

Modulation of the Vietnam Coastal Upwelling in the 2016 Summer by an Abnormal Anticyclonic Eddy



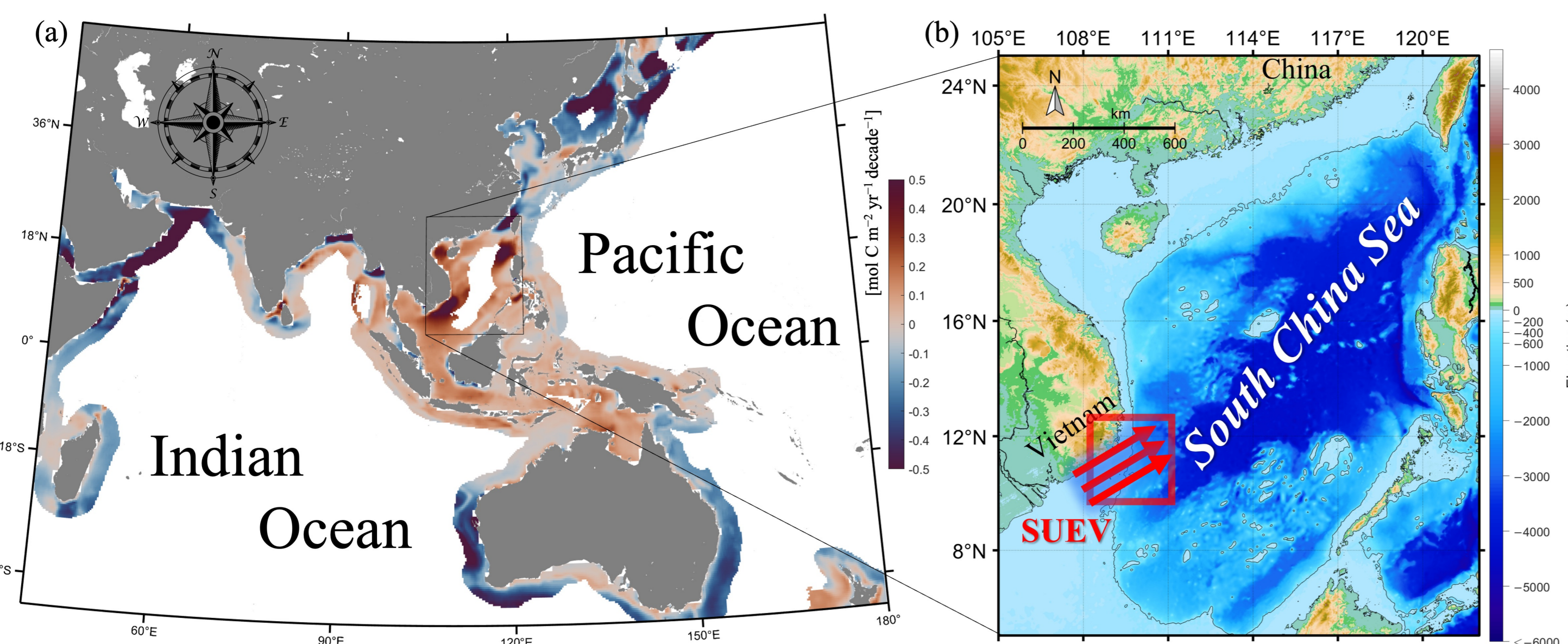
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1. Background and Study Area

During most of the summers from June to August (JJA), the summer upwelling southeast of Vietnam (SUEV) develops along the coastal region of Vietnam in a northeastward direction.



2. Data

Name (Temporal extent)	Variable(s)	Spatial resolution	Temporal resolution
SEALEVEL_GLO_PHY_L4_MY_008_047 (1 Jan 1993 to 31 Dec 2023)	ADT & SLA	0.125° × 0.125°	Daily
ERA5 (1 Jan 1993 to 31 Dec 2024)	U & V at 10 m	0.25° × 0.25°	Daily
Optimum Interpolation SST (OISST) V2 (1 Jan 1993 to 31 Dec 2024)	SST	0.25° × 0.25°	Daily
COPERNICUS-GLOBCURRENT (1 Jan 1993 to 31 Dec 2024)	Surface Ekman + geostrophic currents	0.25° × 0.25°	Daily
ONI index (1 Jan 1950 to 31 Dec 2024)	Oceanic Niño Index (ONI) index		Monthly
Roobaert et al. (2024) (1 Jan 1982 to 31 Dec 2020)	partial pressure of CO ₂ (pCO ₂) & air-sea CO ₂ flux (FCO ₂)	0.25° × 0.25°	Monthly

3. Methods

To accurately quantify the intensity of the SUEV along its privileged streaming direction, we projected the current velocity vectors from the original axes (x1, y1) onto the principal flow (along-stream) axes (x2, y2). The V_c is driven from the long-term mean currents (\bar{u}_c, \bar{v}_c) in axes (x1, y1), expressed as $V_c = \bar{u}_c \mathbf{i} + \bar{v}_c \mathbf{j}$.

$$\begin{cases} u'_c = u_c \cdot \cos\theta + v_c \cdot \sin\theta \\ v'_c = -u_c \cdot \sin\theta + v_c \cdot \cos\theta \end{cases} \quad (1)$$

To quantitatively separate the drivers of the observed FCO₂ anomalies, we performed a linear decomposition analysis following the methodology of Brady et al. (2019). The total FCO₂ anomaly (ΔF) was decomposed into contributions from the dynamic driver (U_{10}), the CO₂ partial pressure gradient driver (ΔpCO_2), and a non-linear residual term, as governed by the following equation:

$$\Delta F_{total} \approx \left(\frac{\partial FCO_2}{\partial U}\right) \cdot U' + \frac{\partial FCO_2}{\partial \Delta pCO_2} \cdot \Delta pCO_2' + \Delta F_{residual} \quad (2)$$

However, given the discrete nature of the monthly data used, we calculated these components by holding specific variables at their climatological mean states:

$$\Delta F_{total} = \Delta F_{WS} + \Delta F_{\Delta pCO_2} + \Delta F_{residual} \quad (3)$$

where the wind-driven component (ΔF_{WS}) and ΔpCO_2 -driven component ($\Delta F_{\Delta pCO_2}$) are defined as:

$$\Delta F_{WS} = FCO_2 \cdot (U_{obs} - U_{clim}) - \bar{F}, \quad (4)$$

$$\Delta F_{\Delta pCO_2} = FCO_2 \cdot (\Delta pCO_{2,obs} - \Delta pCO_{2,clim}) - \bar{F}, \quad (5)$$

where U_{obs} and $\Delta pCO_{2,obs}$ denote the observed U_{10} and ΔpCO_2 , respectively, while subscripts "clim" refer to their monthly or seasonal climatological means. \bar{F} represents the climatological mean FCO₂. The residual term ($\Delta F_{residual}$) accounts for the non-linear coupling between U_{10} and ΔpCO_2 anomalies, capturing the amplification when strong U_{10} are concurrent with large ΔpCO_2 .

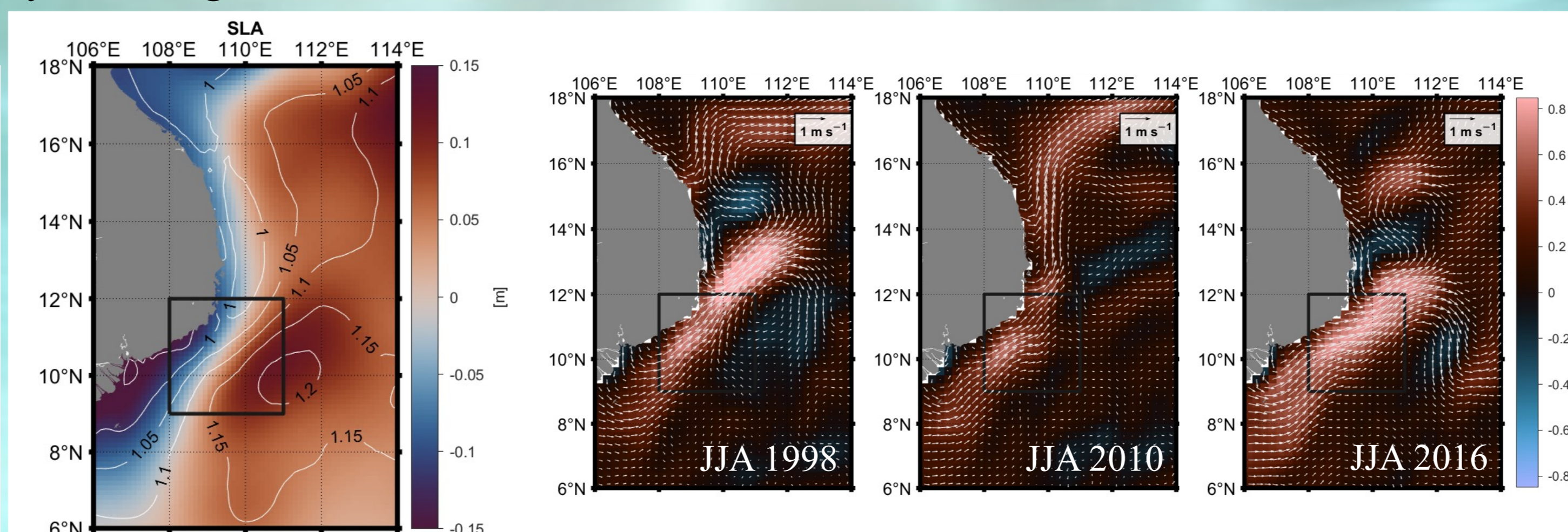
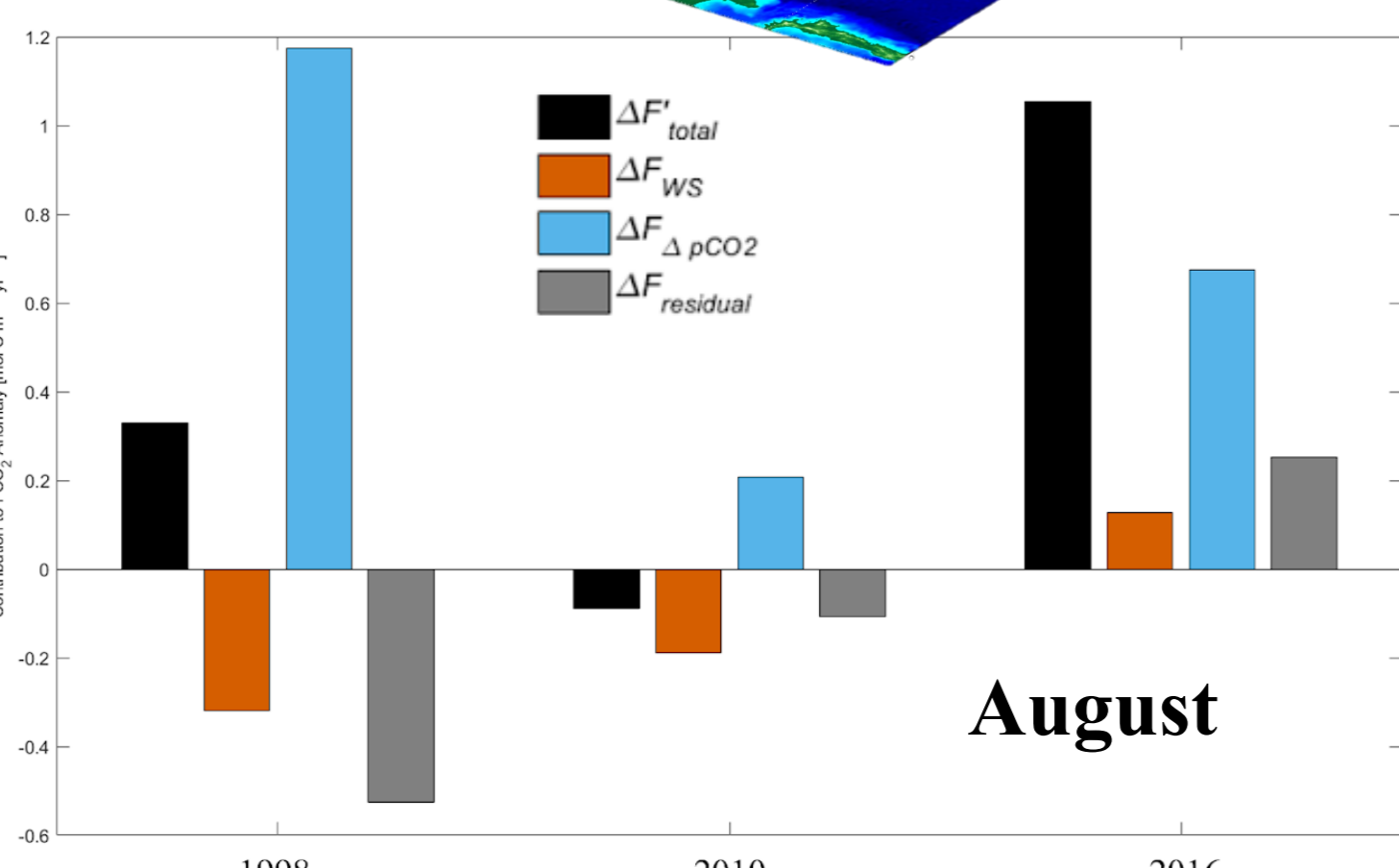
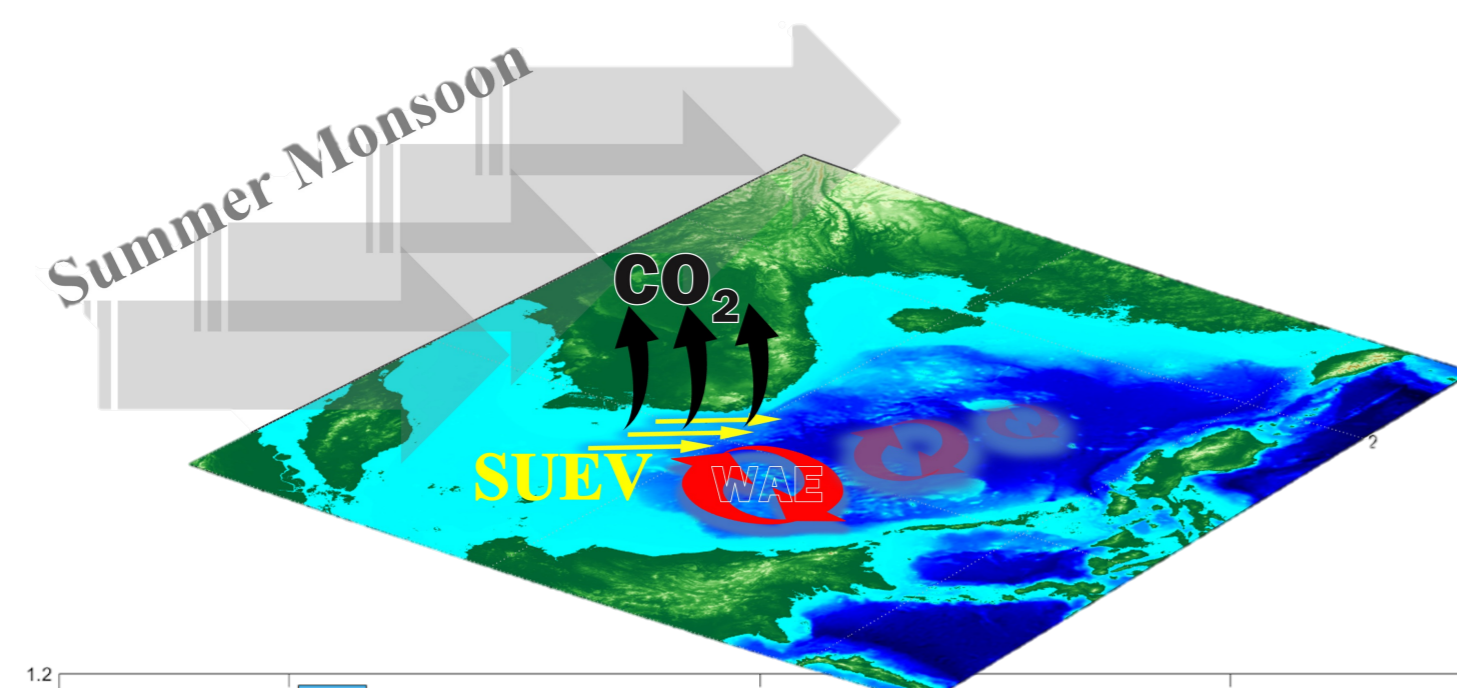
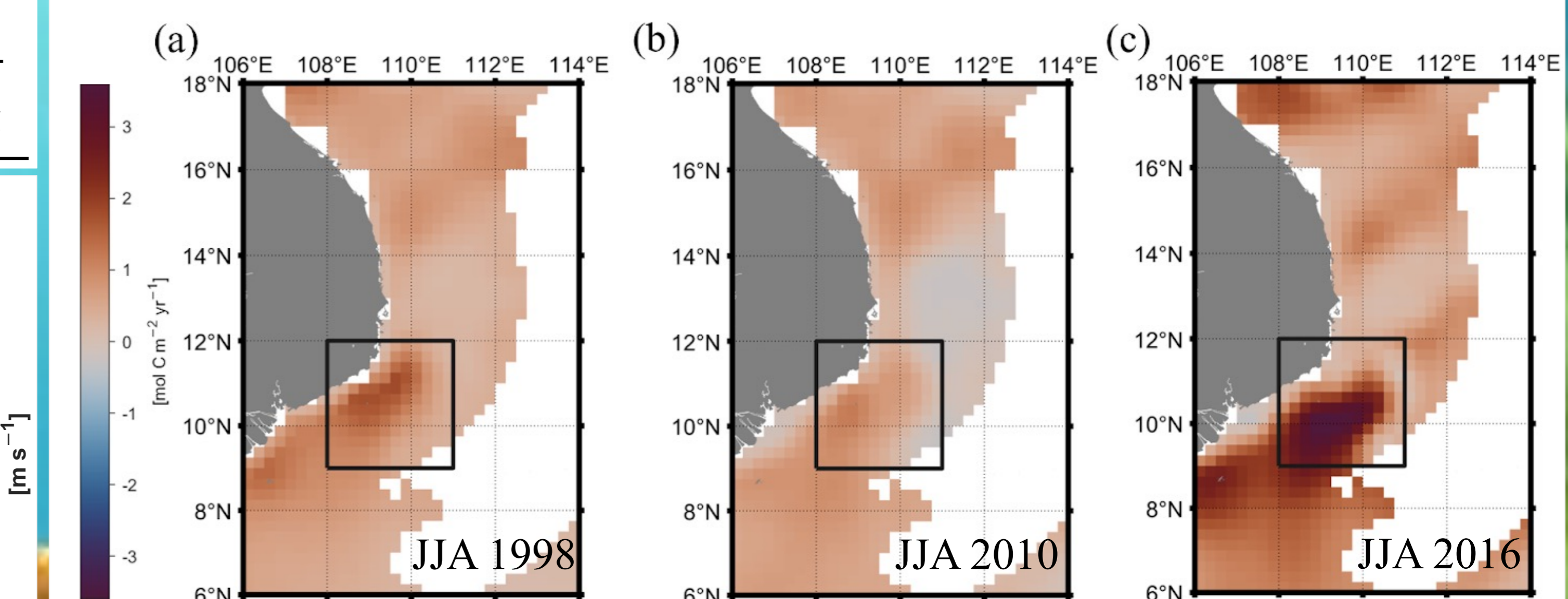
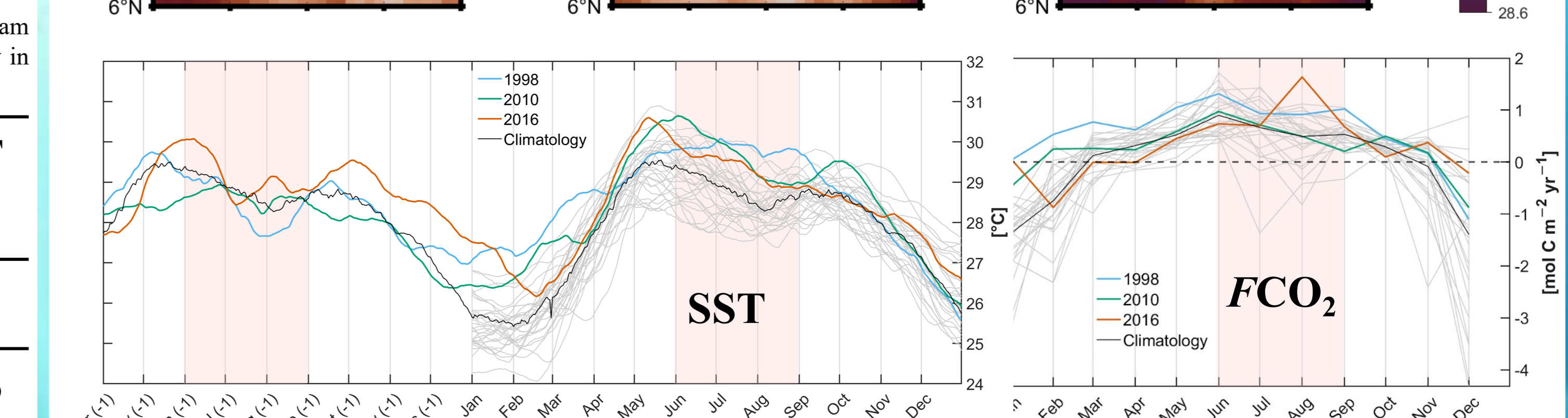
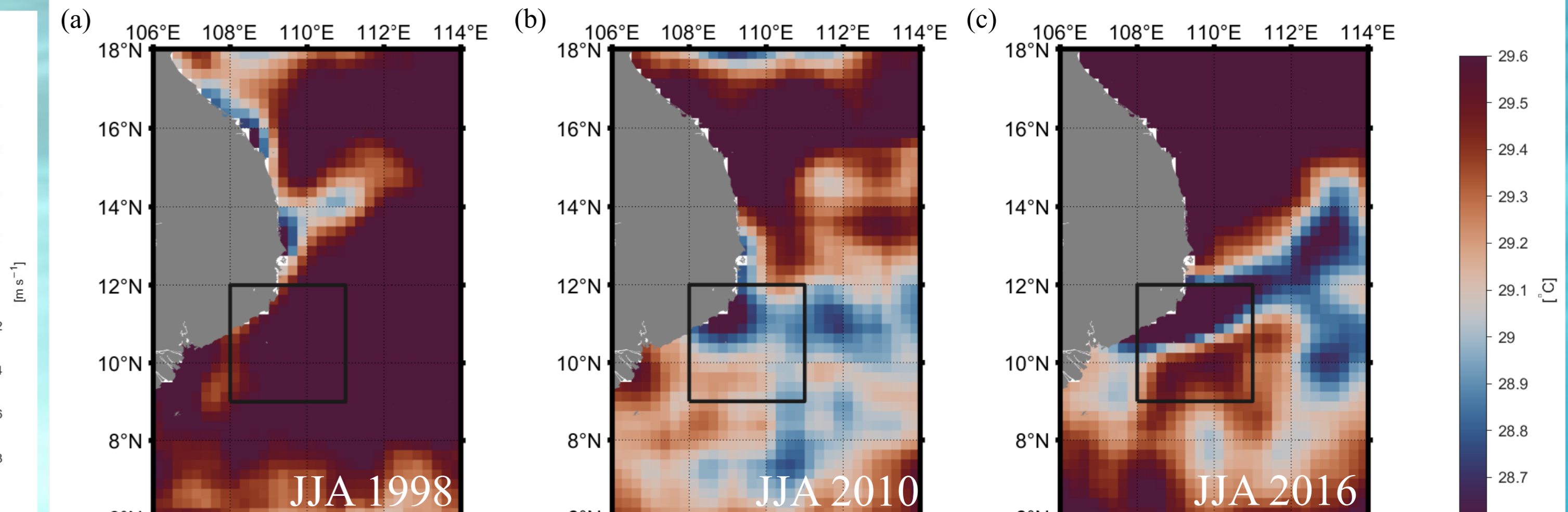
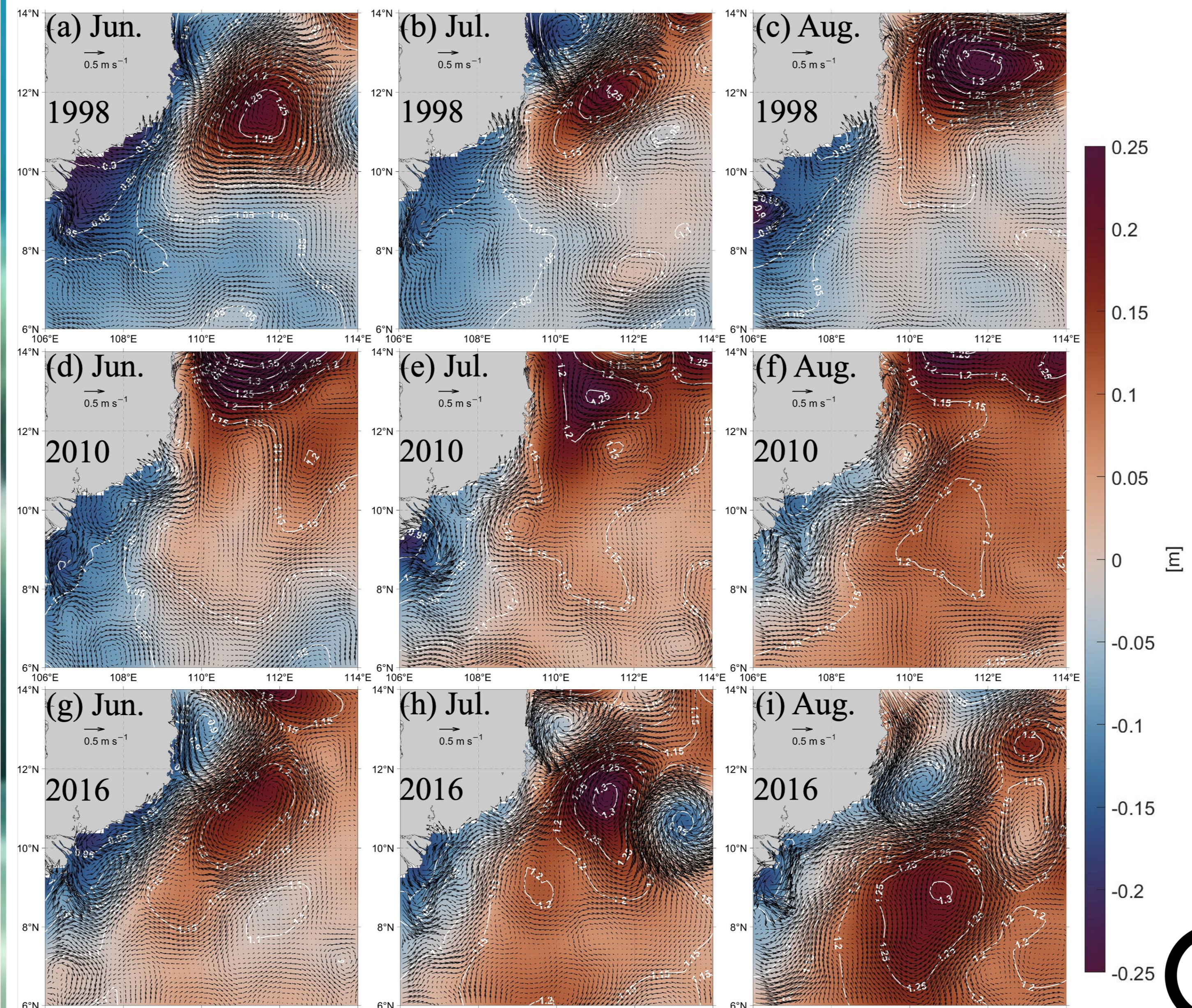
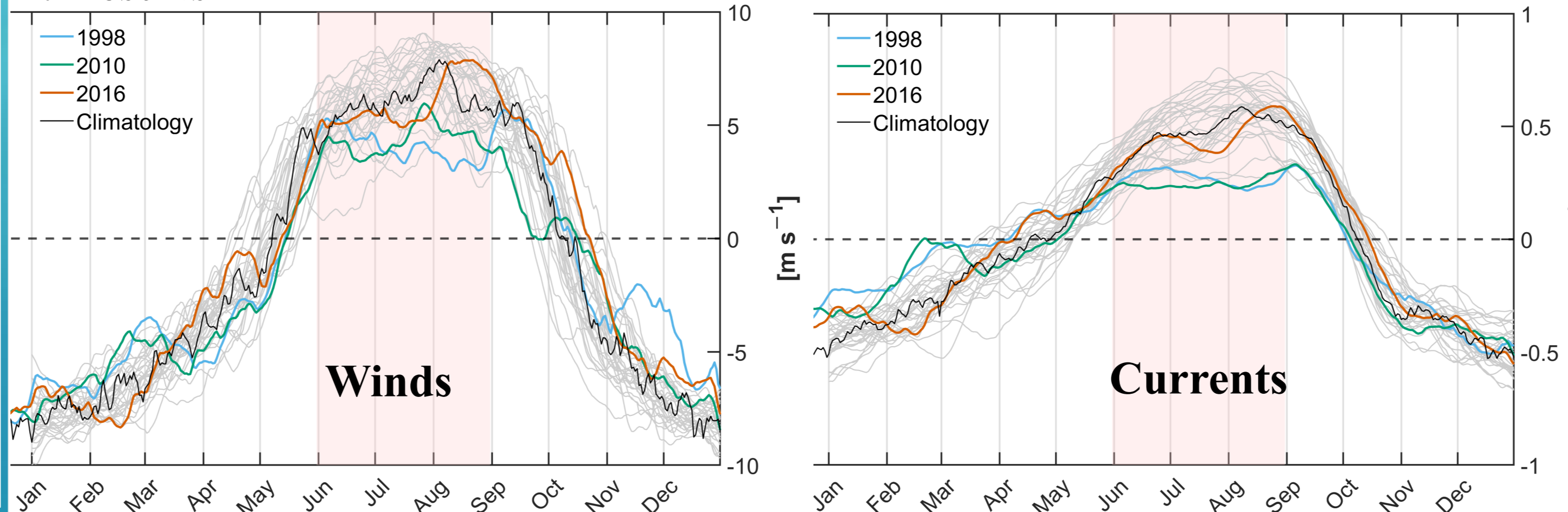


Table 1. The monthly-averaged anomalies of the Niño-Niña SUEV events in the Augusts, deriving from their 31-day moving-average along-stream winds (u'_w , unit: $m \cdot s^{-1}$), along-stream total currents u'_c , combing from u'_e and u'_g (unit: $m \cdot s^{-1}$), and SST (unit: $^{\circ}C$), relative to their climatology in August from 1993 to 2024.

August	along-stream winds (u'_w) ($\theta_w = 31.3^{\circ}$)	along-stream currents ($\theta_c = 25.0^{\circ}$)			SST
		u'_e	u'_g	u'_c	
1998	-3.1	-0.08	-0.23	-0.31	+1.3
2010	-1.9	-0.06	-0.23	-0.29	+0.5
2016	+0.9	+0.02	-0.04	-0.01	+0.4
Climatology	6.5	0.18	0.37	0.55	28.5

4. Results



5. Conclusions

- While Niño-Niña summers typically **suppress the SUEV** due to a **weakened southwest monsoon (as seen in 1998 and 2010)**, the 2016 SUEV was unexpectedly strong, exhibiting cold SST and enhanced northeastward currents.
- The intensification in 2016 was primarily driven by a **long-lasting WAE**. Unlike in other years, the 2016 WAE moved southwestward, positioning its western flank to accelerate the SUEV through **constructive interference between geostrophic and Ekman flows**.
- The eddy-enhanced upwelling in 2016 significantly altered the local air-sea CO₂ exchange. The intrusion of **deep, carbon-rich water** transformed the SUEV into a **strong CO₂ source (outgassing)**, contrasting with the weak outgassing observed in 1998 and 2010.
- These findings highlight that oceanic intrinsic variability, specifically **mesoscale eddy dynamics**, can override basin-scale atmospheric forcing. Consequently, predictions of regional upwelling intensity and carbon fluxes based solely on ENSO indices may be insufficient. Future assessments of the SCS carbon cycle and global coastal carbon budgets must account for the stochastic nature of mesoscale eddies and their interaction with the SUEV.

References & Acknowledgements

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