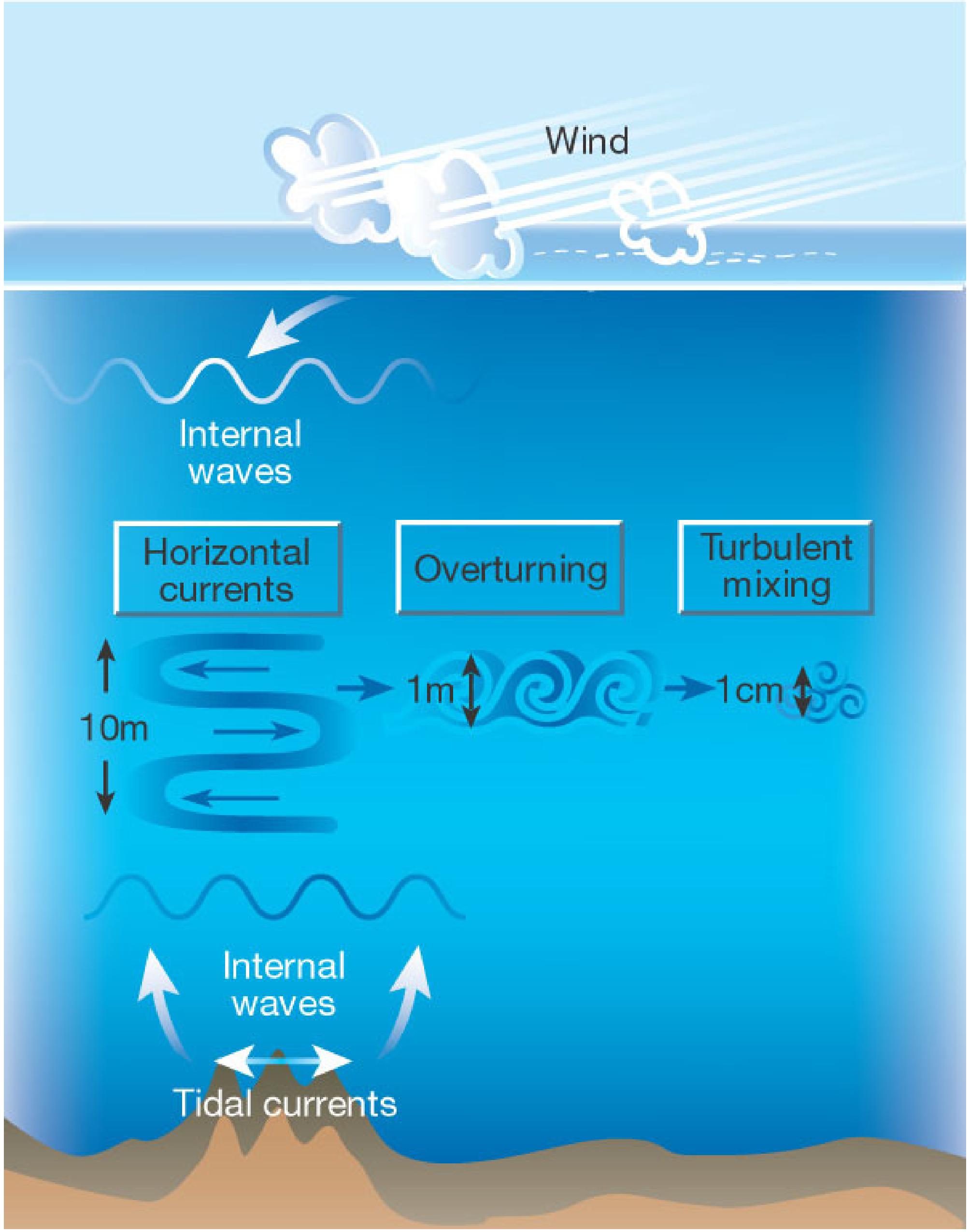
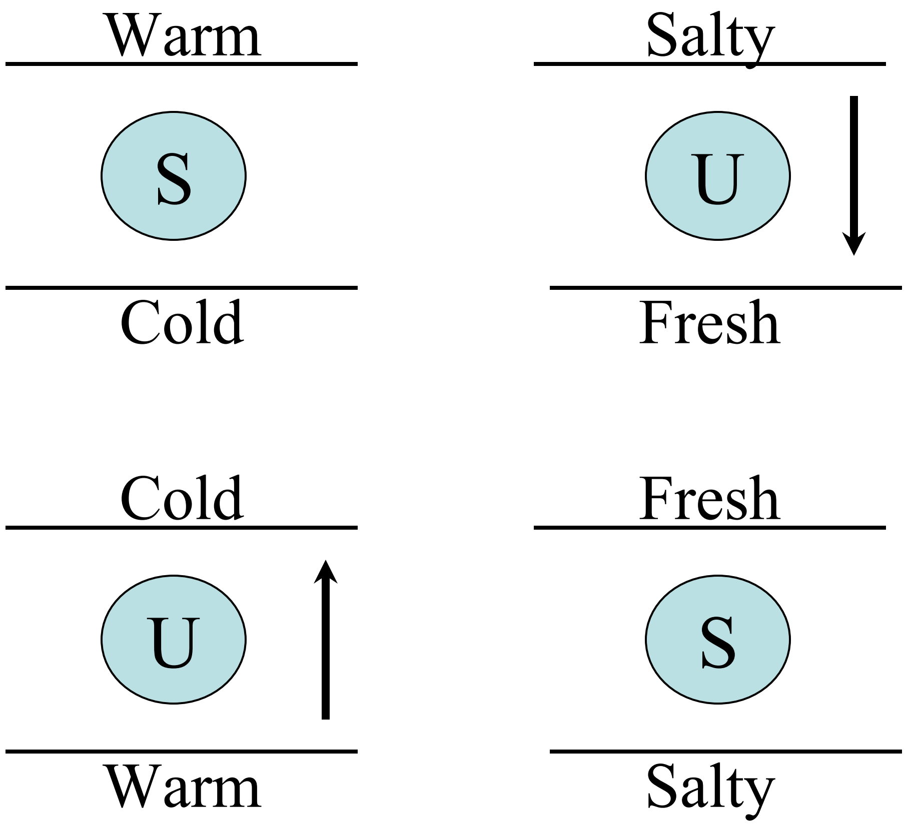


Tidal flow hits topography

=> internal waves
=> dissipation of the energy carried by those waves
=> mixing

[Garrett, Nature 2003]

Double Diffusion



SF (Med.)

DC (water/ice)

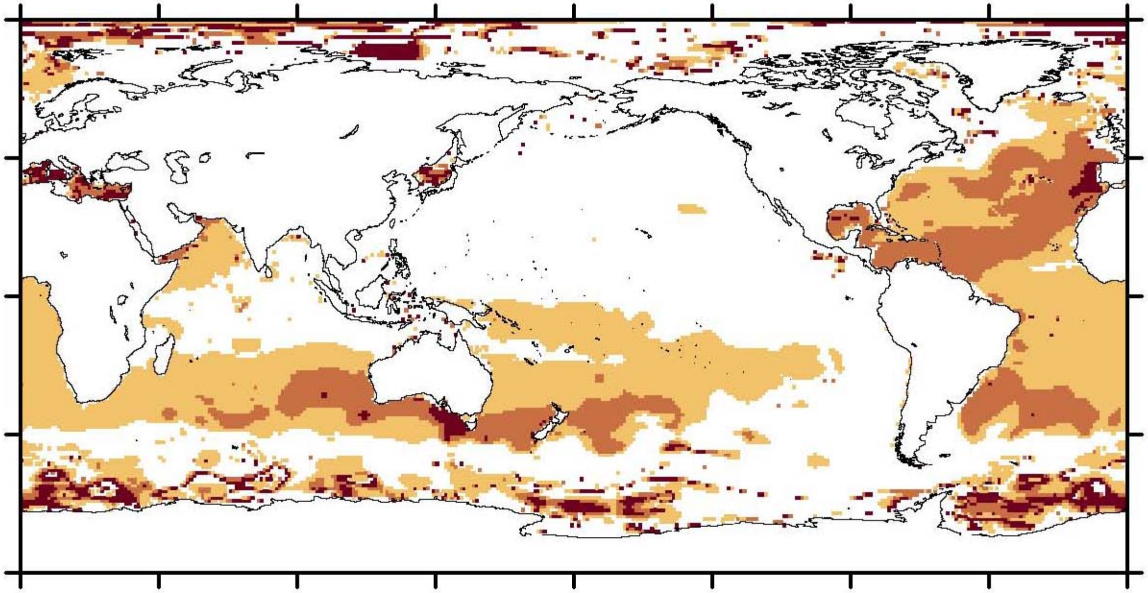
$$R_\rho = \frac{\alpha_S \partial S/\partial z}{\alpha_T \partial T/\partial z}, \qquad \gamma = \frac{\alpha_T \overline{w\theta}}{\alpha_S \overline{ws}}$$

SF: $R_\rho < 1; \quad \gamma < 1$

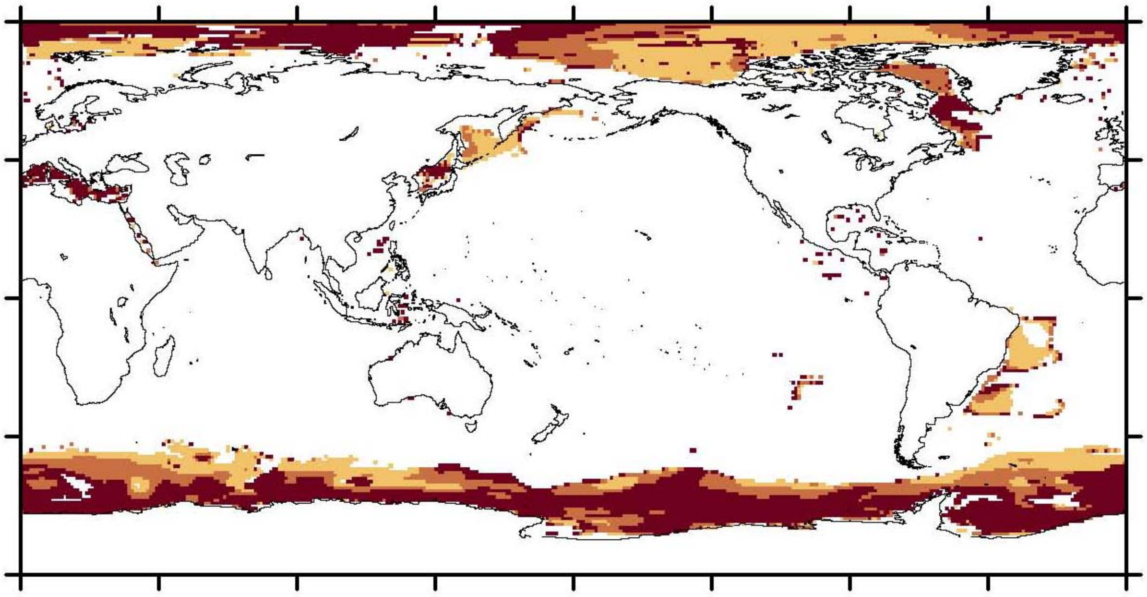
DC: $R_\rho > 1; \quad \gamma > 1$

Double Diffusion SF, DC

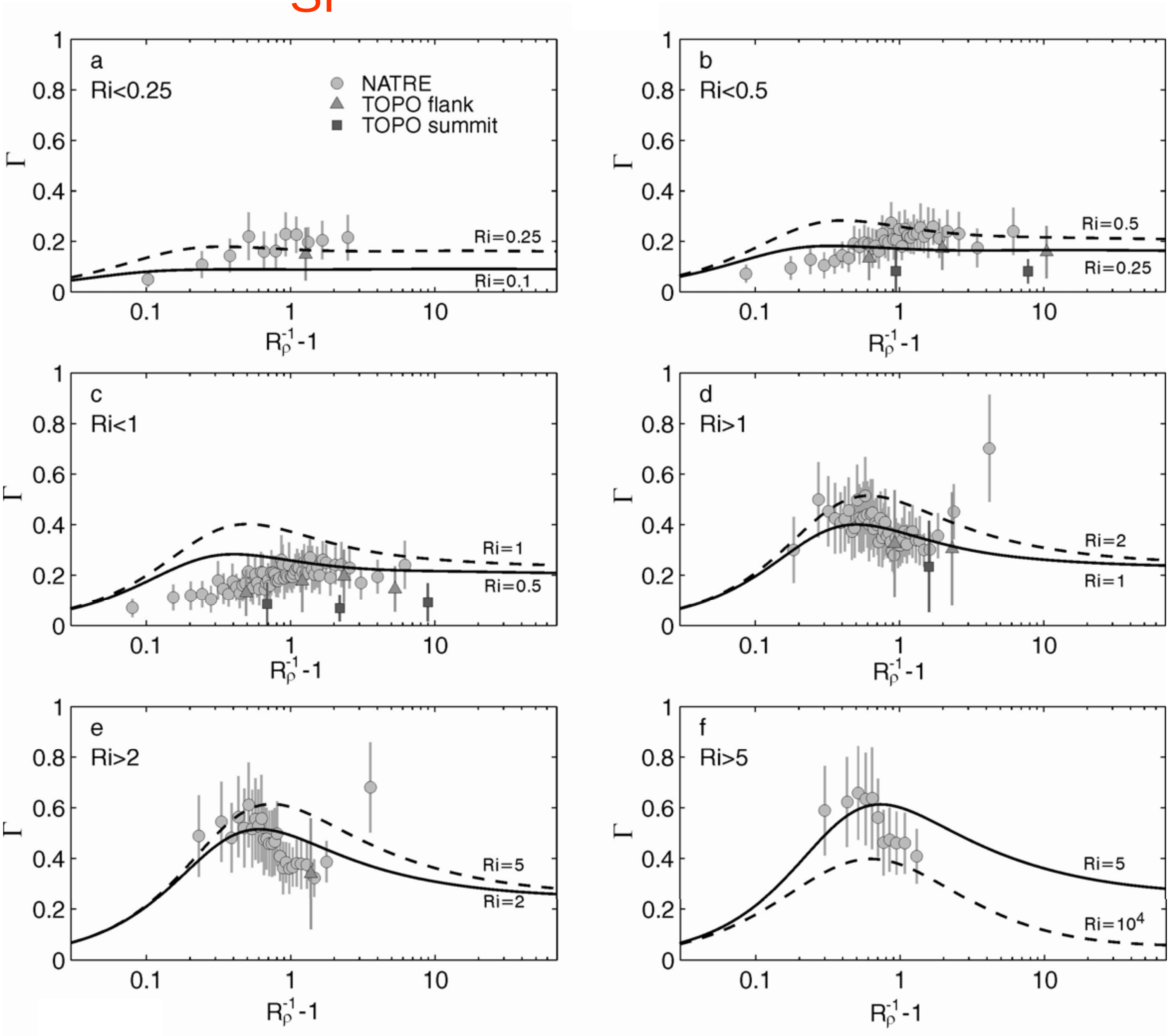
SF



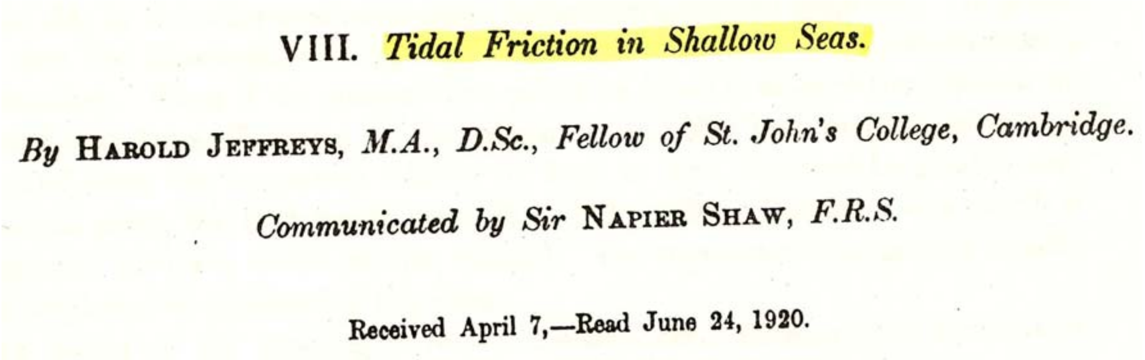
DC



SF



a
Ri<0.25
NATRE
TOPO flank
TOPO summit
Ri=0.25
Ri=0.1
b
Ri<0.5
Ri=0.5
Ri=0.25
c
Ri<1
Ri=1
Ri=0.5
d
Ri>1
Ri=2
Ri=1
e
Ri>2
Ri=5
Ri=2
f
Ri>5
Ri=5
Ri=10^4
Γ
$R_\rho^{-1}-1$

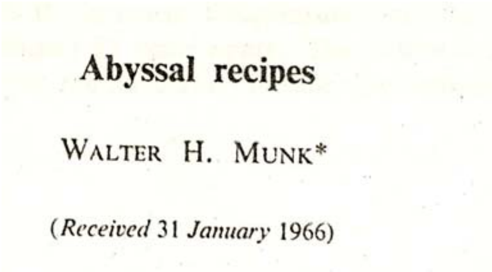
- 

VIII. *Tidal Friction in Shallow Seas.*

By HAROLD JEFFREYS, *M.A.*, *D.Sc.*, *Fellow of St. John's College, Cambridge.*

Communicated by Sir NAPIER SHAW, *F.R.S.*

Received April 7,—Read June 24, 1920.

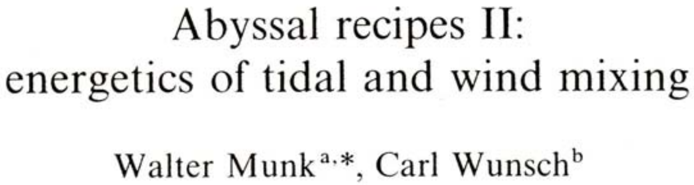
- 

Abyssal recipes

WALTER H. MUNK*

(*Received* 31 *January* 1966)

Deep See Res., 1966

- 

Abyssal recipes II:
energetics of tidal and wind mixing

Walter Munk[a,*], Carl Wunsch[b]

Deep See Res., 1998

TIDES

A few decades ago the suggestion that the Moon played a role in determining global ocean properties was considered lunatic; now it is considered obvious (Wunsch and Munk were more comfortable working in the earlier times).

(Munk and Bills, 2007, JPO)

$$\dot{E} = \frac{\partial}{\partial t}\frac{1}{2} I\Omega^2 \Rightarrow \mathbf{3.5TW}$$

$$E=\frac{1}{2}I\Omega^2$$

$$\frac{dE}{dt}=I\Omega\dot{\Omega}$$

$$\dot{\Omega}\rightarrow \text{astronomical data}$$

$$\varepsilon \simeq 3\text{TW}$$

Significant dissipation of tidal energy in the deep ocean inferred from satellite altimeter data

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How and where the ocean tides dissipate their energy are long-standing questions[1] that have consequences ranging from the history of the Moon[2] to the mixing of the oceans[3]. Historically, the principal sink of tidal energy has been thought to be bottom friction in shallow seas[4,5]. There has long been suggestive evidence[6,7], however, that tidal dissipation also occurs in the open ocean through the scattering by ocean-bottom topography of surface tides into internal waves, but estimates of the magnitude of this possible sink have varied widely[3,8–11]. Here we use satellite altimeter data from Topex/Poseidon to map empirically the tidal energy dissipation. We show that approximately 10^{12} watts—that is, 1 TW, representing 25–30% of the total dissipation—occurs in the deep ocean, generally near areas of rough topography. Of the estimated 2 TW of mixing energy required to maintain the large-scale thermohaline circulation of the ocean[12], one-half could therefore be provided by the tides, with the other half coming from action[13] on the surface of the ocean.

Vertical mixing rates in the deep ocean implied by ocean microsctructure[14] and tracer-release data[15] are typically an order of magnitude too small to balance the rate at which dense bottom

Here ζ is the tidal elevation; **U** is the volume transport vector, equal to velocity times water depth H; **f** is the Coriolis parameter (oriented to the local vertical), and F is a generic frictional or dissipative stress. The forcing is specified through an equilibrium tide ζ_{EQ}, which must allow for the Earth's body tide[21], and an equilibrium-like 'tide' ζ_{SAL} which is induced by the tide's self-attraction and loading[22].

Equations (1) and (2) may be combined and averaged over time to obtain an expression for the local balance between work rate, W, energy flux, **P**, and dissipation rate, D:

$$W - \nabla \cdot \mathbf{P} = D \quad (3)$$

A number of different explicit forms for this balance appear in the literature[21,23], reflecting various groupings of terms, and different definitions for work and flux (as well as omission of supposed secondary terms like self-attraction). Here we adopt simple expressions for these terms based directly on equations (1) and (2):

$$\mathbf{P} = \rho g \langle \mathbf{U}\zeta \rangle \quad W = \rho g \langle \mathbf{U} \cdot \nabla(\zeta_{EQ} + \zeta_{SAL}) \rangle \quad (4)$$

where the brackets $\langle\rangle$ denote time averages, ρ is mean seawater density and g is gravitational acceleration. Note that W represents the mean rate of working on the ocean of all tidal gravitational forces (including self-attraction forces) and of the moving ocean bottom.

Topex/Poseidon altimeter data provide a direct constraint on tidal elevations ζ, and a number of nearly global maps are now

Table 1 Partition of M_2 energy dissipation (in terawatts) between shallow seas and the deep ocean

	TPXO.4a	GOT99hf	TPXO.4b	TPXO.4c	GOT99nf	Prior	Error
Shallow seas	1.60	1.71	1.61	1.62	1.87	1.96	0.06
Deep ocean	0.83	0.74	0.82	0.81	0.57	0.06	0.06
Total	2.44	2.45	2.43	2.43	2.44	2.02	0.01

Results (in TW) are presented for the five empirical estimates discussed in the text, and for the purely hydrodynamic solution used as the prior model for the assimilation. Error bars[28] are for the assimilation solution TPXO.4a. Here shallow seas are defined to include all ocean areas landward of the thin line in Fig. 1b.

	Drag	*Internal tides*	*Total*
Shallow Seas	**1.49**	**0.98**	**2.47**
Deep Ocean	**0.01**	**1**	**1.02**
Total	**1.51**	**1.98**	**3.5**

T/P

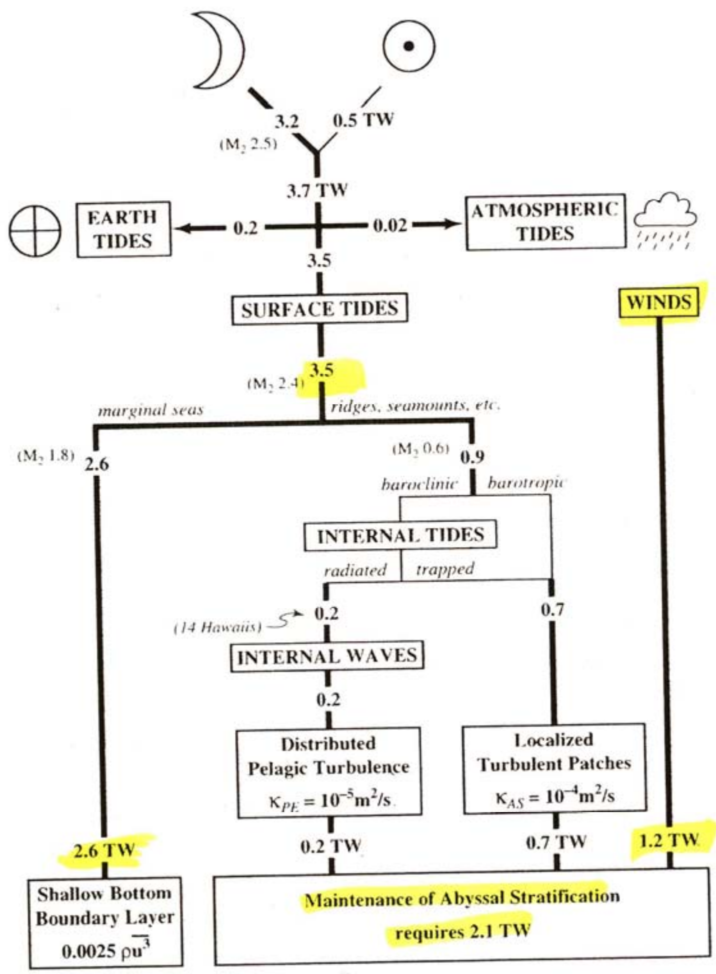


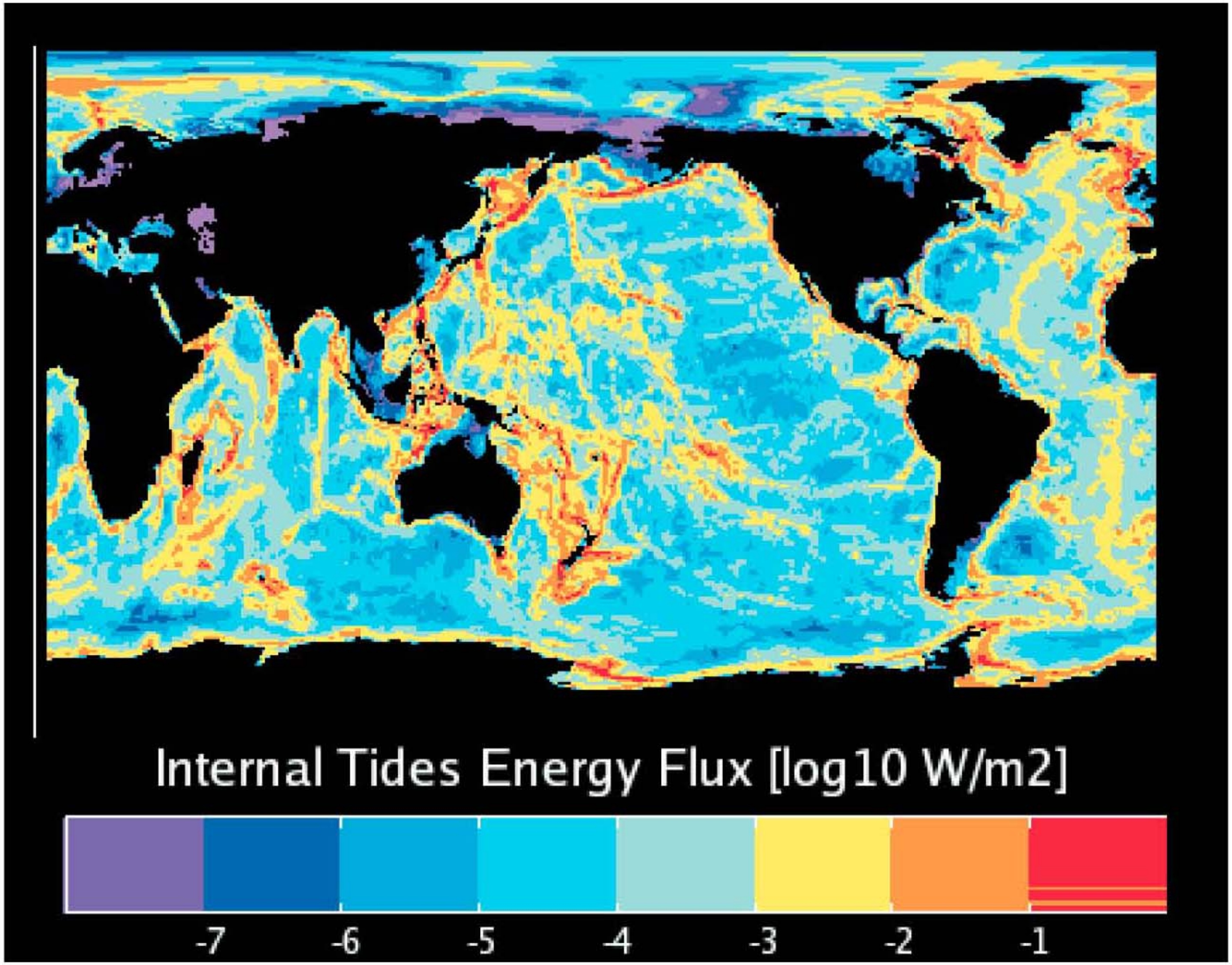
Fig. 4. An impressionistic budget of tidal energy flux. The traditional sink is in the bottom boundary layer (BBL) of marginal seas. Preliminary results from Egbert (1997) based on TOPEX/-POSEIDON altimetry suggest that 0.9 TW (including 0.6 TW of M_2 energy) are scattered at open ocean ridges and seamounts. Light lines represent speculation with no observational support. "14 Hawaiis" refers to an attempted global extrapolation of surface to internal tide scattering measured at Hawaii, resulting in 0.2 TW available for internal wave generation. The wind energy input is estimated from Wunsch (1998), to which we have added 0.2 TW to balance the energy budget. This extra energy is identified as wind-generated internal waves — radiating into the abyss and contributing to mixing processes.

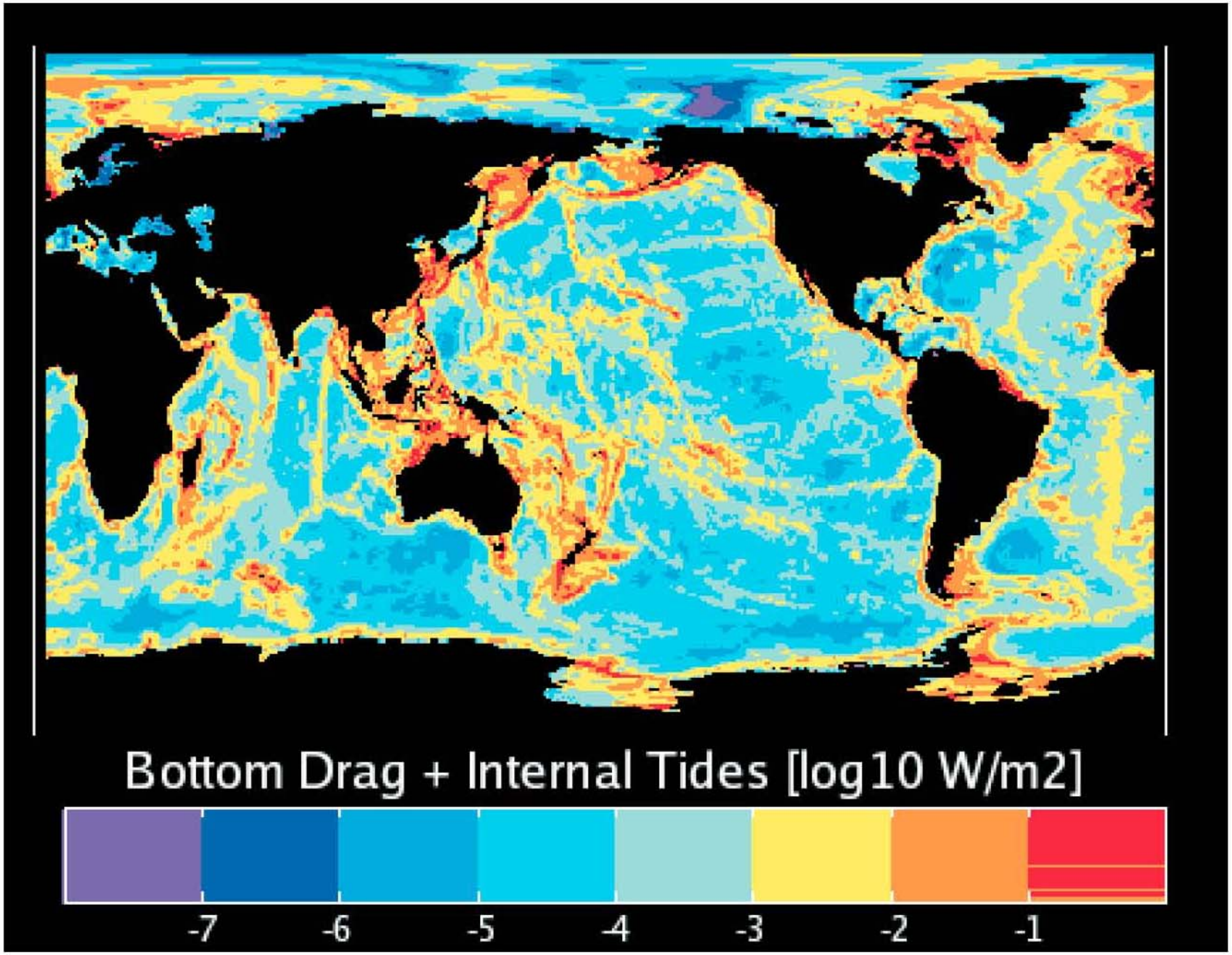
Internal tides are internal gravity waves generated in stratified waters by the interaction of barotropic tidal currents with variable bottom topography. They play a role in dissipating tidal energy and lead to mixing in the deep ocean.

Garrett and Kunze, 2007

$$\overline{u} \approx O(1) \text{ mm/sec}$$

$$u_{tides} \approx O(10) \text{ mm/sec}$$


Internal Tides Energy Flux [log10 W/m2]
-7
-6
-5
-4
-3
-2
-1


Bottom Drag + Internal Tides [log10 W/m2]
-7
-6
-5
-4
-3
-2
-1

INTERNAL TIDES

$$K = K_{bg} + K_t$$

$$K_t = \frac{\varepsilon_t}{N^2} \Gamma$$

Turbulence model

$$\varepsilon_t = qE(x,y)\rho_0^{-1}F(z)$$

?

Tidal model

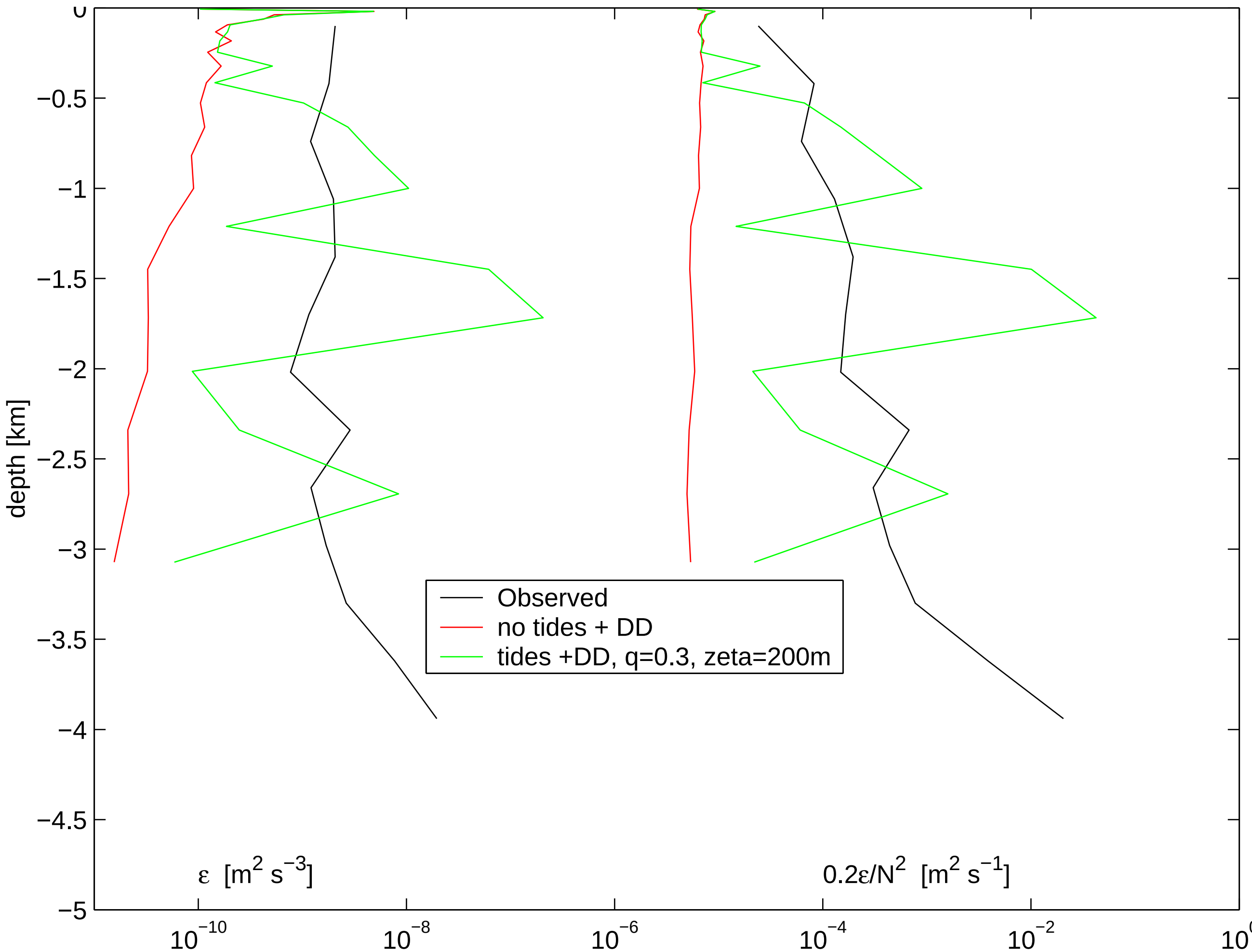
TIDAL DRAG

$$\tau_b = \overline{\mathbf{u}}\sqrt{\overline{\mathbf{u}}^2 + \mathbf{u}_t{}^2}$$

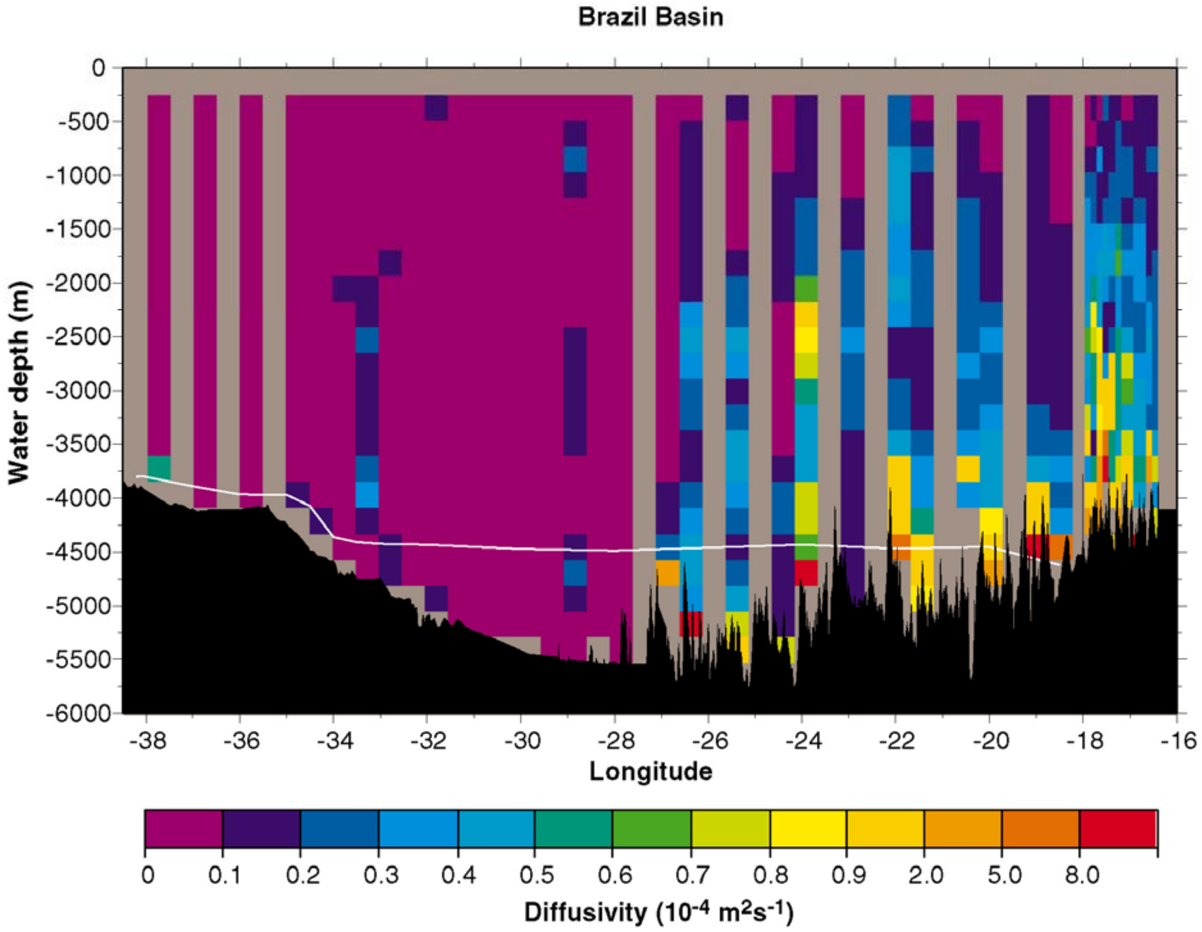
$$\Sigma^2 = \Sigma_{res}^2 + \Sigma_{unr}^2$$

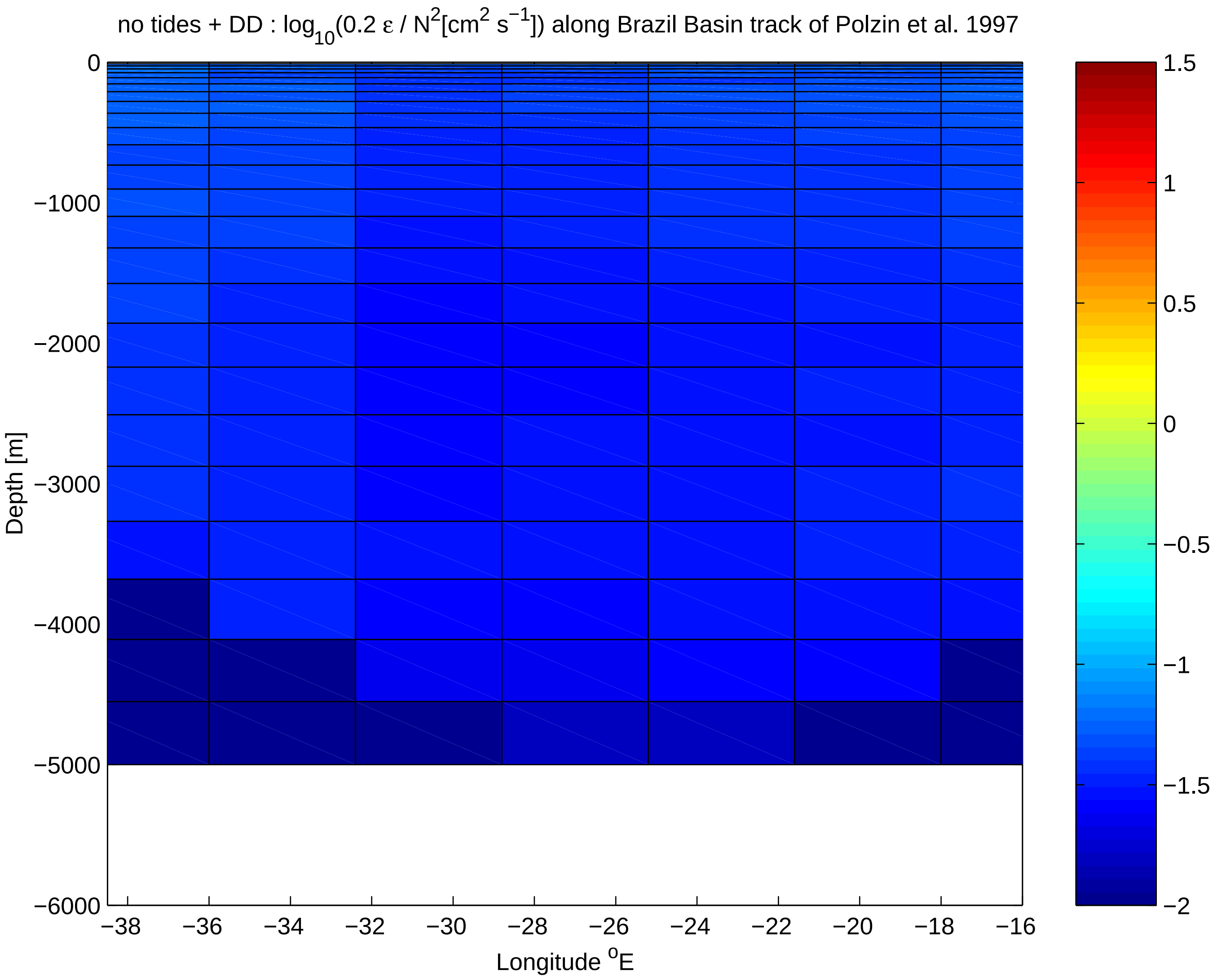
$$\Sigma_{unr} = \frac{u_*}{\kappa z}\Phi(z/L)$$

Section B Western Drake Passage (Garabato et al., 2004)

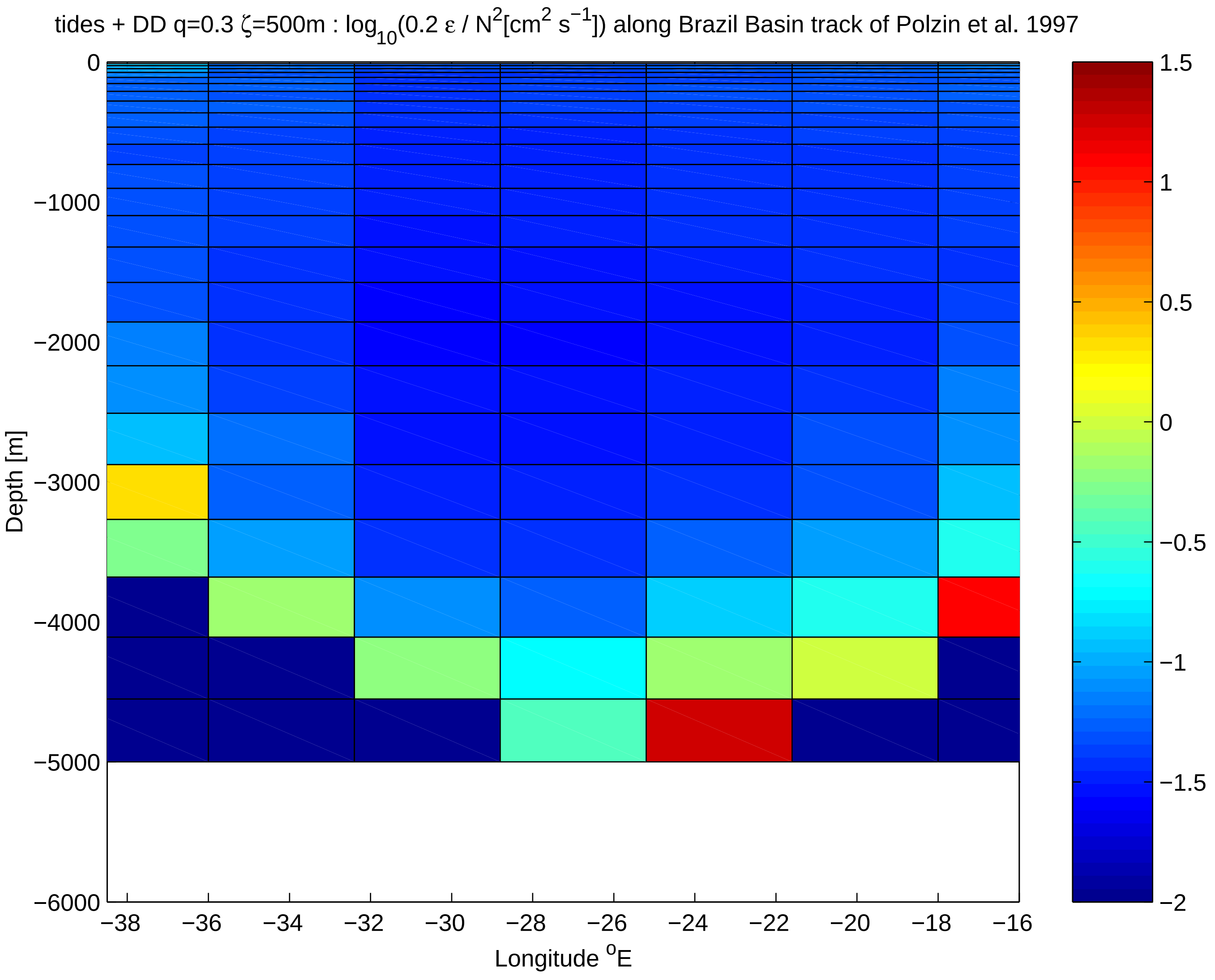


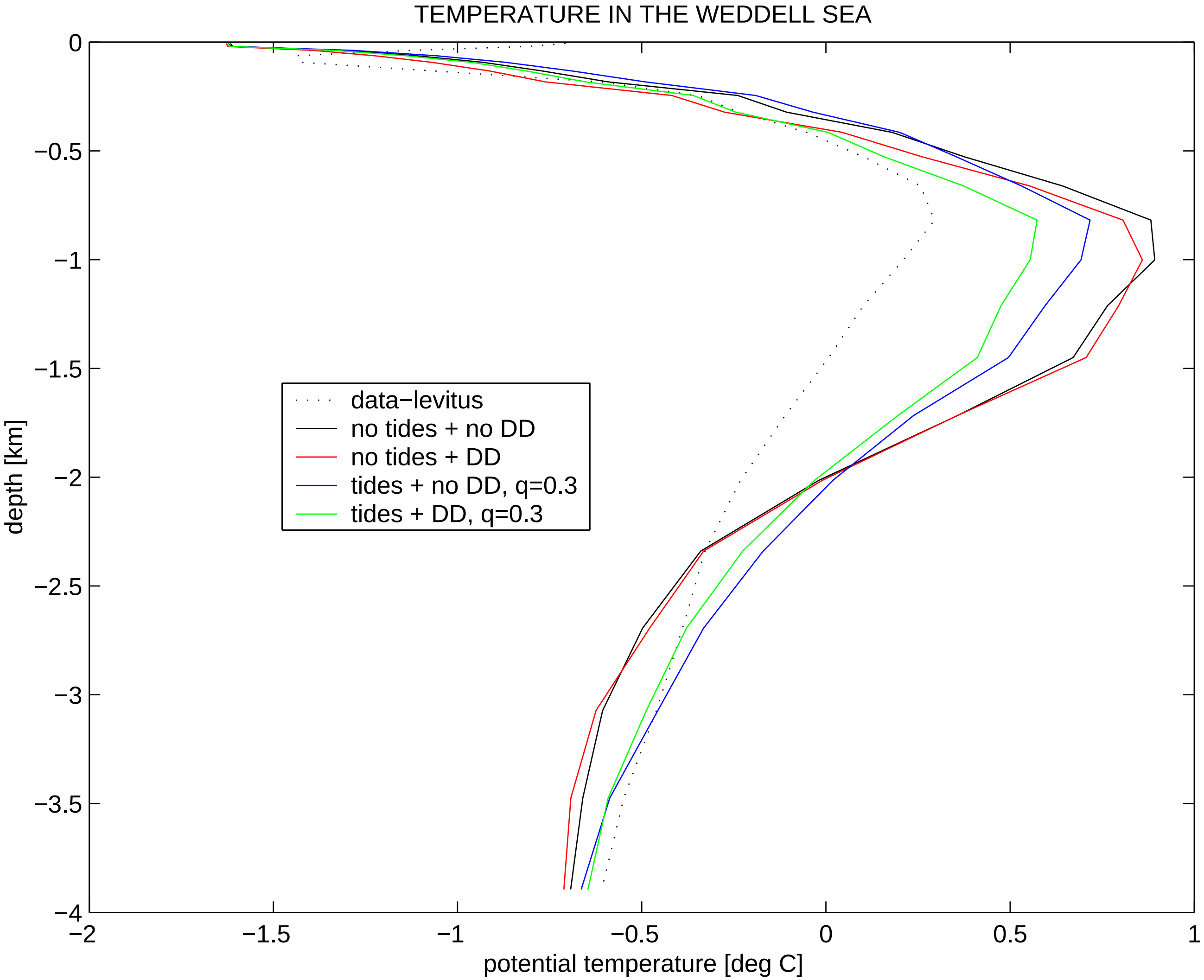
Brazil Basin, Polzin et al. (1997)

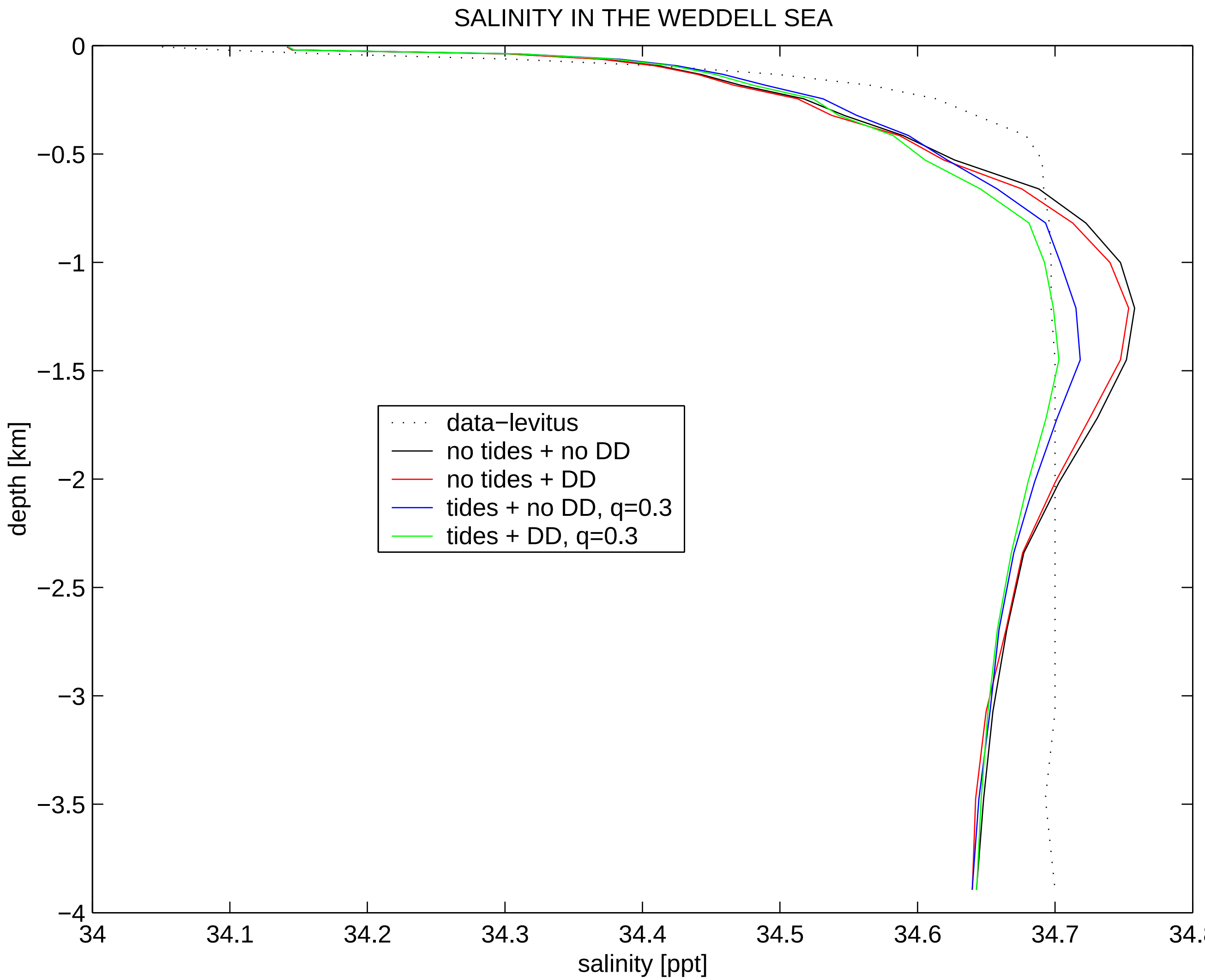


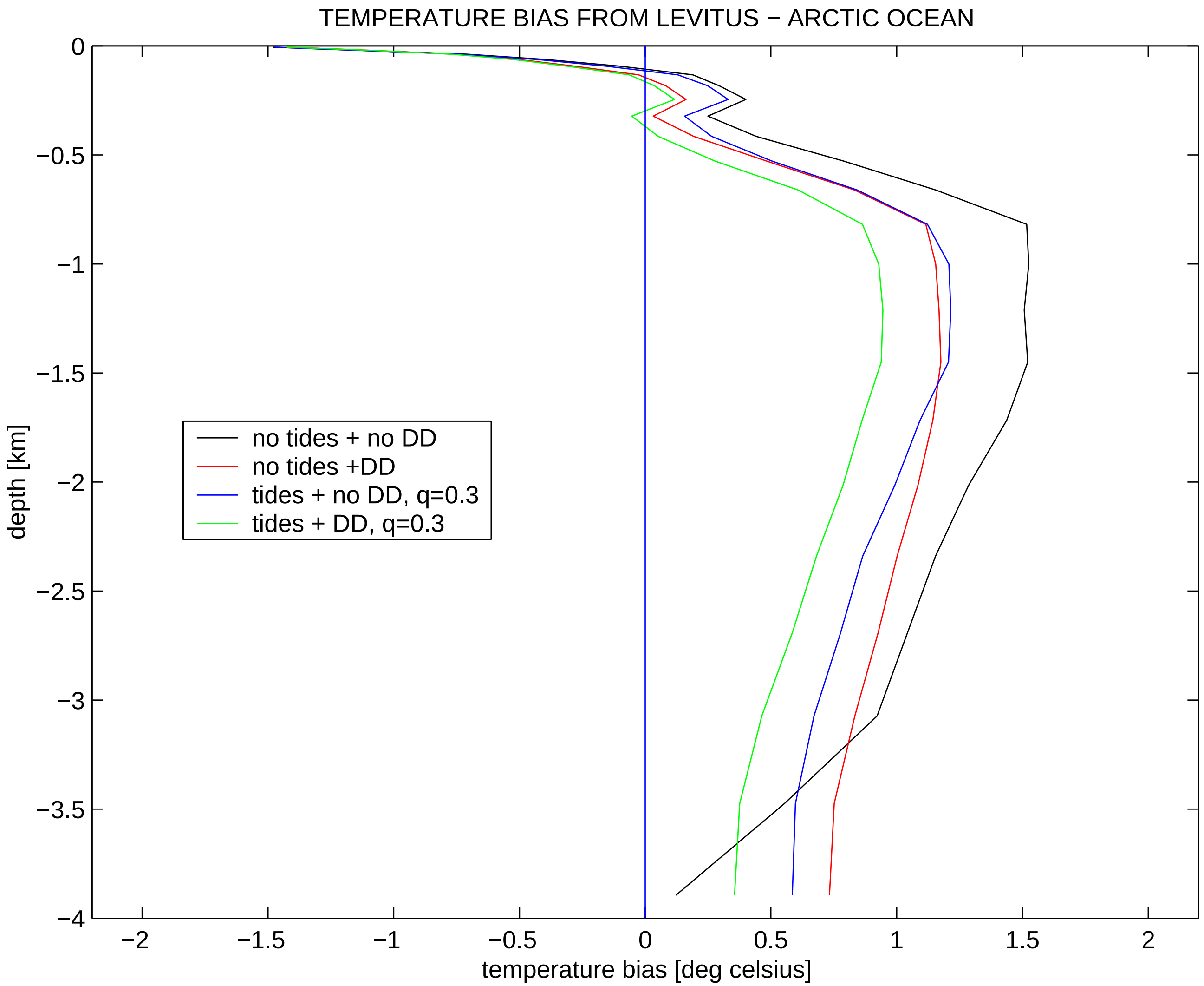


no tides + DD : log$_{10}$(0.2 ε / N^2[cm^2 s^{-1}]) along Brazil Basin track of Polzin et al. 1997
Depth [m]
0
−1000
−2000
−3000
−4000
−5000
−6000
−38
−36
−34
−32
−30
−28
−26
−24
−22
−20
−18
−16
Longitude ^{o}E
1.5
1
0.5
0
−0.5
−1
−1.5
−2

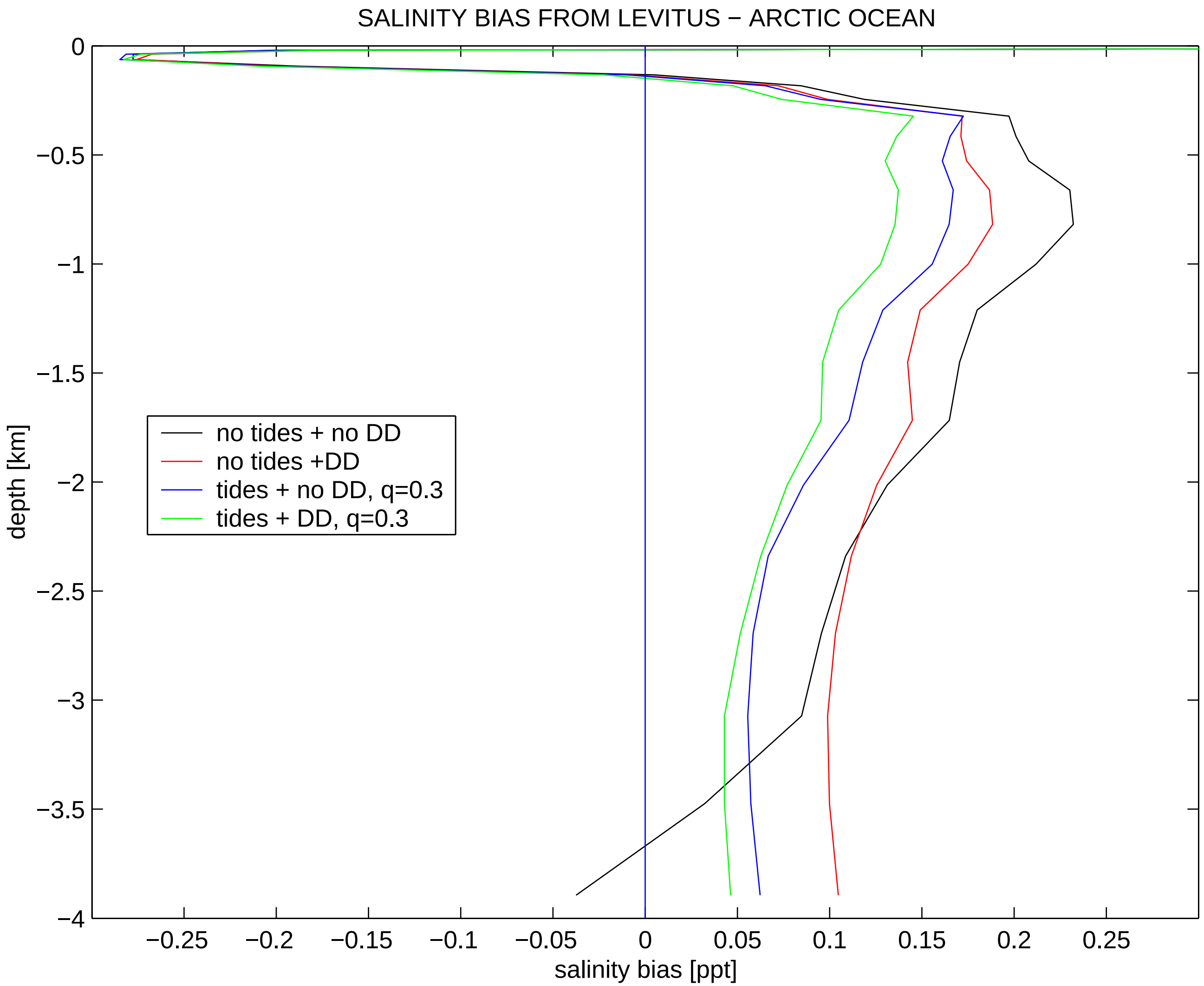

tides + DD q=0.3 ζ=500m : log10(0.2 ε / N2[cm2 s−1]) along Brazil Basin track of Polzin et al. 1997
Depth [m]
0
−1000
−2000
−3000
−4000
−5000
−6000
−38
−36
−34
−32
−30
−28
−26
−24
−22
−20
−18
−16
Longitude oE
1.5
1
0.5
0
−0.5
−1
−1.5
−2


TEMPERATURE IN THE WEDDELL SEA
depth [km]
potential temperature [deg C]
data−levitus
no tides + no DD
no tides + DD
tides + no DD, q=0.3
tides + DD, q=0.3
0
−0.5
−1
−1.5
−2
−2.5
−3
−3.5
−4
−2
−1.5
−1
−0.5
0
0.5
1


SALINITY IN THE WEDDELL SEA
0
−0.5
−1
−1.5
−2
−2.5
−3
−3.5
−4
depth [km]
34
34.1
34.2
34.3
34.4
34.5
34.6
34.7
34.8
salinity [ppt]
data−levitus
no tides + no DD
no tides + DD
tides + no DD, q=0.3
tides + DD, q=0.3



TEMPERATURE BIAS FROM LEVITUS − ARCTIC OCEAN
depth [km]
0
−0.5
−1
−1.5
−2
−2.5
−3
−3.5
−4
−2
−1.5
−1
−0.5
0
0.5
1
1.5
2
temperature bias [deg celsius]
no tides + no DD
no tides +DD
tides + no DD, q=0.3
tides + DD, q=0.3


SALINITY BIAS FROM LEVITUS − ARCTIC OCEAN
0
−0.5
−1
−1.5
−2
−2.5
−3
−3.5
−4
depth [km]
−0.25
−0.2
−0.15
−0.1
−0.05
0
0.05
0.1
0.15
0.2
0.25
salinity bias [ppt]
no tides + no DD
no tides +DD
tides + no DD, q=0.3
tides + DD, q=0.3

Mesoscale vertical flux versus vertical diffusion

----- Diffusion **----- Mesoscales** **------ D+M**