Forcing of mean flow and turbulence by waves in homogeneous zone of Iroise Sea

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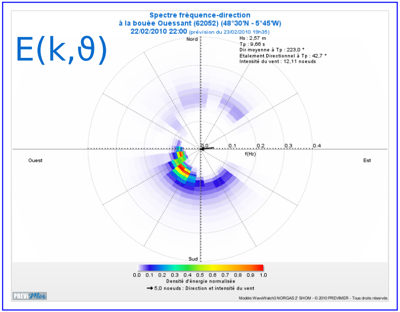
<ins>Motivations :</ins>

Increase the precision of the surface drift

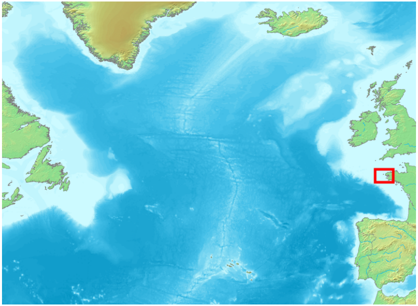
- Pollution
- Search and rescue
- Air-sea fluxes
- Surface transport process



<ins>Methods :</ins>

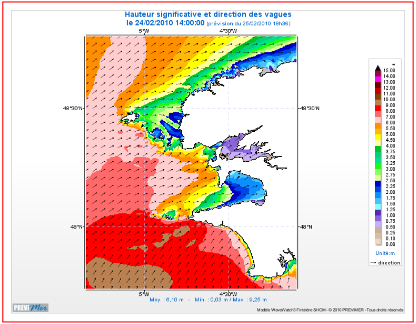
- Whole surface waves spectrum $E(k,\theta)$ given by Wavewatch 3
- 1D water column at one fixed coordinate
- Validation with surface velocity measured by HF radar

Localization and phenomenology of the Iroise sea



North atlantic

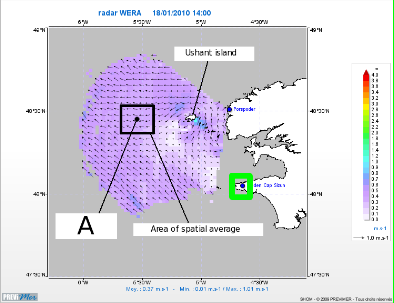
Image from www.demis.nl



Iroise sea

Image from www.previmer.org

- Strong wind : North atlantic depression
- Strong tidal currents
- Extreme waves conditions



Velocity measured by HF radar

Image from www.previmer.org

HF Radar antena

Cléden-Cap-Sizun (© Actimar)

- Use lagrangian surface velocity measured by HF radar for validation *F. Ardhuin & al. [2009]*

$$\overbrace{U_{\text{Lagrangian}}}^{\text{HF Radar}} \approx \overbrace{U_{\text{Quasi Eulerian}}}^{\text{Model}} + \overbrace{U_{\text{Stokes}}}^{\text{Surface waves}}$$

- Hypothesis : horizontal homogeneity in the vicinity of point **A**
- Point **A** : water column, 120 m, time series over 2 years

$$\frac{\partial \mathbf{u}}{\partial t} = \overbrace{-f\mathbf{e}_z \wedge \mathbf{u}}^{\text{Coriolis}} \quad \overbrace{-\frac{\partial}{\partial z}\overline{\mathbf{u}'w'}}^{\text{Mixing by Turbulence}} \quad \overbrace{-g\nabla_H \xi}^{\text{Tide}} \quad \text{Equation for velocities}$$

$$\frac{\partial T}{\partial t} = \underbrace{-\frac{\partial}{\partial z}\overline{\mathbf{w}'T'}}_{\text{Mixing by turbulence}} + \underbrace{\Phi_T(z)}_{\text{Atmospherics flux}} \quad \text{Equation for temperature}$$

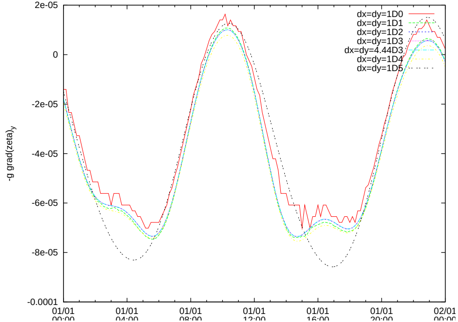
Turbulence feedback : with turbulente viscosity and diffusivity

$$-\frac{\partial}{\partial z}\overline{\mathbf{u}'w'} = \nu_T \frac{\partial}{\partial z}\mathbf{u} \quad \text{in momentum equation}$$
$$-\frac{\partial}{\partial z}\overline{\mathbf{u}'T'} = \kappa_T \frac{\partial}{\partial z}T \quad \text{in temperature equation}$$

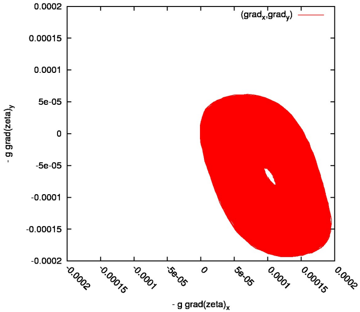
Surface flux of momentum

$$\tau^* = C_{DS}\frac{\rho_{\text{Air}}}{\rho_{\text{Water}}}U_{10}\mathbf{U_{10}} \text{ with } C_{DS} = 1.6\ 10^{-3}$$

Including tide in 1D vertical model



Zonal pressure gradient
Discretization dependencies



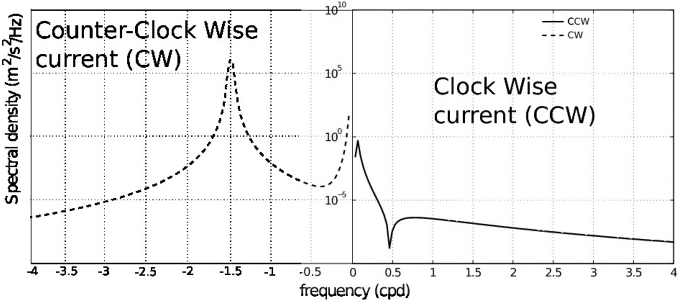
Vector of pressure gradient
01/2007 to 01/2008

The tide pressure $-g\nabla_H \xi$ is computed by finite differences on SSH using CST France from SHOM with 150 main harmonics constituents *R. Le Roy & B. Simon [2003]* $(dx = 1000\ m)$

Wide range of oscillatory phenomenon present at point A

Tide	$\dots$ $M_8 = 89.45\ \mu Hz$ $M_6 = 67.092\ \mu Hz$ $M_4 = 44.72\ \mu Hz$ $M_2 = 22.36\ \mu Hz$ $K_1 = 11.61\ \mu Hz$ $Mf = 847.23\ nHz$ $Mm = 420.03\ nHz$ $\dots$
Radiation of internal gravity waves	$\omega \in\ ]0, O(300)]\ mHz$
Radiation of inertial waves	$\omega \in\ ]0, 17.4]\ \mu Hz$
Mixed inertio-gravity waves	$\omega \in\ ]0, O(300)]\ mHz$
Distortion by shear	?

$\Rightarrow$ spectral analysis



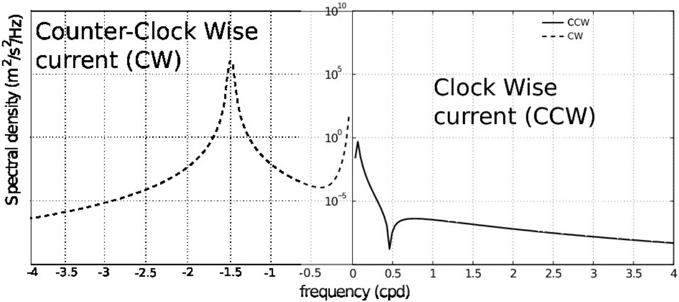
Rotary spectra of a basic Coriolis system with $N_{FFT} = 88$

$$\begin{cases} u(t) = \cos(2\pi ft)u(0) + \sin(2\pi ft)v(0) \\ v(t) = -\sin(2\pi ft)u(0) + \cos(2\pi ft)v(0) \end{cases}$$

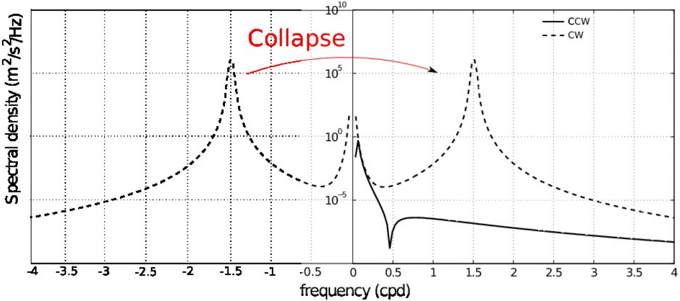
At $\phi = 48.500^\circ$ of latitude and -6.0° of longitude

$f_{Coriolis} = \frac{2\Omega \sin\phi}{2\pi}$ i.e.

$f_{Coriolis} = 17.4\ \mu Hz$ or $f_{Coriolis} = 1.50\ cpd$



We use one sided spectra to compare rotation trend



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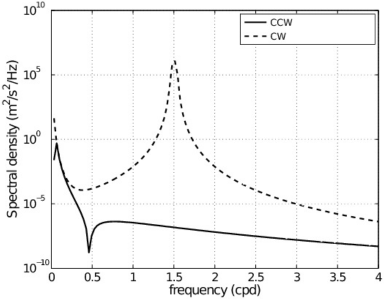
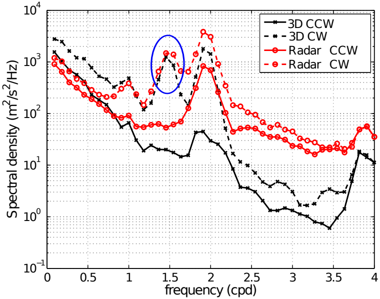
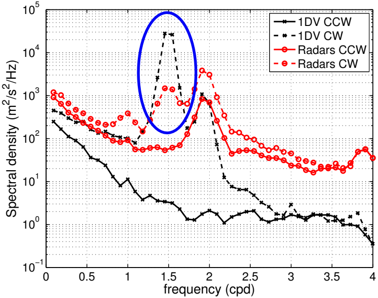


We use one sided spectra to compare rotation trend

Inertial oscillation in 3D and 1D simulation

Same turbulence model, atmopheric forcing, tidal forcing and vertical discretization





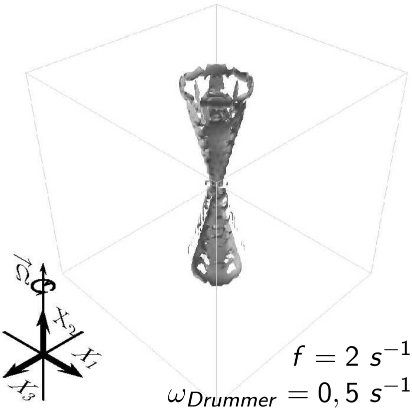
1D code ⇒ well known problem with inertial frequency

R. T. Pollard & R. C. Millard [1969]

G. L. Mellor [2000]

Code MARS3D ⇒ Signature of inertial waves accurate

Inertial wave propagation in 3D



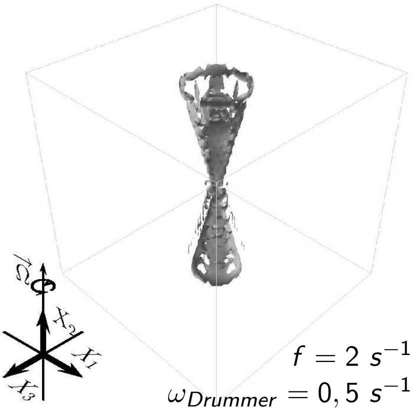
$f = 2\ s^{-1}$

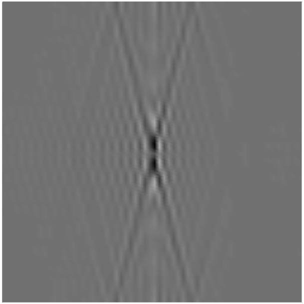
$\omega_{Drummer} = 0,5\ s^{-1}$

Inertial waves as the explanation of over estimation of inertial frequency in 1D oceanic boundary layer model.

Visualization of iso-enstrophy when the rotating fluid is excited by a periodic impulse at the frequency $\omega_{\text{Drummer}} = 0,5$

Inertial wave propagation in 3D





$f = 2\ s^{-1}$

$\omega_{Drummer} = 0,5\ s^{-1}$

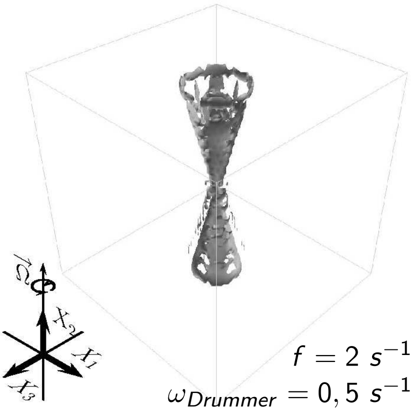
$\omega = \pm 2\Omega \cos\theta$

Theoritical angle 75.52

Measured angle 75.94

Visualization of iso-enstrophy when the rotating fluid is excited by a periodic impulse at the frequency $\omega_{\text{Drummer}} = 0,5$

Inertial wave propagation in 3D



$f = 2\ s^{-1}$

$\omega_{Drummer} = 0,5\ s^{-1}$

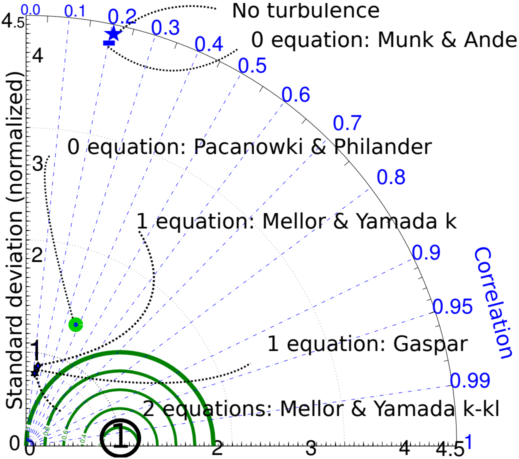
Excitation in real ocean :

Wind ?

Tide ?

Incompatibility of 1D modelling with the nature of the inertial waves
→ 3D anisotropic waves (and inertio-gravity)

Some of tested turbulence models with Taylor diagram



<u>Taylor diagram</u> : polar representation of performance

Radius : Standard deviation normalized

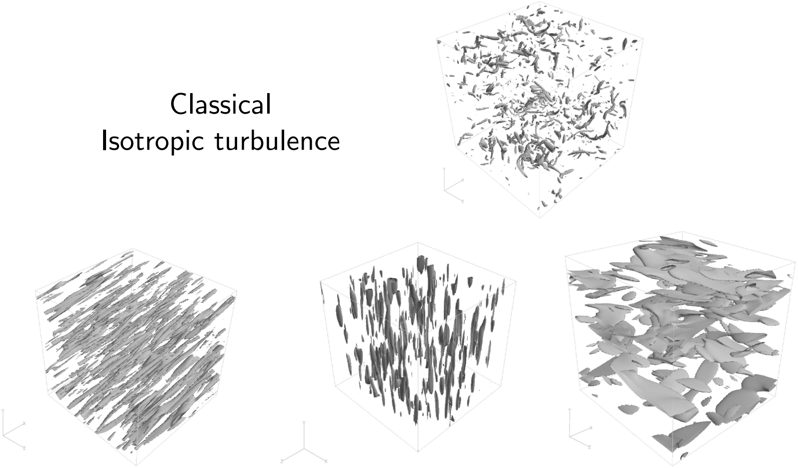
Angle : Correlation coefficien

Distance to ① Unbiased roo mean square difference normalized

Strong dependencie to turbulence model

Why ? ⇒ maybe the anisotropy ?

Why so many differences from one model to another? Because anisotropic turbulence hides a wide range of dynamics



Classical
Isotropic turbulence

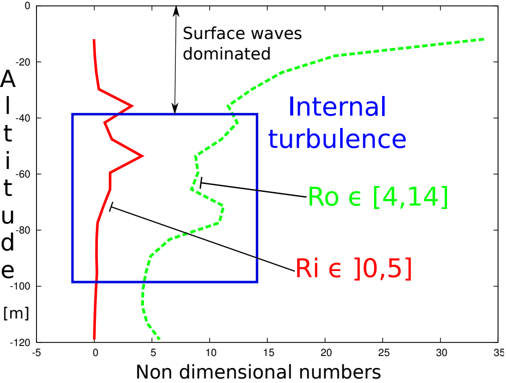
shear S
turbulence

inertial f
waves turbulence

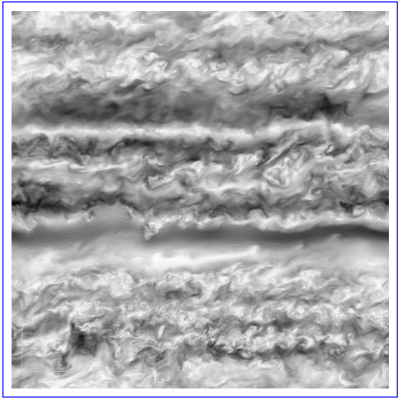
internal gravity N
waves turbulence

Visualization of iso-enstrophy from homogeneous turbulence **D**irect **N**umerical **S**imulation (DNS)

Oceanic turbulence with mean rotation, stratification and shear with DNS



Time averaged profile of $Ro = \frac{S(z)}{f}$ and $Ri = \frac{N(z)^2}{S^2}$. Simulation with 1D code during 3 years in Iroise Sea at point A.



Zonal velocity

$Ro = \frac{S}{f} = 4.94$ $Ri = \frac{N^2}{S^2} = 0,99$

Non-trivial vertical and meridional flux

P. Gaspar & al. [1990] turbulence model

$$\frac{\partial k}{\partial t}\overbrace{-\frac{\partial}{\partial}\left(\nu_T\frac{S_q}{S_M}\frac{\partial k}{\partial z}\right)}^{\text{diffusion}}=\overbrace{\nu_T\left(\left(\frac{\partial u}{\partial z}\right)^2+\left(\frac{\partial v}{\partial z}\right)^2\right)}^{\text{production by mean shear}}-\overbrace{\frac{C_\epsilon k^{3/2}}{l_\epsilon}}^{\text{dissipation}}$$

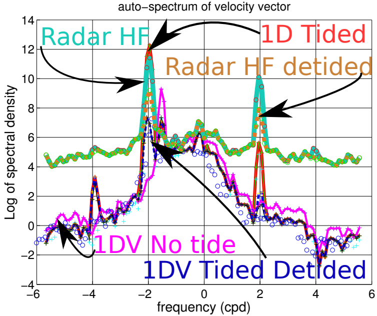
turbulent viscosity $\nu_T = C_k l_k \sqrt{k}$ *and turbulent diffusivity* $\kappa_T = \frac{\nu_T}{Pr}$

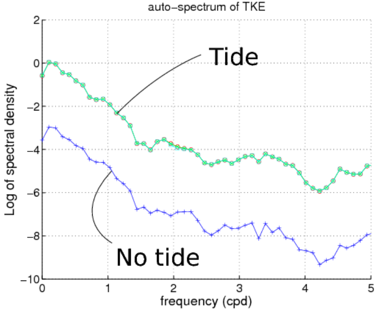
travel upward l_u define by $\frac{g}{\rho_0}\int_z^{z+l_u}[\overline{\rho}(z)-\overline{\rho}(z')]dz' = k(z)$

travel downward l_d define by $\frac{g}{\rho_0}\int_z^{z-l_d}[\overline{\rho}(z)-\overline{\rho}(z')]dz' = k(z)$

energetic scale $l_k = \min(l_u, l_d)$ *and dissipation scale* $l_\epsilon = \sqrt{(l_u\ l_d)}$

- No z_0 for define internal lengths scales
- Successfully used *H. Muller & al. [2007]* and *H. Muller & al. [2010]* in Iroise Sea





01/01/2007 to 01/04/2007

Detiding with r_t_tide *K. E. Leffler & D. A. Jay [2009]*

$\mathbf{u}_{\text{1D No tide}} \neq \text{Detide}(\mathbf{u}_{\text{1D Tided}})$

Frequency analysis of TKE evolution : no significant tidal frequency present, but TKE greater when tide inculded

1D equation with drift Stokes generated by surface waves

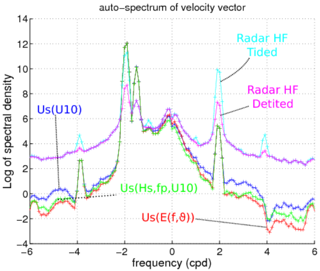
Justification by the generalized Lagrangian Mean :

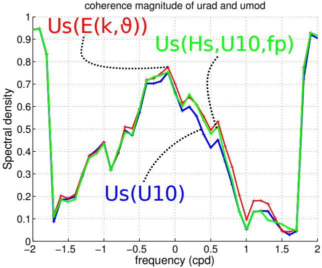
D. G. Andrews & M. E. McIntyres [1978]
F. Ardhuin & al. [2008]

$$\frac{\partial \mathbf{u}}{\partial t} = -f\mathbf{e}_z \wedge \left(\mathbf{u} + \mathbf{U_S}\right) - \frac{\partial}{\partial z}\overline{\mathbf{u}' w'} - g\nabla_H \xi$$

- $\mathbf{U_S} = 4\pi \int_0^{2\pi} \int_0^{\infty} f\ k\ e^{2\ k(f)\ z} E(f,\theta) df d\theta \mathbf{e}_\theta$ *K. E. Kenyon [1969]*
- $\mathbf{U_S} = 0.016\ e^{\frac{(z-h)}{L_w}} \mathbf{U_{10}}$ with $L_w = 0.12\frac{\mathbf{U_{10}}^2}{g}$ *M. Li & C. Garrett [1993]*
- $\mathbf{U_S} = \Big(6.25\ 10^{-4}\mathbf{U}_{10} \min\left\{U_{10}, 14.5\right\}$ $+0.025\ (Hs - 0.4)\mathbf{e}_\theta\ \Big)\ e^{\pi \frac{f_{\text{peak}}}{g}(z-h)}$ *F. Ardhuin & al. [2009]* adapted

Stokes drift : parametrisations or spectral composition ?





Stratified open ocean with Stokes drift in momentum equation following *N. Rascle and F. Ardhuin [2009]*

- $U_S(f,\theta,E(f,\theta))$
- $U_S(U_{10})$
- $U_S(H_S, f_{\mathrm{peak}}, U_{10})$

The Stokes drift based on wind and Hs is more coherent than the one based only on the wind

Modified TKE equation with surface waves

- Production by Stokes drift $Prod_{Stokes}$ in TKE equation :

$$\frac{\partial k}{\partial t} = Diff + Prod_{Mean} + Prod_{Stokes} + Diss$$

1. $Prod_{Stokes} = \nu_T \left(\left(\frac{\partial U_S}{\partial z}\right)^2 + \left(\frac{\partial V_S}{\partial z}\right)^2 \right)$

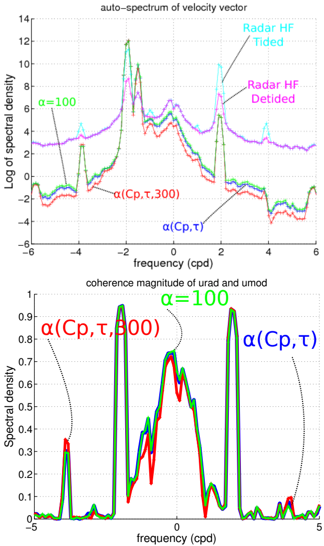
- TKE production by breaking of deep water waves with α parameter at top boundary condition :

$$\frac{\partial k}{\partial z} = \alpha(|\tau_x|^3 + |\tau_y|^3) \text{ at } z = H$$

1. $\boxed{\alpha = 100}$ P. D. Craig & M. L. Banner [1994]
2. $\boxed{\alpha = \frac{\bar{c}}{\sqrt{{\tau_X^*}^2 + {\tau_Y^*}^2}}}$ E. A. Terray & al. [1996]
3. $\boxed{\text{if } \frac{c_{\text{peak}}}{{\tau_X^*}^2 + {\tau_Y^*}^2} < 300 \text{ then } \alpha = \frac{\bar{c}}{\sqrt{{\tau_X^*}^2 + {\tau_Y^*}^2}} \text{ else } \alpha = 150}$

$$c_{\text{peak}} = \frac{g}{2\pi \underbrace{f_{\text{peak}}}_{\text{Peak frequency}}} \text{ and } \bar{c} = \frac{g}{2\pi \underbrace{f_{\text{Mean}}}_{\text{Mean frequency}}}$$

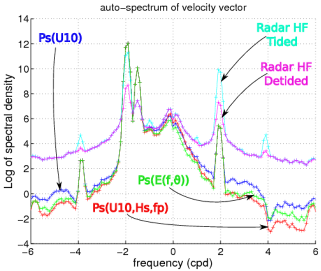
What about white caps parametrisation ?

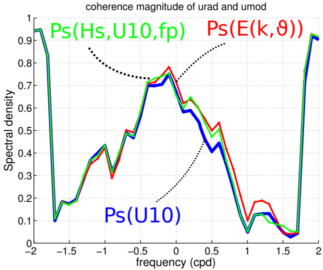


Stratified oceanic mixed layer following *Y. Noh [1996] Y. Noh & H. J. Kim [1999] N. Rascle & F. Ardhuin [2009]*

Creation of turbulence by breaking surface waves based on E. A. Terray & al. [1996] are less energetic that the one of P. D. Craig & M. L. Banner [1994]

Production of TKE by Stokes drift



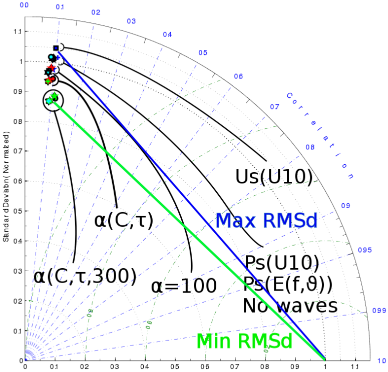


Why ?

- Langmuir cell due to non-linear interaction between the Stokes drift and the vertical shear *A. D. D. Craik & S. Leibovich [1976]* .

Parametrisation based on sea state increase the coherence and the energy in low frequency and decrease the energy in height frequency.

Overview of sea states parametrisations with 37 runs



Correlation coefficient around $R \approx 0.1 \rightarrow$ Not a problem with waves parametrisation but with the overestimation of inertial frequency in 1D modelling

The better normalized RMS difference is obtained for model with $\alpha(\overline{c}, \tau^*, 300)$ parametrisation.

Overview of sea states parametrisations with 37 runs

	Parametrisation	STDd
1	$\alpha(\overline{c}, \tau^*, 300)$ & $Prod_{Stokes}(E(f,\theta))$	0.31547
2	$\alpha(\overline{c}, \tau^*, 300)$ & $U_S(E(f,\theta))$	0.31694
3	$\alpha(\overline{c}, \tau^*, 300)$ & $U_S(E(f,\theta))$ & $Prod_{Stokes}(E(f,\theta))$	0.31694
4	$\alpha(\overline{c}, \tau^*, 300)$ & $Prod_{Stokes}(U_{10})$	0.31761
	...	
32	WITHOUT WAVES PARAMETRISATION	0.33884
33	$Prod_{Stokes}(Hs, U_{10}, f_p)$ & $U_S(Hs, U_{10}, f_p)$	0.33897
34	$\alpha = 100$ & $U_S(U_{10})$ & $Prod_{Stokes}(U_{10})$	0.33946
35	$\alpha = 100$ & $U_S(U_{10})$	0.33946
36	$U_S(Hs, U_{10}, f_p)$	0.33998
37	$U_S(U_{10})$	0.34111

$$STDd = \sqrt{\overline{(v_{Model} - v_{Radar} - (\overline{v}_{Model} - \overline{v}_{Radar}))^2}}$$

Conclusion

- In Iroise sea adding U_{Stokes}, $Prod_{\mathrm{Stokes}}$ and α increase the accuracy
- Coherent parametrization needed
- For breaking surface waves : best formulation $\alpha(\overline{c}, \tau^{*}, 300)$
- $U(z, Hs, U10, f_{peak})) \Rightarrow$ representative of the spectral based

Work in progress

- Link the C_{DS} of velocity boundary condition to the sea states
- Fit more precisely vertical dependency of the Stokes drift
- Evaluate the surface rugosity lenght scale z_0 induces by this sea state parametrisations
- 3D implementations and analysis

Thank you for your attention