Modelling Oceanic Dispersion :
Lagrangian Transport in the Sicily Channel

Alessandra S. Lanotte

CNR-ISAC & INFN
Lecce (Italy)

Workshop on Nonlinear Processes in Oceanic and Atmospheric Flows
Madrid 6-8 July, 2016

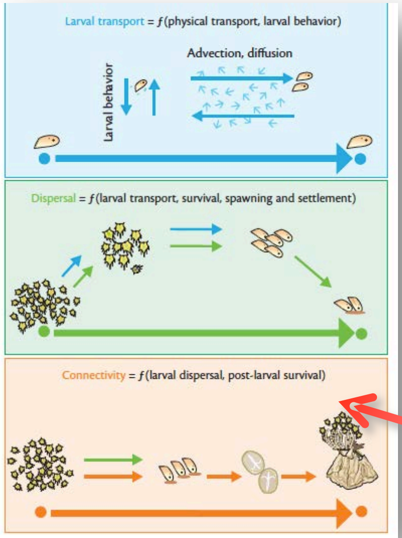
THE RELEVANCE OF LAGRANGIAN DYNAMICS

. beyond pure fluid dynamics

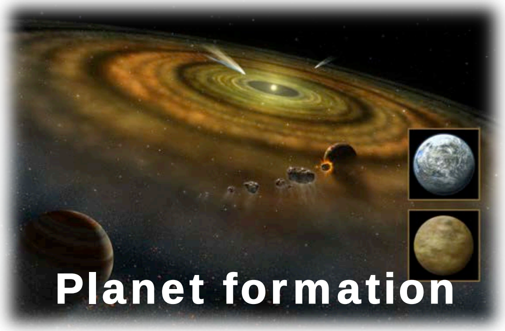
. out-of-equilibrium, multiscale

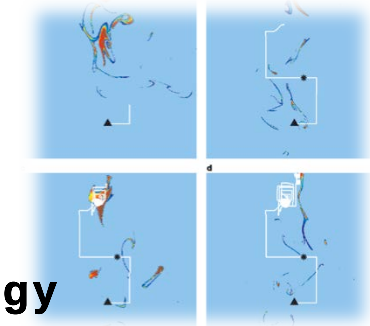
. *challenging & interesting*

. complicate *but* measurable

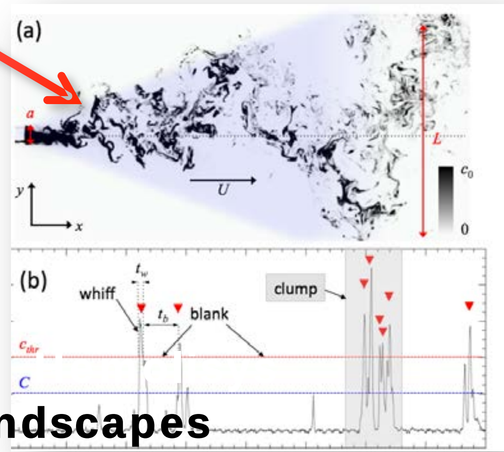


Dispersion & Connectivity





**Infotaxi-
search strategy**



Olfactory landscapes

About the talk

- Develop a suitable model for Lagrangian Transport :
  on the role of vertical shear

- Model calibration from *in-situ* measurements

- An application: Lagrangian dynamics in the Sicily Channel

With:
Luigi Palatella, Guglielmo Lacorata, Federico Falcini, Raffaele Corrado, Rosalia Santoleri

WHAT'S THE PROBLEM WITH LAGRANGIAN MOTION?

1 accurately know the spatial statistics of the flow velocity along Lagrangian paths *high-resolution, high frequency*

2 scale separation to disentangle different dispersion regimes: *exponential, ballistic, turbulent, mean shear, Taylor-like,..*

3 have high statistical accuracy : *long records* along *many* Lagrangian paths

4 limit the impact of *inhomogeneities*, *unsteadiness, anisotropies, stratification, super position of different motions*

DIFFICULT TO FULLFILL ALL THESE!

So observations have to be carefully examined

Mediterranean Surface Circulation

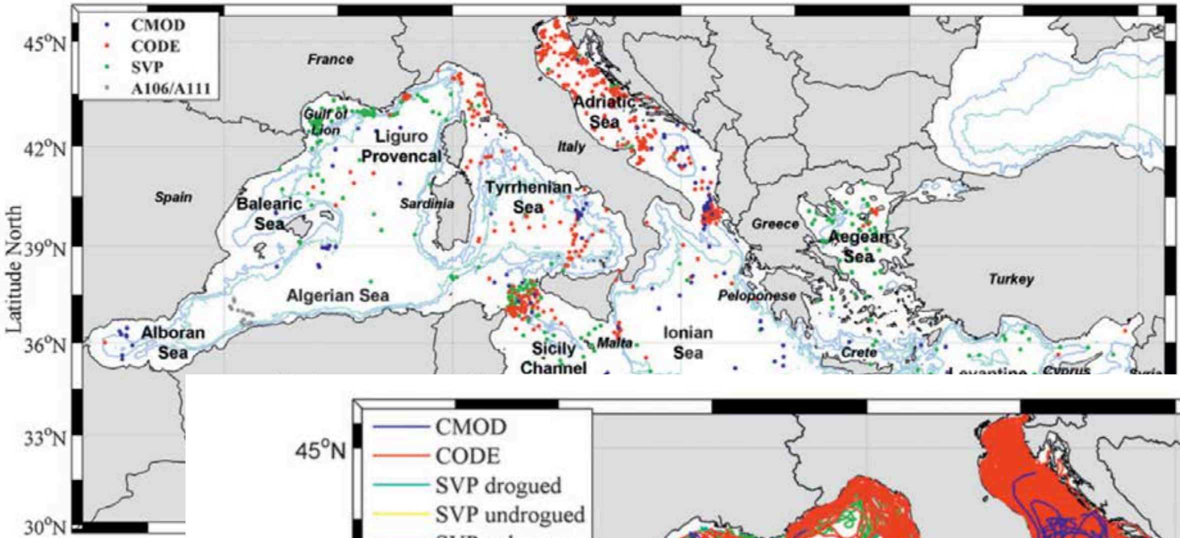


FIG. 1. Geogra

(Poulain et al, J Phys Ocean. 2012)

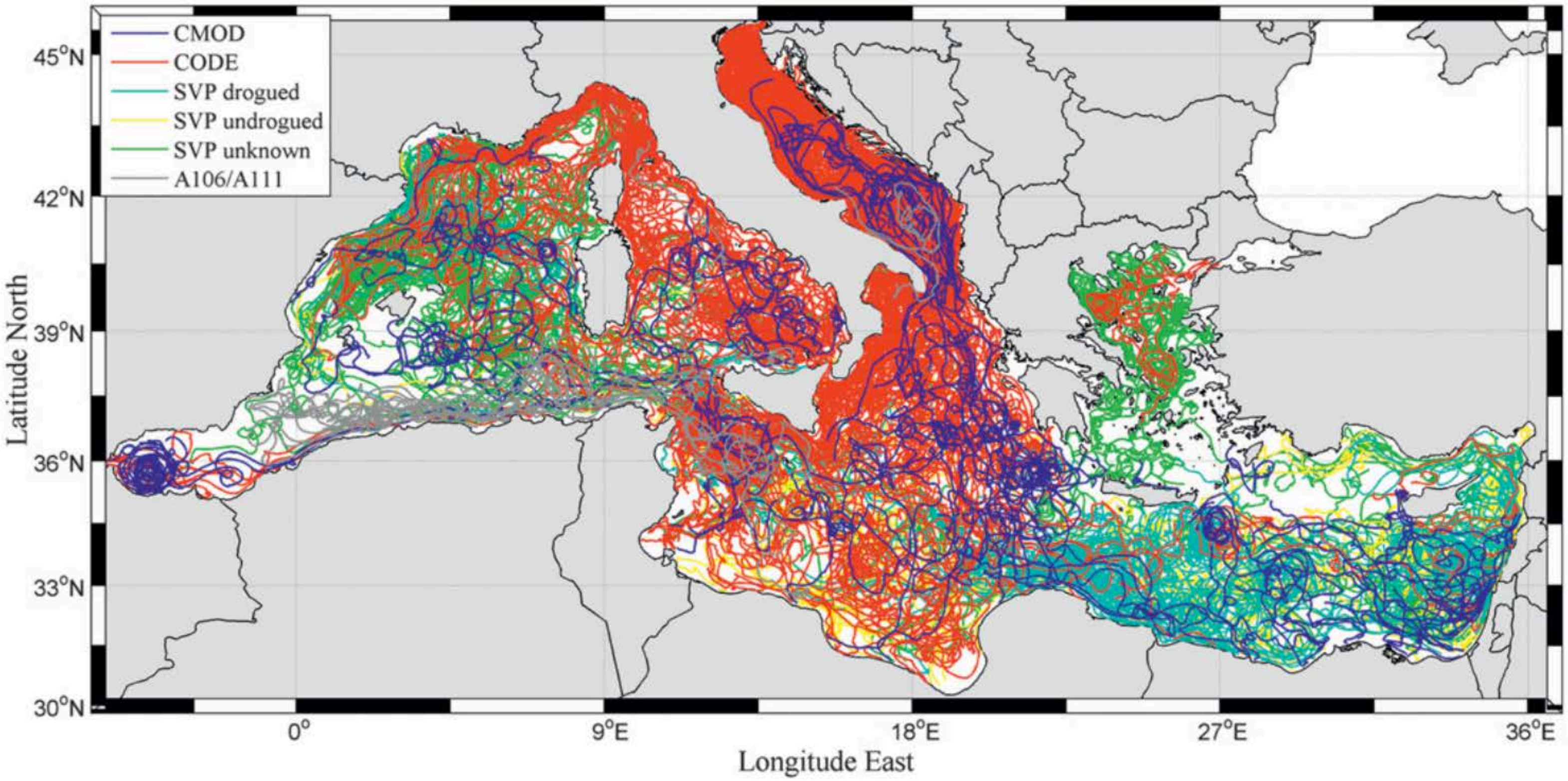


FIG. 2. Composite diagram of the interpolated and low-pass-filtered drifter tracks in the Mediterranean Sea. Different colors correspond to different drifter types and drogue depths.

Modelling Lagrangian dynamics

$$\frac{d\mathbf{X}}{dt} = \mathbf{U}(\mathbf{X}, t) + \mathbf{u}(\mathbf{X}, t)$$

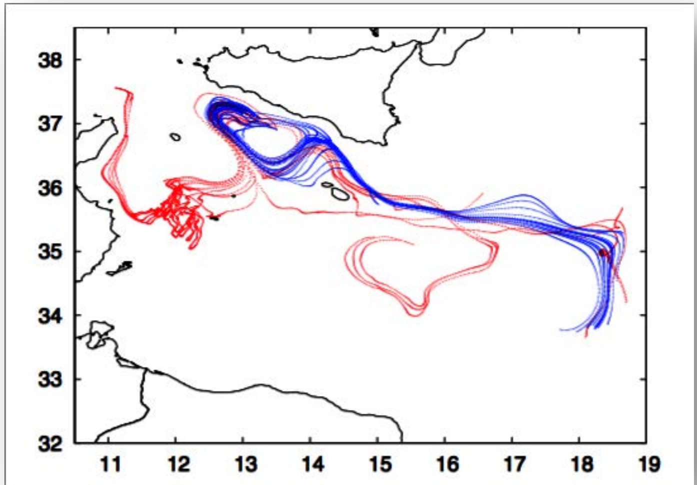
- Large-scale flow **U**(**X**,t) is known at discrete times and on a coarse grid

$$t \in \{t_0, t_1, t_2, \cdots\}$$

$$\mathbf{X} \in \{\mathbf{x}_0, \mathbf{x}_1, \mathbf{x}_2, \cdots\}$$

- Small-scale component **u**(**X**,t) is unknown and generally includes many complicate effects: *anisotropic, non homogeneus (coastal or topographical), transient phenomena*

- Spatio-temporal interpolation of **U**(**X**,t) can not introduce missing information



TIME RESOLUTION ISSUE

example: 3 months daily data of a GCM model

Two Lagrangian simulations of surface dispersion :

RED POINTS : using daily currents
BLUE POINTS: using the monthly averaged currents

Mean dispersion is not equal to mean field dispersion

Problem: Extracting Lagrangian mean properties from Eulerian mean fields

Which missing features should we include ?

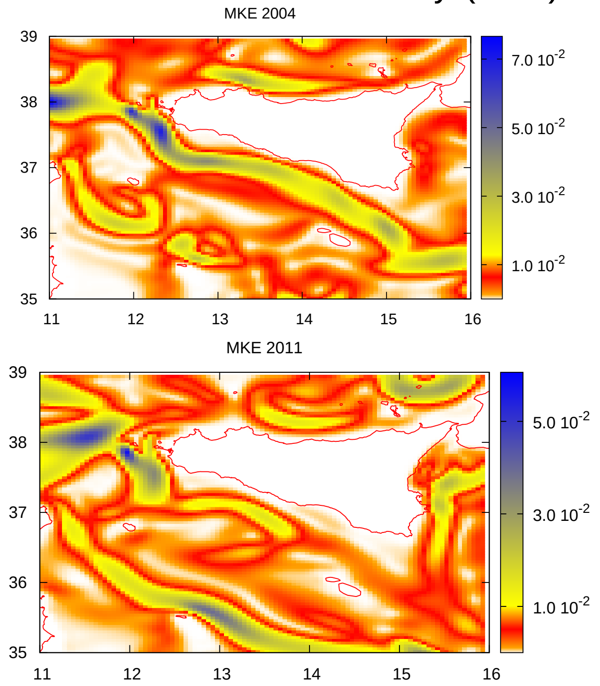
In standard GCM (with data assimilation scheme):
Nominally grid ranges from (10 → 2) km

BUT because of dissipative terms :
Horizontal structures at mesoscales and sub-mesoscales are hardly resolved

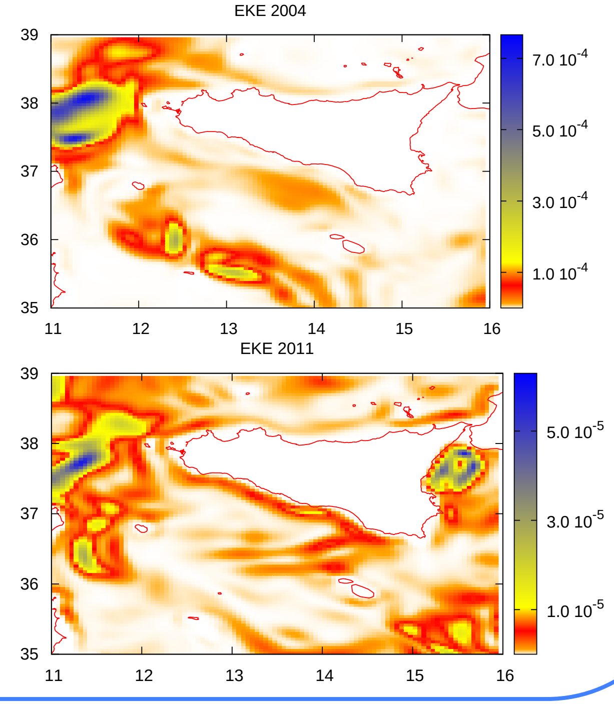
Moreover, no circulation model describes the mixed layer dynamics

Monthly averaged Maps of Kinetic Energy (per unit mass) measured at z = −20 mt

KINETIC ENERGY mean velocity (MKE)



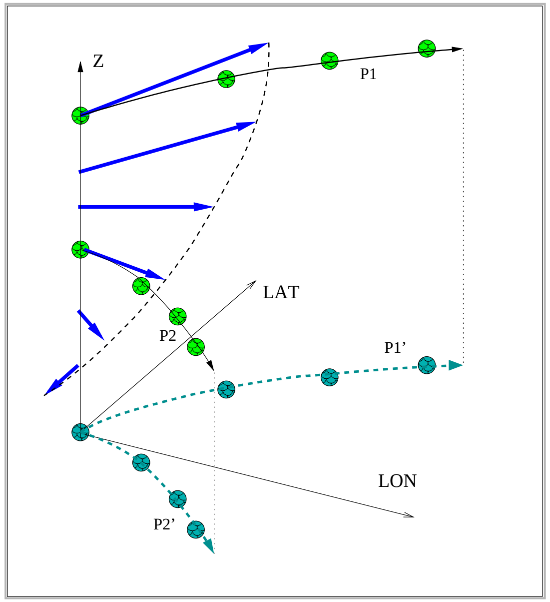
KINETIC ENERGY from velocity fluctuations (EKE)



Mediterranean sea Forecasting System (MFS) model: 1/16° x 1/16° (~ 6.5 km)

The dimensional gap: on *role of the vertical shear*

Pretty good knowledge of 2D processes, **but experimental gap of its vertical variation**
Is vertical shear important for horizontal dispersion?



$$\mathbf{R}(t) \equiv \mathbf{X}_1(t) - \mathbf{X}_2(t)$$

$$\frac{d\mathbf{R}}{dt} = \Delta_{\mathbf{R}}\mathbf{U}(\mathbf{R},t) + \delta_{\mathbf{R}}\mathbf{u}(\mathbf{R},t)$$

Some estimates based on mean velocities:

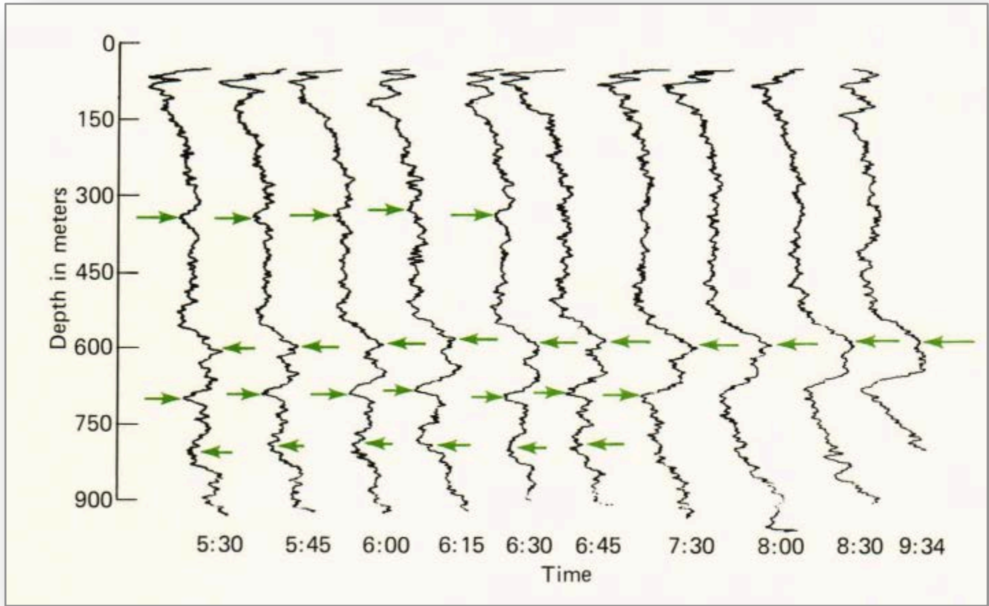
Vertical shear → 10^{-5}/s

Horizontal shear → 10^{-3}/s

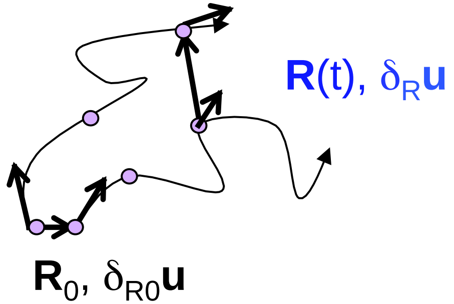
So Vertical shear considered as negligible

But it can increase currents dissipation and Turbulence persistence among ocean layers

OPEN OCEAN MEASUREMENTS



Theoretical expectations



$$\mathbf{R}(t) = \mathbf{X_1}(t) - \mathbf{X_2}(t)$$

$$\frac{d\mathbf{R}}{dt} = \mathbf{u}_1(\mathbf{X}_1, t) - \mathbf{u}_2(\mathbf{X}_2, t)$$

(Richardson 1926)

$$D_{Ric}(R,t) \equiv \frac{1}{2}\frac{d}{dt}\langle \mathbf{R}^2 \rangle \equiv \langle \delta_R \mathbf{u}(\mathbf{R},t) \cdot \mathbf{R}(t) \rangle \equiv \int_0^t \langle \delta_R \mathbf{u}(\mathbf{R}(t),t) \delta_R \mathbf{u}(\mathbf{R}(s),s) \rangle ds$$

Richardson 4/3 Law for Turbulent Eddy Diffusivity

$$D_{Ric}(R,t) \simeq \tau_R \langle \delta_R \mathbf{u}^2(\mathbf{R},t) \rangle \simeq k_0 \, \epsilon^{1/3} R^{4/3}$$

Super-Diffusive growth due to 3D turbulence

$$< R^2(t) >= g\, t^3$$

REMARK

Pair dispersion in the presence of a mean shear (γR_3,0,0) and random walk in other comp.

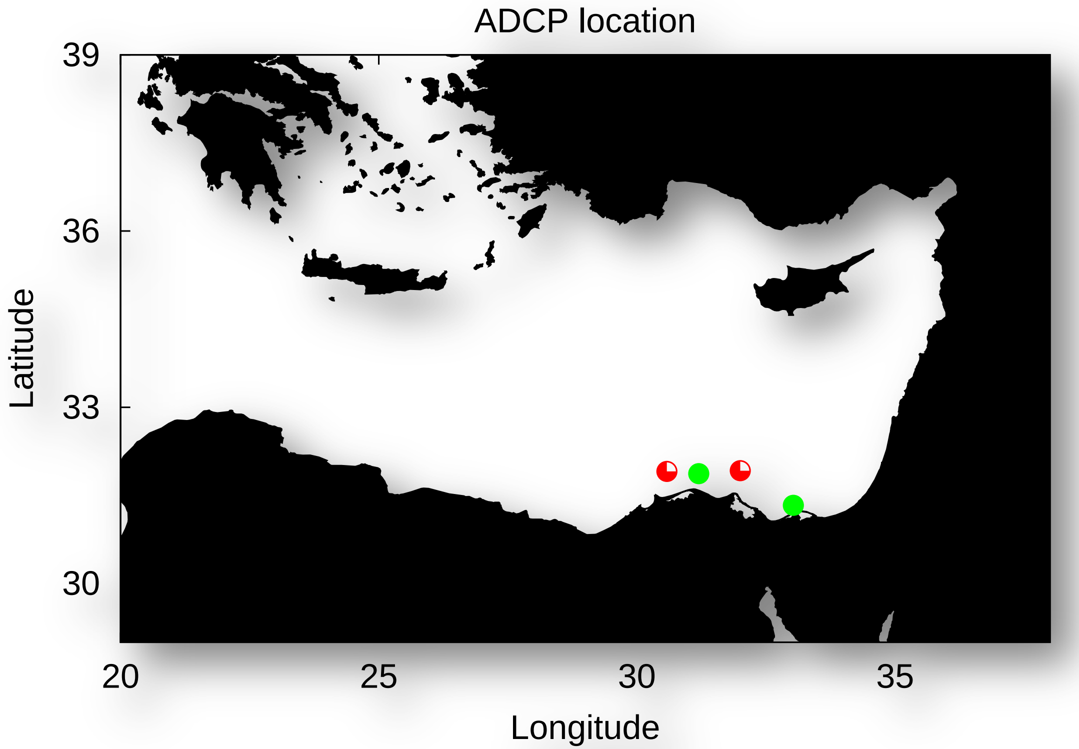
(Okubo 1971)

$$dR_1(t) = \gamma R_3 dt \qquad dR_3(t) = 2\sqrt{D_0} d\eta(t)$$

$$D(R) \propto R_1^{4/3} \qquad \langle R_1^2 \rangle \simeq D_0 \gamma^2 t^3$$

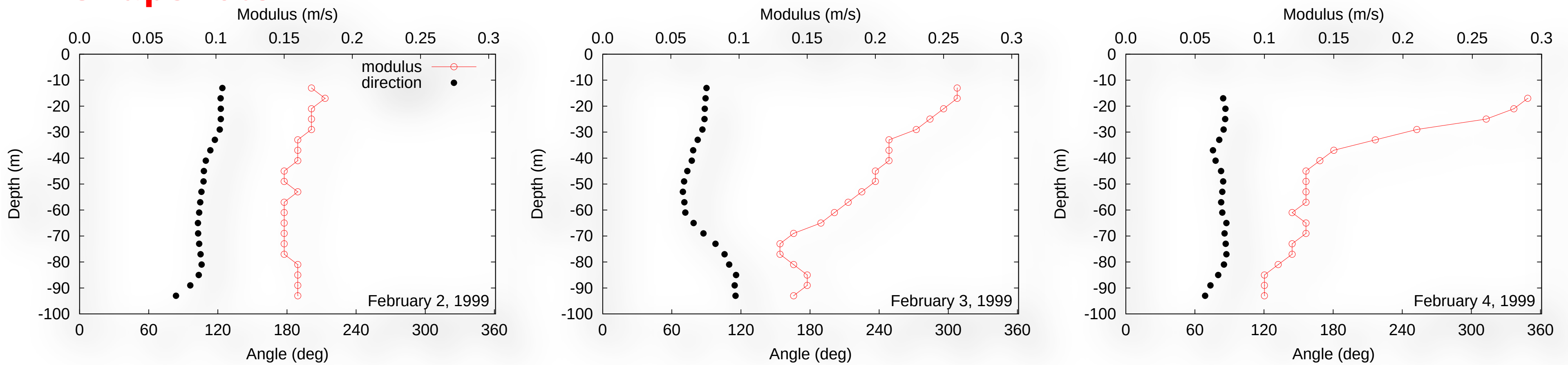
Anosotropic Super-Diffusive growth due to mean shear

Acoustic Doppler Current Profilers



- 4 ADCP 300kHz deployed Feb 1999- Feb 2000, averaged over 10 minutes
- Water depth ~ 100 mt
- Strong thermocline from June-October about z=-30mt (~10° C); then weakens and move to z=- 80mt in November; disappears in February.
- Salinity higher above the thermocline than below(~39 PSU) constant throughout the year.

Snapshots

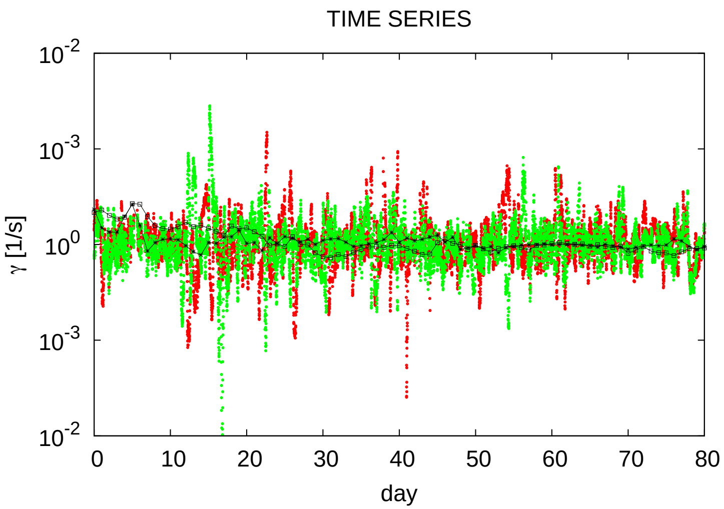


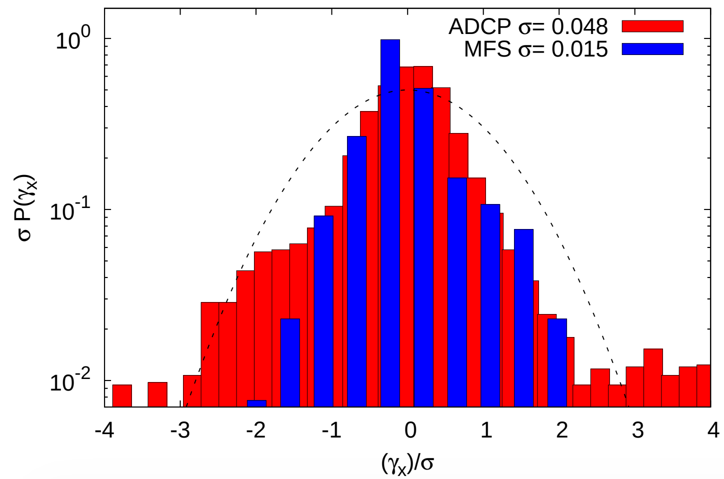
Model vs Experiment: statistics of velocity gradients

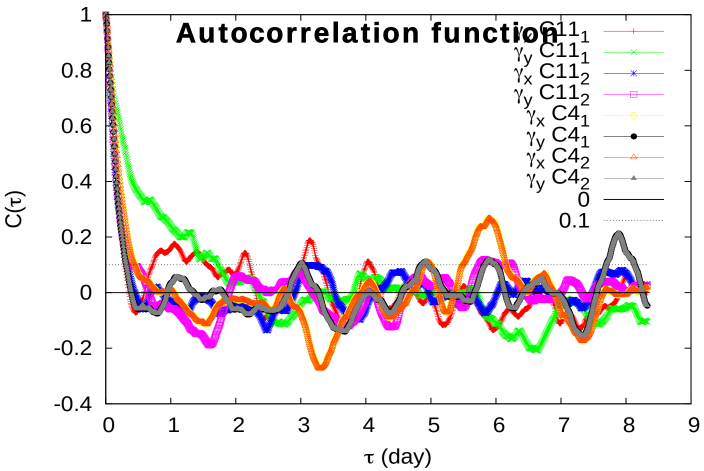
TWO SELECTED PERIODS: **[**February - April 1999**]** **[** December 1999 - February 2000**]**

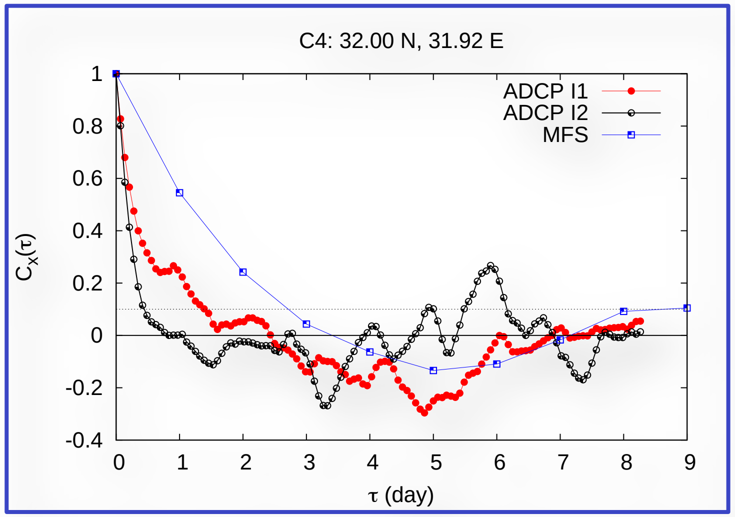
Vertical gradient Stat. : **ADCP** measures vs **MFS** estimates ***at same locations***

$$\gamma_i(t) = \frac{u_i(z_1,t) - u_i(z_2,t)}{z_2 - z_1}$$







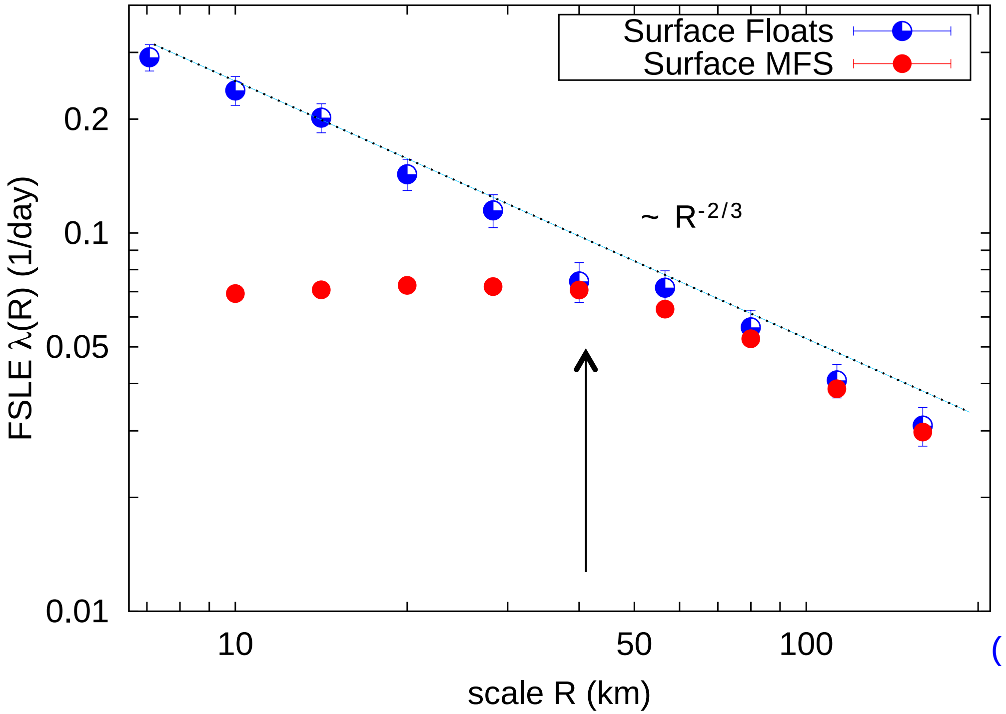


MFS: can not account for temporal variability→ introduces a spurious time persistence of velocity gradients

LAGRANGIAN DISPERSION

How does the model account for ***surface*** relative dispersion?
Finite Size Lyapunov Exponent clearly shows how badly MFS describes Lagrangian dispersion

$$\lambda(R) \equiv \frac{1}{\langle T(R) \rangle} \ln(\rho R/R)$$



(Lacorata et al. JGR-Oc.2014)

- MFS numerical drifters: 50000 pair homogeneously distributed in the Mediterranean
  Integrated over 3 months, Jan- March 2009; initial sep R(0)=5km
- 713 Surface buoys, drogued at 15 mt, 1990-2012 database from Marine Copernicus

TWO OBSERVATIONS

1. Low temporal resolution of MFS model introduces an anomalously long time persistence of vertical velocity gradients → **artifact: enhanced relative dispersion ?**

2. Because of the poor temporal and spatial resolution,
   → **MFS model completely miss surface relative dispersion at scales R < 40km**

PROPOSED SOLUTION

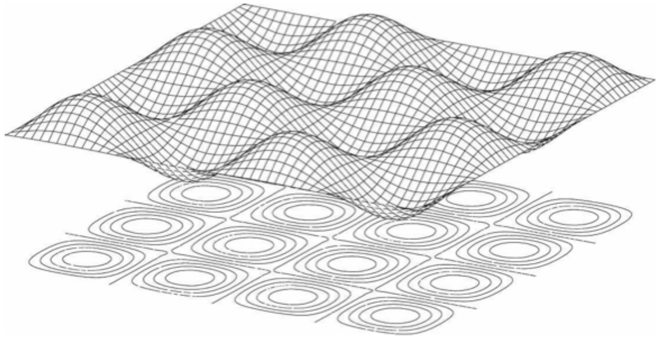
Use **Kinematic Lagrangian Model** to better account for sub-grid motion poorly or un-resolved :

- Introducing mesoscale surface structures (2D KLM)
- Introducing vertical mixing due to 3D turbulent-like motions (3D KLM)

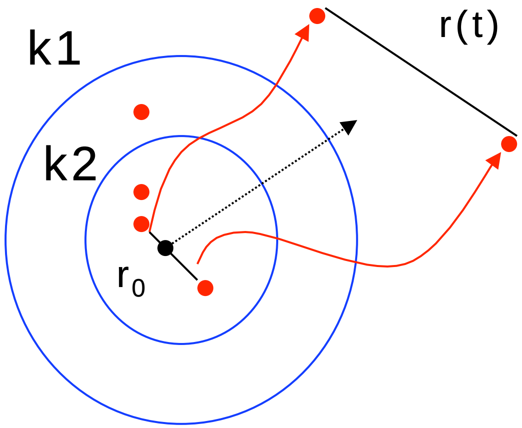
LAGRANGIAN DETERMINISTIC MODELS

The idea is to exploit Lagrangian chaos present also in non-chaotic Eulerian smooth flows (Solomon & Gollup 1988, Crisanti et al. 1991) and fix temporal and spatial scaling according to the desired dynamics

$$\begin{cases} dr_i = U_i(\mathbf{r}, t)dt \\ U_i = \dfrac{\partial \Psi_I}{\partial r_j} + \dfrac{\partial \Psi_{II}}{\partial r_k} \qquad i \neq (j,k) \end{cases}$$



$$\Psi_I(y,z,t) = \sum_{j=1}^{N} A_j sin[k_{j,y}(y - \xi_{j,y} sin(\omega_{j,y} t))] sin[k_{j,z}(z - \xi_{j,z} sin(\omega_{j,z} t))]$$



PROS & CONS

+ model correctly reproduces 1p and 2p diffusion
+ physical content is clear and no indetermination problem (as in stochastic 3D models)
+ correctly accounts for sweeping of small scales by the large ones
- can not account for multi-particle dispersion
  (see Mazzitelli, Toschi, Lanotte PoF 2014)

KINEMATIC LAGRANGIAN MODEL

- **2D MODEL (u_{2D},v_{2D}): mimicking mesoscale structures**

$$u_{2D}(x,y,t) = \sum_{j=1}^{6} A_j \sin[k_j x - k_j s_j \sin(\omega_j t))] \cos[k_j y - k_j s_j sin(\omega_j t + \theta)]$$

$$l_j = \{10.0, 14.120.0, 28.0, 40.0, 56.5\} \text{ km}$$

$$A_j \propto (\varepsilon l_j)^{1/3} \qquad \omega_j = 2\pi A_j / l_j \qquad k_j = 2\pi / l_j$$

$$\varepsilon = 10^{-9} \text{m}^2 \text{s}^{-3} \qquad \tau_j = l_j / A_j = \{13h, ..., 15\, day\}$$

Such that on surface kinetic energy spectrum E(k) ~ $k^{-5/3}$ for scales [10:100] km (Lumpkin & Elipot 2010)

- **3D MODEL (u_{3D}, v_{3D}, w_{3D}): mimicking mixed layer dynamics**

$$u_{3D}(x,y,z,t) = e^{-|z|/L} \times \left[A \sin[k(x - s\sin(\omega t))] \cos[\widehat{k}(z - s\sin(\omega t))] - \frac{A}{L\widehat{k}} \sin[k(x - s\sin(\omega t))] \dots \right]$$

$$l_n = \{25.0, 33, 4, 50.0, 70.7, 100\} \text{m}$$

$$L = 100\,\text{m} \qquad \varepsilon = 10^{-5} \text{m}^2 \text{s}^{-3} \qquad \tau_n = \{6, \dots, 16\} \text{min}$$

$$A_j \propto (\varepsilon l_j)^{1/3} \qquad \omega_j = 2\pi A_j / l_j \qquad k_j = 2\pi / l_j$$

Based on mixing due to Kolmogorov 3D direct cascade of energy

NUMERICAL EXPERIMENTS

- Large-scale flow is given by **MFS daily currents (U_{MFS},V_{MFS})**
- Flow is seeded with **$5*10^4$ pairs** of Lagrangian particles, homogeneously distributed in the Mediterranean, R_0 = (0,0,40) between z=-3m and z=-43 m.
  Coasts = bouncing boundaries

- Numerical simulations are performed over one year (Jan-Dec 1999)

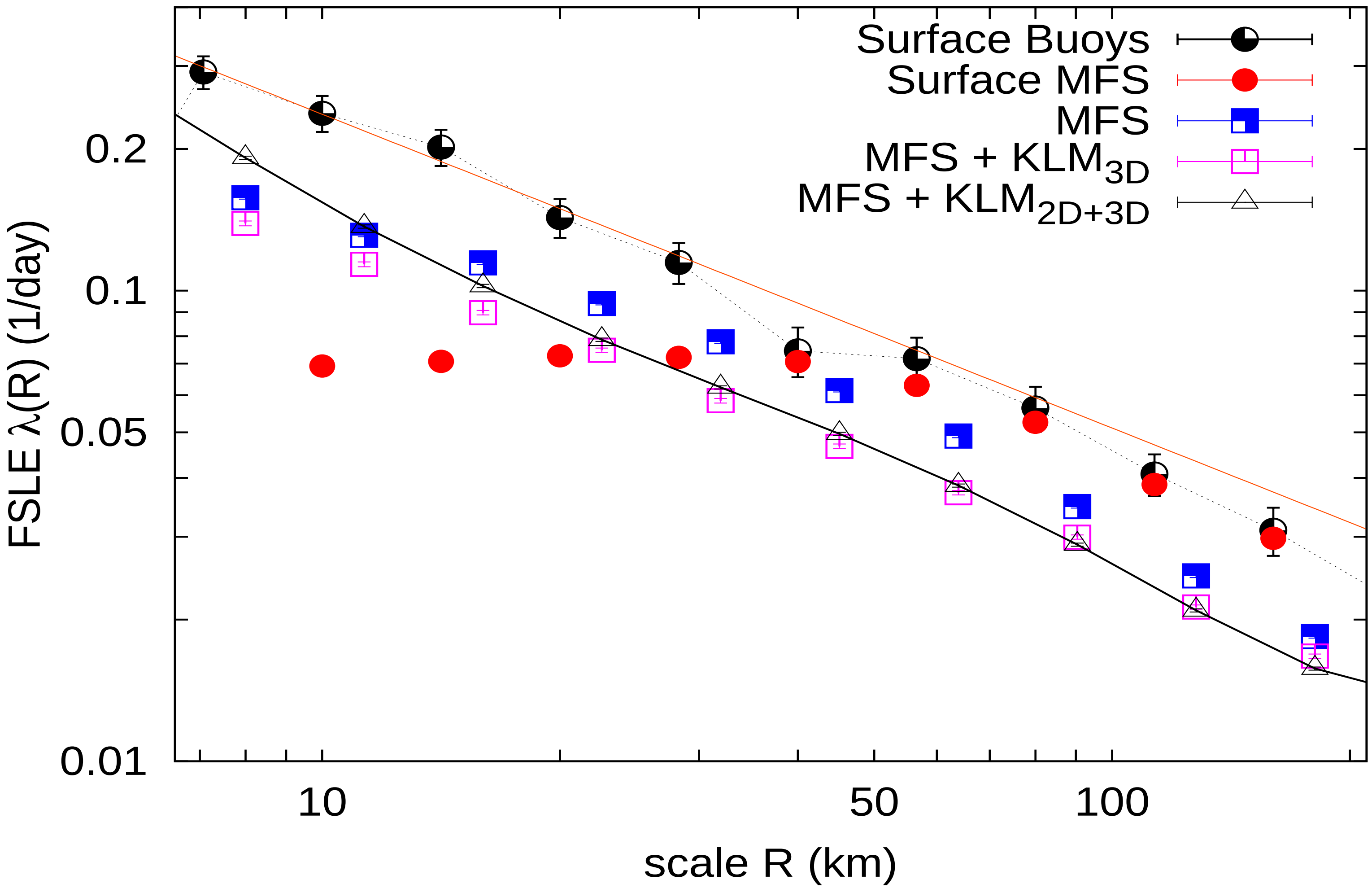
SERIES I: particles are integrated on the basis of with MFS flow only.
They feel the vertical shear given by the MFS model.
so particles keep initial depth forever.

SERIES II: particles are integrated on the basis of with MFS flow +3D KLM
Particles explore mixed layer thanks to 3D KLM model
$\mathbf{U}_{MFS} + \mathbf{u}_{3D\text{-}KLM}$

SERIES III: particles are integrated on the basis of with
MFS flow +3D KLM +2D KLM
Particles explore mixed layer thanks to 3D KLM model
$\mathbf{U}_{MFS} + \mathbf{u}_{3D\text{-}KLM} + \mathbf{u}_{2D\text{-}KLM}$

RESULTS

Finite Size Lyapunov Exponent measured on the surface dispersion only



An application: anchovy egg and larvae transport

We studied the inter-annual variability (1999-2012) in the transport of anchovy eggs And larvae in the Sicily Channel.

Sub-grid-scale dynamics is parameterized in terms of 2D + 3D KLM.

Trajectories are integrated for three months of each year. Eggs are released few km off the coast: fixed spawning rate from June to September.

→ Lagrangian Transport Index (LTI) = the efficiency in the connection between spawning and nursery areas.

→ Lagrangian connectivity can be very efficient (2004, 2008, 2012) and very weak (2000, 2001, 2003, 2010)

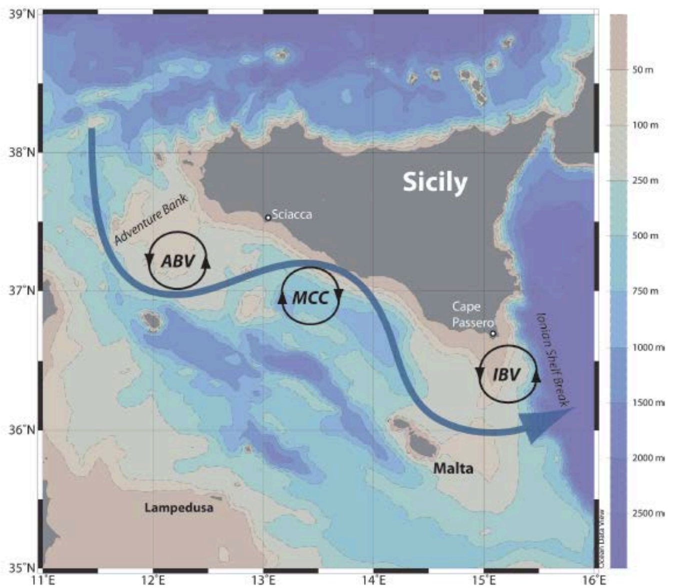


Fig 1. The Sicily Channel. Bathymetry and the climatologic hydrographic setting of the Sicily Channel. Blue arrowed curve: AIS path; black closed lines: ABV, MCC, and IBV gyres (see text). The geographical locations cited in this work are also indicated.

The Lagrangian Transport index

- Tests the robustness of LTI using the 2D and 3D kinematic fields, and Diel Vertical Motion
- Tests also changing KLM parameters

RUN	2D	3D	DVM
RUN A	YES	YES	NO
RUN B	NO	YES	NO
RUN C	YES	YES	YES

✧ eggs are buoyant for age < 1.5 days

✧ larvae are mixed by 3D turbulence without DVM

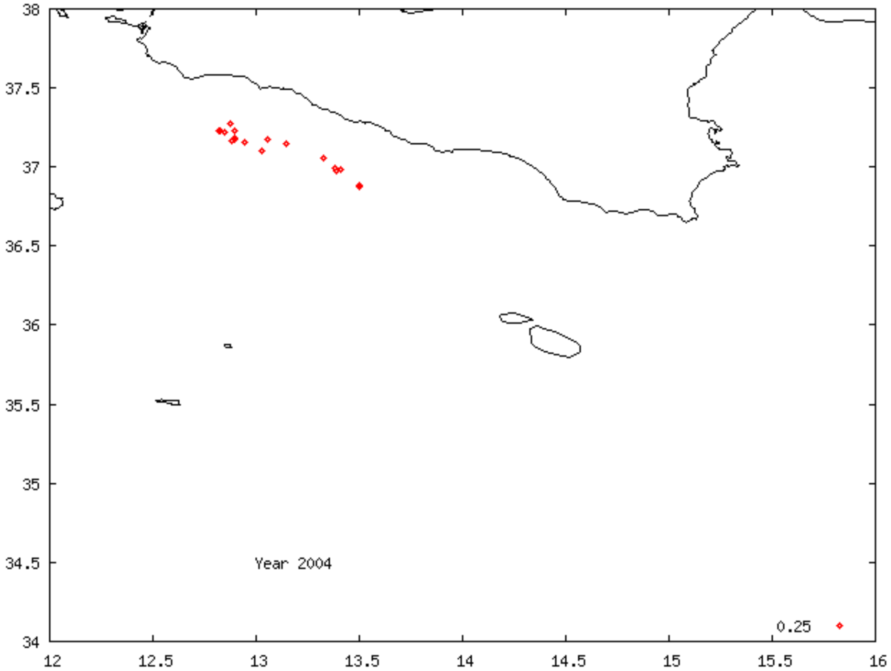
✧ Diel Vertical Motion (DVM): larvae move to surface during daytime and to deeper water during nighttime

✧ A mortality rate is included for both eggs and larvae

Year	LTI-RUN B	LTI-RUN A	LTI-RUN C
1999	0.11	0.12	0.11
2000	$\sim 10^{-5}$	$\sim 10^{-3}$	$\sim 10^{-3}$
2001	$\sim 10^{-3}$	0.01	0.01
2002	0.80	0.87	0.85
2003	$\sim 10^{-3}$	0.02	0.01
2004	1.73	1.72	1.48
2005	0.62	0.58	0.51
2006	0.46	0.41	0.40
2007	0.53	0.49	0.46
2008	1.11	0.80	0.73
2009	0.18	0.20	0.20
2010	0.01	0.06	0.05
2011	0.14	0.20	0.14
2012	1.85	1.49	1.32

Lagrangian Transport Index (LTI) = the percentage of individuals arriving alive in the recruitment area within 25 days after release.

The Lagrangian Transport variability

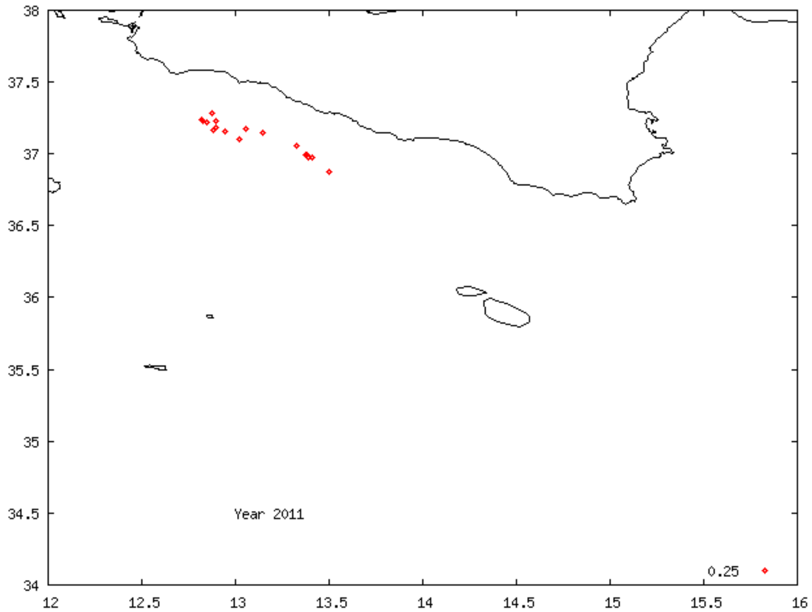


MOVIES FROM RUN MFS + KLM 2D

Colors indicate the age:
red (less than 5 days)

blu (between 5 and 10 days)

green (between 10 days and 25 days)



Anchovy egg and larva density fluctuations can be related to Lagrangian transport variability, without invoking—but clearly not excluding—interannual variations of the spawning area and/or the spawning rate.

SUMMARY

We focused on the modeling of Lagrangian Dispersion
IDENTIFY WHICH ARE THE RELEVANT FEATURES

We examined the role of vertical shear on the Horizontal Dispersion
combining **EULERIAN FLOW from a GCM MODEL & LAGRANGIAN SUB-GRID SCALE DYNAMICS**

Having accurate measurements to compare with is crucial
to **IDENTIFYING MODEL SPURIOUS BEHAVIOURS & ADJUST MODEL PARAMETERS**

CONCLUSIONS

- The resolved field given by the large scale ocean model are not suitable for Lagrangian simulations both from a single-trajectory and multiple-trajectory points of view.

- The use of kinematic models allows to recover, from a statistical point of view, the actual dispersion properties.

- These can be used to have first indications on the motion of small organisms dispersed in the ocean.

- **Effects of vertical shear in modelling horizontal oceanic dispersion**
  A. S. Lanotte, R. Corrado, L. Palatella, C. Pizzigalli, I. Schipa, and R. Santoleri,
  OS 12, 2016

- **Lagrangian simulations and interannual variability of anchovy egg and larva dispersal in the Sicily Channel**
  L.Palatella, F. Bignami, F. Falcini, G. Lacorata, A. S. Lanotte, and R. Santoleri
  JGR-OCEANS 119, 2014