Wave-tide-circulation coupled model: To improve the forecasting ability for FUTURE

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Motivation

The importance of accurate simulation/ forecast of sea temperature doesn't need to be stressed, it is closed related with:

Climate change;

Sea level rise;

Frequency of HAB;

Frequency and intensity of Typhoon/hurricane;

And so on. However,

Motivation

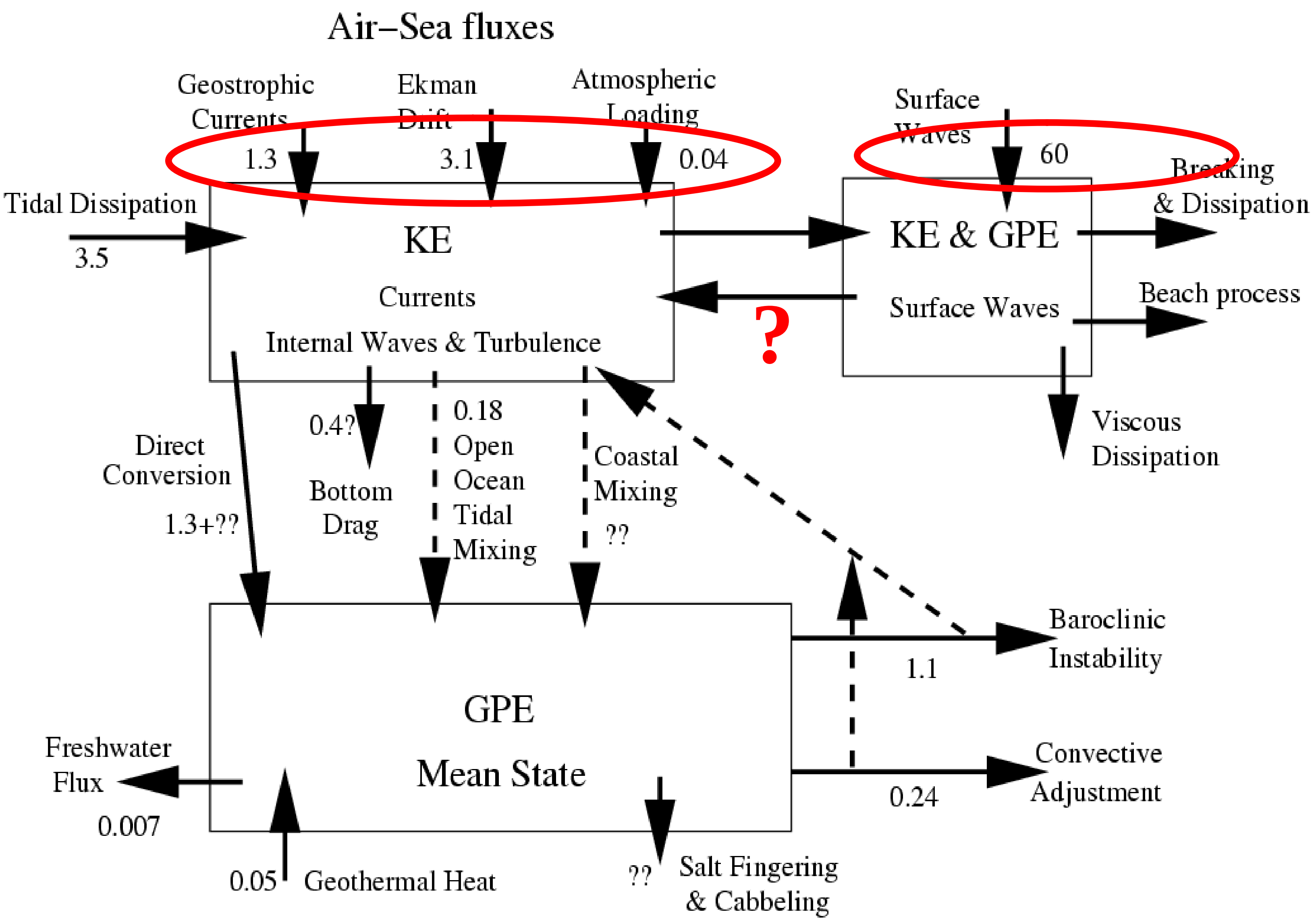
Two of the common problems nearly all models faced

1. OGCMs: 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).

2. Climate Models: Tropical bias for all coupled OGCM-AGCM models, such as too cold tongue

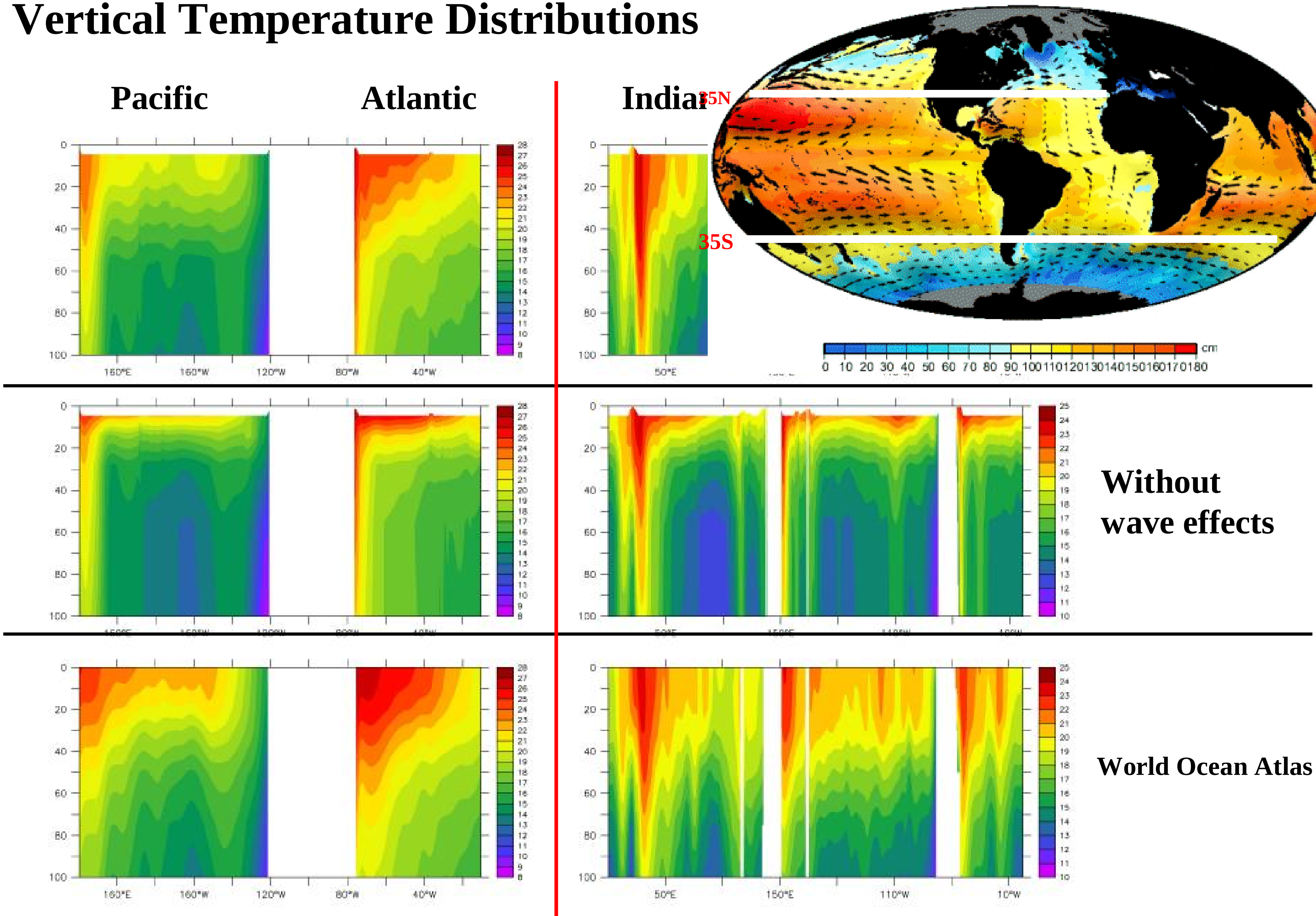
Can the surface wave be a remedy?

The Surface Wave is the most energetic motion



Mechanical energy balance in the oceans ***(C Wunsch, Science)***

Vertical Temperature Distributions

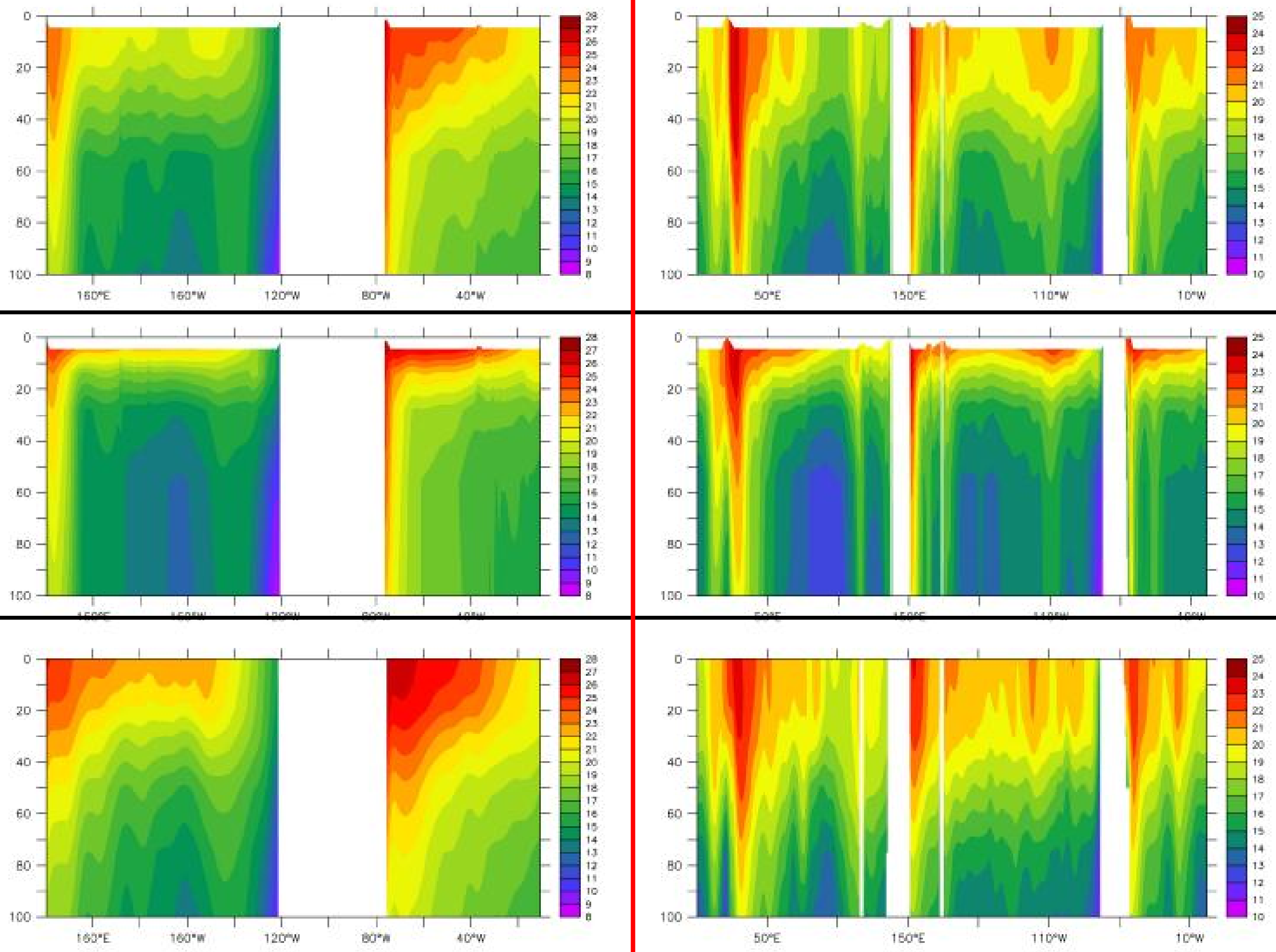


Along 35N transect in Aug.

Along 35S transect in Feb.

Vertical Temperature Distributions

Pacific Atlantic | Indian Pacific Atlantic

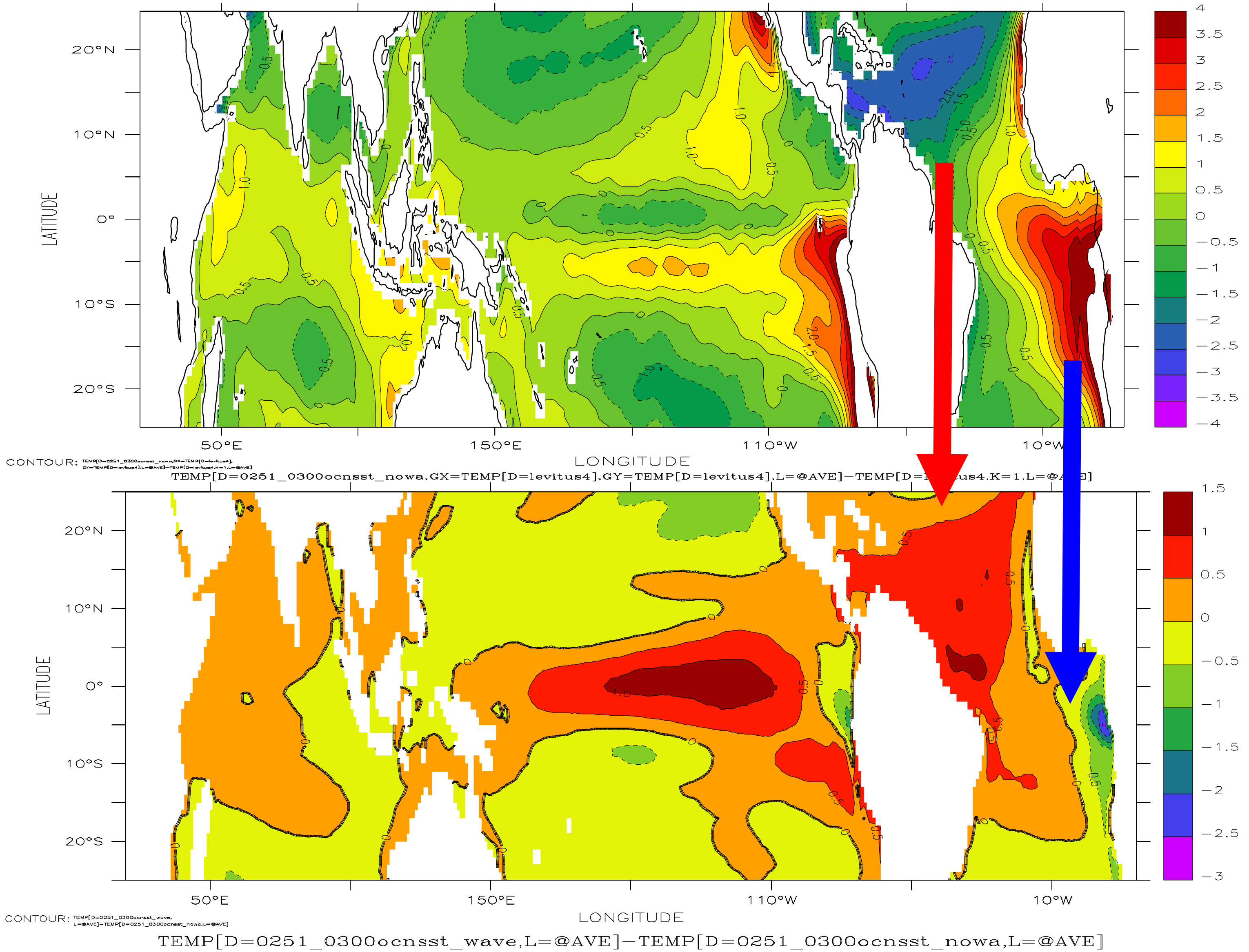


With wave effects

Without wave effects

World Ocean Atlas

Along 35N transect in Aug. | Along 35S transect in Feb.



50a averaged SST (251-300a).

Up: Exp1-Levitus, Down: Exp2-Exp1

Exp1: CCSM3 without Bv

Exp2: with Bv

Outlines

1. **Theories**
2. **Applications in coastal ocean circulation model**
3. **Applications in global ocean circulation models**
4. **Applications in AGCM-OGCM Coupled climate models**
5. **Conclusions**

Theories:

how does wave affect circulation?

Some related work:

1. Wave is proved to be too feeble for any dynamic consequence (Phillips, O. M. , 1974)

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 2002,2003): 2-D

4. Mellor et al, 2003JPO, 2004JPO, 2005JPO and 2008 J. Atmos. Ocean. Technol [wave breaking and internal wave]

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. In 2004, we proposed wave-induced vertical mixing, Bv, as the function of wave number spectrum.

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.

In 2006, Alex Babanin wave motion can directly affect the upper-ocean mixing.

Separate the velocity field into averaged and fluctuation components

$$u_{zi} = U_i + u_i, \quad T_z = T + q, \quad S_z = S + s$$

Separate the fluctuation velocity into wave-related and current-related parts:

$$u_i = \boxed{u_{iw}} + u_{ic}$$

Reynolds stress

$$-\overline{u_i u_j} = -\overline{u_{iw} u_{jw}} \boxed{-\overline{u_{iw} u_{jc}} - \overline{u_{ic} u_{jw}}} - \overline{u_{ic} u_{jc}}$$

Wave-induced stress

Wave Effects

Reynolds stress

$$-\overline{u_i q} = \boxed{-\overline{u_{iw} q}} \boxed{-\overline{u_{ic} q}}$$

$$-\overline{u_i s} = \boxed{-\overline{u_{iw} s}} \boxed{-\overline{u_{ic} s}}$$

Wave-induced **Circulation-related**

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

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**

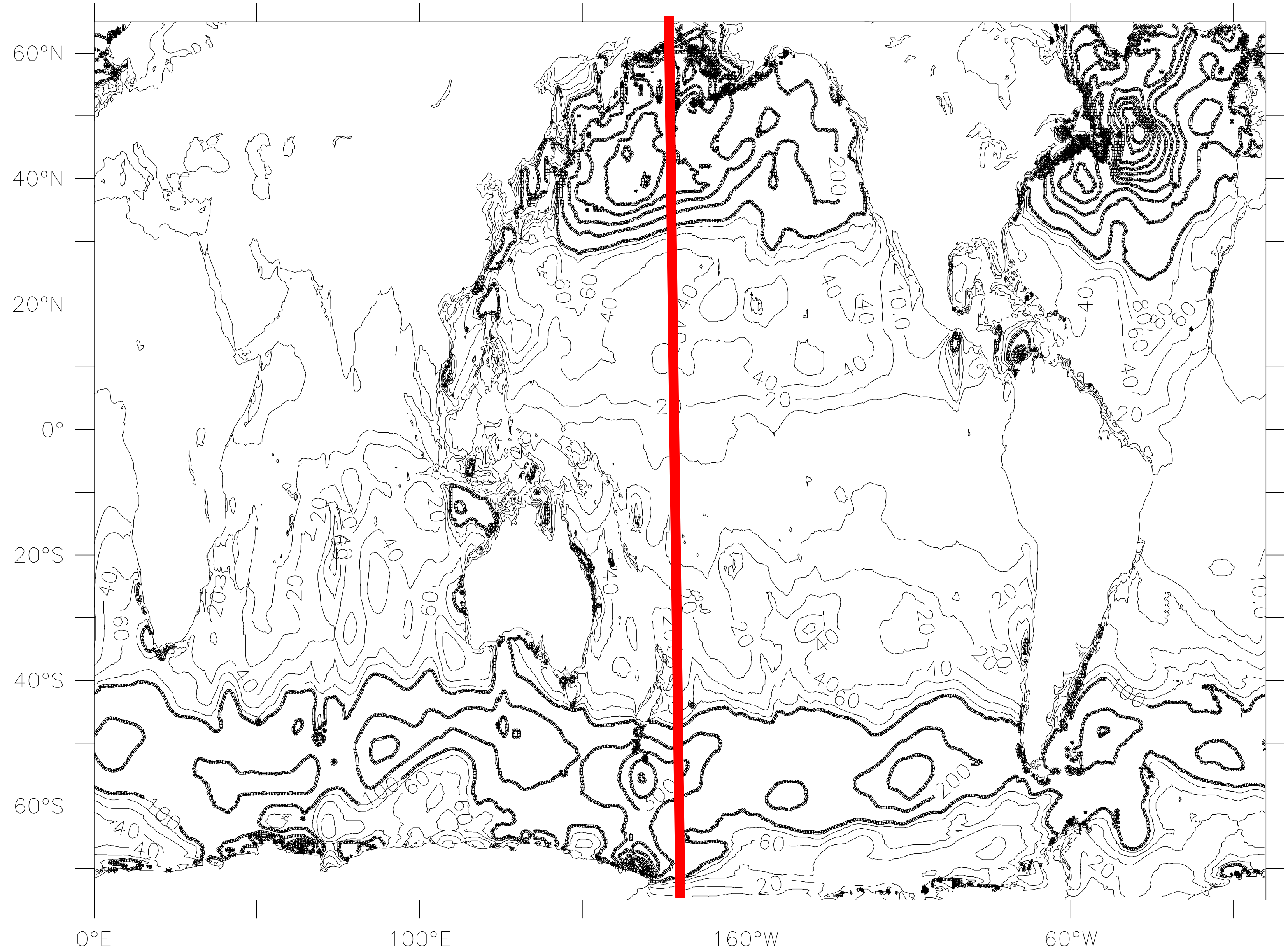
If we regard surface wave as a monochratic wave,

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

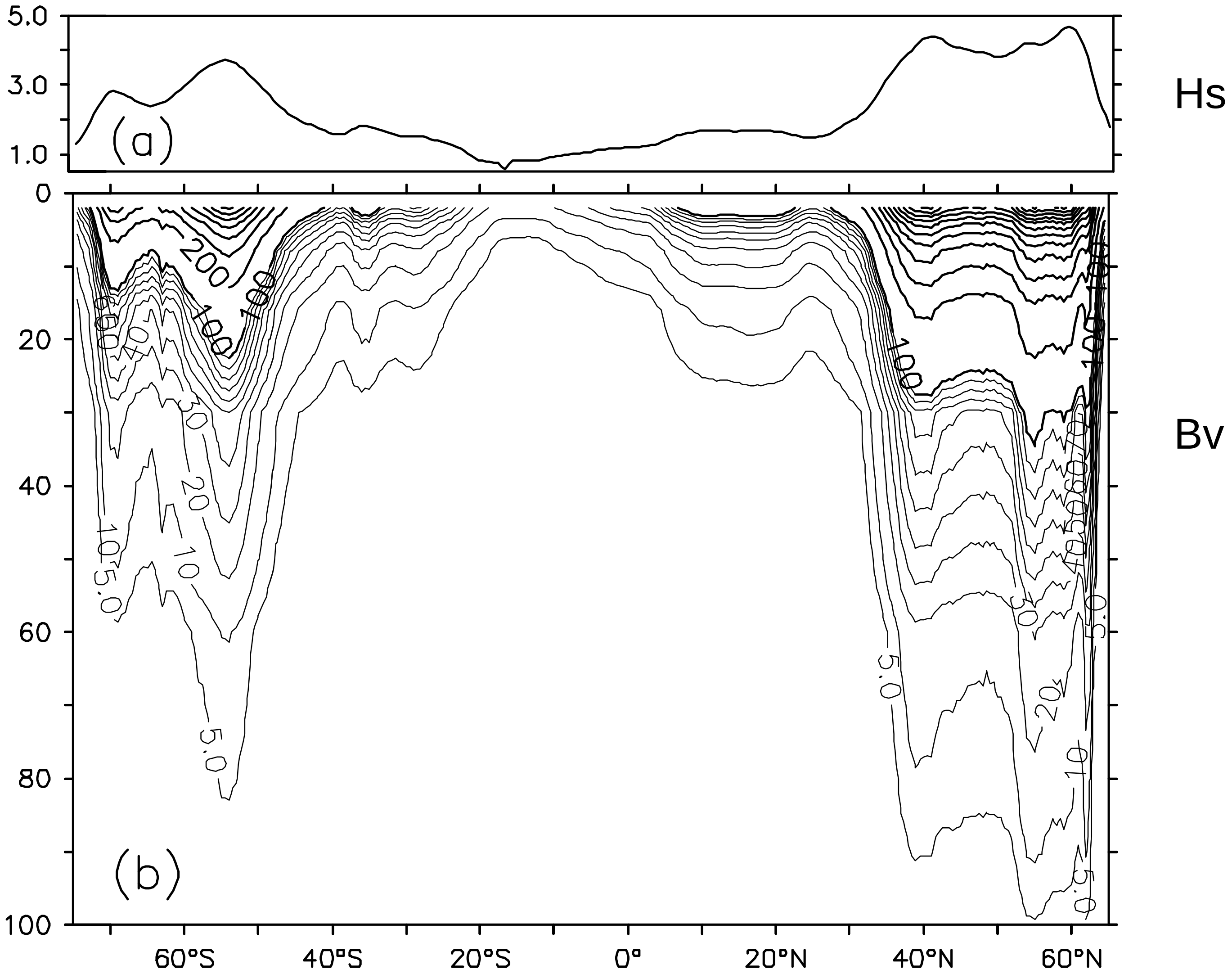
Stokes Drift

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 (cm2/s) in Feb.



The vertical distribution of the Bv (cm^2/s) along dateline in Feb.

(In fact, 0.1 cm^2/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

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

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

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

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

Applications in the coastal area

Special Issue on JGR, 2006

http://www.agu.org/journals/ss/CHINASEAS1/

Now we are here

We apply Bv into:

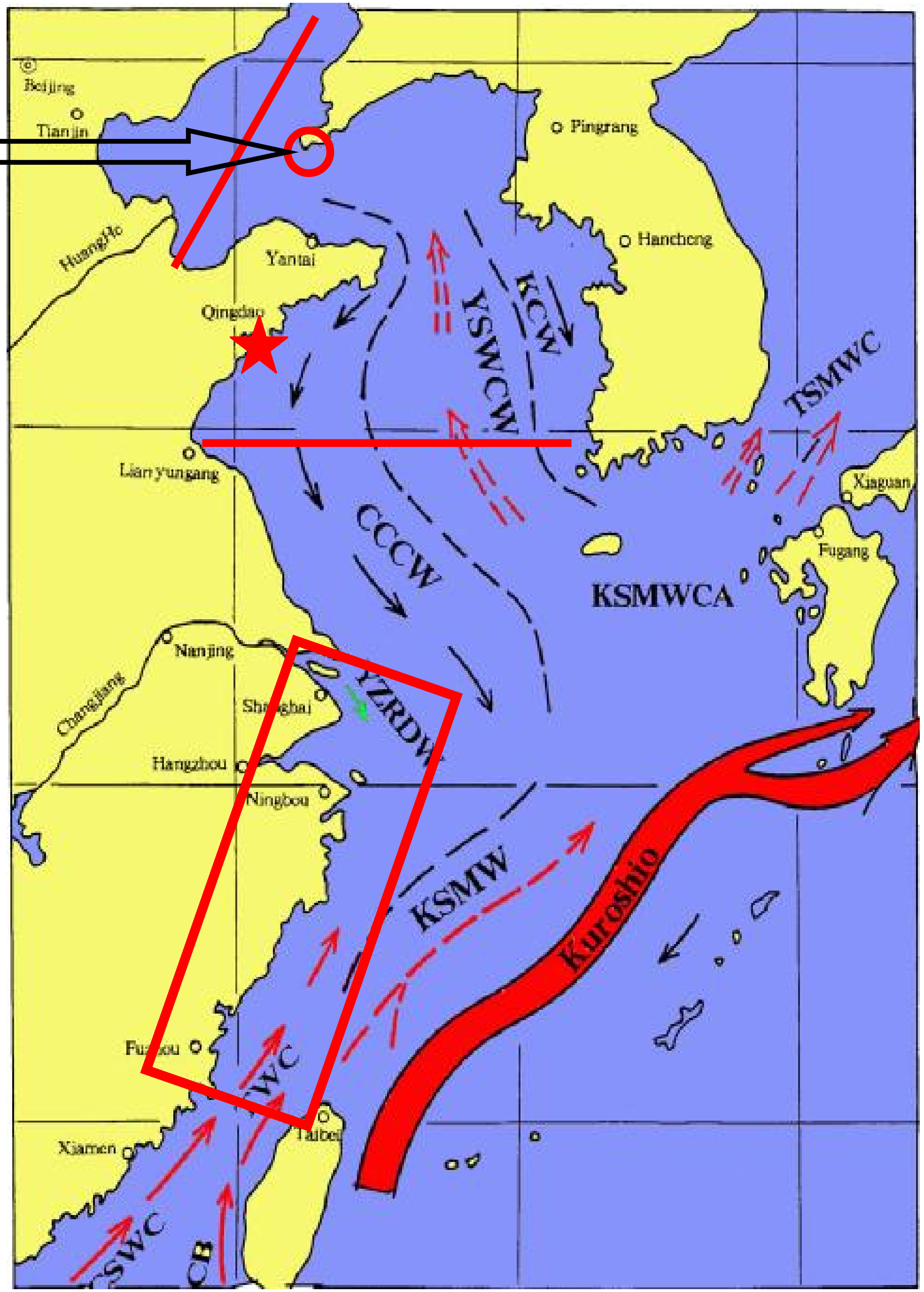
Bohai Sea

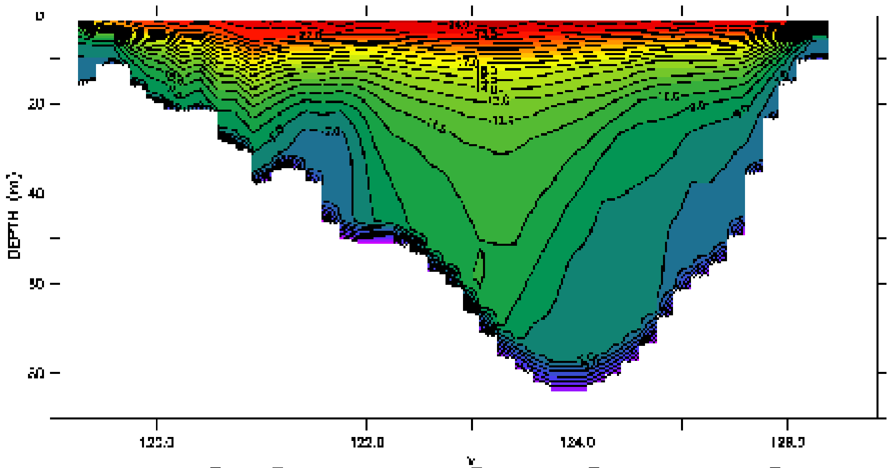
Yellow Sea

East China Sea

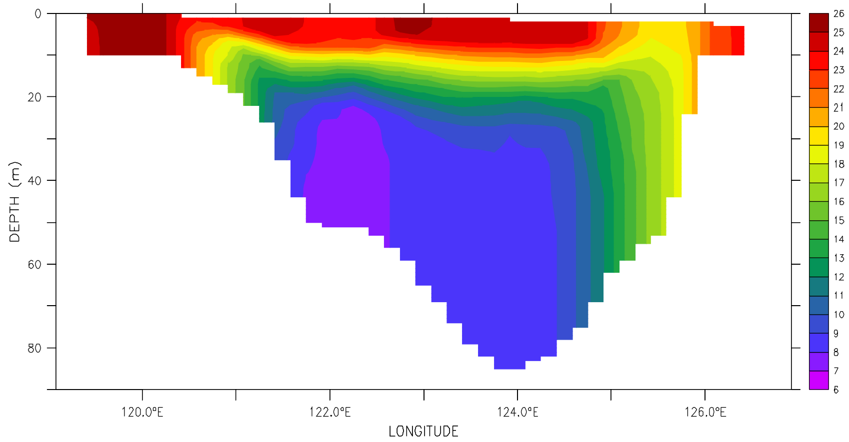
And

South China Sea

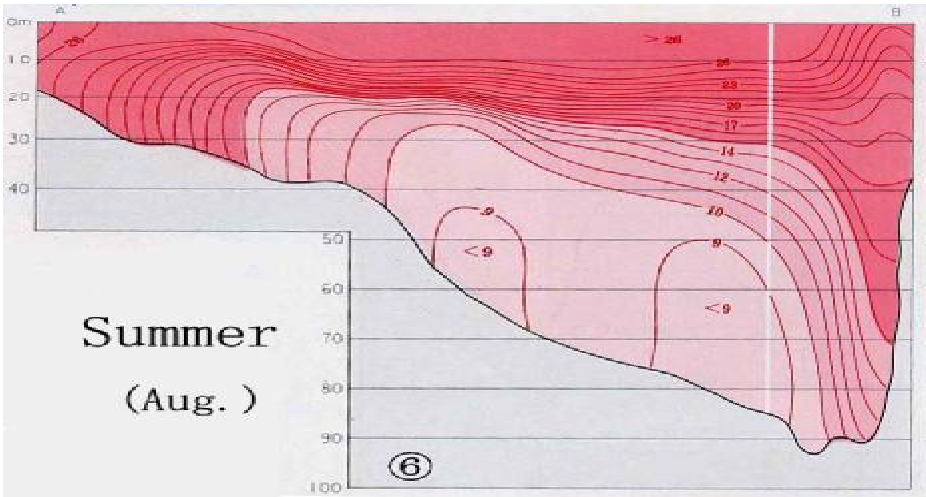




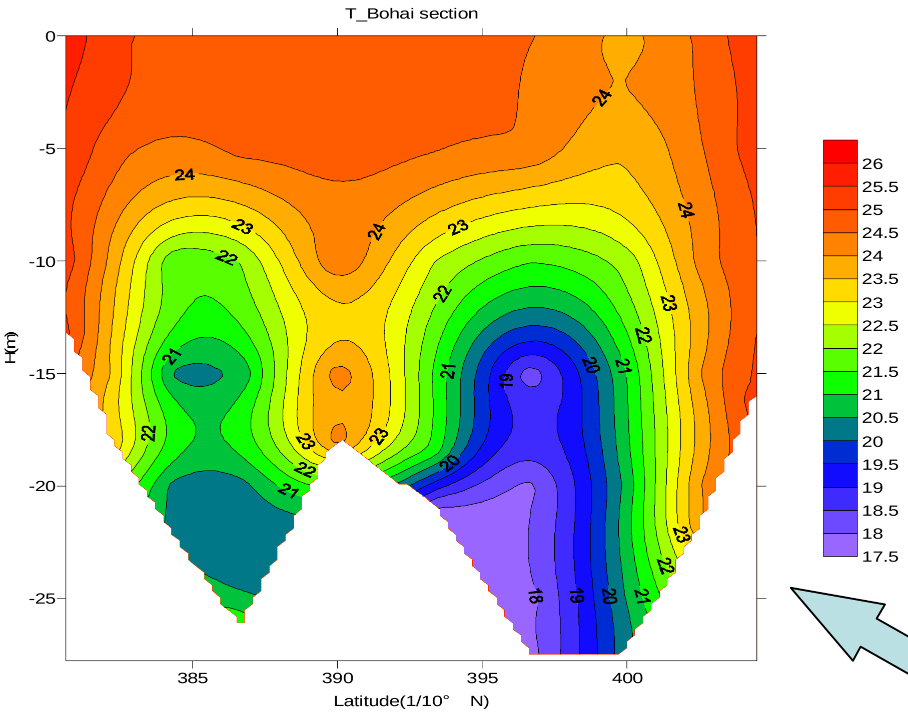
Model results (POM)

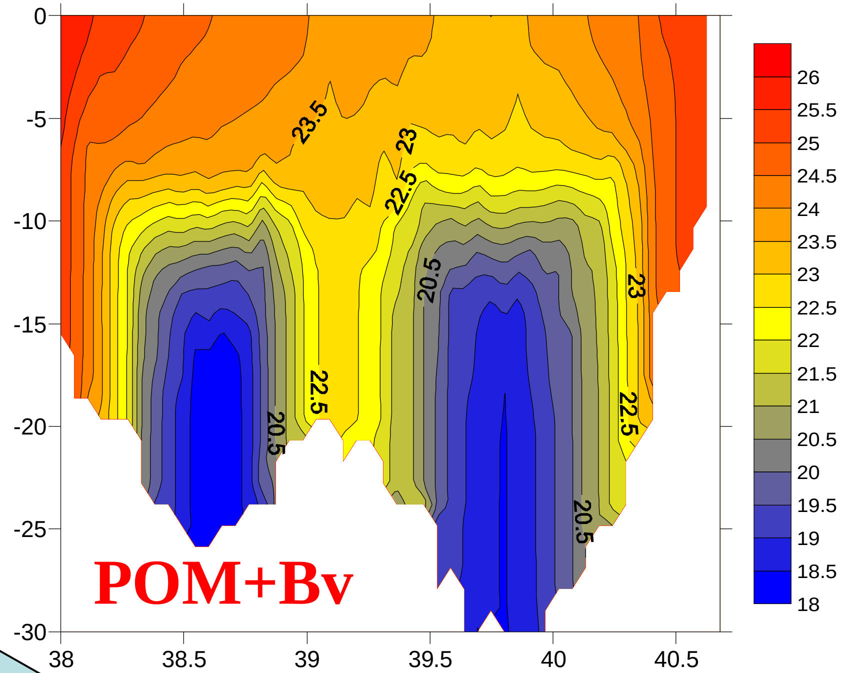


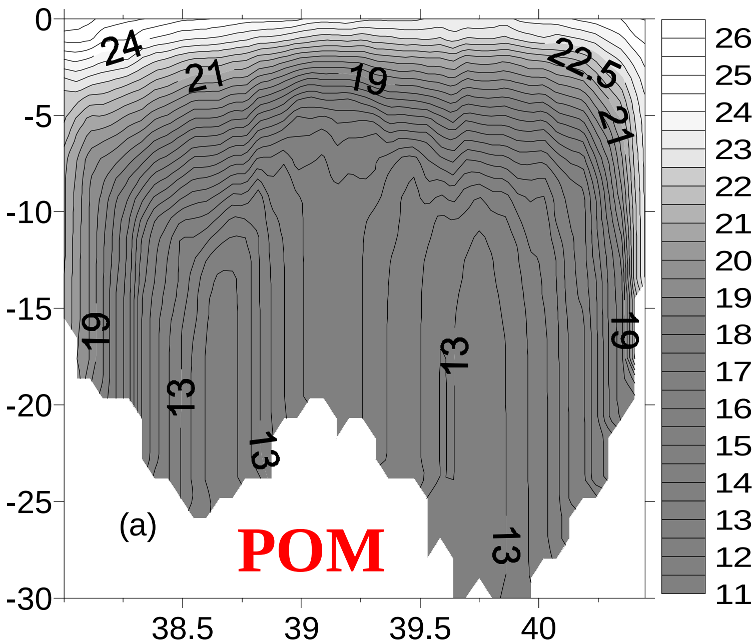
Wave-tide-circulation coupled model



Multi-year observed Temperature along 35N in August

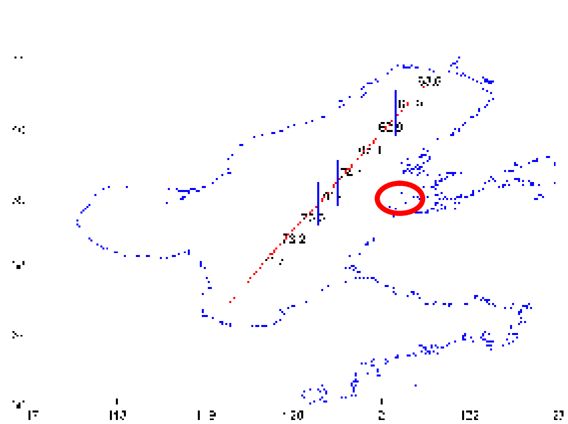




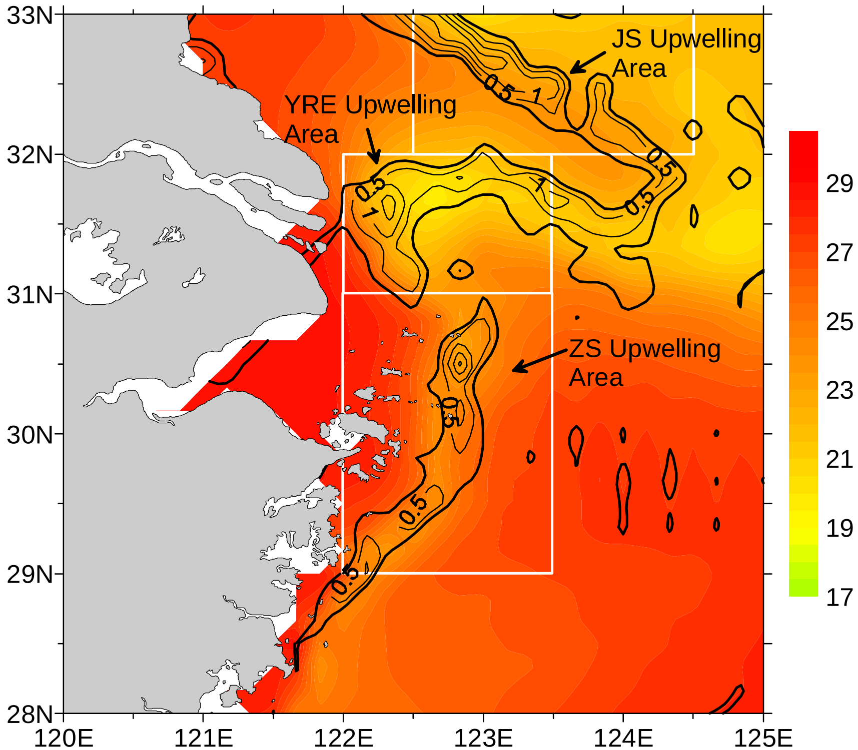


Observation in summer

Lin et al, 2006 JGR

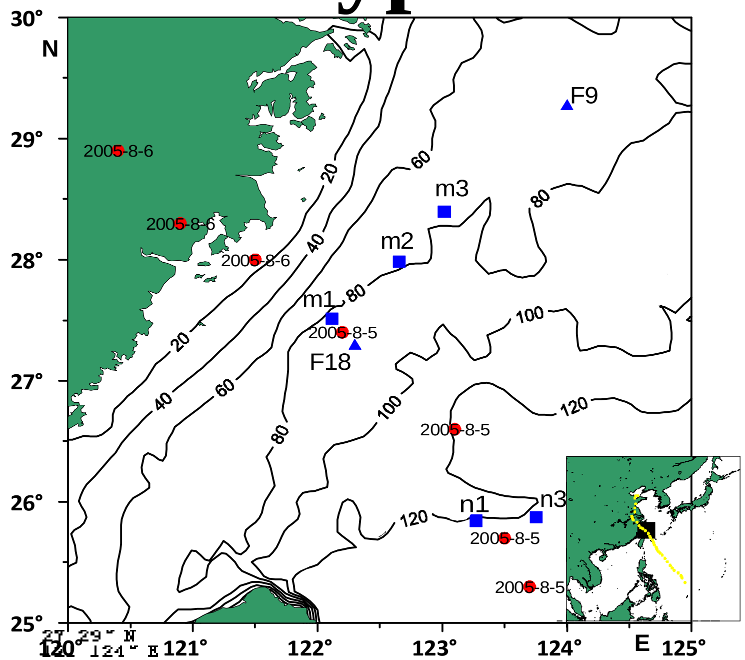


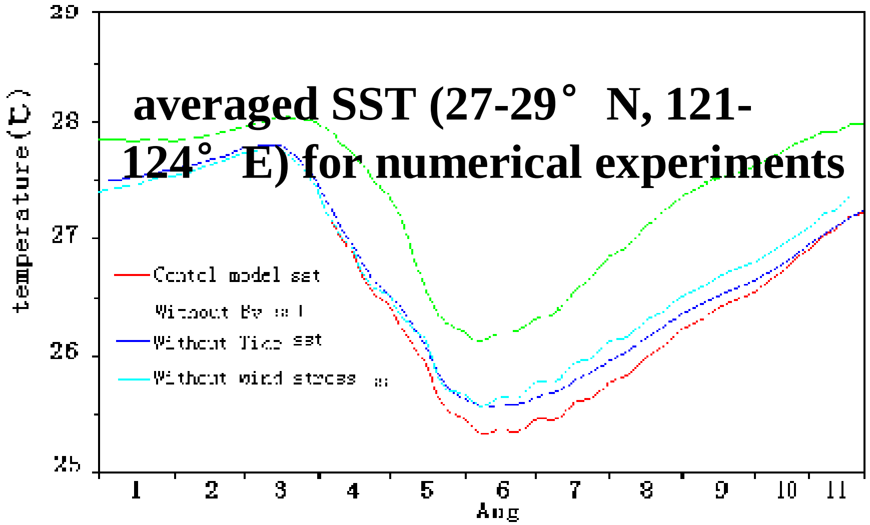
Upwelling and SST response to Typhoon



Model upwelling patterns (10^{-5} m s^{-1}) in ECS

Lv and Qiao et al 2006, JGR.





averaged SST (27-29° N, 121-124° E) for numerical experiments

Wang and Qiao, 2008

Applications in the global ocean

SST, mixed layer, circulation

Qiao F. et al, 2004, Wave-induced mixing in the upper ocean: Distribution and application to a global ocean circulation model. Geophys. Res. Lett., 31:L11303, doi:10.1029/2004GL019824.

POM, MOM4, ROMS, HIM

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

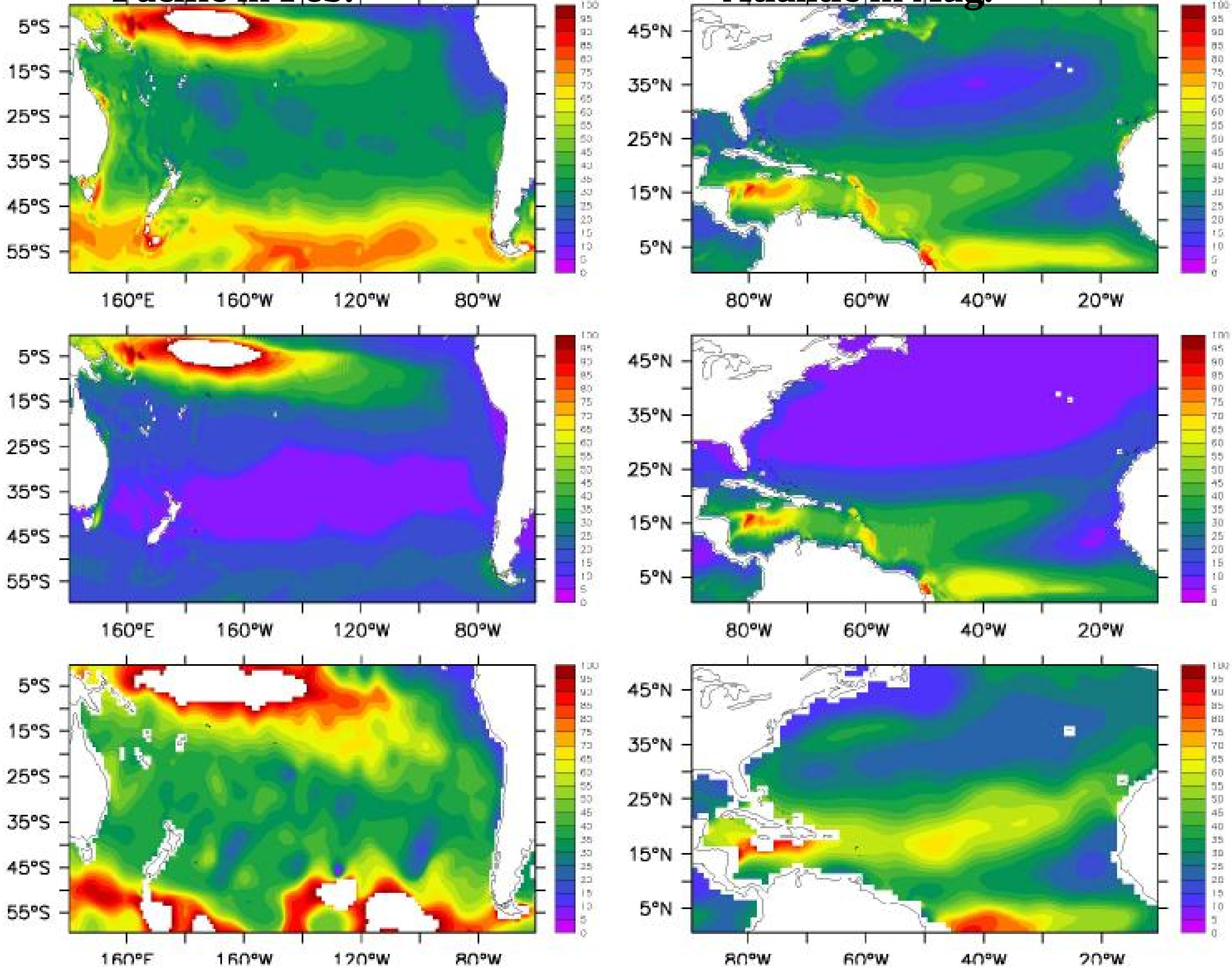
Cold start and run for 10 years

Case 2: POM+Bv

1. MLD in summer

MLD of the Southern Pacific in Feb.

MLD of the Northern Atlantic in Aug.

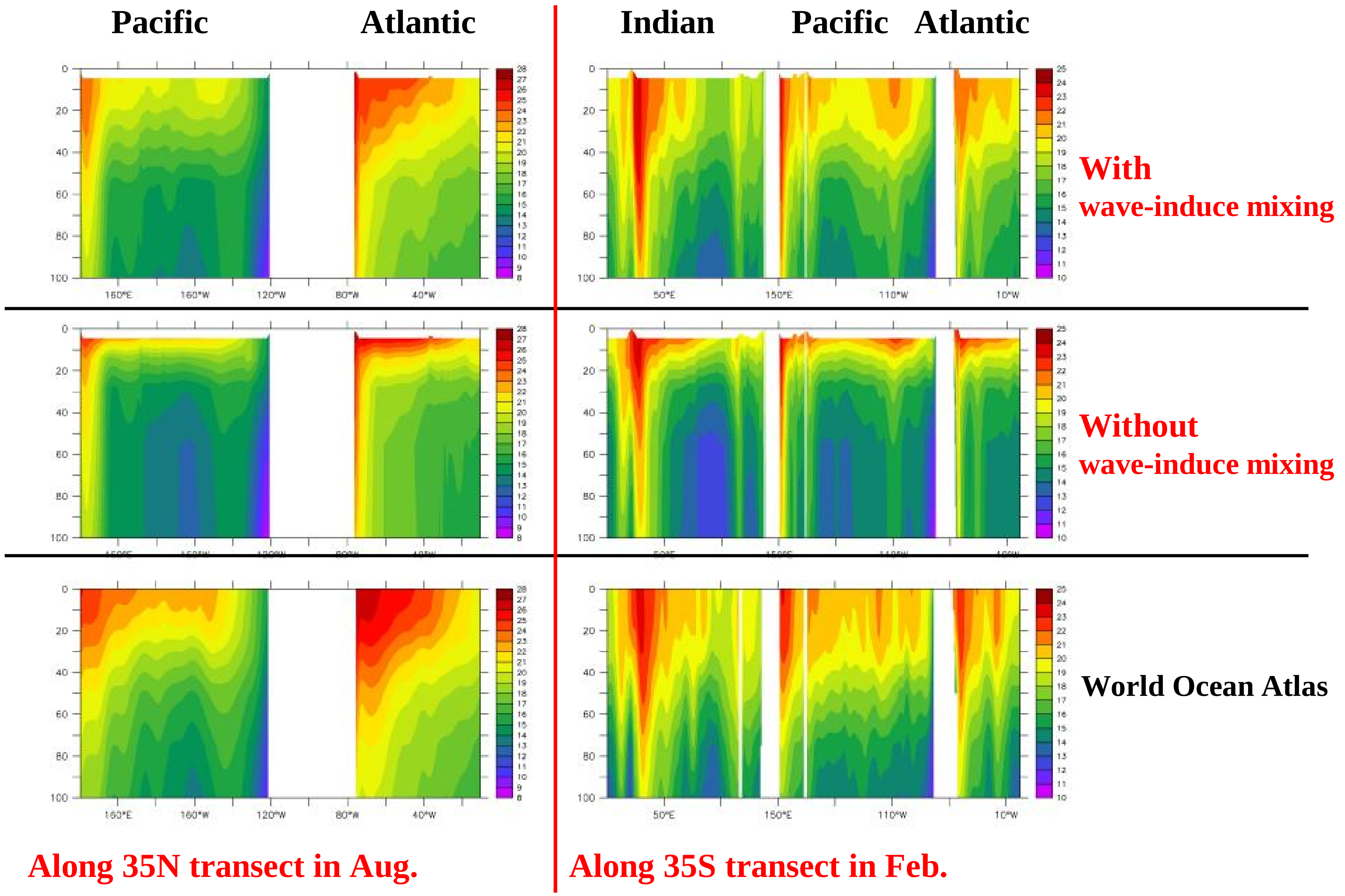


With wave-induce mixing

Without wave-induce mixing

World Ocean Atlas

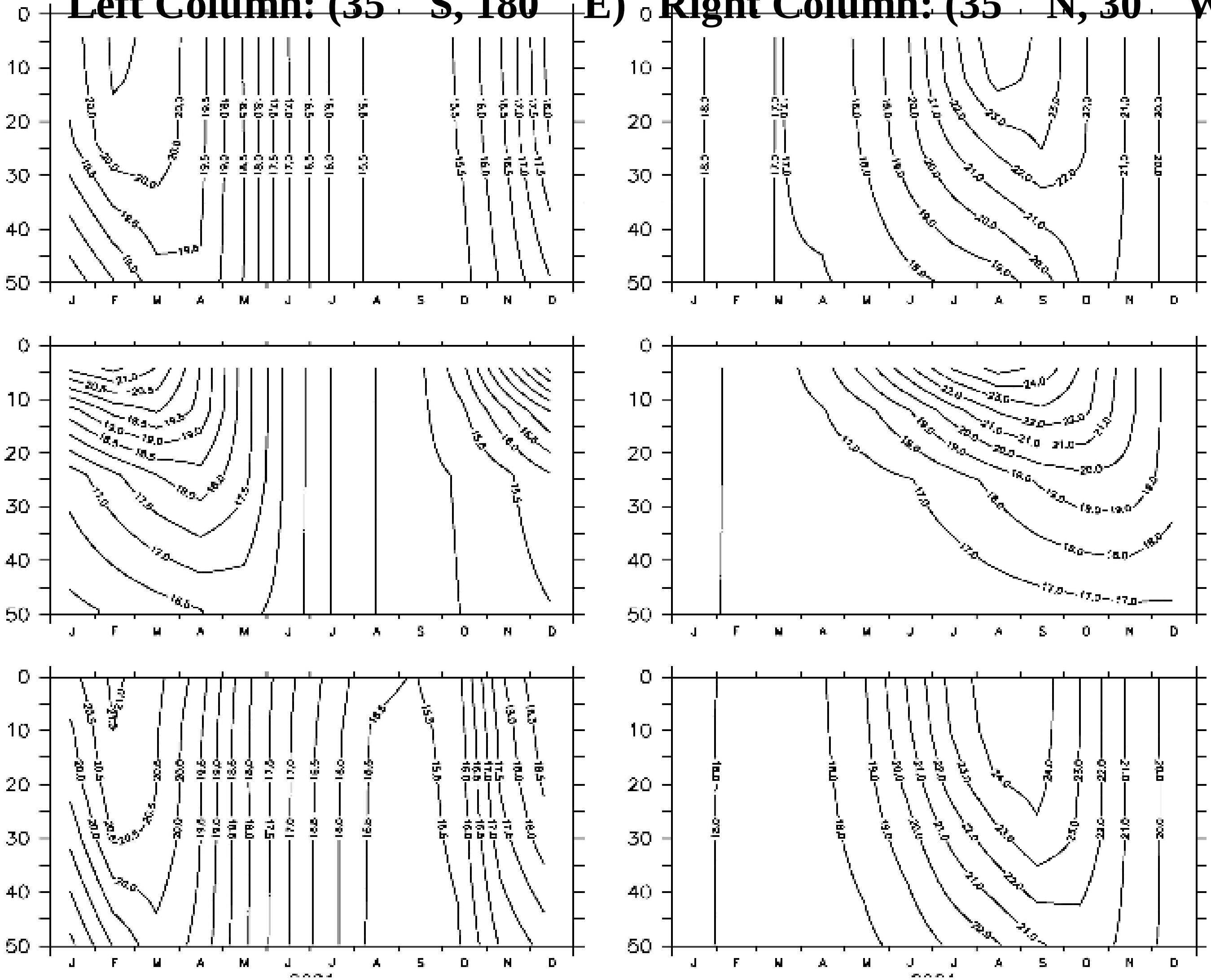
Vertical Temperature Distributions (POM)



2. Annual cycle of T

Time seasonal evolution of temperature at selected points

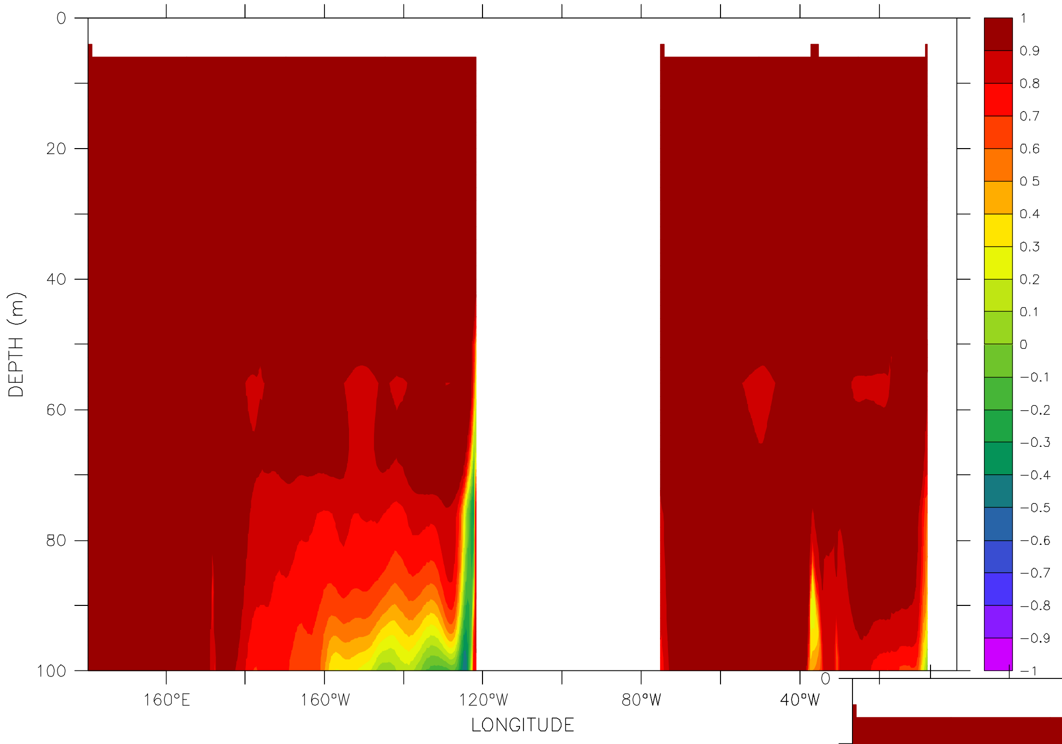
Left Column: (35° S, 180° E) Right Column: (35° N, 30° W)



With wave-induce mixing

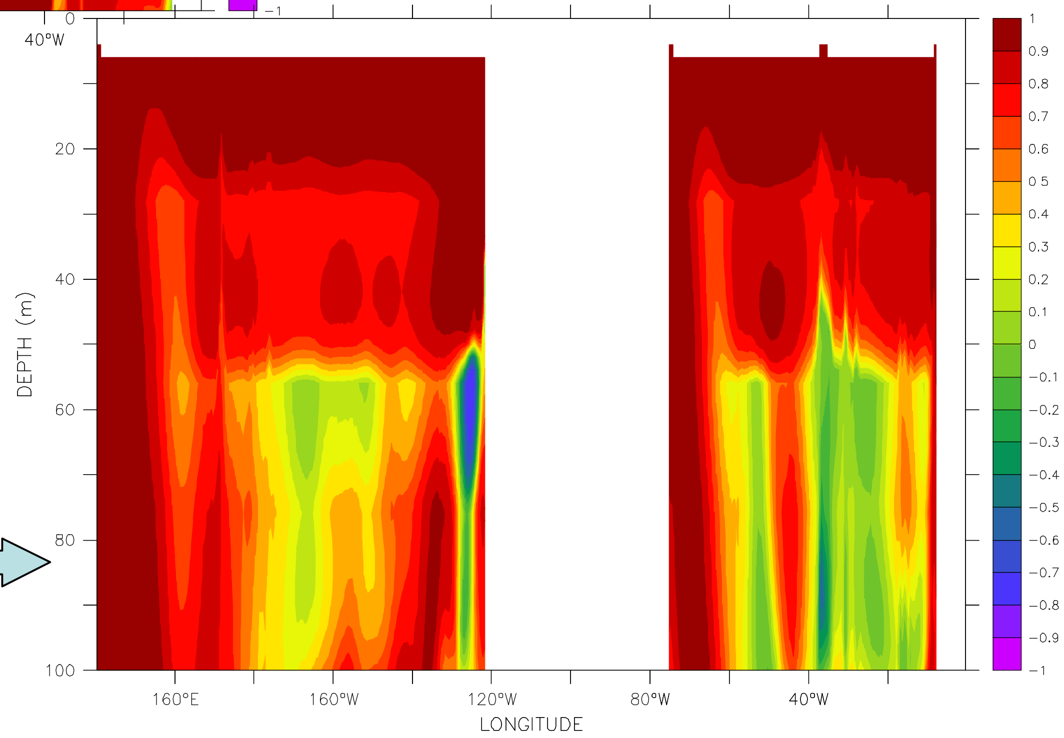
Without wave-induce mixing

Levitus Dataset



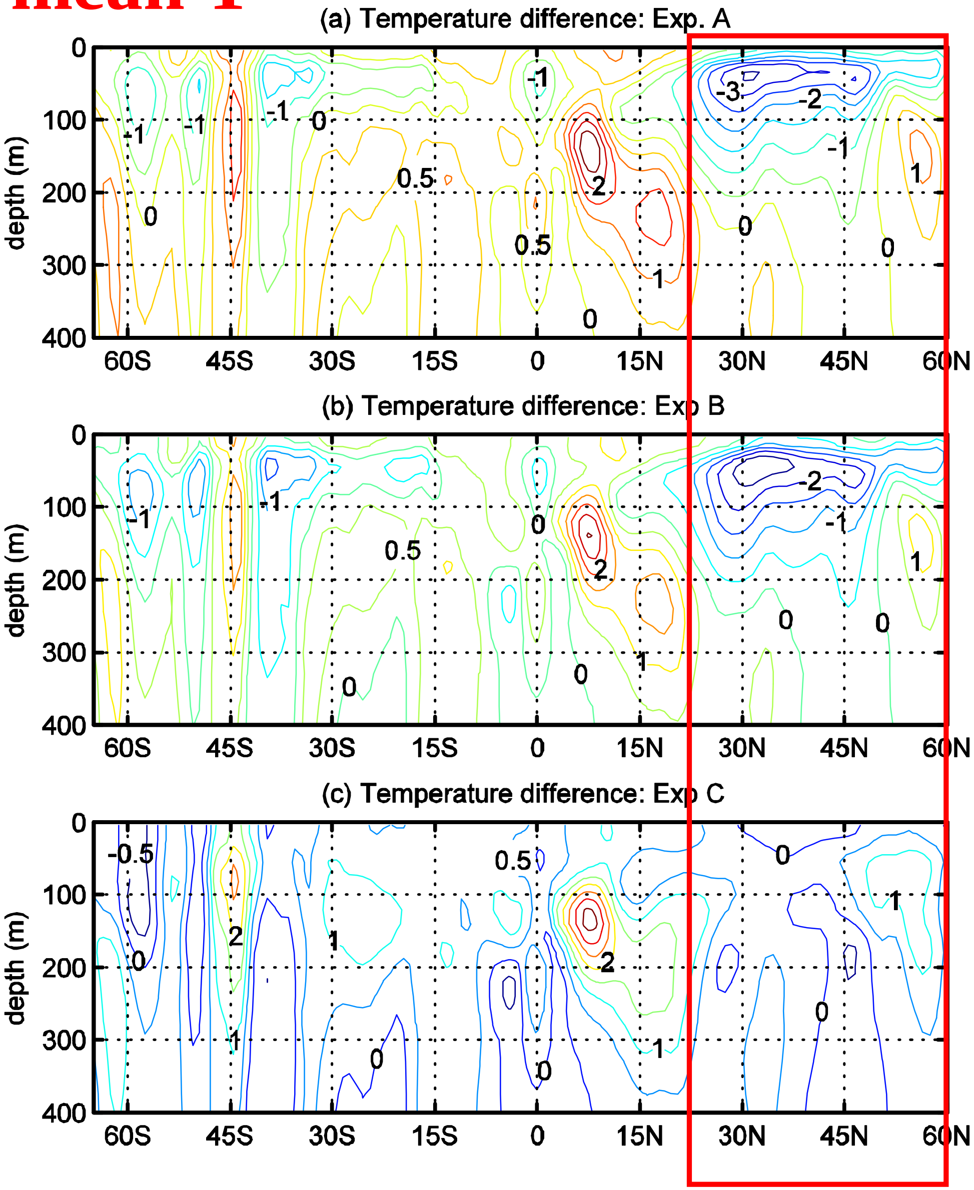
With Bv

Mean Correlation Coefficient: 0.68-0.93 (35N)



Without Bv

3. Annual mean T



POM2008

POM2008+wave breaking and IW by Mellor

POM2008+wave mixing by Qiao

The model annual mean temperature deviation along 180E

Model Linkage of MOM4p0

Topography: ETOPO5

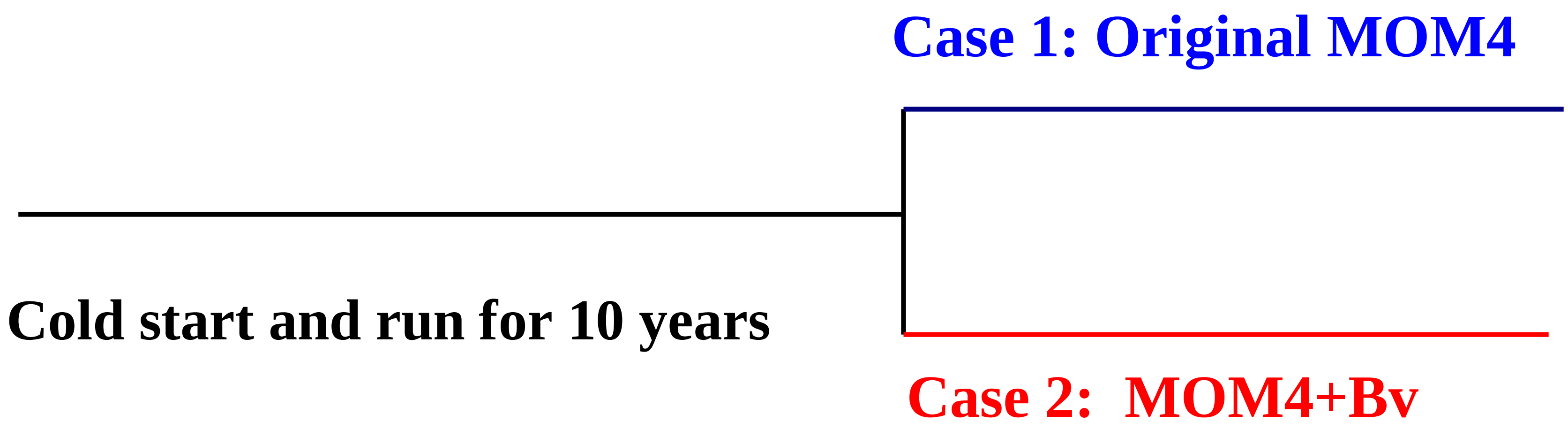
Horizontal resolution: 0.5X0.5

Vertical resolution: 50 layers (5-225: DZ=10m)

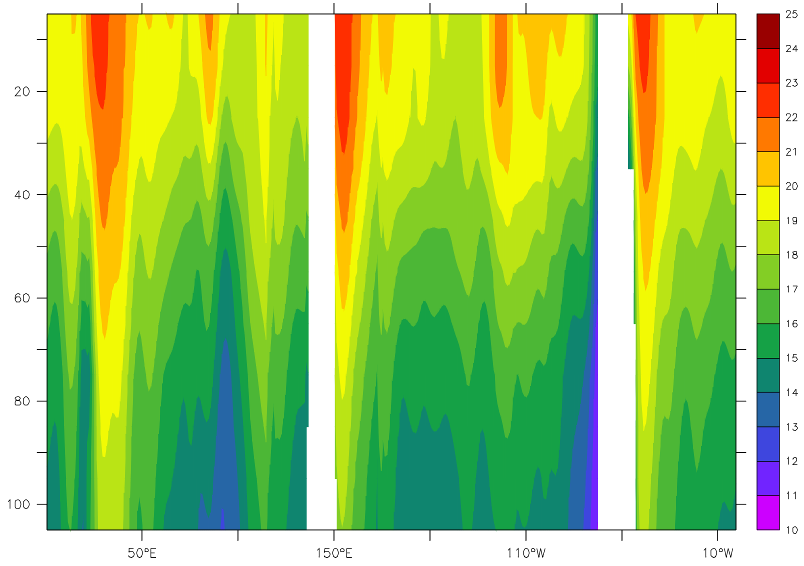
Wind forcing: NCEP monthly mean climatology

Vertical mixing scheme: KPP

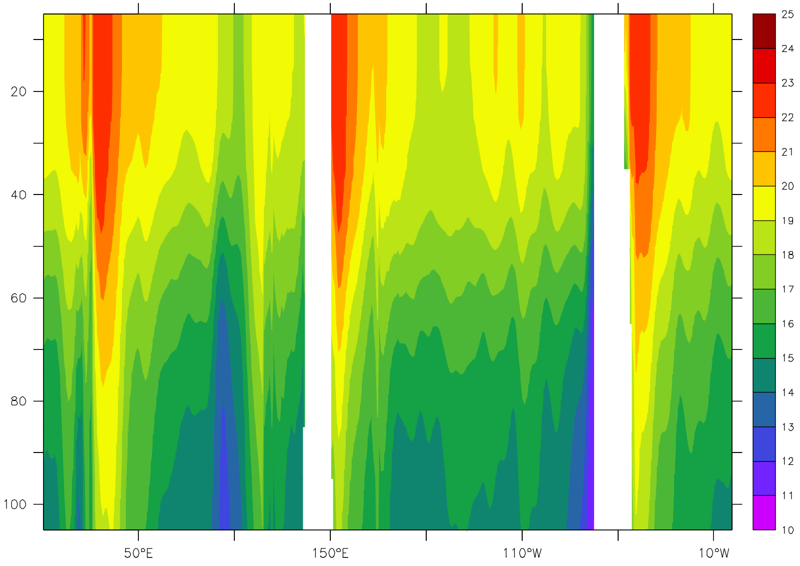
Heat flux: calculated based on the simulation of SST



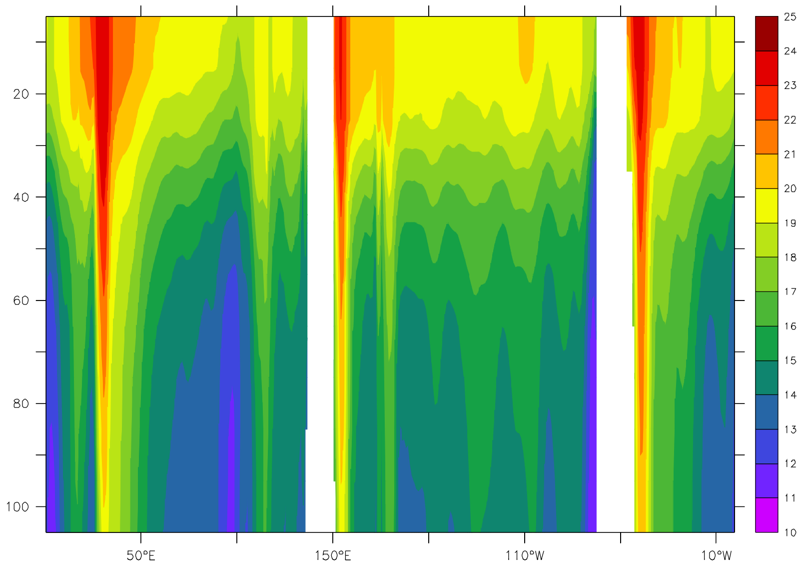
Levitus



MOM4: KPP+BV

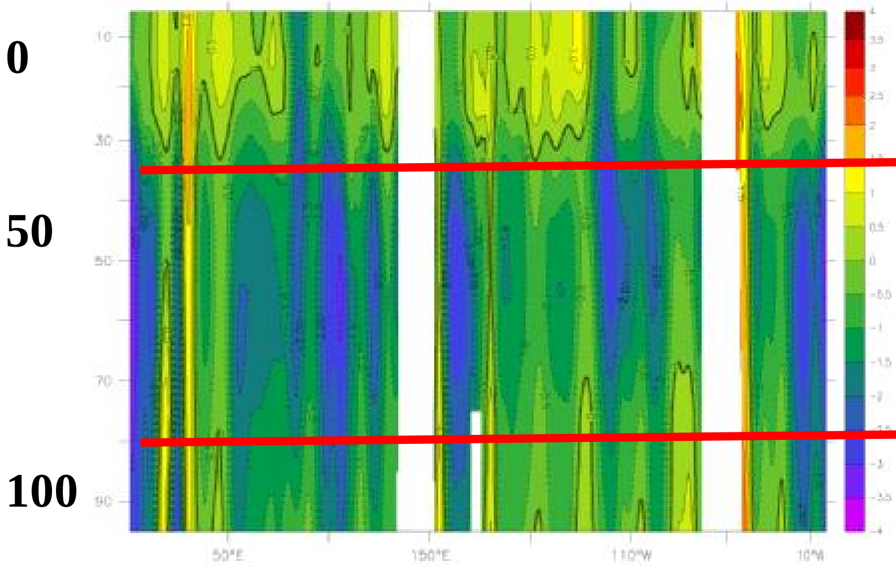


MOM4: KPP

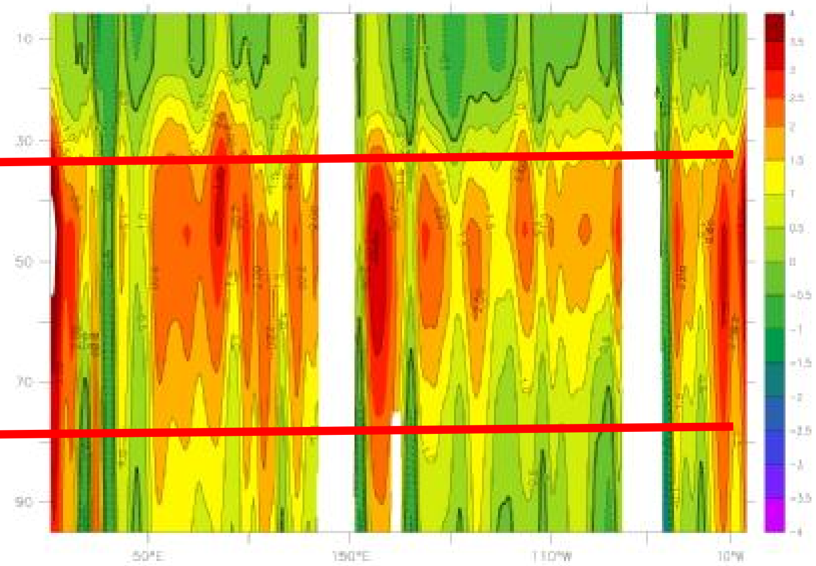


The temperature distributions along transect of 35S in Feb

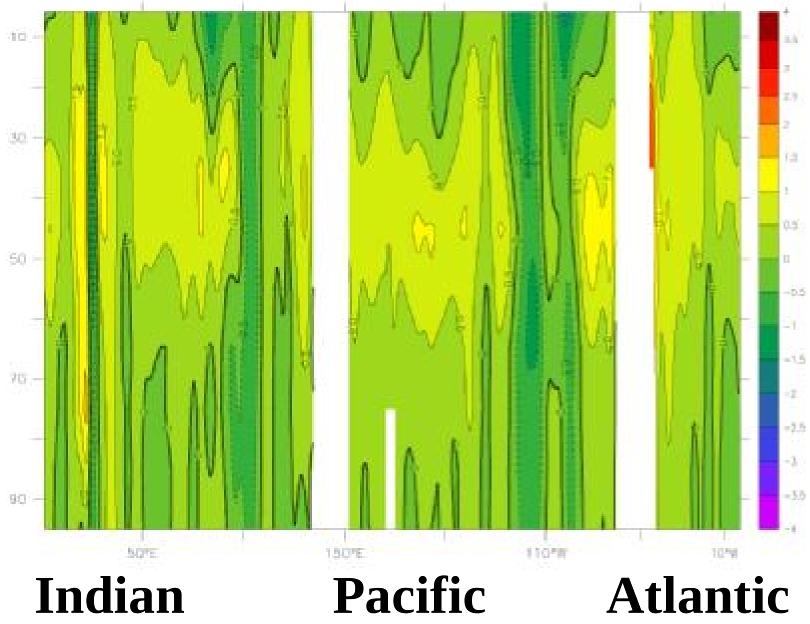
KPP - LEVITUS



(KPP + BV) - KPP



(KPP + BV) - LEVITUS

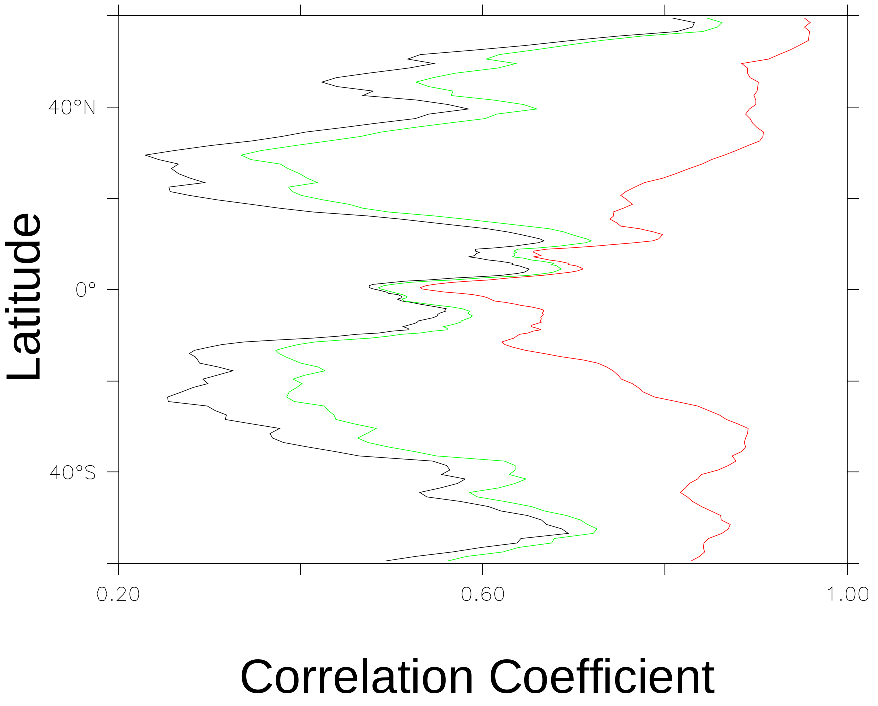


Temperature deviation distributions along transect of 35S in Feb

Applications in the atmosphere-ocean-land-ice coupled 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.

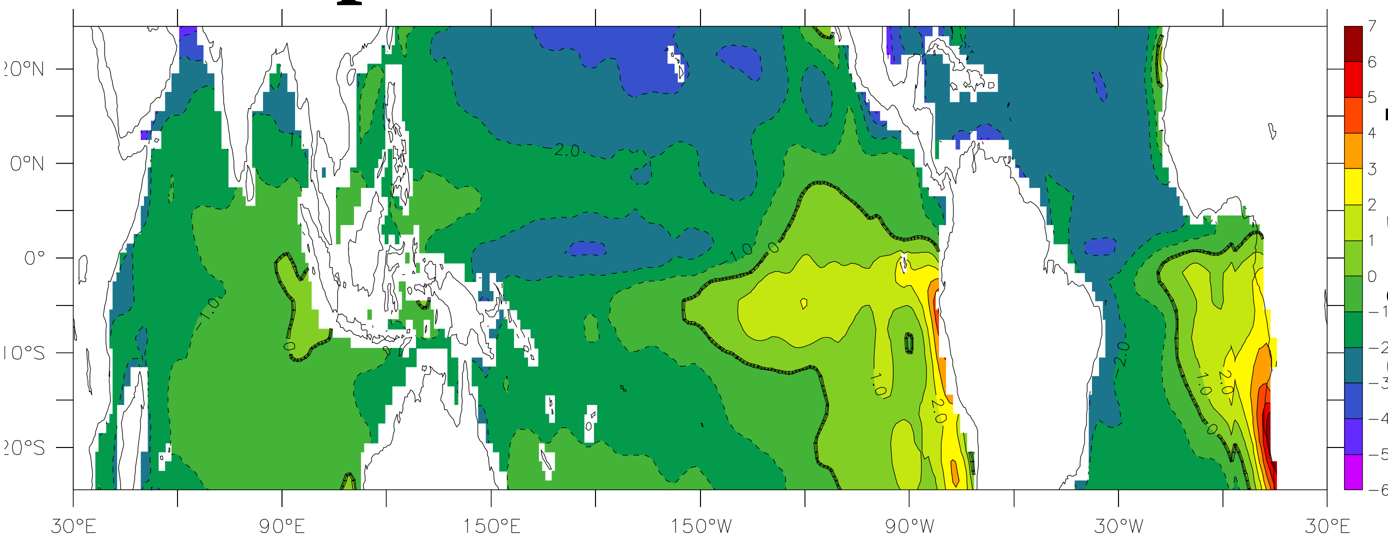
1. **FGCMO, CHINA**
2. **CCSM3, NCAR**



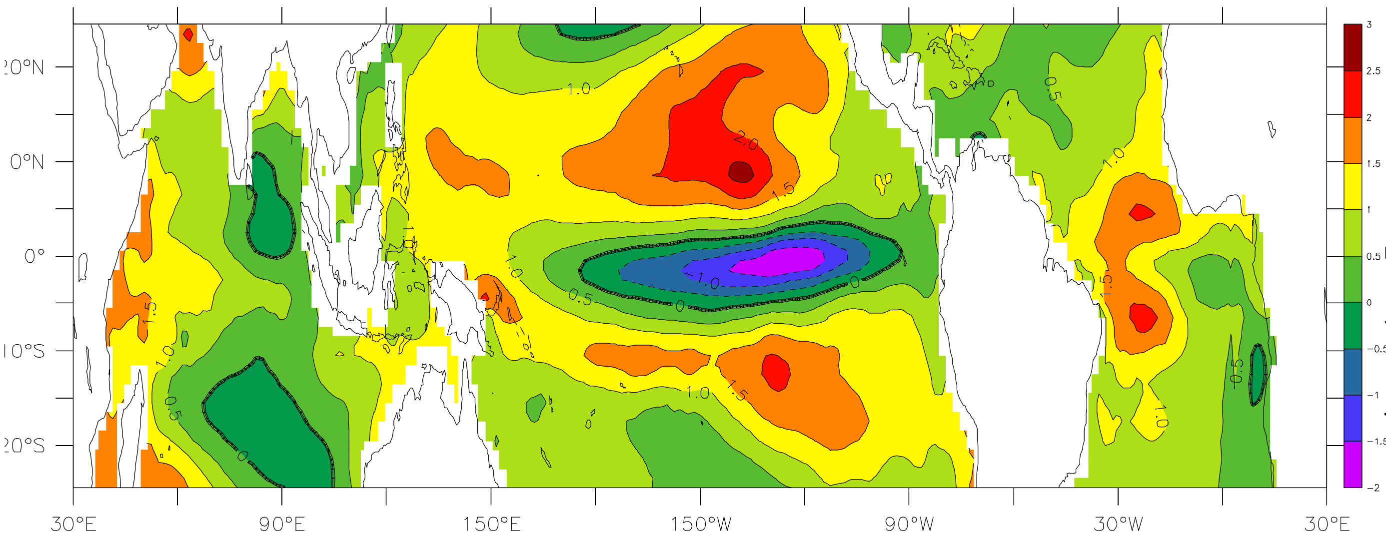
The coupled ocean-atmosphere general circulation model :

(1) Referred to as FGCM-0, LASG, IAP, China;
(2) Almost the same as the NCAR CSM-1;
(3) The atmosphere component is the CCM3 (version 3, T42);
(4) The oceanic component is the OGCM, L30T63;
(5) Its horizontal grid is with a grid size of about $1.875^{\circ} \times 1.875^{\circ}$;
(6)The atmospheric, land, and sea ice models communicate with the flux coupler every model hour, and the oceanic model does this every model day;
(7)MASNUM wave number spectral model incorporated into coupler.

1. Tropical bias

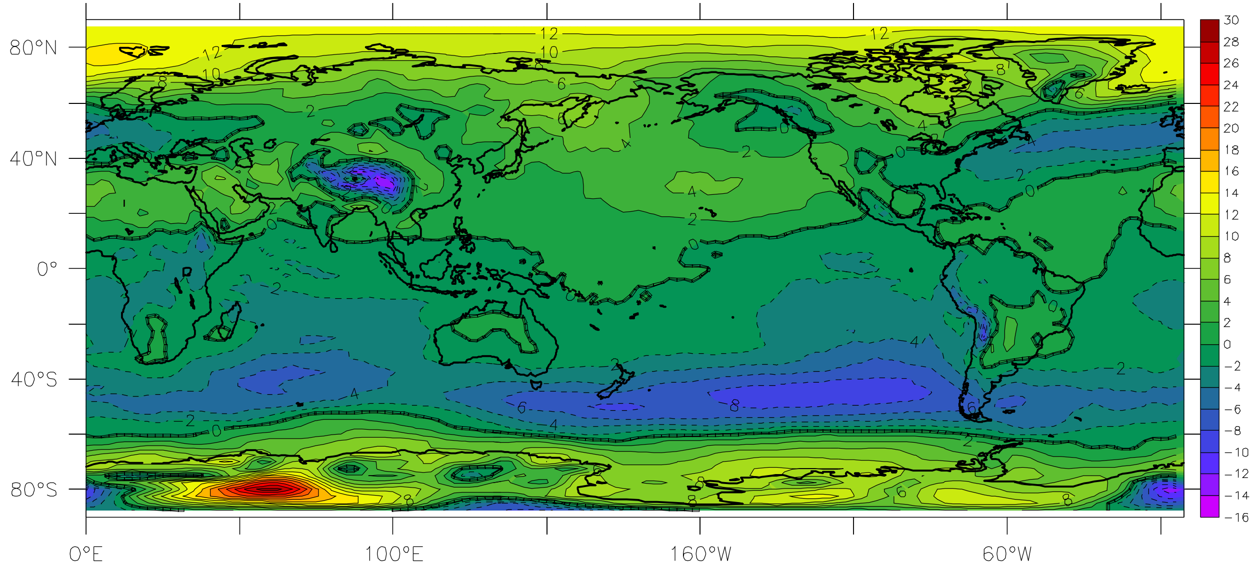


The difference of 50a averaged SST and climatology dataset (Levitus)

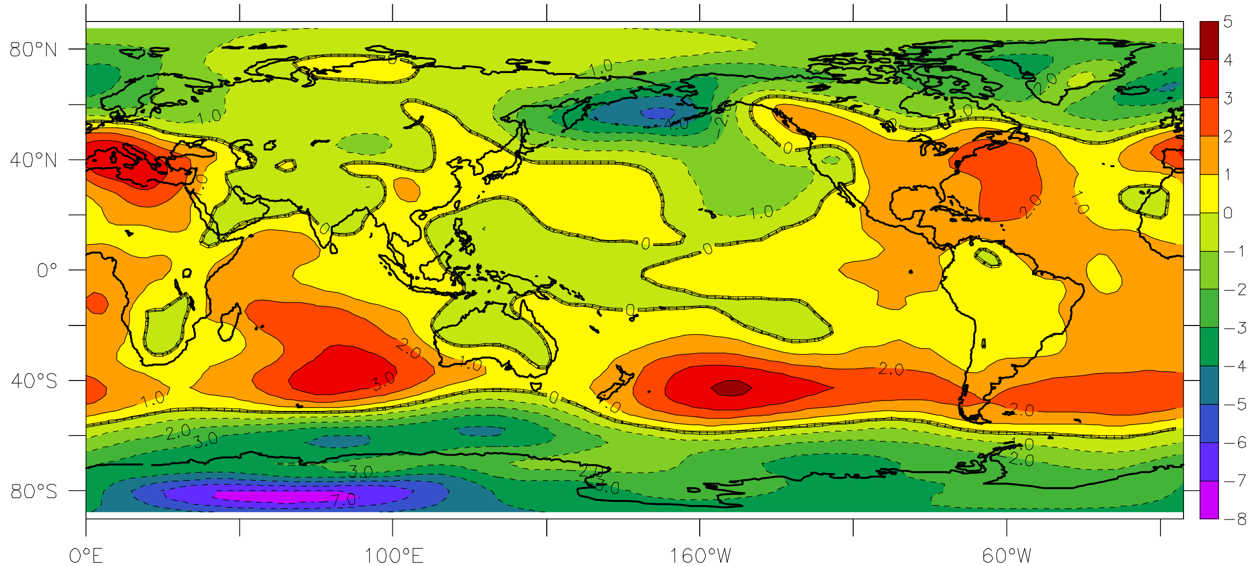


The SST difference between with and without Bv

2. Sea Level Pressure

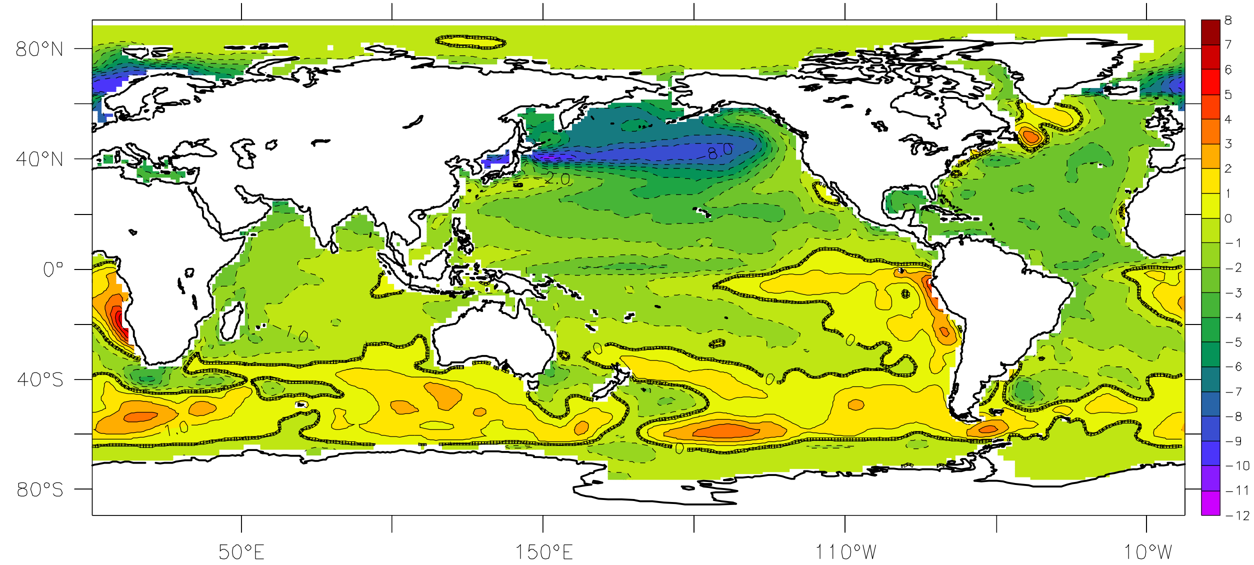


The difference of 50a averaged SLP and climatology dataset

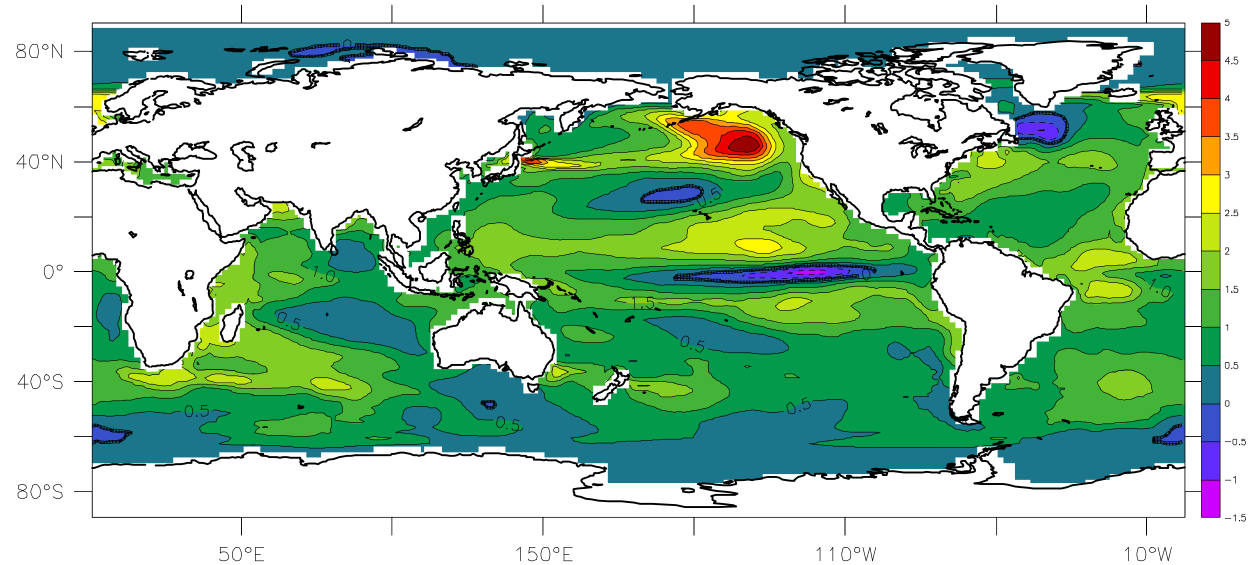


The difference between with Bv and without Bv

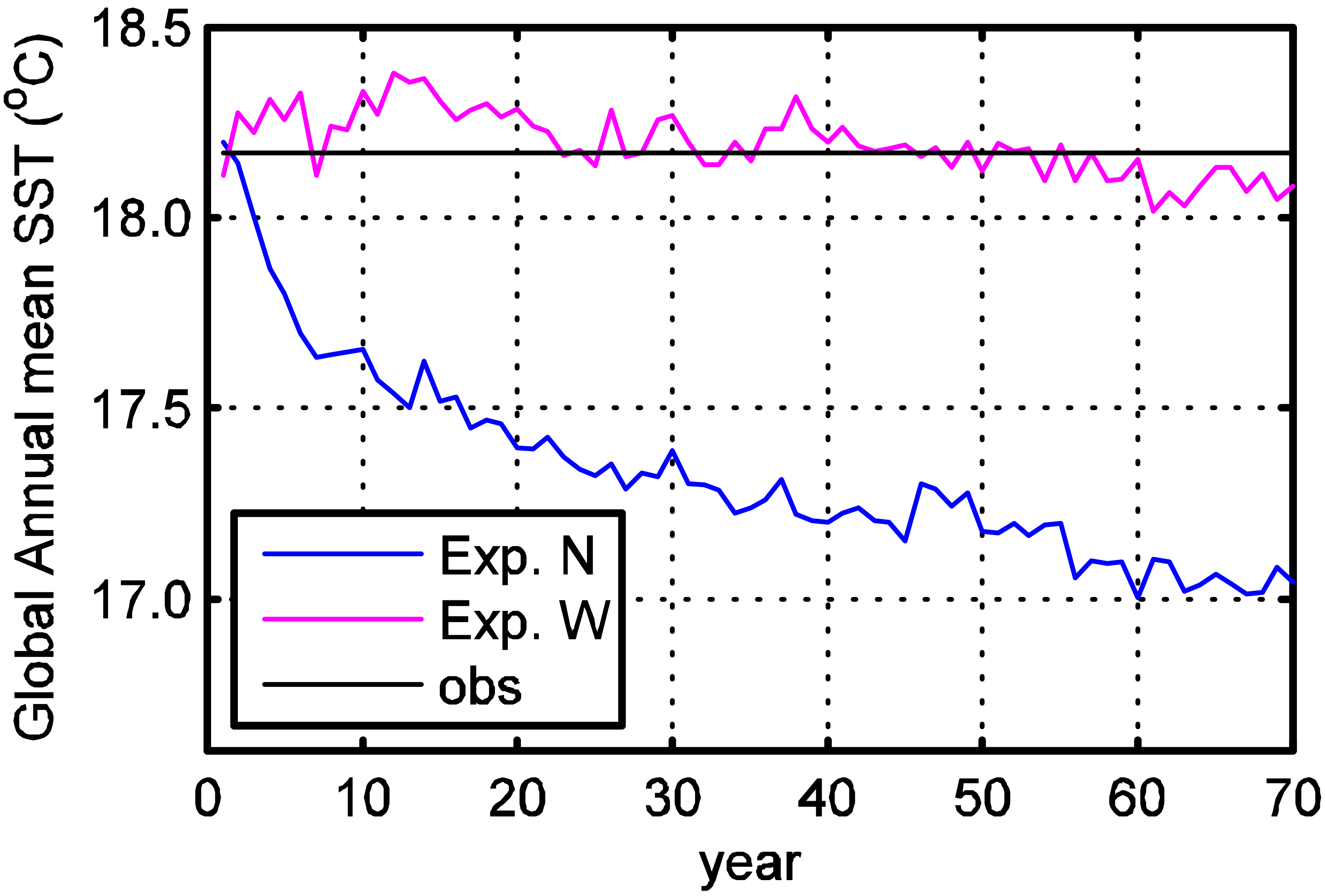
3. SST



The difference of 50a averaged SST and climatology dataset (Levitus)



The difference between with Bv and without Bv



Global annual mean SST

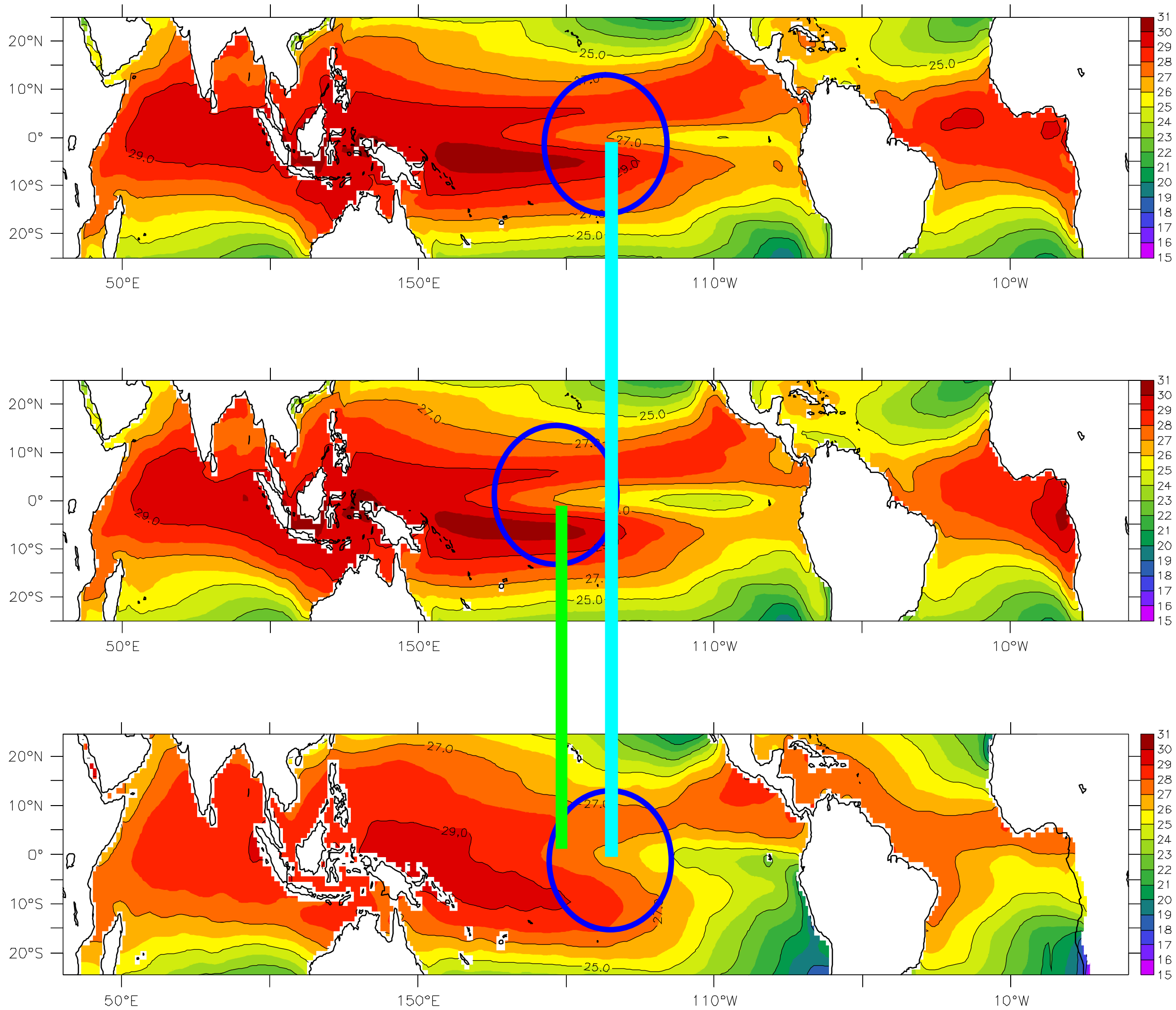
CCSM3（T42, GX1V3）

1. Tropical bias – too cold tongue

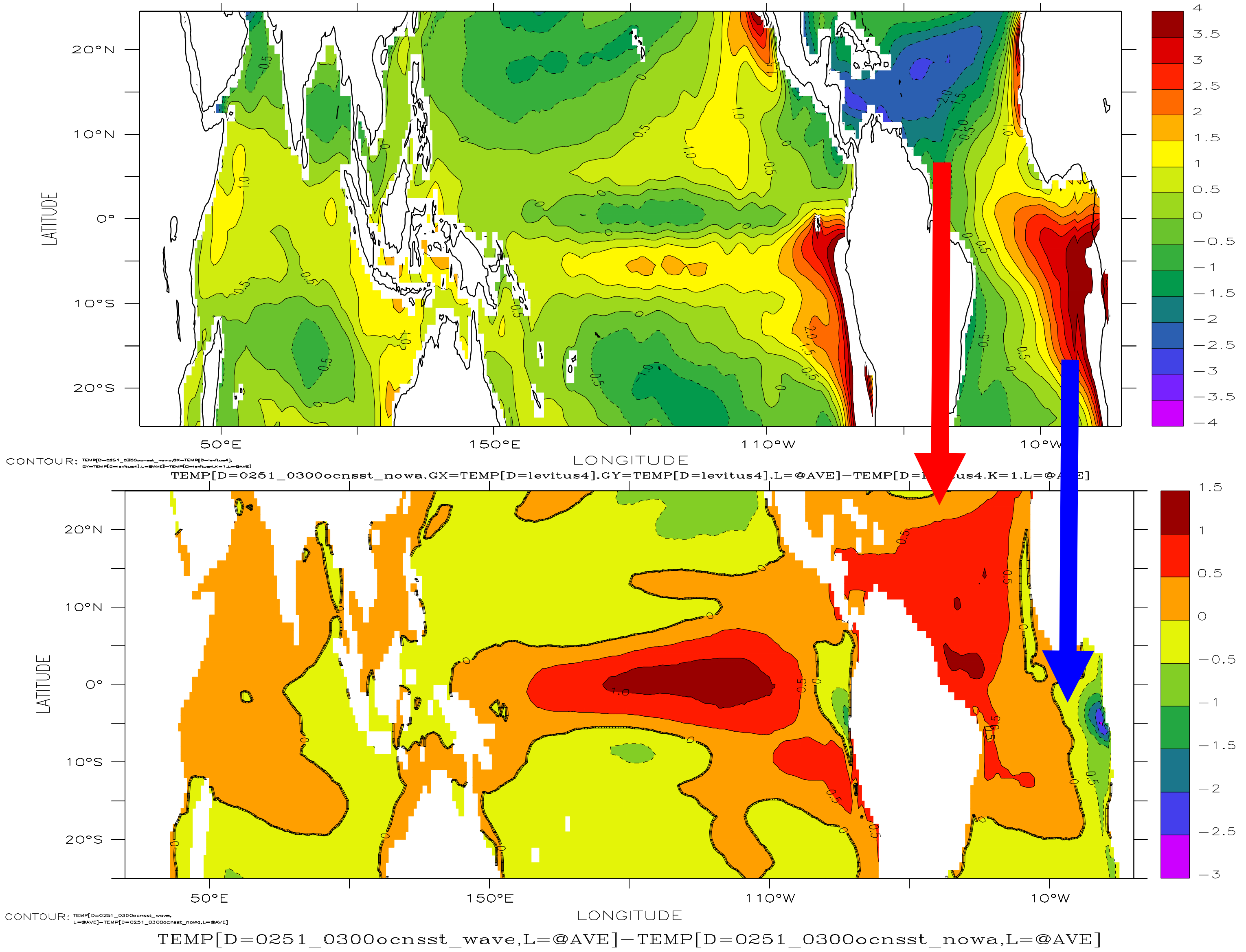
CCSM3+Waves

CCSM3: 251–300a

WOA



The isotherm of 27℃



50a averaged SST (251-300a).

Up: Exp1-Levitus, Down: Exp2-Exp1

Exp1: CCSM3 without Bv

Exp2: with Bv

2. ENSO periodicity

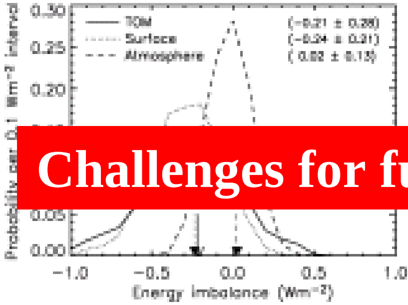


FIG. 10. Probabilities of annual-mean energy imbalances in CCSM3 at the top of the model (TOM), the surface, and in the atmosphere. The probabilities are obtained from years 100 through 600 of the control integration. Vertical arrows represent series-mean imbalances, and horizontal arrows represent the 2σ range of annual imbalances. (top to bottom) Values in the upper right are the mean and 1σ imbalances for the TOM, surface, and atmosphere.

5. Challenges for further development

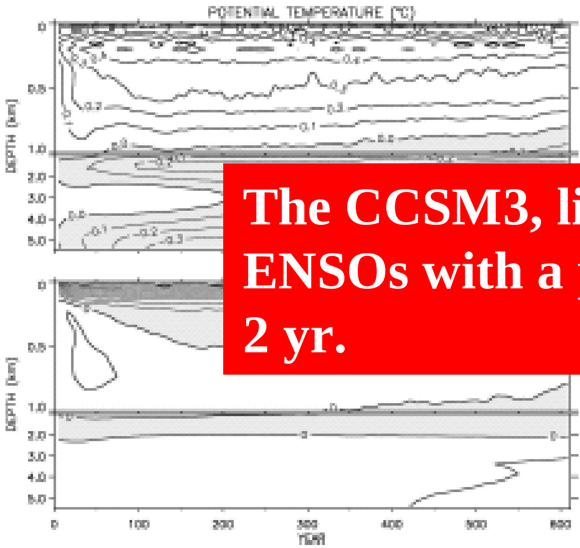
While many features of the climate are simulated with greater fidelity by CCSM3 than CCSM2, there are still significant biases that should be addressed in future generations of CCSM. These systematic errors can be illustrated by comparing the CCSM3 control integra-

Challenges for futher development

a. Representation of major modes of variability

The basic characteristics of the ENSO episodes simulated by CCSM2 and CCSM3 are quite similar. Two of the most important properties are the total variance and power spectrum of SST anomalies in the central Pacific. The results for the Niño-3.4 region (5°S–5°N, 120°–170°W) are representative of other regions in the tropical Pacific.

The meteorological reanalysis by Kistler et al. (2001) for 1951–2000 provides the observed properties for this region. The reanalysis represents a relatively short data record compared to the length of the CCSM2 and



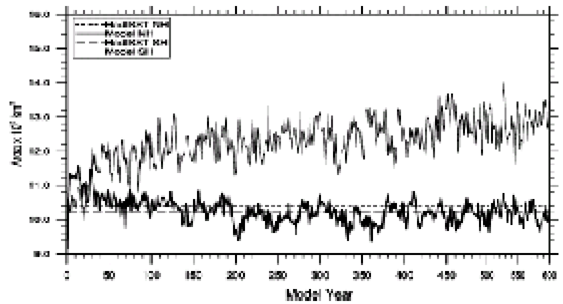


FIG. 12. Annual mean area of sea ice from the CCSM3 control integration in the Northern Hemisphere (solid lines) and Southern Hemisphere. Observational estimates from the HadISST dataset (Rayner et al. 2003) are shown by dashed lines for each hemisphere.

CCSM3 control runs. In addition, the variance simulated for the Niño-3.4 region in CCSM2 and CCSM3 can change considerably on time scales of 50 yr. For these reasons, the control runs for CCSM2 and CCSM3 are divided into 50-yr segments. The variance and power spectra for each segment are determined separately and then aggregated for comparison against the meteorological reanalysis. The model data used for this purpose includes 650 years of the CCSM2 control integration and 500 years of the CCSM3 integration. The

The CCSM3, like CCSM2, tends to produce ENSOs with a periodicity of approximately 2 yr.

CCSM3 have greater variability than observed. The power spectra of the monthly SST anomalies for the low and intermediate resolutions of CCSM3 are discussed in detail in Yeager et al. (2006). The power spectra for the high-resolution (T85 × 1) configuration of CCSM3 are compared against the spectra for CCSM2 and the National Centers for Environmental Prediction (NCEP) reanalysis in Fig. 13. The observed ENSOs have a relatively broad spectrum spanning 3–5 yr. The CCSM3, like CCSM2, tends to produce ENSOs with a periodicity of approximately 2 yr. In fact, the spectra of CCSM3 are even more strongly peaked at periods of 2 yr than those of CCSM2, and the variance at periods of 3–5 yr is smaller and hence less realistic in CCSM3 than in CCSM2.

b. Double ITCZ in the Pacific

Like previous generations of this model, CCSM3 produces a double ITCZ in the tropical Pacific. The

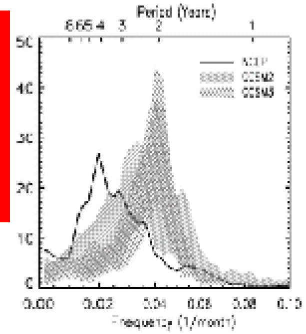
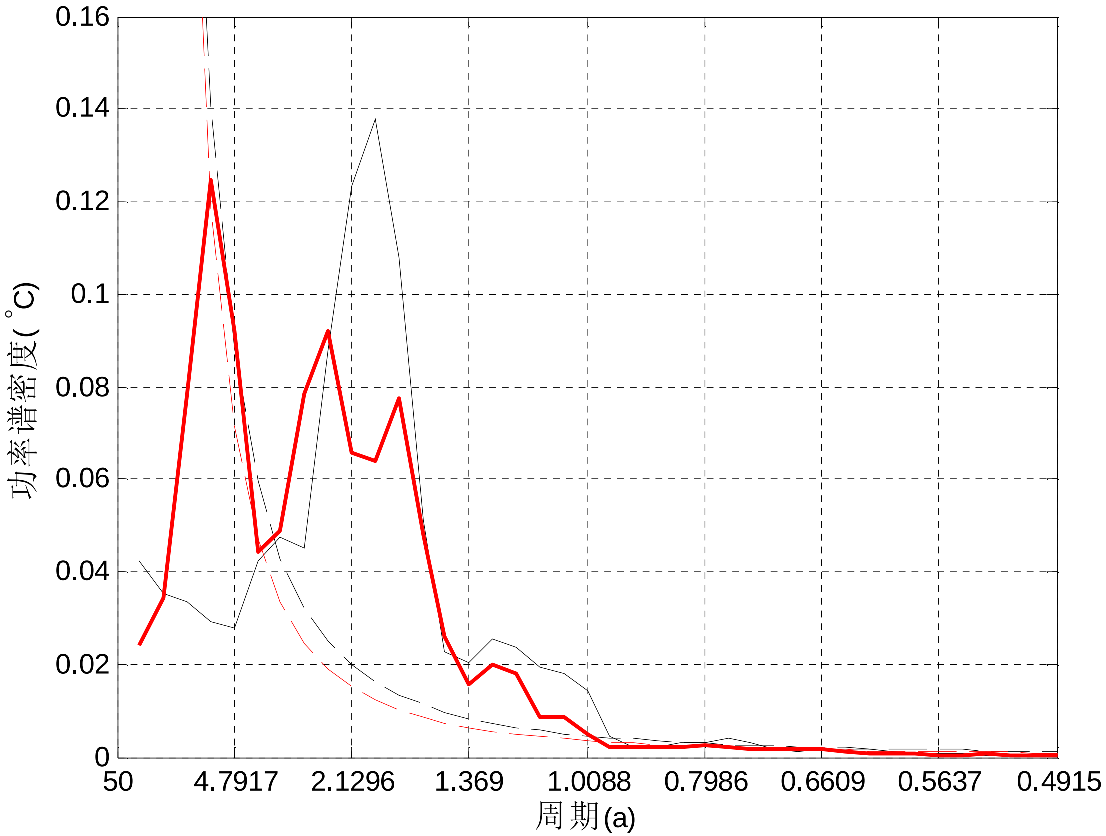


FIG. 13. Power spectra of 1σ monthly Niño-3.4 anomalies for CCSM2, CCSM3, and the NCEP reanalysis (thick line) (Kistler et al. 2001). The range of variance spanned by the spectra of individual 50 yr segments are shown for CCSM2 (light hatching) and CCSM3 (dark hatching).

J Climate, 2006 (Clara Deser et al)

Frequency spectrum for Nino3.4 area



Black: CCSM3, 2a

Red: CCSM3+WAVES
1.8，3.0，7.0a

3. The illusive semiannual SST cycle in the eastern Pacific

eraged over the annual cycle. In the coastal region adjacent to South America, CCSM3 overestimates the SST by 1.8°C. While earlier generations of CCSM overestimated the surface insolation off South America by more than 50 W m^{-2} in the annual mean, CCSM3 tends to slightly underestimate the surface shortwave flux. The much smaller error in insolation results from several modifications to the cloud parameterizations introduced in CCSM3 (Boville et al. 2006) partly to address this issue. The observational comparison suggests that the alongshore surface stress in CCSM3 may still be too weak, and this may partially explain the 1.8°C error in SST. It should be noted that the surface stress produced by CCSM3 is stronger than that in CCSM2 by up to 0.1 N m^{-2}, partly because of the increased resolution in the atmosphere (Hack et al. 2006). In the case of Africa, CCSM3 underestimates the SST by 3.5°C even though it produces a realistic alongshore stress and slightly underestimates the surface insolation. The effects of other physical processes, including ocean upwelling, on the SST biases are examined further in Large and Danabasoglu (2006).

e. The semiannual SST cycle in the eastern Pacific

CCSM3 produces a fairly strong semiannual cycle for SST in the eastern tropical Pacific that does not occur in the real climate system (Large and Danabasoglu 2006). The region where this discrepancy is particularly evident lies between 5°N–5°S and 110°–90°W. An observational climatology for the seasonal cycle in SST for this region can be derived from the Hadley Centre's sea surface temperature dataset (HadISST) (Rayner et al. 2003). The annual and regional mean temperature from CCSM3 is 25.5°C, and this compares well with the HadISST estimate of 25.2°C. However, the simulated and observed seasonal cycles in the regional mean SST are quite different. The CCSM3-simulated annual cycle has a sine-wave amplitude roughly half that observed and is phased 1.4 months late, while the sine-wave amplitude of the semiannual cycle is roughly twice that observed. The causes for these systematic biases in the model physics have not yet been identified.

f. Underestimation of downwelling shortwave radiation in the Arctic

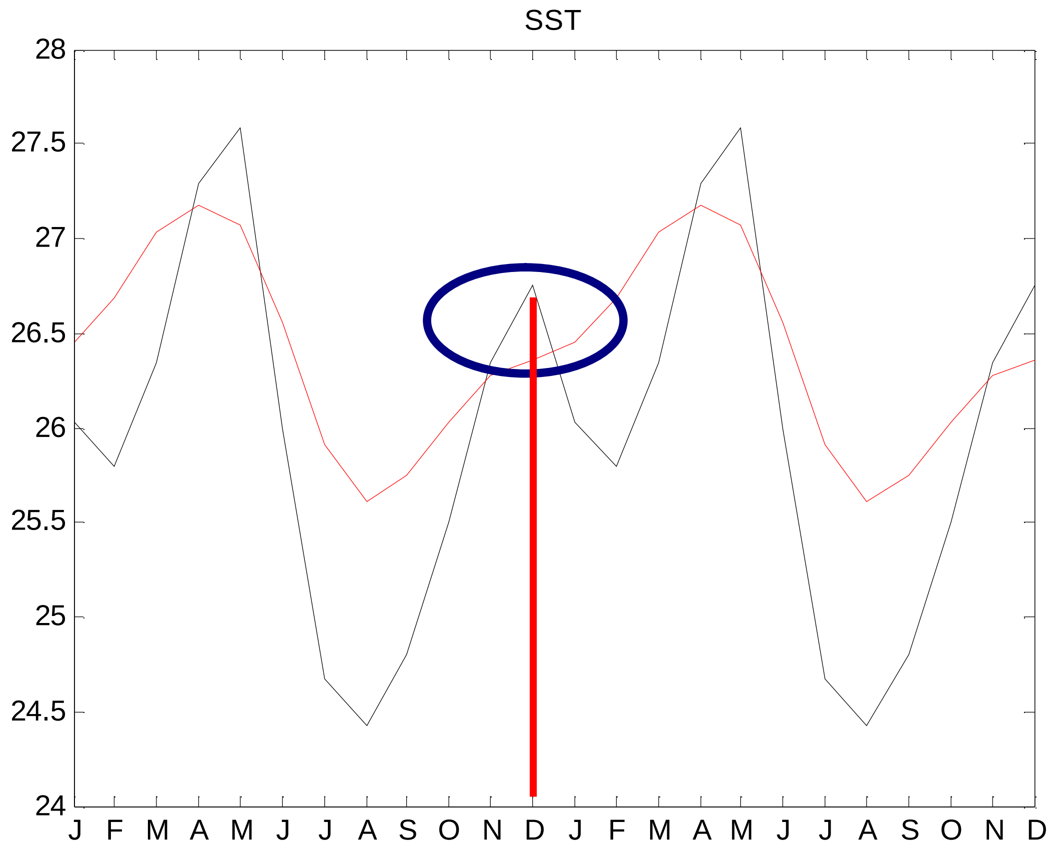
In the Arctic, CCSM3 underestimates the downwelling all-sky shortwave radiation at the surface throughout the annual cycle. The insolation is underestimated relative to in situ observations from the Surface Heat Budget of the Arctic (SHEBA) experiment (Persson et al. 2002) and to estimates from ISCCP (Fig. 15; Zhang et al. 2004). For this comparison, the ISCCP data from 1984 to 2000 has been averaged to produce a climatology. Between 70° and 90°N, the annual-mean downwelling shortwave fluxes for all-sky conditions are 91 W m^{-2} from ISCCP and 78 W m^{-2} from CCSM3. The corresponding annual-mean clear-sky fluxes differ by only −3.9 W m^{-2}, or −3%. The fluxes during the JJA season are 214 W m^{-2} from ISCCP and 169 W m^{-2} from CCSM3. The corresponding JJA-mean clear-sky fluxes differ by only 8.5 W m^{-2}, or 2.7%. Since the clear-sky fluxes are in good agreement, the underestimate of surface insolation by CCSM3 is caused by an overestimate of the surface shortwave cloud radiative forcing. It should be noted that the excessive cloudiness in winter produces an overestimate of downwelling longwave surface flux by 20 W m^{-2} for December through April. The overestimation of longwave flux partly compensates the underestimation of shortwave insolation in the total surface radiation budget. Further analysis will be required to identify the sources of these errors in the modeled cloud amount, cloud condensate path, and cloud microphysical properties.

6. Summary

The semiannual SST cycle in the eastern Pacific

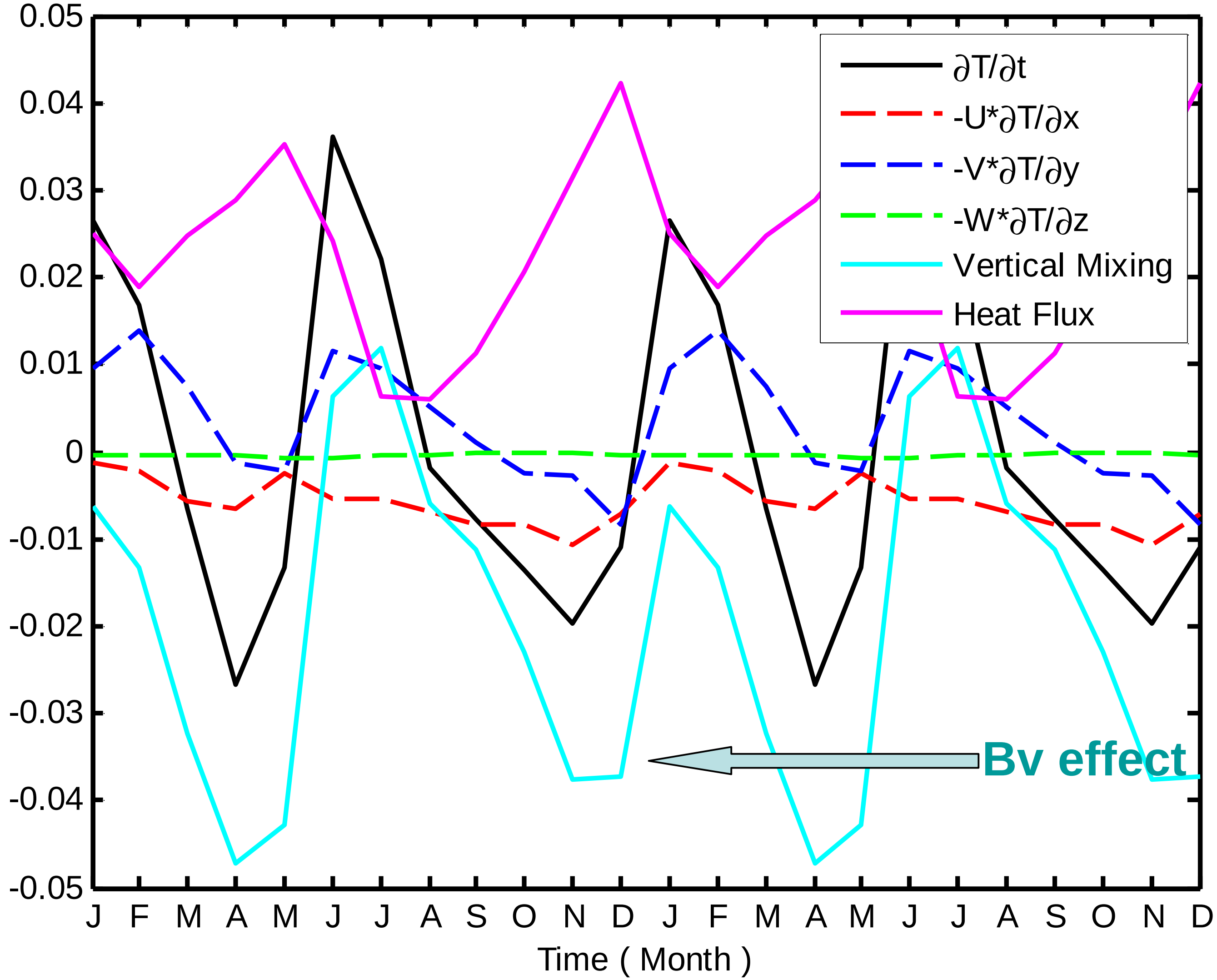
ice share a nominal 1° grid with a displaced pole in the Northern Hemisphere.

The atmosphere incorporates new treatments of cloud and ice-phase processes; new dynamical frameworks suitable for modeling atmospheric chemistry; improved parameterizations of the interactions among water vapor, solar radiation, and terrestrial thermal radiation; and a new treatment of the effects of aerosols on solar radiation. The land model includes improvements in land surface physics to reduce temperature biases and new capabilities to enable simulation of dynamic vegetation and the terrestrial carbon cycle. The ocean model has been enhanced with new infrastructure for studying vertical mixing, a more realistic treatment of shortwave absorption by chlorophyll, and improvements to the representation of the ocean mixed layer. The sea ice model includes improved schemes for the horizontal advection of sea ice and for the exchange of salt with the surrounding ocean. The software has



Time evolution of the averaged SST in the Eastern Pacific（110—90W,5S-5N）.

Black: CCSM3; Red: CCSM3+Bv



Heat Budget analysis in the eastern Pacific（110-90W,5S-5N）

Conclusions

- **A new wave-circulation coupled theory for the wave vertical mixing effects is developed.**
- **The wave-motion related vertical mixing plays an important role in the upper ocean.**

From coastal ocean to global ocean and even to climate system, the wave-induced vertical mixing (a kind of new mixing process) is too important to be ignored.

Wave-tide-circulation coupled model could improve our forecast ability for FUTURE

Qingdao

- The ocean sciences city in China (>60%)
- Olympic Sailing Games in 2008
- Hometown of Qingdao Beer
- Beautiful sightseeing

Thanks for your attention