Challenge to model turbulence in tidally active seas

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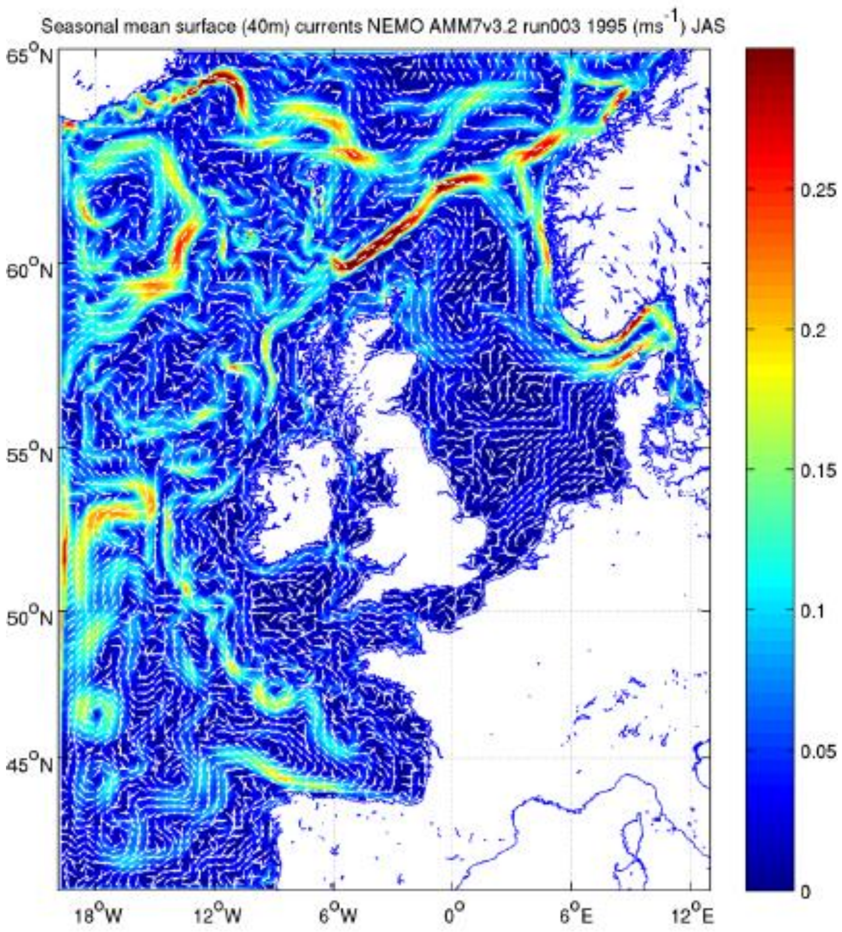
The Northwest European Continental Shelf



O'Dea et al 2012

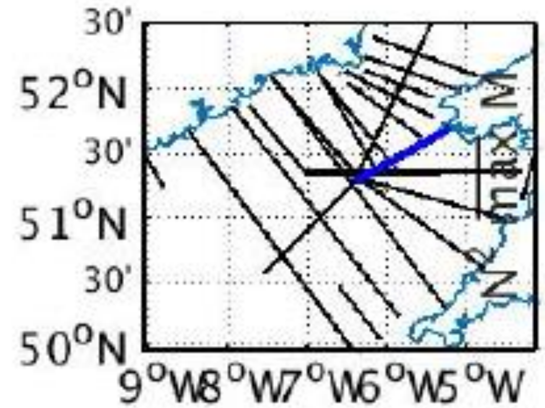
Broad tidally dominated, downwelling shelf;
Boarders subpolar and subtropical gyres
Strong mixing in winter
(shelf mixed over depth)
strong stratification in summer

MODEL: Nucleus for European Modelling of the Ocean (NEMO)
- UK: NOC, Met Office
- France (MERCATOR), Italy

NEMO-shelf (O.Dea et al., 2012)

Domain:
Resolution: 7x7km, 51 vertical s-layers;
Forcing: IRA-interim surface flux
Boundary conditions: Global ORCA-25 runs, tides
Modelling period: 1996-2015, no assimilations.

Model set up and comparison



- Turbulence closure tested: $k_{u,v,T,S} = ql\ \boldsymbol{S}_{u,v,T,S}$
- structural functions $\boldsymbol{S}_{u,v,T,S}$:

  GA: Galperin et al, 1988

  KC: Kantha Clayson, 1994

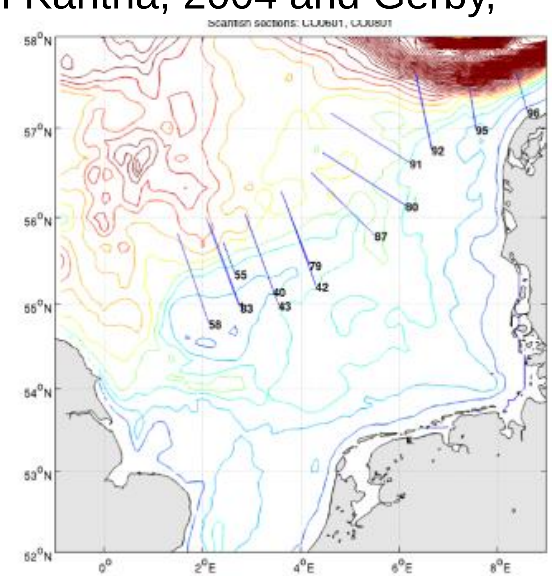
  KC4 – KC with model constants from Kantha 2004, improved convection

  CAA, Canuto et al, 2001

  CAB, same but with different set of constants

!!! In all models surface parameterisations for breaking from Kantha, 2004 and Gerby, 2009. k-eps constants and equations fit observations at the

- ($\ell=\delta(z+0.6H_s)$; $\delta=0.2\neq\kappa$)

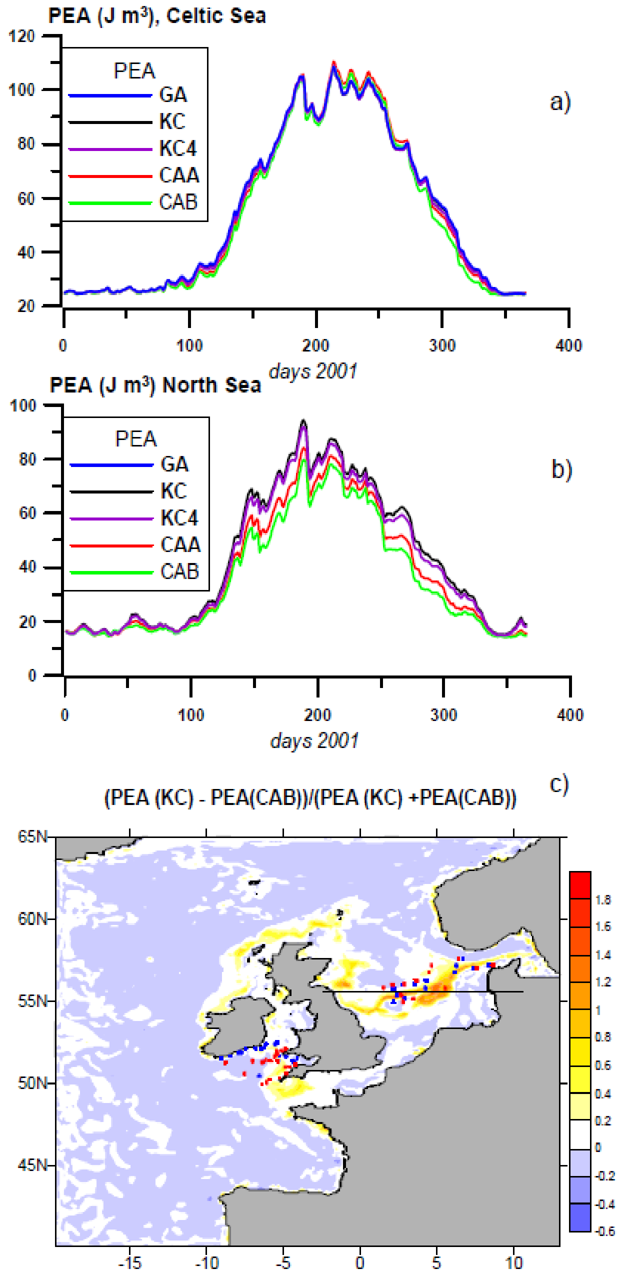


- DATA: High resolution scanfish sections
- Celtic Sea 1998, the North Sea, 2001
- Turbulence observations in the Celtic Sea
- 20 12-24 h long datasets of ε, N2
- years 1998 – 2013

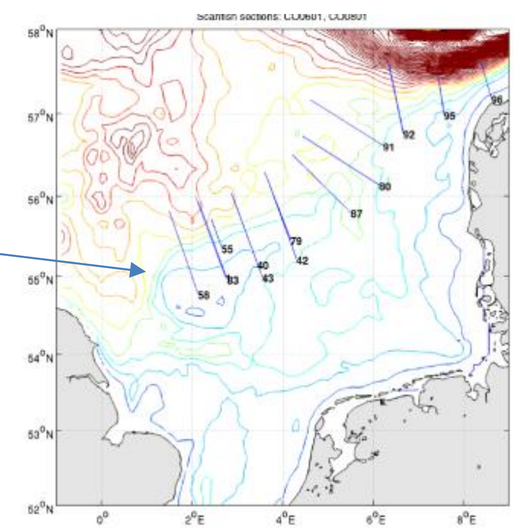
Model inter comparison

Potential Energy Anomaly:
Measure of stratification in water column

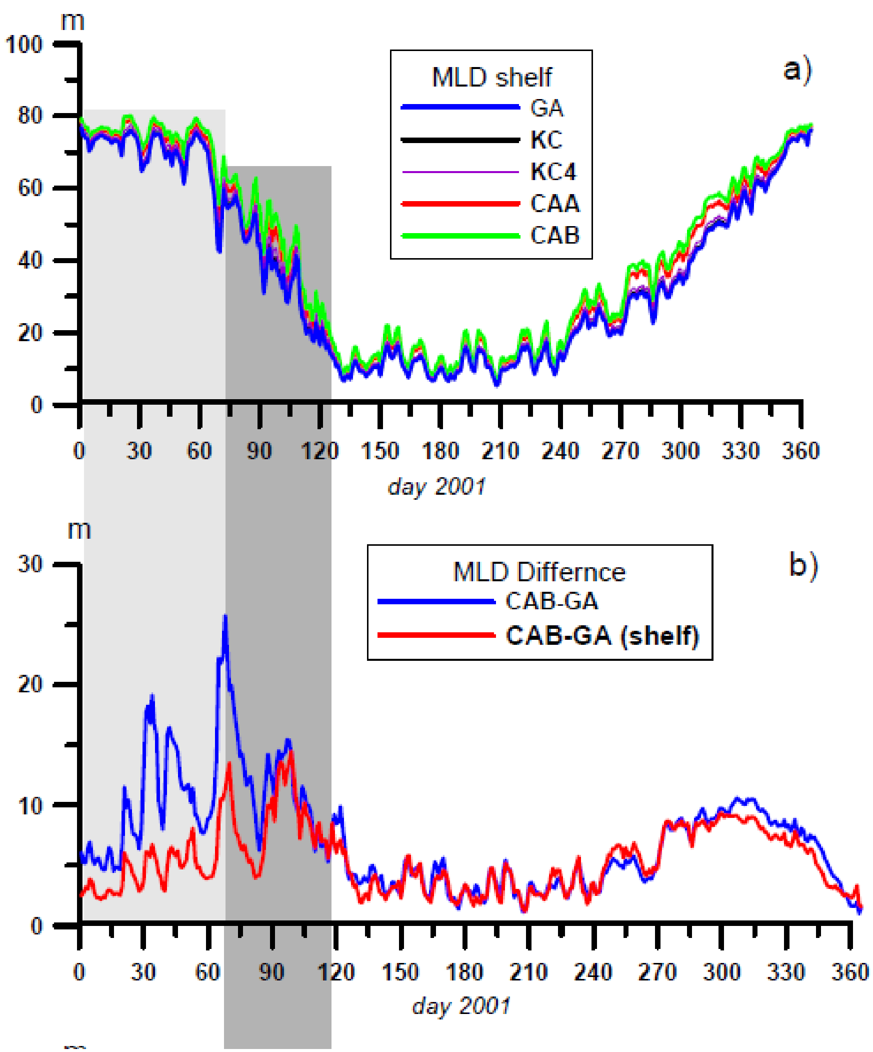
$$PEA = g\int_0^{\max(h,200m)} (\rho - \rho_{mean})zdz/\max(h,200)$$



Shelf-mean differences are small,
locally large in the North Sea:
50-100%



Model inter-comparison 1



Large differences in basin mean mixed layer depth:
winter ~ 10-30%
summer 25%

Turbulence closures can be sorted as

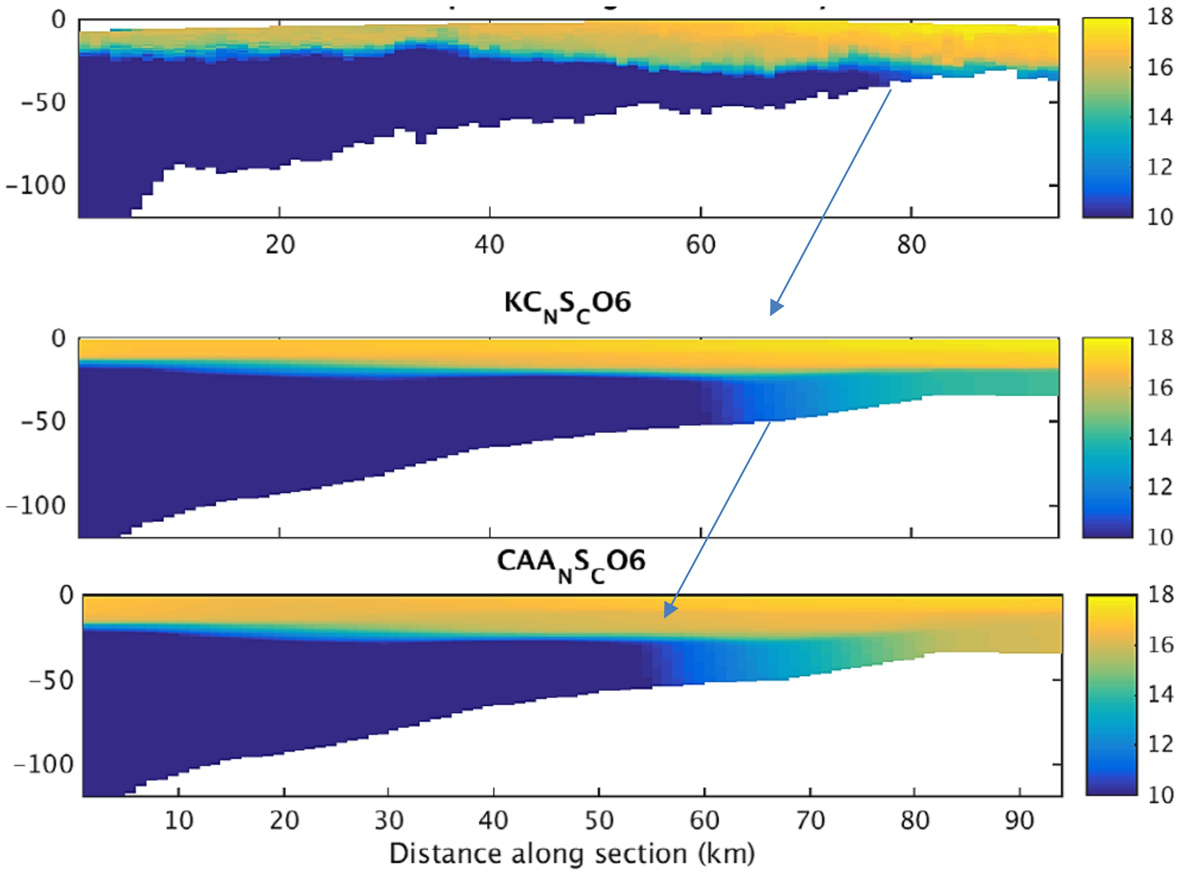
	GA	KC	KC4	CA	CAB
Ri_{cr}:	0.19	0.24	0.28	0.82	1.03

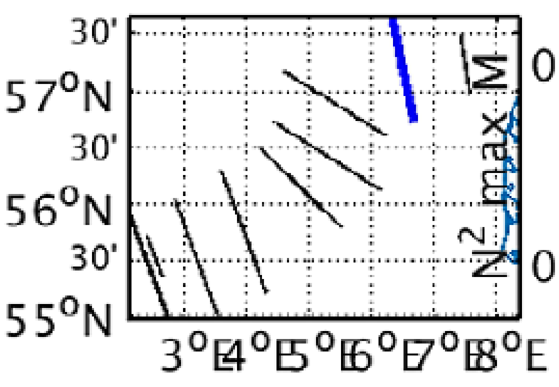
more diffusive

Theoretically derived critical Ri/ Rf correspond to Model gradation

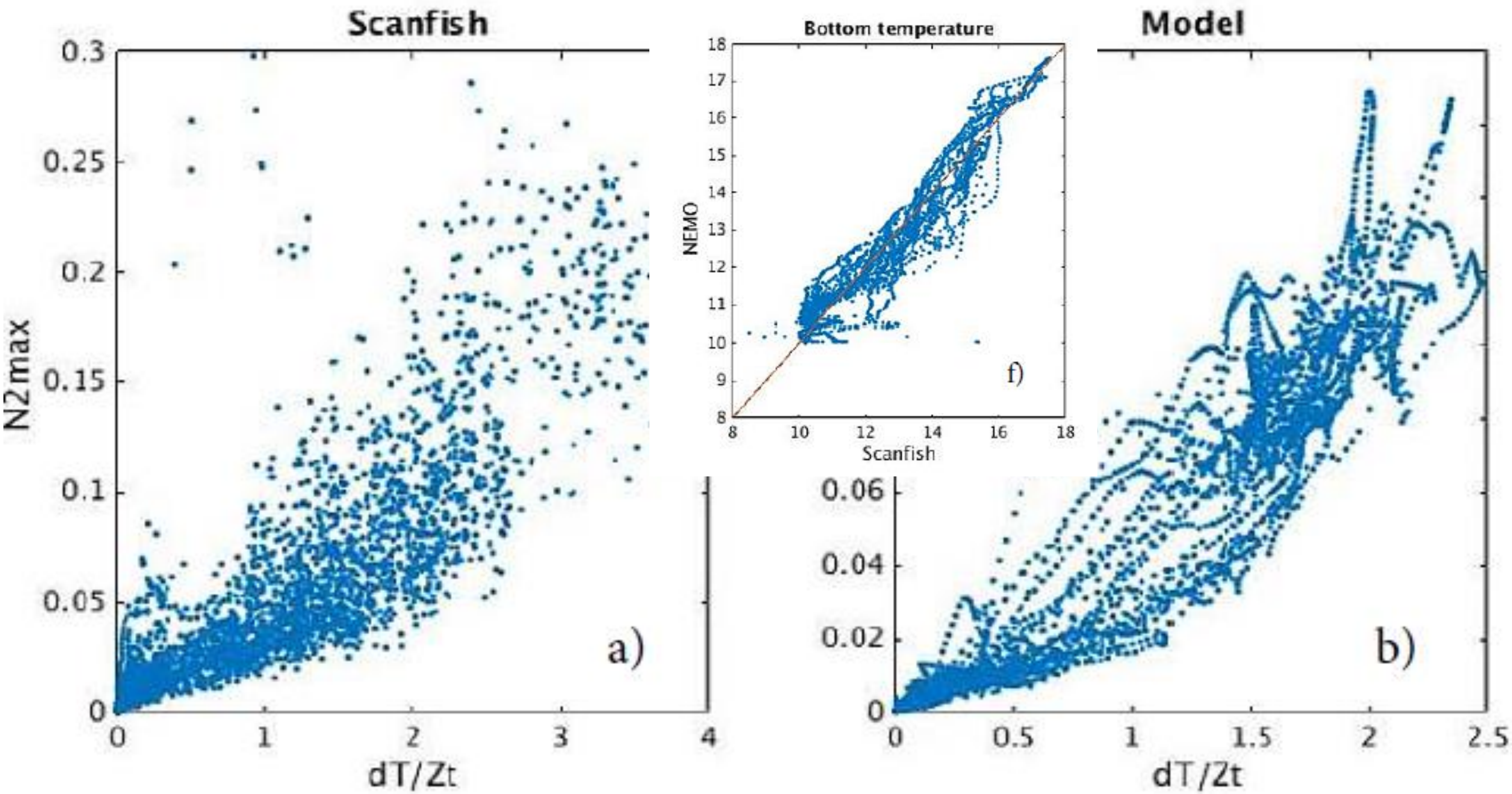
Direct comparison with scanfish section: Across tidal mixing front

- shift of warm front with more diffusive model;
- absence of variability in pycnocline;
- Bottom boundary layer too thick?

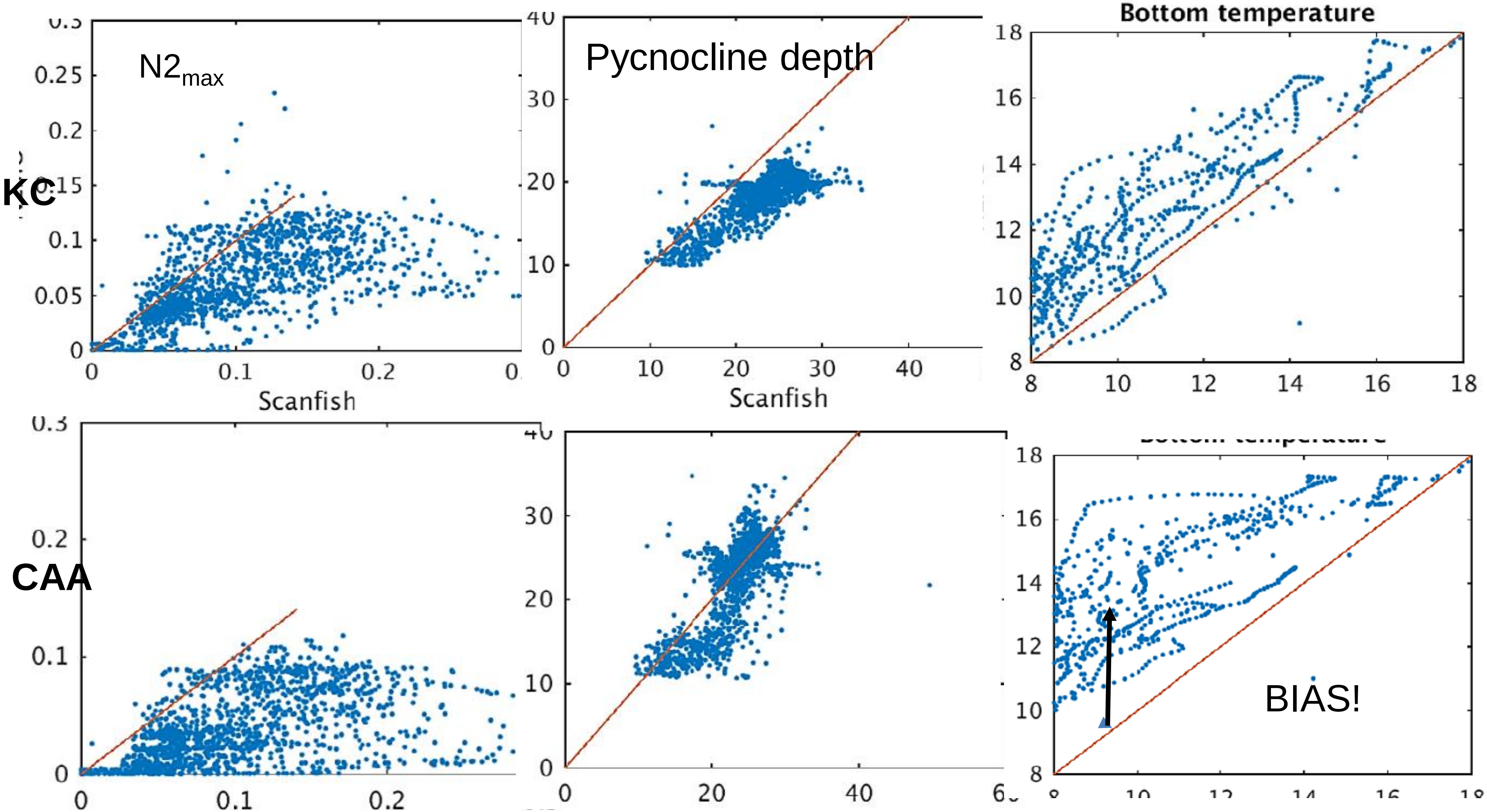




Local pycnocline properties versus integral:
CS : R(DT, Z_T*N2)=0.5
NS: R(DT, Z_T*N2)=0.7
model :0.85-0.9



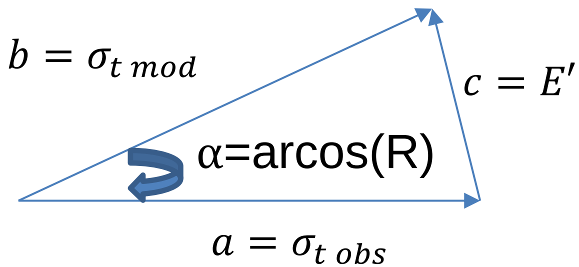
Direct comparison with scanfish sections: Overall statistics



North Sea

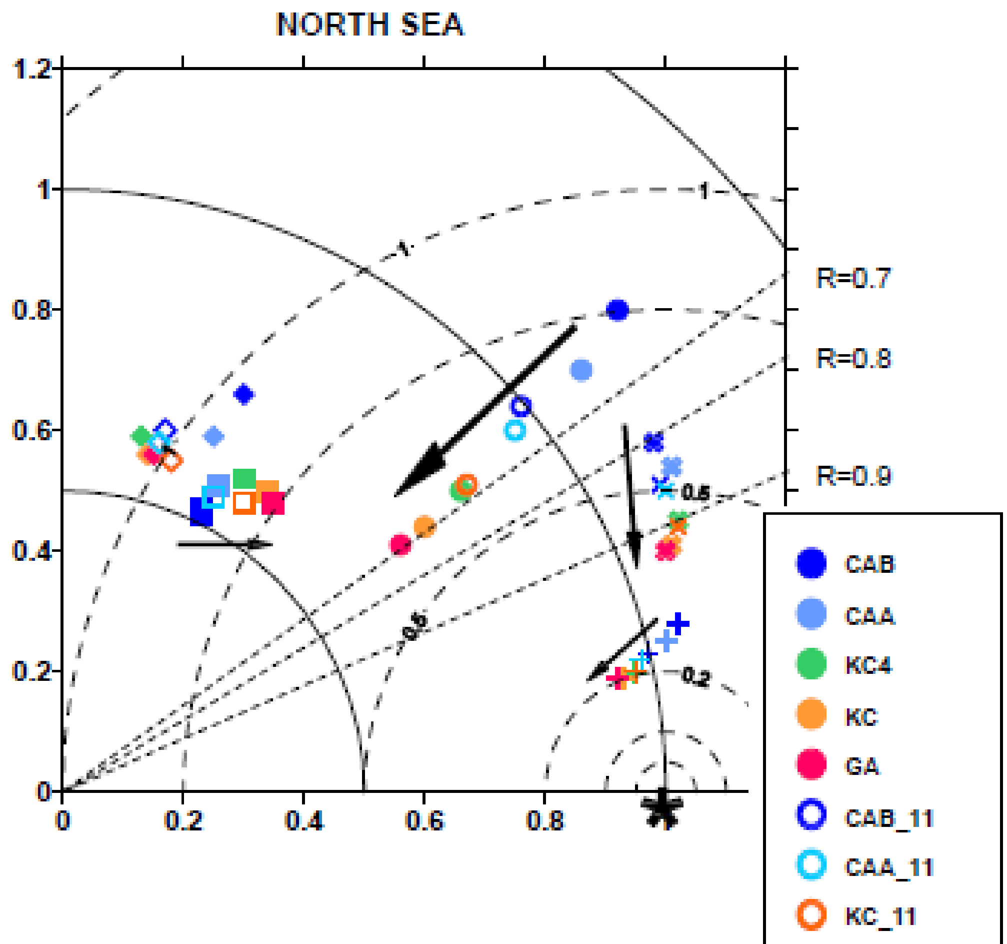
Deficit in pycnocline depth(GA,KC) /or overmixing-warming (Canuto models)

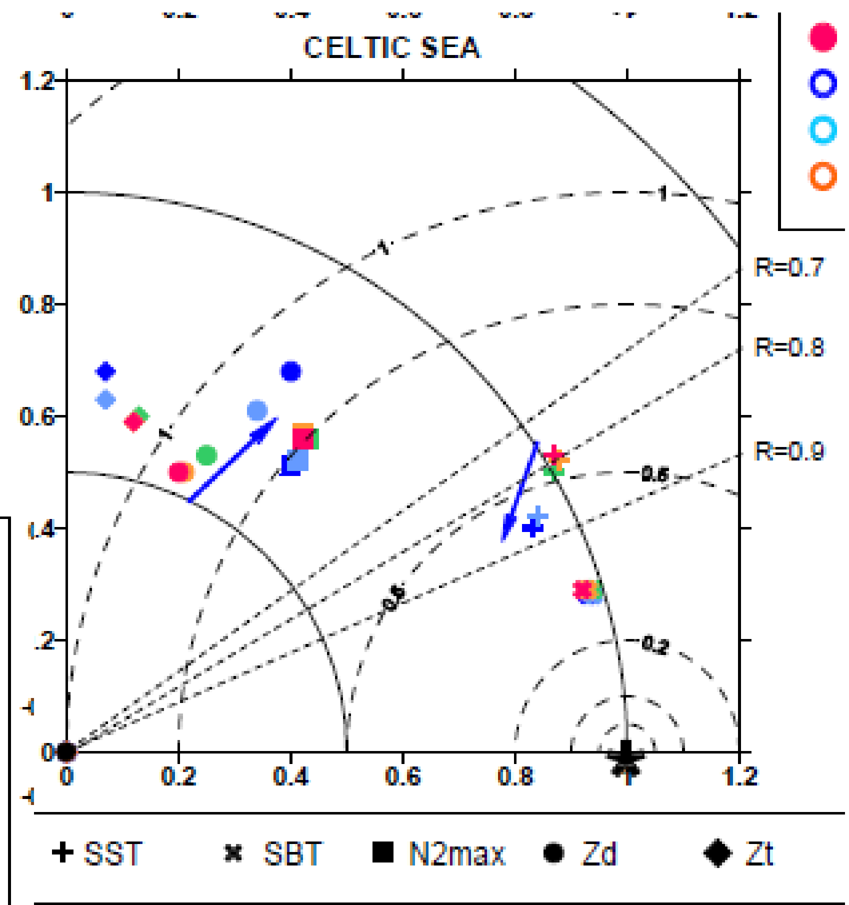
Taylor diagram: all variables on the same diagram.



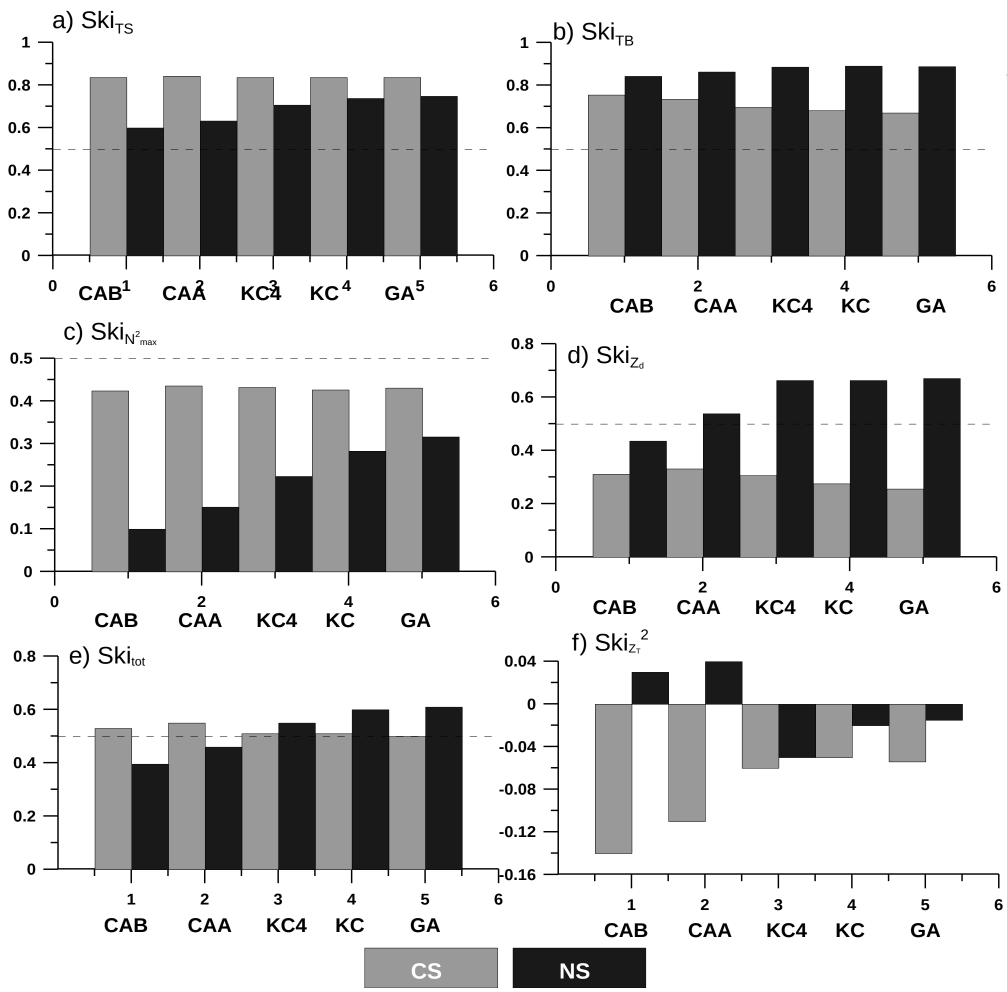
$$c^2 = a^2 + b^2 - 2ab\cos\alpha$$

$$\frac{E'^2}{\sigma_{T0}^2} = 1 + \sigma_{Tm}^2/\sigma_{T0}^2 - 2\sigma_{Tm}/\sigma_{T0}R$$





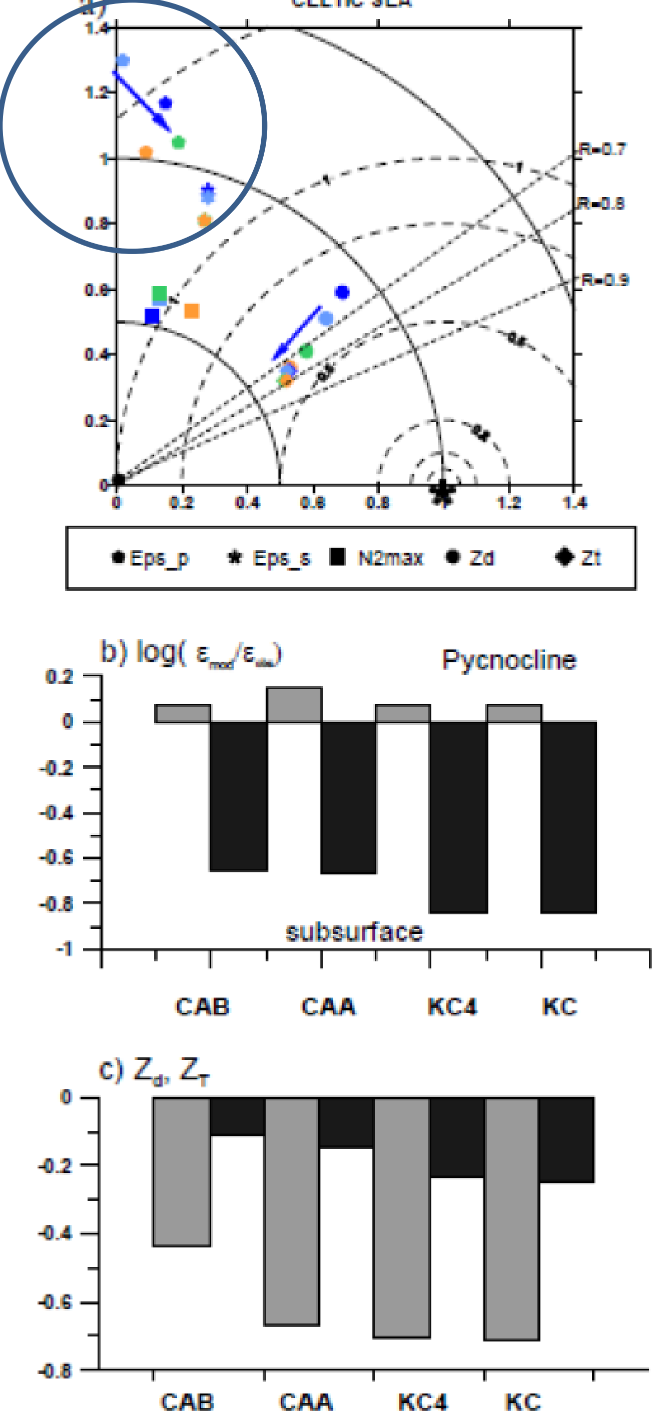
Taylor diagram evaluate only variability: How to evaluate 'model skill'?



$$Ski^i = \{(1 - E')\left(1 - \frac{|M^i - O^i|}{|M^i| + |O^i|}\right)\}^{1/2}$$

$$Ski = \{\prod_{i=1}^{n} Ski^i\}^{1/n}$$

Model skills for prediction of (a) SST, (b) SBT, (c)N^2_{max},(d) Z_d, (e) total skill, (f) Ski(Zd)^2. Grey- in the Celtic Sea, black- in the North Sea



Dissipation rate comparison: 20 datasets

- Dissipation rate comparison:

Subsurface layer :

an order underestimate;

Correlations~0.3

Pycnocline:

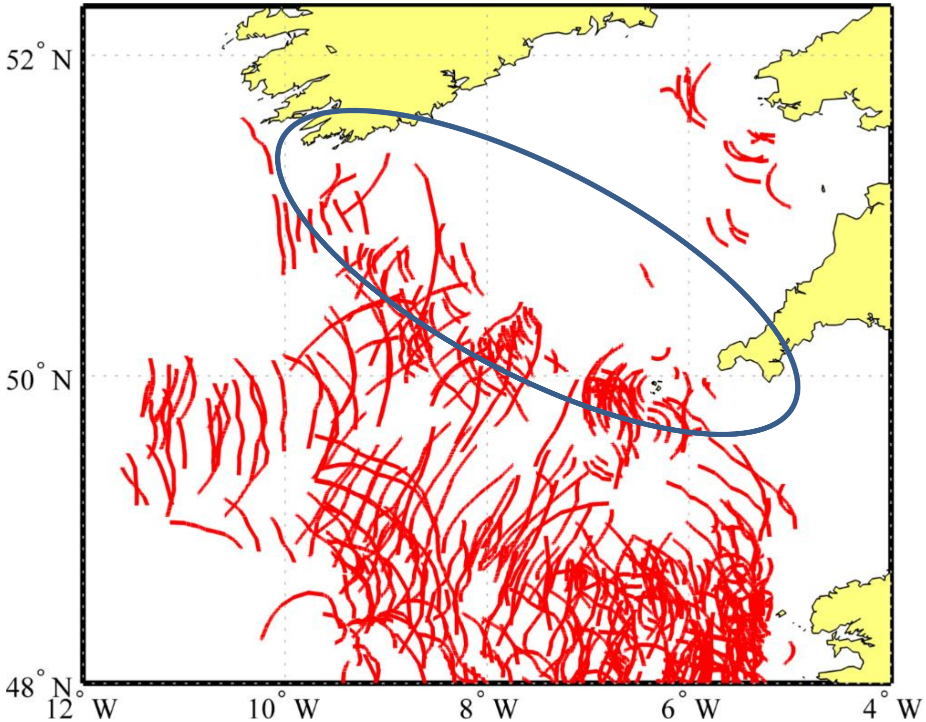
overestimate on the shelf, by orderOver-predicted mixing $K_v \sim \varepsilon/N^2$

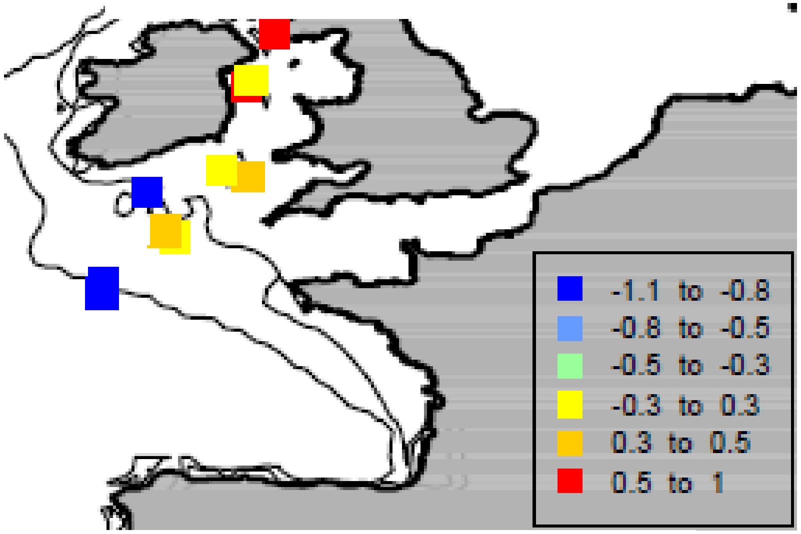
No correlations, relative error>1

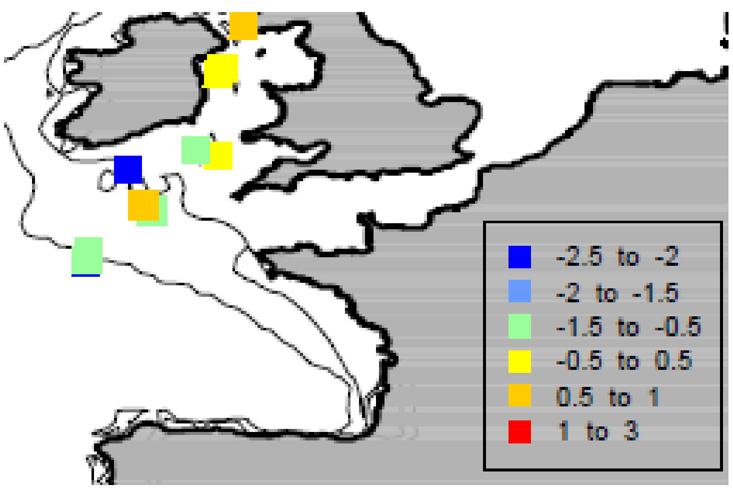
Underestimate on the Celtic Sea shelf break (internal tides)

(a) Taylor diagram dissipation data shown in circle
(b) Relative biases fro dissipation rate in log scale
(c) For pycnocline thickness and depth in the Celtic Sea (grey is thickness), black pycnocline depth

Images of steep Internal waves fronts (summer 2009)





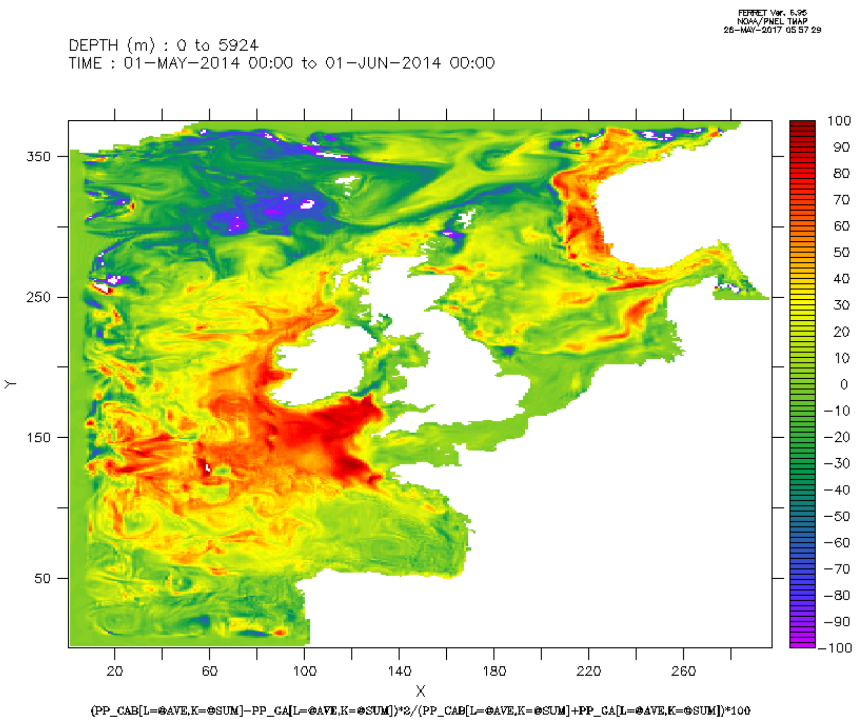


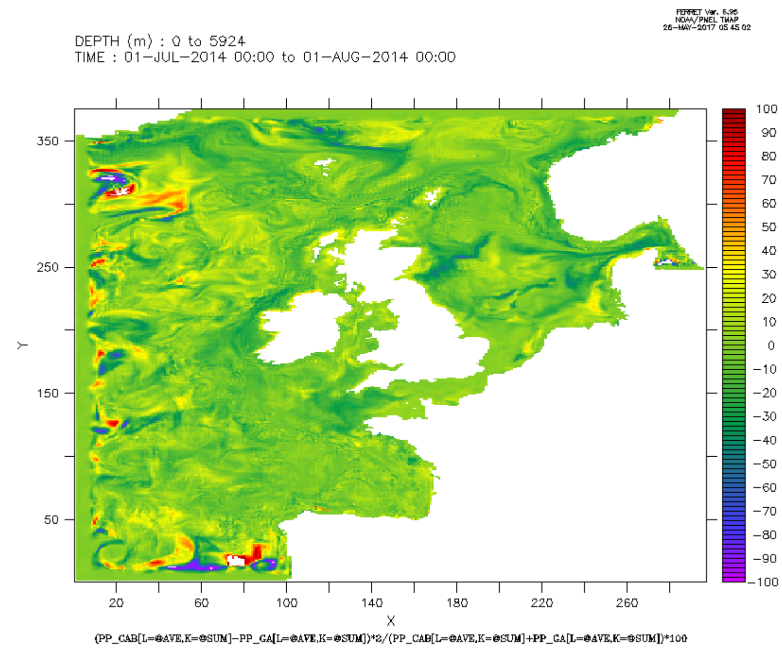
E Zubkova, I Kozlov

Steep solitary internal tides (summer 2008)
Breaking and dissipating, 344 packets

Effect on the Ecosystem

- ERSEM model, 3 closures 2014-2015!
- Just finished, ongoing comparison with data quit
- Differences reach 100%, sign changes in July

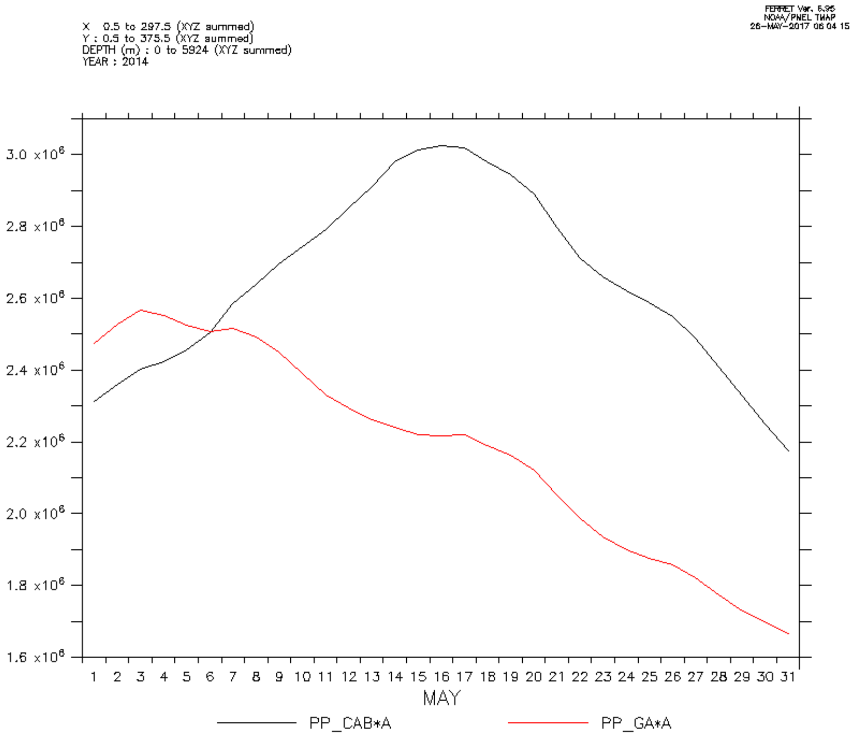


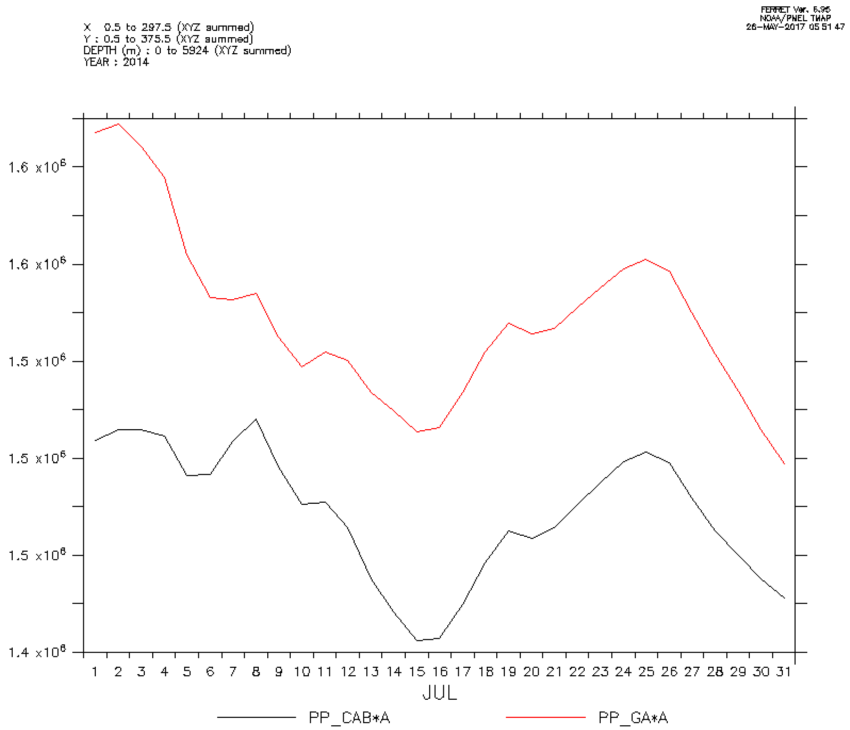


Chlorophyll: (CAB-GA)/(CAB+GA)
May 2014

(CAB-GA)/(CAB+GA)
July 2014

Differences are stronger in May blooming (20%) CAB smaller in summer 10% with dominating GA (less diffusive model)



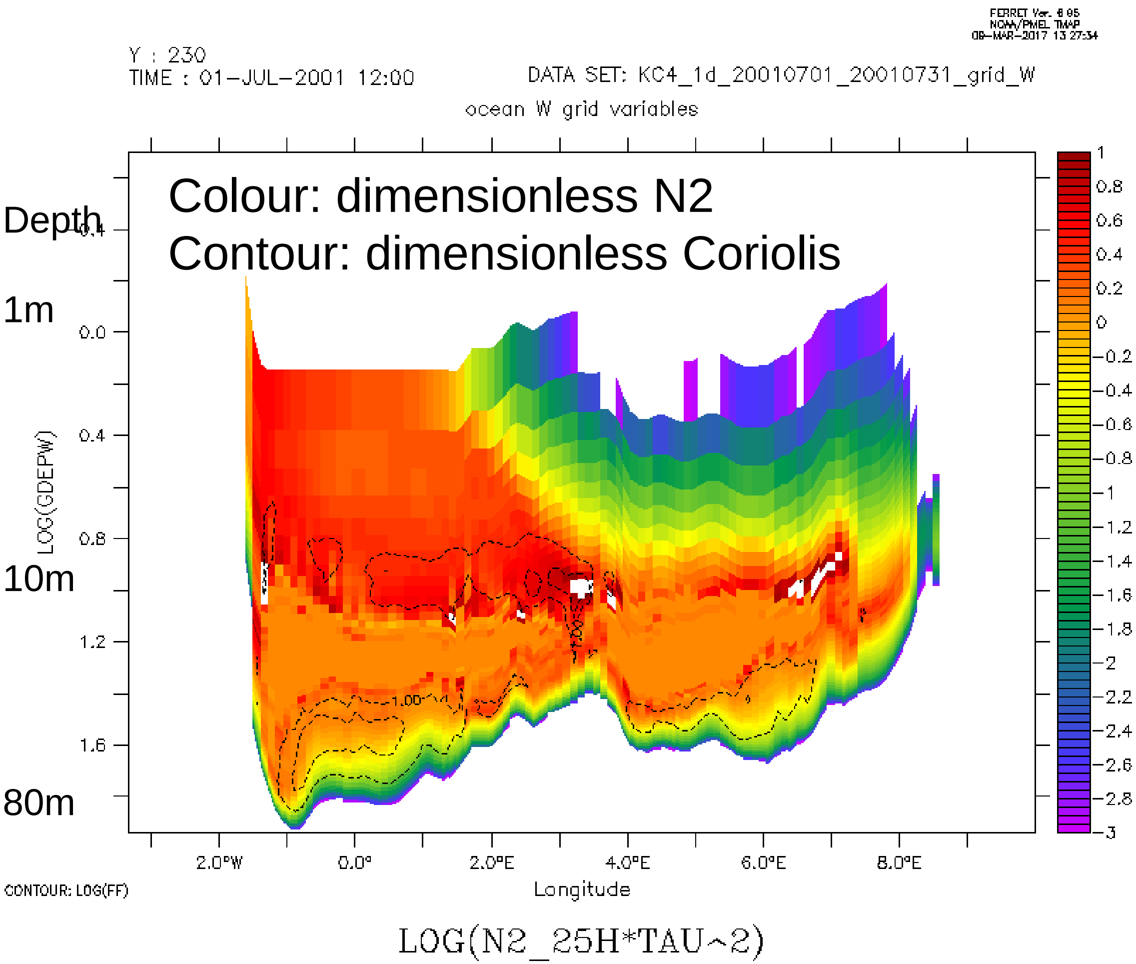


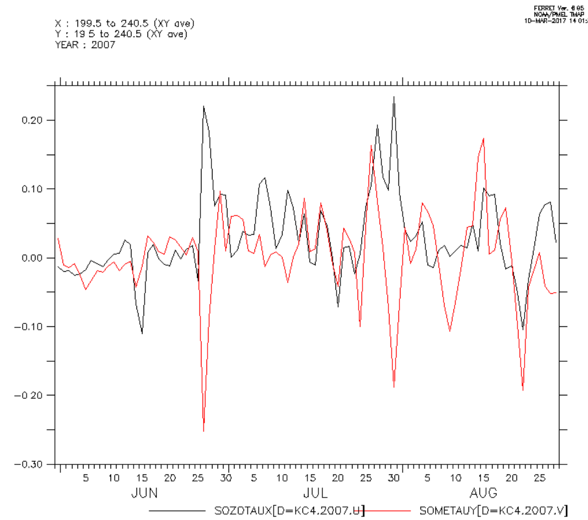
Nontraditional Coriolis: acts as buoyancy force

- $\varphi = \tau\partial_z U,\ \psi = \tau\partial_z V,\ \ f_0 = \tau f,\ h = \tau\breve{f},$
- $\tau = 2.7q^{-1}l$ *is a turbulent timescale,* $q^2 = (u'^2 + v'^2 + w'^2)$
- *Normalise* $u^2 = u'^2 / q^2$
- *System of Equations in the "Equator":*
- $u^2 = \alpha - 2uw(\varphi + h)$
- $v^2 = \alpha - 2vw(\psi)$
- $w^2 = \alpha + 2uwh$
- $uv = -uw\,\psi - vw\varphi - hvw$
- $uw = -\left(w^2 - C_1\right)\varphi + h\left(u^2 - w^2\right)$
- $vw = -\left(w^2 - C_1\right)\psi + huv$

- $uw = -\frac{(\alpha - C_1)\varphi}{1+4(\varphi+h)h};\quad S_{mu} = \frac{3A_1(\alpha - C_1)}{1+4(\varphi+h)h} \approx 0.39(1 - 4\varphi h)$
- If $\partial_z U$ >0 : dumping , if $\partial_z U$ <0, works as unstable stratification

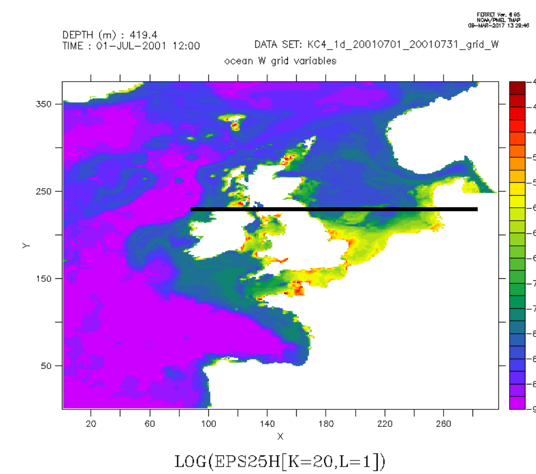
North Sea, July 2001





$$S_m = \approx 0.39(1 - 4\varphi h)$$

$$S_h?$$



Dimensionless $N^2\tau^2$, contours $|\varphi h| > 0.1$. What direction?

New closure, based on KC94 but with Coriolis effects- coming

- $u^2 = \alpha - 2uw(\varphi + h) + 2uvf_0$
- $v^2 = \alpha - 2vw(\psi) - 2uvf_0$
- $w^2 = \alpha + 2uw(h) + 2w\theta$
- $uv = -uw\,\psi - vw(\varphi) - f_0(u^2 - v^2) - f_2 vw$
- $uw = -(w^2 - C_1)\varphi + f_0 vw + h(u^2 - w^2) + u\theta$
- $vw = -(w^2 - C_1)\psi - f_0 uw + huv + v\theta$
- $u\theta = -uw\chi - \frac{A2}{A1}(1 - C_2)w\theta\,\varphi + \frac{A2}{A1}f_0 v\theta - \frac{A2}{A1}h\,w\theta$
- $v\theta = -vw\chi - \frac{A2}{A1}(1 - C_2)w\theta\,\psi - \frac{A2}{A1}f_0 u\theta$
- $w\theta = -w^2\chi - \frac{(1-C_3)}{3}B_2 w\theta\,\chi + \frac{A2}{A1}h\,u\theta$

Require solution of 9 algebraic equations in 4D parameter space.
Now system is reduced to 3 equations in the linear approximation for h.

Missed process 1. Shrira Forget, 2015

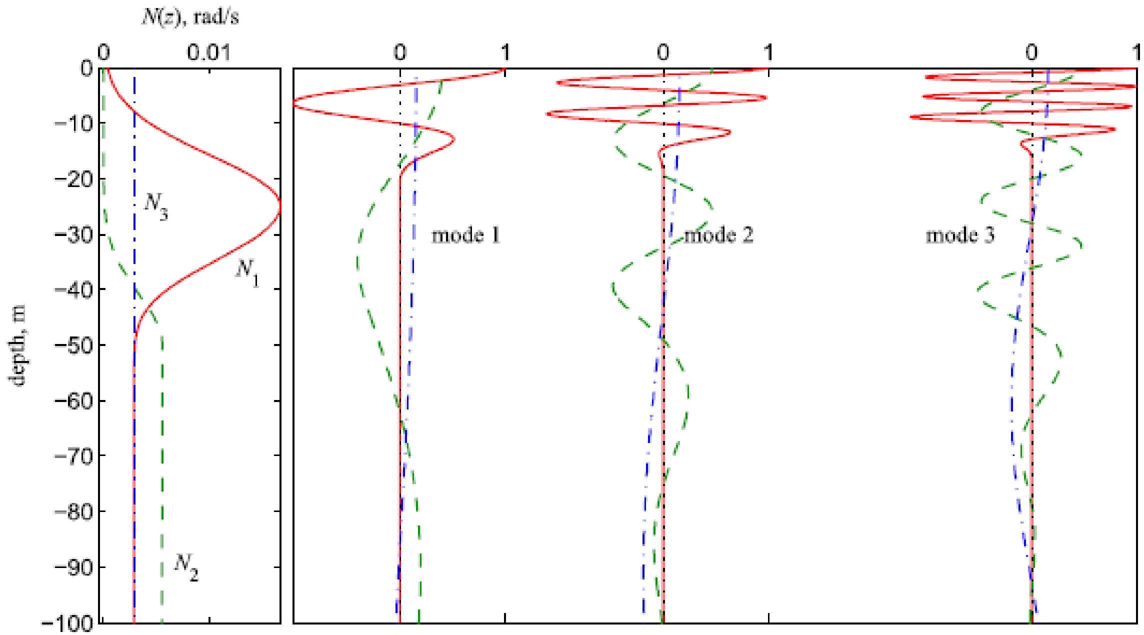


FIG. 1. (left) Three samples of stratification profiles $N_1(z)$, $N_2(z)$, and $N_3(z)$. The full water column depth in the chosen example is 400 m, but only the uppermost 100 m is shown; profiles are shown in full in Fig. 2. (right) An example of vertical distribution of horizontal velocities for the first three subinertial modes for the chosen sample stratification profiles. The horizontal velocities are found from the linearized Euler equations with $f = 0.99 \times 10^{-4}$ rad s^{-1} and $\tilde{f} = 1.06 \times 10^{-4}$ rad s^{-1}. The plots are for a sample frequency from the subinertial range ($\omega = 0.898 \times 10^{-4}$ rad s^{-1}), and the corresponding meridional wavenumbers l (rad m^{-1}) are 9.46×10^{-5}, 2.2×10^{-4}, and 3.44×10^{-4} for $N_1(z)$; 1.72×10^{-5}, 4.58×10^{-5}, and 7.40×10^{-5} for $N_2(z)$; and 3.55×10^{-6}, 7.1×10^{-6}, and 1.106×10^{-5} for $N_3(z)$.

Most frequently observed when strong wind stops or changes in direction

Non-traditional NIW:

Found in analytical solutions

Observed in the stratified ocean

Cannot penetrated through pycnocline!

Generate strong shear

Cannot be resolved in hydrostatic models

Additional shear can be parameterised using wind forcing

$$u_t - fv + \tilde{f}w = -p_x, \qquad (1a)$$

$$v_t + fu = -p_y, \qquad (1b)$$

$$w_t - \tilde{f}u = -p_z + b, \qquad (1c)$$

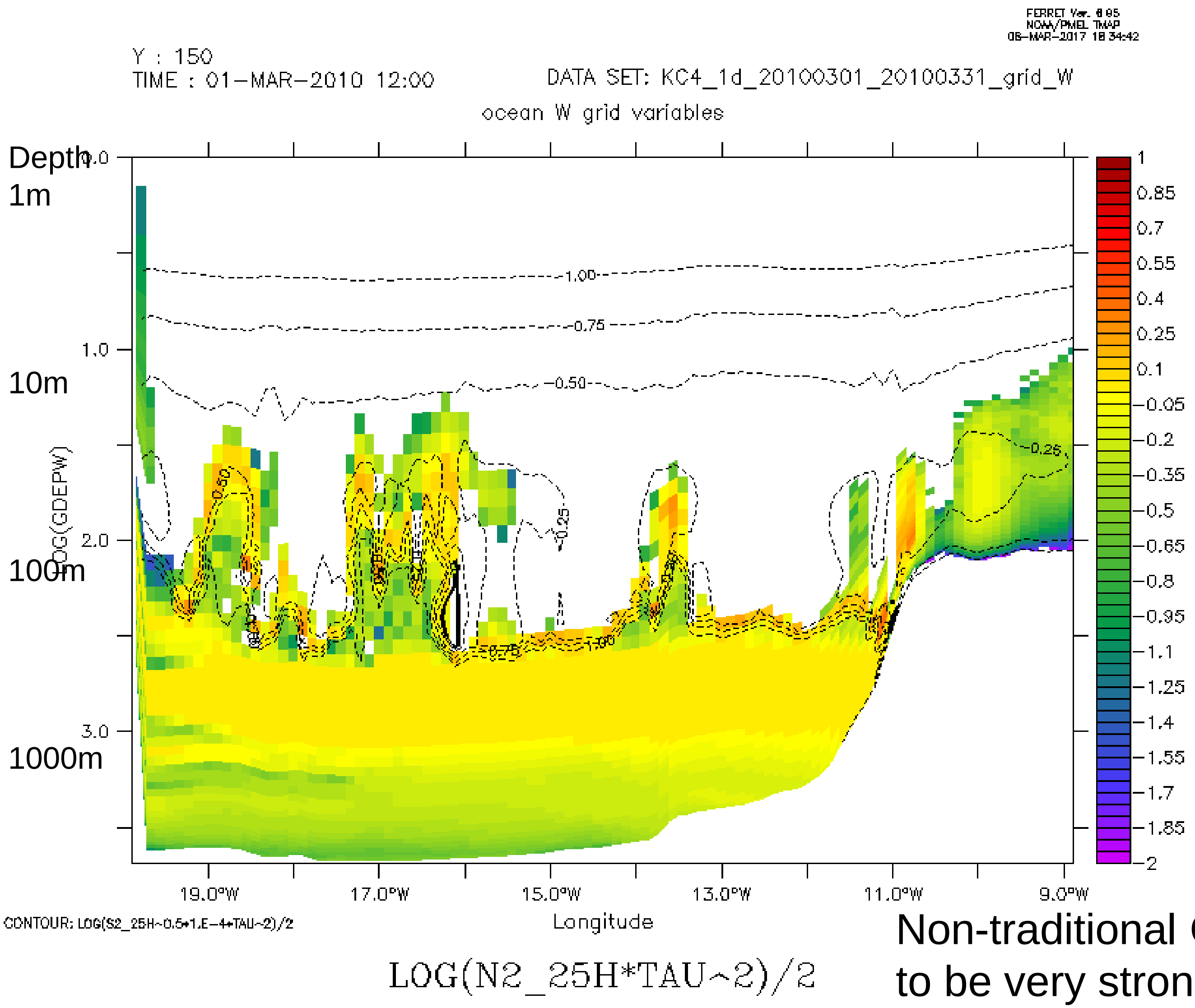
$$u_x + v_y + w_z = 0, \quad \text{and} \qquad (1d)$$

$$b_t + N^2 w = 0. \qquad (1e)$$

Conclusions

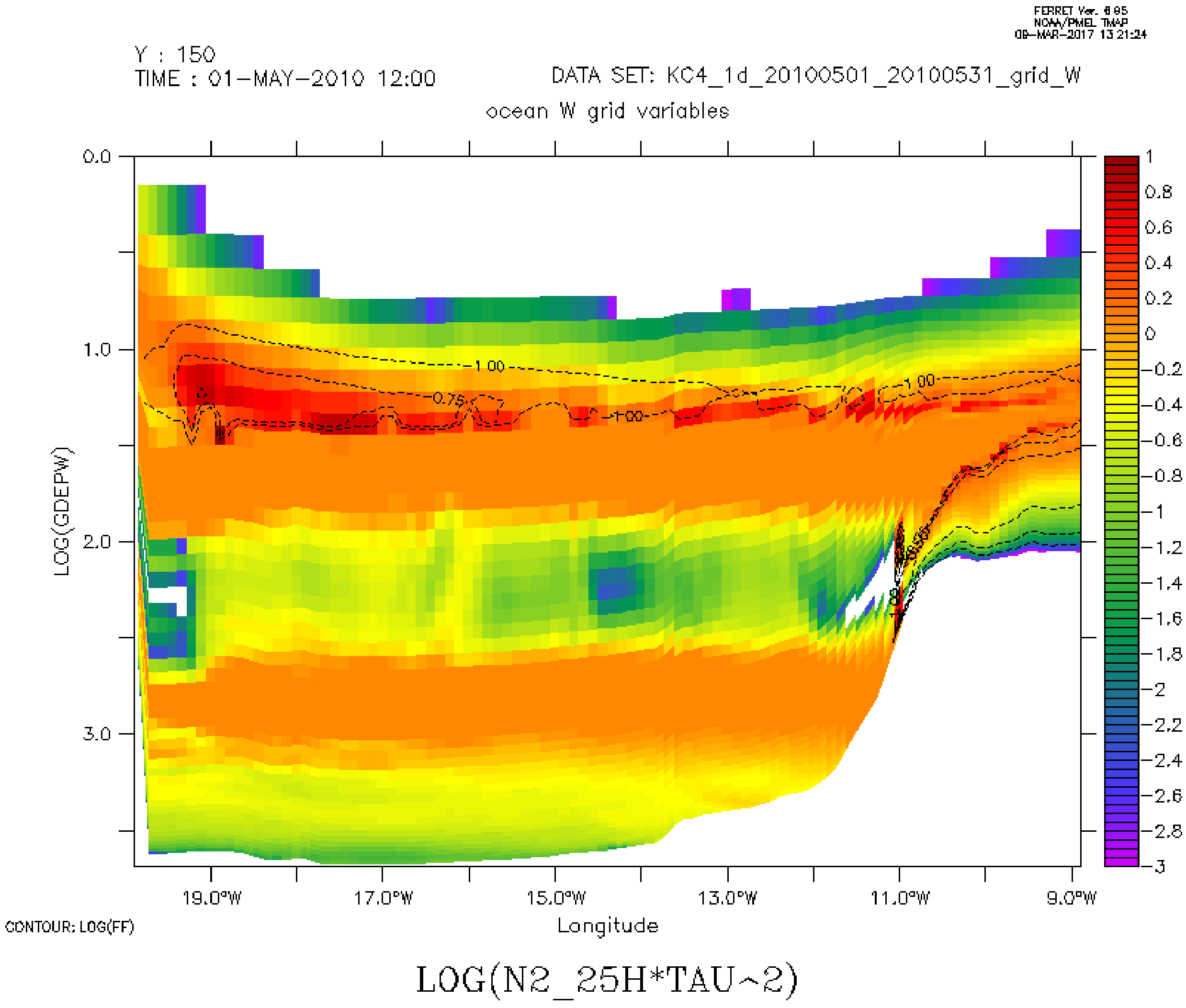
- The choice of structural functions does matter!
- Strong differences in blooming time
- More diffusive model spent nutrients much faster
- Differences in structural functions are essential for ecosystem
- Comparing with turbulence measurement are very poor
- No winners between models, more diffusive work better in active seas
- Less diffusive models work better in the shy seas
- Non-traditional Coriolis force acts as stratification- should be included in models

The Celtic Sea, March

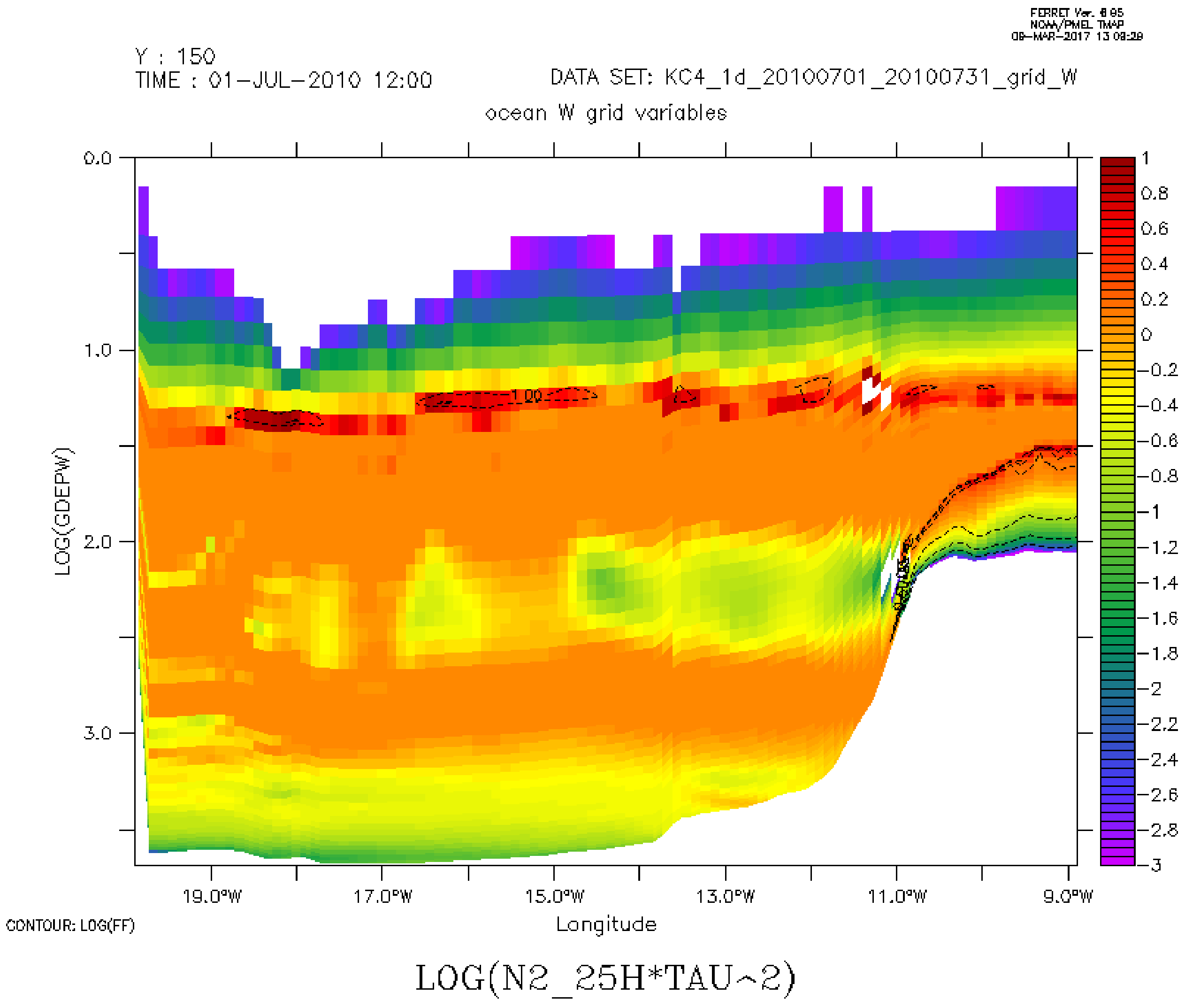


Non-traditional Coriolis effects could be to be very strong: *hφ ~ 0.6*

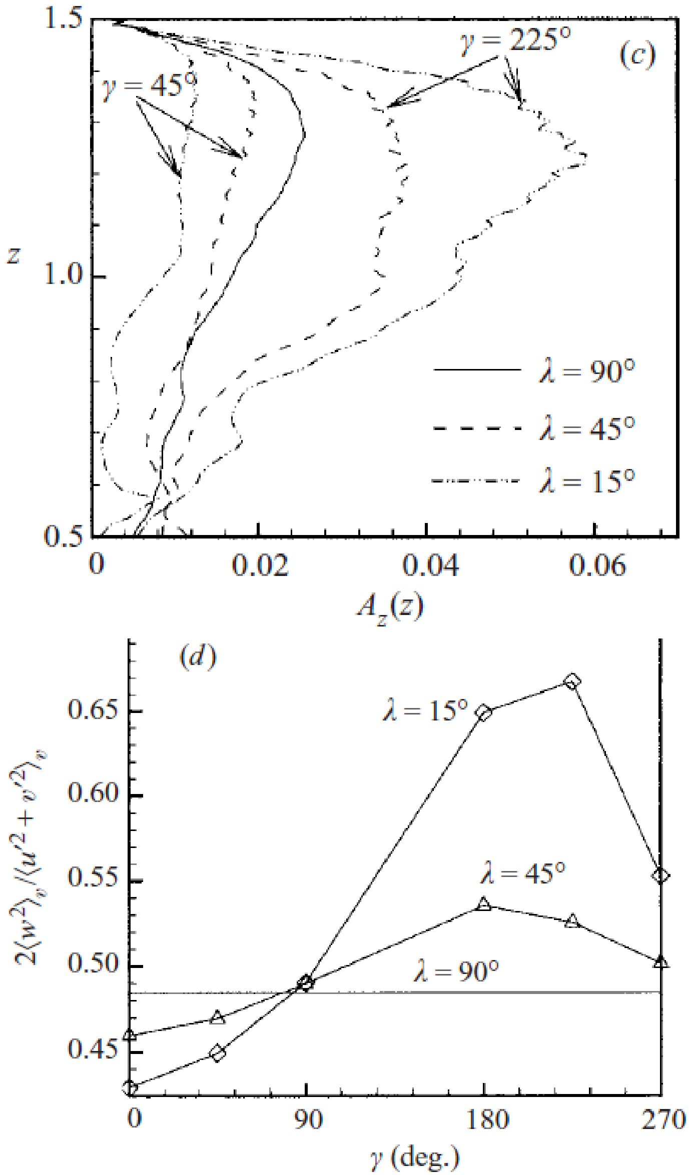
The Celtic Sea, May



The Celtic Sea



“nonstandard” Coriolis effects II



validated versus LES (Zikanov et al, *J.Fluid Mech.* 2003)

$$\frac{1}{2}\frac{\partial}{\partial t}\langle u'^2\rangle = -\frac{\partial U}{\partial z}\langle u'w\rangle - 2\Omega_{\tau y}\langle u'w\rangle + \mathrm{OT},$$

$$\frac{1}{2}\frac{\partial}{\partial t}\langle v'^2\rangle = -\frac{\partial V}{\partial z}\langle v'w\rangle + 2\Omega_{\tau x}\langle v'w\rangle + \mathrm{OT},$$

$$\frac{1}{2}\frac{\partial}{\partial t}\langle w^2\rangle = 2\Omega_{\tau y}\langle u'w\rangle - 2\Omega_{\tau x}\langle v'w\rangle + \mathrm{OT},$$

$$-\frac{\partial}{\partial t}\langle u'w\rangle = -2\Omega_{\tau y}[\langle u'^2\rangle - \langle w^2\rangle] + \mathrm{OT},$$

$$\frac{\partial}{\partial t}\langle v'w\rangle = -2\Omega_{\tau x}[\langle v'^2\rangle - \langle w^2\rangle] + \mathrm{OT}.$$

- •Redistribute energy over components differently
- •Result in strong anisotropy of TKE
- • direction of wind-latitude γ is important
- •(here λ is latitude)
- • 6-fold changes in diffusivity A(z).

$$A_z(z) = \frac{[\langle -\tau_{13} + u'w\rangle_t^2 + \langle -\tau_{23} + v'w\rangle_t^2]^{1/2}}{[(\mathrm{d}\langle u\rangle_t/\mathrm{d}z)^2 + (\mathrm{d}\langle v\rangle_t/\mathrm{d}z)^2]^{1/2}}.$$