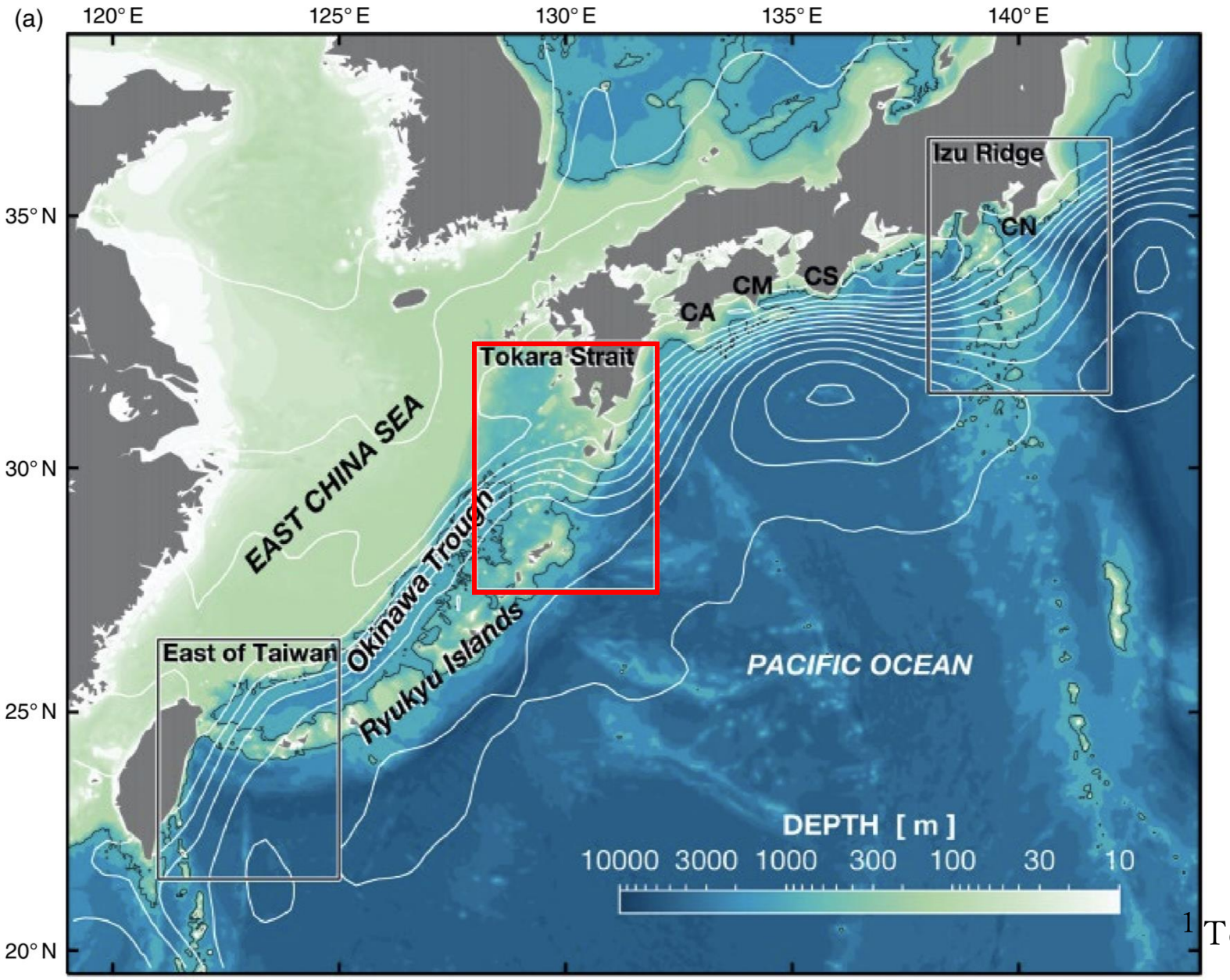

TUMSAT

PICES-2025
Nov 8-14, 2025 | Yokohama, Japan

S07-18212

Submesoscale Eddy Induced Nitrate Upwelling and Effect on Biological Production in the upstream Kuroshio Current

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Takeyoshi Nagai[1]

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Tuesday, 11th November 2025

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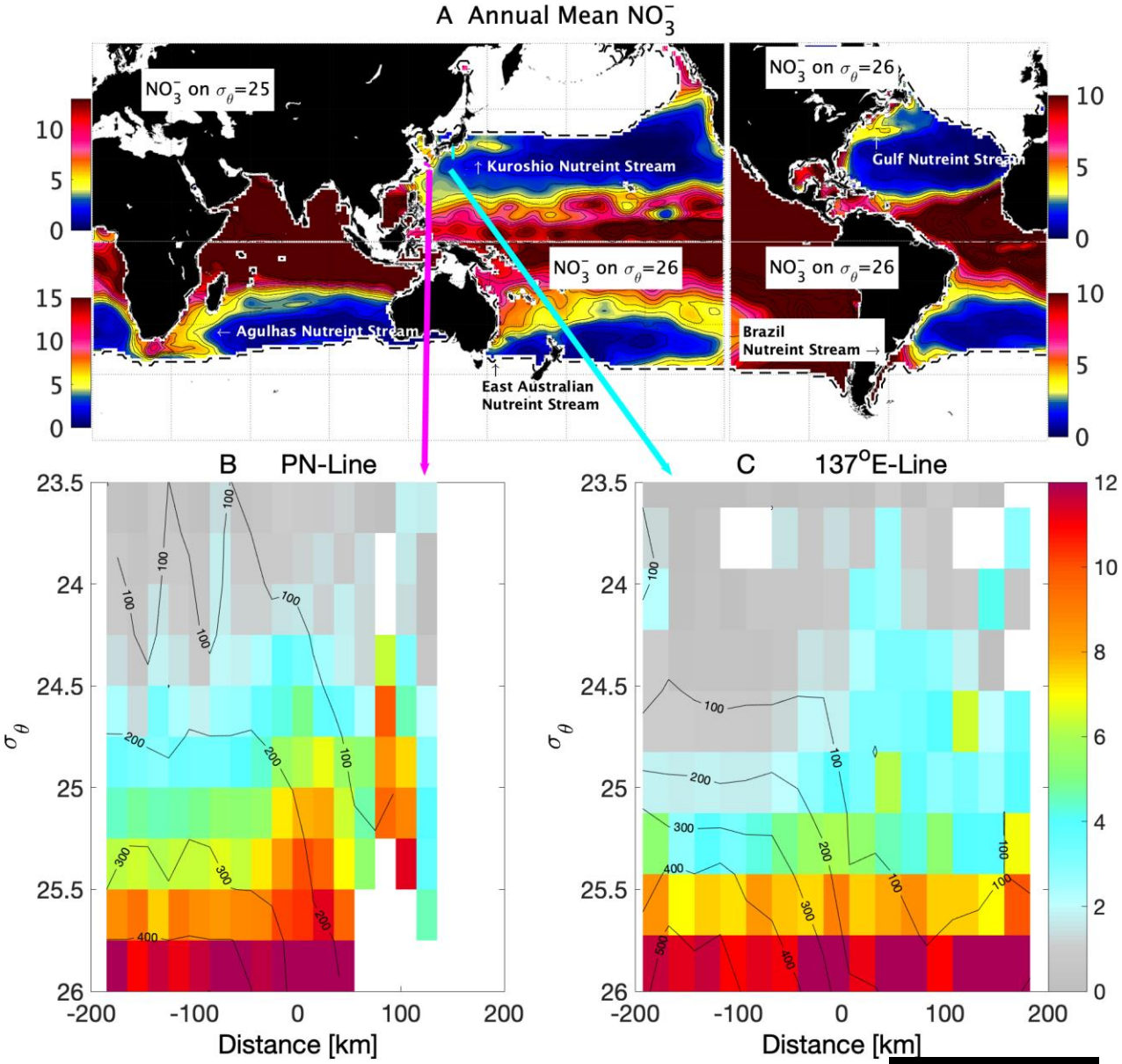
Gloria Silvana Duran Gomez & Takeyoshi Nagai

Scientific Reports **15**, Article number: 22618 (2025) | Cite this article

THE KUROSHIO CURRENT

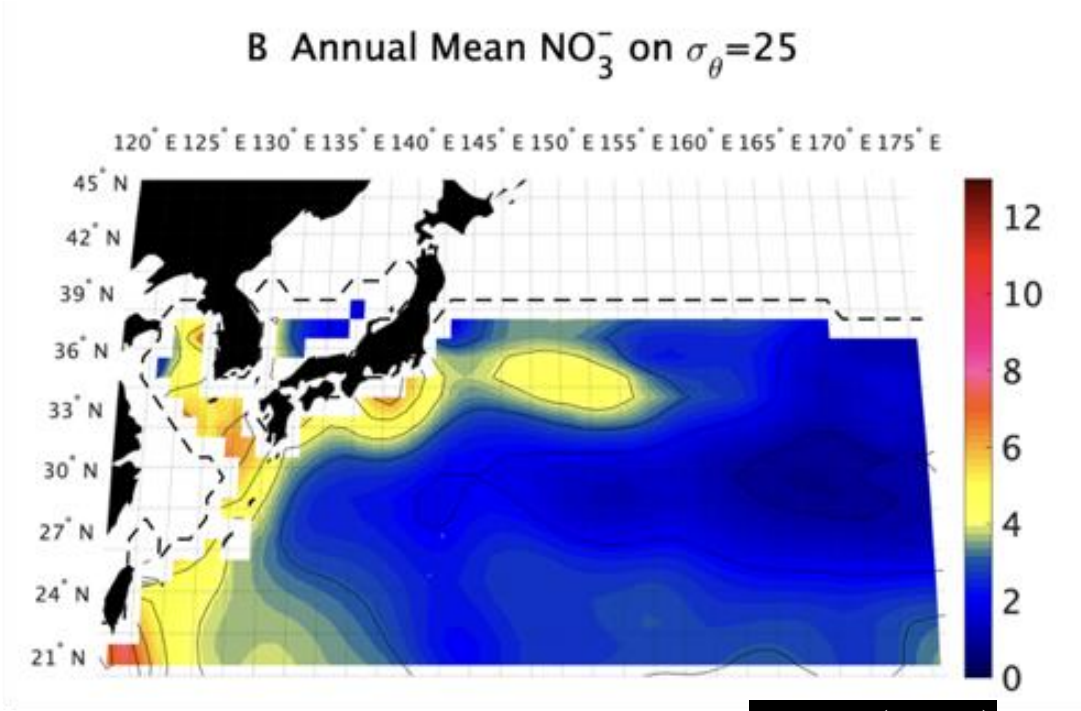


Source: JMA

Kuroshio Paradox (Saito 2019)

Abundant biodiversity despite its oligotrophic surface waters

Fishing industry, local weather, major carbon dioxide sink



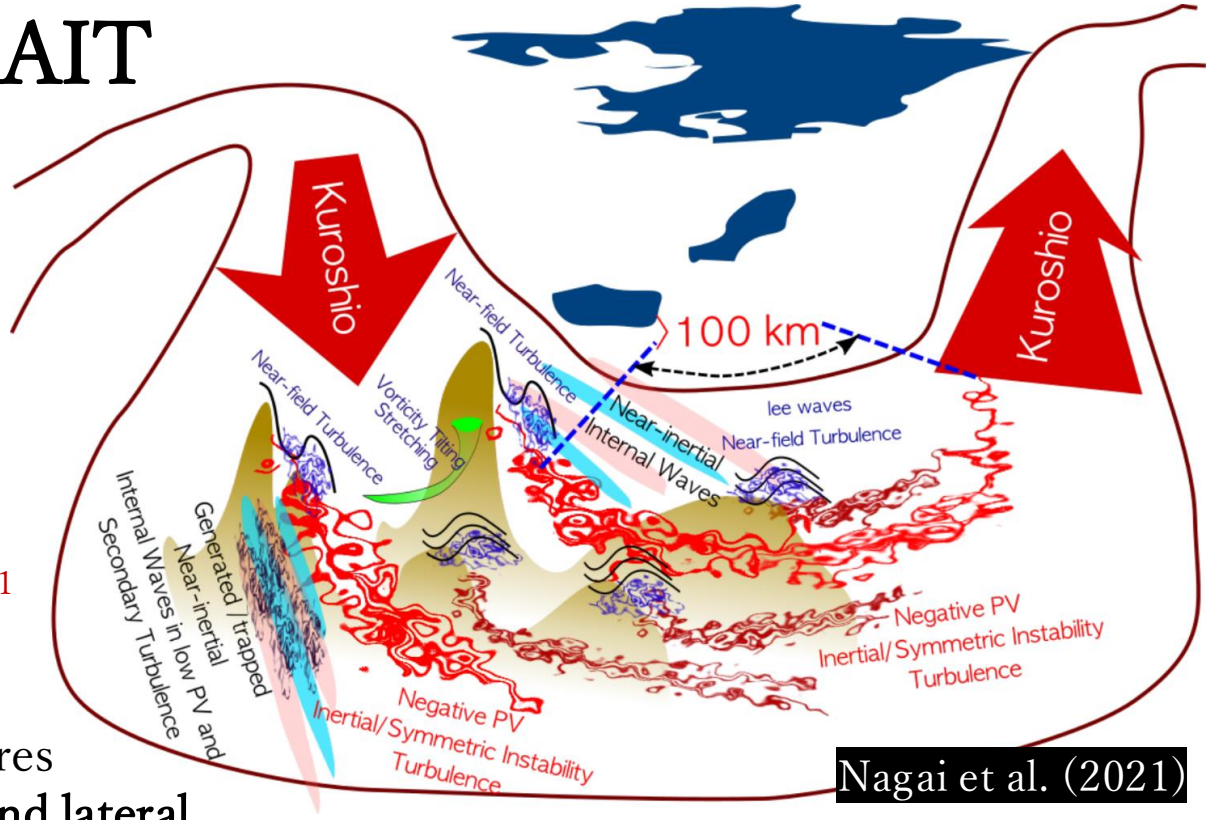
WOA (2023)

STUDY REGION: TOKARA STRAIT

Kuroshio – topography interaction

Strong turbulent mixing
~ enhanced FNO_3
O(1-10) mmol N m^{-2} day^{-1}

Formation of submesoscale structures
~ vertical nutrient fluxes and lateral advective transport



Nagai et al. (2021)

OBJECTIVES:

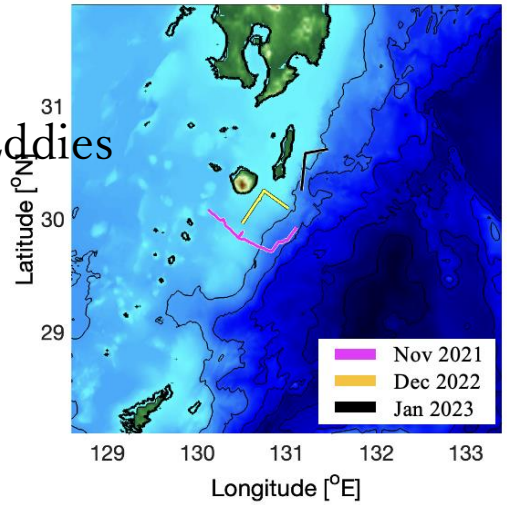
Q1: Quantify the contribution in nutrient supply made by submesoscale surface eddies

Q2: Unravel the lower-trophic ecosystem response to submesoscale nutrient injection

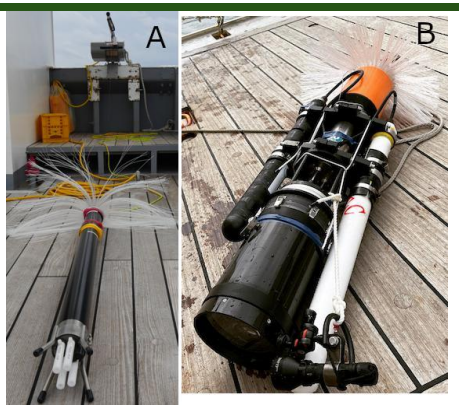
DATA & METHODS

In-situ observations

In the search of Surface Eddies
- Nov 2021
- Dec 2022
- Jan 2023



Tow-yo Profilers:
A) UVMP
Underway Vertical Microstructure Profiler
B) SUNADAYODACAM
chlorophyll-turbidity sensor, and nitrate sensor

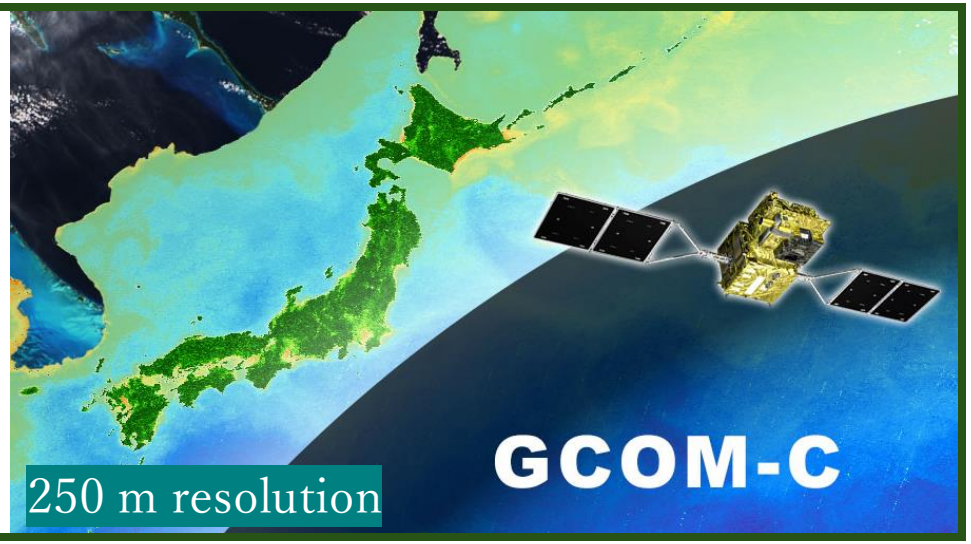


Satellite imagery

- Surface velocity (u,v)
- Sea Surface Height (SSH)
- Sea Surface Temperature (SST)
- Chlorophyll-a

Copernicus Marine Service

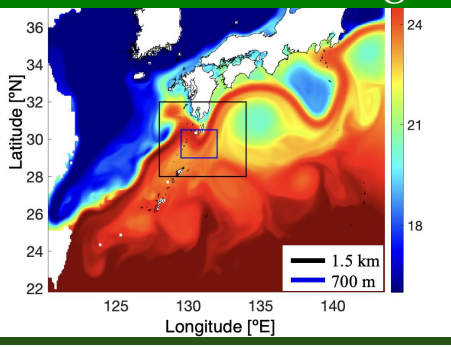
~9 km resolution



DATA & METHODS

Simulations: nested grids

Horizontal resolution ~700m grid

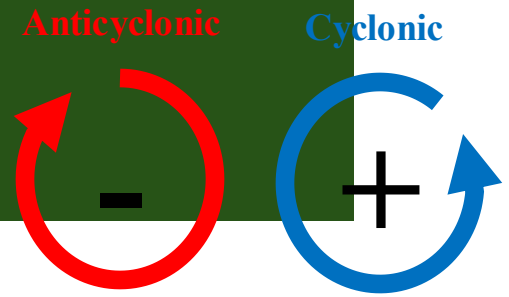


Regional Oceanic Modeling System (ROMS) coupled with a biogeochemical model $N_2P_2Z_2D_2$

- ✓ No tide
- ✓ K-Profile Parameterization KPP
- ✓ 50-m topography data (GtTM Whole Japan)
- ✓ Monthly climatological wind from the Comprehensive Ocean – Atmosphere Data Set (COADS)

DETECTION OF SURFACE EDDIES

- Contours of Sea Surface Height SSH' = -0.04
- $SSH' = SSH_{inst} - SSH_{mov\ avg}$ → smoothed over ~25km
- Relative vorticity: cyclonic – anticyclonic

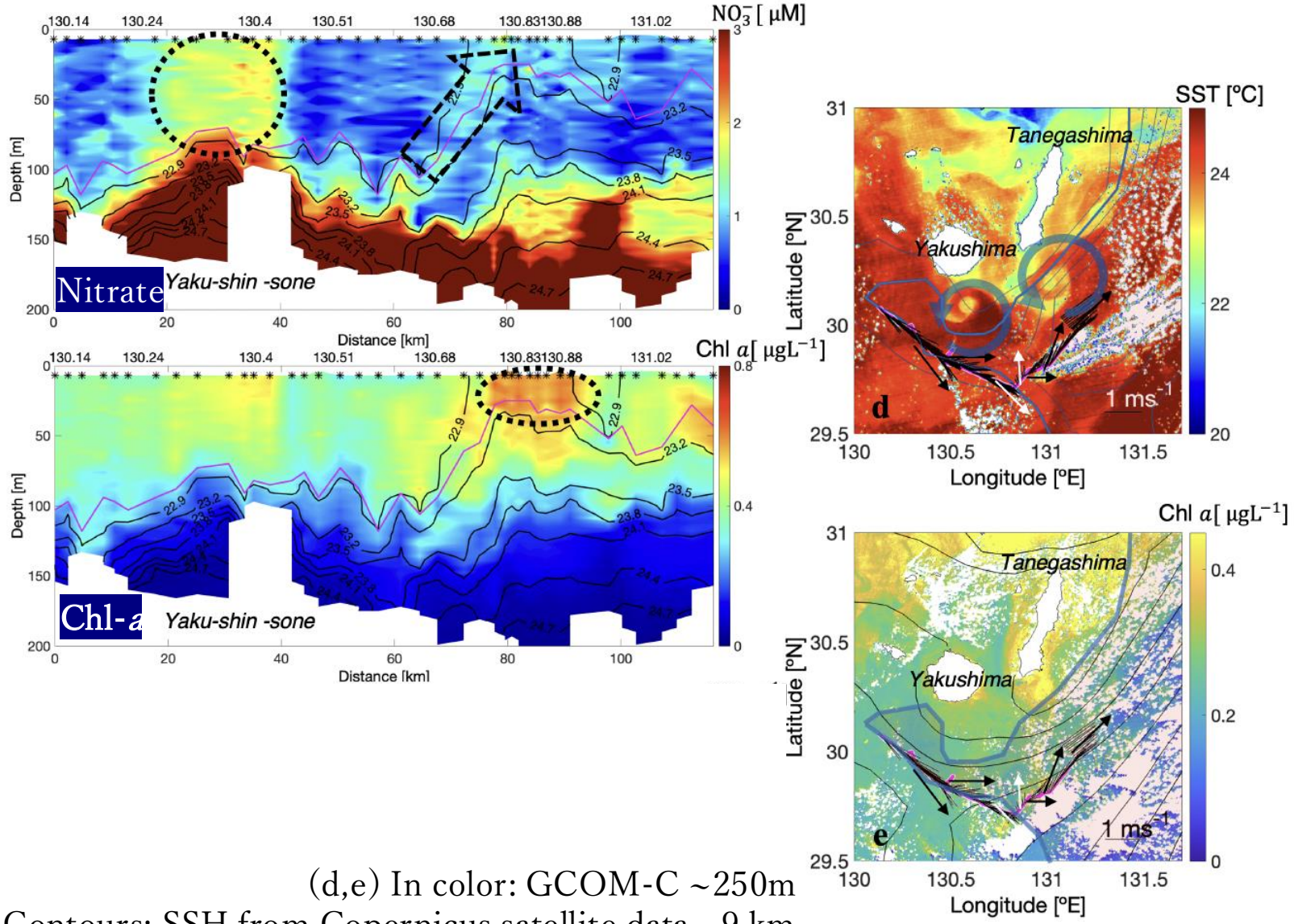


Q1: Quantify the contribution in nutrient supply made by submesoscale surface eddies

In-situ observation:
November 19-21, 2021

— Isopycnals
— MLD

For MLD - density criteria: difference of 0.125 kg m^{-3} from surface

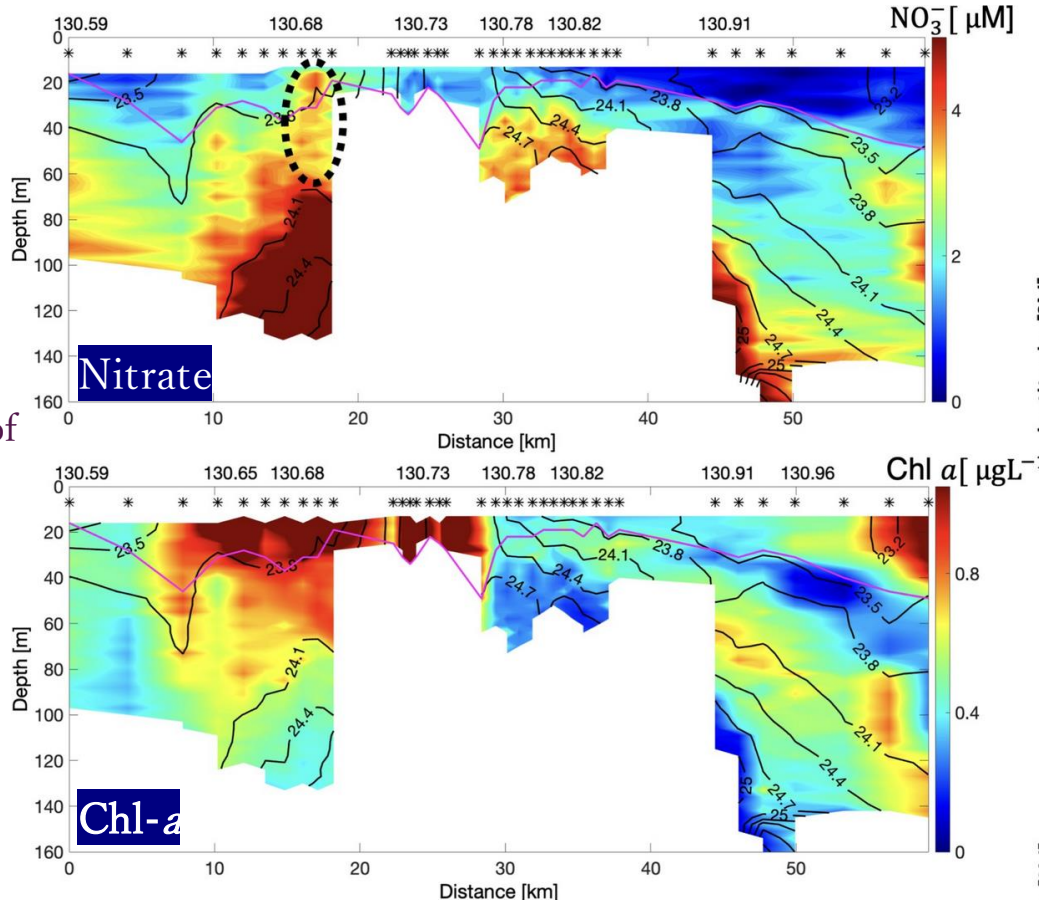


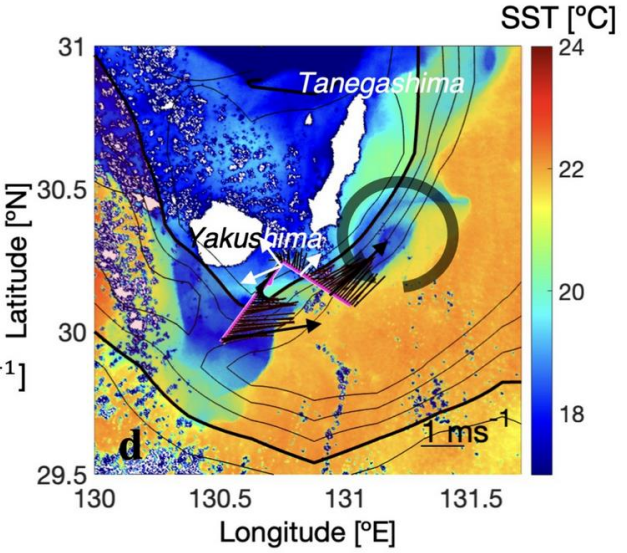
(d,e) In color: GCOM-C ~250m
Contours: SSH from Copernicus satellite data ~9 km

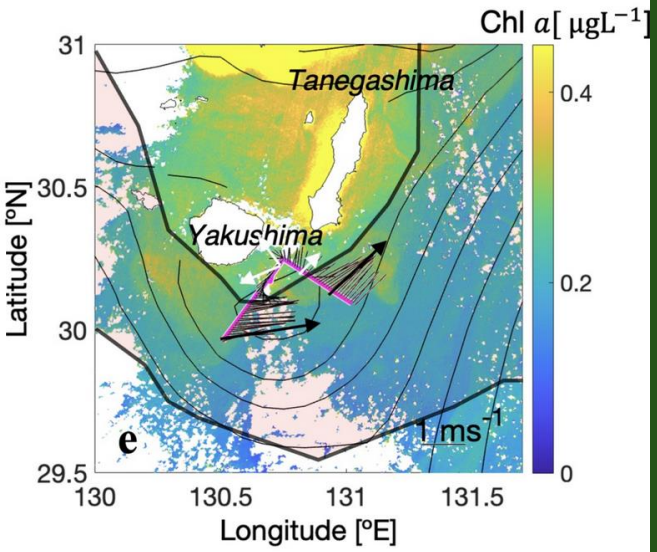
Q1: Quantify the contribution in nutrient supply made by submesoscale surface eddies

In-situ observation:
December 30, 2022

— Isopycnals
— MLD
For MLD - density criteria: difference of 0.125 kg m^{-3} from surface







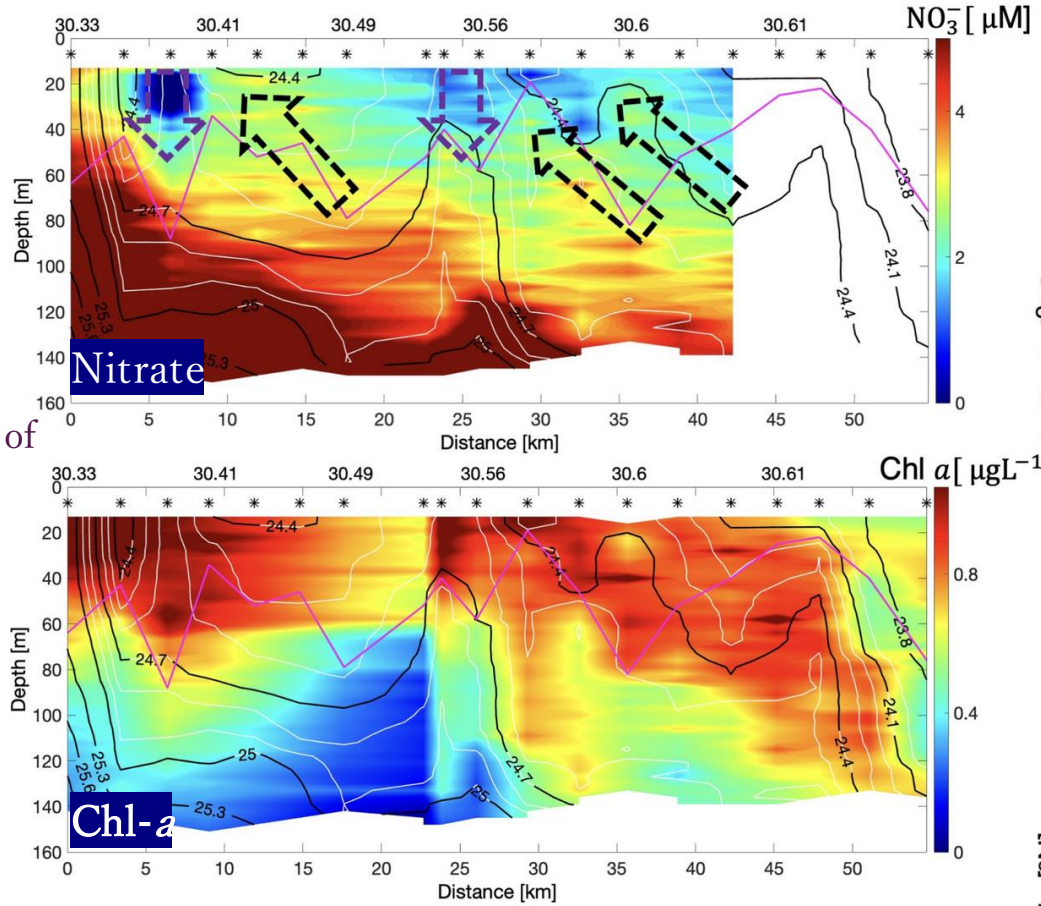
(d,e) In color: GCOM-C ~250m
Contours: SSH from Copernicus satellite data ~9 km

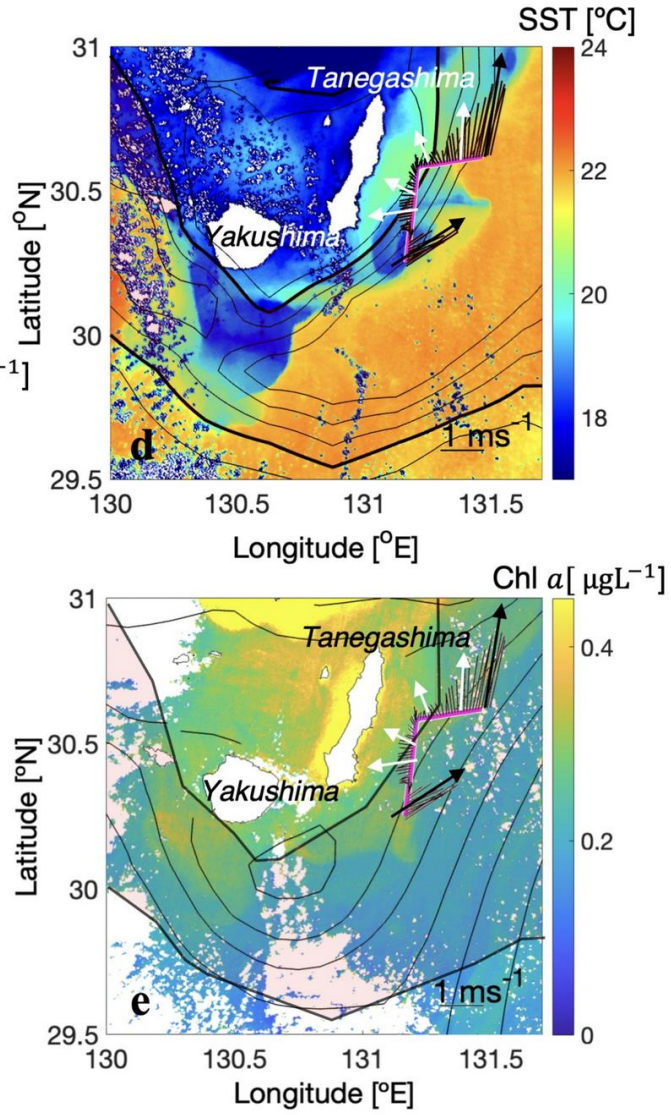
Q1: Quantify the contribution in nutrient supply made by submesoscale surface eddies

In-situ observation:
January 1, 2023

— Isopycnals
— MLD

For MLD - density criteria: difference of 0.125 kg m^{-3} from surface





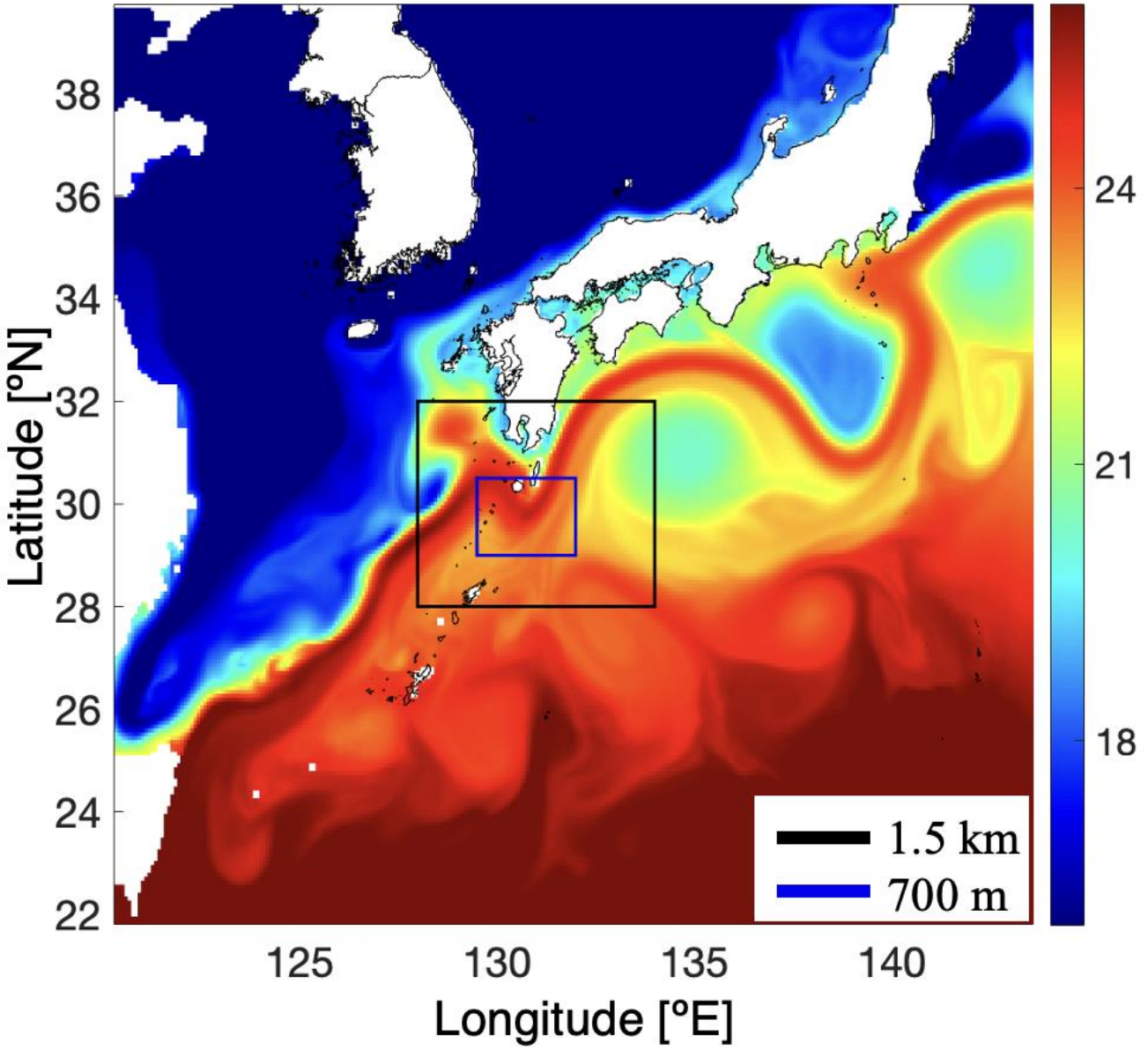
(d,e) In color: GCOM-C ~250m
Contours: SSH from Copernicus satellite data ~9 km

Q1: Quantify the contribution in nutrient supply made by submesoscale surface eddies

Regional Oceanic Modeling System

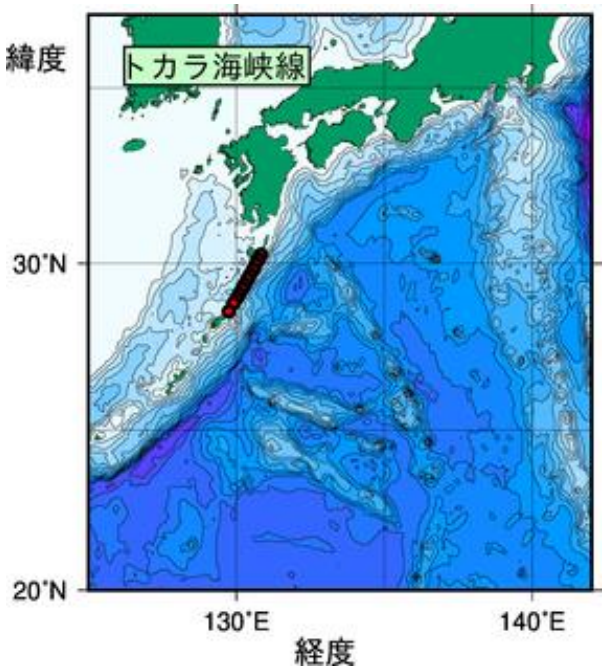
Horizontal resolution ~700m grid

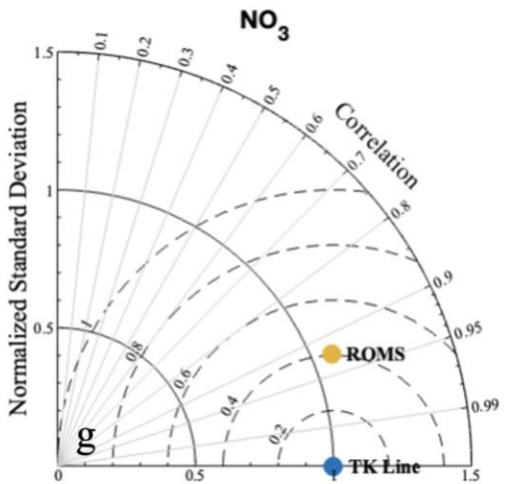
coupled w/ biogeochemical model $N_2P_2Z_2D_2$

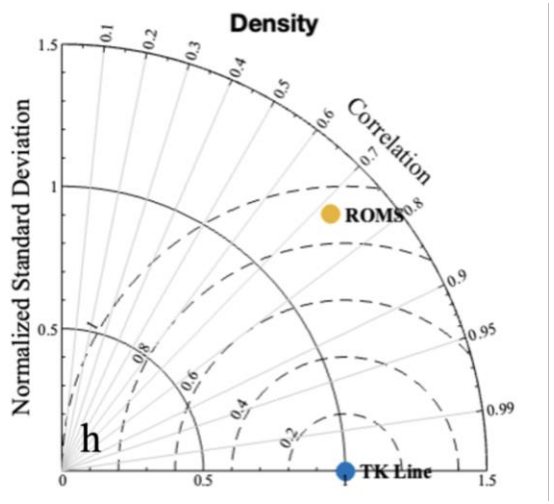


Validation of ROMS simulations

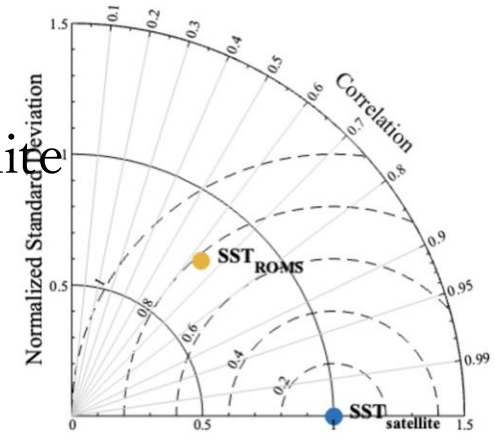
- NO_3 & density with **TK Line (JMA)**

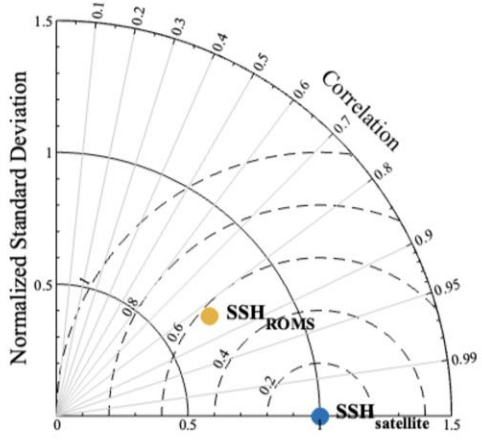


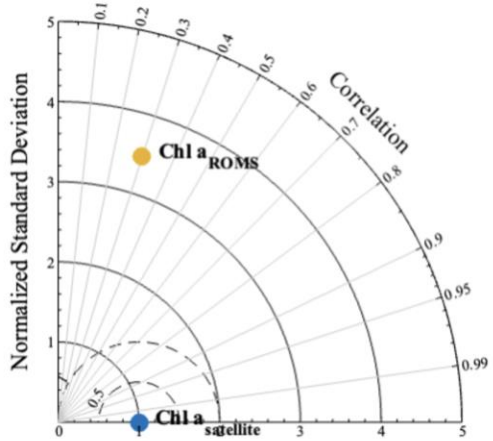




- SST, SSH & Chlorophyll with Satellite information data







Copernicus Marine Service

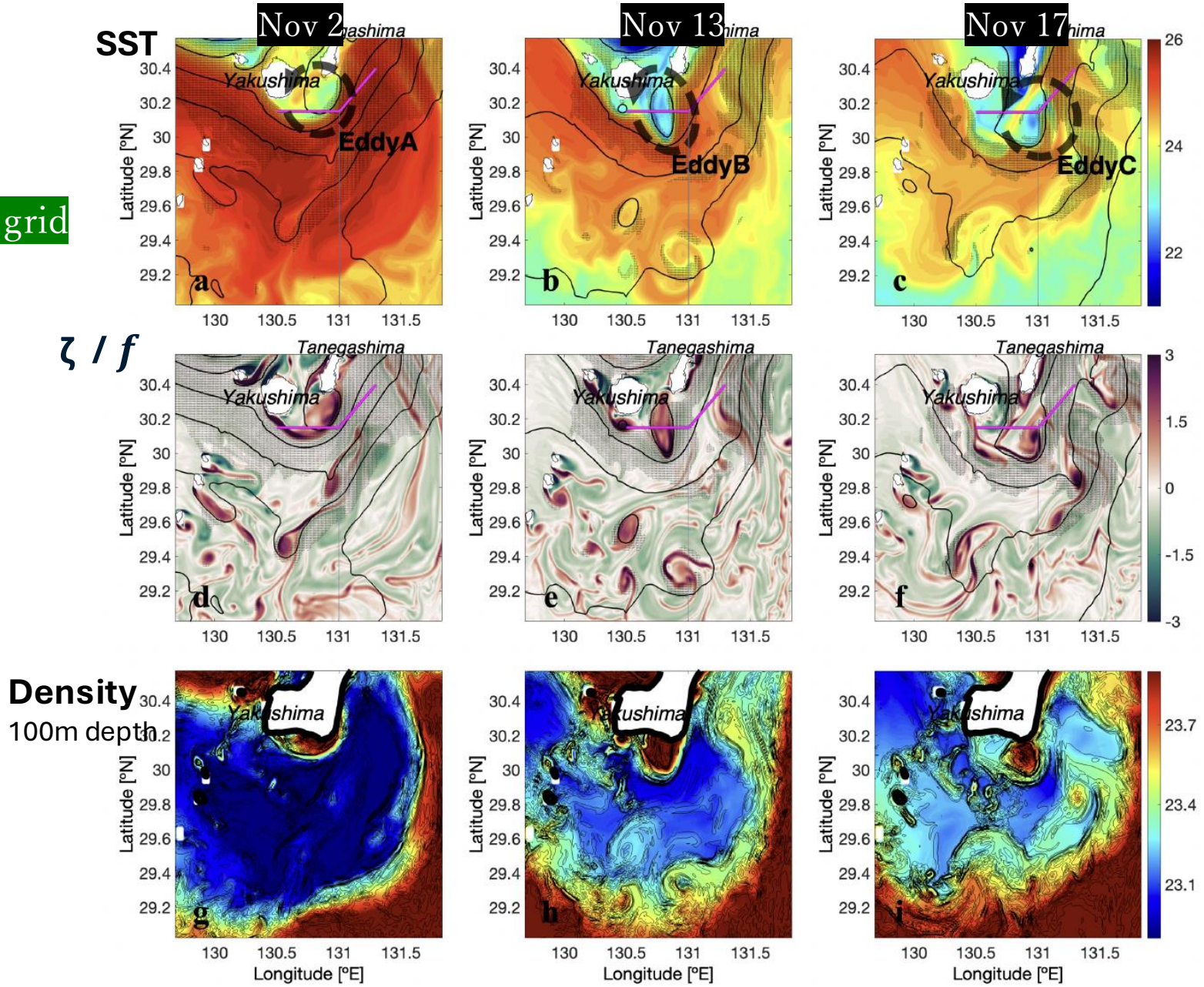
Q1: Quantify the contribution in nutrient supply made by submesoscale surface eddies

Regional Oceanic Modeling System

Horizontal resolution ~700m grid

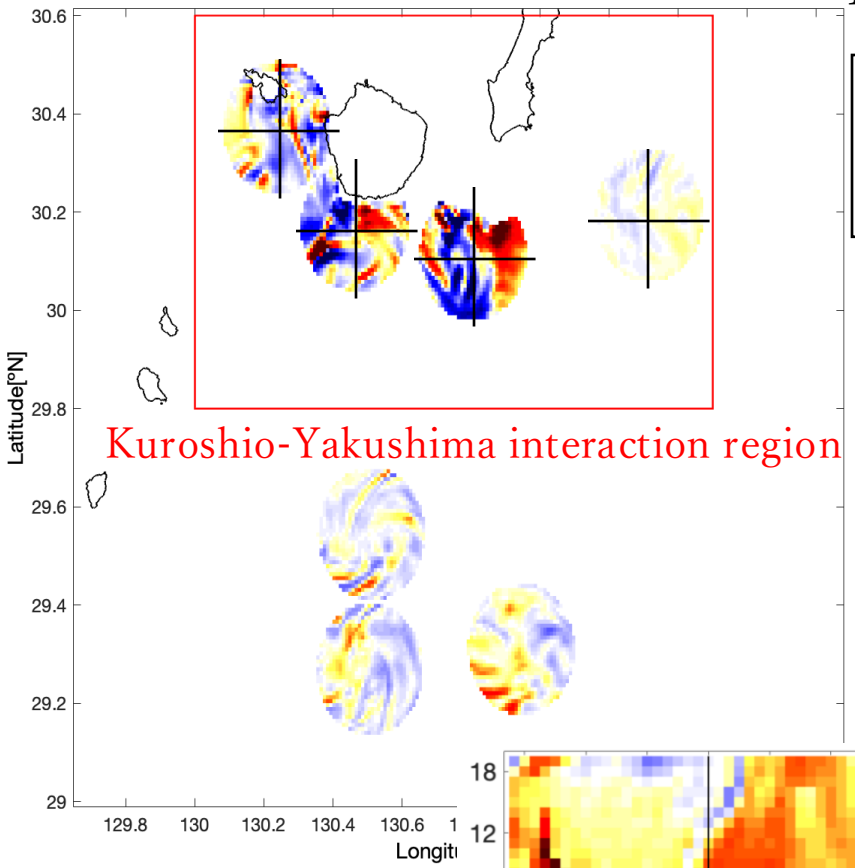
ROMS simulation in November:

- Patterns aligned with satellite images and in-situ observations
- Spinning *wavy structures* emerged at the south of Yakushima Island



Q1: Quantify the contribution in nutrient supply made by submesoscale surface eddies

From **Eddy detection analysis:** SSH' = −0.04

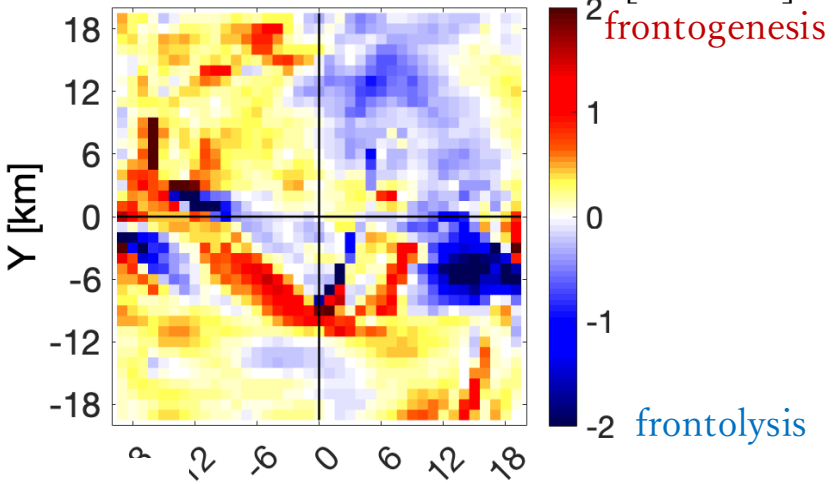


100m depth

1) Frontogenetic Parameter:

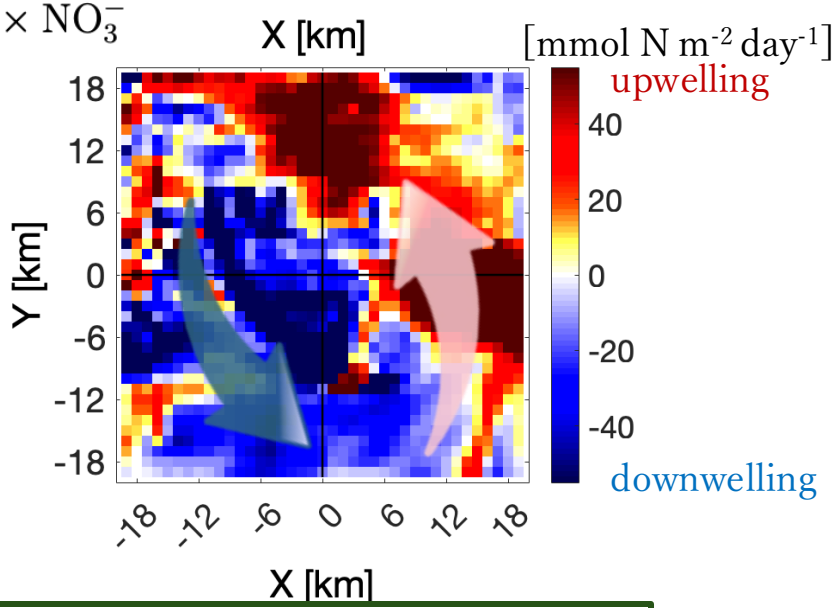
$$\frac{Q \cdot \nabla_h b}{|\nabla_h b|} = 2\frac{D}{Dt}|\nabla_h b|$$

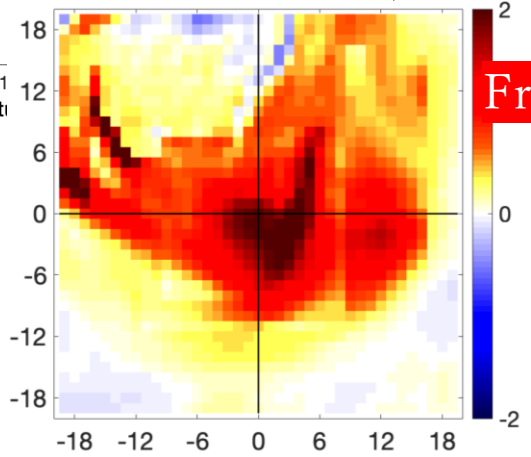
product of velocity and buoyancy gradients: horizontal velocity accros density surface rate



2) Vertical Nitrate Flux: $TNO_3 = w \times NO_3^-$

w: vertical velocity [m s^{-1}]
NO_3^- (uM)





Frontolysis ~ Upwelling

Frontogenesis ~ Downwelling

Only cyclonic eddies were detected

Net nitrate vertical flux within detected eddies in the interaction region at 100 m depth
~17 mmolN m^{-2} day^{-1}

Horizontal Shear Production

$$HSP = -\overline{u'^2}\frac{\partial \bar{u}}{\partial x} - \overline{u'v'}\frac{\partial \bar{u}}{\partial y} - \overline{v'^2}\frac{\partial \bar{v}}{\partial y} - \overline{u'v'}\frac{\partial \bar{v}}{\partial x}$$

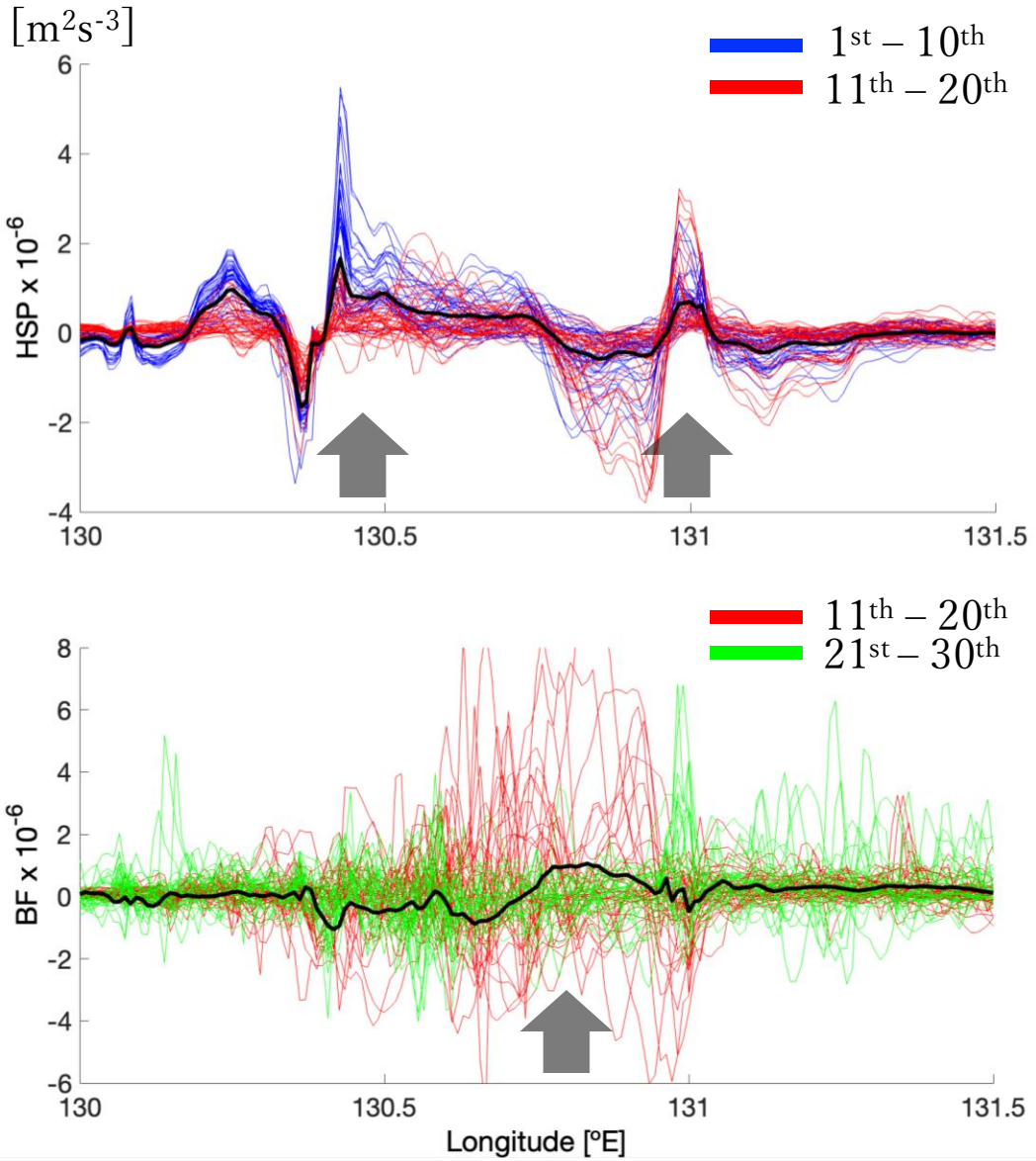
HSP (+) : Barotropic Instability
MKE → EKE

Vertical Eddy Buoyancy Flux

$$BF = \overline{w'b'}$$

BF (+) : Baroclinic Instability
EPE → EKE

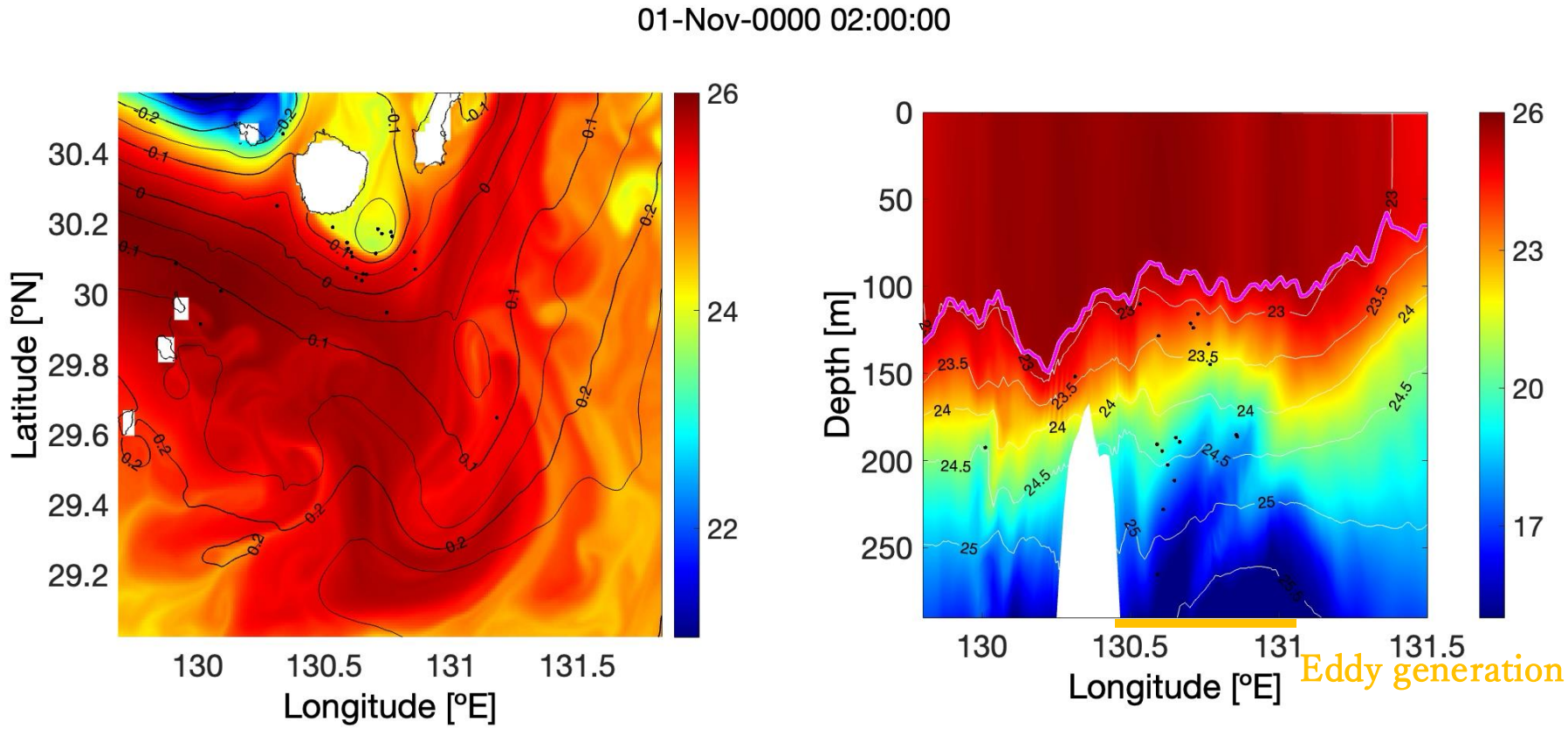
Submesoscale cyclonic eddies produced by barotropic and maintained by baroclinic instabilities



Lagrangian Particle Tracking: Particles coming from Kuroshio

Initial conditions:

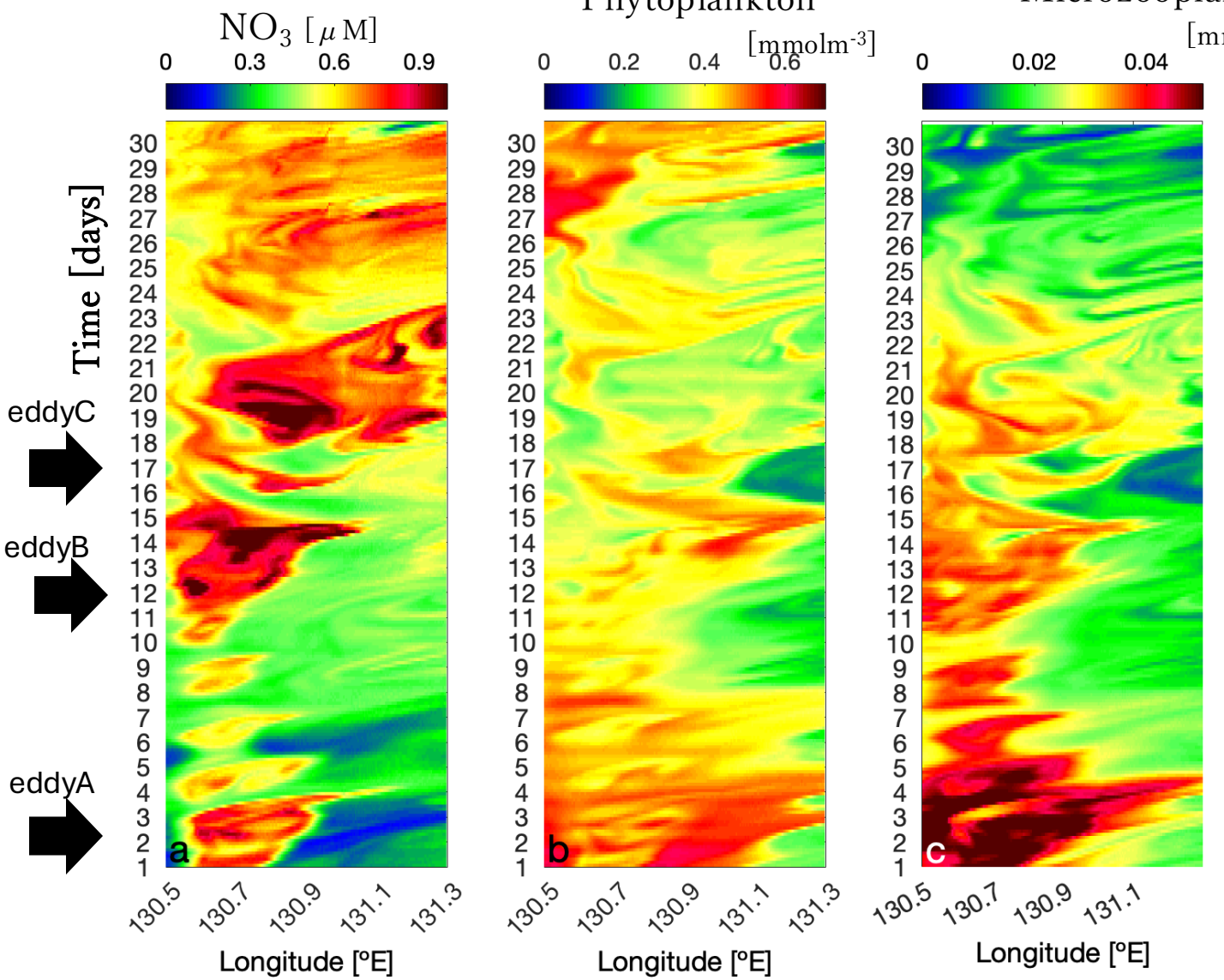
- ✓ Nov 13th in simulation
- ✓ Depth 120 – 200 m
- ✓ Hourly output of ~20,00 particles, but selected 700 for video

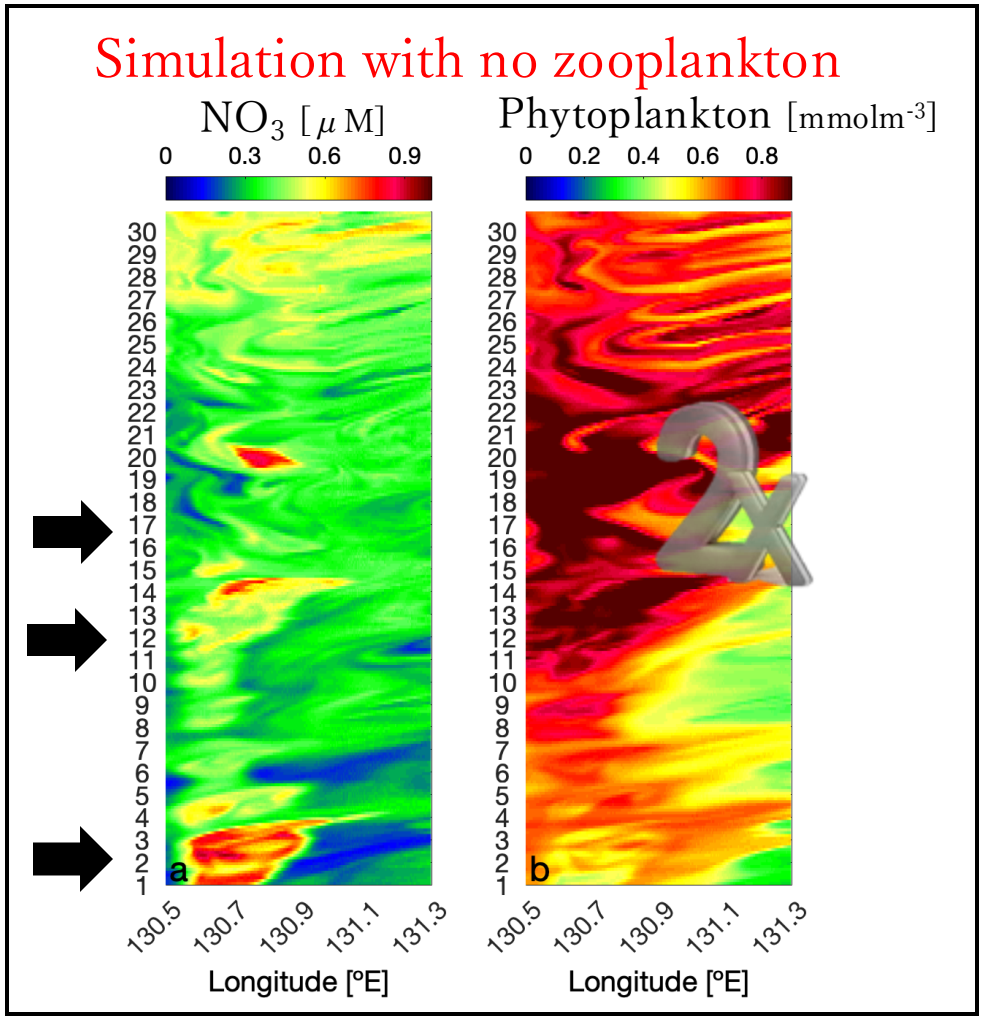


Q2: Unravel the lower-trophic ecosystem response to submesoscale nutrient injection

Parameters averaged above MLD: eddy time ~ ↑NO_3

Increase in phytoplankton followed by a rapid microzooplankton grazing

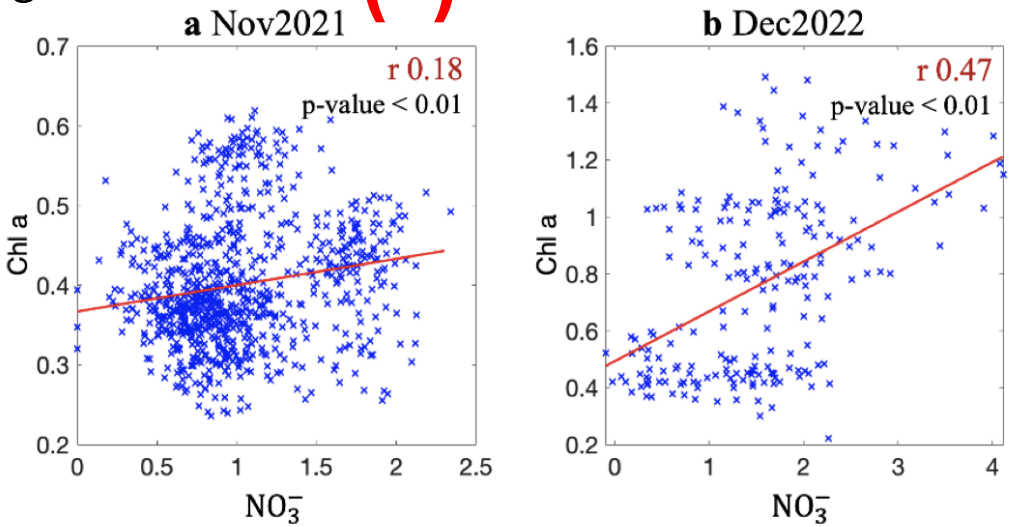




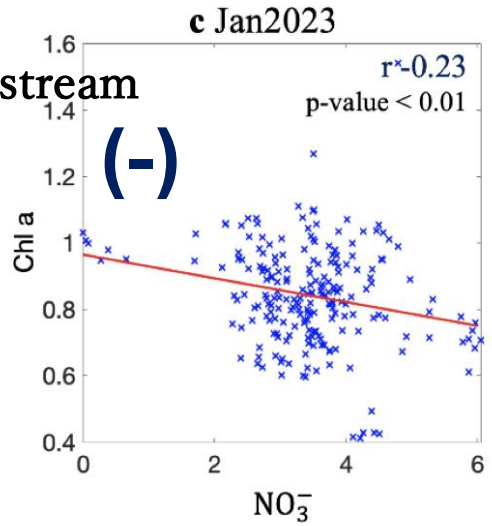
Correlation between NO_3 [µM] and Chl a [μgL^{-1}] (above MLD)

IN-SITU OBSERVATIONS

Near generation site **(+)**



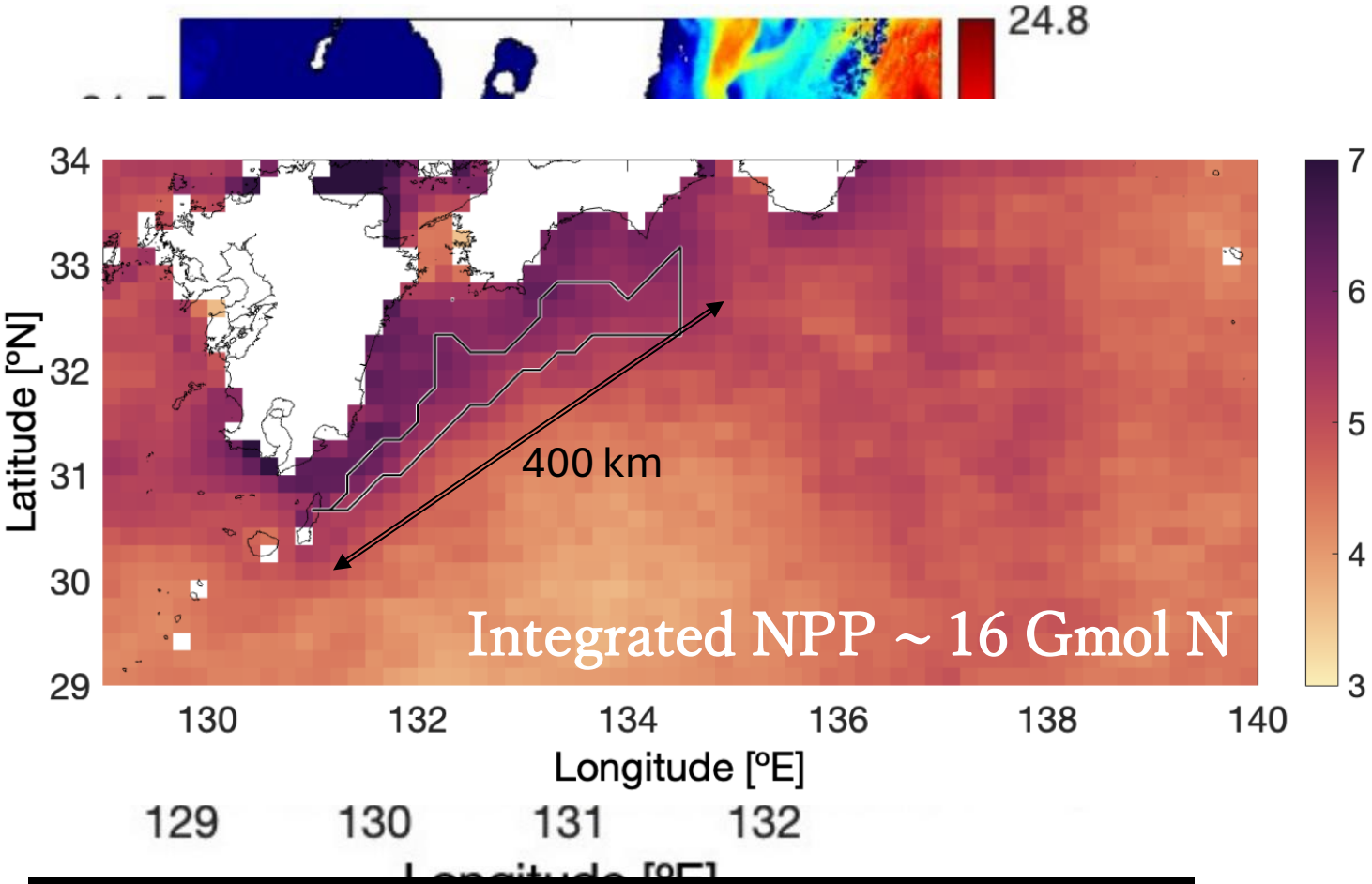
Far downstream region **(-)**



Zooplankton grazing pressure

Q2: Unravel the lower-trophic ecosystem response to submesoscale nutrient injection

ROMS: **6 submesoscale cyclonic eddies** generated in a month south of Yakushima Island



Annual net primary production (NPP, mmolN m^{-2} day^{-1}) integrated for 2021-2022 (Nov-Feb) from Carbon, Absorption, and Fluorescence Euphotic-resolving (CAFE) model

Upwelling ~ 17 mmol N m^{-2} day^{-1}
Duration ~ 5 days / Radius 15 km
NO_3 input is estimated as 1eddy/1month:

60×10^6 mol N (60 Mmol N)

Cyclonic eddies account ~ 9% of the total production of the area 400 km downstream

CONCLUSIONS

Q1: Quantify the nitrate contribution of submesoscale surface eddies

Q2: Unravel the lower-trophic ecosystem response to submesoscale nutrient injection