Sensitivity of cyclone produced ocean mixing to the Langmuir turbulence: a modeling study

Soma Mishra*, Anant Parekh and Phani Murali Krishna R.

Indian Institute of Tropical Meteorology, Pune

*** Presenter Email address : soma.mishra@tropmet.res.in**

Presenting in:

OMDP Commodore Workshop,2024 on

Ocean Model Development, Data-driven Parameterizations, and Machine Learning in Ocean Models of the Earth System Workshop

12 September 2024

9:45 am

Motivation of the study:

- Tropical cyclones (TCs) are intense, and localized weather events characterized by high winds that generate vigorous mixing in the upper ocean (Mei and Pasquero, 2013; Price, 1981).
- The north Indian Ocean accounts for 6% of the global TCs annually, causing extensive damage to the life and property in the north Indian Ocean rim countries (Vineet et al., 2022).
- During tropical cyclones, increased turbulence from wind-wave, wind-current, or wave-current interactions intensifies upper ocean mixing.
- The upper ocean's response to TCs is mainly characterized by surface cooling and subsurface warming (Chen et al., 2021; Mei & Pasquero, 2012; Mrvaljevic et al., 2013; Price, 1981; Zhang et al., 2020).
- Without explicitly accounting for wave effect, boundary layer turbulence models, such as the K-profile parameterization (KPP; Large et al. 1994), which might have implicitly incorporated some effects of Langmuir turbulence by tuning the parameters to ocean observations (Reichl et al. 2016,), tend to misrepresent the entrainment under varying wave conditions.
- **The goal of this study** is to investigate the impacts of cyclone induced enhanced turbulence through the wave driven processes by modifying KPP and study the vertical thermohaline structure biases with respect to in-situ observations over the north Indian Ocean.

Performance of KPP:

- Li et al. (2001) investigated the performances of the KPP scheme and the PP scheme in a Pacific OGCM, revealing that the KPP scheme works better than the PP scheme in both the tropics and the extra tropics.
- Halliwell (2004) evaluated seven different vertical mixing schemes in the Hybrid Coordinate Ocean Model (HYCOM) and found that the KPP scheme had better performances for the climatological simulations of the Atlantic Ocean.
- According to Smyth et al., (2002) among all KPP is the most efficient; it forsakes theoretical development for simple representations of specific processes. The KPP scheme is currently widely used in ocean and climate modelling, was proposed by Large et al. (1994).

❖ KPP has advantages on:

- Providing mixing from surface to bottom.
- Working on relatively coarse and unevenly spaced vertical grids.
- Forsaking the theoretical development for simple representation of specific processes.
- Parameterizes the more number of physical processes than other mixing schemes.
- Giving better results for tropics and extra tropics.

(Halliwell et al.,2004)

Limitations of KPP:

- Previous studies have reported that Modular Ocean Model version 5 (MOM5) shows significant bias in temperature, salinity and density profiles over the Tropical Indian Ocean(TIO). It shows surface cold bias and subsurface warm bias($2°C - 3°C$). (Jasti et. al,2016).
- In the set up of MOM5, K Profile Parameterization scheme consists of shape function which is a third order polynomial and unable to take care of wave driven processes viz. Langmuir turbulence and the mixing is not represented properly. (Chor et. al,2021)

K profile parametrization (KPP):

❖ The standard formula for K profile parameterization of oceanic boundary layer mixing is:

$\overline{wx}(d) = -K_x(\partial_z X - \gamma_x)\ldots$ (1)

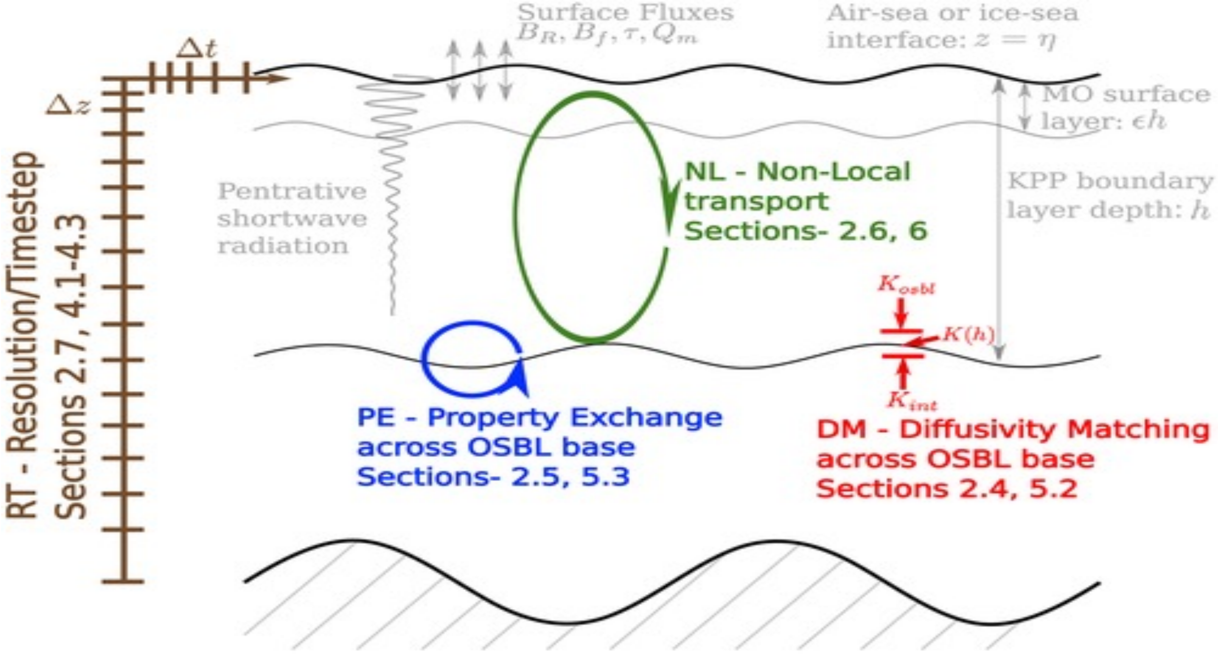
Where, $\overline{wx}(d)$ is the vertical turbulent fluxes of tracer and momentum, K_x is the boundary layer diffusivity term, X is the mean of the tracers and momentum.

❖ Current KPP formulation:

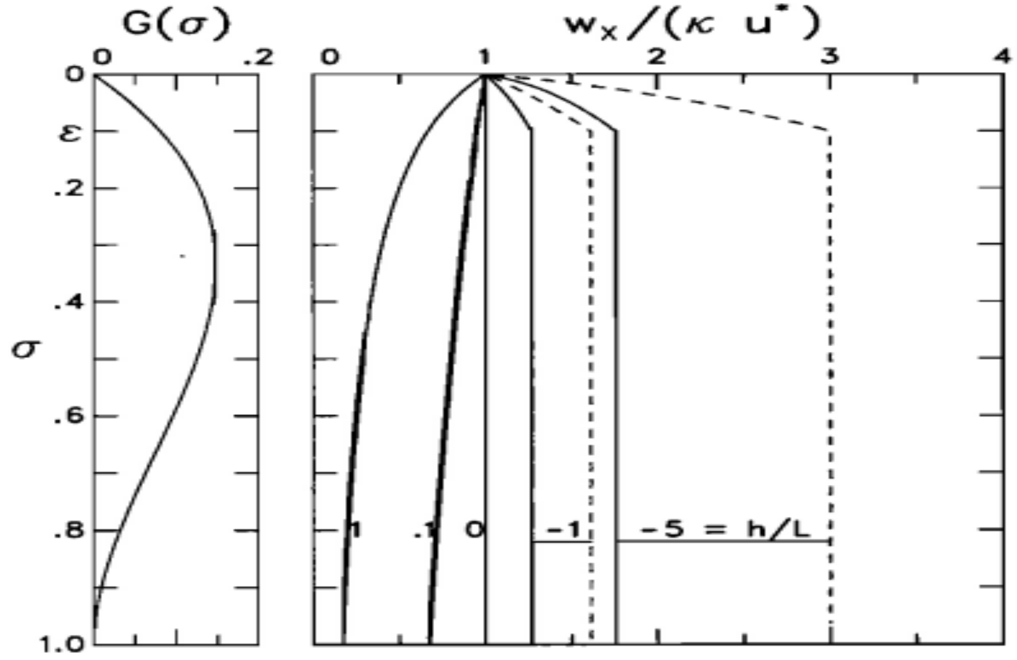
$$K_x(\sigma) = h w_x(\sigma) G(\sigma) \ldots (2)$$

- h is the boundary layer depth.
- $w_x(\sigma)$ is the vertical velocity scale.
- $G(\sigma)$ is the non dimensional shape function approximated as a cubic polynomial,

$G(\sigma) = a_0 + a_1\sigma + a_2\sigma^2 + a_3\sigma^3 \ldots (3)$



Roekel et al.,2018



Large et al.,1994

Methodology for implementing shape function:

Chor et al,2021 parameterization for the shape function implemented inside model source code as,

The vertical diffusivity is being parameterized as,

$$\boldsymbol{K_\lambda(\sigma) = h w_\lambda(\sigma) G(\sigma)}$$

Where, h is the boundary layer depth, $w_\lambda(\sigma)$ is the vertical velocity scale and $G(\sigma)$ is a non-dimensional shape function.

$\sigma = \frac{d}{h}$ is the normalized depth. d is the distance from the ocean surface to a point in the boundary layer.

$G(\sigma)$ is a cubic polynomial defined as,

$$\boldsymbol{G(\sigma) = a_0 + a_1\sigma + a_2\sigma^2 + a_3\sigma^3}$$

Turbulent eddies can not cross the ocean surface. So, the diffusivity must be zero at $\sigma = 0$. Which implies, $\boldsymbol{a_0 = 0}$.

Derivation shows that, $\boldsymbol{a_1 = 1, a_2 = -2 + \left(\frac{3K_\lambda(h)}{hw_\lambda(h)}\right), a_3 = 1 - \left(\frac{2K_\lambda(h)}{hw_\lambda(h)}\right)}$

(by considering continuity of the diffusivity with a matching derivative at the boundary layer base,$\sigma = 1$)

Now, in place of this aforementioned cubic polynomial as shape function, a new sixth order polynomial (Chor et al.,2021) has been used inside the model source code. This new shape function is defined as,

$$\boldsymbol{G(\sigma) = \sigma(1-\sigma)^2[1 + 45\sigma - 33(\sigma + \sigma^2) + 9(3\sigma + 2\sigma^2 + \sigma^3)]}$$

Methodology(for implementing enhanced vertical velocity function):

The vertical velocity scale has been enhanced with respect to the parameterization scheme according as **Smyth et al.,2002** which can be described as following:

$$w_\lambda(\sigma) = \frac{\kappa u_*}{\phi_x} \times \{1 + \frac{C_w(u_*, w_*)}{La^4}\}^4$$

Where,

$$C_w(u_*, w_*) = C_{wo}[\frac{u_*^3}{u_*^3 + 0.6w_*^3}]^l$$

w_* is the convective velocity scale, defined as (Large et al.,1994) $w_*^3 = \kappa B_f h$, where B_f is the surface buoyancy flux, C_{wo} and l are constants.

Studies have suggested that,

- **Only changing the shape function is not sufficient for incorporating wave driven processes (mainly LT). With that it is needed to modify the vertical velocity scale profile accordingly. So that the wave driven processes in the surface can be parameterized more accurately.**

Experiment details:

- Forcing (JRA55)
  - Precipitation
  - Radiation
  - Sea level Pressure
  - Specific humidity
  - Air temperature
  - u & v winds

MOM5
(CTRL)
(With Large et al.,1994 K profile parameterization scheme as mixing scheme)

MOM5
(EXP)
(with revised Shape function and vertical velocity scale)

- Output (Daily)
  - Temperature
  - Salinity
  - Density
  - u & v current
  - Wscale profile
  - Shape function
  - Diffusivity/viscosity

- **0. 25° horizontal resolution**
- **50 vertical levels**
- **Spin up is done with CORE climatological forcing for 50 years.**

Datasets and outputs:

Datasets

- ARGO Temperature and Salinity profile of 10 days averaged with 1° horizontal resolution.
- RAMA buoy daily data of Temperature and salinity .

Outputs analyzed

- Vertical profiles of
  - ❑ Temperature (Temp)
  - ❑ Density
  - ❑ Shear
  - ❑ Stratification
  - ❑ Diffusivity
  - ❑ Viscosity
  - ❑ Vertical velocity scale
- Spatial distribution of
  - ❑ Sea surface temp (SST)
  - ❑ 100m temp.
- Time series of
  - ❑ Oceanic Heat content
  - ❑ Subsurface temp

NIO cyclones track and buoy locations

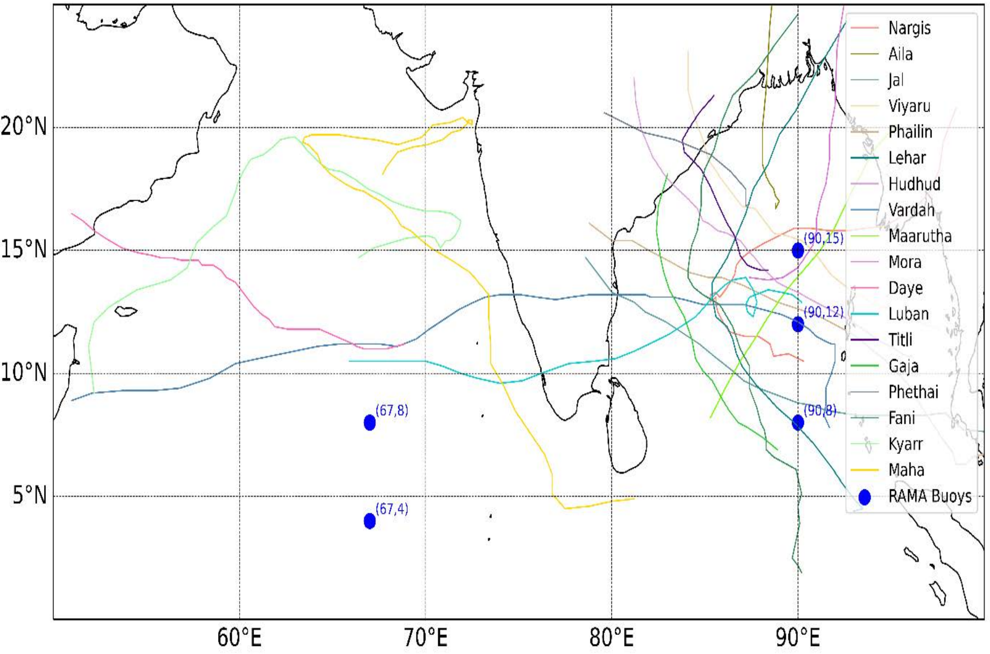


Figure: Analyzed cyclone tracks from 2008-2019 with the RAMA buoy location (blue circle) over Indian Ocean.

Observed & Forced Wind speed over buoy locations

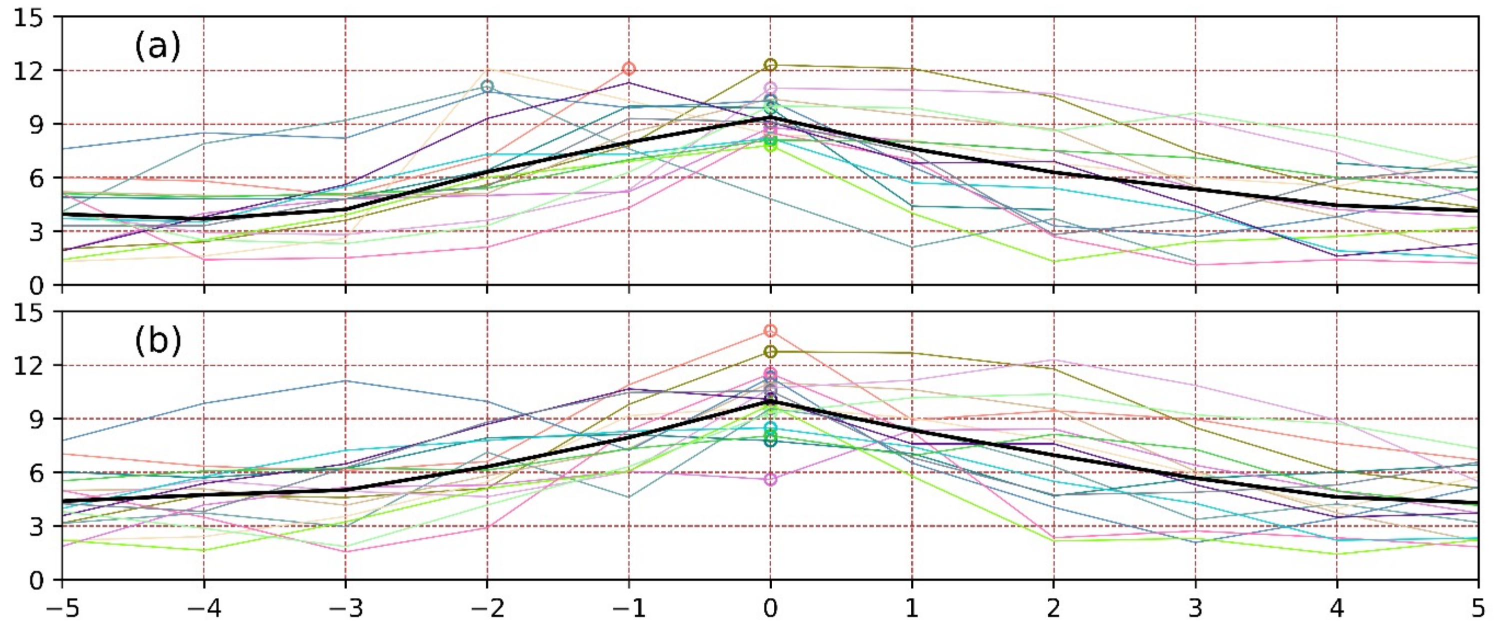
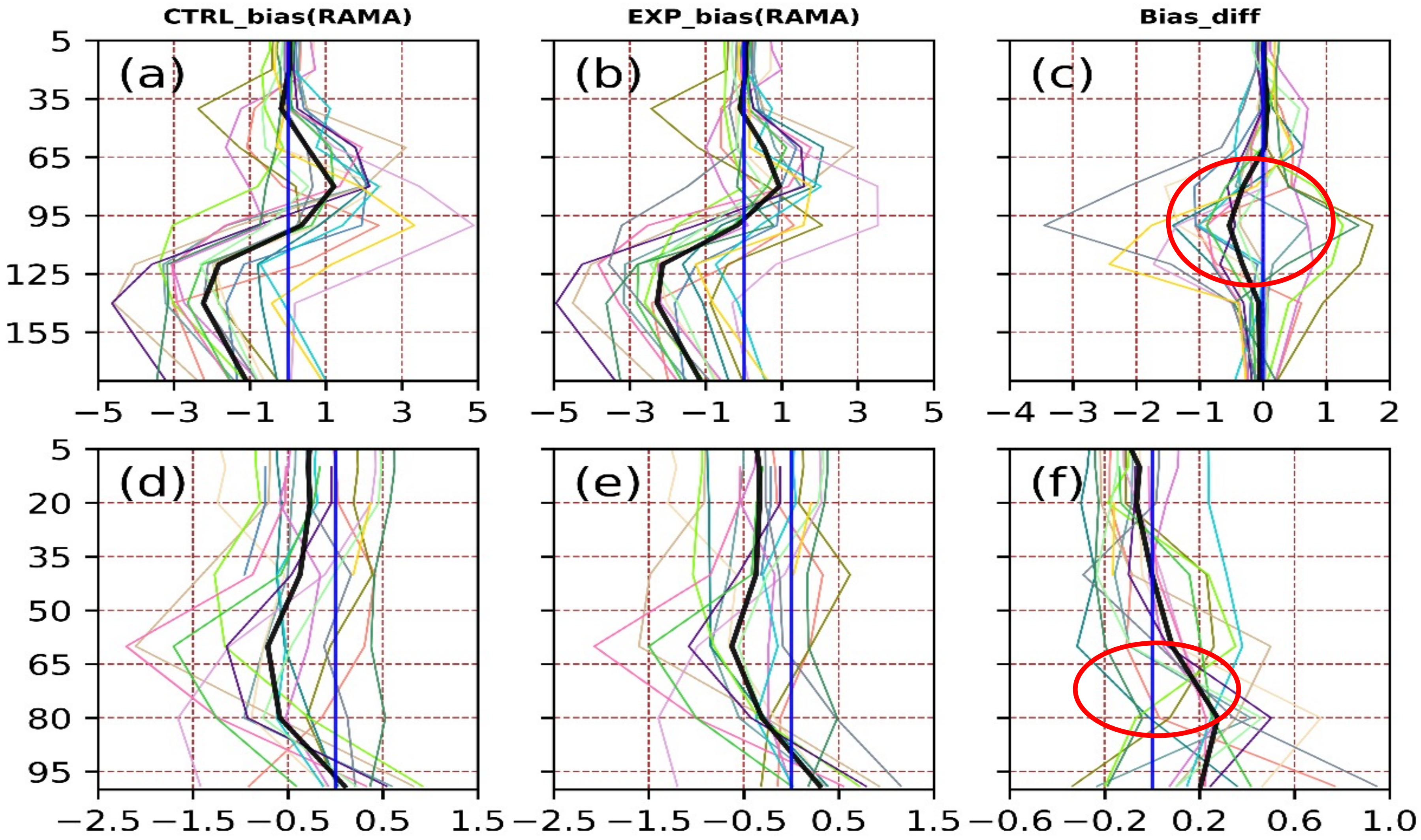


Figure : Wind speed (m/s) time series from different cyclone: (a) from RAMA buoy data; (b) JRA55-do(forcing field). Black line is denoting the mean field for both the cases. The open circles are pointing the day from which the cyclones are closely from buoy.

- In the present study, eighteen North Indian Ocean cyclone has been analyzed from 2008-2023.
- Among which fifteen cyclones are in Bay of Bengal (BoB) and three are in Arabian Sea(AS).

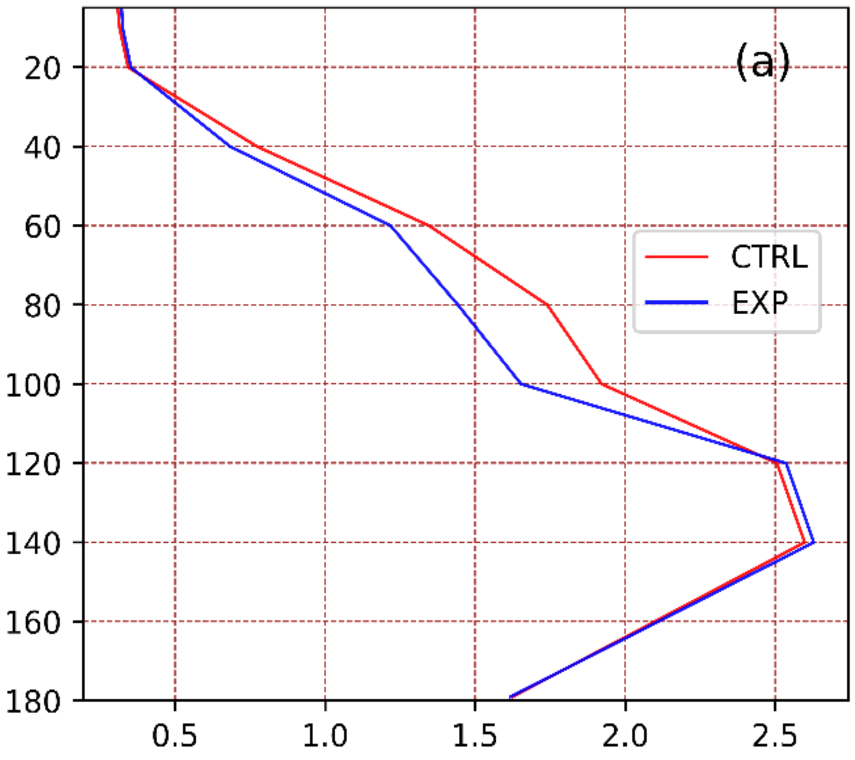
Temperature and Density bias profile

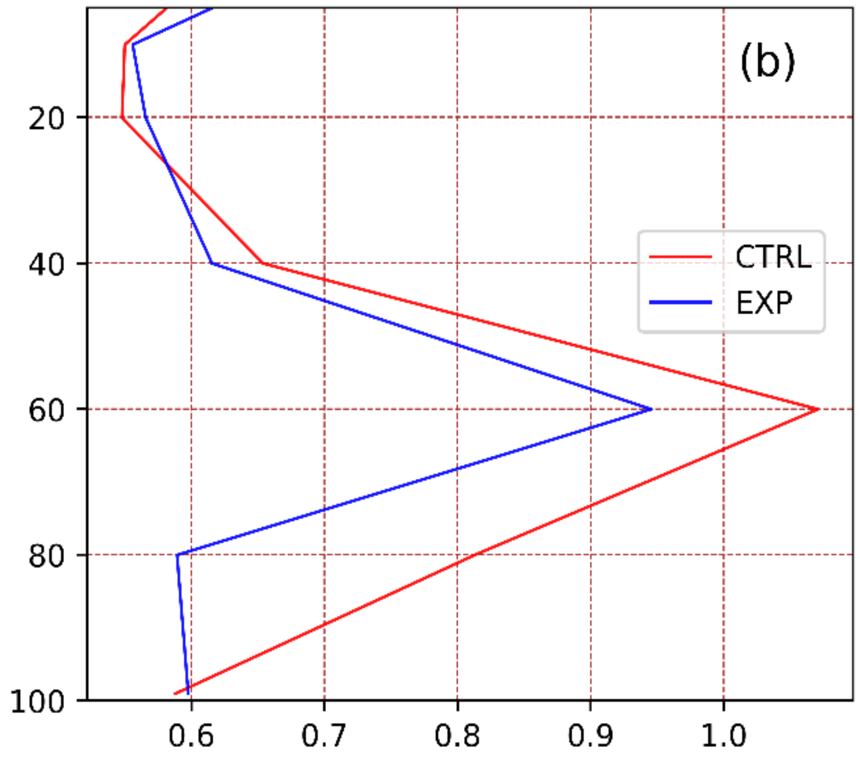


- Surface cold bias and subsurface warmer bias (maximum reduction 0.5 °C in 100m depth) have been reduced.
- The subsurface density bias has been reduced (maximum 0.2 kg/m^3 in 80m depth).

Figure: Vertical profile of temp. bias (°C), density bias (kg/m^3) and bias difference (°C and kg/m^3) for different cyclones: (a) and (b) denotes for CTRL and EXP temp. and (c) shows the temp. bias difference from EXP bias to the CTRL bias for the day cyclone is closest to the buoy location. (d), (e) and (f) are same as (a), (b) and (c) for density. Black lines are denoting the mean of the respective fields.

RMSE profiles of temperature and density

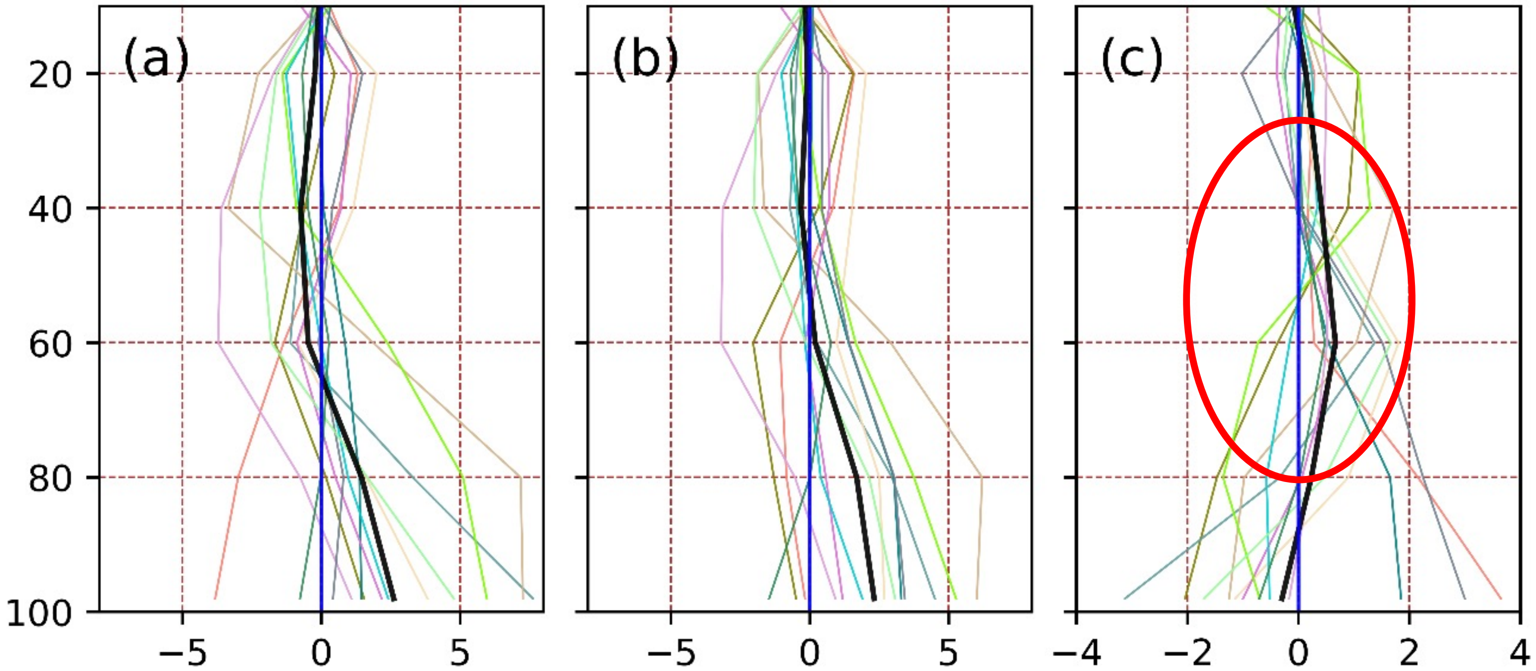




- The temperature RMSE has been decreased by 0.2℃ – 0.3℃.
- The density RMSE also has been decreased the subsurface (maximum at 80m depth about 0.2 kg/m^3).

Figure: Vertical profile of temp. RMSE (left panel; (a)) and density RMSE (right panel; (b)). Red and blue line indicates values from CTRL and EXP respectively.

Reduction of bias in the vertical profile of stratification



- The upper ocean stratification bias has been reduced by $0.5s^{-2}$ ($o(10^{-4})$) at 60m.

Figure: Vertical profile of stratification bias from CTRL(a), EXP(b) and bias difference(c). Black line is signifying mean for each case.

RMSE difference of subsurface temperature and OHC

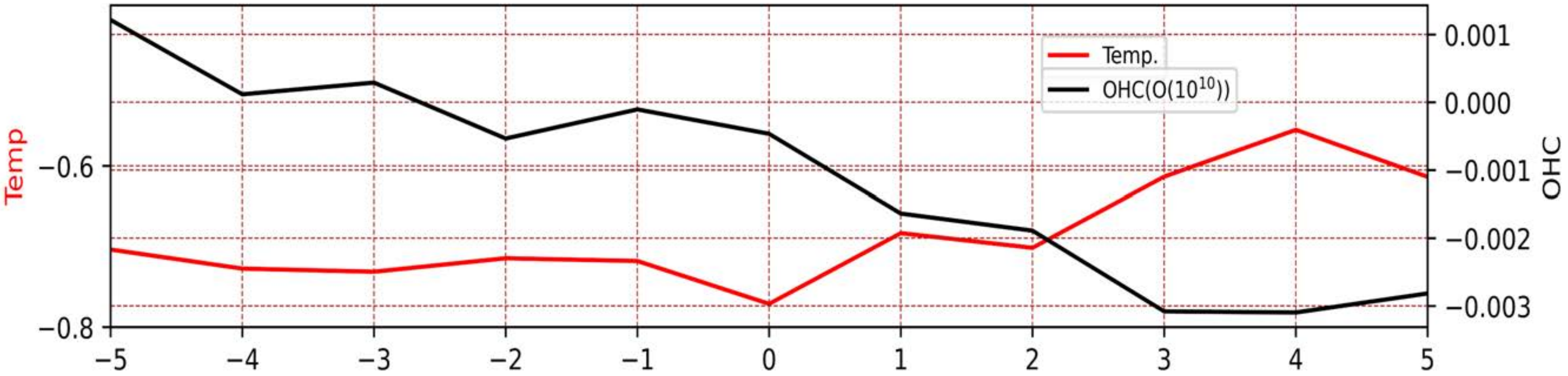
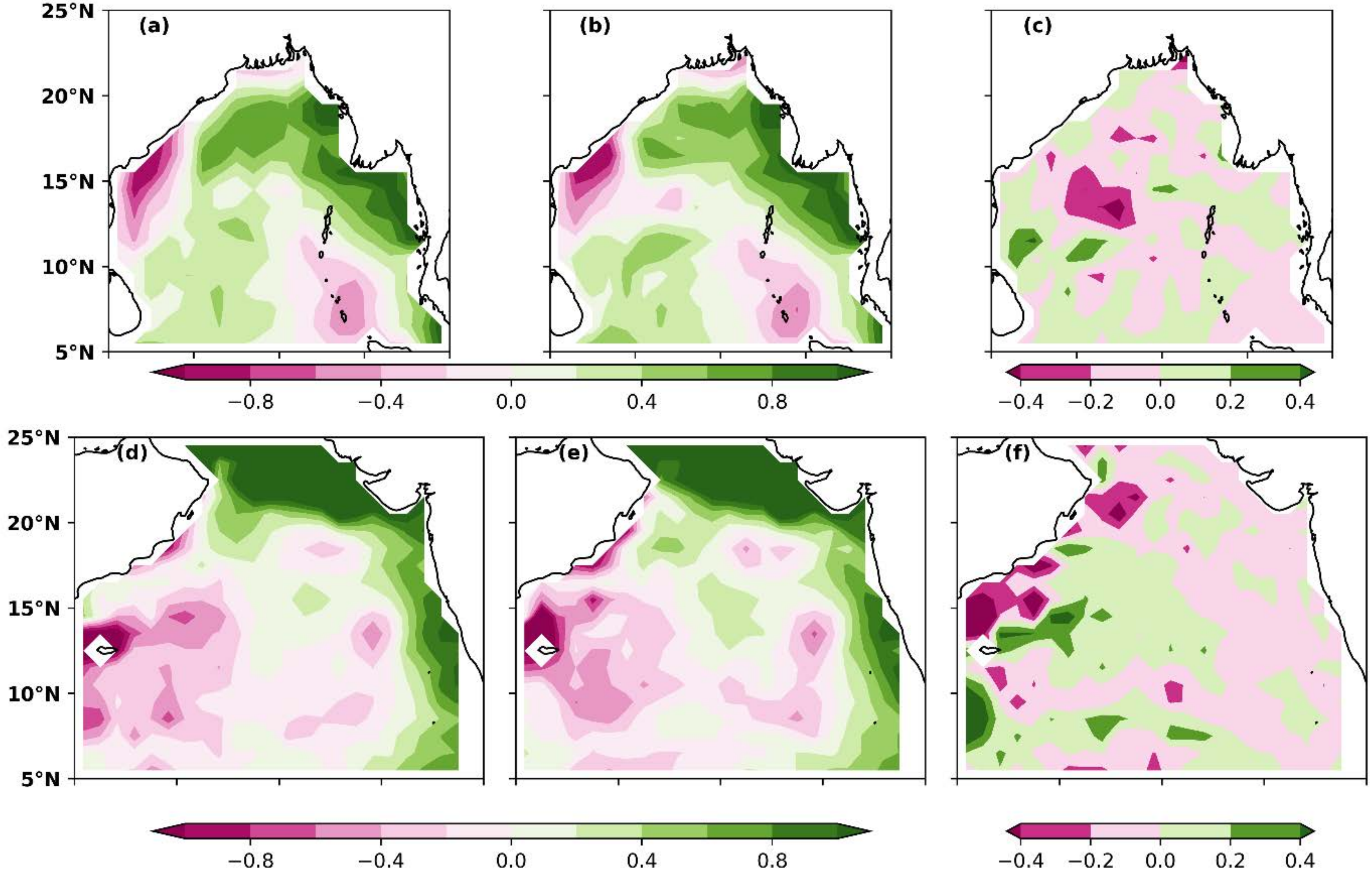


Figure: Red line indicates timeseries of subsurface temperature RMSE difference (RMSE EXP -RMSE CTRL), black line indicates same for OHC.

- The RMSE difference of subsurface temperature (OHC) from CTRL to EXP is 0.5 °C (0.3×10^{8}) in the day cyclone closest to the buoy location closely.

- Maximum difference is about 0.8°C.

Spatial distribution of SST bias



- For Arabian sea(upper panel) and for Bay of Bengal (lower panel) bias have been decreased (maximum reduction is 0.4°C).

Figure: Spatial distribution of SST bias (°C) from CTRL(a) and EXP(b) with respect to Argo dataset for cyclone Phethai in BoB (2018). Bias difference (EXP_bias - CTRL_bias) is shown in (c). (d) and (e) are same as (a) and (b) for cyclone Kyarr (2019) in AS respectively. (f) is same as (c) for the same cyclone as (d) and (e).

Spatial distribution of Subsurface temperature bias

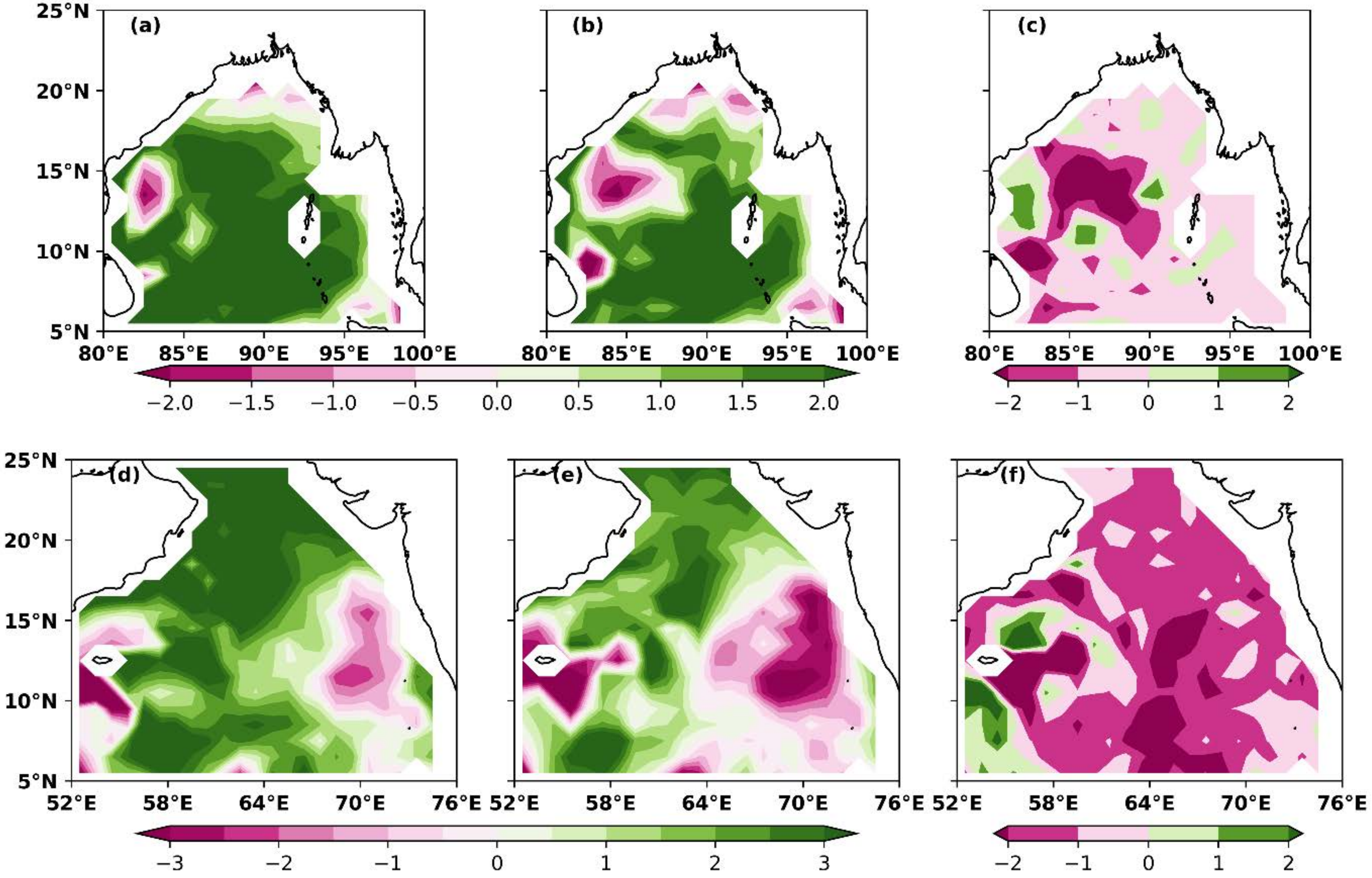


Figure : Same as previous figure for 100m temperature.

- For Arabian sea(upper panel) and for Bay of Bengal (lower panel) bias have been decreased (maximum reduction is 2°C).

Vertical profile of shear

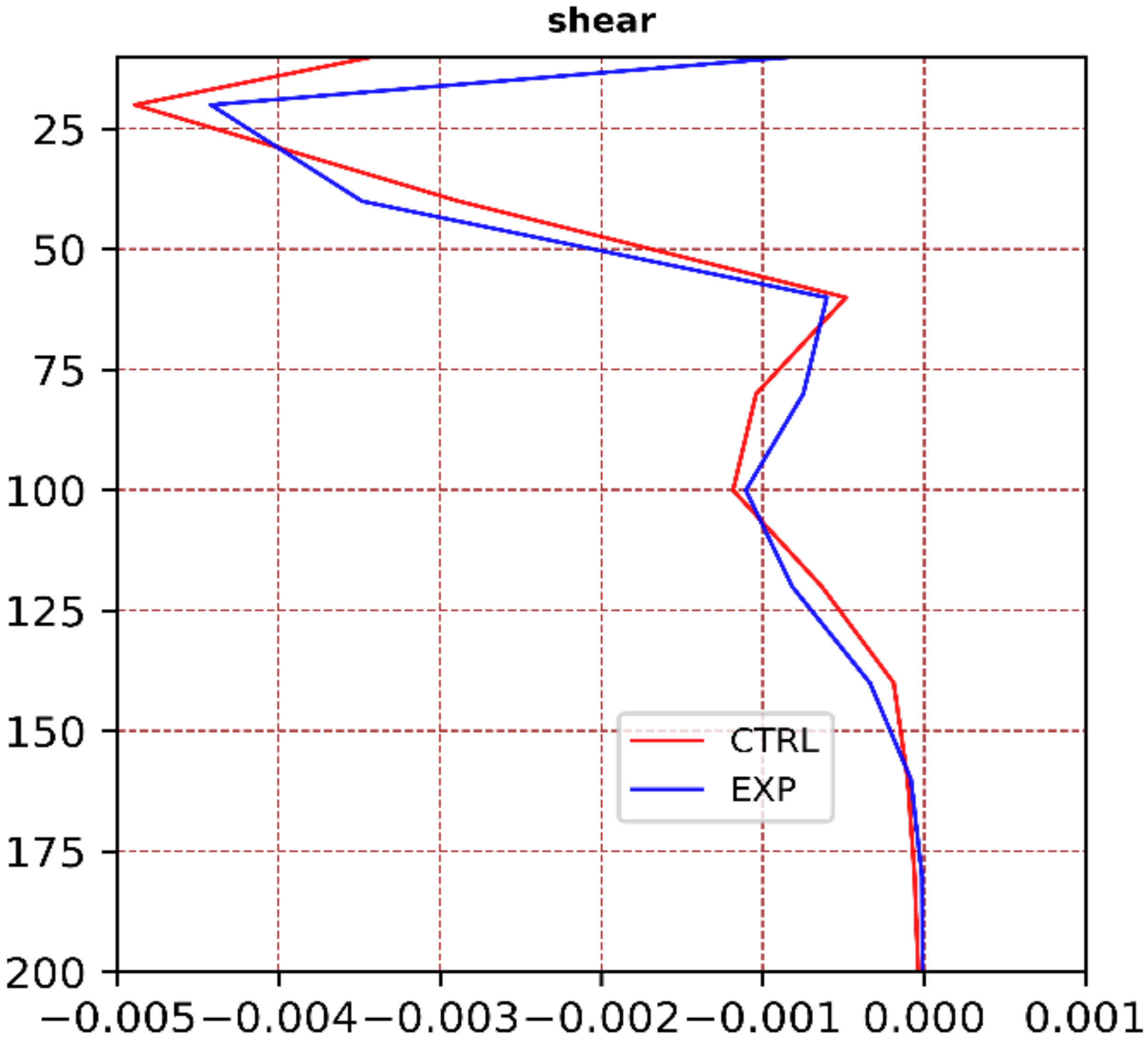
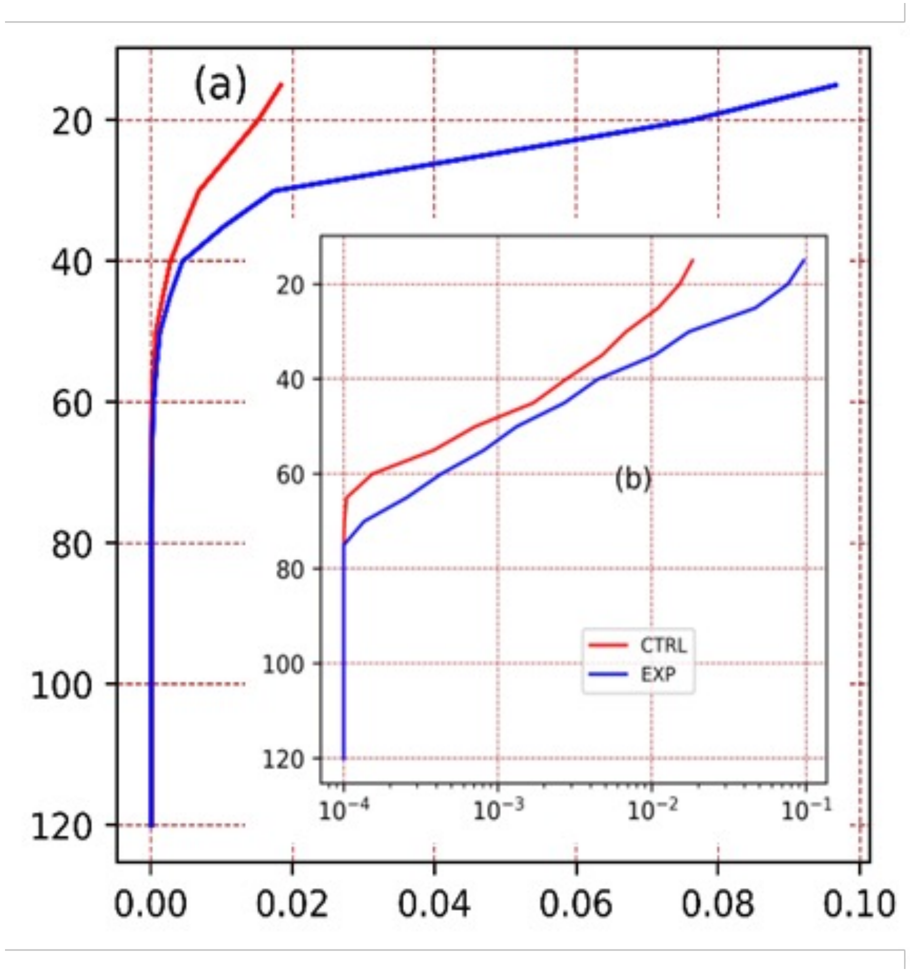
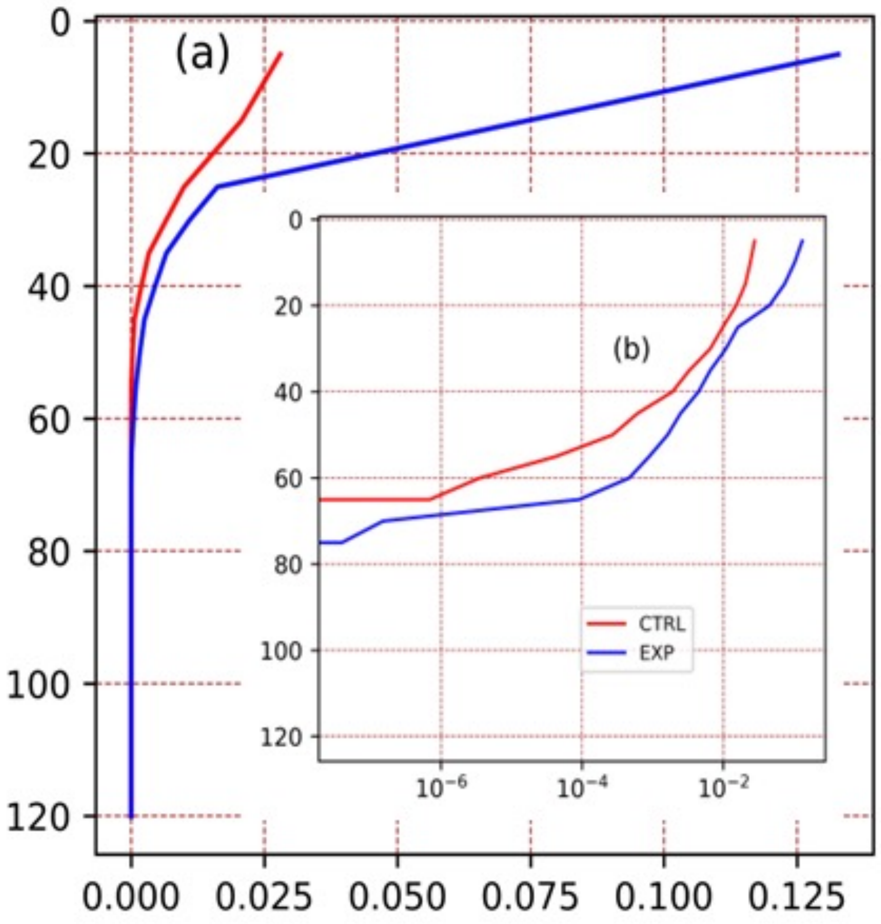


Figure: Vertical profile of shear for CTRL (red line) and EXP (blue line).

- Considering the modulus value, the shear in the EXP simulation is less than in the CTRL simulation within the upper 30 meters.
- The shear increases in the EXP simulation up to 60 meters and then is again underestimated in the EXP simulation compared to the CTRL simulation up to 100 meters.

Vertical profiles of diffusivity & viscosity





- The temperature diffusivity and momentum viscosity is higher up to 80m which is a representation of enhancing of upper ocean turbulence due to the LT.

Figure: (a)Vertical profile of momentum viscosity (kg/m^2, left panel) and temperature diffusivity (kg/m^2, right panel); (b) same with logarithmic scale in x axis. Red and blue lines consecutively signify for CTRL and EXP.

Revised shape function and vertical velocity scale:

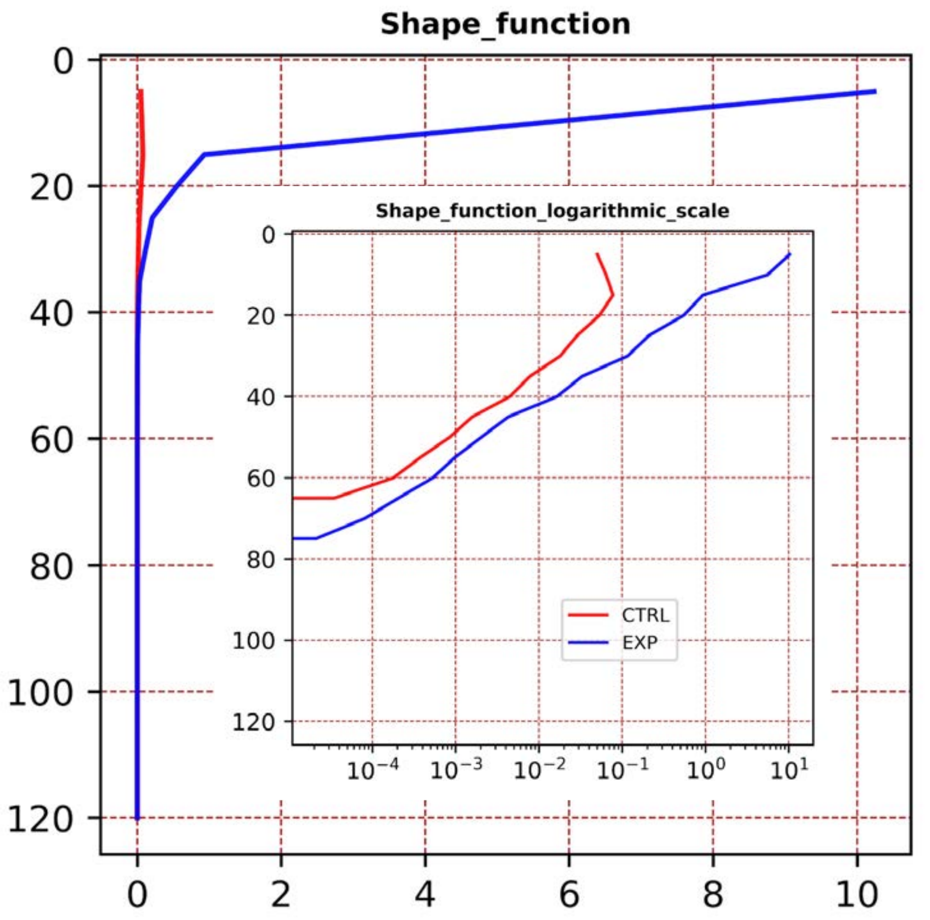


Figure: (a)Vertical profile of shape function from CTRL (3rd order) and EXP (6th order) ;(b) same with logarithmic scale in x axis.

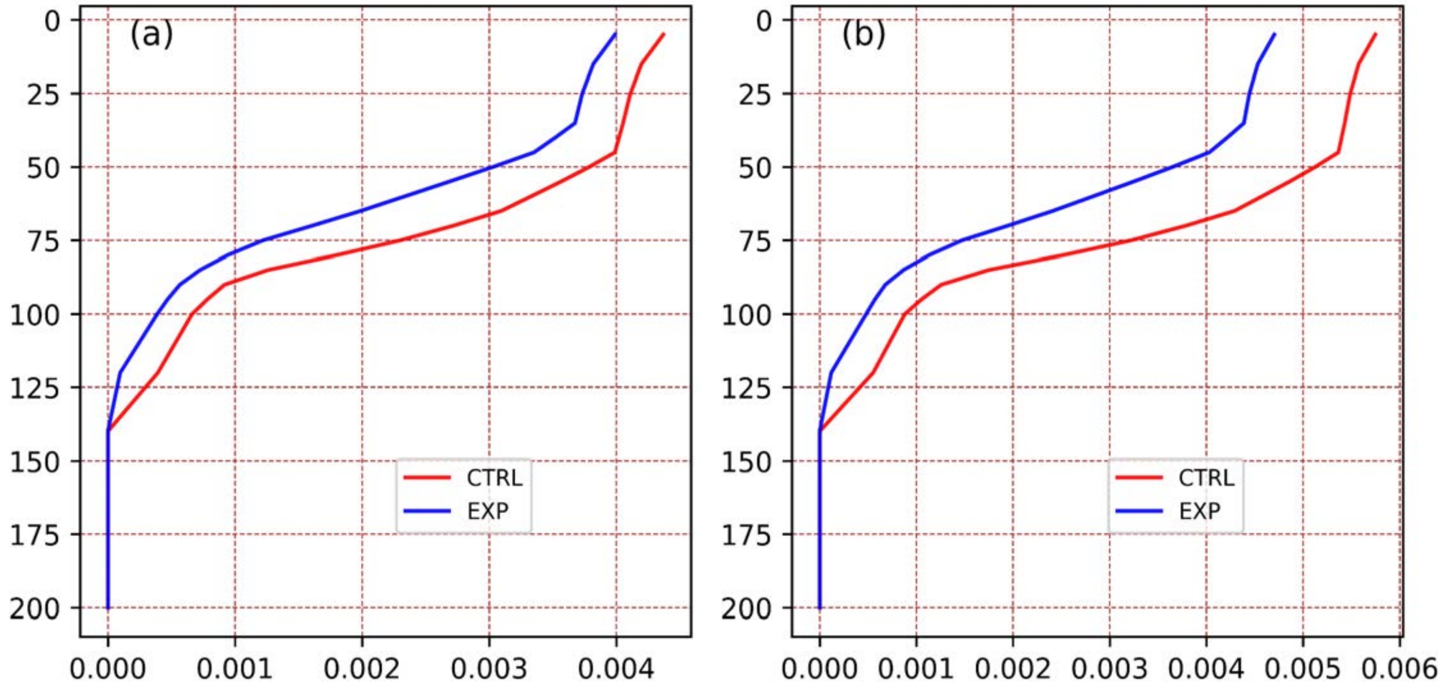


Figure: Vertical profile of wscale of the (a) momentum and (b) scalar fields

- **The sixth order shape function enhanced from cubic up to 80m.**
- **The vertical velocity scale profile which is the representation of turbulence profile in upper ocean is presents the turbulence properly.**

- **Effect of these two has influenced the upper ocean shear profile and the shear has been decreased from the CTRL to the EXP. As a result of it, the overestimation of mixing in the upper ocean has been reduced.**

Concluding Remarks:

- The reduction of biases in the upper ocean stratification and shear manifest better representation of the upper ocean mixing in the model.
- Leads to better simulation of surface and subsurface temperature and density under the cyclone conditions over the north Indian ocean.
- Overall about 30% reduction (i.e., 0.5 °C) in the subsurface mean warm bias, however in some cases it is 3 °C to 4 °C.
- Study conclude that the overall upper ocean mixing representation has been improved by the more accurate turbulent fluxes and enhancement of vertical velocity scale profile inside KPP lead to better representation of the thermohaline structure during Northern Indian Ocean cyclone time.

Acknowledgements:

- Convenor of OMDP Commodore workshop, 2024 for accepting to present this research work.
- WMO and CLIVAR for all the travel and other supports
- IITM, Pune for funding research grant.
- Both of my guides for thoroughly supervising


Thank you . . .