4th International Conference on ENSO

Ocean and Climate Models Improvement by Including the Surface wave：From Surface wave to ENSO

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Outline

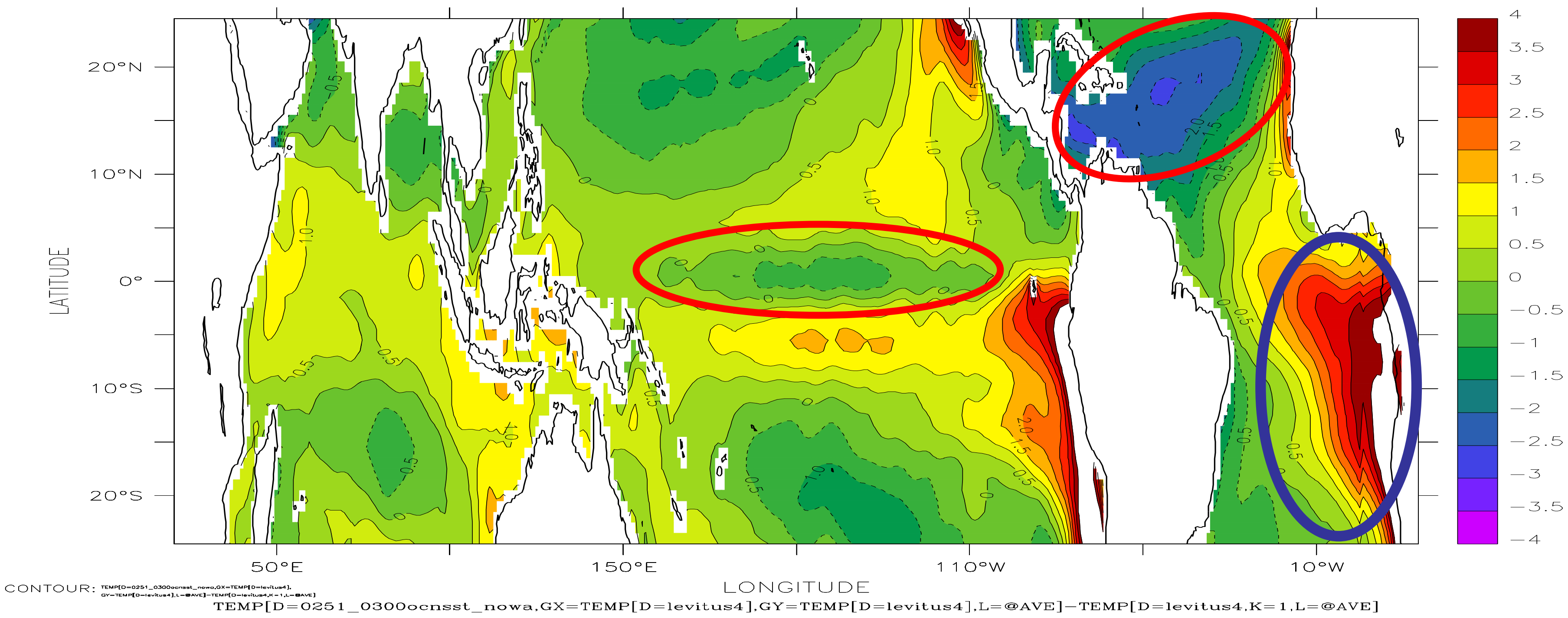
1. Challenges faced and the non-braking surface wave-induced vertical mixing
2. Surface wave in ocean models
3. Surface wave in climate models
4. Summary

1. Challenges faced and the non-braking surface wave-induced vertical mixing

Long-standing challenges for climate models:

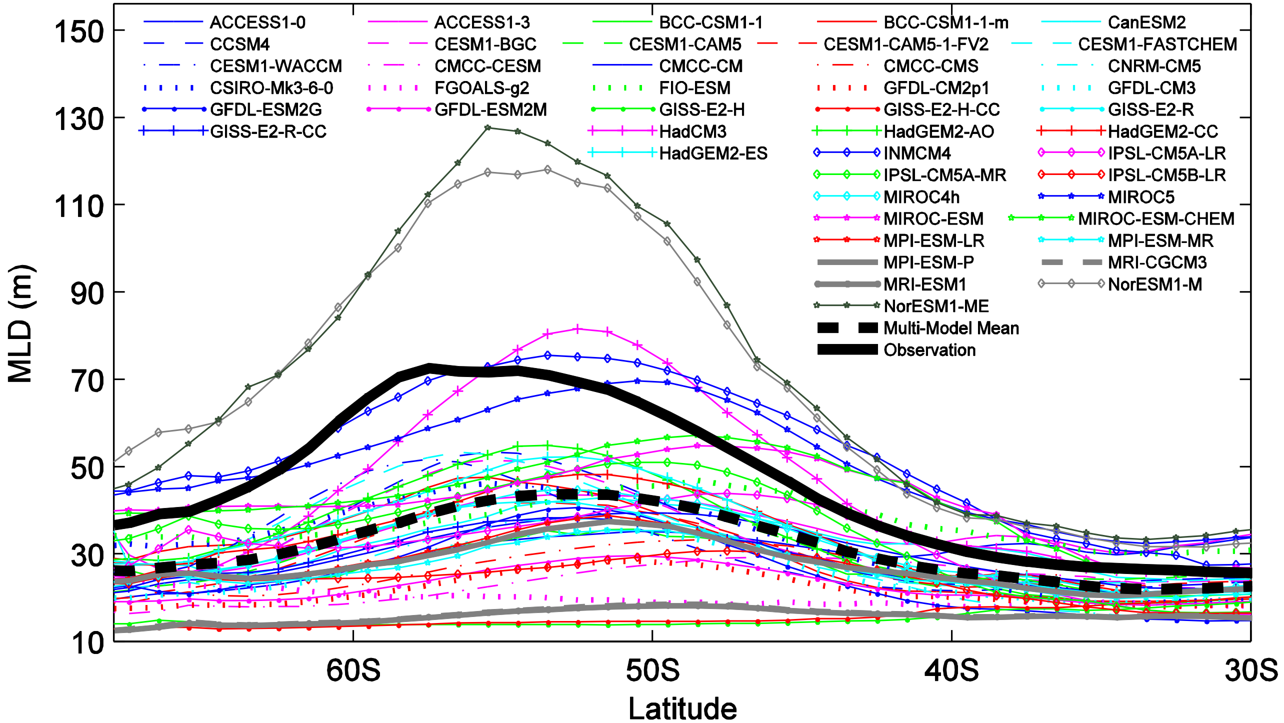
- □ **Why anomaly?**
- □ **Tropical bias such as too cold tongue in tropical Pacific etc.**

Tropical biases: a common problem for all climate models



Song et al, 2012, JGR

MLD in CMIP5 models

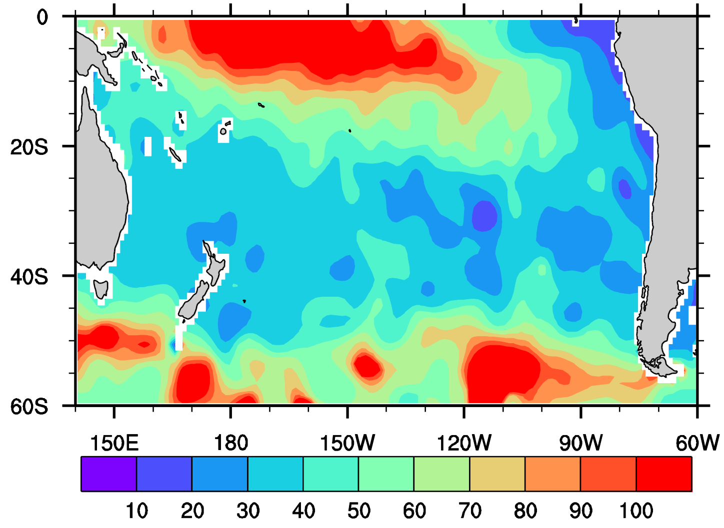


Huang et al, 2014, JGR

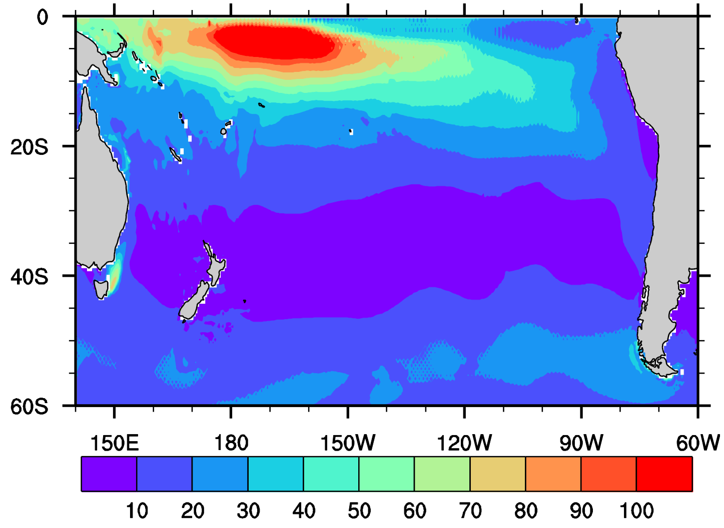
Long-standing challenges for OGCM models:

Simulated SST is overheating in summertime, and mixed layer depth is too shallow (Martin 1985; Kantha 1994; Ezer 2000; Mellor 2003; Qiao etal, 2016).

MLD in OGCM: Lack of mixing in the upper ocean



✓ Observation



✓ Model simulation

Governing equations of OGCMs: two high uncertainties of ocean mixing and air-sea fluxes

$$\frac{\partial U_i}{\partial x_i} = 0$$

$$\frac{\partial U_i}{\partial t} + U_k \frac{\partial U_i}{\partial x_k} + \varepsilon_{ilk} f_l U_k = \boxed{\frac{\partial}{\partial x_k}\left(-\langle u_k u_i \rangle\right)} + \frac{\partial}{\partial x_k}\left(\nu E_{ik}\right) - \frac{1}{\rho_0}\frac{\partial P}{\partial x_i} - g_i\left(\frac{\rho}{\rho_0}\right)$$

$$\frac{\partial T}{\partial t} + U_k \frac{\partial T}{\partial x_k} = \boxed{\frac{\partial}{\partial x_k}\left(-\langle u_k \theta \rangle\right)} + \frac{\partial}{\partial x_k}\left(\kappa \frac{\partial T}{\partial x_k}\right)$$

Turbulence

$$\frac{\partial S}{\partial t} + U_k \frac{\partial S}{\partial x_k} = \boxed{\frac{\partial}{\partial x_k}\left(-\langle u_k s \rangle\right)} + \frac{\partial}{\partial x_k}\left(D \frac{\partial S}{\partial x_k}\right)$$

$$\rho = \rho(T, S, P)$$

Surface boundary conditions including heat, moment, and E_P fluxes

What is turbulence?

Richard Feynman (Nobel Prize, 1965)
“turbulence is *the most important unsolved problem of classical physics."*

Werner Heisenberg (Nobel Prize, 1932) was asked what he would ask God, given the opportunity. His reply was: *"When I meet God, I am going to ask him two questions: Why relativity? And why turbulence? I really believe he will have an answer for the first."*

How surface waves affect OGCM?

- Breaking wave induced stress and energy flux (*Craig and Banner, 1994; He and Chen, 2011*)
- Coriolis-Stokes force (*Polton et al., 2005*)
- Langmuir circulation (*Kantha and Clayson*, 2004)
- Wave-induced shear (*Pleskachevsky et al., 2011)*
- Wave-turbulence interaction enhanced mixing

(Qiao et al, 2004, 2010,2016) . The non-breaking wave induced vertical mixing is the key

$$B_V = \alpha \iint_{\vec{k}} E\left(\vec{k}\right) \exp\left\{2kz\right\} d\vec{k} \, \frac{\partial}{\partial z} \left(\iint_{\vec{k}} \omega^2 E\left(\vec{k}\right) \exp\left\{2kz\right\} d\vec{k} \right)^{1/2}$$

E(K) is the wave number spectrum which can be calculated from a wave numerical model. It will change with (x, y, t), so Bv is the function of (x, y, z, t).

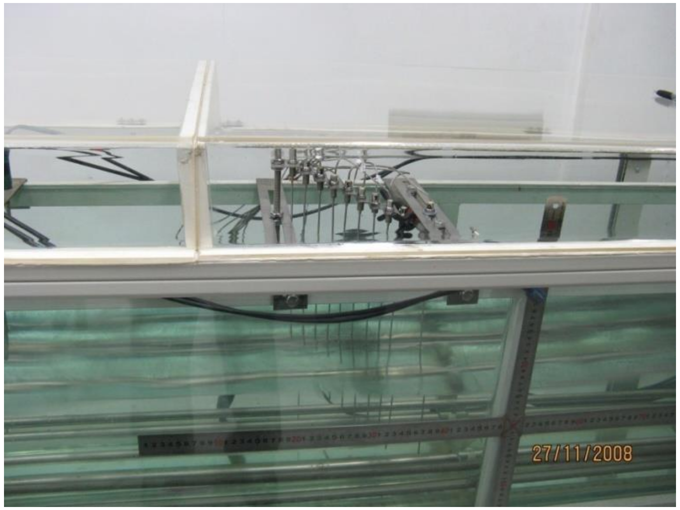
Qiao et al, GRL, 2004; OD, 2010; RS, 2016

If we regard surface wave as a monochramatic wave,

$$B_v = \alpha A^3 k \omega \, e^{(-3kz)} = \alpha A \, u_s \, e^{(-3kz)} \; ,$$

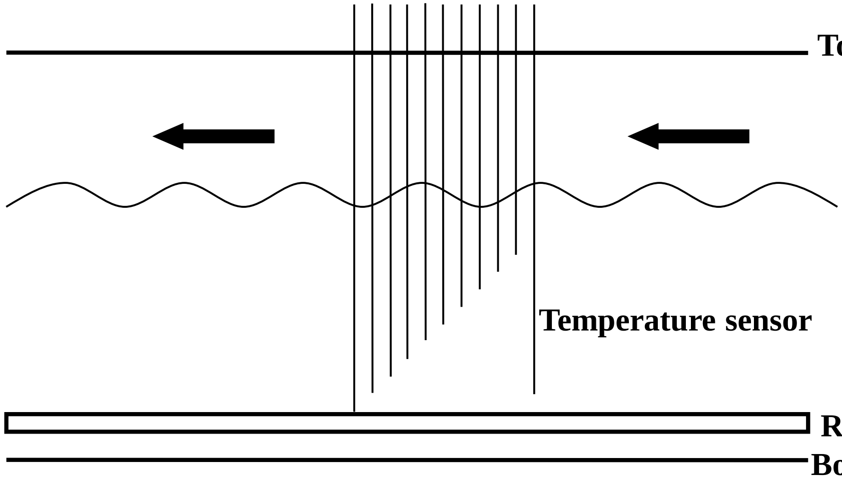
Stokes Drift

Bv is wave motion related vertical mixing instead of wave breaking.



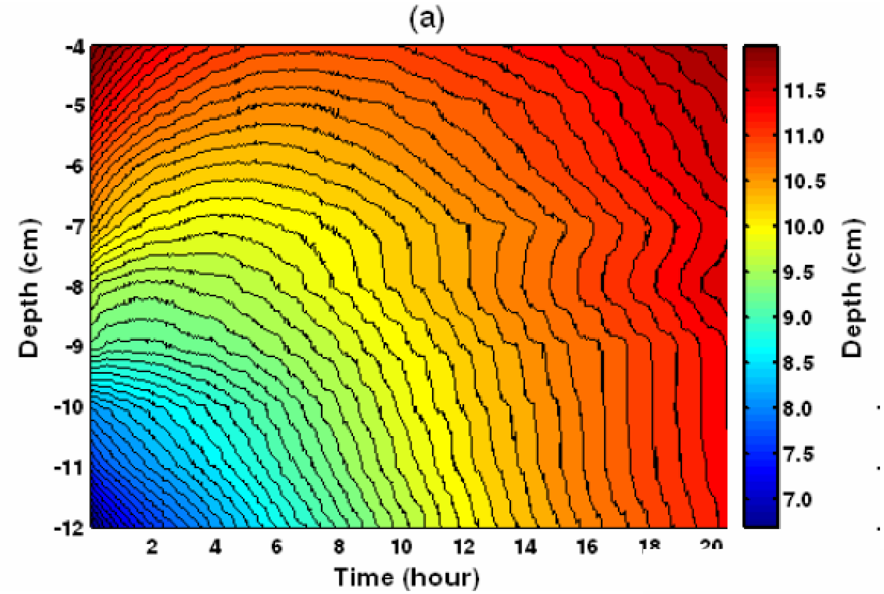
Laboratory experiments reveals that the non-breaking surface wave can generate strong turbulence:

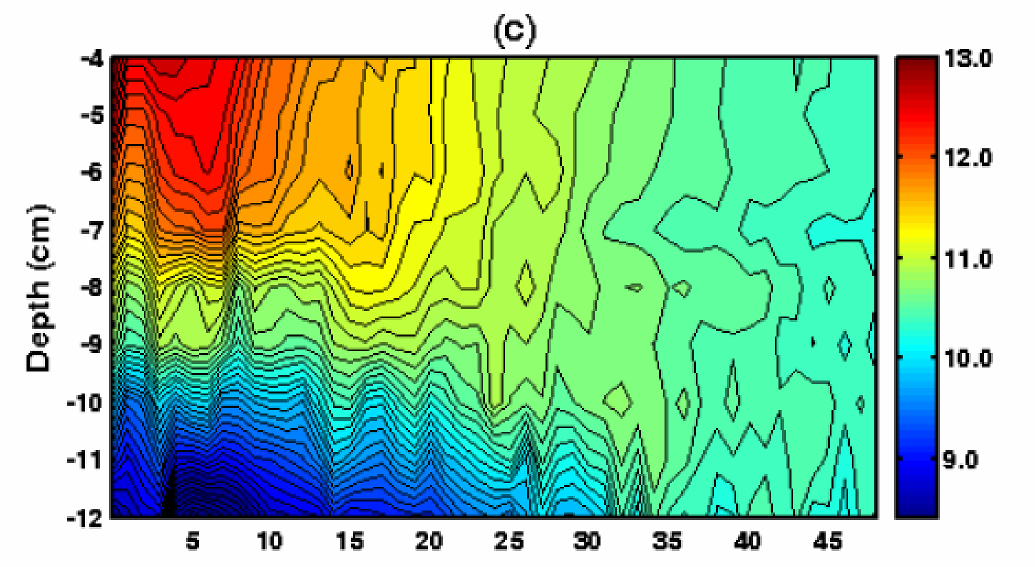
To generate temperature gradient through bottom cooling of refrigeration tubes.



Dai and Qiao et al, JPO, 2010

Experiment results without and with waves

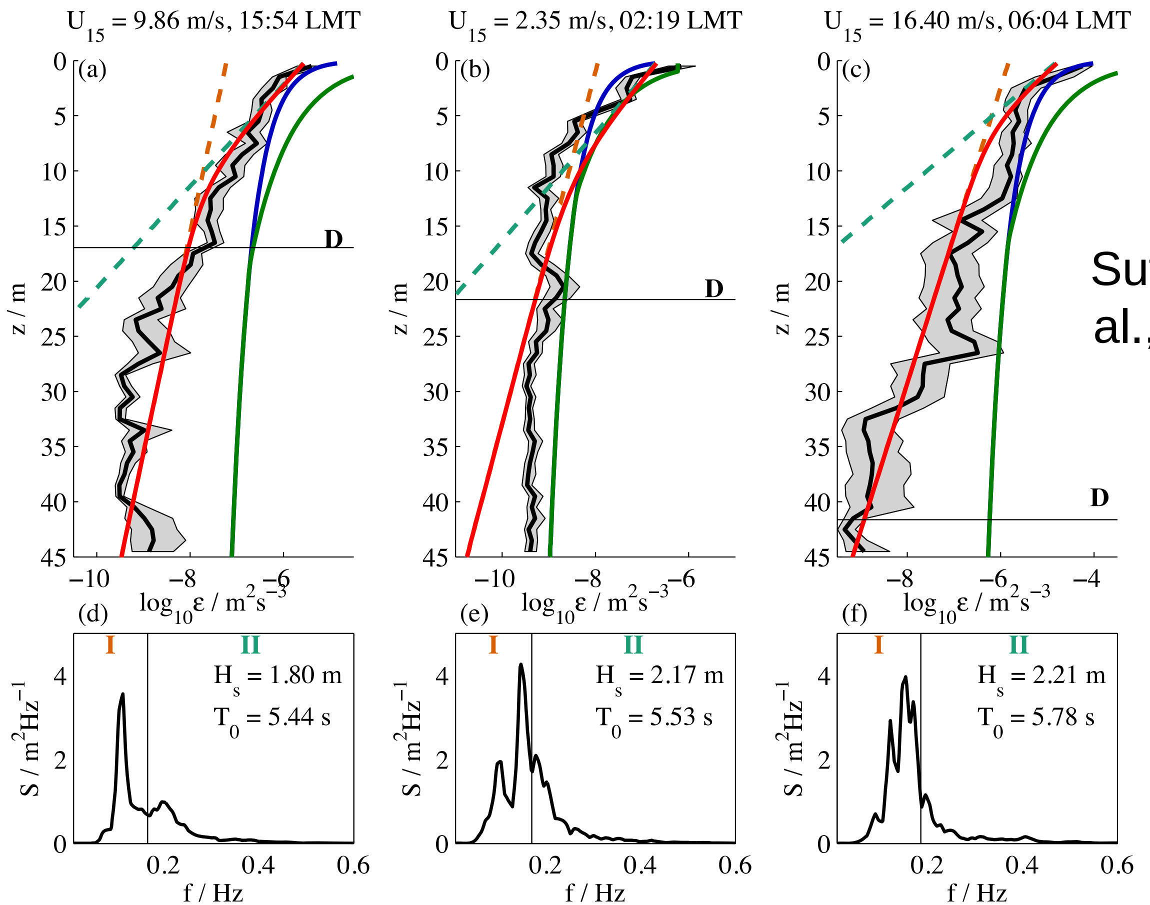




Blue line
Osborn, 1980

Green line
Terray et al. (1996)

Red line
Huang and Qiao (2010)



Sutherland et al., 2013, OS

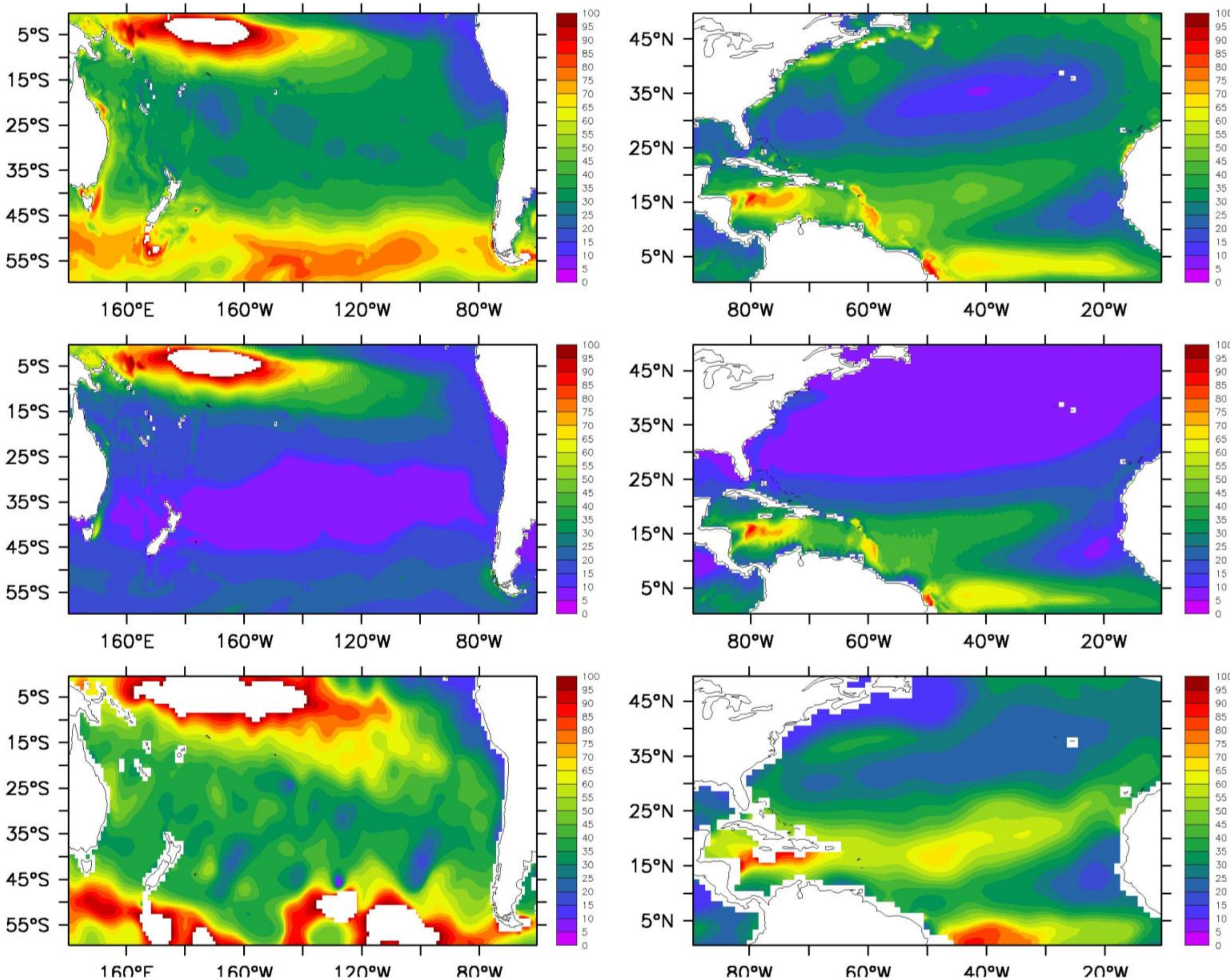
Fig. 10. Profiles of turbulent kinetic energy dissipation **(a–c)** for a particular wave spectra **(d–f)**. Five successive profiles of ϵ taken over one hour are averaged vertically into 1 m bins with the solid black line showing the mean and the grey shaded region the 95 % confidence intervals determined using a bootstrap method. The depth dependence of ϵ is compared with Eq. (5) (blue line), scaling of Terray et al. (1996) (green line), and the wave scaling of Huang and Qiao (2010) (red line) using portions of the wave spectra along with Eq. (6) (dashed lines with colours matching the corresponding spectral region marked by I, and II in **d–f**). The red line denotes the sum of the wave scaling turbulence profiles from section I and II, i.e. the dashed orange line plus the dashed green line. The values of H_s and T_0 for each wave spectra are computed for the entire spectra. The mixed layer depth is the black horizontal line denoted by D.

2. Surface wave in ocean models

Wave effects: MLD in summer (Qiao et al, OD, 2010)

MLD of the Southern Pacific in Feb.

MLD of the Northern Atlantic in Aug.



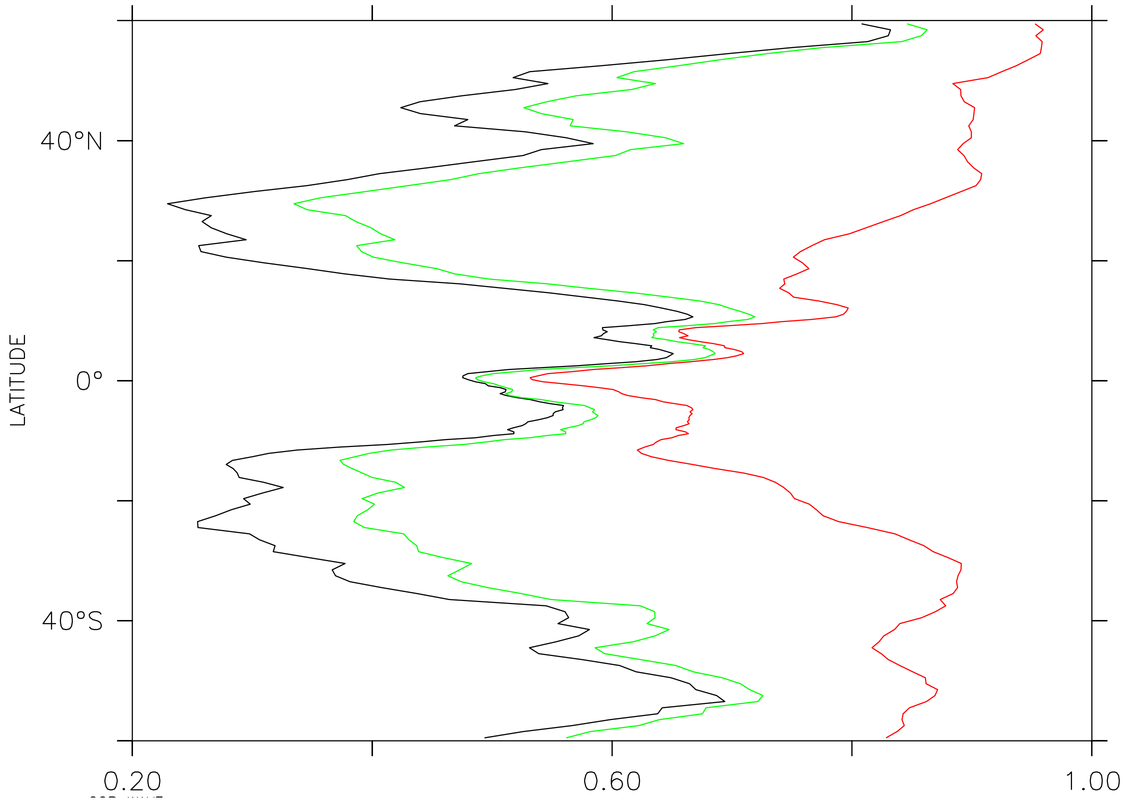
With wave-induce mixing

Without wave-induce mixing

World Ocean Atlas

The two lines represent the whole upper ocean: Zonal (x-direction) and upper 100m (z-direction) averaged correlation coefficient (t).

Black, POM2008 without wave effects; Green: with wave breaking (and IW) suggested by Mellor (2004, JPO); Red: with Bv



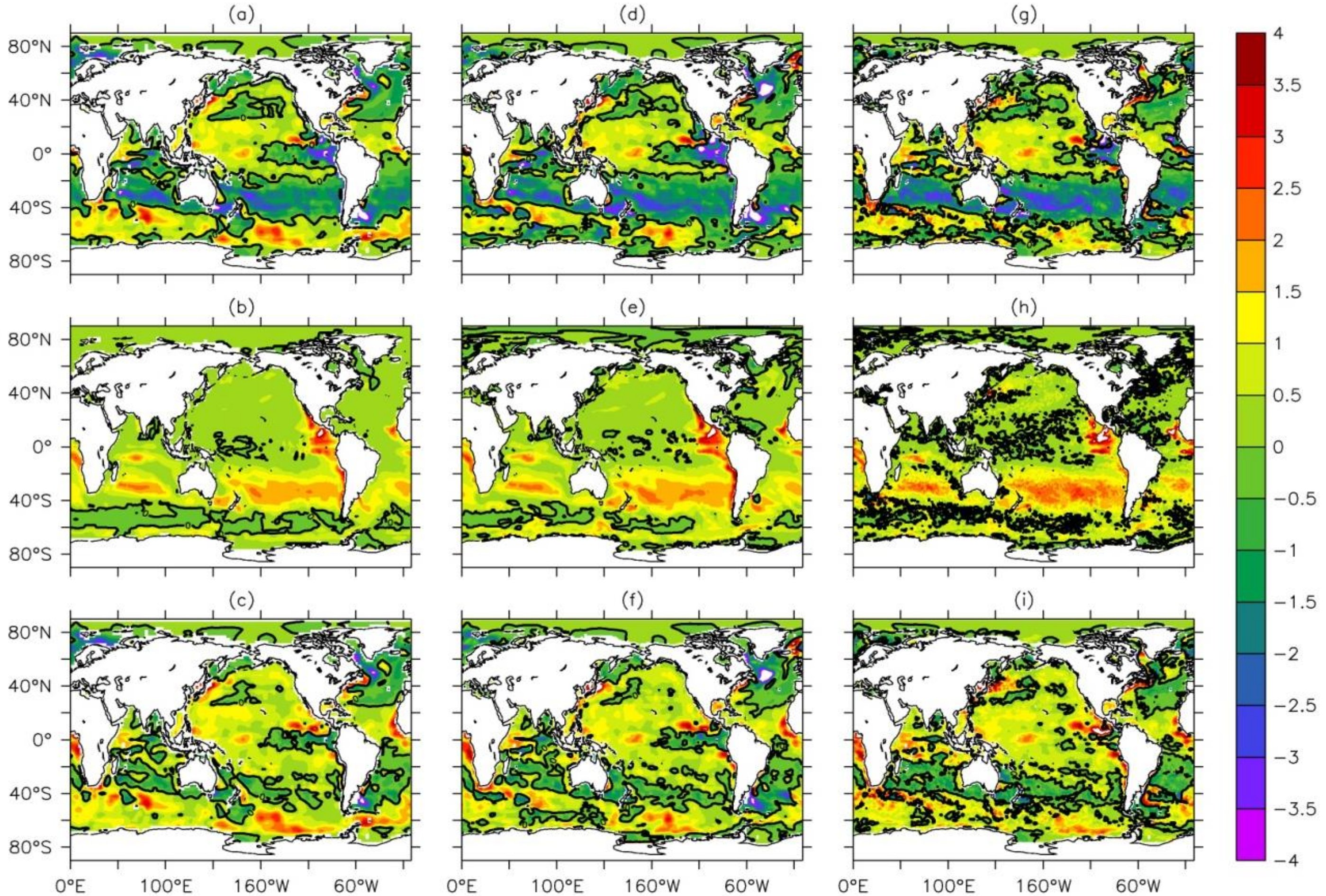
Bv in NEMO: cooperated with Prof Adrian New of NOC, UK

2° **1°** **1/4°**

No Bv

Bv effect

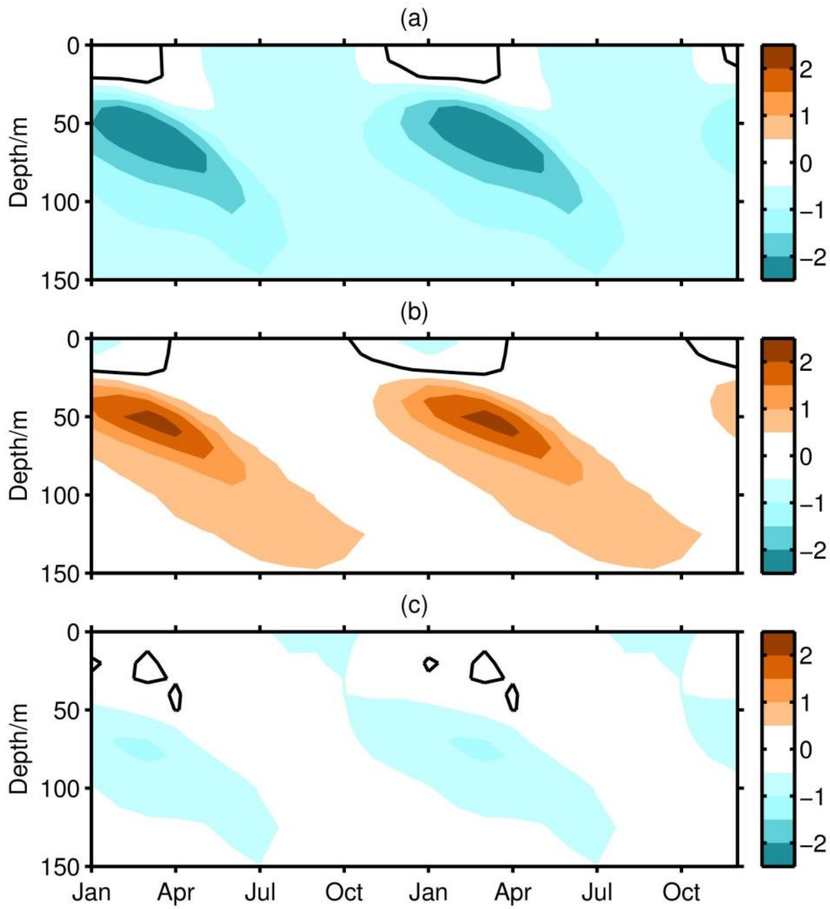
With Bv



Simulated temperature difference at 50m in February

Temperature differences: cooperated with Prof G Lohmann of AWI, Gernany

Temperature Difference of 30S



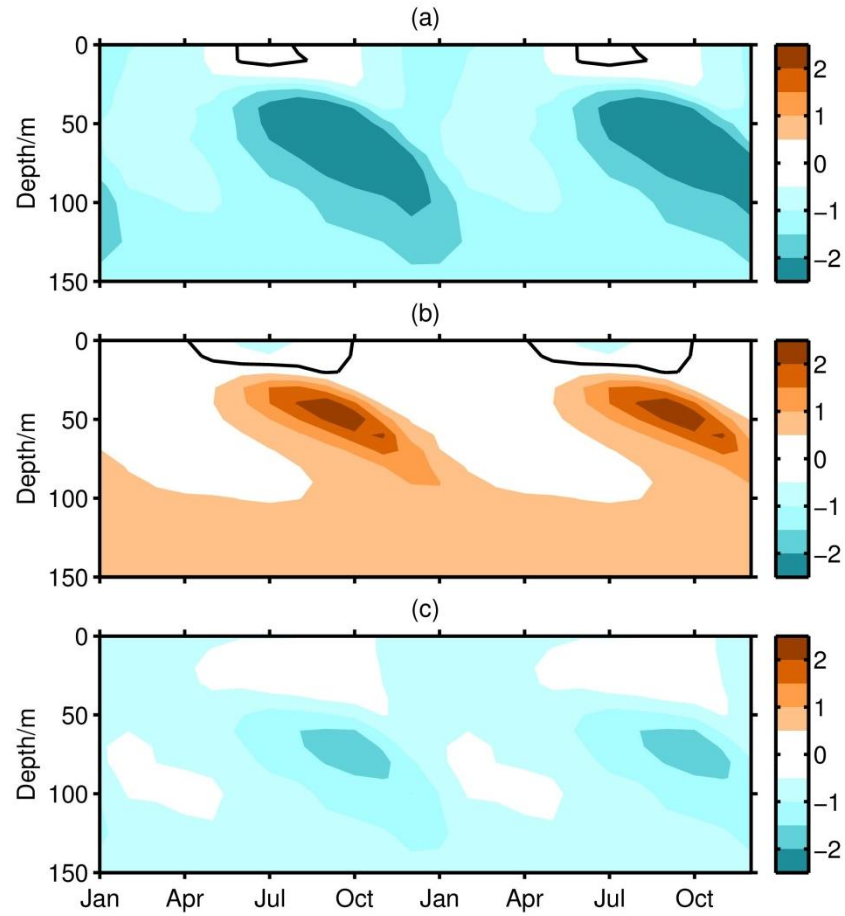
(a) without Bv - WOA09

(b) with Bv - without Bv

(c) with Bv - WOA09

black line - zero line

Temperature Difference of 30N



(a) without Bv - WOA09

(b) with Bv - without Bv

(c) with Bv - WOA09

black line - zero line

To close the traditional shear-induced turbulence

$$\frac{D}{Dt}\left(\frac{q^2}{2}\right) - \frac{\partial}{\partial z}\left[K_q \frac{\partial}{\partial z}\left(\frac{q^2}{2}\right)\right] = P_S + P_b - \varepsilon,$$

(Mellor and Yamada, 1982)

Numerical experiments for closing the shear-related vertical mixing
POM covering 72°S -65°N is selected;
Zonal resolution 1°, while meridional resolution is 1/3° between 10°S-10°N, and gradually increases to 1° by 20°N and 20°S;
32 sigma levels;
The background mixing of 1×10^{-4} m^2 s^{-1} (K_{m0}) for viscosity and 1×10^{-5} m^2 s^{-1} (K_{h0}) for diffusivity.

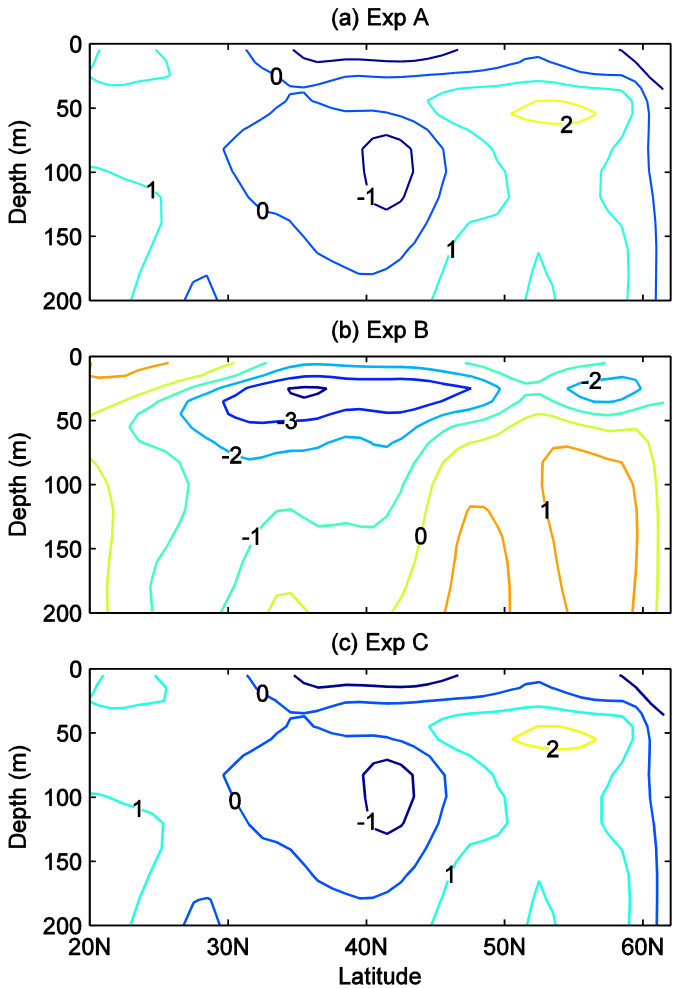
Experiment A: MY(Ps) + MY(Pb) + Bv + BG
Experiment B: MY(Ps) + MY(Pb) + BG
Experiment C: MY(Pb) + Bv + BG

- Too cold subsurface temperature in Exp B
- Temperature difference in Exp C is very similar as that in Exp A

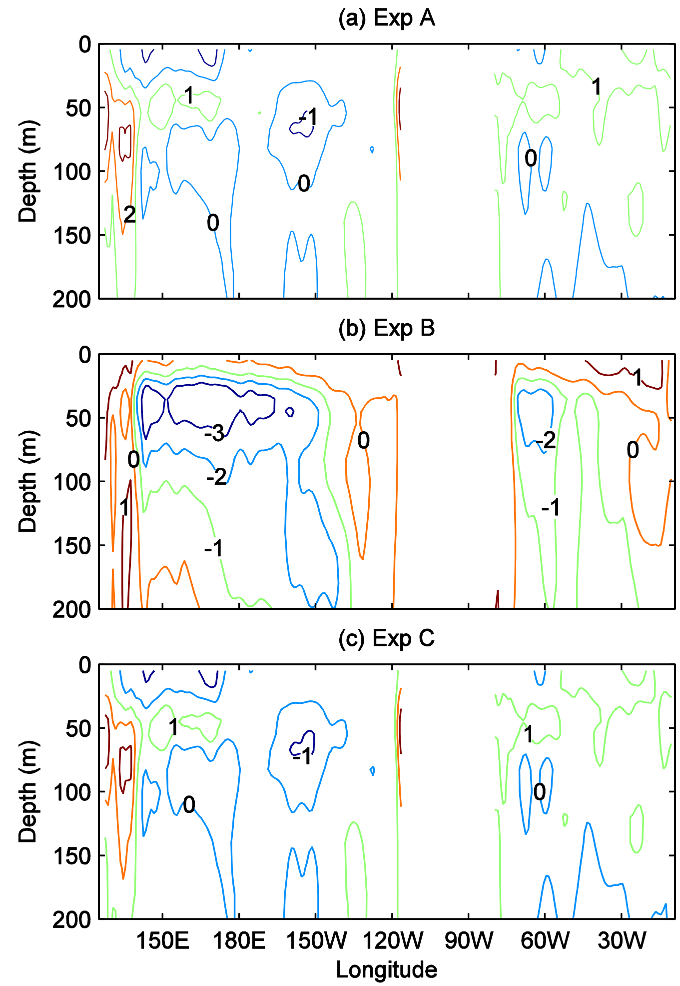
MY+Bv

MY

Bv

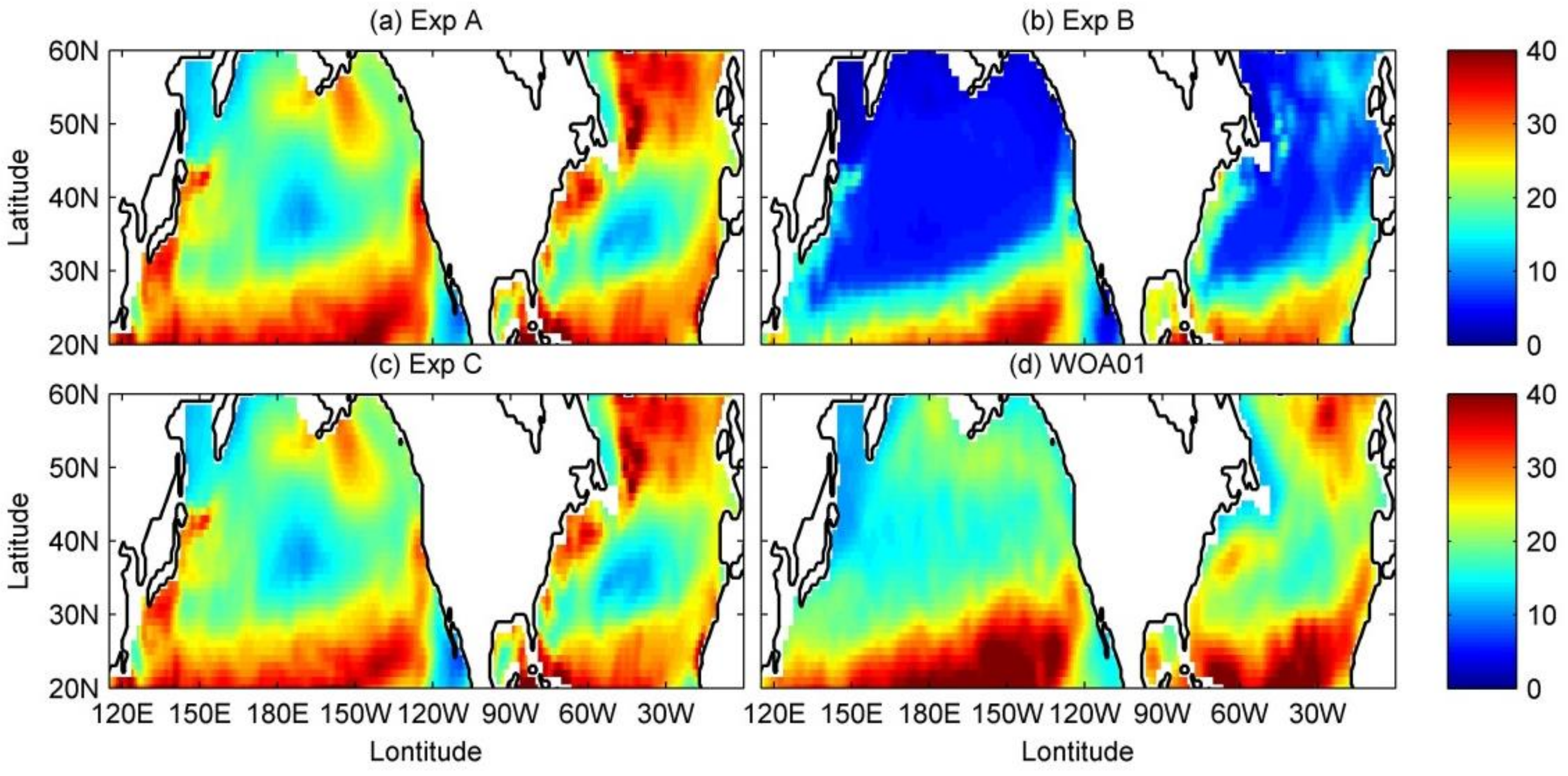


Temperature deviations from the climatology averaged in August along the dateline



Temperature deviationss from the climatology averaged in August along 30ºN

Simulated MLD (in m) in August from (a) Exp A, (b) Exp B, (c) Exp C, and (d) that from the climatology.



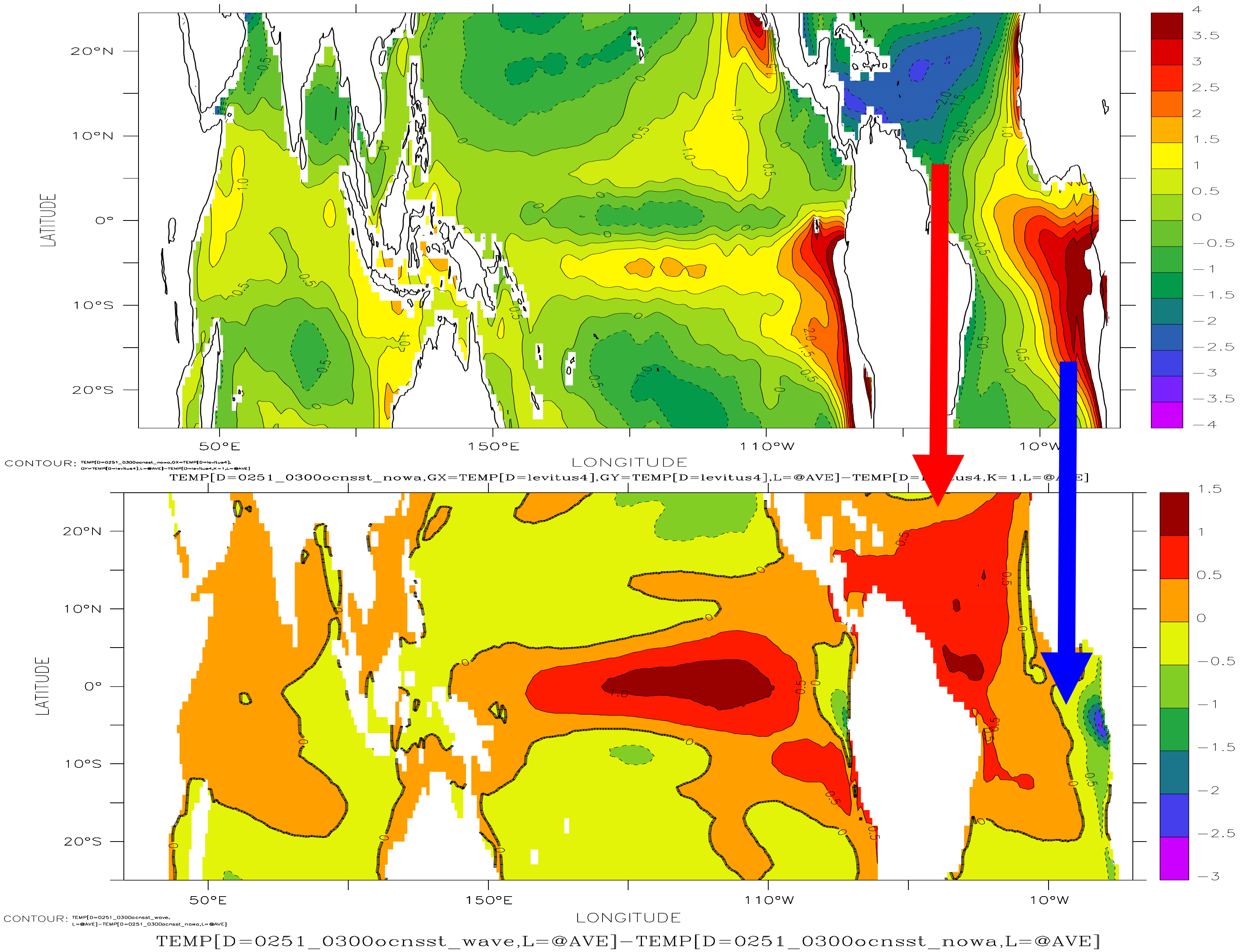
Applications of Bv in their ocean models

- Lin, X., S.-P. Xie, X. Chen, and L. Xu (2006), J. Geophys. Res., 111, C11017, doi:10.1029/2006JC003504.【**China, USA**】
- Fan, Y., and S. M. Griffies (2014), Journal of Climate, DOI: 10.1175/JCLI-D-13-00583.1【**GFDL, USA**】
- Ghantous, M., andA.V.Babanin(2014), Acta Physica Slovaca, 64 (1): 1-56 【**France, Australia**】
- Wu, L., A. Rutgersson, and E. Sahlee (2015), J. Geophys. Res. Oceans, 120, 8210–8228, doi:10.1002/ 2015JC011329【**Uppsala University, Swe**den】.
- Torma1, P., and T Krámer1 (2016), Periodica Polytechnica Civil Engineering, DOI: 10.3311/PPci.8883 【**Budapest University of Technology and Economics, Hungary** 】
- Sun, Y., J. Pan and W. Perrie (2016), doi:10.5772/64099【**Bedford Institute OF Oceanography, Canada**】
- Lohmann, G., Q. Shu, Q. Wang et al (2016), FESOM【**AWI，Germany**】
- New, A et al （2015）NEMO【**NOC，UK**】

4. Surface wave in climate models

FGCM0, LASG

CCSM3, NCAR

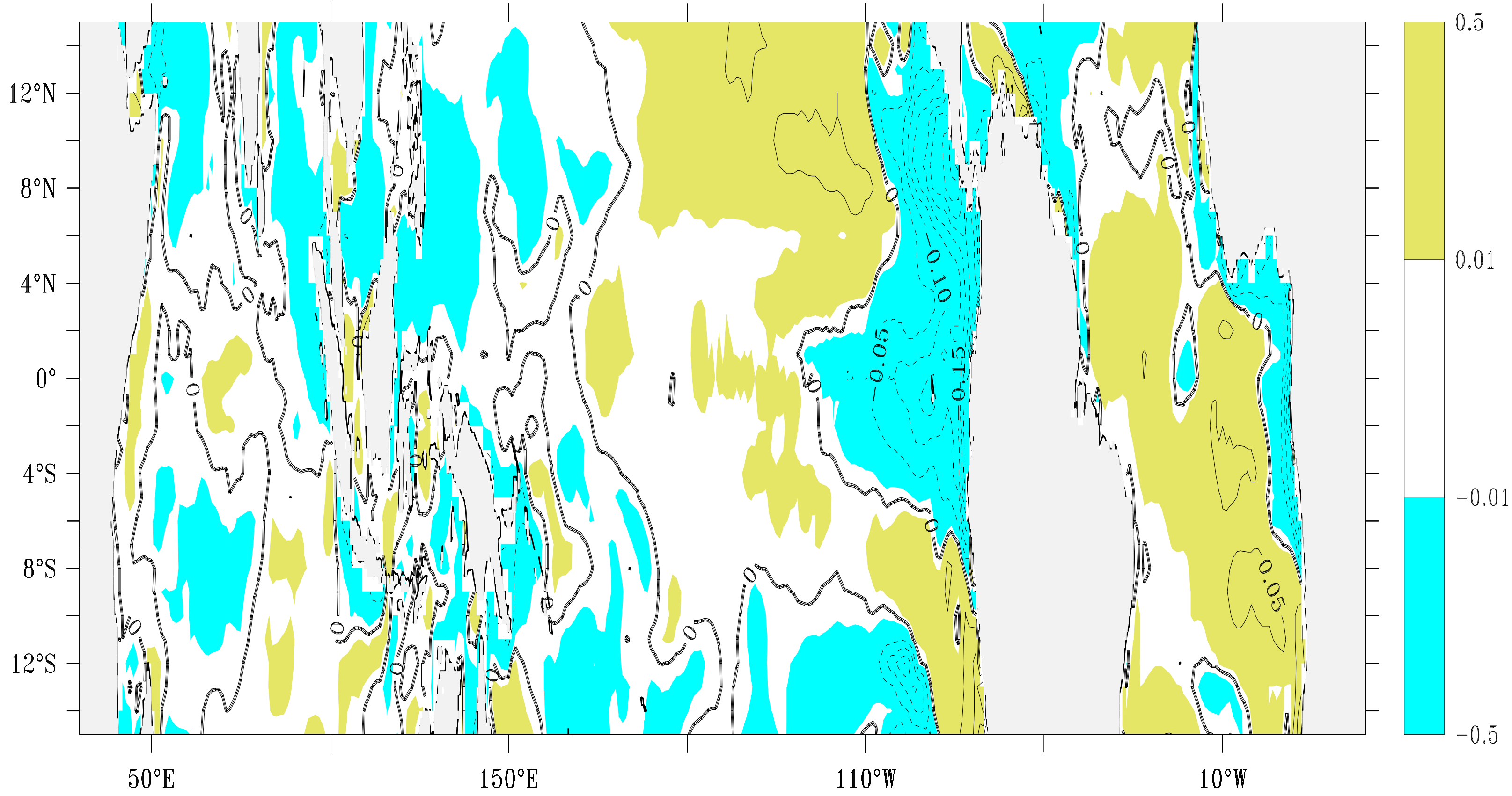


50a averaged SST (251-300a).

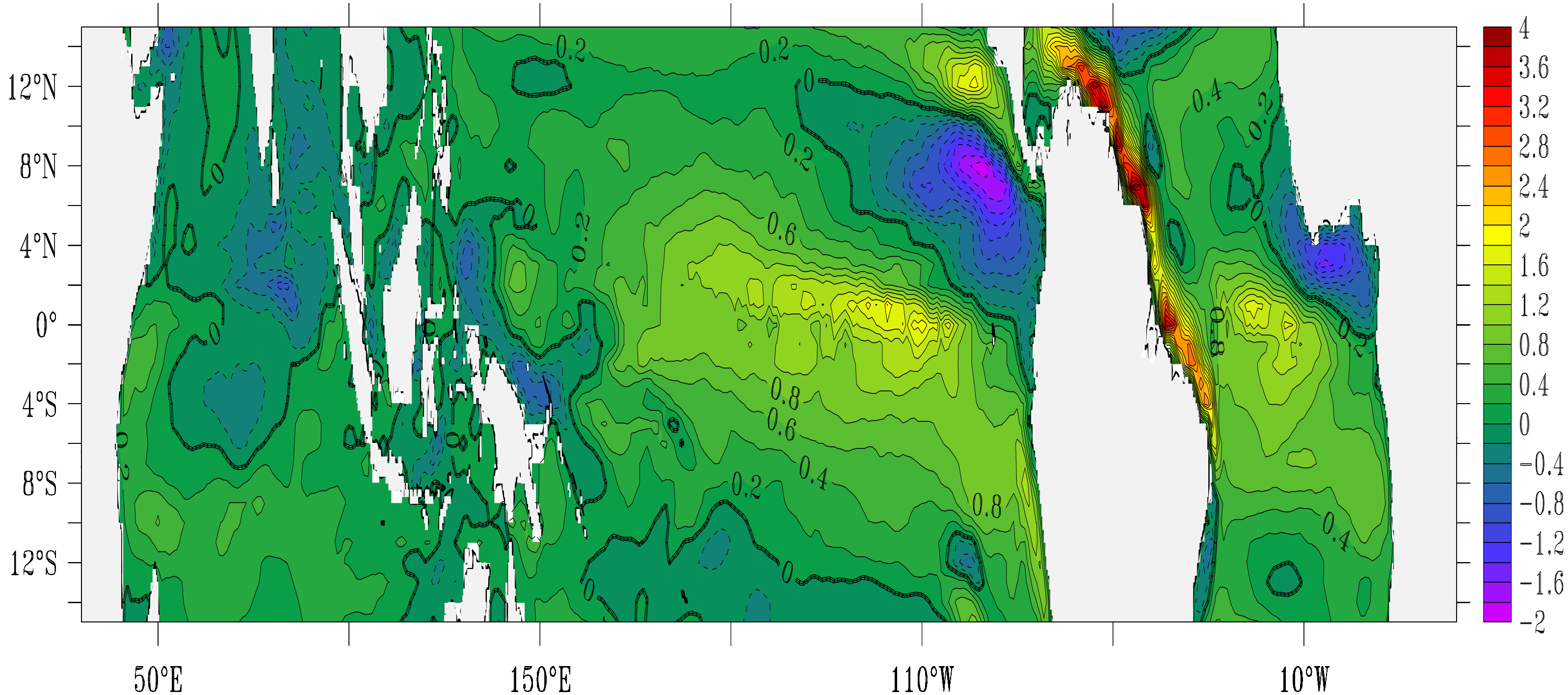
Up: Exp1-Levitus, Down: Exp2-Exp1

Exp1: CCSM3 without Bv

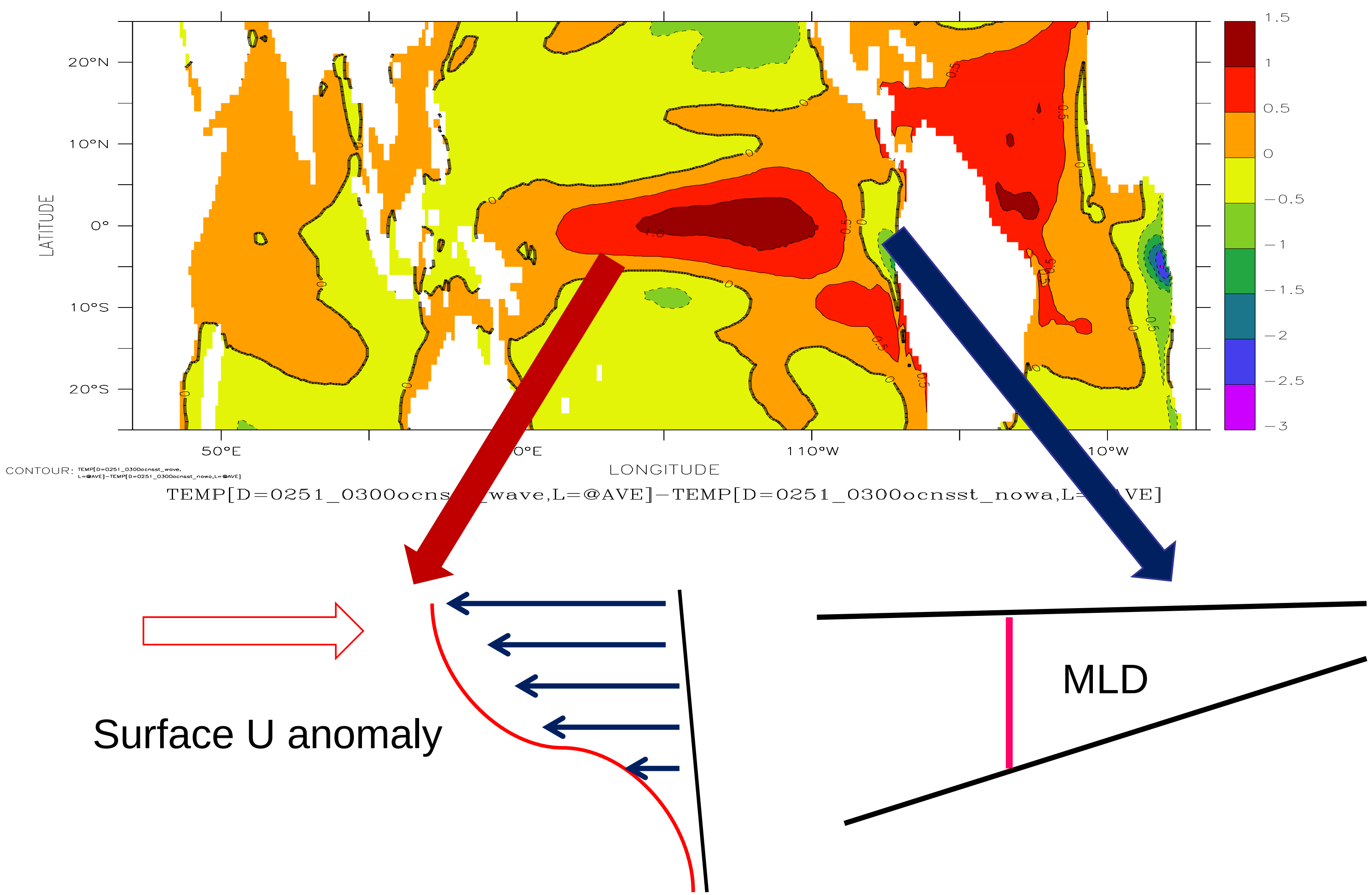
Exp2: with Bv



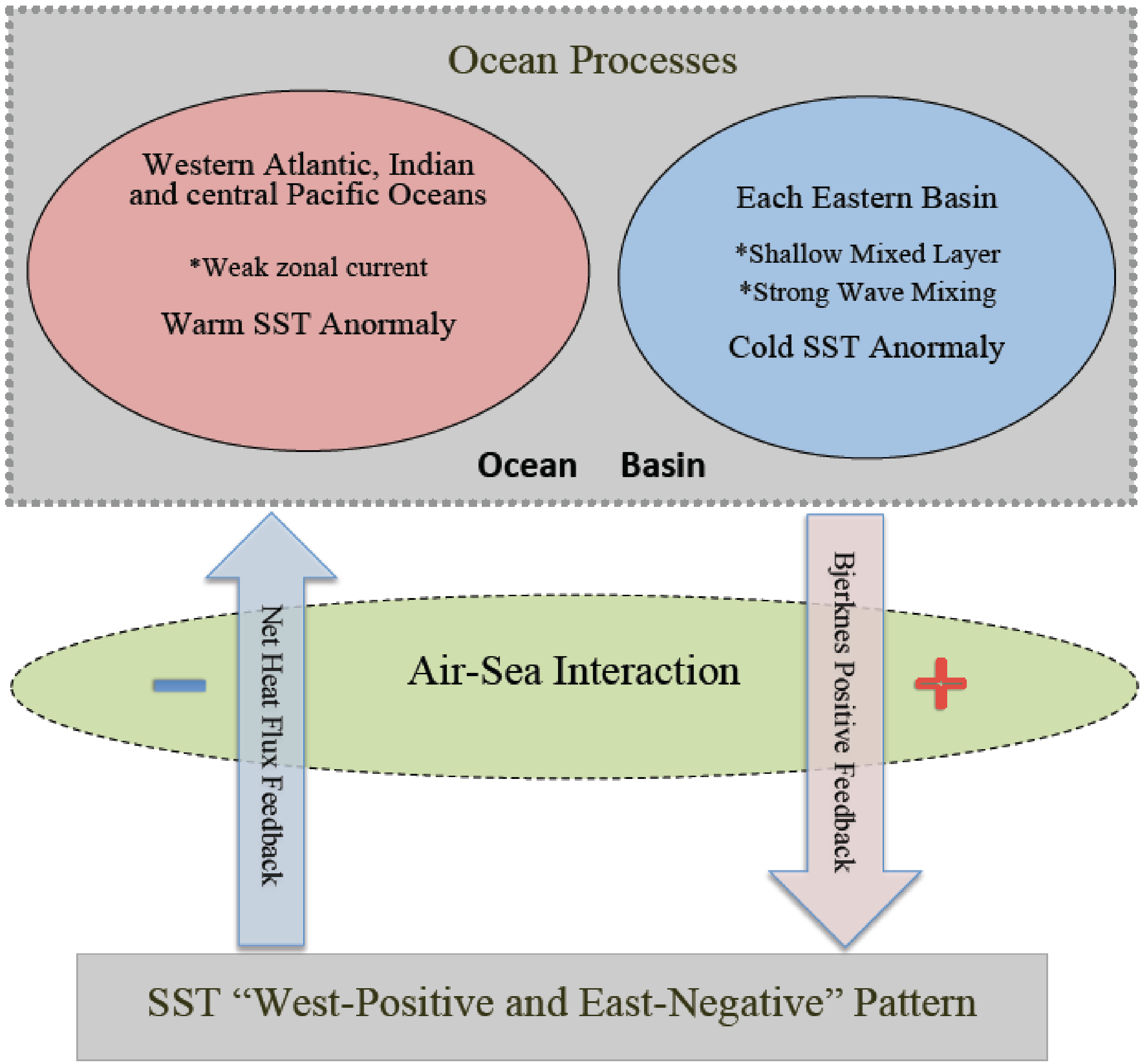
Bv effects on SST in the stand-alone ocean model



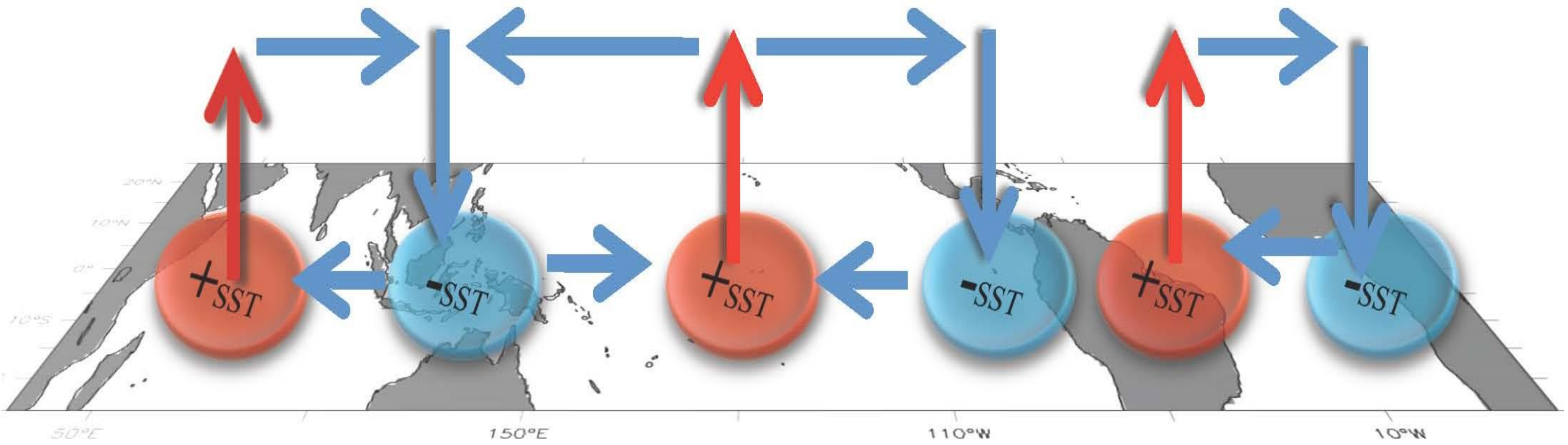
U difference due to Bv in stand-alone ocean model (cm/s)



20°N
10°N
0°
10°S
20°S
LATITUDE
50°E
110°W
10°W
LONGITUDE
1.5
1
0.5
0
−0.5
−1
−1.5
−2
−2.5
−3
CONTOUR:
TEMP[D=0251_0300ocnsst_wave,L=@AVE]−TEMP[D=0251_0300ocnsst_nowa,L=@AVE]
Surface U anomaly
MLD

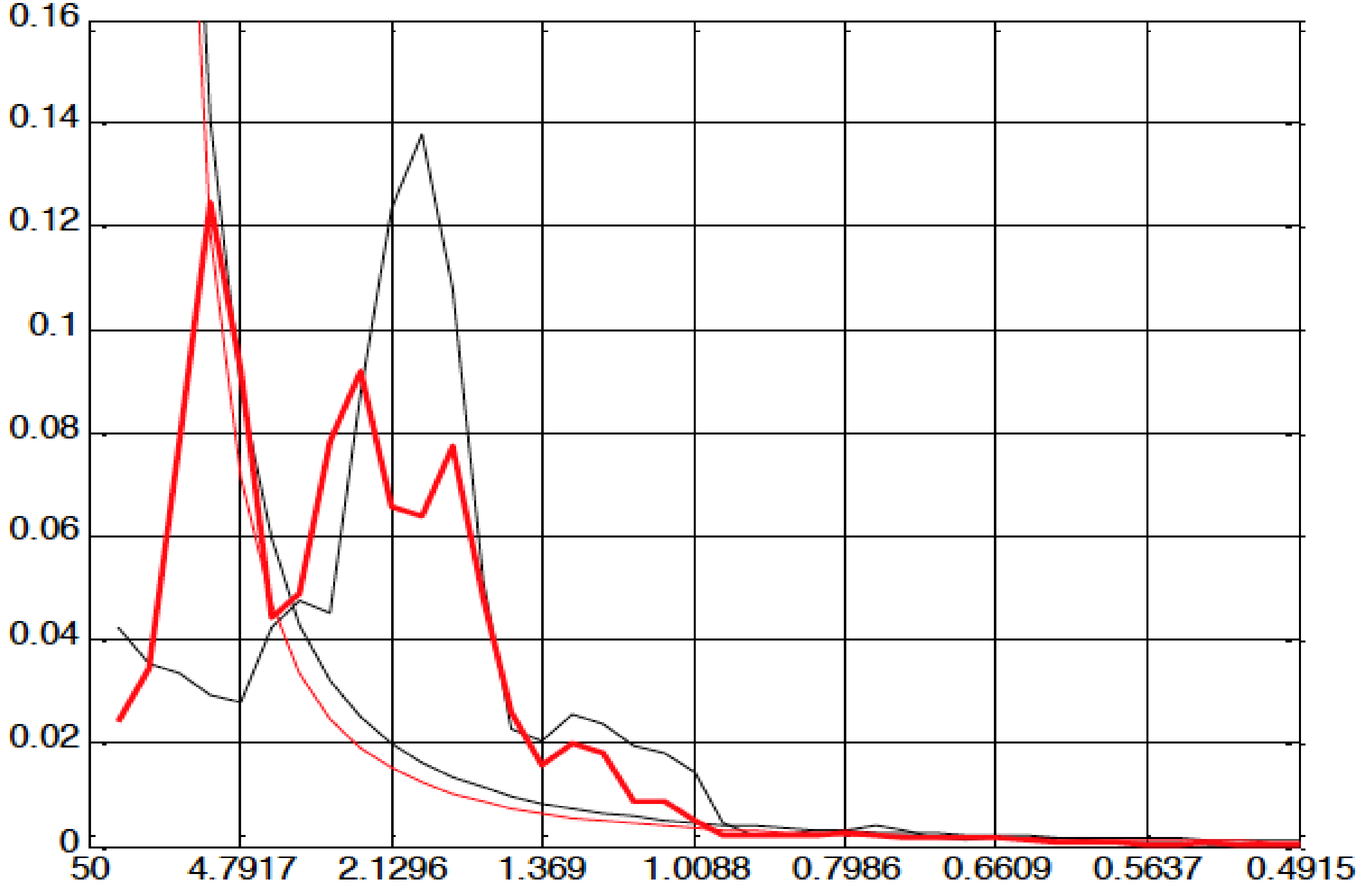


Song et al, 2012, JGR

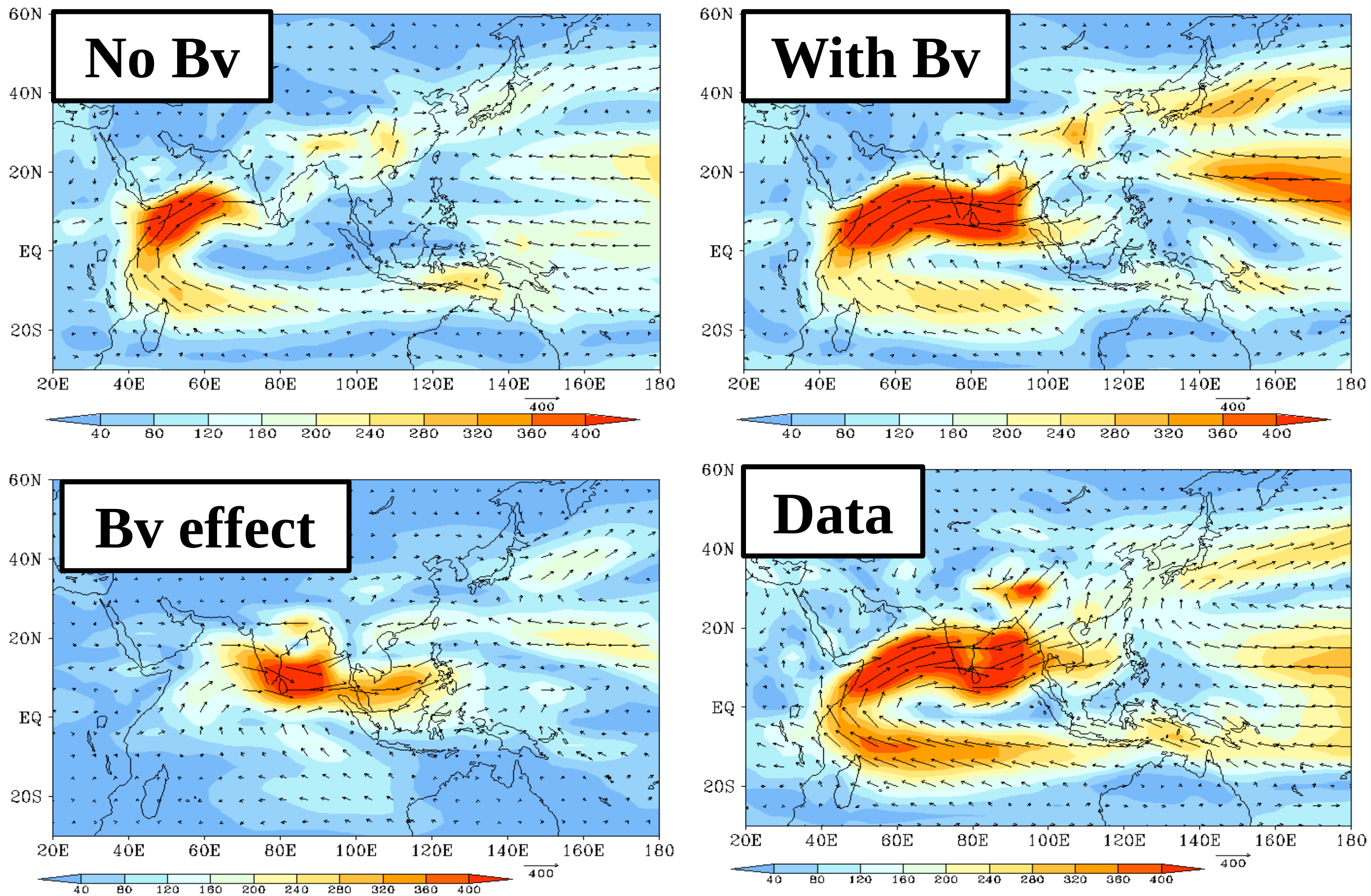


Schematic responses of SST and wind (arrow) to Bv in a climate system

CCSM3: ENSO periods

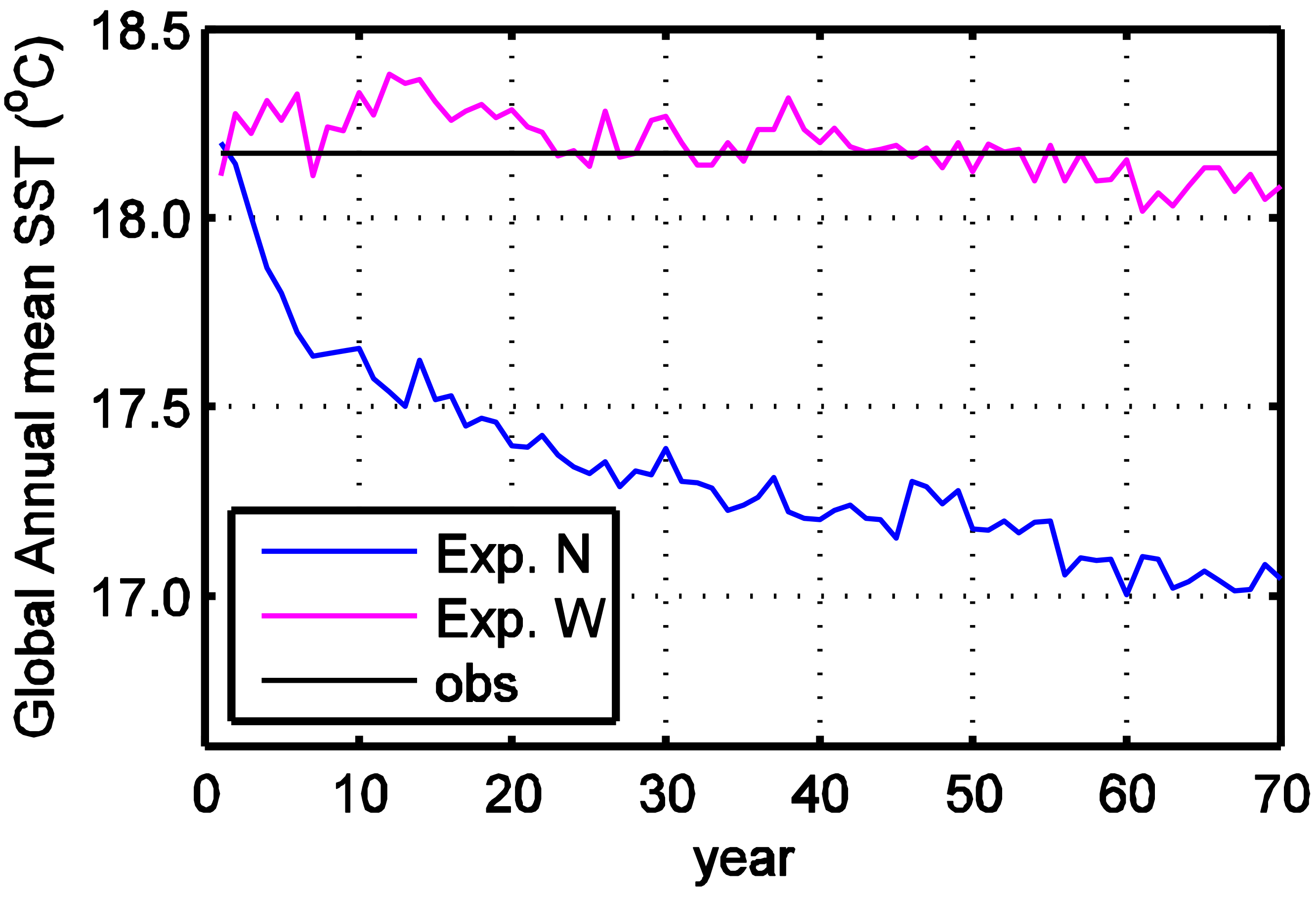


Water vapor transport in Australian-Asian Monsoon area



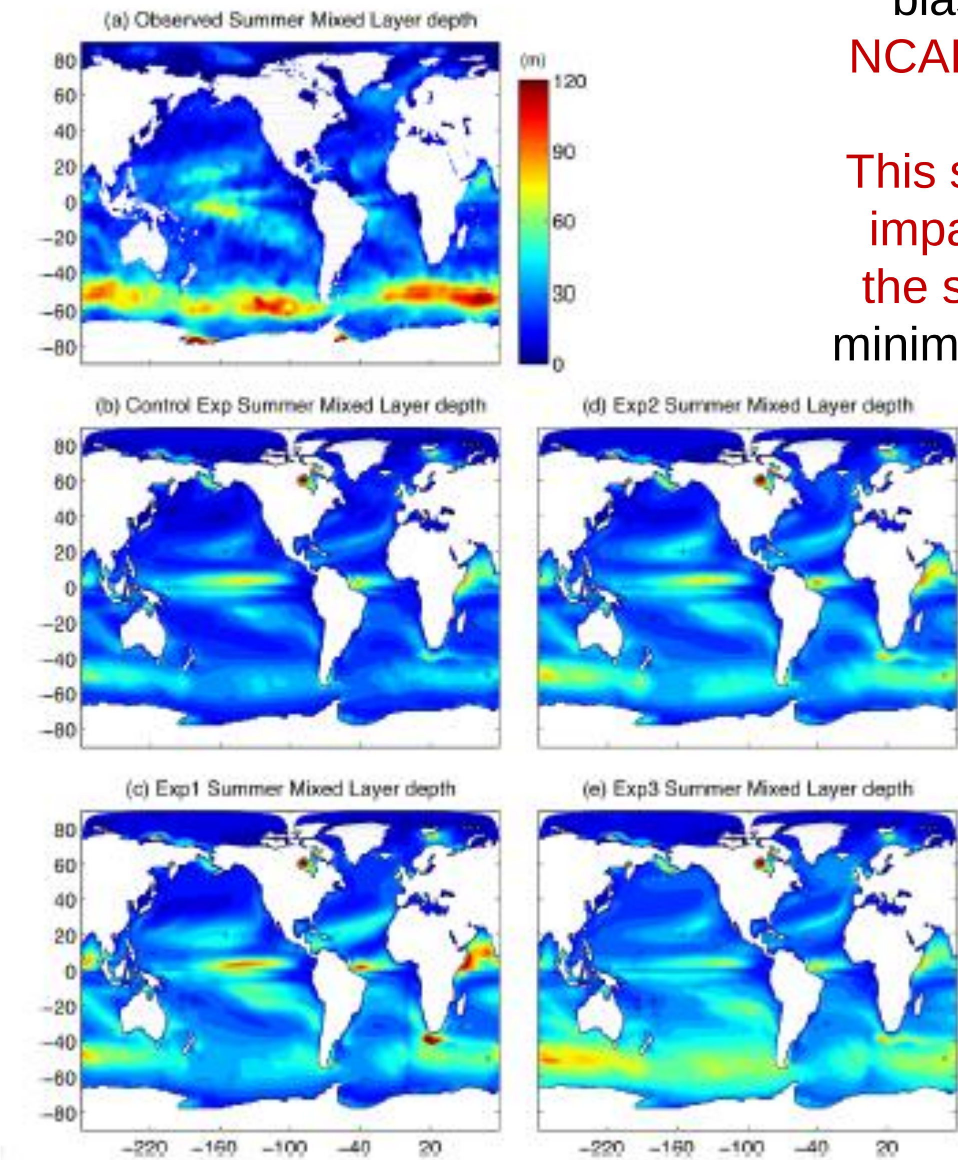
Song and Qiao et al, 2012, JAS

Climate drift: surface wave effects



Time evolutions of global mean SSTs simulated in Exp. N (blue line for without Bv) and Exp. W (pink line for with Bv) for FGM0, and that from the WOA01 climatology (black line). Huang et al, AOS, 2008

Summertime oceanic mixed layers are biased shallow in both the GFDL and NCAR climate models (Bates et al. 2012; Dunne et al. 2012, 2013).
This scheme (Qiao et al., 2004) has most impact in our simulations on deepening the summertime mixed layers, yet it has minimal impact on wintertime mixed layers.



Yalin Fan, and Stephen M. Griffies, 2014, JC (Fig 3)

Schematic View

ENSO simulation and prediction

Climate model

Ocean's key role

Upper ocean MLD

Bv's dominant role in upper ocean mixing

Bv can cutoff more than half of the Tropical Biases

Summary

- Turbulence remains the most important unresolved classical dynamical problem. We demonstrated that, small scale surface waves play key role in improving global ocean circulation models and climate models.
- Surface waves can modulate ENSO through changing the mean state of climate system.

Thank you for your attention

Observing the Ocean, Predicting its Future