Excitation of Internal Gravity Waves through mixed layer turbulence

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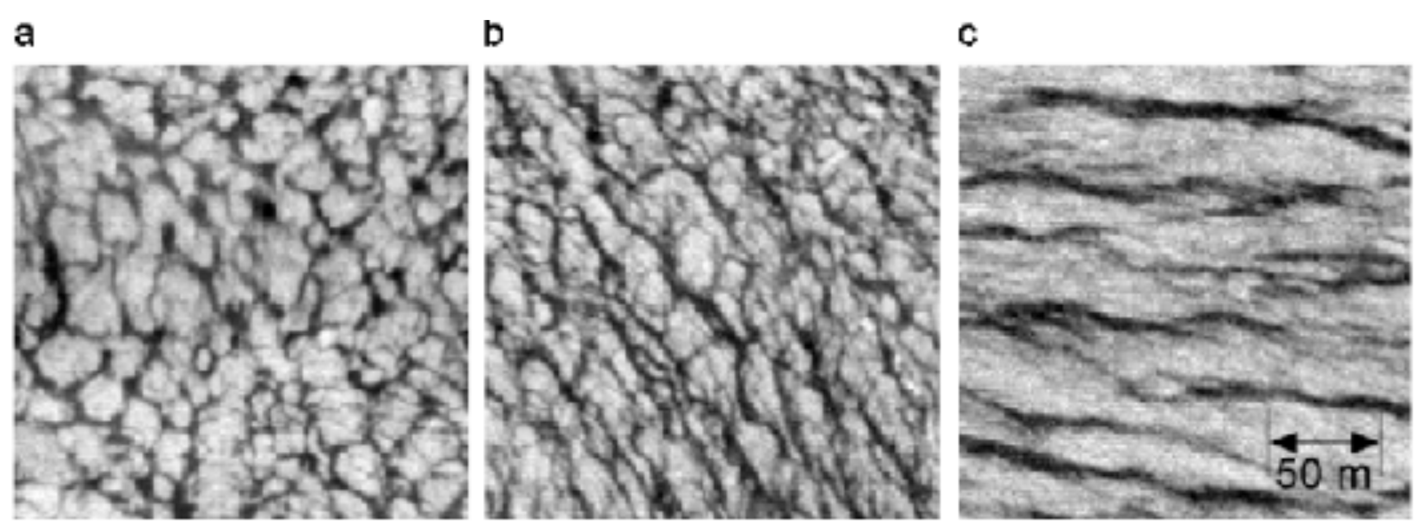
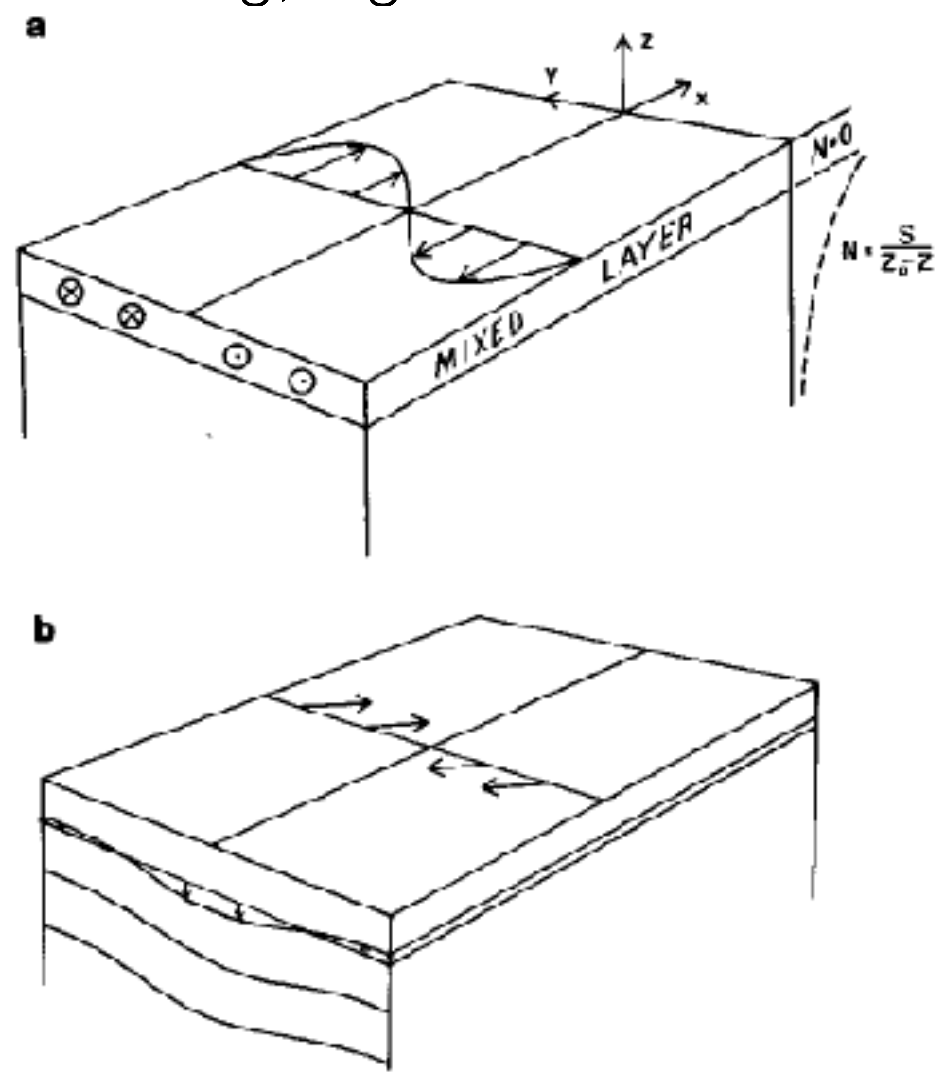


Marmorino et al. 2009

Mechanisms: inertial pumping

1. divergent Inertial Oscillation , caused by horizontally divergent forcing, e.g. in a wake of a storm.

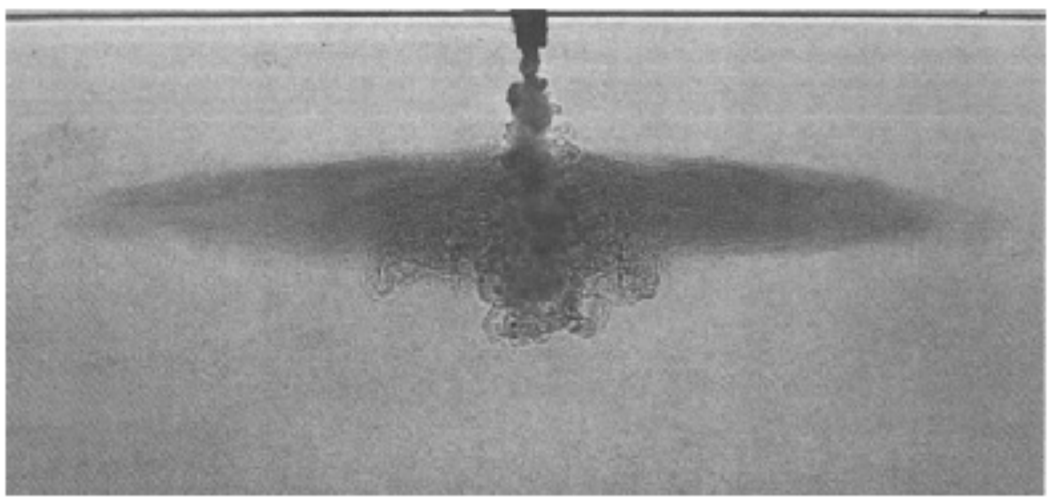


Gill, 1984

~ 5% to 30% of the near inertial energy surface flux penetrates below the mixed layer [Furuichi et al.(2008), Zhai et al.(2009), Rimac et al.(2016), Jurgenowski et al.(2017)]

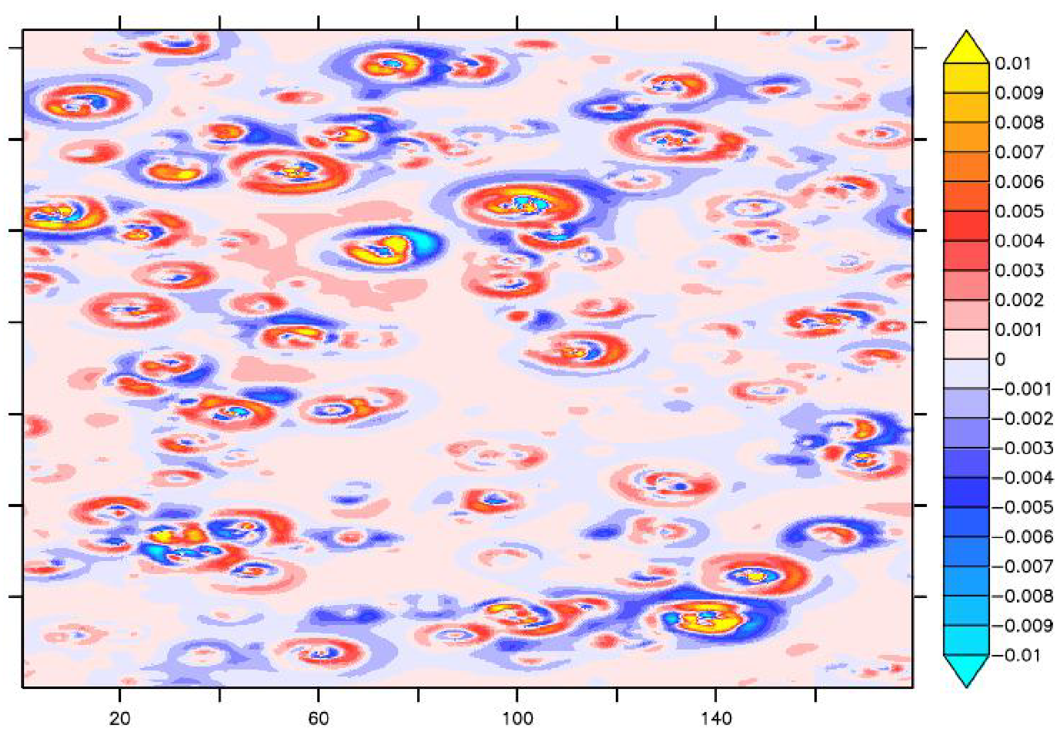
Mechanisms: mechanical oscillator

2. overshooting of a descending plume
   which penetrate into the stratified interior



Turner (1986)

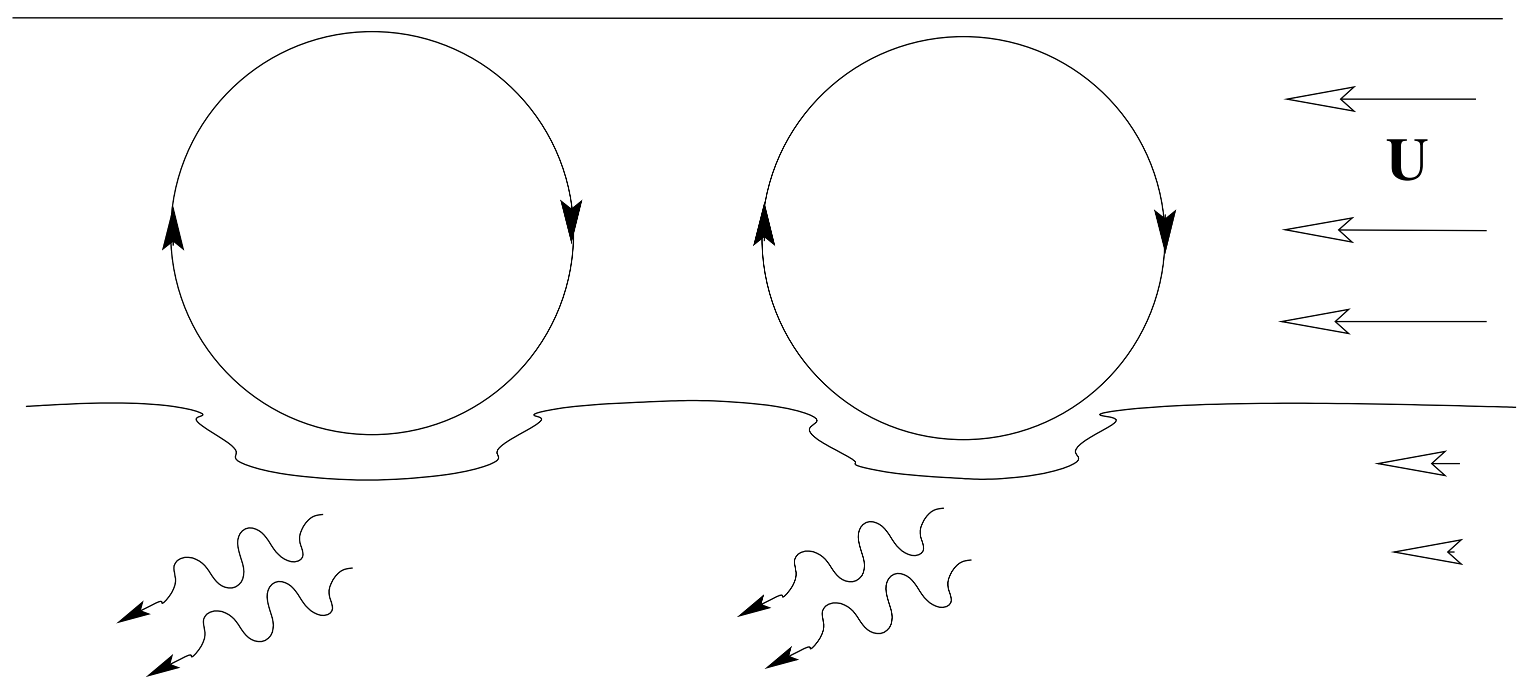
LES simulation of free convection.
T ' at the base of the mixed layer



<- Lx = 180 m ->

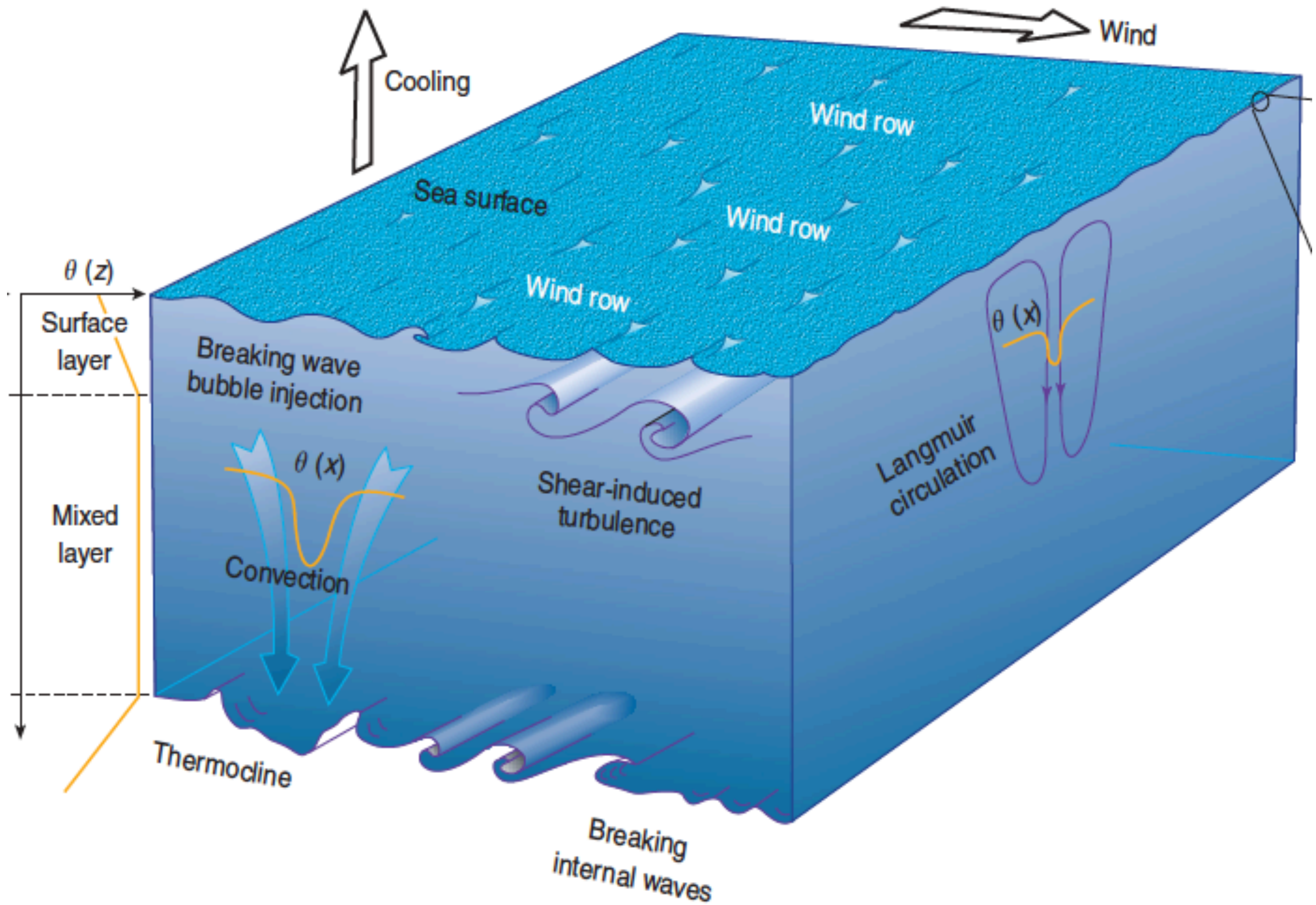
Mechanisms: obstacle effect

3. turbulent eddies cause bumps at the base of the mixed layer. Velocity shear at the base will then disturb underlying stratified ocean.



Bell (1978), Polton et al.(2008)
Gayen et al., (2010) for BBL

coherent structures (obstacles) in the mixed layer



Moum and Smyth, 2008

LES model

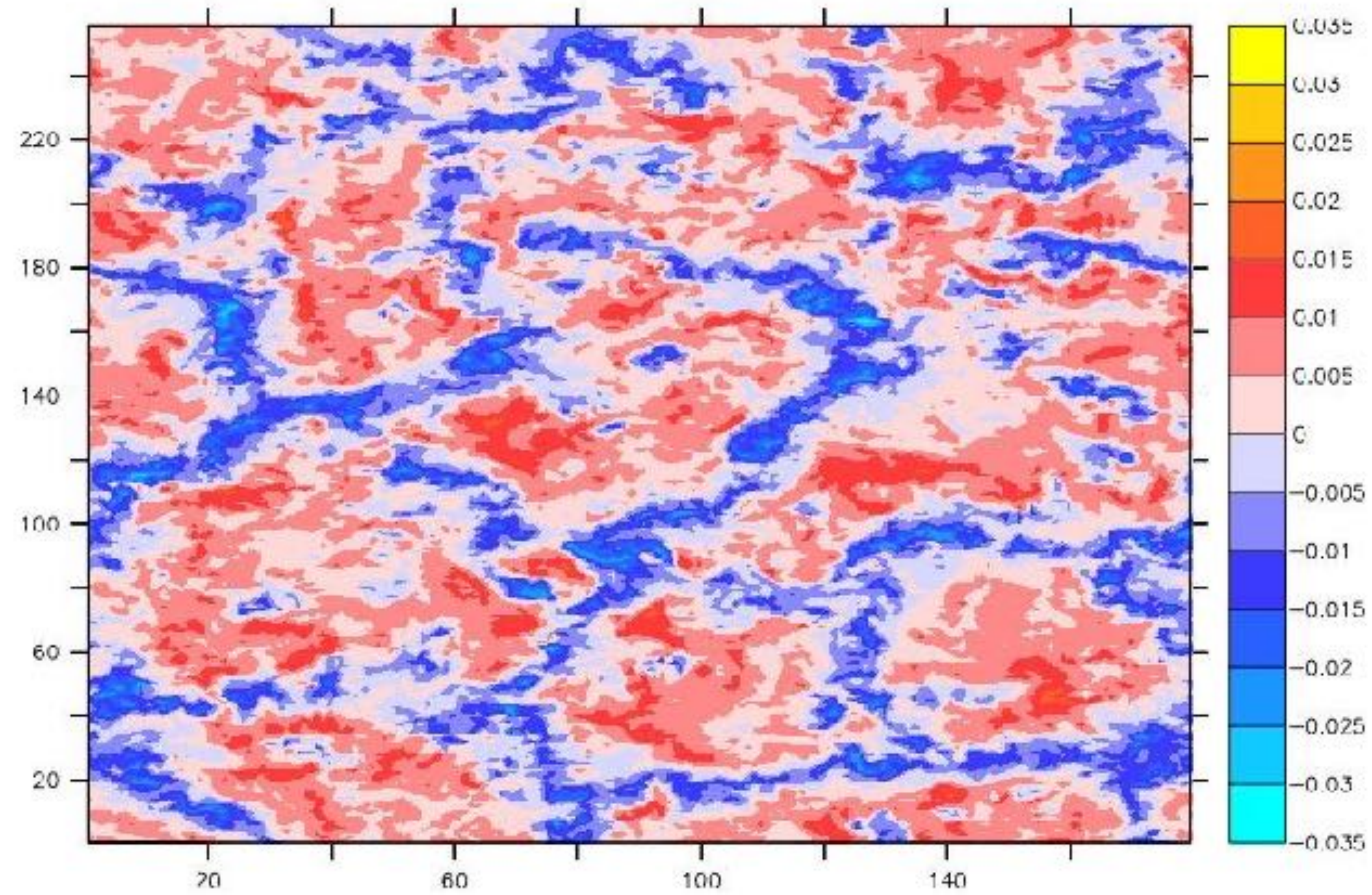
- Mitgcm, (prognostic subgrid-TKE, diagnostic λ)
- $180 \times 520 \times 120$ grid points
- $dx = dy = 1m$, $dz = 0.25m$ to $0.5m$
- $N^2 = 1.2e^{-4}\frac{1}{s^2}$ below a mixed layer depth $D(t_0 = 0) = -30m$
- constant f , inertial period = 1d

Forcing

- const zonal windstress $\tau_x = 0.08\frac{N}{m^2}$
- const heat loss $W = 100\frac{W}{m^2}$
- Monin-Obukhov lengthscale $L_{MO} = -36.5m$
- homog. Langmuir -/ Craik-Leibovich forcing

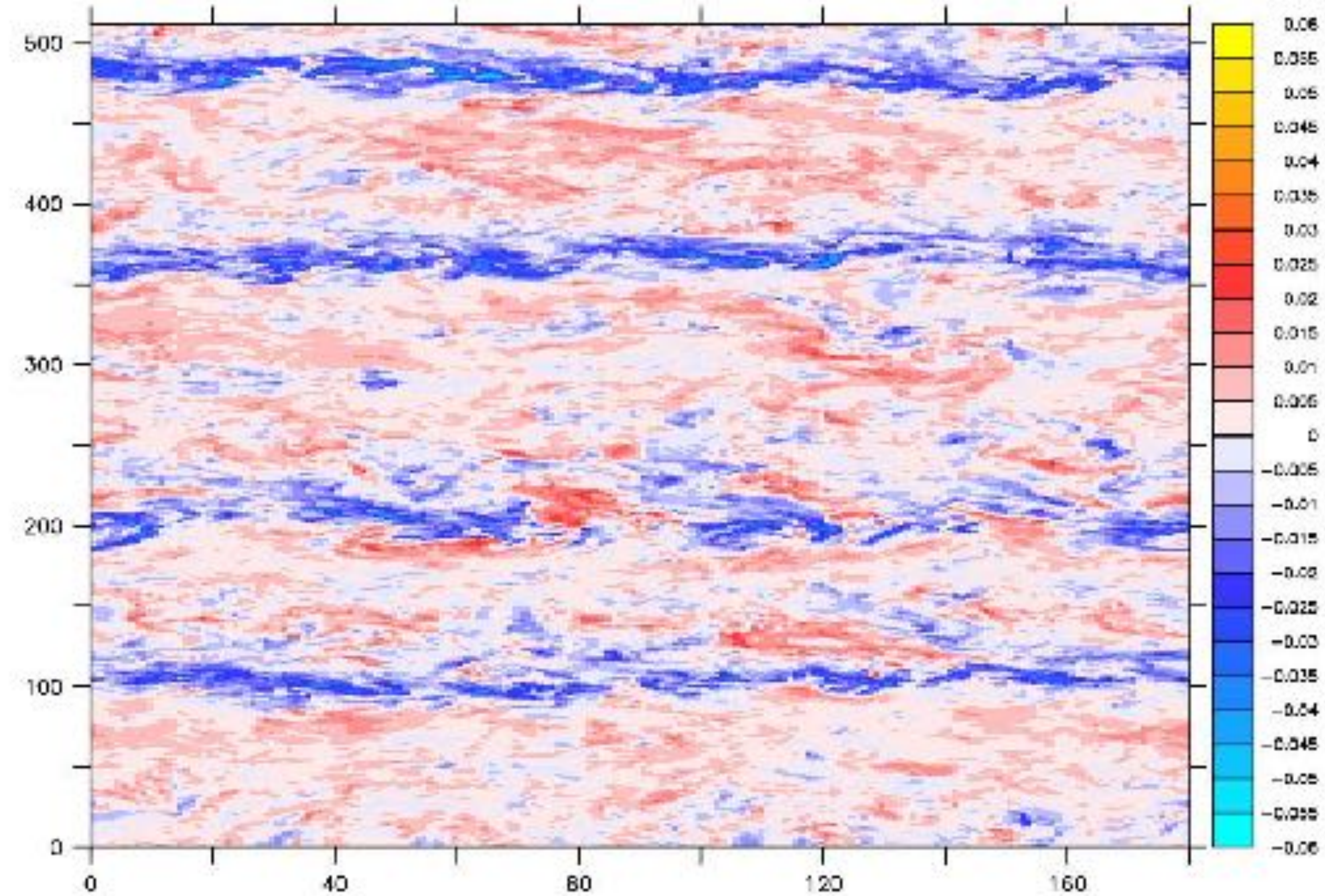
Experiment	**C**ooling	**W**indstress	**L**angmuir
C+W	X	X	
C	X		
W		X	
W+L		X	X
C+W+L	X	X	X

‘free’ convection

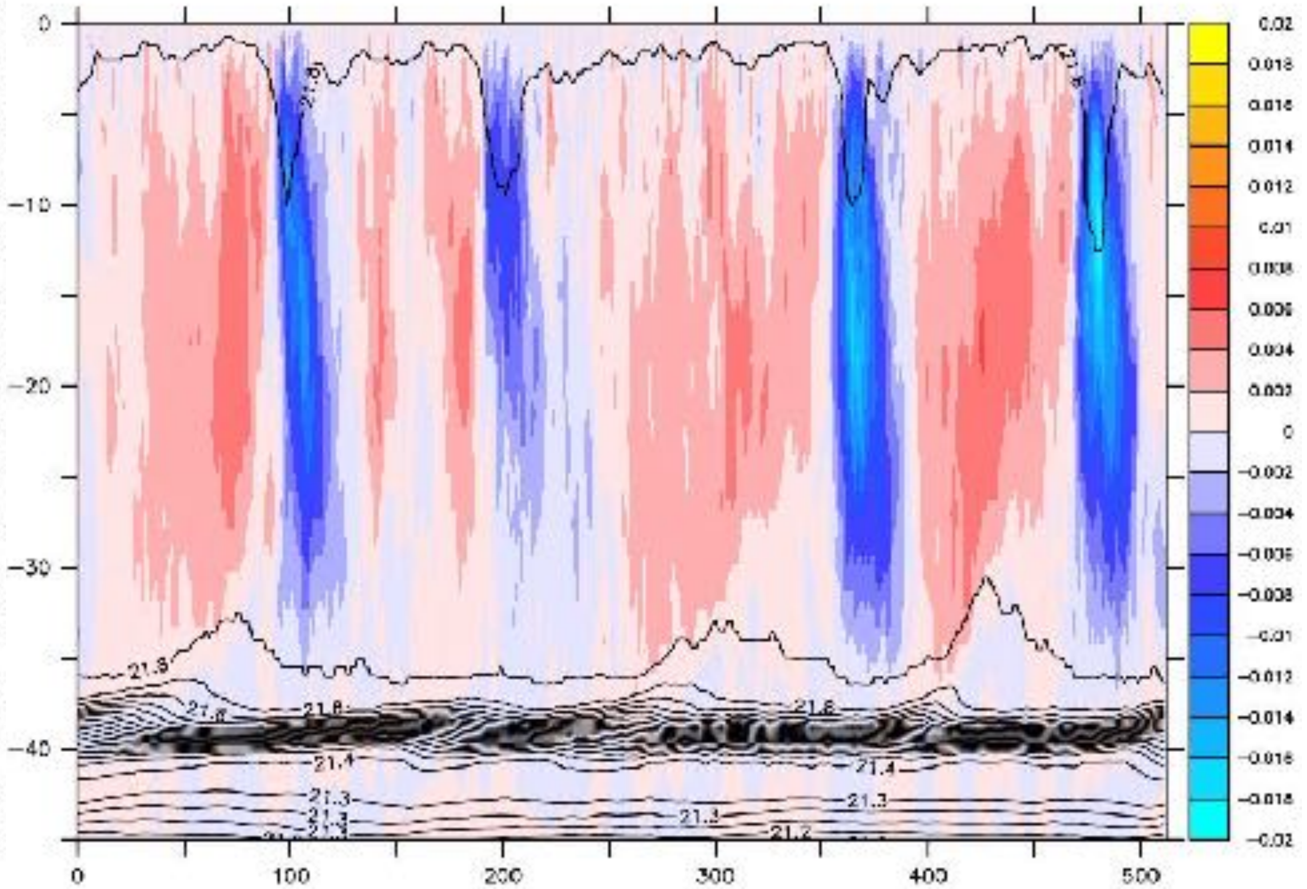


w at z/D = 0.5

Combined effect of wind stress and cooling

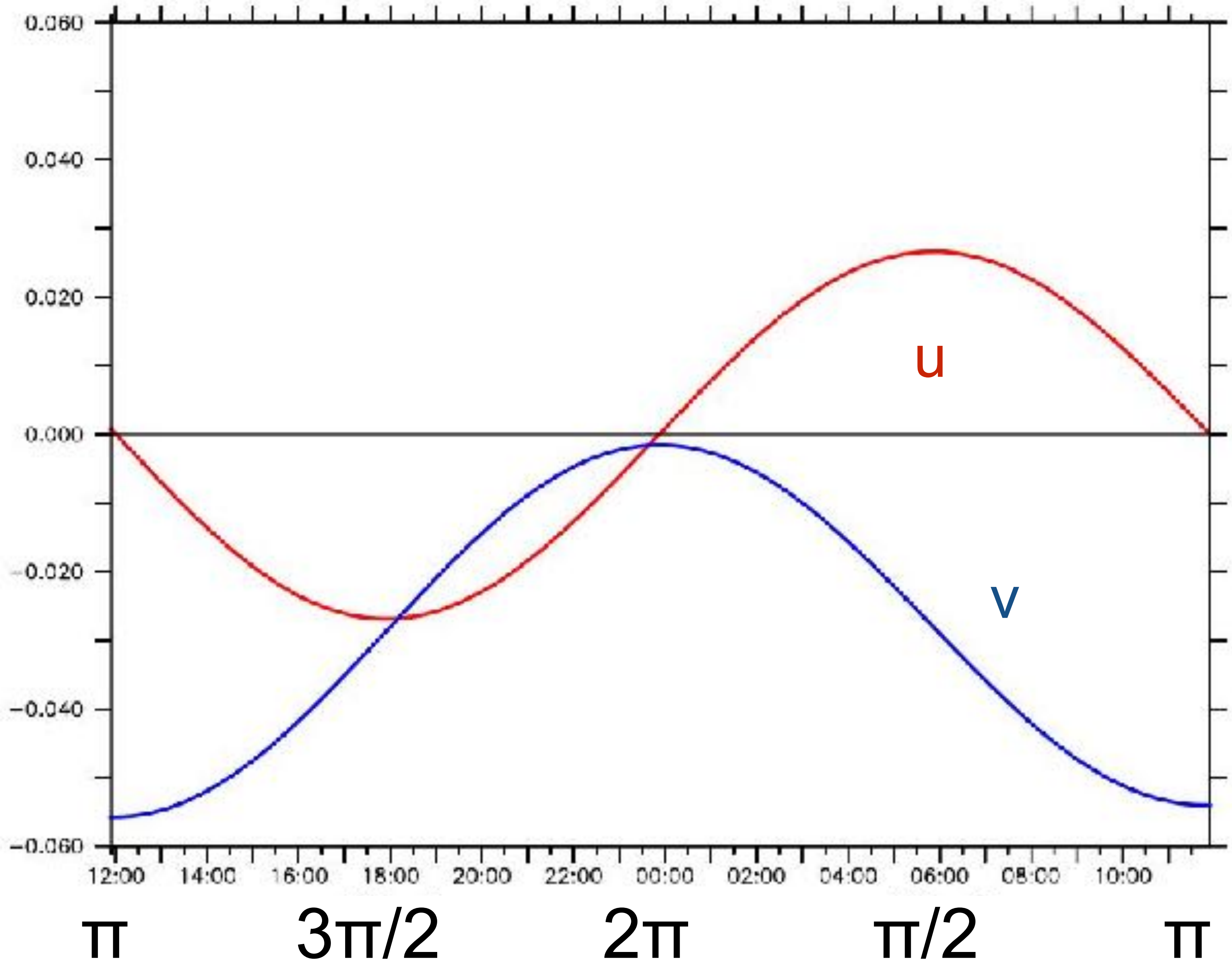


w at z/D = 0.5



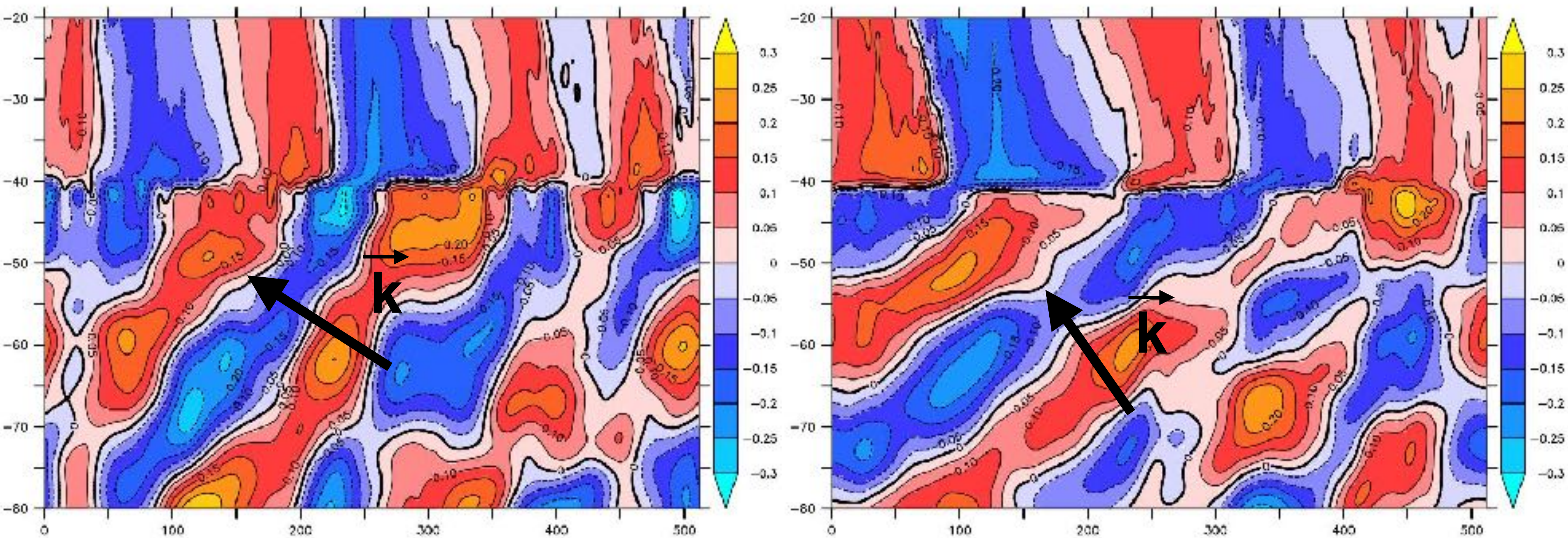
zonally averaged w
and temperature contours

Mean mixed layer velocities



Zonally averaged pressure anomalies

at t = π　　　　　　　　at t = π/2



$$\omega \approx \boldsymbol{U_{mxl}} \cdot \boldsymbol{k_h}$$

$$\omega^2 = N^2 \cos^2\phi + f^2 \sin^2\phi$$

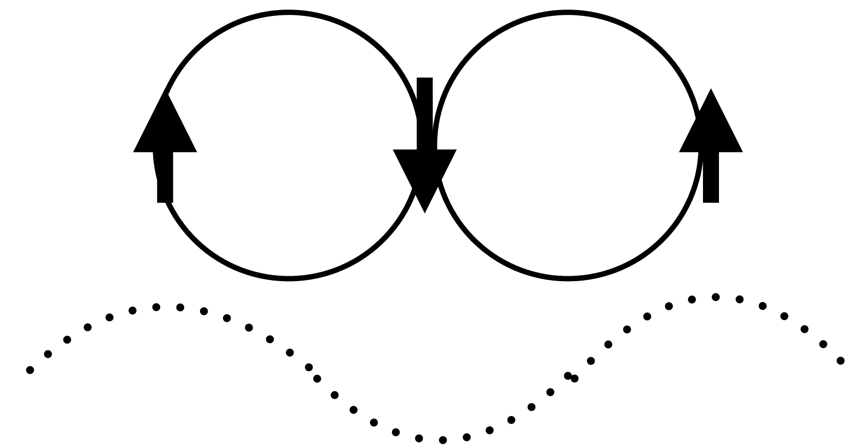
$$\phi(\pi) = 76.3^\circ\ ,\ \phi(\pi/2) = 84.3^\circ$$

$$0.002 = \frac{f}{\boldsymbol{k_h}} < \boldsymbol{U_{mxl}} < \frac{N}{\boldsymbol{k_h}} = 0.3$$

What sets eddy size / hor. wavelength of IW ?

assumption:

$$k_h D = \pi$$
$$\lambda_h = 2D$$



Exp	D (t=0)	number of roll vortices	hor. wavelength (m)	2D (m)
C+W	15.0	12	85	30
C+W	30.0	6/8	170/127	60
C+W	60.0	4/6	256/170	120
Couette (no f)	30.0	16	64	60

What sets eddy size / hor. wavelength of IW ?

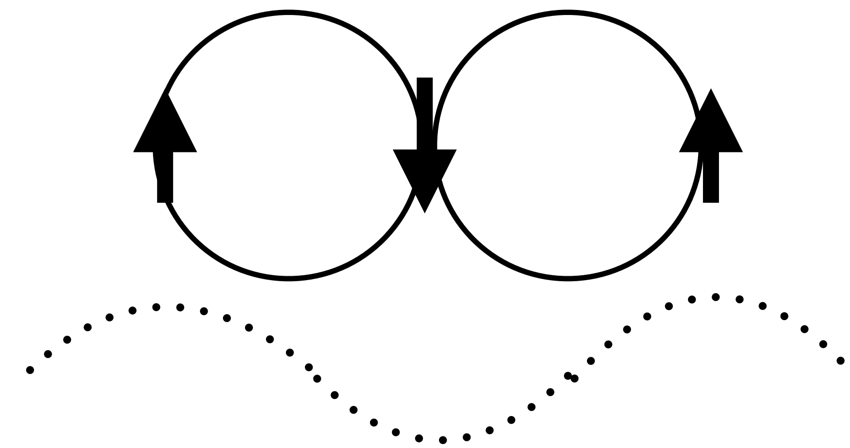
new scaling:

$$\lambda_h = 2D + T^* \int_{z=-D}^{0} \frac{\partial v}{\partial z} dz$$

$$T^* = \frac{D}{u^*} \; or \; \frac{D}{w^*}$$

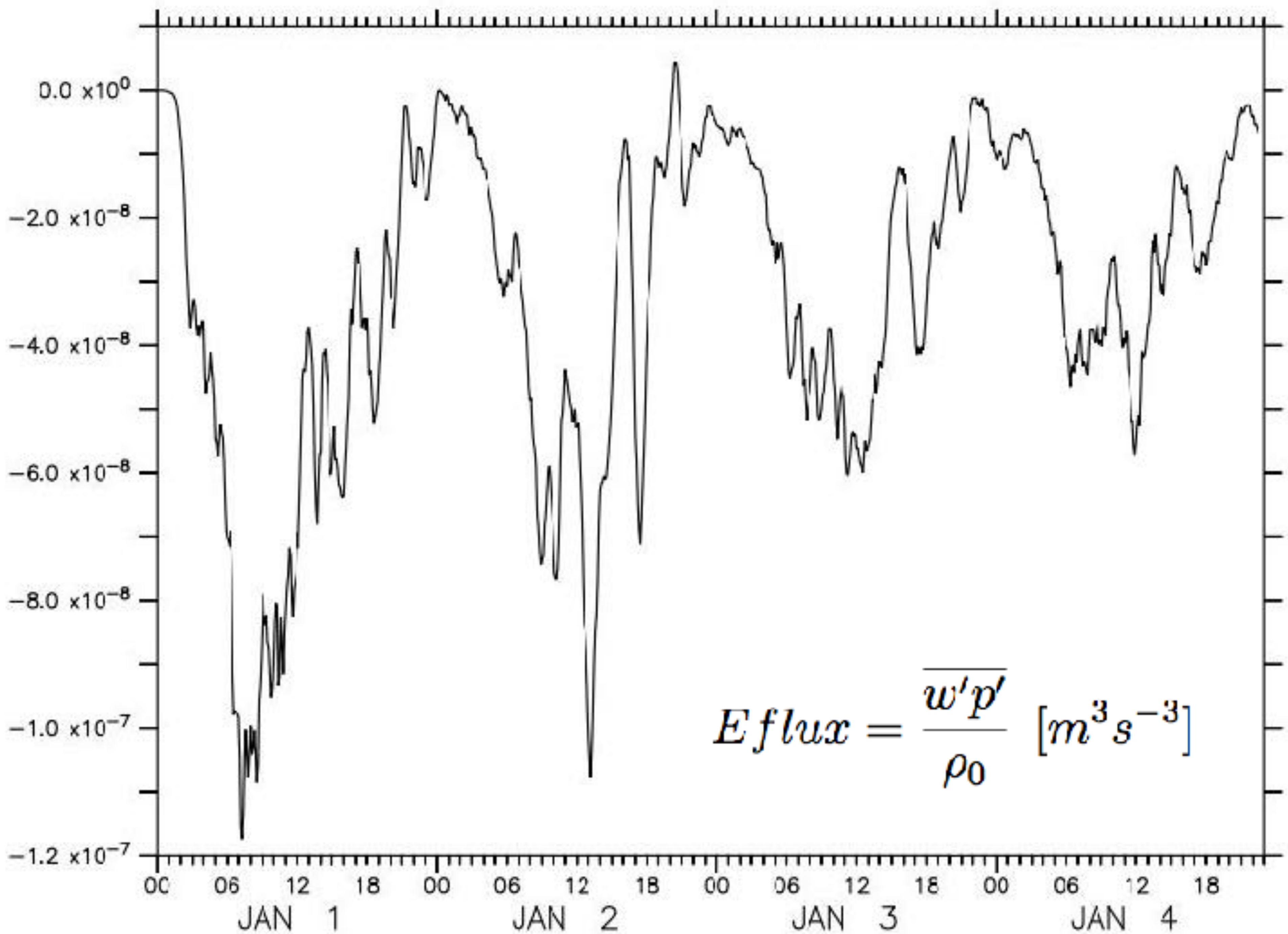
$$u^* = \sqrt{\tau/\rho_0}$$

$$w^* = (D\,\overline{w'b'}_{z=0})^{\frac{1}{3}}$$



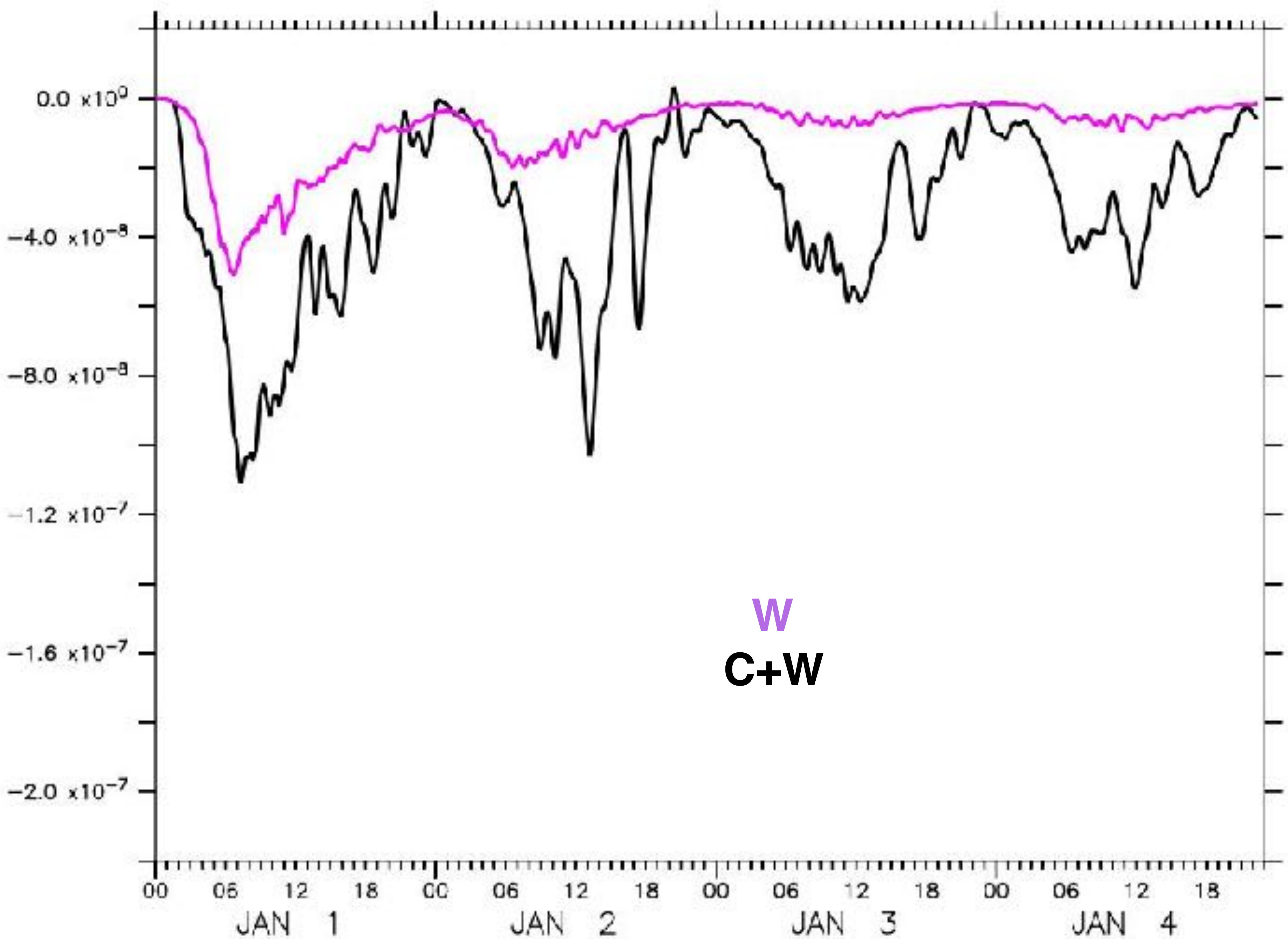
Exp	D (t=0)	number of roll vortices	hor. wavelength (m)	new scaling (m)
C+W	15.0	12	85	60 - 75
C+W	30.0	6/8	170/127	120 - 150
C+W	60.0	4/6	256/170	240 - 300
Couette (no f)	30.0	16	64	60

Internal wave energy flux



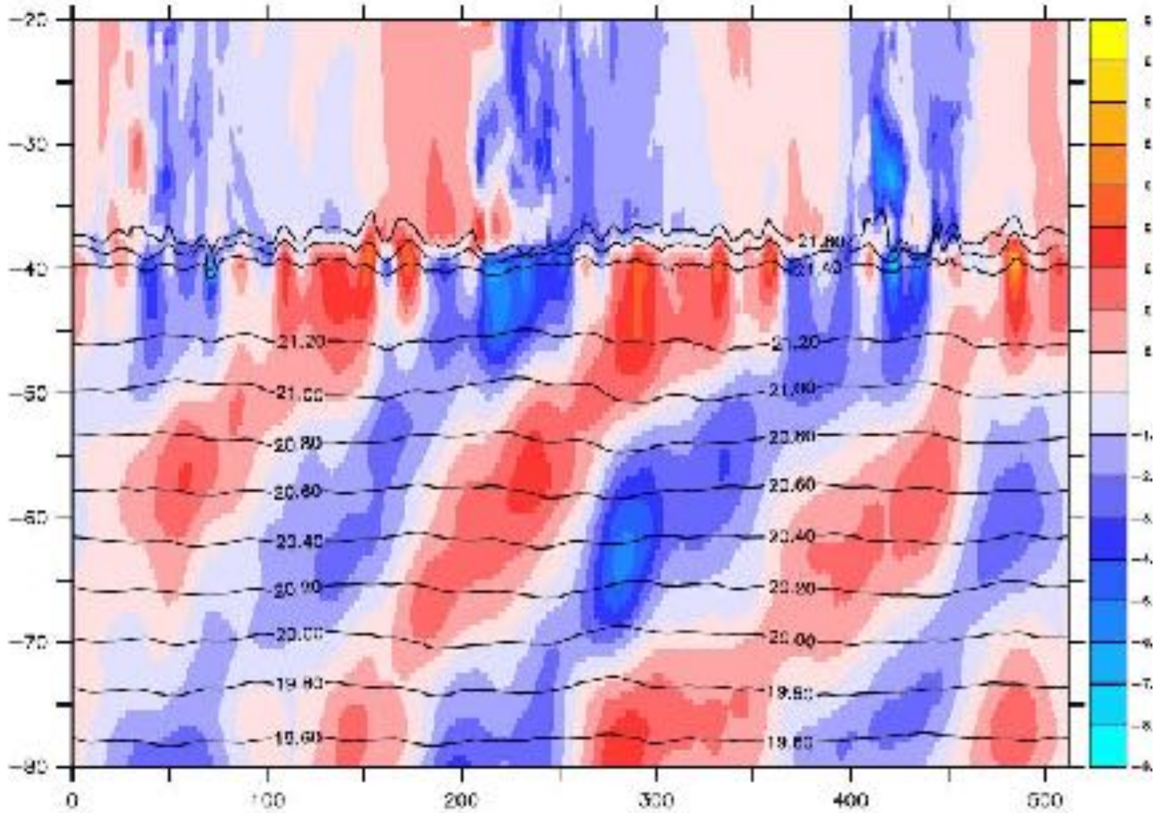
$z = -55m$

Internal wave energy flux



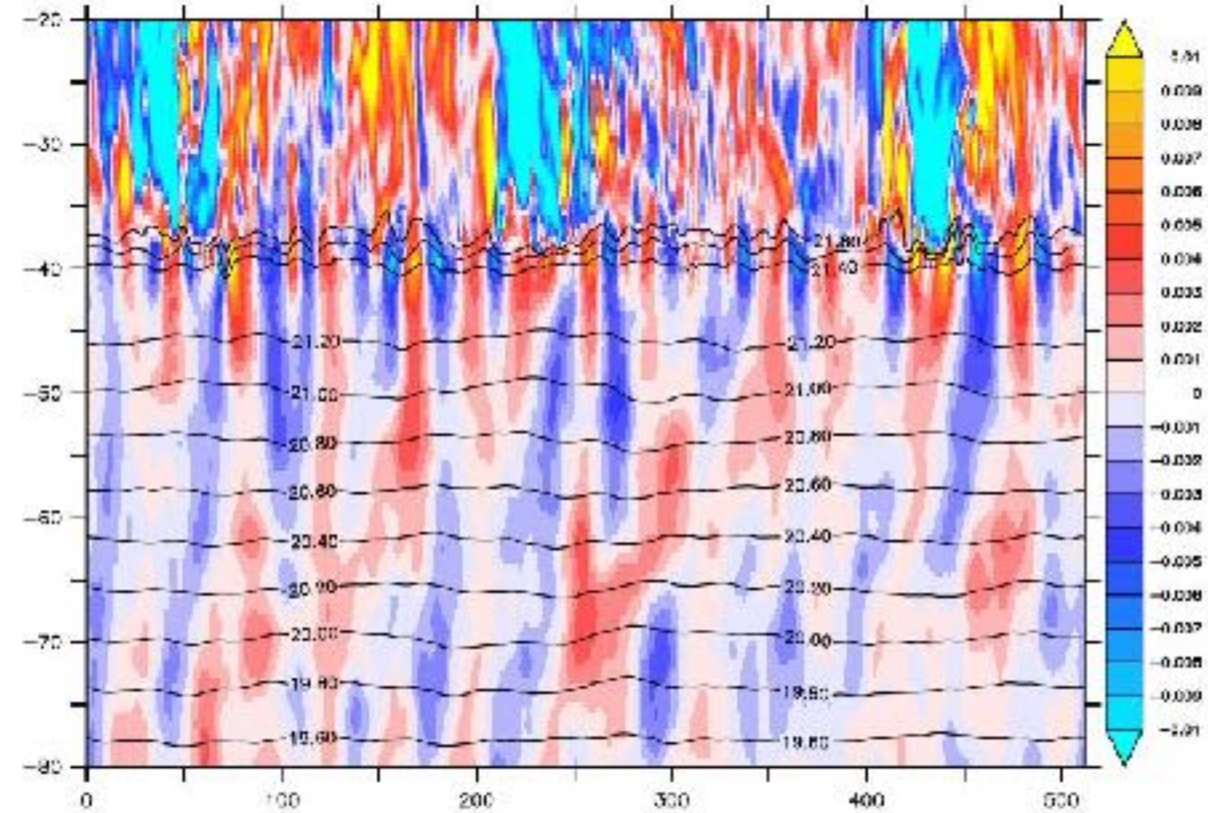
Two distinct wavelength regimes

P’



$\lambda_h \approx 120m - 180m,\ \phi \approx 75^\circ - 90^\circ$

W’



$\lambda_h \approx 35m,\ \phi \approx 35^\circ - 45^\circ$

Amplitude ratio from polarisation equations:

$$\mathcal{A}_w = -i\omega\,\mathcal{A}_\zeta$$

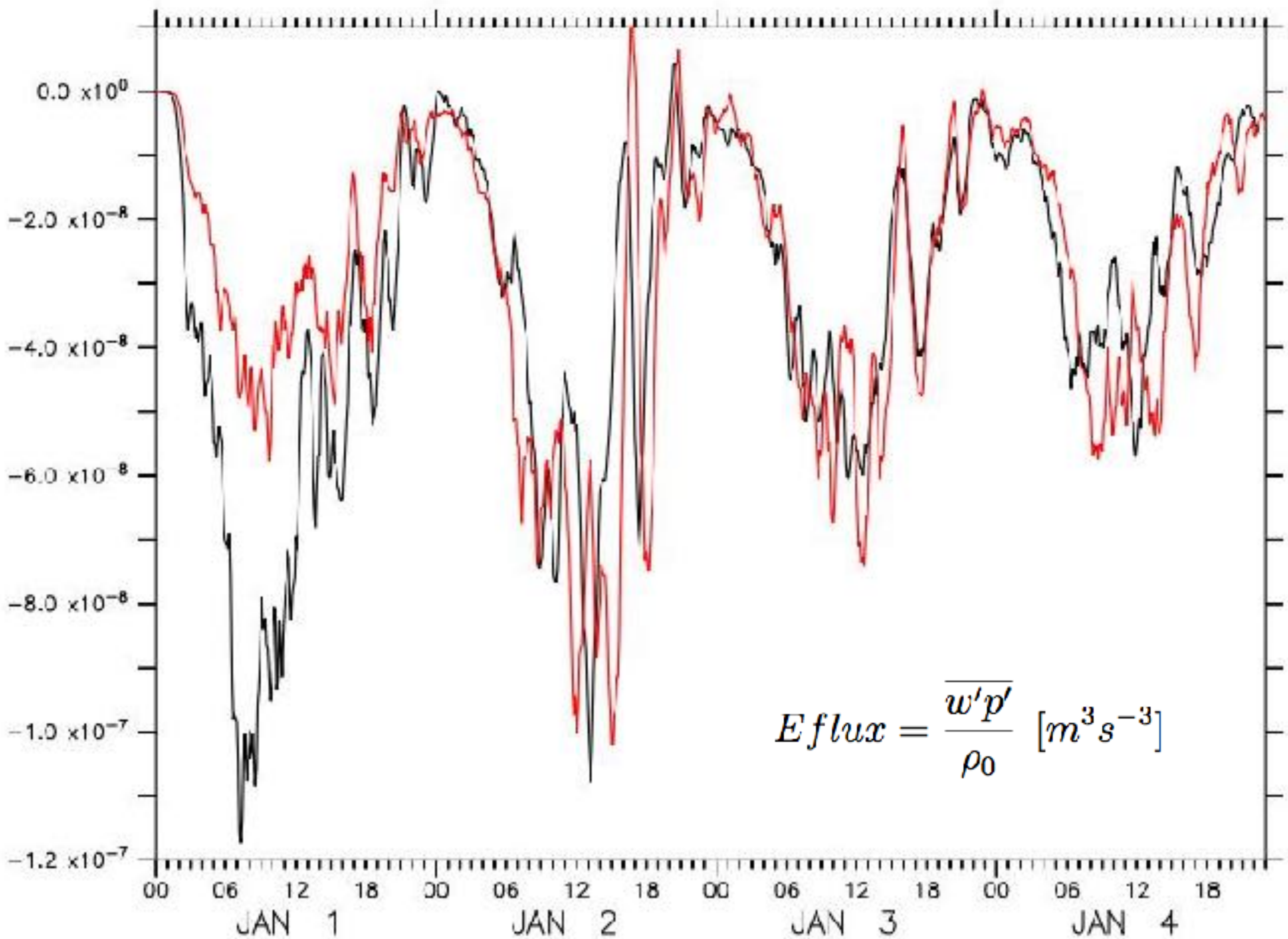
$$\mathcal{A}_p = i\rho_0\omega^2 k_x k_z^{-2}\,\mathcal{A}_\zeta$$

$$\frac{\mathcal{A}_p}{\mathcal{A}_w} = -\rho_0 N k_x^{-1}\sin(\phi)$$

$$\max(\overline{\boldsymbol{u}'w'})\ at\ \phi = 45^\circ$$

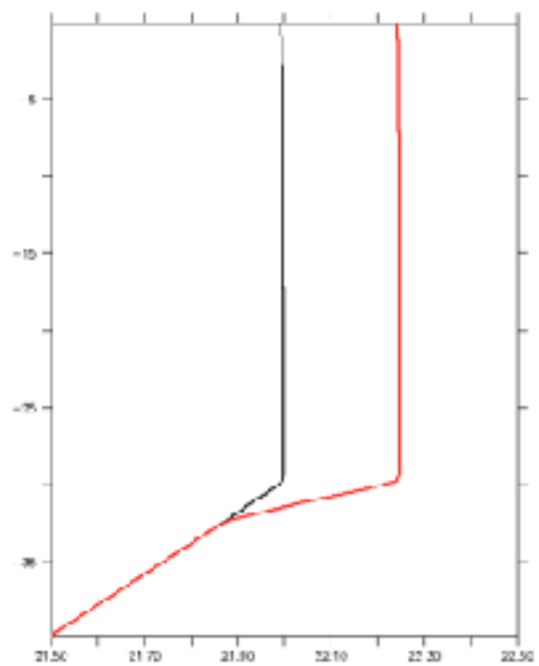
$$\max(cg_z)\ at\ \phi = 35^\circ$$

Effect of transition layer:

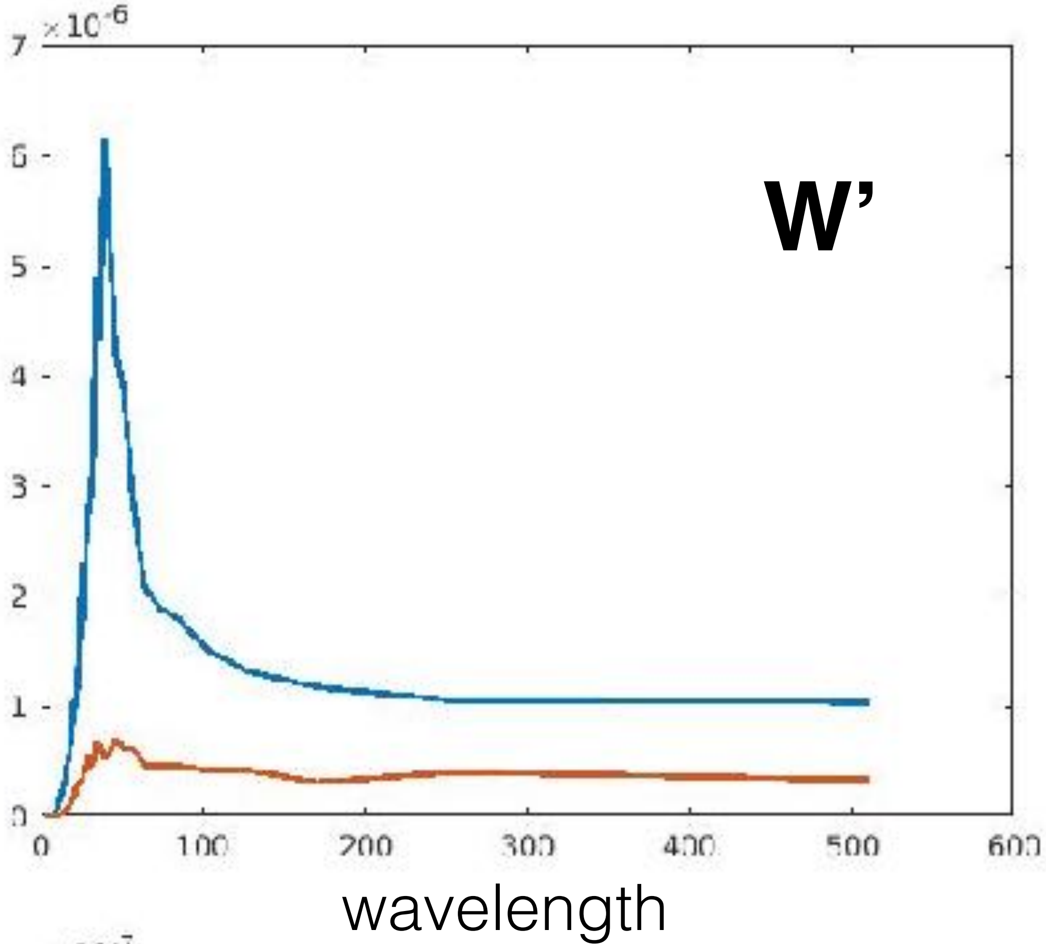


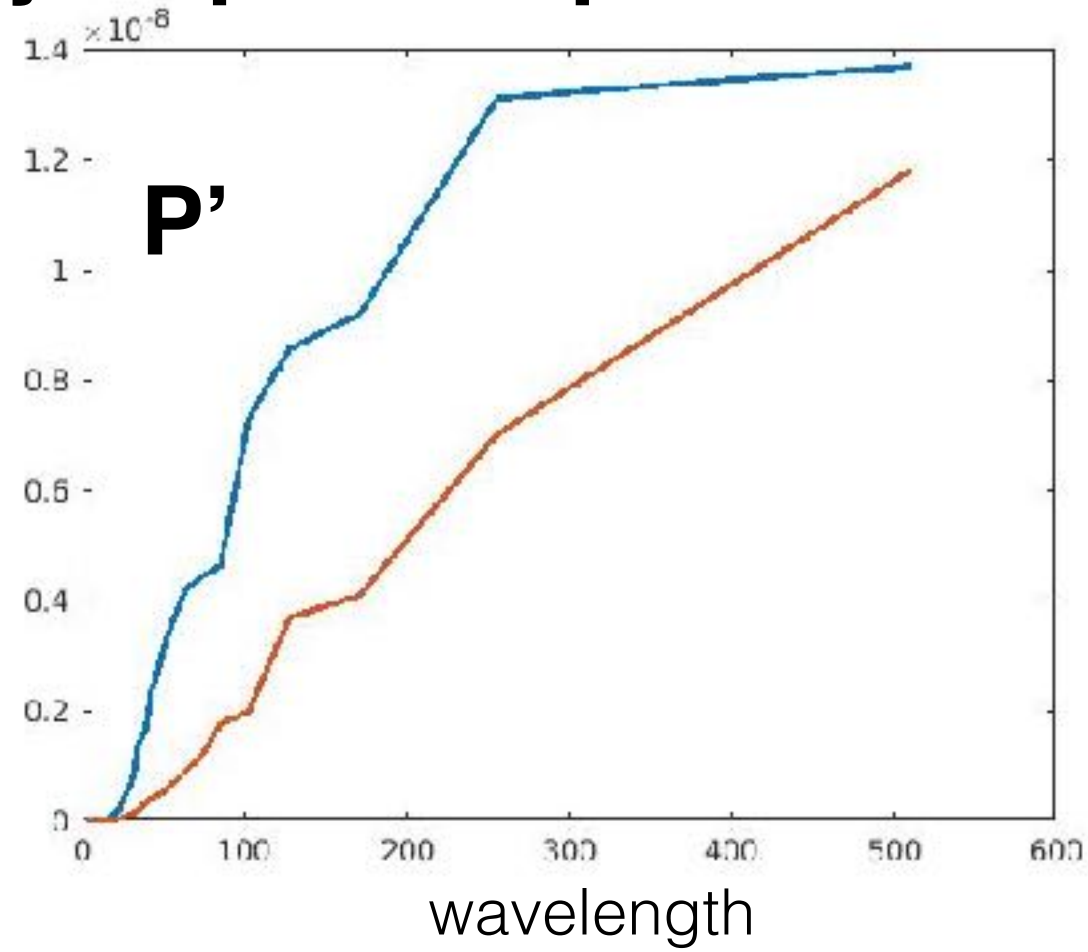
$z = -55m$

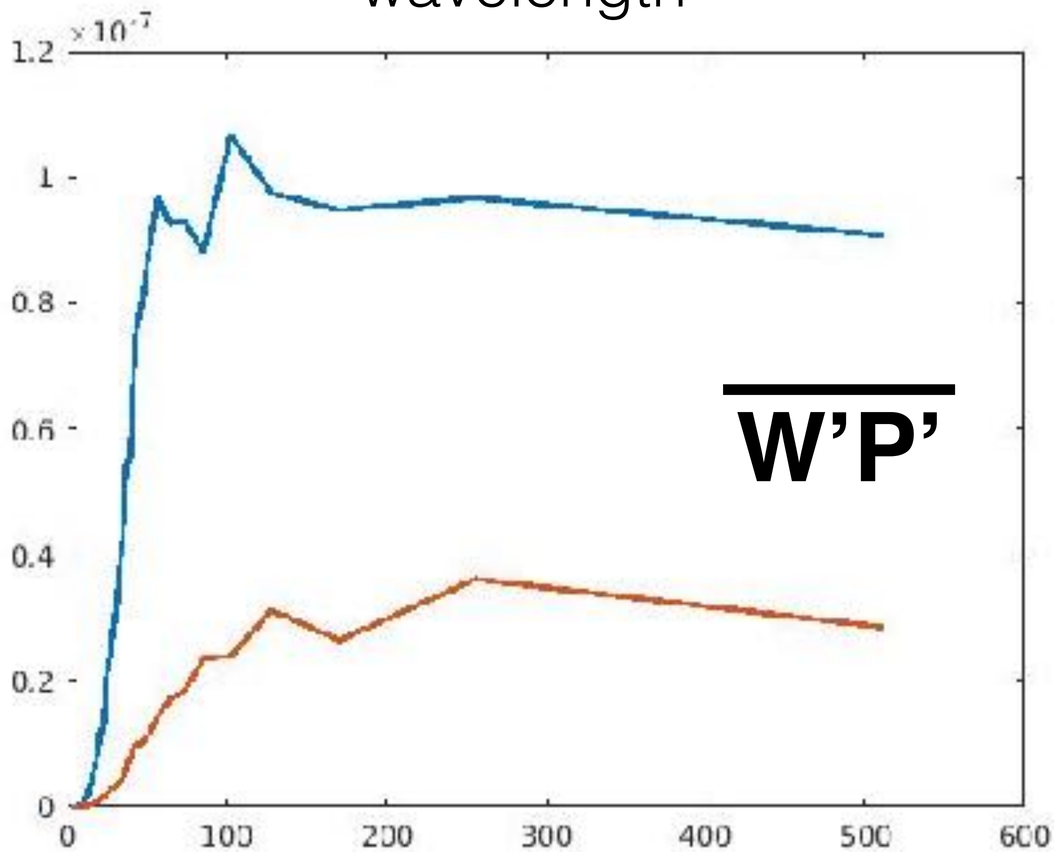
exp C+W



Effect of transition layer: power spectra





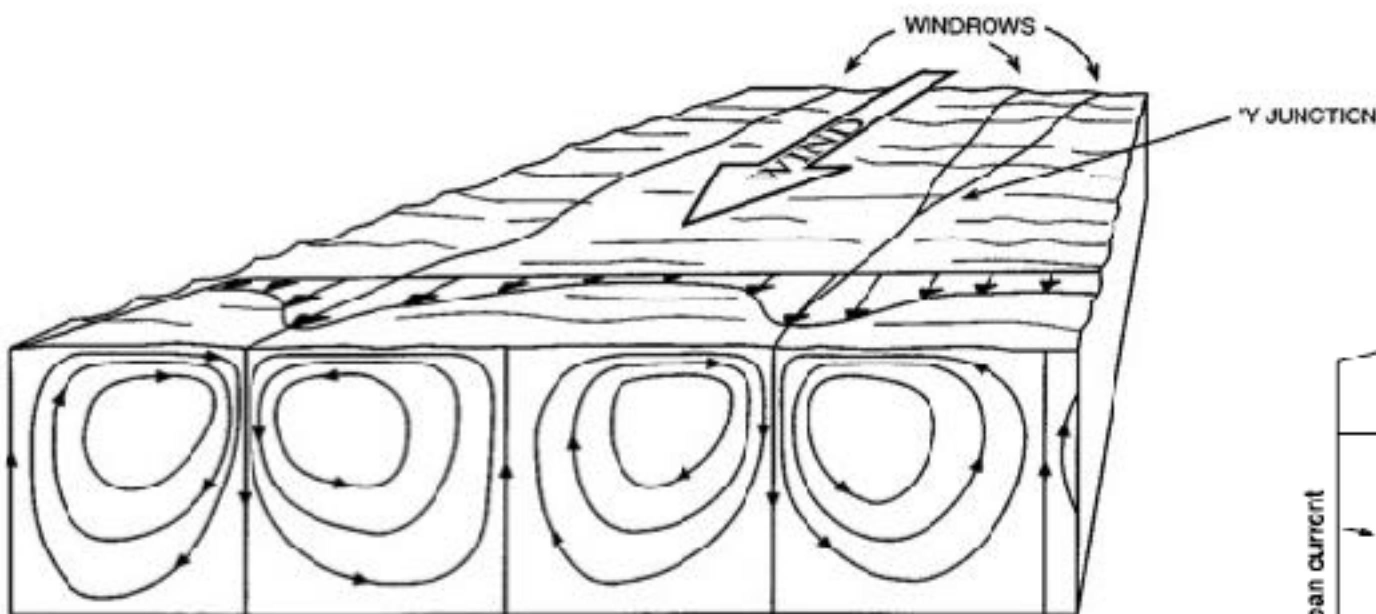


day 1

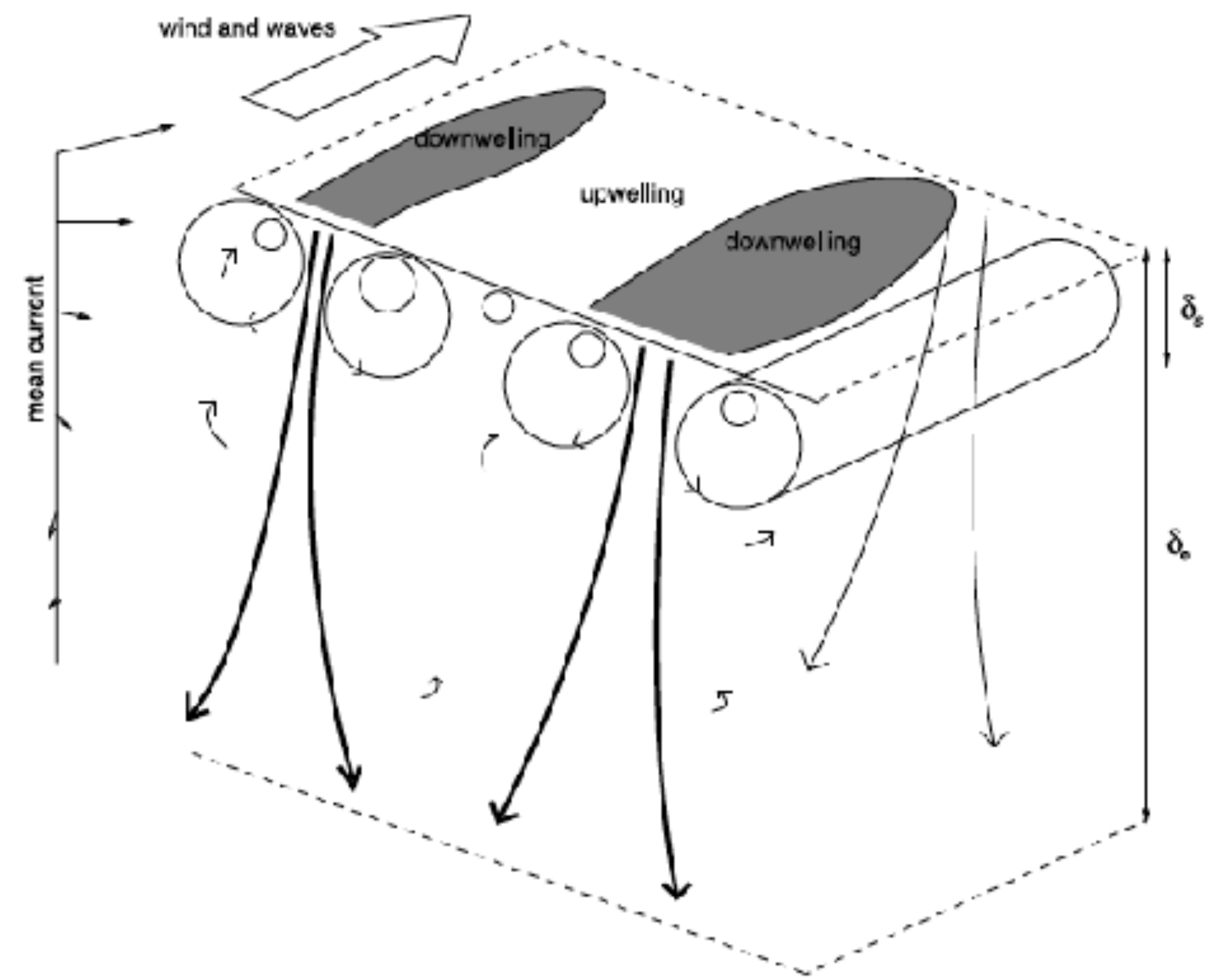
day 3

Impact of Langmuir circulation

Craik - Leibovich forcing

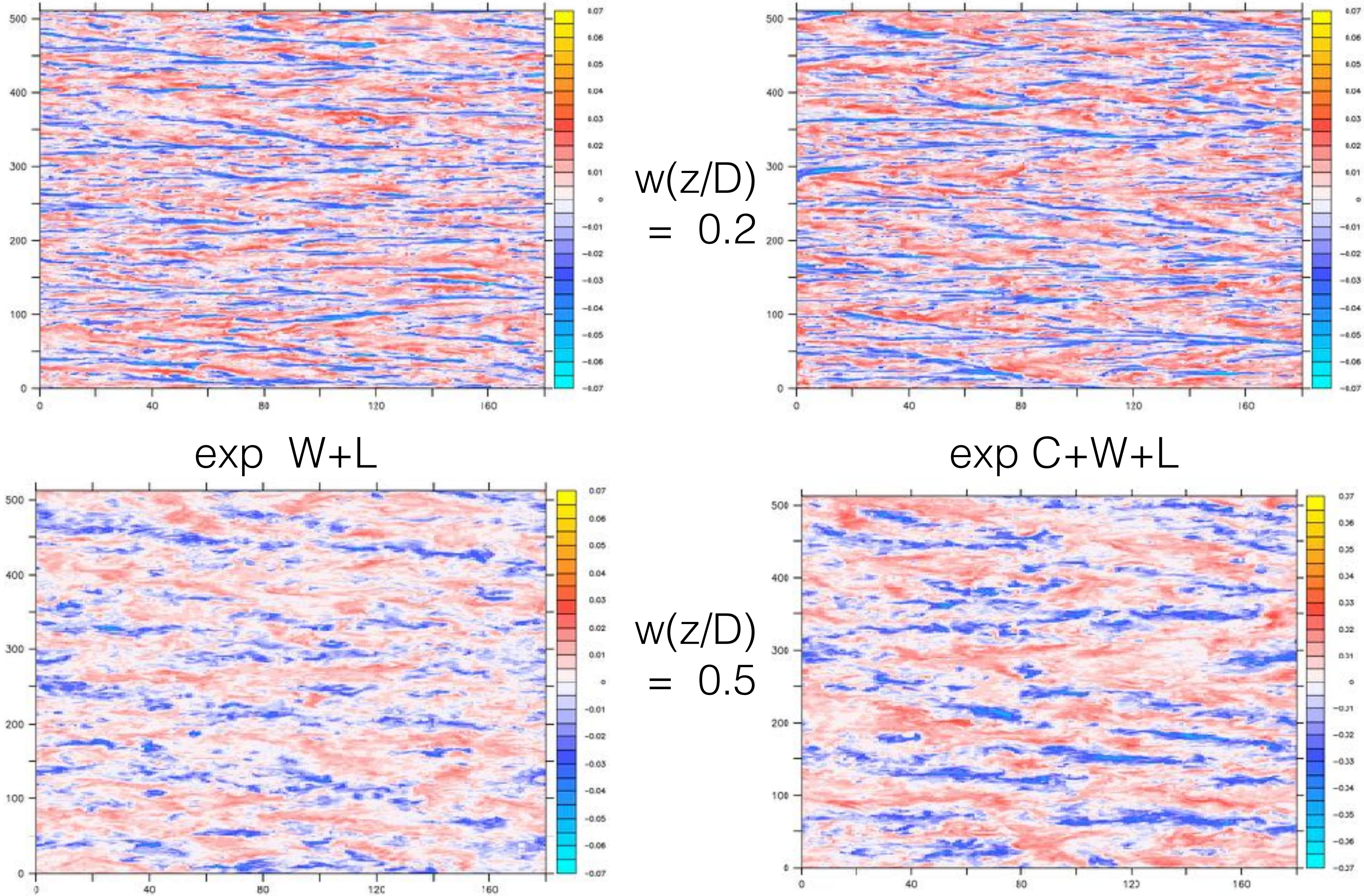


Thorpe, 2005

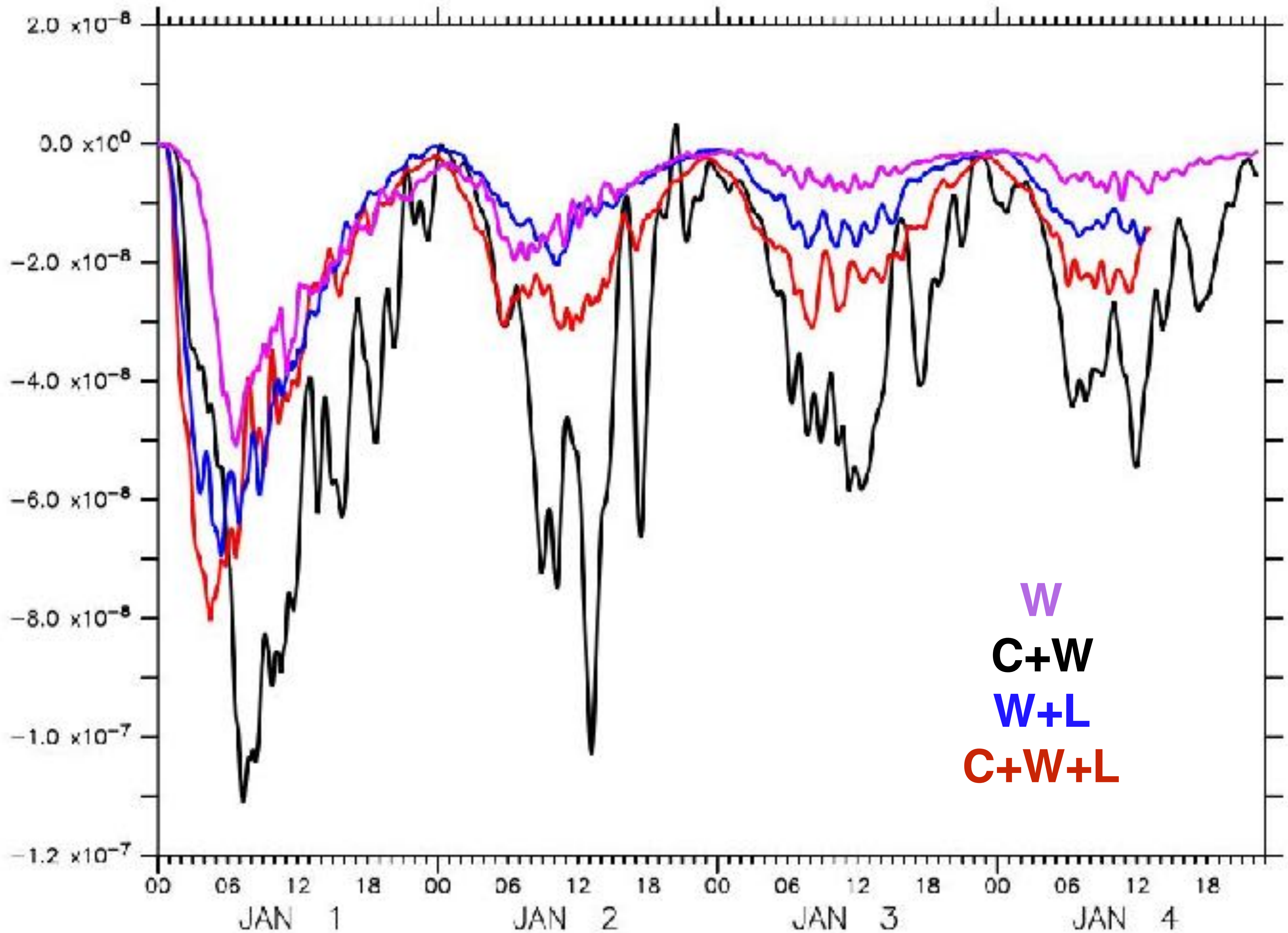


Polton & Belcher , 2007

Impact of Stokes forcing

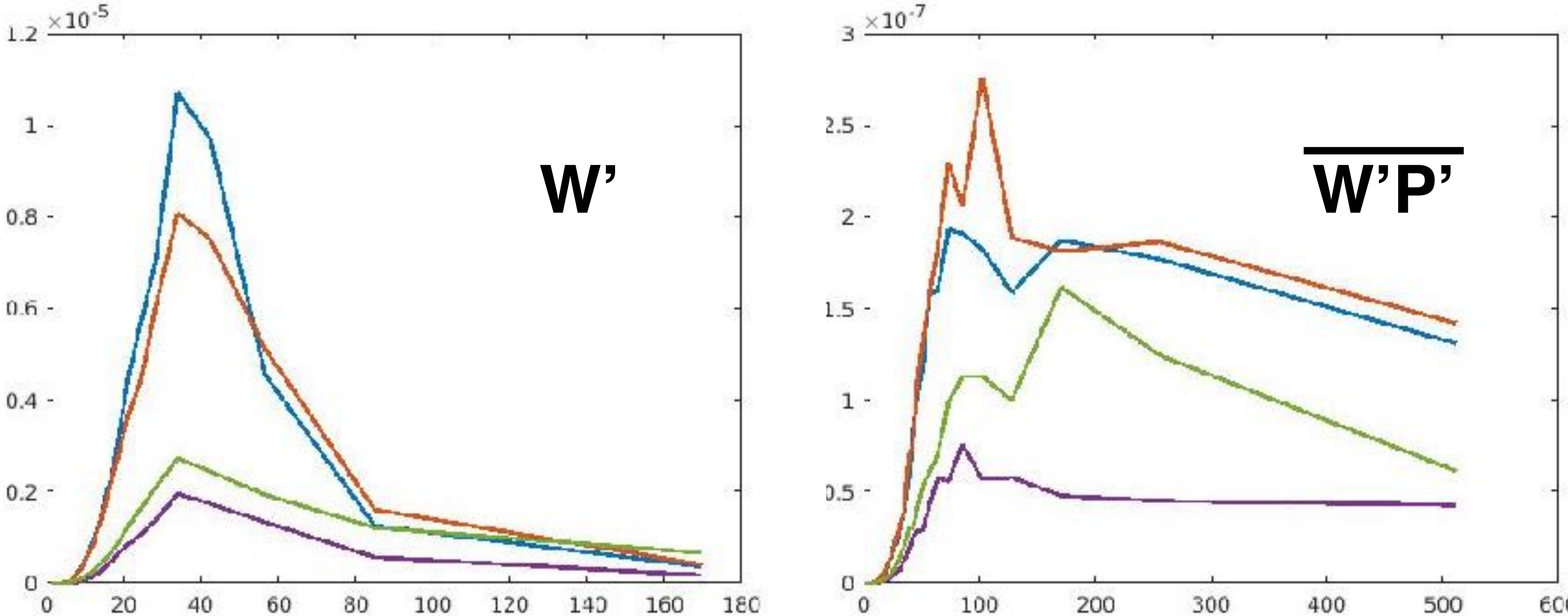


Internal wave energy flux



$z = -55m$

power spectra



C+W+L (day 1) W+L (day 1)
C+W+L (day 3) W+L (day 3)

Damping of Inertial Oscillation

$$\tau \approx \frac{\int_{ML} \frac{1}{2}\bar{\boldsymbol{u}}^{\mathbf{2}}_{\boldsymbol{IO}} dz}{\overline{w'p'}}$$

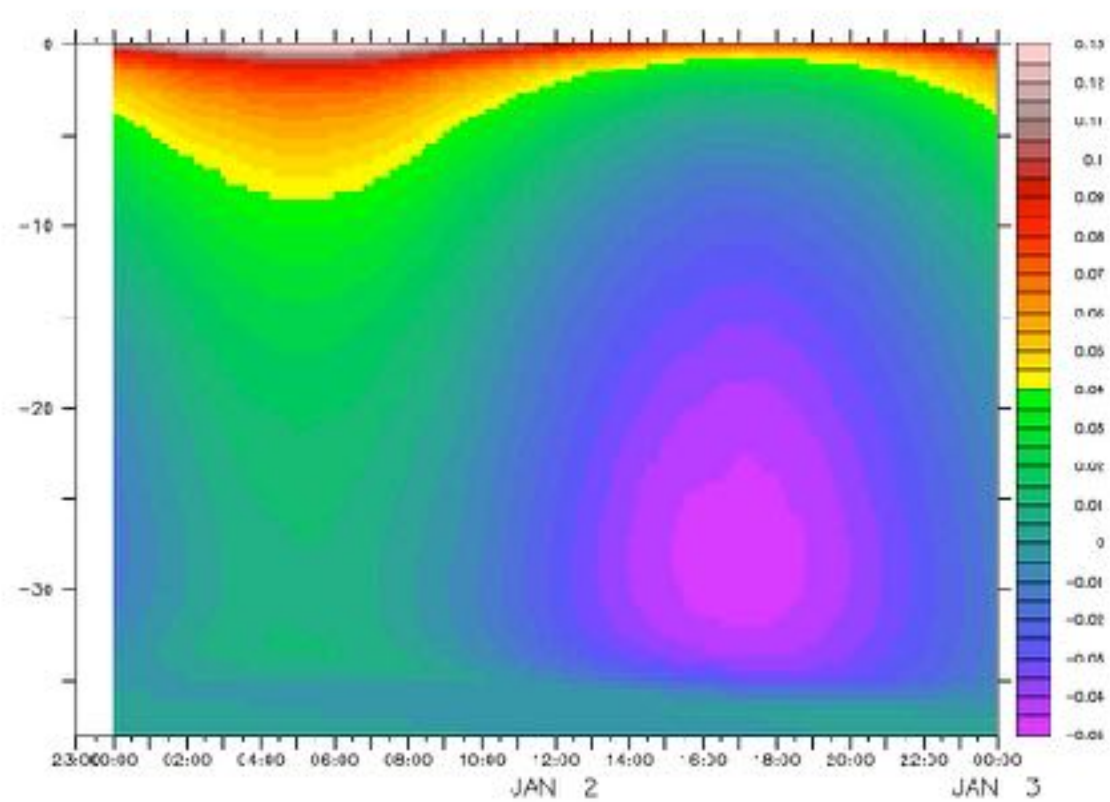
$$\bar{\boldsymbol{u}}_{\boldsymbol{IO}} = \bar{\boldsymbol{u}} - \int_{\tau_{IO}} \bar{\boldsymbol{u}}\, dt$$

Exp	τ (day 1)	τ (day 3)
C+W	3.9	5.6
W	8.6	49.0
W+L	7.6	21.1
C+W+L	6.5	11

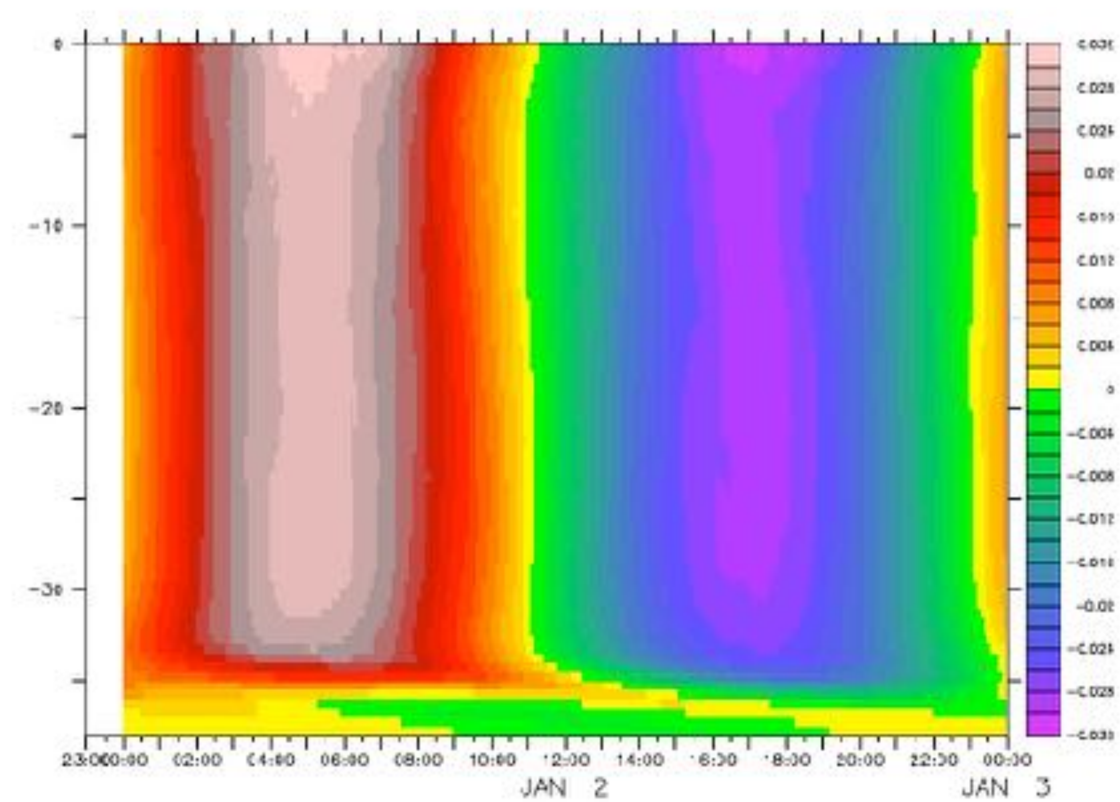
Observations: τ = 20 days after storm (D'Asaro et al., 95)
τ = 5 to 20 inertial periods at OWS Bravo (Altford et al., 2012)

Damping of Inertial Energy

$$\frac{\partial KE_{IO}}{\partial t} = \frac{\partial \frac{1}{2}\bar{\boldsymbol{u}}^{\boldsymbol{2}}_{\boldsymbol{IO}}}{\partial t} = -\frac{1}{\rho_0}\frac{\partial \overline{w'p'}}{\partial z} + \overline{\boldsymbol{u}'w'}\,\frac{\partial\,\bar{\boldsymbol{u}}_{\boldsymbol{IO}}}{\partial z}$$



$\bar{\boldsymbol{u}}$



$\bar{\boldsymbol{u}}_{\boldsymbol{IO}}$

exp w

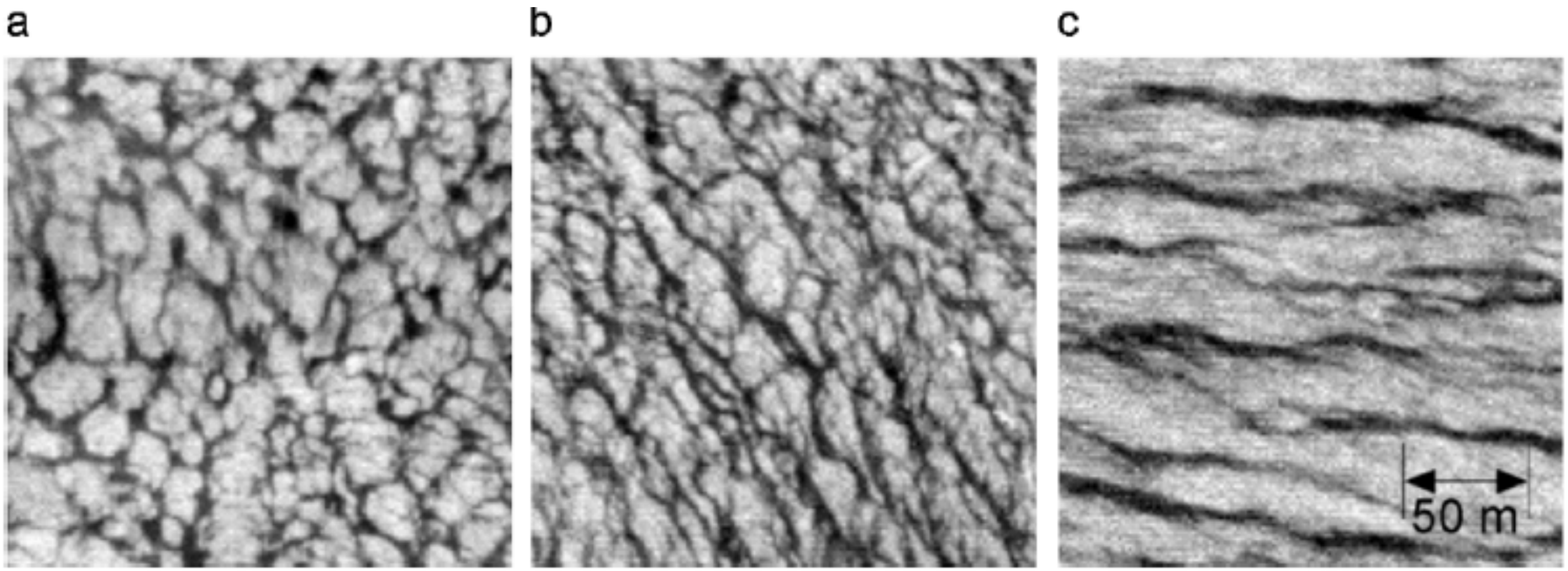
Discussion

- inertial oscillations are able to excite large parts of IW spectrum through the 'obstacle mechanism'

- transition layer is a low pass filter

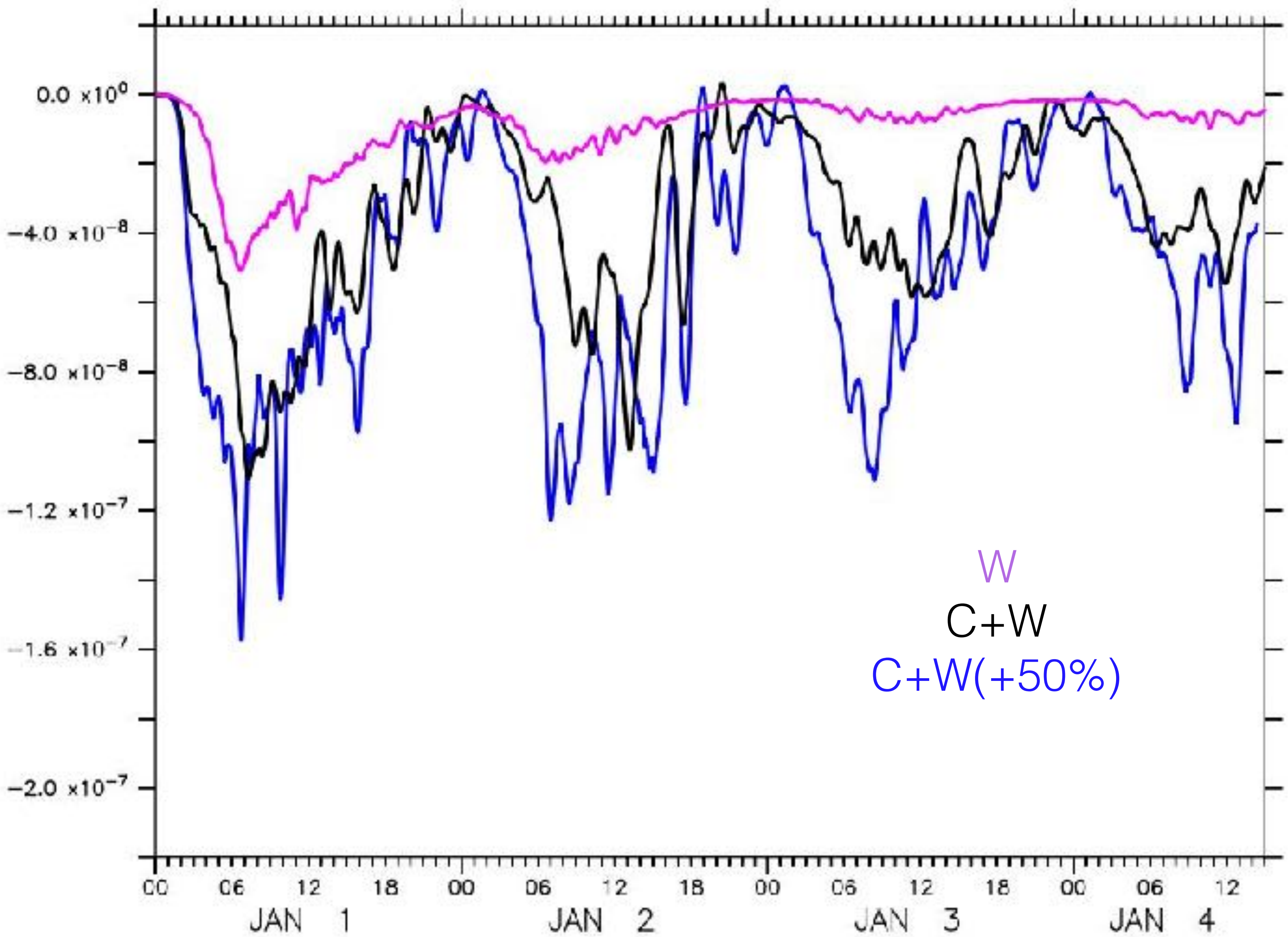
- in exp. C+W obstacle effect is most efficient

- 'obstacle mechanism' is able to explain observed damping timescales of inertial oscillation



Marmorino et al. 2009

Internal wave energy flux



Internal wave energy flux