On the low latitude turbulent boundary current

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Introduction(1)

Strong western boundary currents (WBC) are conspicuous feature at low latitudes in the Atlantic and the Indian Ocean called the North Brazil Current and the Somali Current. Strong anticyclonic eddies are observed (Richardson et al. 1994, Schott and McCreay 2001, Wirth et al. 2001). In the equatorial Atlantic the trade winds are the major force. Whereas in the Indian Ocean the seasonally reversing Monsoon winds dominate.

The near boundary layer dynamics is a major source of turbulent kinetic energy production in the region.

There is sofar no description or theory of near wall turbulence, that goes beyond the anti-cyclonic eddies.

Shallow Water Model(2)

The basin is a rectangular box spanning from 1000km south of the equator to 3000km north of it.

Domain size:$L_y = 4000$km , $L_x = 6000$km; resolution: $\Delta x = \Delta y = 2.5$km ($7\Delta x <$ min(δ_M)), $\Delta t = 90$s ($10\Delta t < \Delta t_{CFL}$).

The equatorial β-plane geometry is used.

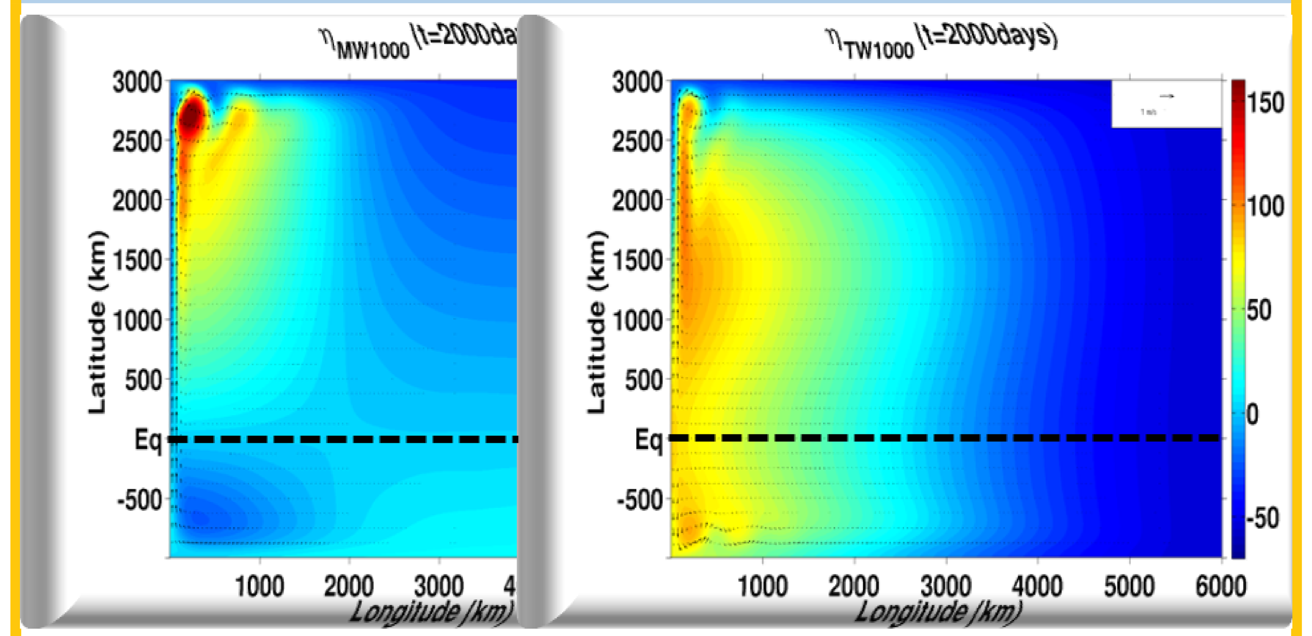
The numerical method is a centered, second-order finite difference scheme in space and second order Runge-Kutta. **No grid refinement.**

Model parameters

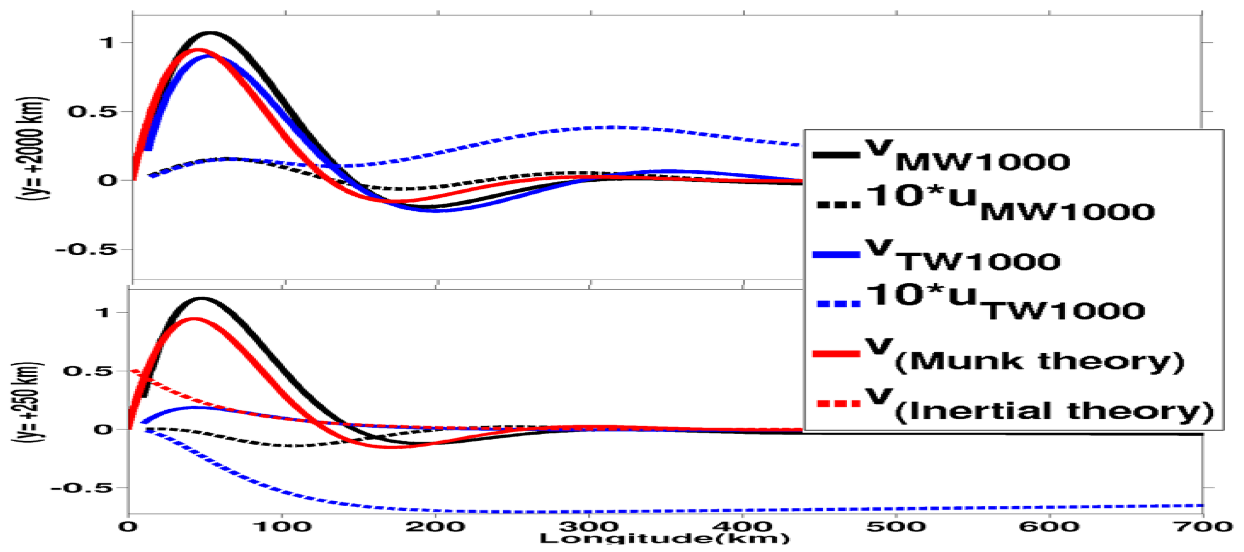
g'	β	H	ρ	Re
$0.03\mathrm{ms}^{-2}$	$2*10^{-11}\mathrm{m}^{-1}\mathrm{s}^{-1}$	200m	$1000\mathrm{kgm}^{-3}$	20-110

Idealize trade wind (TW) and monsoon wind (MW) forcing are used.

Linear Solutions(3)



- √ One anticyclonic gyre straddle the equator over the domain
- √ cross-equatorial WBC
- √ Relative small westward zonal velocity
- √ Two anticyclonic gyres in each hemisphere
- √ Two poleward WBCs
- √ Northern WBC is the centre of interest



- √ Fair agreement between Munk-layer theory ($v_M(x) = v_M^0 \exp(-x/2\delta_M)\sin(x\sqrt{3}/2\delta_M)$) and the MW1000, and the TW1000 at the higher latitude, where inertial effects vanish
- √ Inertial theory $v_I(x) = v_I^0 \exp(-x/\delta_I)$, where $\delta_I = \sqrt{-u_I(y)/\beta}$ (*Pedlosky* 1990) describes well TW1000 at the latitudes where u < 0
- √ Inertial effect alters completely the Munk-layer of TW1000
- √ **Dynamic difference between MW and TW due to the inertial effects.**

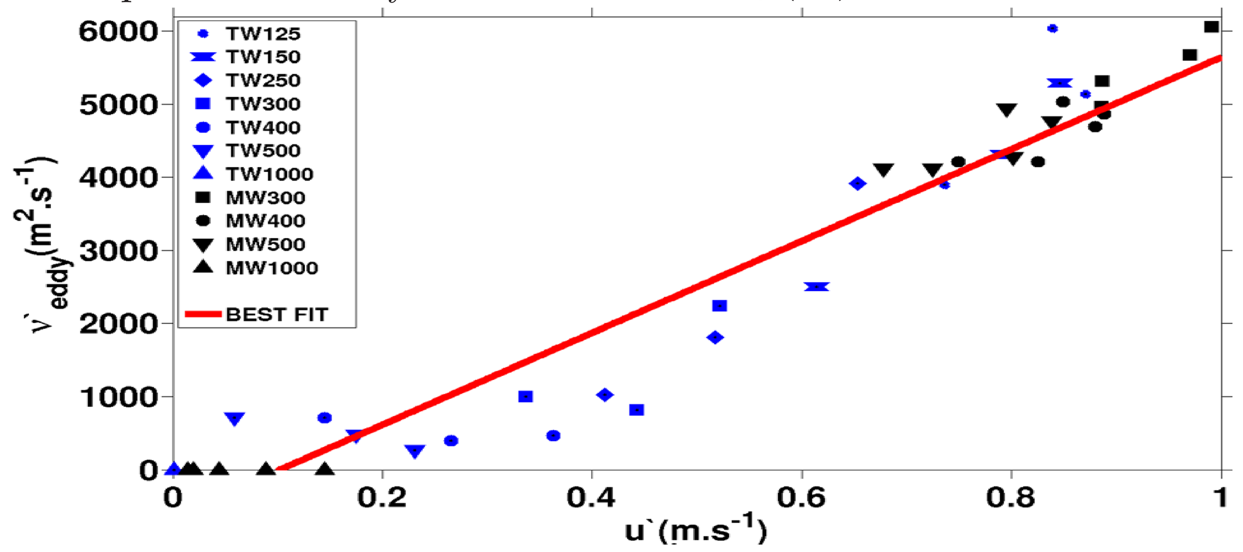
Eddy Viscosity via Munk Formula(4)

The stationary boundary v is close to the shape of the Munk-layer.

v vanishes at the distance $x_o = 2\pi\delta_M/\sqrt{3}$ from the boundary.

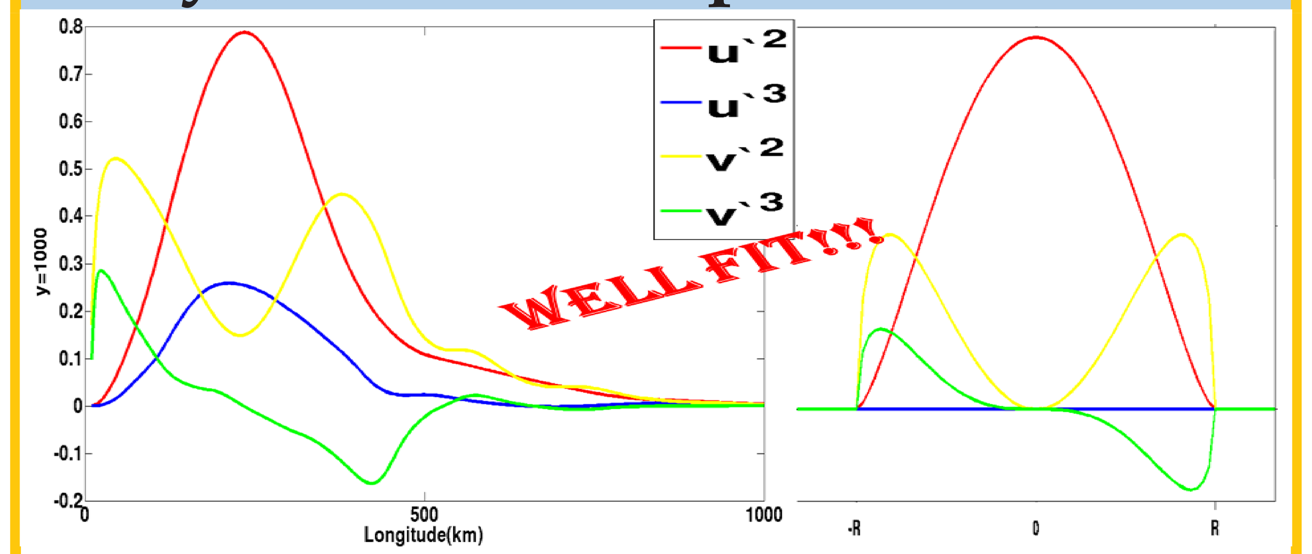
The eddy viscosity ν_{eddy} of the turbulent non-linear runs is estimated by $\nu_{eddy} = \left(\frac{x_0}{x_{0(stat)}}\right)^3 \nu_{stat}$, ν_{stat} is a viscosity of stationary flow.

Scatterplot of $\nu_{eddy} - \nu = f(u')$ is shown below:

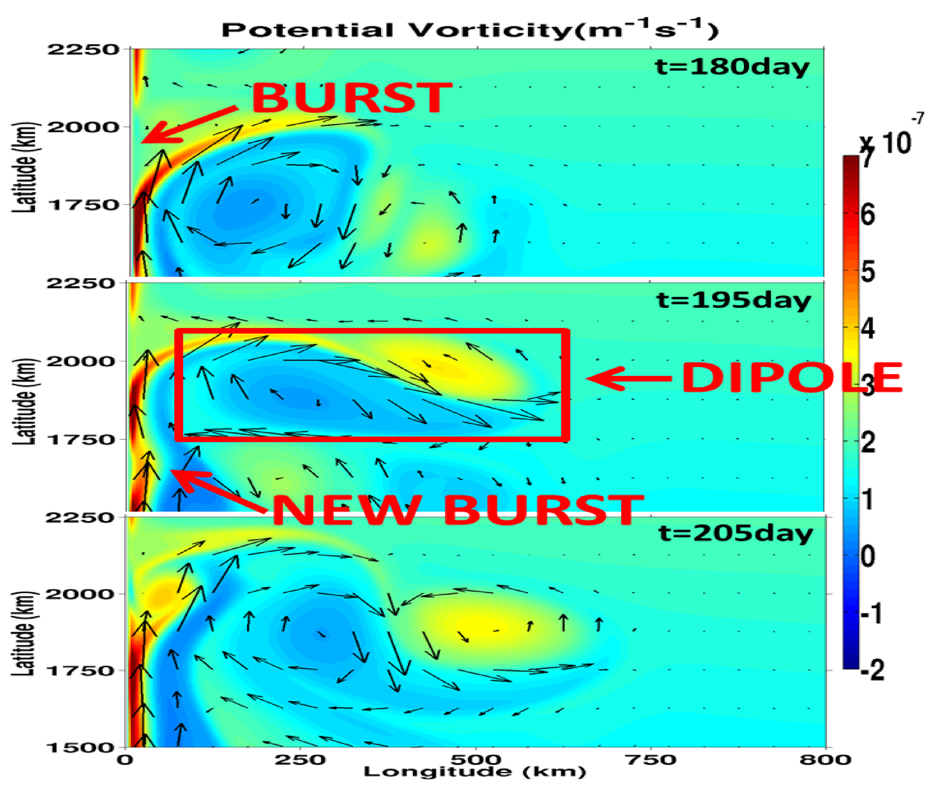


- √ **Best fit equation $\nu'_{eddy} = u'.6283\mathrm{m} - 639\mathrm{m}^2\mathrm{s}^{-1}$**
- √ Correlation of **R = 0.97** within ν'_{eddy} and u'
- √ **Proportionality formula of Prandt (1925) $\nu'_{eddy} = \alpha\lambda u'$ is confirmed and lead to $\alpha \approx 0.1$.**

Eddy, Burst and Dipole(5)



(a) Zonal profils of second and third moment of the fluctuating velocity from MW300 at y = 1500km and (b) analytic solutions from idealize perfect disc of radius R in anticyclonic solid-body rotaion of equation $x^2 + y^2 = R^2$.

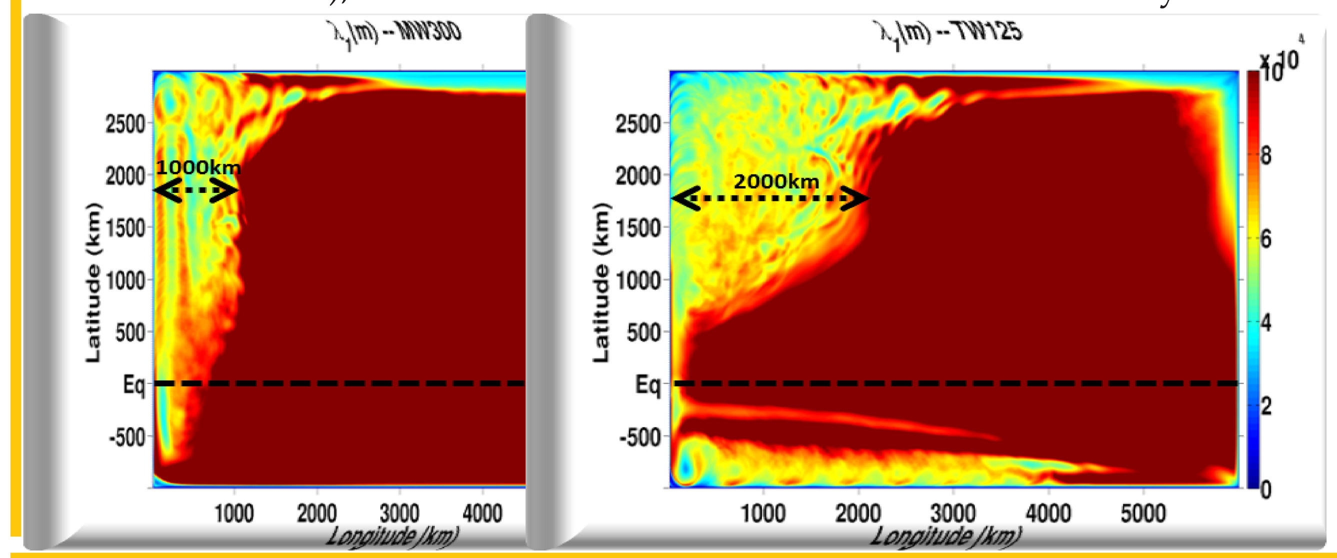


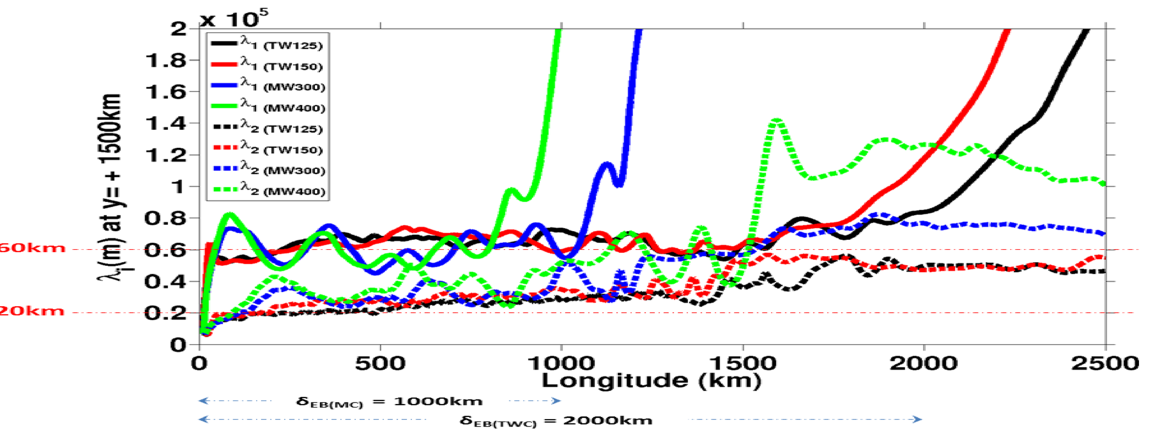
- √ Analog to bursts or ejections in the classical boundary layer (Robinson 1991) and are thus given the same name
- √ **Bursts are initiated by anticyclones**
- √ **Burst is always followed by the formation of dipole away from the boundary**
- √ **Burst needs fine resolution in both horizontal directions, not only in the vicinity of the boundary layer.**

Extended Boundary Layer(6)

$\lambda_1 = \frac{\text{Energy}}{\text{Enstrophy}}$ $\lambda_2 = \frac{\text{Enstrophy}}{\text{Palinstrophy}}$

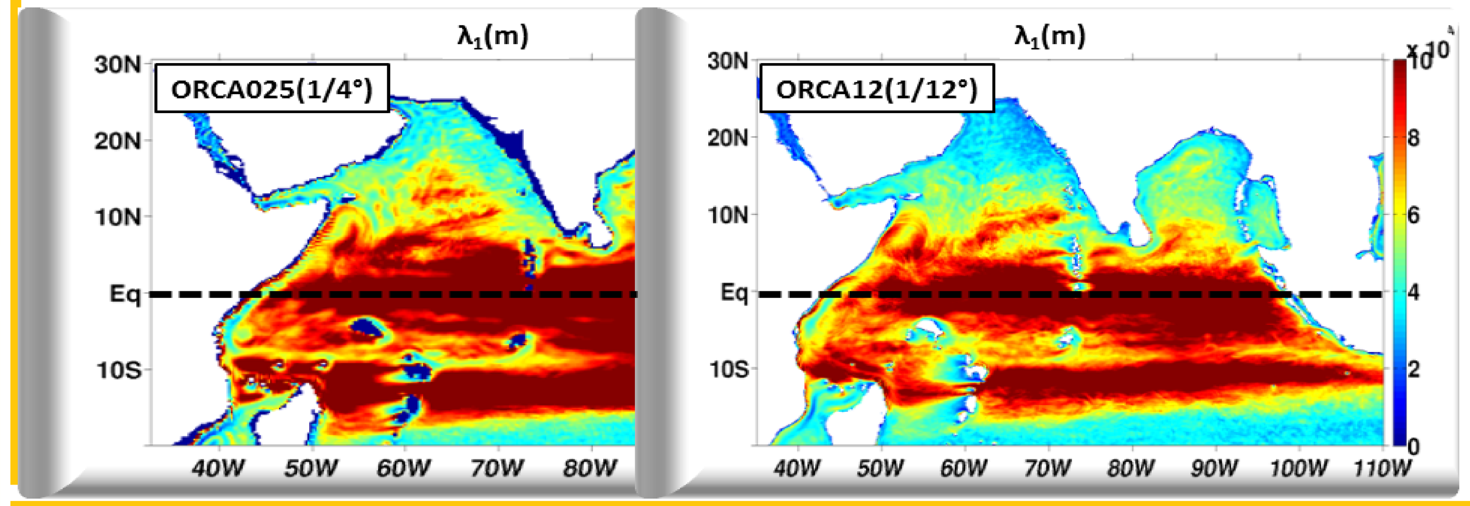
λ_1 is the Taylor scale in 3D turbulence, it characterizes the size of the velocity gradients. λ_2 characterizes the viscous dissipation length scale in the enstrophy cascade (*Bofette & Ecke* 2012), the smallest scales in the vortical dynamics.





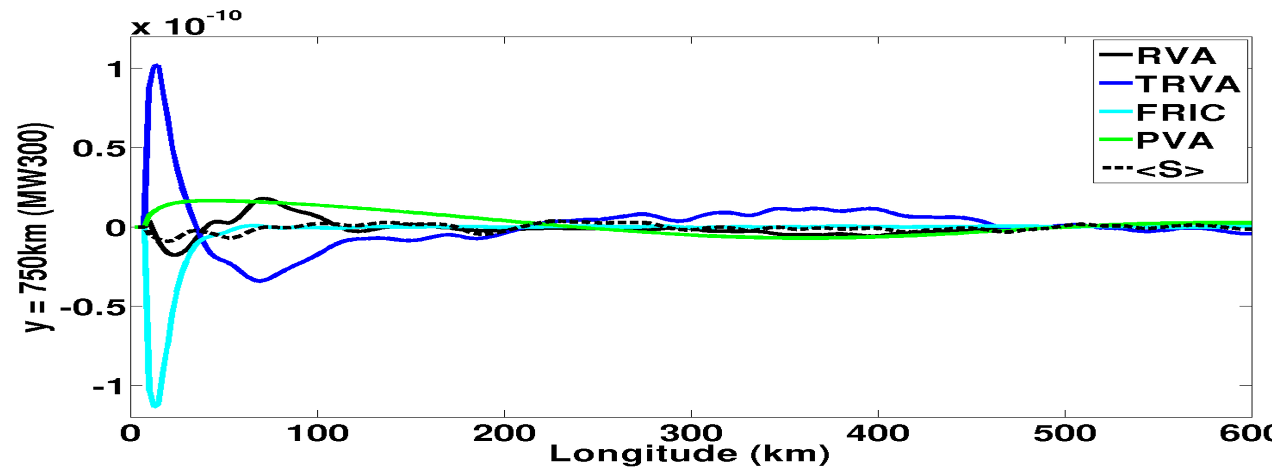
- √ The area of the plateau at around the scale of 60km is the **extended boundary layer (δ_{EBL}).**
- √ The scale of λ_1=60km is easily explained by the eddy size of 400km $\approx 2\pi$60km.
- √ $\delta_{EBL(MW300)}$=1000km, $\delta_{EBL(TW125)}$=2000km, **the width of the EBL depends on viscosity and the inertial effects.**

Application to Eddying OGCM (NEMO, DRAKKAR Configuration)(7)



- √ Roughly the same patterns for the three configuration for λ_1 >100km
- √ Along the Somali coast 50km<λ_1<60km signature of NSC and SSC associate with the SG and the GW migration (**Somalian extended boundary**) and its breakdown into small eddies towards the interior of Arabian Sea (**Arabian extended boundary**)
- √ **Amazing most small scales along the coast of India which is contrary to the common knowledge that the most small scales must be at the western boundary.**

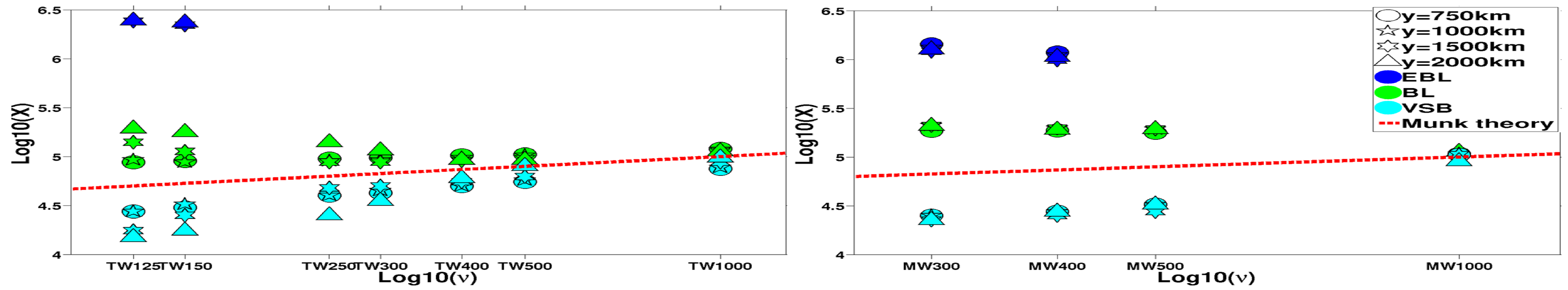
Viscous Sublayer and Boundary Layer(8)



acronym:
(T)RVA: (Turbulent)Relative Vorticity Advection
FRIC: Friction term
PVA : Potential Vorticity Advection

$$\underbrace{\partial_x[\langle u\rangle\langle\xi\rangle] + \partial_y[\langle v\rangle\langle\xi\rangle]}_{RVA} + \underbrace{\partial_x\langle u'\xi'\rangle + \partial_y\langle v'\xi'\rangle}_{TRVA} + \underbrace{\beta\langle v\rangle}_{PVA} - \underbrace{\nu\nabla^2\langle\xi\rangle}_{FRIC} = \langle S\rangle$$

- √ balance between TRVA and FRIC: **viscous sublayer (VSB)**
- √ balance between PVA and the TRVA: **boundary layer (BL)**



√ **When turbulence is present, the thickness of the viscous sublayer is well below the boundary layer thickness predicted by Munk theory.**

Conclusions and Perspectives(9)

- √ **Inertial effects dominate boundary layer dynamics**
- √ **Discovery of eddy viscosity estimation method via Munk formula**
- √ **Grid refinement near the boundary might be useful in laminar low Reynolds number simulations but is not adapted for the fully turbulent case where small scale structures penetrate into the ocean interior**
- √ **The low Reynold number Munk layer separates into three boundary layers at higher Reynolds number: viscous sublayer, boundary layer, and extended boundary layer.**

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