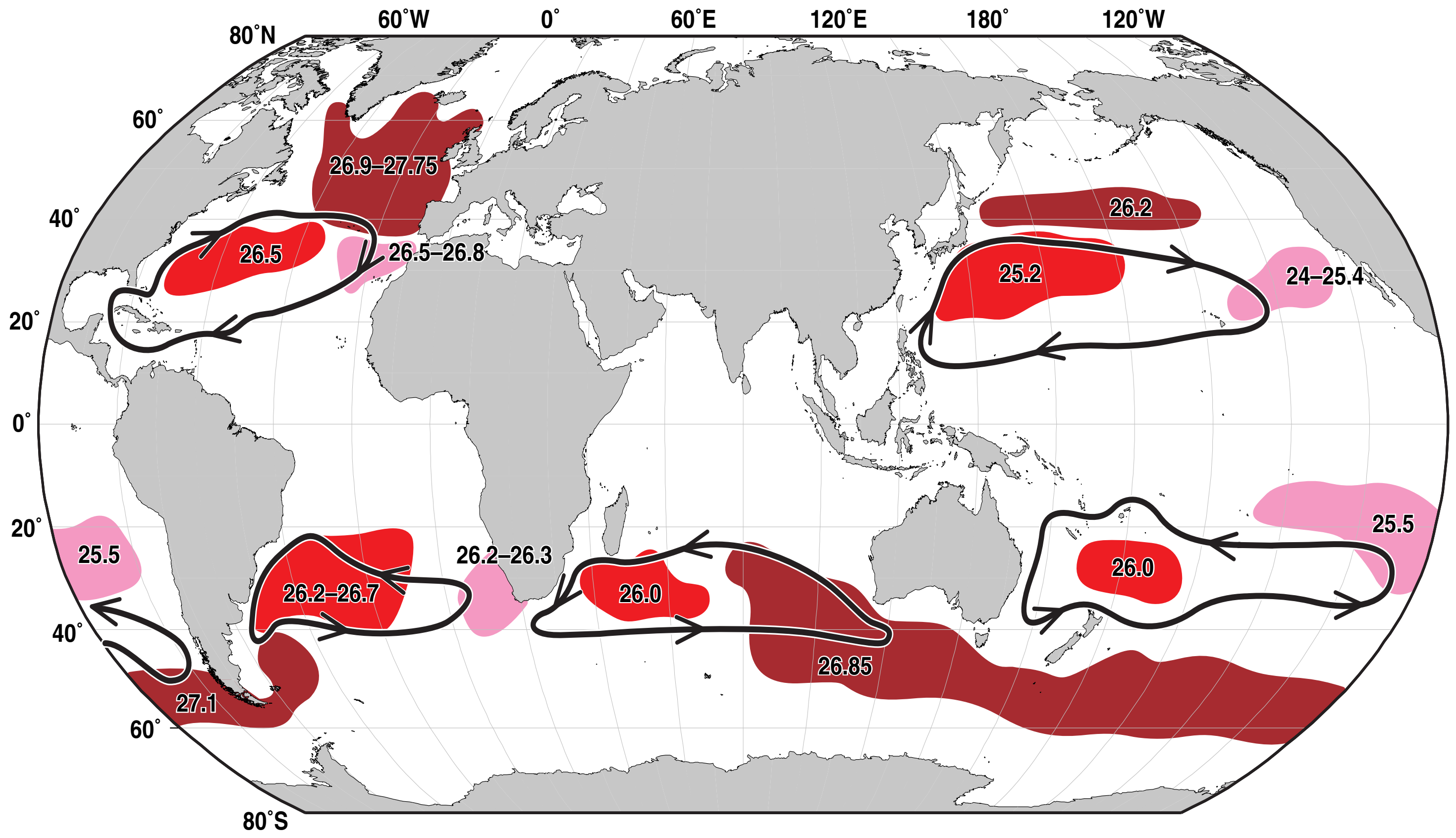
What is mode water?

$$PV = \frac{f}{h}$$

low-PV water between the seasonal and permanent thermocline



different types of mode water occupying ~20% of the upper 2000 m

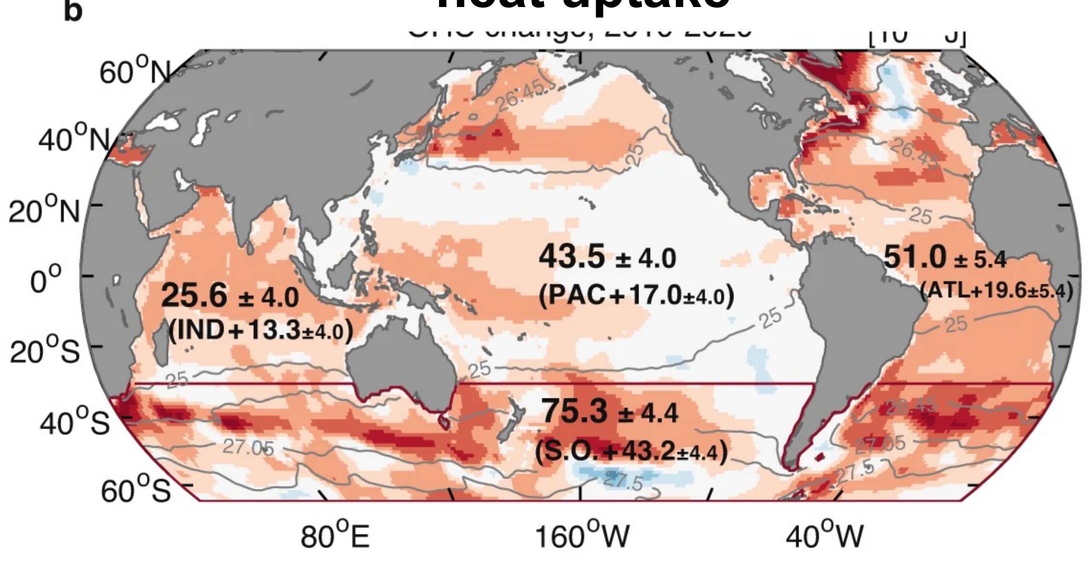


Hanawa and Talley (2000)

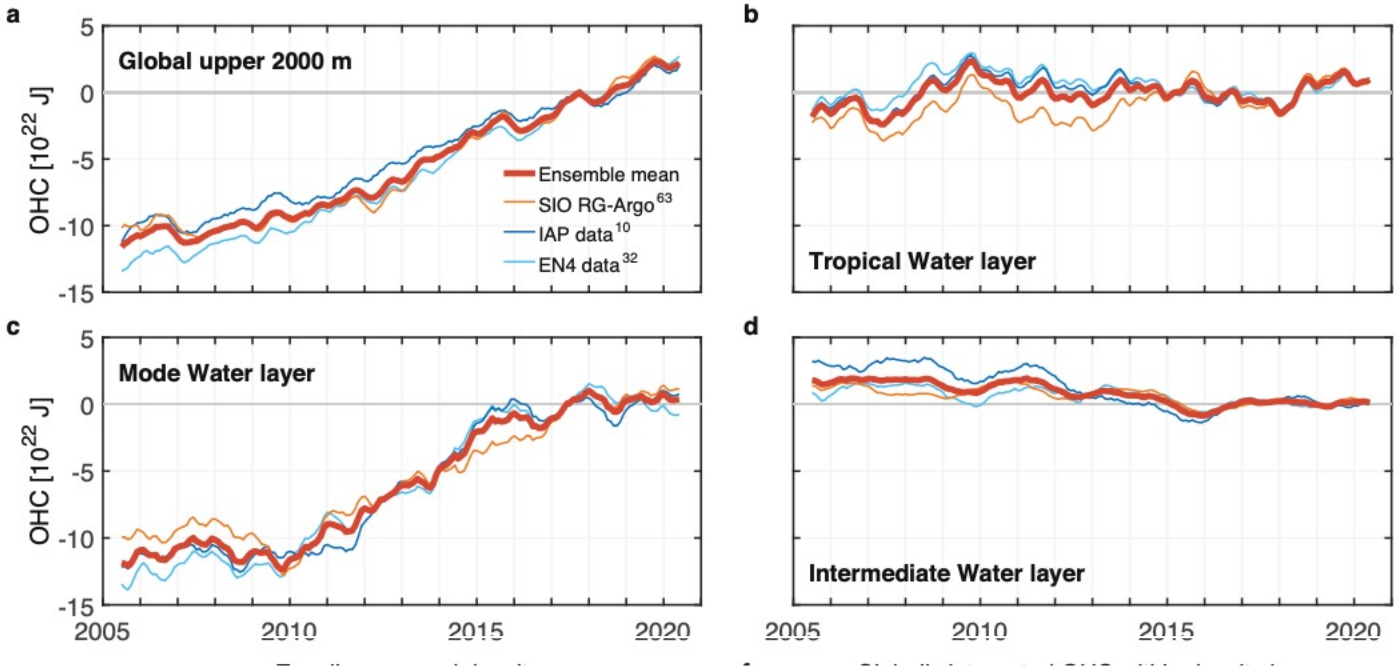
backgrounds

- key in anthropogenic heat and carbon uptake
- MW+AAIW: ~89% of the net global ocean warming

heat uptake

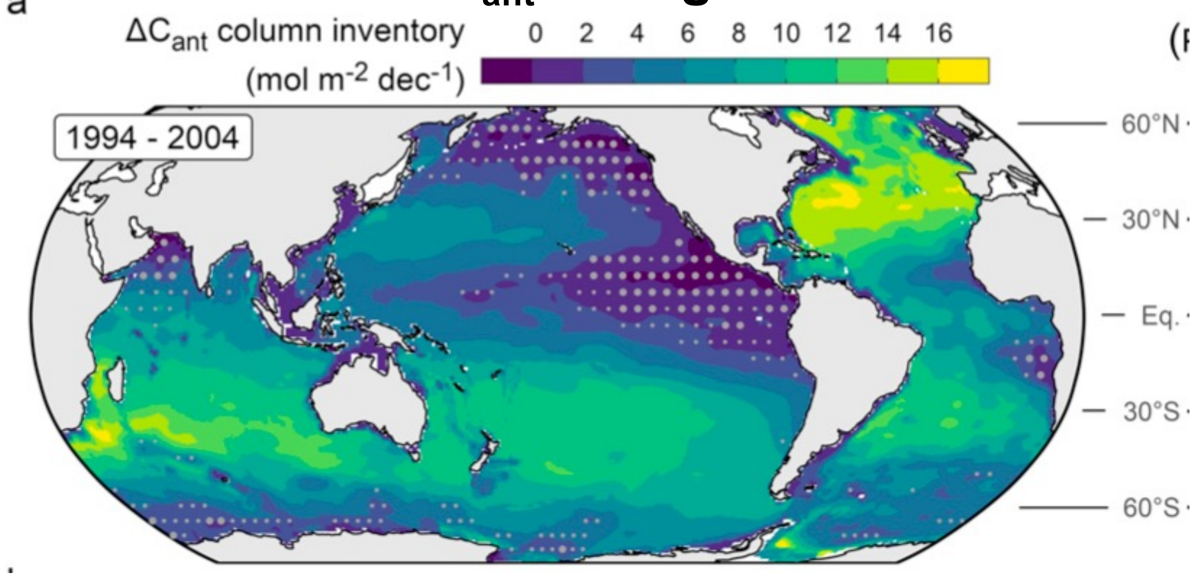


Li et al. 2023

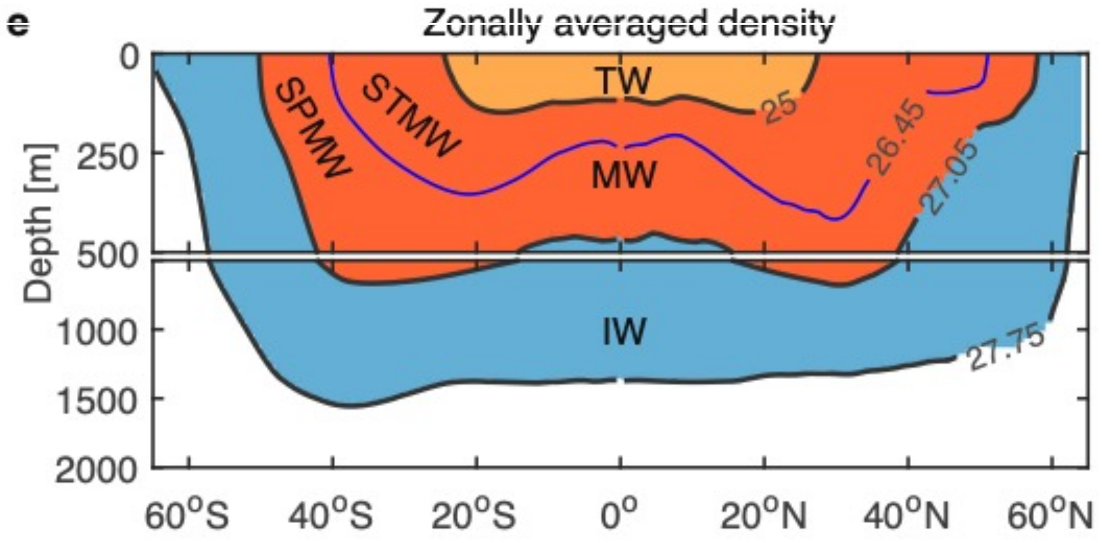


(Argo era ; Li et al., 2023)

C_{ant} storage

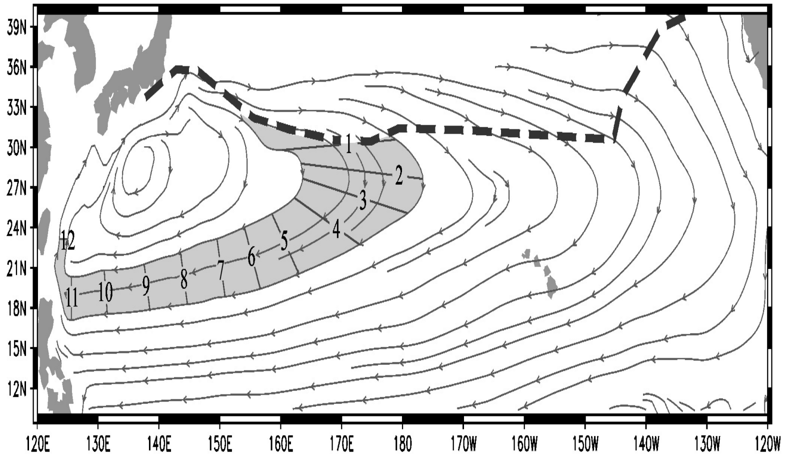


Muller et al. 2023

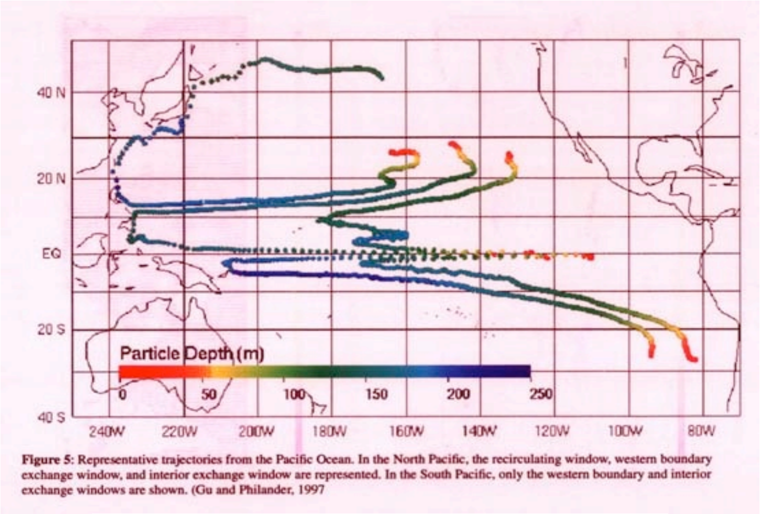


backgrounds

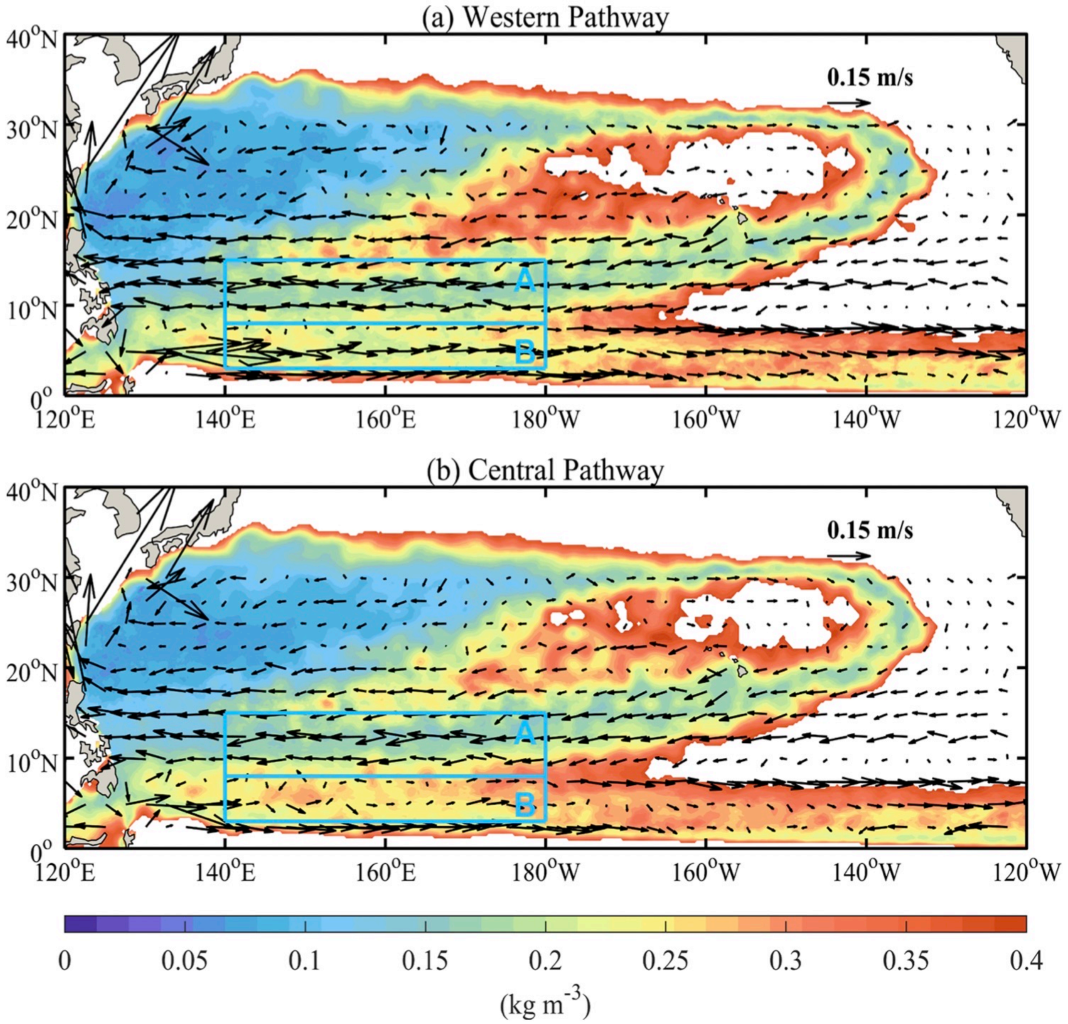
- recording and reemerging long-term ocean memories
- important in decadal / multi-decadal variability



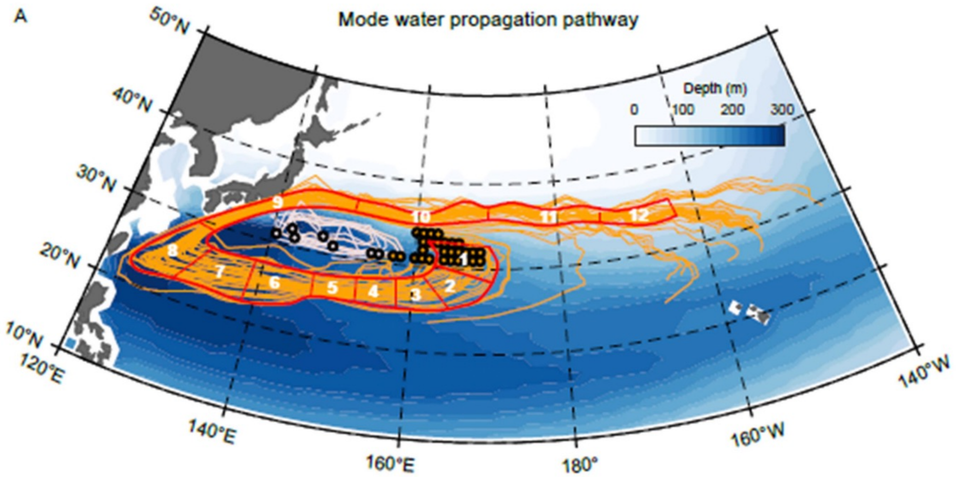
Liu and Hu, 2007



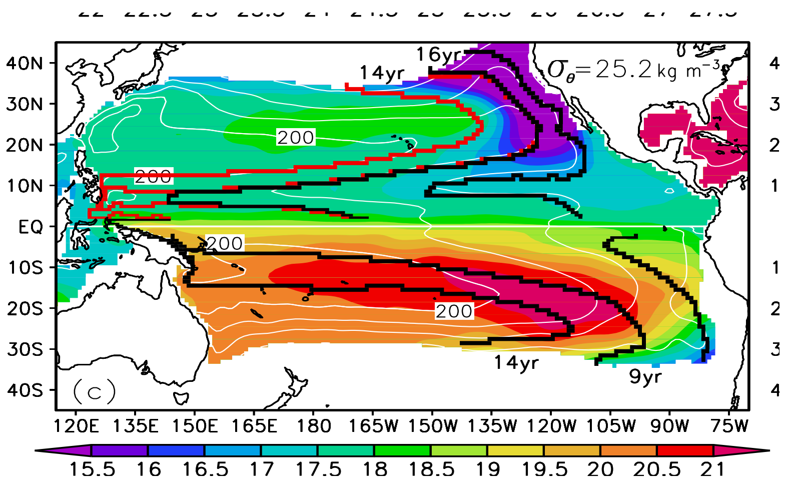
Gu and Philander, 1997



Ju et al., 2025



Wu et al., 2025



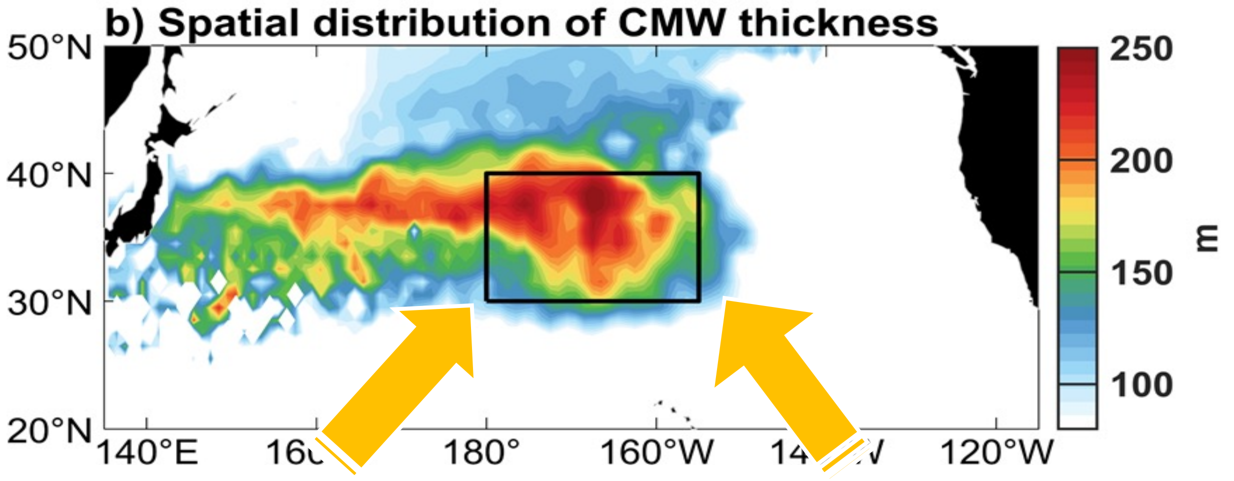
Wang and Huang，2005

climate impacts

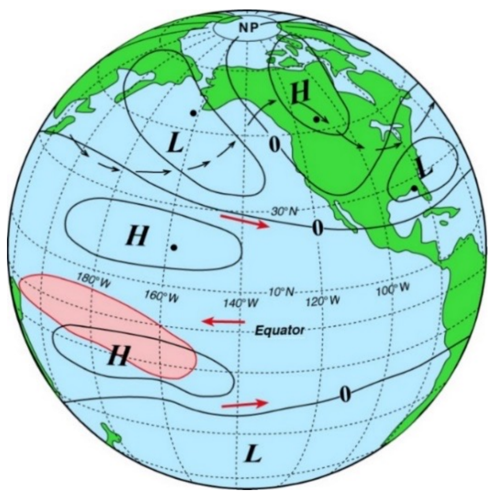
- λ of ocean memories is achieved through mode water
- strength controlled by relative phase of ENSO & PDO

Hasselmann模型(1976)

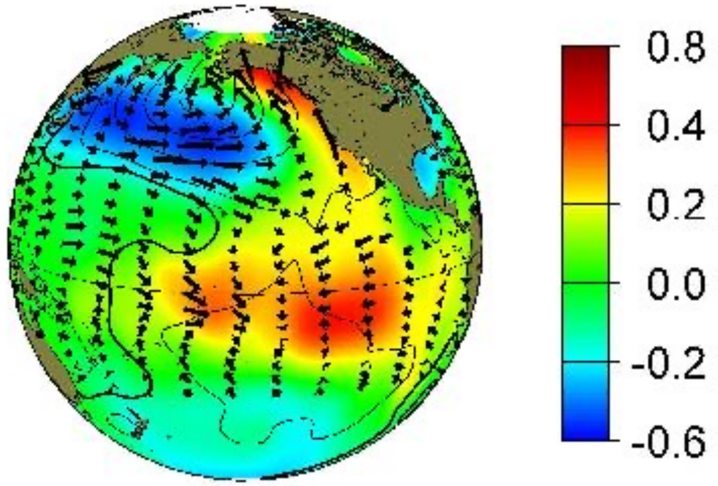
$$\partial T'/\partial t = F' - \lambda T'$$

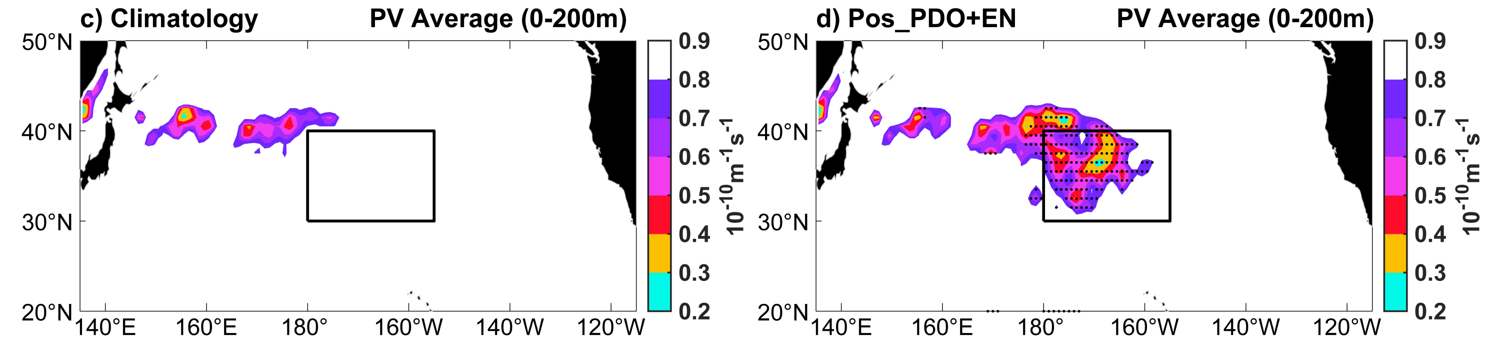


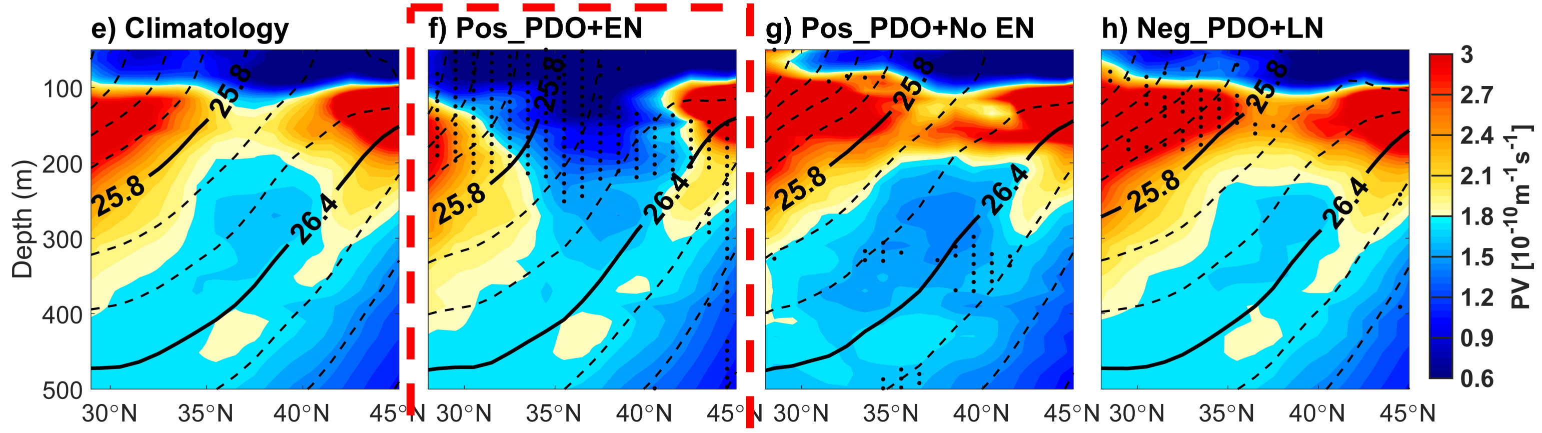
PNA

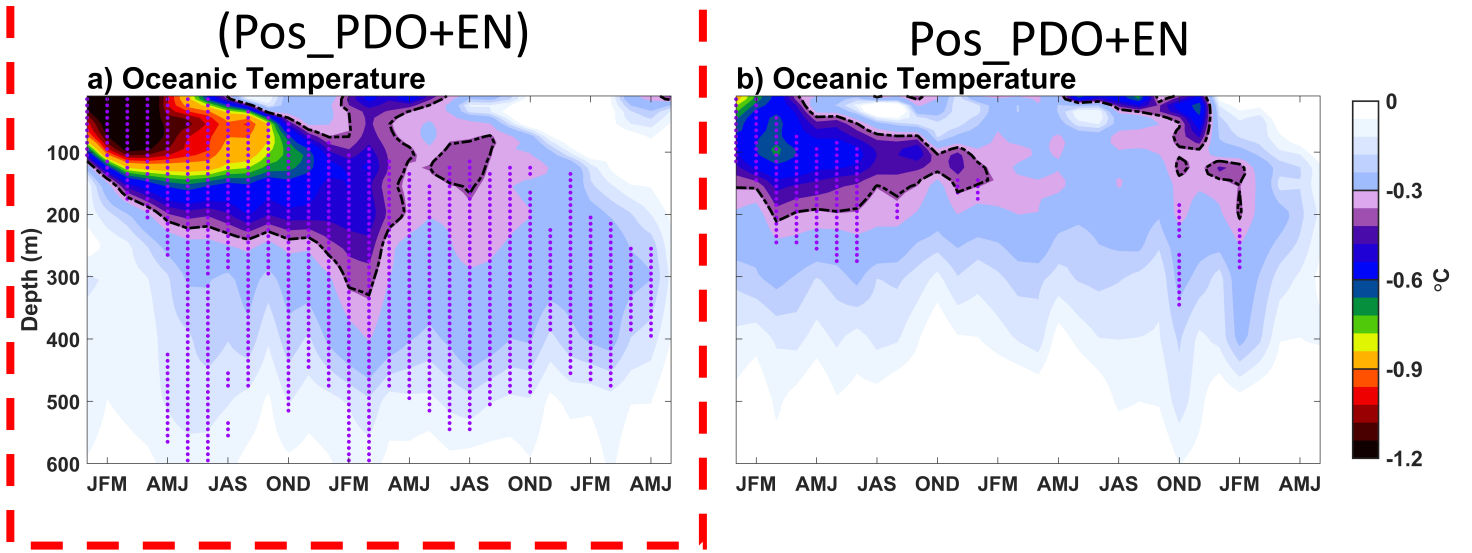


PDO(+)







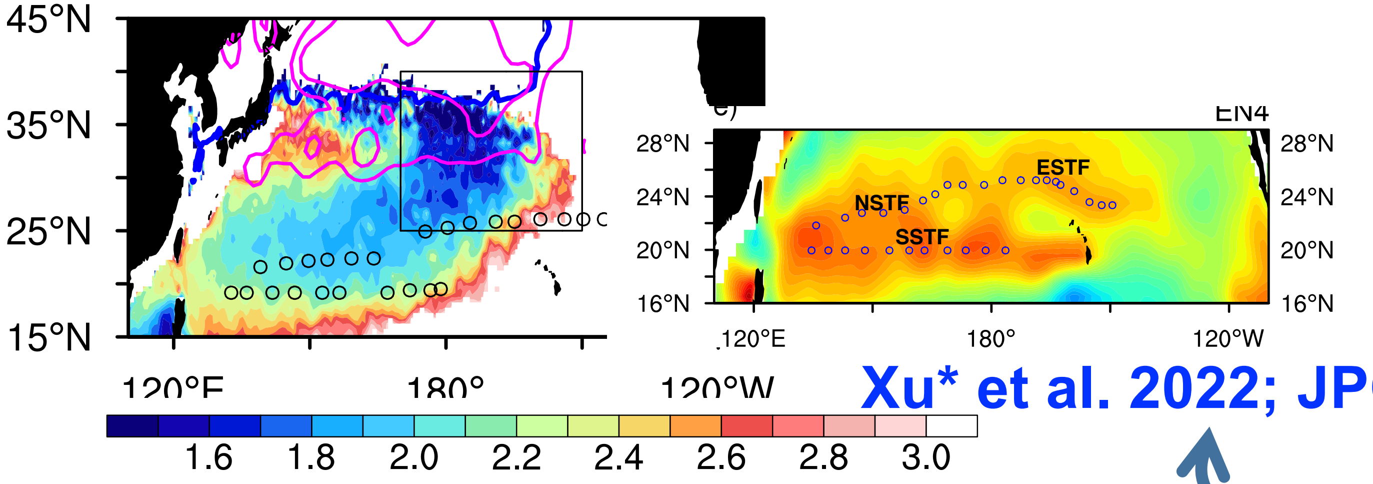


Liu, Xu*et al., 2025;GRL **<- Our own work in bold blue**

climate impacts

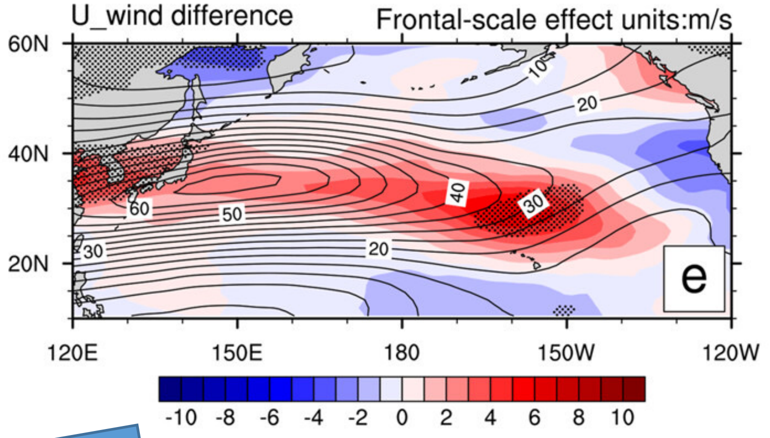
mode water -> subtropical fronts ->mid-latitude storm tracks

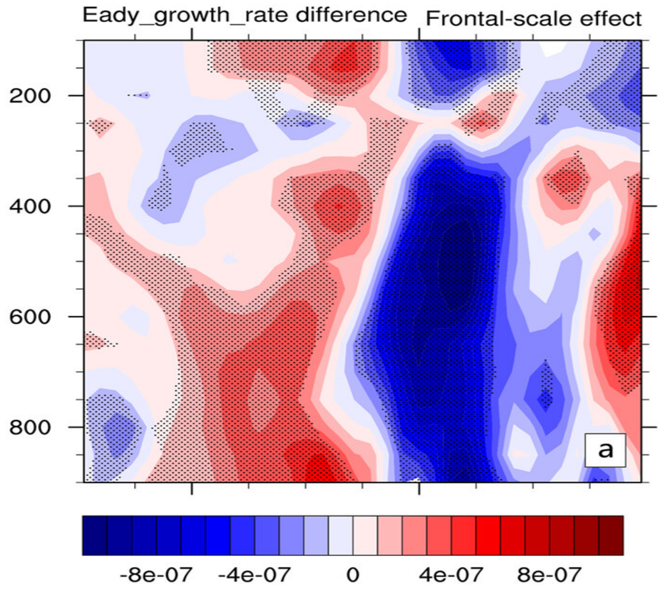
North Pacific subtropical fronts



Xu* et al. 2022; JPO

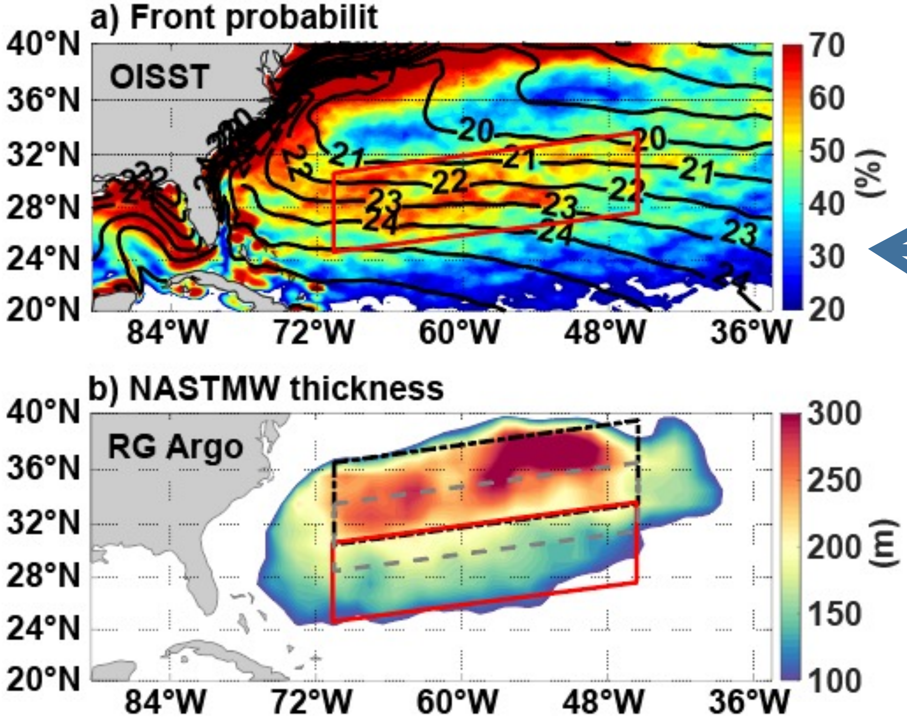
storm tracks

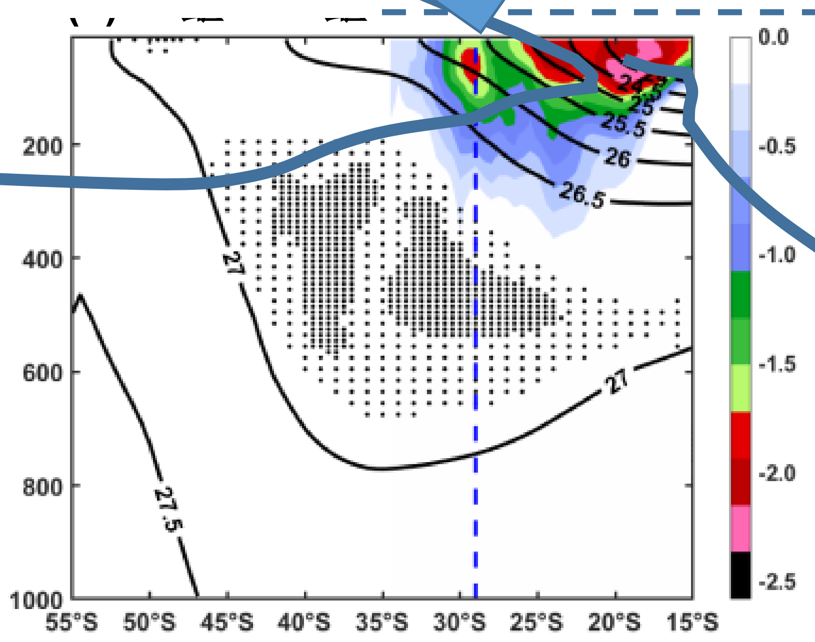




Hu et al., 2022; 2023

North Atlantic

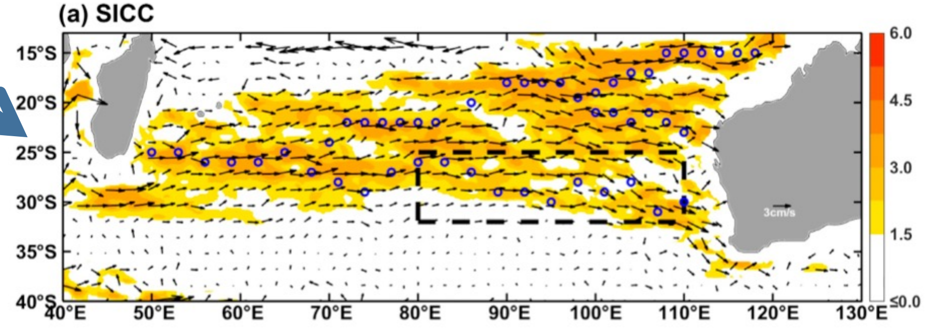




Zhang Xu* et al. 2026; JGR-O

<- Our own work in bold blue

southeast Indian Ocean subtropical fronts



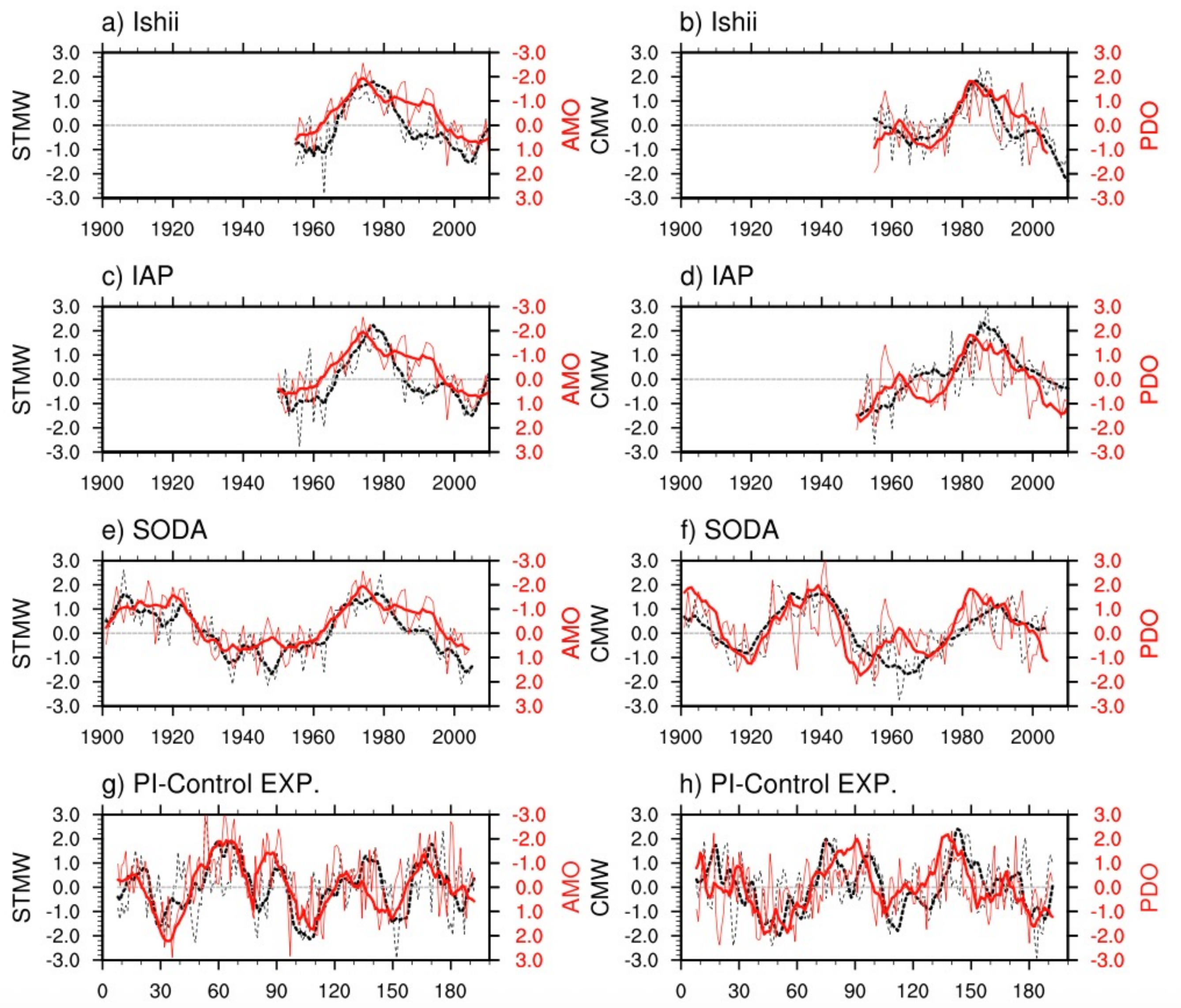
Liang … & Xu* 2025;JGR-O

climate impacts

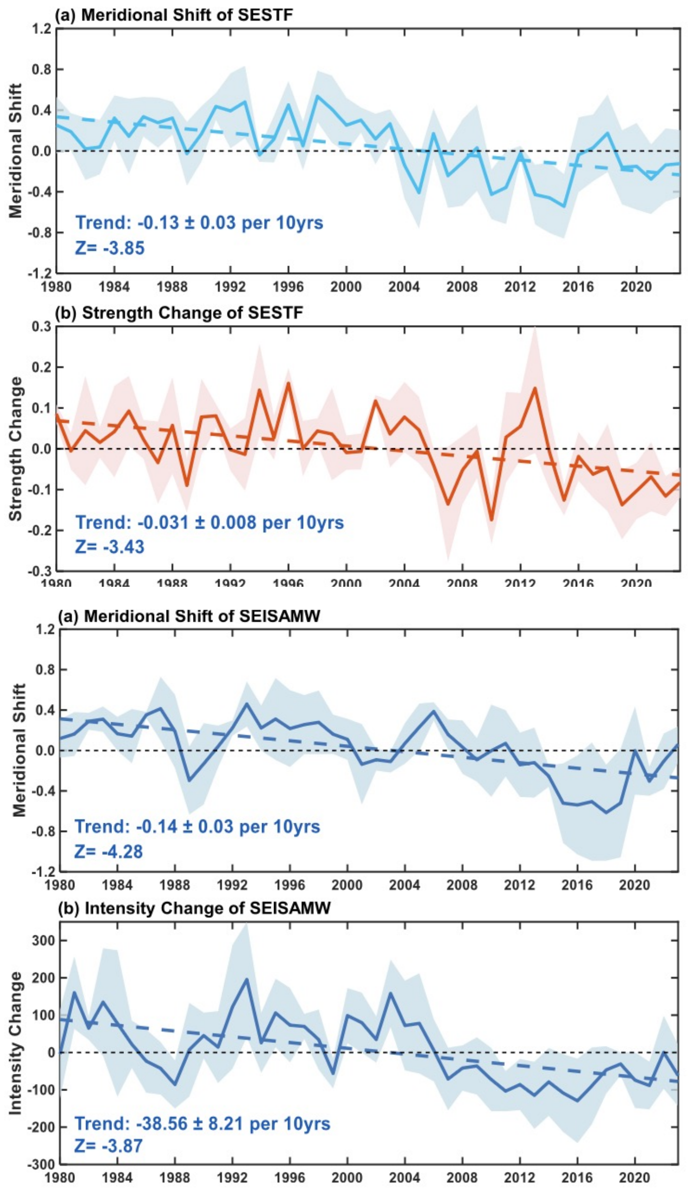
Synchronously variability of mode water & subtropical fronts on decadal & longer scale

PDO-> STMW ->NPESTF

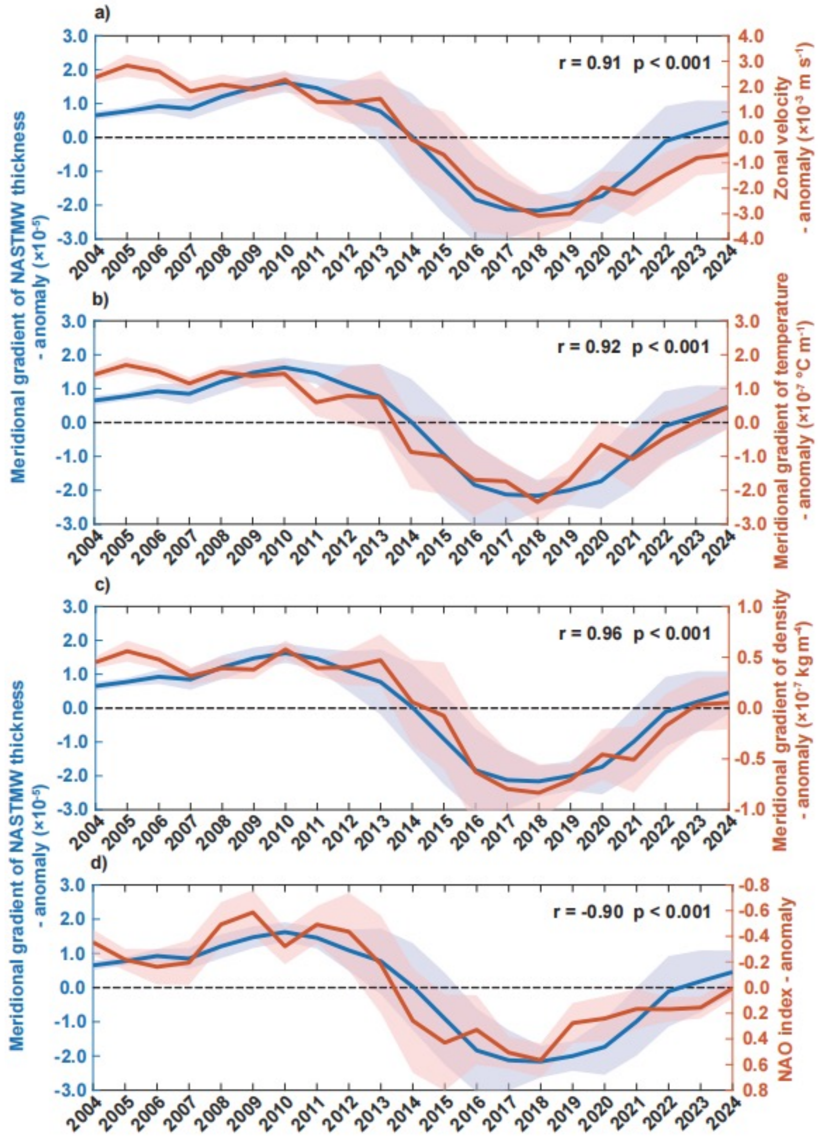
AMO->CMW-> NPCSTF



SAM->SEISAMW->SEISTF



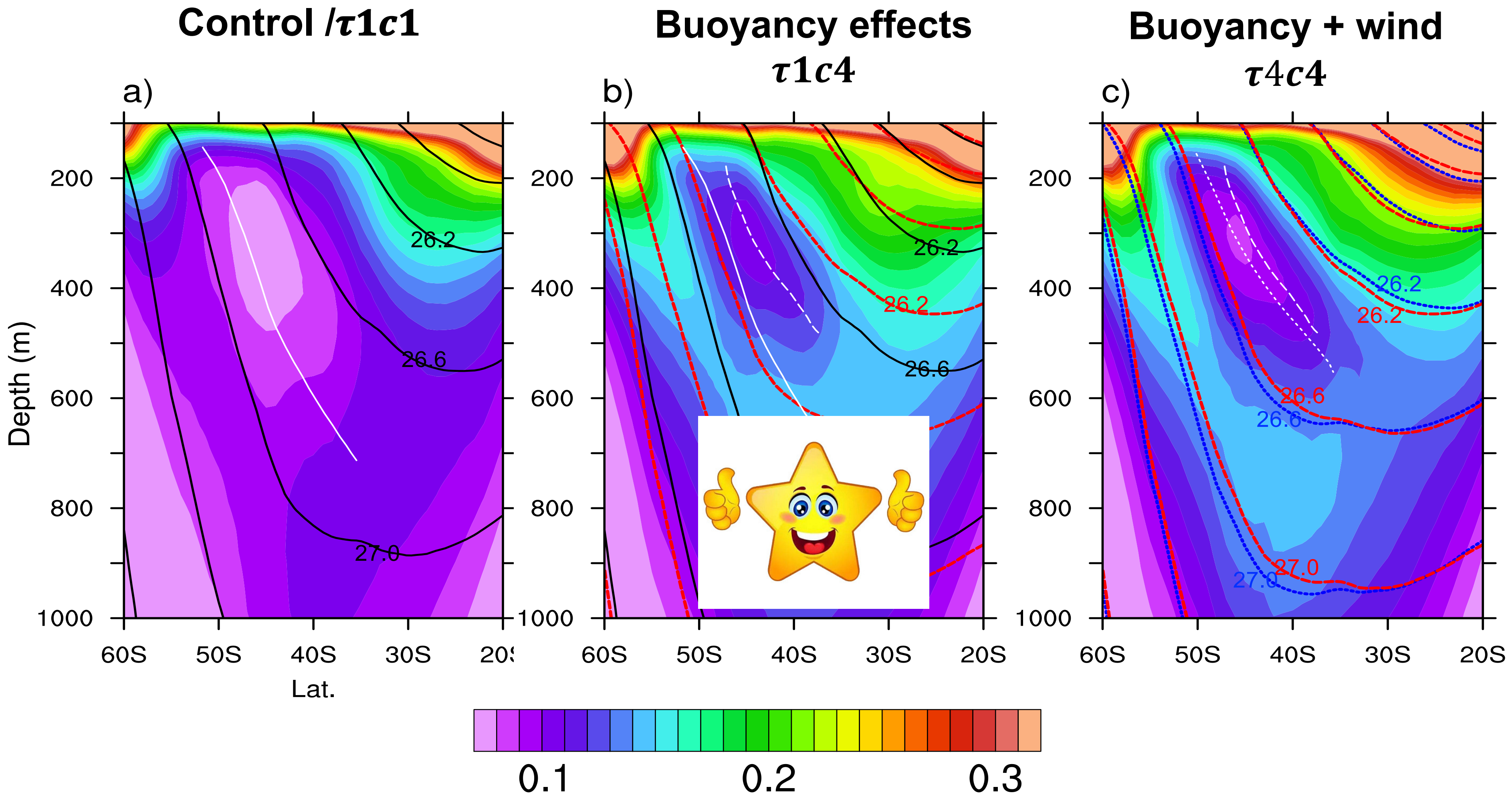
NAO->NASTMW->NASTF



Wu & Xu*, 2023 JC; Liang….Xu* et al., 2025; Zhang, Xu* et al, 2026

climate impacts

wind/dynamical v.s buoyancy forcing, who wins?



Partially coupled experiments with CESM1.

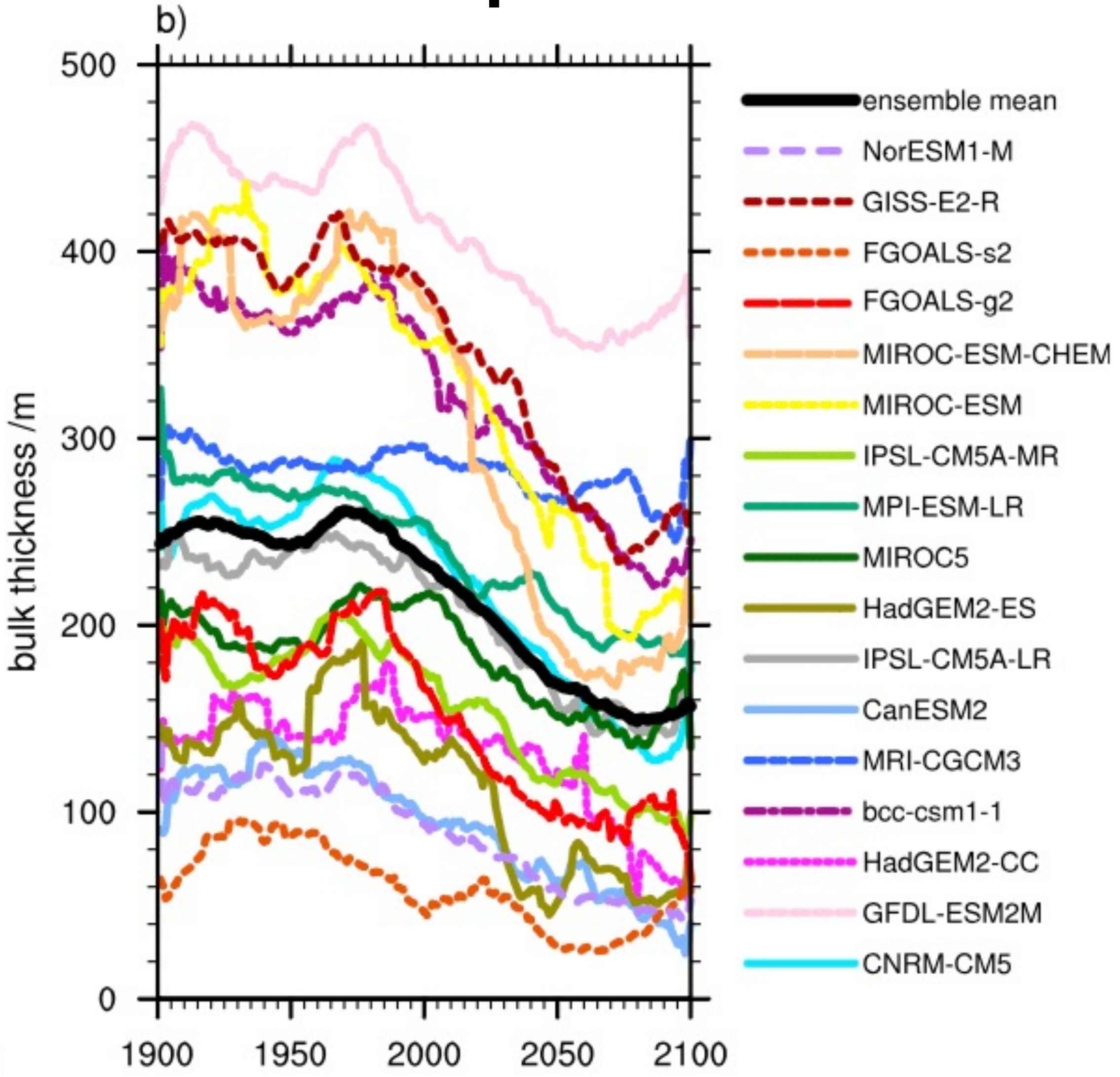
Name	Description
$\tau 1c1$	Same as CTRL, but the wind stress is overridden with a one-year forward drift
$\tau 1c4$	Same as $4xCO_2$, but the wind stress is overridden by that in CTRL and with a one-year forward drift
$\tau 4c4$	Same as $4xCO_2$, but the wind stress is overridden with a one-year forward drift

Xu et al, 2021 GRL

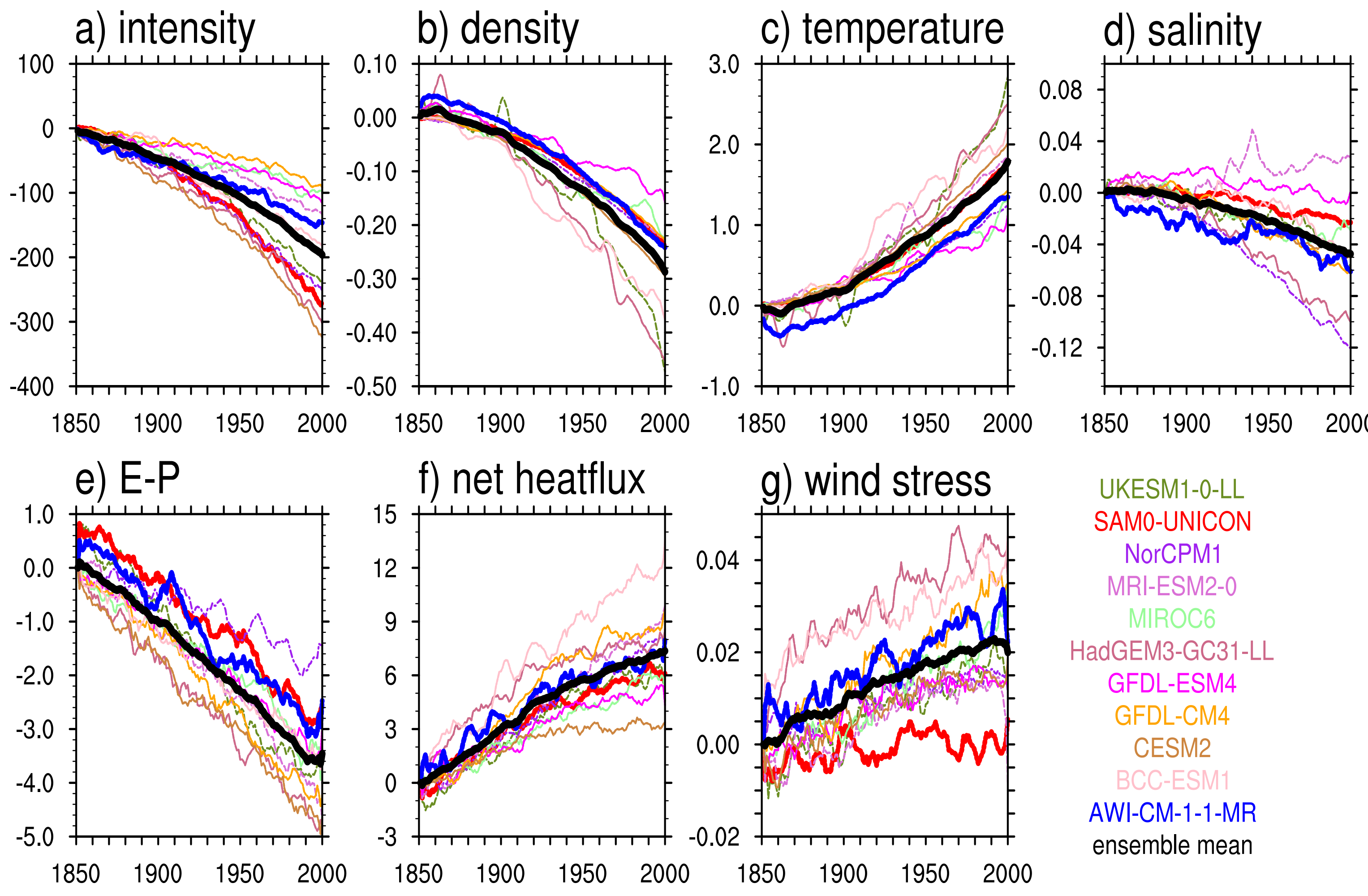
climate impacts

climate models predict a weakening of mode waters under global warming, but not shut down …

Subtropical mode water



Subantarctic mode water

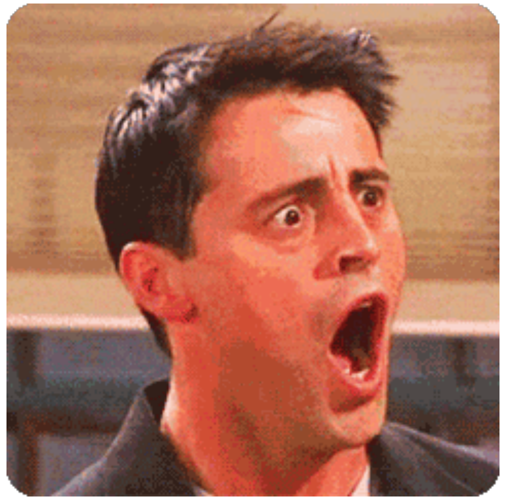


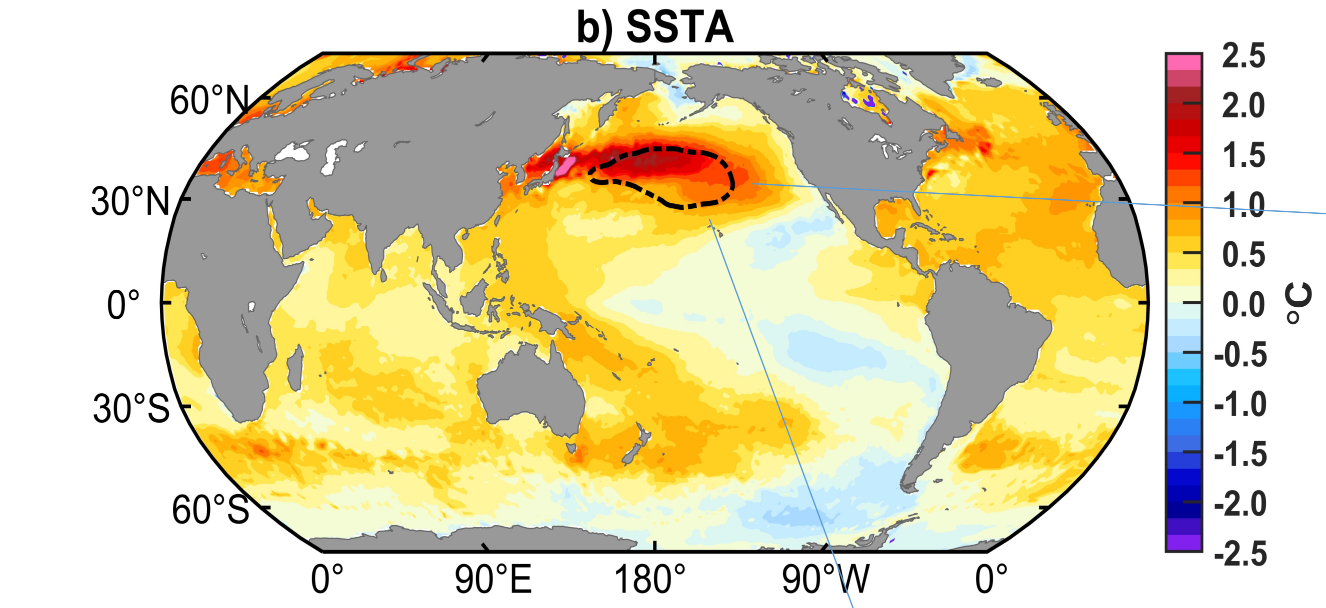
Xu et al., 2011; JGR-O <- Our own work in bold blue

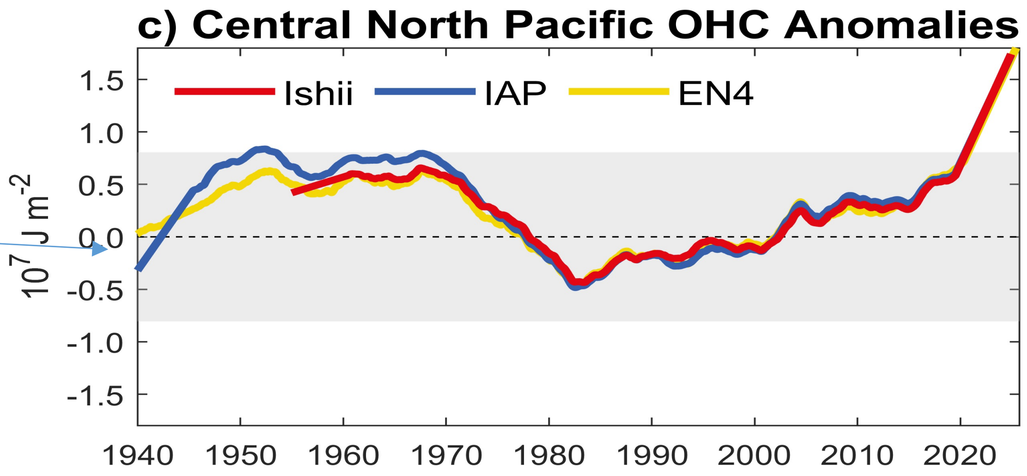
Xu et al., 2021; GRL

climate impacts

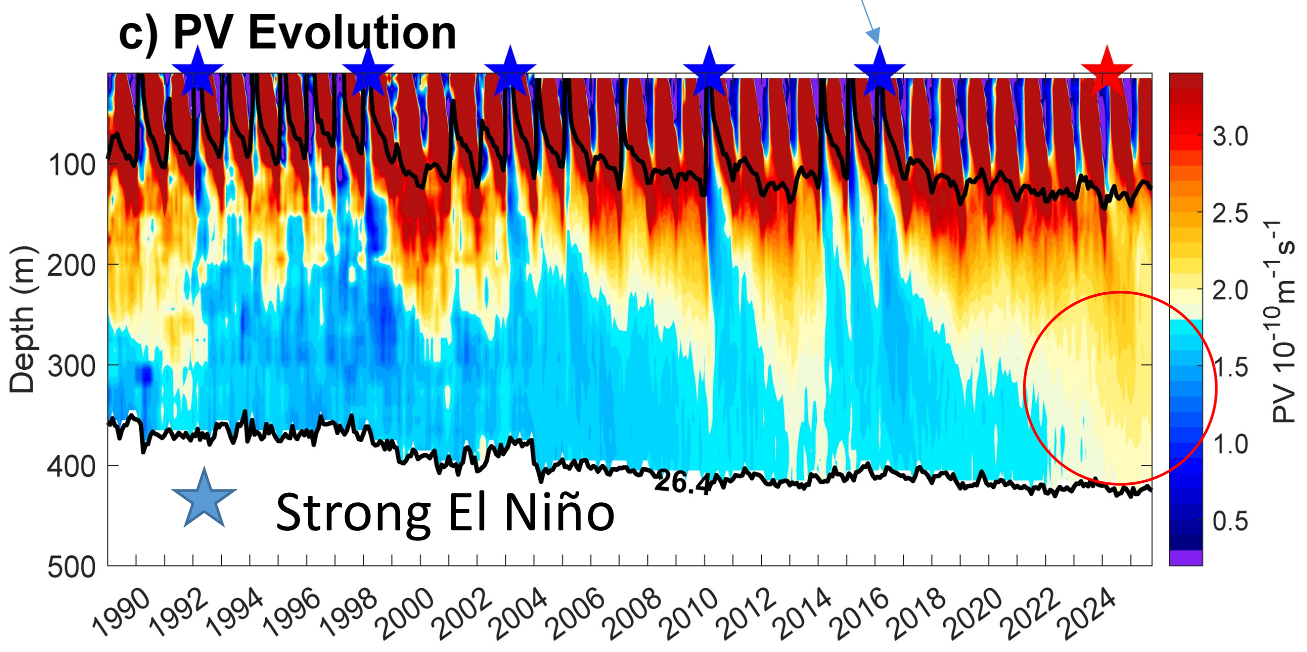
Observed collapsing NP central mode water after 2020s

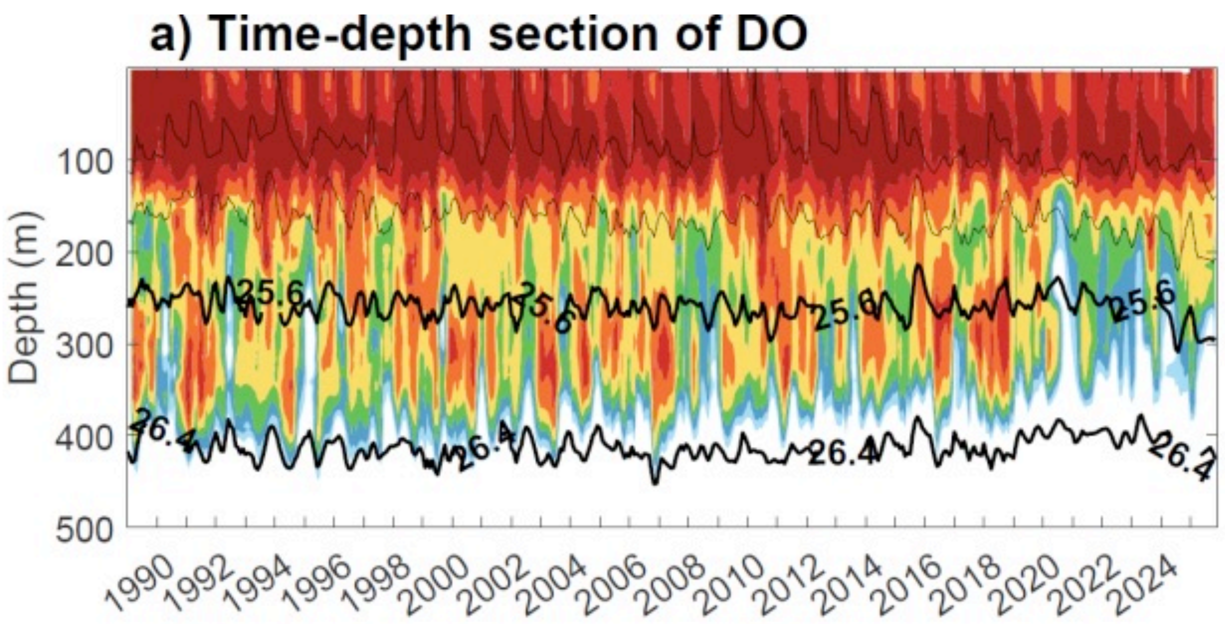






accompanied by a disappearance of subsurface oxygen maximum

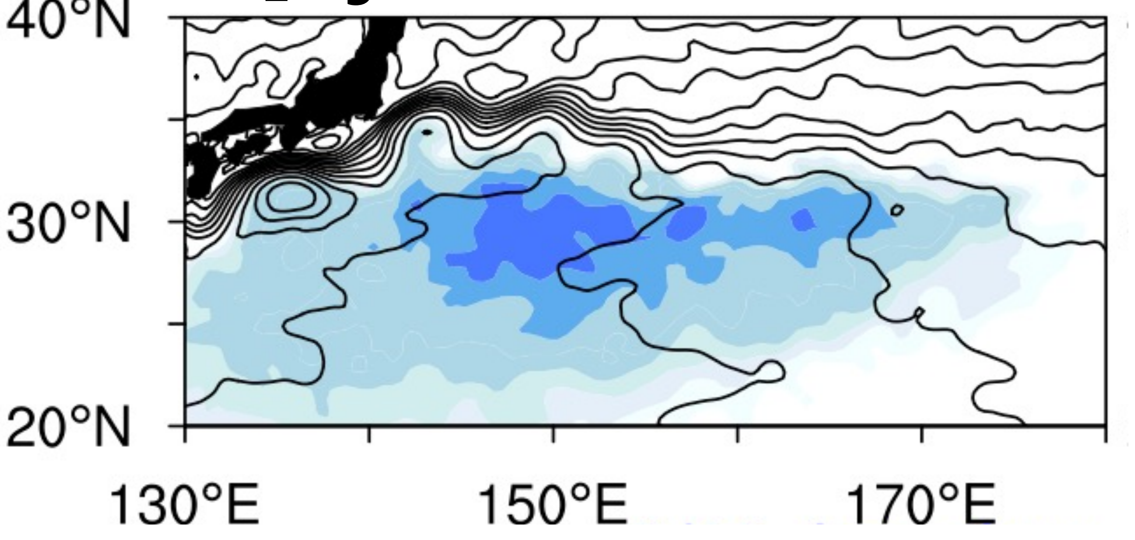




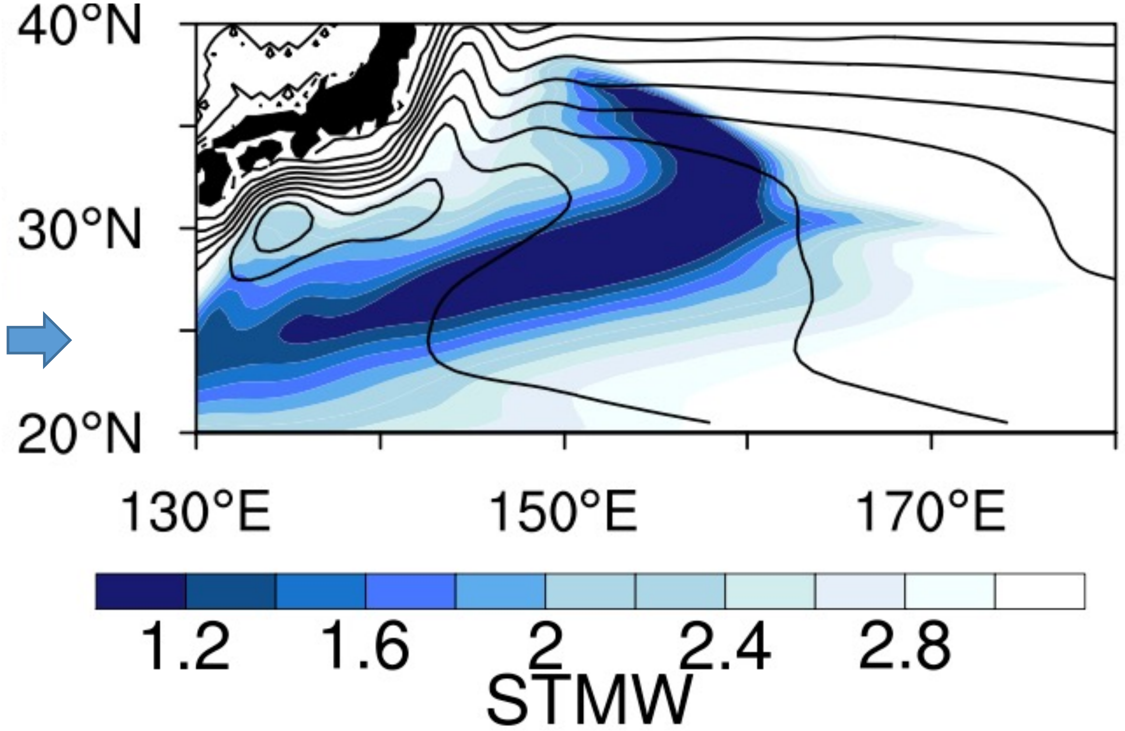
Xu et al., 2026 NC; 2nd review

A large bias b/w climate model and observations

RG_Argo observations



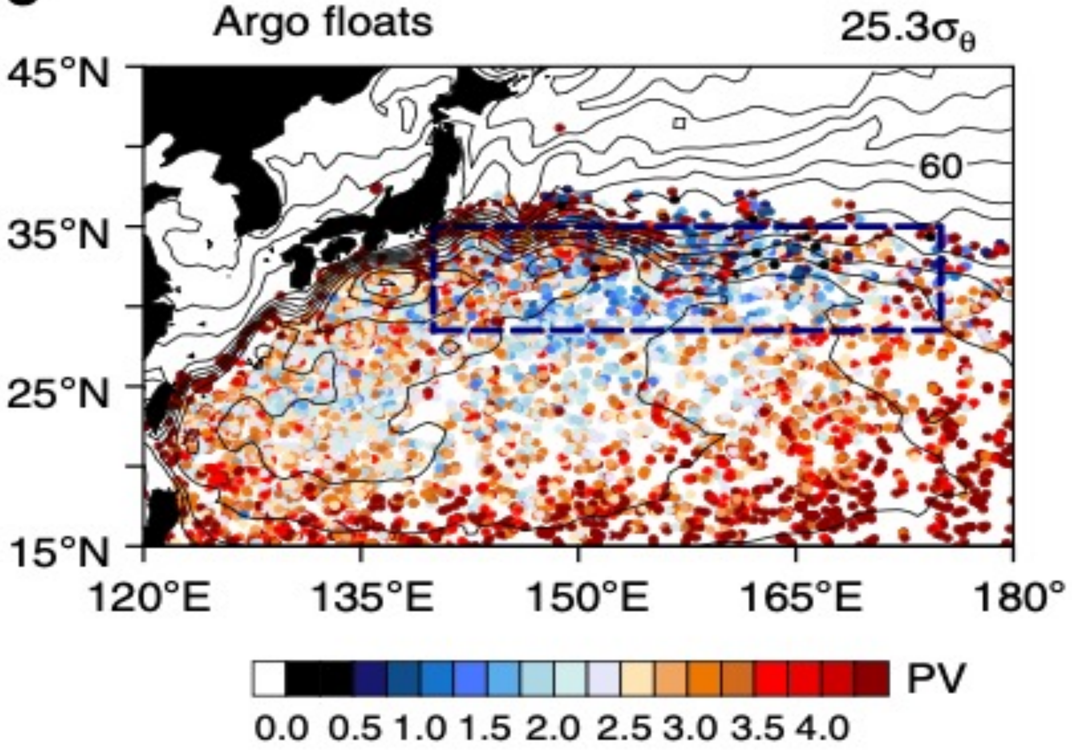
Climate models



too strong

There's 50% percentage of no MW detected in this region

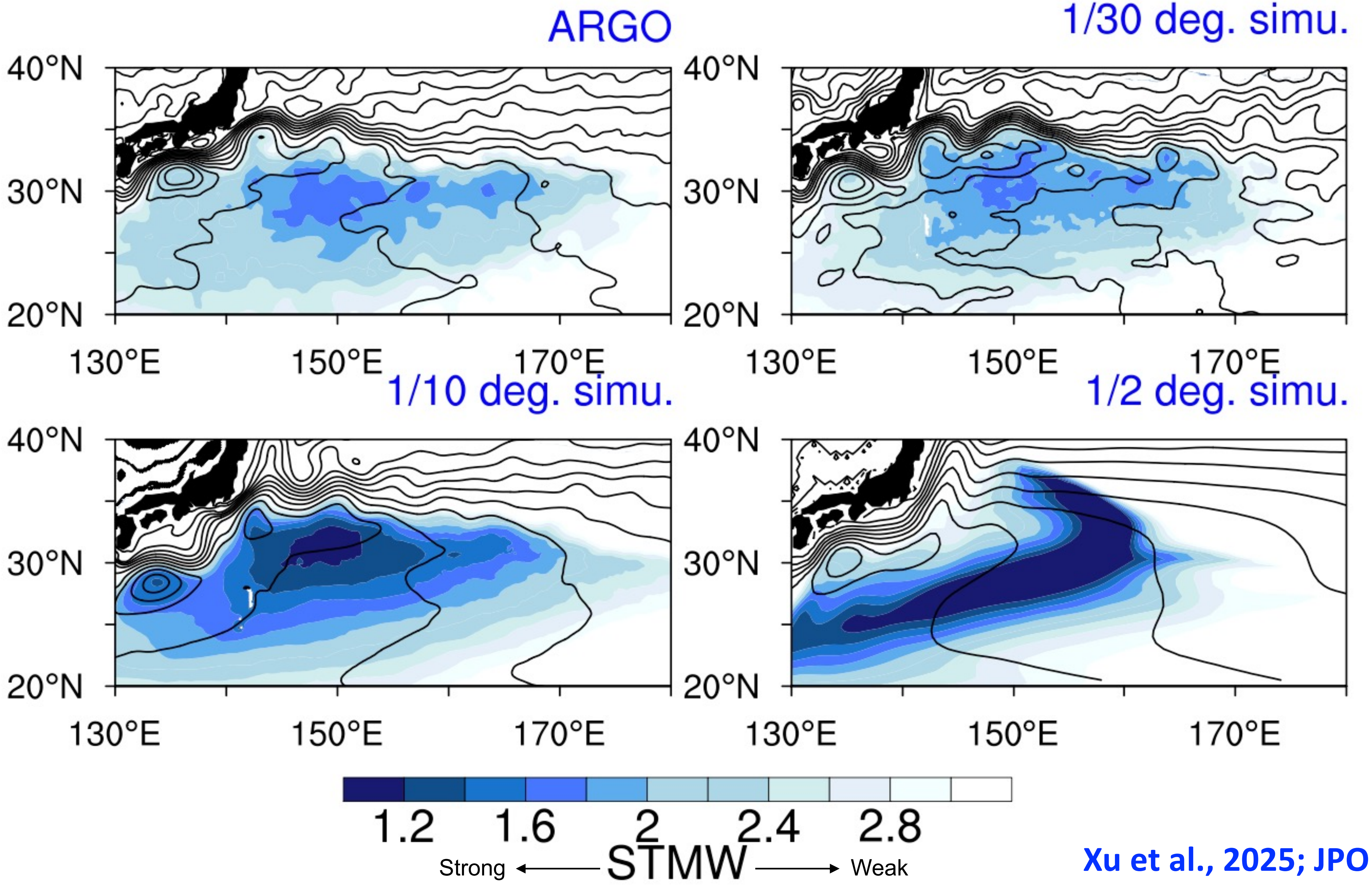
Observed transient state



spatially non-uniform

Xu et al., 2016 NC； 2025 JPO

A large bias b/w climate model and observations



Xu et al., 2025; JPO

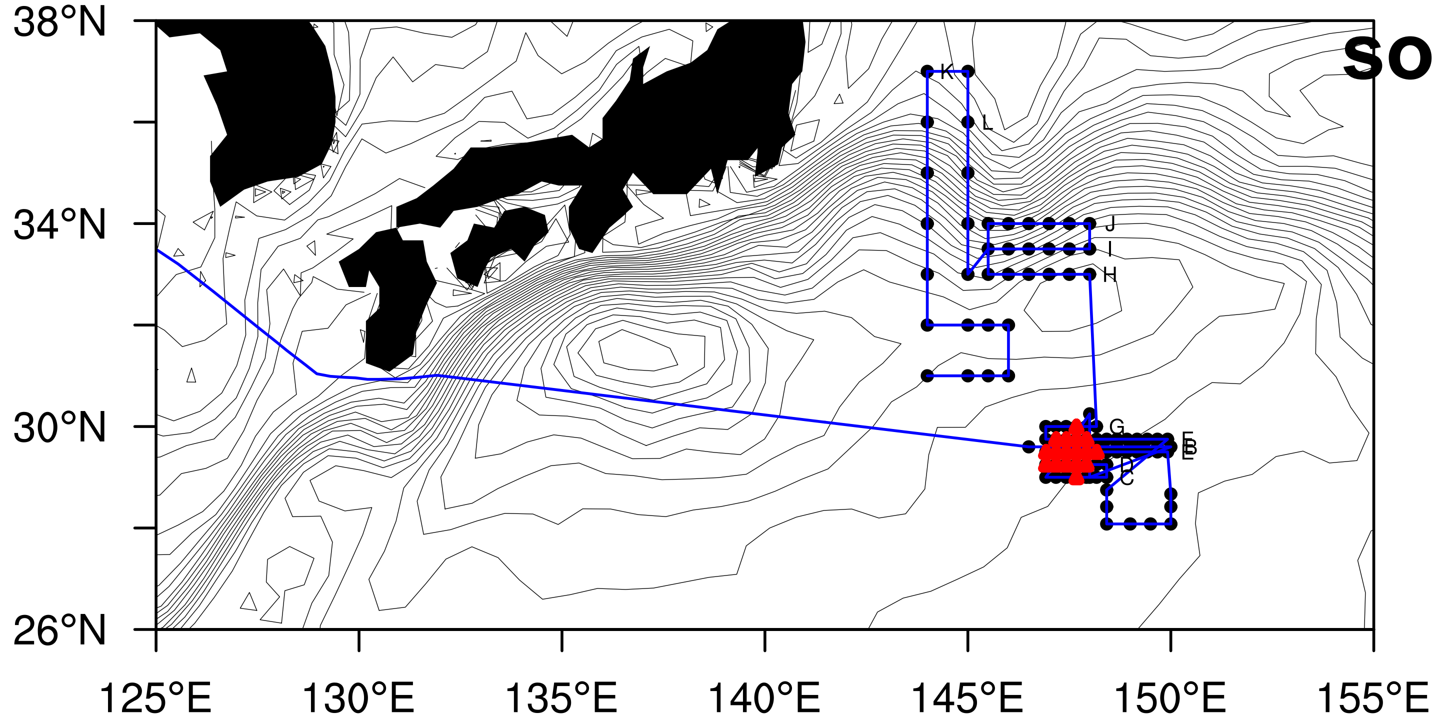
Outline

- Climate impacts
- Role of mesoscale eddies
- Role of submesoscales
- Summary with discussion

Mesoscale eddy effect

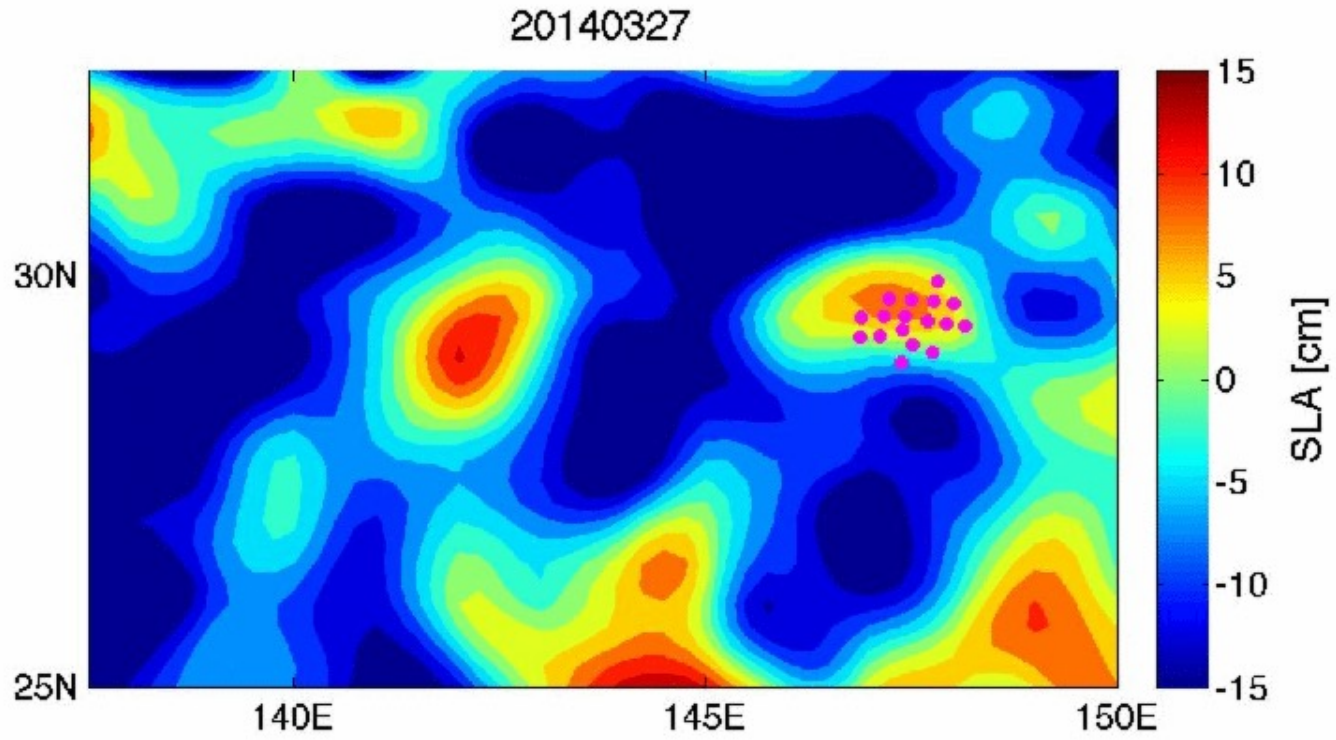
The Pacific Mode-water field experiment (P-MoVE)

2014.03.17-2014.04.23



Black contours: MDT

The P-MoVE Argo floats and the target eddy south of the Kuroshio Extension east of Japan



Parking depth: 500 m
Vertical resolution: 2-10 m
Enhanced daily sampling

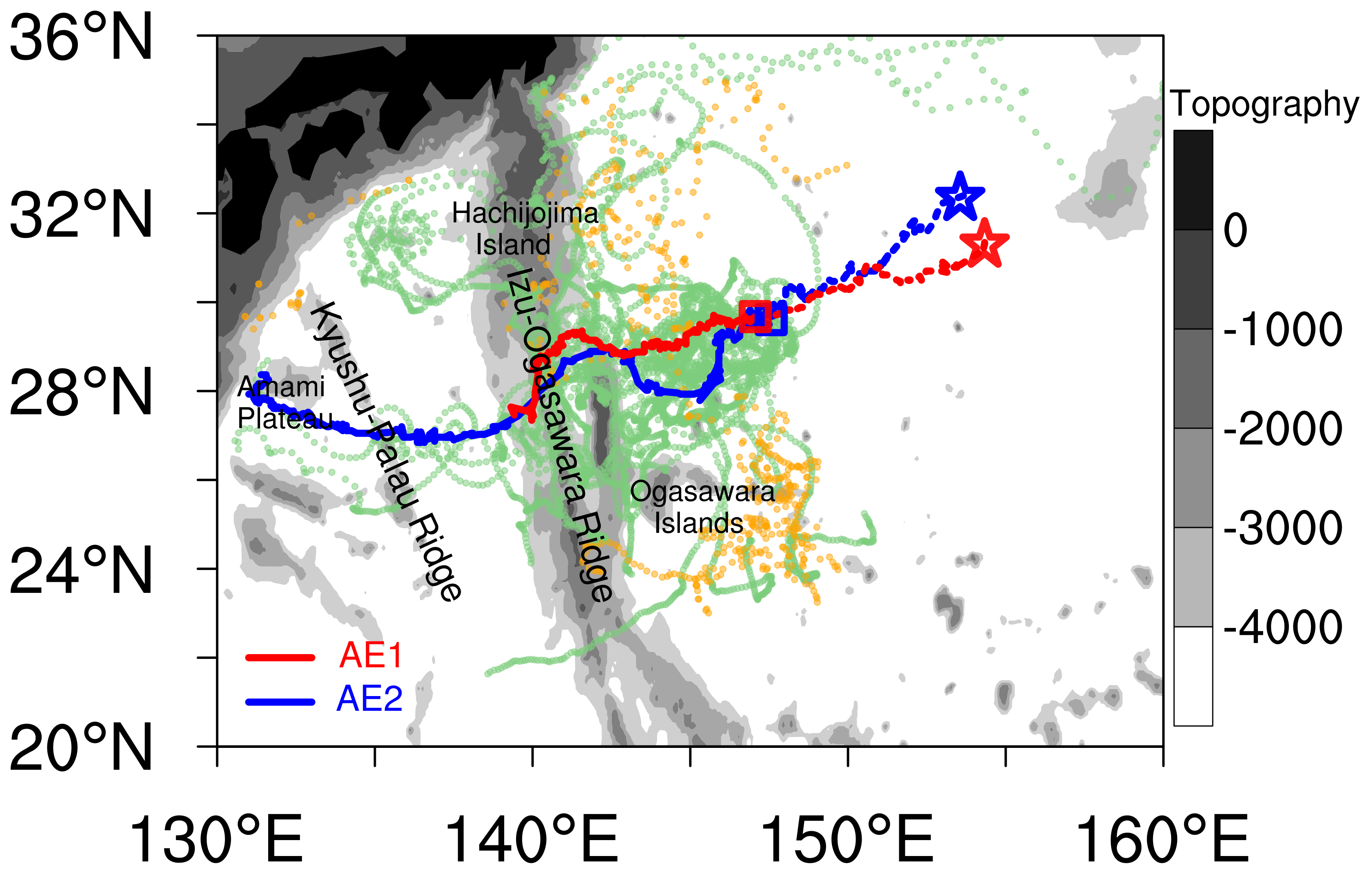
Xu et al. 2016; *Nature Comm.*

Mesoscale eddy effect

- track two AEs (AE1; AE2) originated south of KE with 17 Argo floats for 1.5 years.
- obtained more than 5, 000 Argo profiles following the two AEs

veritcal resolution: <10 m

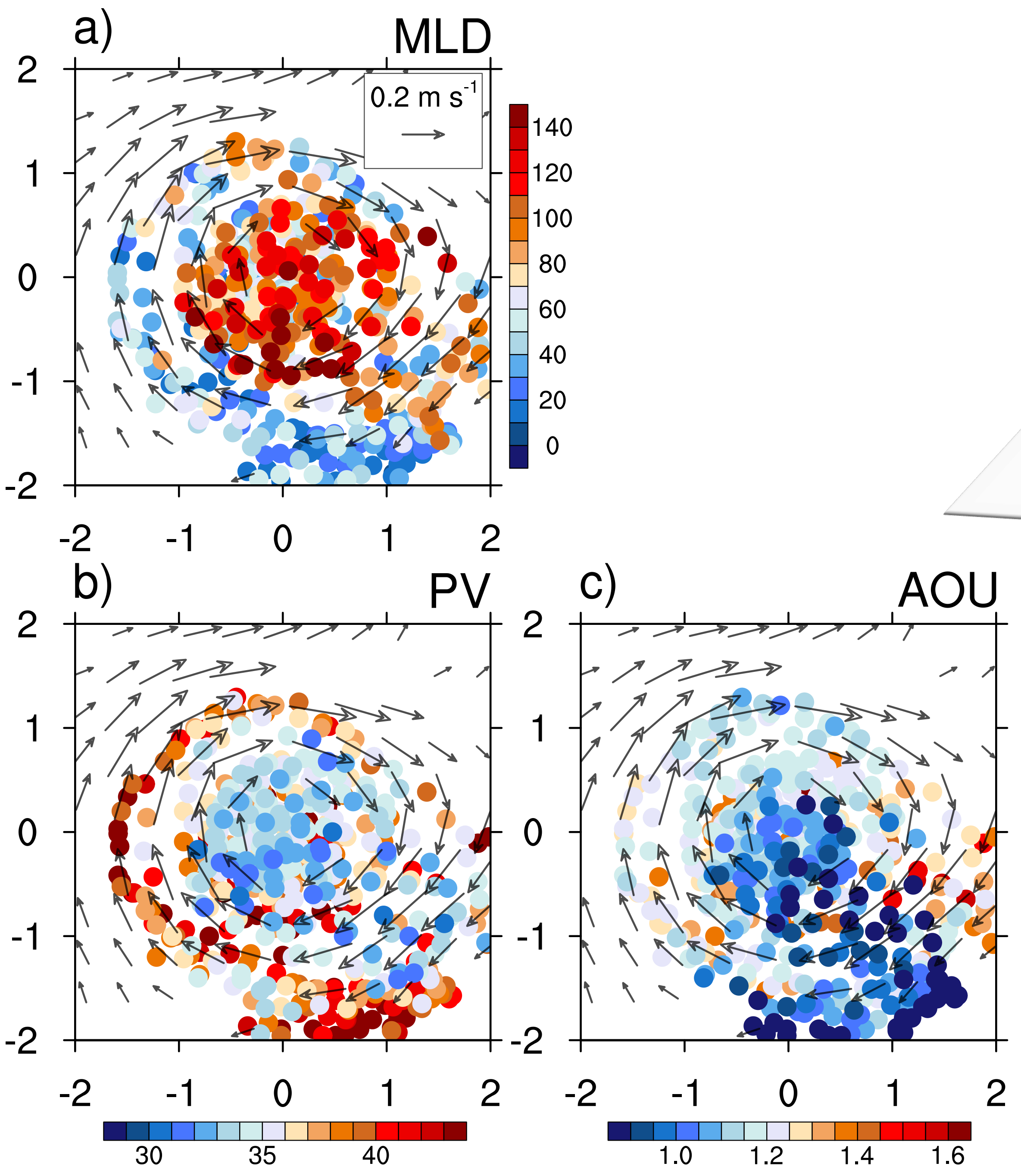
P-MoVE profiles
Historical profiles
by that time

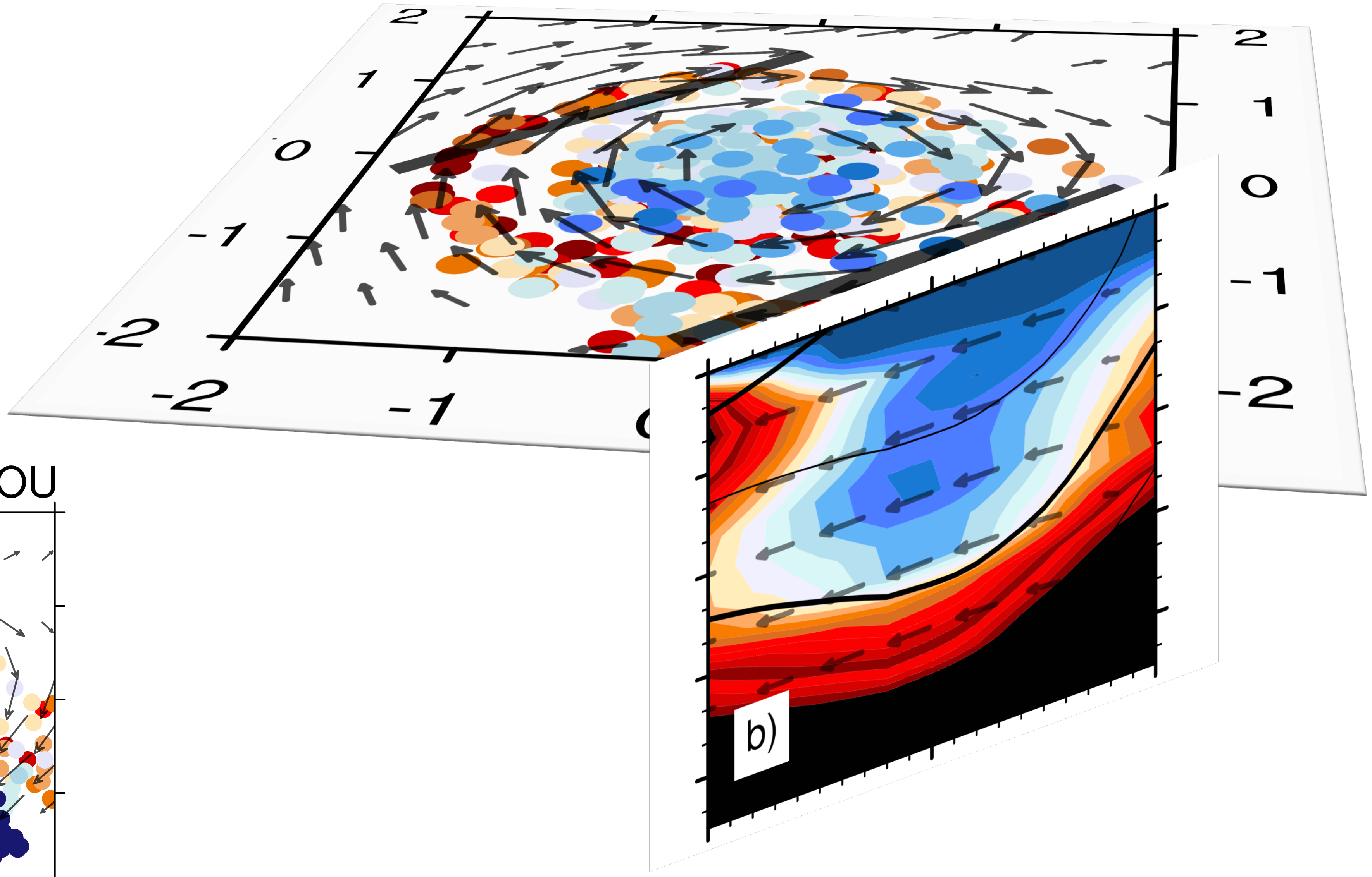


Xu et al., 2017; GRL

Mesoscale eddy effect

Maximum subduction takes place near the southeastern rim of the AE.

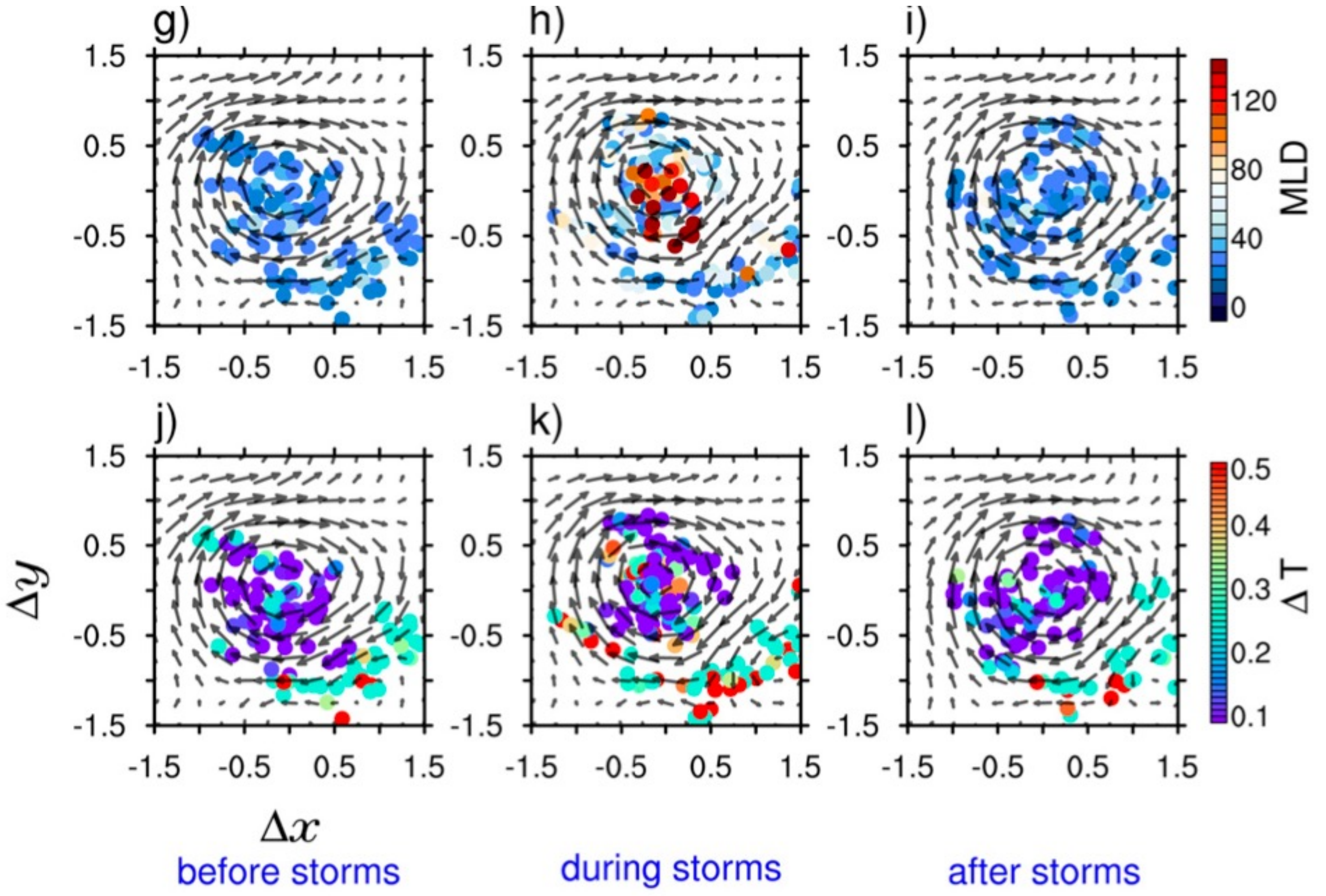


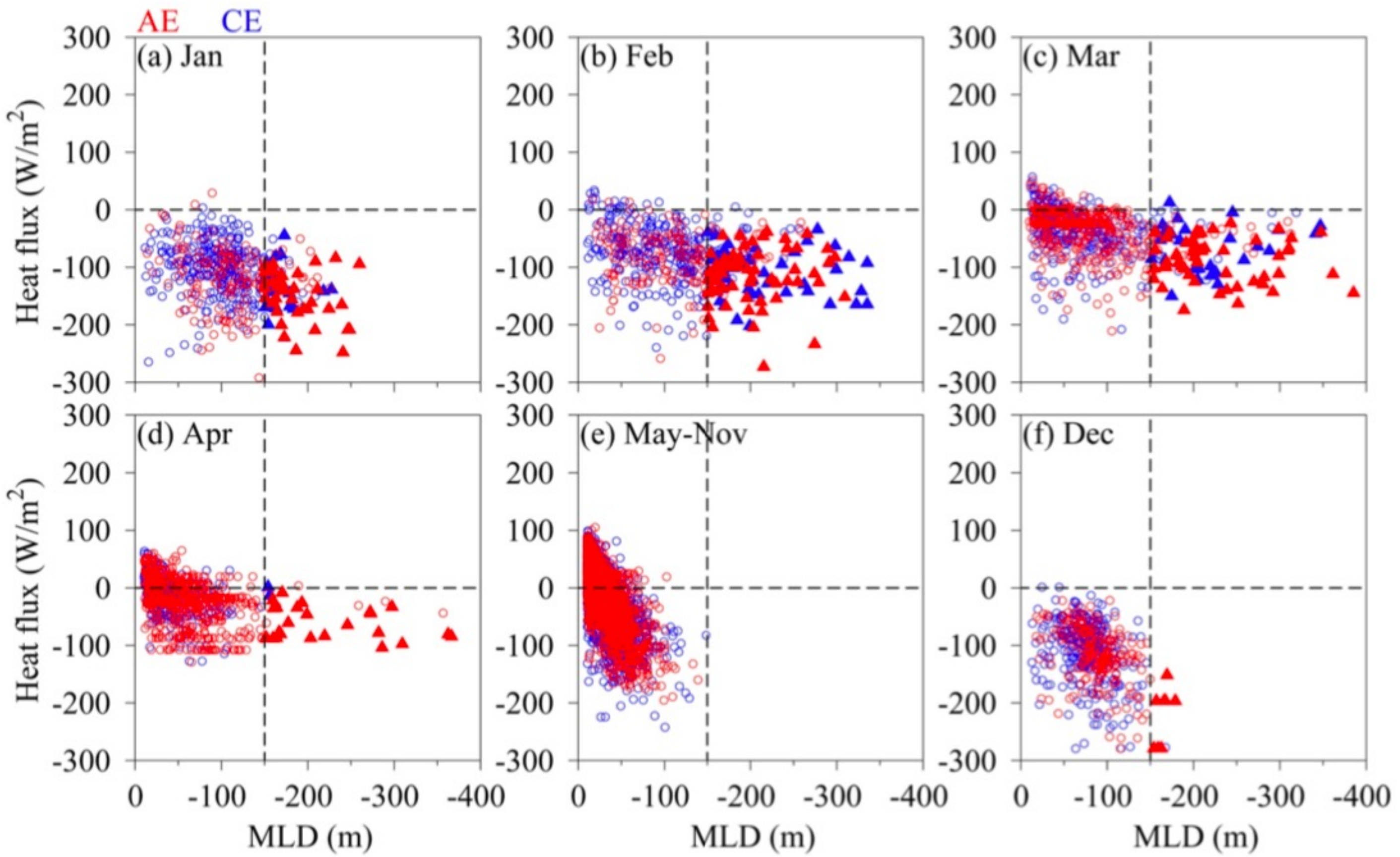


Xu et al. 2016; *Nature Comm.*

Mesoscale eddy effect

- The time period for mixed layer deepening and mode water formation inside AEs are longer than that outside
- In April, the mixed layer inside AEs >150 m during storms, while only 50 m outside





Ding Xu* et al. 2021; *JGR-O*

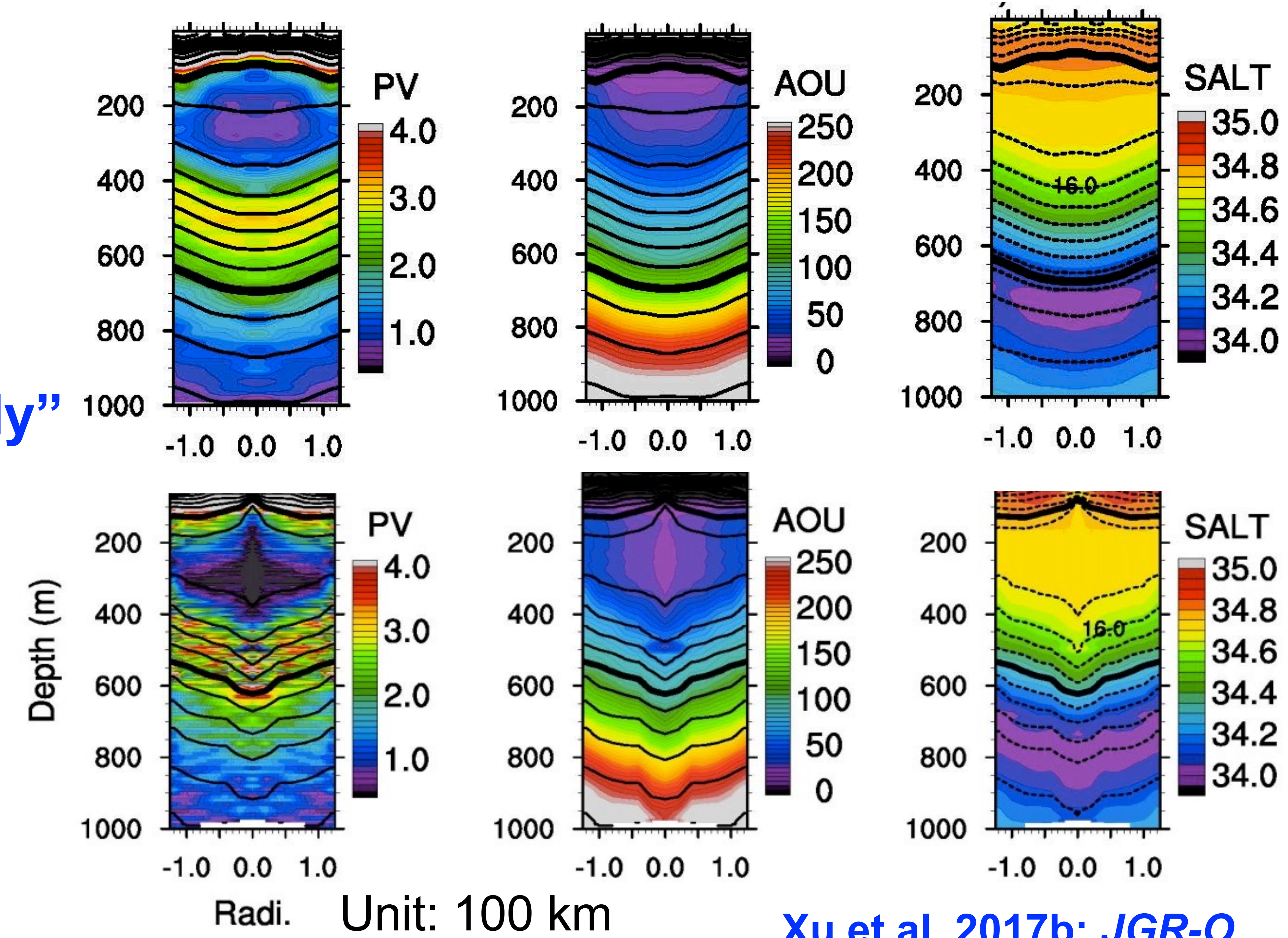
Mesoscale eddy effect

AE1

Lens-shaped

"Mode water eddy"

AE2

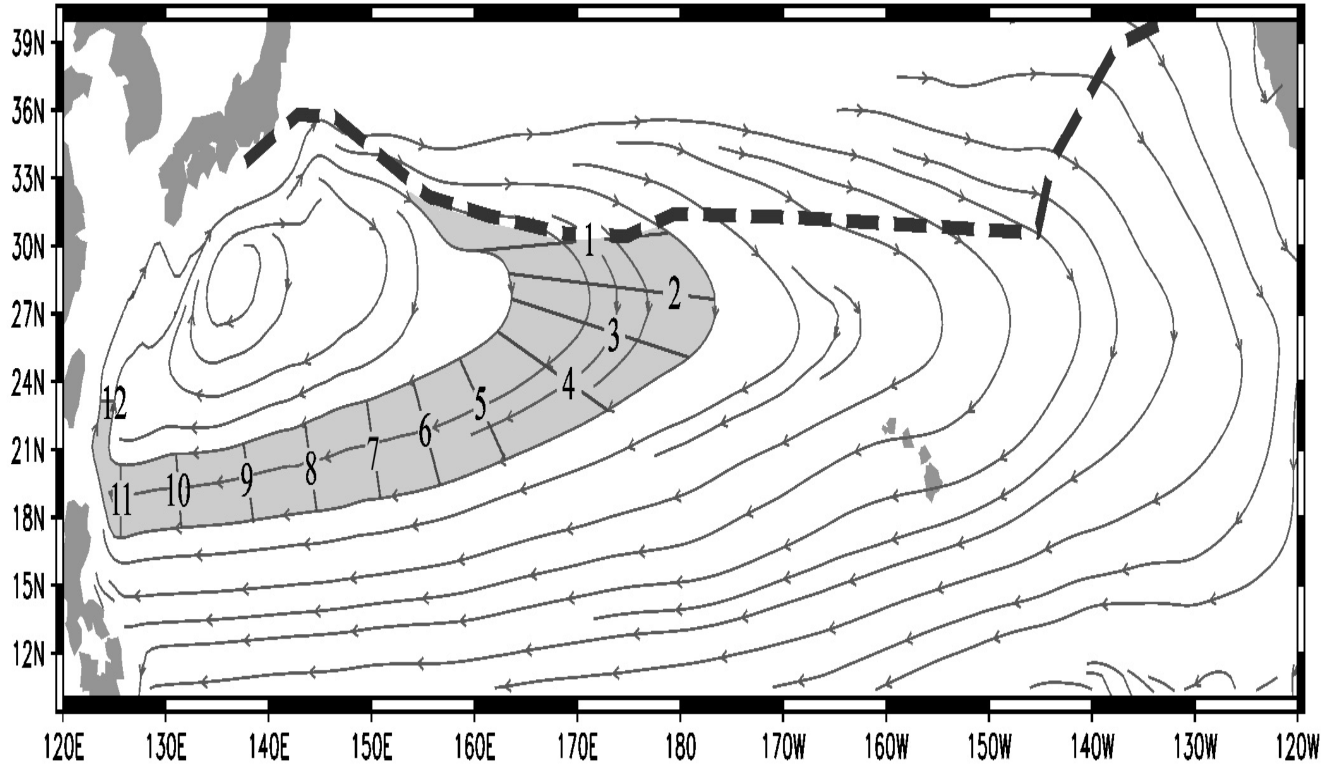


Unit: 100 km

Xu et al. 2017b; *JGR-O*

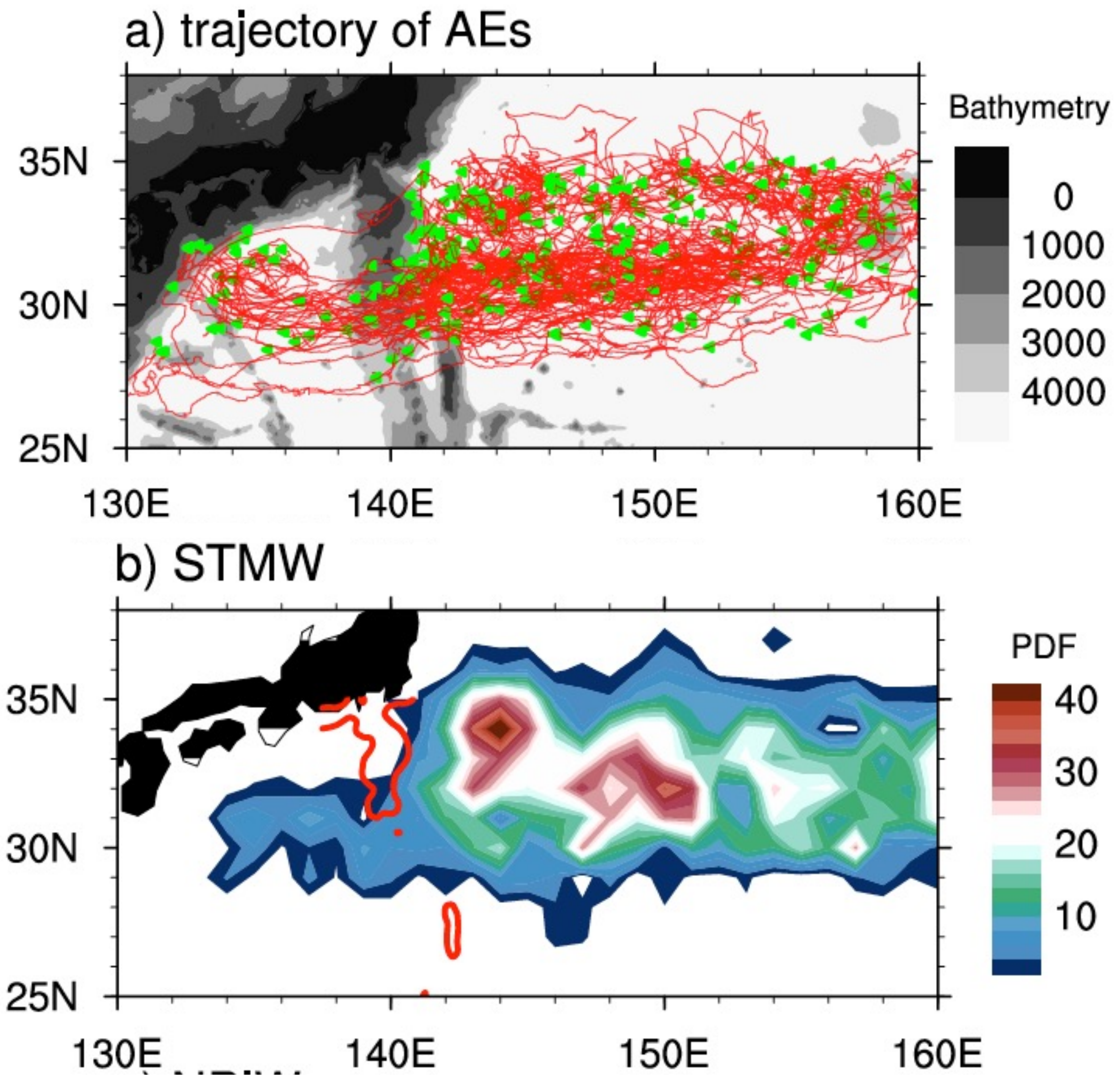
Mesoscale eddy effect

By mean flow, it takes 10 years to arrive western boundary



Liu and Hu, 2007

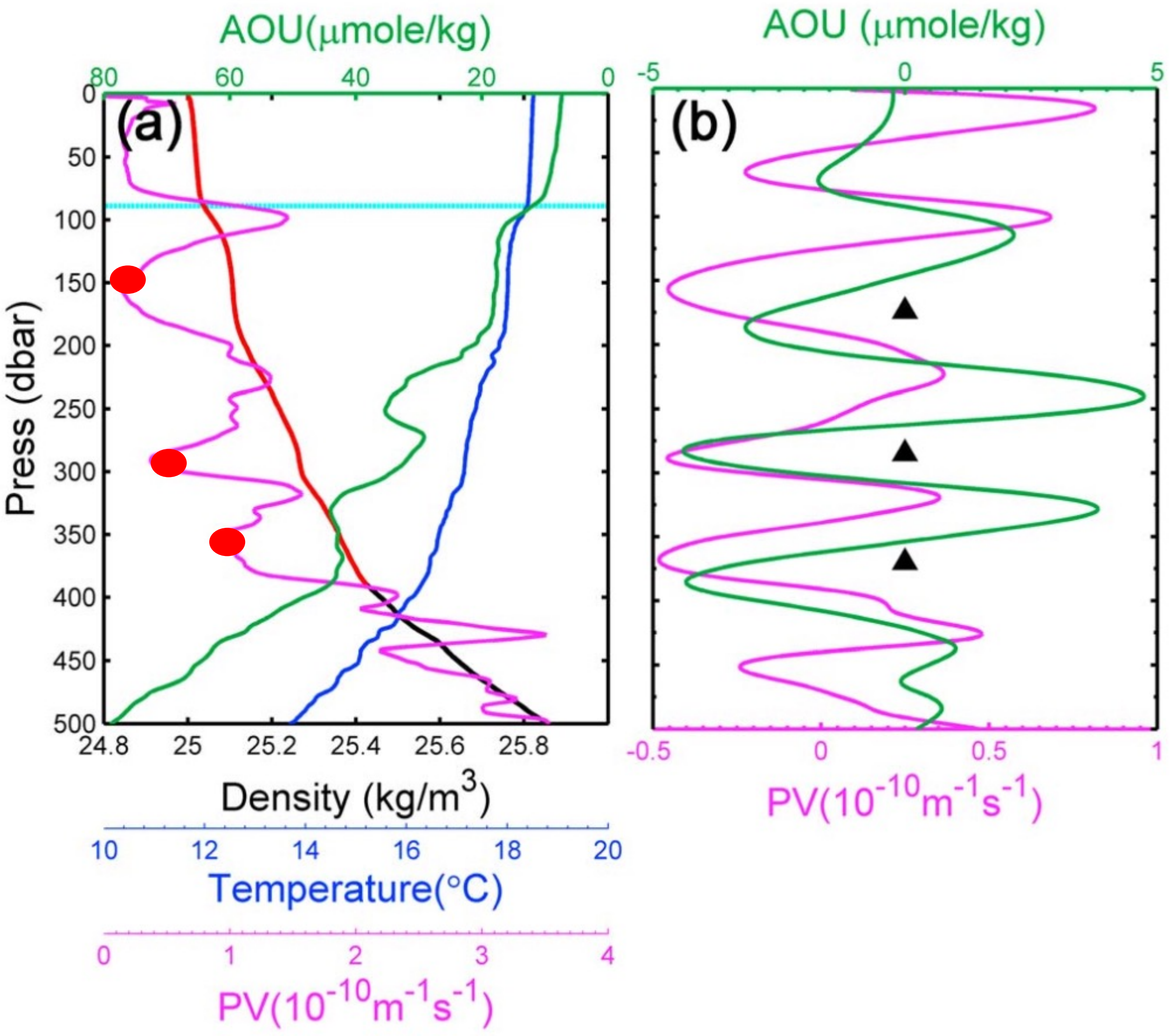
By mesoscale eddies, only 1-2 years



Xu et al. 2017a; GRL
Xu et al. 2017b; JGR-O

Mesoscale eddy effect

STMW multicore structure



with more than one minimum in the vertical PV profile

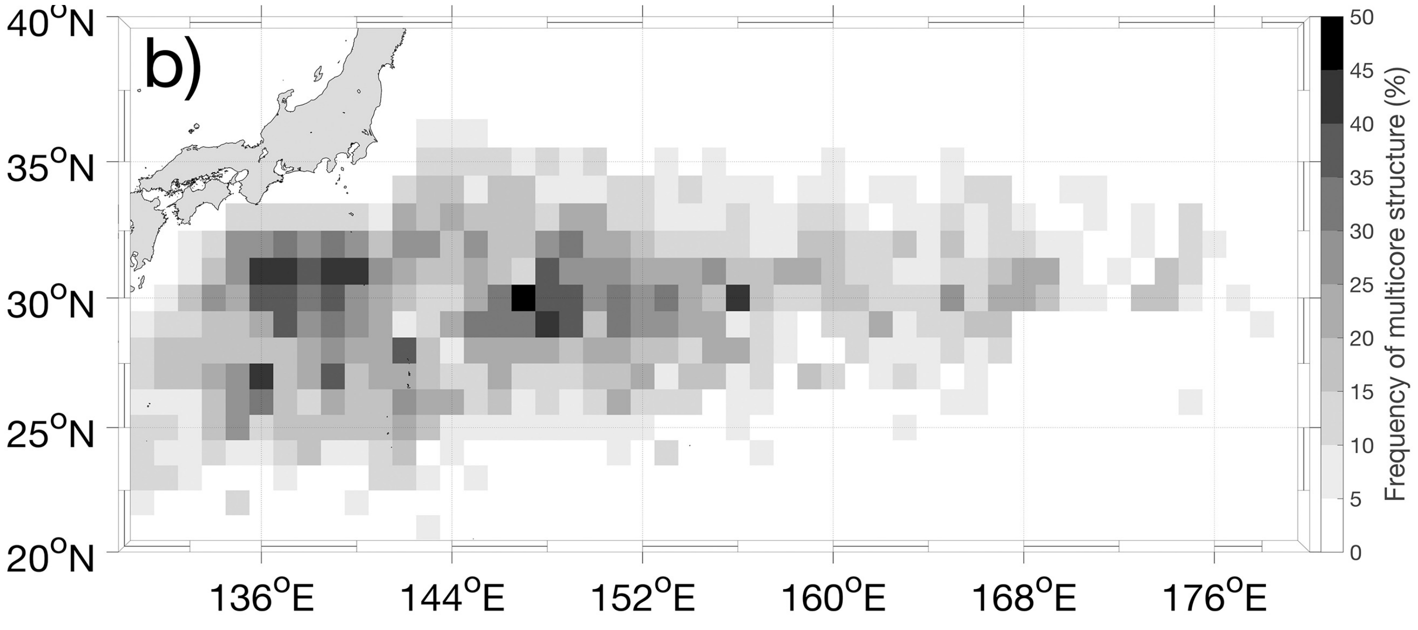
a) Argo Float 2901561 at 29.68°N, 146.83°E on 30 March 2014
b) vertically band passed

Gao et al., 2016; *GRL*

Mesoscale eddy effect

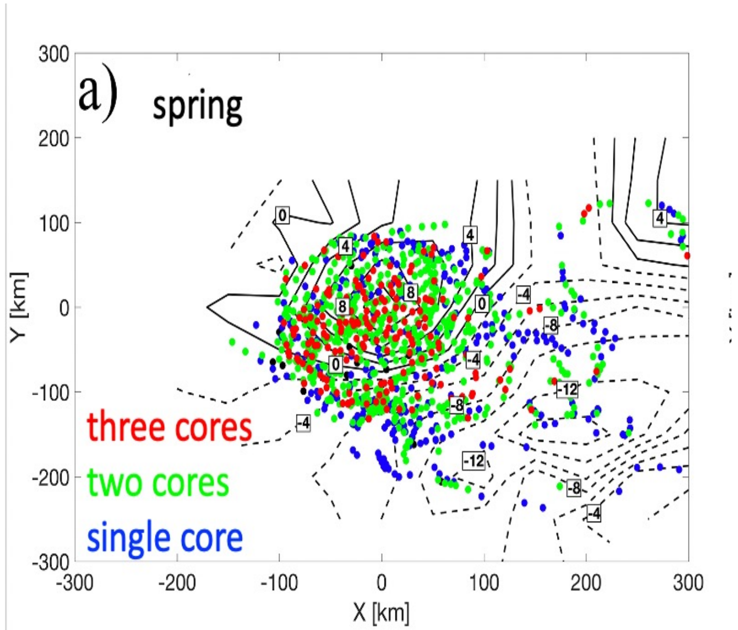
STMW multicore structure widely distributed

PDF of the multicore structure

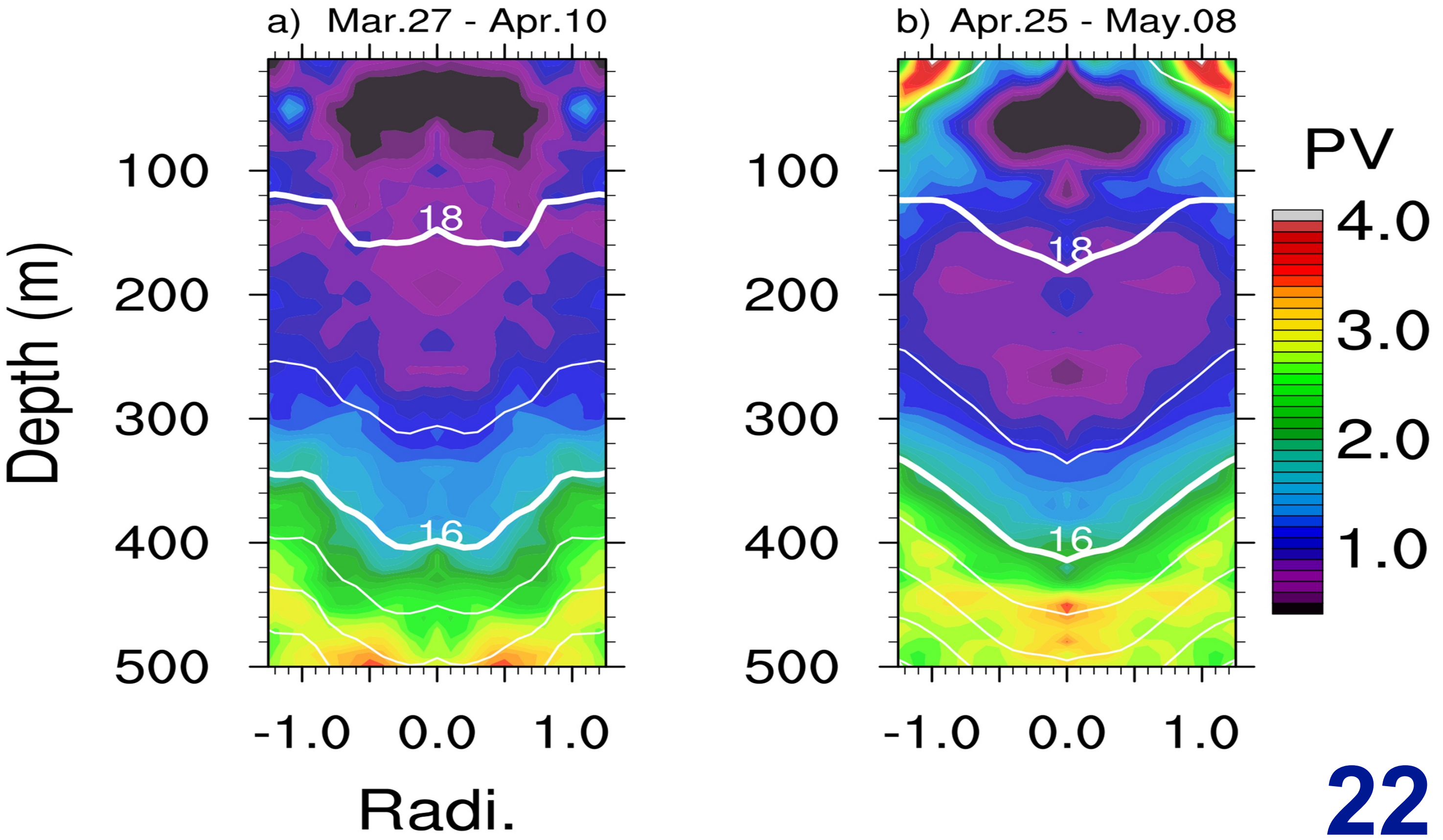


Liu et al., 2017; JGR-O

Liu et al., 2019; *JGR-O*



induced by mesoscale eddies



Outline

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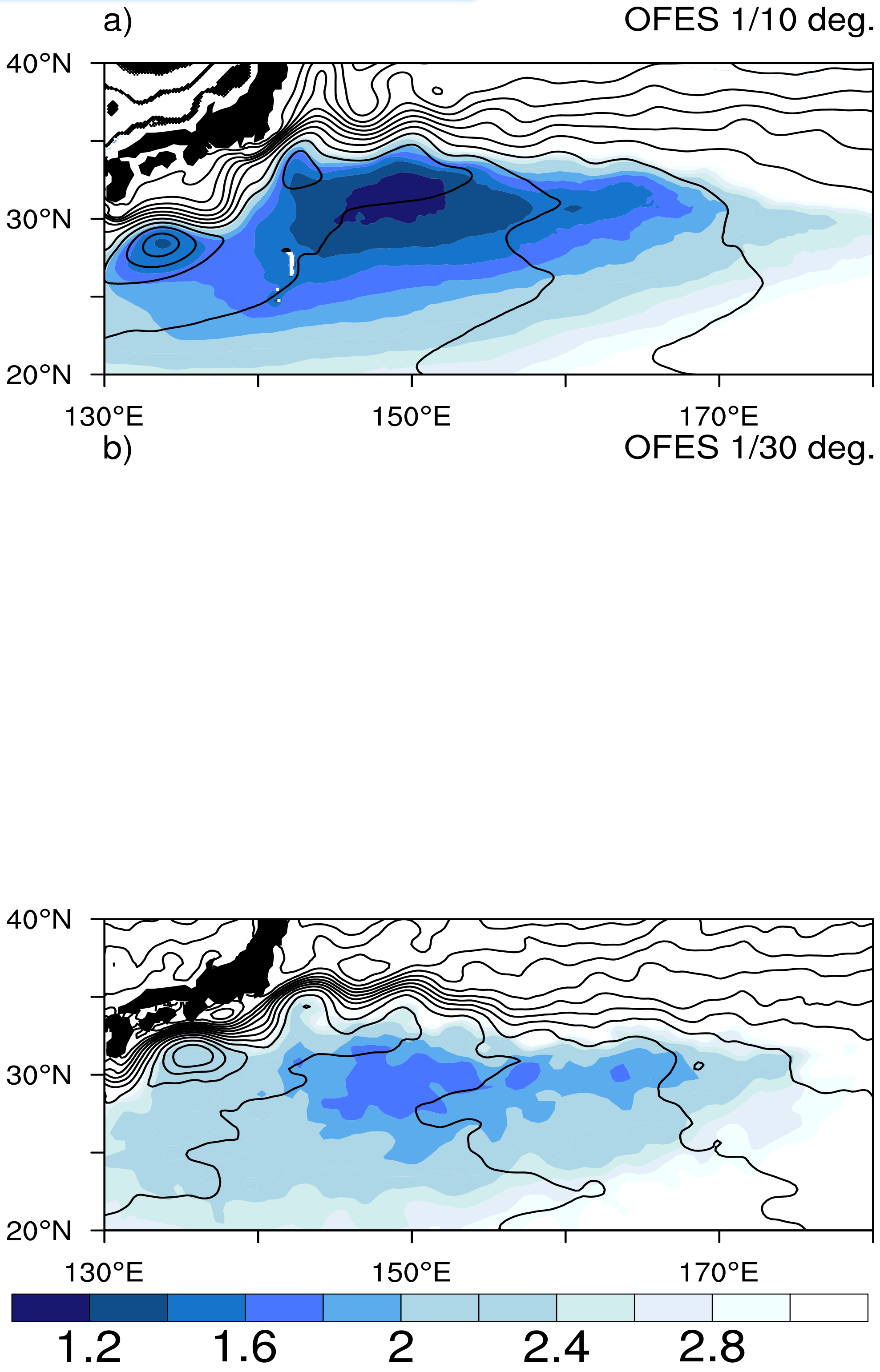
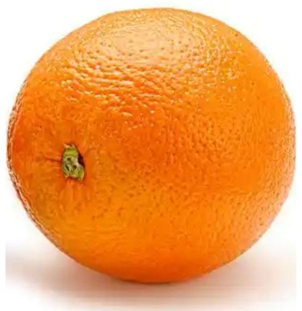
Submesoscale effects

Meososcale resolving

Argo observations



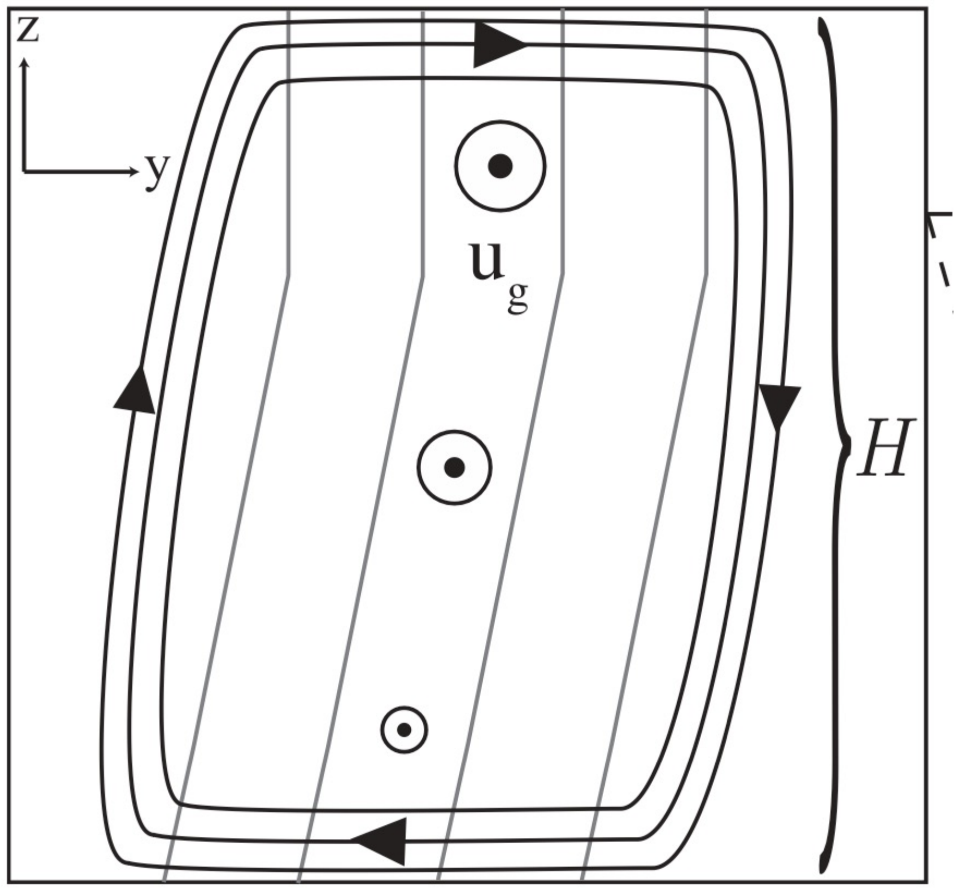
submesoscale effects?



Submesoscale effects

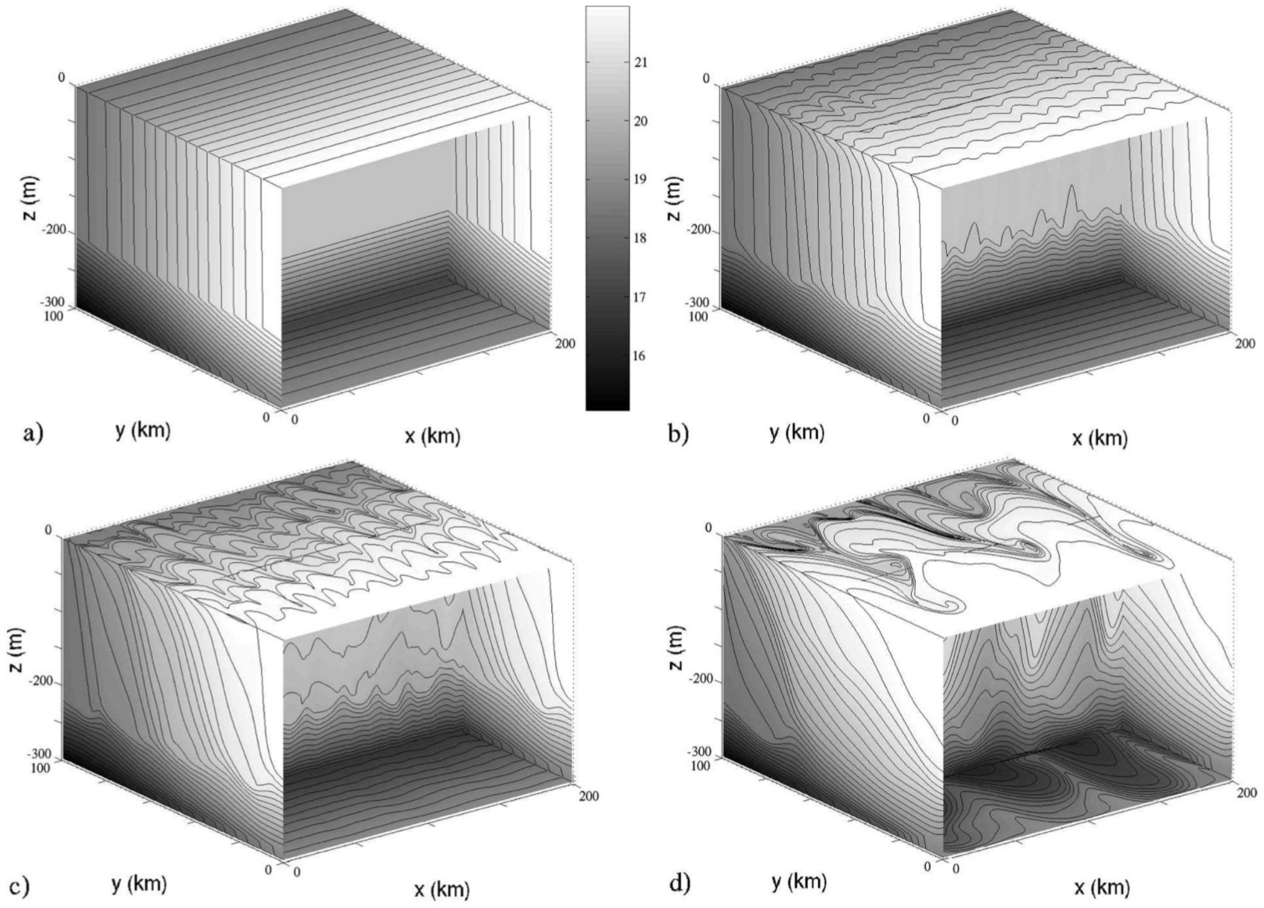
Submesoscale restratification inhibits mode water formation

a restratifying tendency of the TTW circulation



Wenegrat et al. 2018

Mixed layer baroclinic instabilities



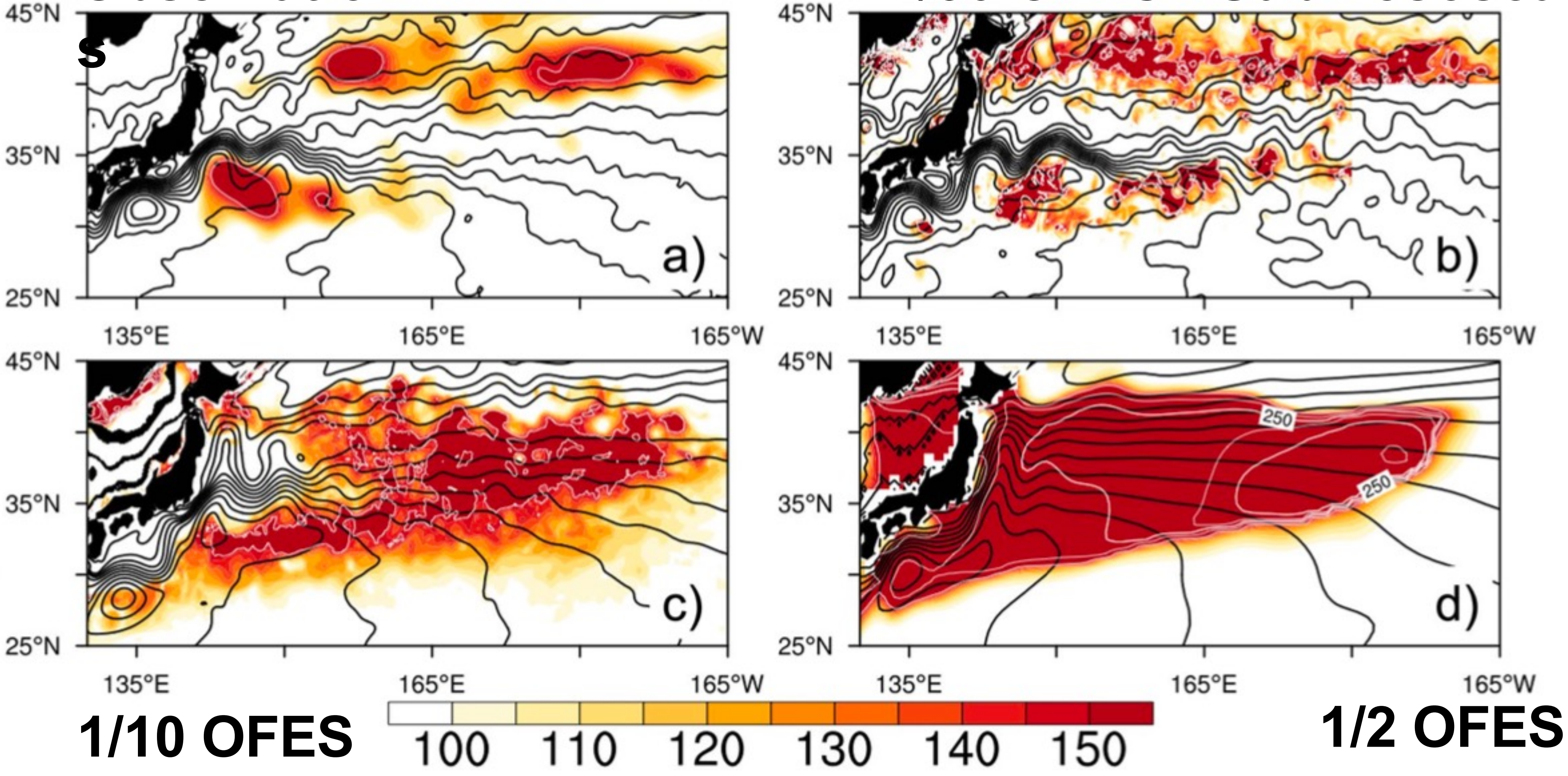
Boccaletti et al. 2007

Hakim et al. 2002; Fox-Kemper et al. 2008; McWilliams 2019; Zhang et al., 2019; Jing et al., 2020; Zhang 2024 … …

Submesoscale effects

changes the winter deep MLD

Observations | 1/30 OFES **Submesoscale permitting**



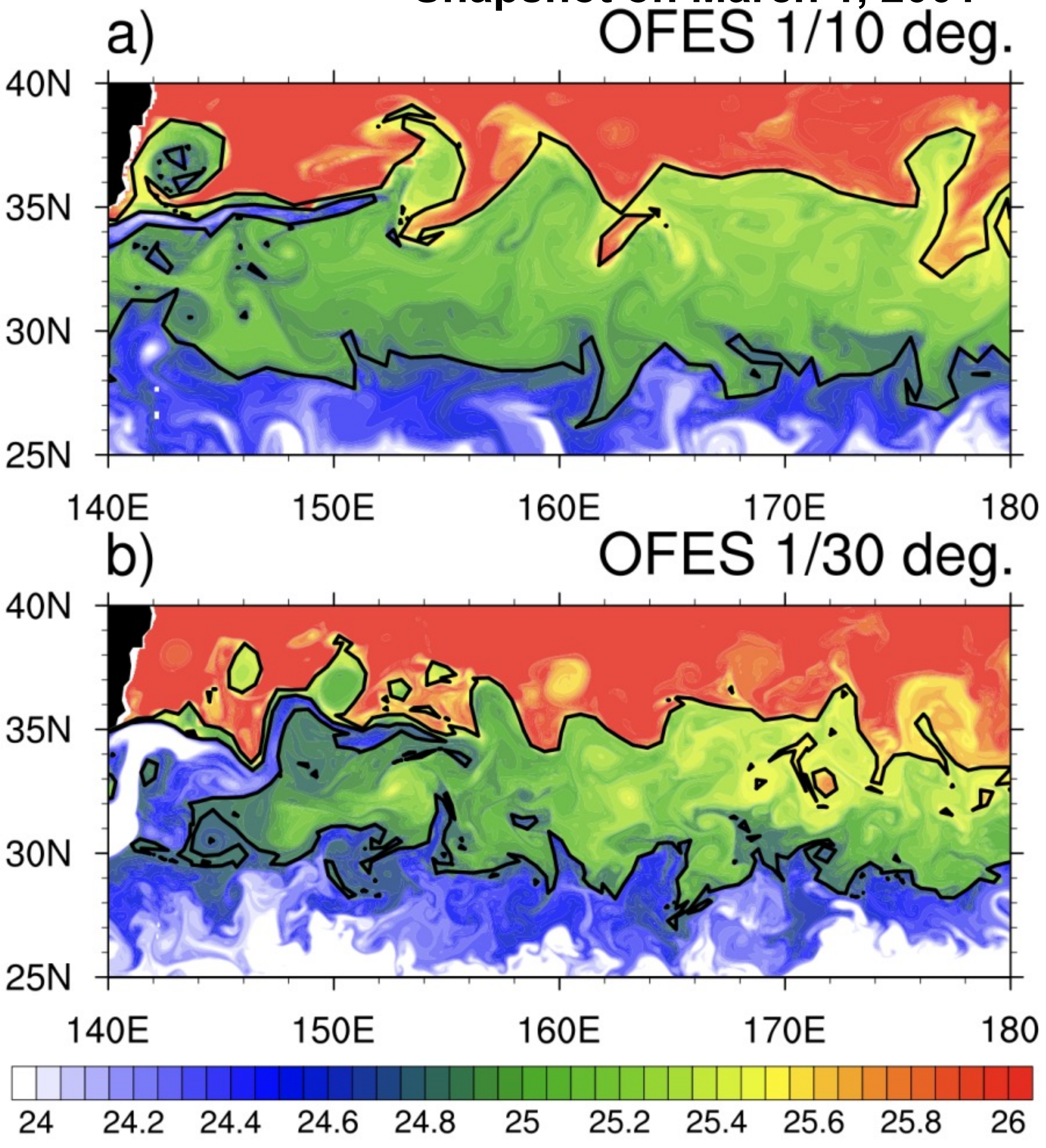
1/10 OFES | **1/2 OFES**

Ding Xu* et al. 2022; *JGR-O*

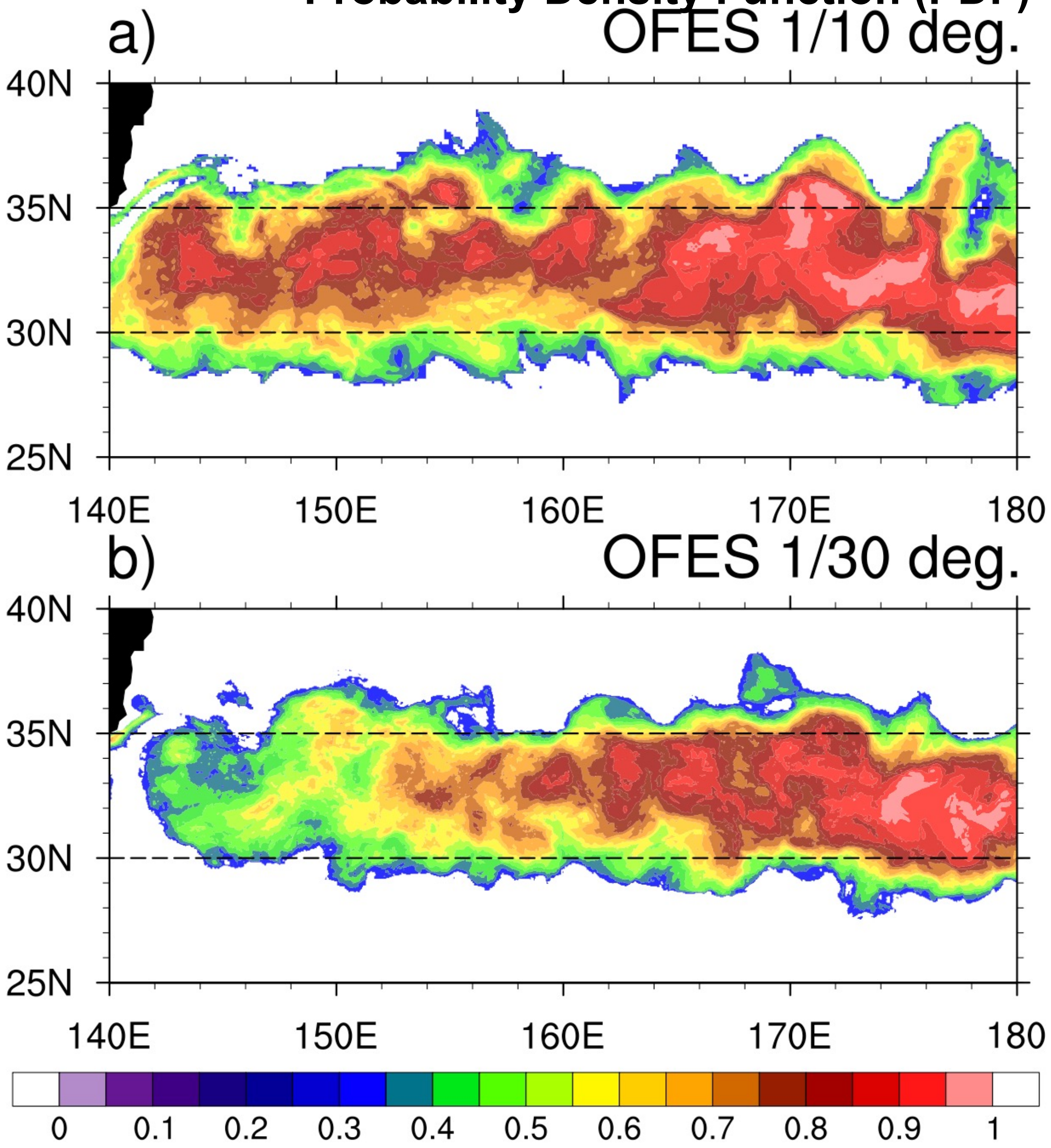
Submesoscale effects

shrinks the ventilation zone

Snapshot on March 1, 2001



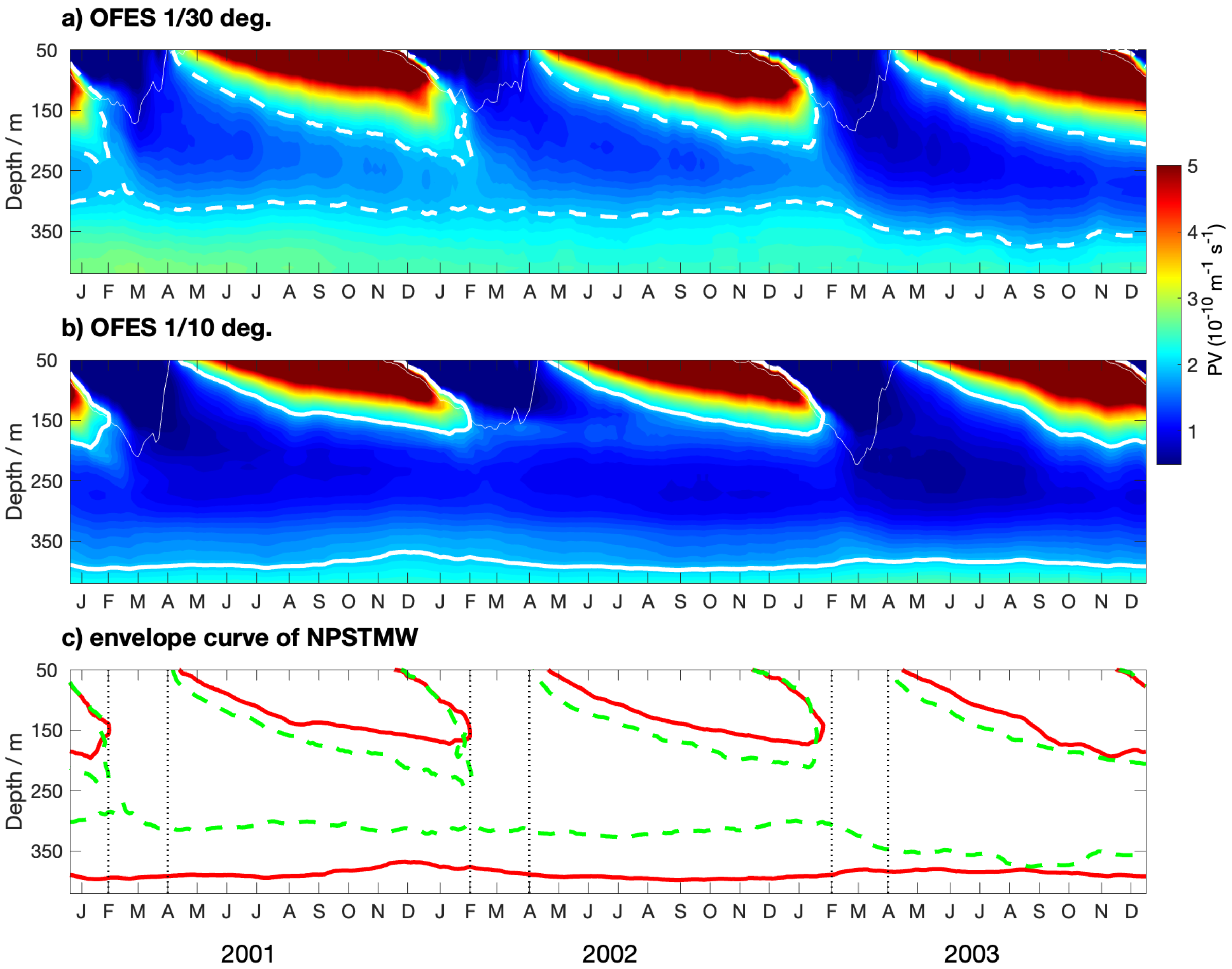
Probability Density Function (PDF)



Xu* et al., 2025；JPO

Submesoscale effects

shortens the ventilation time



Xu* et al., 2025；JPO

Take home messages

- Mode waters are not just a passive water mass, they modulate climate in different ways: thermal-winds, re-emergence of memories

- Caution for the M-W volume budget in climate models (too strong)

- Mesoscale increase subduction & accelerate transport, while submesoscale reduce its formation

Related publications

1. XU L. -X.*, S.-P. Xie, J., McClean, Q. Liu and H., Sasaki, （2014）: Mesoscale Eddy Effect on Subduction of the North Pacific Mode Waters. Journal of Geophysical Research: Oceans, 119, 4867-4886.
2. XU L. -X., P. Li, S. -P. Xie*, Q. Liu, C. Liu, and W. Gao, （2016）: Observing mesoscale eddy effects on mode-water subduction and transport in the North Pacific. Nature communications, 7.
3. GAO W, LI P*, XIE S P, *et al.* Multicore structure of the North Pacific subtropical mode water from enhanced Argo observations[J]. *Geophysical Research Letters,* 2016, 43(3):1249-1255.
4. Xu, L.*, Xie, S.-P., Liu, Q., Liu, C., Li, P., & Lin, X. （2017）. Evolution of the North Pacific subtropical mode water in anticyclonic eddies. Journal of Geophysical Research: Oceans, 122, 10,118-10,130.
5. XU L. –X*, S. -P. Xie, Z. Jing, L. -X. Wu, Q. Liu, P. -L. Li, and Y. Du, （2017）: Observing subsurface changes of two anticyclonic eddies passing over the Izu-Ogasawara Ridge. Geophysical Research Letters, DOI: 10.1002/2016GL072163.
6. Liu, C., Xie, S.-P.*, Li, P., Xu, L., & Gao, W. (2017). Climatology and decadal variations in multicore structure of the North Pacific subtropical mode water. Journal of Geophysical Research: Oceans, 122, 7506–7520.
7. Liu, C., Xu, L.*, Xie, S.-P., & Li, P. (2019). Effects of anticyclonic eddies on the multicore structure of the North Pacific subtropical mode water based on Argo observations. Journal of Geophysical Research: Oceans, 124, 8400–8413.
8. Ding, Y., Xu, L.*, & Zhang, Y. (2021). Impact of anticyclonic eddies under stormy weather on the mixed layer variability in April south of the Kuroshio Extension. Journalof Geophysical Research: Oceans, 126, e2020JC016739
9. XU Lixiao, LIU Qinyu*. (2021). Mesoscale Eddy Effects on Subduction and Transport of the North Pacific Subtropical Mode Water. Advances in Earth Science, 36(9): 883-898. DOI:10.11867/j.issn.1001-8166.2021.085
10. Ding, Y., Xu, L.*, Xie, S.-P., Sasaki, H., Zhang, Z., Cao, H., & Zhang, Y. (2022). Submesoscale frontal instabilities modulate large-scale distribution of the winter deep mixed layer in the Kuroshio-Oyashio Extension. Journal of Geophysical Research: Oceans, 127,e2022JC018915.

Related publications

11. Xu, L., Ding, Y.*, & Xie, S.-P. (2021). Buoyancy and wind driven changes in Subantarctic Mode Water during 2004-2019. Geophysical Research Letters, 48, e2021GL092511. https://doi. org/10.1029/2021GL092511.
12. Xu, L.*; Wang, K.; Wu, B. (2022). Weakening and Poleward Shifting of the North Pacific Subtropical Fronts from 1980 to 2018. Journal of Physical Oceanography, 52(3): 399-417.
13. Wu, B., Xu, L.*, & Lin, X. (2022). Decadal to multidecadal variability of the western North Pacific subtropical front and countercurrent. Journal of Geophysical Research: Oceans, 127, e2021JC018059.
14. Wu, B. & Xu, L.* (2023). Zonally Asymmetric Multidecadal Variability of the North Pacific Subtropical Fronts. Journal of Climate, https://doi.org/10.1175/JCLI-D-22-0299.1.
15. Song, Z., Xie, S.*, Xu, L.*, Zheng, X., Lin, X., & Geng, Y. (2024). Deep Winter Mixed Layer Anchored by the Meandering Antarctic Circumpolar Current: Cross-Basin Variations. Journal of Climate, 37, 3741-3757.
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18. Liang, W., Ding, S., Wang, K., Long, S.-M., Liu, Q., Jin, Y., & Xu, L.* (2025). The weakening and poleward migration of the Southeastern Front associated with the South Indian Countercurrent from 1980 to 2023. Journal of Geophysical Research: Oceans, 130, e2024JC021961
19. Wang, K., L. Xu, Y. Luo, Z. Li, and J. Li, 2025: Eddy-Induced Subduction of the Subantarctic Mode Water in the Southern Ocean from 2004 to 2023. J. Phys. Oceanogr., 55, 2297–2311
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Thanks!

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https://pol.ouc.edu.cn/2020/0526/c18909a288386/page.html

Photos: 2026 New year in Qingdao, hiking with my students