Wind forcing impact over water dynamics and shelf - deep sea exchange processes

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Content of the presentation

- some theoretical aspects of wind-driven circulation in coastal zone and open sea;

- wind forcing impact on Black Sea dynamics and shelf-deep sea interaction (field observations, laboratory and numerical modeling);

- influence of Black Sea dynamics on zooplankton distribution between coastal zone and open sea.

Wind stress: definition and bulk formula

The horizontal force of the wind on the sea surface is called the **wind stress**

$$\tau = \rho_a \cdot C_d \cdot U_a^2 \qquad \tau = \{\tau_x, \tau_y\}$$

$\rho_a \approx 1.3 \cdot 10^{-3}$ g/cm^3 – air density; $C_d \approx (1\text{-}2) \cdot 10^{-3}$ – drag coefficient; U_a – wind speed at 10 m

U_a, m/s	τ, dyn/cm^2
2	0.05
7	1.0
20	10

Basic equations

boundary conditions

$$\frac{du}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + fv + \frac{\partial}{\partial z}(A_z \frac{\partial u}{\partial z})$$

$$\tau_x = \rho A_z \frac{\partial u}{\partial z}\Big|_{z=0}$$

$$\frac{dv}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial y} - fu + \frac{\partial}{\partial z}(A_z \frac{\partial v}{\partial z})$$

$$\tau_y = \rho A_z \frac{\partial v}{\partial z}\Big|_{z=0}$$

$$\frac{dw}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

Ekman's solution *(Ekman, 1905)*

$$\frac{\partial}{\partial t} = \frac{\partial}{\partial x} = \frac{\partial}{\partial y} = 0; \rho, A_z = const; H \rightarrow \infty$$

$$fv + A_z \frac{\partial^2 u}{\partial z^2} = 0 \qquad u = V_0 \exp^{-az} \cos(\pi/4 + az)$$

$$fv + A_z \frac{\partial^2 u}{\partial z^2} = 0 \qquad v = V_0 \exp^{-az} \sin(\pi/4 + az)$$

$$a = \sqrt{\frac{f}{2A_z}} \qquad V_0 = \tau \Big/ \sqrt{\rho^2 f A_z} \qquad H_E = \pi \Big/ a = \sqrt{\frac{2\pi^2 A_z}{f}}$$

Example:

τ=1 dyn/cm^2, f=10^{-4} c^{-1}, A_z=10 cm^2/s $\implies$ V_0=30 cm/s, H_E=13 m

Inertial oscillations

$$\frac{\partial}{\partial x} = \frac{\partial}{\partial y} = 0; \quad \tau, A_z = 0; \quad \rho = const; \quad H \to \infty$$

$$\frac{du}{dt} = fv \qquad u = V_i \sin(ft)$$

$$\frac{dv}{dt} = -fu \qquad v = V_i \cos(ft)$$

$$V_i^2 = u^2 + v^2 \quad R_i = \frac{V_i}{f}$$
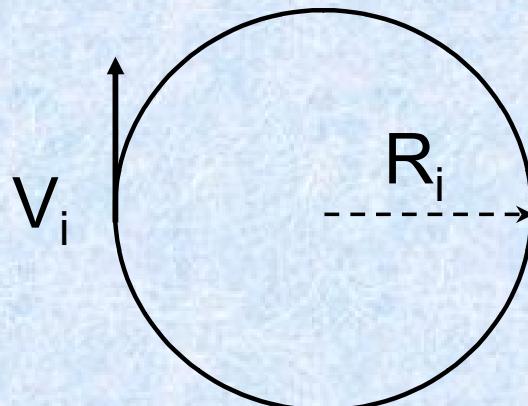
Example:

$f = 10^{-4}$ c^{-1}, $V_i = 30$ cm/s $\implies$ $R_i = 3$ km

Manifestation of inertial oscillations at the Lagrangian drifter trajectory in the Black Sea
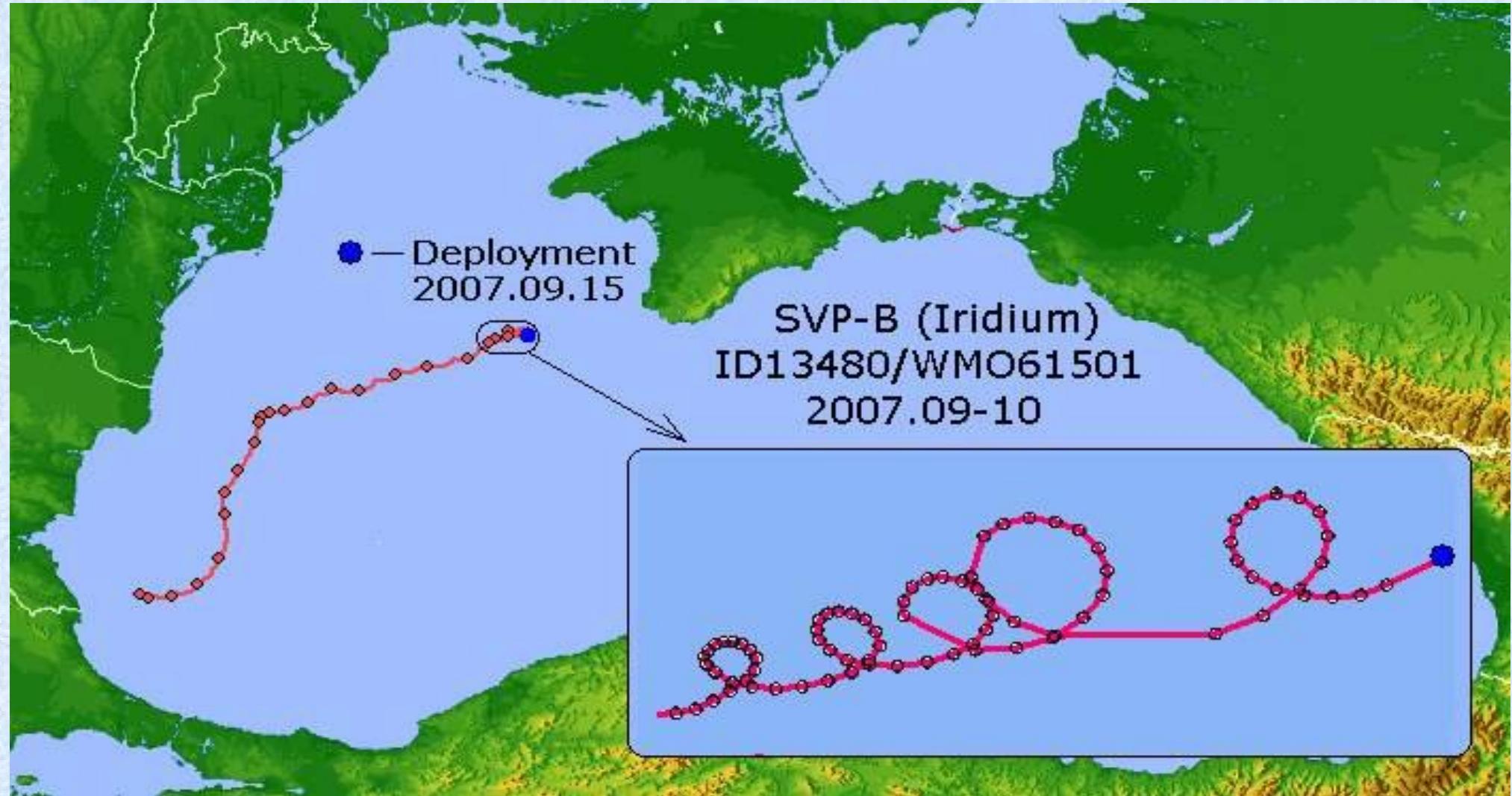
Power spectra of Lagrangian velocity components (Black Sea drifter experiment)
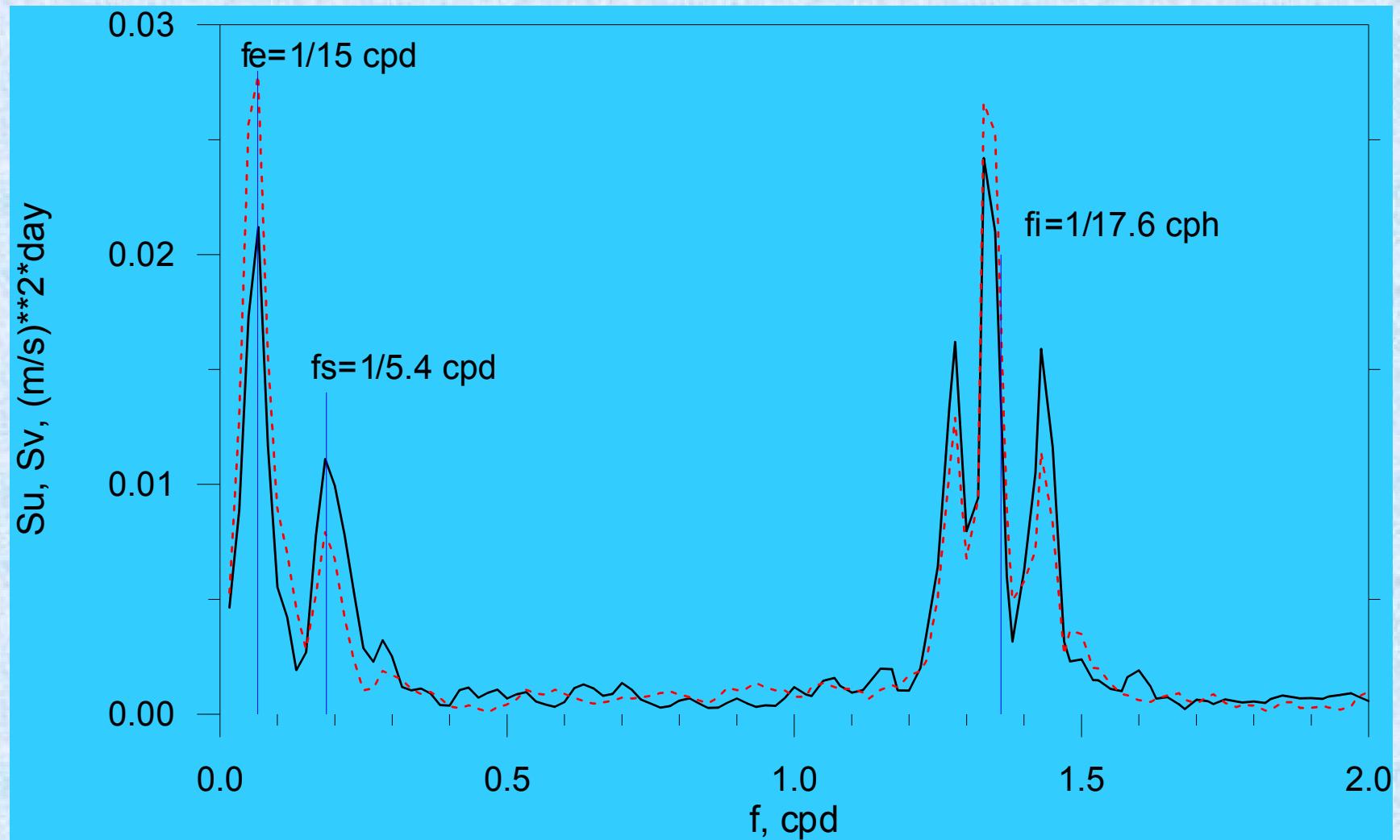
Ekman mass transport

$$M_{Ex} = \int\limits_{-H \gg H_E}^{0} (\rho u)\,dz \qquad\qquad M_{Ey} = \int\limits_{-H \gg H_E}^{0} (\rho v)\,dz$$

Using Ekman's solution for u and v, we obtain:

$$M_{Ex} = {\tau_{yz}}\big/{f} \qquad M_{Ey} = -{\tau_{xz}}\big/{f} \qquad \overset{\rho}{M}_E = {(\tau \times k)}\big/{f}$$

M_E - Ekman mass transport, directed to the right angle of wind stress in Northern Hemisphere
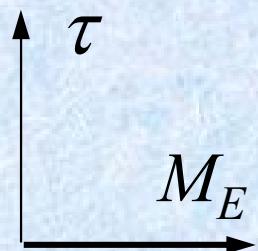
Wind induced nearshore circulation

Coastal upwelling

Wind

M_E

Cold Upwelled Water

F_C F_P

front

warm water

cold water

100 m
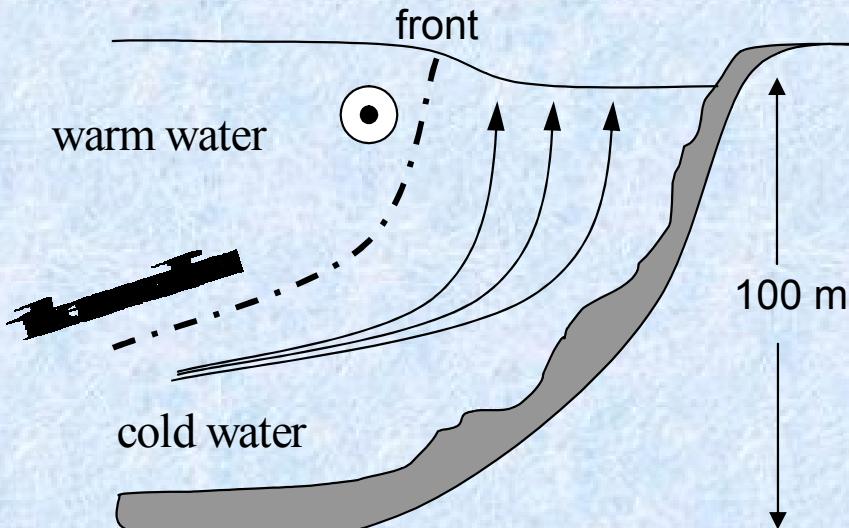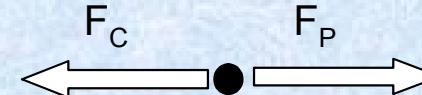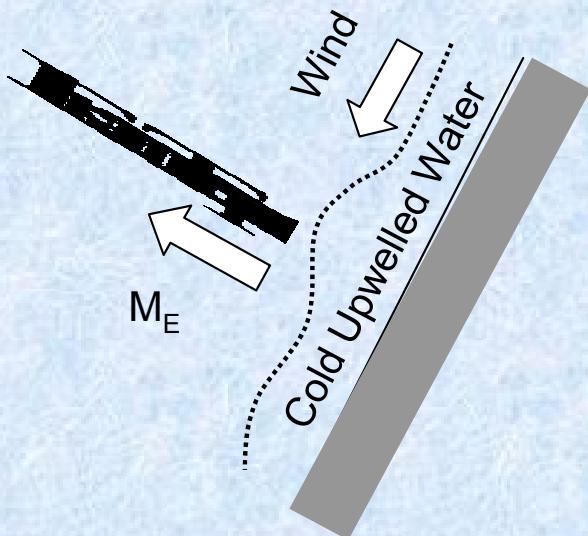
Coastal downwelling

M_E

Wind

F_P F_C

warm water

cold water

100 m
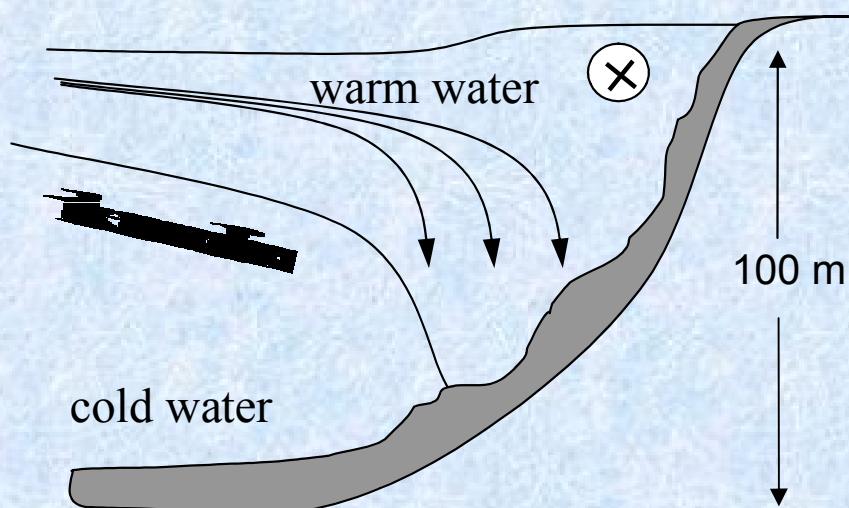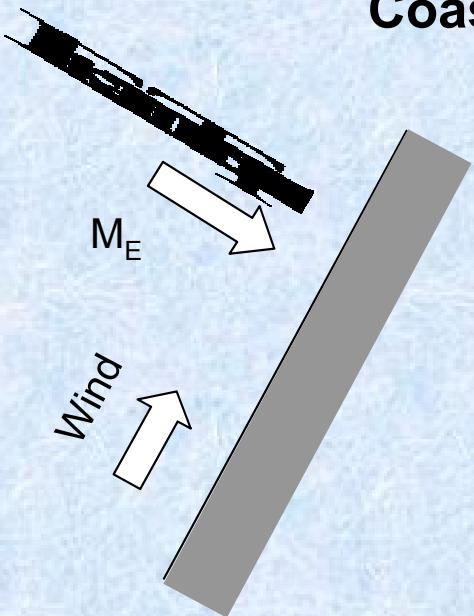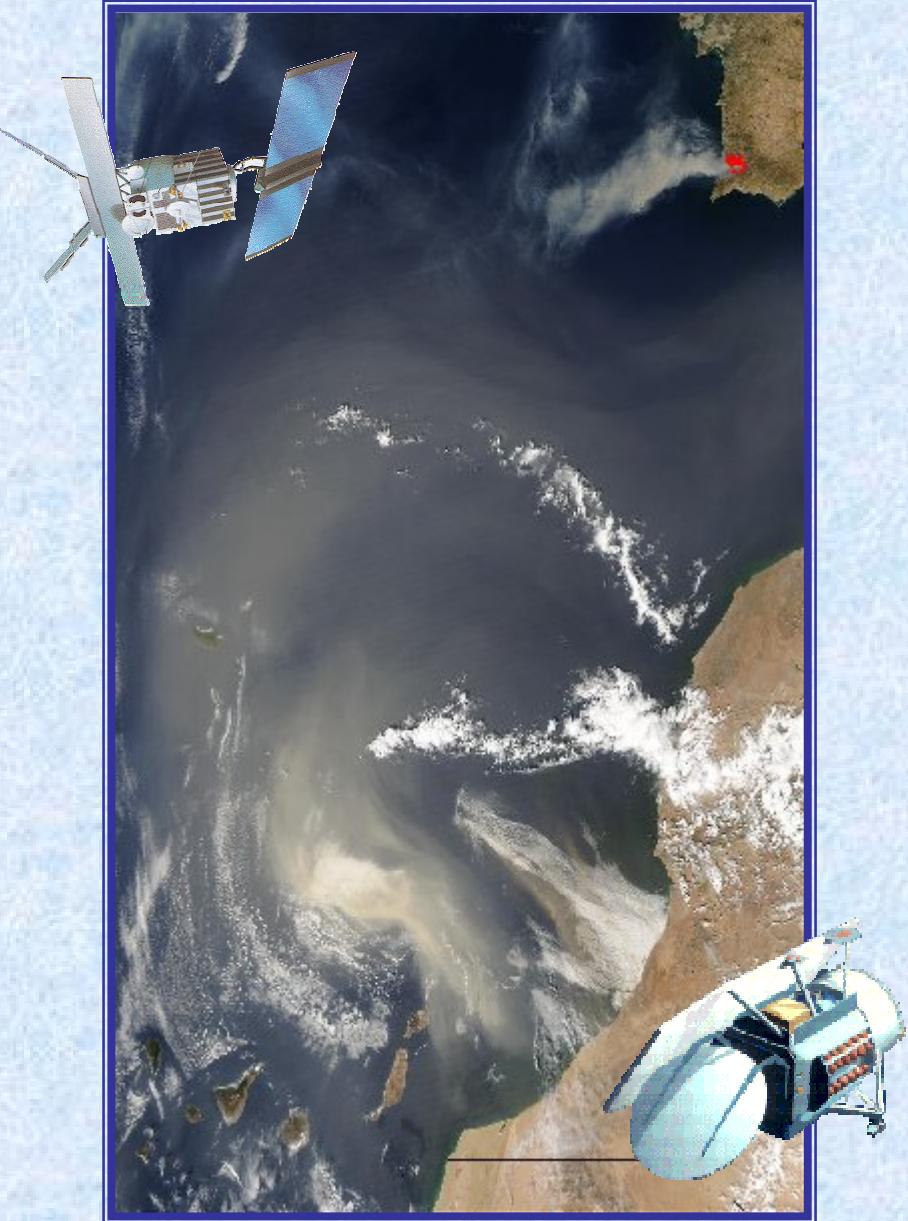
Andrey G. Kostianoy
Sergey A. Lebedev
Alexander M. Sirota

Canary Upwelling: Satellite Monitoring

Seasonal Circulation
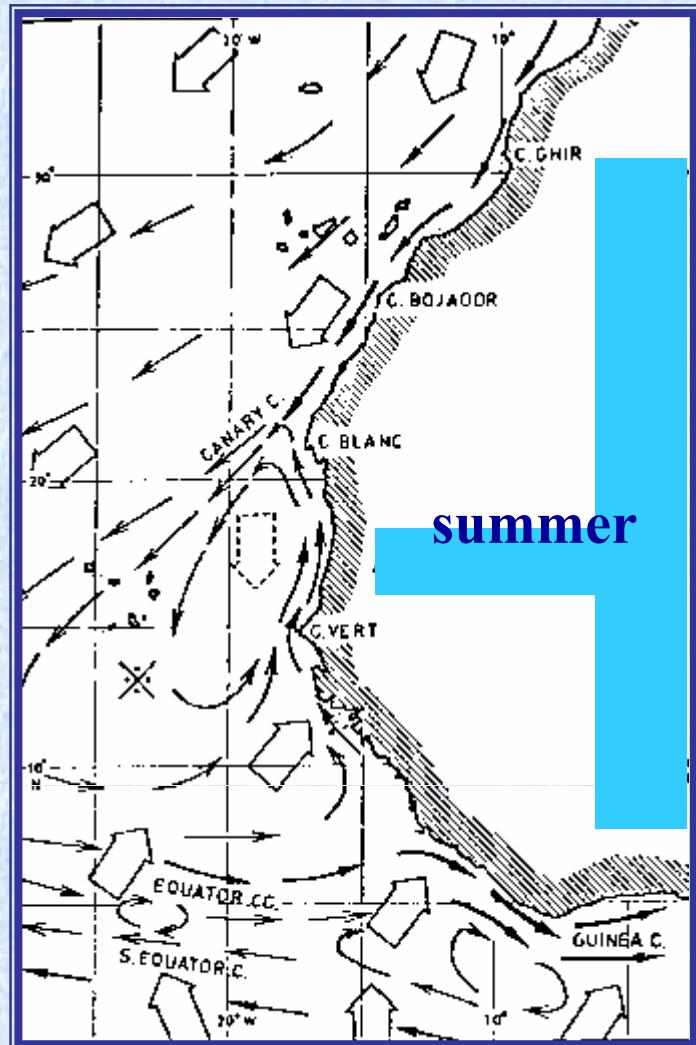
summer
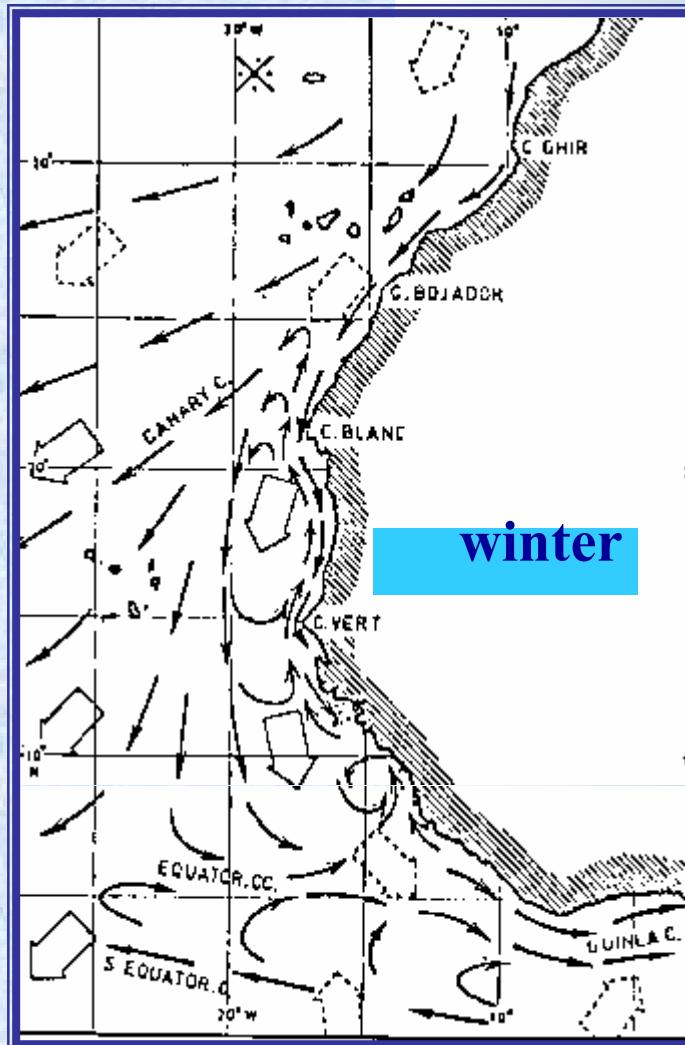
winter

⇒ dominating wind

⇒ gentle and changeable winds

⌧ regions of weak winds with variable direction

→ sea surface currents

Mittellstaedt (1983)

Upwelling Features

Warm wake · Gran Canaria · Warm wake · Cold eddy · Warm wake · Filament · C.Yubi · Cold upwelled water · C.Bojador · 10-AUG-93 TIME 16:52 · Filament · Cold upwelled water

www.bangor.ac.uk/.../des/ o2p03/text/o2p03-04.htm

Des Barton

Chl "a" concentration in February and August 2000

Chl "a"
concentration

February 2000

0   0.2 0.4 0.6 0.8 1 1.2
mg/m³

Chl "a"
concentration

August 2000

0   0.2 0.4 0.6 0.8 1 1.2
mg/m³

Geostrophic balance

$$t \gg \frac{1}{f}: \quad \frac{du}{dt} = \frac{dv}{dt} = \frac{dw}{dt} = 0; \; A_z = 0$$

$$\frac{1}{\rho}\frac{\partial p}{\partial x} = fv \qquad v = \frac{1}{f\rho}\frac{\partial p}{\partial x} \qquad\qquad v = \frac{1}{f\rho}\frac{\partial}{\partial x}\int_{-H}^{0} g\rho(z)dz - \frac{g}{f}\frac{\partial \zeta}{\partial x}$$

$$\frac{1}{\rho}\frac{\partial p}{\partial y} = -fu \qquad u = -\frac{1}{f\rho}\frac{\partial p}{\partial y} \qquad u = -\frac{1}{f\rho}\frac{\partial}{\partial y}\int_{-H}^{0} g\rho(z)dz - \frac{g}{f}\frac{\partial \zeta}{\partial y}$$

$$\frac{1}{\rho}\frac{\partial p}{\partial z} = -g \qquad p = p_a + \int_{-H}^{\zeta} g\rho(z)dz \qquad u_s = -\frac{g}{f}\frac{\partial \zeta}{\partial y} \qquad\qquad v_s = \frac{g}{f}\frac{\partial \zeta}{\partial x}$$

Example:

$$f=10^{-4} \text{ c}^{-1}, \; g = 10^{3} \text{ cm/s}^2, \; \frac{\partial \zeta}{\partial y} = 3cm/10km \implies u_s = 30 \text{ cm/s}$$

Wind stress vorticity as a driving mechanism of basinscale circulation in seas

$$\frac{\partial}{\partial x}(M_{Ex}) + \frac{\partial}{\partial y}(M_{Ey}) = \frac{1}{f}\left[\frac{\partial \tau_{yz}}{\partial x} - \frac{\partial \tau_{xz}}{\partial y}\right] = \frac{curl\,\tau}{f}$$

$$\frac{\partial}{\partial x}(M_{Ex}) + \frac{\partial}{\partial y}(M_{Ey}) = -\rho w_E$$

$$w_E = \frac{curl\,\tau}{f\rho}$$ - Ekman pumping velocity

Predominantly positive (negative) wind stress vorticity at the sea surface area produces the divergence of Ekman mass transport and associated upwelling (downwelling). As a result horizontal pressure gradients (related to the elevation of sea level and isopycnal surfaces) appear and the basinscale geostrophic currents are generated.

Baroclinic instability of currents, formation of meanders and mesoscale eddies

Nearly geostrophic currents in stratified ocean in many cases are unstable. Two types of instability are widespread: barotrophic (related to the horizontal shear of the flow) and baroclinic (related to the vertical shear of the flow). Due to the baroclinic instability flow becomes meandering. Sometimes meanders are growing to high amplitude. In these cases they could be transformed into mesoscale eddies which "break" the basic flow and produce an intensive horizontal mixing. The necessary condition for the development of baroclinic instability is $L \gg R_d$, where L is the width of the flow and $R_d = NH/f$ – the baroclinic deformation radios. The typical wave length of meander $\lambda \approx 2\pi R_d$ and the radios of mesoscale eddy $R_e \approx \pi R_d$.

Studies of wind forcing impact on basinscale currents, mesoscale eddy dynamics and the interaction between the coastal zone and the deep basin in the Black Sea.
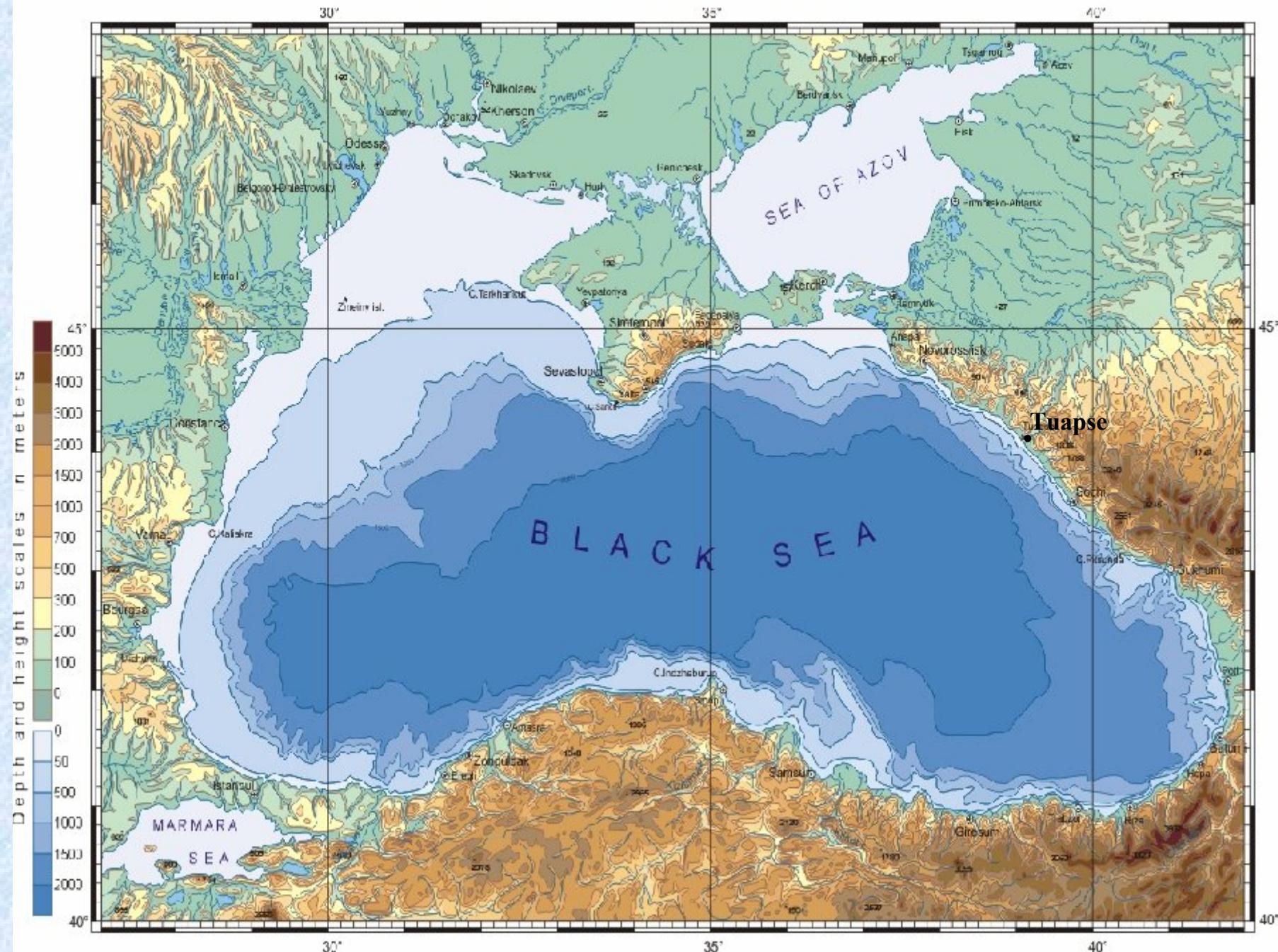
Black Sea hydrological structure
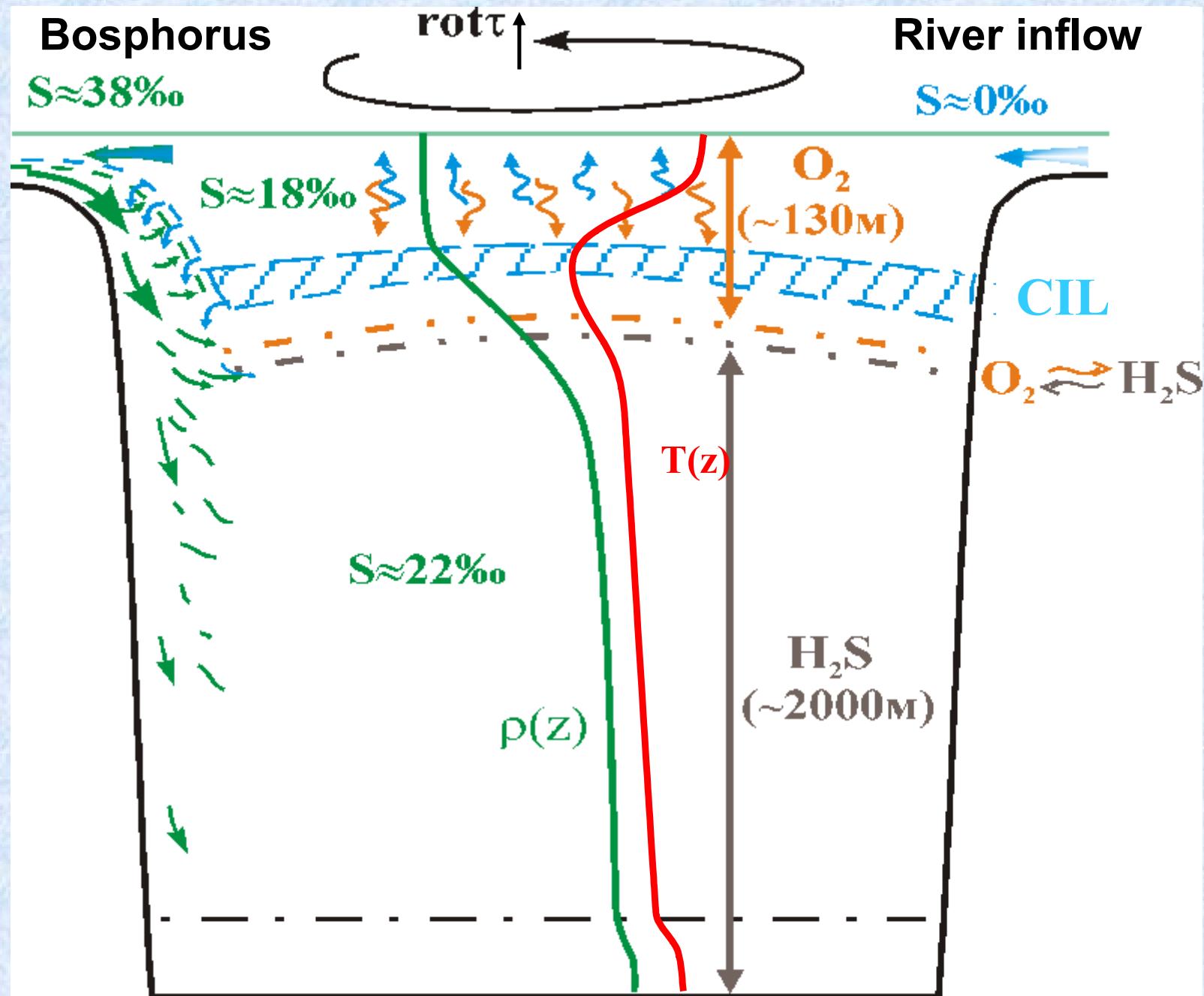
The scheme of the Black Sea upper layer circulation
(Ovchinnikov and Popov, 1990)
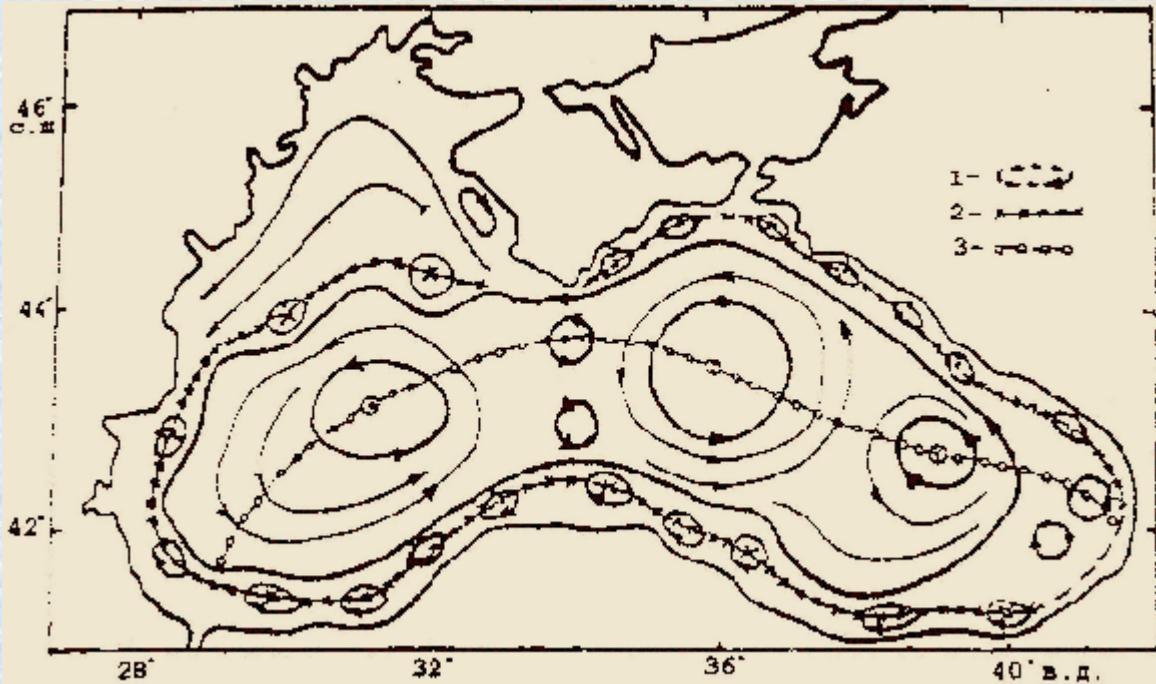
Satellite image of mesoscale eddy structures in the Black Sea
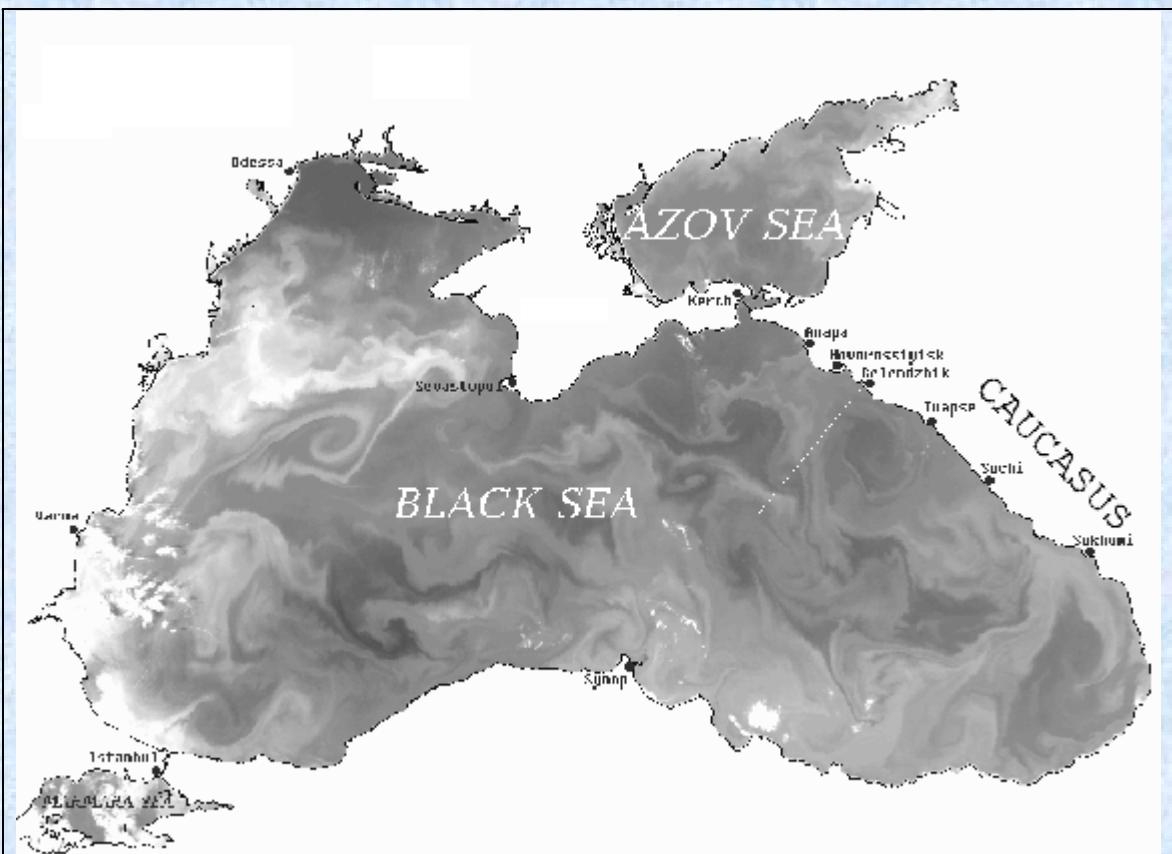
International Black Sea drifter experiment 1999-2003
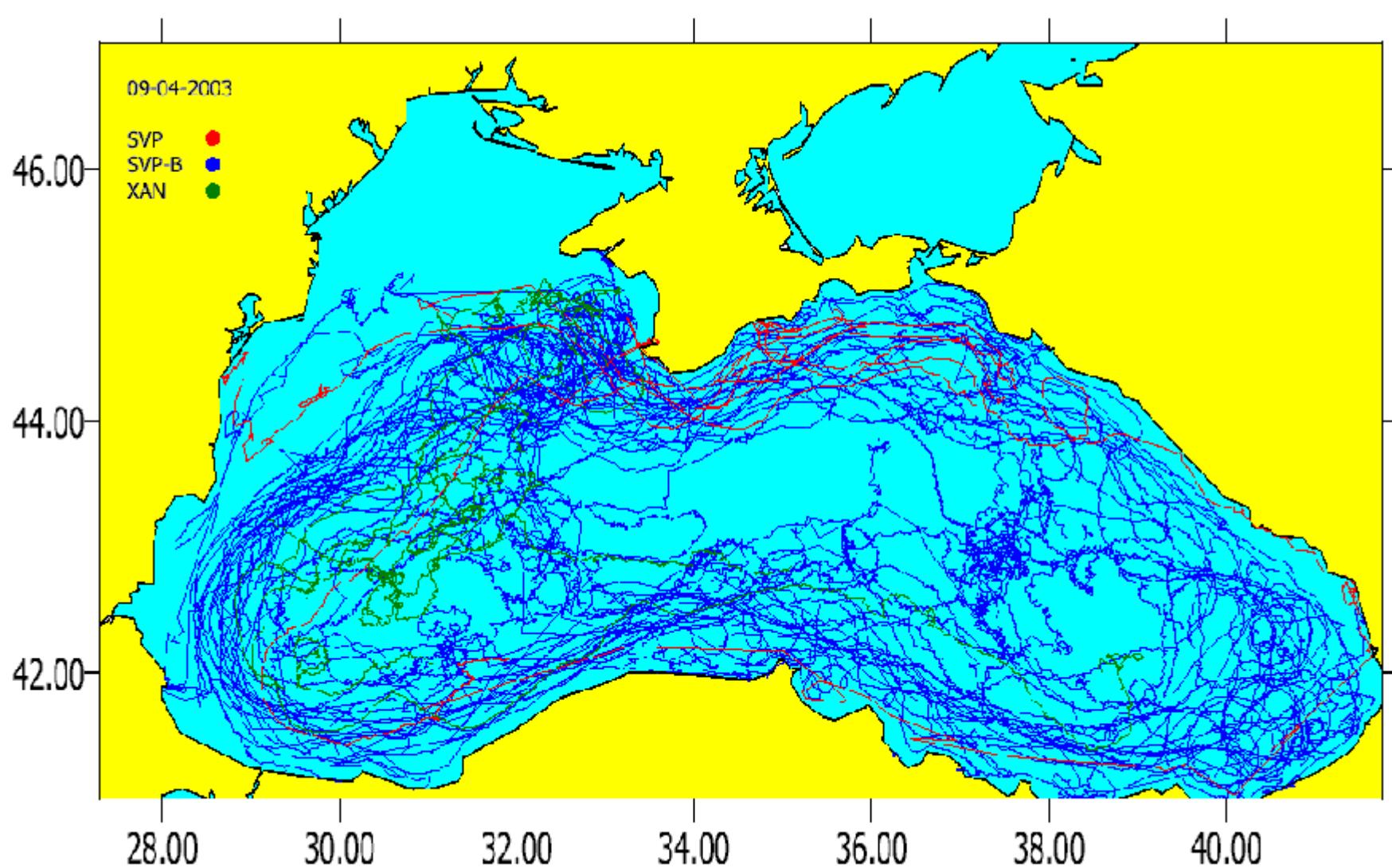
Zhurbas, Zatsepin et al., 2004;

Poulain, Barbatini, Motyzhev, Zatsepin, 2005.

Fragments of trajectories of drifters trapped by eddies
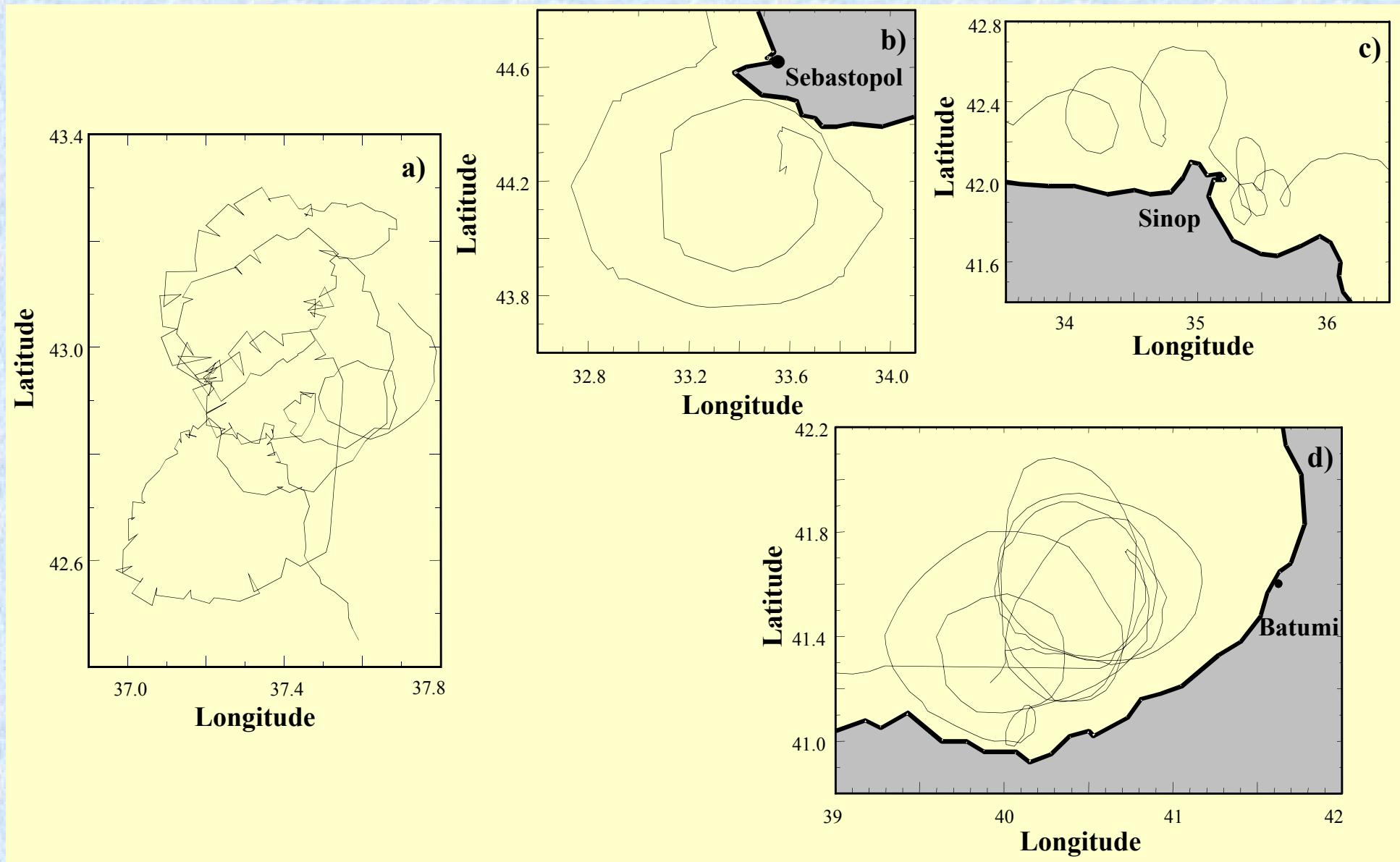
Ekman pumping velocity (W_E 10^6 m/s) distribution

winter

summer
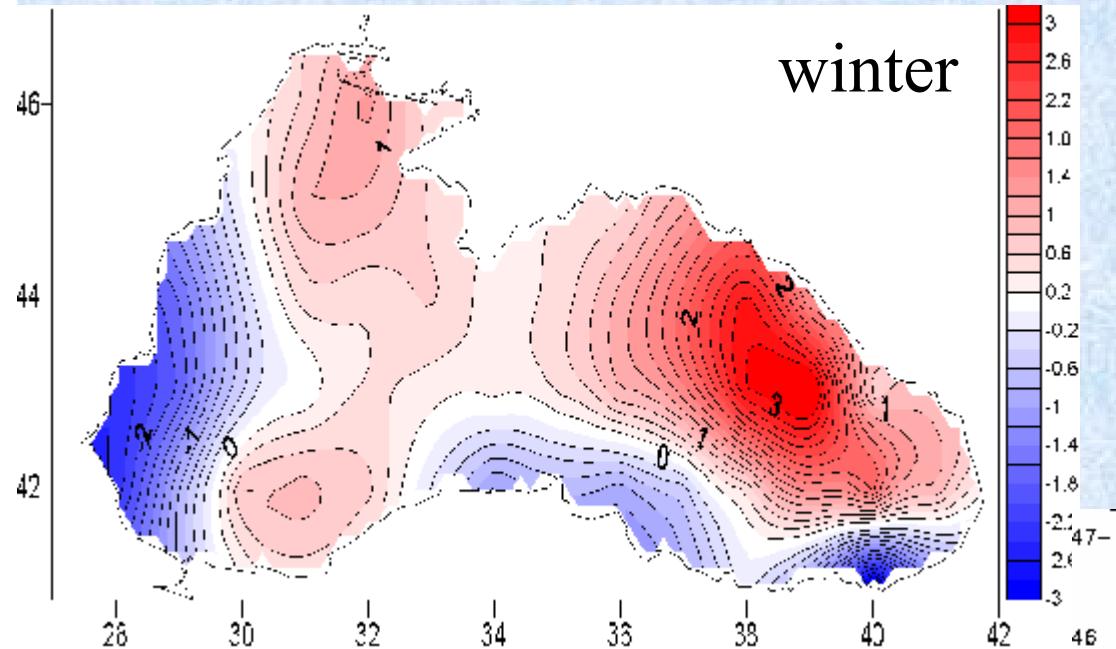
$$-\nabla_H M_E /\rho_w = W_E = \mathrm{curl}\tau/(\rho f)$$

Positive values (red) – cyclonic wind vorticity.

Negative values (blue) – anticyclonic wind vorticity.
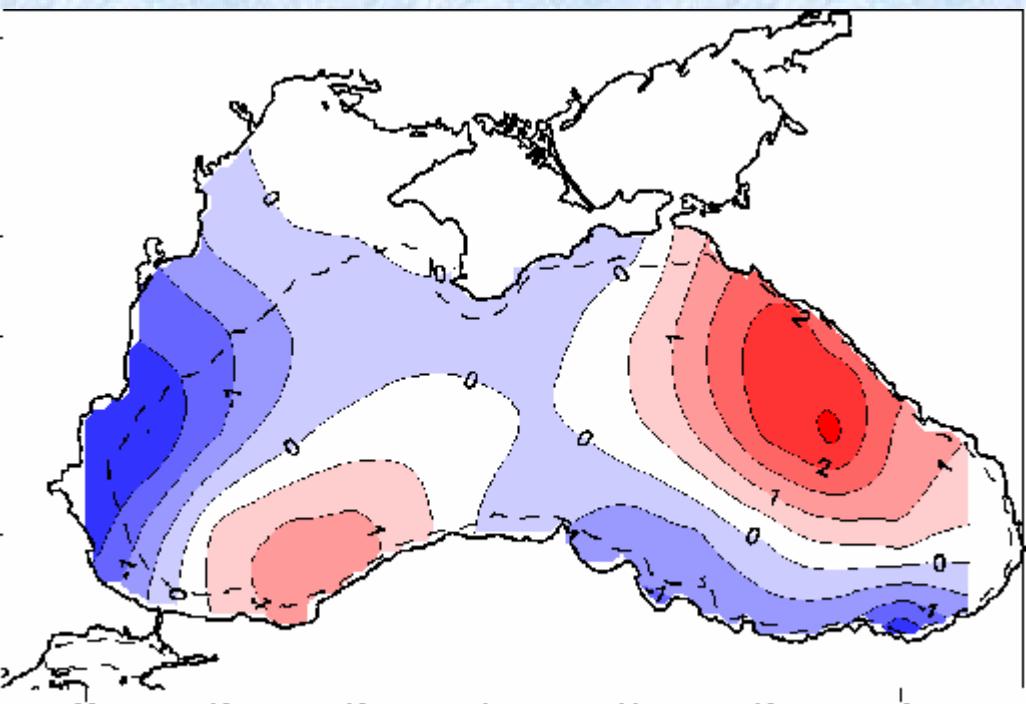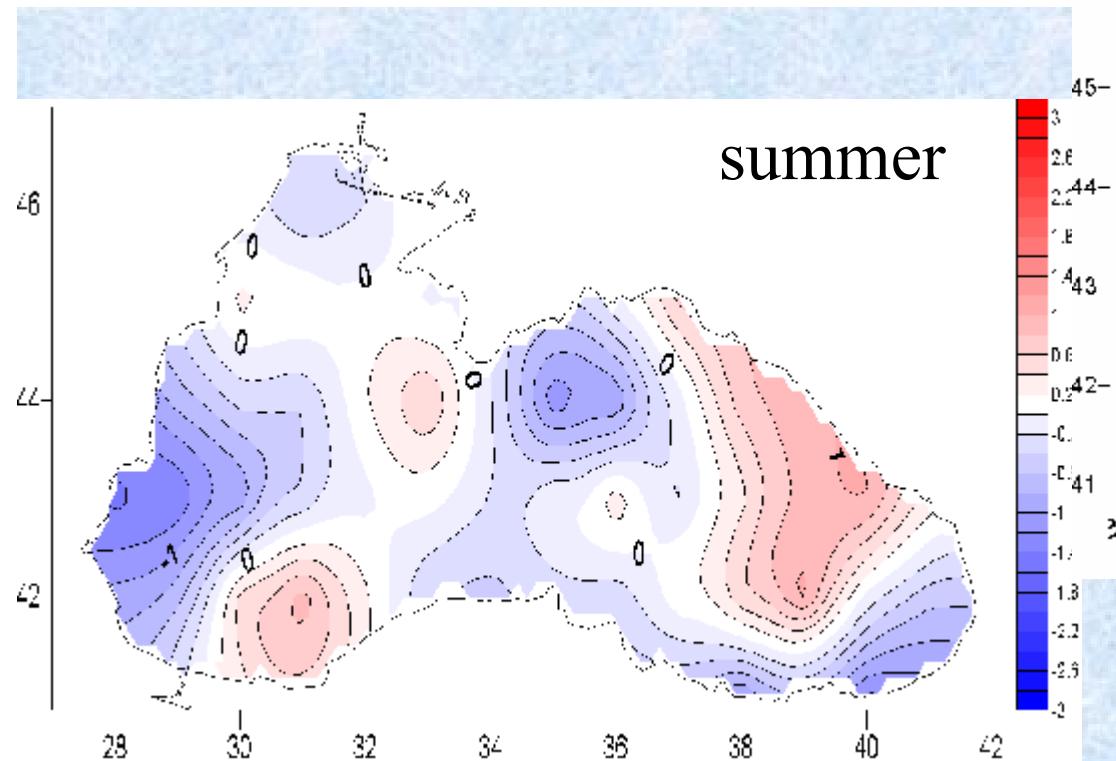
averaged over 7 years period (1998-2004)

Within-year variability of $< W_E >$ and $<V_g>$ in the NE Black Sea

Ekman pumping velocity
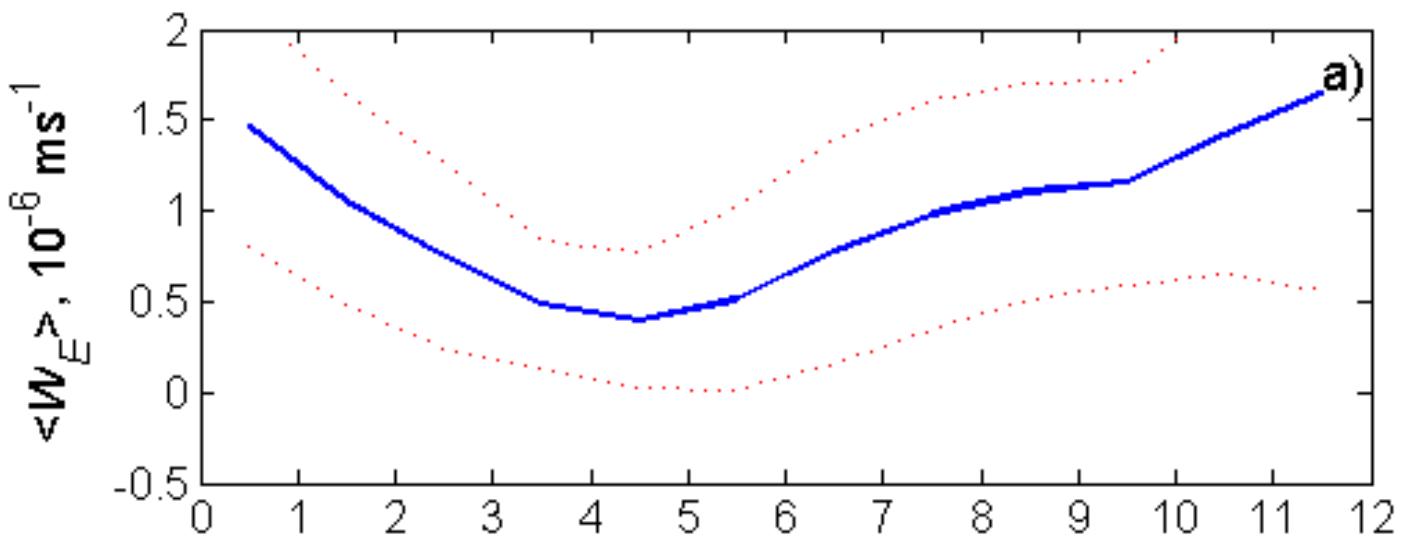
Mean alongshore surface geostrophic velocity
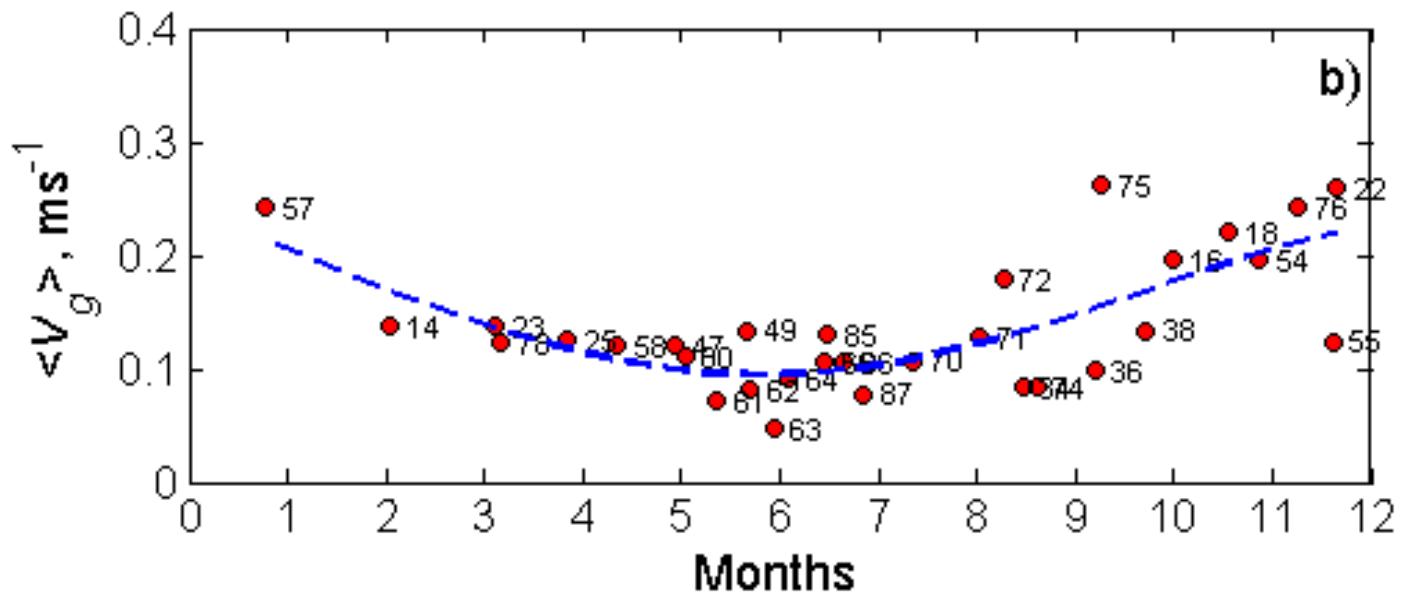
Intra-annual variability of wind stress (blue) and Ekman pumping velocity (black)

Tau and W_{Ek} 15 days smoothed

Black Sea North-Eastern region (2003)
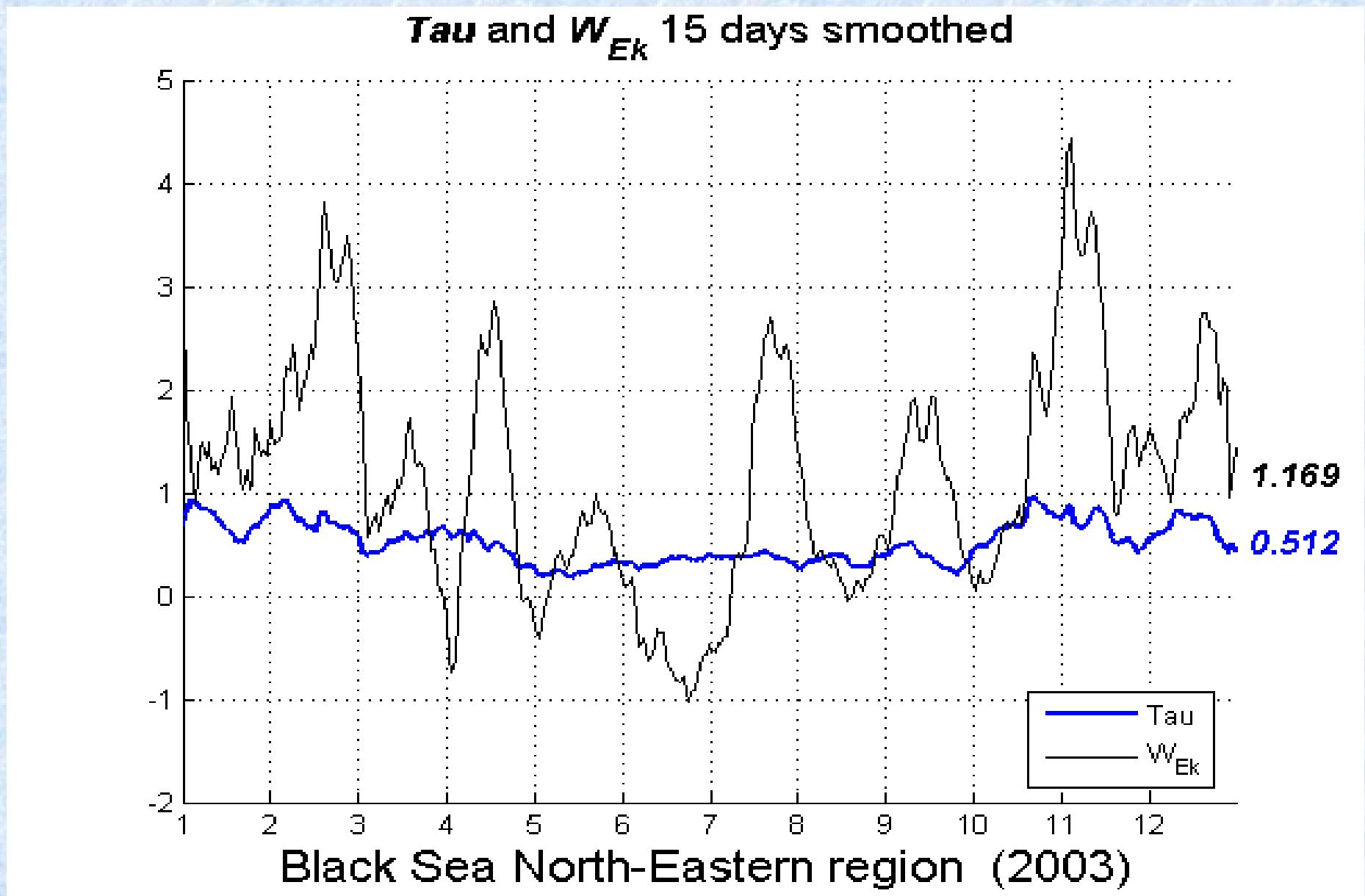
The high level of Ekman pumping causes intensification of the Rim current (November 2000)
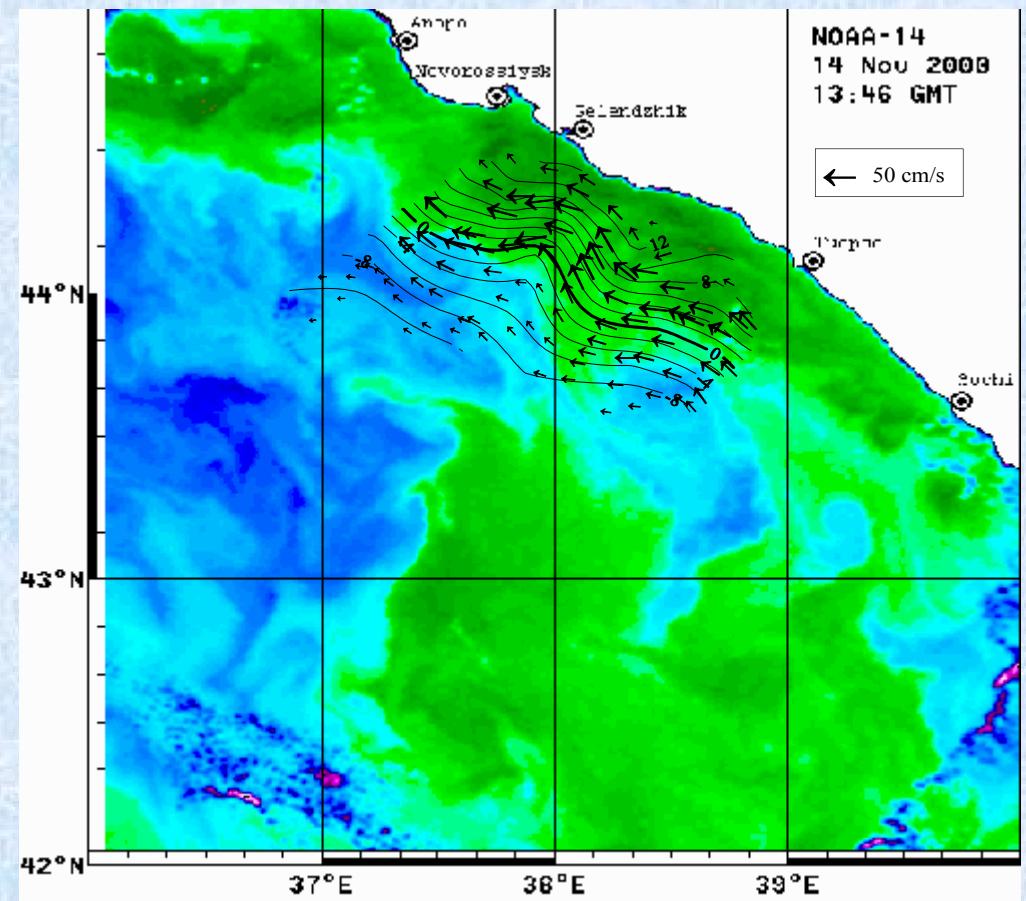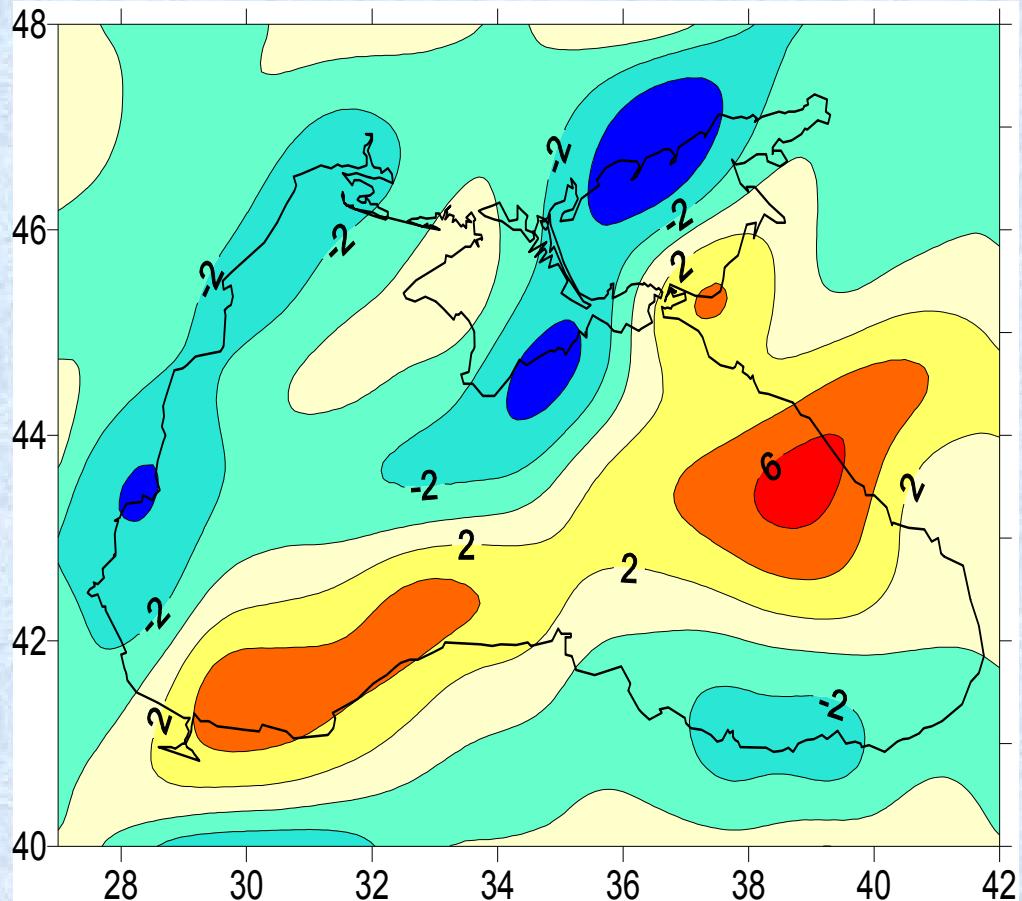
Zatsepin et al., 2002

The low level of Ekman pumping causes the Rim current instability and degradation. Meanwhile eddy dynamics and lateral mixing increase (October 2001)
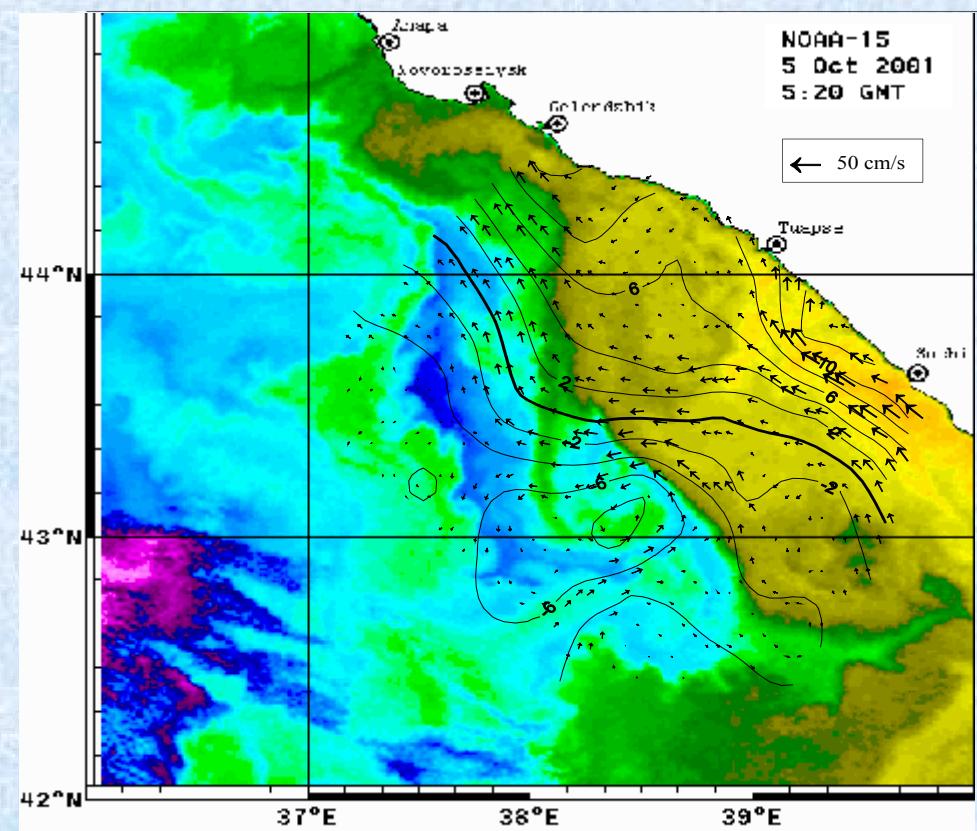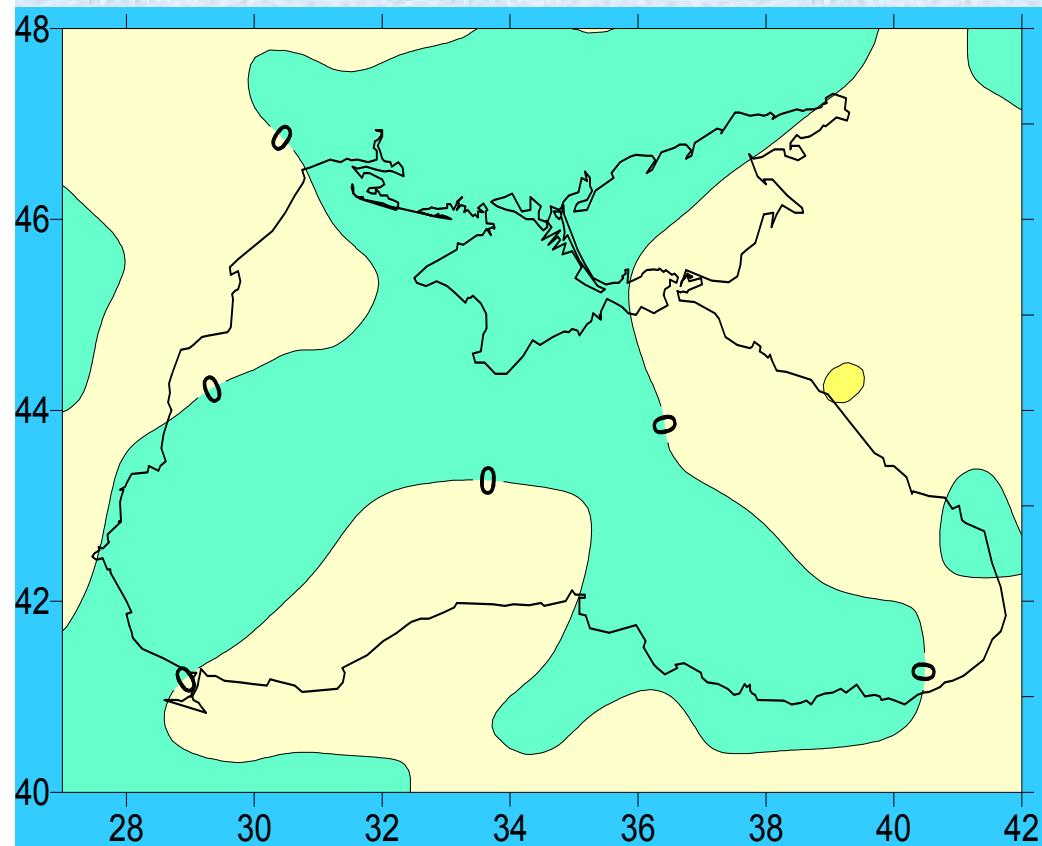
Zatsepin et al., 2002

Surface geostrophic velocity in the Rim current core (V_{MAX}) as a function of $<W_E>$

The maximal velocity in the Rim current is positively correlated with Ekman pumping velocity
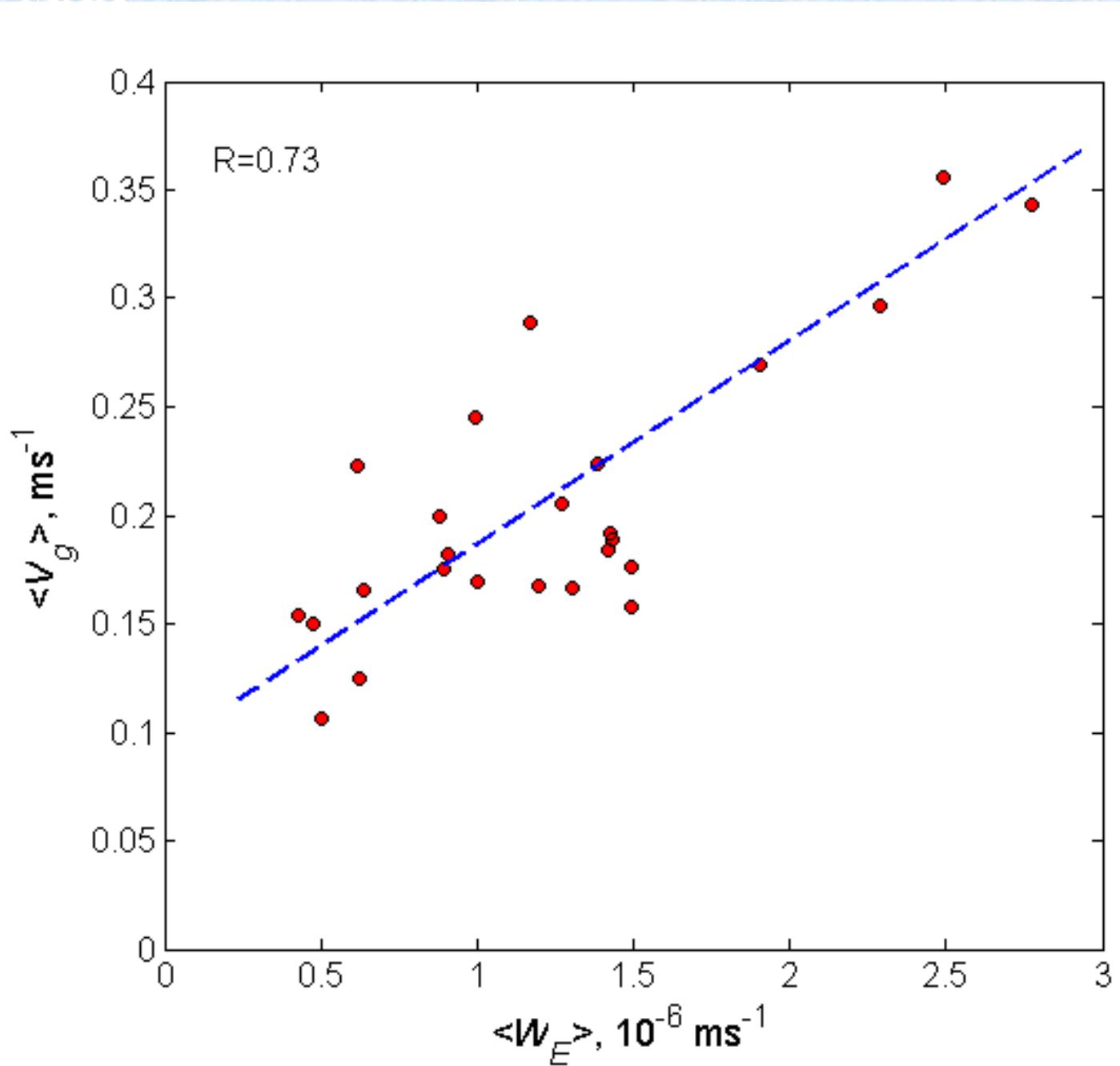
Correlation coefficient between the V_{max} and the $<W_E>$ as a function of time averaging interval

The correlation coefficient between the V_{max} and the $<W_E>$ peaks when

the averaging time interval equals to 20-30 days _before_ the observations
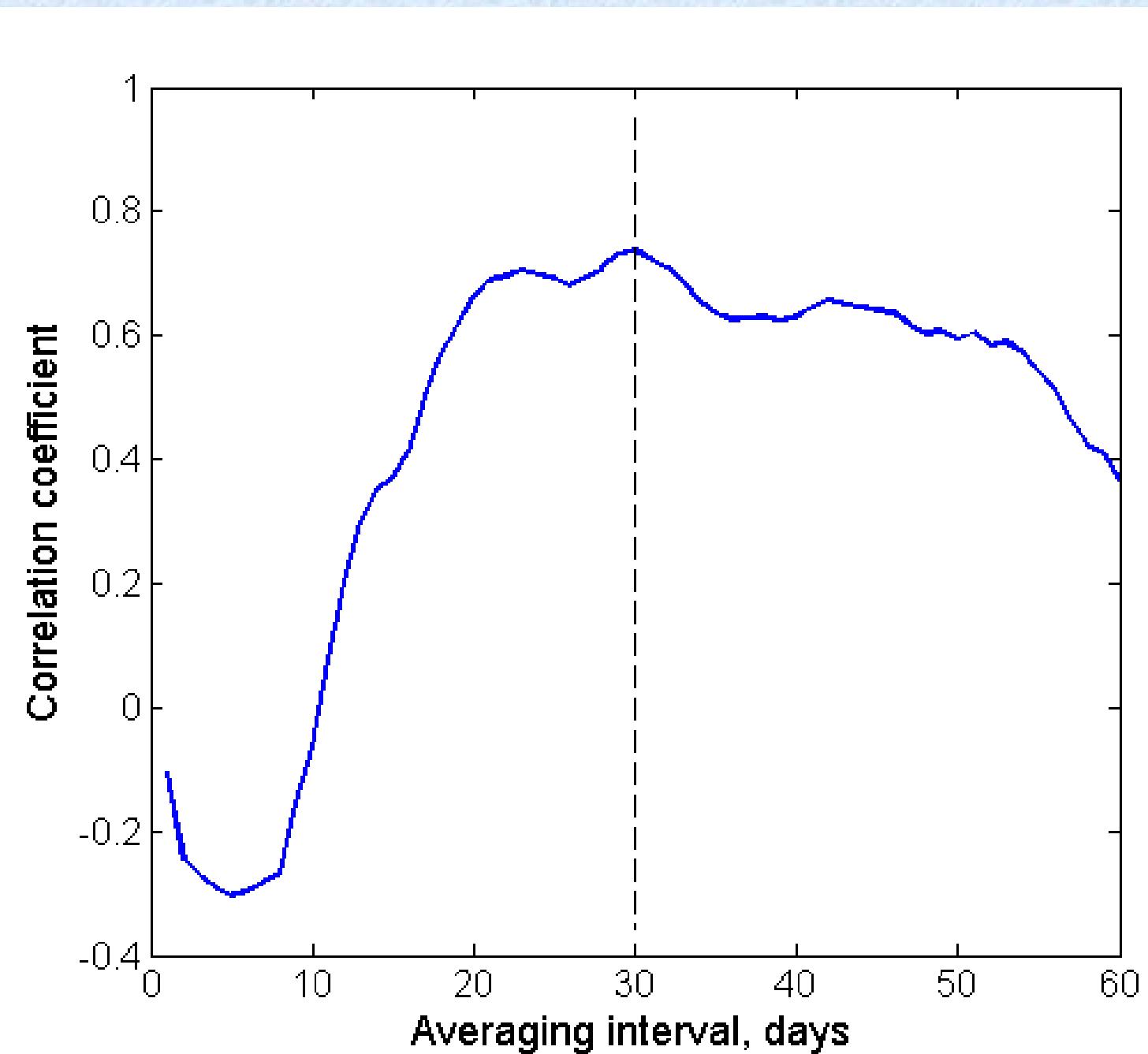
Alongshore surface geostrophic velocity distribution in the north-eastern part of Black Sea (dashed line - continental slope)

The Rim current is not topographically controlled in the north-eastern part of the Black Sea

Maximal velocity in the Rim current core is observed when the jet is located over the continental slope
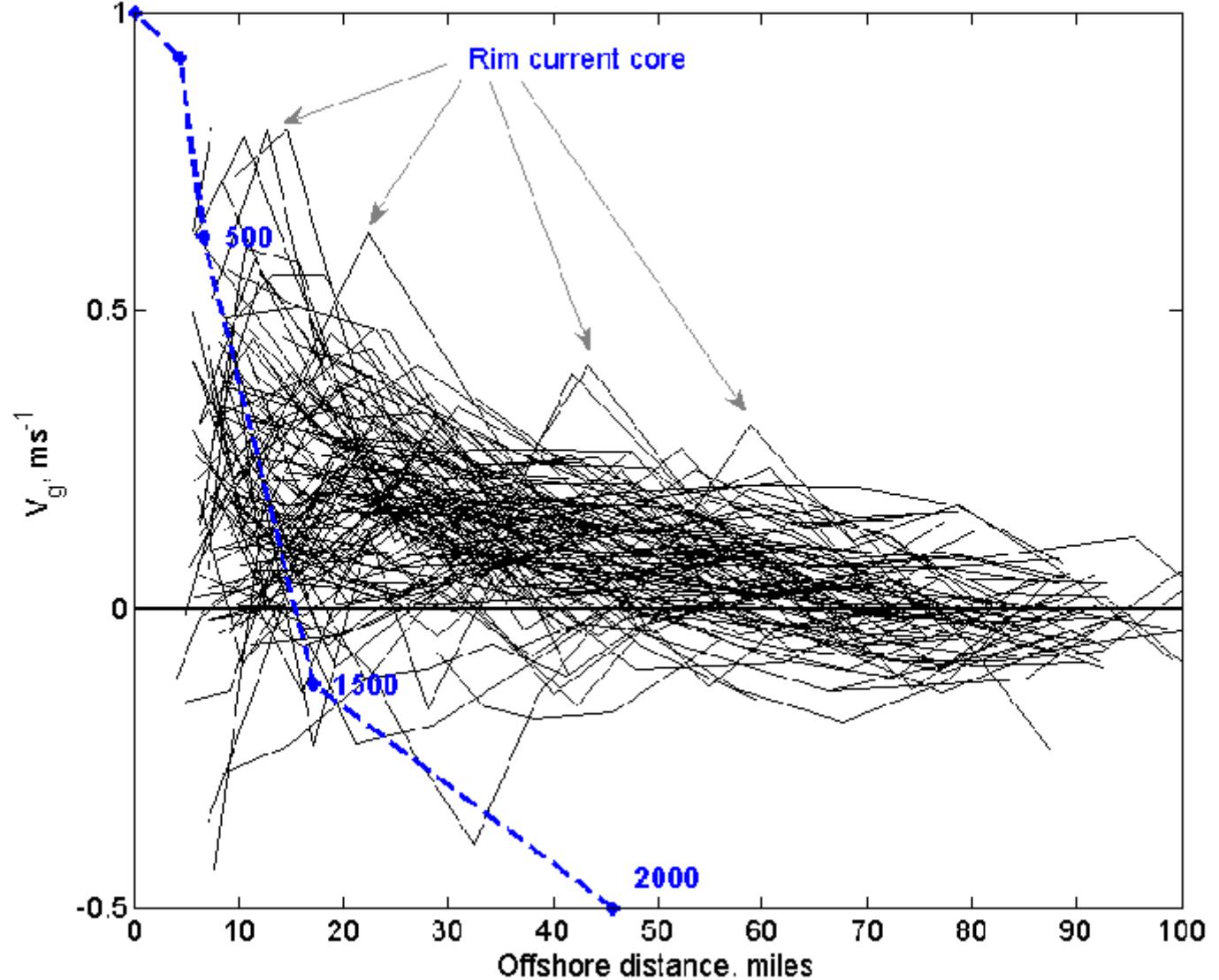
Location of the Rim current core versus the time averaged Ekman pumping velocity ($<W_E>$) in the north-eastern Black Sea

In case of strong Ekman pumping ($W_{ek} > 10^{-6}$ m/s) the Rim current core is located over the continental slope.

In case of weak Ekman pumping ($W_{ek} < 10^{-6}$ m/s) the Rim current core may be located far from the continental slope.
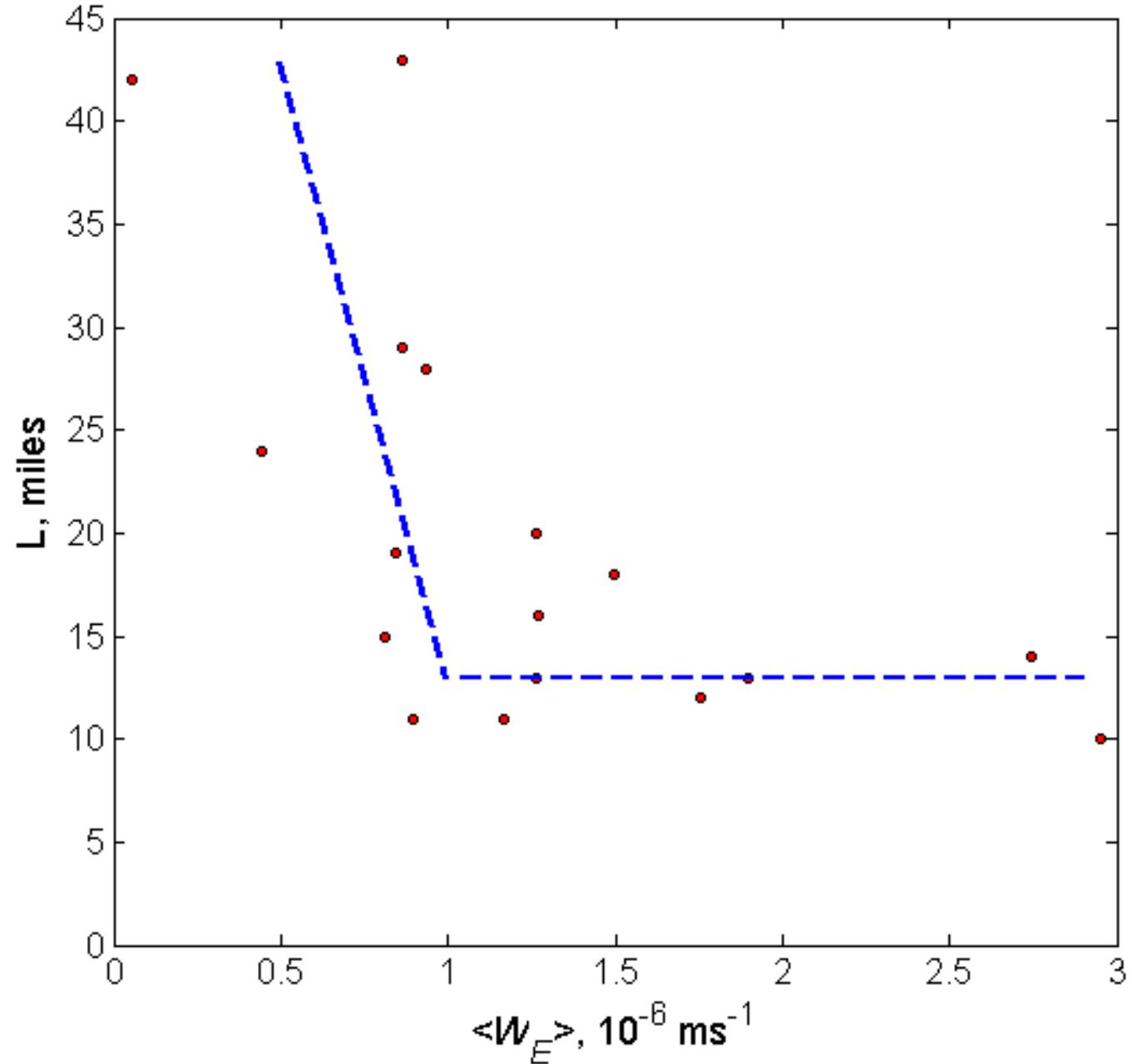
Laboratory modeling of wind and bottom slope impact on the boundary current in two-layered rotating fluid
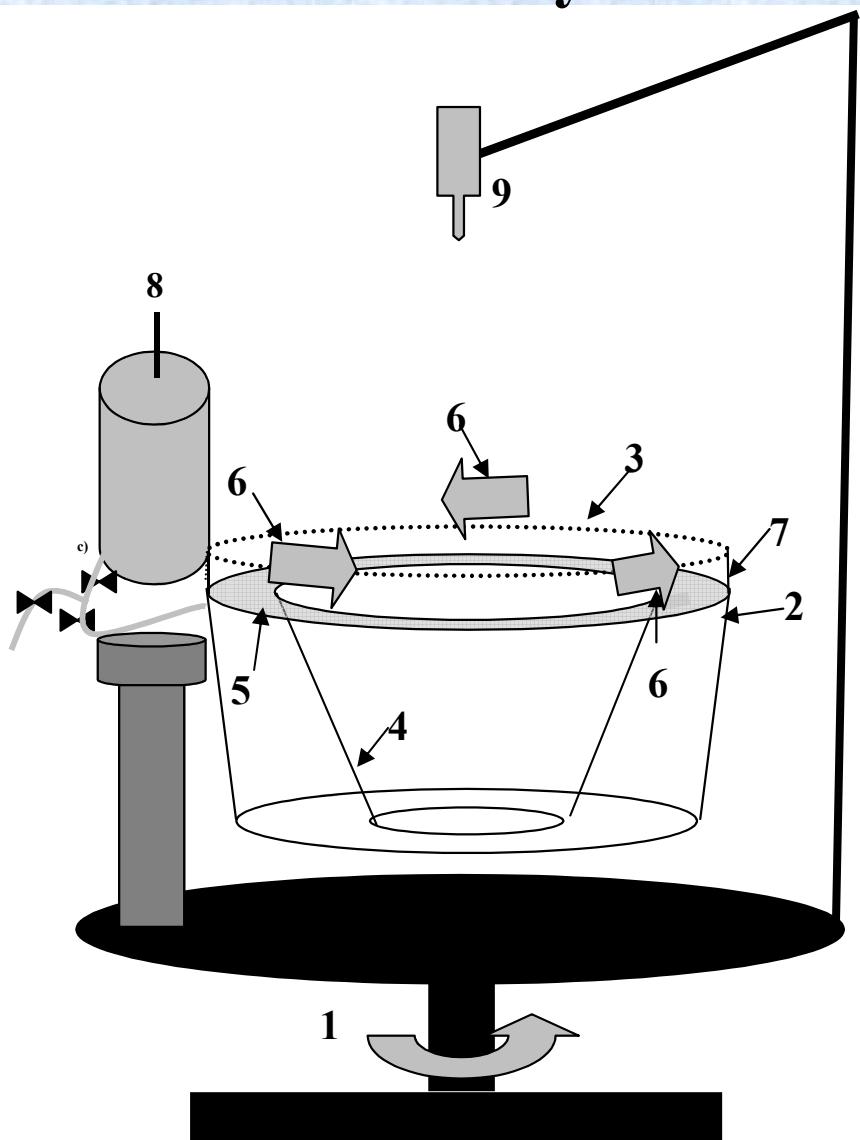
1-rotating platform; 2 –plastic tank with 2-layered fluid; 3 – the tank cap; 4 – sloping bottom; 5 –shelf zone; 6 –wind generators; 7 – wall; 8 – constant flux source; 9 – video camera.
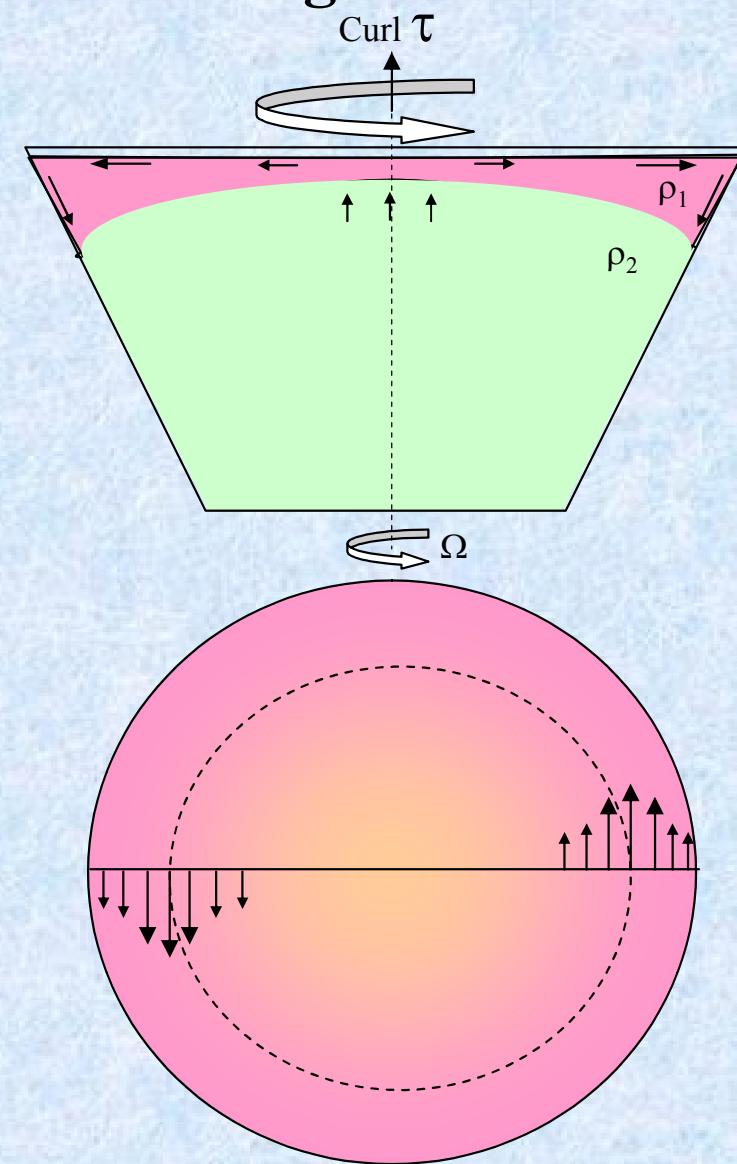
Scheme of baroclinic circulation during the wind forcing phase: side (upper) and top (lower) views

Non- dimensional parameters for the Black Sea and the laboratory model

Parameters (non-dimensional)	Black Sea	Laboratory model
$\theta = h_0/H$	$(0.5\text{-}1)*10^{-1}$	$(0.7\text{-}1.4)*10^{-1}$
$Bu_0 = (R_d/L_o)^2$	$(0.6\text{-}2)*10^{-2}$	$\sim 10^{-2}$
L_S/R_d	0.5-5	1-8
$E = \nu/(f\,h_0^2)$	$(0.01\text{-}1)*10^{-4}$	$\sim 10^{-3}$
$Fr_{Rim} = U_{Rim}/(g'\,h_0)^{0.5}$	$(0.4\text{-}2.0)*10^{-1}$	$(0.3\text{-}3.0)*10^{-1}$

Relaxation of the boundary current formed by Ekman pumping in case of narrow (steep) slope: $L_S/R_d = 1$ (Zatsepin et al., 2005)
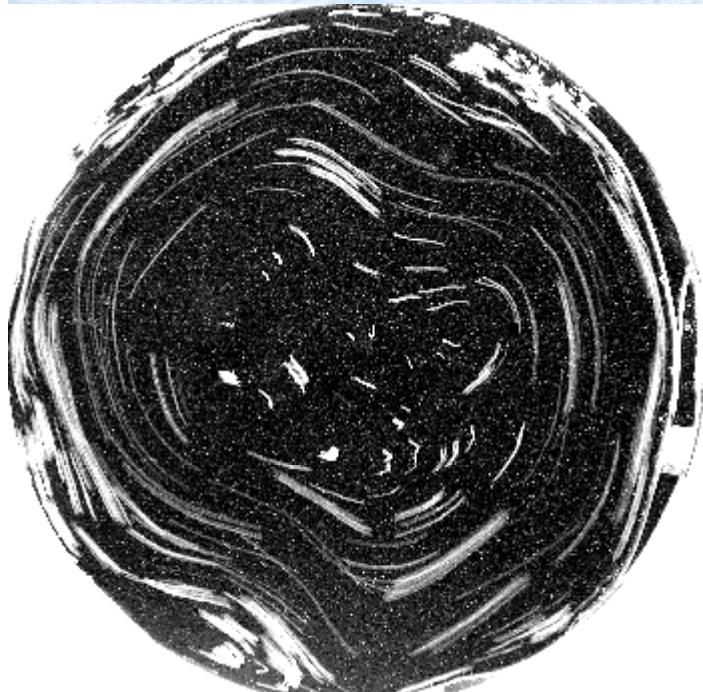
Developed boundary current at the end of wind forcing
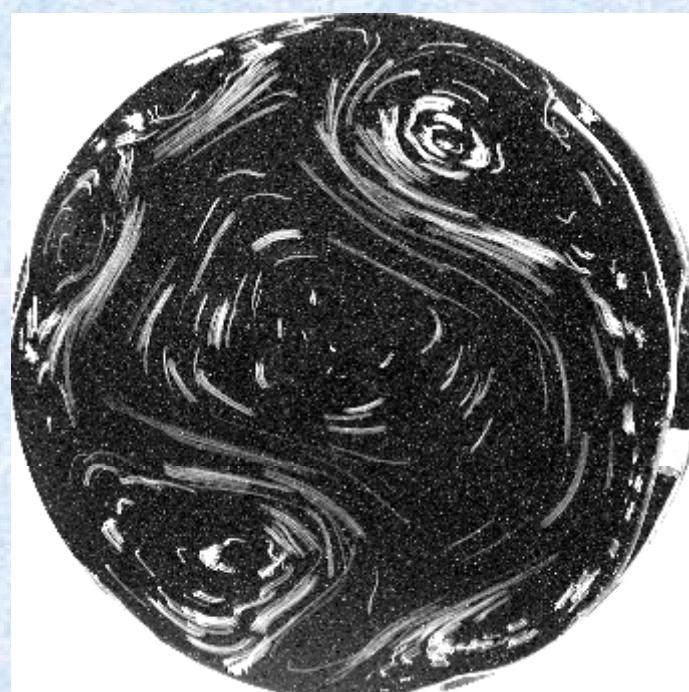
4 lab. days
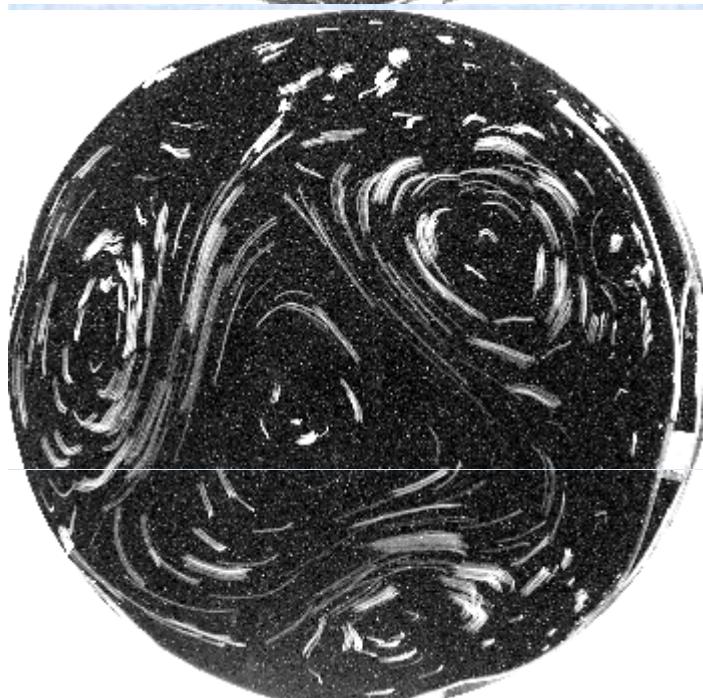
17 lab. days

45 lab. days

Relaxation of the boundary current formed by wind stress in case of wide (gentle) slope, $L_s/R_d = 4$ *(Zatsepin et al., 2005)*
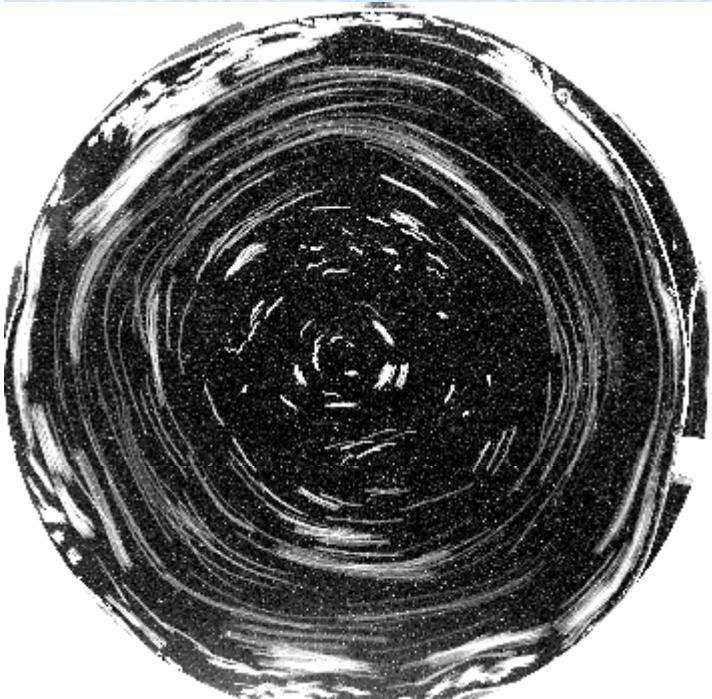
Developed boundary current at the end of wind forcing
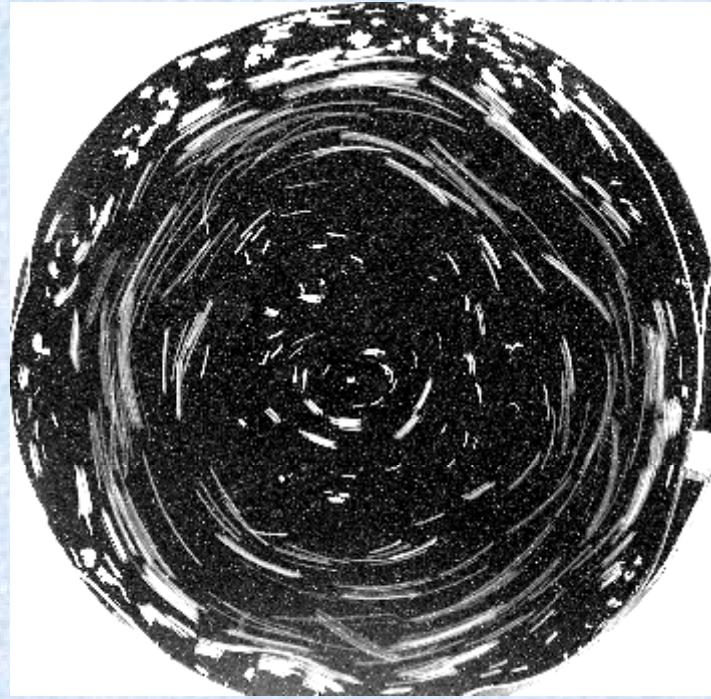
17 lab. days
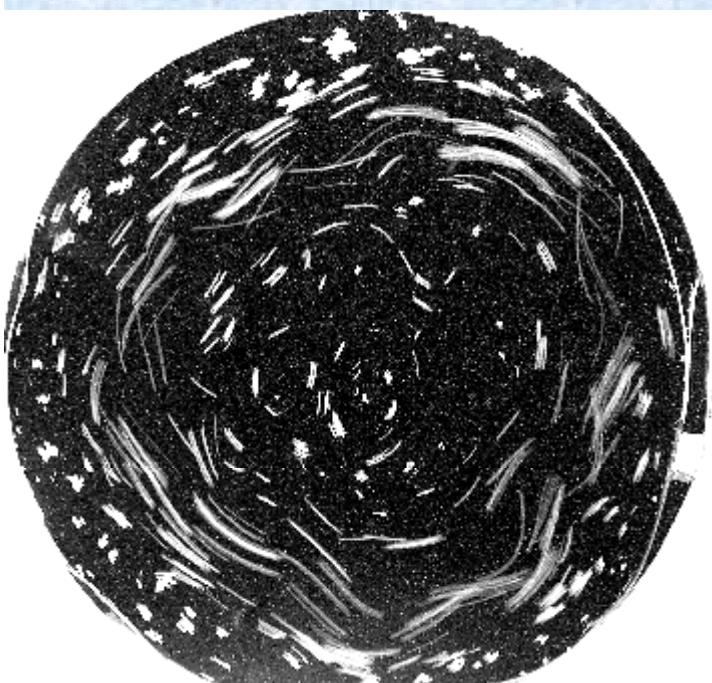
34 lab. days
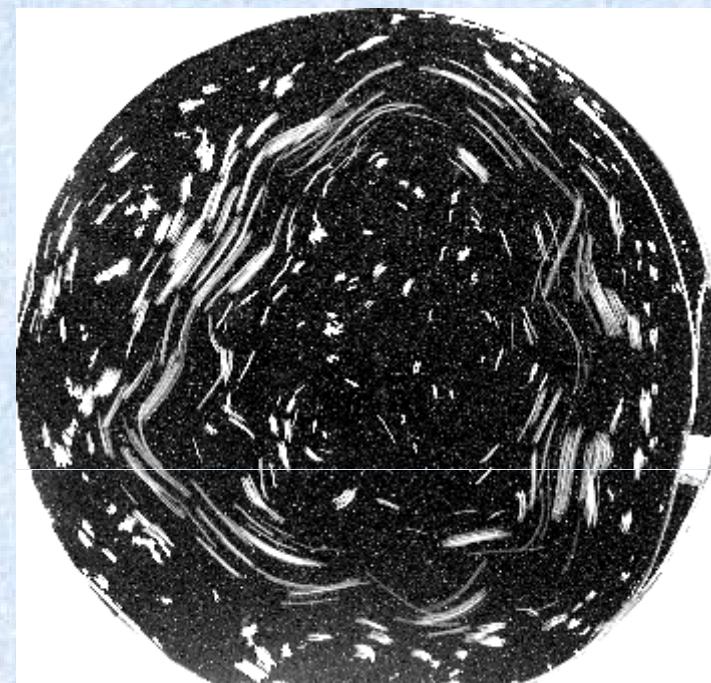
45 lab. days

Numerical modeling
(cyclonic wind vorticity)
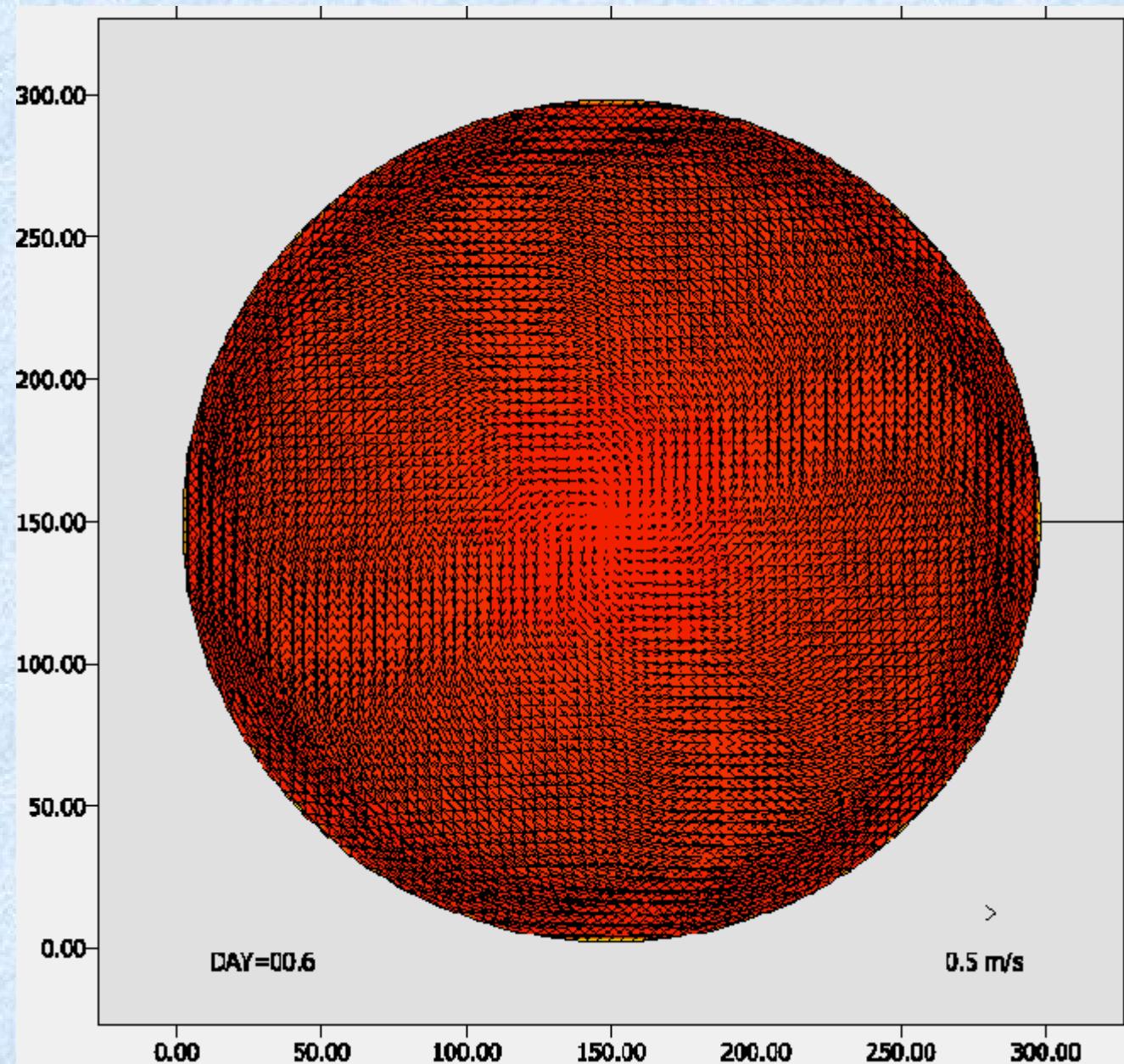
Zhurbas et al., 2005

Numerical modeling
(anticyclonic wind vorticity)
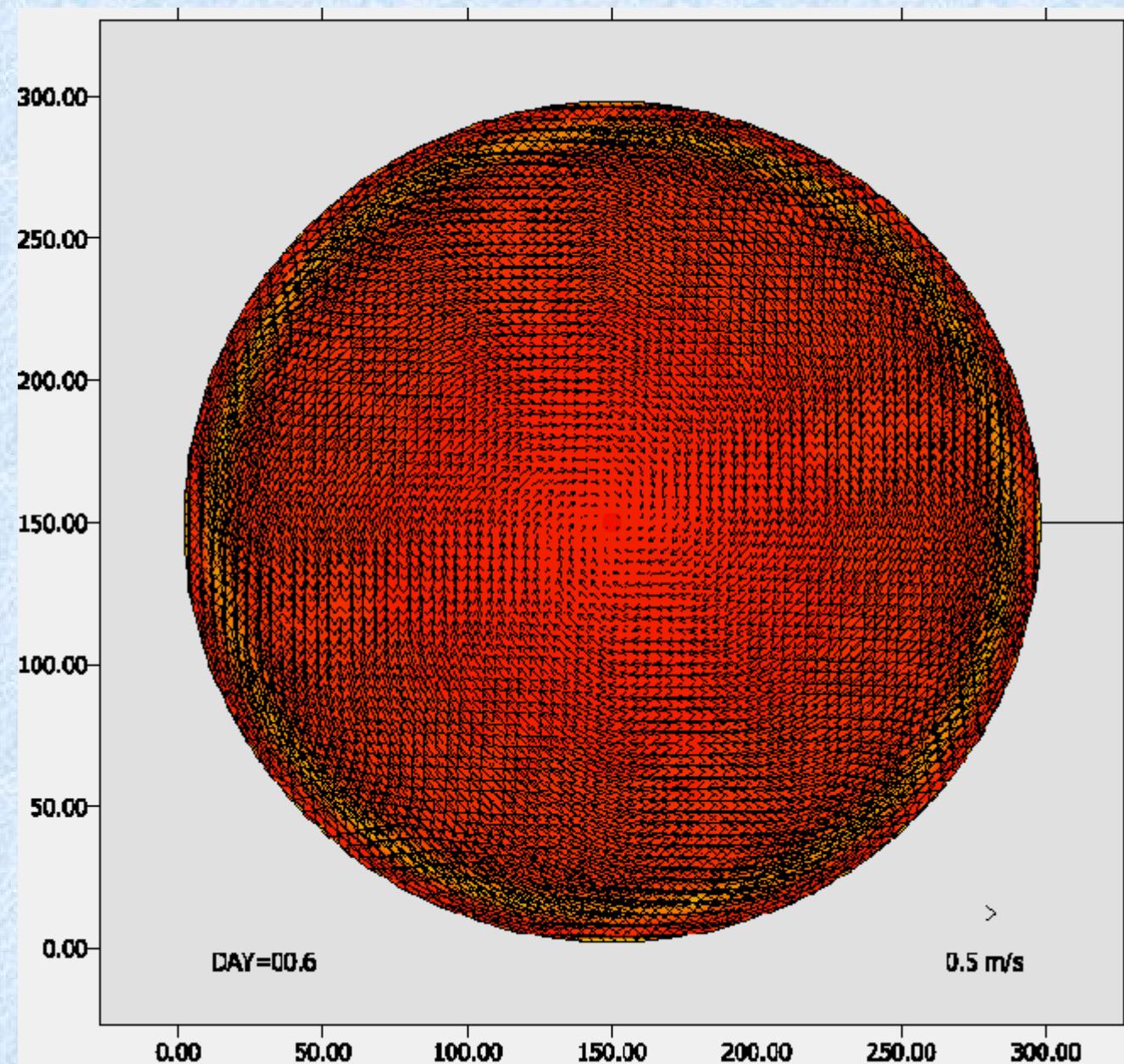
Zhurbas et al., 2005

Effect of Ekman pumping temporal variability on the Rim current and mesoscale eddy dynamics
in case of N.E. Black Sea, cyclonic circulation upon narrow continental slope

Ekman pumping

strong

weak

Intensification of Rim current, its location close to the continental slope

decrease of mesoscale eddy activity and horizontal exchange

Weakening and meandering of Rim current due to baroclinic - barotropic instability , formation of mesoscale eddies, increase of horizontal exchange
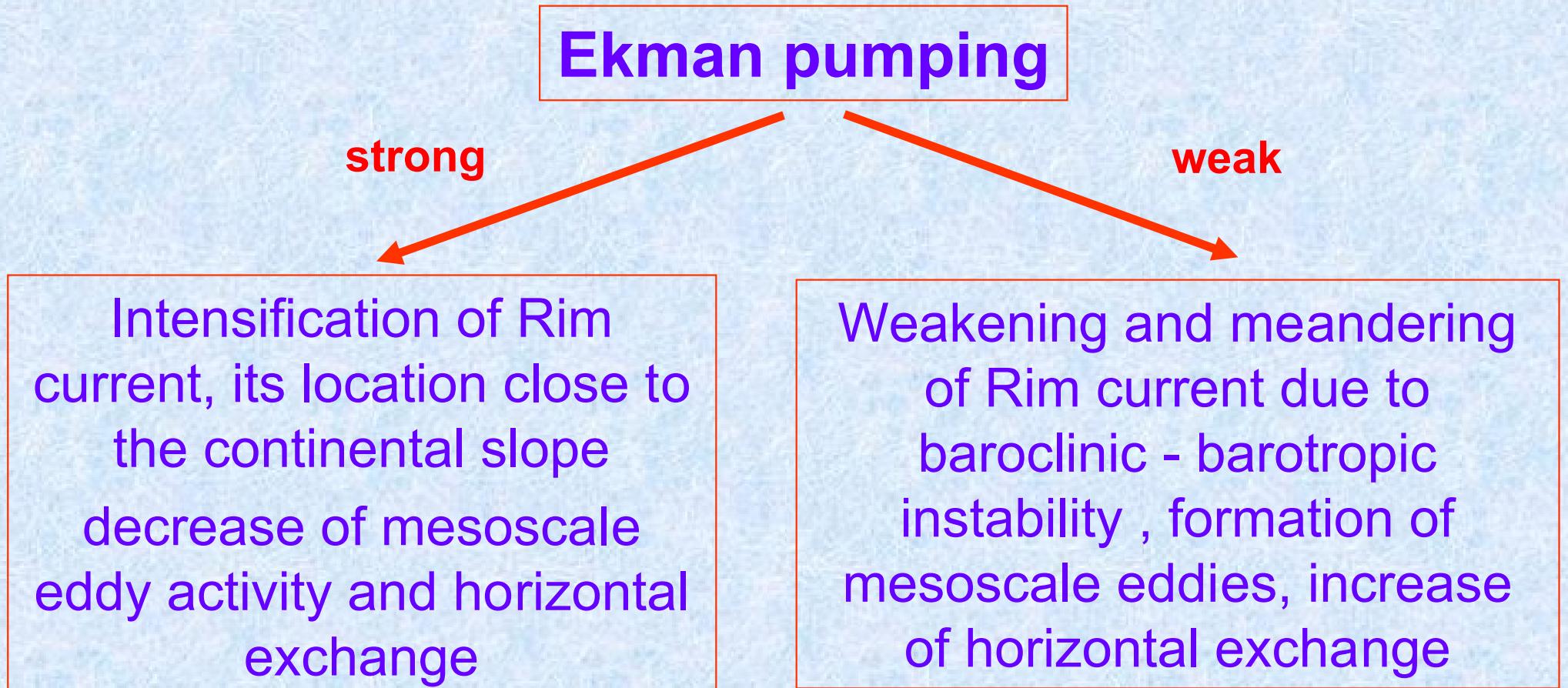
Adjustment time scale to the new Ekman pumping level is about 1 month
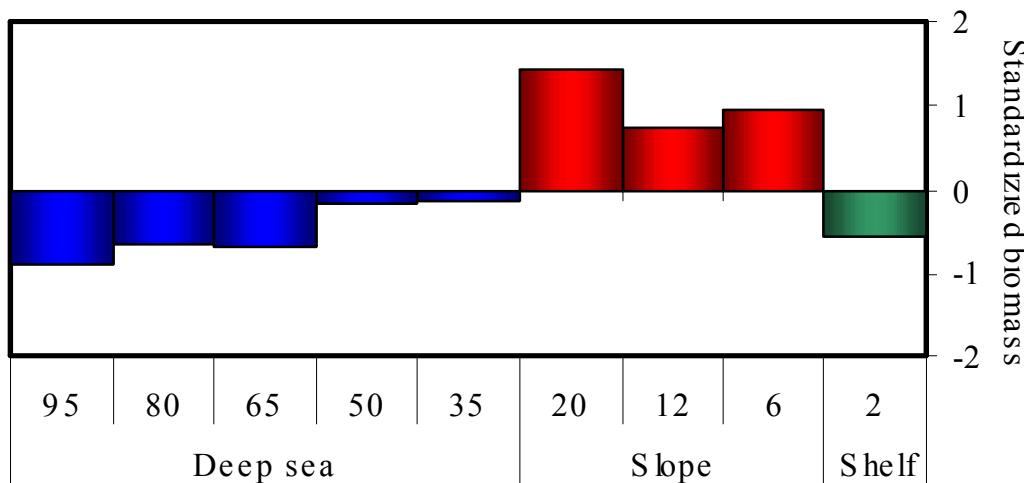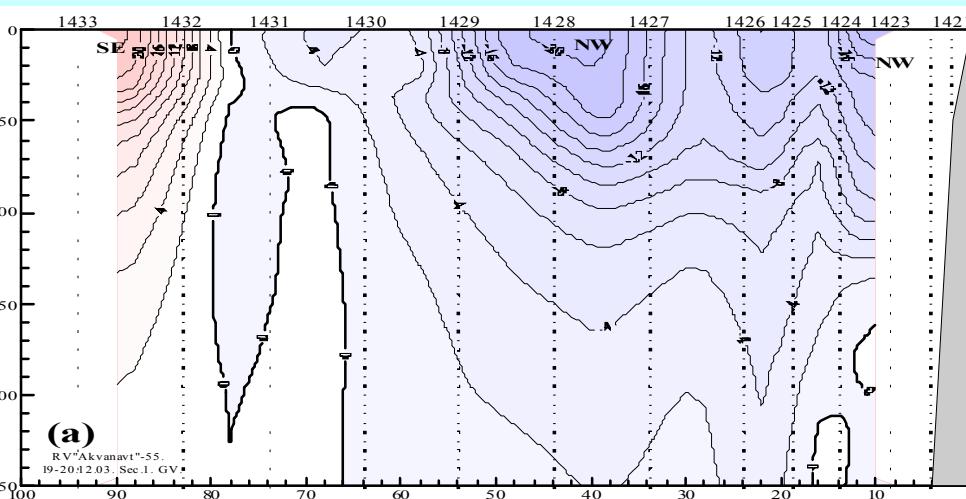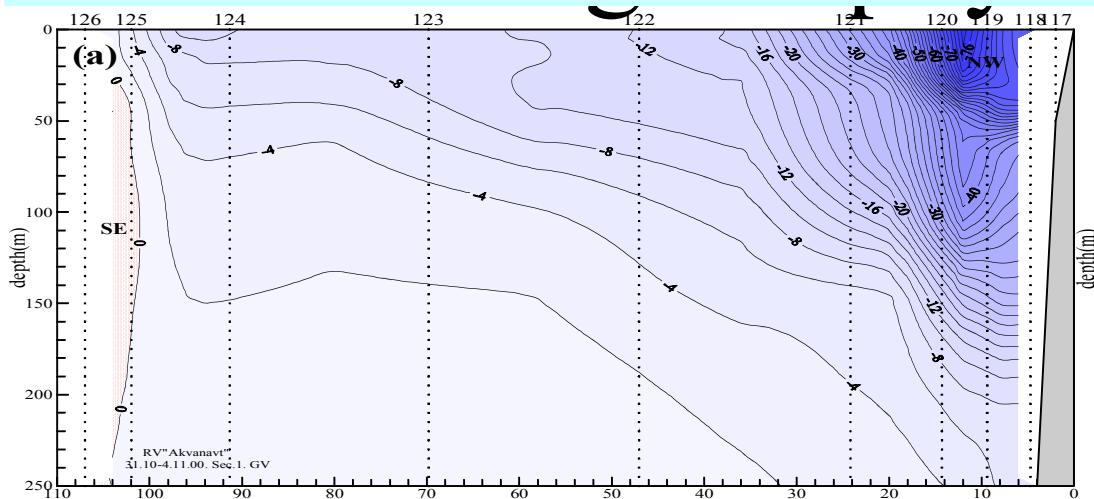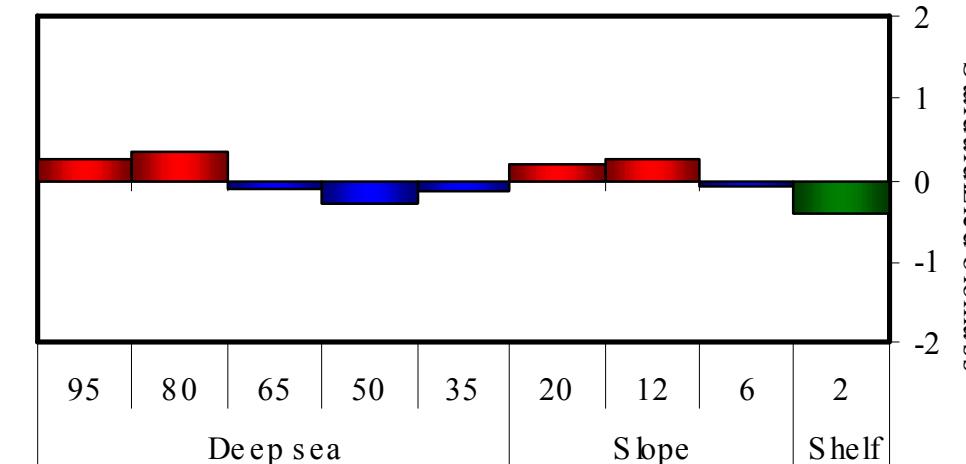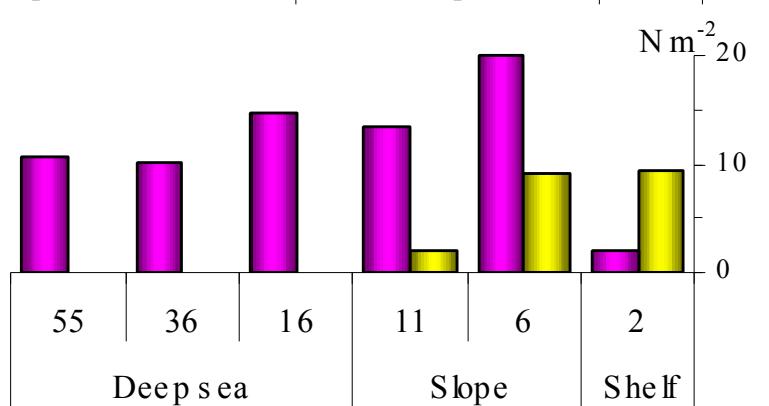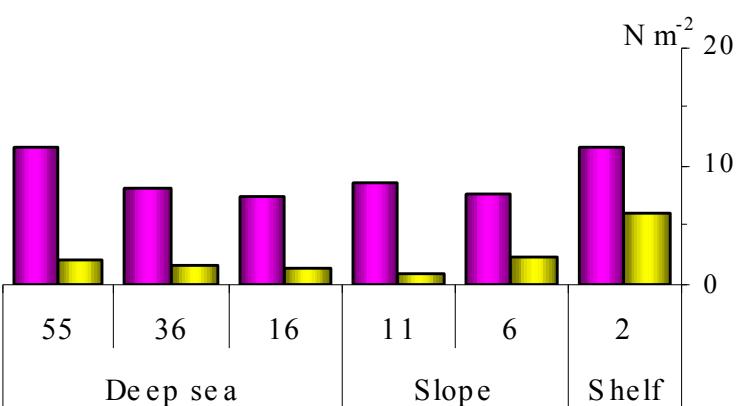
THANK YOU!

БЛАГОДАРЮ
ЗА ВНИМАНИЕ