

The dynamical mechanism controlling the equilibrium state transition within the Mindanao-New Guinea Confluence

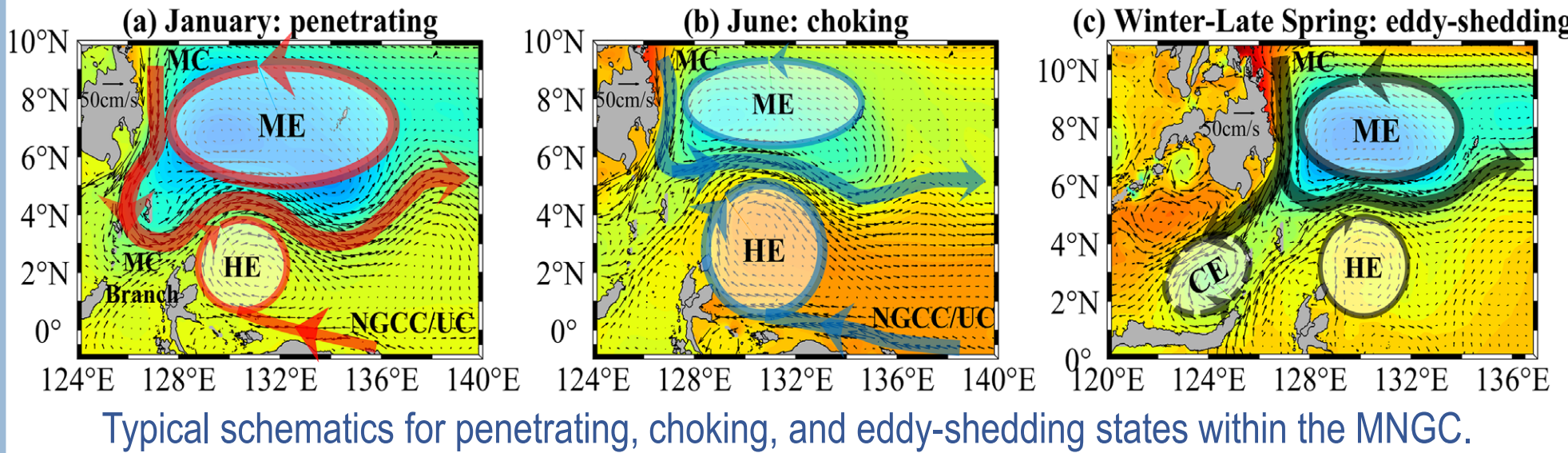
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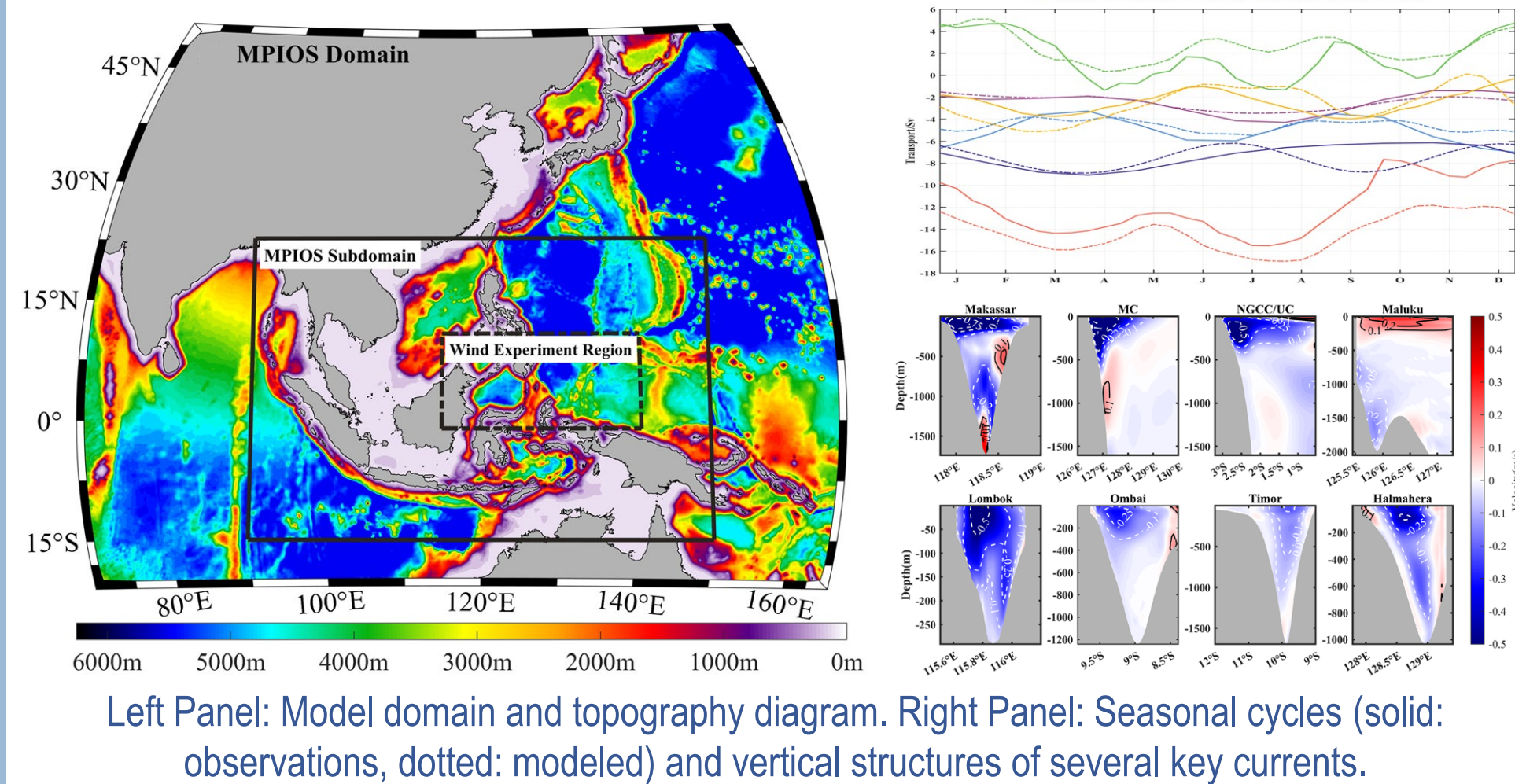
Introduction

The two western boundary currents of the low-latitude Pacific: the Mindanao Current (MC) and the New Guinea Coastal Current/Undercurrent (NGCC/UC), meet at an area north of New Guinea and south of Mindanao Island, forming the **Mindanao-New Guinea Confluence (MNGC)**. Previous studies demonstrated three kinds of equilibrium states: **penetrating, choking, and eddy-shedding**, exist within the MNGC, and the three has been confirmed by satellite and in-situ observations. However, the dynamical mechanism controlling the transition among three equilibrium states was not clear. Consequently, based on a well-established regional ocean model, entitled Modeling Pacific and Indian Oceans System (MPIOs), the **meridional sea surface height (anomaly) seesaw mechanism** was uncovered by multiple numerical experiments. Firstly, the zonal-mean sea surface height and relative vorticity fields within MNGC were found to be good indicators for the equilibrium state transition. The experimental results indicated that **the local monsoon and the remote equatorial Rossby waves** from the central Pacific are the primary processes modulating the seasonal transitions between penetrating and choking states. The analysis revealed that the sea surface height anomaly between Mindanao Eddy and Halmahera Eddy was highly related to the seasonal state transition, which was controlled by the local winds and the remote Rossby waves and their phase relationship. Moreover, this meridional sea surface height anomaly seesaw could induce geostrophic transport anomalies, modulate the leakage and retroflection of the MC, and thus lead to **variation of upper-layer Indonesian Throughflow (ITF)**. Through experimental results, this mechanism is applicable not only to seasonal variability, but can also to interannual variability within MNGC and the upper-layer ITF. Besides, under some specific conditions of local winds and remote Rossby waves, the **eddy-shedding state appears** and consequently breaks the seasonal transition between penetrating and choking states. This study has proposed a novel mechanism for the equilibrium state transitions within the MNGC and has provided new insights into the ITF variations.



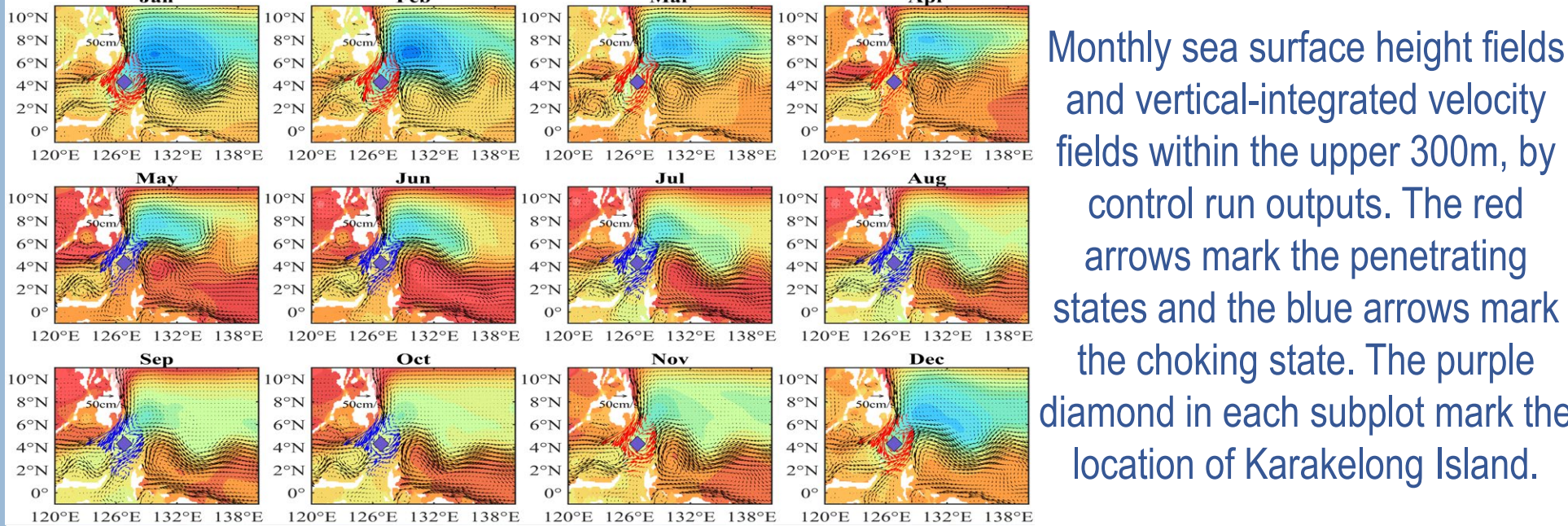
Data and Model

The MPIOs is based on ROMS. The model covers the western Pacific Ocean, eastern Indian Ocean, and Indonesian archipelago (69° E-166° E, 21° S-51° N). The high-resolution model has a horizontal resolution of $1/30^\circ \times 1/30^\circ \cos \phi$. Vertically, the model is divided into **50 terrain-following sigma layers**, and adopts the KPP scheme. The bathymetry was derived from ETOPO dataset. The model was **initiated** with the monthly mean temperature and salinity in January derived from WOA13. It is integrated for 20 years to spin-up and **forced by monthly mean climatological data** with a 360-day cycle. The climatology data at the air-sea interface was from COADS. The **open boundary conditions** are provided by monthly mean HYCOM dataset. The MPIOs also forced with **explicit tidal forcing** from the TPX08 tidal model with ten constituents. As we focus on the Indonesian seas and the related Pacific low-latitude WBCs dynamics, a **subdomain model covering 90° E-150° E, 15° S-23° N** was then established, whose configurations are the same as the MPIOs. Both the MPIOs and the subdomain model have been validated with satellite and in-situ observations, that the model can well reproduce the three-dimensional oceanic dynamics around the Indonesian seas. We also used AVISO data to conduct analysis.



Equilibrium State Diagnostics

Qualitatively, the transitions between the penetrating and choking states can be easily diagnosed by **the emergence and disappearance of the branch of MC around Talaud Island**. The MC branch recirculates in the northern Maluku Sea and finally returns eastward in boreal winter and disappear through boreal summer. It has been identified quantitatively by calculating transport anomaly crossing the zonal section between Karakelong Island and Sangihe Island. The meridional transport anomaly cross the zero line in April and October, with negative values under penetrating state and positive values under choking state.



Experimental Designs

Table Designs of local winds sensitivity experiments and ideal Rossby waves adding experiments. BRY is the model boundary condition, FRC is the model forcing, and INI is the model initial condition. The model outputs of the third year were used to analyze to ensure the model reach a steady state.

EXP List	BRY	FRC	INI
Control	Monthly	Monthly	Dec/30&June/30
EXP1	Annual mean	Annual mean	Dec/30
EXP2	Monthly	Annual mean	Dec/30
EXP3	Annual mean	Monthly	Dec/30
Exp4	Jan(penetrating)	Monthly	Dec/30
Exp5	Jul(choking)	Monthly	June/30
Exp6	Jan(penetrating)	Annual mean	Dec/30
Exp7	Jul(choking)	Annual mean	June/30
EXP8	Annual mean but added ideal equatorial Rossby waves	Monthly	Dec/30
EXP9	The phases of added Rossby waves lag EXP8 3 months	Monthly	Dec/30
EXP10	The phases of added Rossby waves lag EXP8 6 months	Monthly	Dec/30
EXP11	The phases of added Rossby waves lag EXP8 9 months	Monthly	Dec/30

The ideal equatorial Rossby waves were conducted by the linear equatorial dynamics, where the sea surface height and velocity anomalies are as follows:

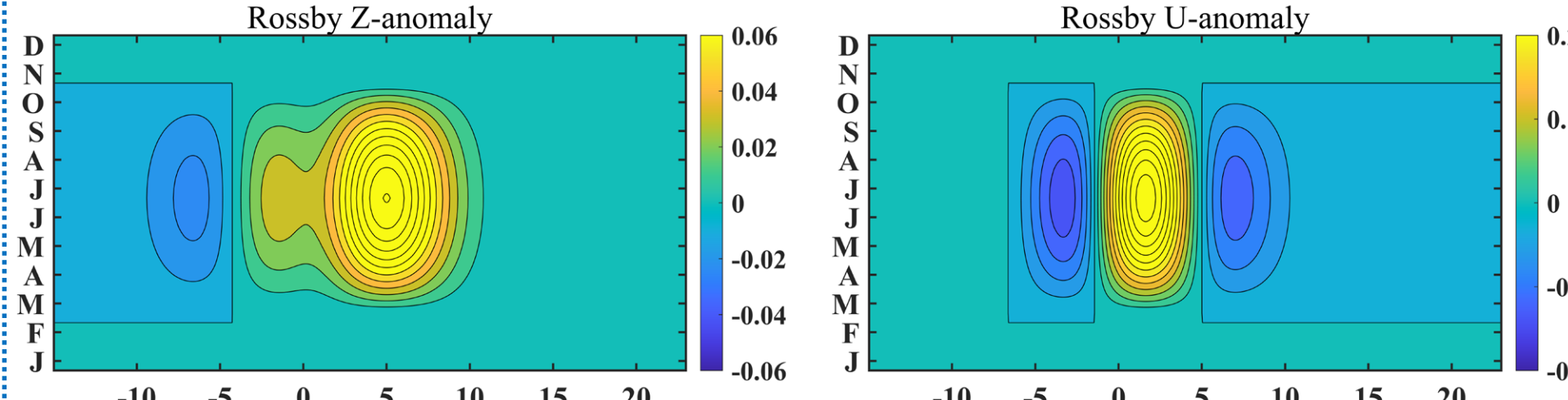
$$v_{n,k} = e^{i(kx - \omega t)} V_n(y) \quad h_{n,k} = i \frac{2n\hat{\omega} V_{n-1} - \hat{k} \hat{y} V_n}{k^2 - \hat{\omega}^2} e^{i(kx - \omega t)} \quad u_{n,k} = i \frac{2n\hat{k} V_{n-1} - \hat{\omega} \hat{y} V_n}{k^2 - \hat{\omega}^2} e^{i(kx - \omega t)}$$

where $V_n(y) = e^{-\sqrt{2}/2} \mathcal{H}_n(\hat{y})$, $\mathcal{H}_n(\hat{y})$ is the Hermite polynomials of nth order; $\hat{y} = \sqrt{\frac{\beta}{c}} y = \frac{1}{R_{eq}} y$, $\hat{\omega} = \frac{\omega}{\sqrt{\beta c}}$, $\hat{k} = R_{eq} k$, are dimensionless parameters;

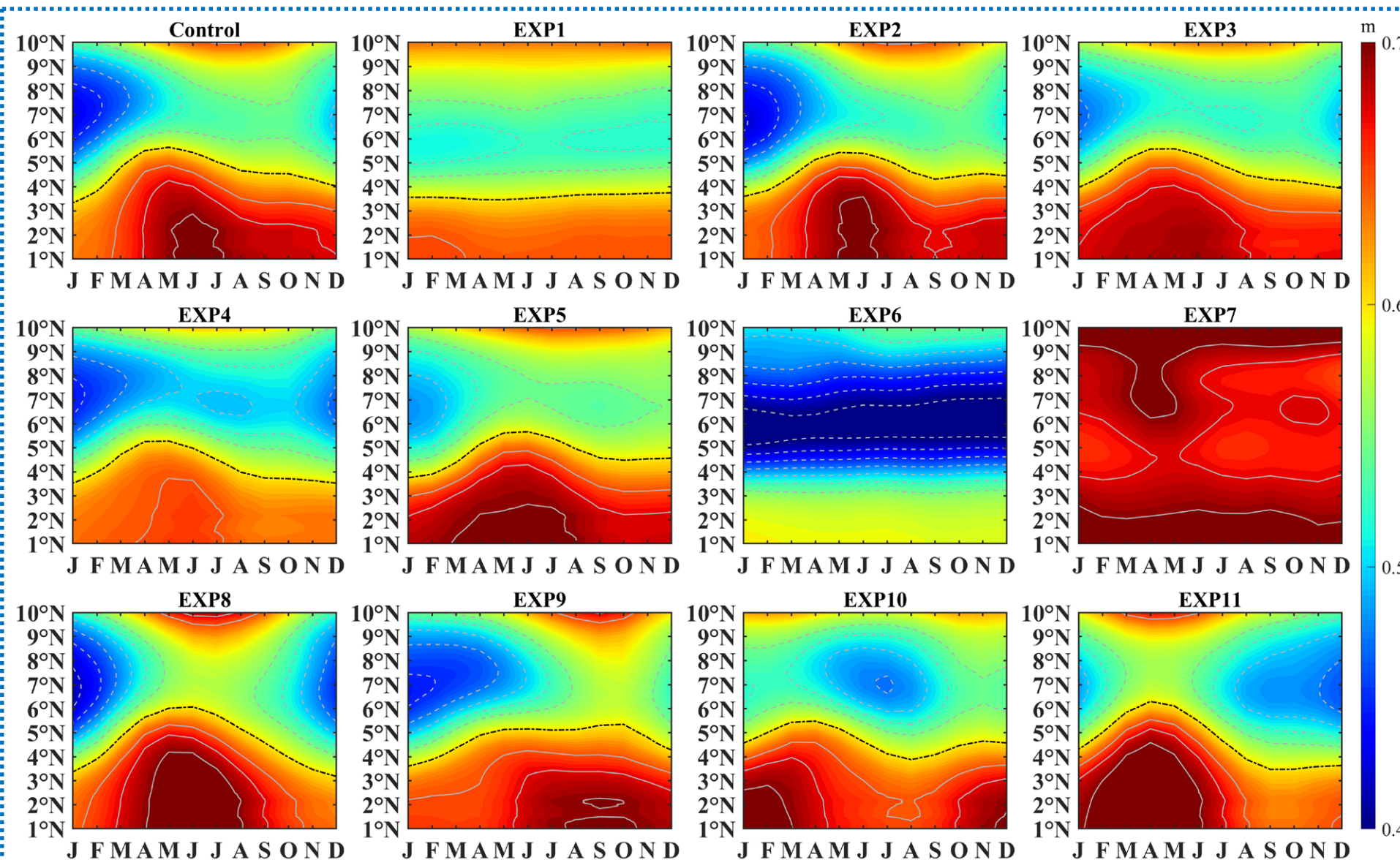
We chose $\omega = 360$ days, and k was calculated by the dispersion relation:

$$\omega = -\frac{\beta k}{k^2 + (2n+1)\frac{\beta}{c}}$$

We superimposed the first meridional mode with the second meridional mode to construct the ideal equatorial Rossby waves based on the AVISO SSHA field. We have checked that the added anomaly signal can propagate westward.

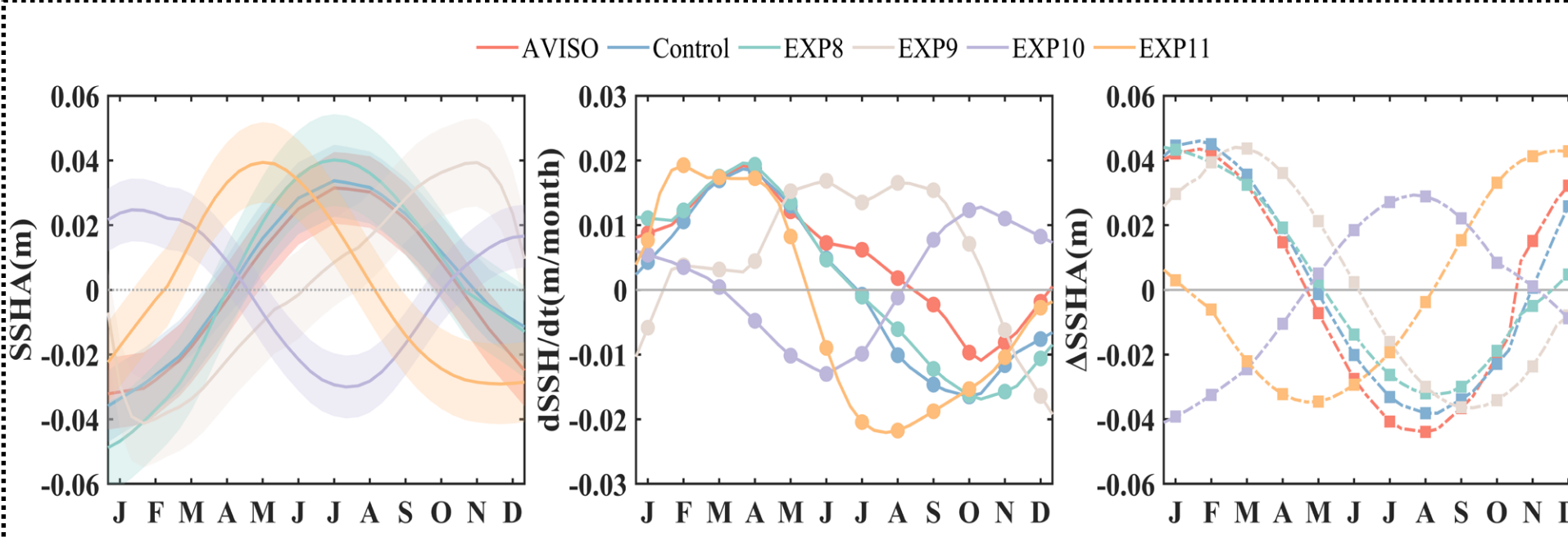


Meridional SSH(A) Seesaw Mechanism



The SSH distributions of zonal mean results within MNGC in the aforementioned experiments.

From results of control run and **EXP1-3**, as shown by zonal mean SSH fields, the **local wind forcing and boundary-related dynamics** are the key factors leading to the meridional movement of retroflection position of MC and NGCC/UC, which is responsible for the occurrence of state transitions. The wind sensitivity experiments (**EXP4-EXP7**) showed that if the local monsoon vanished, the seasonal state transition could be eliminated. Thus, the local monsoon is an important driving factor for the seasonal transitions between penetrating and choking states. In ideal Pacific equatorial Rossby wave experiments (**EXP8-EXP11**), although the local monsoon exists, the equatorial Rossby waves with different positive and negative phases can significantly alter the equilibrium state transition timing. Thus, the Pacific equatorial Rossby waves were confirmed as another key factor controlling the state transition.

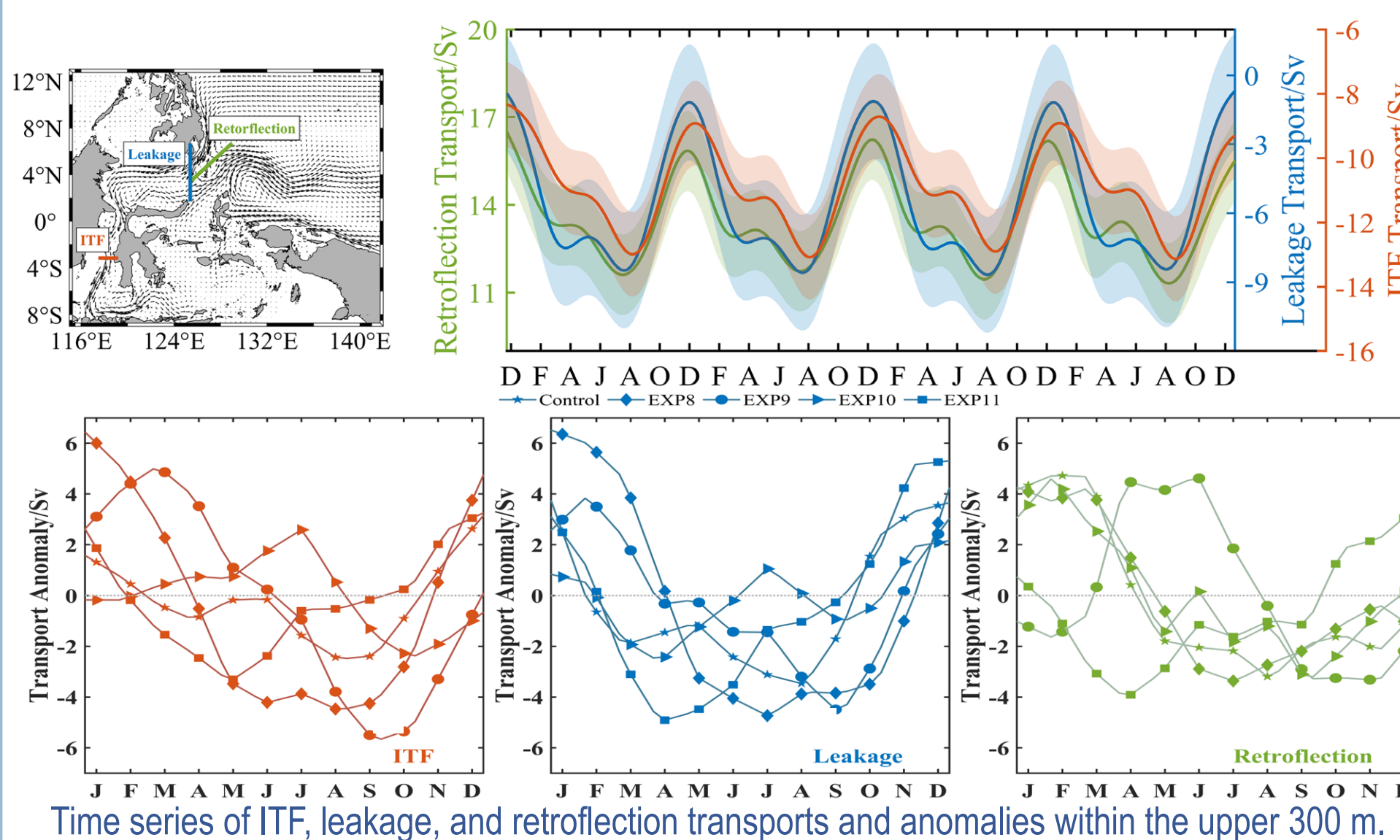


The time series of regional mean SSHA and dSSH/dt within the MNGC, and dSSH between Halmahera Eddy and Mindanao Eddy in Rossby wave experiments (EXP8-EXP11).

The seasonal transition of the local monsoon in April and October results in opposite wind stress curl anomalies, which alter the **relative strengths of the MC and the NGCC/UC**. This dynamic process, in turn, prompts a meridional shift in the retroflection position of the two western boundary currents, finally leads to a state transition between the penetrating and choking states. We further found that Rossby waves with different phases **cause SSHA oscillation between the Halmahera Eddy (HE) and Mindanao Eddy (ME)**, triggering the equilibrium state transition. Analogous to the ENSO-related zonal thermocline seesaw mechanism, we propose the meridional SSH(A) seesaw mechanism, which can well explain the state transition within MNGC and may be applicable to different timescales. The results also indicate that, within the MNGC, the MC-NGCUC and the ME-HE should be considered as a system, rather than focusing on one side or the other.

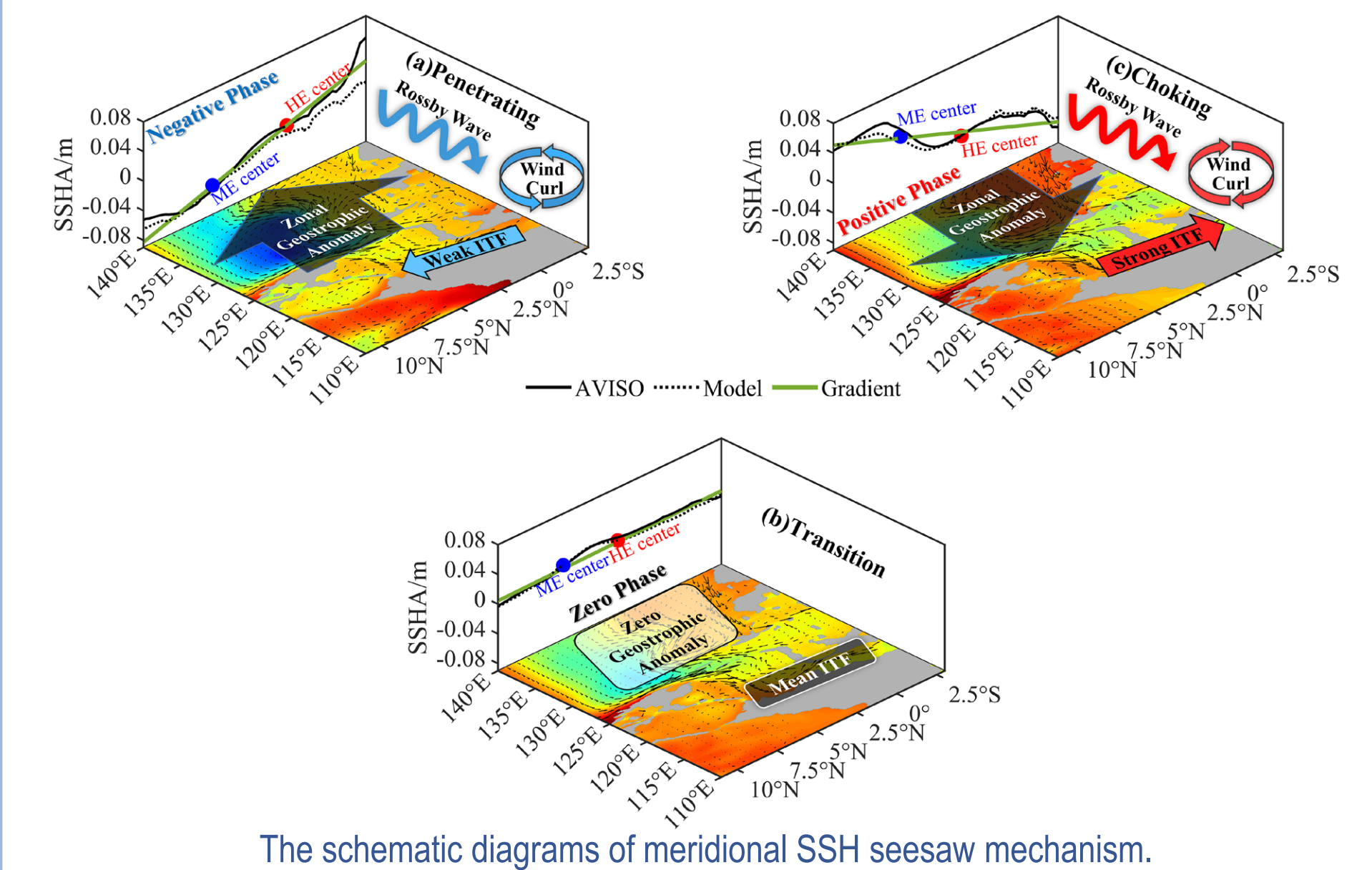
Relation with ITF

The results indicated that the **upper-layer ITF** is modulated by the **net intrusion transport of the MC into the Sulawesi Sea (leakage)** and the **MC's return flow to the Pacific (retroflection)**. The leakage and the ITF transports exhibit consistent seasonal variability, while the retroflection transports show significant negative correlations with both the leakage and ITF transports, as shown in the following figure. The seasonal variations in three transport anomalies exhibit temporal shifts in Rossby wave experiments with different phases, indicating that changes in the equilibrium state primarily regulate the seasonal variability of the upper-layer ITF by modulating the leakage and retroflection flows. **Furthermore, the meridional seesaw mechanism can also be applied to explain the seasonal variability of the upper-layer ITF**. According to the geostrophic relationship, the meridional gradient of SSHA corresponds to zonal geostrophic flow anomalies. 4 cm meridional SSHA gradient can cause approximately 4.7Sv zonal transport anomaly, which is consistent with the amplitudes of leakage, retroflection, and ITF transport anomalies.



Conclusion

Based on a high-resolution regional model: MPIOs, the key mechanism controlling seasonal equilibrium state transitions within the MNGC: the meridional SSH(A) seesaw mechanism, was uncovered. We deem that any dynamic process altering the meridional SSH(A) gradient can trigger a state transition. Moreover, the mechanism can effectively explain the upper-layer ITF transport variations on different timescales. This study proposes a novel mechanism for the equilibrium state transitions within the MNGC and provides new insights into the ITF variations, confirms the dynamical link between the western boundary current system and the ITF, and improves understanding of basin-scale material and energy exchanges.



The schematic diagrams of meridional SSH seesaw mechanism.

Acknowledgements

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Reference:

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