Effects of freshwater forcing on the Indian monsoon; Regional coupled modeling study

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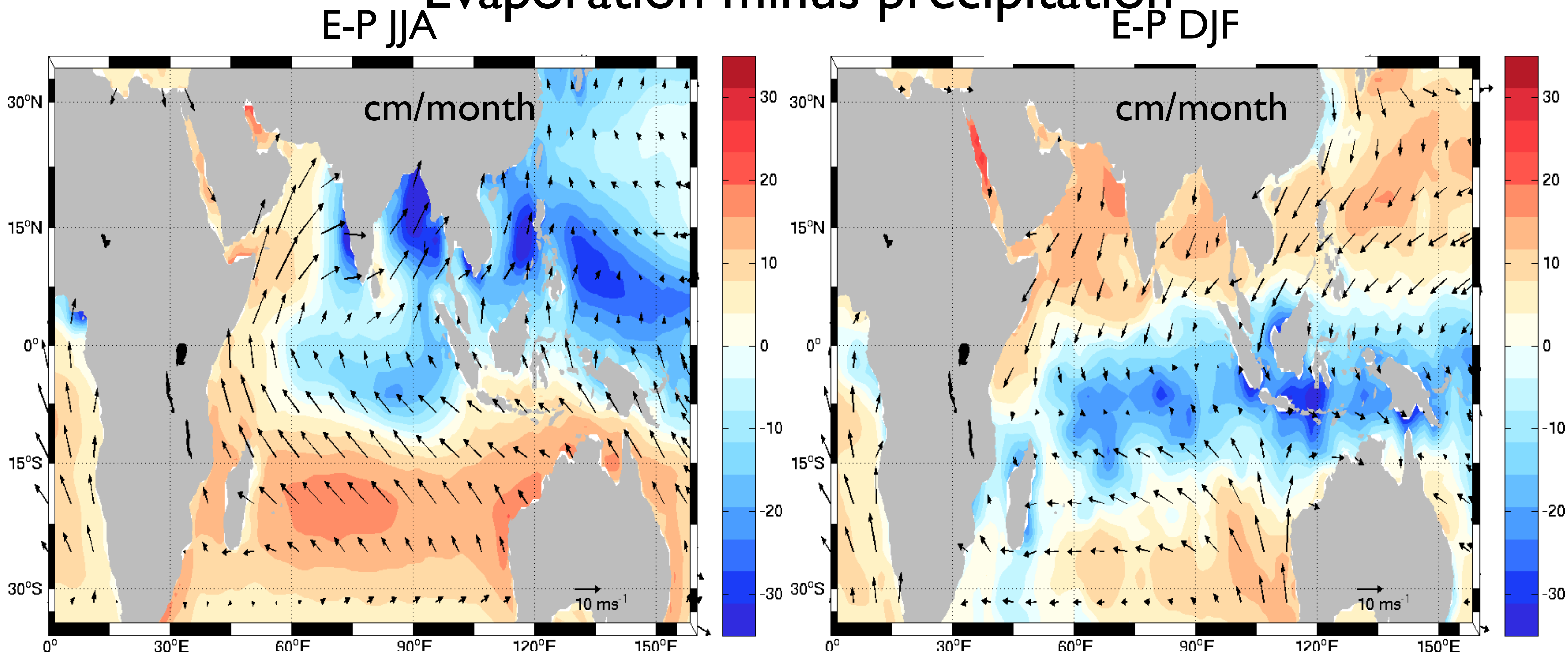
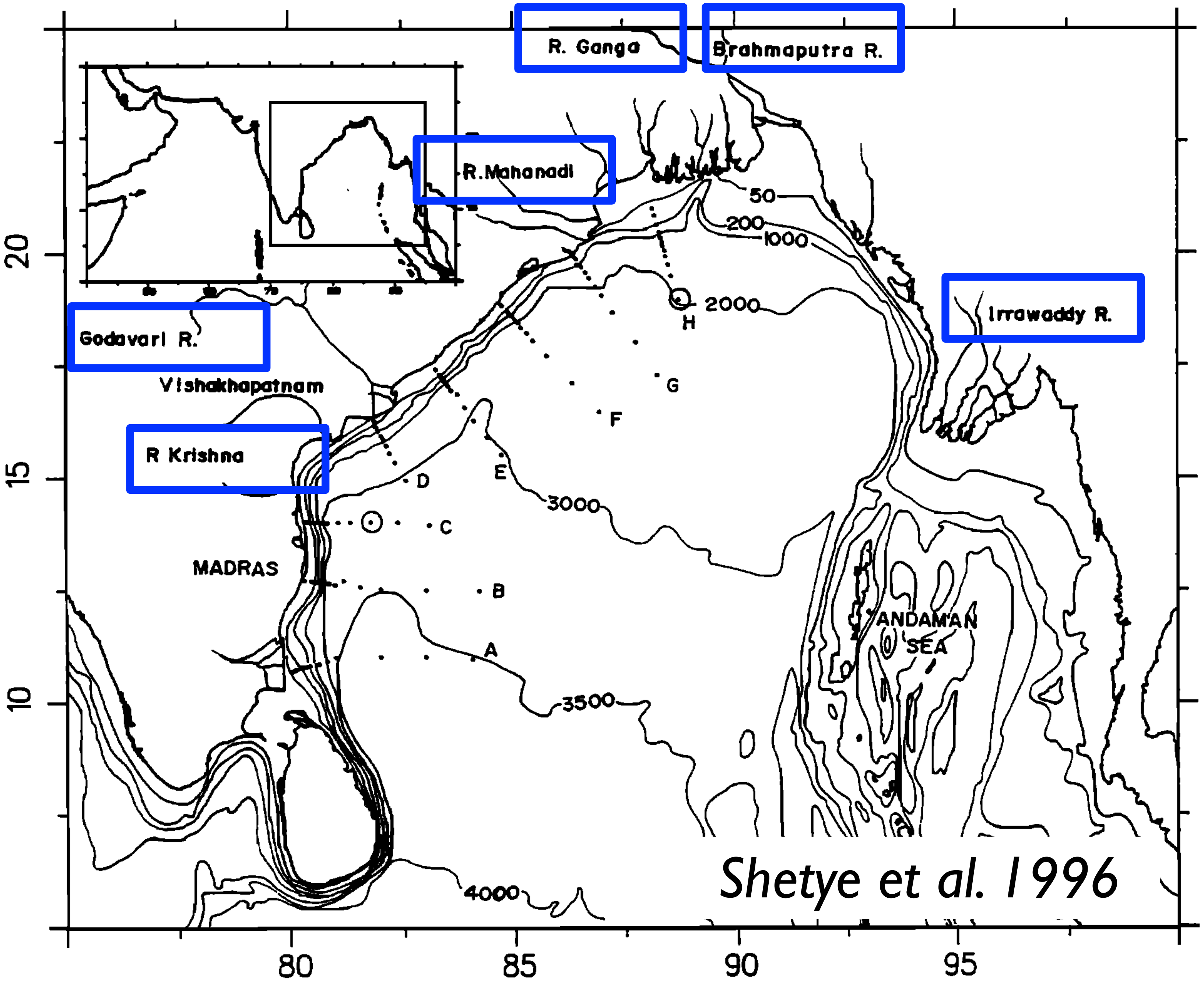
Freshwater forcing in Bay of Bengal: Evaporation minus precipitation



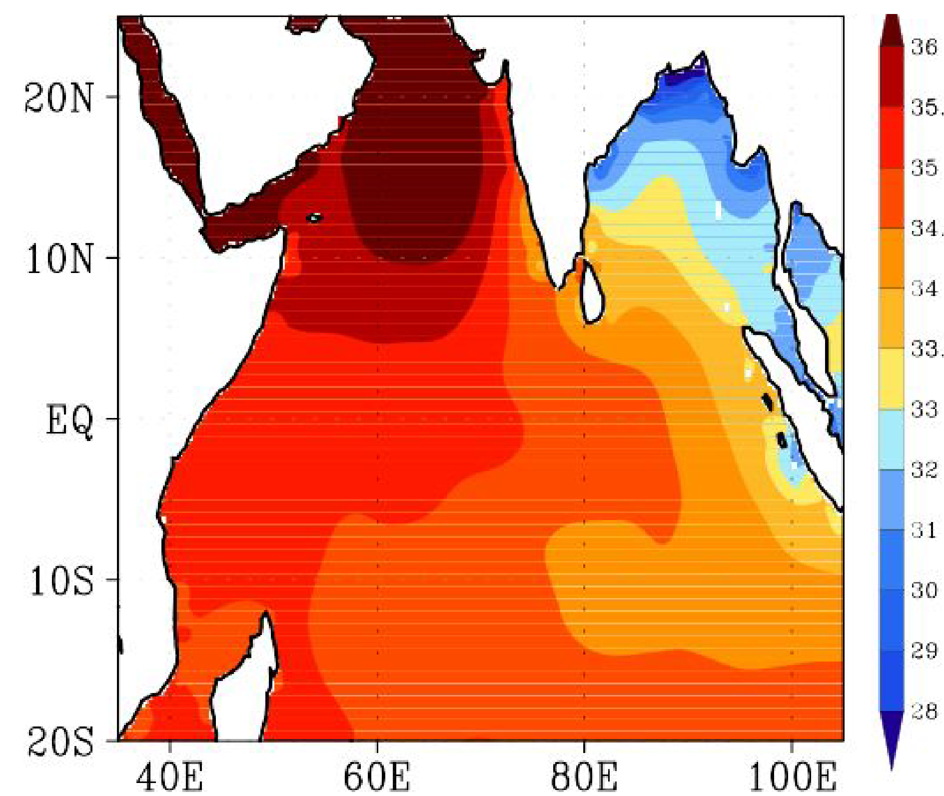
OAFLUX (Yu and Weller 2007) E minus GPCP P, NCEP2 10m wind

- SW monsoon season: Net freshwater gain from rainfall; ~>30 cm / month
- NE monsoon season: Net freshwater loss by evaporation: 10-20 cm / month
- In BOB, river discharges play an important role in hydrography, SST, and ocean-atmosphere system [e.g., Shetye et al. 1996; Vinayachandran et al. 2002; Sanilkumar et al. 1994].

Freshwater forcing in Bay of Bengal

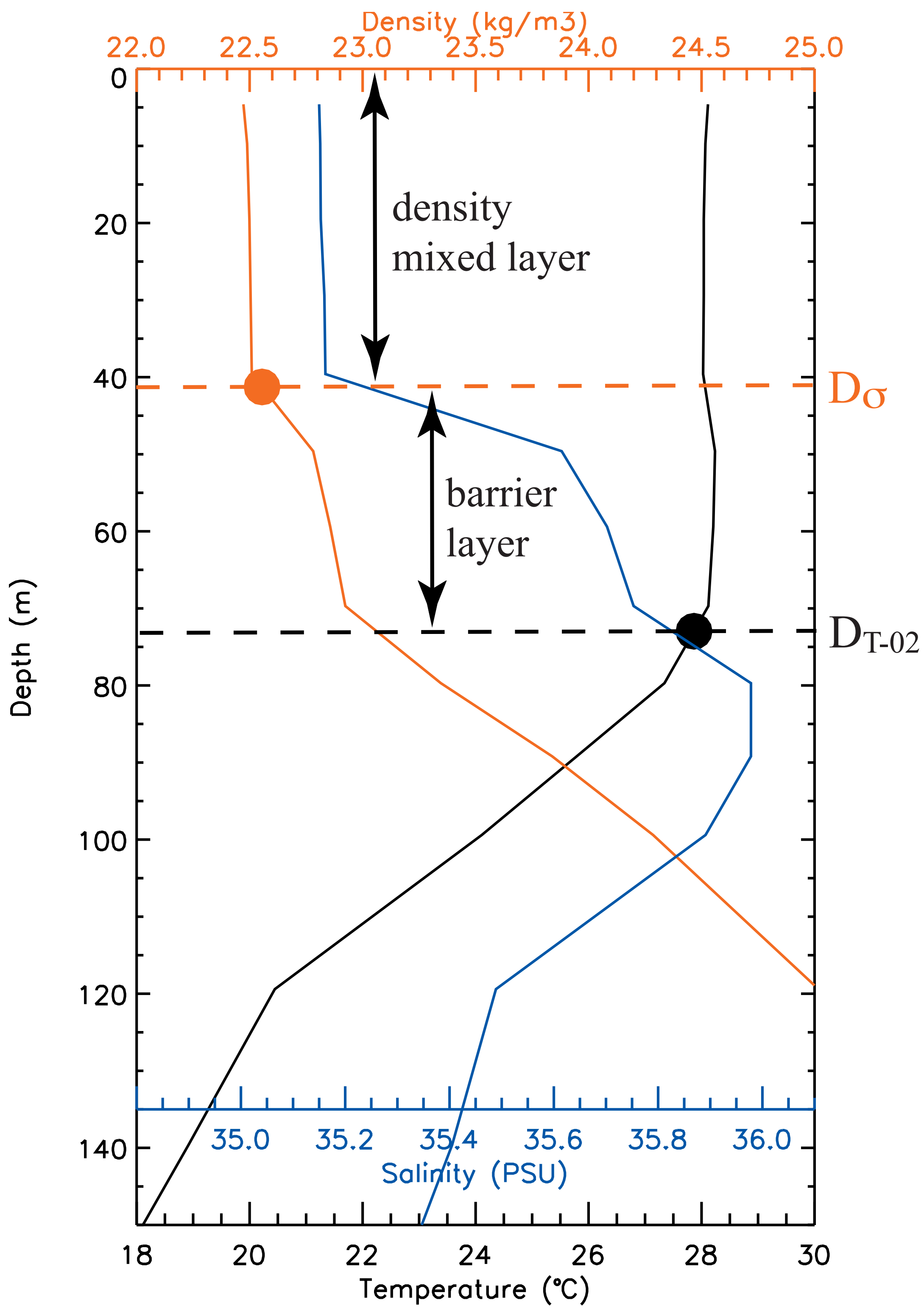


Annual Mean WOA05 SSS



- Major Rivers discharges from the **Ganga, Brahmaputra**, Irrawaddy, Mahanadi, Krishna, Godavari, etc.
- BOB is the freshest region in the Indian Ocean.
- Receives large quantities of freshwater from river discharges (1500-3000 km^3 annually), more in summer than winter [e.g., Martin et al. 1981; Varkey et al.1996].

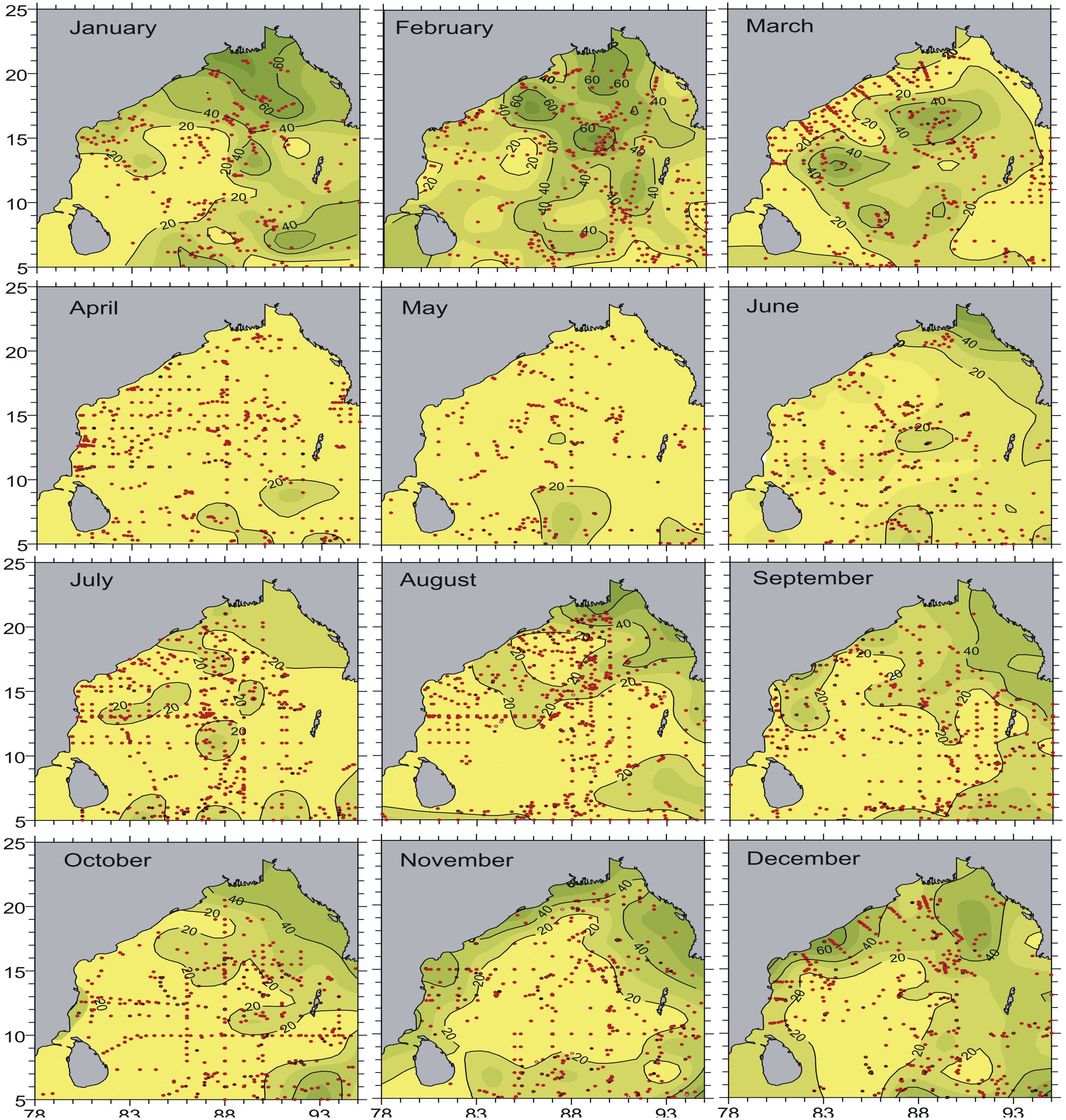
Isothermal layer depth, mixed later depth and barrier layer thickness



- **ILD=depth where T=SST-△T**
  - △T=0.2C~1.0C [e.g., Wyrtki 1971; Thadathil et al. 2007]
- **MLD = depth where $\sigma_\theta = \sigma_{\theta ref} + \triangle\sigma$**
  - $\triangle\sigma = \sigma_\theta(T_{ref} - \triangle T, S_{ref}, P_0) - \sigma_\theta(T_{ref}, S_{ref}, P_0)$
  - [e.g., Lukas and Lindstrom 1991; Sprintall and Tomczak 1992; Vialard and Delecluse 1998]
- **BLT=ILD-MLD**
- BLs have important impacts on air-sea interactions and climate.

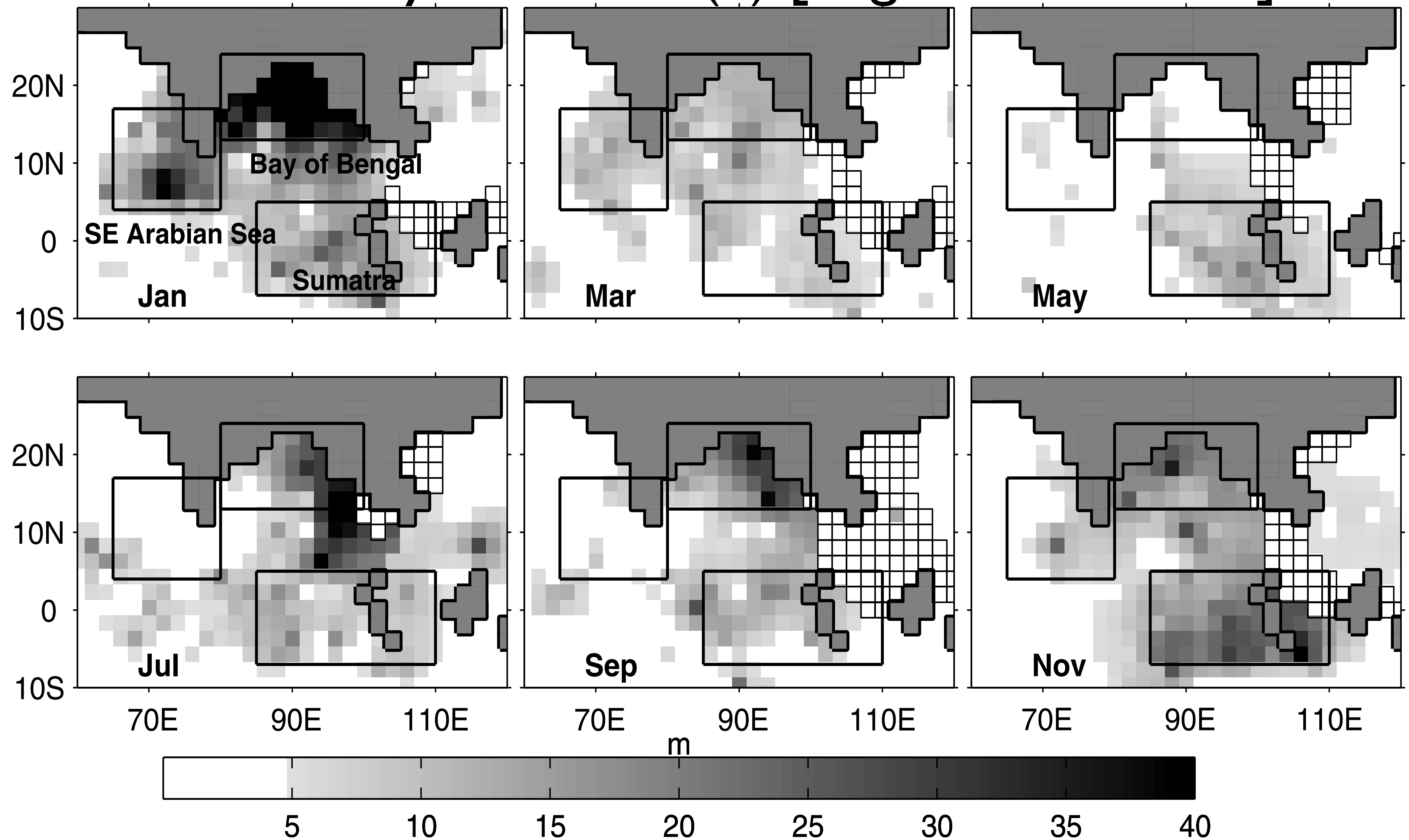
de Boyer Montegut et al. 2007, SEAS

Seasonal cycle of BLT (1) [Thadathil et al. 2007]



- Based on ARGO, historical hydrographic datasets (IODC) and WOA stations
- Quasi-permanent BL persisting throughout the year (>10 months)
- Summer: Develops from the northern tip by river and rainfall
- Winter: Maximum in thickness and horizontal extent [Rao and Sivakumar 2003], despite E-P>0

Seasonal cycle of BLT (2) [Mignot et al. 2007]

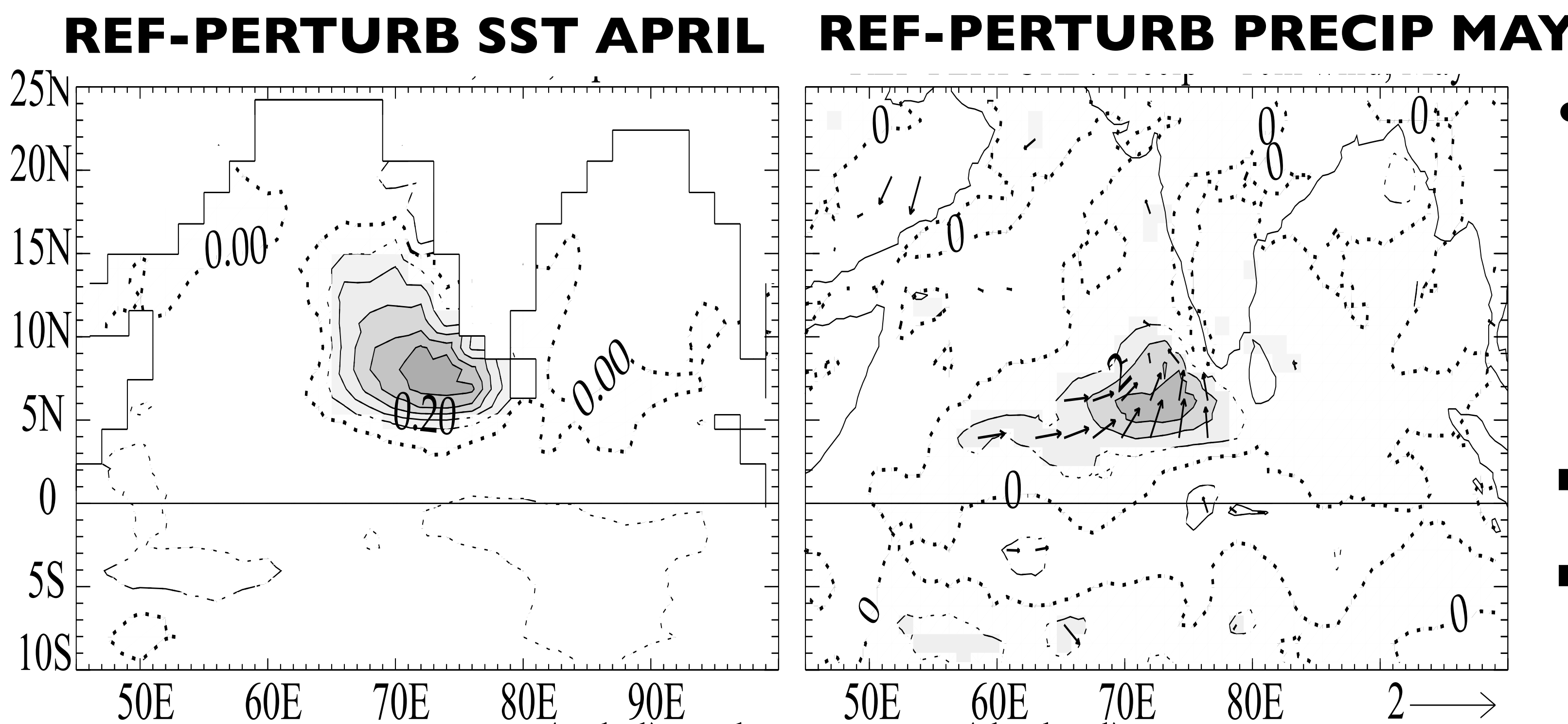


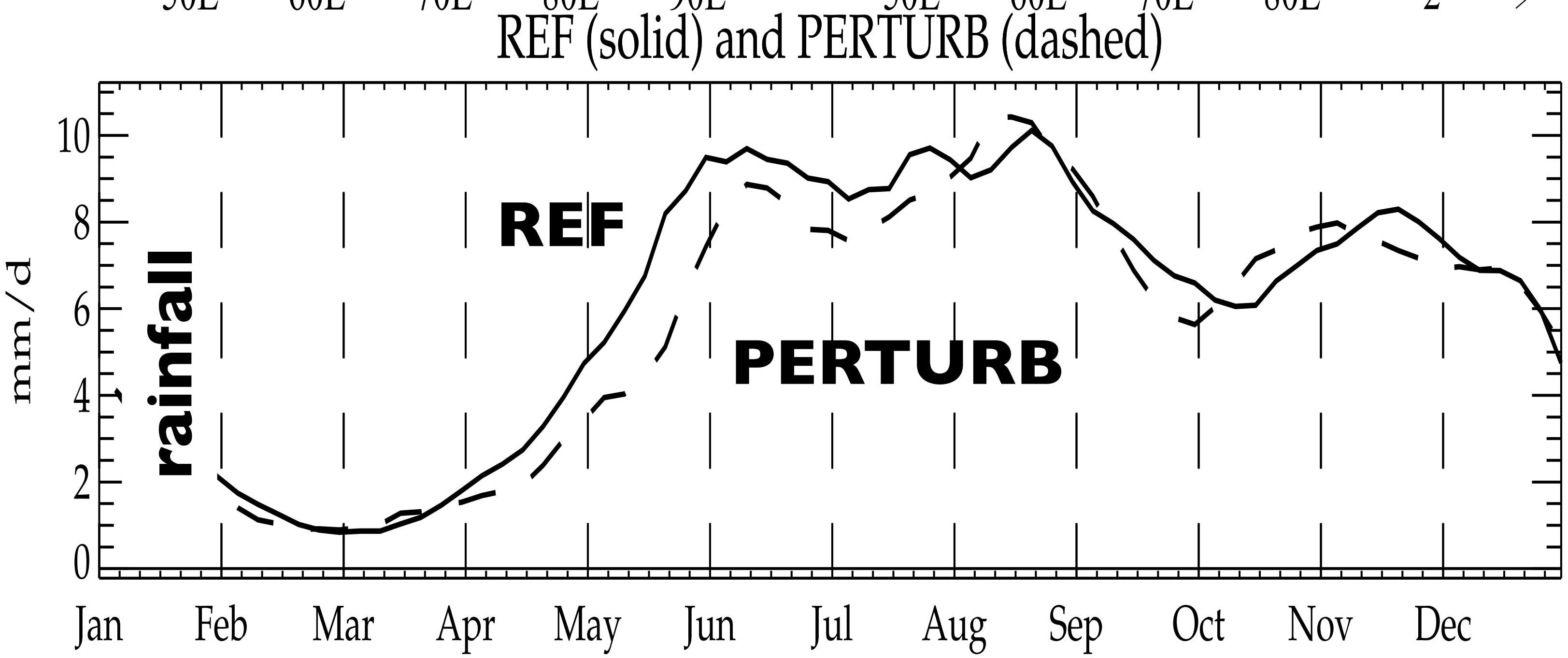
• BL developing from summer, but reaching the maximum in winter.

• BL (and inversion) in winter [Thadathil and Gosh 1992] by monsoon current and downwelling Rossby wave [e.g., Thadathil et al. 2008].

• Known to contribute to the formation of boreal spring mini warm pool, warming faster than other Arabian Sea [Shenoi et al. 1999].

How would the SW monsoon respond to the BL in SEAS?
Masson et al. 2005 GRL





- One of a few fully coupled GCM studies for the salinity stratification and BL in the Indian Ocean.
- ➡ **REF: control**
- ➡ **PERTURB: no salinity effect on density in SEAS**
- Boreal spring SST is warmer in SEAS leading to more and earlier precipitation events.
- BL advection from the BOB affects the onset of the SW monsoon.

- There was no significant change in monsoon rainfall over continental India and BOB, and the BL effect is local.

Main research questions:

1. What are the impacts of seasonal cycle in BL from river discharges on *summer and winter mean stratification and SST*?

2. How would the wind and rainfall respond and how different are they?

3. What is the spatial scale of atmospheric response?

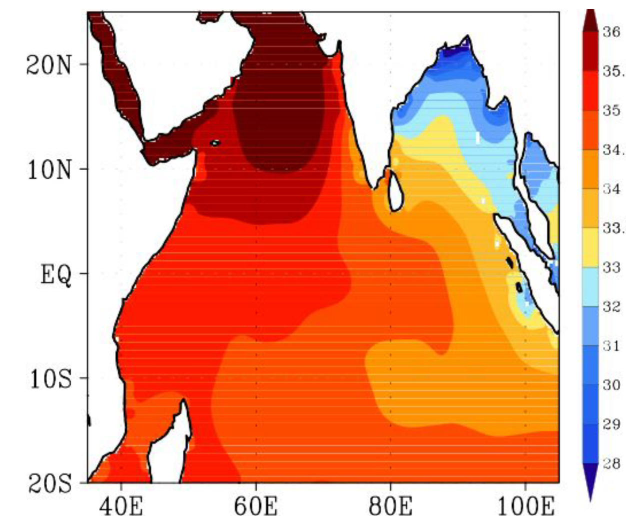
We will use a fully-coupled high-resolution model

Seo, Xie, Murtugudde, Jochum, and Miller, 2009: Seasonal Effects of Indian Ocean Freshwater Forcing in a Regional Coupled Model. J. Climate.

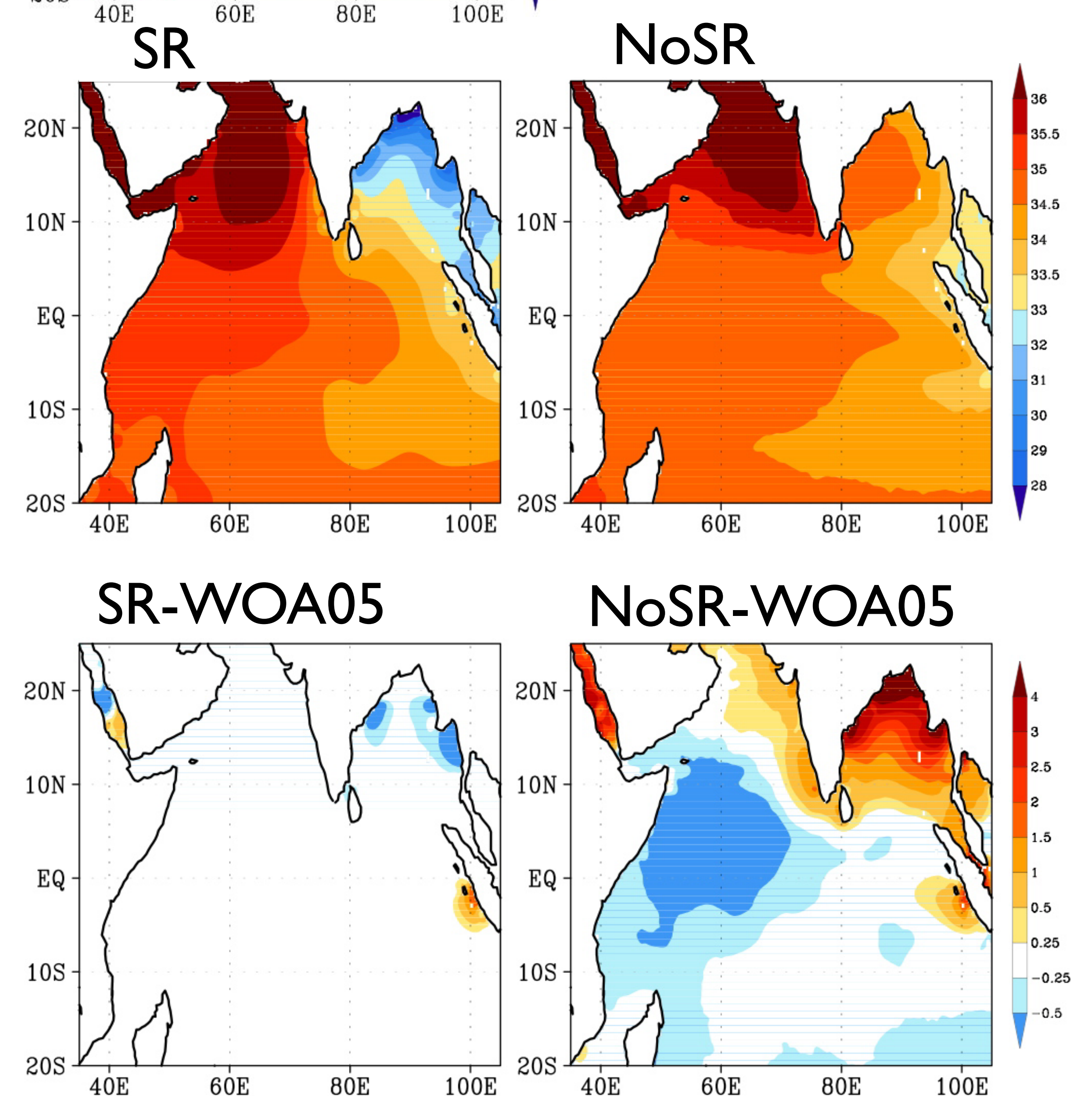
Regional Ocean-Atmosphere Coupled Model

- Scripps Coupled Ocean-Atmosphere Regional (SCOAR) Model (Seo et al. 2007 J. Climate):
- Couples RSM with ROMS
- Resolution: 25km ocean / atmosphere with 20 layers in the ocean
- Coupling: Daily coupling, Period: 1993-2004
- BCs: NCEP2 for Atm, WOA05 for Ocean

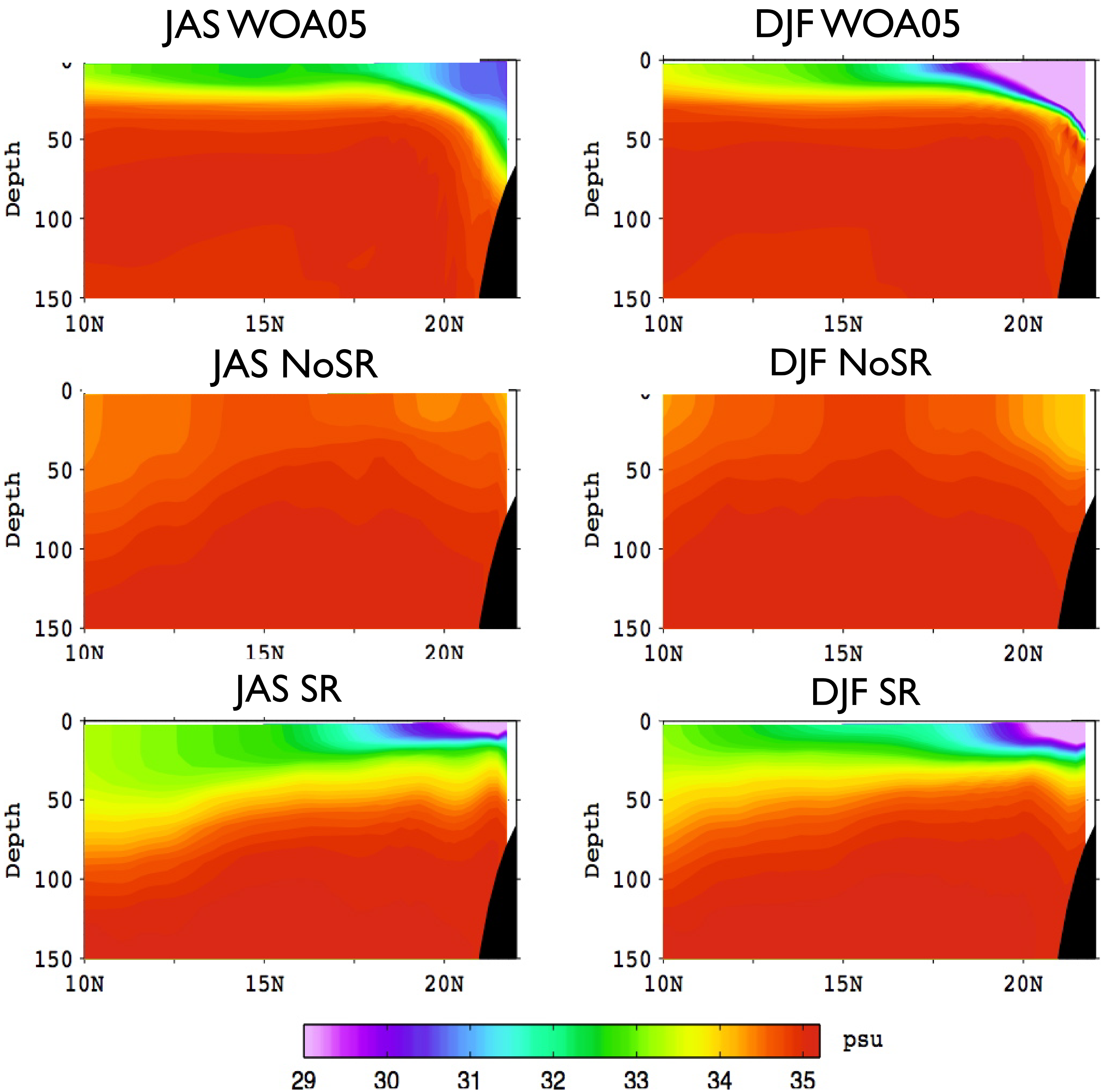
EXPs	Sea Surface Salinity
SR (CTL)	Relaxed towards the WOA05 monthly climatology SSS=observed E-P-R
NoSR	No SSS relaxation; SSS= simulated E-P only

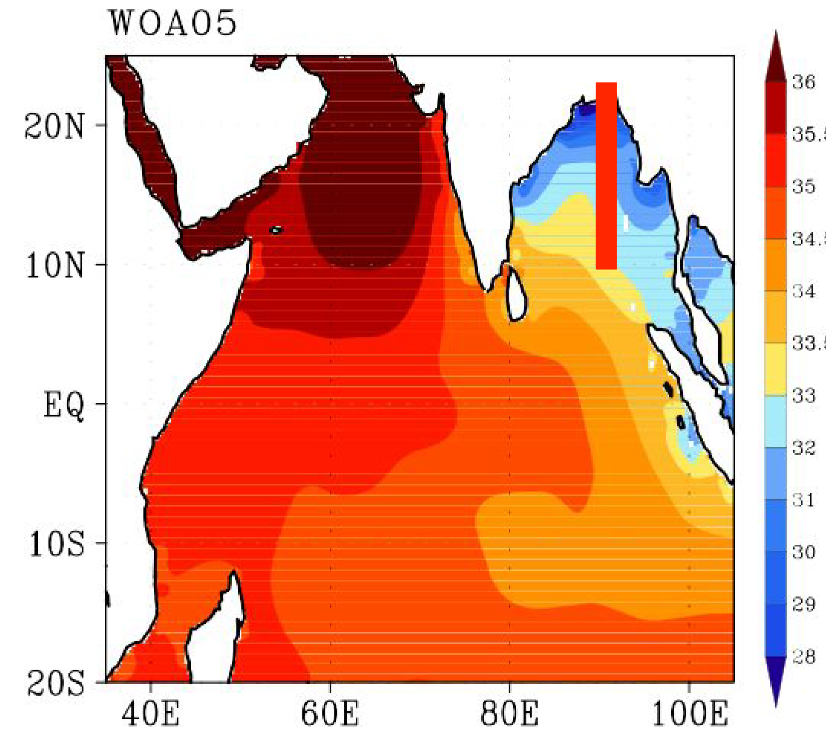


Climate sensitivity to >4 psu change in SSS in BOB



Depth-latitude diagrams of salinity along 90E





- Salinity minimum in northern BOB.
- Greater low salinity signal in winter than summer.
- Halocline is too diffuse and doe not slope down towards the coast [e.g., Shetye et al. 1996].

SST/SSH/Wind NoSR

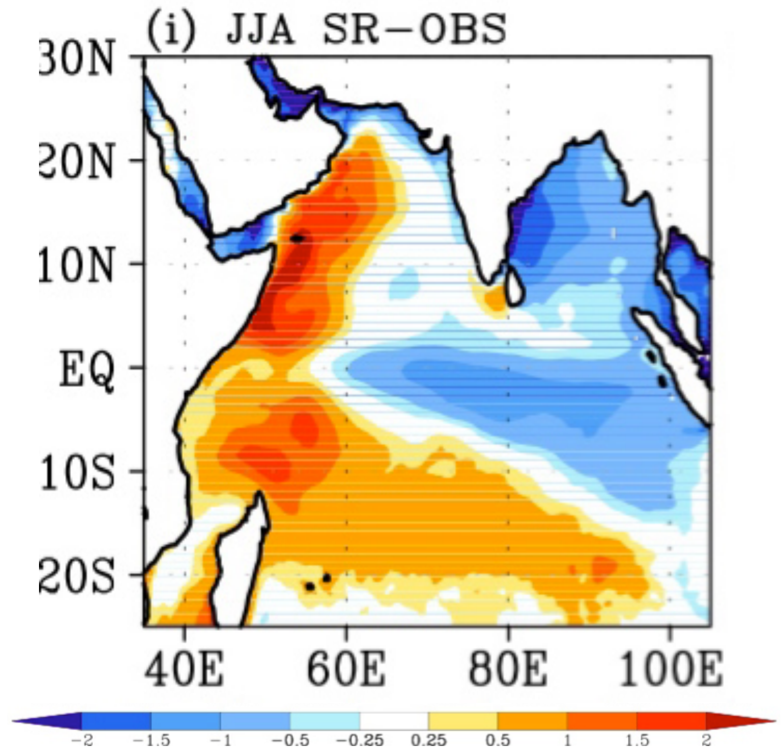
SSS/Current/Rain NoSR

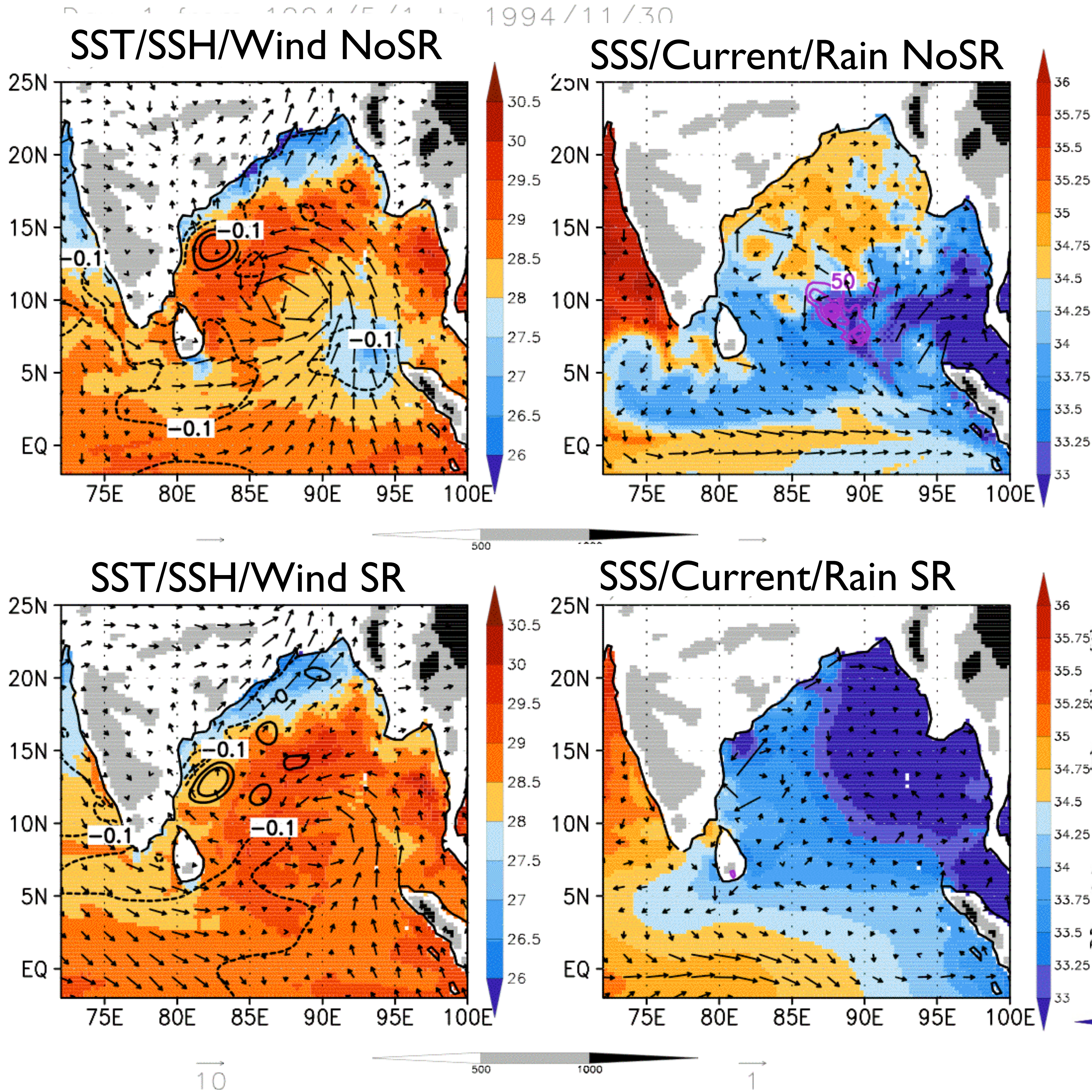
Summer of 1994
May to November

- Too intense upwelling even with the strong stratification.
- Significant cold bias in BOB

SST/SSH/Wind SR

SSS/Current/Rain SR





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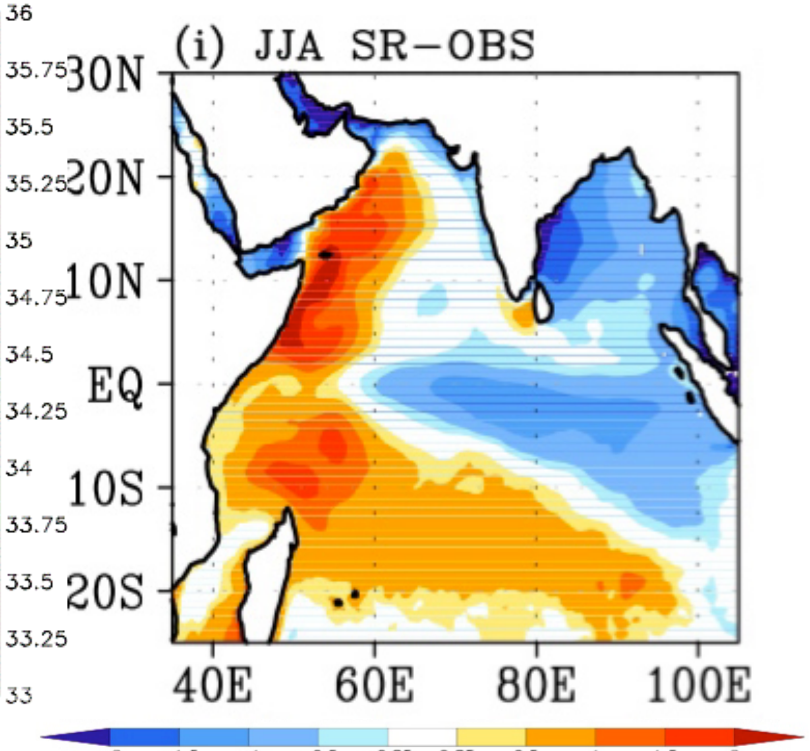
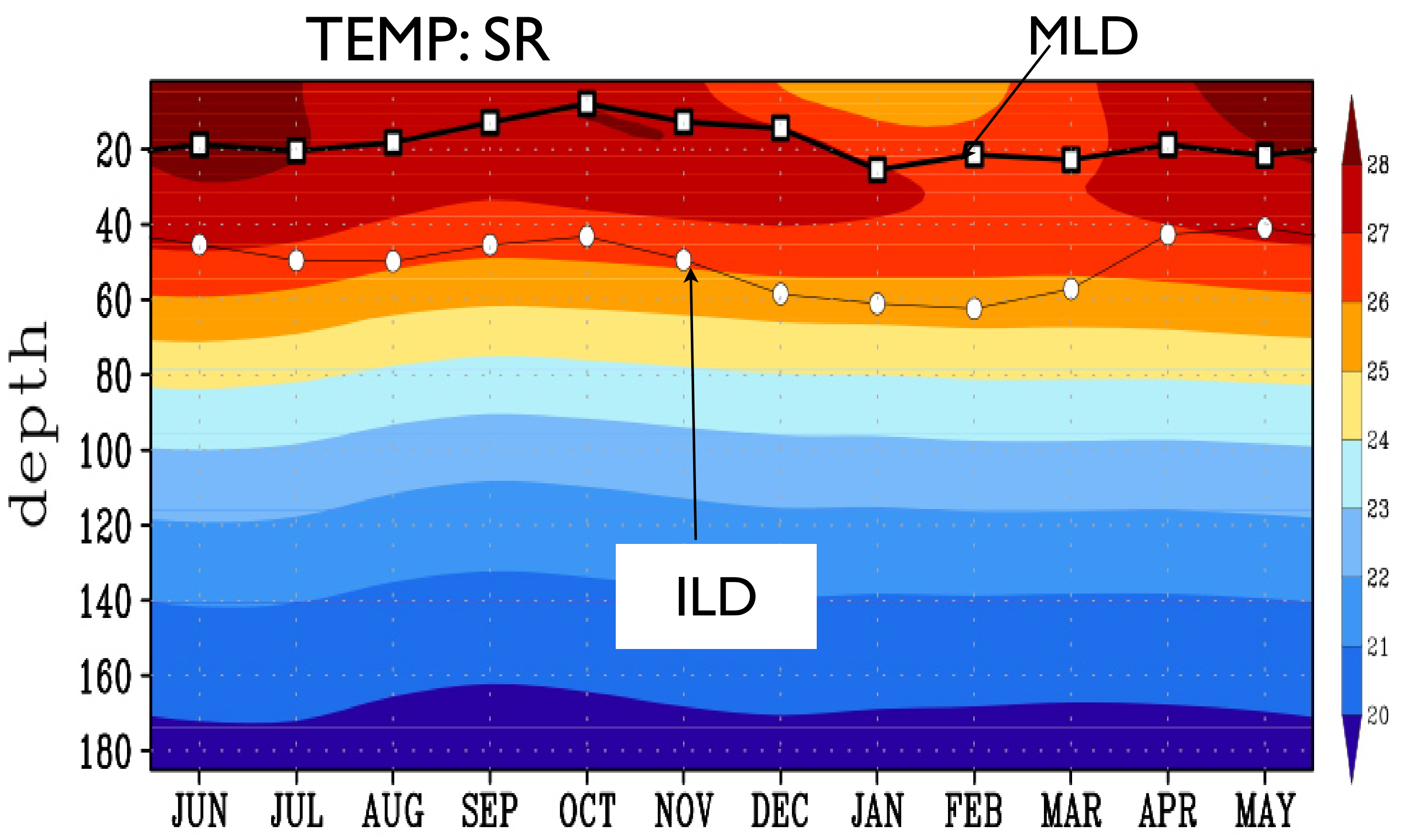
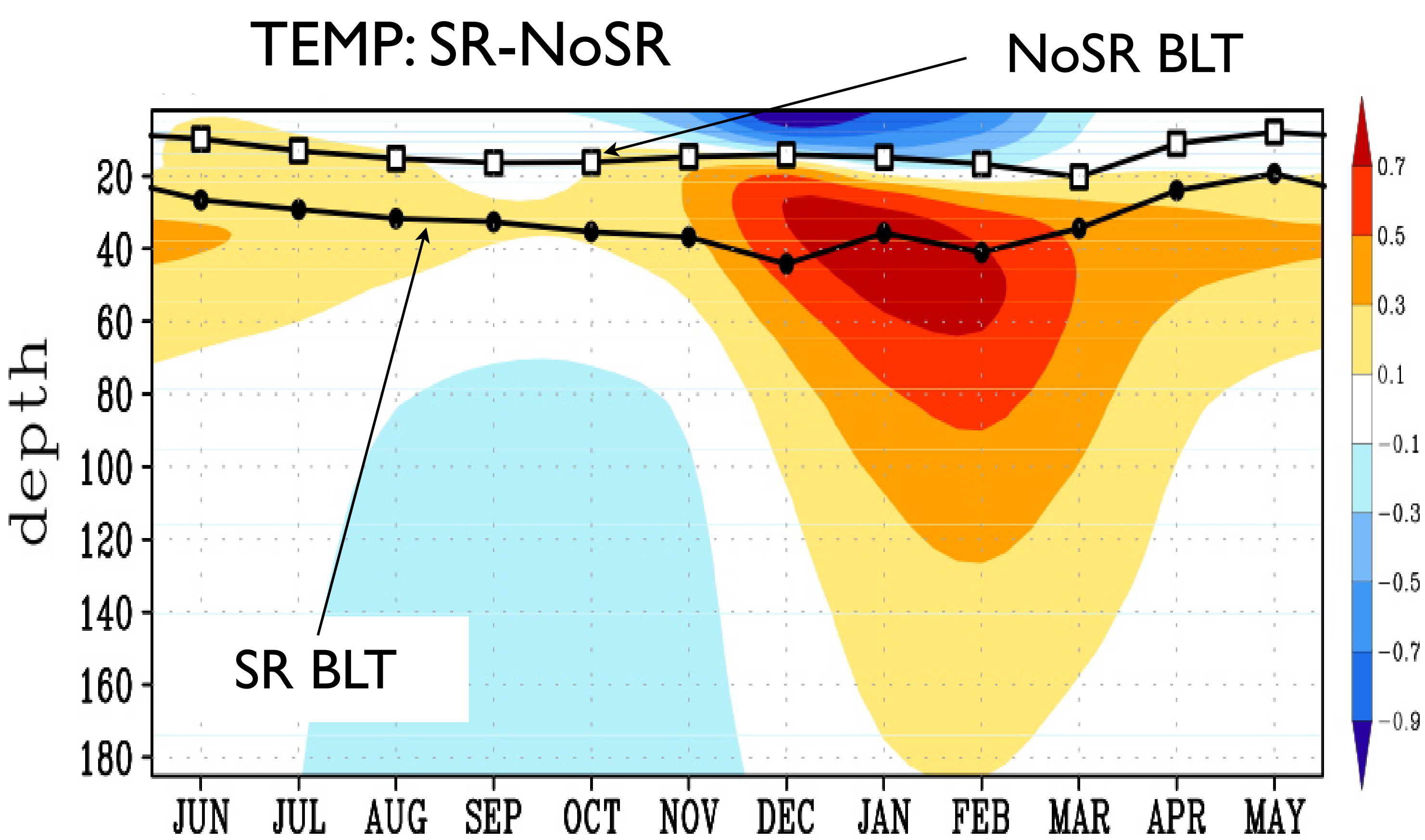


Seasonal cycle of vertical temperature in Bay of Bengal

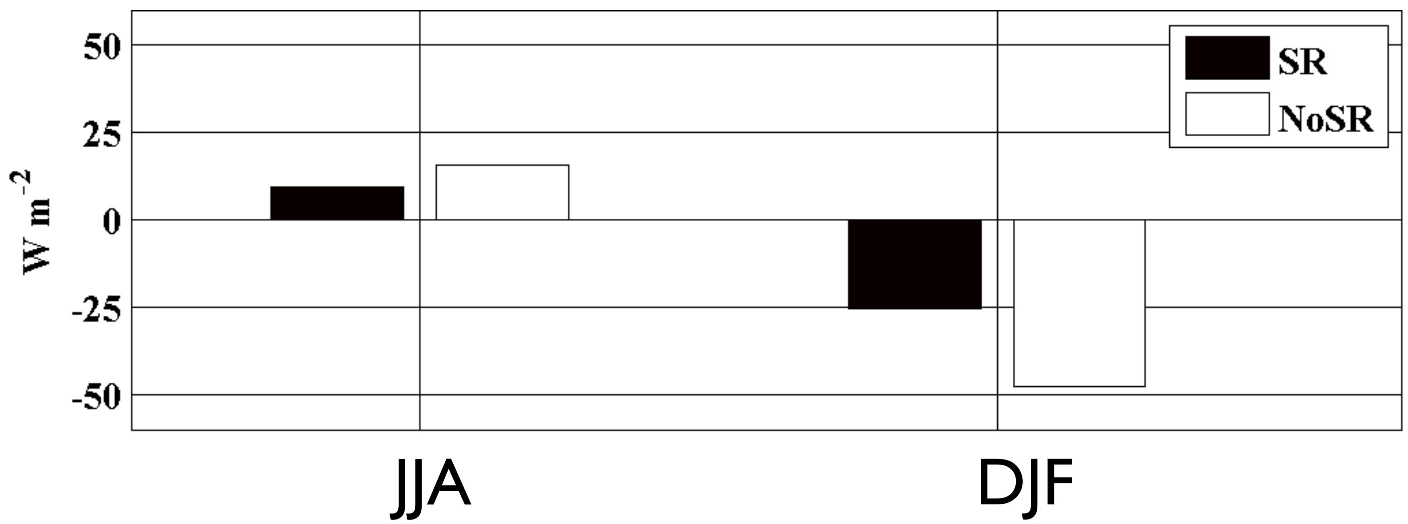




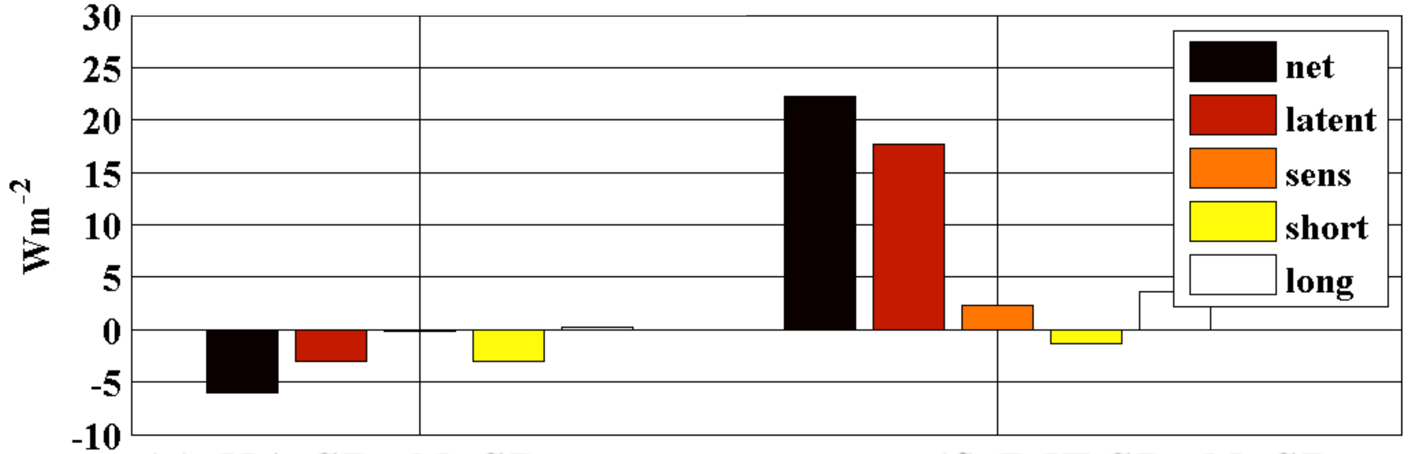
- MLD (~25m) is always shallower than ILD
- Both deepen during the SW and NE monsoons.
- Change in surface temperature is negligible in summer.
- BLT difference is greatest during winter.
- Large cooling at surface and warming at subsurface in winter.

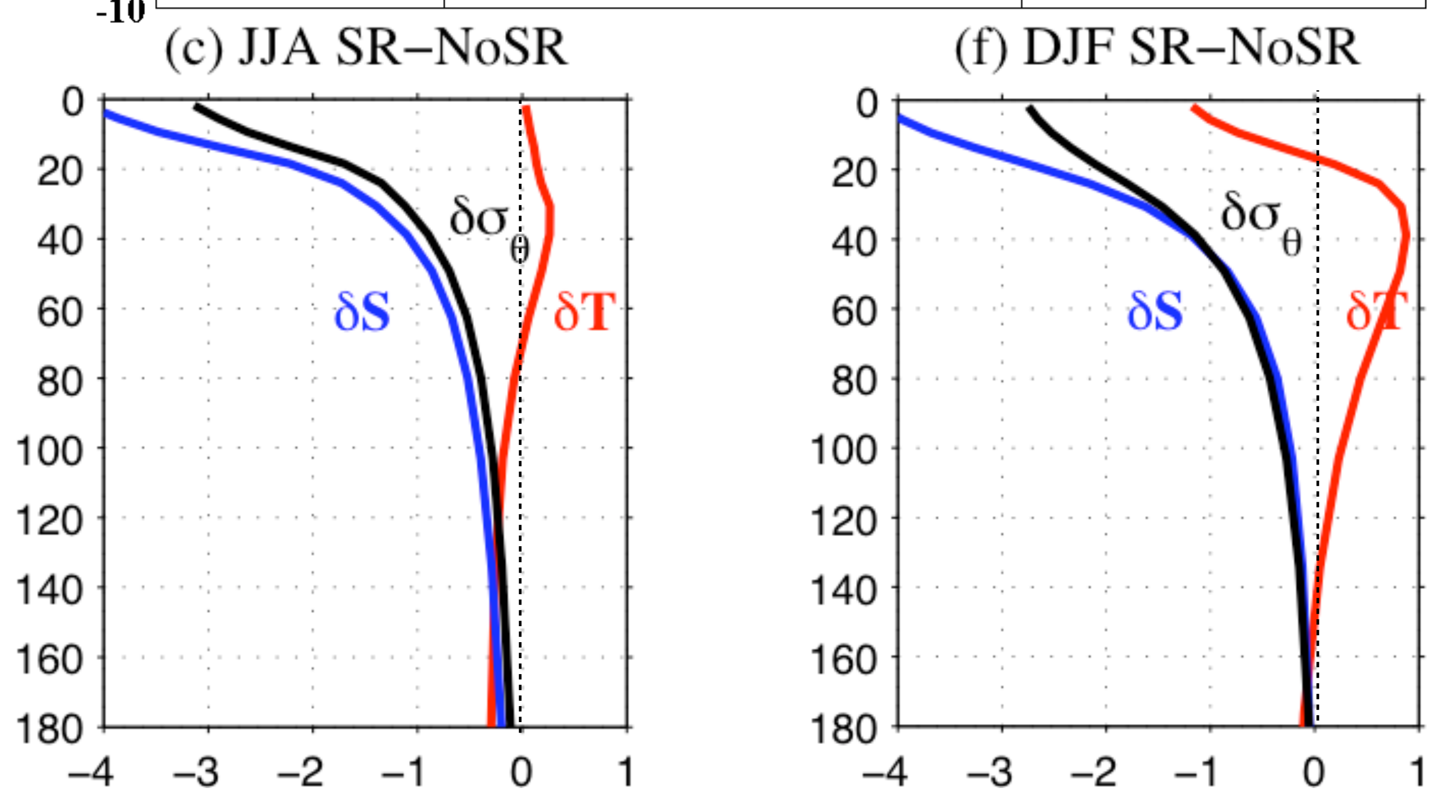
Change in heat flux over BOB

Net Heatflux



Heatflux: SR-NoSR

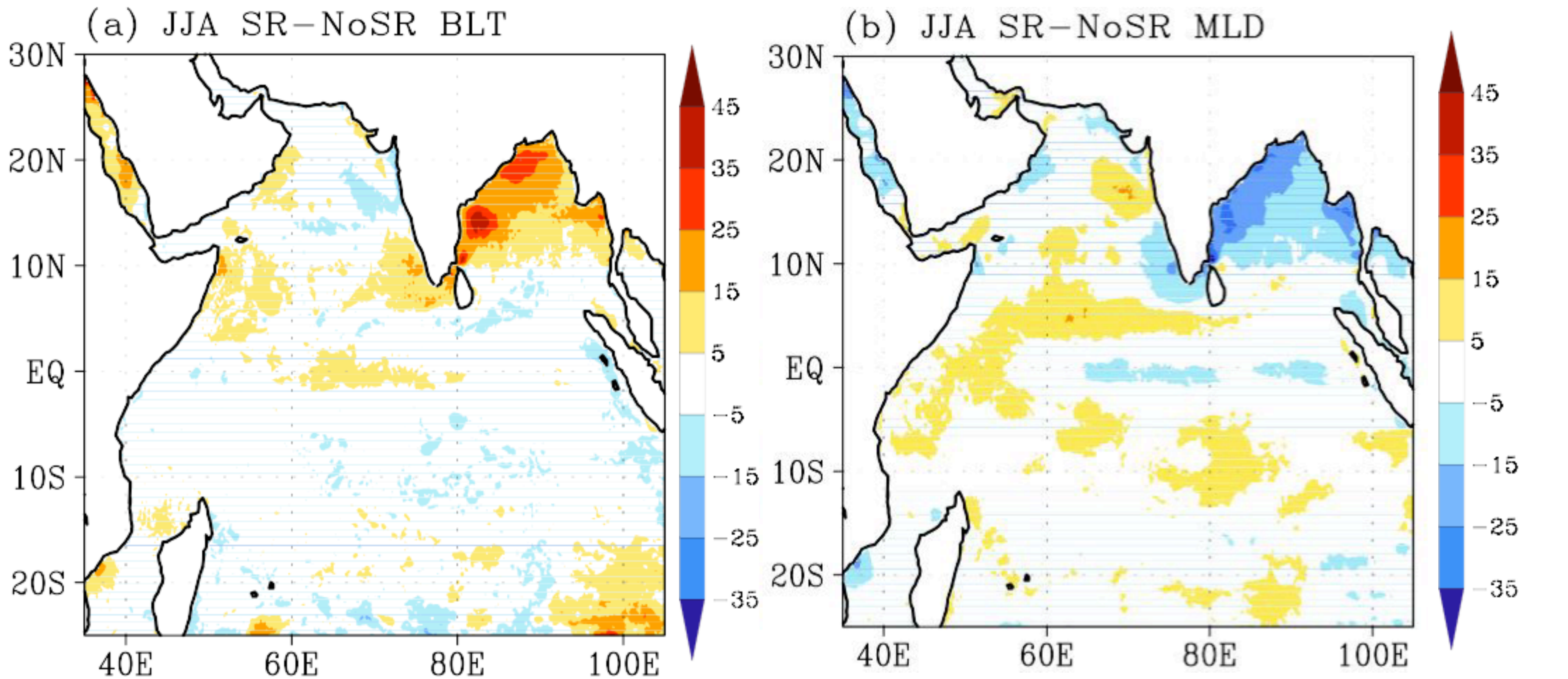




- **Summer**: Neat heat input to ocean: Warming of SST
- With BL, there are two cooling factors:
- 1) Reduced SW due to penetrative loss [Howden and Murtugudde 2001] and increased cloudiness [Vinayachandran et al. 2002].
- 2) Evaporative cooling
- **Winter**: Net heat loss to atmosphere.
- Cooling is confined to even shallower mixed layer (~20 m).
- Enhanced stratification keeps the subsurface from cooling.
- A very strong inversion-like feature.

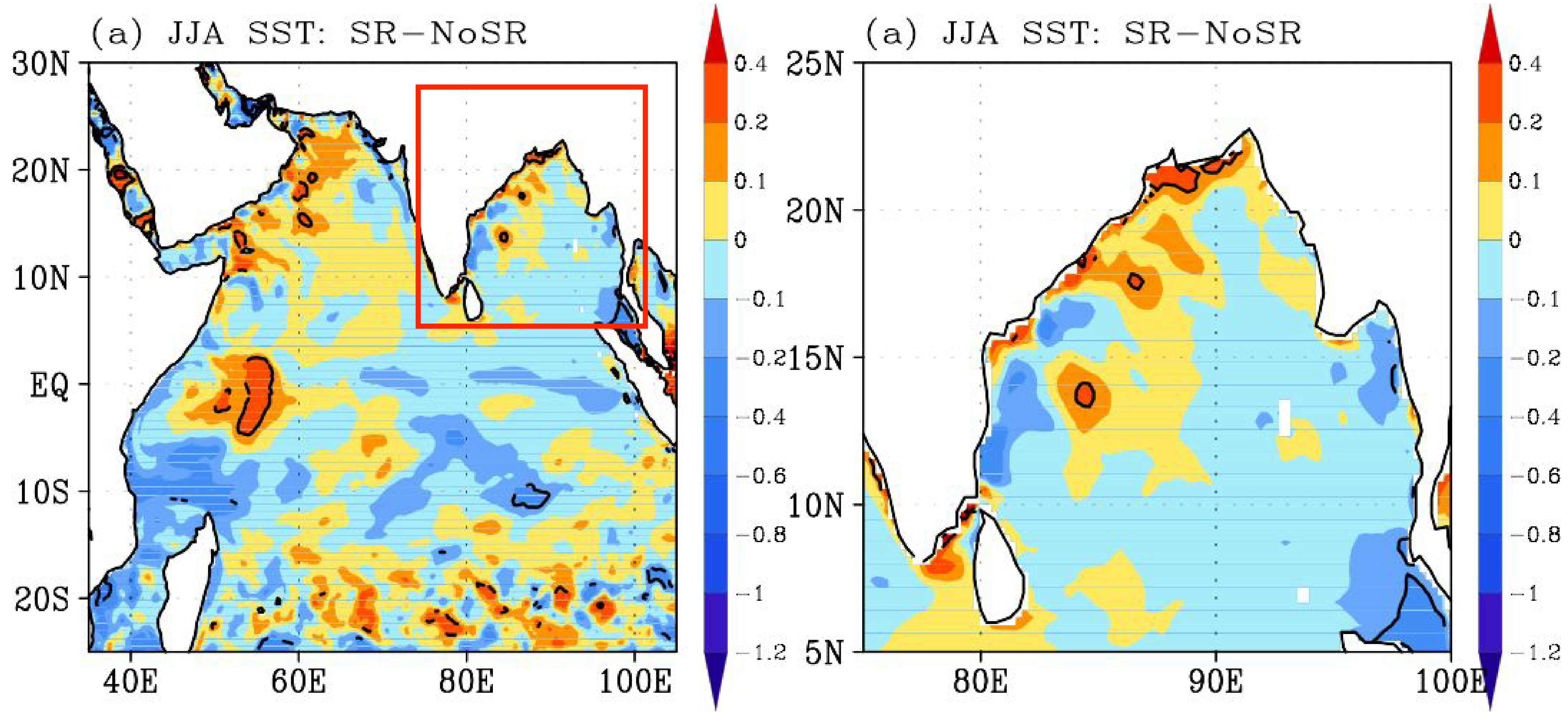
Summer BL, MLD, SST, wind and rainfall

Impact on summer BLT/MLD



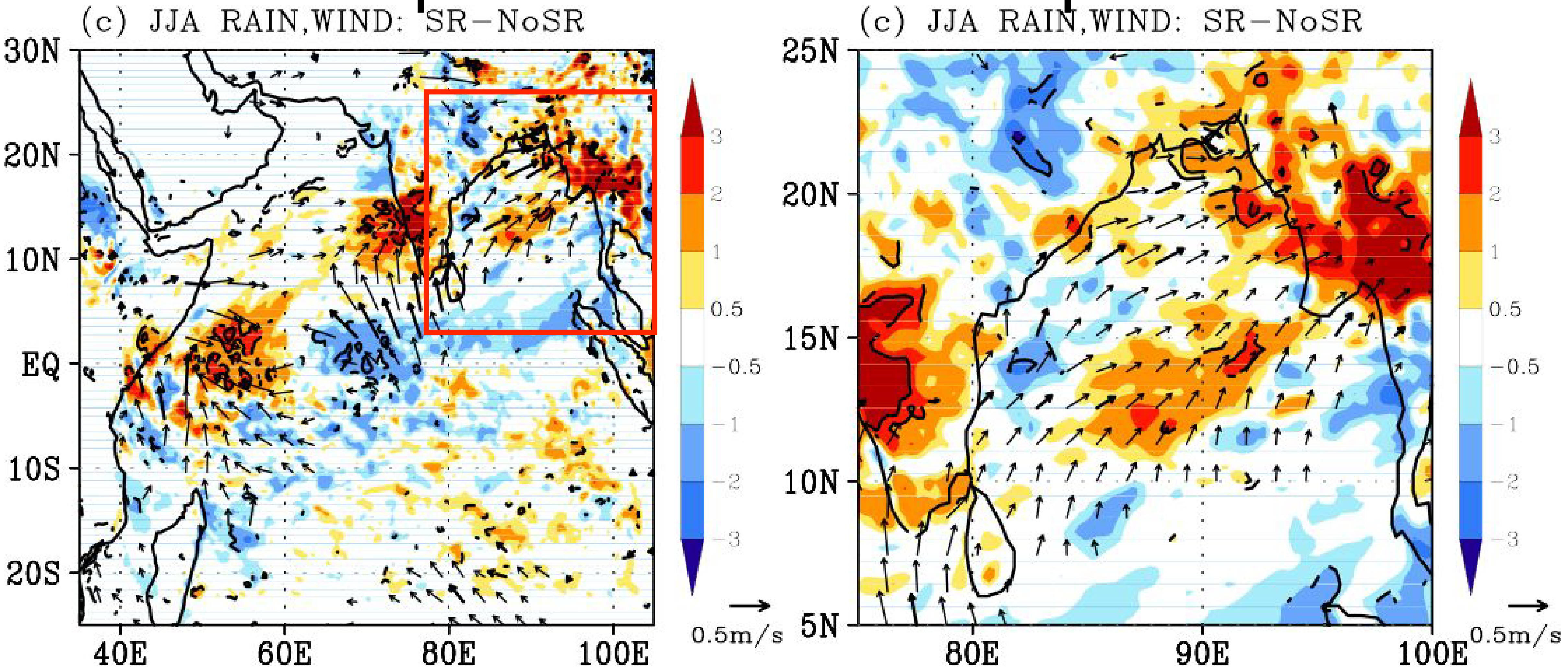
- BL thickens by up to 25-35 meters in summer confined to the coast.
- Enhanced stratification shoals the MLD by 25 meters, corresponding to the pattern in BL change.

Impact on summer SST



- Despite the *significant* change in BLT/MLD, there is *no significant* change in Bay-wide SST.
- because of the two competing effects...
- There are some localized patch of significant warming ~0.4C near the coast.

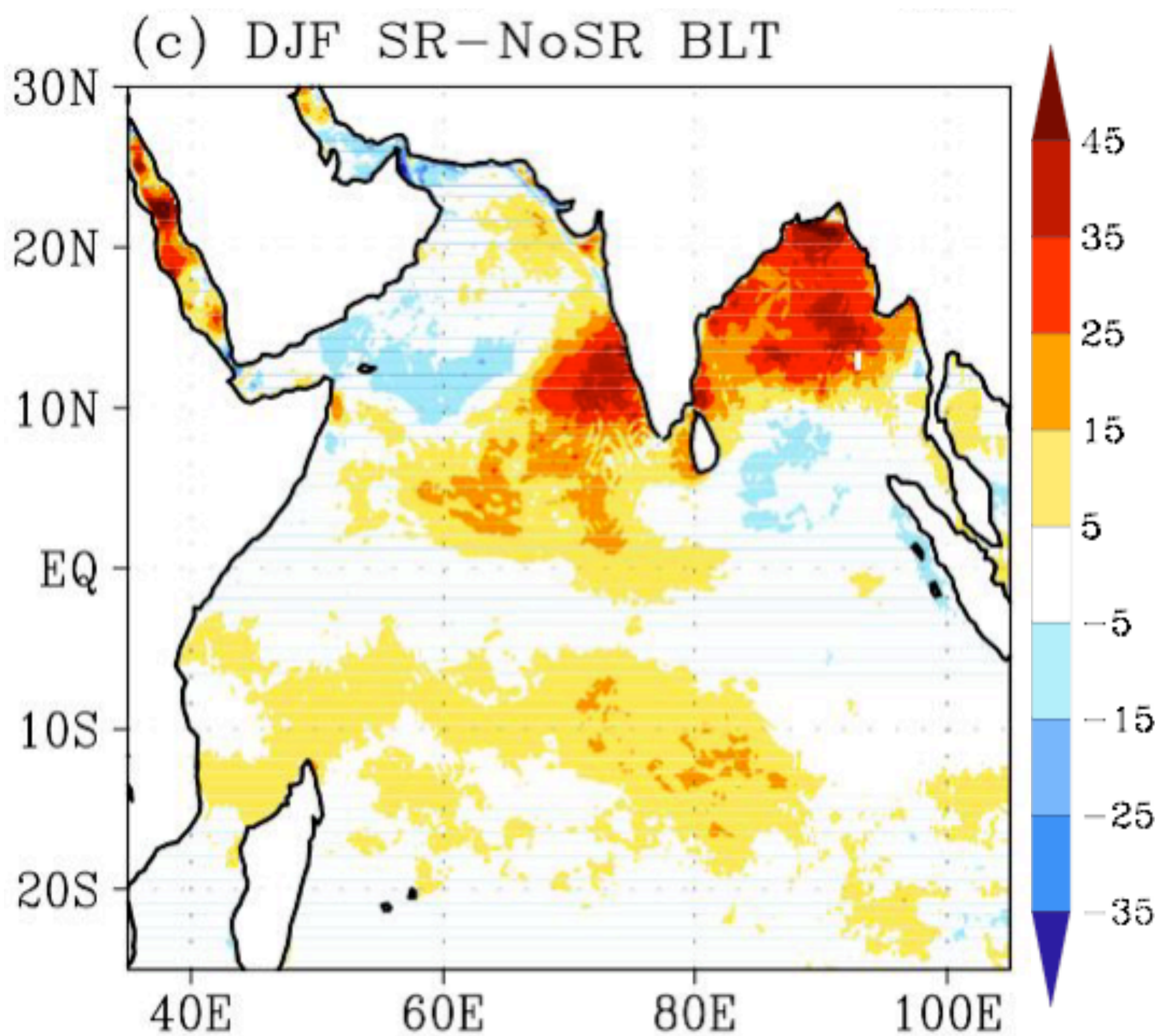
Impact on summer atmosphere

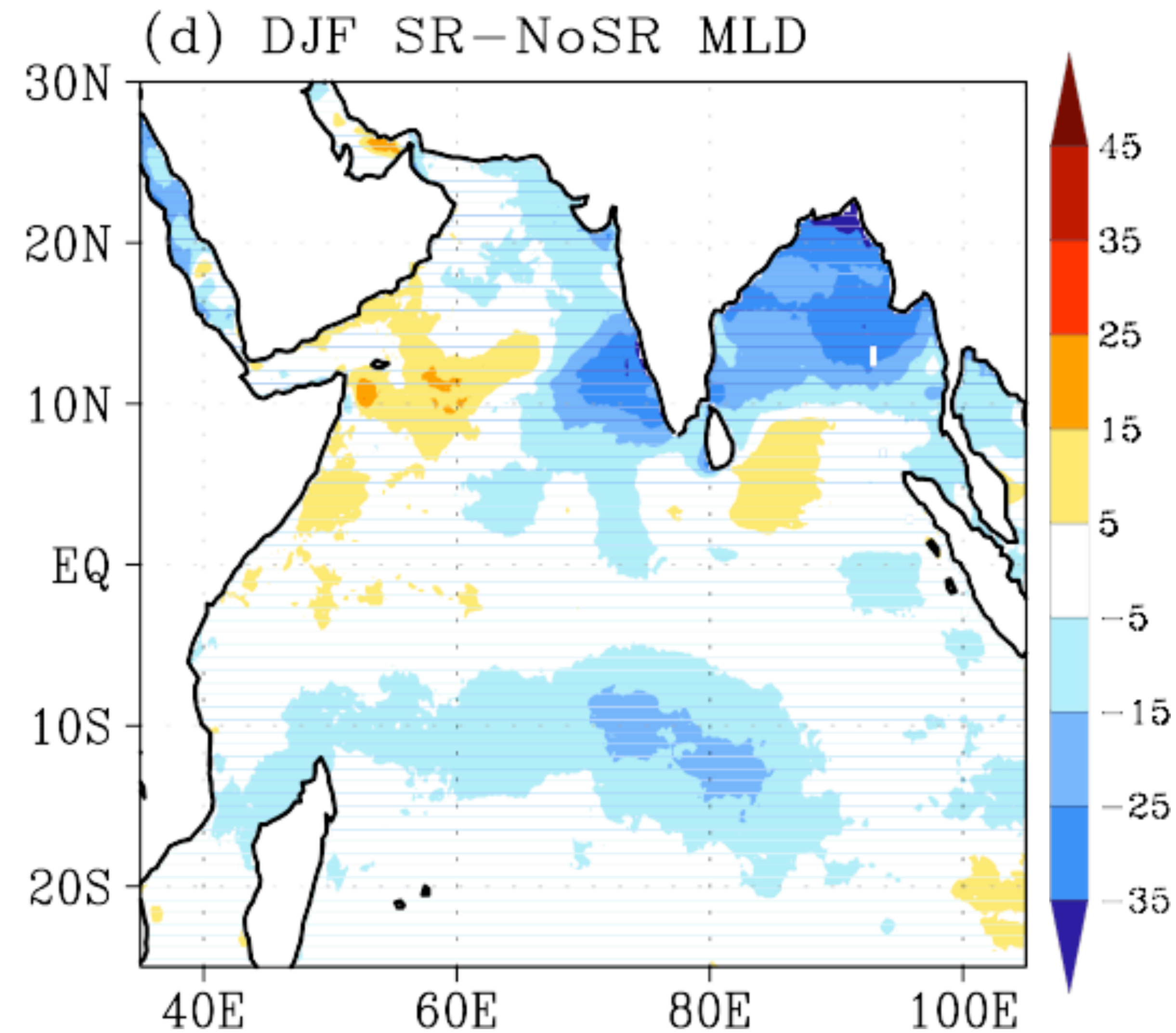


- Atmospheric response to *local SST change* seems weak.
- Remote influence (equatorial process), possibly involving northward propagating ISO anomalies, would be more important.
- Large model bias could have also played a role in weak response.

Winter BL, MLD, SST, wind and rainfall

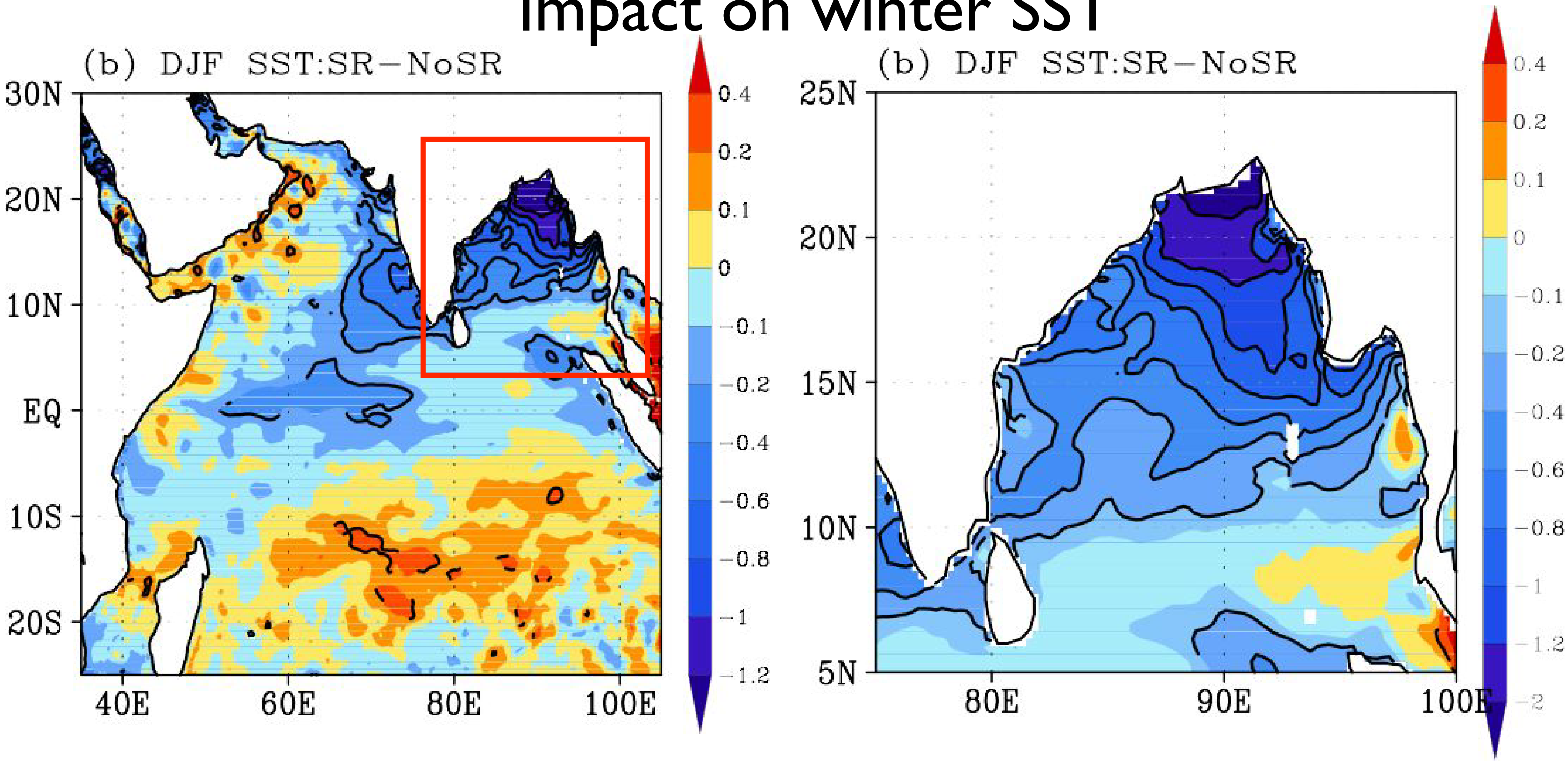
Impact on winter BLT/MLD





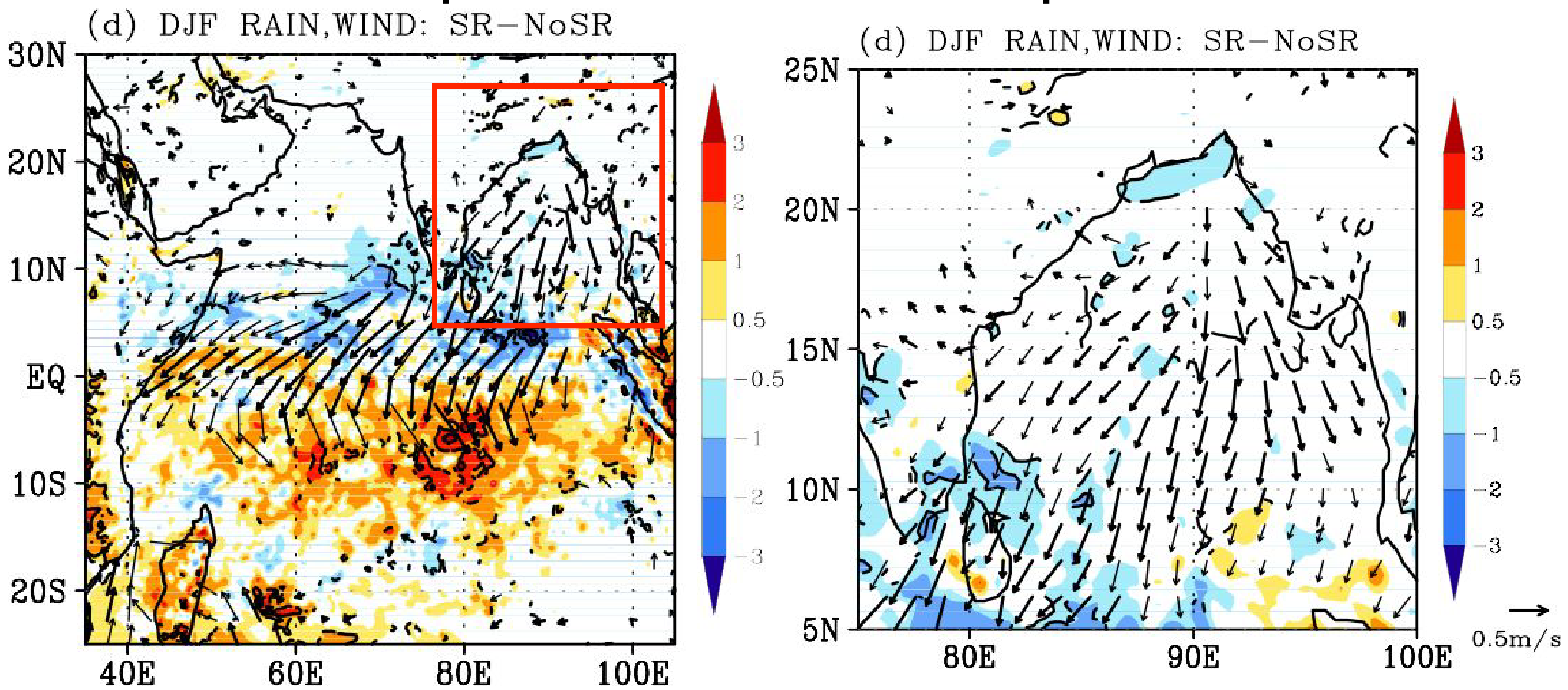
- BLT substantially increases by 40 meters over the entire BOB
- Thick BL also extends towards the SEAS via monsoon current.
- MLD again shows similar spatial pattern to BLT, shoaling more than 25 m in BOB and SEAS.

Impact on winter SST



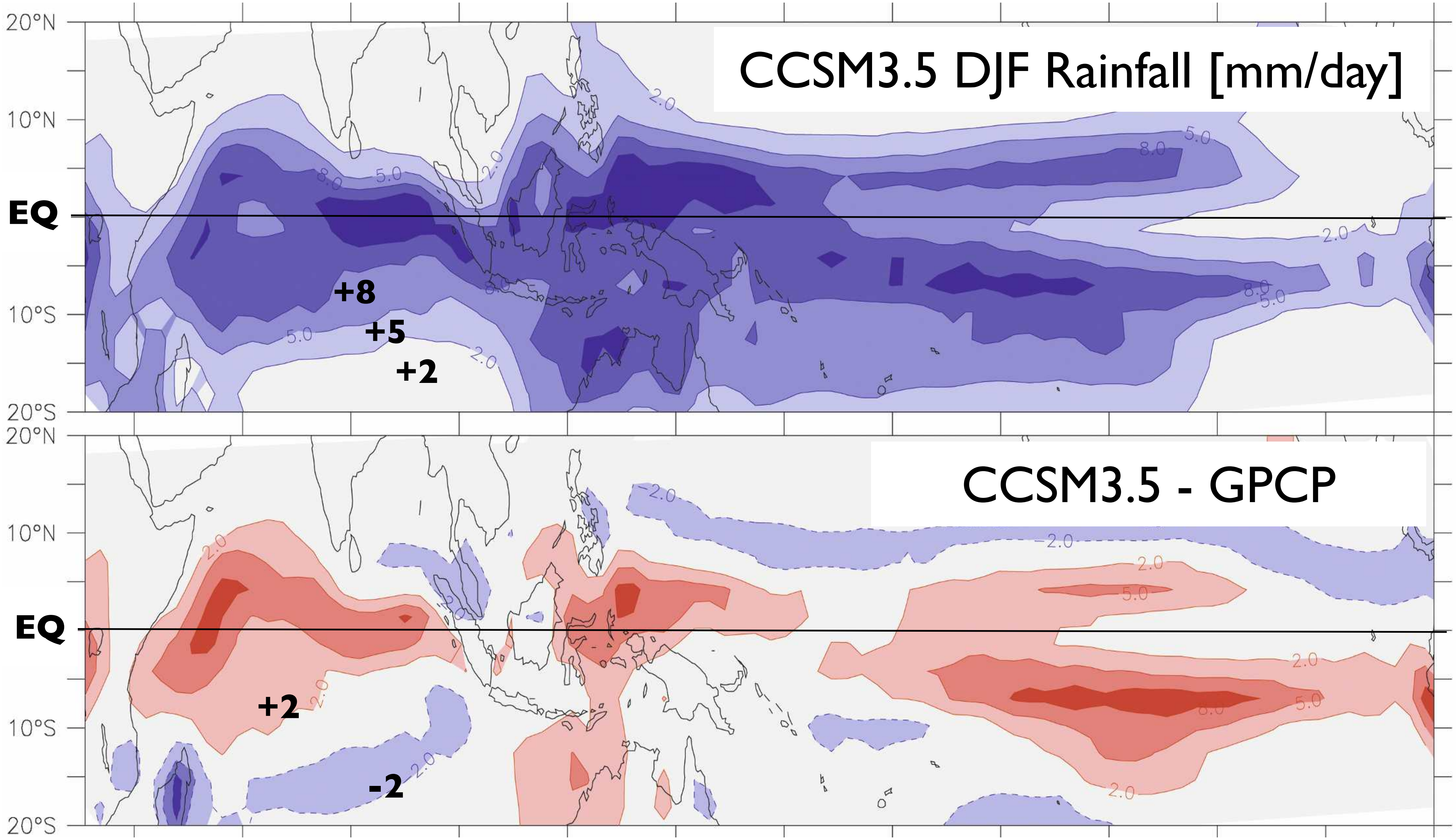
- Significant and spatially extensive reduction in SST over BOB and SEAS.
- Stronger surface cooling by
  - 1) wintertime surface cooling
  - 2) even shallower ML (~20 m)
- Cooling is trapped within this shallow ML

Impact on winter atmosphere



- Surface divergent flow originating from BOB and SEAS amplifies the NE monsoonal wind.
  - A linear baroclinic response of the troposphere to the diabatic cooling
- No significant change in local rainfall in BOB
  - Nonlocal response in rainfall beyond the Northern Hemisphere. Displaces the ITCZ southward.

DJF Rainfall bias in CCSM3.5 [*Jochum and Potemra 2008*]



- BL is known to be weak in CCSM3.5,
- DJF Rainfall bias: Excess precipitation north and near the equator
- Precipitation deficit south of the equator 10-15S
  - Any connection of BL dynamics to the rainfall bias?

Summary and discussions (1)

- A fully coupled high-resolution regional climate model is used to study the seasonal effect of freshwater forcing on the upper ocean stratification and the atmosphere over the Indian Ocean (Seo et al. 2009, J. Climate).
- BL begins to develop with the onset of SW monsoon, and reaches its maximum spatial extent and thickness during the NE monsoon.
- Boreal summer; despite the significant change in BLT and MLD, two competing effects lead to **no significant change in SST** [Howden and Murtugudde 2001; Sengupta and Ravichandran 2001].
  - Net surface heating
  - Thinning of ML (loss in SW and enhanced entrainment)
  - Enhanced evaporation
- Monsoon wind and rainfall are not sensitive to local SST change.
- Instead, the remote process from the equator seems more influential.

Summary and discussions (2)

- The freshwater forcing is most influential during the winter monsoon
  1) Maximum extent and thickness of BL (reaching over SEAS)
  2) Much shallower ML
  3) Net surface heat flux cooling
- Surface cooling (>-1C) is confined within the surface layer (~20 m)
  - Extensively over BOB and SEAS
  - Large subsurface (~40 m) warming (>+1C) below ML
- Heat flux damps this SST cooling with reduced evaporation.
- Non-local atmospheric response:
  - Strong divergent flows extending from BOB/SEAS into the Southern Hemisphere.
  - Shift the ITCZ southward at 10S

- *Future work*
  1) More rigorous way to implement the river discharge,
  2) Reduce the model bias,
  3) Survey of BL effect in the AOGCMs for robust sensitivity

Thanks!