Interannual to Decadal Variability of the Ocean Heat Content in the Western North Pacific and its Nonstationary Relationship with Major Climate Modes

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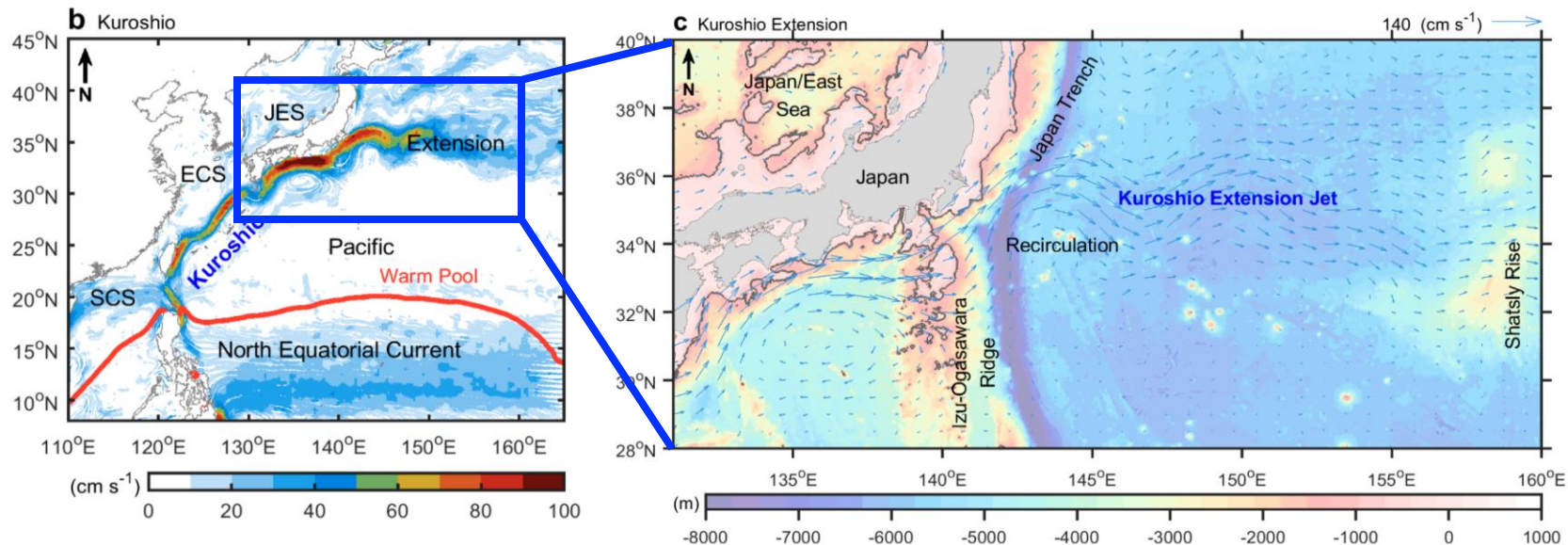**Email:** suna.cho@snu.ac.kr

Introduction

➢ **Kuroshio Extension (KE)**

- Prominent western boundary current system in the North Pacific
- Transports substantial amounts of heat and salt from the tropics to midlatitudes
  - Plays an important role in the midlatitude ocean-atmosphere interaction

    (Kelly et al., 2010; Kwon et al., 2010; Qiu, 2023)

*(Wang and Wu, 2019)*

Introduction

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     (Kelly et al., 2010; Kwon et al., 2010; Qiu, 2023)

➢ **Variability of the KE**

- Sea surface height (SSH) variability along 35°N: Changes in the ① **latitude** and ② **strength**

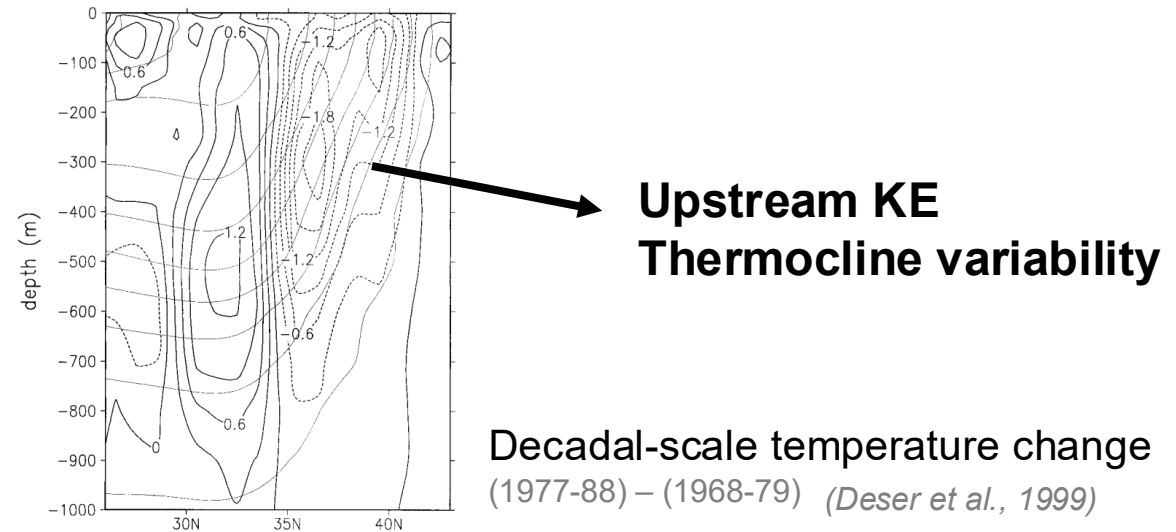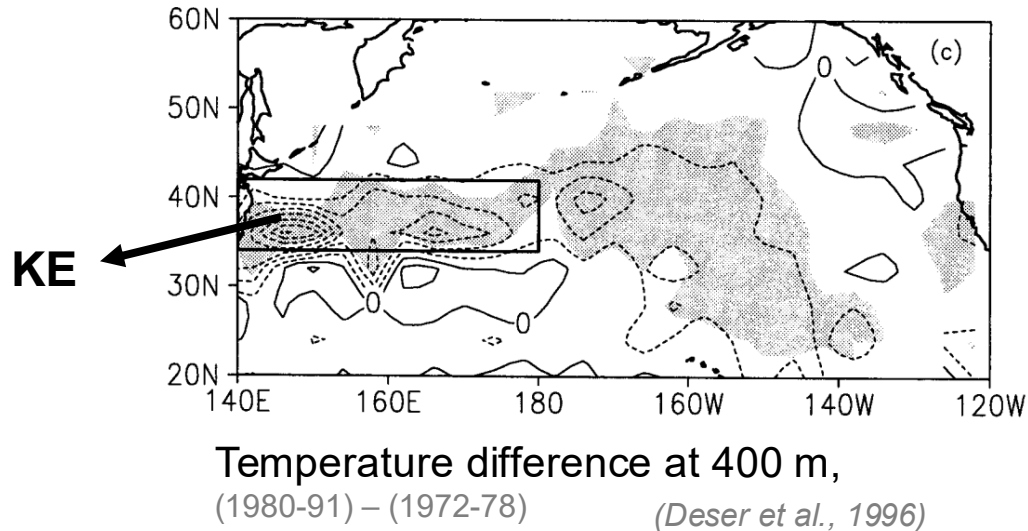(a) zonal mean (145-155E) SSH [cm]
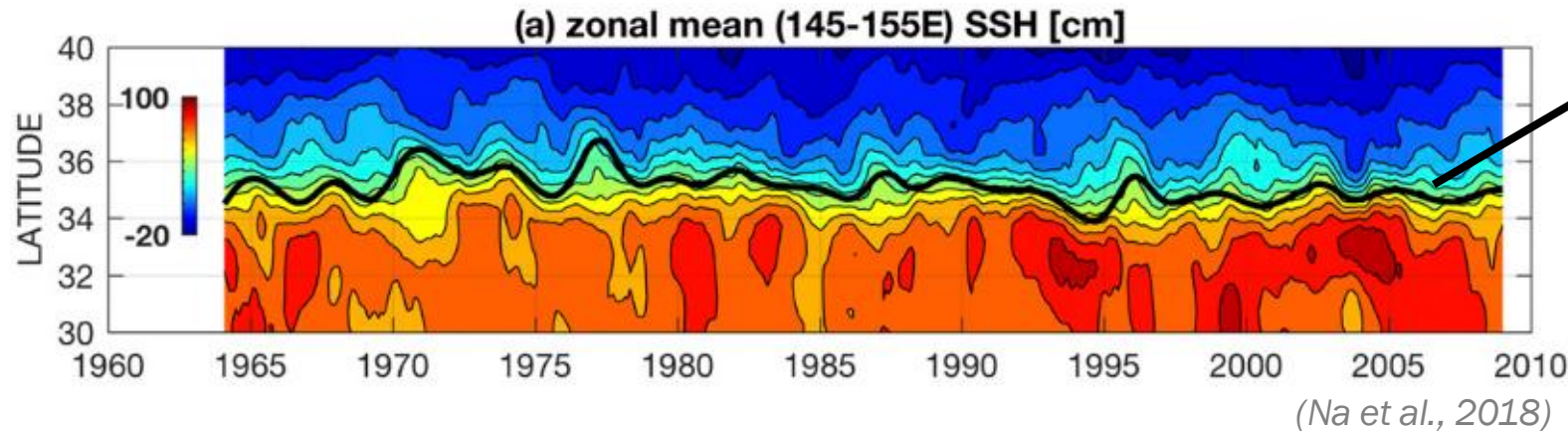
(Na et al., 2018)

Defined as the ① **latitude** and ② **value** of the maximum meridional SSH gradient

(Nonaka et al., 2006; Na et al., 2018; Wu et al., 2021)

Introduction

➢ **Variability of the KE**

- Subsurface temperature variability *(Deser et al., 1996, 1999; Tourre et al., 1999)*

    - Observed cooling along the thermocline (200~400 m) with the southward **shift** of the KE

    - Decadal-scale thermocline variation is related to the **intensification** of the KE

KE

Upstream KE
Thermocline variability

Temperature difference at 400 m,
(1980-91) – (1972-78)   *(Deser et al., 1996)*

Decadal-scale temperature change
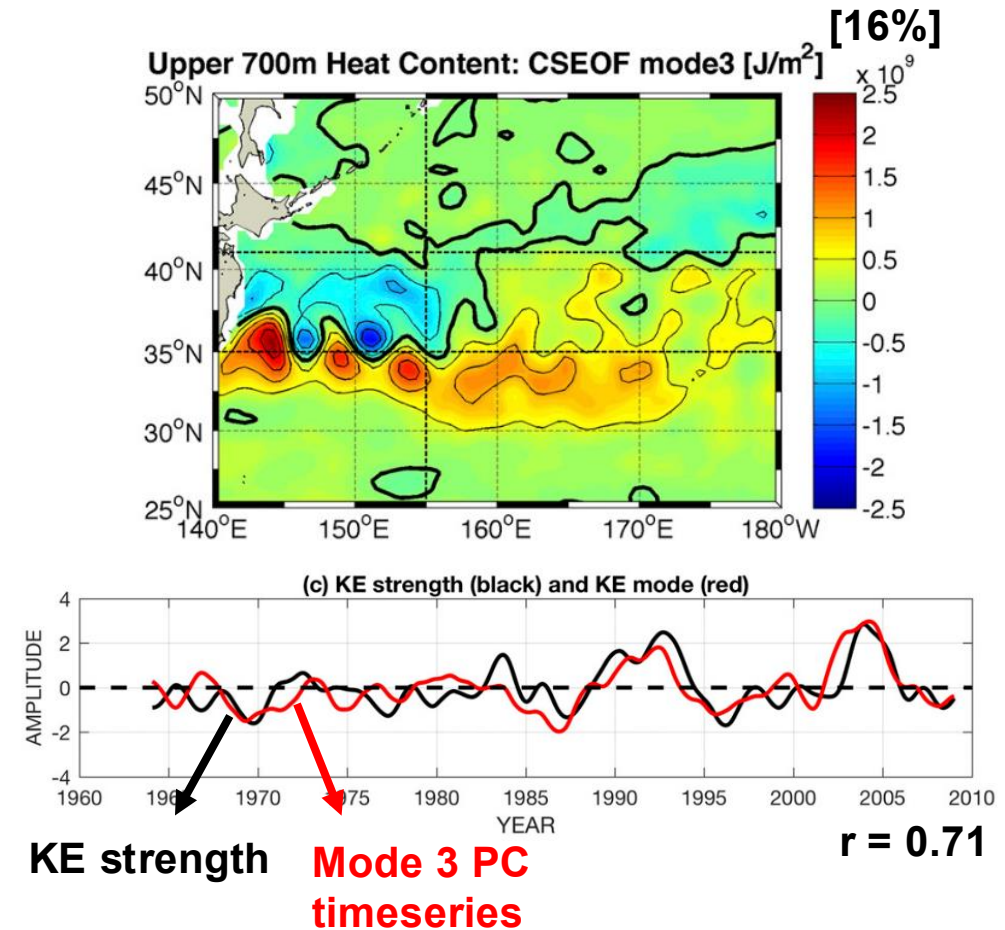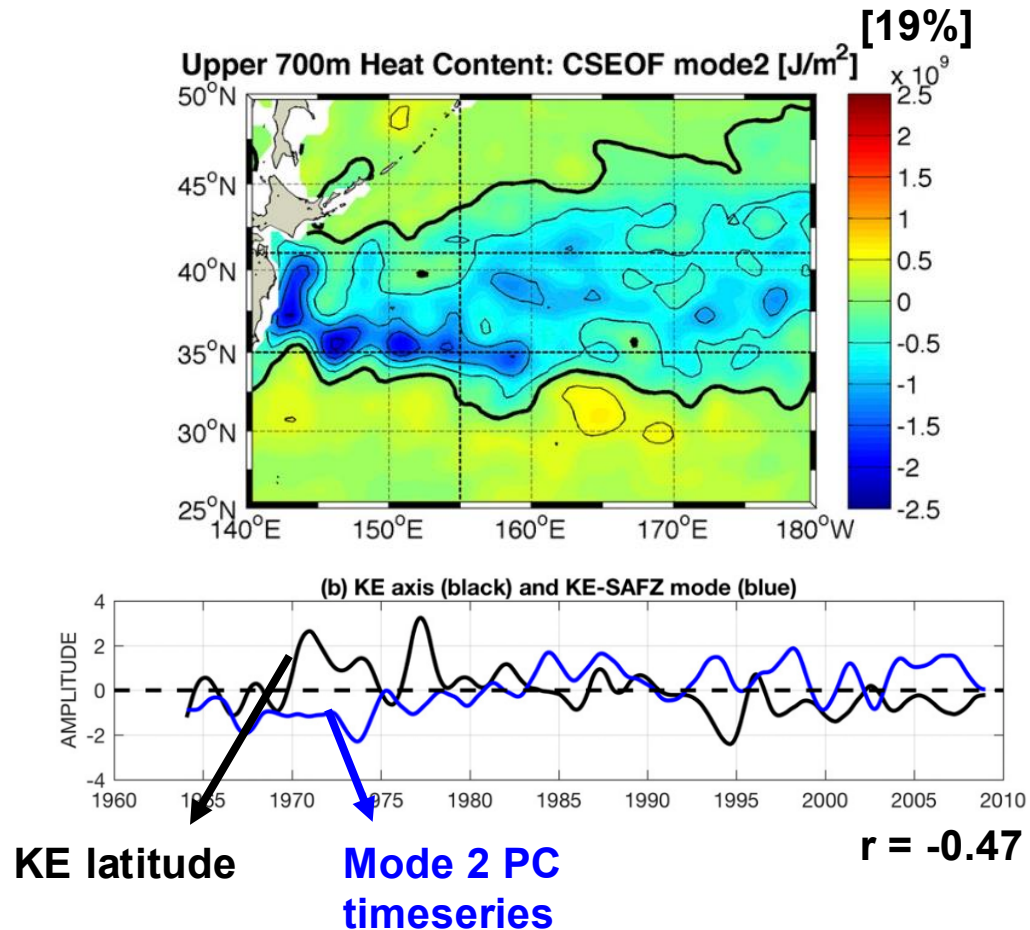(1977-88) – (1968-79)   *(Deser et al., 1999)*

While **SST** have been widely used to investigate North Pacific climate variability,
Variables related to the subsurface temperature are suitable for capturing the variability of the KE.

Introduction

➤ **Heat content (HC) variability of the KE (1964 – <mark>2008</mark>)** *(Na et al., 2018)*

- **Mode 2:** Reduction in HC with southward shift of the KE jet   (**PDO**: 6-mon. lead)
- **Mode 3:** Dipole pattern with intensified KE jet   (**NPGO**: 3-year lead)

[19%]

Upper 700m Heat Content: CSEOF mode2 [J/m²]

(b) KE axis (black) and KE-SAFZ mode (blue)

KE latitude   **Mode 2 PC timeseries**   **r = -0.47**

[16%]

Upper 700m Heat Content: CSEOF mode3 [J/m²]

(c) KE strength (black) and KE mode (red)

KE strength   **Mode 3 PC timeseries**   **r = 0.71**

Introduction

➢ **Recent characteristics of the KE** (<mark>1993</mark>-present)

(Qiu and Chen, 2005; 2010; Kawakami et al., 2023)

- Poleward-shifted and intensified KE
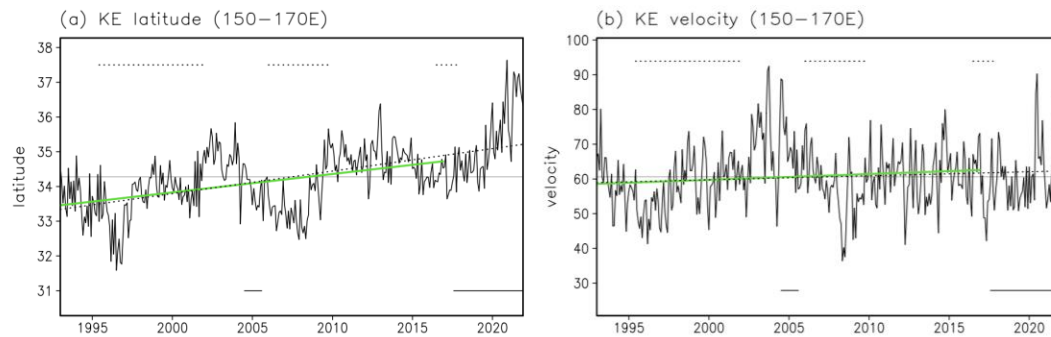
➢ **New regime of the Pacific climate variability**

(Qiu and Chen, 2010; Sasaki et al., 2013; Litzow et al., 2020)

- PDO and NPGO indices may not be separated
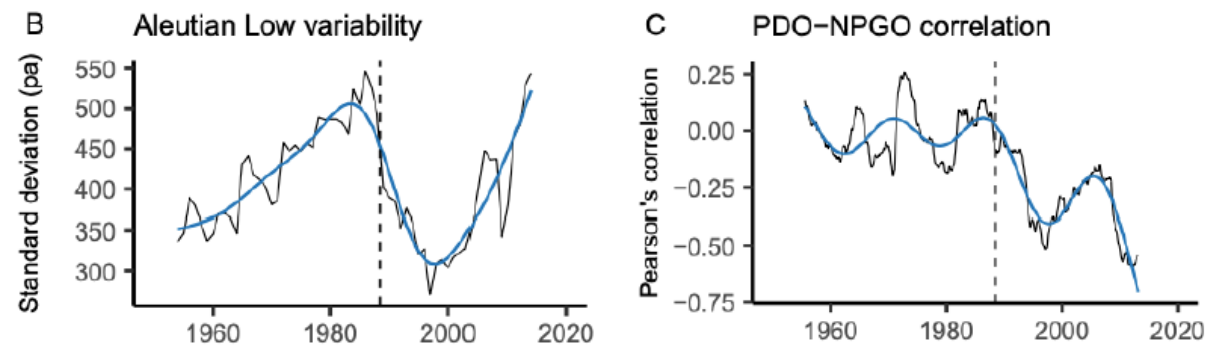
Negative correlation appeared after **1988/89** climate shift

➢ **Research Questions**

Has the relationship between dominant modes of HC variability in the North Pacific, and their associated variability of the KE and climate modes changed in <mark>**1993 – 2020**</mark>?

Data and Methods

➢ Data

Name	Resol.	Period	Variables
SODA 2.1.6	½° 21 Lev.	1964–2008 (45 years)	(Monthly) temperature, salinity, velocity, sea surface height, wind stress
SODA 3.4.2	½° 26 Lev.	1993–2020 (28 years)	
NCEP-NCAR Reanalysis	2.5°	1993–2020 (28 years)	(Monthly) sea level pressure
PDO/NPGO index	-	1993–2020 (28 years)	(Monthly) PDO/NPGO index *NOAA NCEI* *Di Lorenzo et al., 2008*

➢ KE variability *(Nonaka et al., 2006; Na et al., 2018; Wu et al., 2021)*

(a) zonal mean (145-155E) SSH [cm]
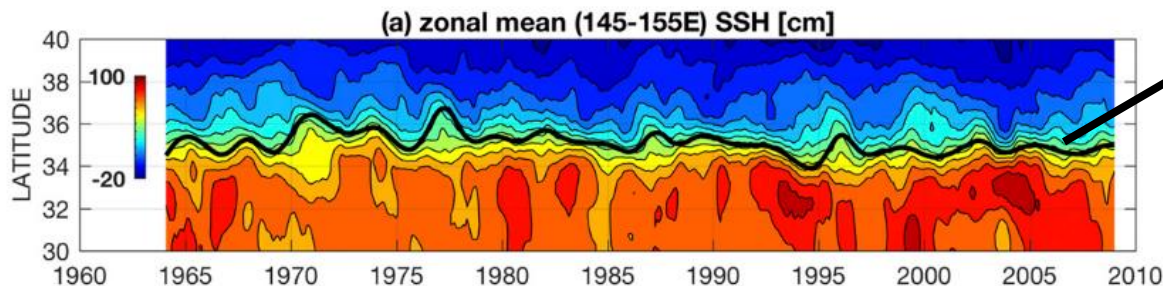
Defined as the ① **latitude** and ② **value** (strength) of the maximum meridional SSH gradient

➢ Upper 700 m HC *(Na et al., 2018)*

(1-m linear interpolated)

$$HC = \int_{700}^{0} \rho(T,S,0)\, c_p(T,S,0)\, T(z)\, dz$$

T, S, P: temperature, salinity, and density
c_p : specific heat capacity at constant pressure

➢ Cyclostationary EOF (CSEOF)

(Kim and North, 1997; Kim et al., 2015)

$$HC(r,t) = \sum_n CSLV_n(r,t)\, PC_n(t)$$

$$CSLV_n(r,t) = CSLV_n(r, t+d)$$

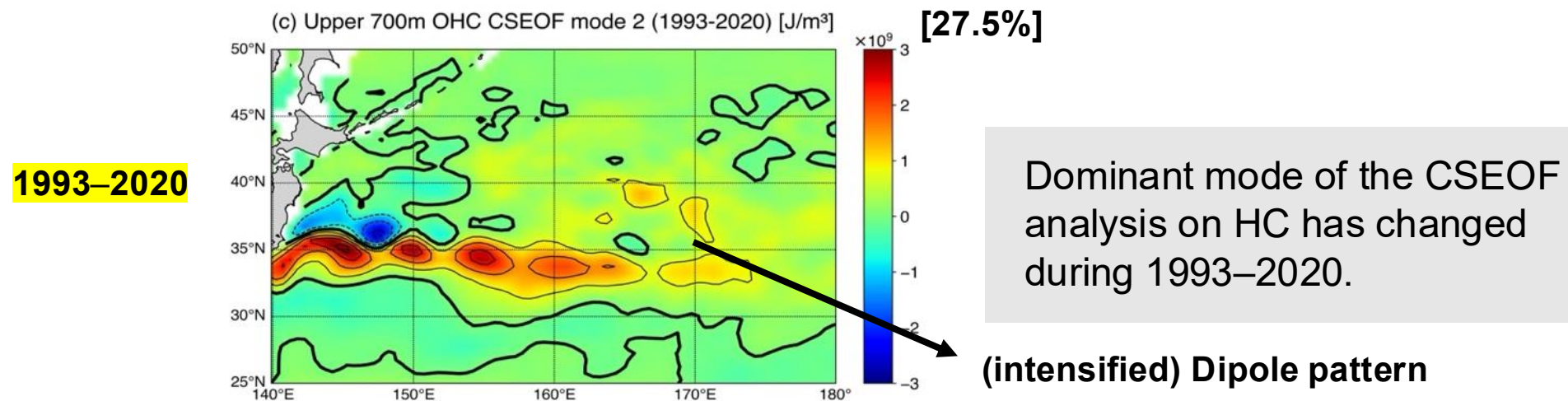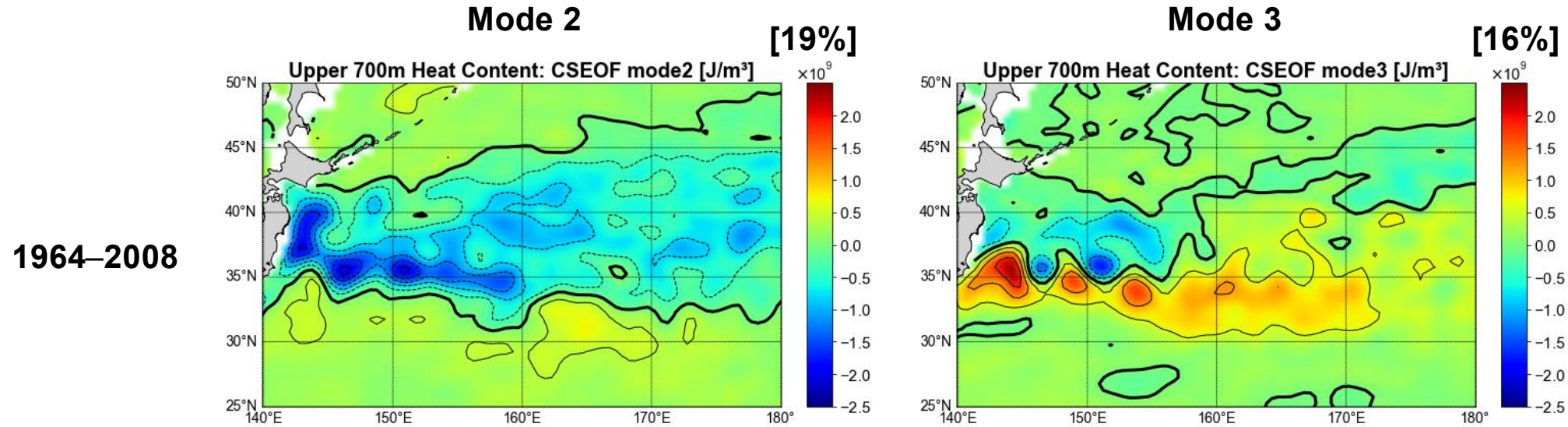n: mode number
r, t: space and time

CSEOF Analysis: Upper 700 m HC
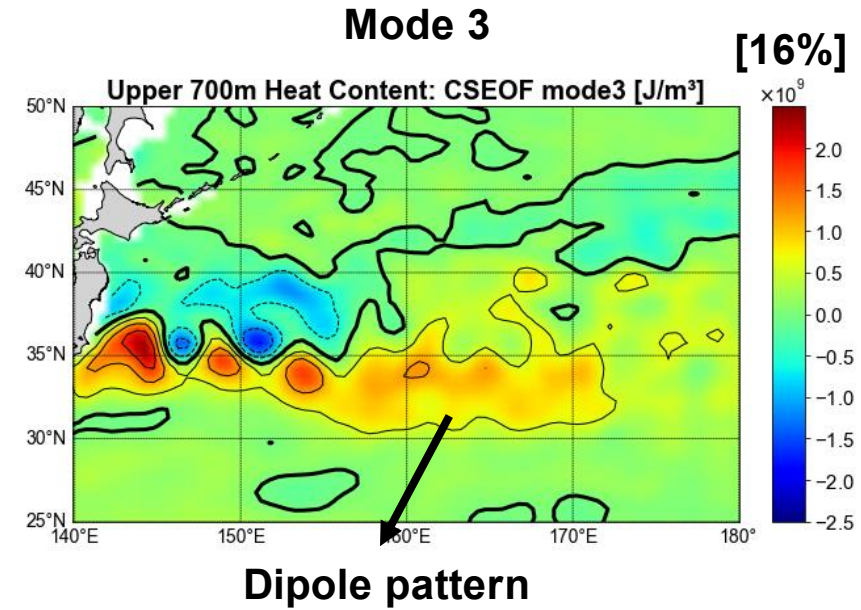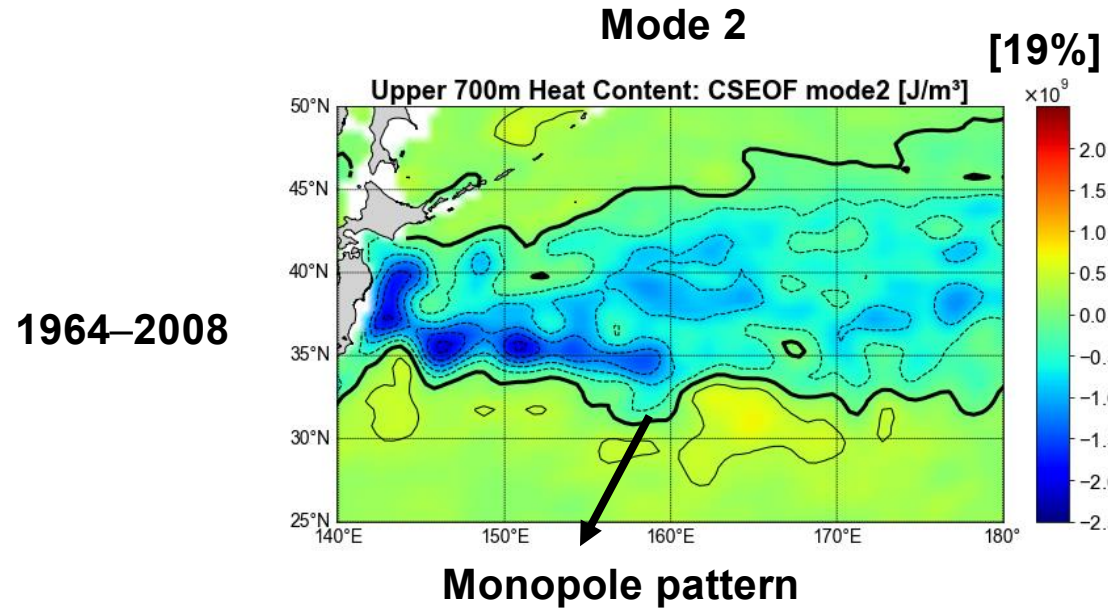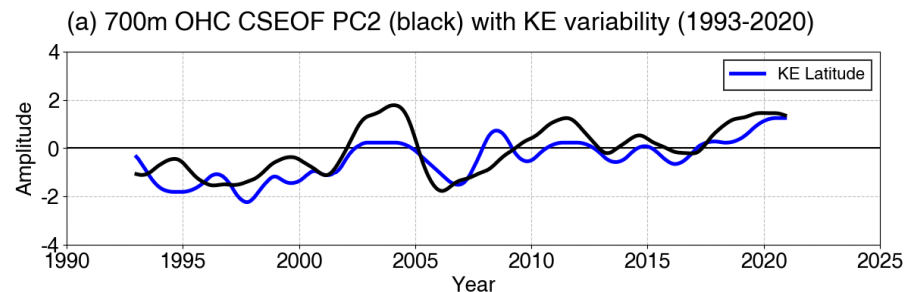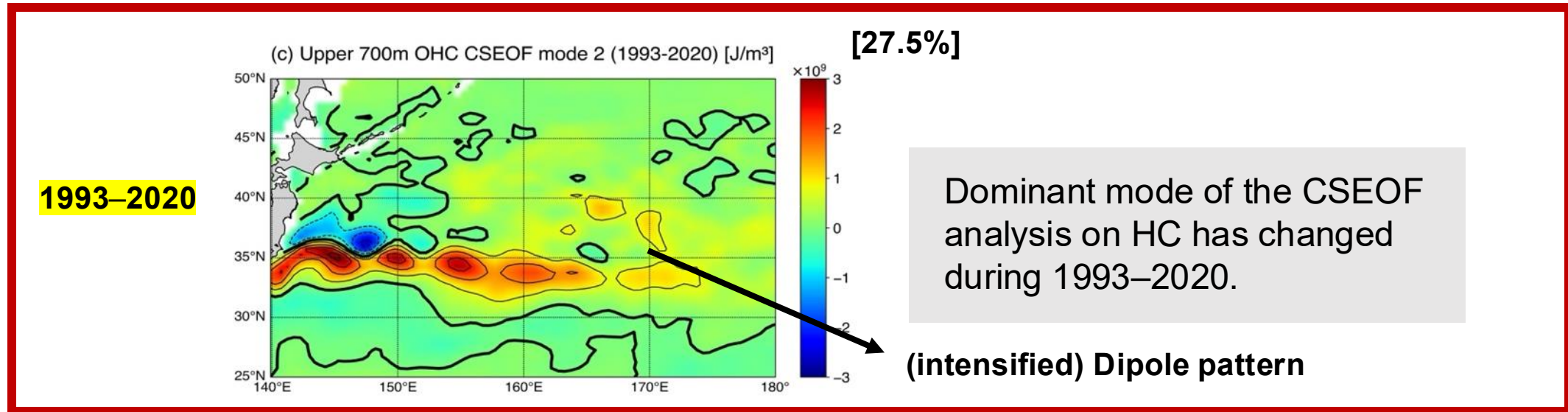
➢ **CSEOF analysis and its physical interpretation**

Mode 2 [19%]

Mode 3 [16%]

1964–2008

Monopole pattern

Dipole pattern

CSEOF Analysis: Upper 700 m HC

➢ **CSEOF analysis and its physical interpretation**

Mode 2 [19%]

Mode 3 [16%]

1964–2008

1993–2020

Dominant mode of the CSEOF analysis on HC has changed during 1993–2020.

(intensified) Dipole pattern

CSEOF Analysis: Upper 700 m HC

➢ **CSEOF analysis and its physical interpretation**

[27.5%]

(c) Upper 700m OHC CSEOF mode 2 (1993-2020) [J/m³]

1993–2020

Dominant mode of the CSEOF analysis on HC has changed during 1993–2020.

(intensified) Dipole pattern

(a) 700m OHC CSEOF PC2 (black) with KE variability (1993-2020)

KE Latitude

Meridional shift of the Kuroshio Jet

(b) 700m OHC CSEOF PC2 (black) with KE variability (1993-2020)
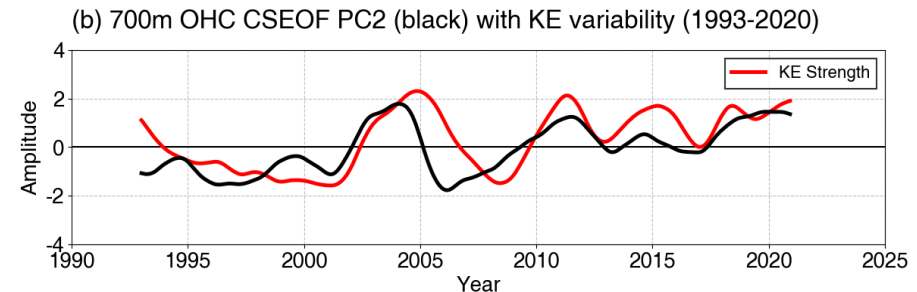
KE Strength

Strength change of the Kuroshio Jet

PC time series explains both of the latitude and strength variability of KE.

Relationships with Major Climate Modes
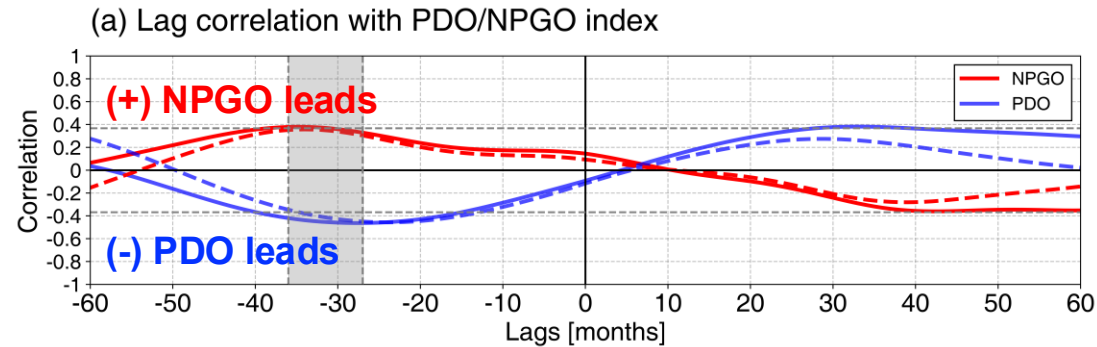
➢ **Regressed patterns onto the PDO/NPGO index**

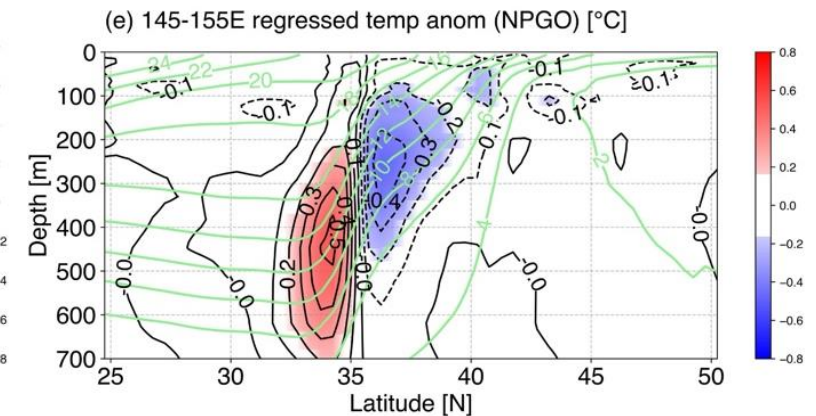(a) Lag correlation with PDO/NPGO index
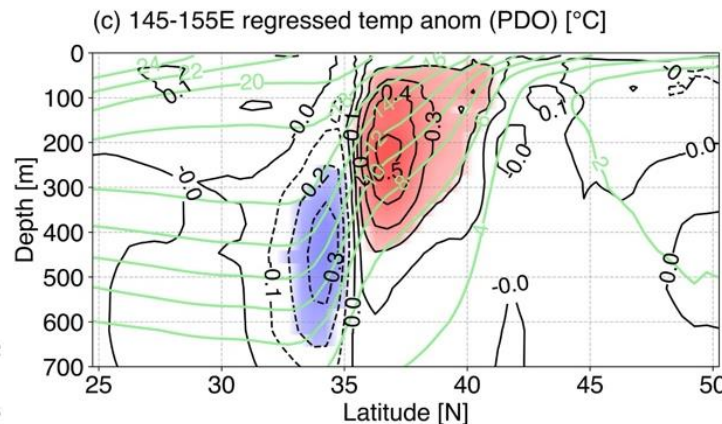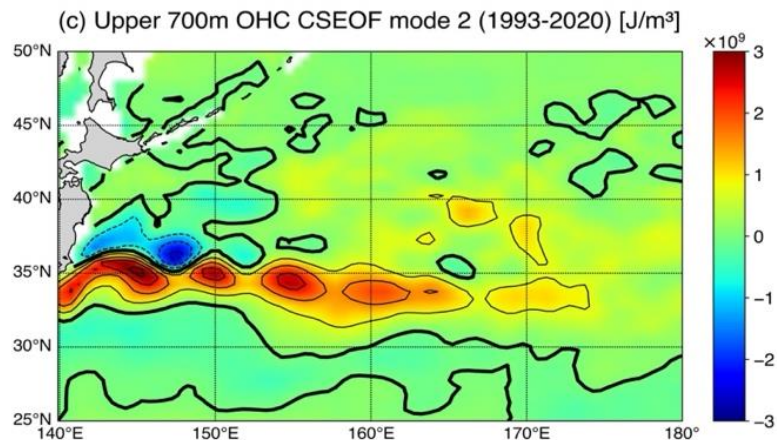
(+) NPGO leads

(-) PDO leads

Maximum correlation at **~3 years**

PC time series is correlated to the PDO (-) and NPGO (+) index at about 3-year lag.

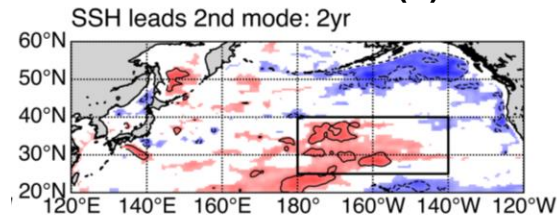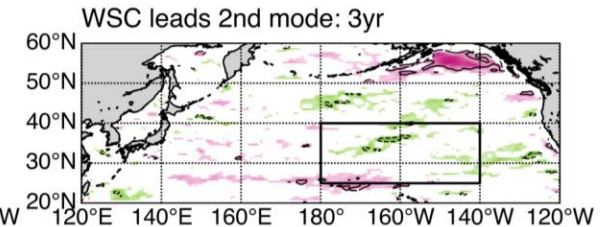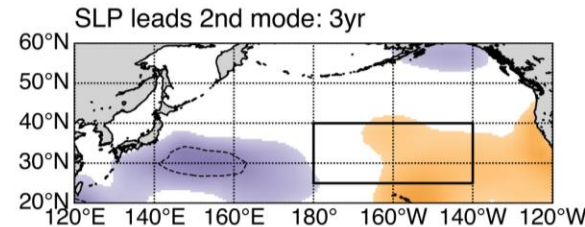**Mode 2**   **Regressed** (Target: PDO)   **Regressed** (Target: NPGO)

(c) Upper 700m OHC CSEOF mode 2 (1993-2020) [J/m³]

(c) Reg. OHC (PDO: 35 months, R²: 0.52) (1993-2020) [J/m³]

(d) Reg. OHC (NPGO: 29 months, R²: 0.63) (1993-2020) [J/m³]

Relationships with Major Climate Modes

➢ **Regressed patterns onto the PDO/NPGO index**

(a) Lag correlation with PDO/NPGO index

Maximum correlation at **~3 years**

PC time series is correlated to the PDO (-) and NPGO (+) index at about 3-year lag.

| **Mode 2** | **Regressed** (Target: PDO) | **Regressed** (Target: NPGO) |

(c) Upper 700m OHC CSEOF mode 2 (1993-2020) [J/m³]

(c) 145-155E regressed temp anom (PDO) [°C]

(e) 145-155E regressed temp anom (NPGO) [°C]

Relationships with Atmospheric Variability

➤ **Lagged correlation map with the CSEOF 2ⁿᵈ mode PC timeseries**

(+) SSH
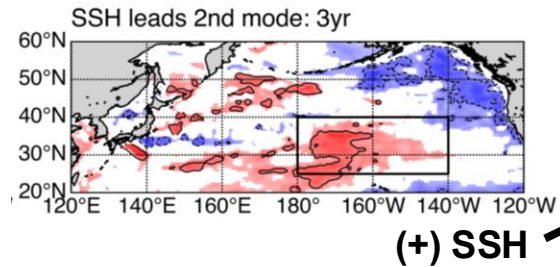
Atmospheric Forcings

Westward Propagation
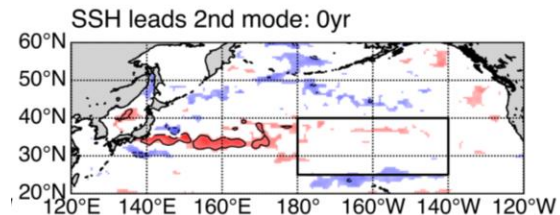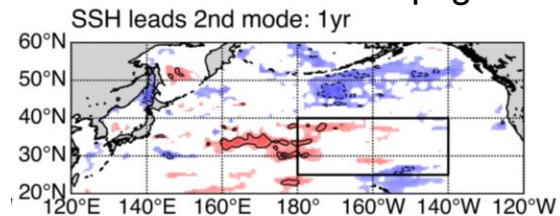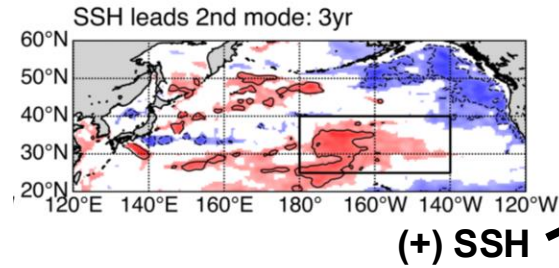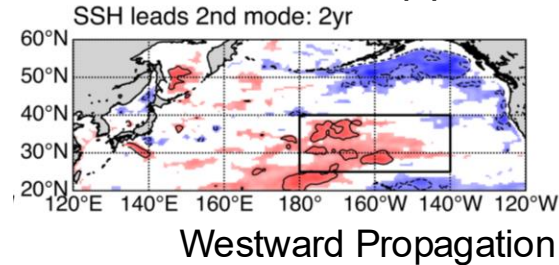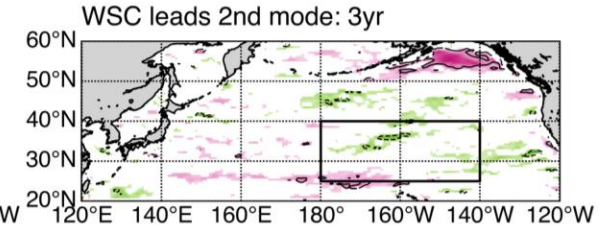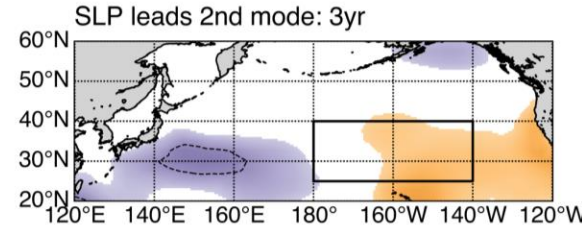
Jet-trapped Rossby Waves

(Sasaki et al., 2013)

Relationships with Atmospheric Variability

➢ **Lagged correlation map with the CSEOF 2nd mode PC timeseries**

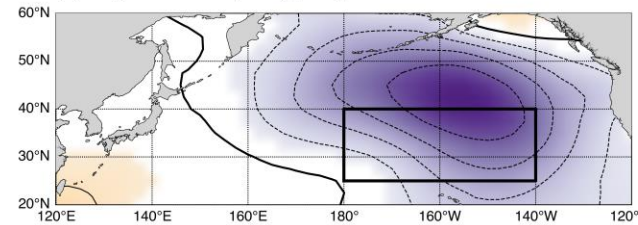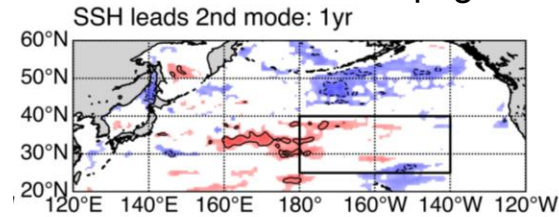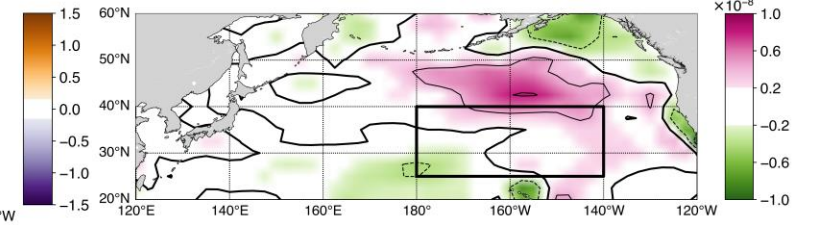Atmospheric Forcings

(+) SSH

Westward Propagation

Jet-trapped Rossby Waves

(Sasaki et al., 2013)

Regressed (Target: PDO)
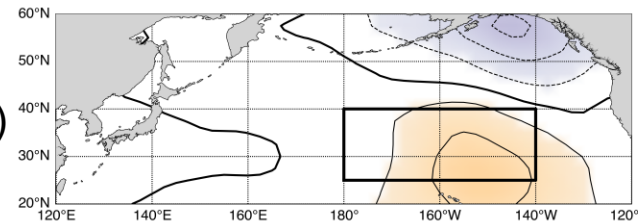
Regressed (Target: NPGO)
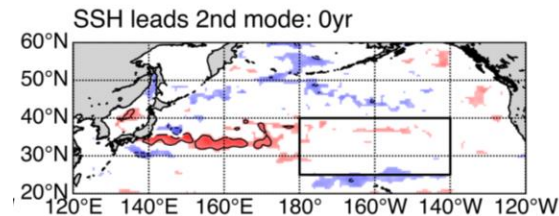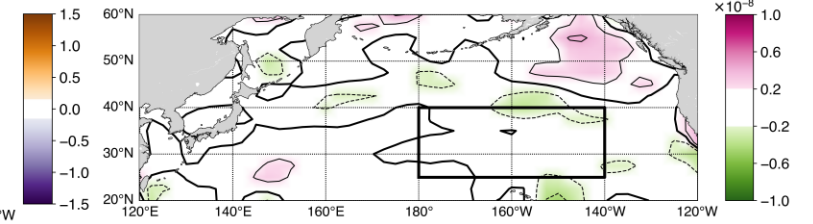
Atmospheric variability related to the PDO and NPGO at 3-year lag triggers jet-trapped Rossby Waves and changes HC in the western North Pacific.

Take-home messages

- This study investigated the recent changes in the relationship between Ocean Heat Content (OHC) variability in the western NP and major Pacific climate modes.

- Results highlight the limitation of these Pacific climate modes under the assumption of their stationarity.

Previous Work [1964 – 2008]

Downstream KE WSC (~1 yr)

Internal air-sea Coupled system [Na et al., 2018]

KE — PDO — NPGO

2nd mode – KE latitude (-) (6 mon.)

Fast SSH adjustment

Jet-trapped Rossby wave Propagation

3rd mode – KE strength (+) (3 yrs.)

Current Work [1993 – 2020]

Downstream KE WSC (~1 yr)

Internal air-sea Coupled system [Current work]

KE — PDO NPGO

2nd mode – KE latitude (+) & KE strength (+) (~3 yrs.)
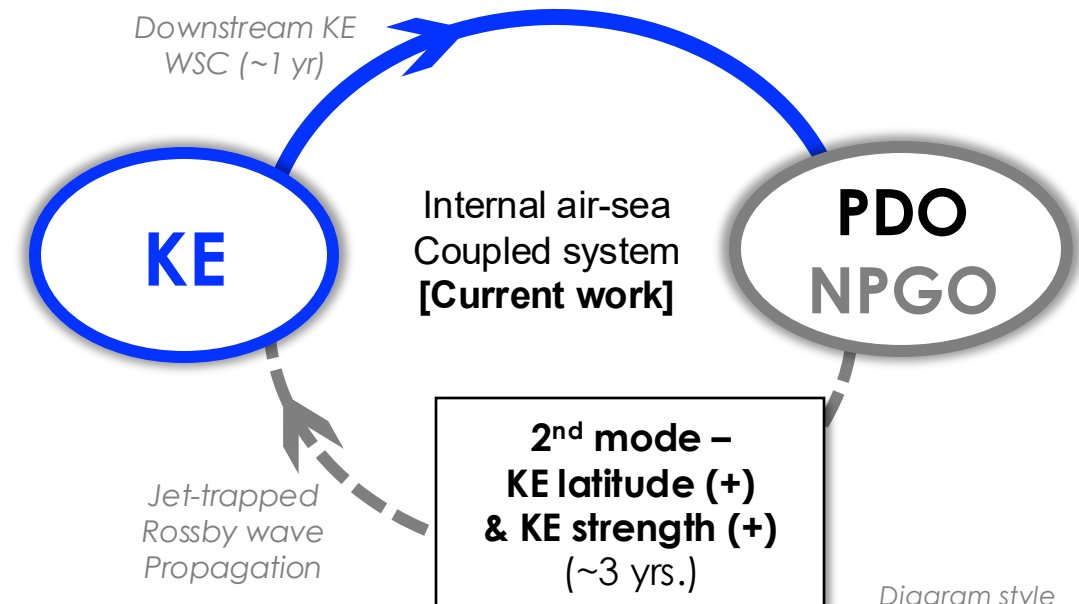
Jet-trapped Rossby wave Propagation
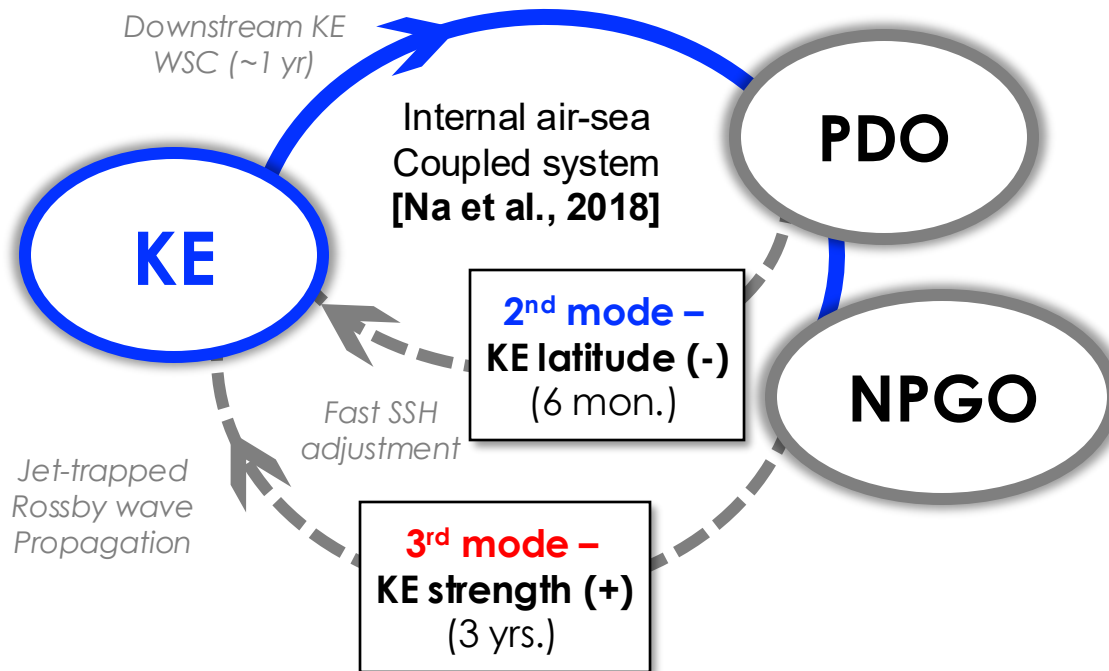
Diagram style Adapted from Di Lorenzo et al. (2023)

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