Surface Wave Enhanced Turbulence as an important source energy maintaining/regulating Thermohaline Circulation

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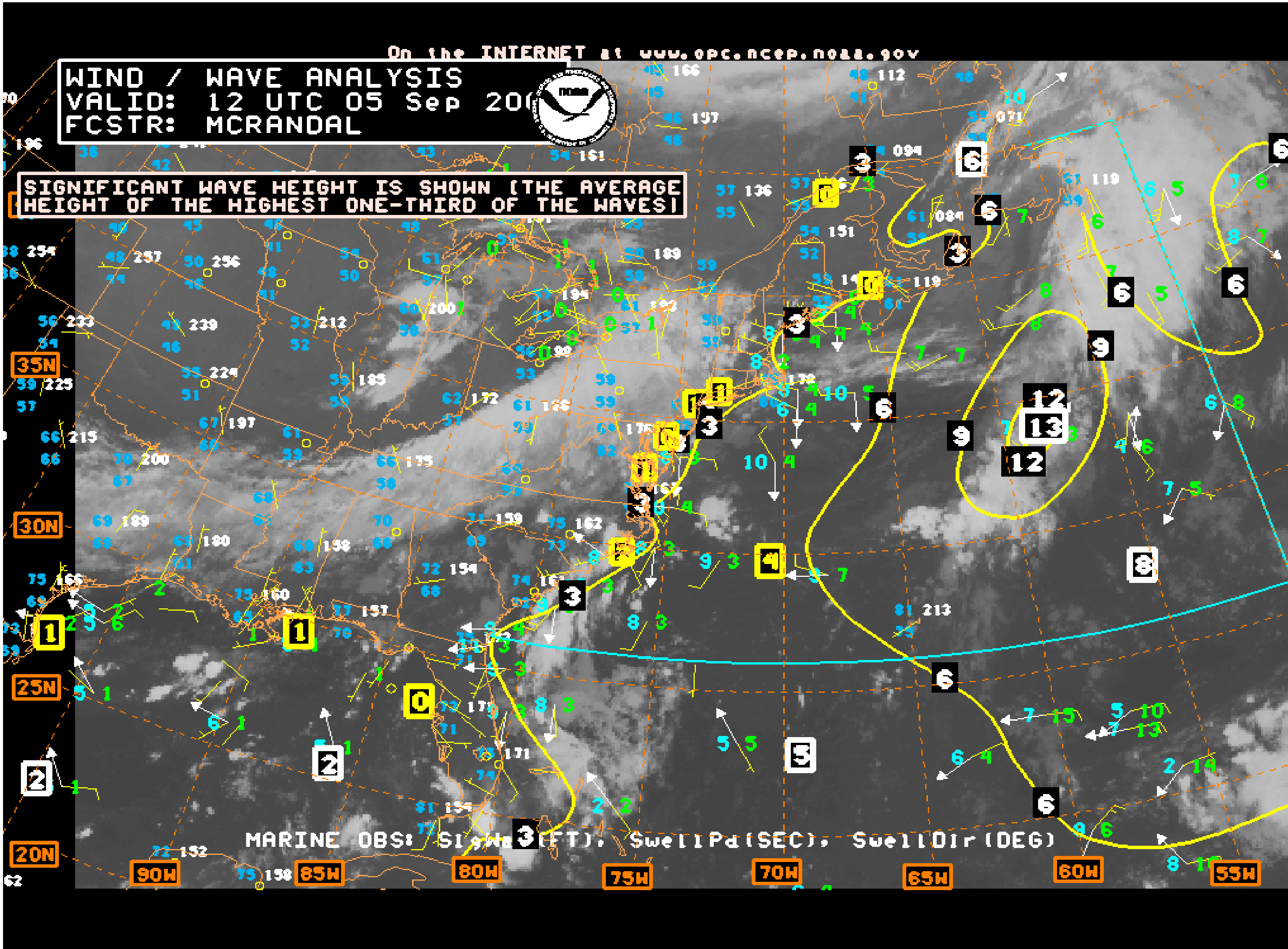
Why should we care about surface waves?

1) Surface waves affect the upper ocean only?

2) Most OGCMs assume kappa drops to 0.1 Munk below the mixed layer.

3) This is wrong! Due to surface wave enhance turbulence, kappa can be much larger than 0.1 below the base of mixed layer, and this strong mixing can affect the THC greatly.

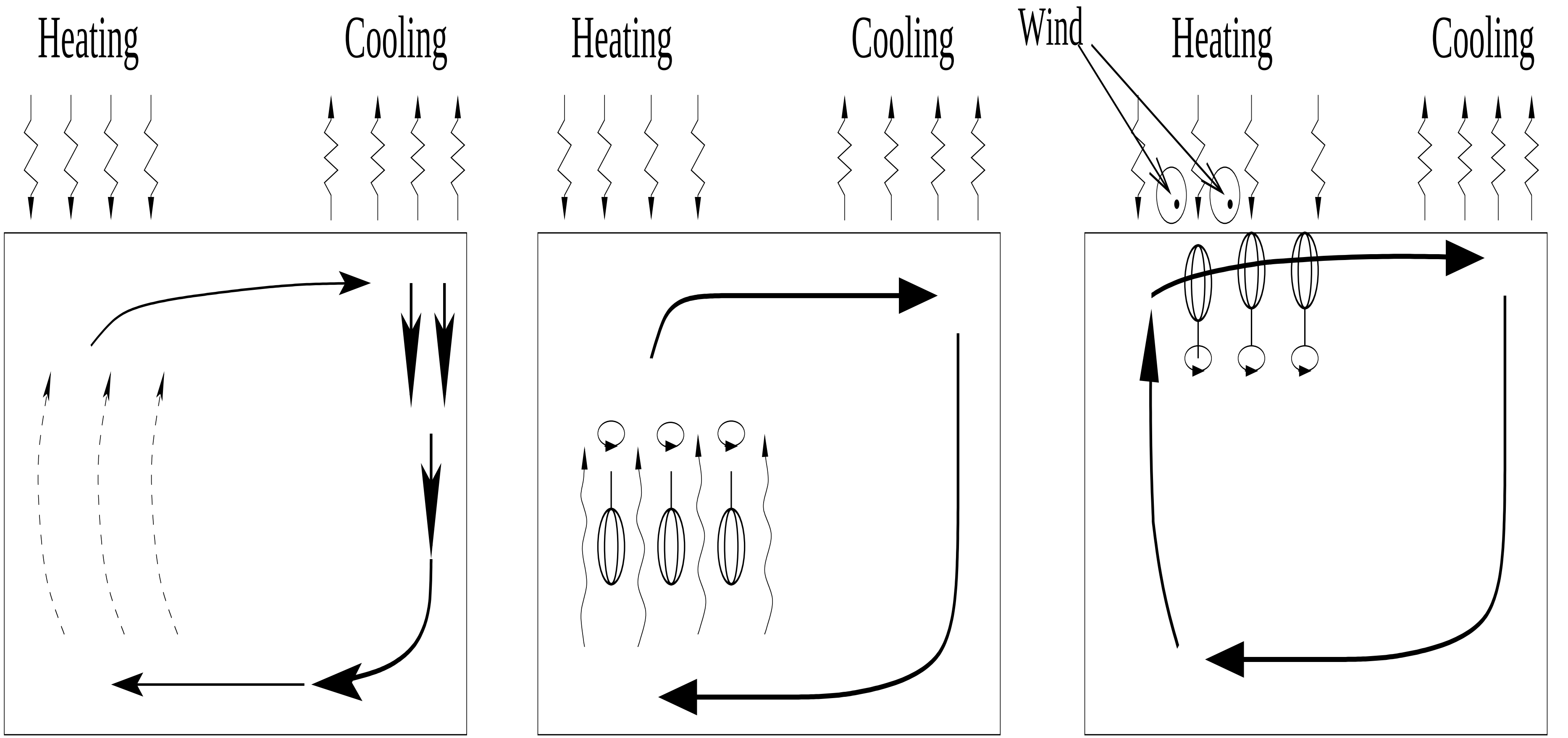

On the INTERNET at www.opc.ncep.noaa.gov
WIND / WAVE ANALYSIS
VALID: 12 UTC 05 Sep 20
FCSTR: MCRANDAL
NOAA
SIGNIFICANT WAVE HEIGHT IS SHOWN (THE AVERAGE HEIGHT OF THE HIGHEST ONE-THIRD OF THE WAVES)
MARINE OBS: SigWv(FT), SwellPd(SEC), SwellDir(DEG)
35N
30N
25N
20N
90W
85W
80W
75W
70W
65W
60W
55W

Three schools: What drives THC?

a) Pushing by deepwater formation

b) Pulling by deep mixing

c) Pulling by wind stress & surface waves



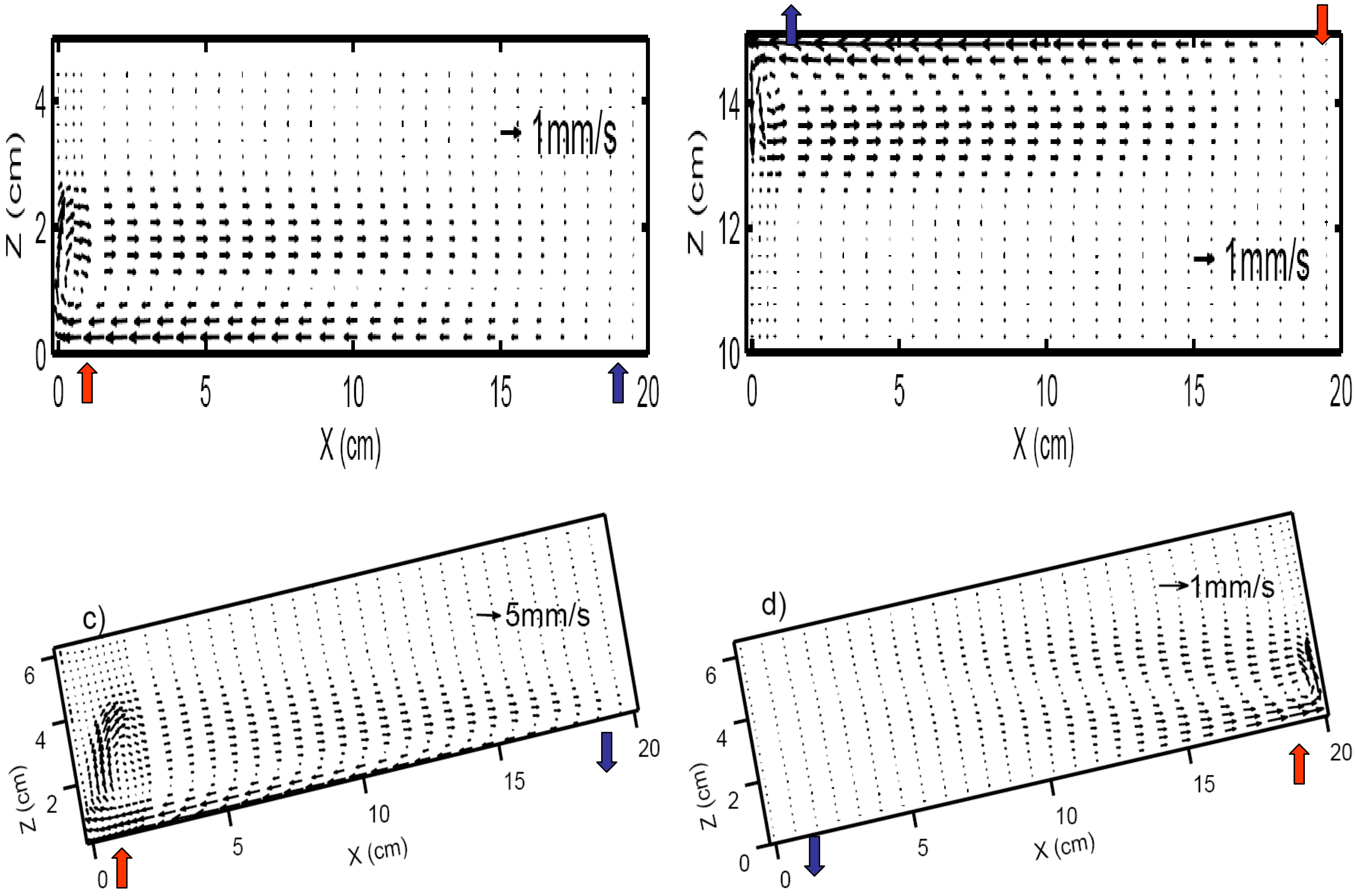
New energetic theory of THC

1) Mechanical energy is required for overcoming friction/dissipation

2) Surface heating/cooling cannot maintain THC observed in the oceans.

   Sandstrom Theorem and the new debate

3) Deep mixing is proposed as an important mechanism in maintaining THC



Wang, W. and R. X. Huang, 2005, *Journal of Fluid Mechanics*

Inverse energy cascade in the oceans:

1) Large-scale gravitational potential energy

→ Tidal energy

→ Small scale mixing

→GPE of large scale ocean circulation

2) Wind stress → small scale waves

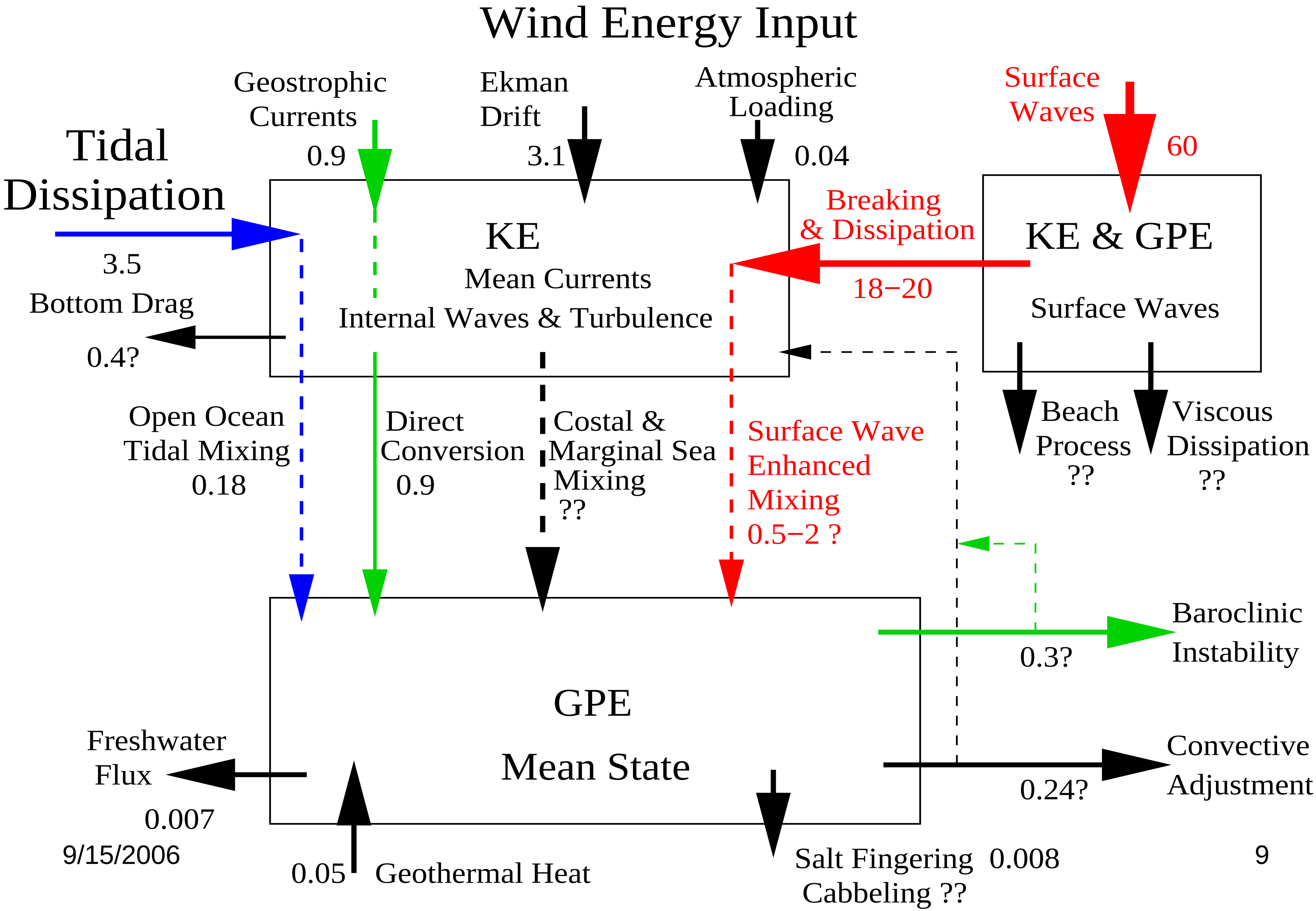
→Small scale mixing

→GPE of large-scale ocean circulation

Outline

- The role of wind waves on the energy budget of the ocean
- Observed distribution of wave-breaking enhanced dissipation rate
- Numerical experiments with idealized surface-intensified diffusivity
- Circulation driven by realistic surface wave enhanced diffusivity
- Conclusion

Mechanical energy balance in the oceans



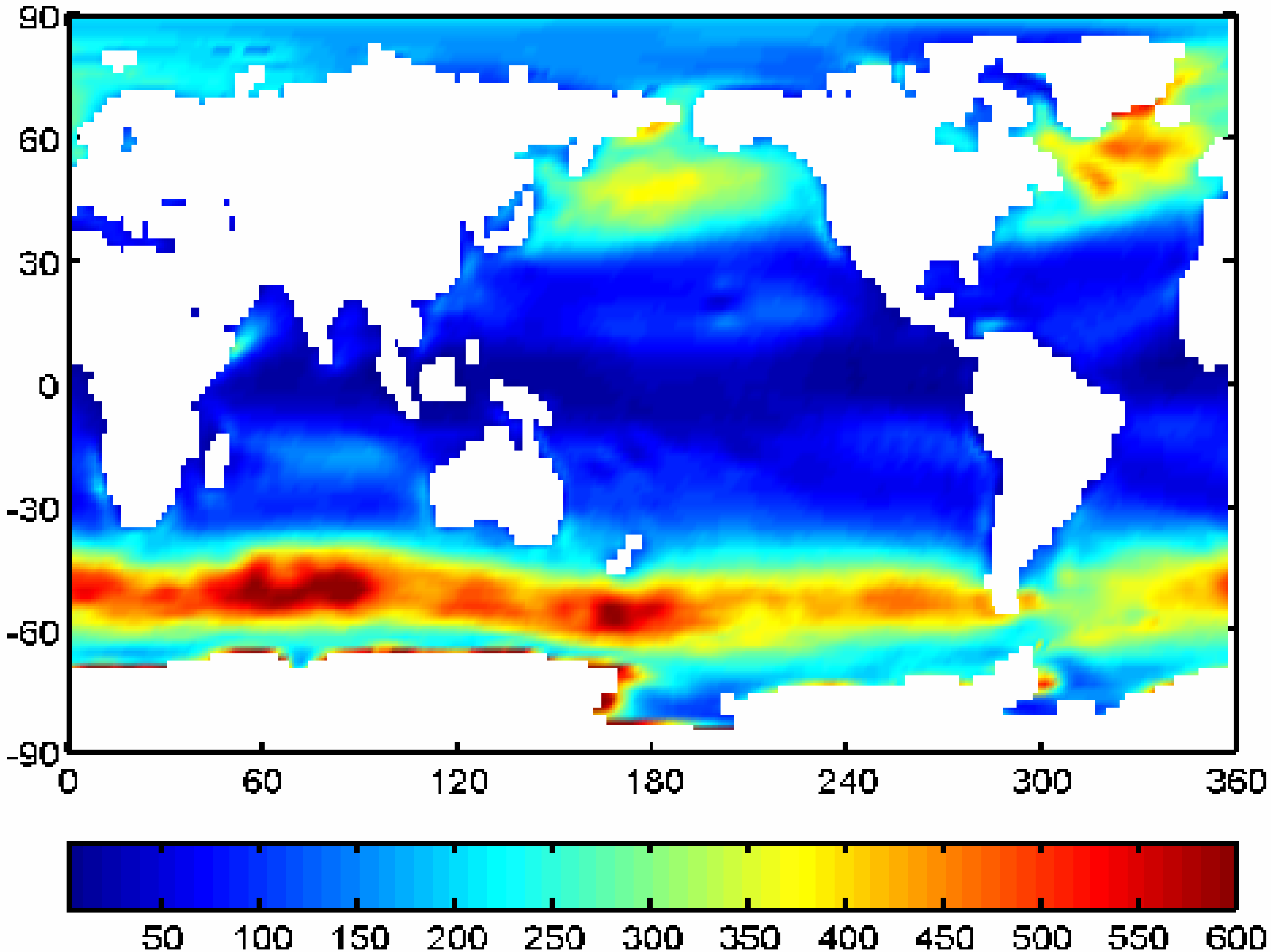
Motivation

- Thermal energy to mechanical energy conversion rate

$$-\left\langle p\nabla\cdot\mathbf{u}\right\rangle = g\left\langle k\rho_z\right\rangle$$

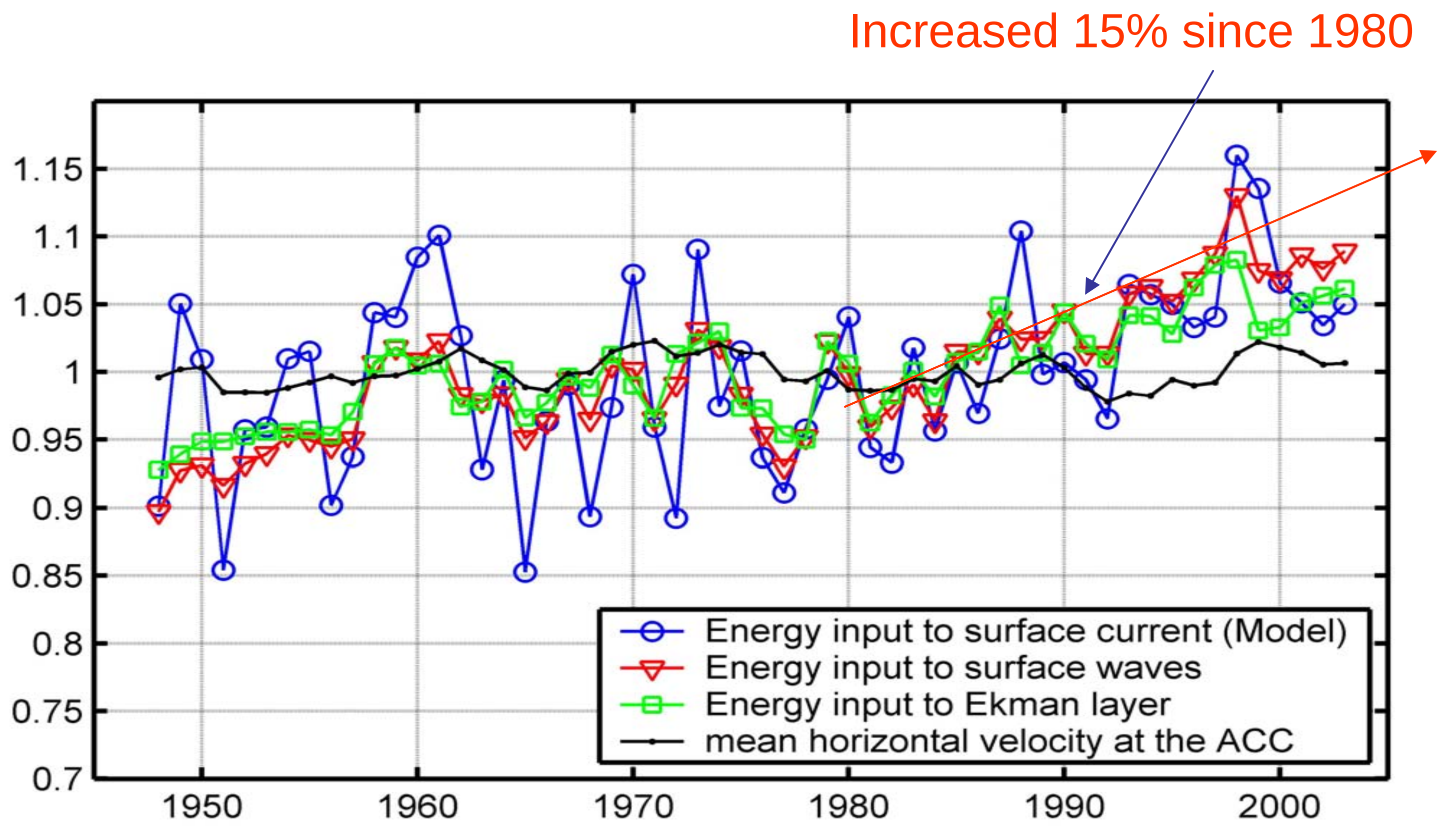
- Need more energy? Strong mixing applies to place with strong stratification!
- Upper ocean where surface wave enhanced turbulence is the right place

Surface wave energy input (mW/m/m, Wang & Huang, 2004)



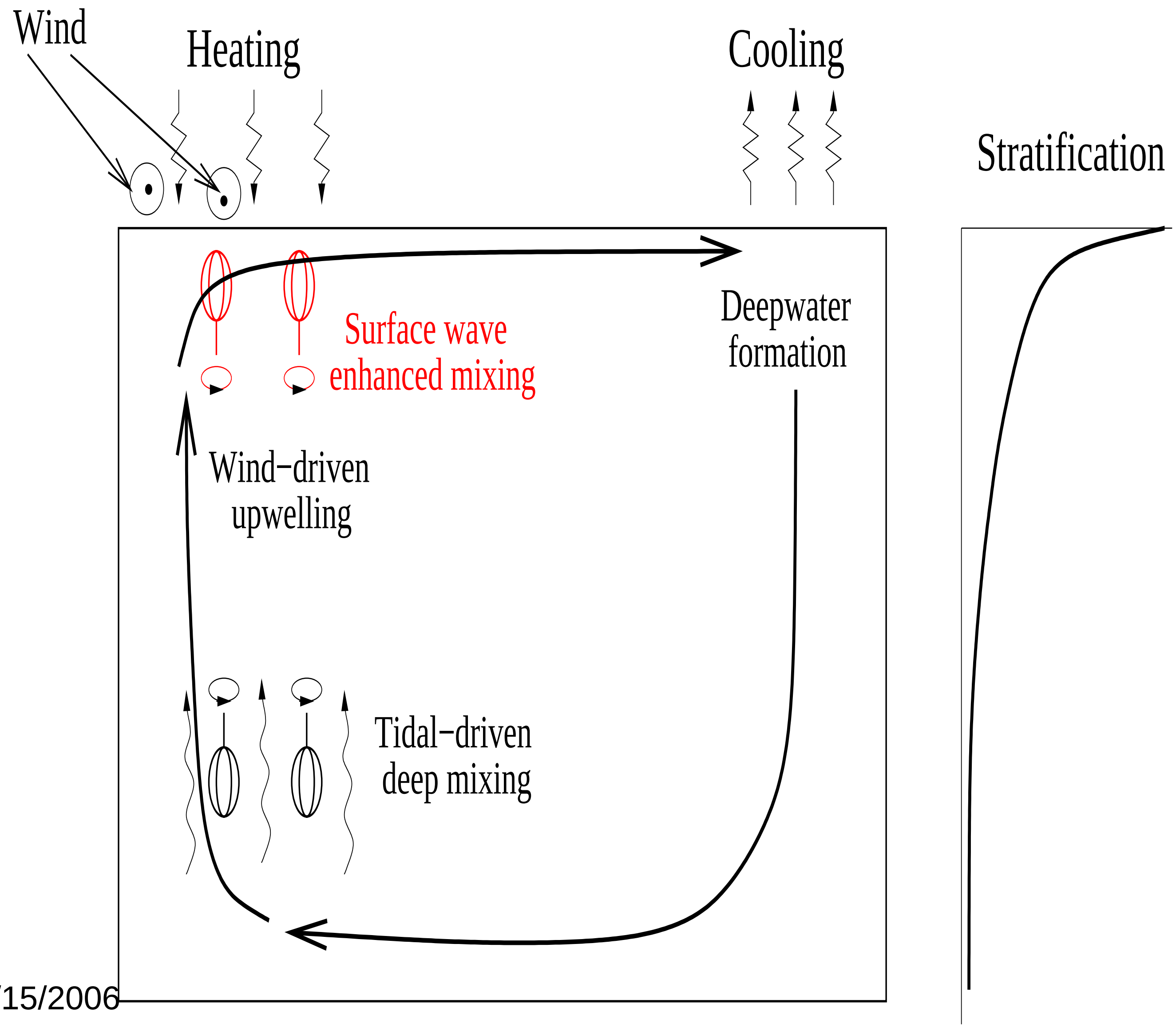
Wind energy is more important:

1) It is much larger than tidal energy (64 vs 0.9TW)
2) It dominates the circulation in the upper ocean
3) It varies greatly on time scale shorter than 100 yr



Huang, R. X., W. Wang, and L. L. Liu, 2006, *Deep Sea Research II*

Surface wave enhanced mixing, wind-driven upwelling and deep tidal mixing



0−500m
Strong stratification
Strong mixing
Large source of GPE

500−2000m
Weak stratification
weak mixing
Small source of GPE

2500−bottom
Very weak stratification
Strong mixing
Small source of GPE

How much GPE can be generated?

(in units of TW, assuming conversion efficiency of 0.2)

- Tidal dissipation: In open ocean, 0.8X0.2=0.16
- Wind to geostrophic currents; 0.9?
- A substantial portion of this is transferred to meso-scale eddies
- How meso-scale eddies loose their energy remains unclear --- breaking down of balance? Bottom form drag? Bottom friction? Lee waves in ACC?
- Final contribution may be much smaller, this will an important subject for future study.
- Wave enhanced turbulence: 1-2 ??.

Can Surface Waves affect THC?

- Vertical mixing in deep ocean can drive THC. How can surface waves affect mixing through generation of internal waves and turbulence in the ocean ?.
- Answer: Enhanced mixing in the upper ocean can drive strong THC
- At the upper ocean, there is a mixed layer and there is no stratification there; thus, mixing cannot generated GPE.
- Answer:
- 1) can be 0, infinite or finite.
- 2) $0 \times \infty$ se of mixed layer might be a site of large source of GPE.

Surface enhanced mixing

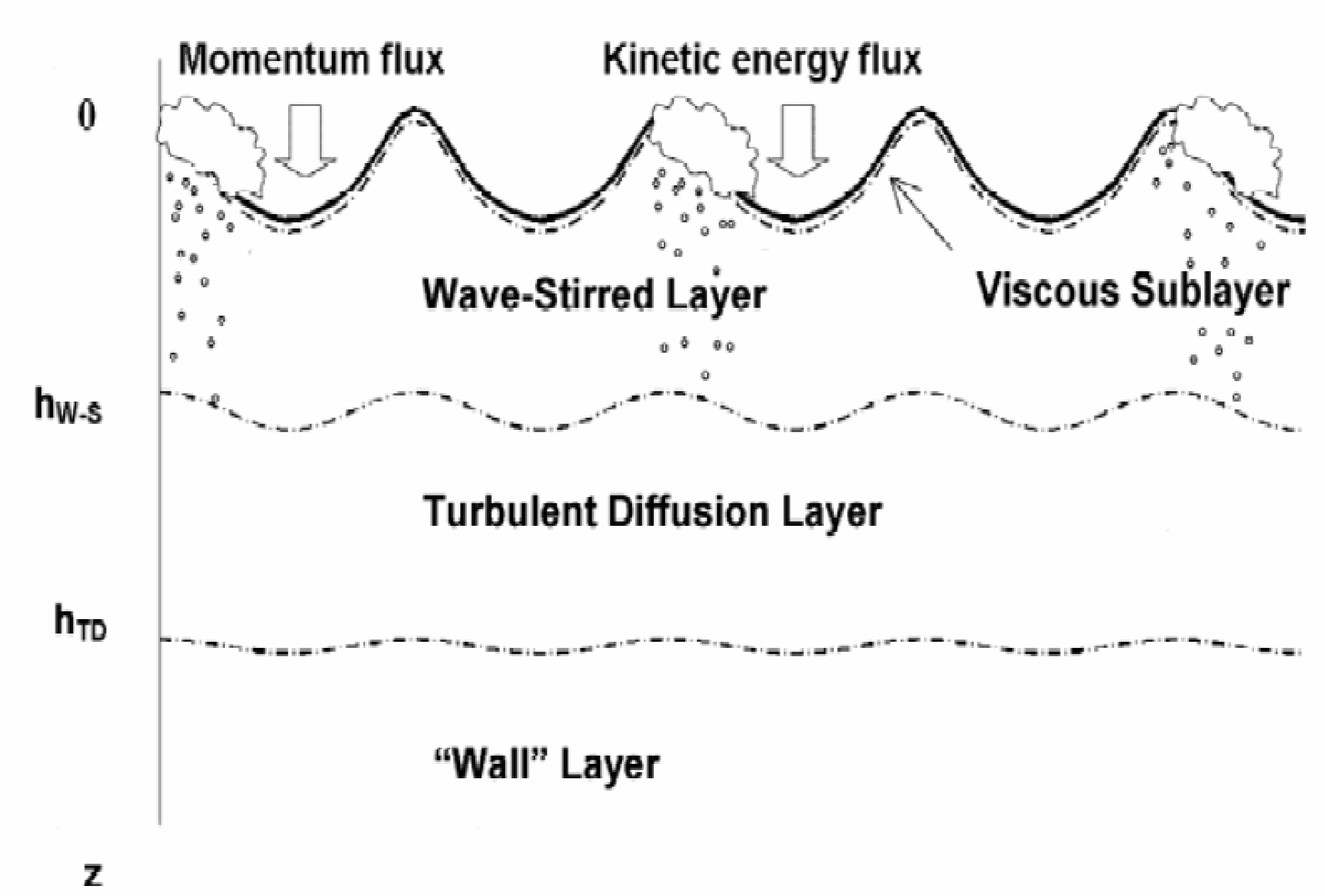
Strong Meridional baroclinic pressure difference

Strong meridional overturning

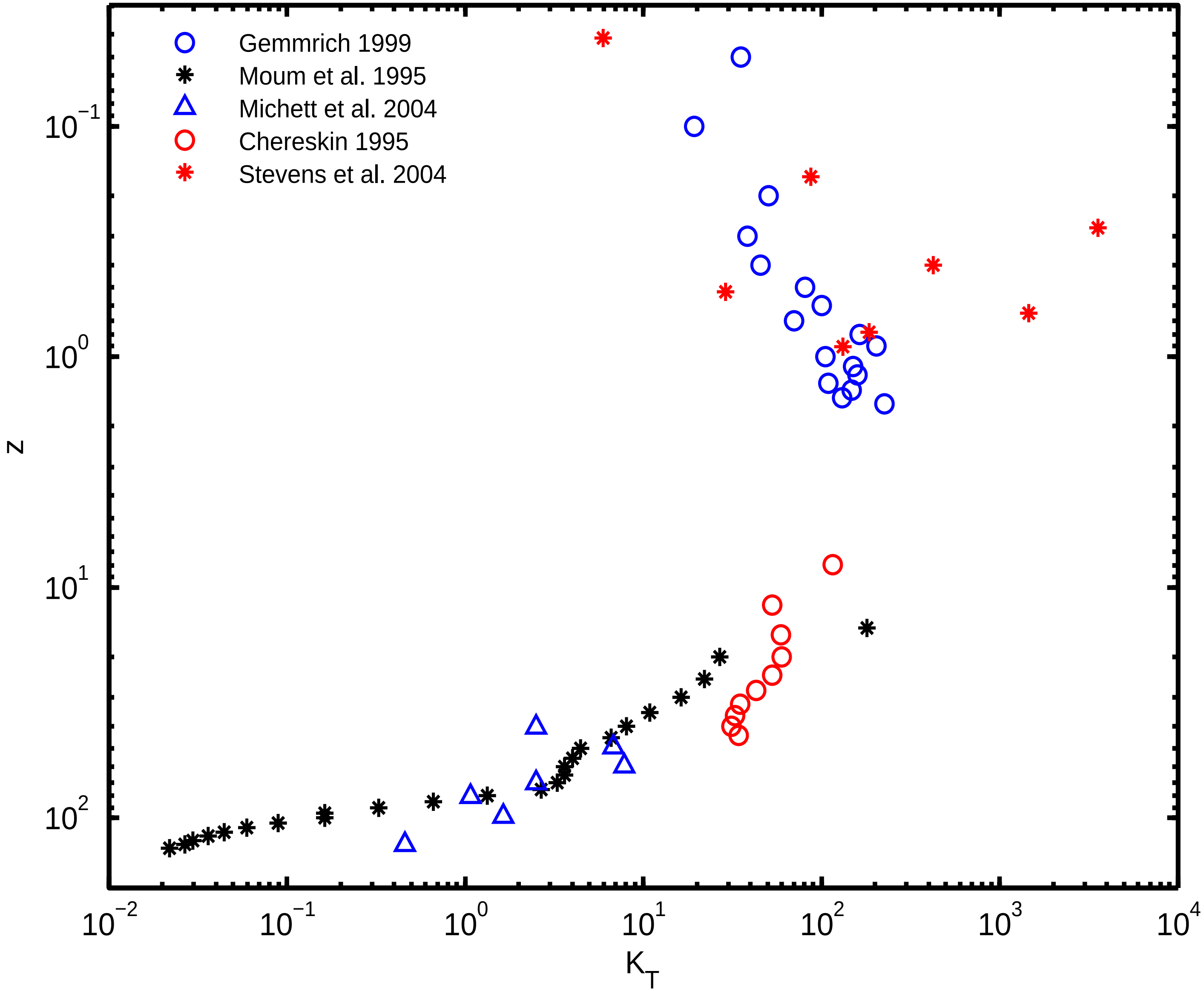
More heat penetration into the thermocline

Stronger poleward heat flux

Dynamic structure of the turbulent boundary layer in the upper ocean



Diffusivity profiles
Observations and theory



Dissipation Rate Profiles
Two-segment models

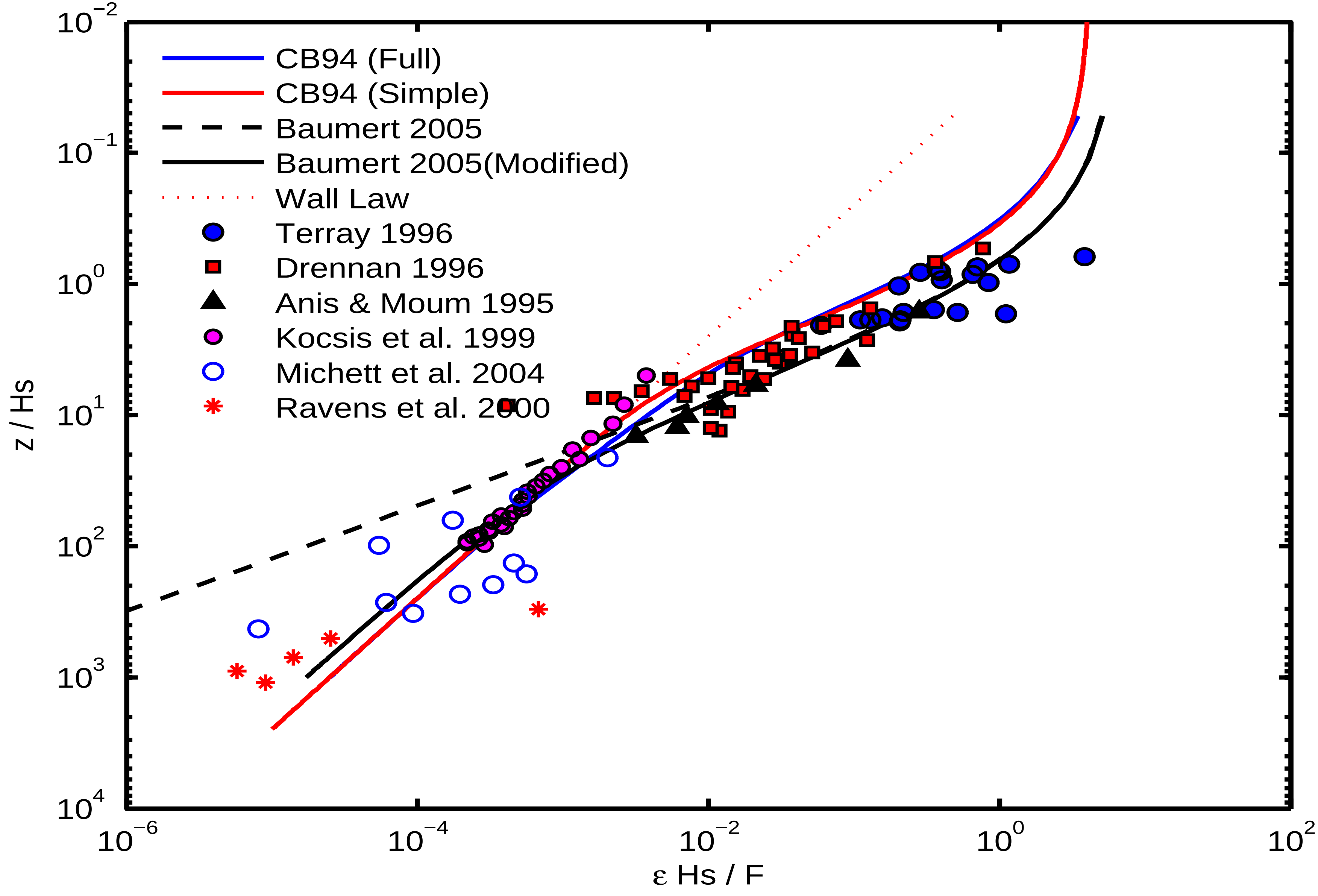
- The Craig & Banner (1994) model

$$\varepsilon(z) = \frac{u_{*w}^3}{\kappa(z+z_0)}\left[1+\sqrt{3}\alpha_w\left(BS_q\right)^{-1/2}\left(\frac{z_0}{z+z_0}\right)^n\right], \qquad z < z_b$$

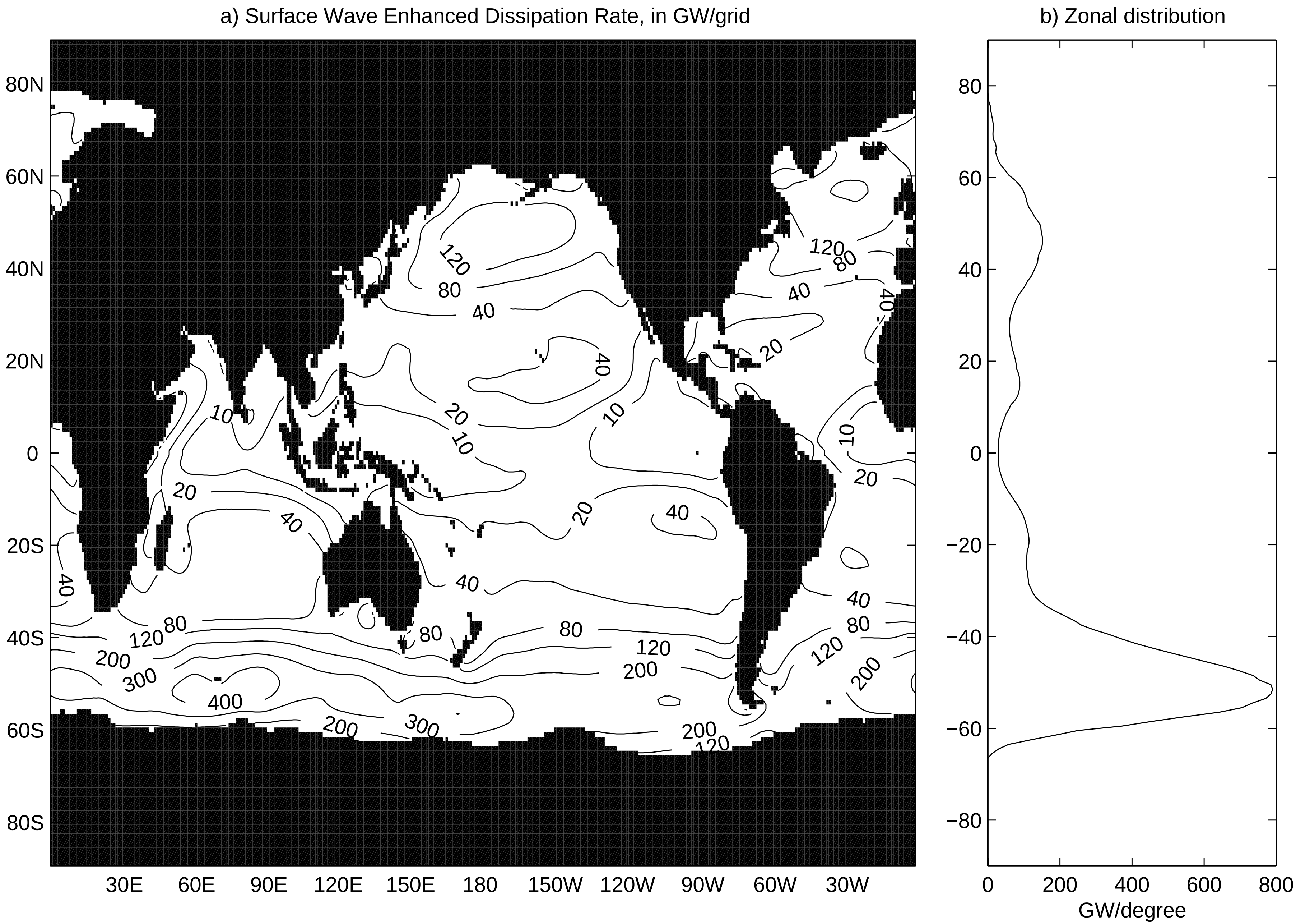
- The Hybrid model (Baumert, 2005)

$$\varepsilon(z) = \frac{150\mathrm{u}_{*w}^3 z_0^{3/2}}{\kappa\left(\mathrm{z}+\mathrm{z}_0\right)^{5/2}} + \frac{\mathrm{u}_{*w}^3}{\kappa\left(\mathrm{z}+\mathrm{z}_0\right)}, \qquad z < z_b$$

Surface wave enhanced turbulence dissipation



Wave enhanced turbulence dissipation rate in mW/m/m

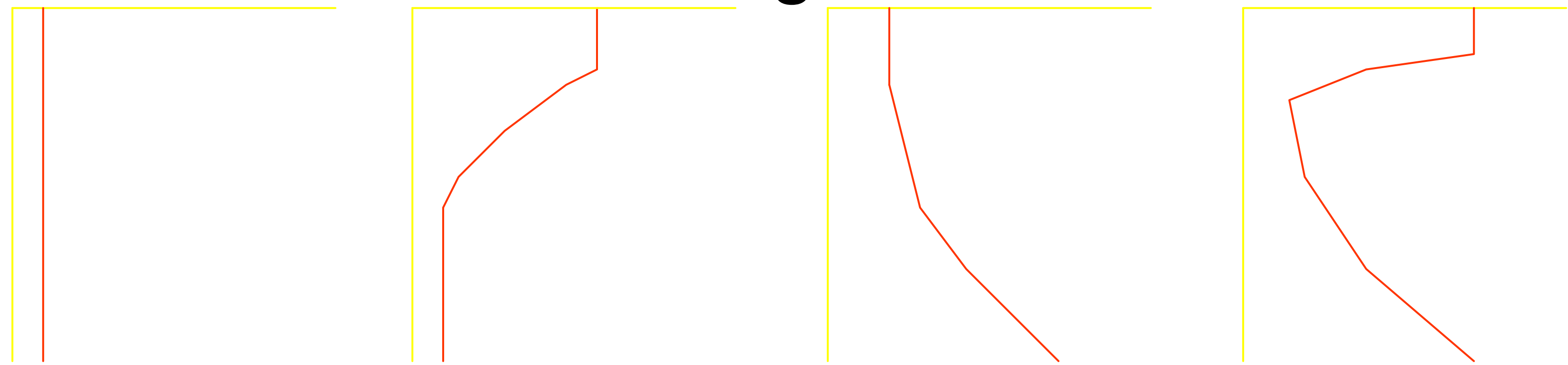


III. Idealized Numerical experiments

- A mass-conserving model, PCOM (pressure-coordinate ocean model, Huang et al., 2001)
- Temperature relaxation, linear equation of state
- A 60X60 degree model, mimicking the North Atlantic
- Flat bottom, 5000 m deep.
- Spin up from a state of rest and T=0^oC.
- No freshwater flux forcing
- No wind stress forcing --- wind stress is to provide small-scale turbulence energy only.
- Vertical mixing profiles specified *a priori*.

Surface-enhanced vs Bottom-enhanced mixing

kappa profiles



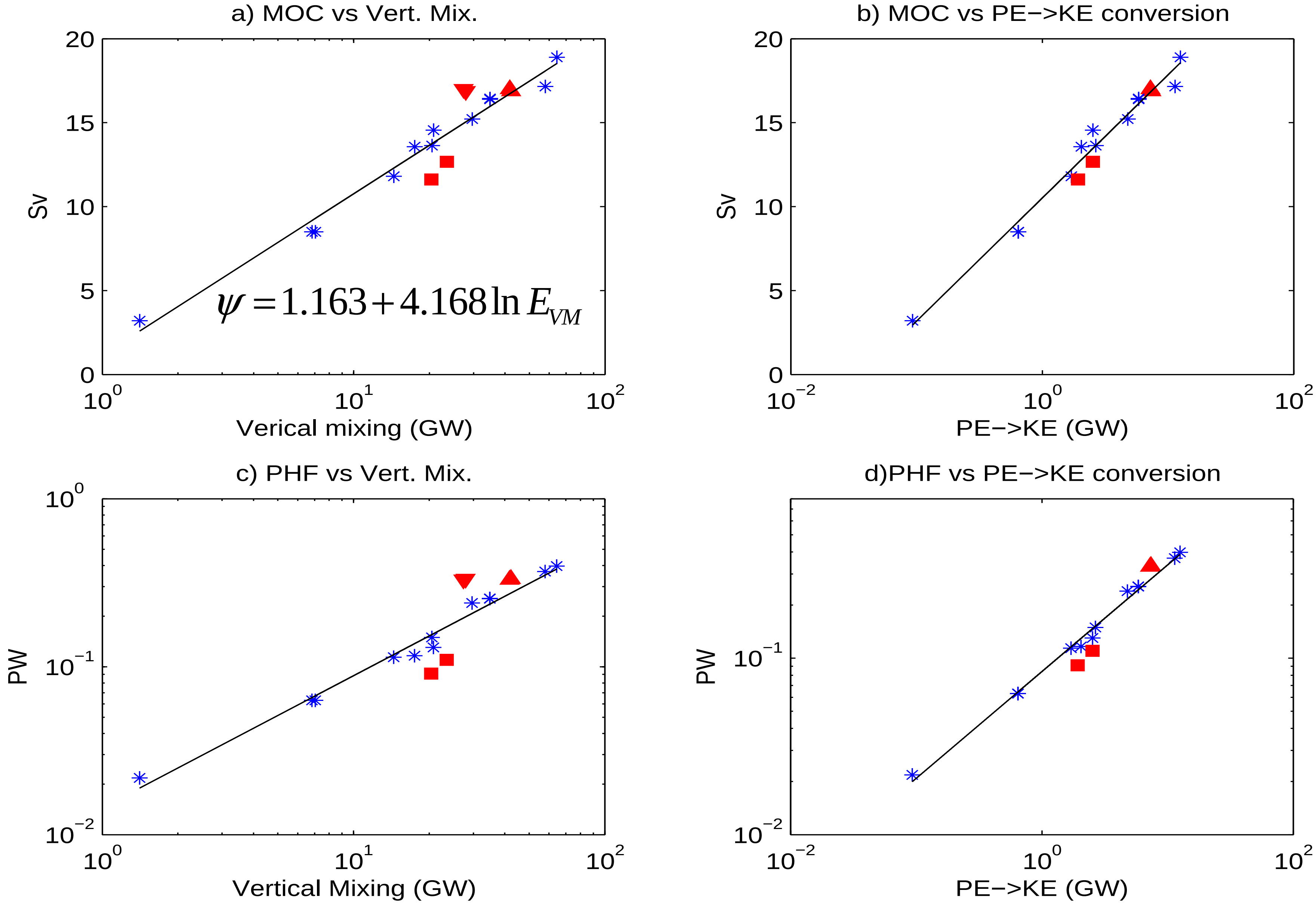
	A1	B1	E1	F1
MOC (Sv)	8.50	16.40	8.55	16.44
PHF(PW)	0.063	0.255	0.063	0.255
VM(GW)	6.96	34.86	6.87	34.90
CV(GW)	6.17	28.87	6.21	28.91

Result from Set 2

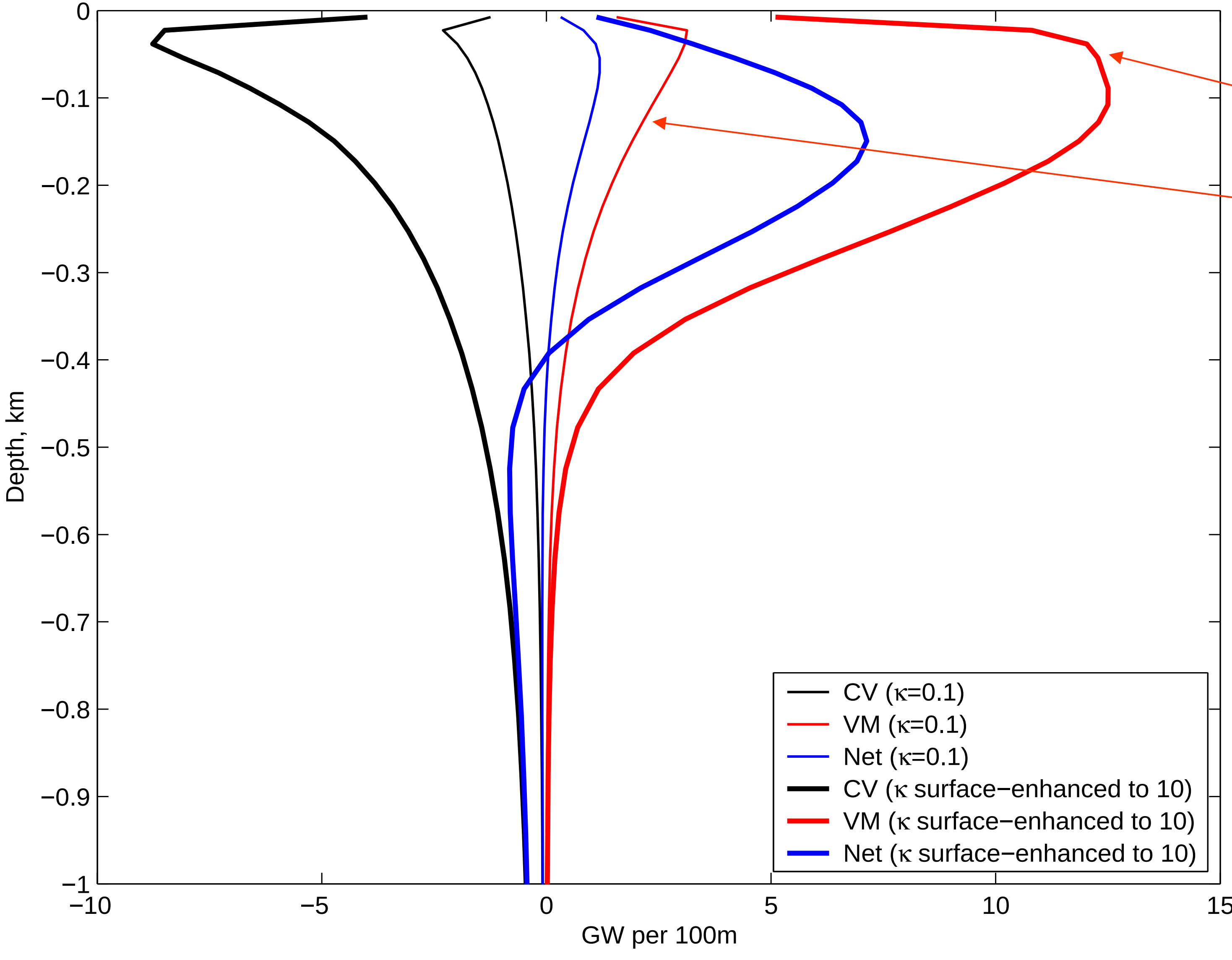
	$\overline{\kappa}\left(10^{-4} m^2/s\right)$	MOR (Sv)	PHF (PW)	KE (TJ)	GPE Balance (GW)				
					PE -> KE	CA	Vertical Mixing		
							Backgro und	Enhanc ed	Total
A2	0.02	3.20	0.022	62	0.09	1.31	1.43	0.0	1.43
B2	0.235	15.21	0.240	2360	4.79	24.75	1.34	28.33	29.67
C2	2.169	17.16	0.369	5522	11.42	46.18	1.30	56.57	57.87
D2	0.791	11.81	0.114	955	1.71	12.68	1.37	13.09	14.46

Table 3. Basic values for Set II; see caption of Table 2.

MOC/PHF vs
GPE source and PE->KE transfer

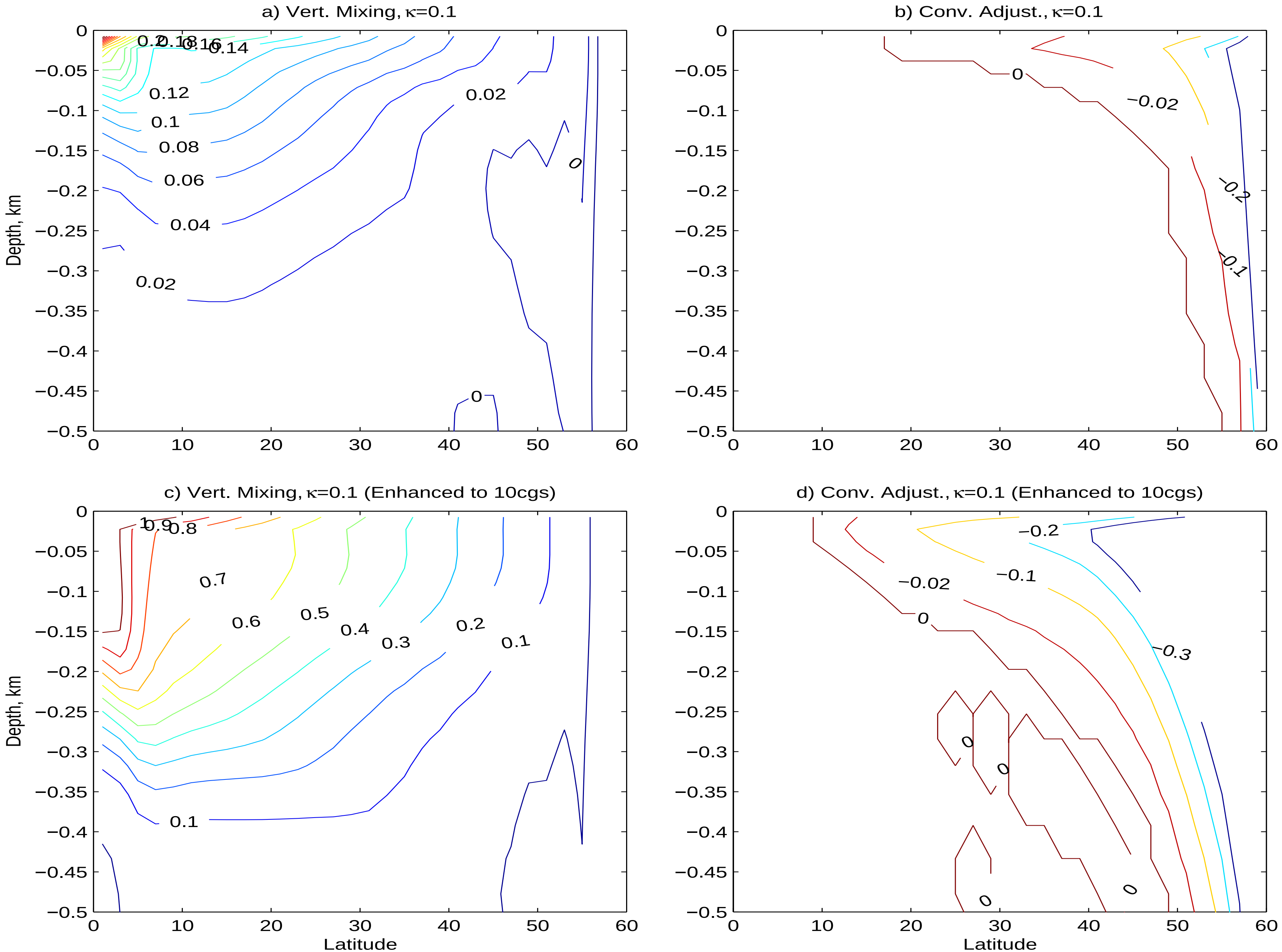


GPE due to vertical mixing and convective adjustment

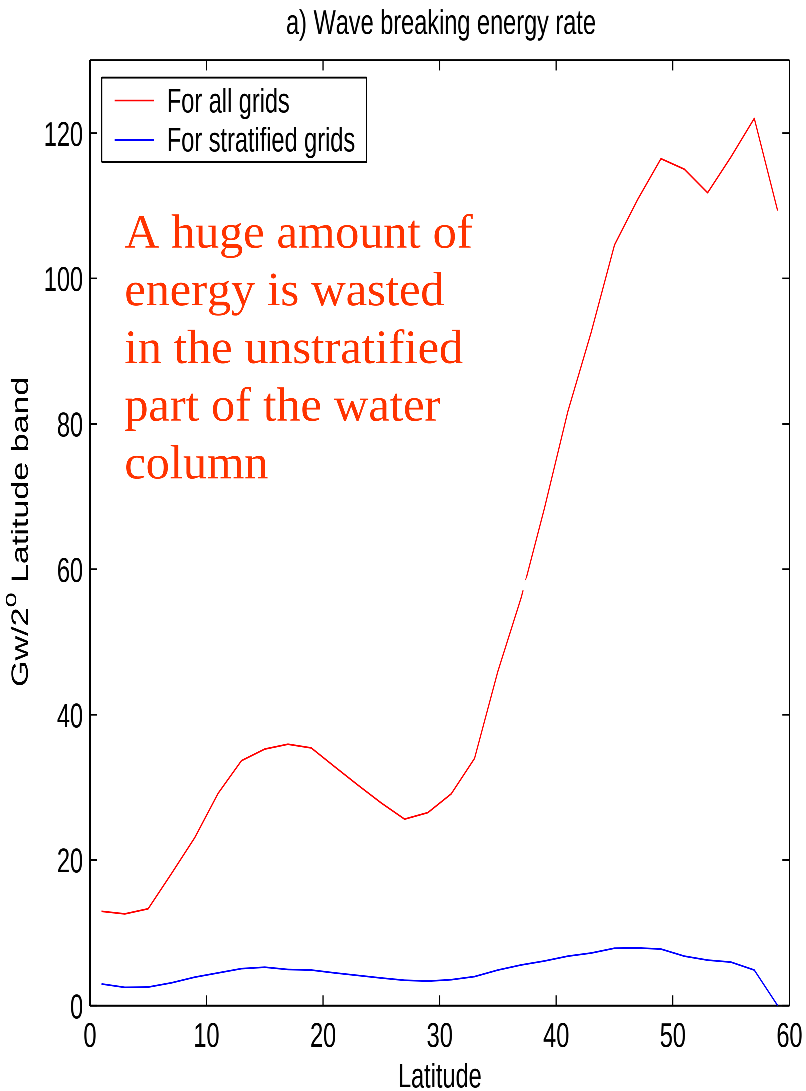


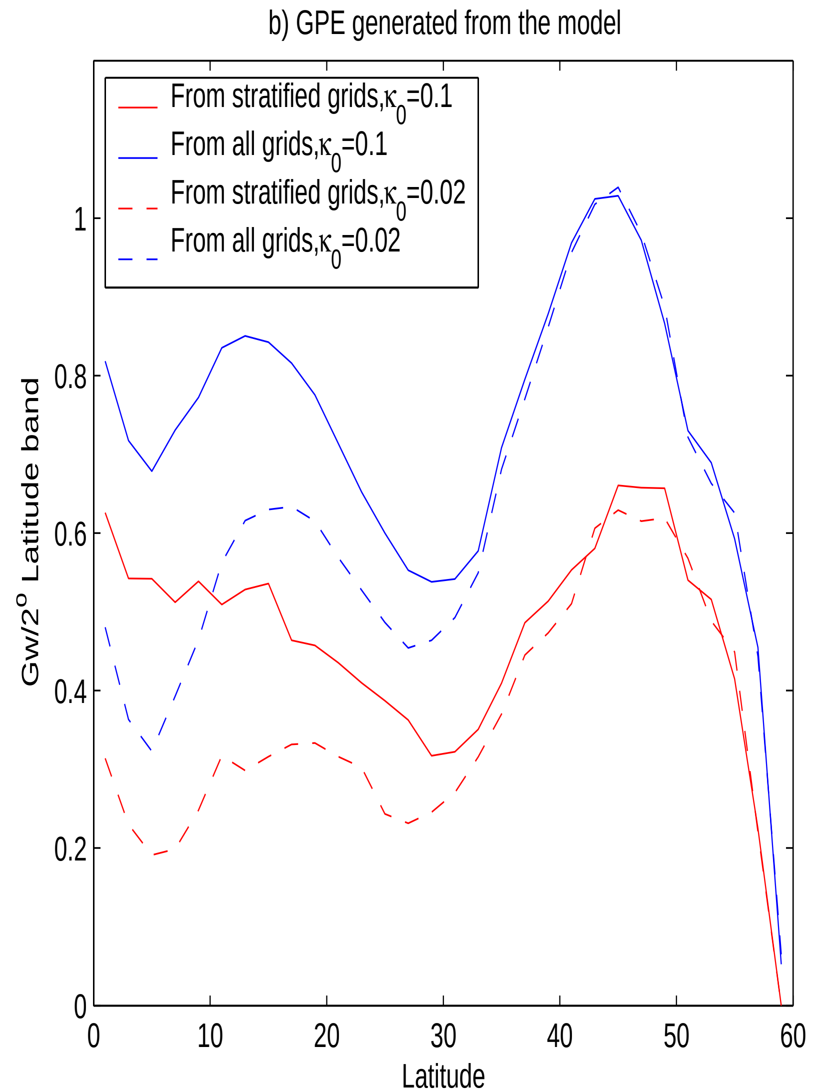
It is always surface trapped

GPE source/sink (GW/2 degree/100m)



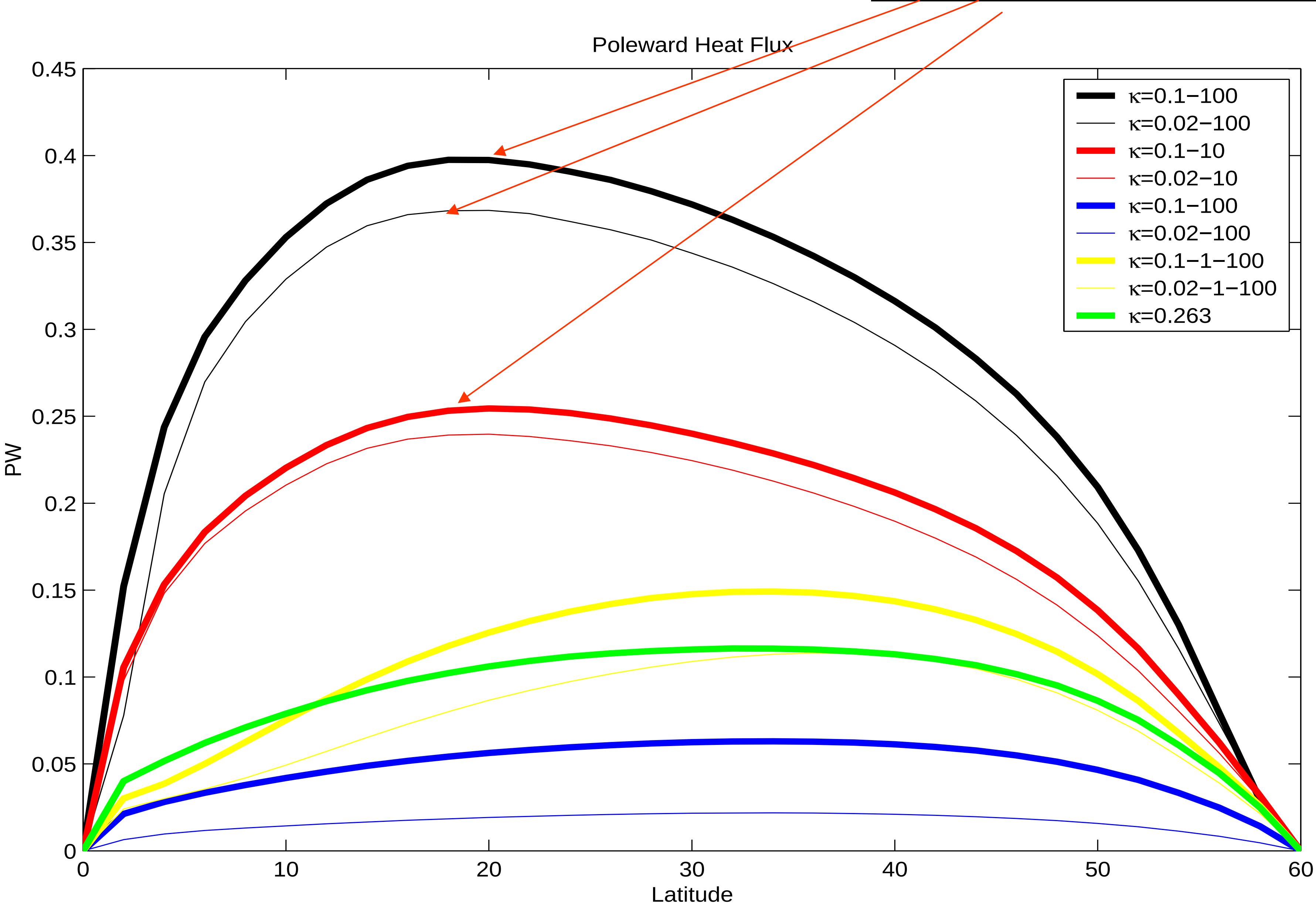
GPE usable and generated





Poleward heat t

Equatorward shift due to Surface-enhanced mixing



IV. THC driven by wave enhanced turbulence

- A. Wind stress treated as a source of kinetic energy for turbulence and internal wave only, i.e., there is no large-scale wind stress
- B. Wind stress contribute to large-scale wind-driven circulation and small scale mixing in the upper ocean

IV. A. Wave enhanced turbulence only

- Temperature relaxation and no freshwater flux.
- Wind interpreted as meridional-vertical distribution of wave enhanced turbulence dissipation rate average over the North Atlantic Ocean (60x60 degrees).

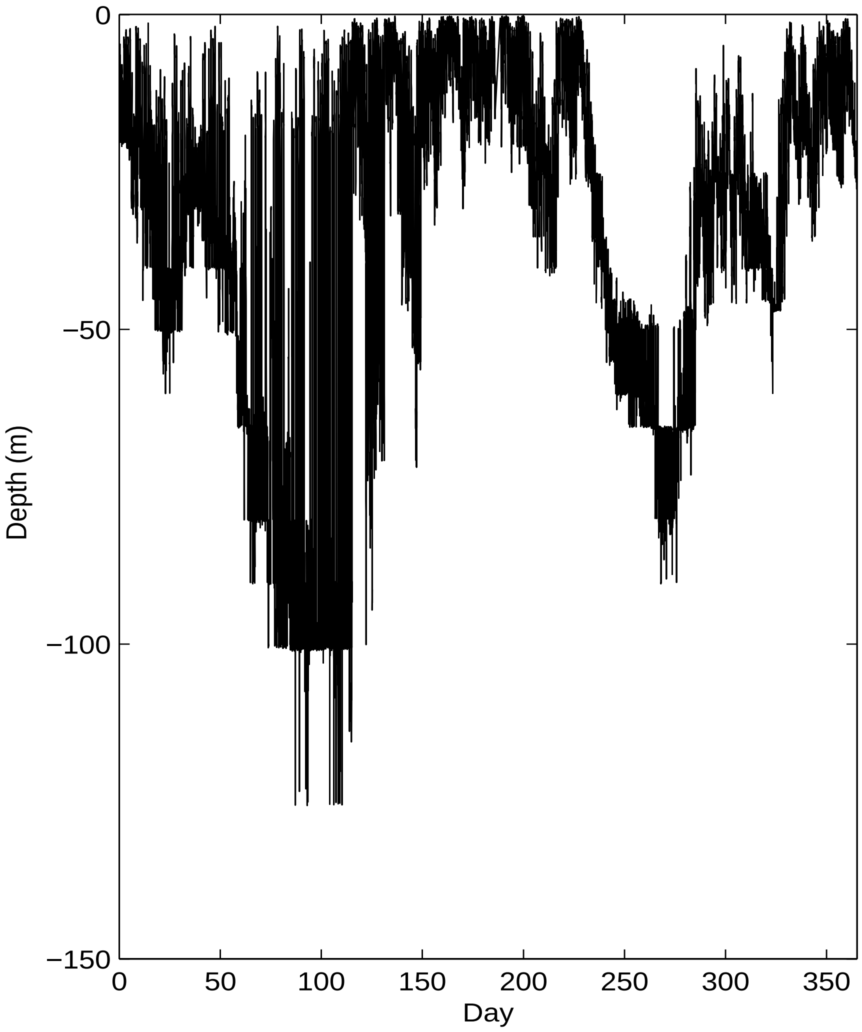
$$\kappa = \alpha\varepsilon / N^2, \alpha = 0.2$$

- Mixing coefficient sets to be < 100cm^2/s.

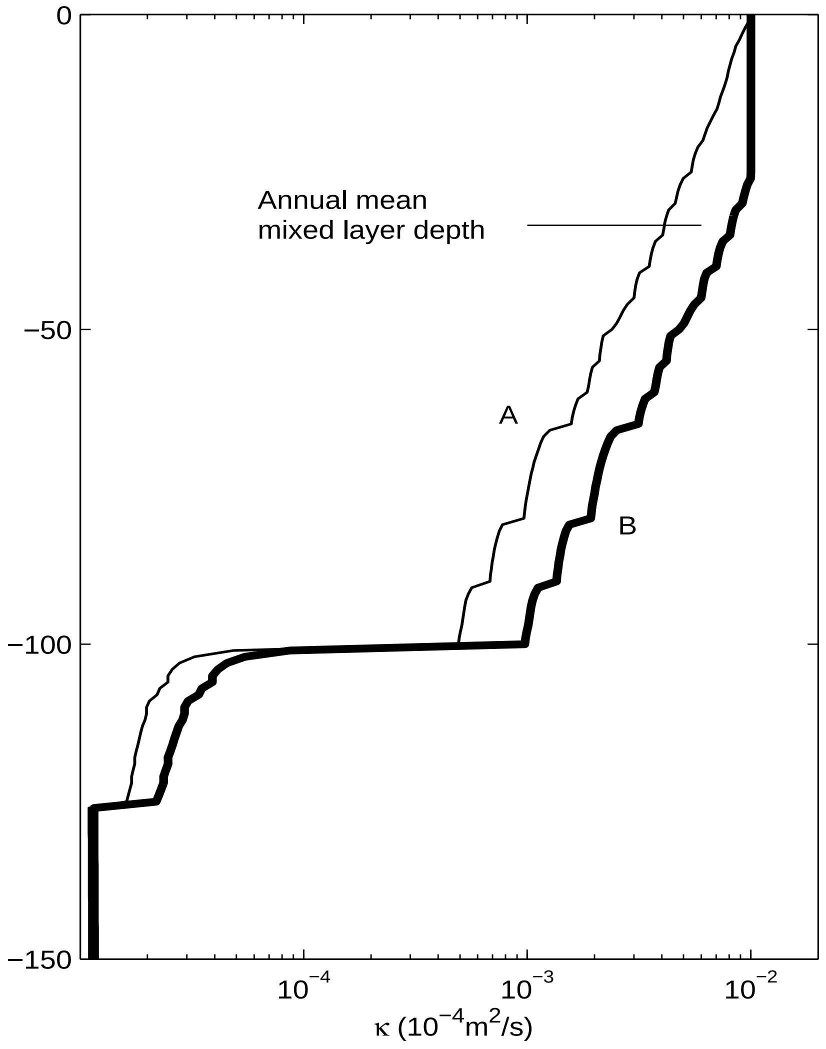
Diffusivity profiles inferred from Arabic Sea Experiment

Asuume: kappa=200/100 in ML, kappa=0.1 below ML

a) MIxed layer depth



b) Annual mean mixing profile



Implications

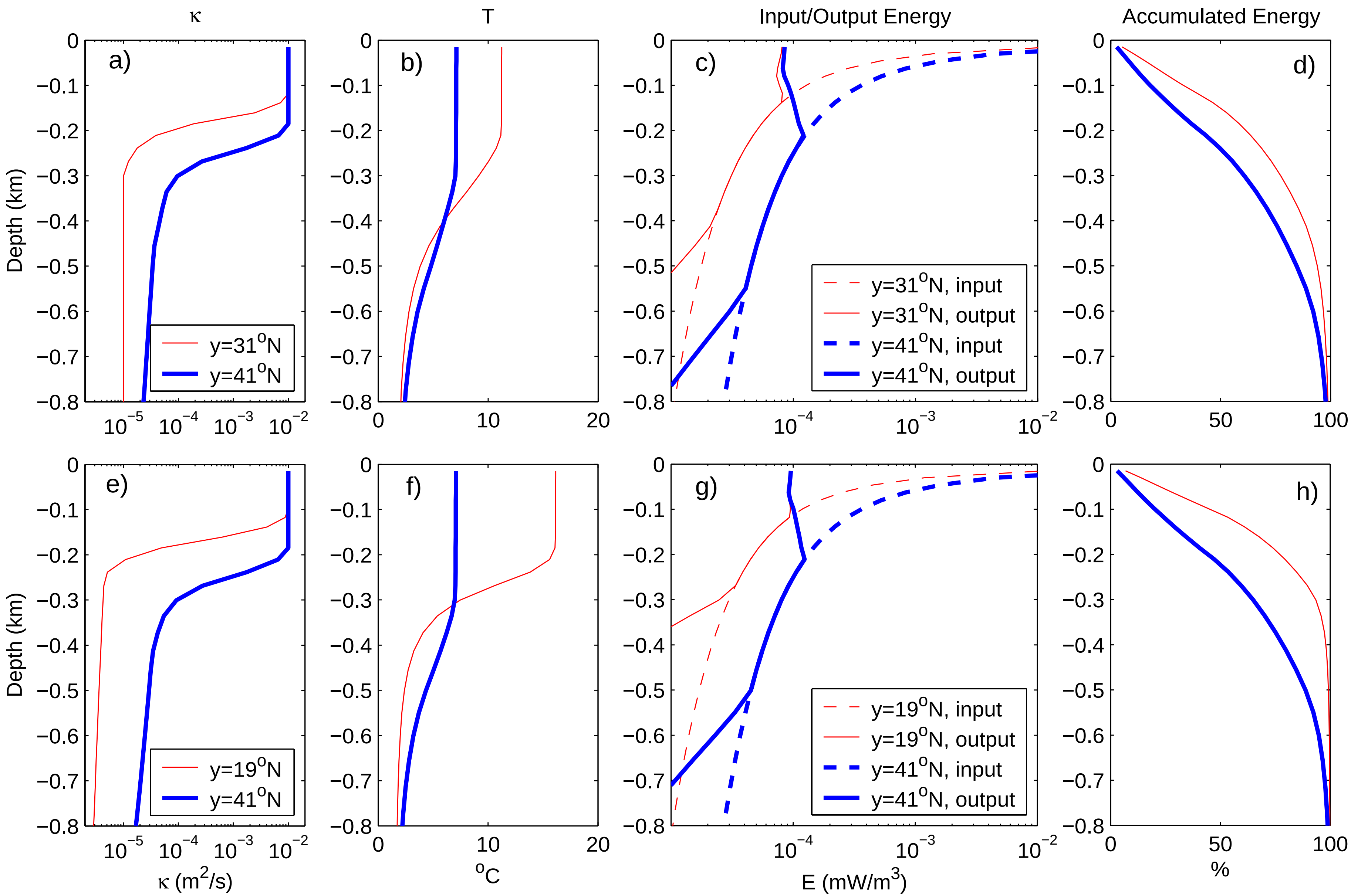
- For models that do not resolve the diurnal cycle of mixed layer, strong diffusion just below the base of the mixed layer is needed in order to simulate the dynamic effect of surface wave enhanced turbulence in the upper ocean.

Result from Set 3

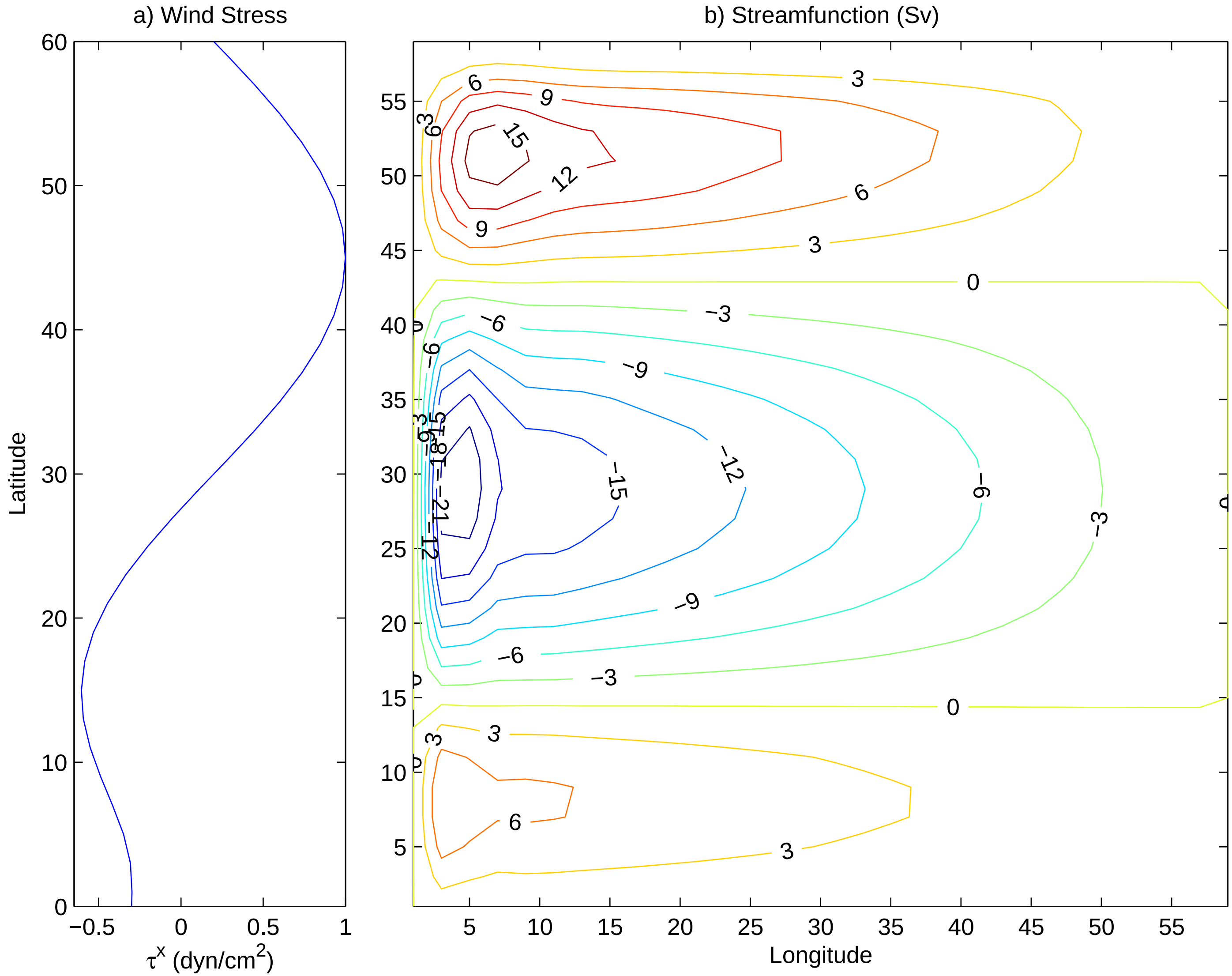
	K_0 ($10^{-4} m^2/s$)	MOR (Sv)	PHF (PW)	KE (TJ)	GPE Balance (GW)				
					PE -> KE	CA	Vertical Mixing		
							Background	Enhanced	Total
A2	0.02	3.20	0.022	62	0.09	1.31	1.43	0.0	1.43
W2	0.02	11.62	0.091	1189	1.76	18.62	1.77	18.63	20.40
WW2	0.02	17.00	0.330	10740	-14.40	41.77	3.82	23.55	27.37
A1	0.1	8.50	0.063	383	0.65	6.17	6.96	0.0	6.96
W1	0.1	12.68	0.110	1285	2.09	12.68	6.67	16.85	23.52
WW1	0.1	16.88	0.333	10920	-14.35	42.30	6.74	21.18	27.92

Table 4. Basic values for Set III, compared with A1 and A2; see caption of Table 2. W1 and W2 include wave breaking; WW1 and WW2 include both wave breaking and wind forcing.

Energy balance of the model ocean



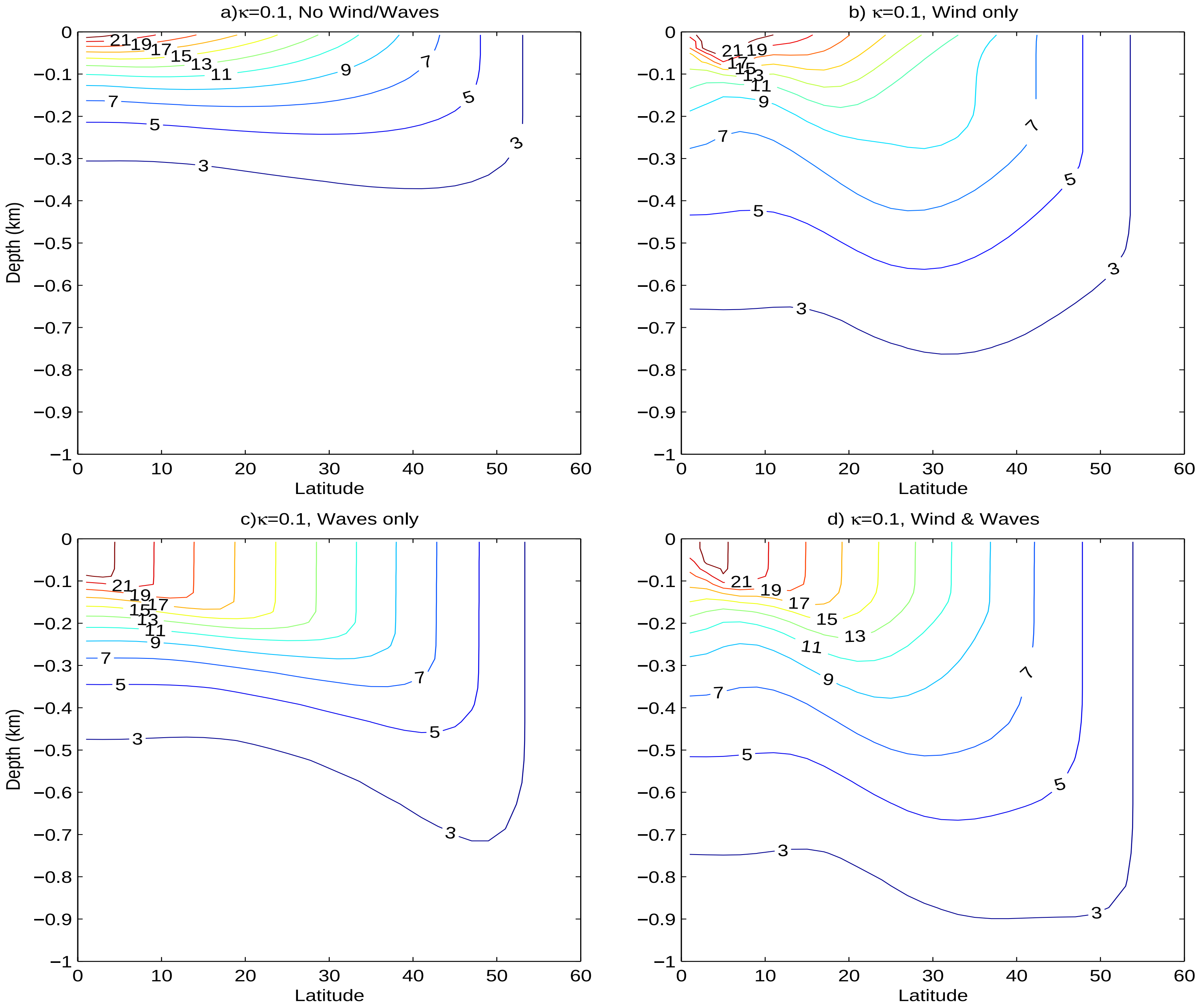
IV. B. How does wind stress change the dynamical picture?



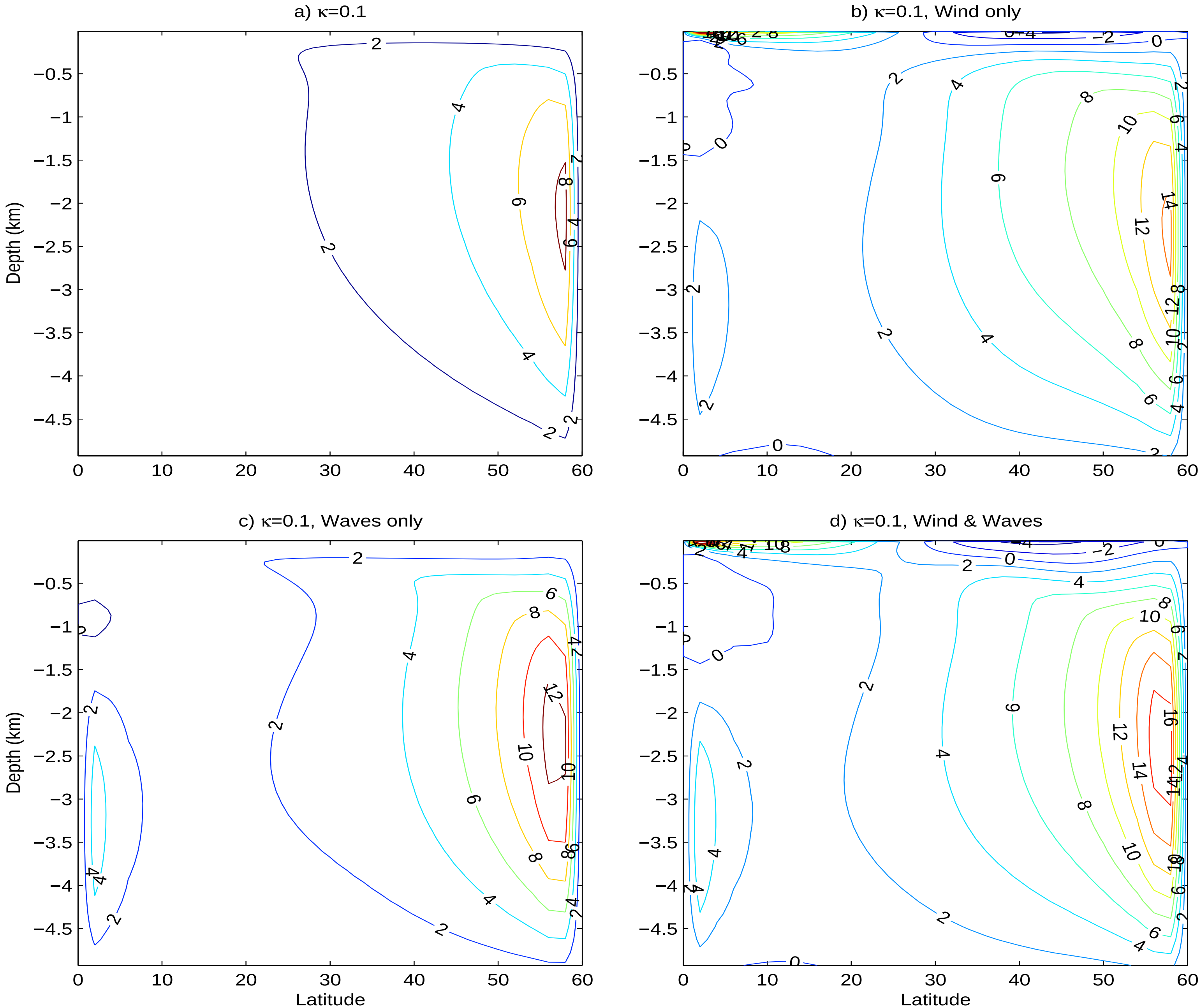
How does adding on the wind stress modify the dynamical picture?

- Introducing the wind-driven gyres modifies stratification in the upper ocean, and thus enhances the generation of GPE through mixing.
- Other processes, such as the seasonal cycle and the diurnal cycle of the mixed layer can also help to maintain a strong stratification in the ocean, and thus gives rise to a large source of GPE generated by wave enhanced turbulence dissipation.

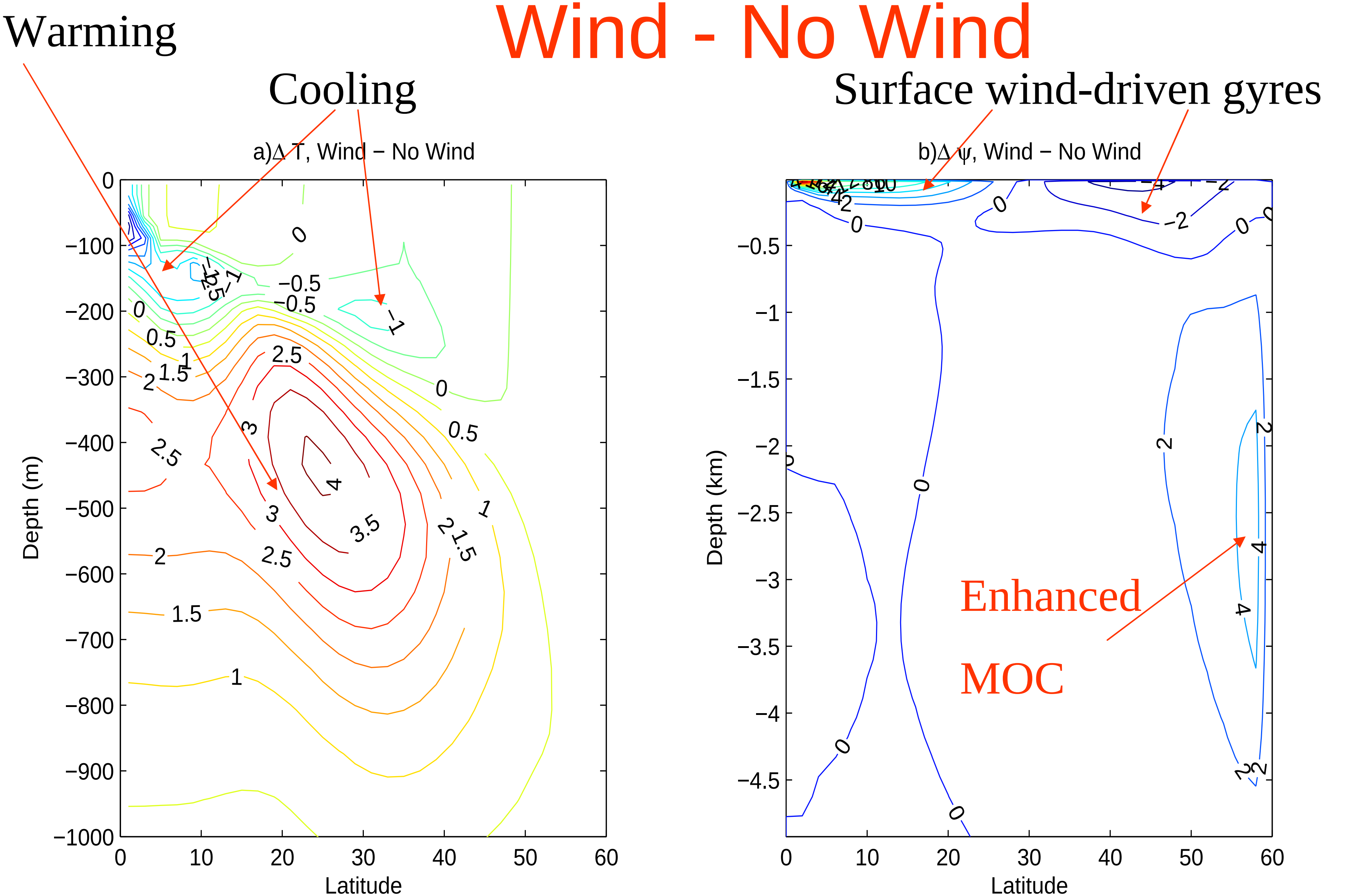
Temperature sections



Overturning streamfunction

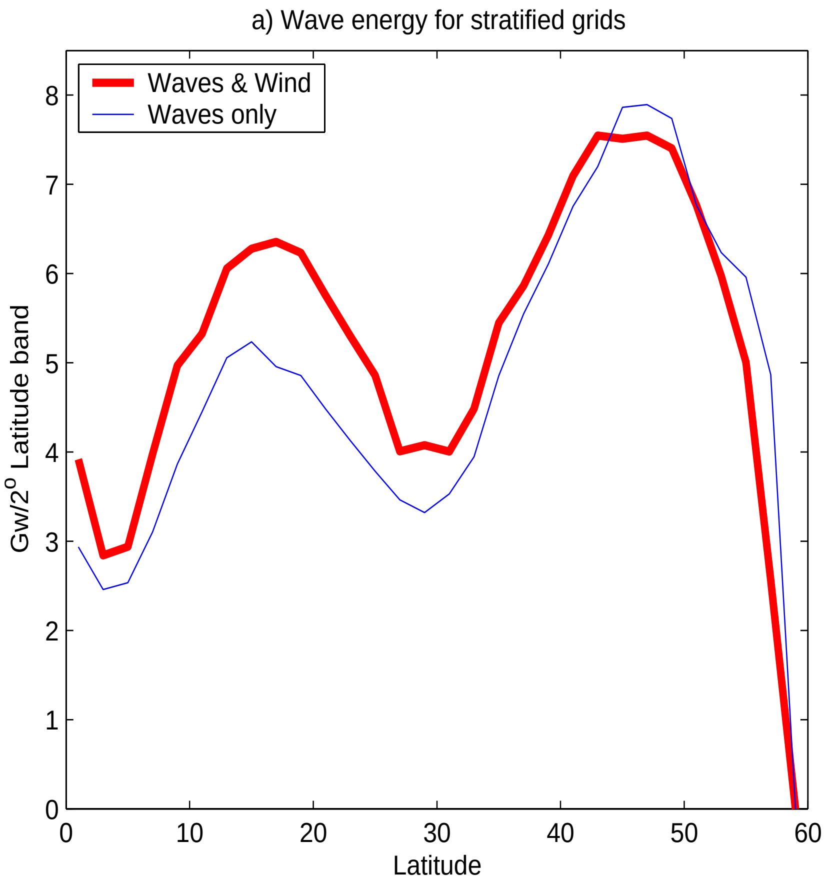


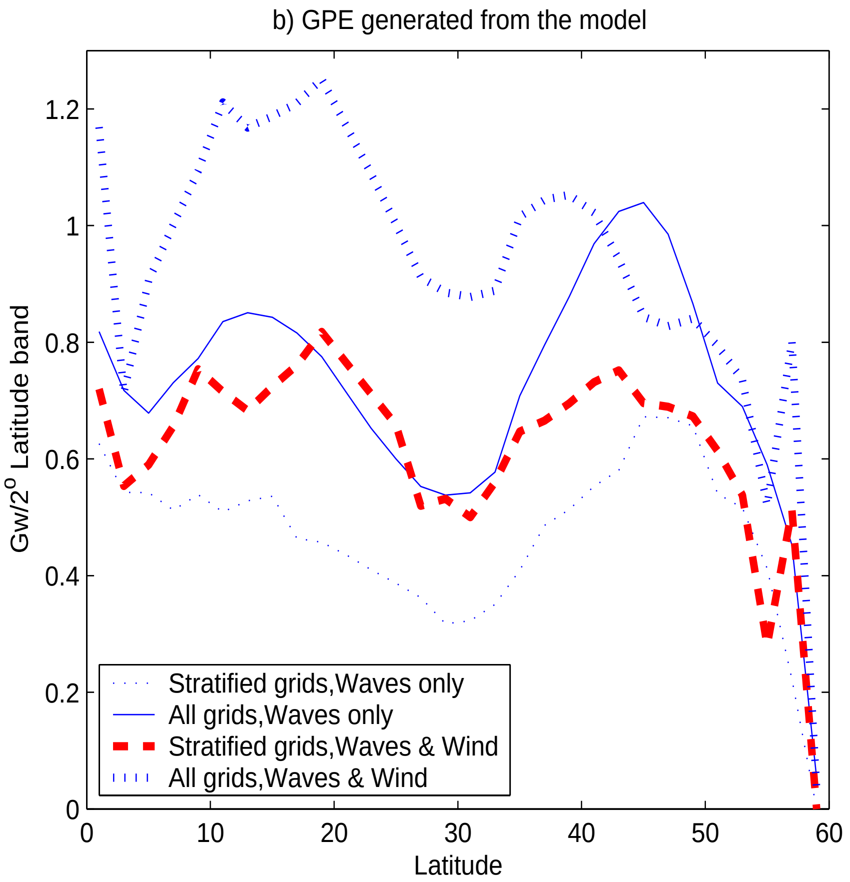
Diff. in Temp & MOC, with wave Wind - No Wind

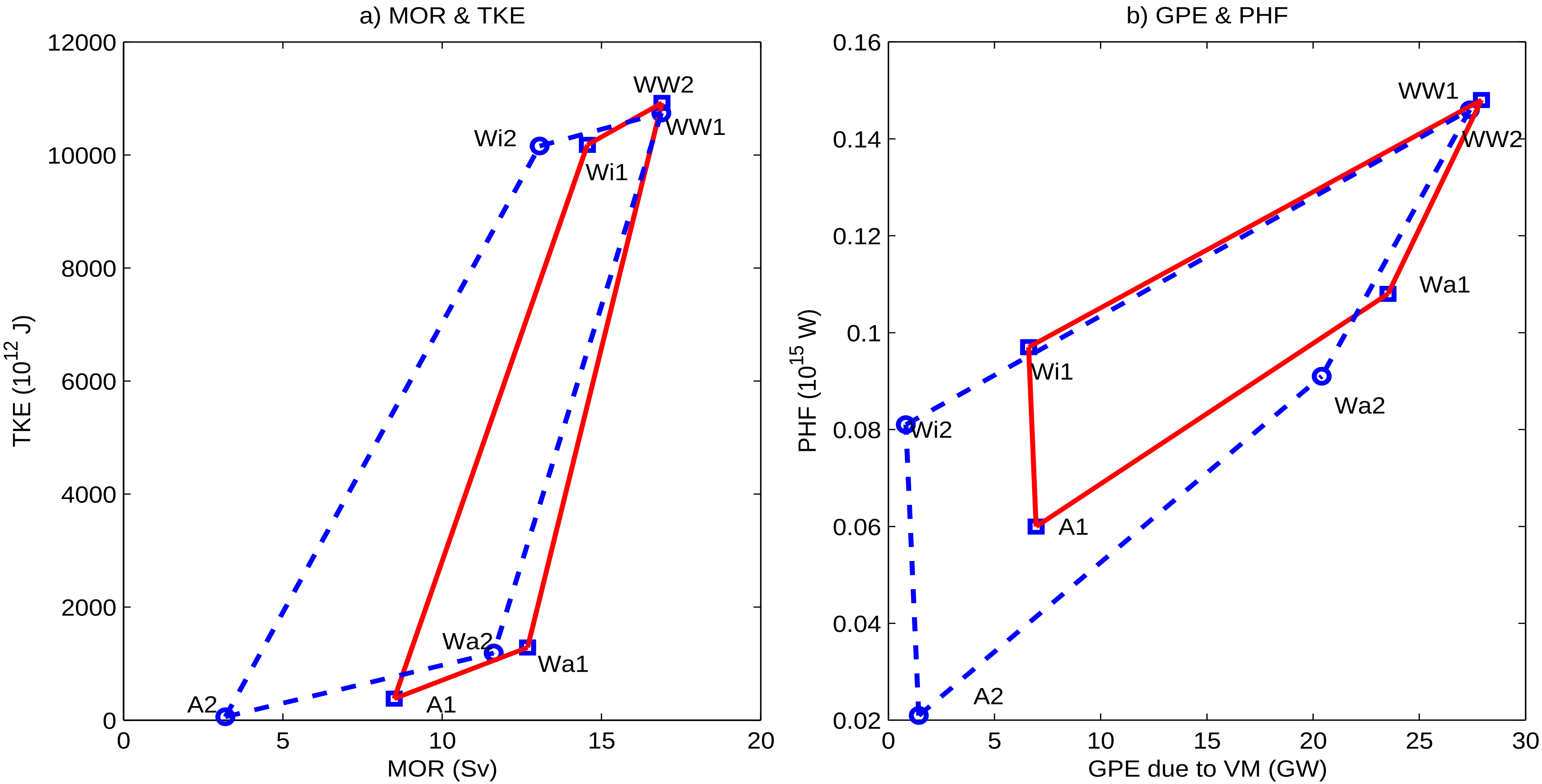


GPE balance, with/without wind

Enhanced GPE usable and generated from the model






a) MOR & TKE
TKE (10^{12} J)
MOR (Sv)
12000
10000
8000
6000
4000
2000
0
0
5
10
15
20
WW2
WW1
Wi2
Wi1
Wa2
Wa1
A2
A1
b) GPE & PHF
PHF (10^{15} W)
GPE due to VM (GW)
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
5
10
15
20
25
30
WW1
WW2
Wa1
Wi1
Wa2
Wi2
A1
A2

Conclusion:

- Wind energy input through surface waves may be one of the most important unknowns
- Relatively weak stratification in combination of strong stirring in the upper ocean may produce large amount of GPE
- Surface wave enhanced turbulence may be one of the most important source of GPE driving THC
- Parameterizing wave enhanced turbulence is an important aspect of OGCM
- Including the seasonal/diurnal cycles may substantially increase the source/sink of GPE