Comparision of MOM6 model output for Bay of Bengal with observation

April 2022

1 Model setup

- We setup a model for Bay of Bengal spanning from 77° E to 99° E and 4° N to 25° N.
- We use GFDL MOM6 ocean model which has Arakawa C grid settings and is hydrostatic in nature.
- The model has a resolution of 0.073° in zonal direction(300 cells) amd 0.073° in meridional direction(250 cells).
- The GEBCO 15 arc second topography dataset is used to generate the model bathymetry.
- The model has 41 vertical hybrid layers. In the upper surface of the ocean the model has z^* coordinate that smooth out to isopycnal coordinates in the ocean interior.
- The model is initiated from a HYCOM Reanalysis product(for potential temperature and salinity only)
- We compare the two model runs with the observation datasets : first run without any open boundary conditions and second run with open boundary conditions.

2 Model physics

2.1 Time

- We run the model for 720 days from 01-01-2012 to 21-12-2013.
- We use coupled MOM6-SIS2(sea-ice model) as it works as a coupler which provides atmospheric forcings to the ocean.
- The coupling time step is 3600s which leads to very low CFL(0.05 most of the time) but ensures that model is forced hourly(since the frequency of most of the forcings is also hourly).
- The baroclinic timestep is 900s and the thermodynamic and tracer advection timestep is 1800s.

2.2 Parameterizations

- **Mesoscale Eddy Kinetic Energy** : Applied.
- **Vertical mixing** : KPP parameterization of Large(1994) is used.
- **Horizontal viscosity** : Laplacian horizontal viscosity is used.
- **Mixed Layer Restratification** : Fox-Kemper parameterization.
- **Shear mixing parameterization** : Jackson kappa parametrization.
- **Tracer** : advection and diffusion is used.

2.3 Initial conditions

- The 41 layers of the model are initialised from the HYCOM Re-analysis for the time 2012-01-01 00:00:00.
- We initialise potential temperature, salinity, zonal velocity and meridional velocity.

2.4 Boundary conditions

- In Run2 and Run3, we apply open boundary conditions, whereas the Run1 is closed boundary condition case.
- With regards to Run2 and Run3, the western and southern boundaries are open boundary and the eastern boundary is closed. In Run1, all the three boundaries are closed.
- In MOM6, we can apply upto five type of boundary conditions at a time.
- Active open boundaries in which the outside information is advected into the domain(Nudged and Nudged-tan) and passive open boundaries where the interior domain information is radiated outside the domain both are applied(Flather,Orlanski,Orlanski-tan).
- We apply the following boundary conditions:
  - **Flather** : passive condition for barotropic mode that advects flow information in the direction normal to the boundary.
  - **Orlanski** : passive condition for baroclinic mode that advects flow information in the direction normal to the boundary.
  - **Orlanski-tan** : passive condition for baroclinic mode that advects flow information in the direction tangent to the boundary.
  - **Nudged** : nudges the normal component of any information.
  - **Nudged-tan** : nudges the tangential component of any information.
- We apply a strong nudging for inflow case(0.3 day) and weak nudging for outflow case(365 days).
- Boundary files were generated using NEMO Reanalysis data(`https://resources.marine.copernicus.eu/product-detail/GLOBAL_REANALYSIS_PHY_001_031/INFORMATION`) which is an data assimilated model ensemble. There is a horizontal resolution of 0.25*0.25 and 75 vertical layers which is interpolated to the model's 41 vertical layers.

3 Forcings

Field	Frequency	Dataset	Notes
Air temperature(K)	Hourly	ERA5 Re-analysis	Air Temp at 2m
Shortwave Downward Flux(W/m^2)	Hourly	ERA5 Re-analysis	Both diffuse and direct
Longwave Downward Flux(W/m^2)	Hourly	ERA5 Re-analysis	
Specific humidity	Hourly	ERA5 Re-analysis	Generated from Dew point temp and surface pressure taken from ERA5
Sea surface pressure(Pa)	Hourly	ERA5 Re-analysis	
Precipitation($kgm^{-2}s^{-1}$)	Hourly	ERA5 Re-analysis	
Wind speed(ms^{-1})	Hourly	ERA5 Re-analysis	Both u and v at 10m height
River Runoff($kgm^{-2}s^{-1}$)	Monthly	JRA55-do	

- In addition, tides are also forced using amplitude data provided in MOM6 test cases.
- For the third run, JRA55-do dataset was used for each of the fields listed above.(`https://climate.mri-jma.go.jp/pub/ocean/JRA55-do/`)

4 Runs

We have three model runs with different configurations:

- **Run1** : Forcings from ERA5 and no boundary conditions.
- **Run2** : Forcings from ERA5 and boundary conditions.
- **Run3** : Forcings from JRA55 and boundary conditions.

All the three runs take approximately 10 hrs to run on 168 cores of Makaram with the highest CFL encountered being about 0.135

5 Observation datasets

Field	Observation dataset	Horizontal resolution	Temporal resolution	Notes
SST	NOAA OISST	0.25*0.25	Daily	1
SSH	AVISO SSALTO/DUACS	0.25*0.25	Monthly	2
SSS	AQUARIUS L3	1.0*1.0	Monthly	3
SSU	OSCAR	0.25*0.25	Daily	4
SSV	OSCAR	0.25*0.25	Daily	4

Links:
1 : `https://psl.noaa.gov/data/gridded/data.noaa.oisst.v2.highres.html`
2 : `https://www.aviso.altimetry.fr/en/data/products/sea-surface-height-products/global/gridded-sea-level-anomalies-mean-and-climatology.html`
3 : `https://podaac.jpl.nasa.gov/dataset/OISSS_L4_multimission_7day_v1?ids=&values=&search=SSS&provider=POCLOUD`
4 : `https://podaac.jpl.nasa.gov/dataset/OSCAR_L4_OC_FINAL_V2.0?ids=&values=&search=OSCAR&provider=POCLOUD`

6 Comparision metrics

We use the following metrics to compare the model output with the observations to assess the quality of the model output. In the following, all the observation are given by O_i for the i^{th} point with the domain consisting of N number of points. Similiar goes for model output M_i. O and M can represent any field variable.

- **Difference/bias** : Simple differencing, $Bias = M_i - O_i$
- **RMSE** : Root mean squared error, greater is the value, greater is the deviation of the model from the observation.
  $RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(M_i - O_i)^2}$
- **Correlation coefficient** : Between -1 and 1 with 1 showing perfect correlation and -1 showing an inverse correlation and 0 showing no correlation between the model output and observation.
  $CC = \frac{\sum_{i=1}^{N}(M_i-\bar{M})(O_i-\bar{O})}{\sqrt{\sum_{i=1}^{N}(M_i-\bar{M})^2.\sum_{i=1}^{N}(O_i-\bar{O})^2}}$
- **Skill** : between 0 and 1, with 1 showing model and observation agree perfectly and 0 showing complete disagreement.
  $Skill = 1 - \frac{\sum_{i=1}^{N}|M_i-O_i|^2}{\sum_{i=1}^{N}(|M_iN-\bar{O}|+|O_i-\bar{O}|)^2}$

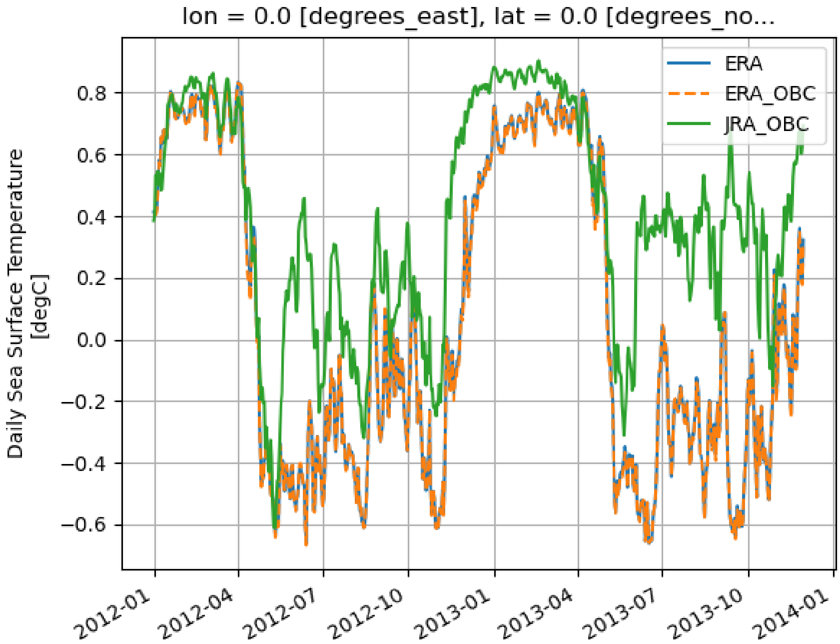

Figure 1: Correlation coefficient calculated daily for two runs: with OBCs and without OBCs

7 Comparisions

7.1 Sea Surface Temperature

- The dataset is a data assimilated dataset from NOAA group, assimilated using data from various sources like satelitte sensors, ships, buoys and Argo floats to produce a gridded dataset.

- We use bicubic interpolation to increase the resolution of observational dataset(0.25 *0.25) to that of model output dataset(0.073 * 0.073).

- The model output is written every 6th hour giving four readings a day. We take a daily mean of the model output.

- This daily mean of both the model output and observation is used to calculate the correlation coefficient shown in figure 1. As is apparent, the correlation plots are nearly coincident, though applying OBCs does lead to negligble improvement.

- Every run has good correlation(about 0.75 to 0.8) in the January to April period of both the years, but do not perform well for rest of the year.

- In fact, we get negative correlation for most of the year, peaking in June to October of the year.

- The JRA55 forcings produce a significant improvement in the monsoon period. The improvement is even better in the second year of the run.

- We plot the difference plots for the region for the June, July, August of 2012. We see that the model is erroneously warmer(4 ° C) in the central bay which appears to advect to the north. This false warming is the reason for negative correlation during the monsoon.(Figure 2). This false heating is largely absent in the JRA/OBC run, which might be the reason for improved correlation in the monsoon for this run.

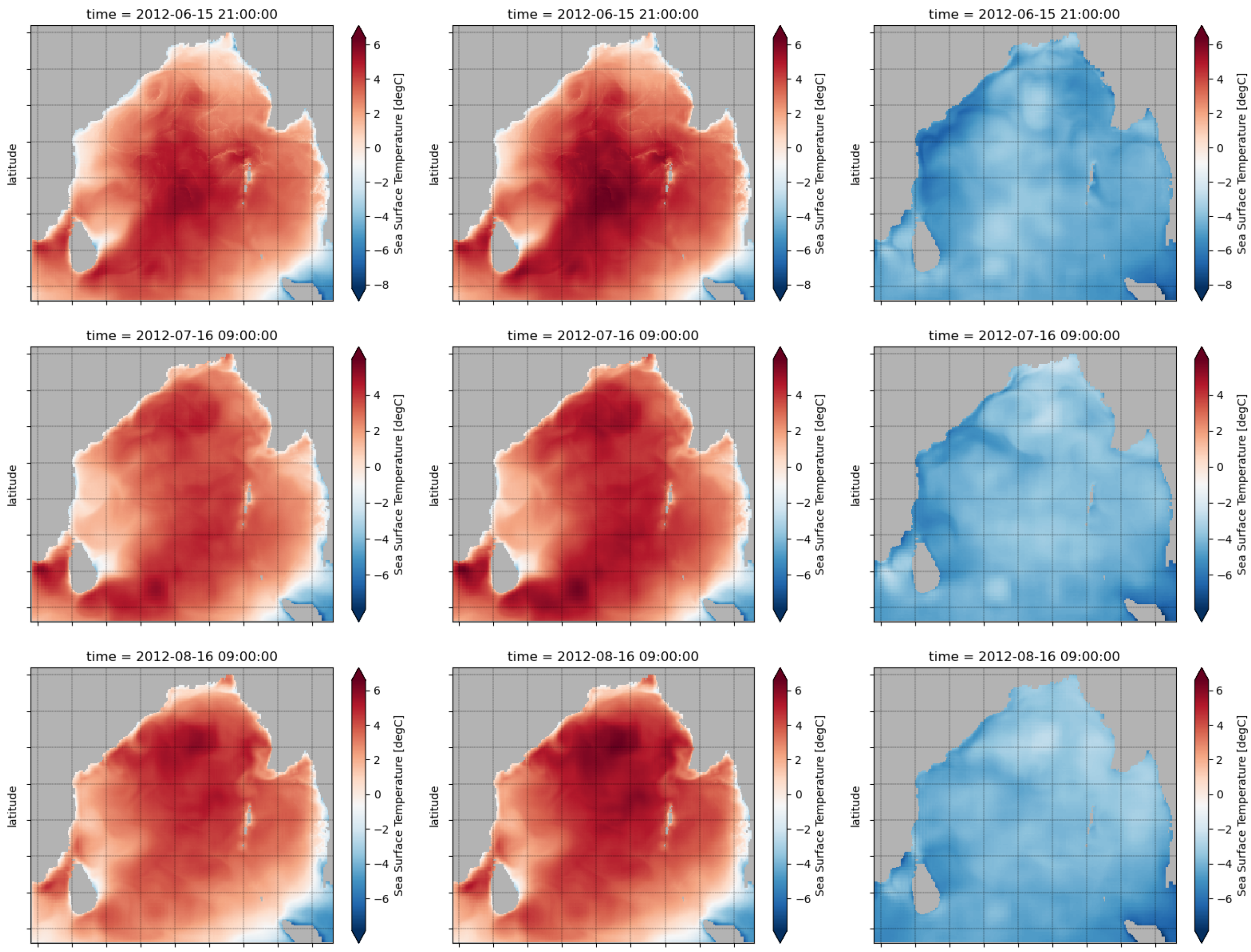

Figure 2: Comparision of model runs with observation for 2012: The left column images depict difference between ERA NoOBC and observation(ERA - Obs), the middle column is the difference between OBC run and observation(ERA/OBC - Obs) and the right column is the difference between JRA OBC run and observation(JRA/OBC - Obs)

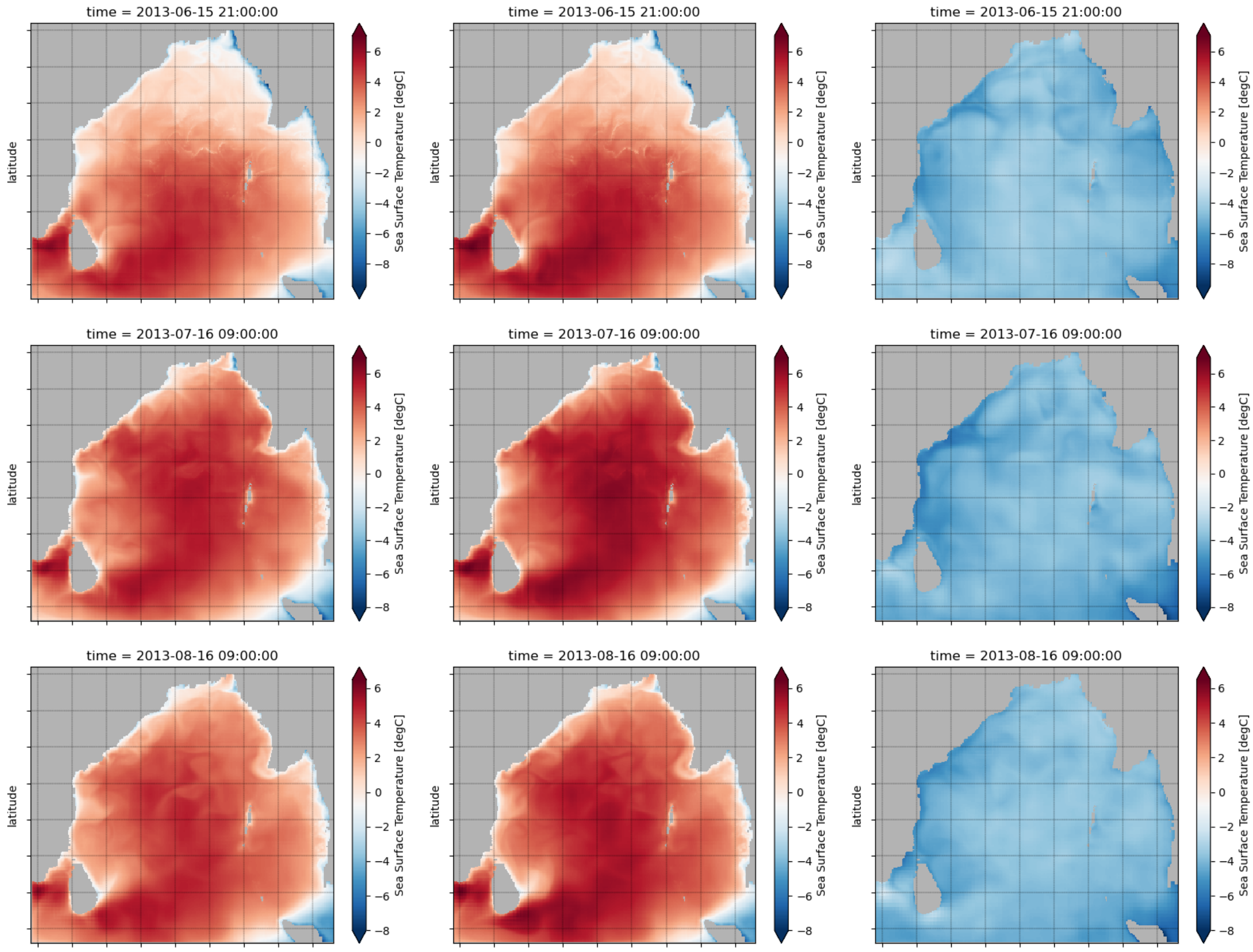

Figure 3: Comparision of model runs with observation for 2013: The left column images depict difference between ERA NoOBC and observation(ERA - Obs), the middle column is the difference between OBC run and observation(ERA/OBC - Obs) and the right column is the difference between JRA OBC run and observation(JRA/OBC - Obs)

- The trend of negative correlations in monsoon is repeated in 2nd year of the run with the same North advecting false warm pool.(Figure 3)
- The ERA runs might be producing negative correlations due to specific humidity forcing that is to be generated from ERA using Boltons formula(it is not available directly and we have to calculate it from dew point temperature and surface pressure) and which is a given in JRA55-do dataset.

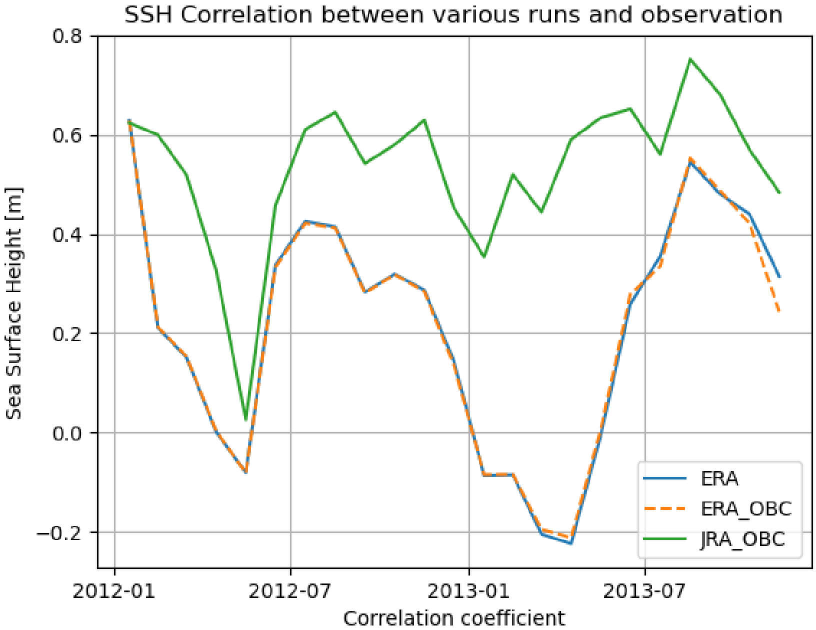

Figure 4: Correlation coefficient for runs for SSH

7.2 Sea Surface Height

- The dataset is a multi-mission altimetry product from AVISO which are gridded to produce a final product.
- We increase the resolution of the observation data(0.25 * 0.25) to that of model output(0.073 * 0.073) for comparision using bicubic interpolation.
- We take the 6 hourly output and produce a monthly output.
- We first plot the correlation between various runs and observation as shown in figure 4.
- The JRA55-do forcing with OBC has better correlation than the other two runs.
- We also plot the variance for observation and the runs.
- We next plot the standard deviation for observations and runs for first year of run(Fig. 5).
- Even though the standard deviation is less than 1 for all cases, the model output standard deviations are an order of magnitude greater than the observation.

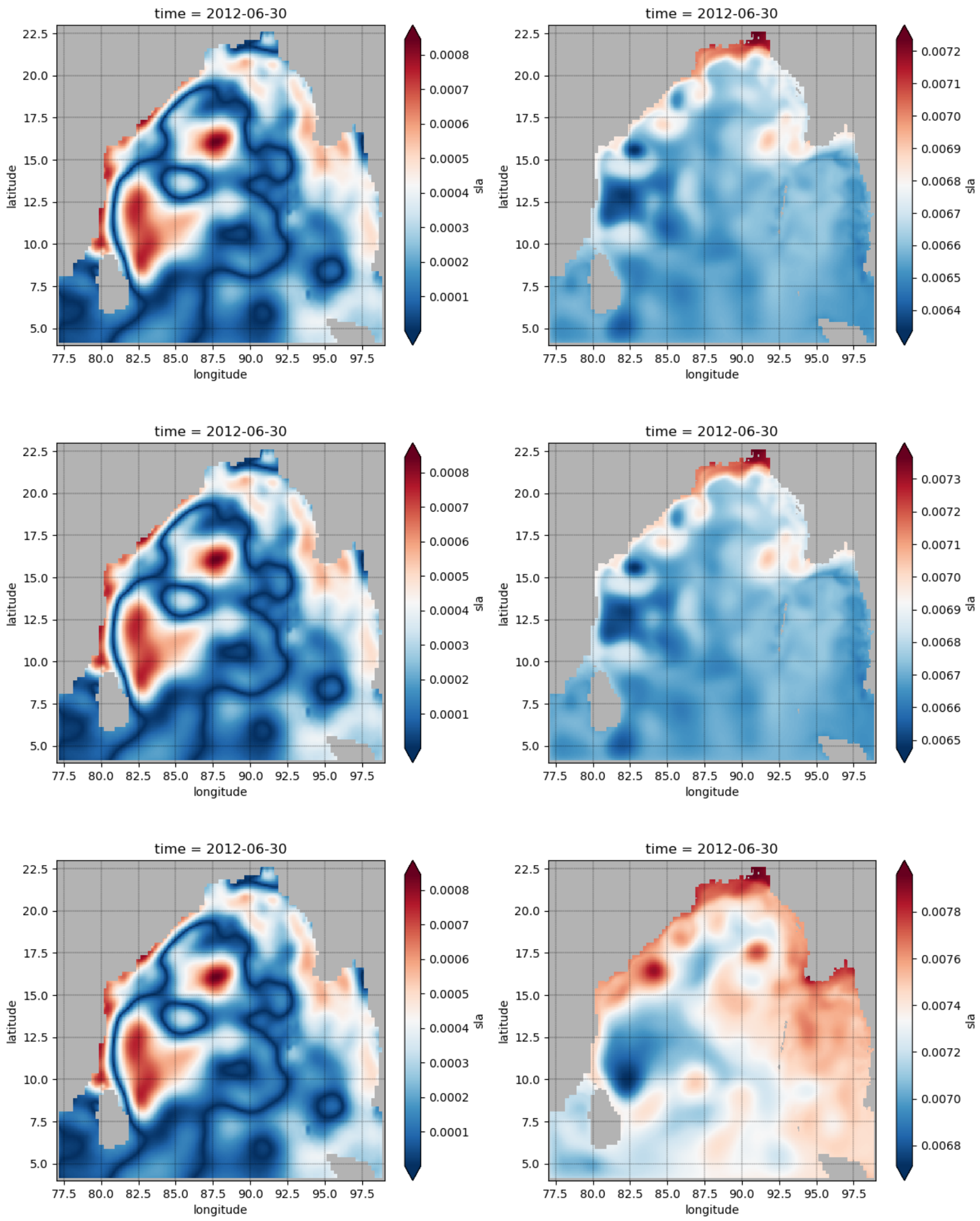

Figure 5: Here, we see the standard deviation plots for observation(in left column) and the various runs(in right column) : ERA, ERA/OBC and JRA/OBC. For first year of run.Units are in cm

7.3 Sea Surface Velocity

- We compare the model output velocity with the OSCAR dataset.
- The observational dataset resolution(0.25*0.25) is increased to model output resolution(0.073*0.073) using bicubic interpolation.
- The observational dataset has a temporal resolution of one day. The model output is every 6 hours. We thus average the dataset to produce a daily frequency output.
- We compare the behaviour of EICC(East India Coastal current) for the model runs. Here, we only compare for model runs ERA/OBC and JRA/OBC with the observation.
- The EICC flows poleward during Feb-March-April-May. We take the average for these months for the model runs for both the years of the runs.(Fig. 6 to 8)
- We see that both ERA/OBC and JRA/OBC predict the poleward EICC. However, ERA/OBC severly underestimates the strength of the current(0.28 m/s to 0.56 m/s). In this regards, the JRA/OBC predicts better current magnitude (0.63 m/s to 0.56 m/s). In ERA/OBC an erroneous southwards flow is present in the southern boundary(south of 12.5 $^\circ$ N). This feature is absent in JRA/OBC consistent with the observation.
- During the summer monsoon period of June-July-August, the EICC has equatorward flow in Northern Bay(north of 16 $^\circ$ N), poleward in southern Bay(8 $^\circ$ N to 16 $^\circ$ N).
- We take the Jun-July-August average of the model run outputs for both years of run.(Fig. 9 to 11)
- In the northwestern bay, consistent with the observations, the models show an southwestward flow.
- In the southern bay, from around 12.5 $^\circ$ N to 17.5 $^\circ$ N, we see that JRA/OBC is consistent with the observation, showing a northeastward current which converges with the southwestward northern bay current at approximately 17.5 $^\circ$ N. ERA/OBC predicts the flow in this area completely wrong.
- Also, the ERA/OBC model run under-estimate the velocities for whole the domain.
- In the south east of Sri-Lanka, there is an intrusion of flow into the south-central bay, which consistent with the observations, both the model runs predict correctly.
- Finally, during November and December, there is a southwestward flowing coastal current which is captured in both the model runs. JRA/OBC model run underestimates the current velocity slightly. The ERA/OBC severely underestimates the current velocity(0.32 m/s for model and 0.7 m/s for observation.)
- Regarding the RMSE, we plot the root mean square error between the model runs and the observational datase. We find that both the model runs have a maximum RMSE of 0.004, and almost all the time the ERA/OBC has greater values of RMSE that the JRA/OBC run.(See Fig. 15,16)
- The RMSE is greater in the EICC and any other region of the domain.

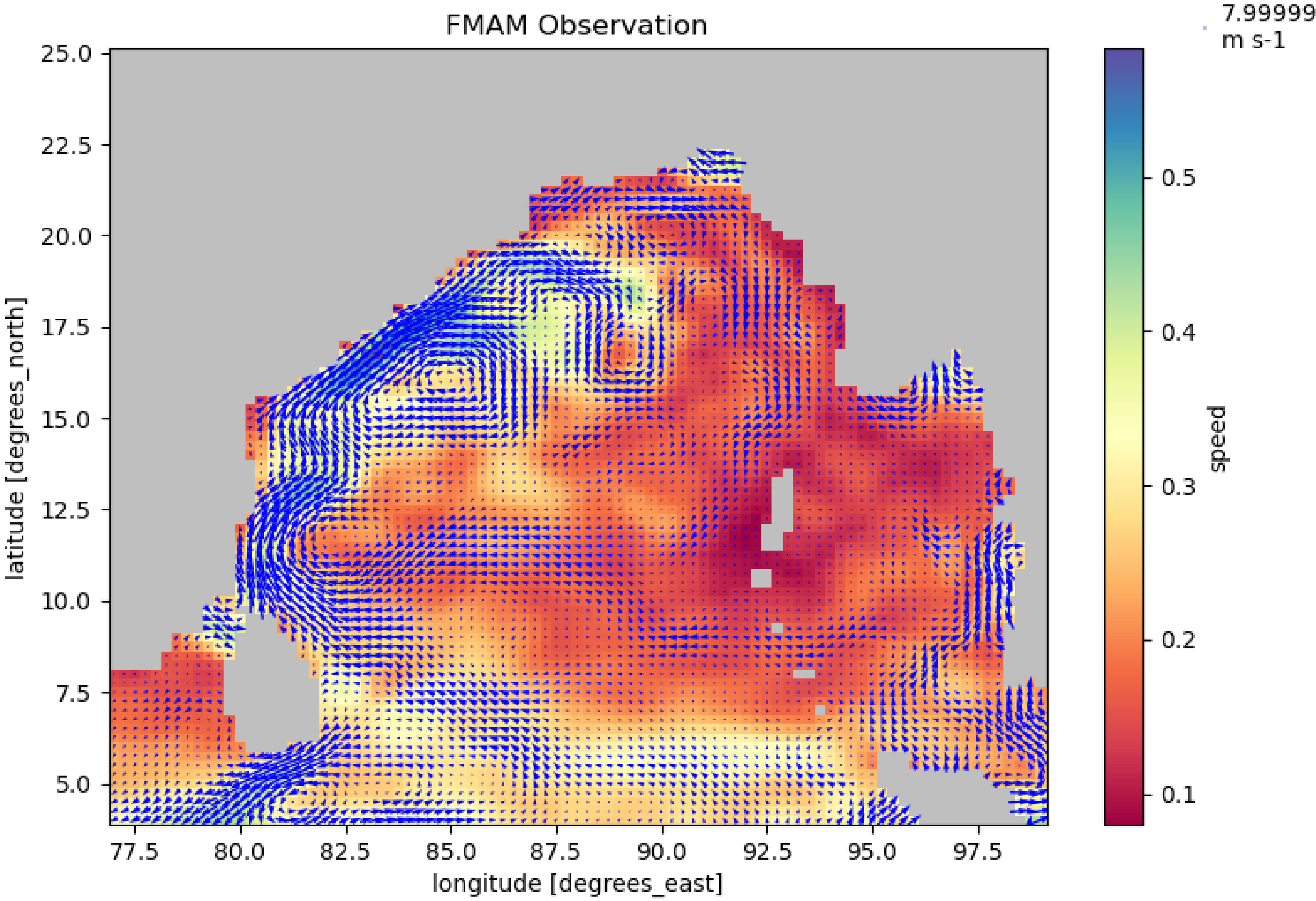

Figure 6: Feb to May average of OSCAR observation dataset. We see a northeastward coastal current in the western boundary of domain. The maximum value is around 0.7*7.9 m/s roughly 0.56 m/s

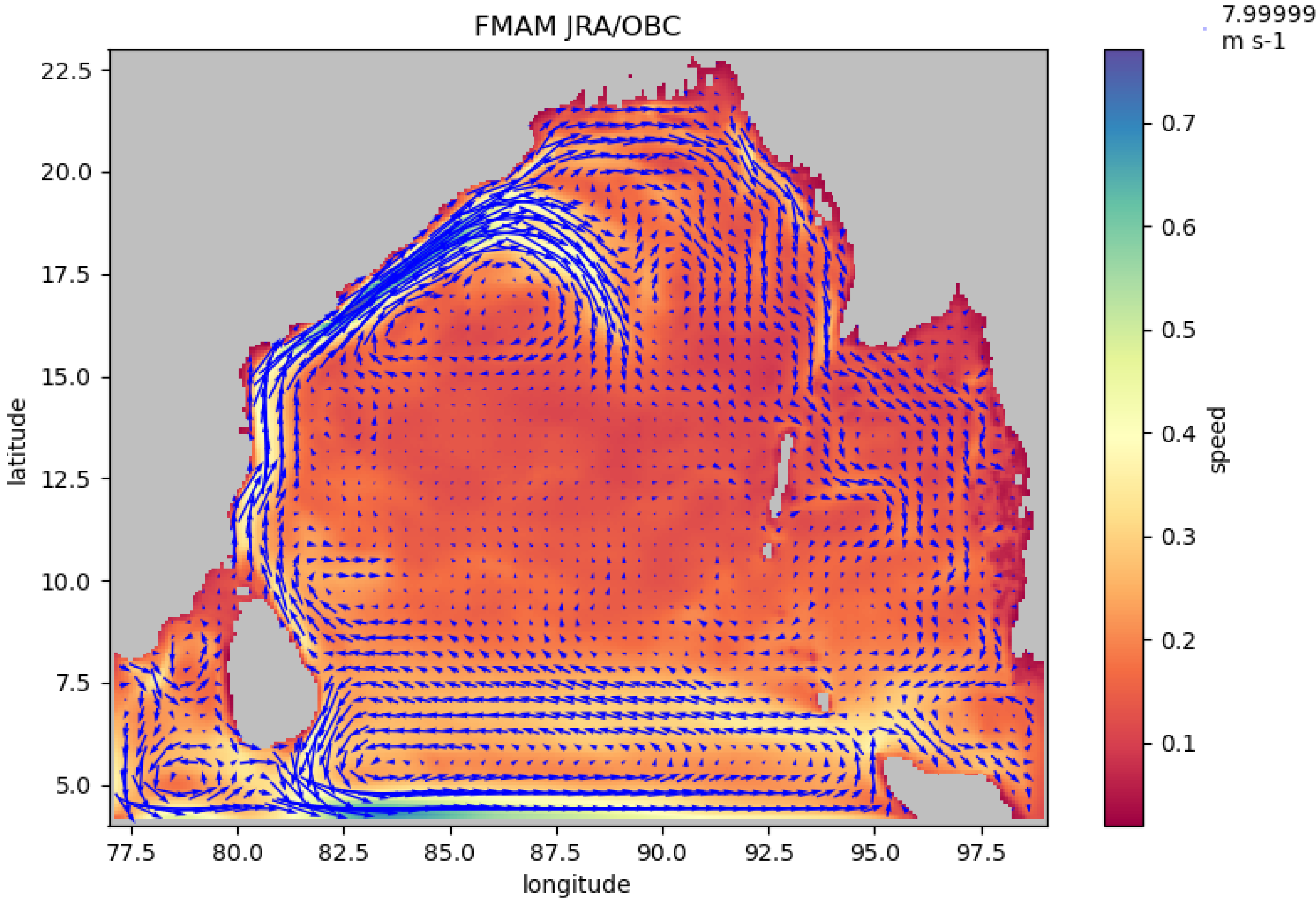

Figure 7: Feb to May average of JRA/OBC model output. The maximum value is around 0.8*7.9 m/s roughly 0.63 m/s. Only every fifth vector is plotted.

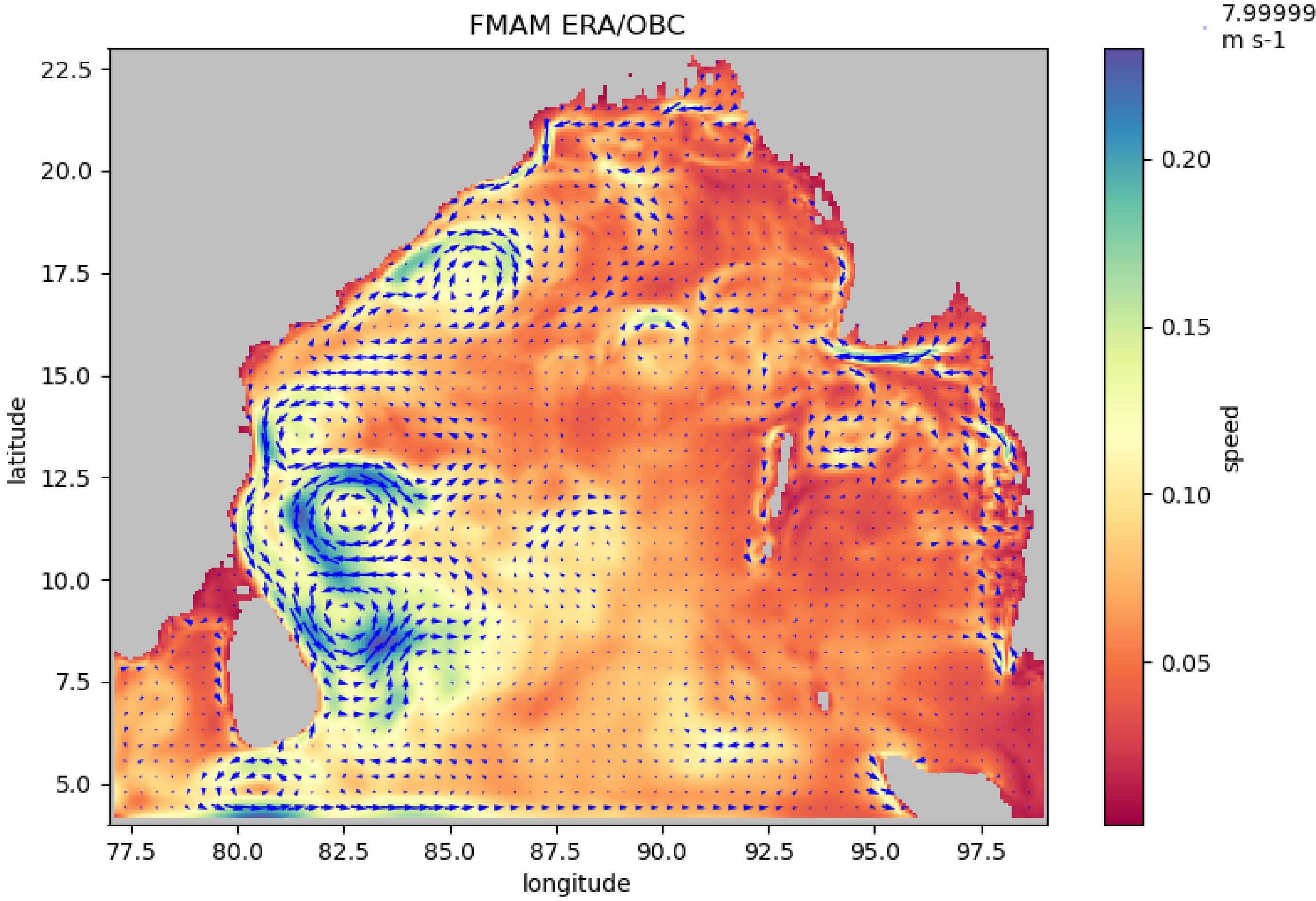

Figure 8: Feb to May average of ERA/OBC model output.The maximum value is around 0.35*7.9 m/s roughly 0.28 m/s. Only every fifth vector is plotted.

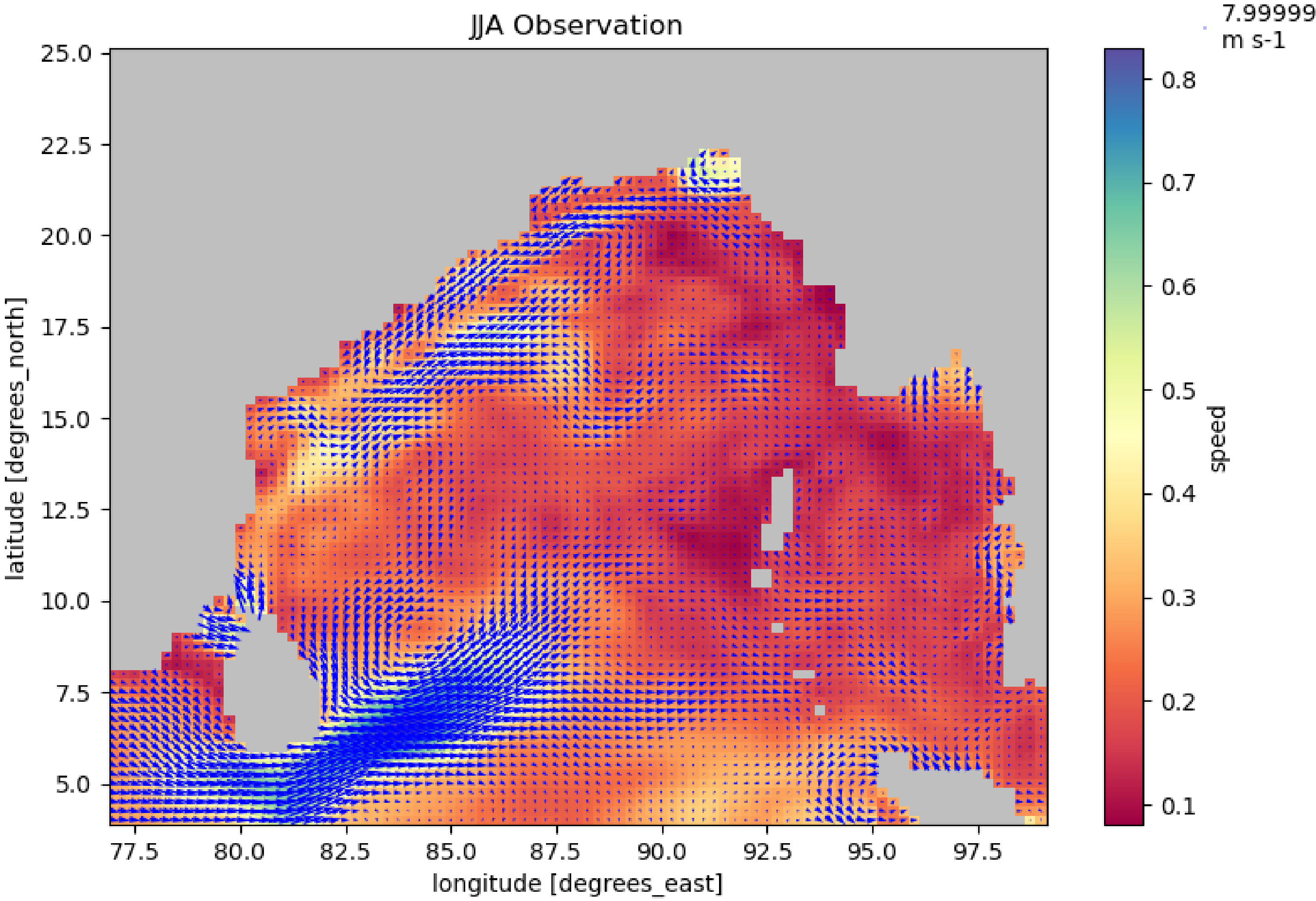

Figure 9: June to August average of OSCAR observation dataset.

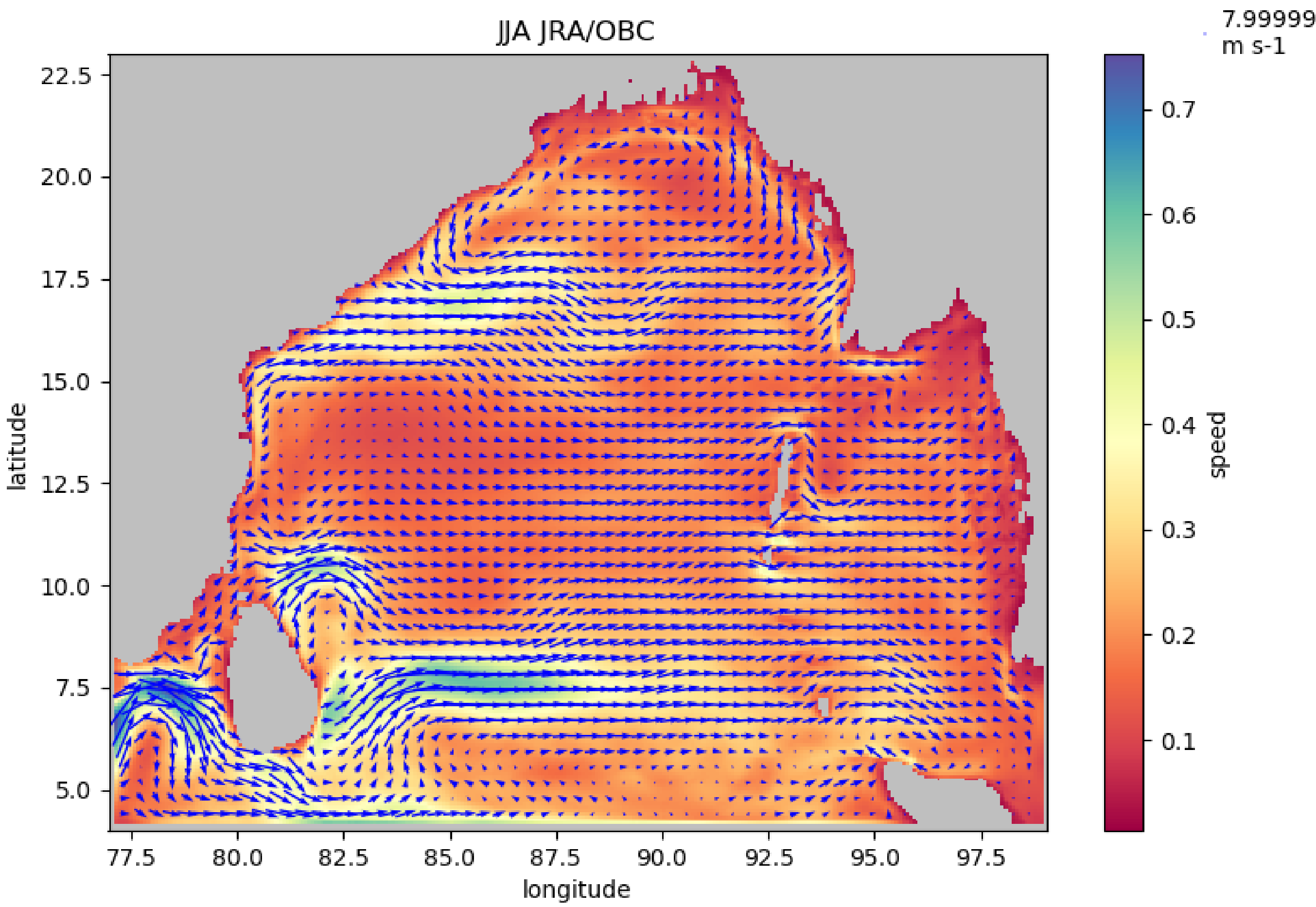

Figure 10: June to August average of JRA/OBC model output. Only every fifth vector is plotted.

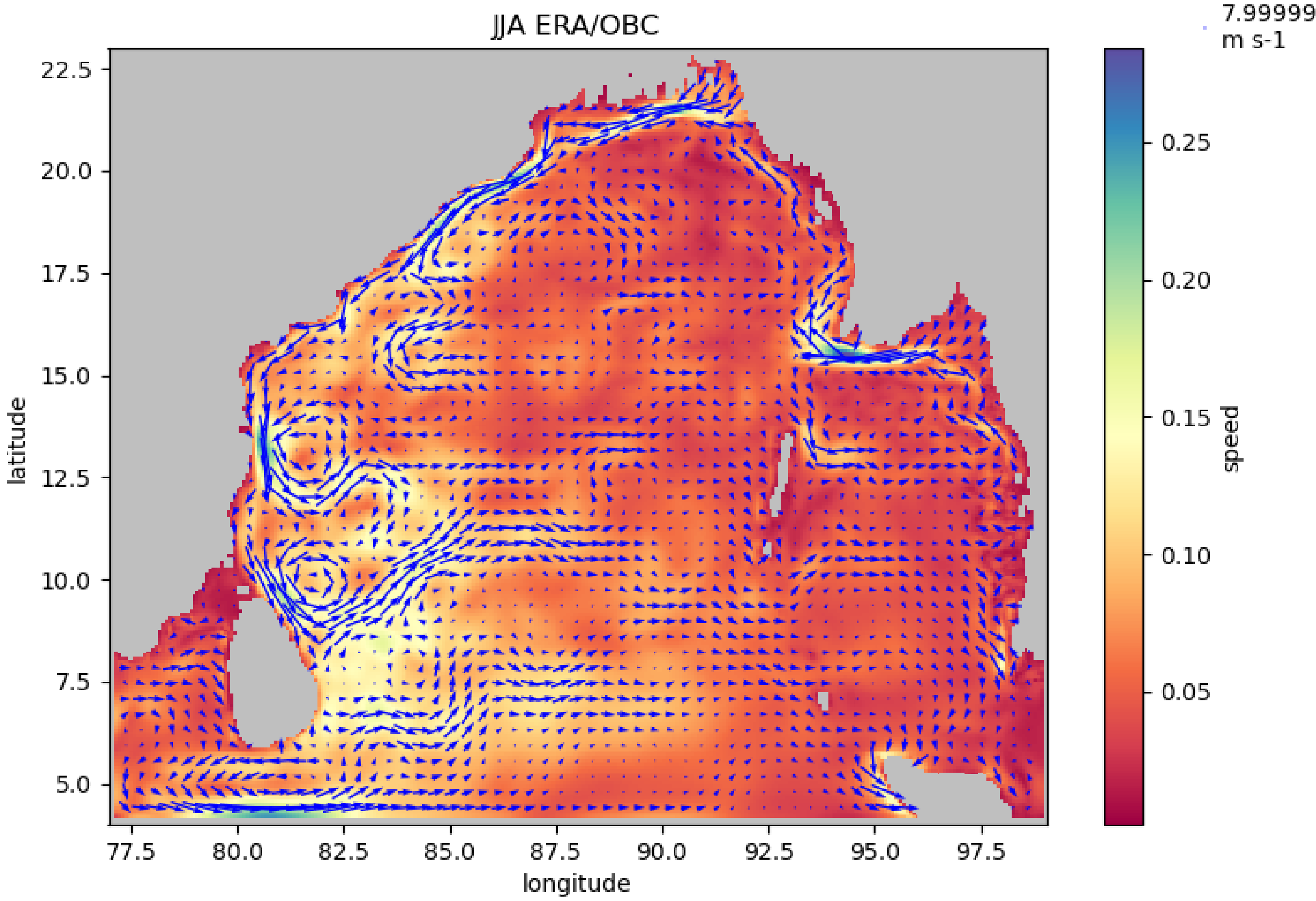

Figure 11: June to August average of ERA/OBC model output.Only every fifth vector is plotted.

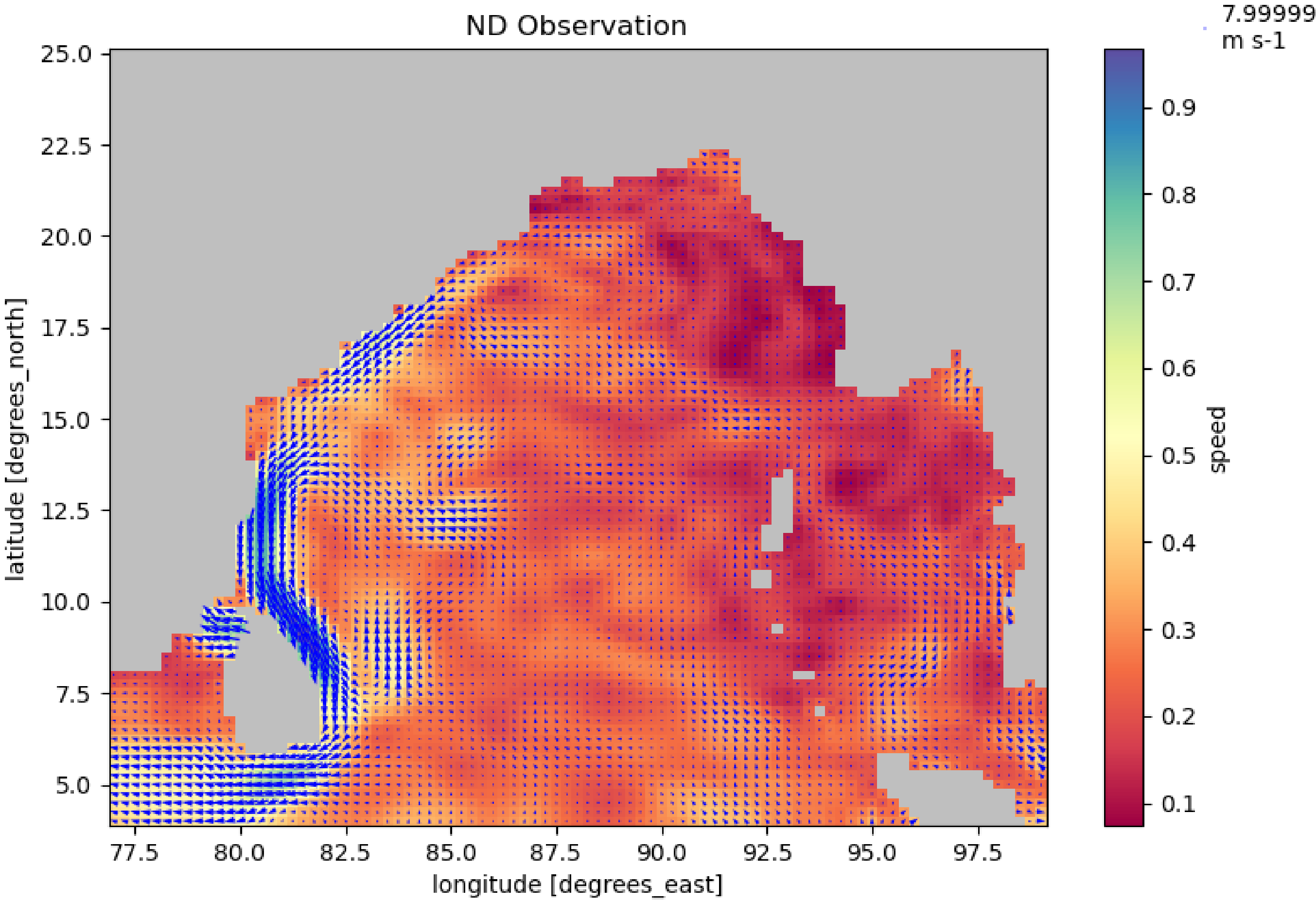

Figure 12: Nov,Dec average of OSCAR observation dataset.

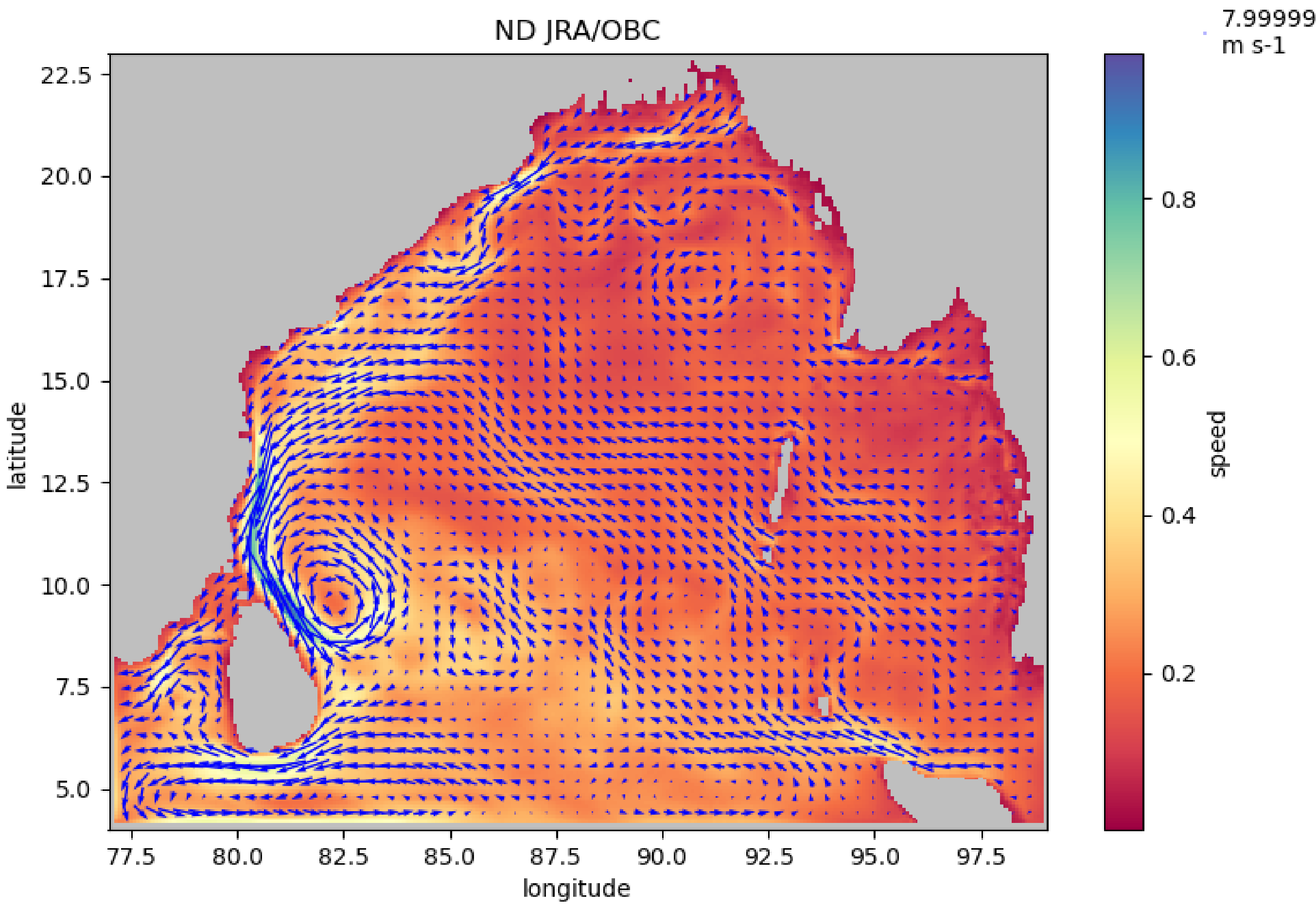

Figure 13: Nov,Dec average of JRA/OBC model output. Only every fifth vector is plotted.

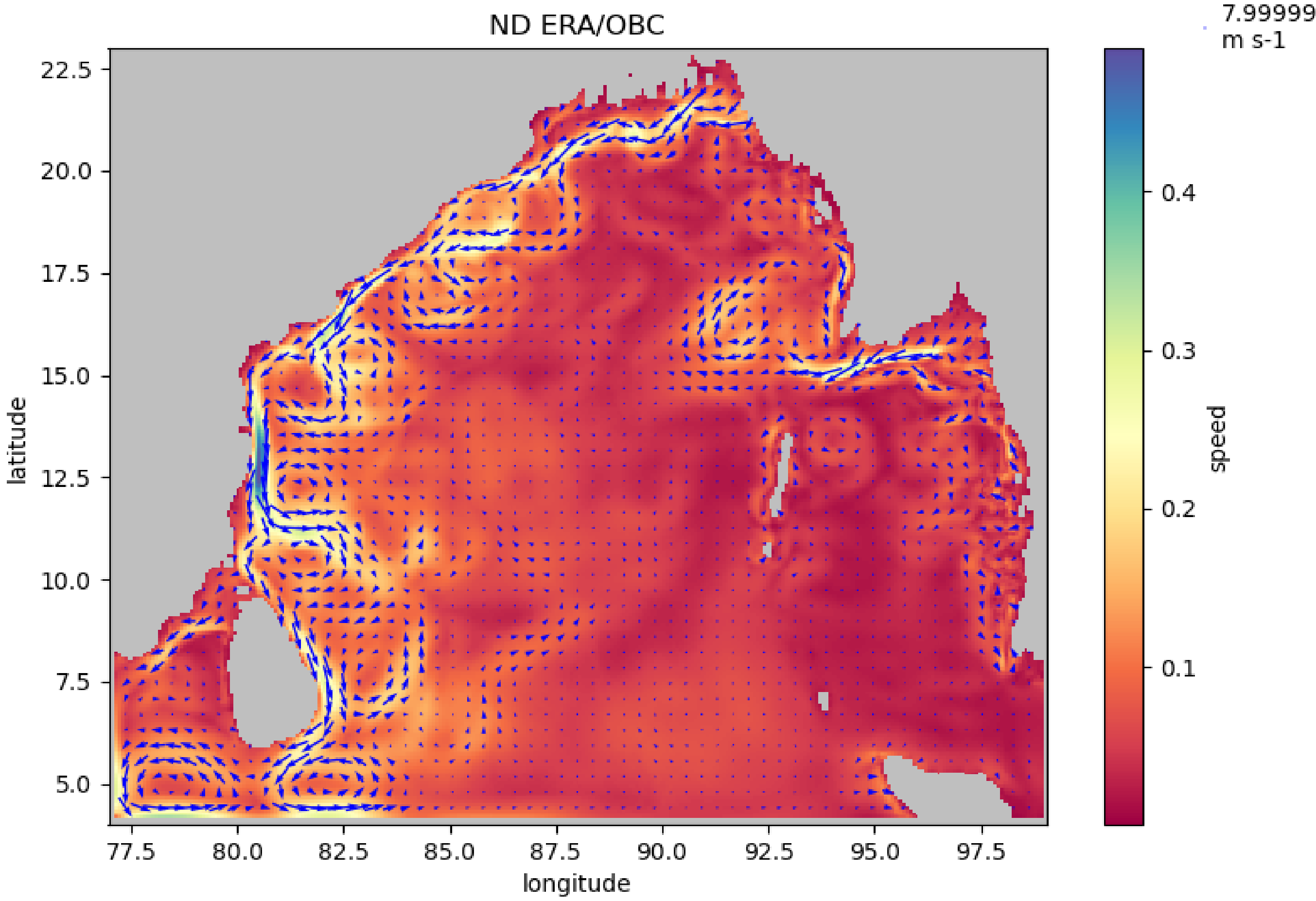

Figure 14: Nov,Dec average of ERA/OBC model output.Only every fifth vector is plotted.

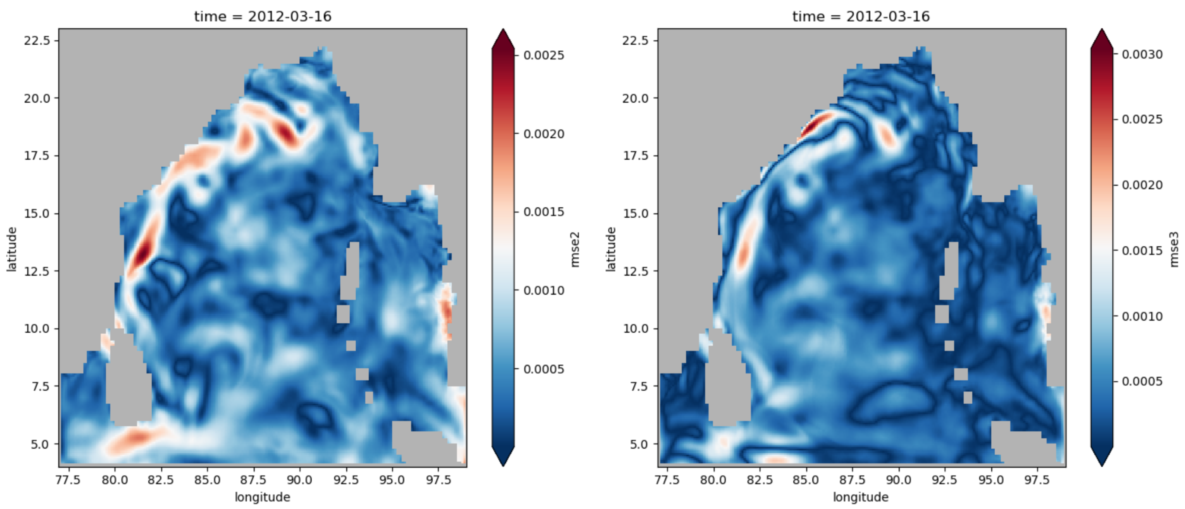

Figure 15: RMSE for the March-2012. Left is the ERA/OBC run and right is JRA/OBC run.This time of the year there is a northeastward EICC flow.

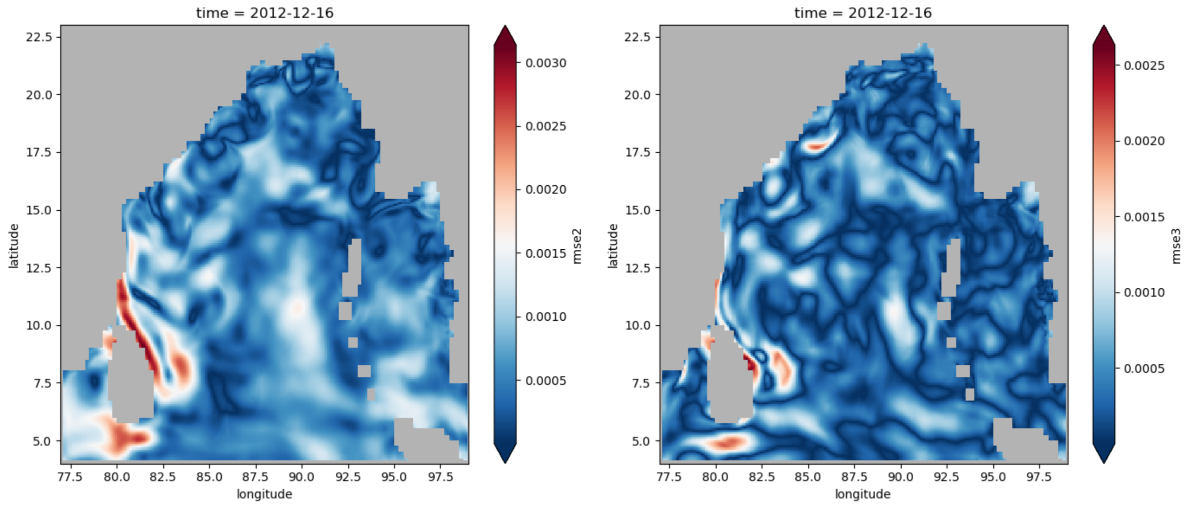

Figure 16: RMSE for the Dec-2012. Left is the ERA/OBC run and right is JRA/OBC run.This time of the year there is a southwestward EICC flow.

8 Conclusions

- JRA forcings model run perform better than the ERA model runs.
- We have used KPP parameterization for vertical mixing, there is another one that can be applied(energetic planetary boundary layer,ePBL).
- In ERA forcings, we seems to incorrectly calculate of specific humidity which may be causing erroneous heating in model.