PICES Annual Meeting

Wave turbulence interaction induced vertical mixing and its effects in ocean and climate models

Fangli Qiao, Yeli Yuan, Jia Deng, Dejun Dai and Zhenya Song

First Institute of Oceanography, SOA, China

Nov 9, 2016   San Diego, USA

qiaofl@fio.org.cn

Outline

1. Challenges and solution
2. Surface wave in ocean models
3. Surface wave in climate models
4. Suggestion and discussion

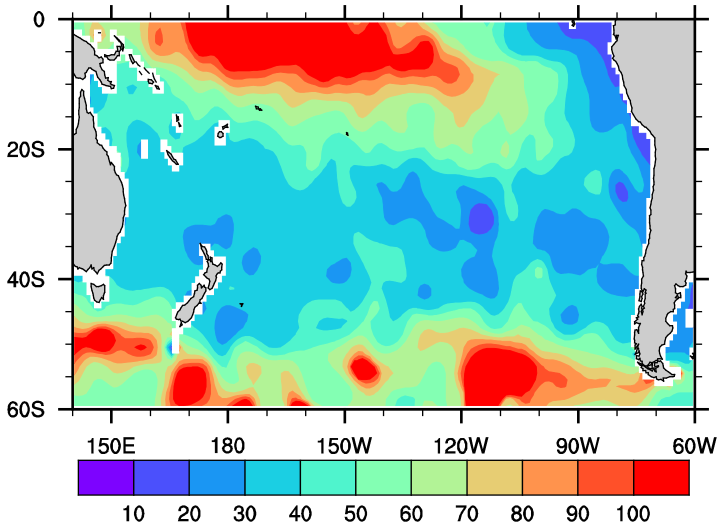
1. Challenges and solution

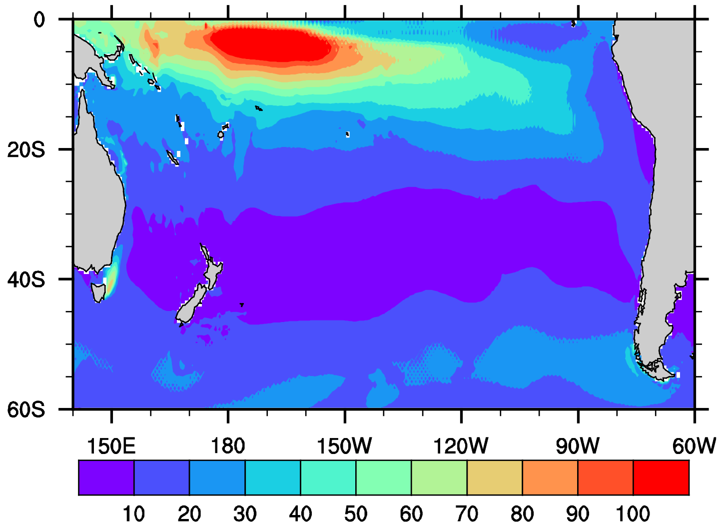
Motivation

Ocean is dominant in climate system, and upper ocean (not sea surface) plays key role in air-sea interaction. However,

Common problems nearly all OGCM models faced: Simulated SST is overheating in summertime, and mixed layer depth is too shallow while the thermocline is too weak (Martin 1985, Kantha 1994, Ezer 2000, Mellor 2003, Qiao et al. 2016).

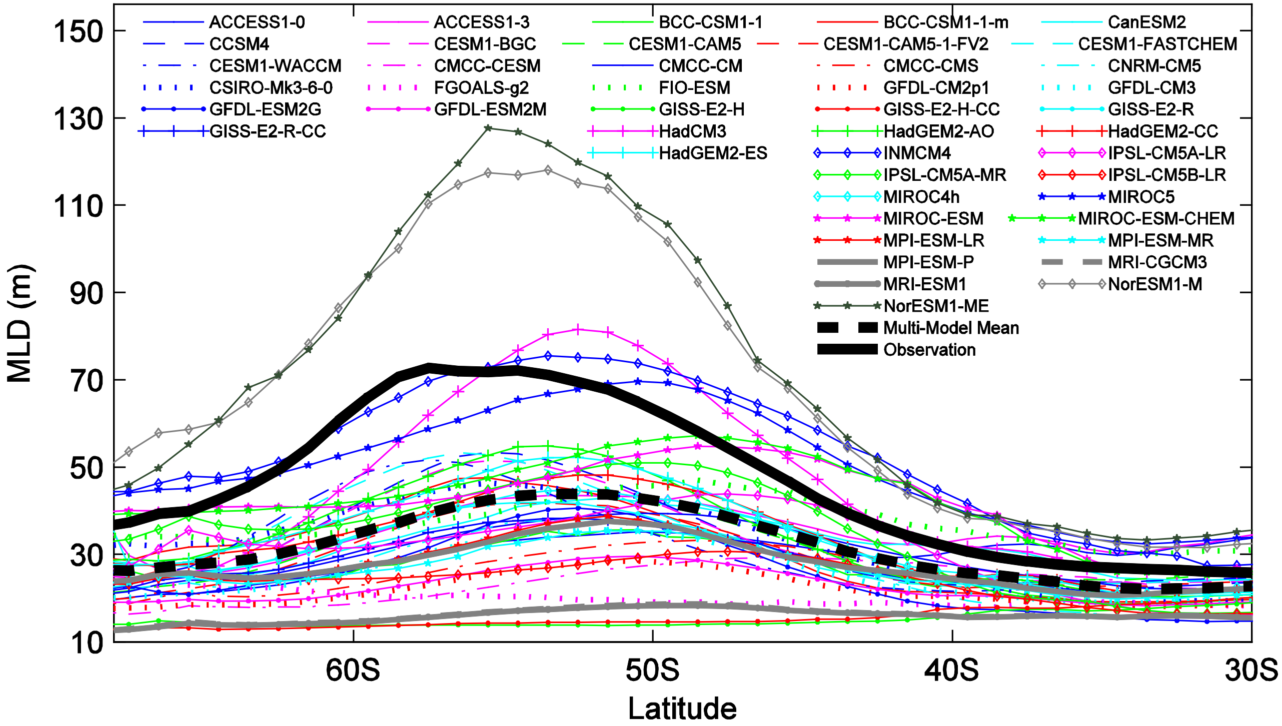
MLD in OGCM





- ✓ Observation
- ✓ Model from POM

MLD in CMIP5 models

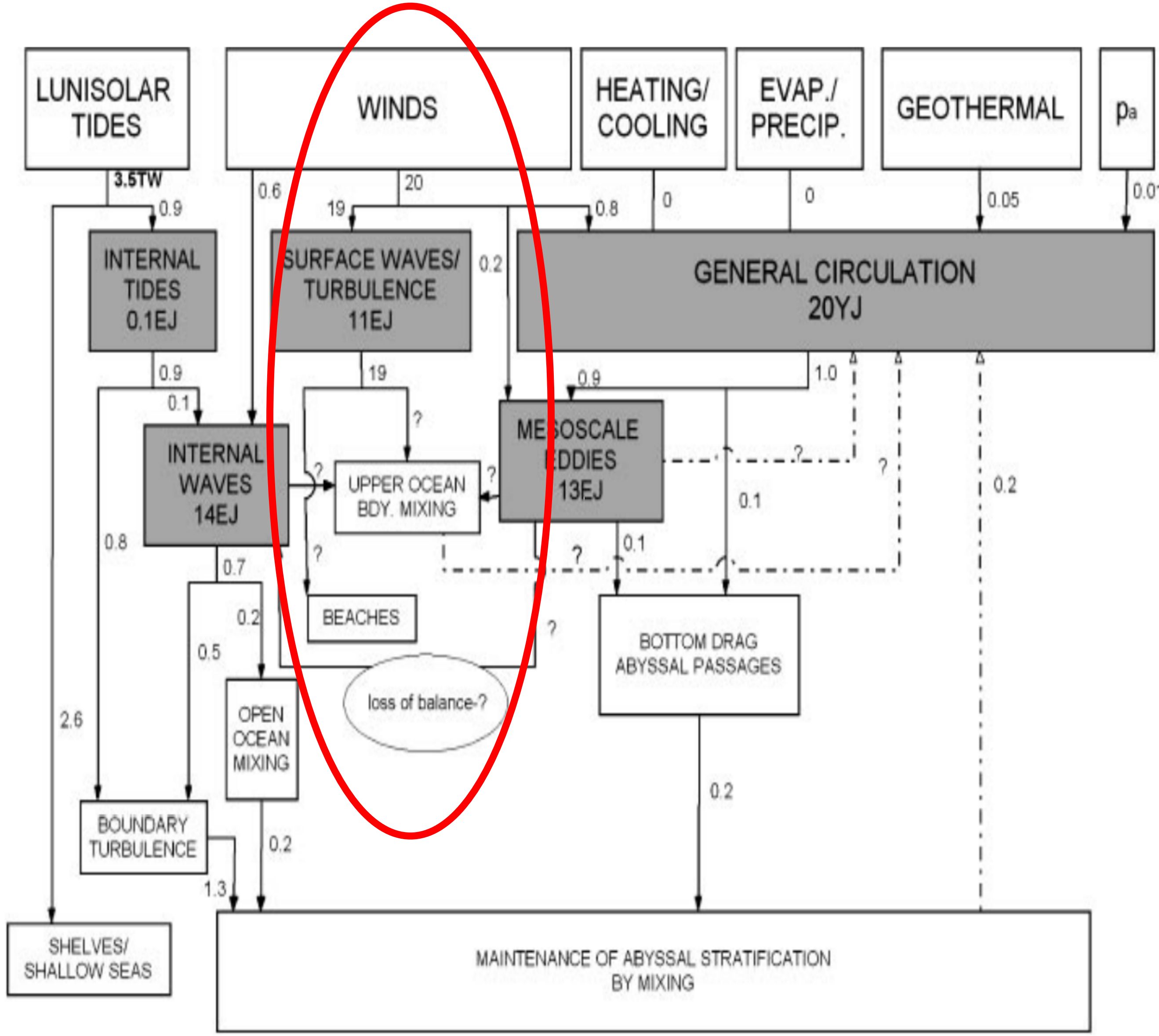


Huang et al, 2014, JGR

Scientific clue: Lack of mixing in the upper ocean

As the mixing process is essentially an energy balance problem, waves, as the most energetic motions at the ocean surface, should play a controlling role. Surface wave: 60 TW, Circulation: 4 TW

Wunsch, C. and R. Ferrari, 2004: Vertical mixing, energy and the general circulation of the oceans, *Ann. Rev. Fluid Mech*., 36, 281-314.



How surface waves affect OGCM?

- Breaking wave induced stress and energy flux (*Craig and Banner, 1994; He and Chen*, *2011*)

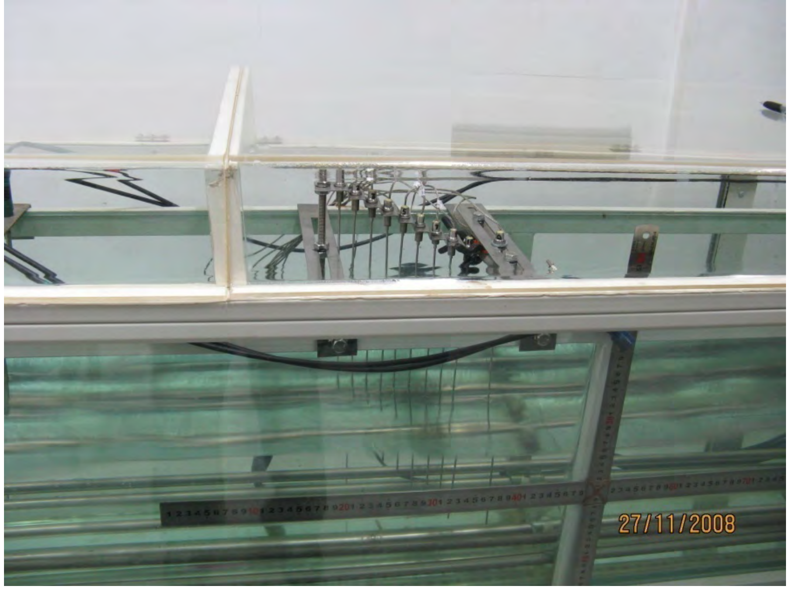
  Too shallow, in the order or wave amplitude

- Langmuir circulation (*Kantha and Clayson*, 2004)

  Still too weak and too shallow

- Wave-turbulence interaction enhanced mixing *(Qiao et al, 2004, 2010,2016; Pleskachevsky et al., 2011)*

  In the order of wave length (100 m or more)

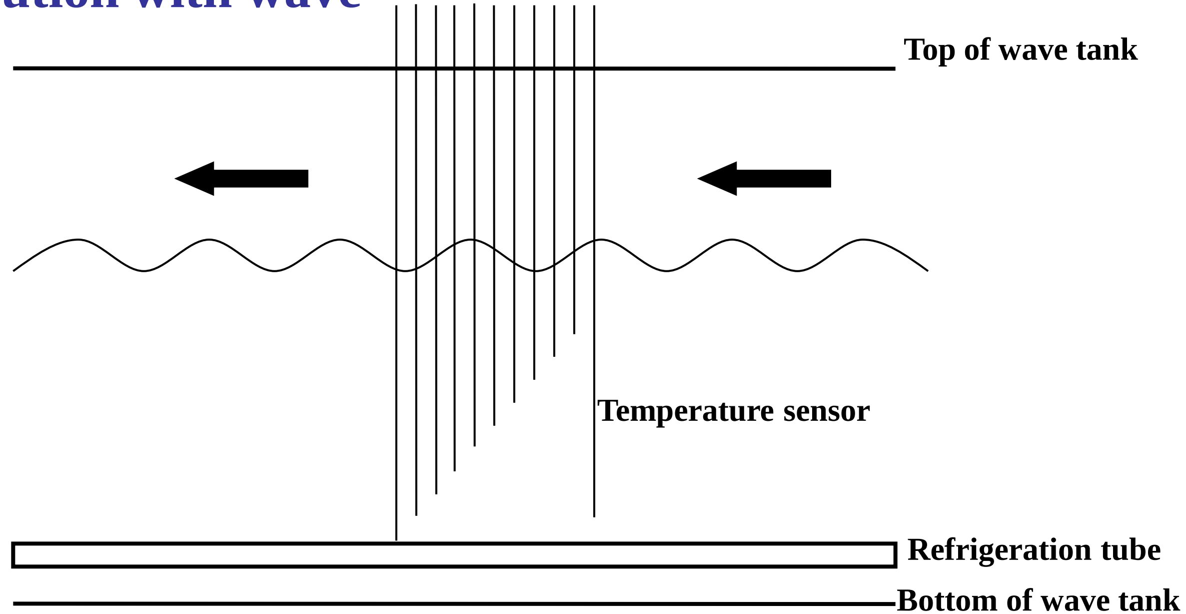


Laboratory experiments:

Wave tank: 5m in length with height of 0.4m and width of 0.2m. To generate temperature gradient through bottom cooling of refrigeration tubes, and temperature sensors are self-recorded with sampling frequency of 1Hz.

(1) Temperature evolution in natural condition

(2) Temperature evolution with wave

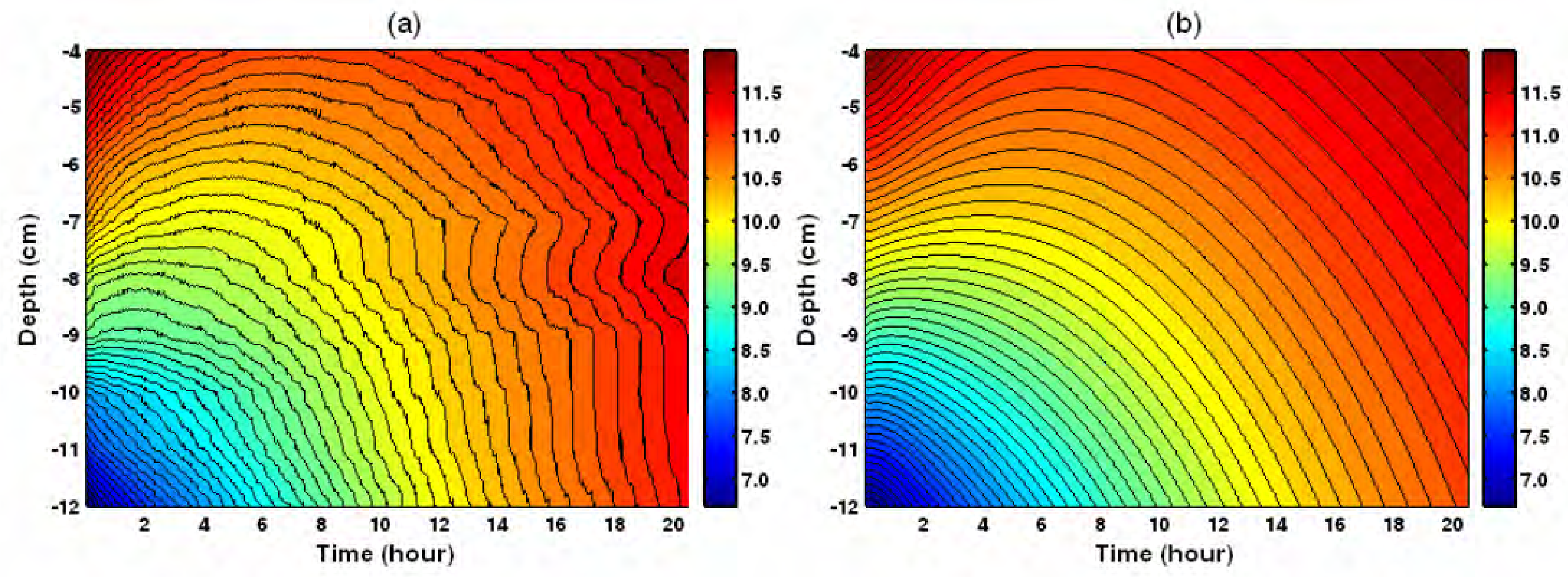


Dai and Qiao et al, JPO, 2010

Experiment results without and with waves

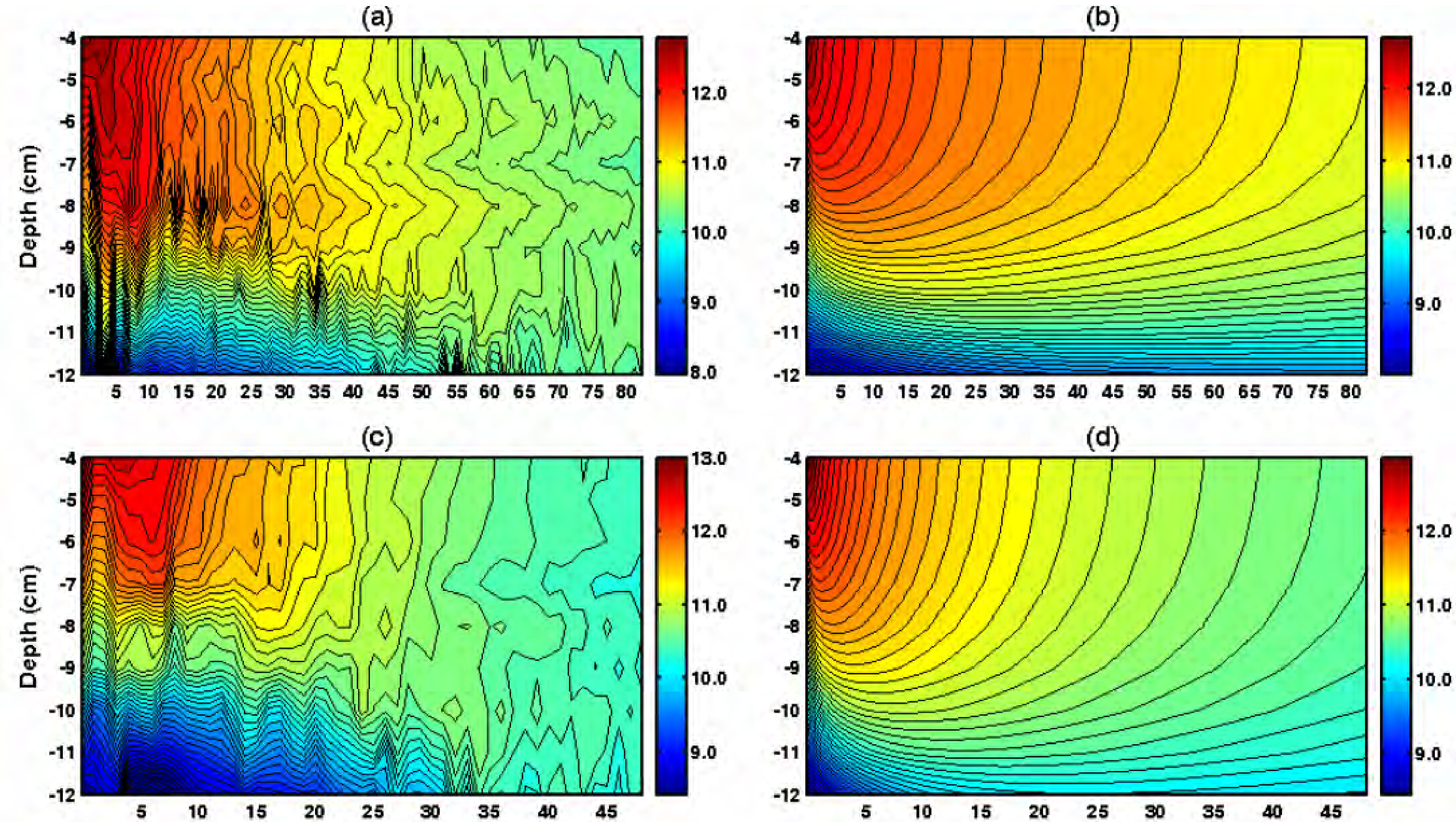
$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right)$$

kz=k0+Bv



Evolution of water temperature without waves.
(a) Observation; (b) simulation.

Simulation results with waves



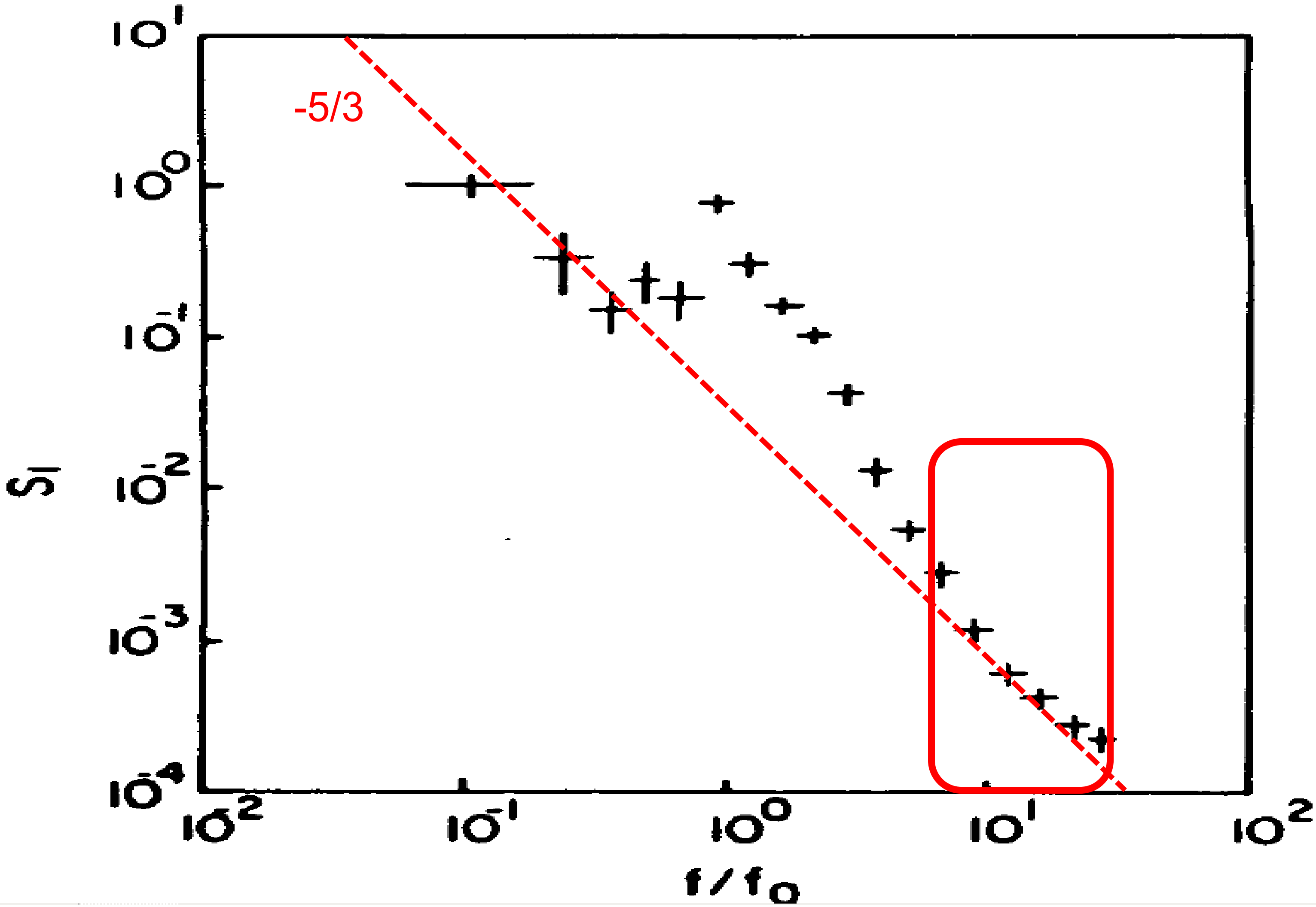
Evolution of water temperature with waves. Left: observation; right: simulation; (a,b) 1.0cm, 30cm; (c,d) 1.0cm, 52cm;

Field data reveals the strong interaction between surface wave and turbulence

Qiao et al., Phil Trans. Royal Society 2016

The *best* field ‘turbulence’ spectrum

(from Lake Ontario by Kitaigorodskii et al 1983)

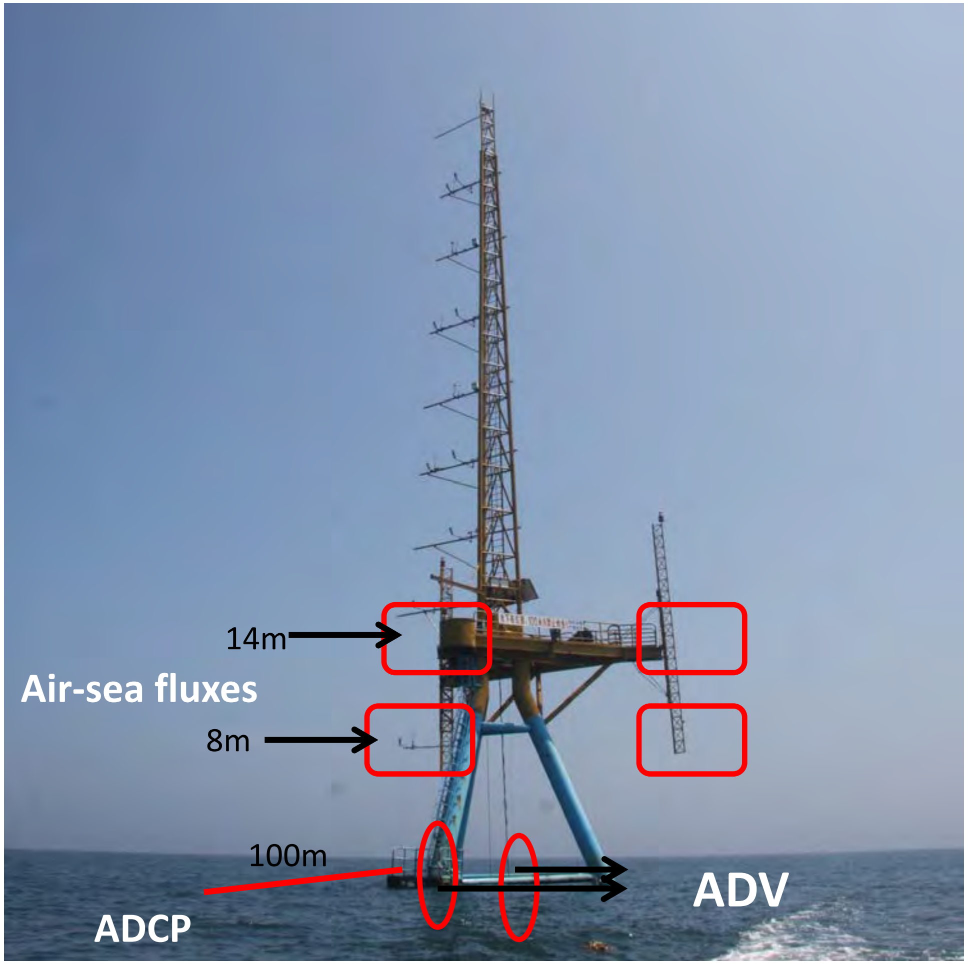


Our present knowledge

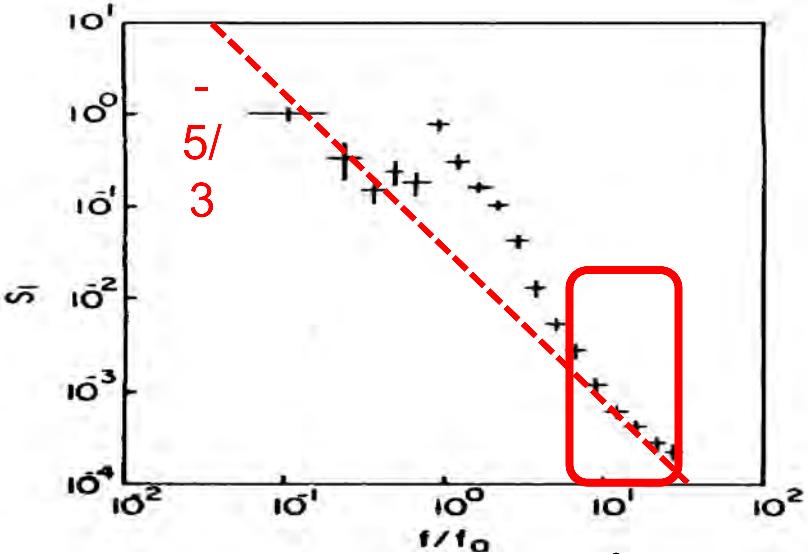
Lumley, J. L. & Terray, E. A. 1983: Kinematics of turbulence convected by a random wave field. JPO **13,** 2000-3007

"The shape of (the longitudinal) turbulence velocity spectra (but not the magnitude) in the ocean surface layer could be understood through kinematics without recourse to the dynamics."

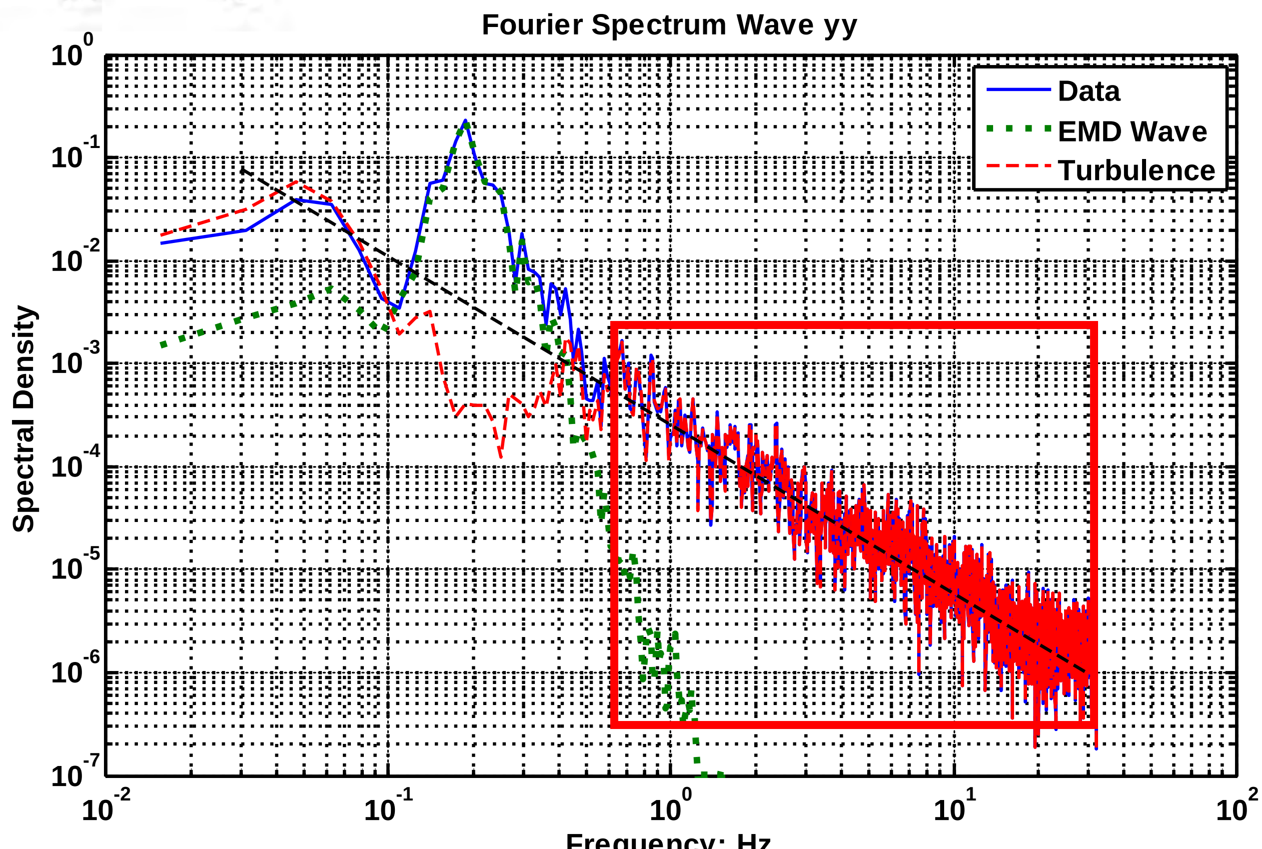
However, this last word on turbulence is totally incorrect.



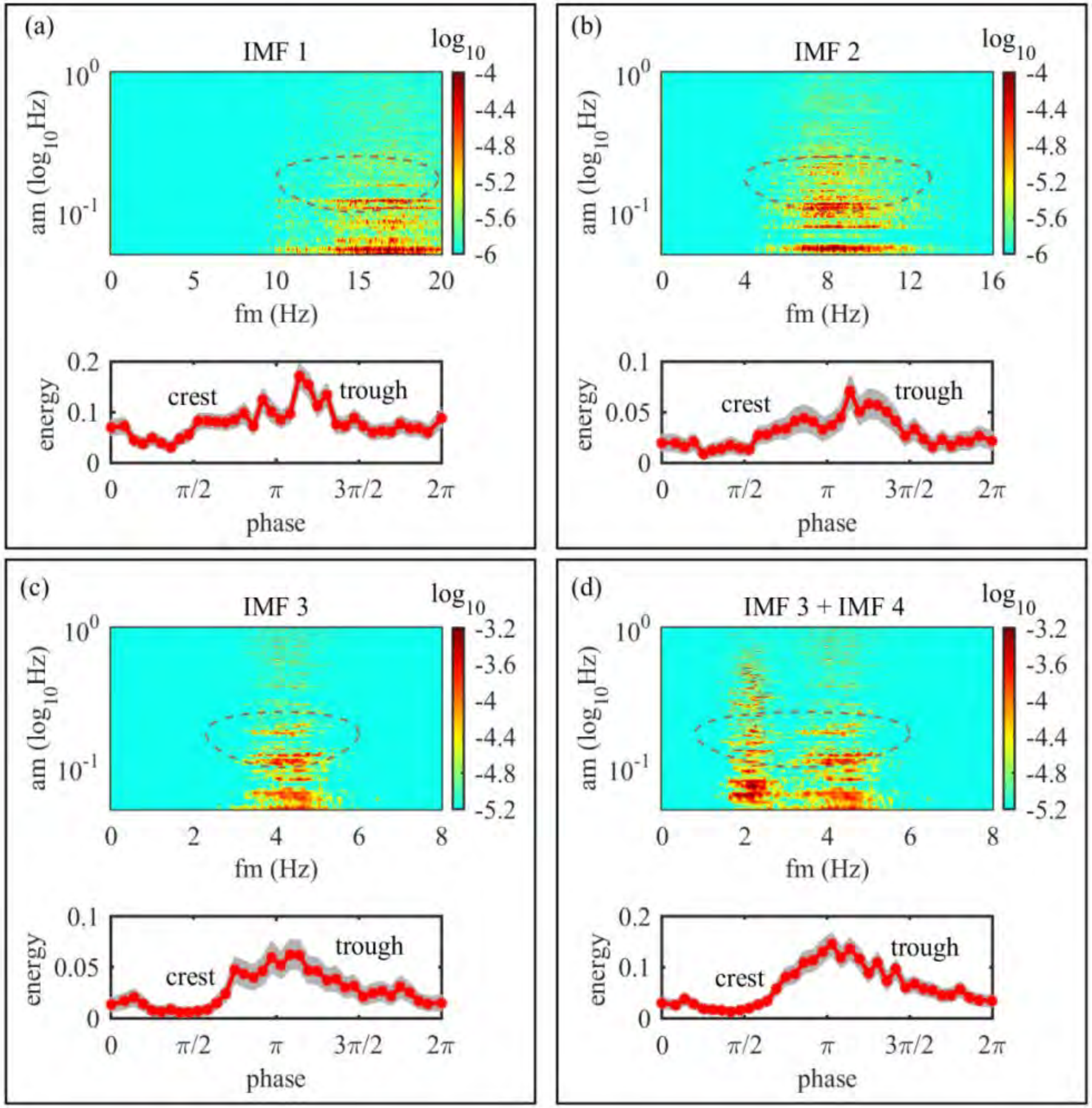
Typhoon Rammasun: 17 July 2014



-5/3
S_l
f/f_o

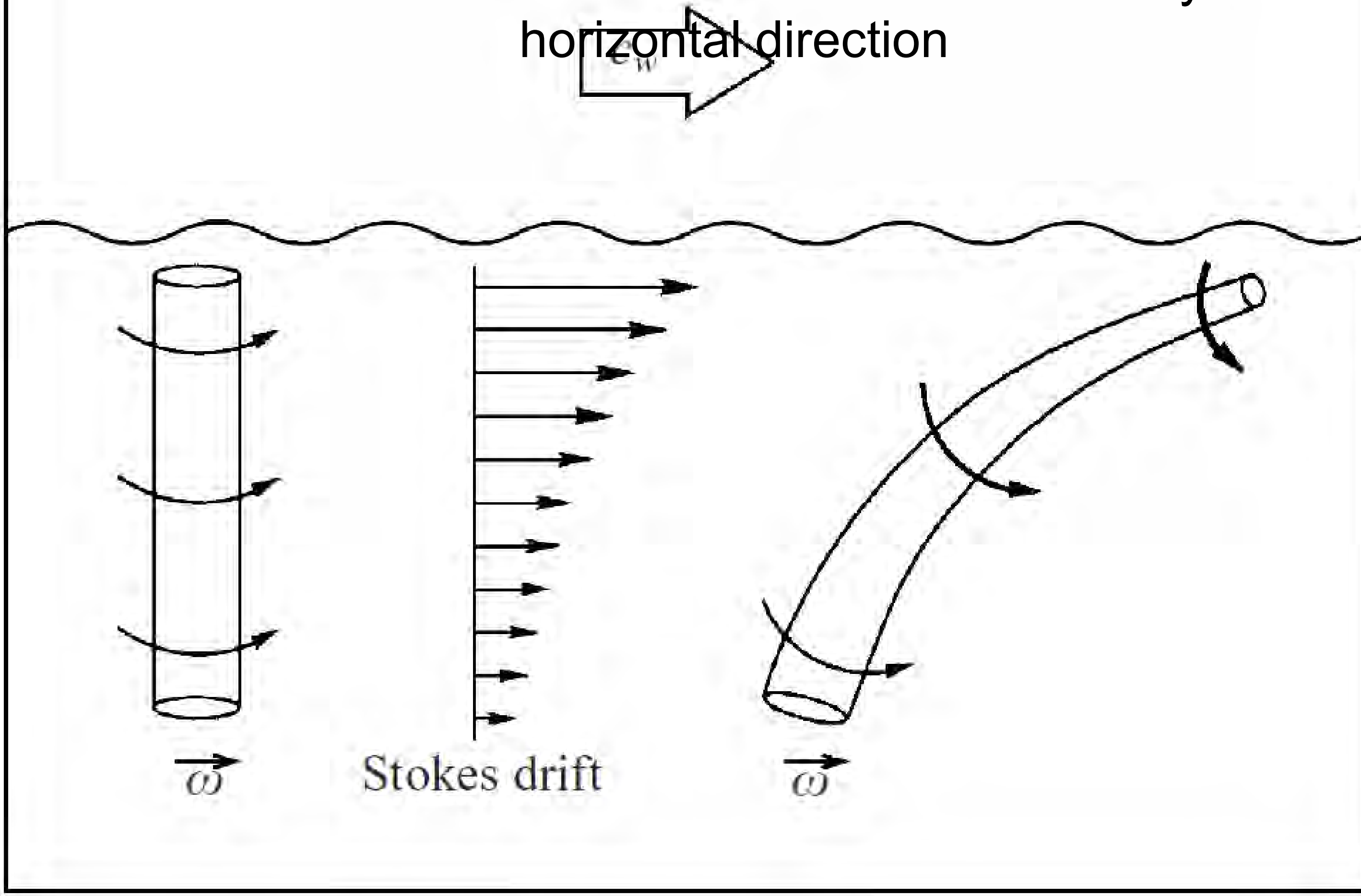


Fourier Spectrum Wave yy
Data
EMD Wave
Turbulence
Spectral Density
Frequency: Hz


(a)
IMF 1
log10
am (log10Hz)
fm (Hz)
energy
crest
trough
phase
(b)
IMF 2
log10
am (log10Hz)
fm (Hz)
energy
crest
trough
phase
(c)
IMF 3
log10
am (log10Hz)
fm (Hz)
energy
crest
trough
phase
(d)
IMF 3 + IMF 4
log10
am (log10Hz)
fm (Hz)
energy
crest
trough
phase

Teixeira, M. A. C. And Belcher, S. E., 2002, JFM

The Physics of Turbulence Wave interactions: the Stokes drift associated with the wave tilts vertical vorticity into the horizontal direction



Our field observation indicates that there is strong interaction between turbulence and waves. Wave energy is much larger than turbulence. So, we can propose a phenomenological viscosity/diffusivity based on dimensional considerations as

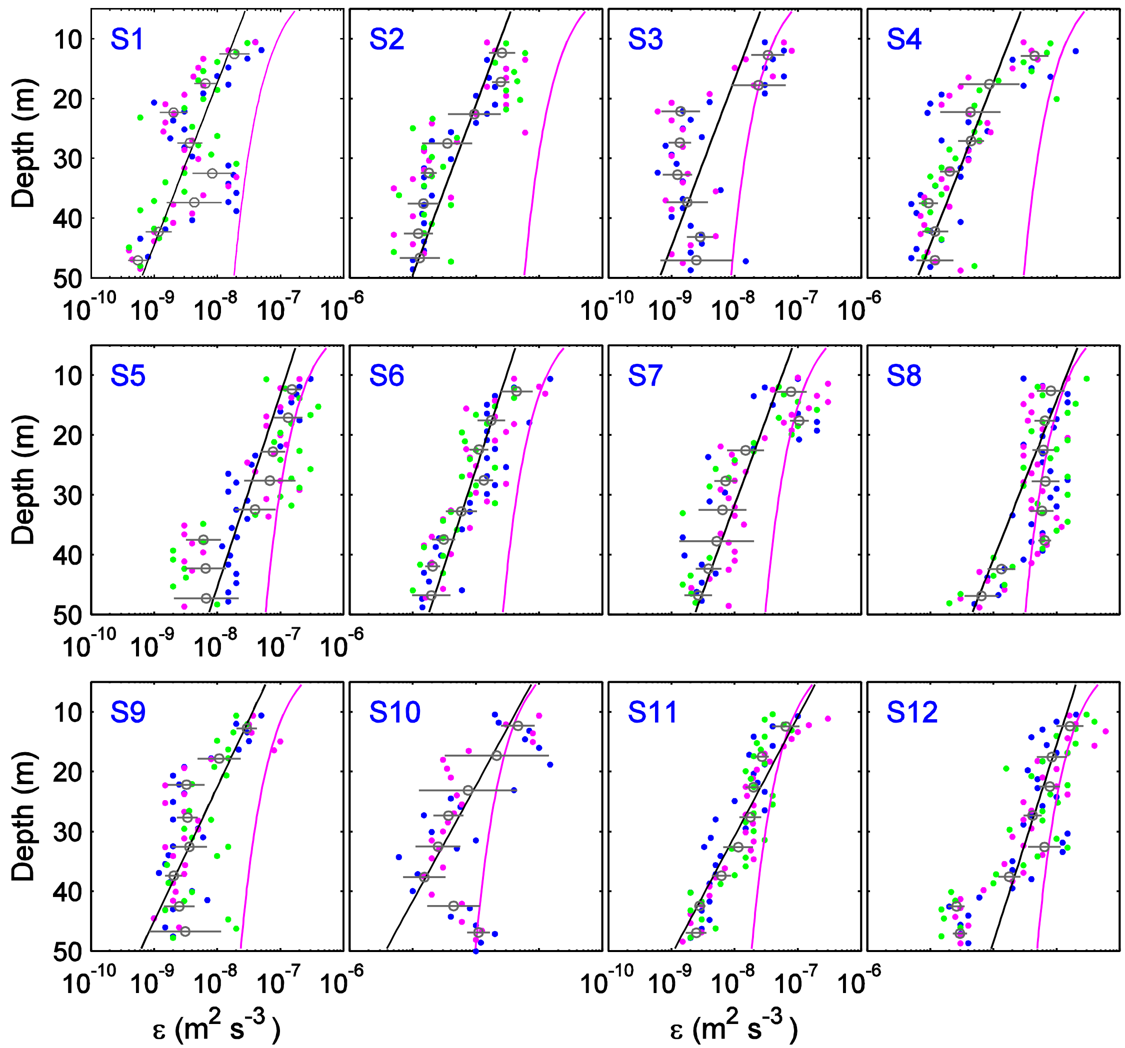
$$v_w = \overline{u_{ws} \cdot l_{wp}} = \textit{(Stokes drift)} \cdot \textit{(Particle excursion)}$$

$$u_{ws}(z) = \int_k 2\omega k\ S(k) e^{-2|k|z} dk \qquad l_{wp}(z) = \left[\int_k S(k) e^{-2|k|z} dk \right]^{1/2}$$

$$v_w(z) = \int_k 2\omega k\ S(k) e^{-2|k|z} dk \cdot \left[\int_k S(k) e^{-2|k|z} dk \right]^{1/2}$$

Qiao et al, 2016, Phil Trans of R S = Qiao et al, 2004, GRL

Observation evidences

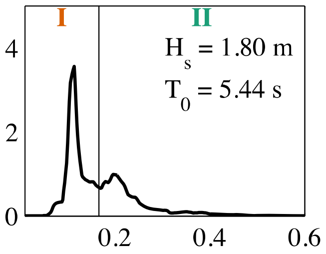


Vertical profiles of the measured dissipation rates ε_m (dots), and those predicted by wave ε_{wave} (black lines) and the law of the wall ε_{wall} (pink lines) at Station S1~S12 (in $m^2\ s^{-3}$). Observation is conducted in SCS during October 29 to November 10, 2010. Huang and Qiao et al, 2012, JGR

Blue line
Osborn, 1980

Green line
Terray et al. (1996)

Red line
Huang and Qiao (2010)

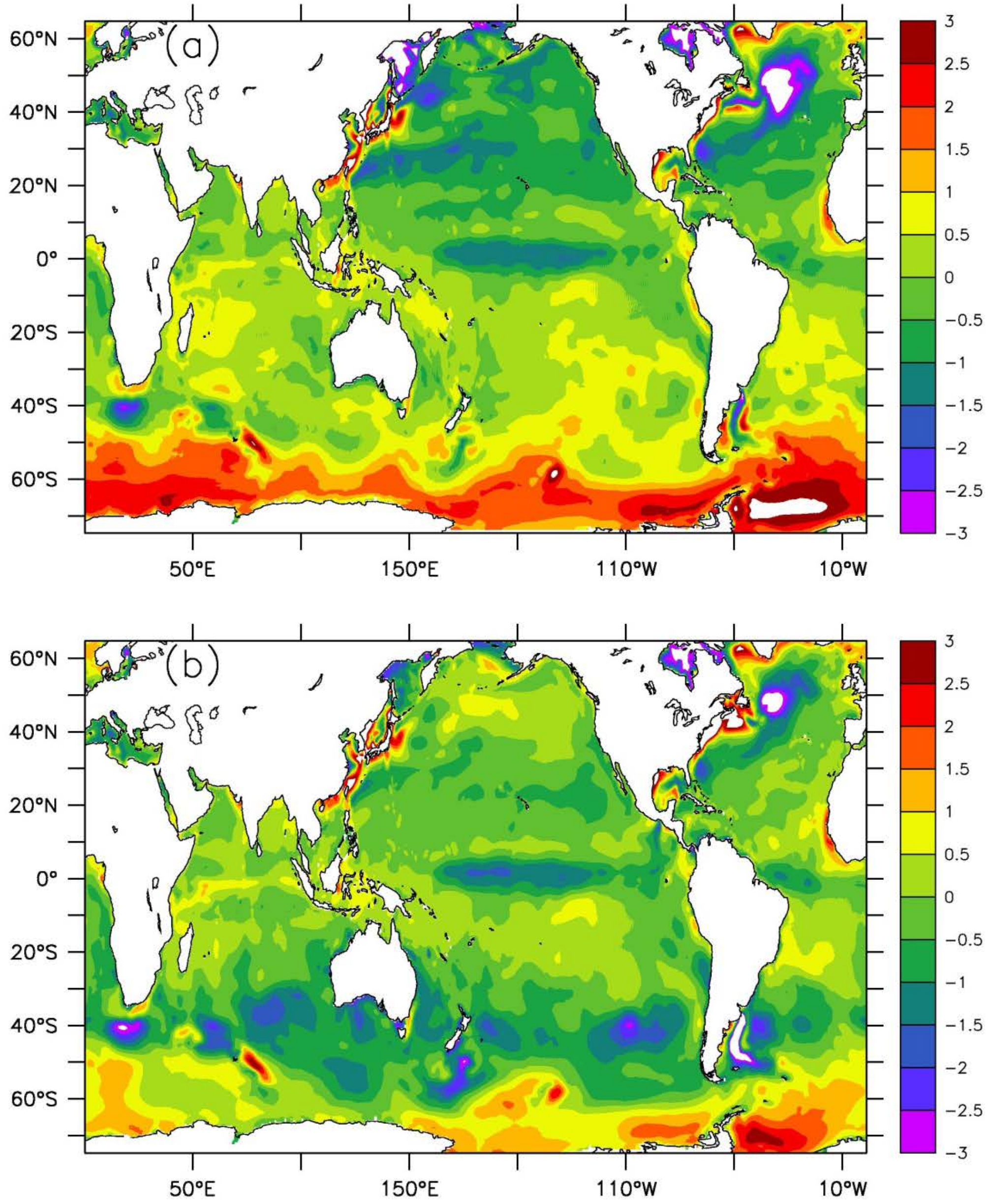


Turbulent kinetic dissipation rate

Sutherland, G., B. Ward, K. H. Christensen (2013), Wave-turbulence scaling in the ocean mixed layer, ***Ocean Sci***., 9(4), 597-608, doi: 10.5194/os-9-597-2013

2. Surface wave in ocean models

Wave effects on SST: simulated SST bias without wave (up) and with wave (down).



NEMO: CORE numerical experiments on Bv

ORCA2_LIM: a coupled ocean / sea-ice configuration based on the ORCA tripolar grid at 2° horizontal resolution and 31 vertical levels. 182(x)×149(y)×31(z).
http://www.nemo-ocean.eu/Using-NEMO/Configurations/ORCA2_LIM

ORCA1: 362(x)×292(y)×75(z). http://www.noc.soton.ac.uk/nemo/

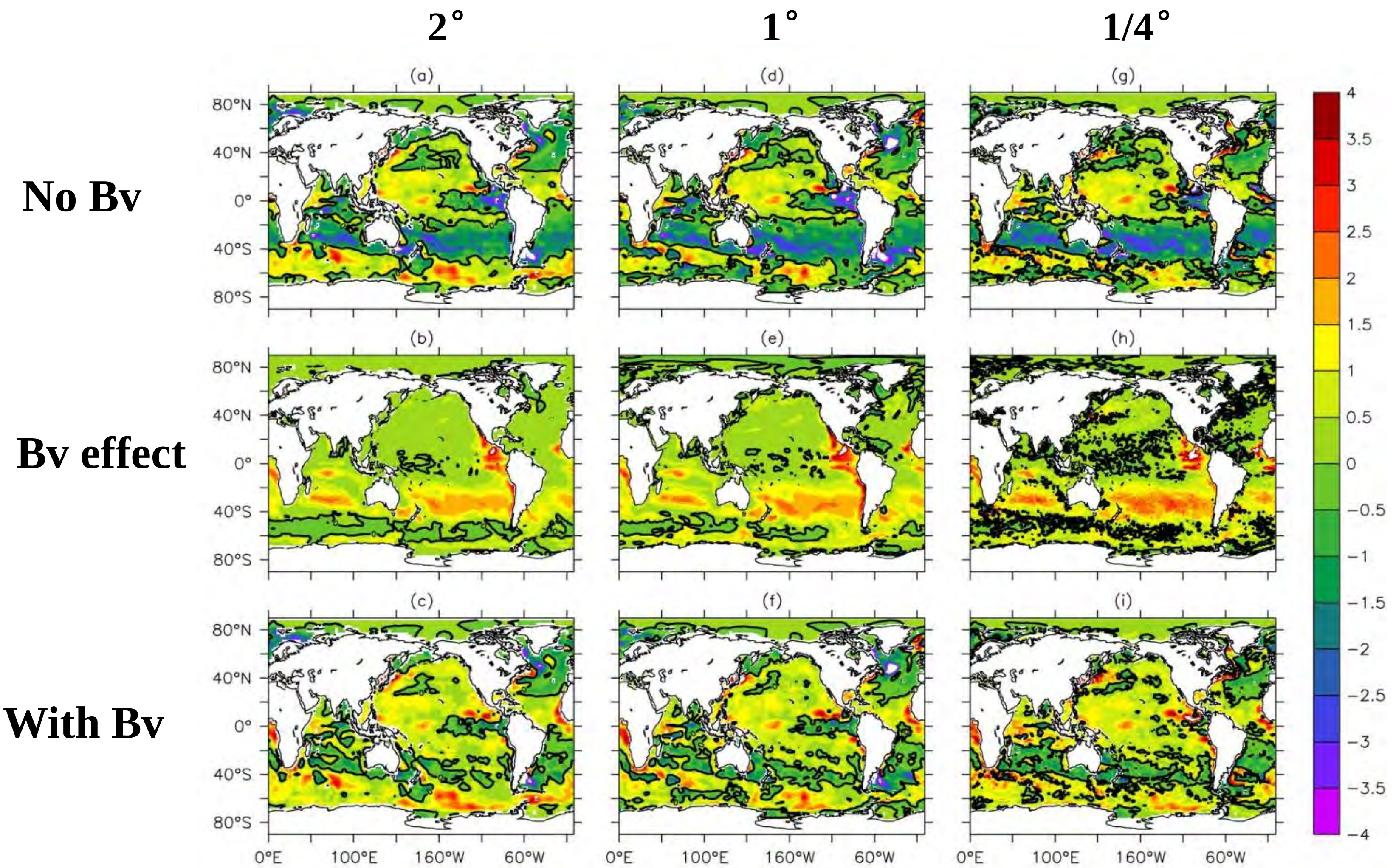
ORCA025: a coupled ocean / sea-ice configuration based on the ORCA tripolar grid at (1/4)° horizontal resolution and 75 vertical levels. 1442(x)×1021(y)×75(z).

Climatological ***Bv*** data are from a global wave model with 0.5 degree resolution in x/y direction and 32 levels in z direction.

$$\mathbf{avm} = \mathbf{avm} + \boldsymbol{B_v}$$
$$\mathbf{avt} = \mathbf{avt} + \boldsymbol{B_v}$$

Shu Q. et al, 2016

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



Simulated temperature difference at 50m in February

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^{o}S -65^{o}N is selected;
Zonal resolution 1^o, while meridional resolution is 1/3^o between 10^{o}S-10^{o}N, and gradually increases to 1^o by 20^{o}N and 20^{o}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.

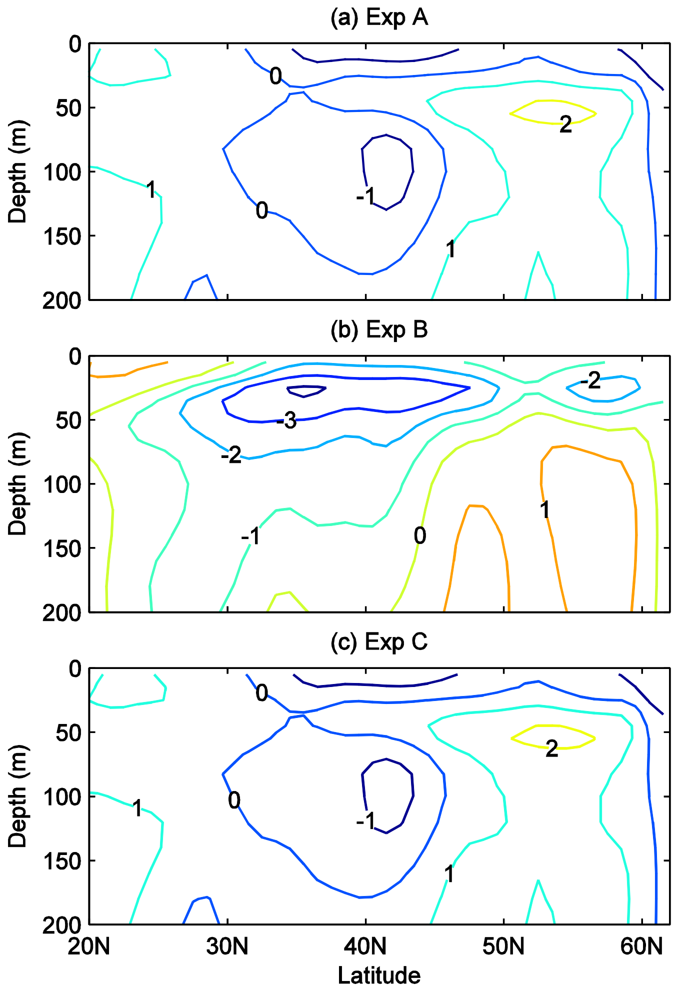
Experiment A: MY(Ps) + MY(Pb) + Bv + BG
Experiment B: MY(Ps) + MY(Pb) + BG
Experiment C: MY(Pb) + Bv + BG

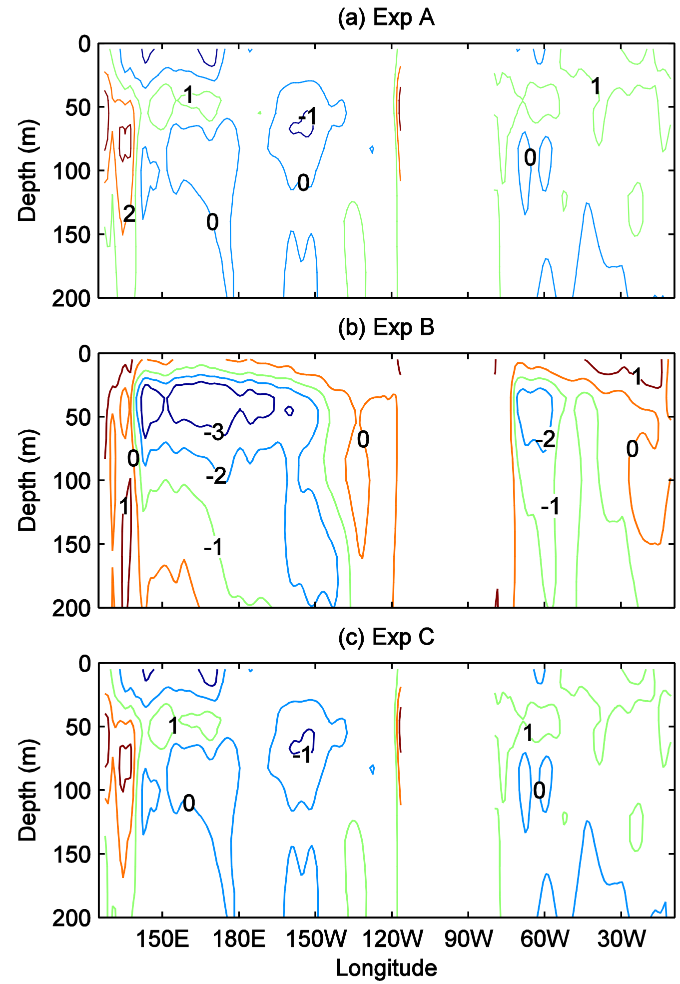
- Too cold subsurface temperature in Exp B
- Temperature difference in Exp C is very similar as that in Exp A

MY+Bv

MY

Bv

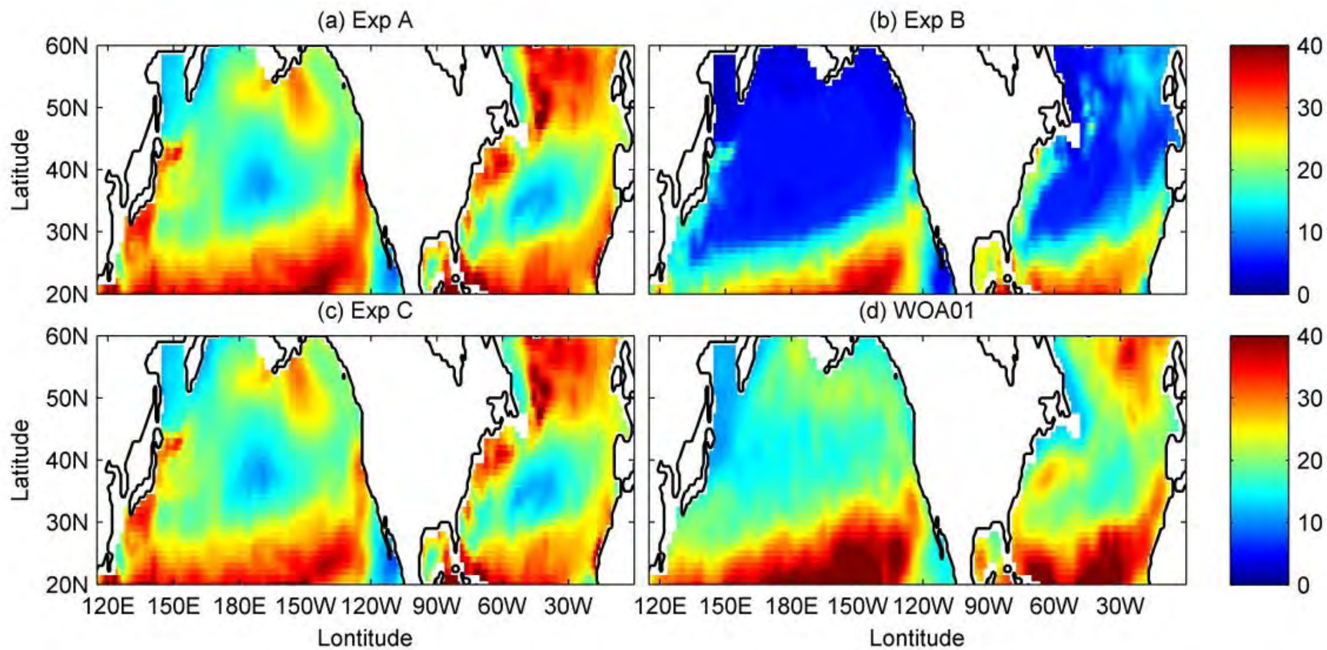




Temperature deviations from the climatology averaged in August along the dateline

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.



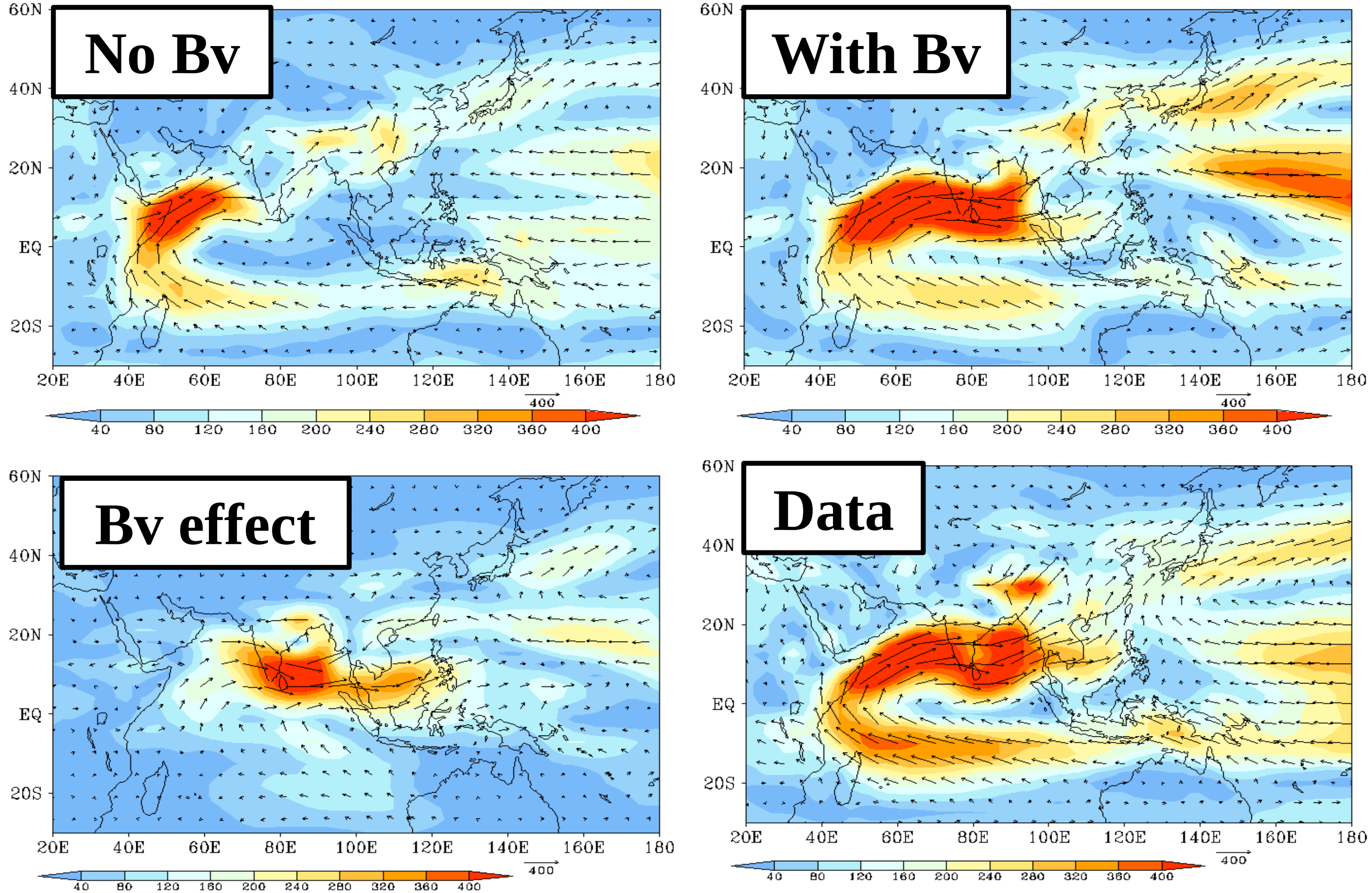
3. Surface wave in climate models

In tropical area, Bv has no much improvements for the ocean circulation model compared with mid- and high latitudes. For full coupled climate model, it is a different story because of the feedback and nonlinearity.

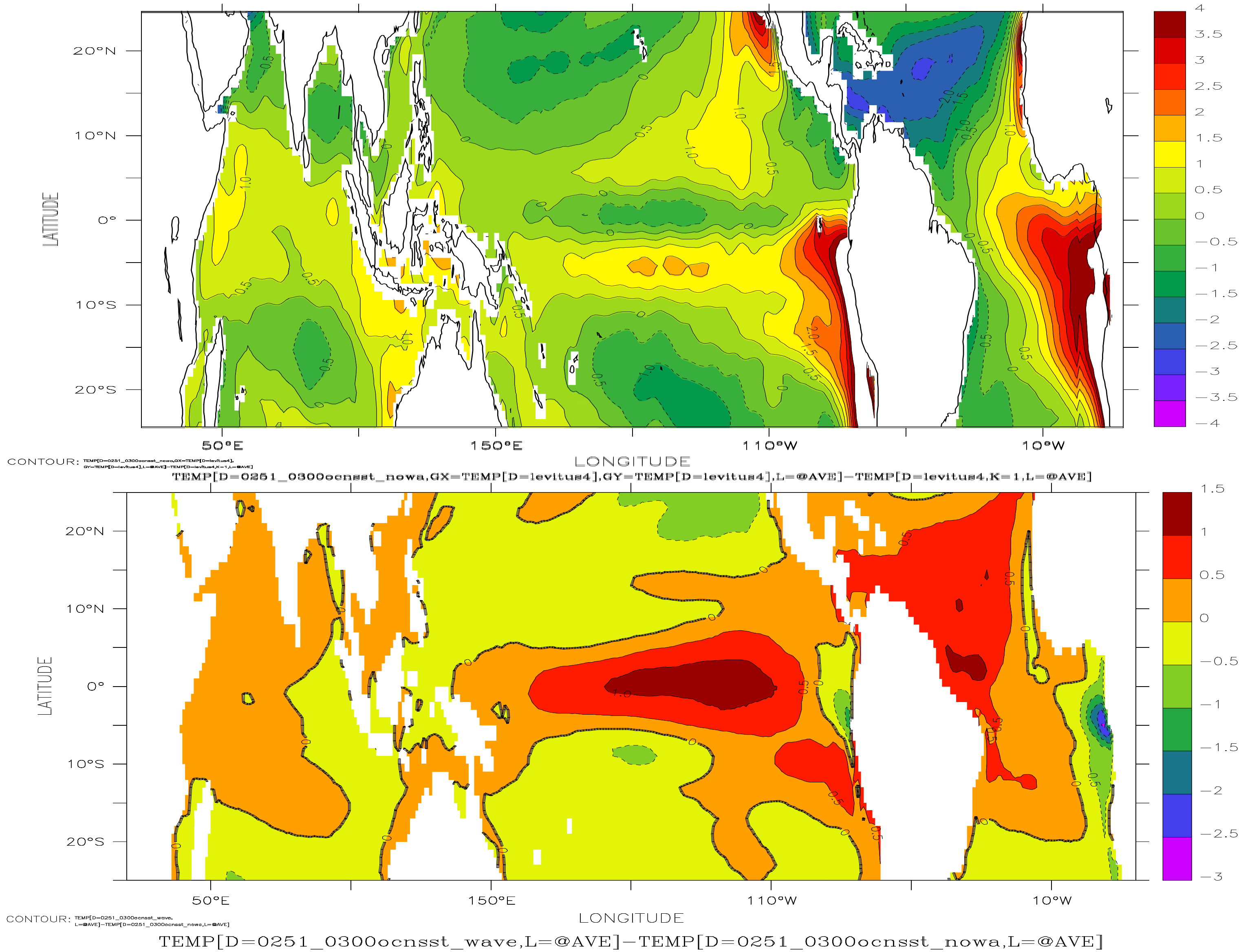
(1) FGCM0, LASG

(2) CCSM3, NCAR

Water vapor transport in Australian-Asian Monsoon area (FGCM0)



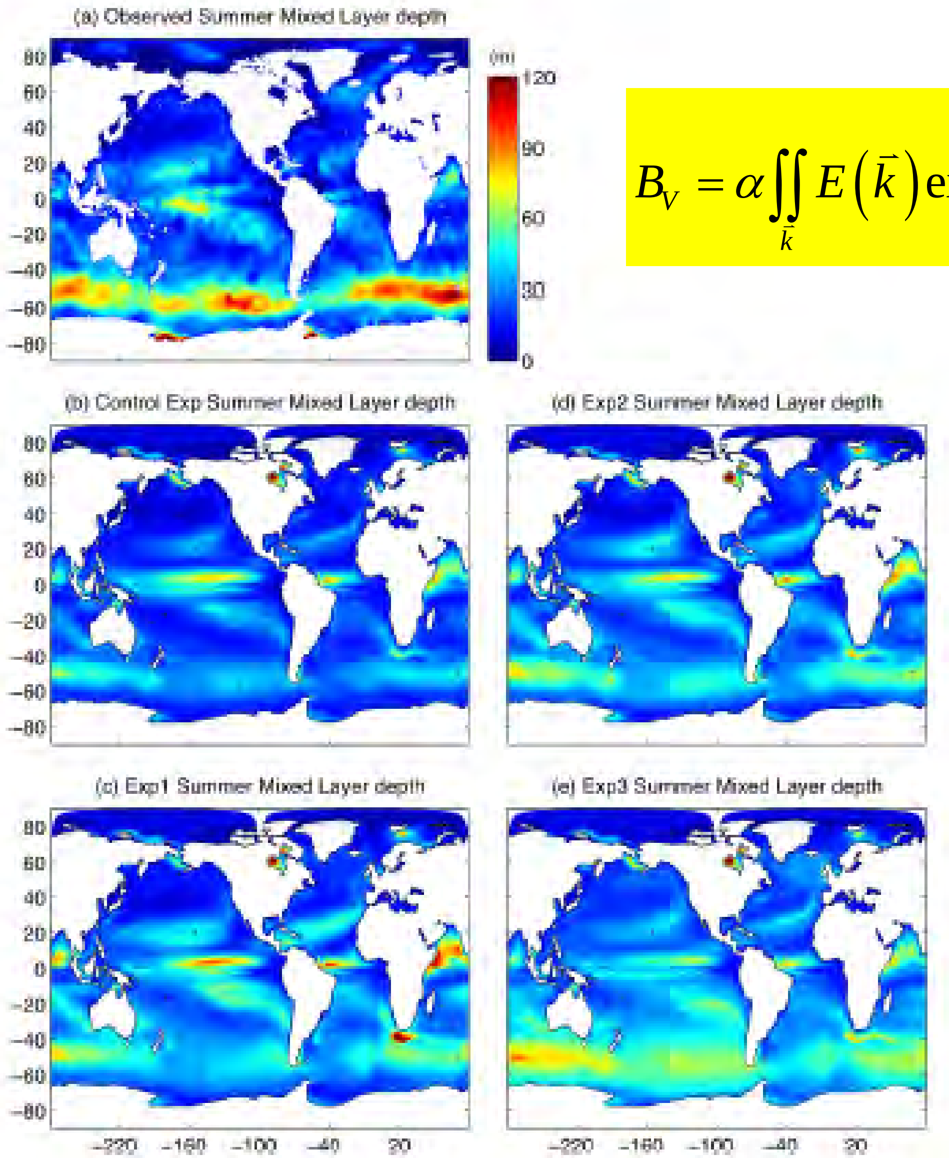
Song and Qiao et al, 2012, JAS



50a averaged SST (251-300a) of CCSM3.

Up: NoBv-Levitus, Down: Bv-NoBv

Song et al, 2012, JGR



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

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)

4. Suggestion and discussion

(1) **The non-breaking surface wave-induced vertical mixing (Bv) plays a key role in improving ocean and climate models. Even excluding shear-induced mixing, ocean circulation model (POM) can work quite well, which indicates that Bv plays dominant role in the upper ocean.**

(2) **Numerical experiments indicate that the non-breaking surface wave induced vertical mixing can much improve different OGCMs.**


Thanks for your attention