Comparison between vertical shear mixing and surface wave-induced mixing in the global ocean

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Outline

1. Introduction of Bv and its applications
2. Vertical shear mixing vs Bv
3. Summary

1. Introduction of Bv and its applications

Some related work:

1. Phillips, O. M. , 1961: "Although the use of potential theory has been very successful in describing certain aspects of the dynamics of gravity waves, it is known that in a real fluid the motion can not be truly irrotational". And Phillips (1974): **Wave is proved to be too feeble for any dynamic consequence**

2. Wave enhanced turbulence (Craig & Banner,1994; Terray, E.A. et al, 1996; Le Ngoc LY 2000; Burchard &Karsten, 2001; Mellor & Blumberg, 2004): Wave-breaking

3. Wave-current interaction (Xie et al 2002, 2003): 2-D

4. Mellor et al, 2003JPO, and 2008 J. Atmos. Ocean. Technol [wave breaking]

While these studies (wave-breaking) have shown some improvements in simulation, the surface wave effects are mostly limited to the top few meters, and too weak

Some related work:

5. We wave-induced vertical mixing, Bv, as the function of wave number spectrum(Yuan, Qiao et al, 1999; Qiao et al, 2004,2010).

6. In 2005 and 2006 (GRL), Alex Babanin: There is accumulating evidence that in absence of wave breaking, and even wind stress, turbulence still persists through the water column and not only the boundary layers.

7. The non-breaking wave-induced mixing was measured in Lab (Babanin et al, 2009, JPO; Dai et al, 2010, JPO; Savalyev et al, 2012, JGR) and in the ocean (Huang et al, 2010, 2012).

8. We have done interesting numerical experiments to close the shear-related mixing, ocean circulation model can work quite well (Qiao et al, 2012, JGR).

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

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**

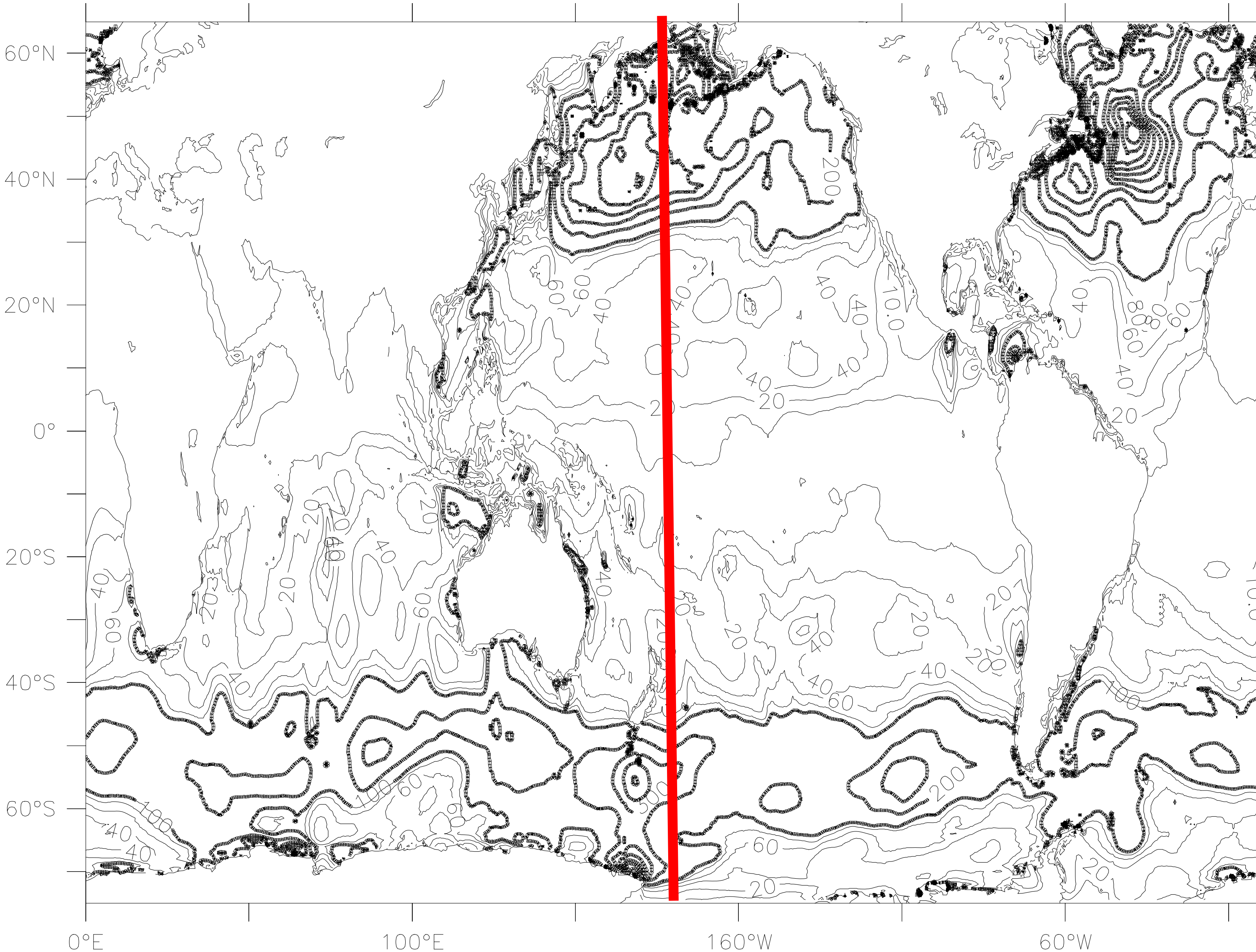
If we regard surface wave as a monochramatic wave,

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

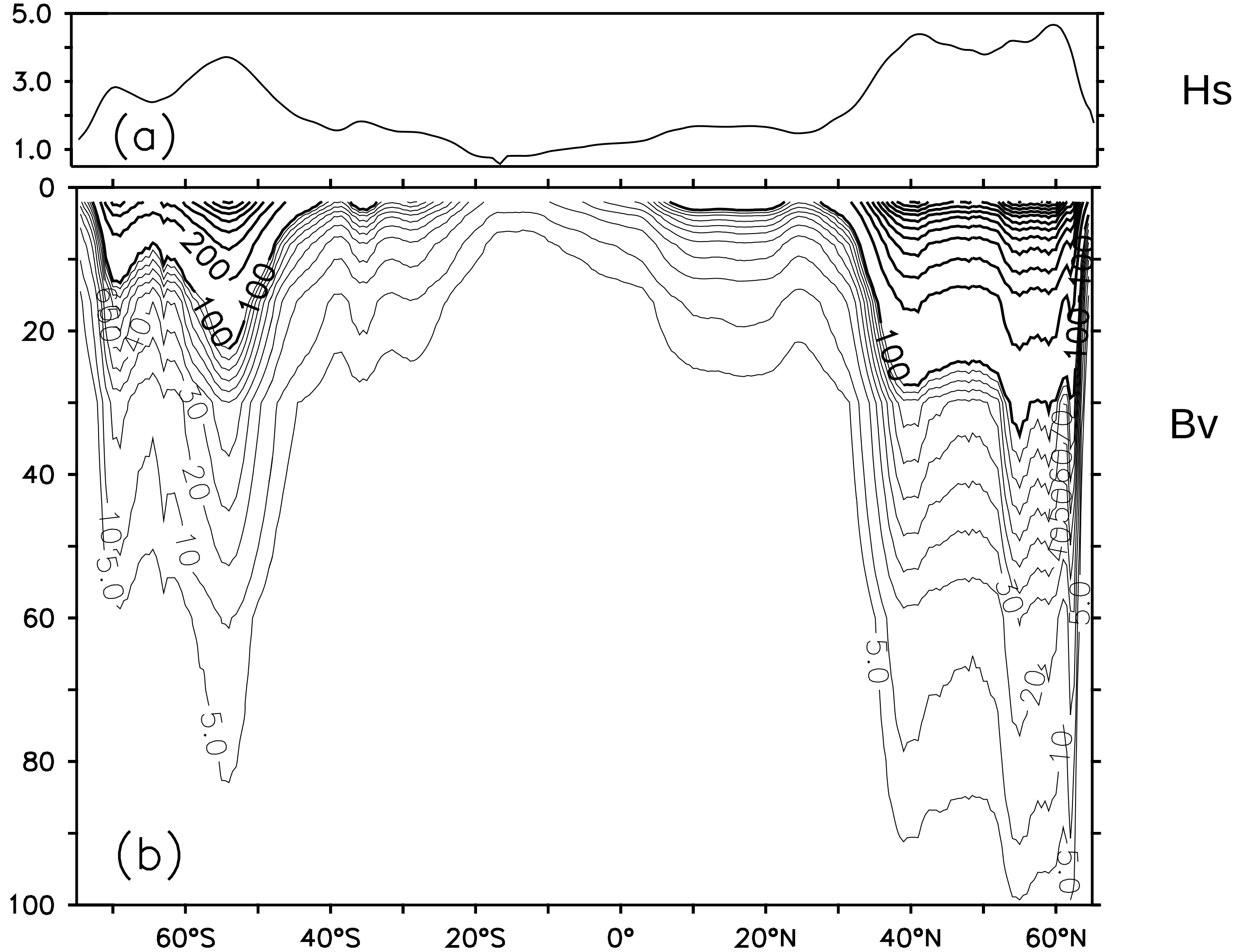
Stokes Drift

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

Although the horizontal scale of surface wave, 100m, is much smaller than that of circulation, however, the wave-induced vertical velocity in the upper ocean could be stronger than vertical current turbulence velocity.



The distribution of the 20m-averaged Bv (cm^2/s) in Feb.



The vertical distribution of the Bv (cm²/s) along dateline in Feb.

(In fact, 0.1 cm²/s means a lot for circulation processes)

Wave-circulation coupled model: How to use Bv

(1) To include current effects into a wave model is another story, but not so important.

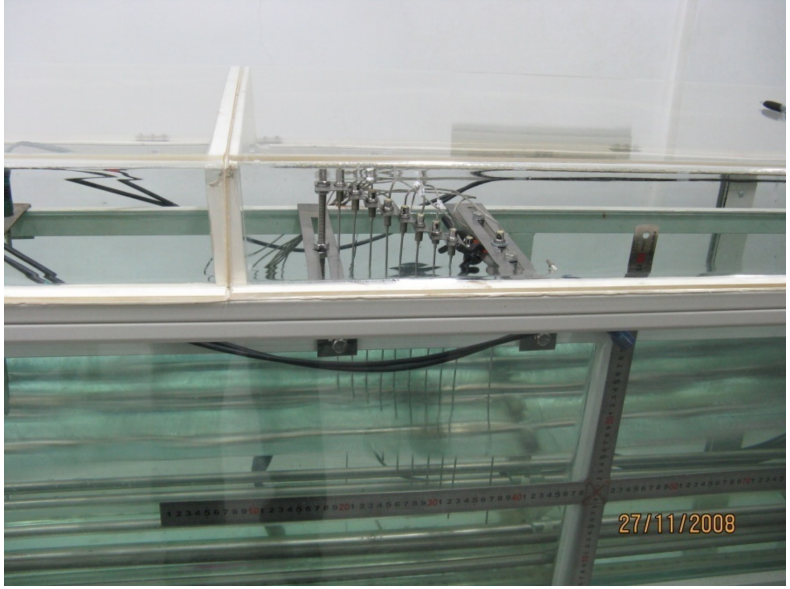
(2) To include wave effects into a circulation model is so simple, just add Bv

$$\frac{\partial}{\partial z}(K_M \frac{\partial U}{\partial z}) \Rightarrow \frac{\partial}{\partial z}[(K_M + B_V)\frac{\partial U}{\partial z}]$$

$$\frac{\partial}{\partial z}(K_M \frac{\partial V}{\partial z}) \Rightarrow \frac{\partial}{\partial z}[(K_M + B_V)\frac{\partial V}{\partial z}]$$

$$\frac{\partial}{\partial z}(K_H \frac{\partial T}{\partial z}) \Rightarrow \frac{\partial}{\partial z}[(K_H + B_V)\frac{\partial T}{\partial z}]$$

$$\frac{\partial}{\partial z}(K_H \frac{\partial S}{\partial z}) \Rightarrow \frac{\partial}{\partial z}[(K_H + B_V)\frac{\partial S}{\partial z}]$$

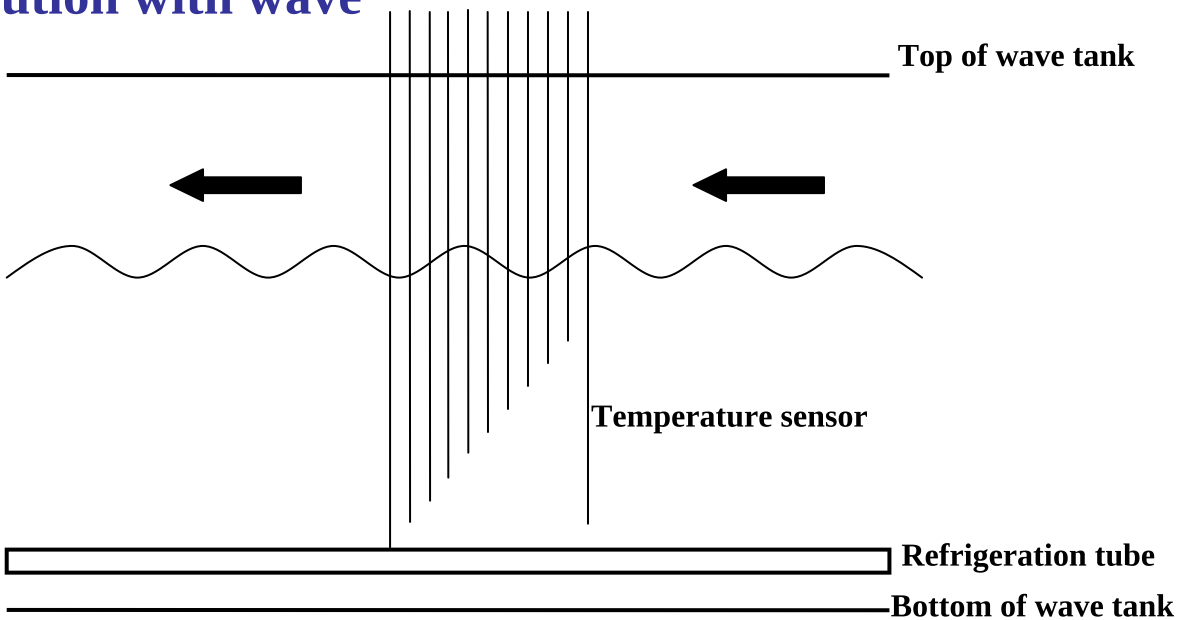


Laboratory experiments:

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

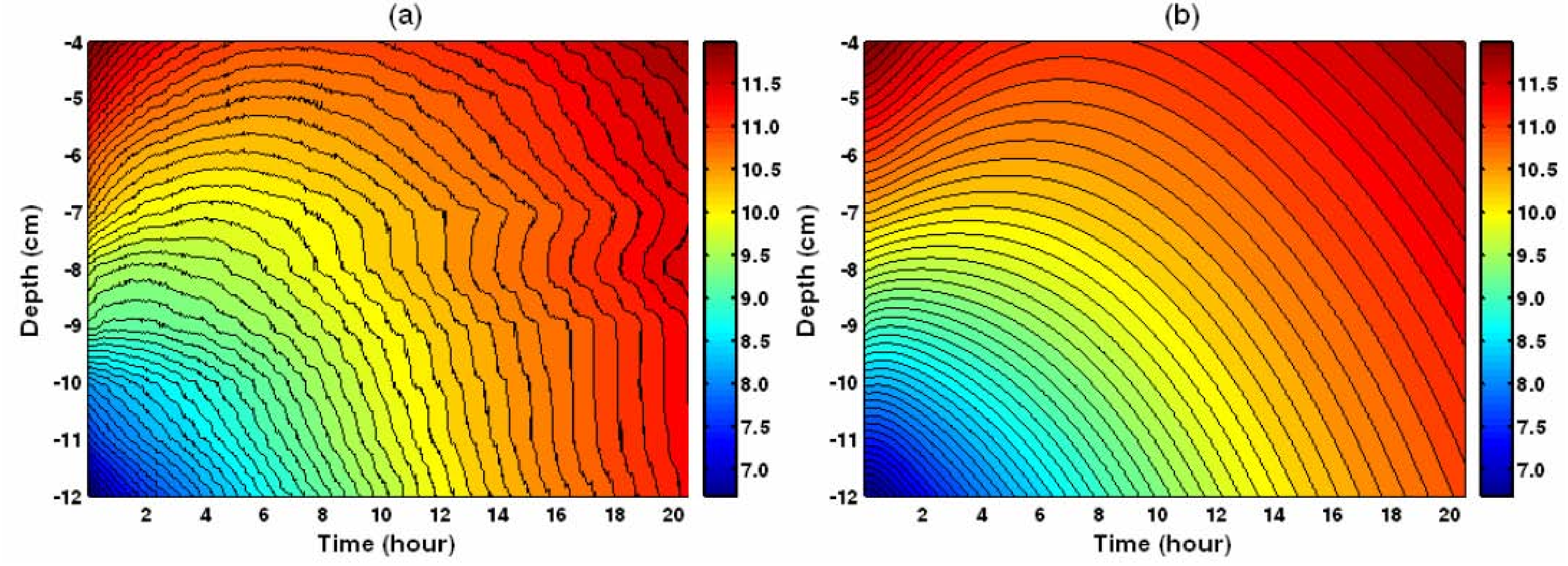


Dai and Qiao et al, JPO, 2010

Experiment results without and with waves

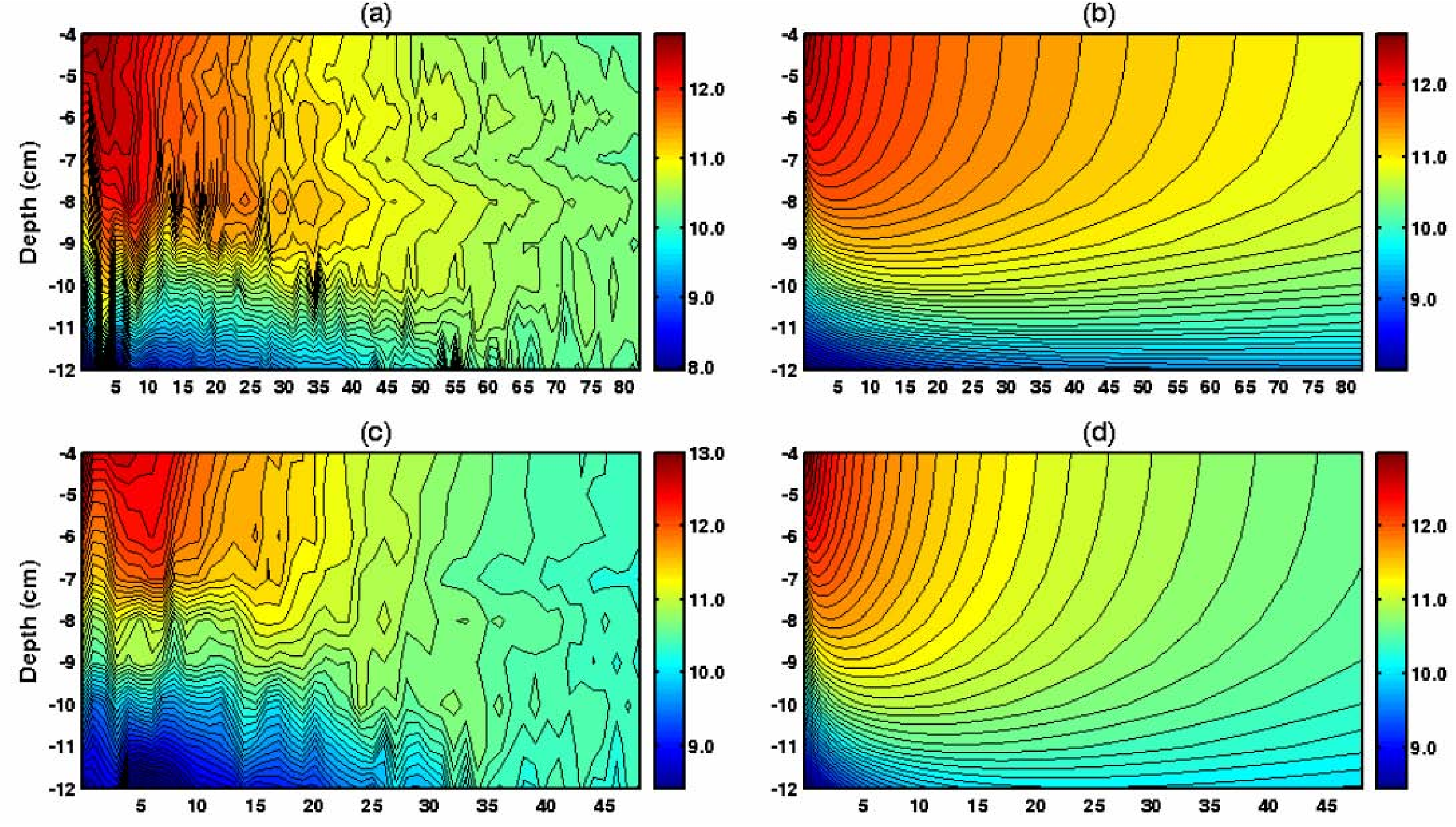
$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z} \right)$$

kz=k0+Bv



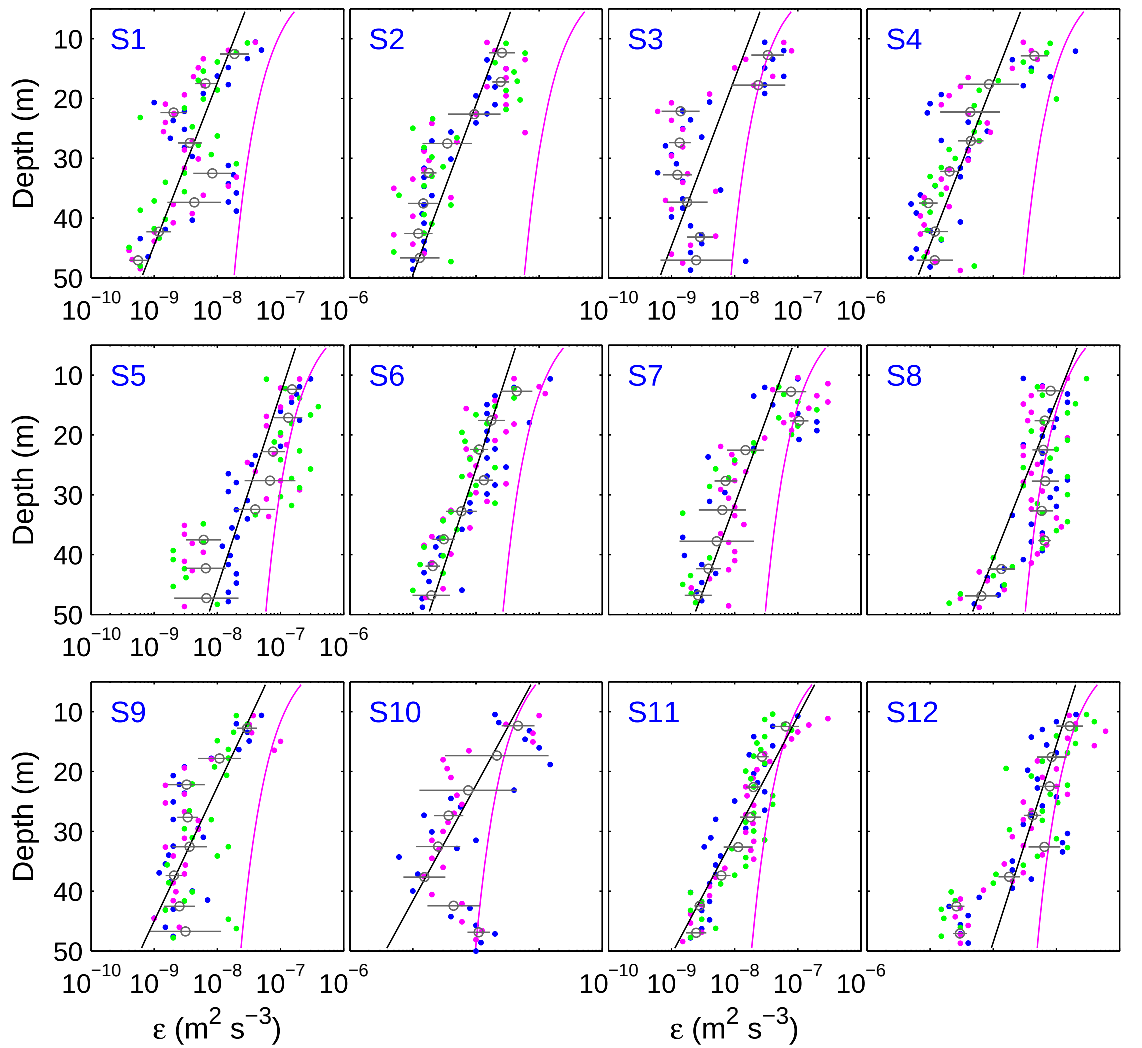
Evolution of water temperature without waves.
(a) Observation; (b) simulation.

Simulation results with waves



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

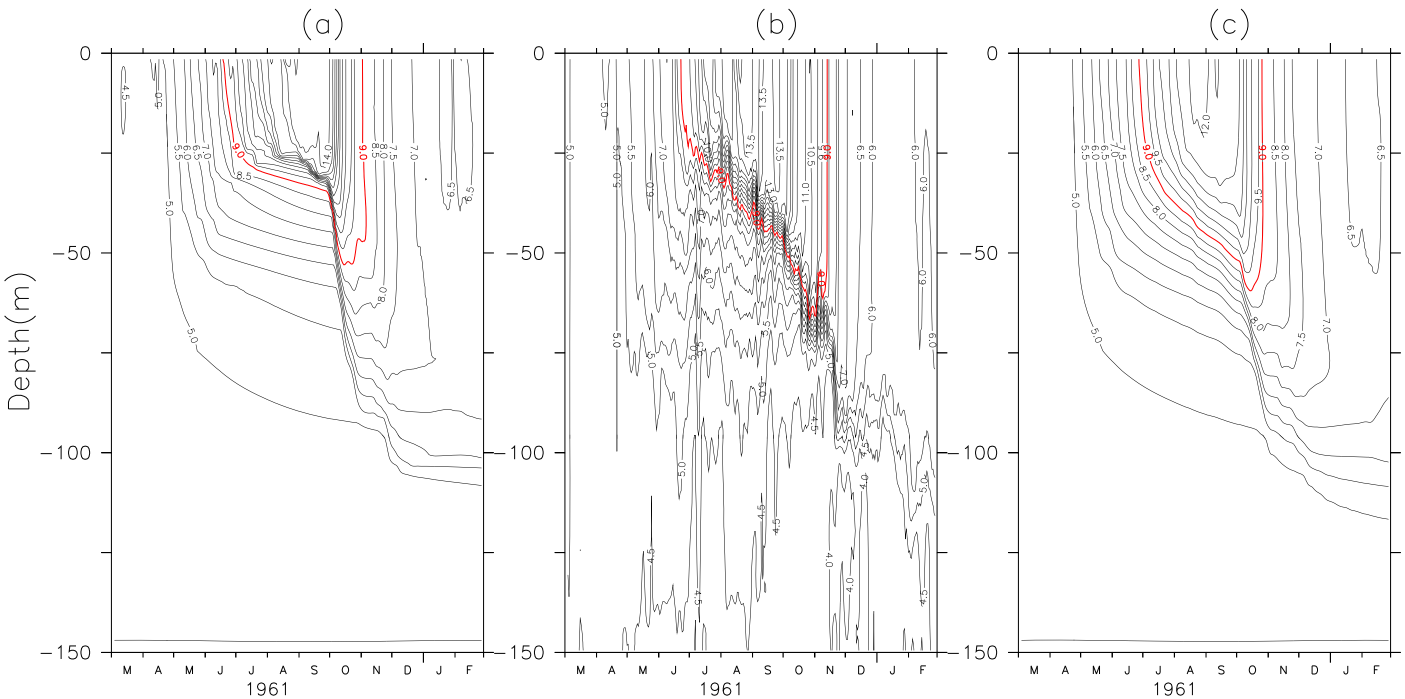
In-situ observation evidences



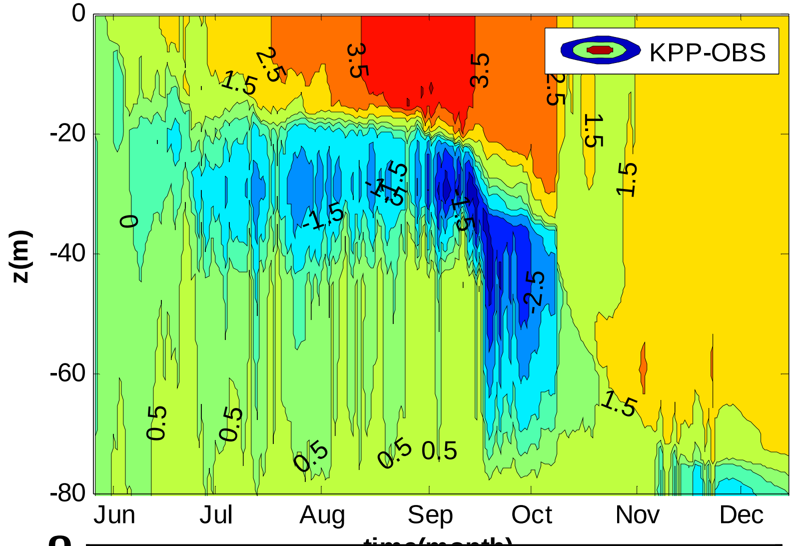
Vertical profiles of the measured dissipation rates ε_m (dots), and those predicted by wave ε_{wave} (black lines) and the law of the wall ε_{wall} (pink lines) at Station S1~S12 (in $m^2\ s^{-3}$). Observation is conducted in SCS during October 29 to November 10, 2010. Huang and Qiao et al, 2012,

Applications in ocean models

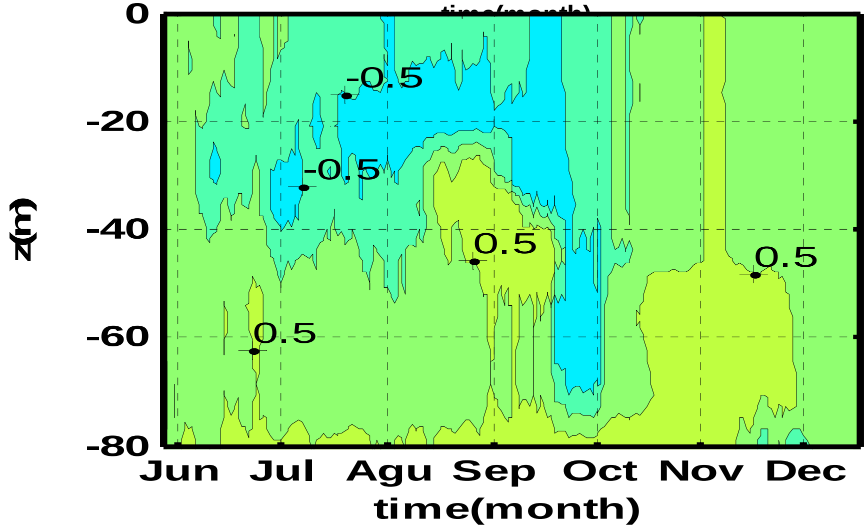
1-D numerical models



Time-depth sections of temperatures for ocean weather station (OWS) Papa (a) simulated by one-dimensional KPP scheme, (b) observed and (c) simulated by one-dimensional KPP scheme with B_v. The the red contour line indicates 9ºC isotherm. **Shu and Qiao et al, 2011, OM**



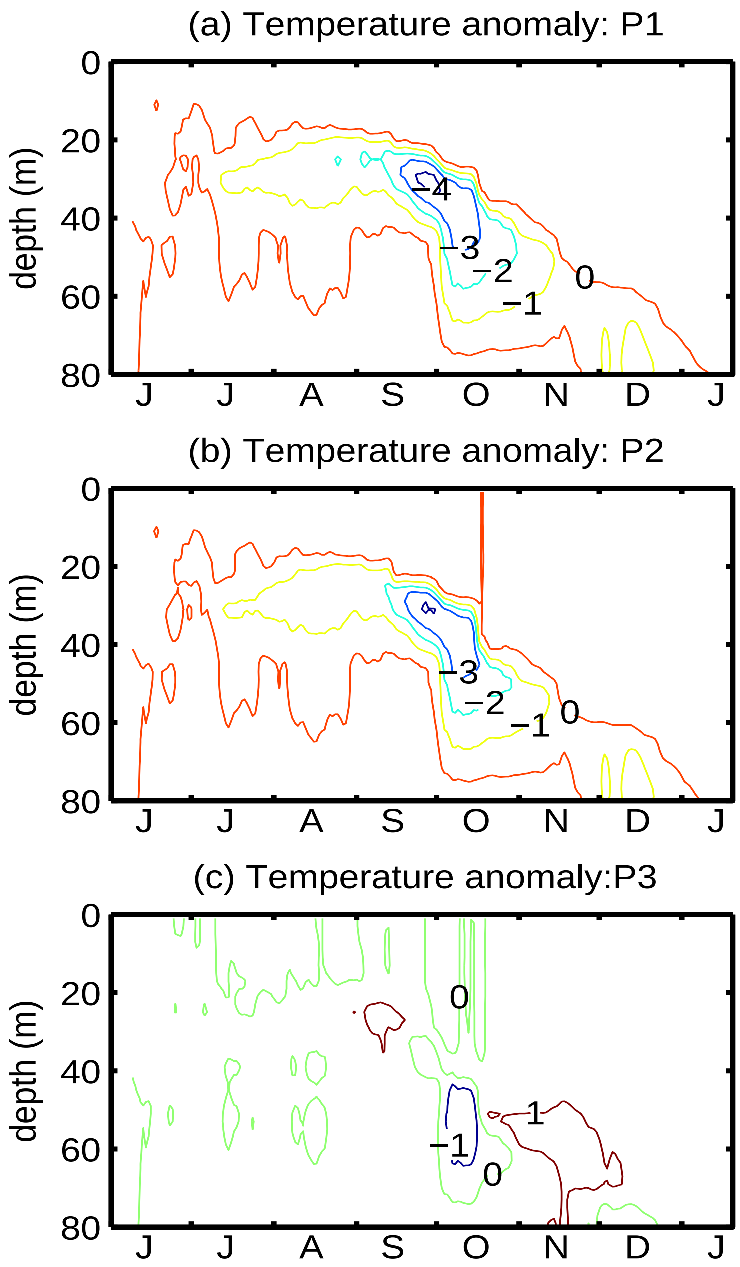
KPP



KPP+Bv

The simulation deviation for Papa Station in 2007 (Li and Qiao, 2012, AOS)

Simulated daily mean temperature deviations from the observation (ºC)



MY

MY+ wave breaking by Mellor

MY+ Bv

Huang and Qiao, 2011, JGR

3D coastal circulation models

We apply Bv into:

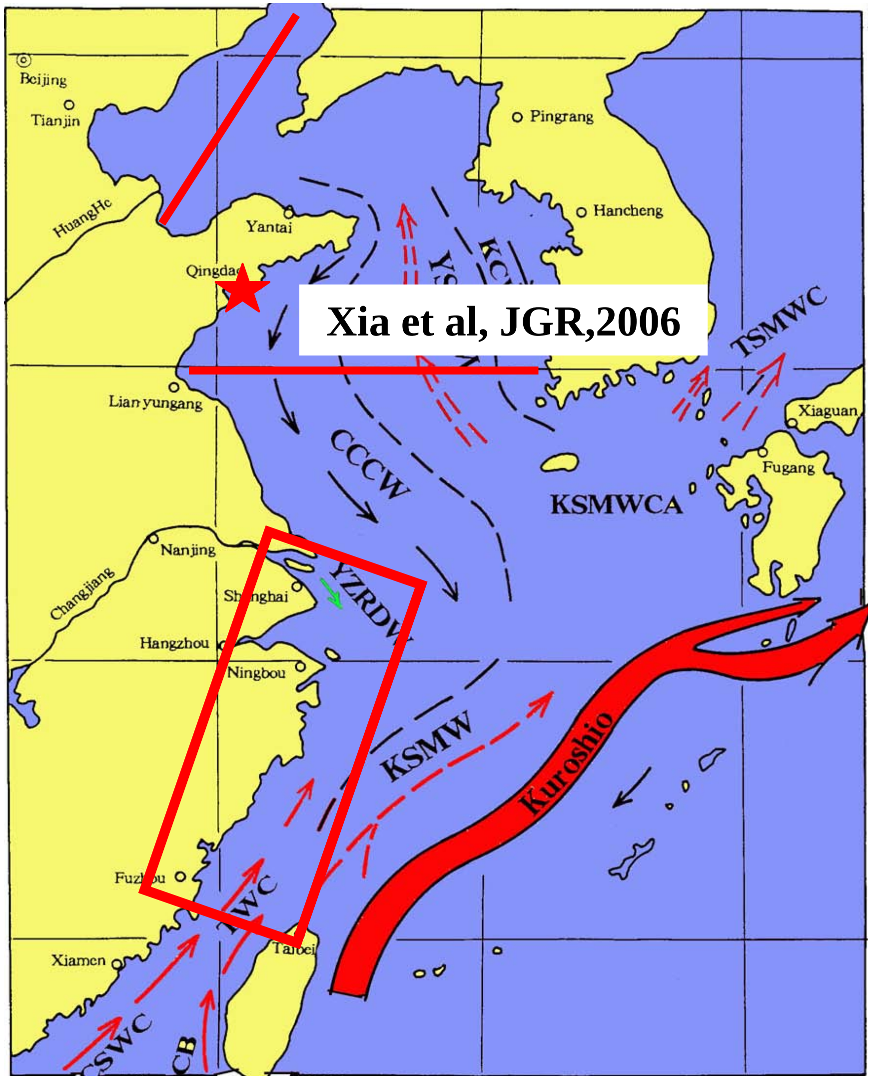
Bohai Sea

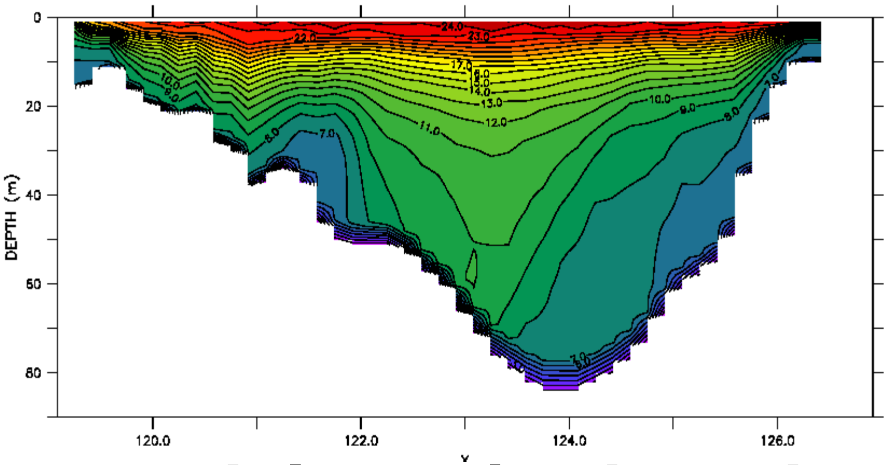
Yellow Sea

East China Sea

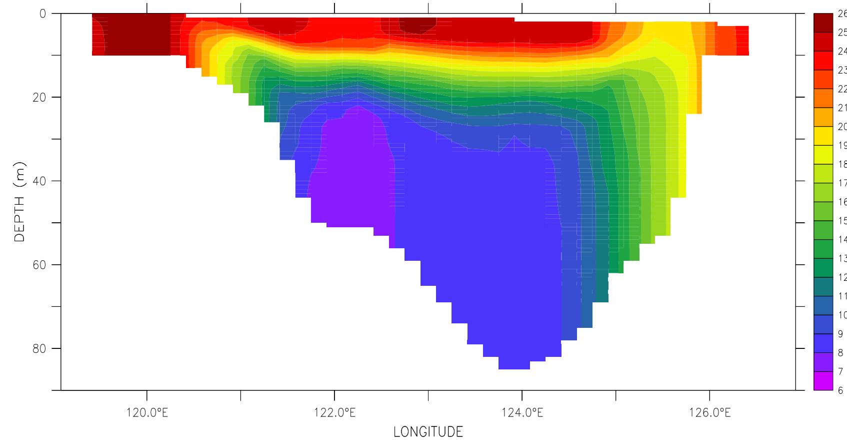
And

South China Sea



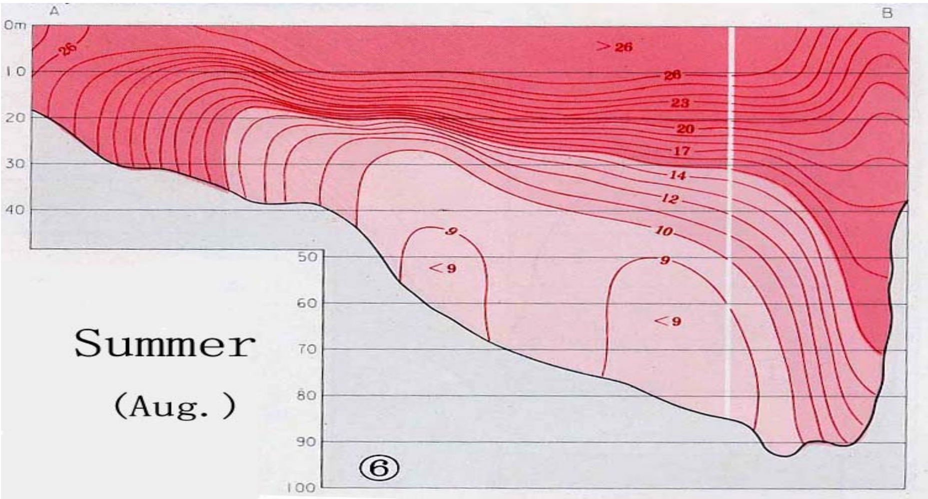


Model results (POM)

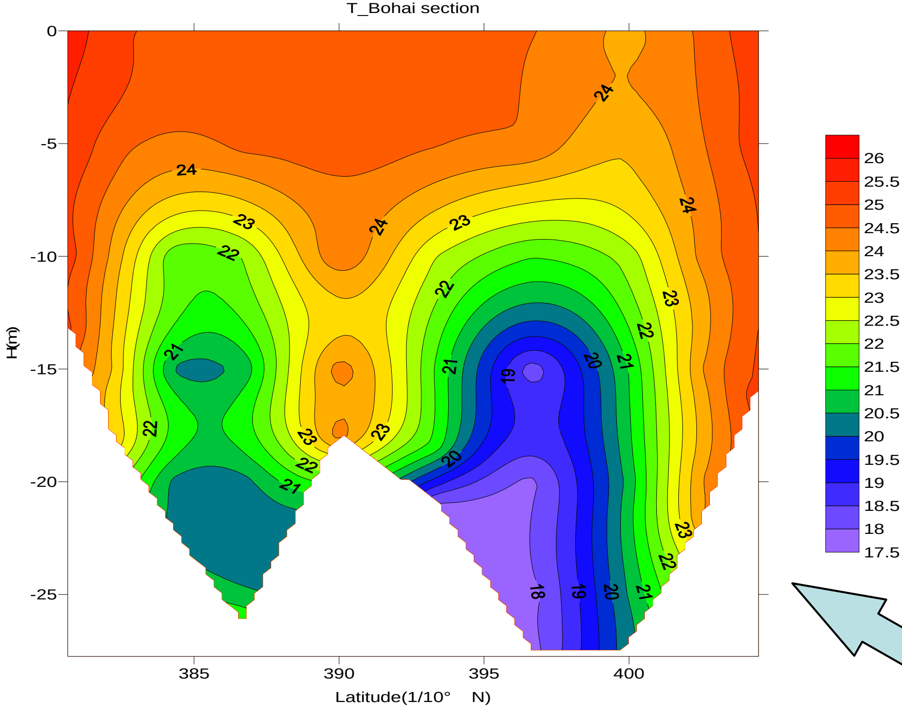


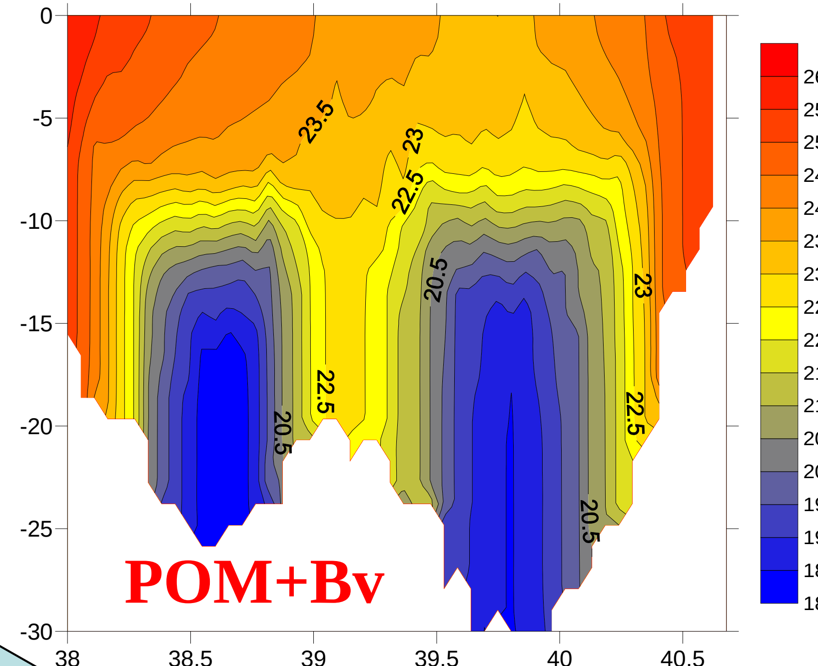
Wave-tide-circulation coupled model

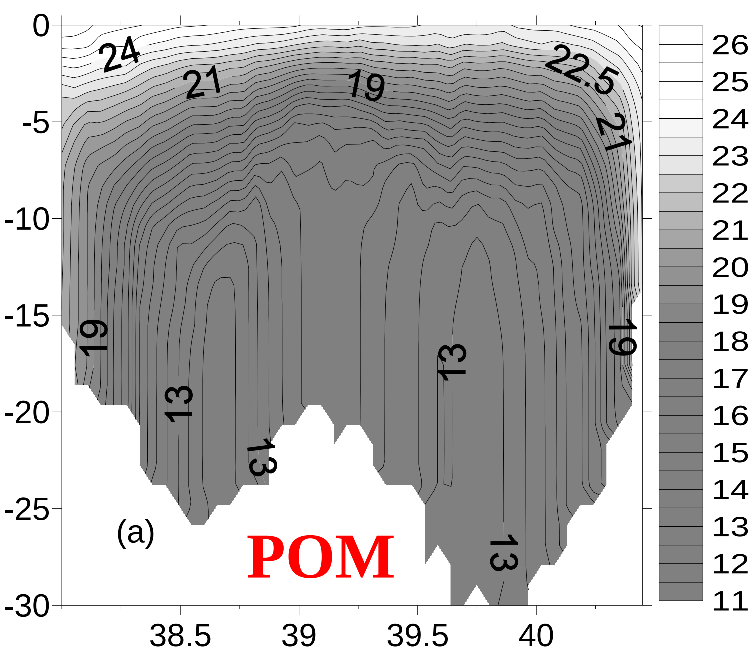
Multi-year observed Temperature along 35N in August



Qiao et al, Ocean Dynamics, 2010

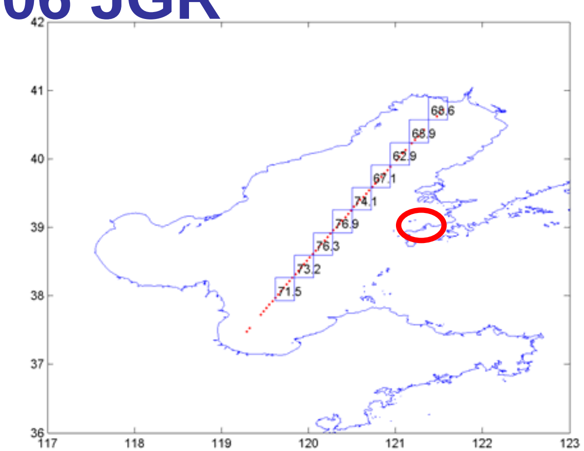






Observation in summer

Lin et al, 2006 JGR



Applications in the global ocean

SST, mixed layer, circulation

POM: Qiao et al, 2010, OD

MOM4: Shu and Qiao et al, 2011, OM

ROMS: Wang and Qiao et al, 2010, JGR

HIM: Huang and Qiao, 2012, AOS

POP: Huang and Qiao, 2012, JGR

Apply Bv into different ocean circulation models

POM: Mellor-Yamada turbulence closure model (1982) and new scheme (2004, JPO)

Circulation model linkage:

(1) Topography from ETOPO5;

(2)78° S-65° N, 0-360° E, Solid Boundary along 65° N;

(3)Horizontal resolution of 0.5° by 0.5°

(4) 16 vertical sigma layers

(5) Wind stress and heat flux from COADS.

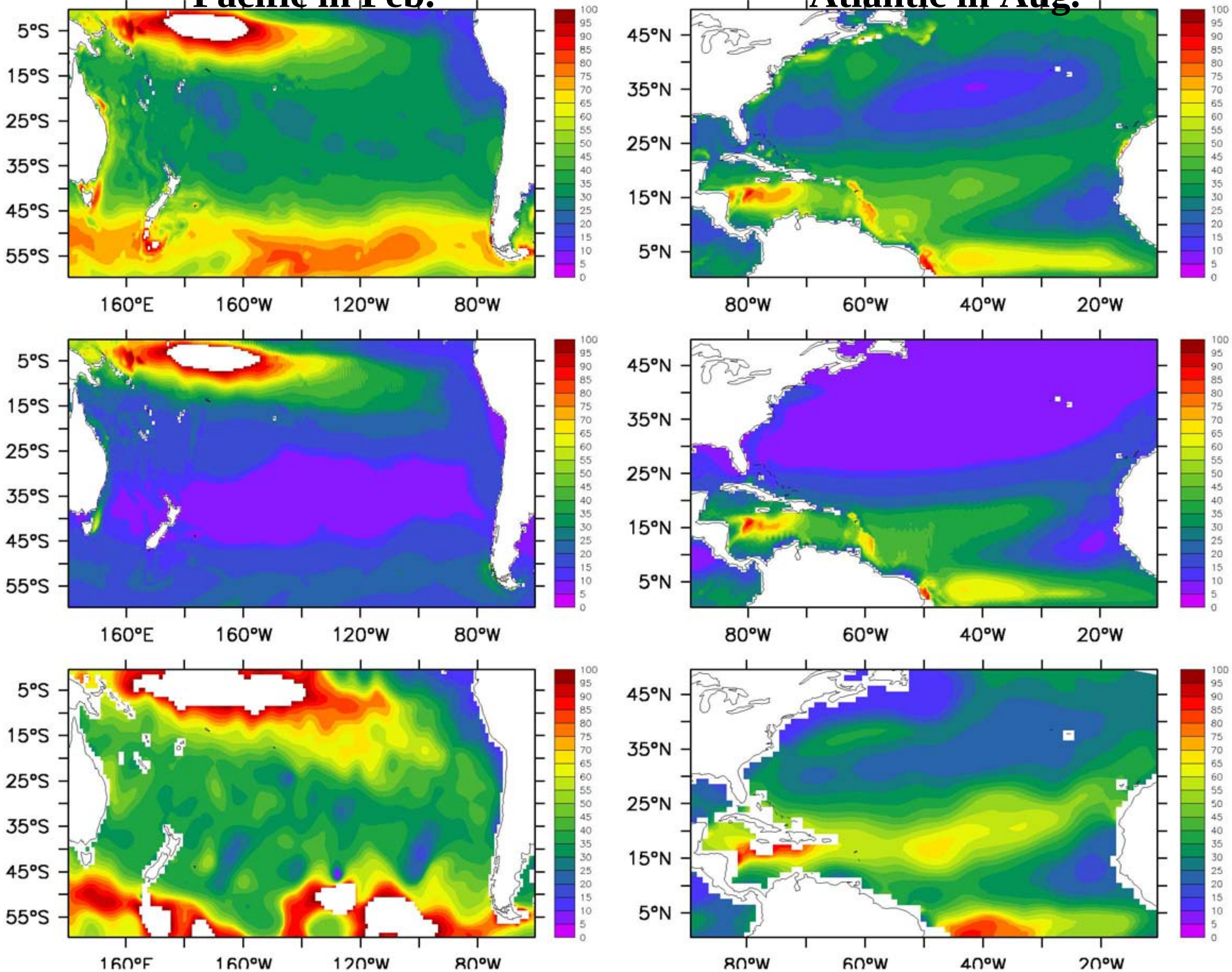
Case 1: Original POM

Cold start and run for 10 years

Case 2: POM+Bv

MLD in summer (Qiao et al, OD, 2010)

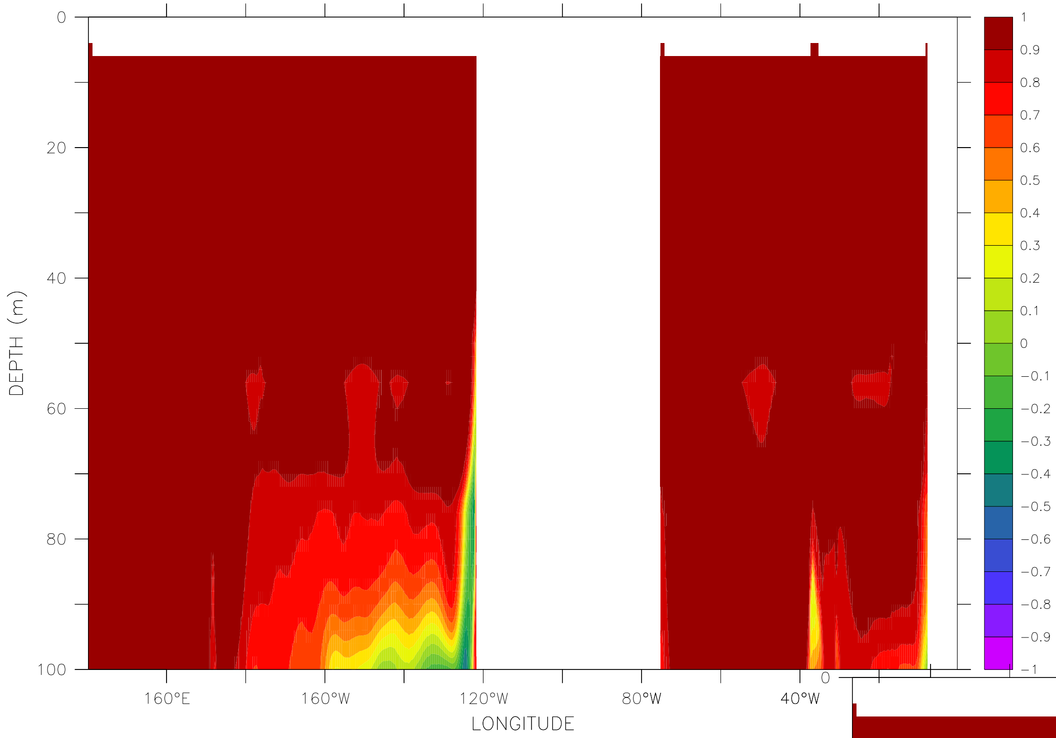
MLD of the Southern Pacific in Feb. | **MLD of the Northern Atlantic in Aug.**



With wave-induce mixing

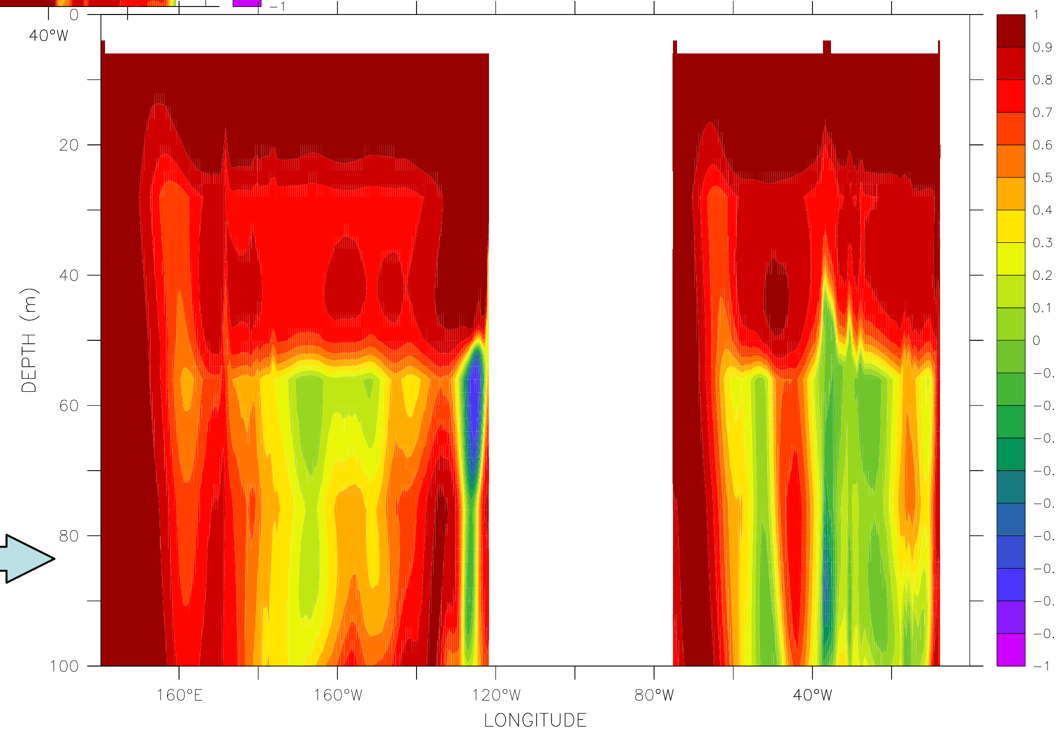
Without wave-induce mixing

World Ocean Atlas



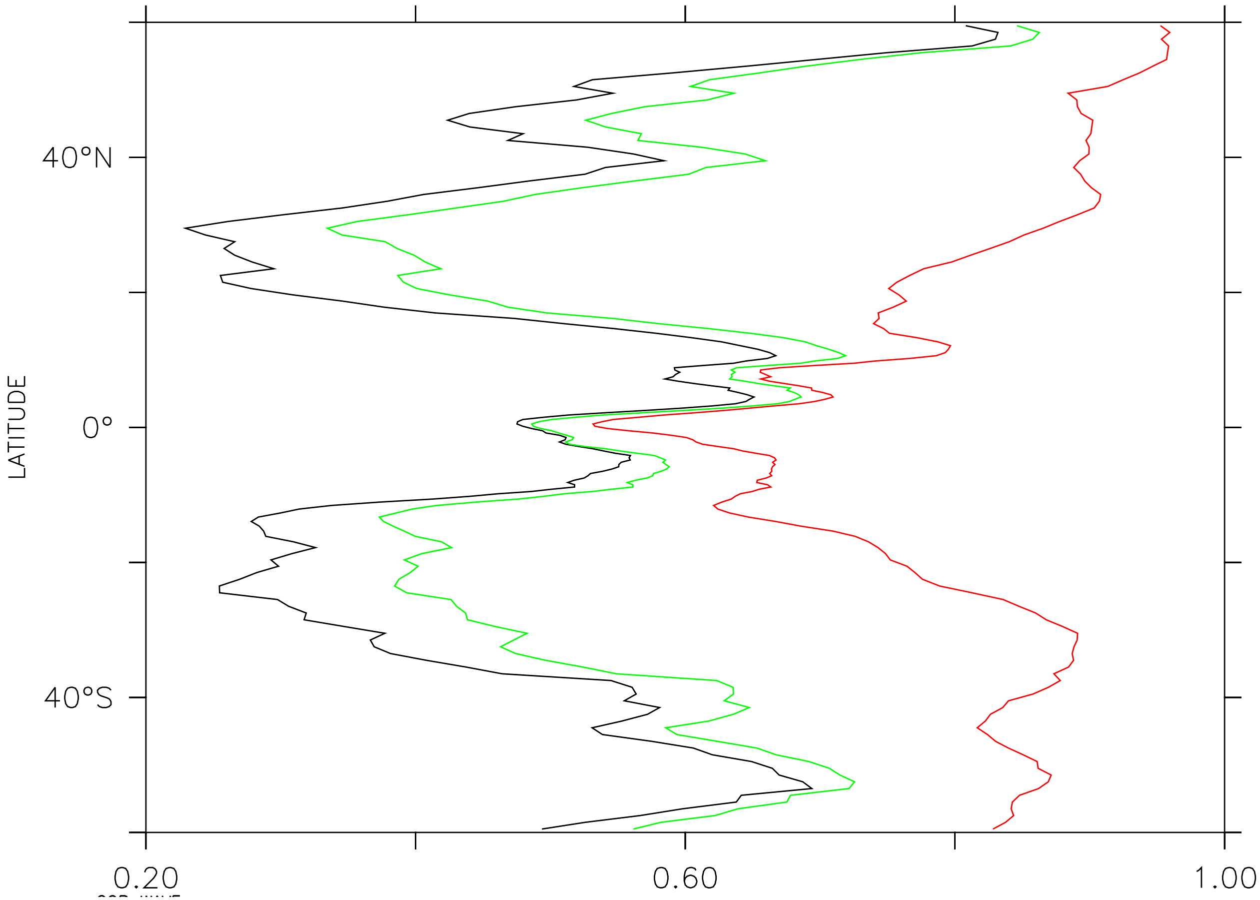
With Bv

Mean Correlation Coefficient: 0.68-0.93 (35N)



Without Bv

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



Based on POM2008. Bleck, POM2008 without wave effects; Green: with wave breaking (and IW) suggested by Mellor (2004, JPO); Red: with Bv suggested by Qiao et al (2004)

2. Comparison between vertical shear and surface waves mixing

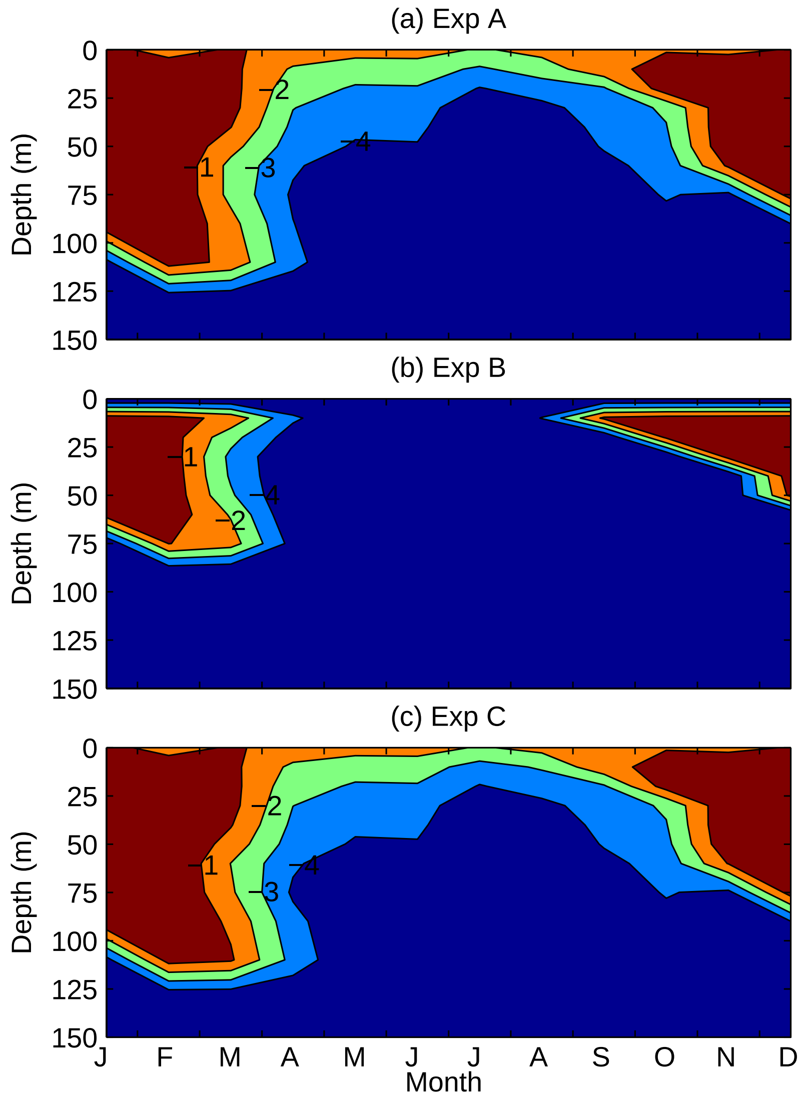
Bv vs Shear Mixing

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

(Mellor and Yamada, 1982)

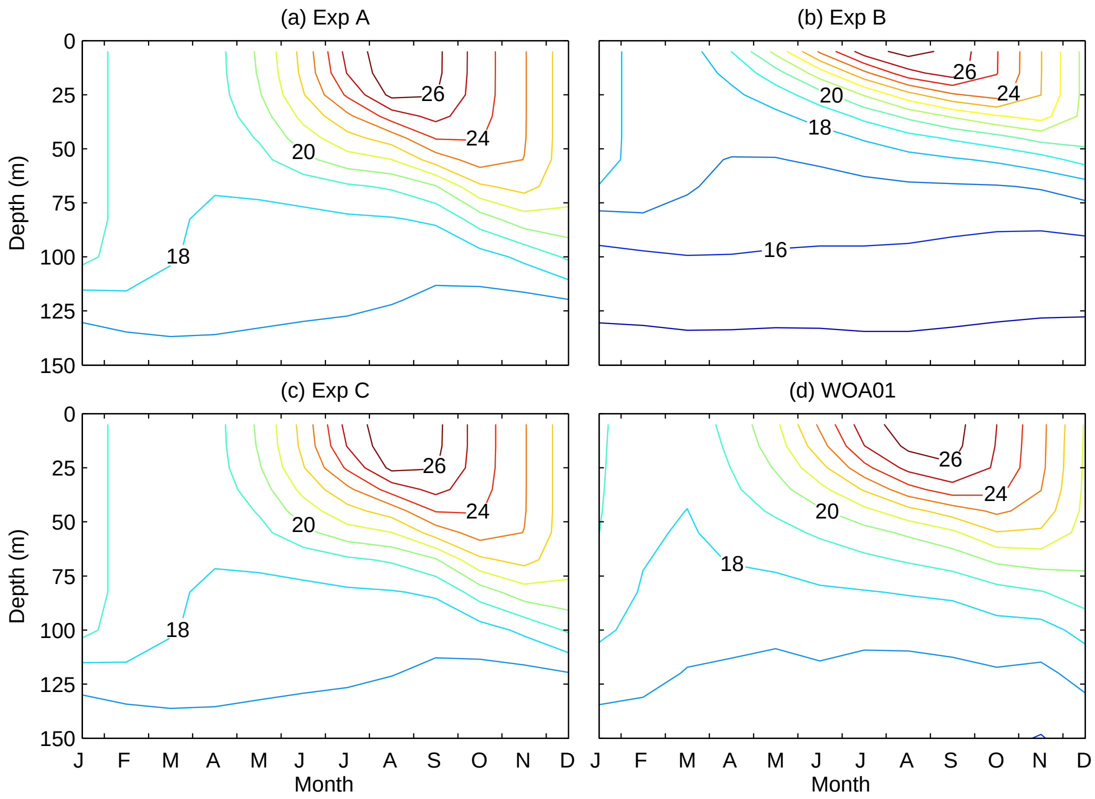
Numerical experiments for closing the shear-related vertical mixing
POM covering 72°S -65°N is selected;
Zonal resolution 1°, while meridional resolution is 1/3° between 10°S-10°N, and gradually increases to 1° by 20°N and 20°S;
32 sigma levels;
The background mixing of 1×10^{-4} m^2 s^{-1} (K_{m0})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



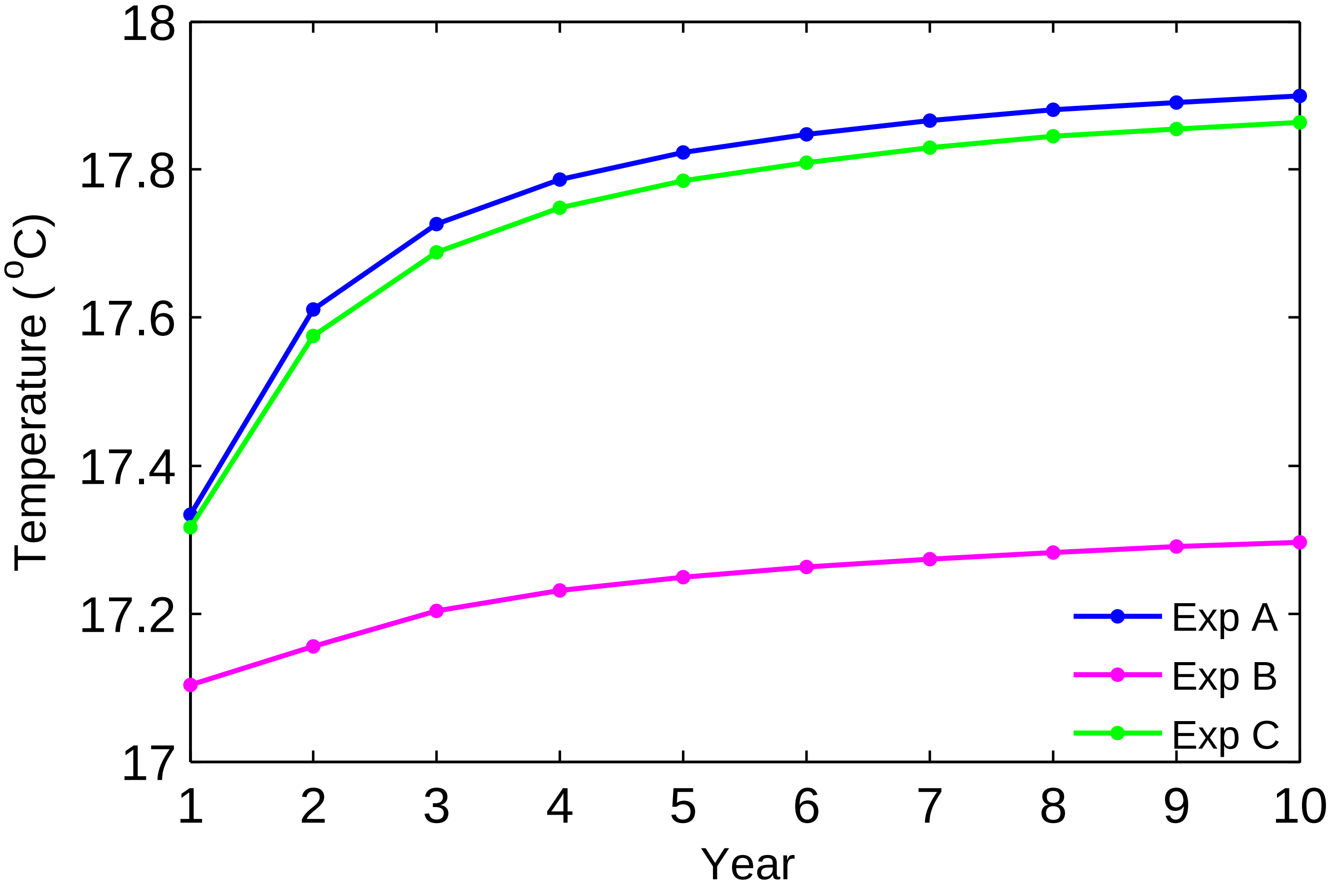
Monthly-mean vertical diffusivity (in $m^2\ s^{-1}$) as a function of depth and time at 30°N, 180°E. The diffusivities have been taken by denary logarithm

- Too shallow and too strong thermocline in Exp B
- Thermocline in Exp C is very similar as that in Exp A



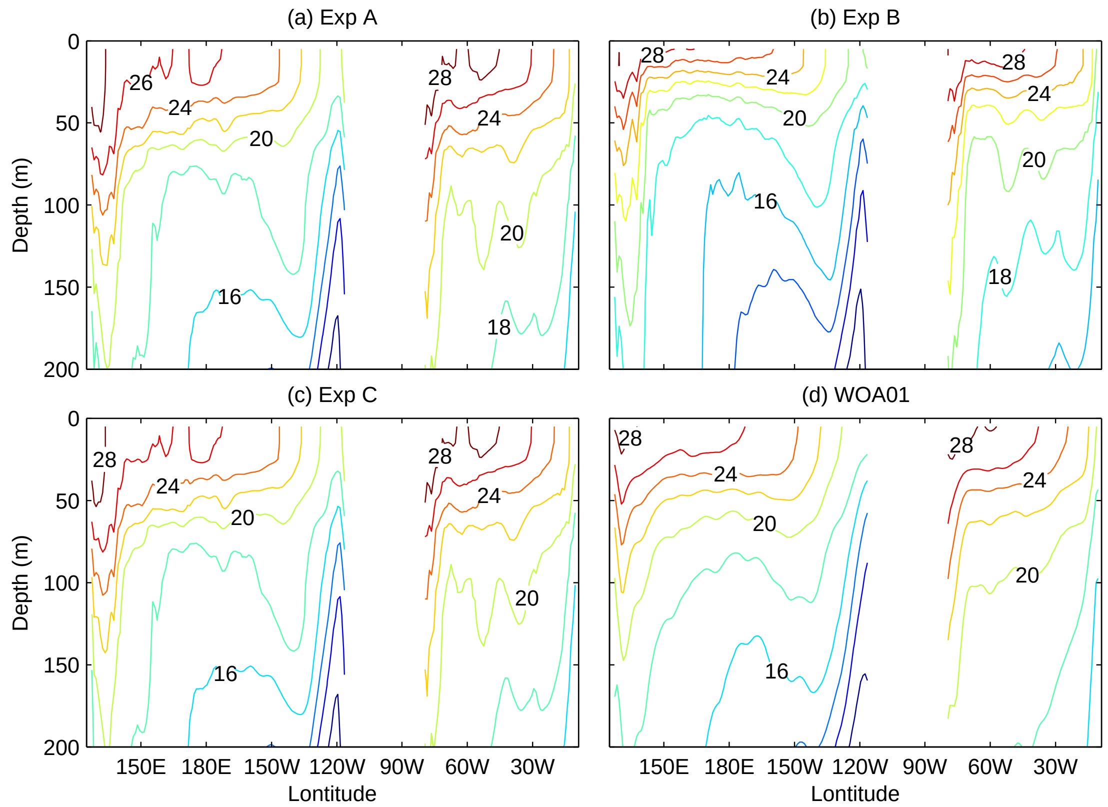
At 30°N, 180°E

Monthly-mean temperature as a function of depth and time at 30°N, 180°E from (a) Exp A, (b) Exp B, (c) Exp C, and (d) the climatology. Contour interval is 1°C.



Time evolutions of annual-mean temperature within the upper 200 m averaged between 65°S and 65°N

- Too shallow and too strong thermocline in Exp B
- Thermocline in Exp C is very similar as that in Exp A



Along 30^{o}N

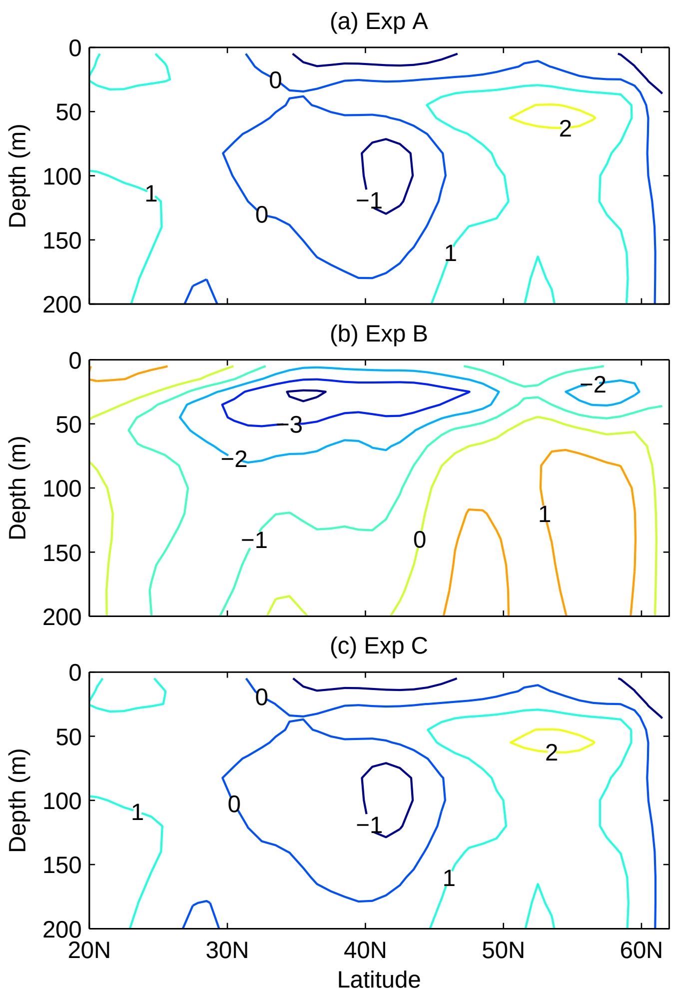
Temperature distribution along 30^{o}N in August from (a) Exp A, (b) Exp B, (c) Exp C, and (d) the climatology. Contour interval is 2^{o}C.

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

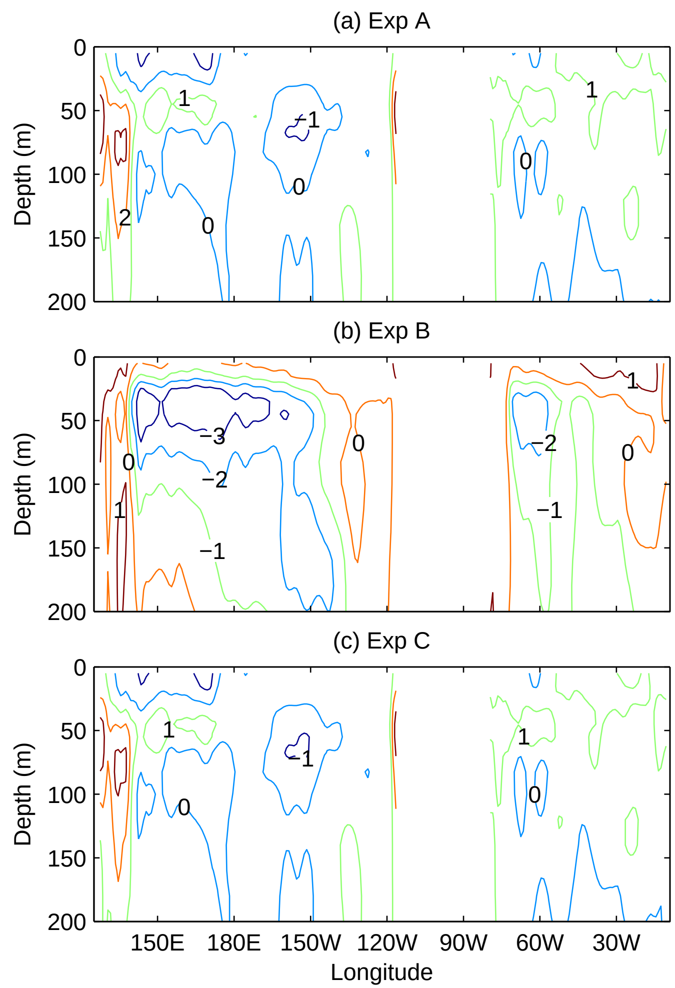
MY+Bv

MY

Bv

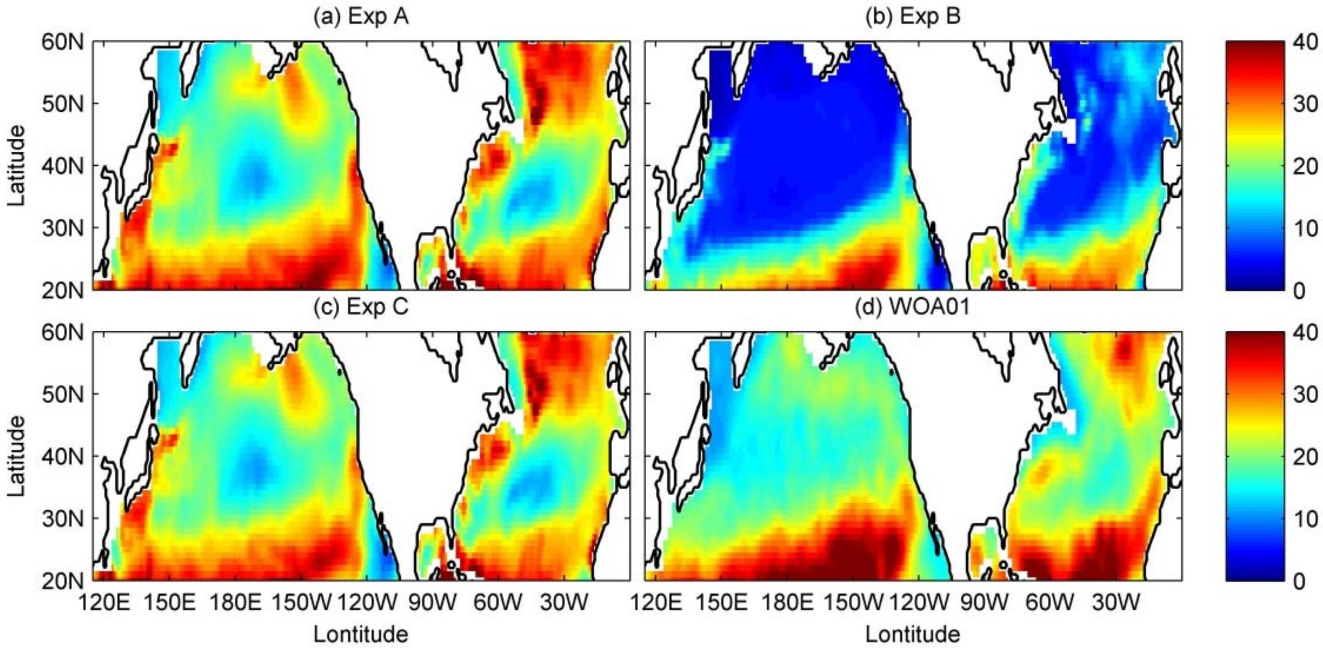


Temperature deviations from the climatology averaged in August along the dateline



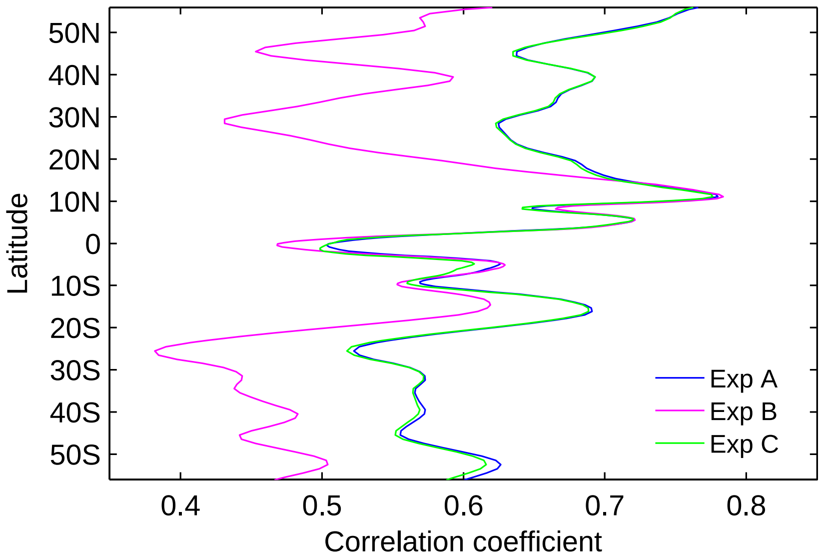
Temperature deviationss from the climatology averaged in August along 30ºN

- Too shallow mixed layer depth (MLD) in Exp B
- MLD in Exp C is very similar as that in Exp A



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

- **In the extra-tropical region: correlation coefficient in Exp B is smaller than those in Exps A and C**
- **In the tropical region: correlation coefficient in Exp B is similar as those in Exps A and C**



Zonally averaged correlation coefficients in the upper 200 m between the simulated and monthly-mean climatological temperature.

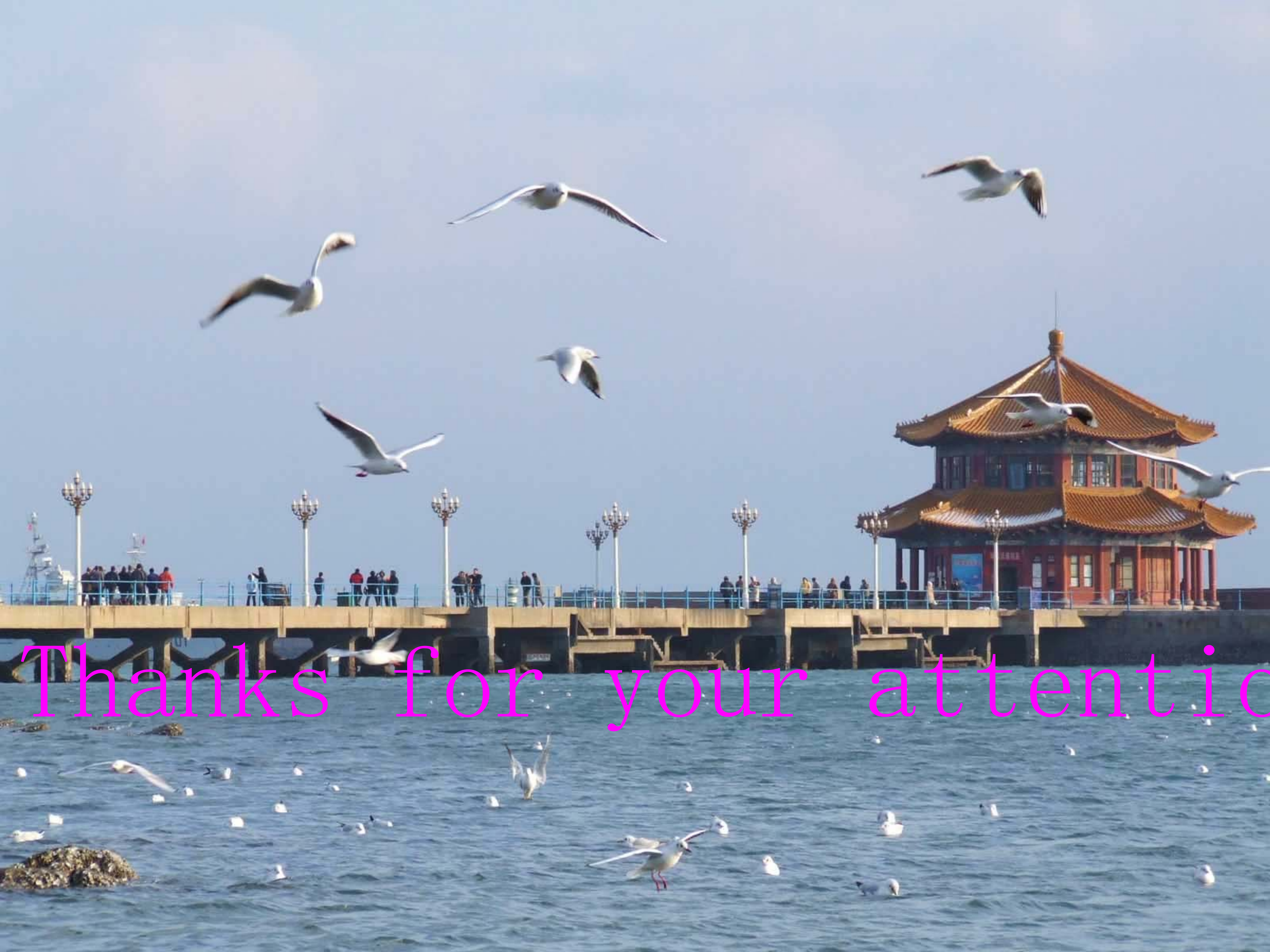
Conclusions

Surface wave is quite import for ocean circulation models through vertical mixing.

1. The non-breaking surface wave-induced vertical mixing (Bv) plays a key role in improving ocean circulation models, so it may be a low-lying fruit for improving forecasting ability of ocean, and then climate.

2. Bv is nearly not model dependent, it can be easily included into coastal circulation models and global ocean circulation models, and more important, Bv is effective.

3. Even excluding shear-induced mixing, POM can work quite well, which suggests that Bv plays much more important role than that of shear-induced mixing.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