Modelisation : Kuroshio Current

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1 Introduction - Kuroshio Current

The Kuroshio Current is the second strongest current after the Gulf Stream. It plays a pivotal role in transporting both salt and heat. Originating from the North Equatorial Current, it flows northward towards Taiwan Island and the continental shelf margin of the East China Sea (ECS). Upon exiting the ECS, it veers eastward along the southern coast of Japan, extending further to form the Kuroshio Extension east of Japan. Our focus lies on the segment of the current between Taiwan Island and the southern coast of Japan (SJ), near the separation point from the western boundary. For analysis purposes, we will delineate our study into two regions: the ECS, encompassing latitudes [121°N : 130°N], and SJ, spanning latitudes [130°N : 144°N]. The simulation studied was run for 2 simulation years and comes from the oceanic modeling CROCO. The analysis is performed using xarray in Python.

2 Question 1 - Model parameters

Using CROCO model, we parameterized the grid at longitudes[121°,144°] and latitudes[21°,43°] . The grid resolution is dx = 1/3° = 31 km and the time step dt = 1800 secondes = 30 minutes. We want a 2 years simulation, so the number of time steps is ntimes = 35040. And we use a barotropic time steps ndtfast = 60. We check if it respects the 3D advection stability constrain.

$$\Delta t \leq \frac{0.89 \cdot \Delta x}{2 \cdot \sqrt{g \cdot H}} \cdot \Delta t_{barotropic} \tag{1}$$

And we have :

$$\Delta t \leq \frac{0.89 \cdot 31 \cdot 10^3}{2 \cdot \sqrt{9.81 \cdot 4 \cdot 10^3}} \cdot 60 \tag{2}$$

$$1800s \leq (69.6 \cdot 60 = 4178s) \tag{3}$$

So we respect the stability constrain.

3 Question 2 - Time evolution Surface Kinetic energy

The parameters are located in the grid in a standard way : rhopoints are located at the center of the grid and the velocities are located at the edges. To calculate the kinetic energy (KE), we need to find u and v at the same point - Rhopoint. So we use an interpolation to have the same dimensions and locations of u and v. The interpolation on u is on the x axis because this is where the u is on its edge. We select the surface level by selecting the last level : srho = -1, in the velocities. We calculate KE = $0.5 \cdot (u^2 + v^2)$. Next, we compute the kinetic energy integration by multiplying it with the grid cells (dx, dy) = (1/pm, 1/pn) and then sum across the grid for each time step. Additionally, we adjust the time to represent dates for plotting the time series of Integrated Kinetic Energy (IKE). (Figure 1)

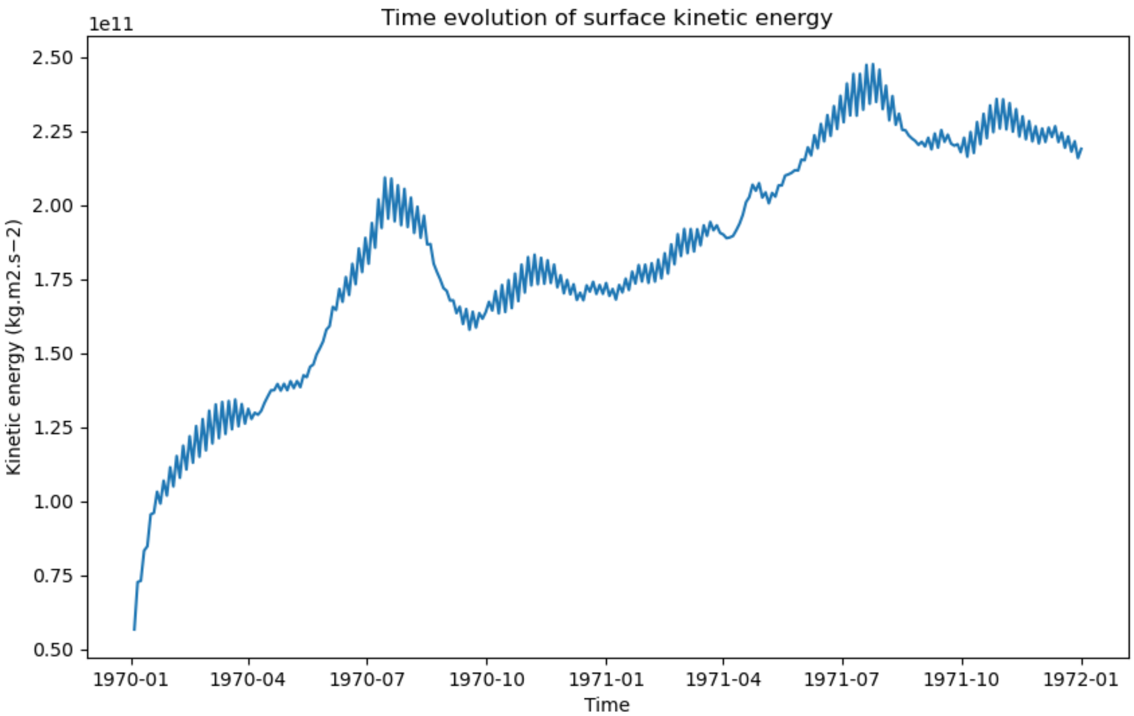

Figure 1: Time series of the integrated surface kinetic energy $[kg.m^2.s^{-2}]$

Throughout the initial year, the time series of Integrated Kinetic Energy (IKE) exhibits increases exponentially during the first 6 months and then linearly during one year. The IKE seems to stabilize around $2.25{\cdot}10^{11}$ the second half.
To confirm the stability of the simulation it would be necessary to examine a third year of simulation data.

4 Question 3 - Surface Relative vorticity (RV) normalized by the local Coriolis parameter (f) at the surface

We plot the Relative vorticity $RV = \frac{dv}{dx} - \frac{du}{dy}$ normalized by f, $nRV = RV/f$. The simulation's 'time' is measured in seconds from the start of the simulation. To obtain the time index corresponding to a specific number of days, we locate the closest index in time to the desired number of days (in seconds). Subsequently, we can plot the normalized Relative Vorticity for a particular day since the beginning of the simulation (Figure 2).

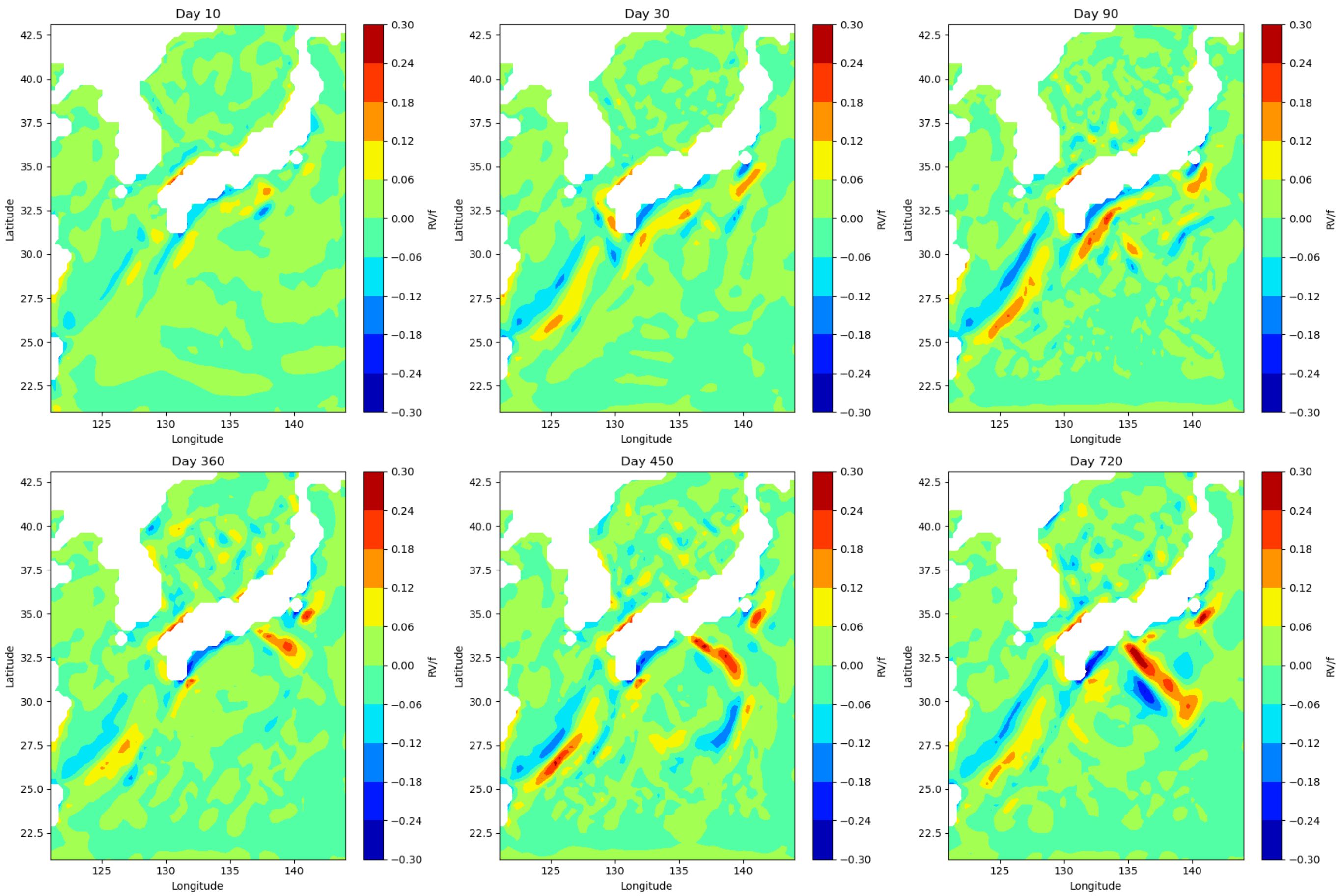

Figure 2: Normalized relative vorticity by f, at the surface

Except for the 10th day, we can see the Kuroshio current in the East China Sea (ECS), at the boundary between vorticity bands of opposite signs. The amplitude of the nRV is around 0.2, which matches the intensity depicted in Figure 3.
As the simulation progresses into its second year, mesoscale eddies emerge in the Japan Sea (JS).

The Figure 3 has been plot using data from Copernicus Marine Environment Monitoring Service(CMEMS) between January 2006 and December 2016.[SW21] The vorticity bands associated with the Kuroshio in the East China Sea are based on the mean state. Vorticity has been normalized by Coriolis parameter. The black line: identified vorticity interface. It shows that Kuroshio possesses strong current shear in the ECS. The nRV is stronger in this plot than in the surface vorticity from the simulation.

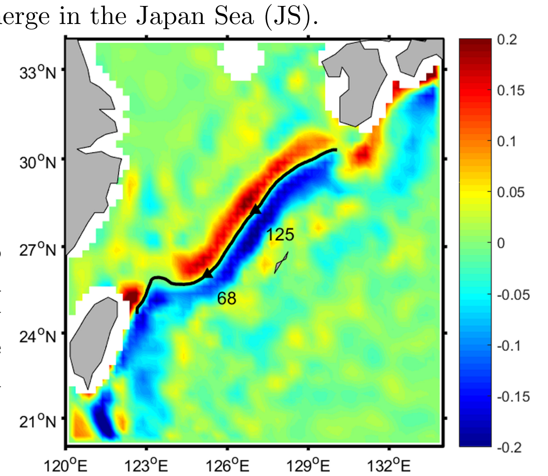

Figure 3: Mean state, normalized relative vorticity by f

5 Question 4 - nRV at the depth -400m

We plot the normalized relative vorticity at a depth of 400 meters. Since the simulation comprises only 32 depth levels, we utilize tools and topographical data to determine the corresponding depth for each level within each cell. Subsequently, we perform interpolation to establish a level at -400 meters.

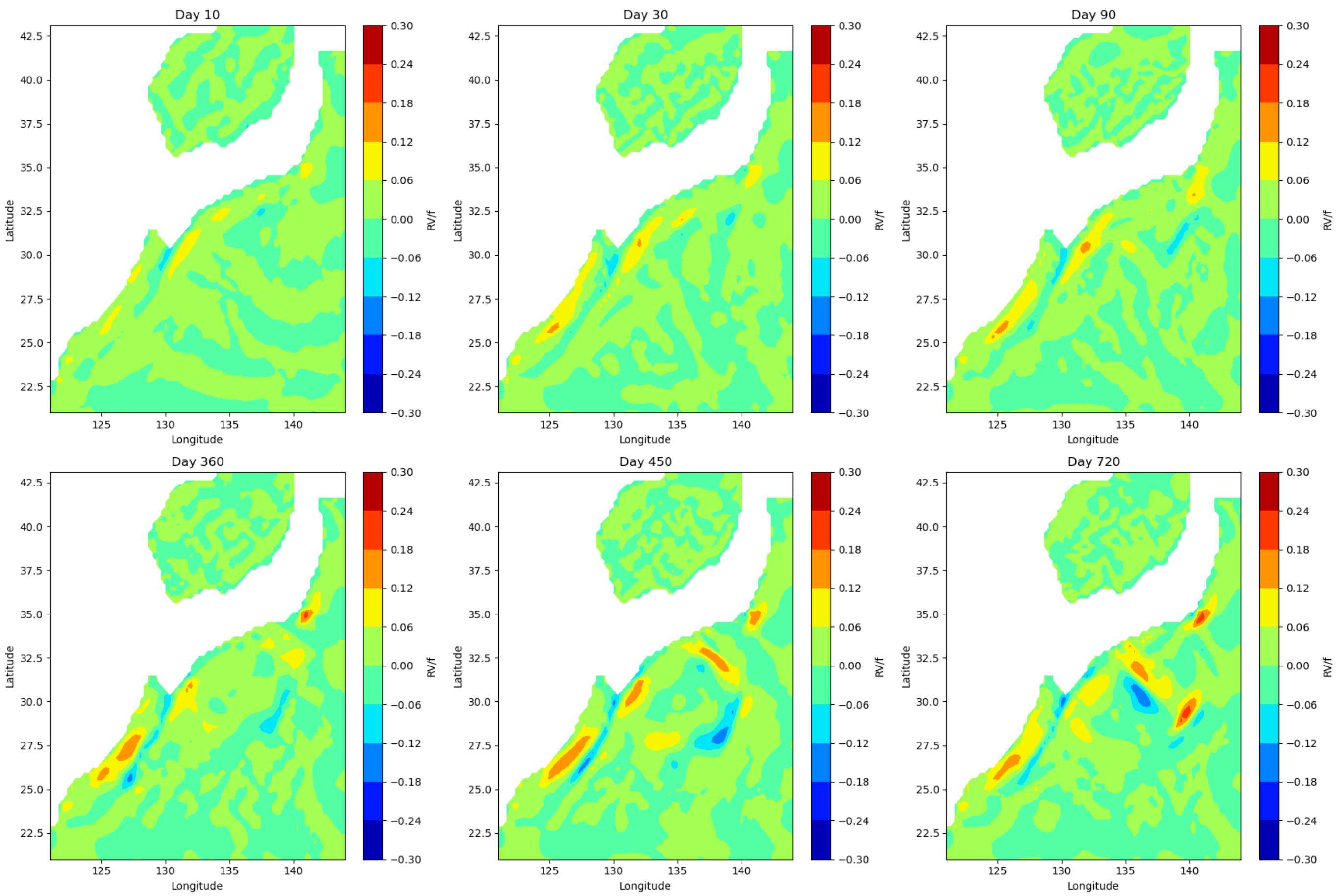

Figure 4: Normalized relative vorticity by f, at z = -400 m

There is a change in the appearance of the map between the 400 meters depth and its surface representation. It is due to shallow waters on the western side of the Current and the ground reaches -400m there. (Figure 5)
At a depth of 400 meters, there is are residuals of the surface's relative vorticity patterns. From the 30th day, we can still see a strong Kuroshio current in the ECS with nRV around 0.1. And in the Japan Sea (JS) mesoscale eddies are still visible.

The topography surrounding the Kuroshio Current indicates that the Yellow Sea has a depth of less than 400 meters, which accounts for the alteration in the map depicted at -400 meters.

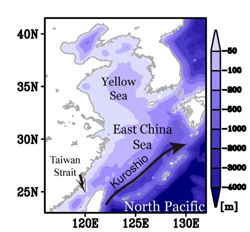

Figure 5: Topography Kuroshio

6 Question 5 - Temperature at the depth -400m

We plot the temperature at depth at -400m.

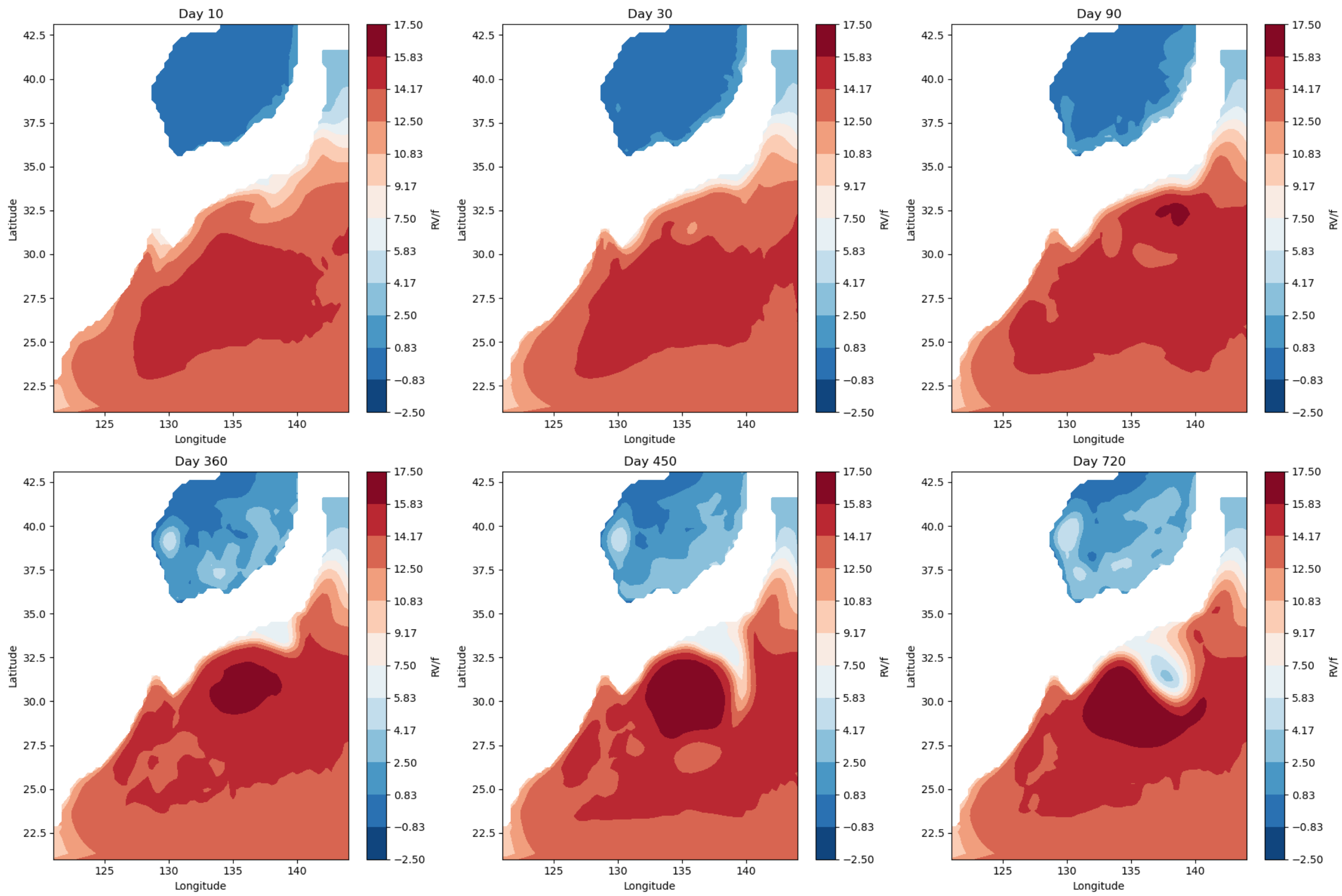

Figure 6: Potential temperature [°C] at z = -400 m

The data from the first year reveals a strong temperature gradient, indicating a notable 12°C contrast between the southern and northern regions of Japan. This gradient is attributed to the influence of the Kuroshio Current and Kuroshio Extension. They bring warm water to the north and diverge eastward from Japan. The presence of this temperature gradient is associated with the generation of mesoscale eddies in the SJ.
In the second year of the simulation, the mesoscale eddies in the Sea of Japan are stronger. These eddies play a significant role in displacing cold water from the northern regions of Japan towards the warmer waters of the Kuroshio Current. Notably, the northernmost eddy displays remarkable strength and maintains a stationary pattern throughout the simulation. This observation suggests its substantial influence on the movement of water masses in the area.

7 Question 6 - Zonal section of density and velocity

We plot a zonal section in depth at latitude 30°N and longitude 130° to 140°. From salinity and temperature, we look at the density at depth using gsw.sigma0 which calculates potential density anomaly with reference pressure of 0 dbar. It is the particular potential density minus 1000 kg/m3. Next, we plot the zonal section of the zonal velocity at depths. The positive velocity means it is eastward. Specifically, we create plots for the zonal velocity and potential density at 10 and 360 days.

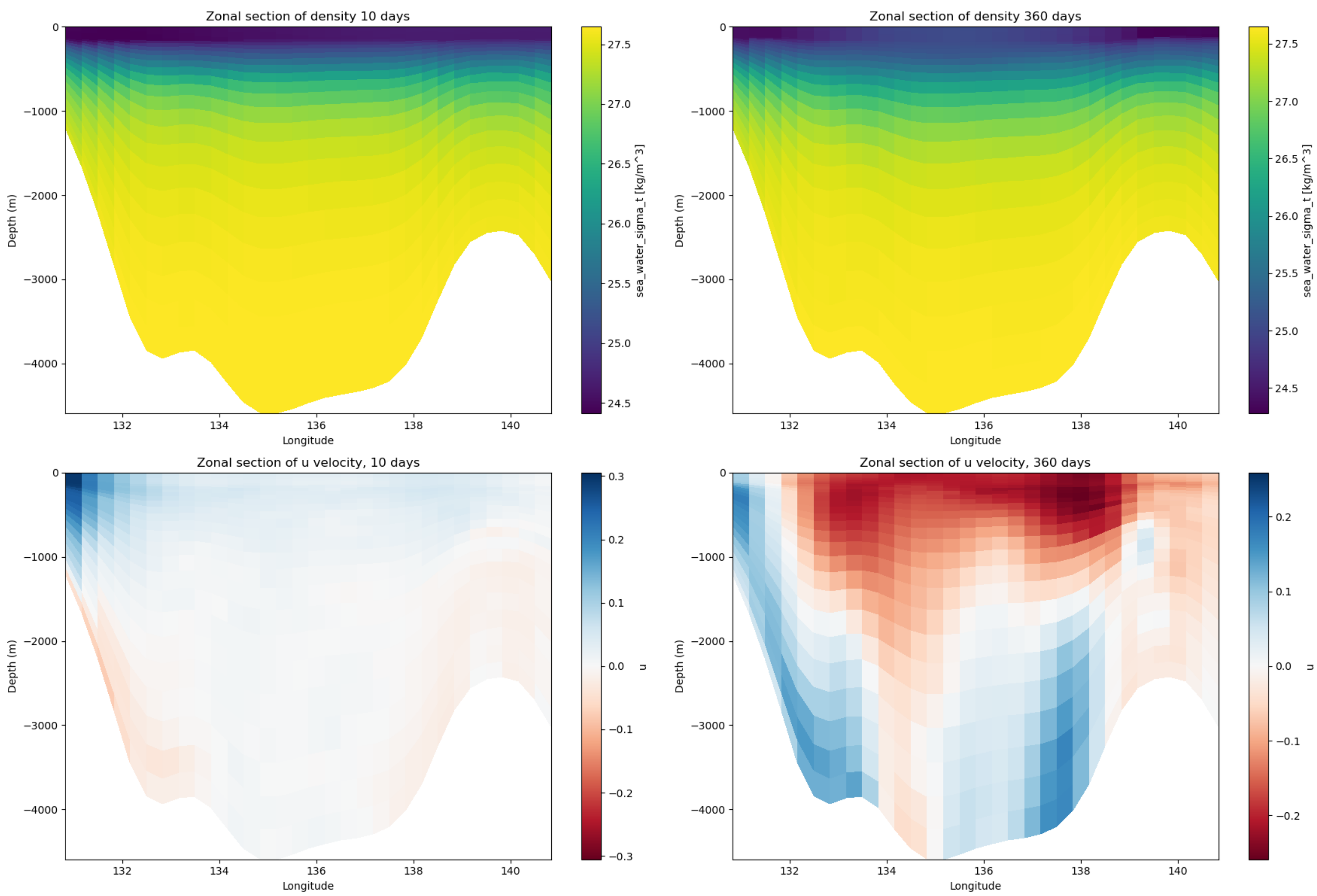

Figure 7: Density and velocity zonal section with lon = [130°N , 140°N] and lat = 30°

We observe density gradients aligned with the topography. After 10 simulation days, a distinct shallow mixed layer at approximately 200 meters depth is evident, characterized by a density of around 24.5 kg/m$^{\mathbf{3}}$. However, by the 360th day of the simulation, the mixed layer depth exhibits variability along the longitude. While the mixed layer persists above the seamount, it dissipates in the deeper regions, where the density hovers around 25.5 kg/m$^{\mathbf{3}}$. If a biological option were to be included, such variability could result in a range of diverse biological outcomes within the simulation.

The depth-profile of zonal velocities indicates that the Kuroshio current extends to considerable depths, reaching around 1000 meters below the surface. Furthermore, there is a counter bottom current observed beneath the Kuroshio Current, within the deeper waters.

8 Question 7 - Average norme of the surface velocity

We plot the average norme of the velocity at the surface $\sqrt{u^2+v^2}$ over the last year of the simulation. (Figure 8)

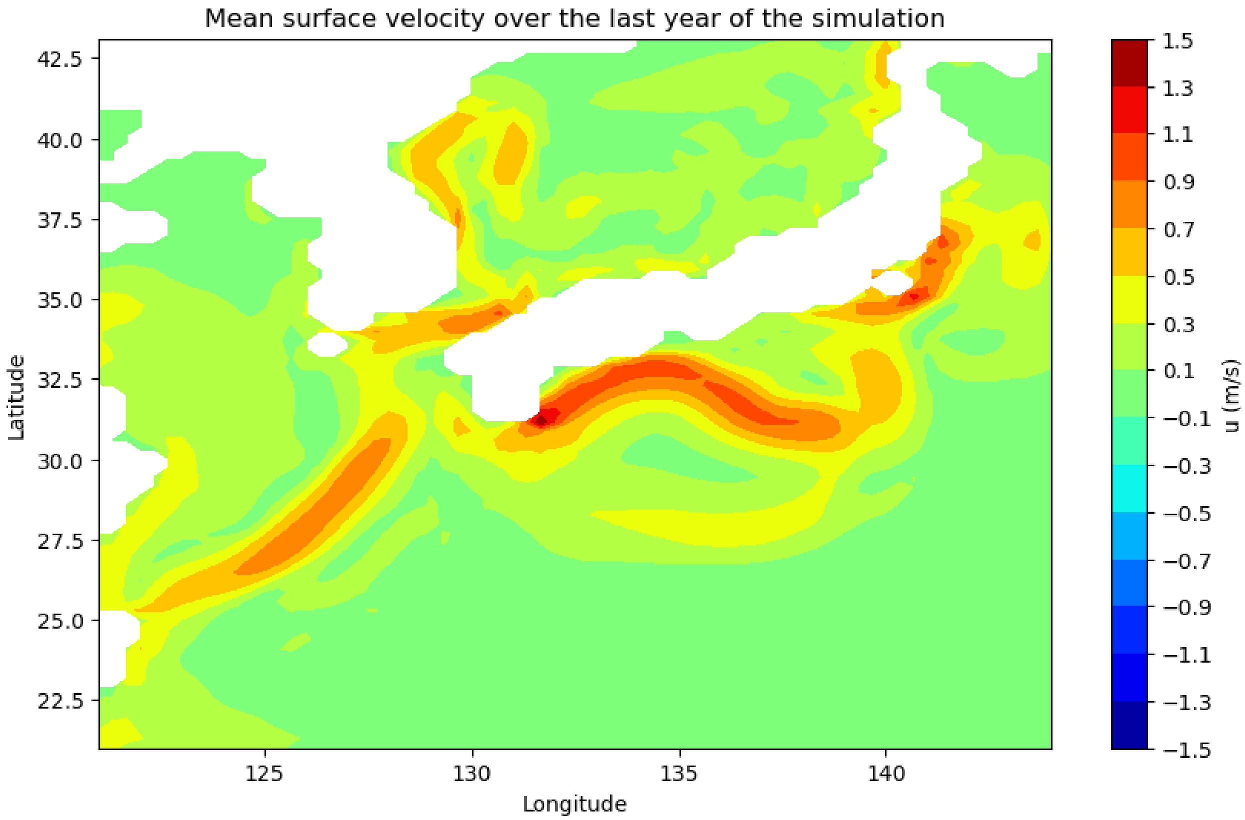

Figure 8: Mean norme of the surface velocity over the last year of the simulation

In the simulation, the velocity of the current in the ECS near the Kuroshio Current is approximately 0.8 m/s. Within 80 meters below the surface, the current is expected to range between 0.36 m/s and 2.02 m/s, indicating that we are within the expected range.[And+08] In the JC, the current is more intense, measuring around 1.3 m/s.

9 Question 8 - Sea Surface Height variance

We plot the Sea Surface Height (SSH) variance over the second year of the simulation (Figure 9). And we compare it to a study using the FORA-WNP30 reanalysis from in-situ observations like altimeter-derived sea level anomalies (SLAs). (Figure 10)[Usu22]

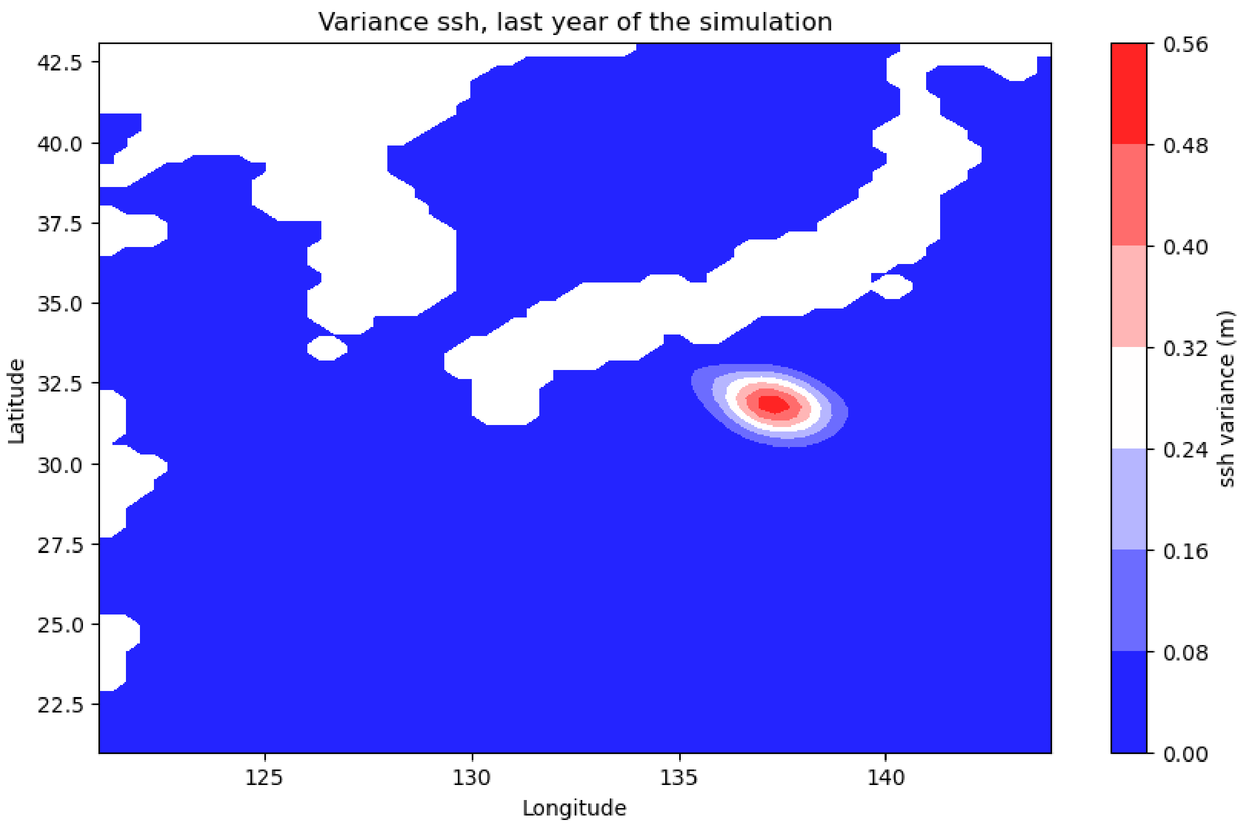

Figure 9: Sea surface height variance over the last year of the simulation

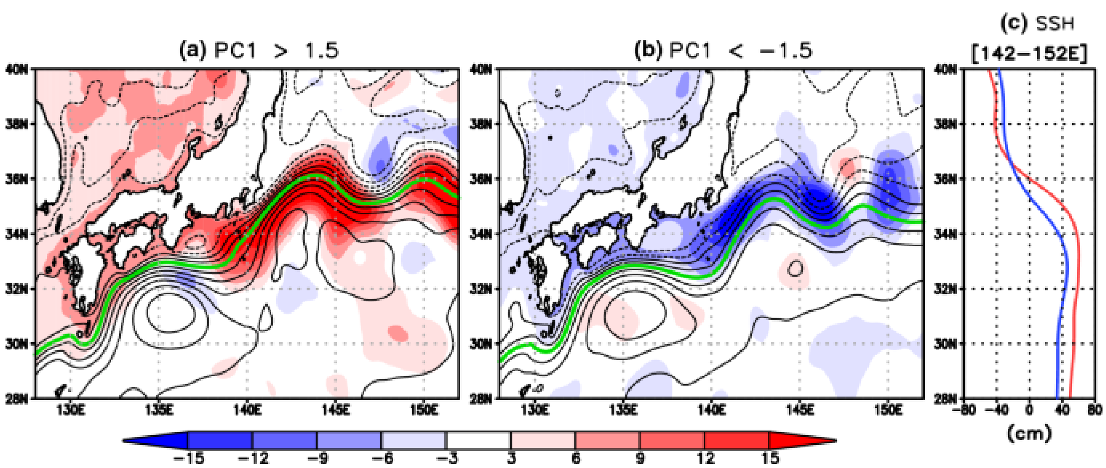

Figure 10: Composite SSH anomalies for (a) PC1 ≥ 1.5 and (b) PC1 ≤ 1.5. Black contour lines indicate mean SSH field with an interval of 10 cm, and green thick solid lines are the SSH contour line of 20 cm, which is regarded as a proxy of the mean Kuroshio axis. (c) Meridional distributions of zonally averaged SSH between 142E and 152E for (red line) PC1 ≥ 1.5 and (blue line) PC1 ≤ 1.5

The Figure 10 shows composite maps of SSH and its anomalies for positive (PC1 ≥ 1.5) and negative (PC1 ≤ 1.5) phases.

In both the reanalysis and our simulation, we observe sea surface height variance occurring within the same geographical region, longitude [135° : 140°] and latitude [30°N : 32°N]. Additionally, panel c) illustrates that the amplitude of this variation appears consistent at approximately 50cm in both the simulation and the reanalysis around this region.

10 Question 9 - Eddy Kinetic Energy

We compute the Eddy Kinetic Energy (EKE) by deducting the velocities from their mean state during the second year of the simulation and calculating the kinetic energy based on these velocities (Figure 11).

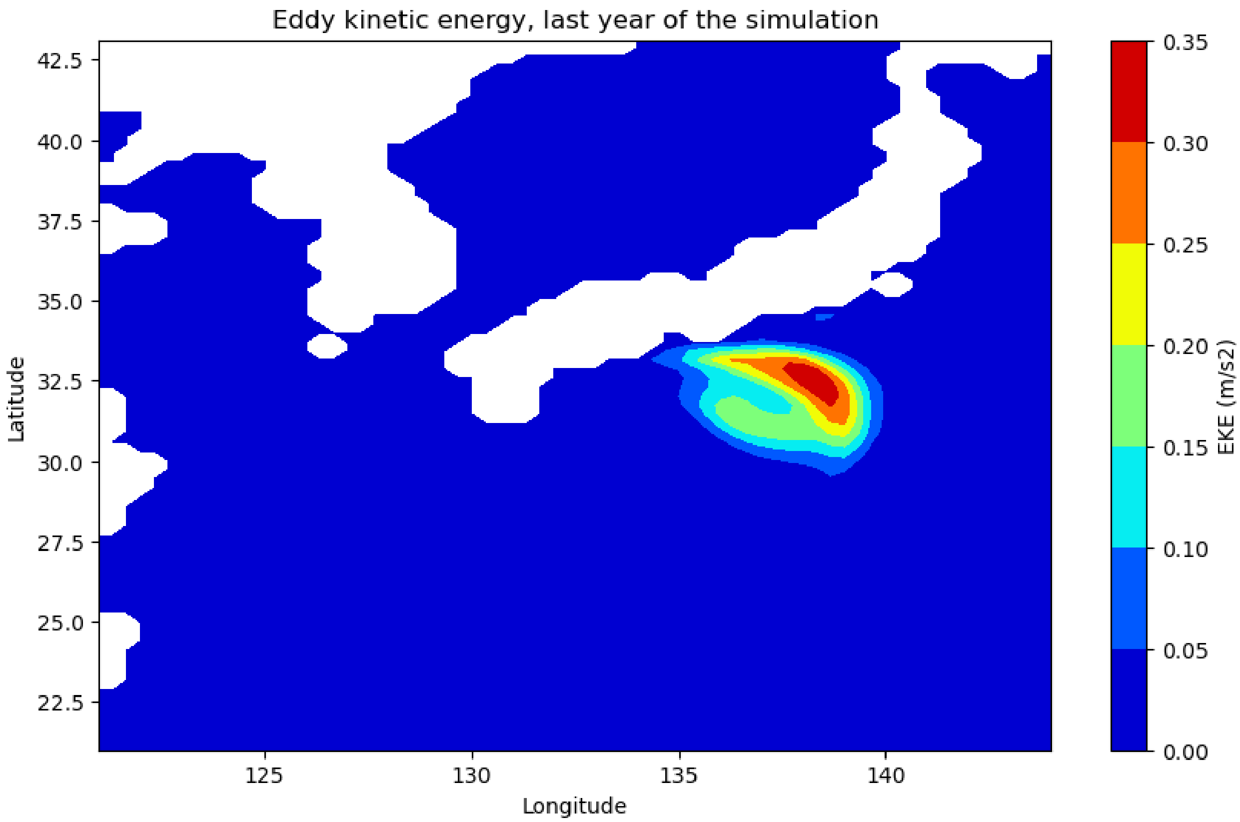

Figure 11: EKE (m^2/s^2) estimated over the last year of the simulation

The Figure 12 comes from observational data sourced from the Validation and Interpretation of Satellite Oceanographic Data (AVISO). It represents the mean surface eddy kinetic energy for each year. The black curve illustrates the primary axis of the Kuroshio. [WT22]

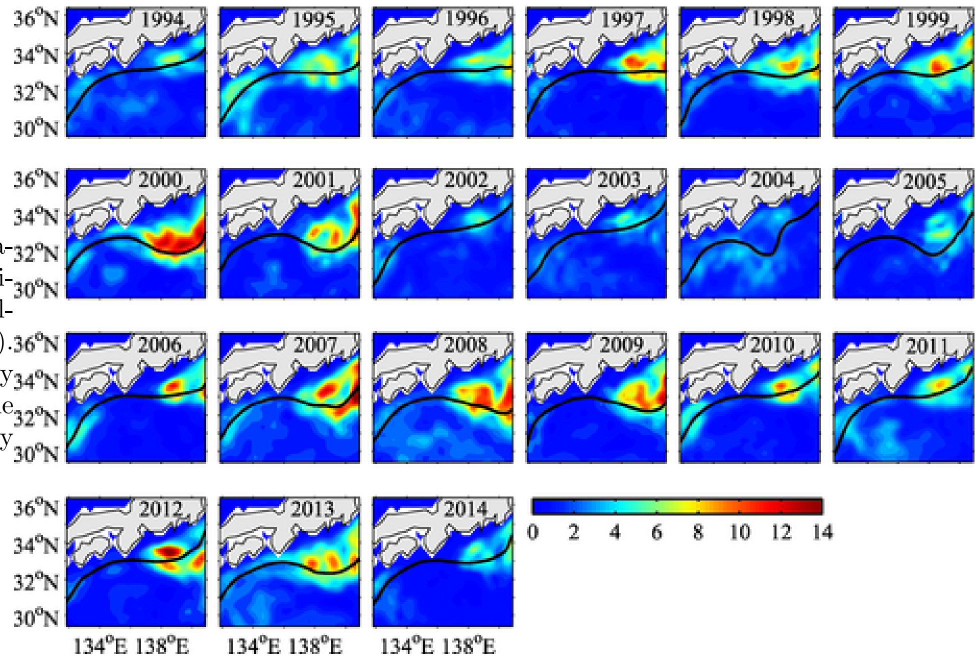

Figure 12: Surface EKE ($10^{-2}.m^2/s^2$)

We can see that the zone of strongest EKE in the simulation is well placed compared to observations. It seems a little strong in the simulation as the highest is around 0.35 m^2/s^2 and peaks in the observations are around 0.12 m^2/s^2. And the strenght of the EKE varies in function of the year observed. For exemple in 2014, it only goes up to 0.04 m^2/s^2.

11 Conclusion

In this study, we conducted an analysis of the Kuroshio Current using a simulation of the oceanic model CROCO and observational data. Our focus was primarily on understanding various aspects of the current's behavior, including its spatial distribution, temporal evolution, and associated phenomena.

We initiated our investigation by parameterizing the model grid and ensuring its stability constraints. Then, we looked at the time evolution of surface kinetic energy, revealing periodicity in the second year of the simulation, which could mean that the simulation is stabilized. Through the examination of surface relative vorticity normalized by the local Coriolis parameter, we identified distinct features such as mesoscale eddies and the Kuroshio current's structure.

Further exploration involved analyzing the behavior of normalized relative vorticity at depths, which showed similar but stronger patterns at 400 meters depth than at the surface. We also investigated temperature distributions at depth, showing the influence of the Kuroshio Current an Kuroshio Extension on regional temperature gradients.
By examining zonal sections of density and velocity, we gained a deeper understanding of the current's vertical structure, specially the depth of the Kuroshio Current.
Comparisons with observational data, such as sea surface height variance and eddy kinetic energy, allowed us to validate our model's performance and identify areas for improvement. One of the limitations could be the random time taken by the simulation. I don't think it is initialize with observation from 1970. So the random dates of the simulation makes it hard to compare with observation, we can only compare the order of magnitude in space of each variable.

Despite limitations inherent in model simulations, such as temporal variability and domain size, our analysis corresponds to observations.

References

[And+08] M. Andres et al. "Observations of Kuroshio flow variations in the East China Sea". In: *Journal of Geophysical Research: Oceans* 113.C5 (2008). DOI: https://doi.org/10.1029/2007JC004200. eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2007JC004200. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2007JC004200.

[SW21] Qian Shi and Guihua Wang. "Meander Response of the Kuroshio in the East China Sea to Impinging Eddies". In: *Journal of Geophysical Research: Oceans* 126.9 (2021). e2021JC017512 2021JC017512, e2021JC017512. DOI: https://doi.org/10.1029/2021JC017512. eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2021JC017512. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2021JC017512.

[Usu22] Norihisa Usui. "Sea level variability along the Japanese coast forced by the Kuroshio and its extensio". In: *Journal of Oceanography* (2022). DOI: https://doi.org/10.1007/s10872-022-00657-2. URL: https://link.springer.com/article/10.1007/s10872-022-00657-2.

[WT22] Qiang Wang and Youmin Tang. "The Interannual Variability of Eddy Kinetic Energy in the Kuroshio Large Meander Region and Its Relationship to the Kuroshio Latitudinal Position at 140°E". In: *Journal of Geophysical Research: Oceans* 127.2 (2022). e2021JC017915 2021JC017915, e2021JC017915. DOI: https://doi.org/10.1029/2021JC017915. eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2021JC017915. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2021JC017915.