EDDY-TOPOGRAPHY INTERACTIONS AND THE FATE OF THE PERSIAN GULF OUTFLOW

SYNBIOS workshop

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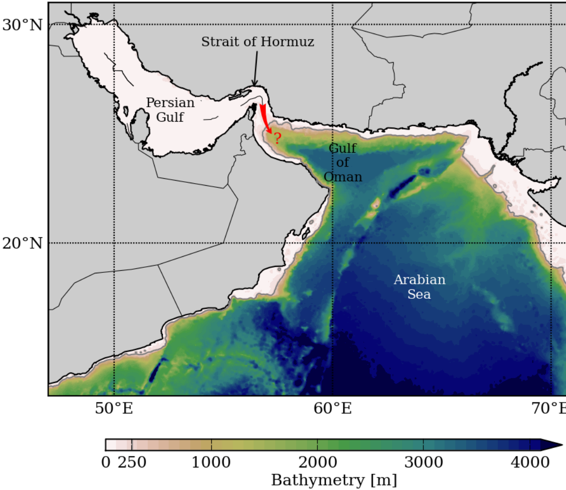
OUTLINE

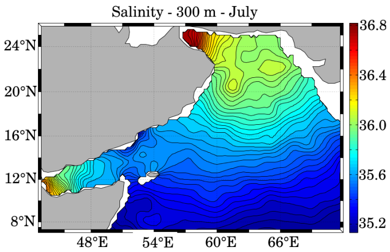
INTRO

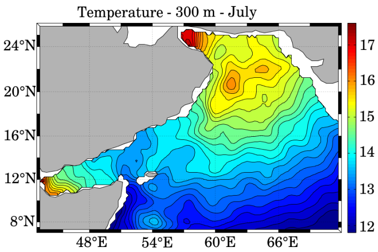
CONTEXT - GEOGRAPHY



CONTEXT - OUTFLOW PROPERTIES

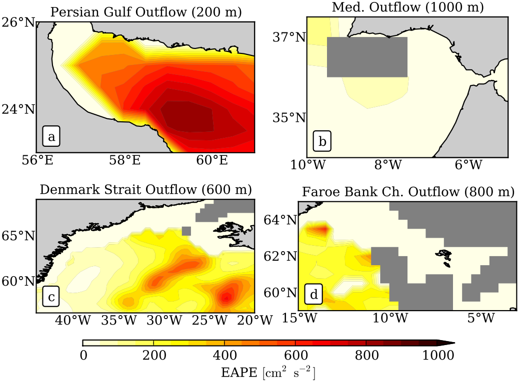
- → Persian Gulf Outflow (warm and salty waters) through the Strait of Hormuz (∼ 40-100 m).
- → Neutral buoyancy at ∼ 200-300 m.





[climatologies derived from ARGO floats (2006-2010), figures from Carton et al. 2012]

CONTEXT - DYNAMICAL ENVIRONMENT

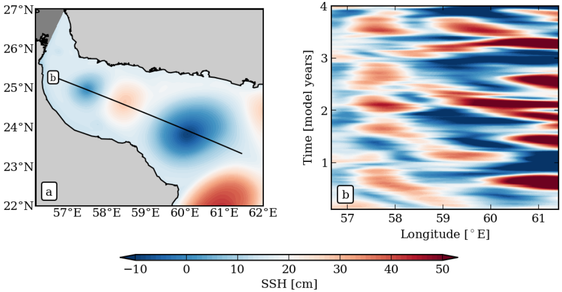


[Eddy Available Potential Energy derived from ARGO floats, Roullet et al. 2014]

→ Shallow equilibrium depth ($\sim$ 200-300 m)

→ Western Boundary : high level of mesoscale turbulence (remotely forced)

CONTEXT - DYNAMICAL ENVIRONMENT



→ Shallow equilibrium depth (∼ 200-300 m)

→ Western Boundary : high level of mesoscale turbulence (remotely forced)

→ Confined environment : westward drifting eddies are trapped and interact with the topography (continental slope)

Similarity with the Red Sea Outflow → Eddy-outflow interactions are to be expected [Ilicak et al. 2011, Bower & Furey 2012]

ISSUES & METHODS

Issues

How mesoscale eddies interact with the Persian Gulf Outflow ?
How is Persian Gulf Water (PGW) spread in the Gulf of Oman ?

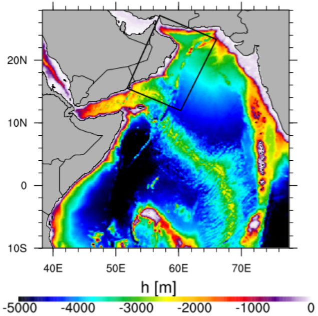
Methods

→ High resolution (2 km) nested regional numerical simulation (ROMS)

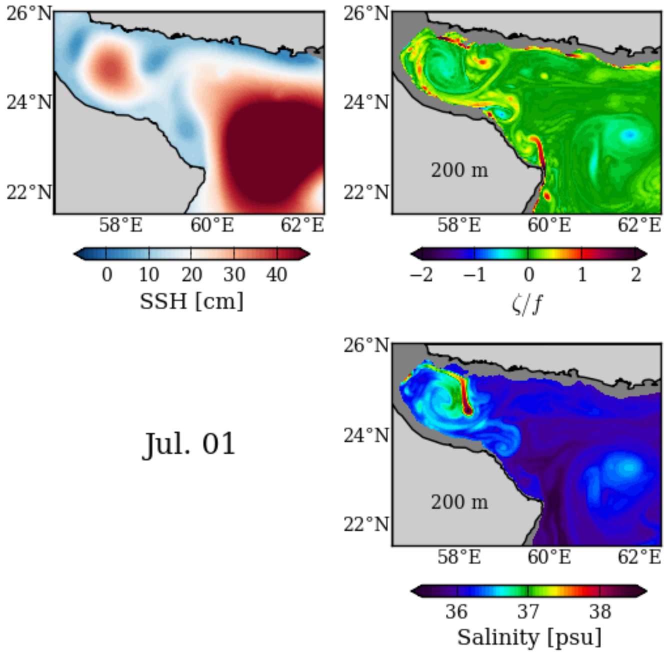
→ Idealized simulations (ROMS)

PHENOMENOLOGY

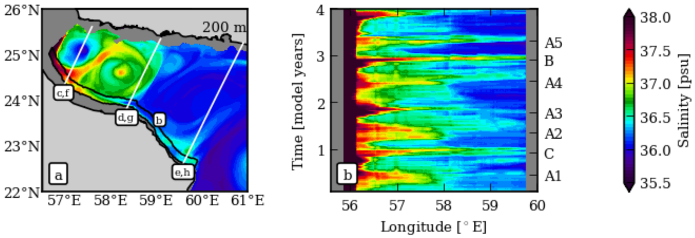
REALISTIC SIMULATION (4 YEARS)



- → ROMS one-way nested configuration (black rectangle) from an Arabian Sea solution at $\Delta x = 6.6$ km.
- → $\Delta x = 2$ km, submesoscale permitting ($R_d = 41$ km).
- → Monthly climatological forcing : QuikSCOW wind stress and ICOADS heating and freshwater fluxes.
- → Semi-analytical western boundary in the shallow Strait of Hormuz from moored ADCPs and T-S measurements [Johns et al. 2003]

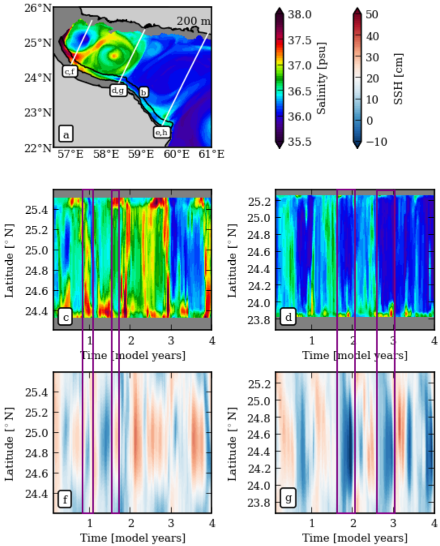

26°N
24°N
22°N
58°E
60°E
62°E
0 10 20 30 40
SSH [cm]
200 m
−2 −1 0 1 2
ζ/f
Jul. 01
200 m
36 37 38
Salinity [psu]

AN INTERMITTENT SLOPE CURRENT CONTAINING PGW



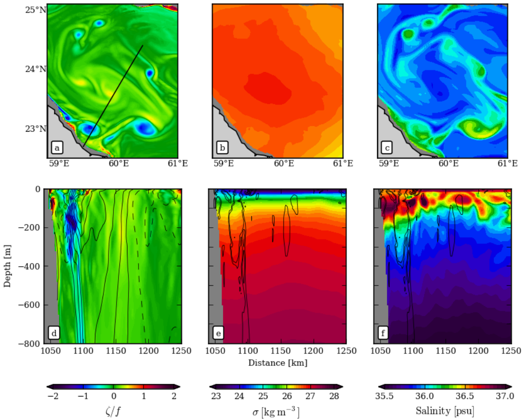
- → The slope current is discontinuous and intermittent along the southern boundary (expected from Coriolis force).
- → Salt is rapidly diluted from the Strait to the end of the Gulf.

ROLE OF MESOSCALE EDDIES



→ The fate of the outflow is tightly linked with surface intensified mesoscale eddies, at a seasonal time scale.
→ Cyclones steer PGW southward.
→ Anticyclones steer PGW northward.

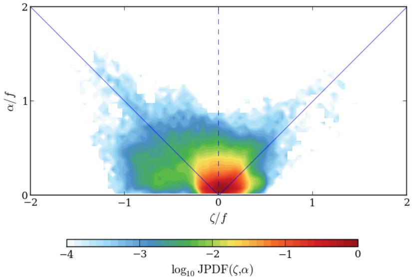
SUBMESOSCALE COHERENT VORTICES (SCVS) CONTAIN PGW



- → Mesoscale eddies, remotely formed and propagating into the Gulf, detach fragments of PGW from the slope.
- → PGW is trapped into, above or beneath SCVs.

- → SCV properties : $|\zeta|/f \sim 1$, $L < R_d$, core located at depth ∼100-300 m
  polarity : opposed to the neighbouring mesoscale eddy,
  trajectory : advection along the edges of mesoscale eddies.

SCV LIFE CYCLE

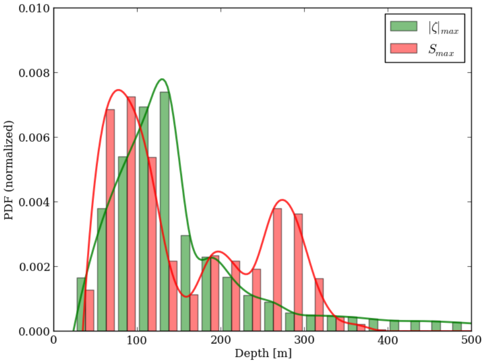


Joint Probability Density Function of $\zeta = v_x - u_y$ and $\alpha = \left[(v_x + u_y)^2 + (u_x - v_y)^2\right]^{1/2}$.

- → Short life cycle : < 10 days
- → Strong surrounding deformation field :
  - → div. $\delta = u_x + v_y \sim f$
  - → shear $s = v_x + u_y \sim f$
  - → strain $\sigma = u_x - v_y \sim f$

  Thus competing with ζ.
- → Limit of resolution of the model ?

PASSIVE ROLE OF THE OUTFLOW ?

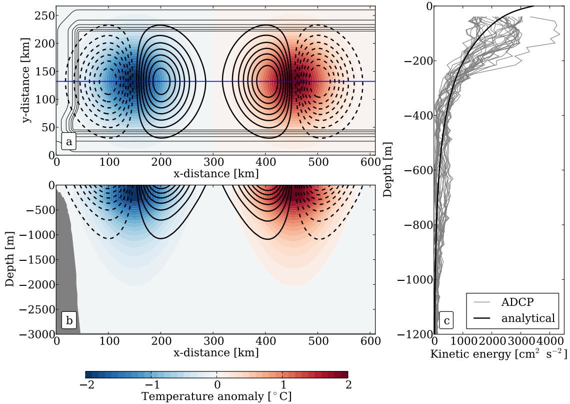


- → Non Co-localization of the salt (hydrological) and relative vorticity (dynamical) cores.
- → PGW is embedded into SCVs but is not necessarily in their cores.

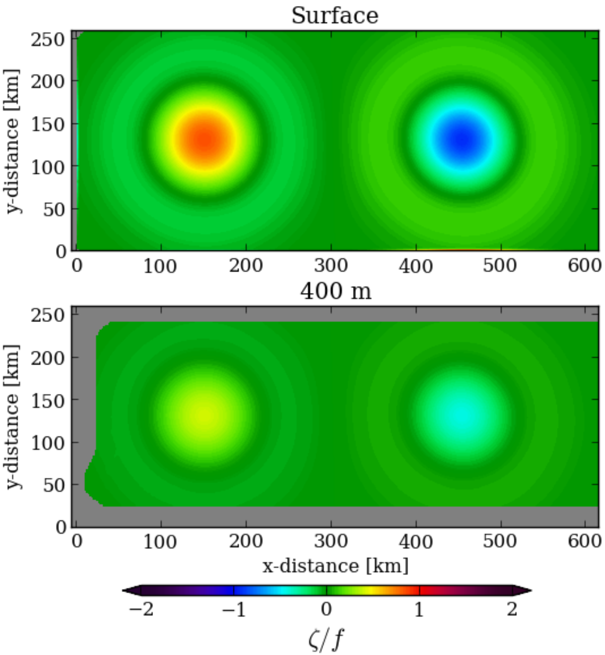
- → How SCVs are formed ?
- → Is the outflow passive in the formation of SCVs ?

PROCESSES

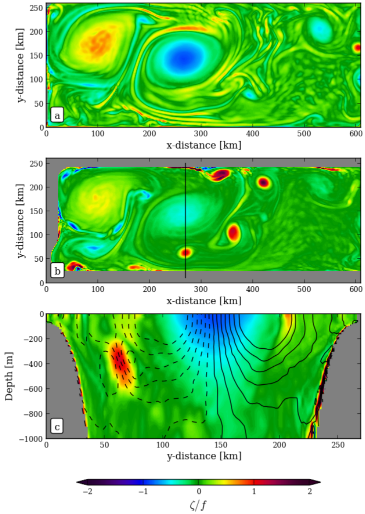
IDEALIZED EXPERIMENT - SET UP



- → Idealized Gulf of Oman : extents, R_d, Δx, ...
- → Free decay of mesoscale eddies with a realistic energy level.
- → With/without bottom friction (linear drag, $C_D = 3\,10^{-4}\ \mathrm{m\,s^{-1}}$)


Surface
250
200
150
100
50
0
y-distance [km]
0
100
200
300
400
500
600
400 m
x-distance [km]
−2
−1
0
1
2
ζ/f

BOUNDARY LAYER DYNAMICS



→ Mesoscale eddies have a strong imprint on ζ at depth [Carton et al. 2012, L'Hégaret et al. 2013].

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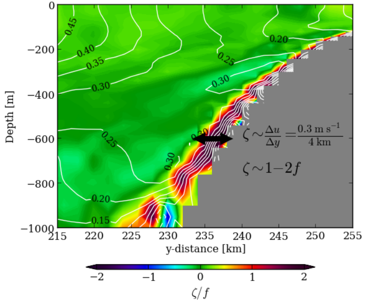

- → Mesoscale eddies have a strong imprint on ζ at depth [Carton et al. 2012, L'Hégaret et al. 2013].
- → Intense vorticity strips are generated in boundary layers $|\zeta|/f > 1$. They roll up in the interior into SCVs, being unstable for the centrifugal instability ($\zeta < 0$) or barotropic (shear) instability ($\zeta > 0$) [D'Asaro 1988, Molemaker et al. 2014, Gula et al. 2015].

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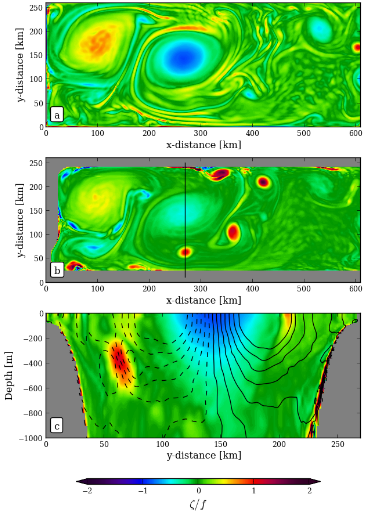

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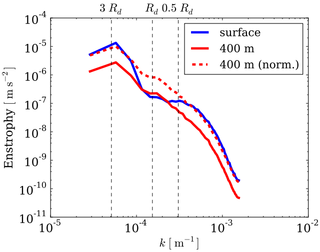
→ Friction acts on mesoscale eddy velocity and neither topographic irregularity nor density current is required for detachment of SCVs.

ENSTROPHY SOURCE ON THE CONTINENTAL SLOPE



→ The enstrophy $\zeta^2/2$ source is localized on the continental slope where mesoscale eddies drag.

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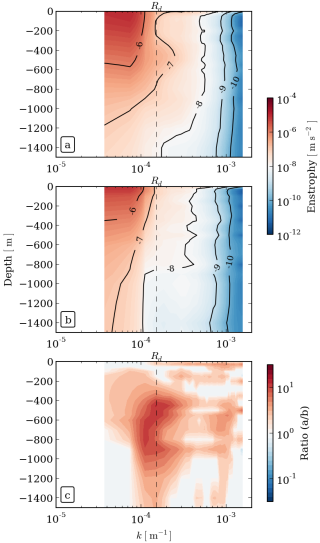

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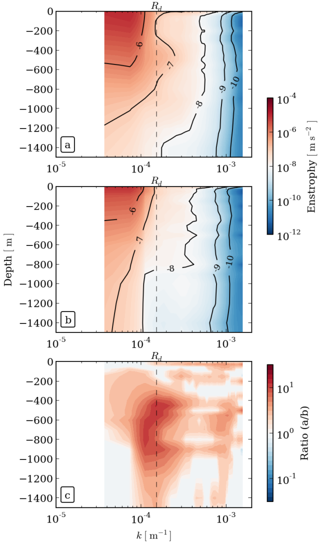
→ Experiments with/without bottom stress highlight that the enstrophy source is due to friction.

ENSTROPHY SOURCE ON THE CONTINENTAL SLOPE



→ The enstrophy $\zeta^2/2$ source is localized on the continental slope where mesoscale eddies drag.

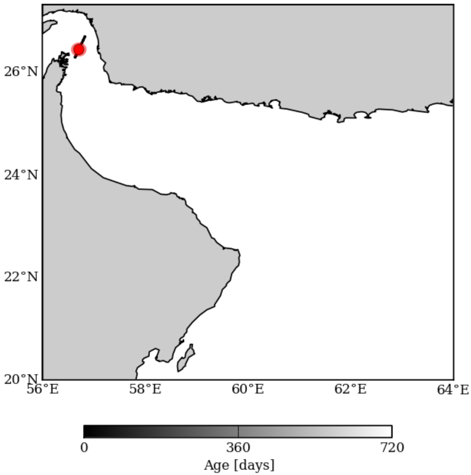
→ Experiments with/without bottom stress highlight that the enstrophy source is due to friction.

→ The ROMS model (σ-coordinates) vertical boundary layer implies a horizontal shear layer

[Molemaker et al. 2014, Gula et al. GRL 2015].

CONSEQUENCES

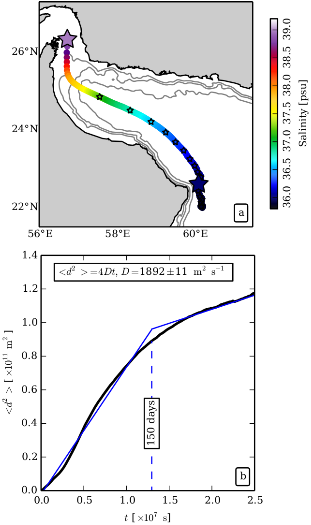
LAGRANGIAN PERSPECTIVE



→ Continuous release of synthetic particles in the Strait at the outflow depth

[code described in Gula et al. JPO 2014]

LAGRANGIAN PERSPECTIVE



→ Continuous release of synthetic particles in the Strait at the outflow depth

[code described in Gula et al. JPO 2014]

→ Diffusion-like dispersion of particles : linear in time, typical of a random-walk process.

$$< d^2(t) >= 4D\ t$$

→ Eddy diffusivity $D \sim 2000\ \mathrm{m^2\ s^{-1}}$, similar to highly diffusive regimes (ACC, $D \sim 3000\ \mathrm{m^2\ s^{-1}}$ [Abernathey et al. 2010])

CONCLUSIONS

CONCLUSION

How mesoscale eddies interact with the Persian Gulf Outflow ? How is PGW spread in the Gulf of Oman ?

→ Eddy-topography interactions produce high vorticity strips that roll up into Submesoscale Coherent Vortices. Friction is responsible for the generation of enstrophy in boundary layers, especially on the continental slope.

→ These SCVs trap Persian Gulf Water and participate actively to its spreading in the Gulf of Oman.

→ Small-scale eddy-topography interactions lead to turbulent diffusion processes that have a large-scale effect on the salt distribution.

SENSITIVITY TO THE BOTTOM STRESS [1/2]

How is the boundary layer sensitive to the bottom stress parameterization?

Same experiments with :

1. Linear bottom stress : $\boldsymbol{\tau}_b = -\rho_0 C_D^{lin} \boldsymbol{u}$, constant C_D
2. Quadratic bottom stress : $\boldsymbol{\tau}_b = -\rho_0 C_D^{quad} ||\boldsymbol{u}|| \boldsymbol{u}$, constant C_D
3. Quadratic bottom stress with a variable C_D :
   $C_D^{VonKarman} = \left(\frac{\kappa}{\log(\Delta z_b / z_r)} \right)^2$,
   $\kappa = 0.41$: Von Karman constant,
   z_r : roughness parameter $O(10^{-2} - 10^{-3} \text{ m})$

SENSITIVITY TO THE BOTTOM STRESS [2/2]

Type	C_D	$<\|\|\boldsymbol{\tau}\|\|>$ $[\times 10^{-3}\mathrm{N\ m^{-2}}]$	$\mathrm{std}(u_{bottom})$ $[\mathrm{cm\ s^{-1}}]$
Linear	$3.0\ 10^{-4}\ \mathrm{m\ s^{-1}}$	12.4	4.7
Linear	$6.0\ 10^{-4}\ \mathrm{m\ s^{-1}}$	17.1 (+38%)	3.3 (-30%)
Quadratic	$2.5\ 10^{-3}$	8.7	5.1
Quadratic	$5.0\ 10^{-3}$	12.2 (+28%)	4.2 (-18%)
Quadratic with Von Karman C_D	varying	7.9	5.1