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Subtropical Indian Ocean Dipole Changes Weather and Ocean Conditions, Increasing Harmful Algal Blooms in South Korea

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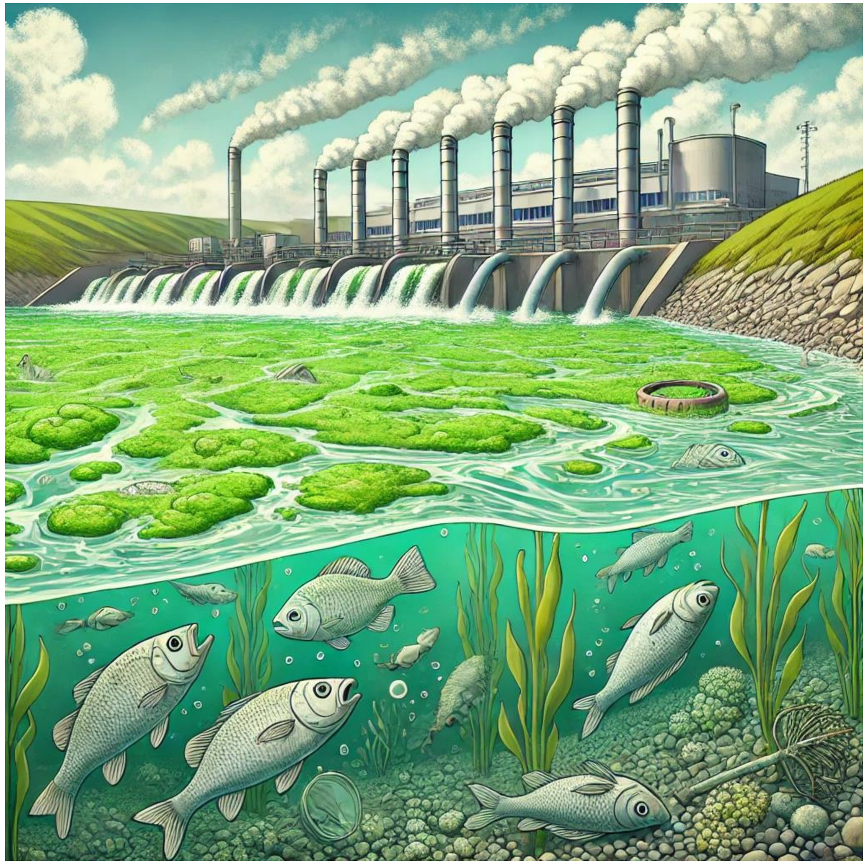
Harmful Algal Bloom (HAB)

Definition: HABs occur when algae proliferate, producing toxic or harmful effects on people, fish, shellfish, marine mammals, and birds.



Causes:

- **Nutrient Pollution:** Excess nutrients (especially nitrogen and phosphorus) from agricultural runoff, sewage discharge, and urban development fuel the growth of algae.
- **Climate phenomenon: Changing water temperatures** can promote conditions that are **more favorable for algae**.

Impacts:

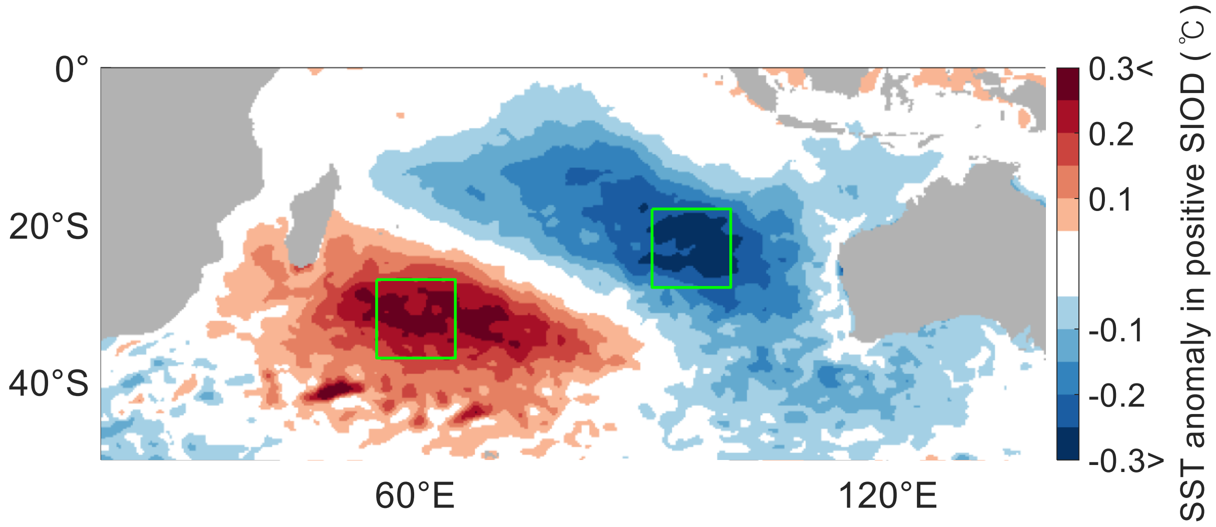
- **Marine Life:** HABs produce toxins that can kill fish, shellfish, and other aquatic life, leading to ecosystem imbalances.
- **Human Health:** Toxins from some HABs can contaminate seafood, causing illnesses when consumed by humans.
- **Economic Costs:** Fisheries, tourism, and water treatment can all suffer significant financial losses due to HAB-related disruptions.

Subtropical Indian Ocean Dipole (SIOD)

Definition: The Subtropical Indian Ocean Dipole (SIOD) is a climate phenomenon characterized by sea surface temperature (SST) anomalies in the subtropical Indian Ocean.

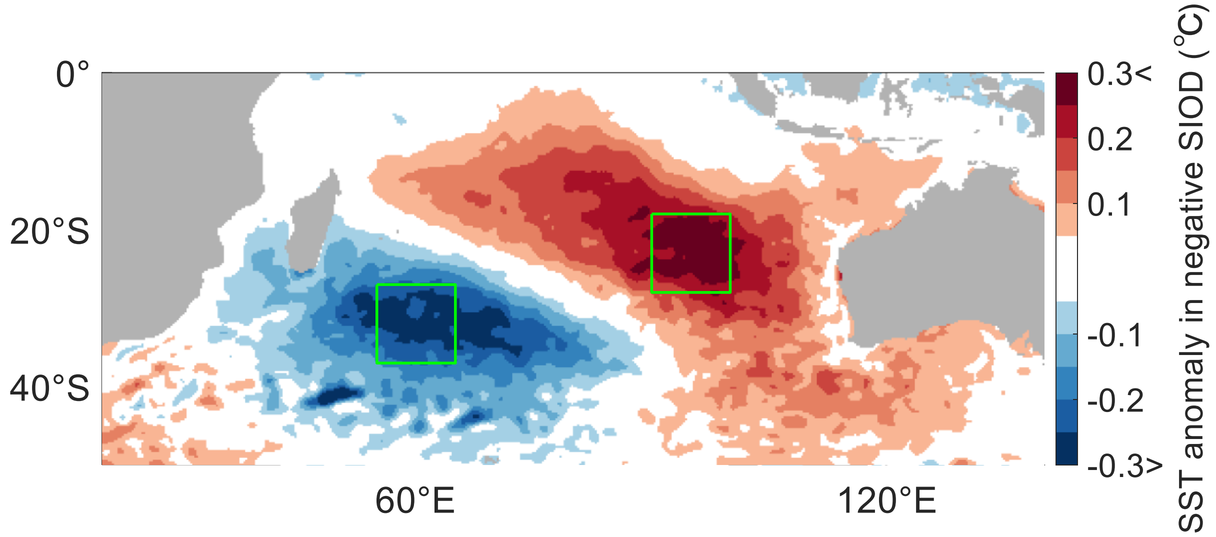
Positive Phase

Warmer-than-average SSTs in the southwestern Indian Ocean and cooler-than-average SSTs in the southeastern Indian Ocean.



Negative Phase

Cooler-than-average SSTs in the southwestern Indian Ocean and warmer-than-average SSTs in the southeastern Indian Ocean.



SIOD index (SIODI): SST anomaly difference between western (55–65°E, 37–27°S) and eastern (90–100°E, 28–18°S) Indian Ocean. (SIODI > 0: positive phase, **SIODI < 0: negative phase**).

Correlation between global phytoplankton bloom in coastal waters and SIOD

Increasing trend of phytoplankton bloom metrics

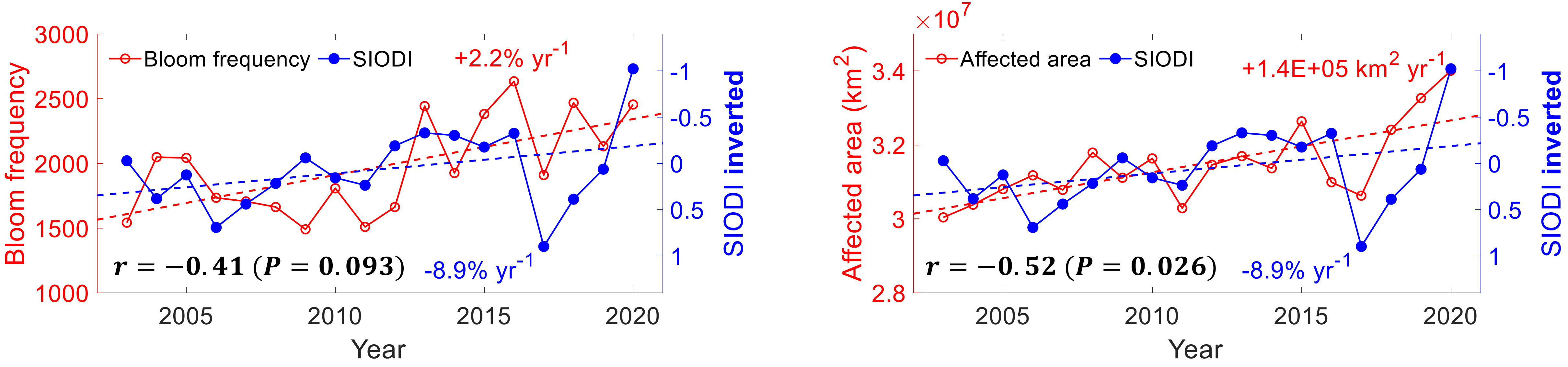
Global phytoplankton bloom frequency and bloom-affected area showed increasing trends between 2002 and 2020 (Dai et al., 2023).

Decreasing trend of SIODI

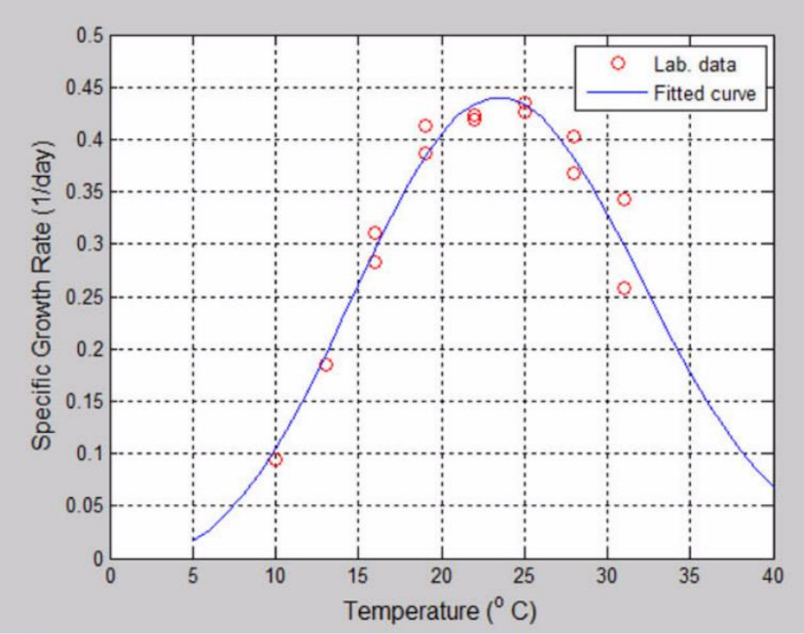
SIODI showed a decreasing trend between 2002 and 2020.

Negative correlation between SIODI and phytoplankton blooms

The SIODI showed **negative correlation** with the global phytoplankton bloom frequency and affected area.



So how does SIOD connect with HAB?

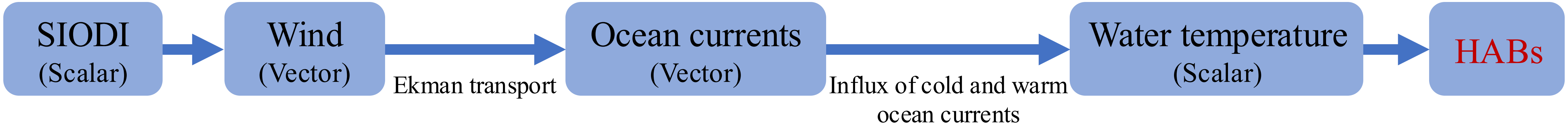


Optimal water temperature for HABs

Optimal water temperature is 23.1–23.7°C for *Cochlodinium polykrikoides,* which is the primary species causing HABs in South Korea (Cho and Cho, 2014). The closer the water temperature is to the optimal range, the more likely HABs are to occur.

Coastal water temperature

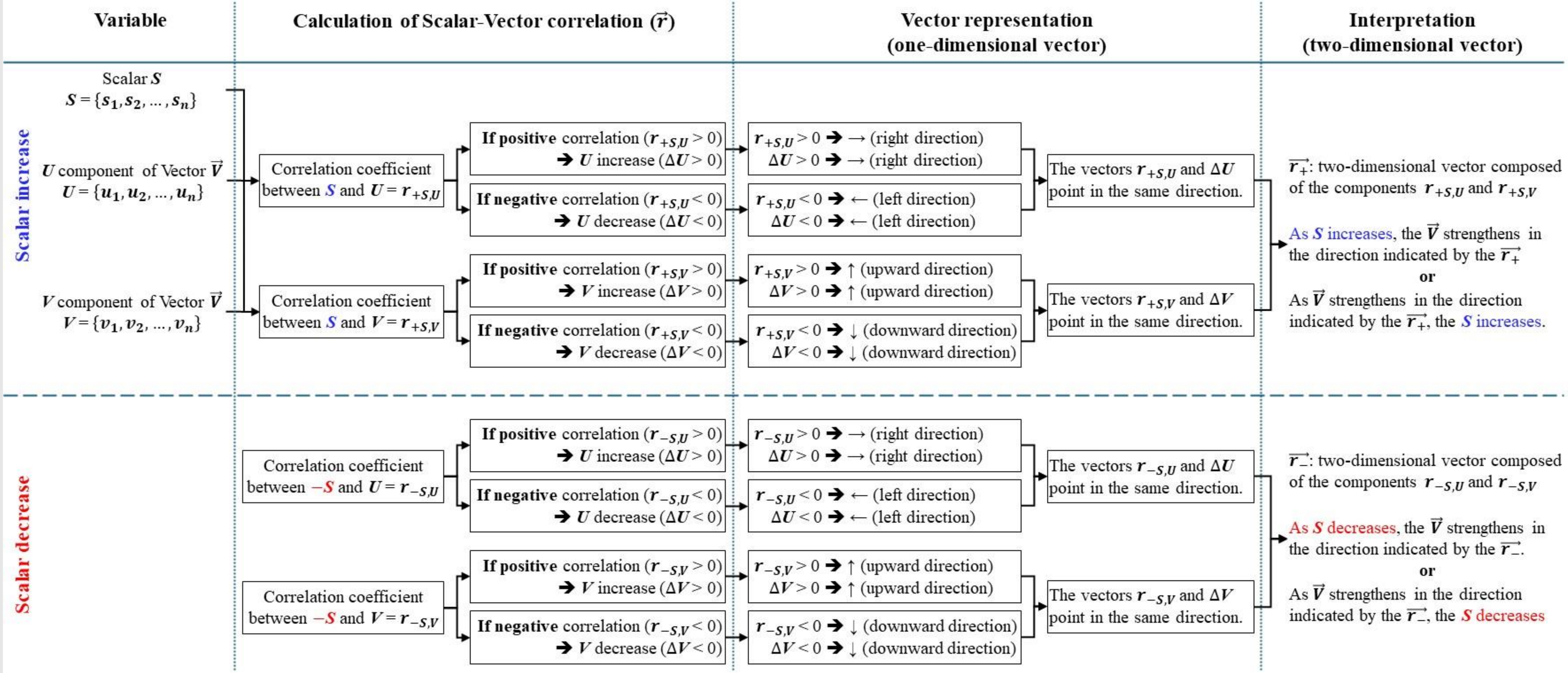
Coastal water temperatures vary with the influx of cold and warm ocean currents, which are, in turn, strongly affected by wind patterns.



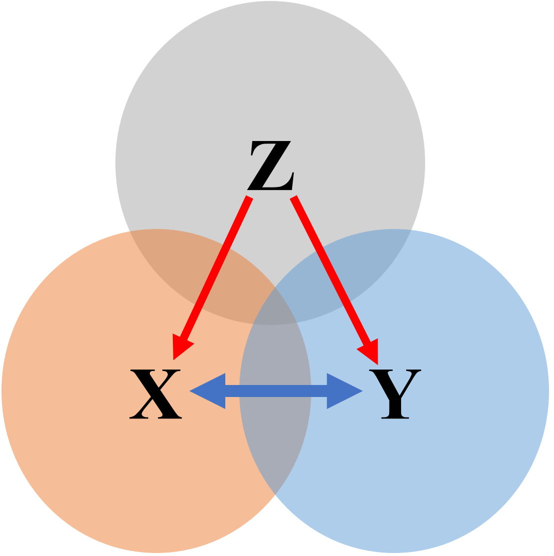
➔ How to determine the correlation between scalar and vector variables.

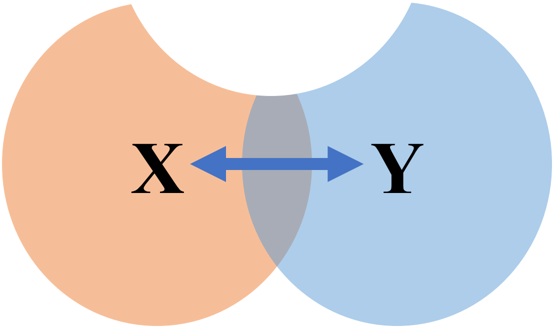
Methos

Scalar-Vector correlation



Partial correlation analysis





$$r_{XY,Z} = \frac{r_{XY} - r_{XZ}r_{YZ}}{\sqrt{1 - r_{XZ}^2}\sqrt{1 - r_{YZ}^2}}$$

$r_{XY,Z}$: partial correlation coefficient between X and Y controlling for the impacts of Z

Correlation coefficient

Variables are interconnected, and failing to account for a third variable (Z) may lead to misleading conclusions regarding the direct relationship between X and Y

Partial correlation coefficient

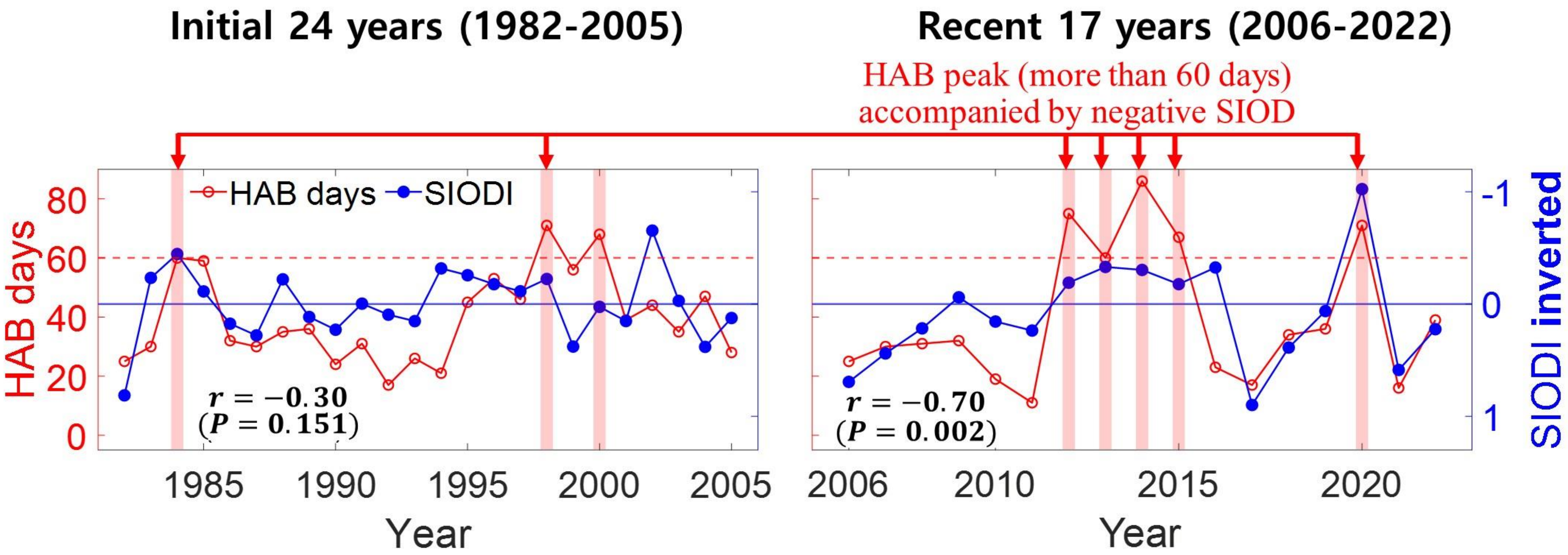
By calculating the partial correlation, researchers can isolate the relationship between X and Y, ensuring that the observed correlation is not confounded by the influence of Z.

Results

Increase in HABs in South Korean coastal waters during the negative SIOD phase

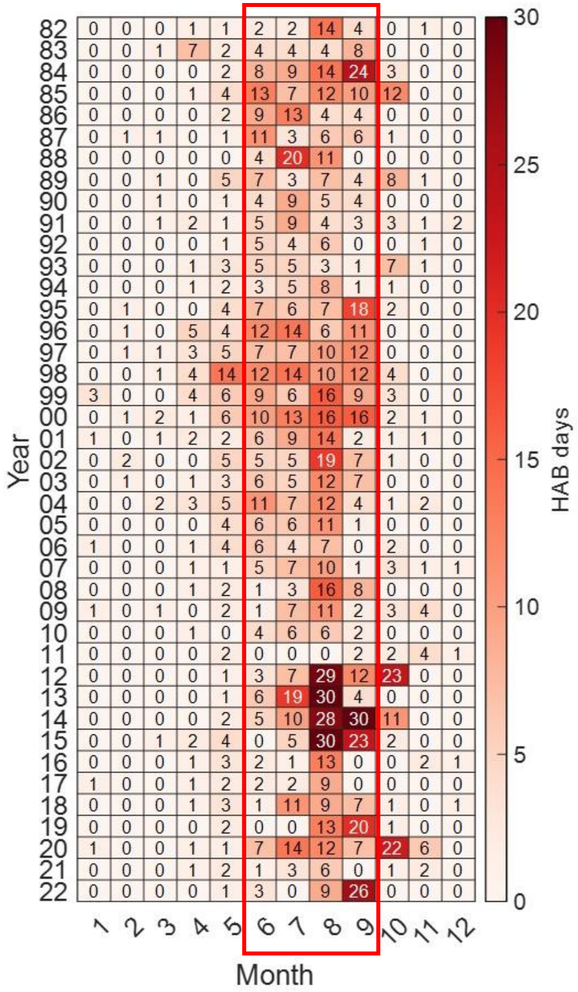
- From 1982 to 2022, annual **HAB days** and annual average **SIODI** were **negatively correlated** ($r = -0.55$; $P < 0.05$).
- Of the eight years with **HAB peaks** (>60 HAB days per year), all except for 2000 were **associated with negative SIOD events**.
- This **negative correlation** between HAB days and SIODI has **strengthened over time.**

  For 2006–2022, the correlation between HAB days and SIODI was $r = -0.70$ ($P < 0.05$), significantly stronger than in 1982–2005.

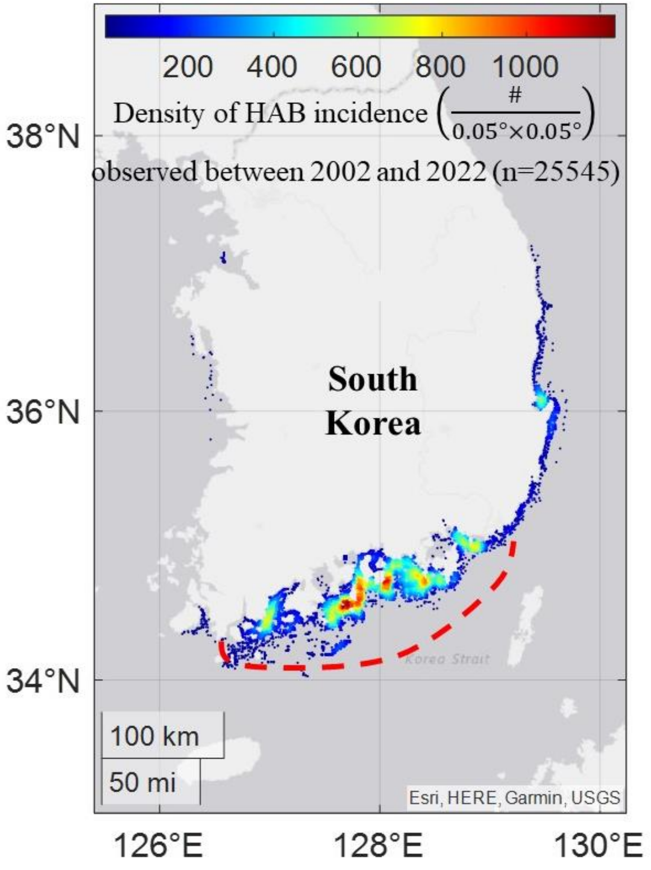


Characteristics of HAB in South Korean coastal waters

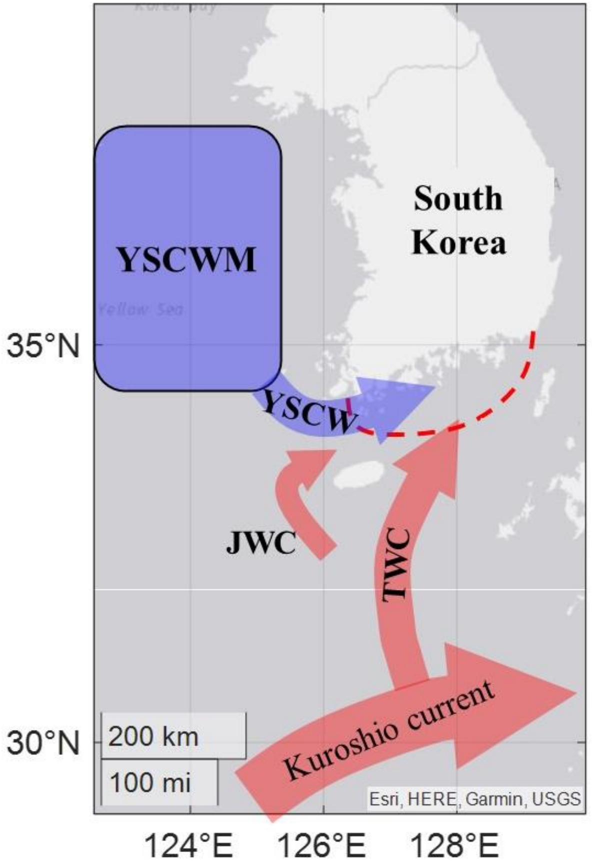
HABs occur relatively frequently from June to September, when water temperature and precipitation are high.



Annual average of **HAB days** on the **southern coast of South Korea (SCK)** was 33.9 days, **more than** on the **western coast** (0.4 days per year) and **eastern coast** (3.0 days per year)



SCK is influenced by the northward-flowing **Tsushima Warm Current (TWC)** and **Jeju Warm Current (JWC)** and by the eastward-flowing **Yellow Sea Cold Water (YSCW)**.



Characteristics of HAB in South Korean coastal waters

- The average SST during HABs (SST_{HAB}) in South Korean coastal waters was 24.2℃ (SD=3.1℃; n=2,581).

June

- Mean SST in June on the SCK = 21.0℃ < SST_{HAB}
  ➔ **Positive correlation** between **HAB days and SST**
  ➔ **The higher the SST, more frequent the HABs**

August

- Mean SST in August on the SCK = 26.4℃ > SST_{HAB}
  ➔ **Negative correlation** between **HAB days and SST**
  ➔ **The lower the SST, more frequent the HABs**

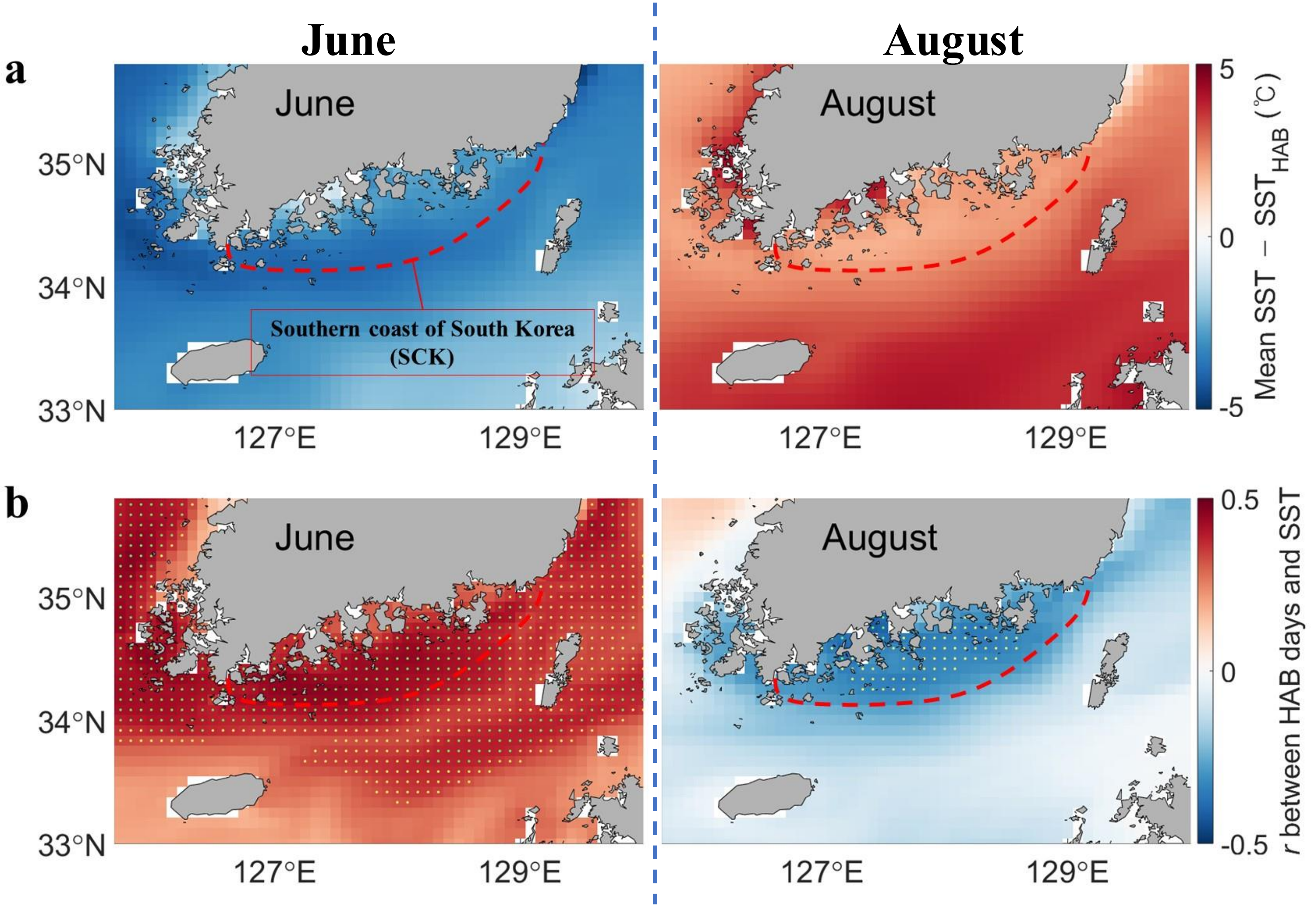


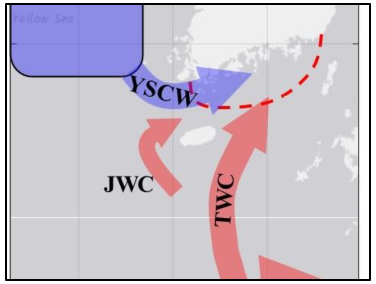
Figure b: Partial correlation coefficient (r) between HAB days and SST, controlling for solar radiation and terrestrial precipitation (green dots: $P<0.05$, yellow dots: $P<0.10$).

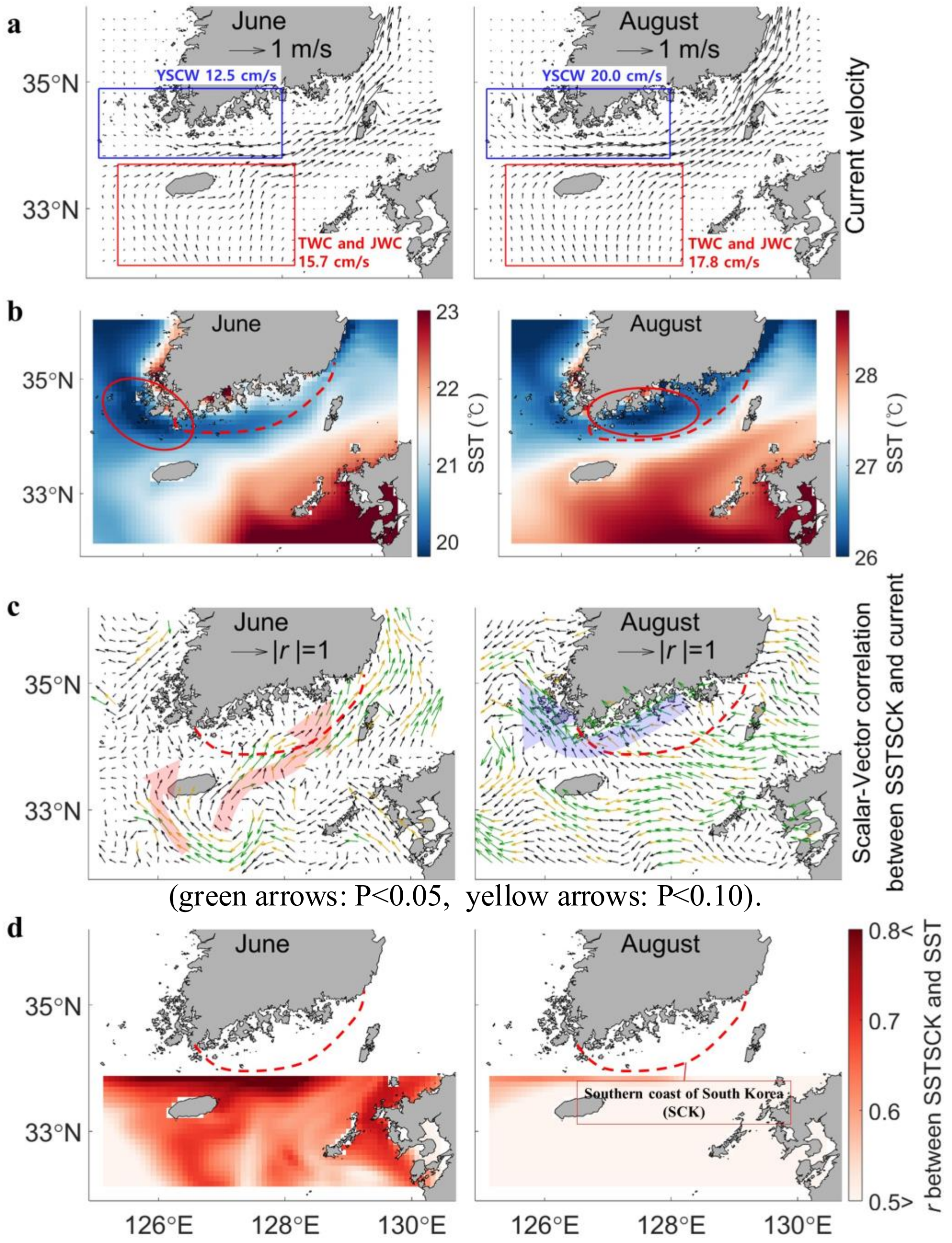
Characteristics of HAB in South Korean coastal waters

TWC and JWC ➔ June SST / YSCW ➔ August SST

- **Figure a**: In **June**, the average velocity of the **TWC and JWC** was 15.7 cm s^{-1}, i.e., 3.2 cm s^{-1} **faster than** that of the **YSCW** (12.5 cm s^{-1}).
  Conversely, in **August**, the average velocity of the **YSCW** increased to 20.0 cm s^{-1}, i.e., 2.2 cm s^{-1} **faster than** that of the **TWC and JWC**.
- **Figure b**: In **August**, the **YSCW intruded into the central SCK**, **whereas** in **June**, its **intrusion** was confined to the **western SCK**.
- **Figure c**: In **June**, **SSTSCK increased with** the northward flow of the **TWC and JWC**, in **August**, **it** was **higher when** the **intrusion** of the **YSCW** was **weaker**.
- **Figure d**: In **June**, **SSTSCK** was **strongly positively correlated** with the **SSTs** of the **TWC and JWC**, **whereas this correlation** was relatively **weak in August**.

SSTSCK: mean SST in the southern coast of South Korea (SCK).

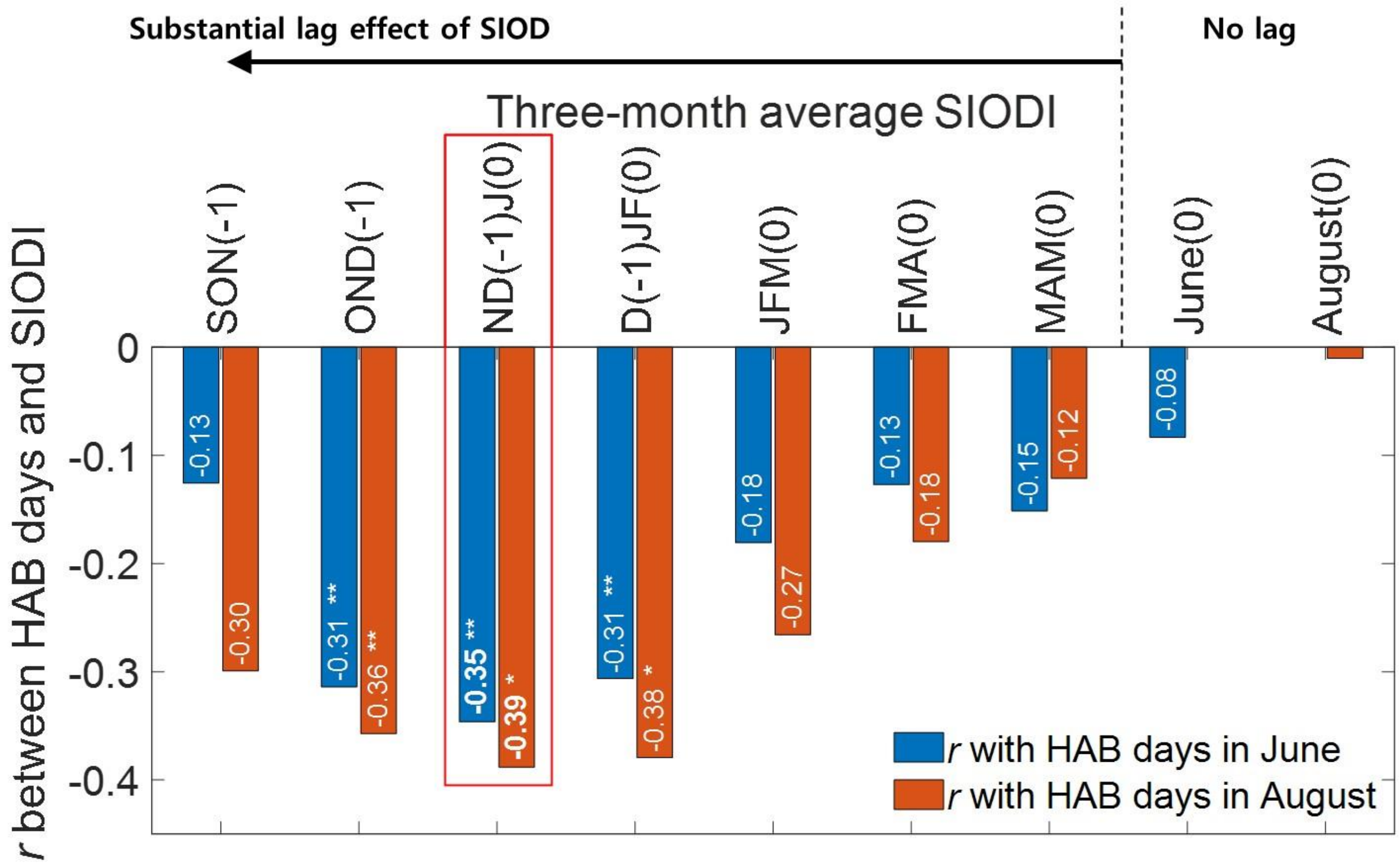




(green arrows: P<0.05, yellow arrows: P<0.10).

Correlation between three-month average SIODI and monthly HAB days with time lag

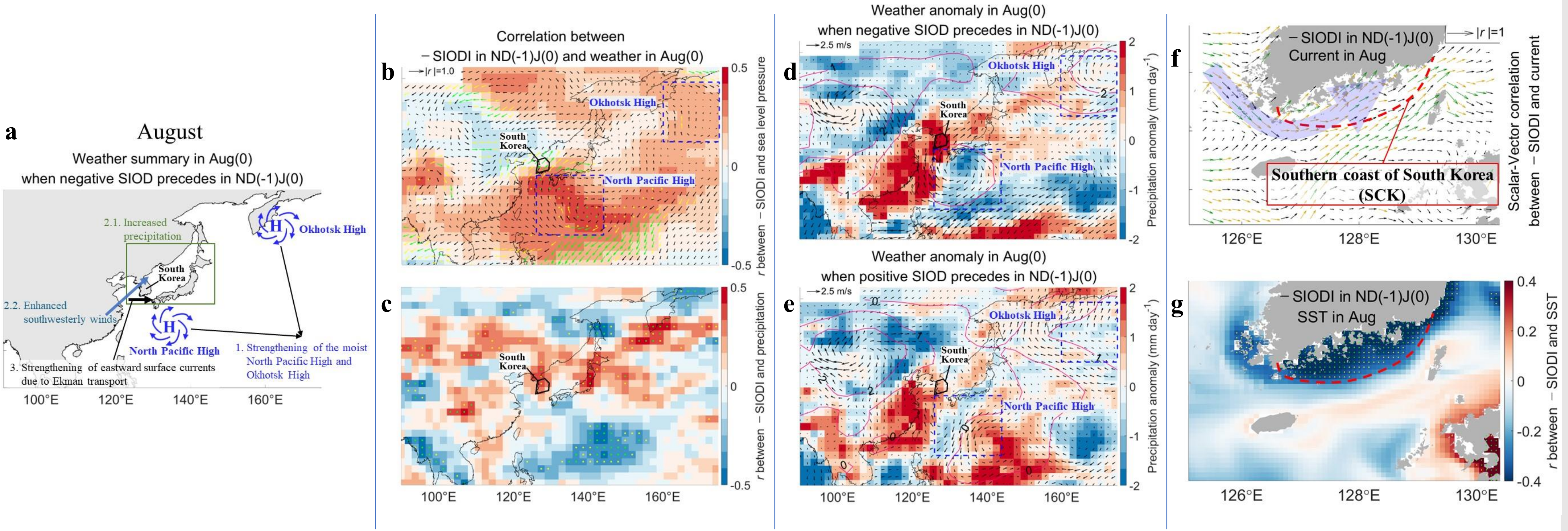
- The influence of the IOD on the East Asia–Western Pacific region can exhibit a time lag of 1–3 seasons (Kripalani et al, 2010).
- Both **June** and **August HAB days** were **most strongly negatively correlated** with the three-month average **SIODI from November of the previous year to January of the current year** (denoted $SIODI_{ND(-1)J(0)}$).



S: September, **O**: October, **N**: November, **D**: December, **J**: January, **F**: February, **M**: March, **A**: Apr.
(−1): Previous year, **(0)**: Current year
*: P<0.05, **: P<0.10

Links between HABs and the SIOD – August

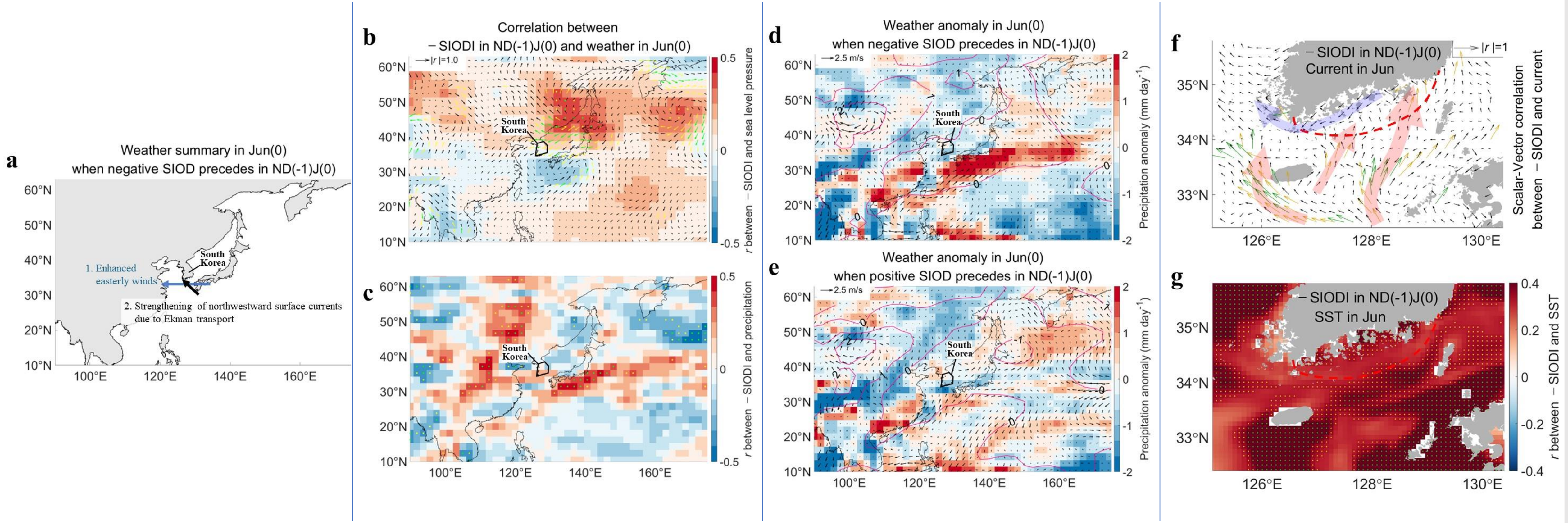
Figure g: Partial correlation coefficient (r) between negative $SIODI_{ND(-1)J(0)}$ and SST, controlling for solar radiation and air temperature.
(green dots and arrows: $P<0.05$, yellow dots and arrows: $P<0.10$).



- Negative $SIOD_{ND(-1)J(0)}$ → Strengthening of North Pacific High and Okhotsk High → Strengthening of southwesterly wind → Strengthening of intrusion of YSCW → Reduce the SST toward SST_{HAB} → Increase in HABs
- Strengthening of North Pacific High and Okhotsk High → Increase in precipitation → Increase in nutrient load → Increase in HABs

Links between HABs and the SIOD – June

Figure g: Partial correlation coefficient (r) between negative $SIODI_{ND(-1)J(0)}$ and SST, controlling for solar radiation and air temperature.
(green dots and arrows: P<0.05, yellow dots and arrows: P<0.10).



Negative $SIOD_{ND(-1)J(0)}$ → Strengthening of easterly wind → Strengthening of TWC and JWC → Increase in the SST toward SST_{HAB} → Increase in HABs

- SIODI showed a decreasing trend (8.9% yr^{-1}; 2002–2020), while global phytoplankton blooms were on the rise.

- SIODI was negatively correlated with global bloom frequency (r = –0.41; P = 0.093) and area (r = –0.52; P = 0.026), as well as with the HAB days in South Korea (r = –0.70; P = 0.002).

- SIOD altered East Asian weather conditions, leading to changes in ocean currents and SST, which contributed to an increase in HABs in South Korea.

- Scalar-Vector correlation can be applied not only to assess the impacts of climate variability on the ocean but also in various other fields.

1. Behera, S. K., & Yamagata, T. (2001). Subtropical SST dipole events in the southern Indian Ocean. Geophysical Research Letters, 28(2), 327-330.
2. Dai, Y., Yang, S., Zhao, D., Hu, C., Xu, W., Anderson, D. M., ... & Feng, L. (2023). Coastal phytoplankton blooms expand and intensify in the 21st century. *Nature*, *615*(7951), 280-284.
3. Cho, H. Y., & Cho, B. J. (2014). Optimal growth model of the Cochlodinium polykrikoides. *Journal of Korean Society of Coastal and Ocean Engineers*, *26*(4), 217-224.
4. Kripalani, R. H., Oh, J. H., & Chaudhari, H. S. (2010). Delayed influence of the Indian Ocean Dipole mode on the East Asia-West Pacific monsoon: possible mechanism. International Journal of Climatology, 30(2), 197.
5. Martínez-Moreno, J., Hogg, A. M., England, M. H., Constantinou, N. C., Kiss, A. E., & Morrison, A. K. (2021). Global changes in oceanic mesoscale currents over the satellite altimetry record. Nature Climate Change, 11(5), 397-403.

1. HAB data in South Korea: https://www.nifs.go.kr/red/
2. Global phytoplankton bloom data: https://doi.org/10.1038/s41586-023-05760-y
3. SIODI: https://www.jamstec.go.jp/apl/j/members/behera/iosd.html
4. Ocean current and SST data for South Korea: https://data.marine.copernicus.eu/product/GLOBAL_MULTIYEAR_PHY_001_030/description
5. SST data for Indian Ocean, Malvinas Current, and Alaska Current: https://psl.noaa.gov/data/gridded/data.noaa.oisst.v2.highres.html
6. Chl a concentration: https://oceancolor.gsfc.nasa.gov/
7. Gridded weather data: https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html
8. Terrestrial precipitation data for South Korea: https://data.kma.go.kr/

Thank you.