Study of inter-annual variability of BoB mixing and Barrier layer using an Ocean Dynamic Thermodynamic Model (ODTM)

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Contents

- ➢Design and validation of an Ocean Dynamic Thermodynamic Model (ODTM) for the tropical ocean studies

- ➢Basic formulation of dynamical and physical core, numerical implementation

- ➢Validation of the model: Tropical Indian Ocean

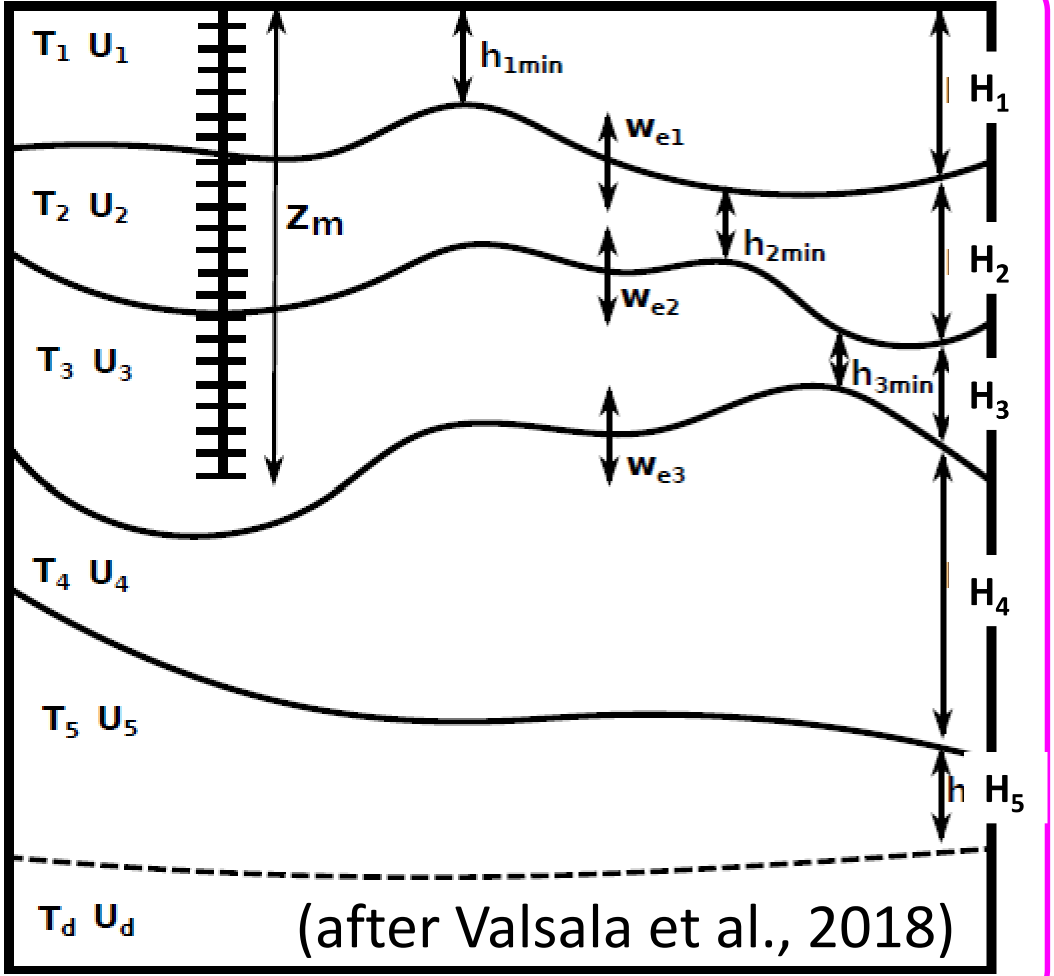
- ➢A case study of Bay of Bengal mixing and barrier layer formation using ODTM: A few new insights

Introducing Thermodynamic term to Reduced gravity models: Design of ODTM

- The basic structure of ODTM

- Dynamic core is same as in Valsala (2009), Valsala and Rao (2016), but modified with Thermodynamic terms

- It also incorporates a fine vertical mixing module, penetrating first few layers at very high resolution.



(after Valsala et al., 2018)

Introducing Dynamic height pressure gradient to Reduced gravity model: Design of ODTM

Free surface term

Overhead pressure term

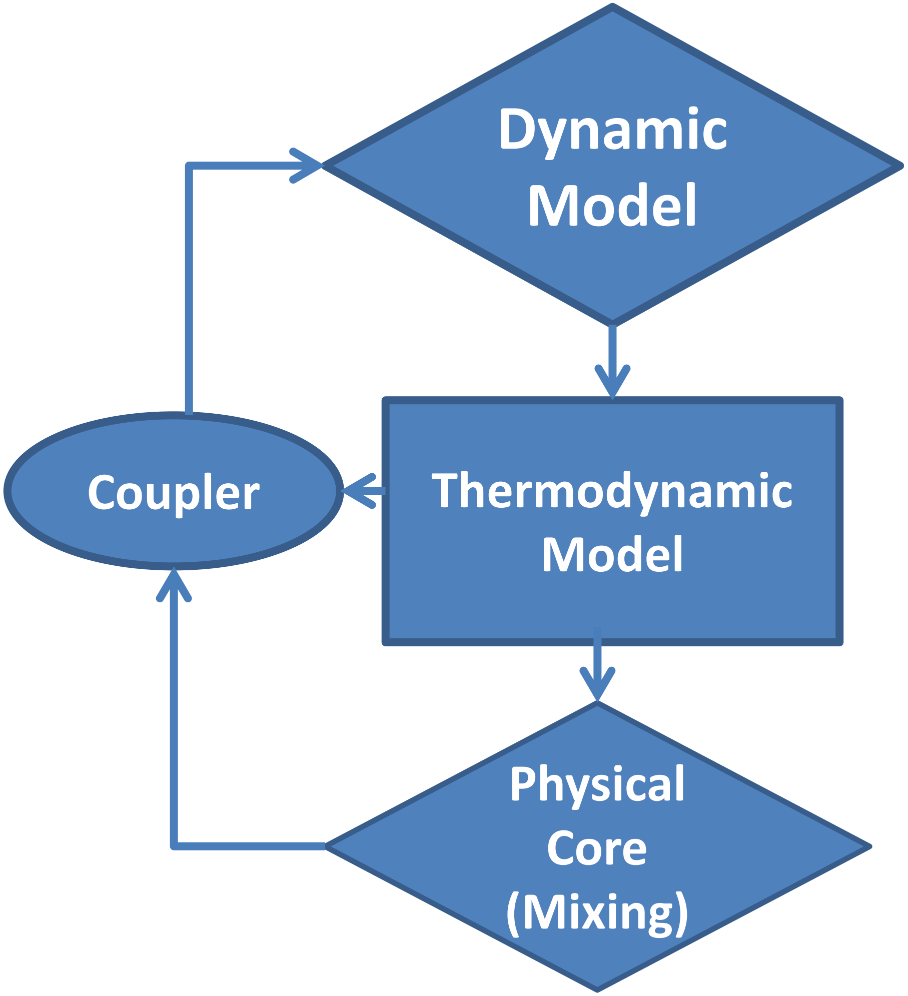
$$\nabla P = \boxed{g\rho_k \Sigma_{i=1}^{N-1} \left[\frac{\rho_N - \rho_i}{\rho_N}\right] \nabla H^i} - \boxed{g\Sigma_{i=1}^{k-1}(\rho_k - \rho_i)\nabla H^i}$$

$$+ \boxed{\rho_k g \Sigma_{i=k}^{N-1} H^i \nabla_{\mathrm{H}} \left[\frac{\rho_N - \rho_i}{\rho N}\right]}$$

Dynamic height term

- ➢ Under the approximation $\frac{\rho_{k-1}}{\rho_k} \approx 1$
- ➢ $\rho_k = \rho_0 + \alpha_T[T_k - T_0] + \beta_S[S_k - S_0]$ Valsala et al., (2018)

ODTM flow-chart

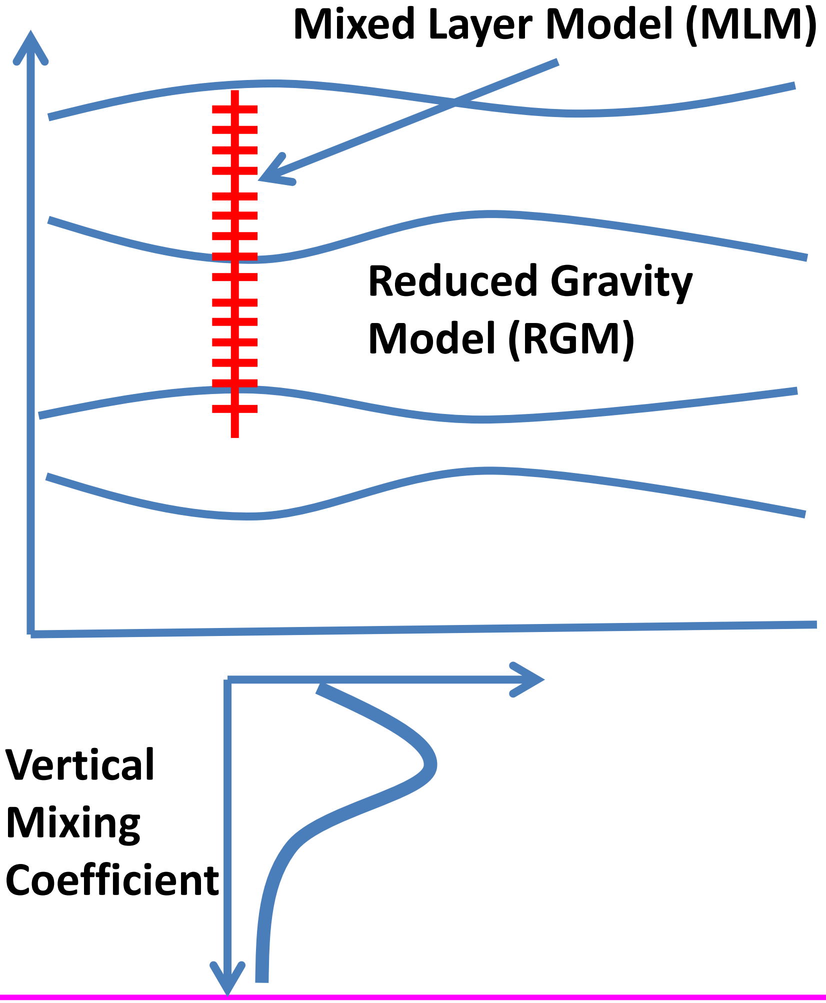


Dynamic Model

Thermodynamic Model

Coupler

Physical Core (Mixing)



Mixed Layer Model (MLM)

Reduced Gravity Model (RGM)

Vertical Mixing Coefficient

The complete equations of ODTM

Tracer (layer average T_k, S_k, and mixed layer model T_m and S_m)

$$\frac{\partial T_k}{\partial t} + \delta \nabla_H (U_k^{i,j} T_k) - A_{HRG} \nabla_H^2 T_k = \boxed{\alpha \frac{\partial \bar{T}'_m}{\partial t};} \qquad \delta = \begin{cases} 0 & \text{if } 0 \leq \mathrm{Z} \leq \mathrm{Z}_m \\ 1 & \text{if } \mathrm{Z} > \mathrm{Z}_m \end{cases} \tag{3}$$

$$\frac{\partial T_m}{\partial t} + \boxed{\beta \nabla_H (U_k^{i,j} T_m)} - A_{HML} \nabla_H^2 T_m = \frac{\partial}{\partial z} K_H \frac{\partial T_m}{\partial z} - \boxed{\gamma w_{e(m)} \frac{\partial T_m}{\partial z}} + \varepsilon \frac{I_z - I_{z-1}}{dz \rho_m C_p};$$

$$K_H \frac{\partial T_m}{\partial z} = \begin{cases} -\frac{Q}{dz\,\rho C_p} & \text{at z = 0 for temperature} \\ -\frac{(E-P) S_{ref}}{\rho_m} & \text{at z = 0 for salinity} \end{cases} \tag{4}$$

$$\epsilon = \begin{cases} 1 & \text{for temperature} \\ 0 & \text{for salinity} \end{cases}$$

□: Coupling term

The complete equations of ODTM

Momentum (layer average U_k, V_k, and mixed layer model U_m and V_m)

$$\frac{\partial U_k^{i,j}}{\partial t} + \nabla_H (U_k^{i,j} U_k^{j,i}) - A_{MRG} \nabla_H^2 U_k^{i,j} = -\frac{\nabla_H P_k}{\rho_k} - 2\Omega \times U_k^{j,i} + \frac{\tau^{i,j}}{\rho(1)} + \boxed{\alpha \frac{\partial \bar{U}_m^{\prime (i,j)}}{\partial t}} \qquad (5)$$

$$\frac{\partial U_m^{i,j}}{\partial t} + \boxed{\beta \nabla_H (U_k^{i,j} U_m^{j,i})} = \frac{\partial}{\partial z} K_m \frac{\partial U_m^{i,j}}{\partial z} - \boxed{\gamma w_{e(m)} \frac{\partial U_m^{i,j}}{\partial z}} - 2\Omega \times U_m^{j,i};$$

$$K_m \frac{\partial U_m}{\partial z} = \left\{ \frac{\tau^{i,j}}{\rho(1)} \text{ at z} = 0 \right. \qquad (6)$$

$$\frac{\partial H_k}{\partial t} + \nabla_H (U_k^{i,j} H_k) = w_{ek} - we_{ek-1} \qquad (7)$$

$$w_{ek} = \frac{(H_k - H_{min(k)})^2}{\tau_e H_{kmin}} \theta_{(H_{min(k)} - H_k)}; \qquad \theta = \begin{cases} 1 & \text{if } H_k \leq H_{kmin} \\ 0 & \text{if } H_k > H_{kmin} \end{cases} \qquad (8)$$

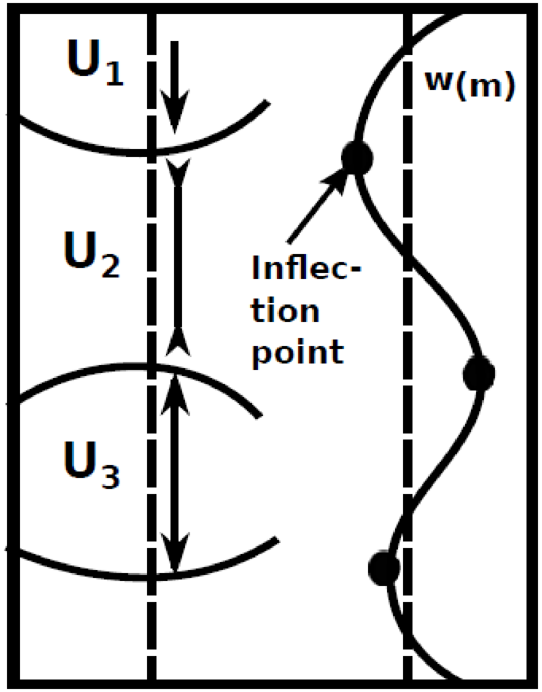
☐: Coupling term

Treatment for Entrainment velocity: Confluence of interface undulations and baroclinic inflections

$$w_{ek} = \frac{(H_k - H_{min(k)})^2}{\tau_e H_{kmin}} \theta_{(H_{min(k)} - H_k)}; \qquad \theta = \begin{cases} 1 & \text{if } H_k \leq H_{kmin} \\ 0 & \text{if } H_k > H_{kmin} \end{cases}$$

$$\sum_{m=z_1}^{m=z_2} w_e(m) = -\nabla_H (U_k^{i,j} H_k); \qquad w_{e(z)} = \begin{cases} \frac{\partial \eta}{\partial t} & \text{at z} = 0 \\ 0 & \text{at z} = Z_m \end{cases}$$

$$0 \leq \alpha \leq 1, \qquad 0 \leq \beta \leq 1, \qquad 0 \leq \gamma \leq 1$$



- ➢Vertical velocity is calculated from convergence/divergence of layers, interpolated to mixed layer model grids at each time step → implying a baroclinic mode in ‘w_e’.

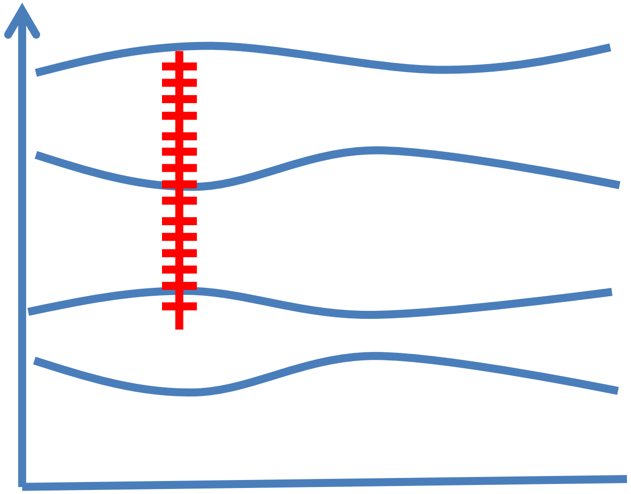
Mixed Layer Model: Level-2 Turbulent Closure Model

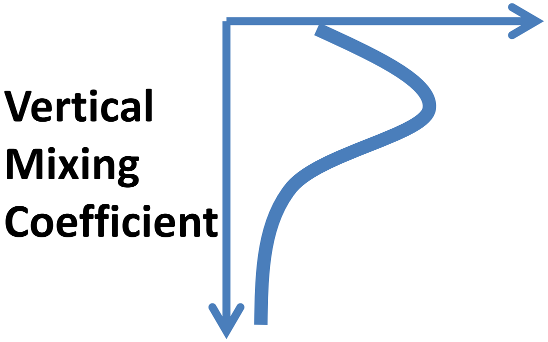
- ➢ ODTM has Mellor-Yamada level 2 mixed layer scheme from Ikeda (1992).

- ➢Mixed layer model has very fine resolution of 5m thickness upto 255m of the upper ocean.

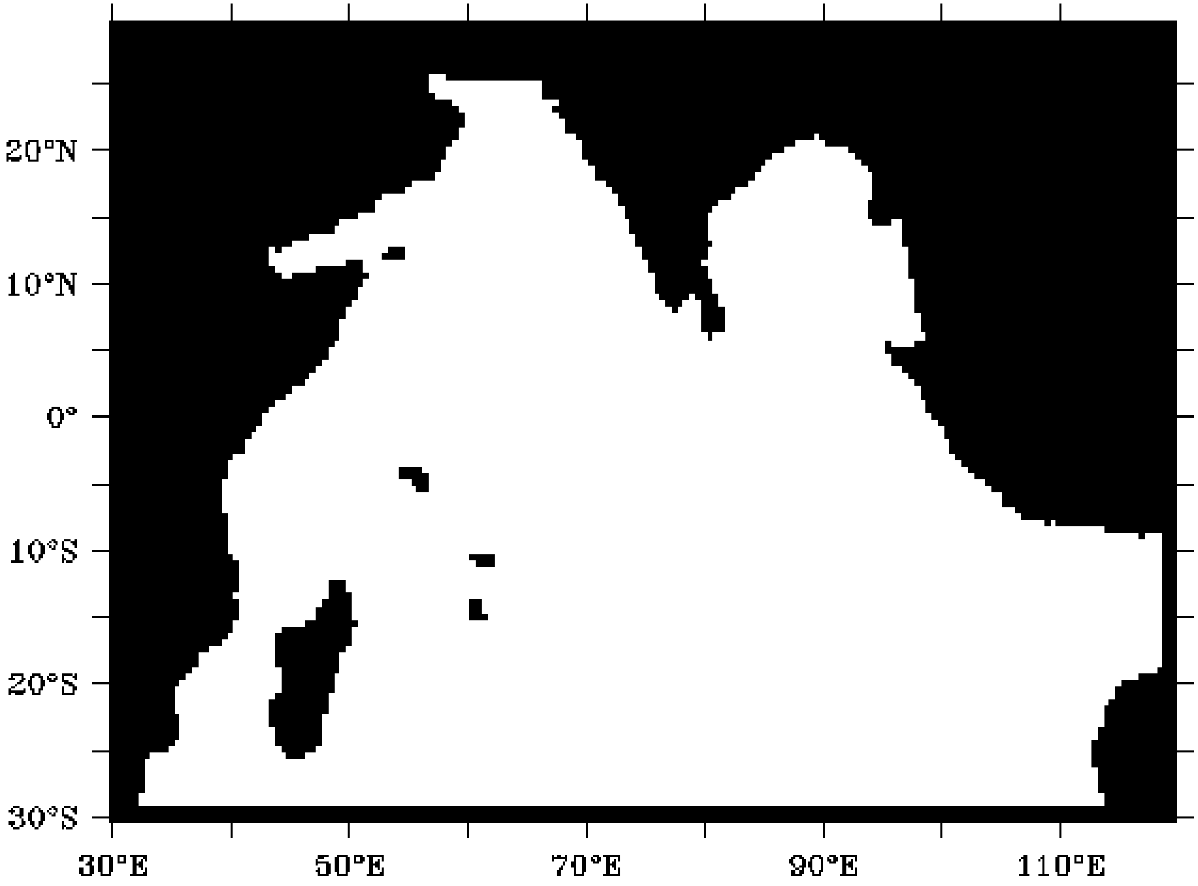
- ➢At each time step the tendency due to mixing (both tracer and momentum) are updated to dynamic model.

- ➢Large scale dynamics advects the mixed layer model horizontally and vertically.





Model domain for test experiment: Indian Ocean

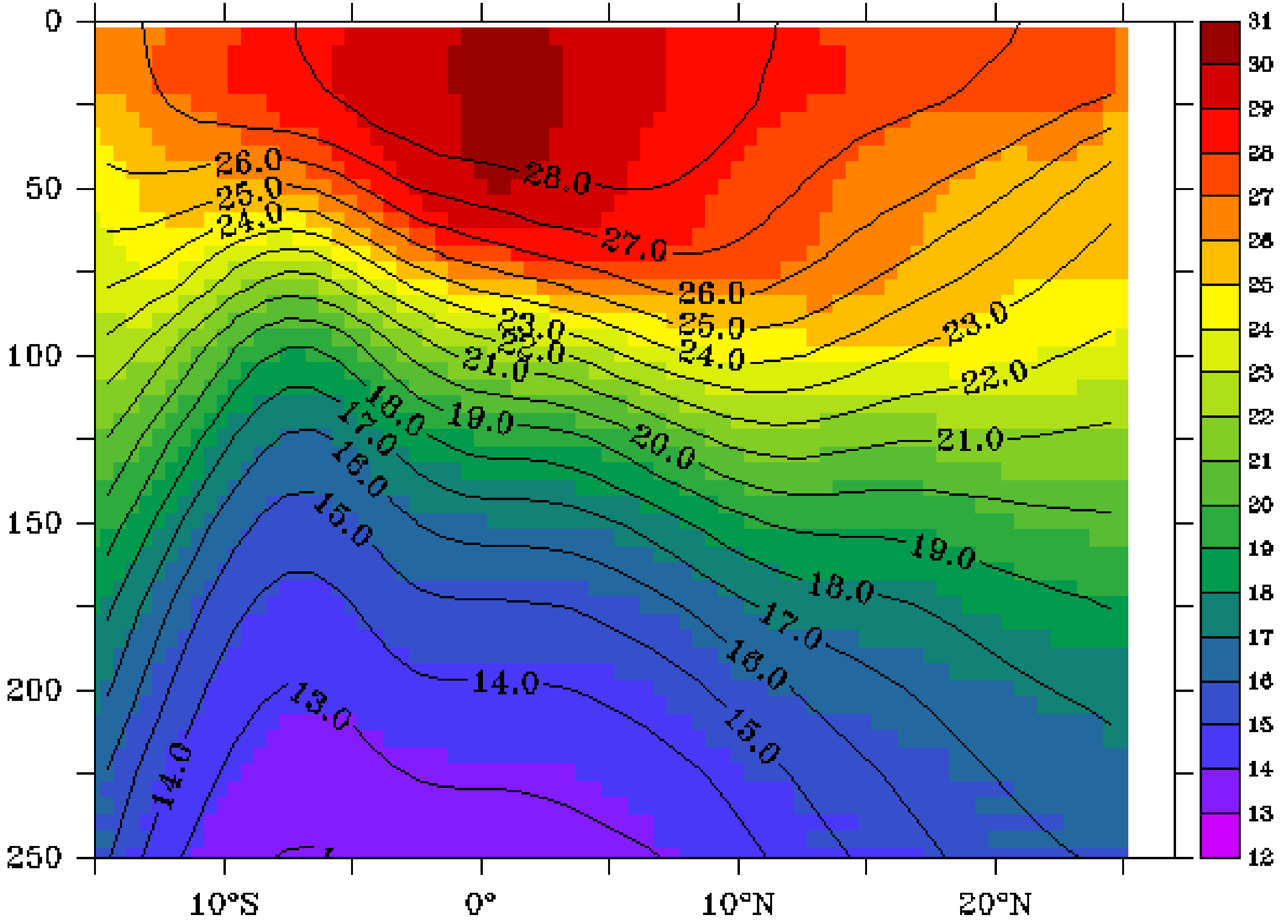


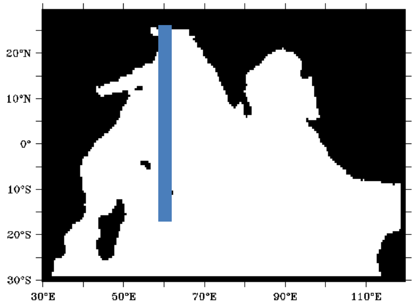
0.5x0.5 resolution

Coastal topography from 200m isobath of ETOPO5

South and East are closed wall with sponging for Temp and Salt to WOA13

Validation of model mean thermal structure from 50 years of simulation

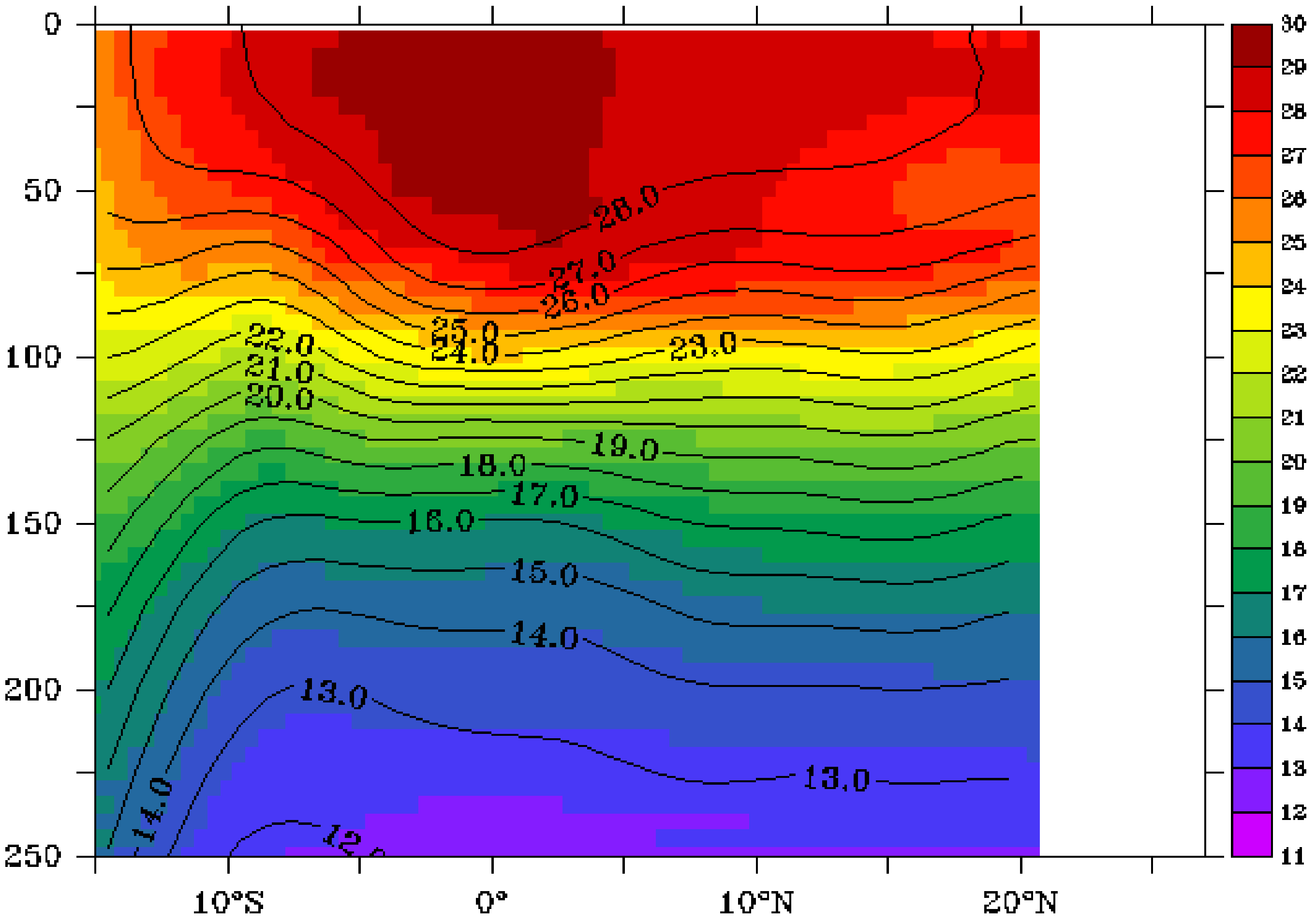


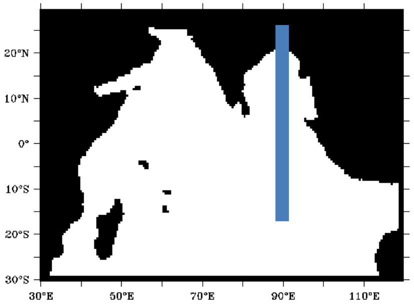


Comparison of mean thermal structure of model (color) with WOA13 (contour).

The thermal structure is maintained very well in the model

Validation of model mean thermal structure from 50 years of simulation





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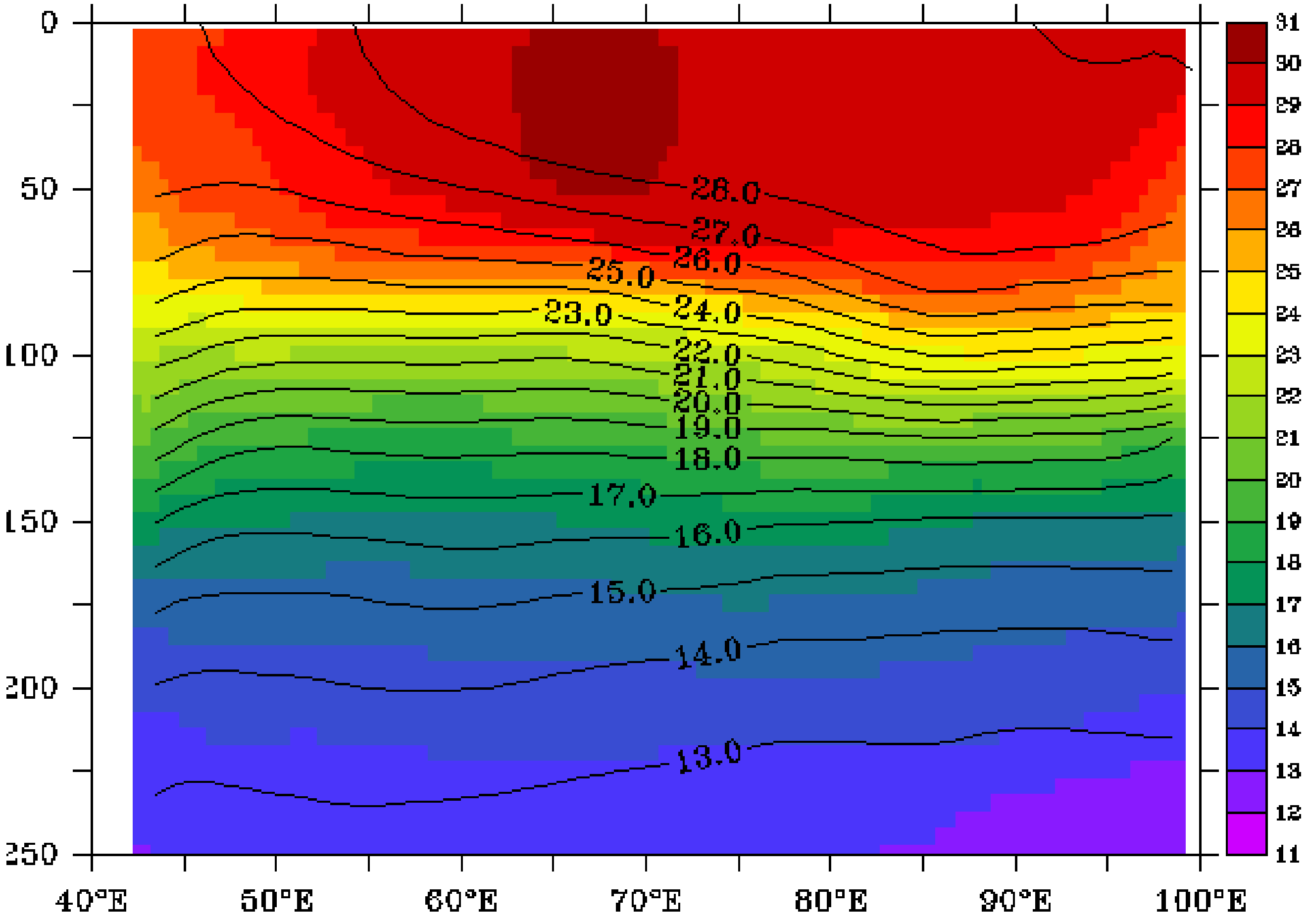

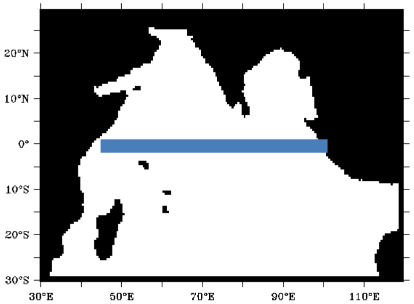

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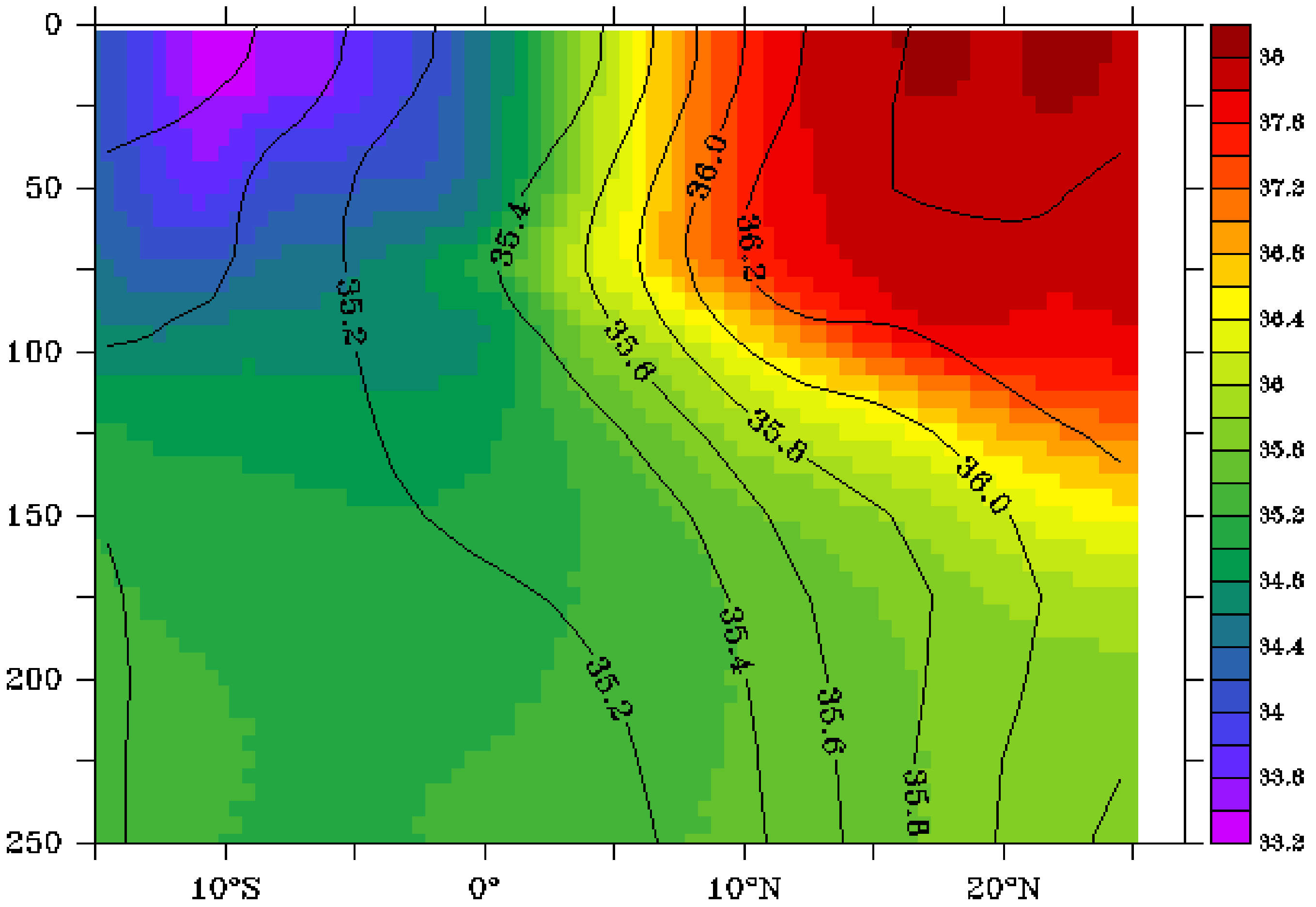
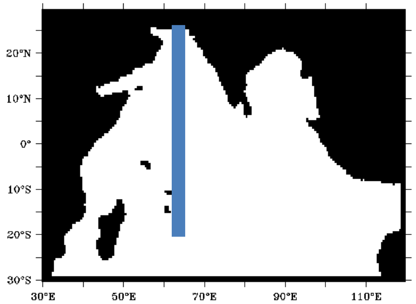
Validation of model mean salinity structure from 50 years of simulation





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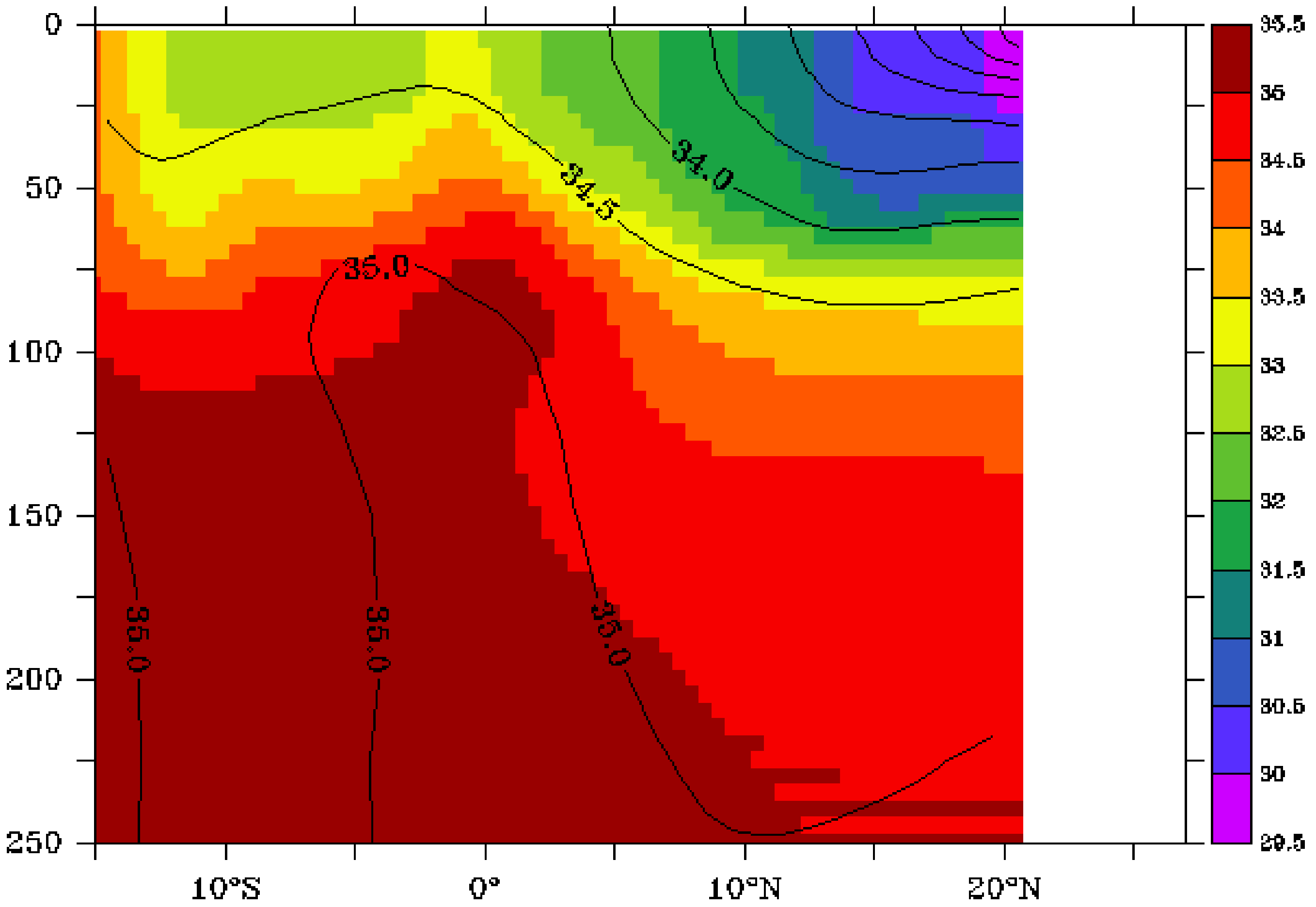

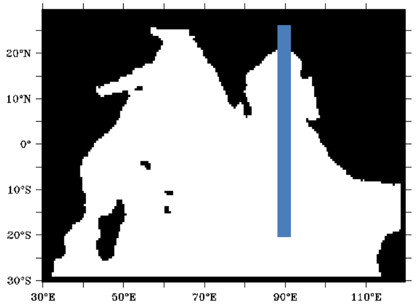

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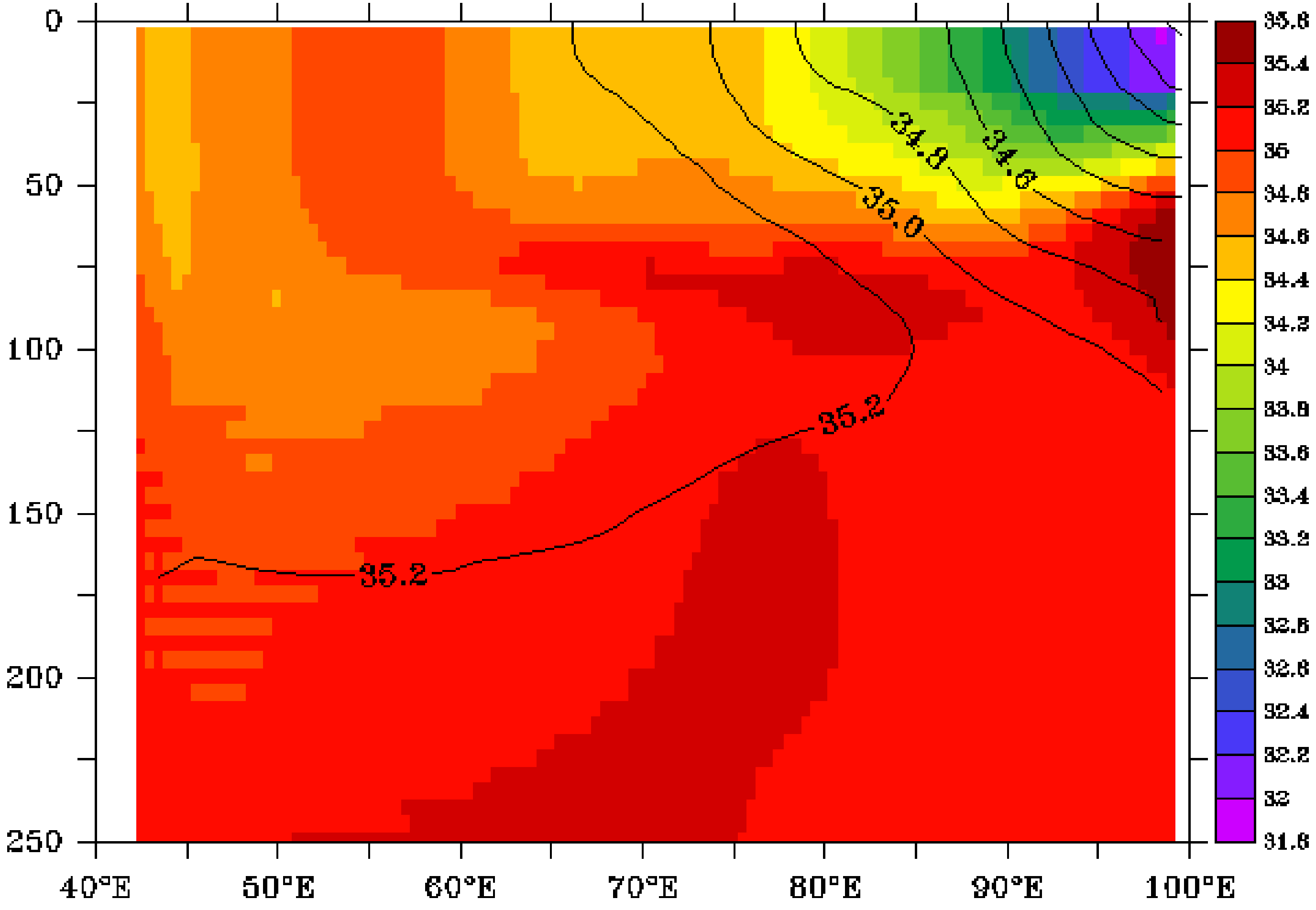

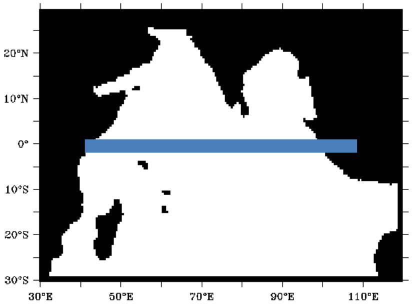

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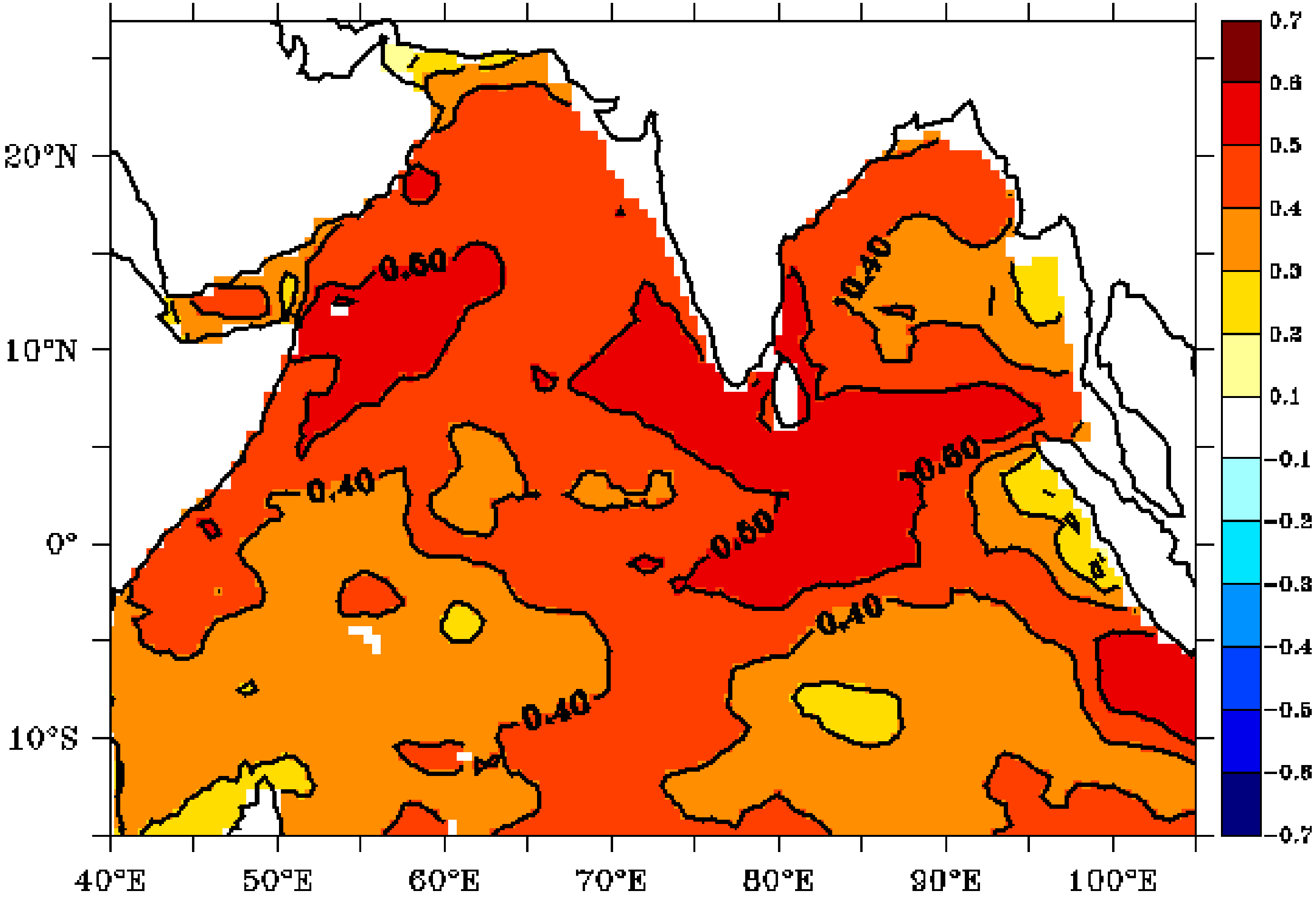
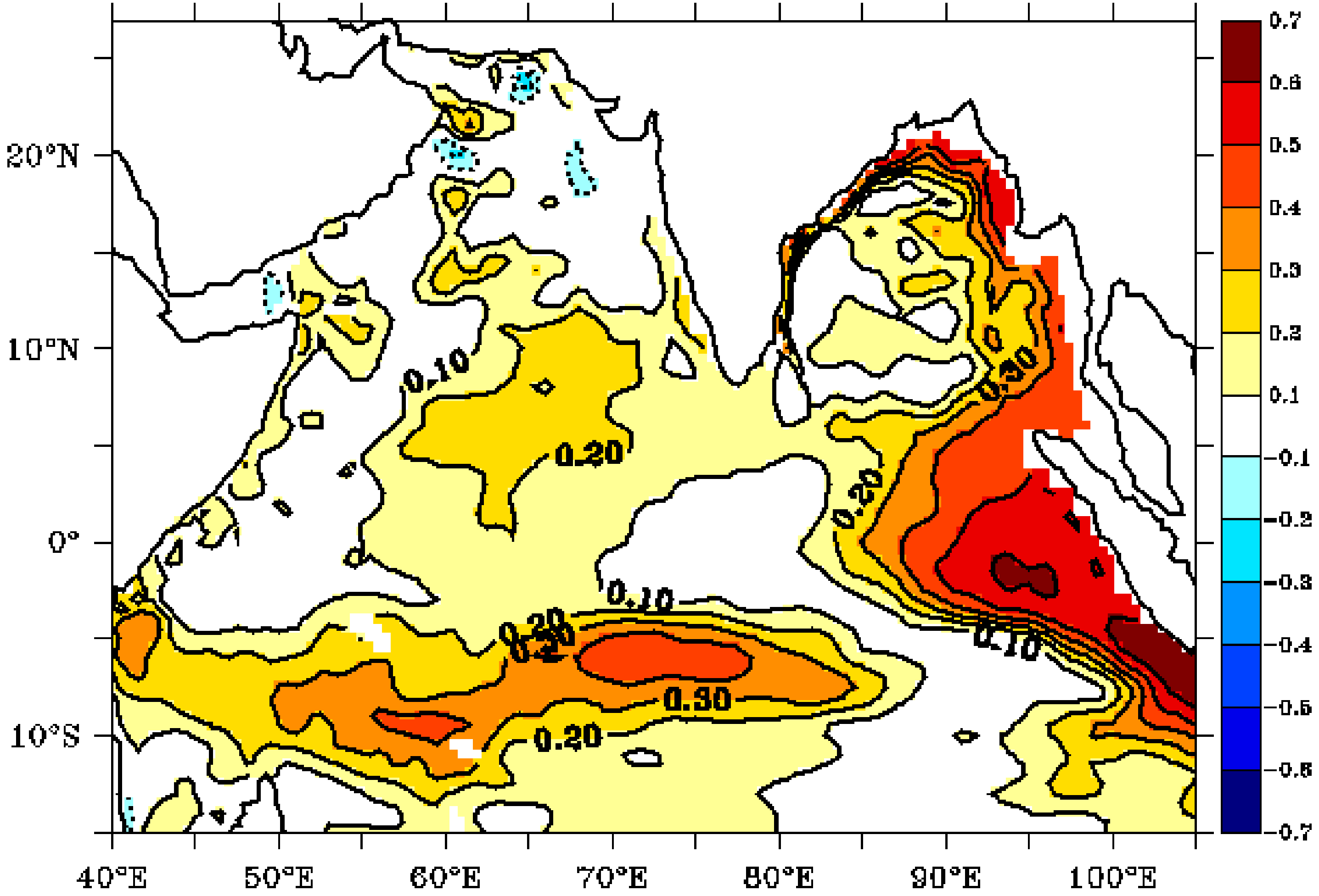
Correlation of 60-years of SST anomalies (1950-2009) between ODTM and HadISST



Monthly anomalies of SSTs between ODTM and HadISST (1950-2009) are correalated above 99% significance throughout the Indian Ocean.

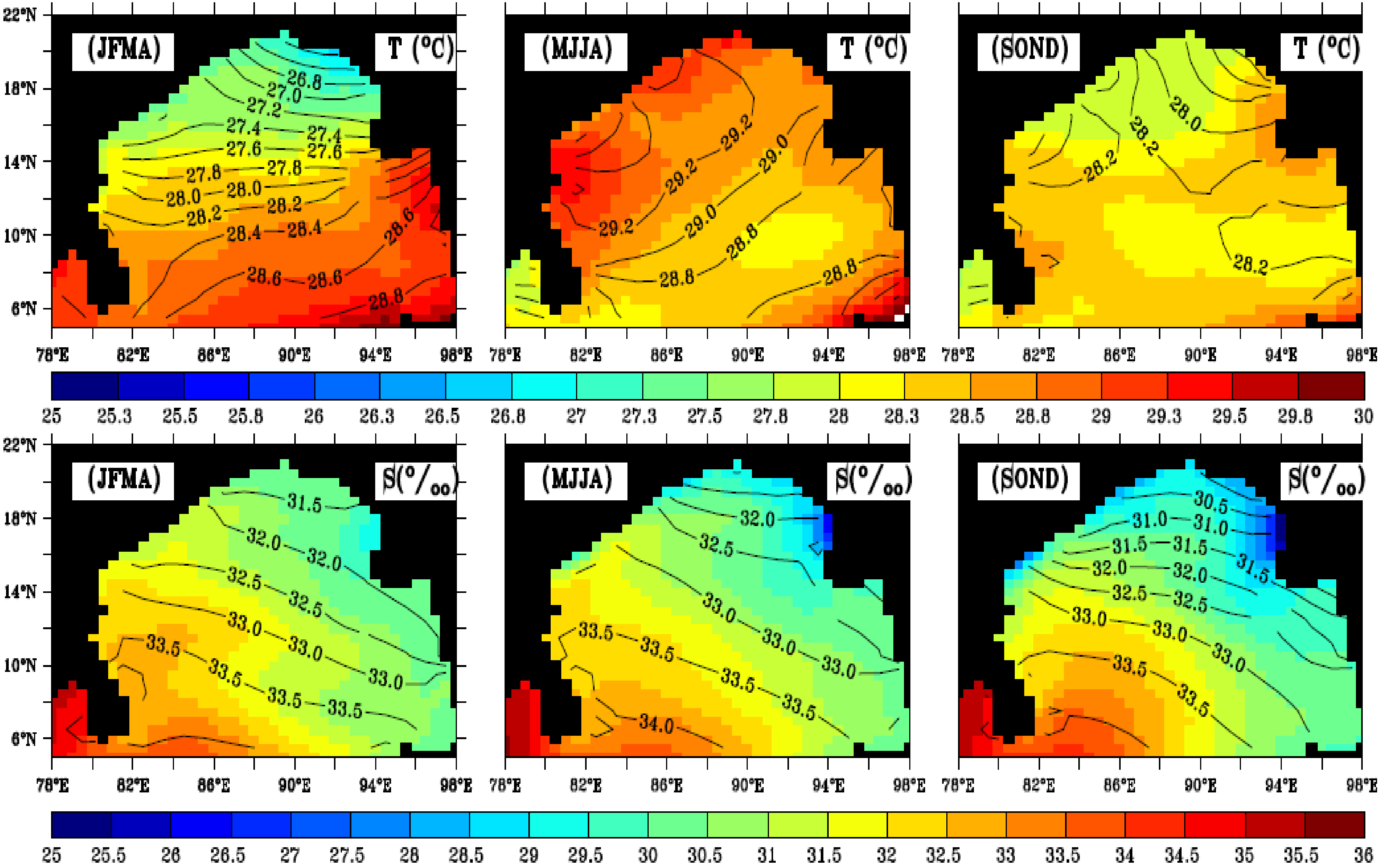
Correlation of 18-years of SSH anomalies (1994-2009) between ODTM and Satellite Obs.



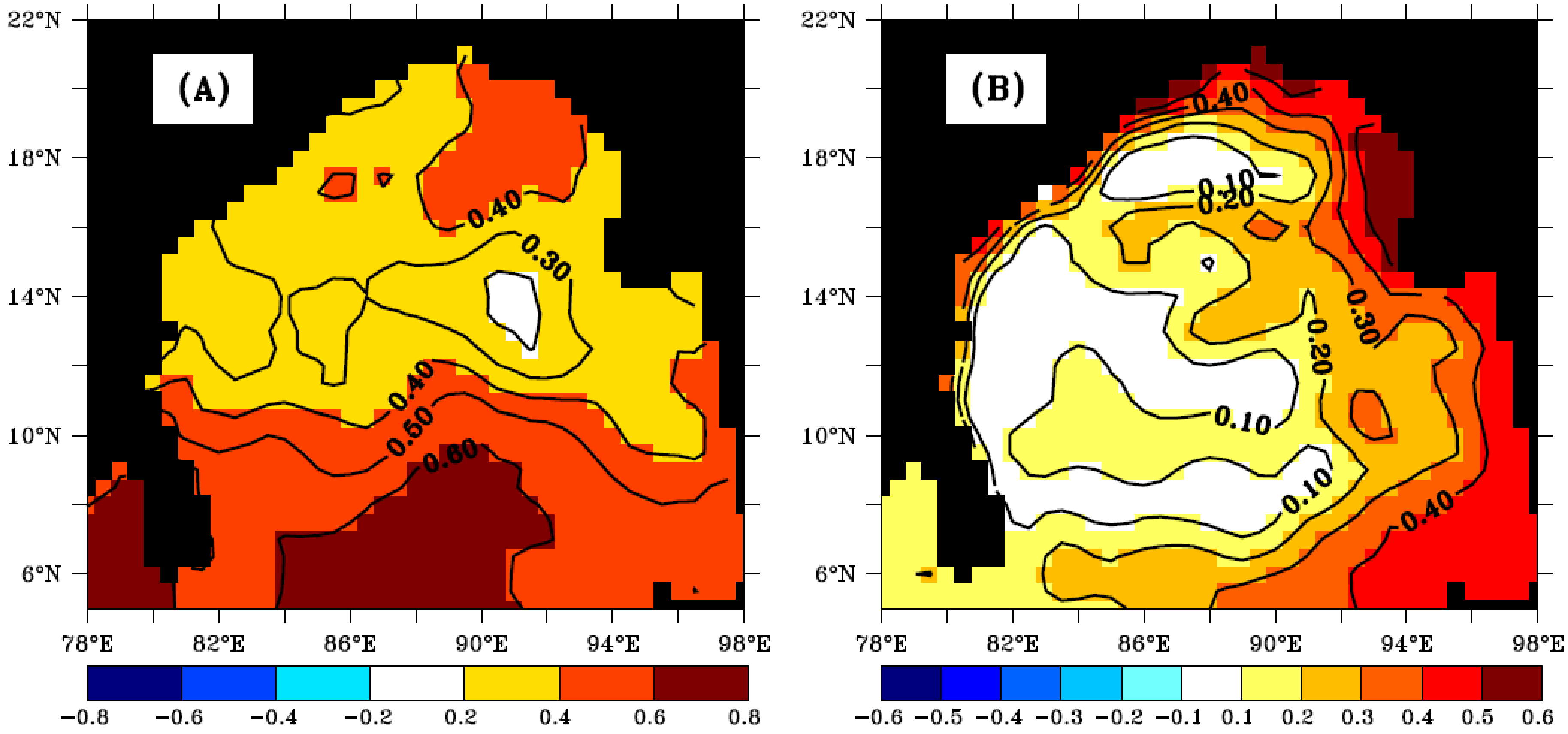
Monthly anomalies of SSH between ODTM and satellite (1993-2009) are correlated well.

SCTR, East Indian Ocean, BoB are very well correlated

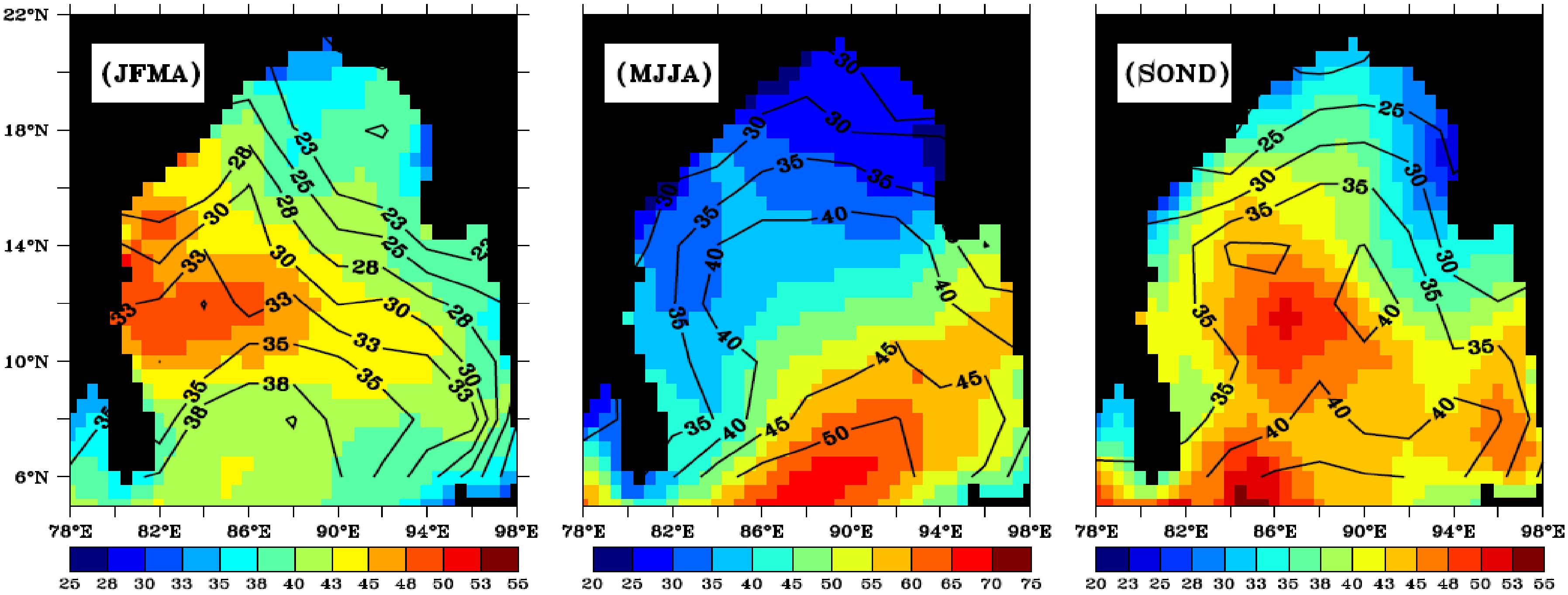
Model SST and SSS (color) and WOA(contour) for BoB



Correlation coefficients between ODTM SST (left) and SSH (right) with observations.

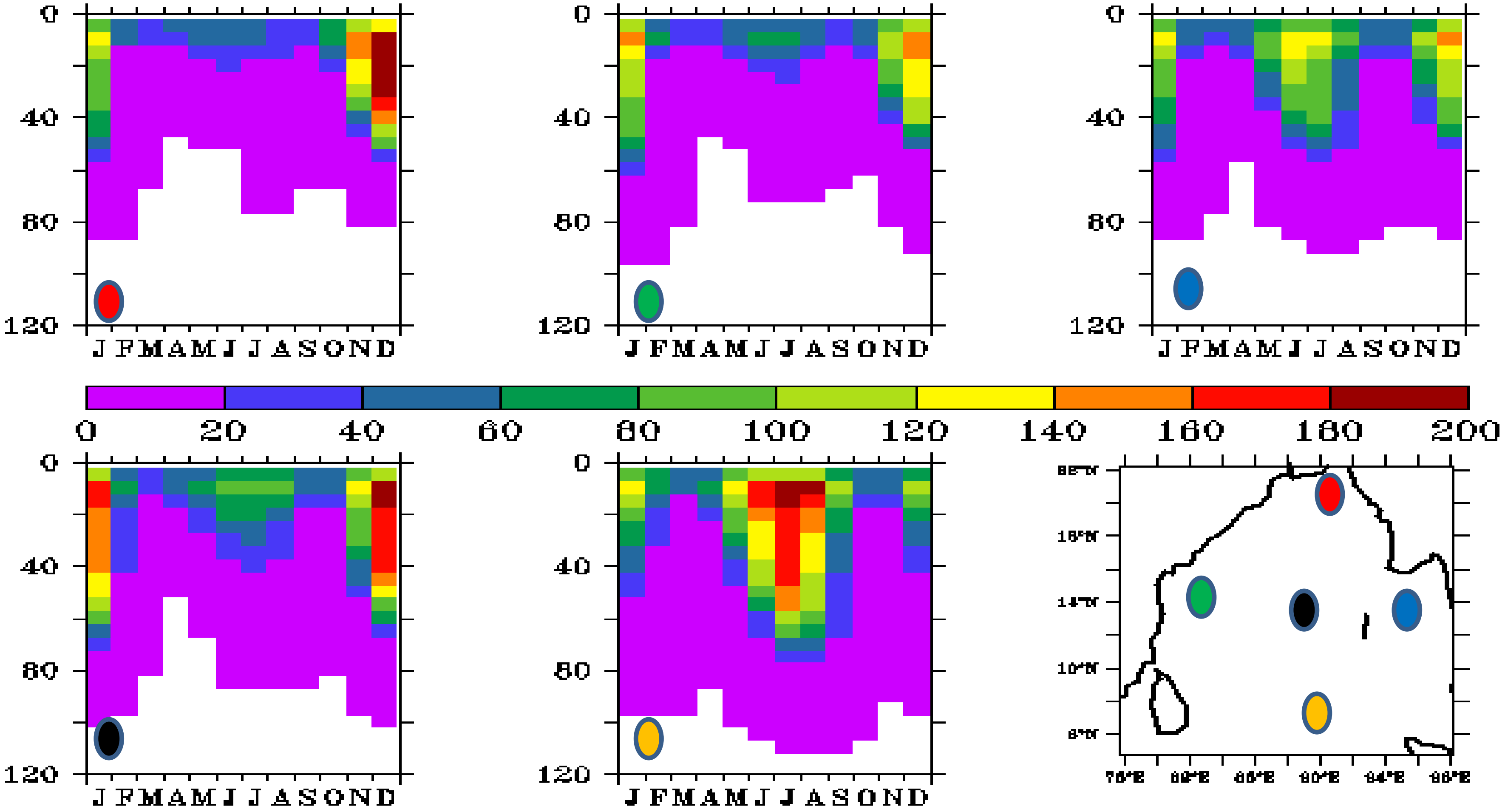


Seasonal Cycle of Mixed Layer Depth from ODTM (shade) and observations (De Boyer et al., 2004)

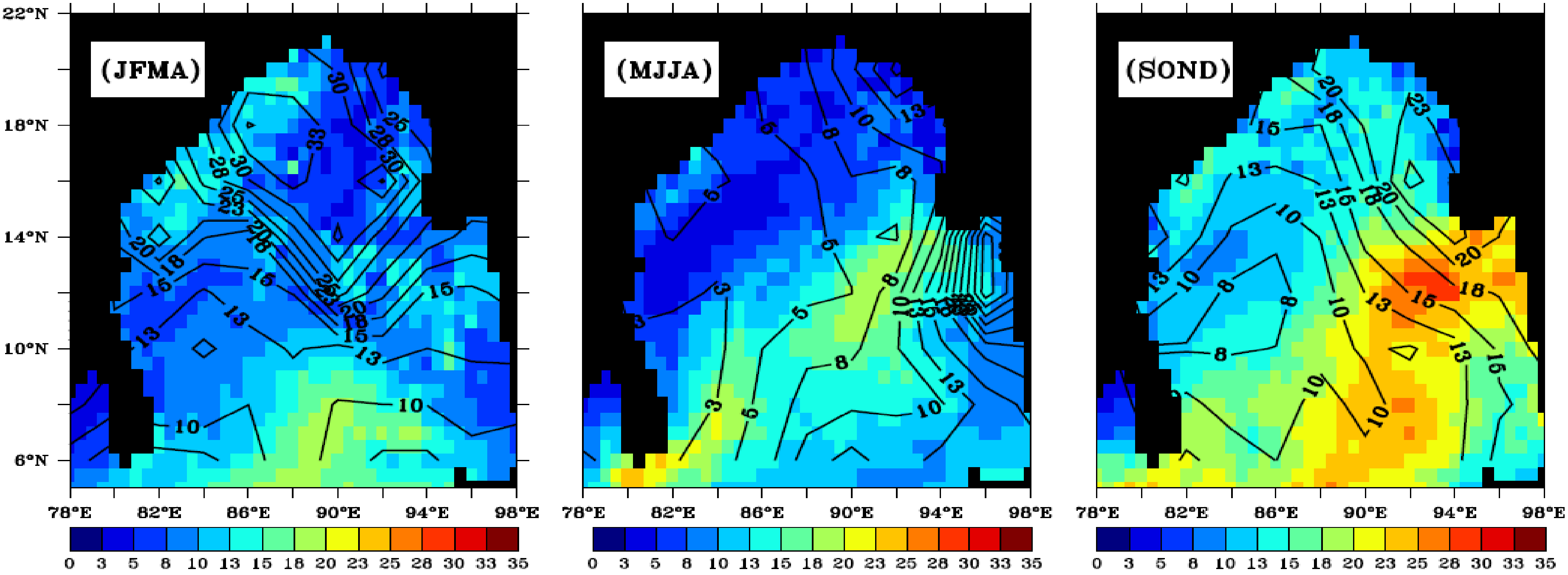


Seasonal evolution of MLD of ODTM is comparable with the observations.

Seasonal cycle of Vertical mixing coefficient of tracers resolved in MY-2 model in ODTM (cm^2 s^{-1})

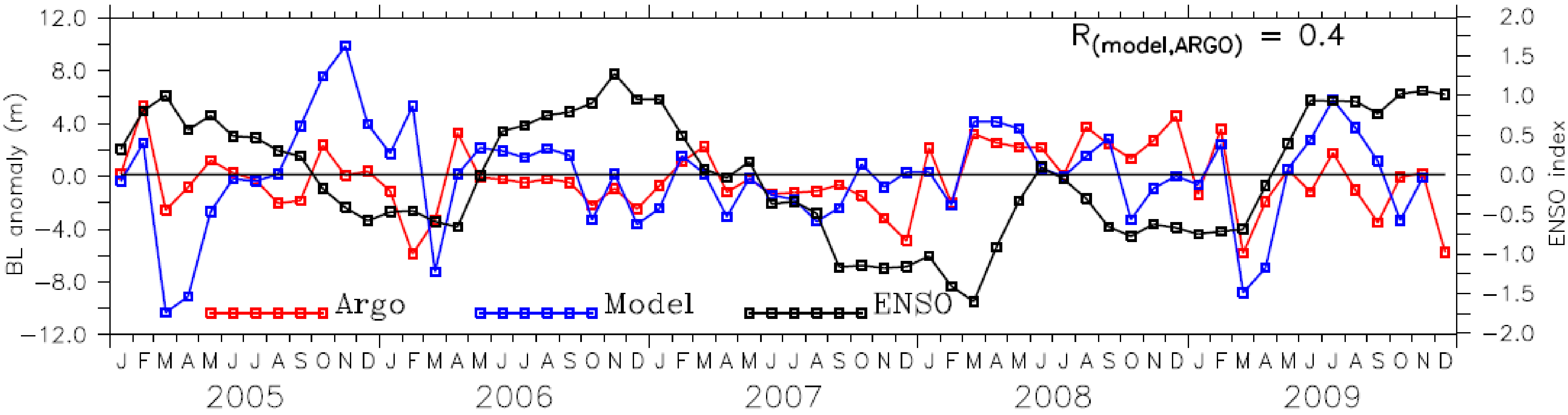


Seasonal cycle of Barrier Layer formation resolved in MY-2 model in ODTM and comparison with observations.



Seasonal evolution of Barrier layer depth of ODTM is comparable with the observations.

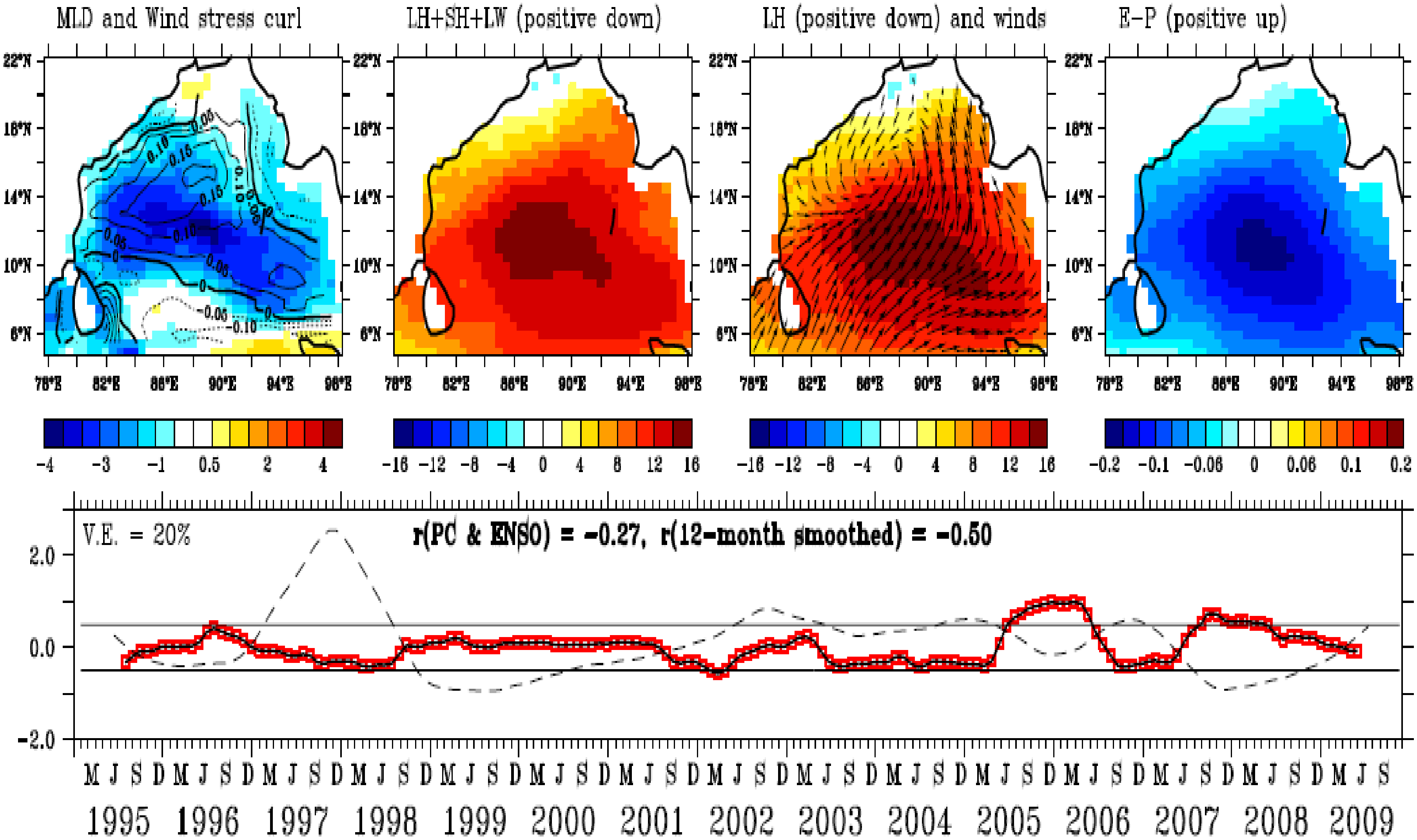
Anomalies of Barrier Layer (BL): Comparison between ODTM and Argo derived BL.



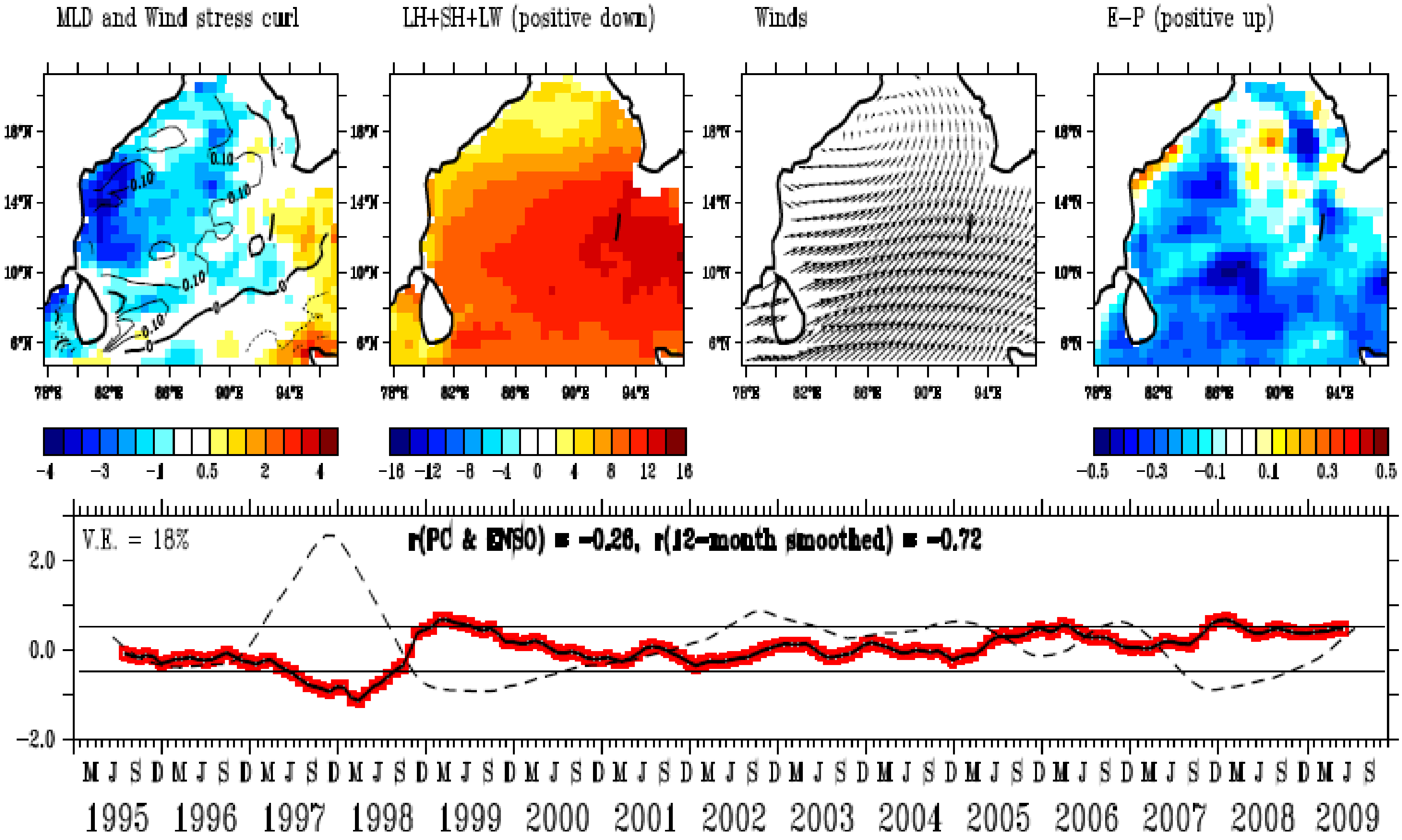
BoB averaged ODTM and Argo derived BL are correlated at above 95% significance confidence level

ODTM BL evolution is reliable compared to the corresponding observations

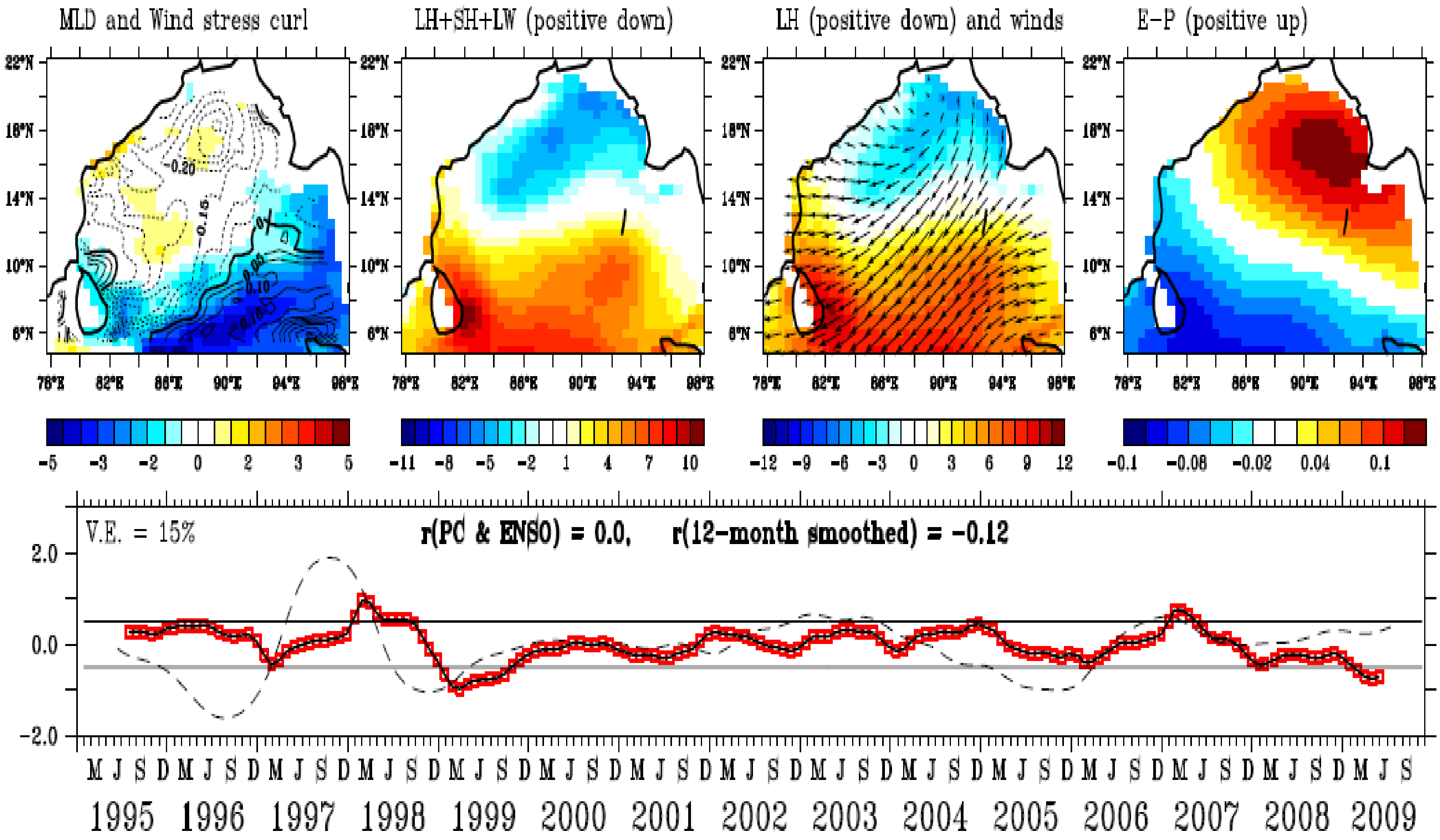
Interannual Variability of MLD and BL is analyzed with C-EOF analysis



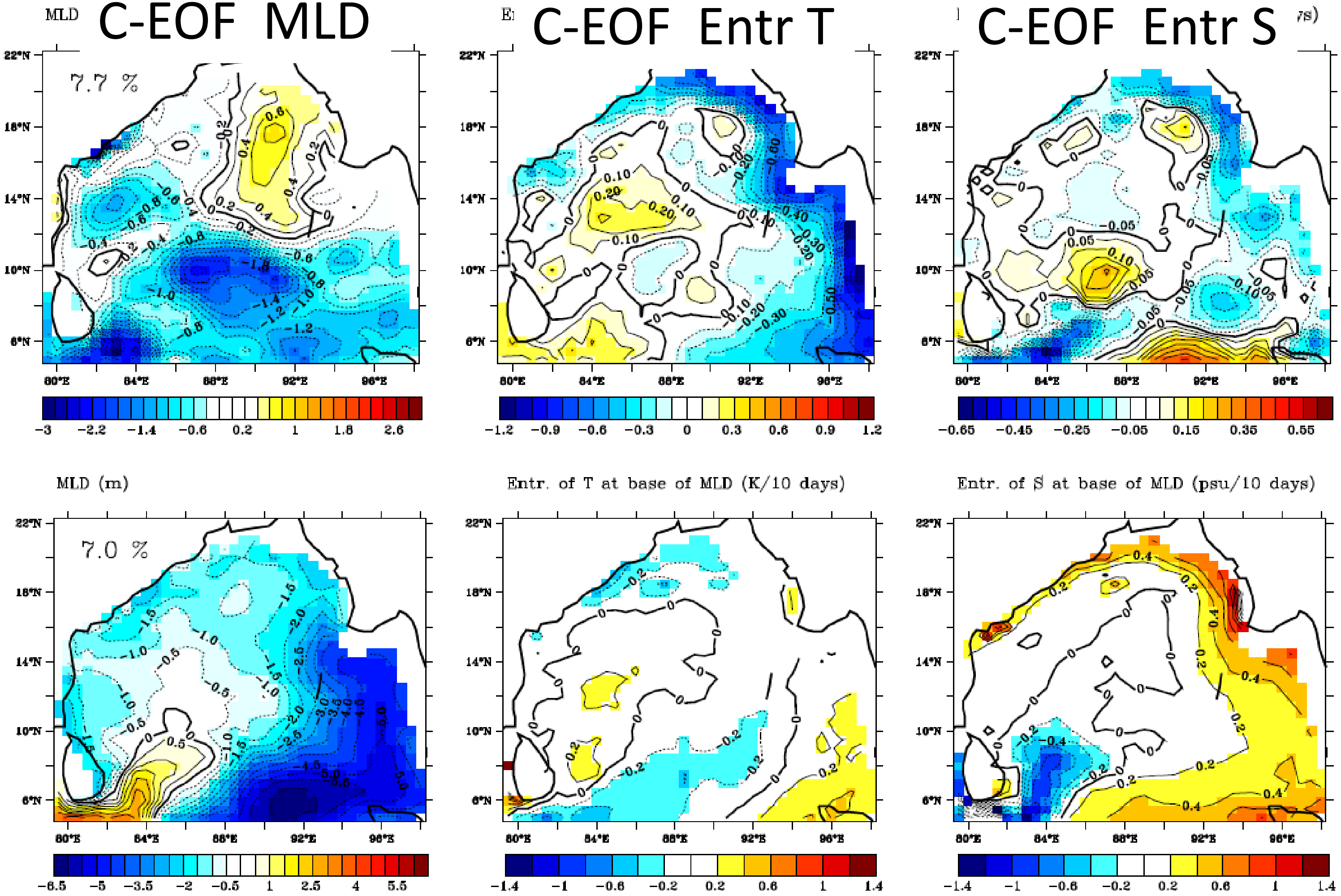
Interannual Variability of MLD and BL is analyzed with C-EOF analysis in SODA



Mechanism of Interannual Variability of BoB MLD: Mode-2 and IOD



Entrainment at base of MLD appears no role in Interannual variability of BoB Mixing



C-EOF MLD

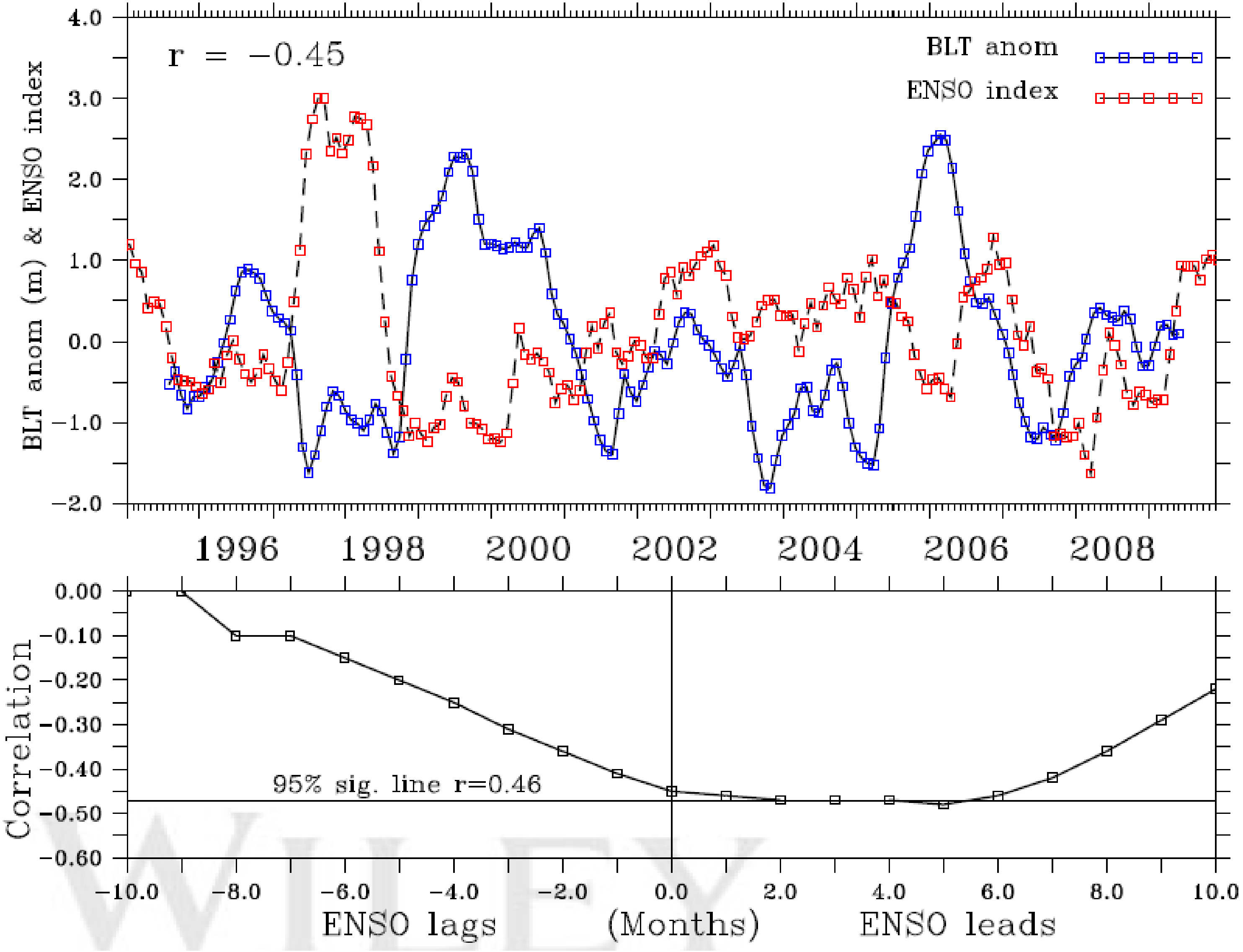
C-EOF Entr T

C-EOF Entr S

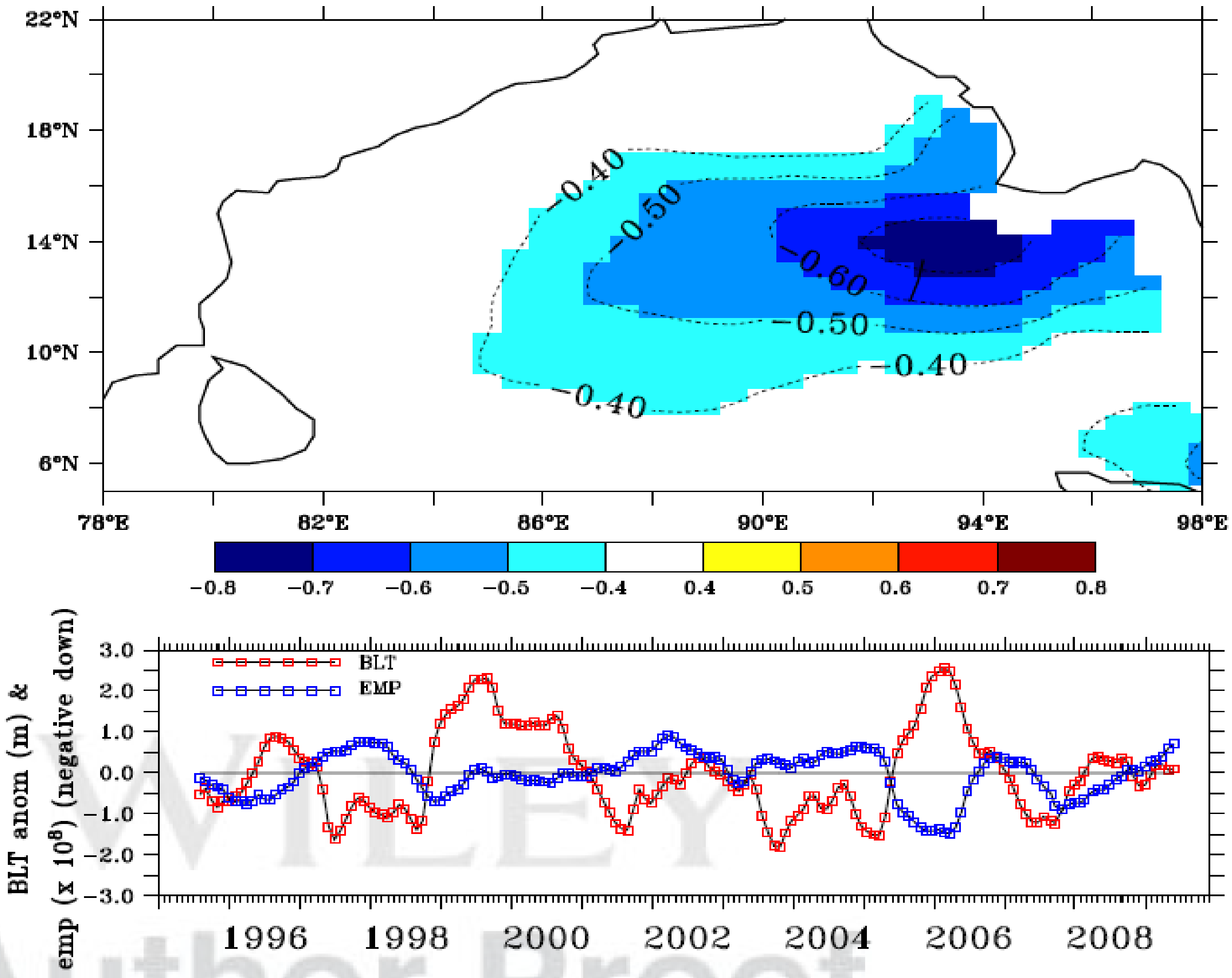
Mode-1

Mode-2

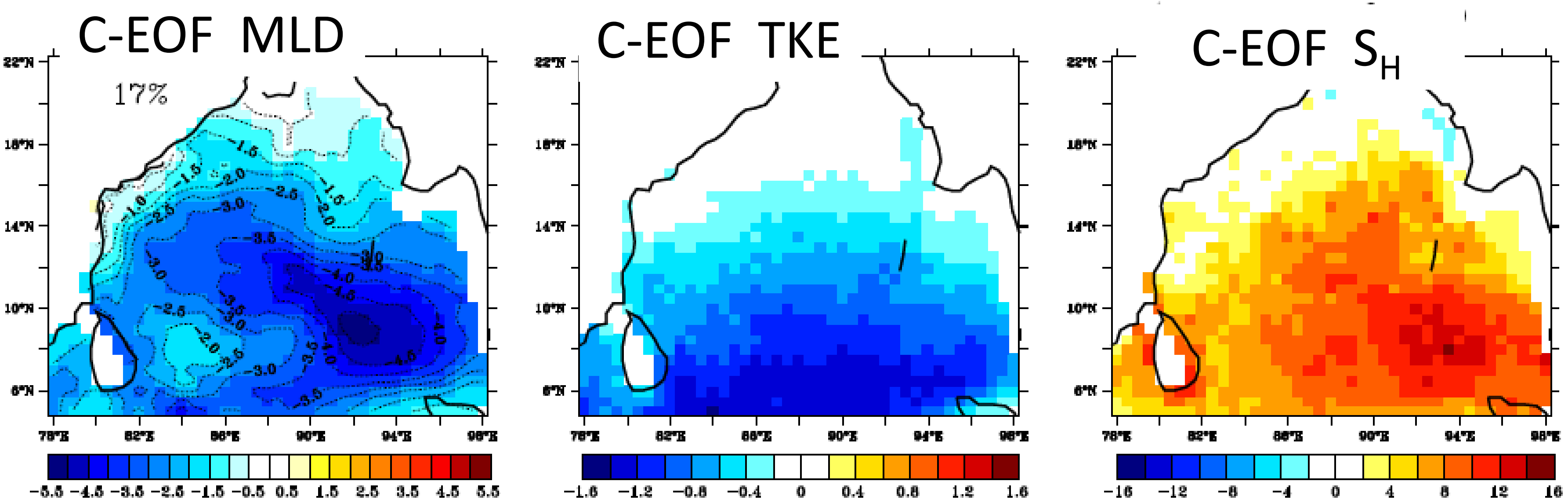
Interannual Variability of BL and ENSO: BoB average



Correlation of IAV of BL and Precipitation anomalies



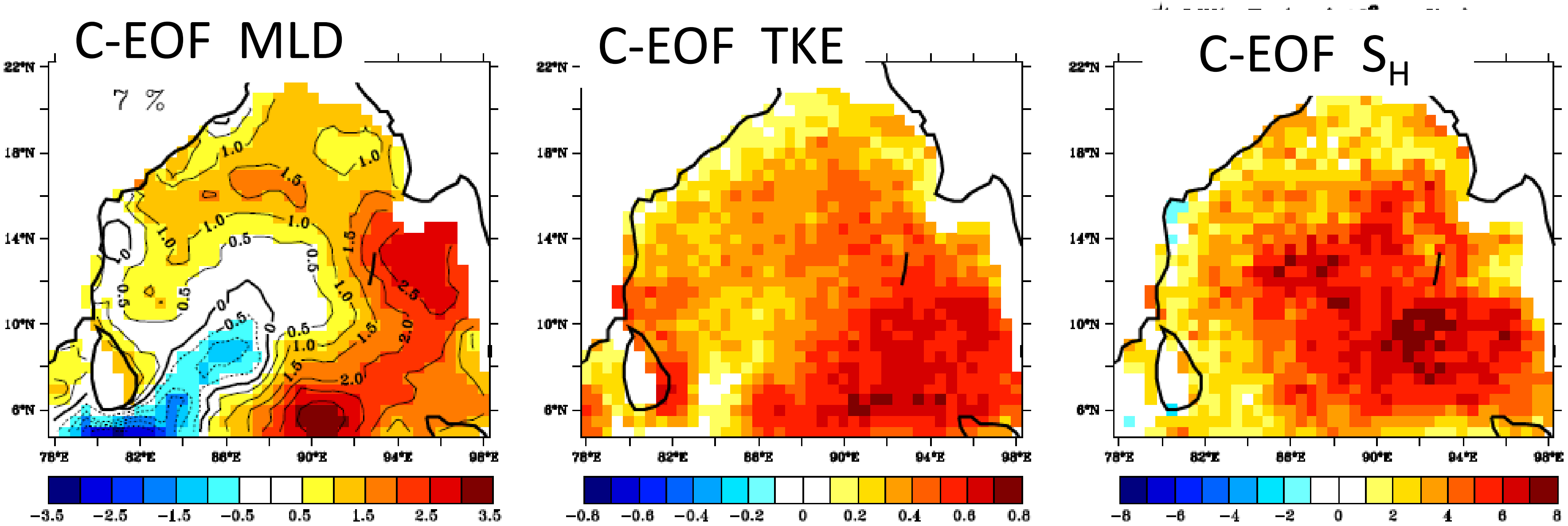
Mixed layer energetics and IAV of BoB MLD: Mode-1 response to ENSO



The TKE and Stability factor (S_H) appears to respond in opposite directions.

As $K_H = q\ l\ S_H$ is a linear function of TKE and SH, they dissociate in mode-1 and reduced amplitude of IAV of BoB MLD

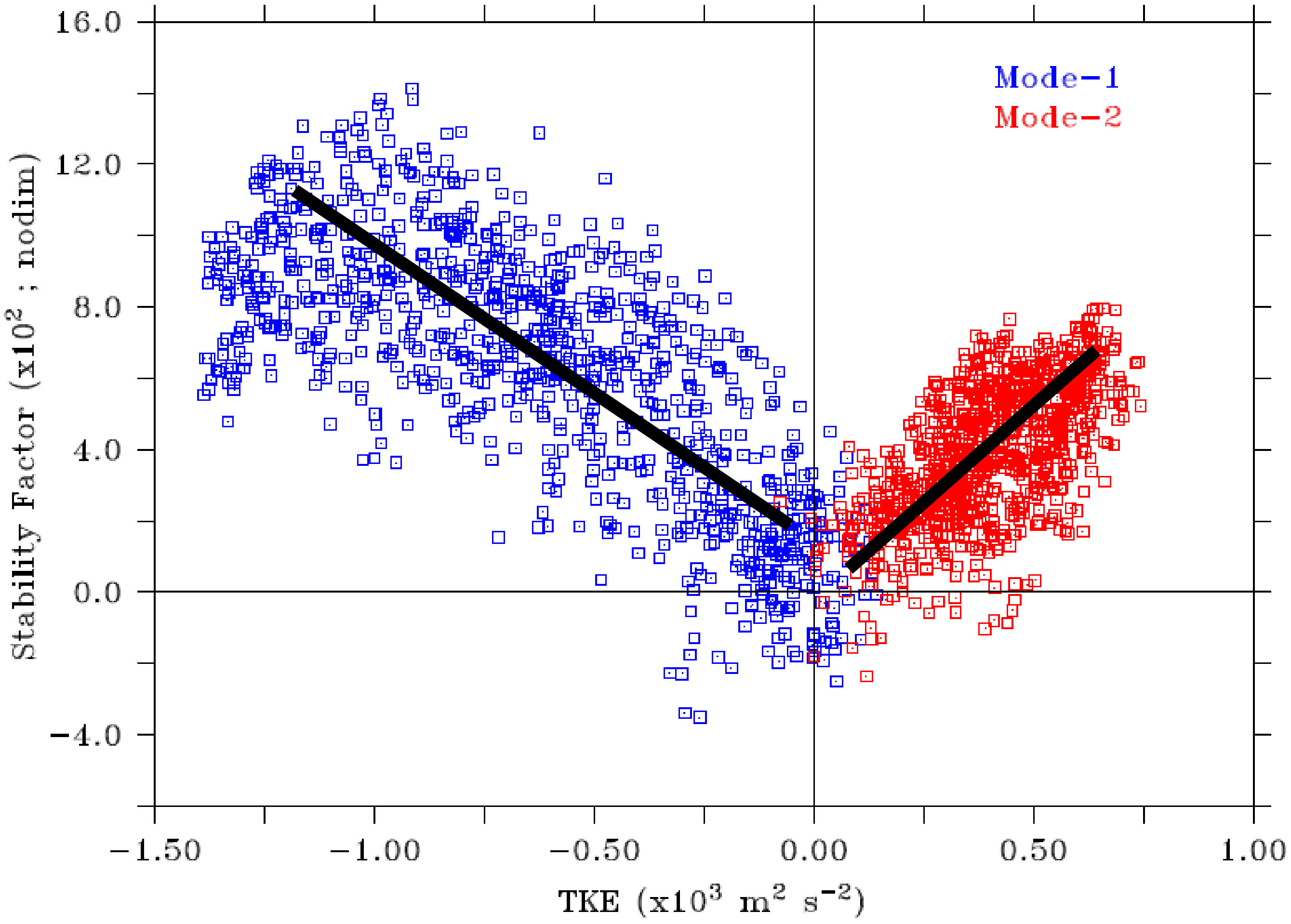
Mixed layer energetics and IAV of BoB MLD: Mode-2 response to IOD?



The TKE and Stability factor (S_H) appears to respond in same directions.

As $K_H = q \, l \, S_H$ is a linear function of TKE and SH, they associate in mode-2

Mixed layer energetics and IAV of BoB MLD: Mode-1 response to ENSO

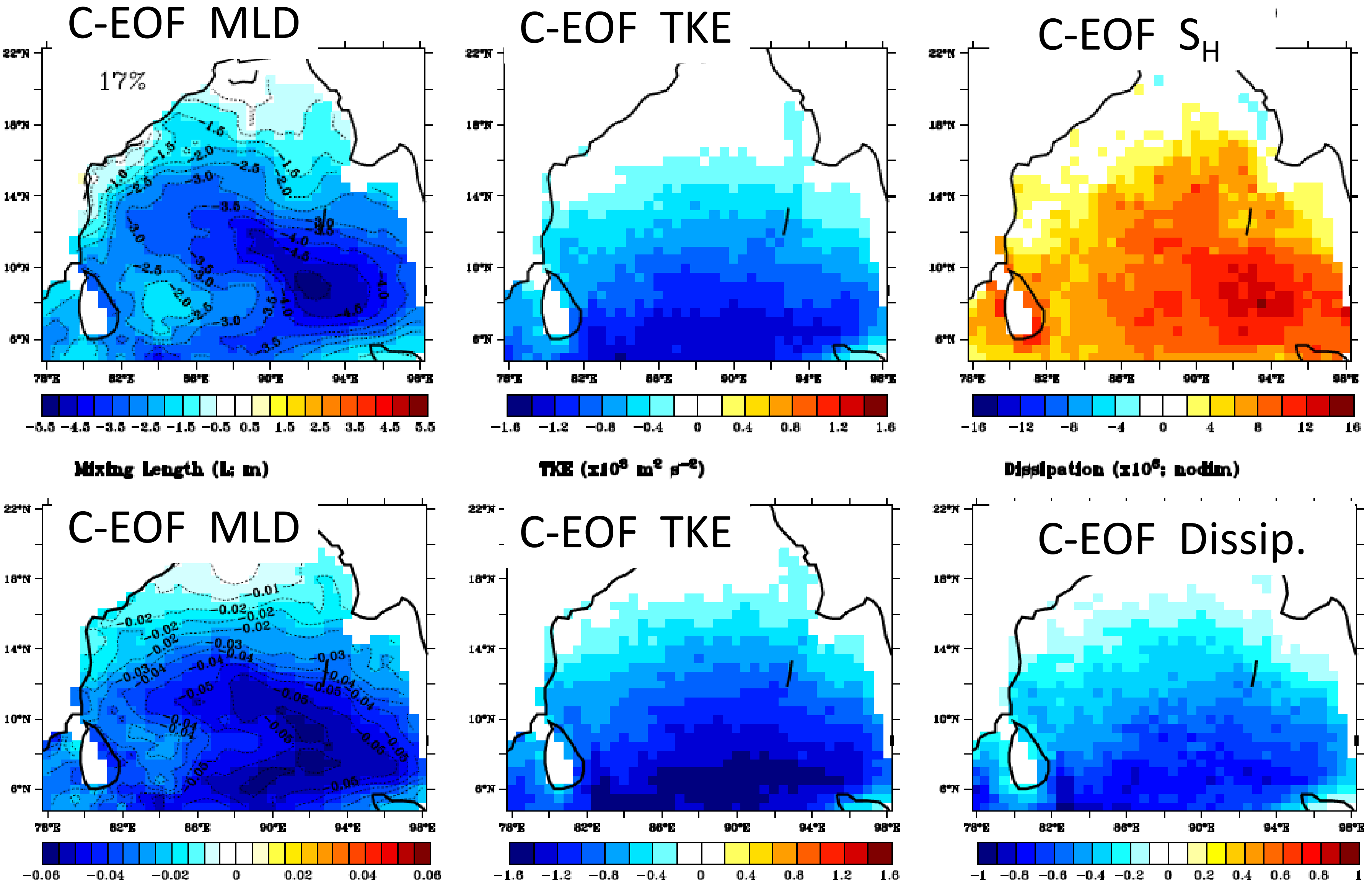


In Mode-1, the TKE and S_H dissociate to mitigate the IAV amplitude of BoB MLD.

$K_H = q\ l\ S_H$

This explains why BoB MLD IAV is weaker compared to seasonal cycle.

Mixed layer energetics and IAV of BoB MLD: Mode-1 response to ENSO


C-EOF MLD

C-EOF TKE

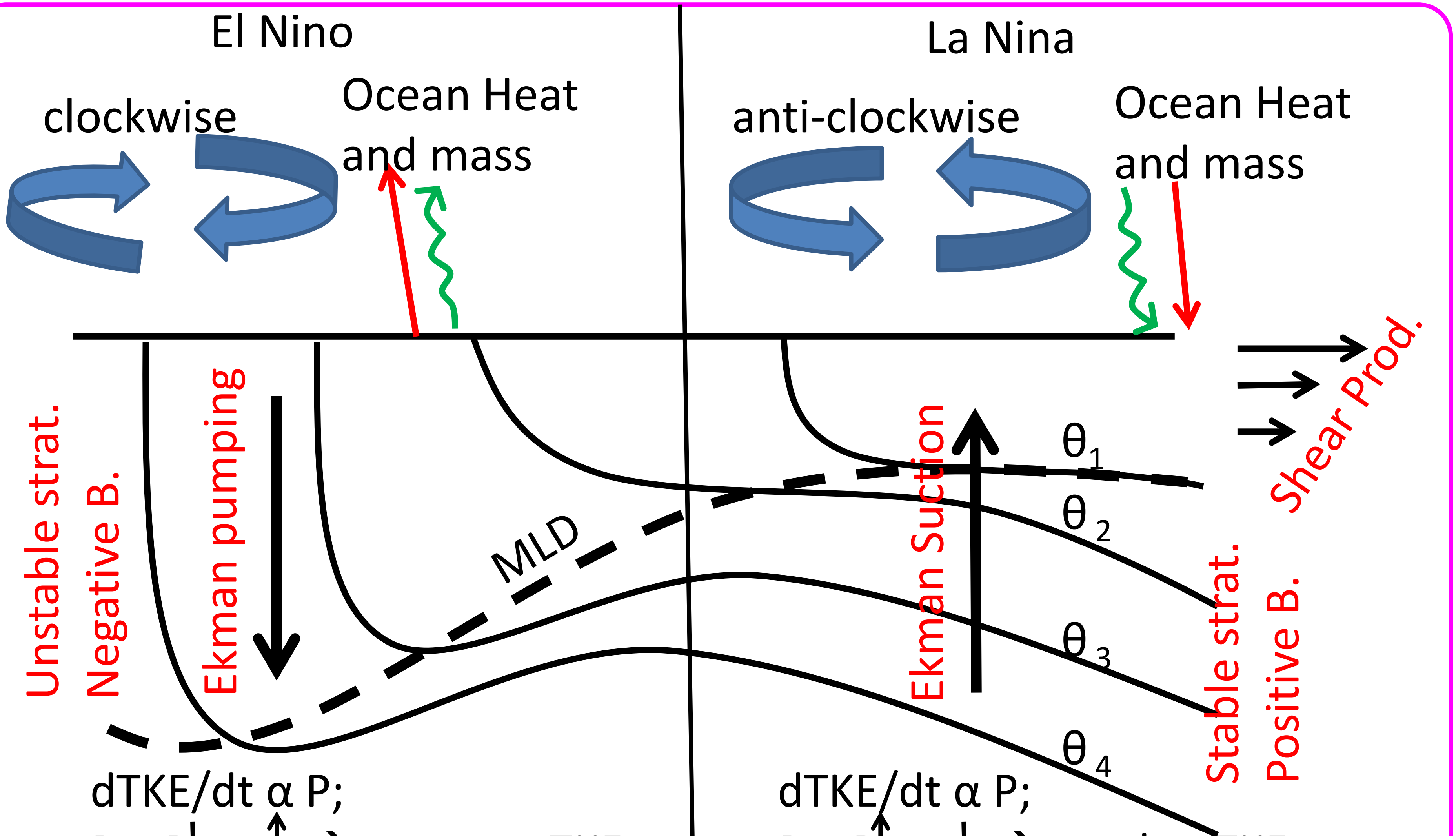
C-EOF S_H

C-EOF MLD

C-EOF TKE

C-EOF Dissip.

Mechanism of BoB MLD IAV in response to ENSO



$dTKE/dt \; \alpha \; P;$

$P + B\downarrow = \varepsilon\uparrow \rightarrow$ stronger TKE

$S_H \; \alpha \; \Gamma \; ; \; \Gamma = B\downarrow/\varepsilon\uparrow \rightarrow$ Weak S_H

$dTKE/dt \; \alpha \; P;$

$P = B\uparrow + \varepsilon\downarrow \rightarrow$ weaker TKE

$S_H \; \alpha \; \Gamma \; ; \; \Gamma = B\uparrow/\varepsilon\downarrow \rightarrow$ Strong S_H

Conclusion

- A dynamic-thermodynamic reduced gravity ocean model embedded with a high resolution vertical mixed layer model is introduced. Further the model is utilized to study the Bay of Bengal mixing and variability.

- The year to year variability of Bay of Bengal mixing and barrier layer are predominantly controlled by ENSO.

- Turbulent Kinetic Energy (TKE) and Stability of water column dissociate and mitigate the variability of Bay of Bengal mixing interannual variability when ENSO is a controlling factor.

- The study has implications for fine tuning the state of the art general circulation models and climate models in order to represent a robust spatio-temporal variability of surface mixing in the Bay of Bengal.

(Valsala, V., S. Shikha and S. Balasubramanyam (2018), A Modeling Study of Interannual Variability of Bay of Bengal Mixing and Barrier Layer Formation, J. Geophysical Res., https://doi.org/10.1029/2017JC013637)