Sea-surface currents in the Sicily Channel: a comparative study based on AIS, HF Radar, Satellite and Model-Derived Data

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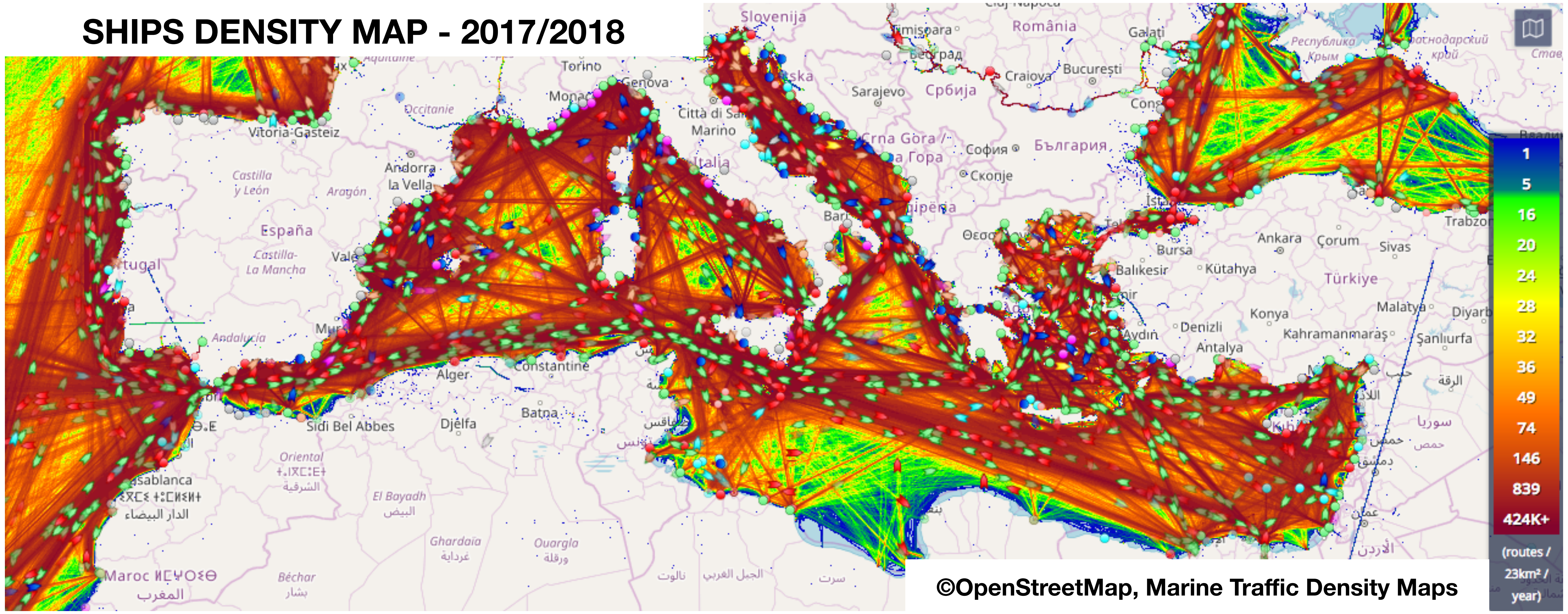
Context

Sea-surface currents: key variable in environmental sciences

Transport of oceanic tracers, Climate Studies, Application to human activities in the marine context

A Practical Example at Regional Scale: The Mediterranean Sea



- Ship routing in the Mediterranean Sea: up to more ~400 k routes/20 km^2/year
- Relevance for the Marine Safety and Rescue Activities
- Estimated Illegal Oil Spill = 600 kTonnes per year (Pisano et al. 2016)

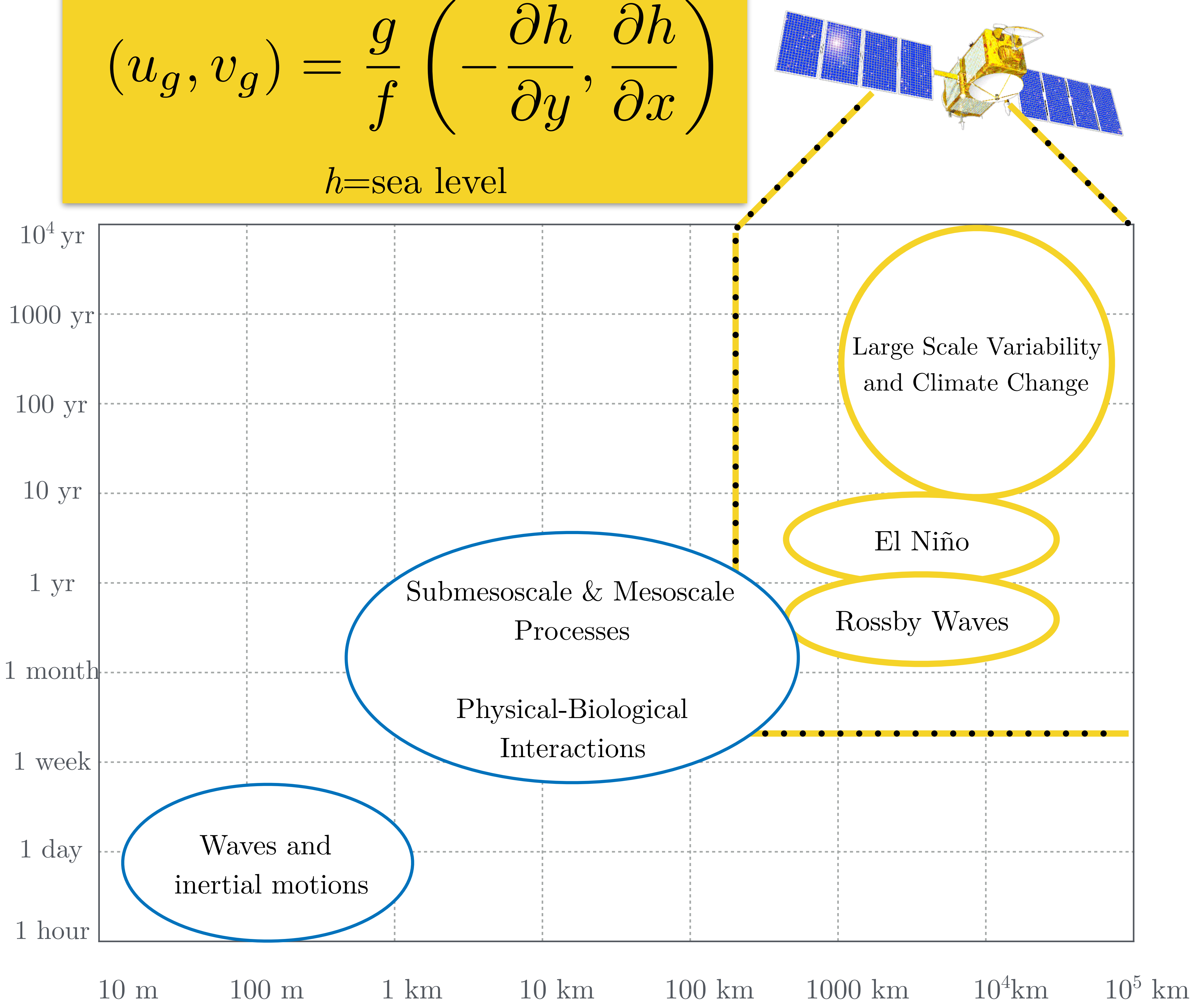
We need Synoptic, Repetitive, High Spatial and Temporal Resolution observations of the surface-currents

Context

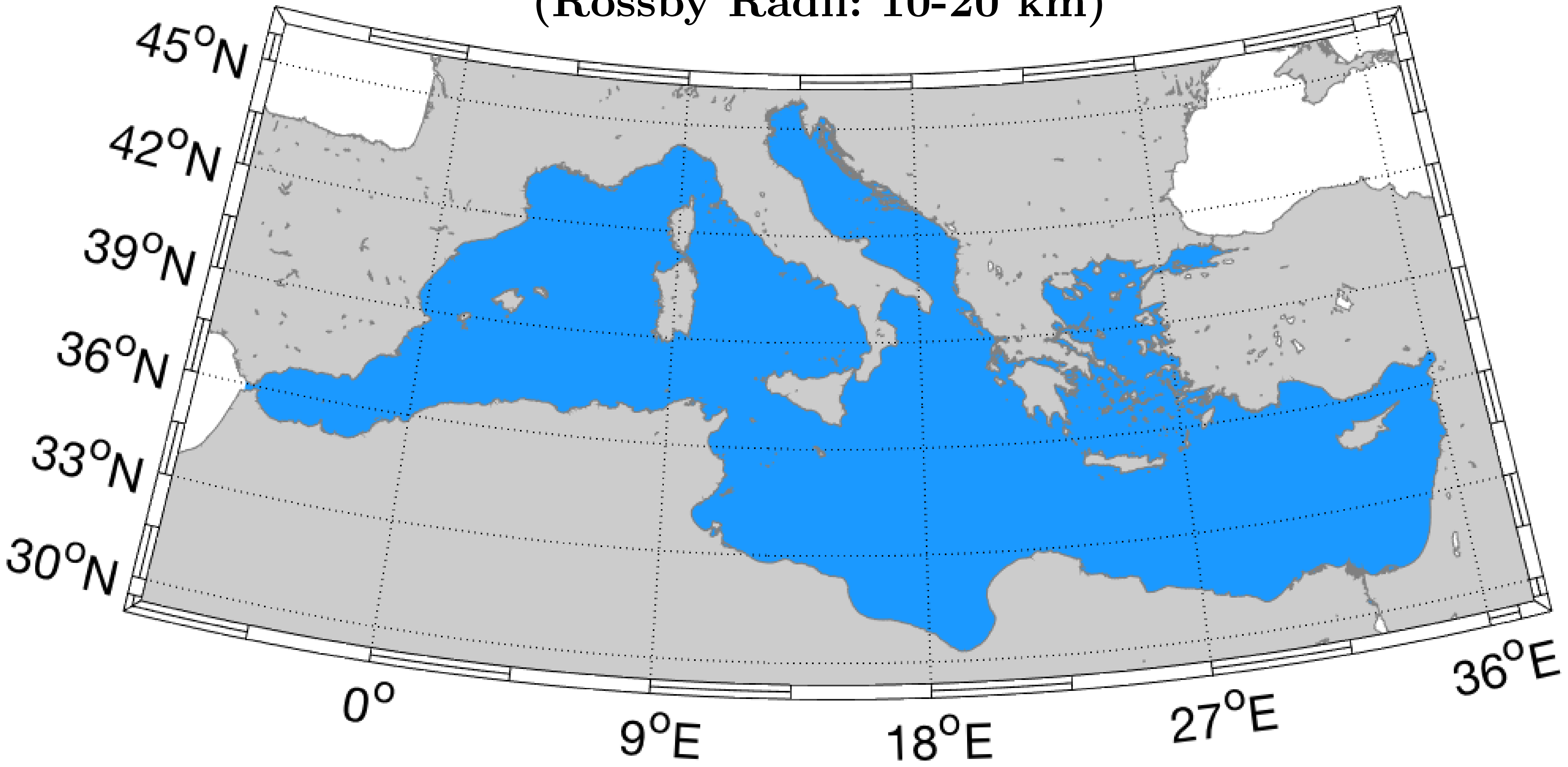
Satellite Altimetry: present-day synoptic monitoring of the sea-surface currents

$$(u_g, v_g) = \frac{g}{f}\left(-\frac{\partial h}{\partial y}, \frac{\partial h}{\partial x}\right)$$

h=sea level



Only the geostrophic component of the surface current is obtained: not satisfactory for the Mediterranean Basin (Rossby Radii: 10-20 km)

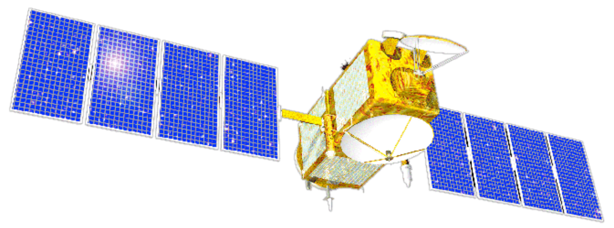


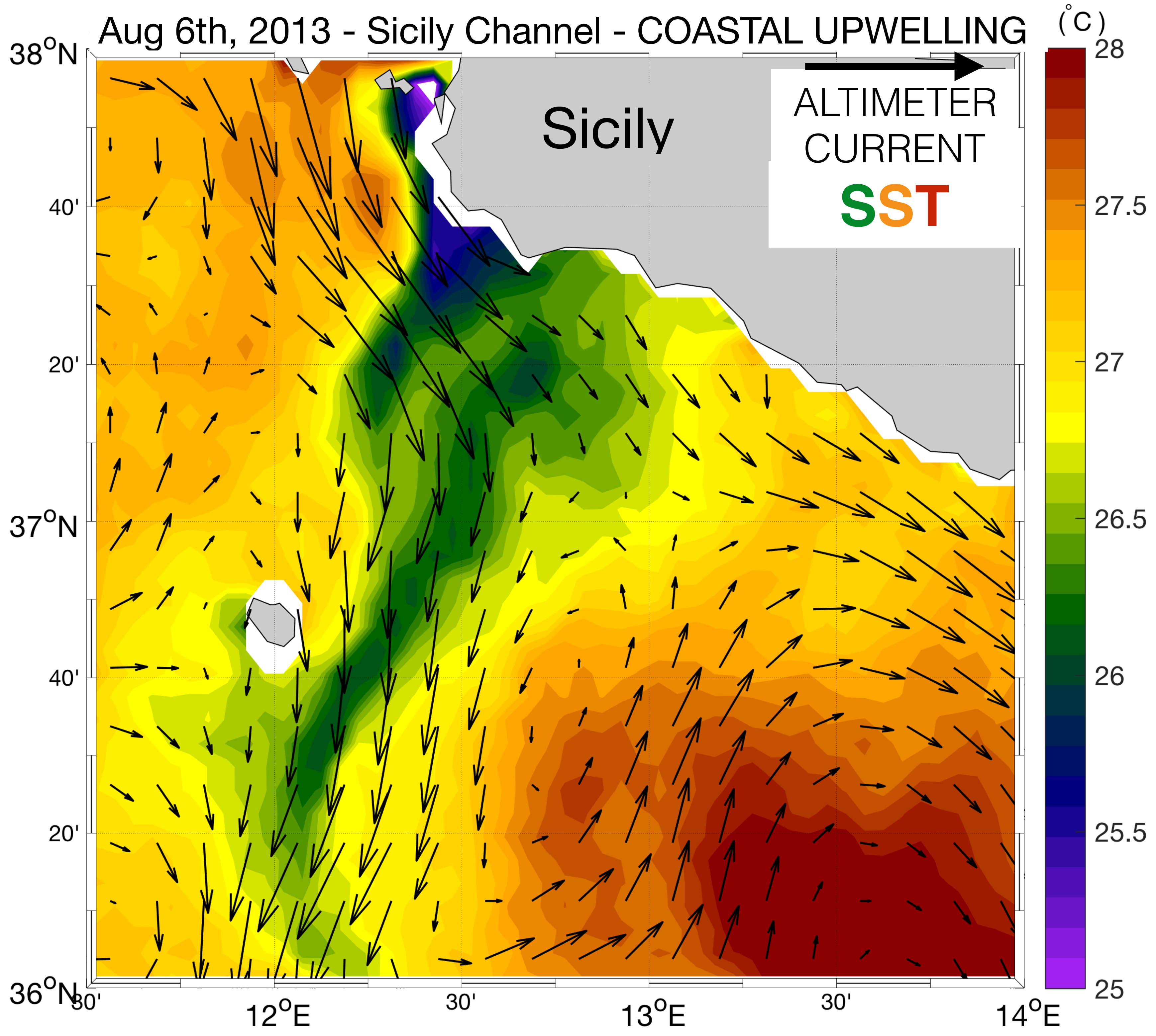
The Altimeter-derived circulation cannot entirely describe the surface motion in the Mediterranean Basin
In order to go beyond the altimeter system limitations, **new methodologies must be explored**

Context

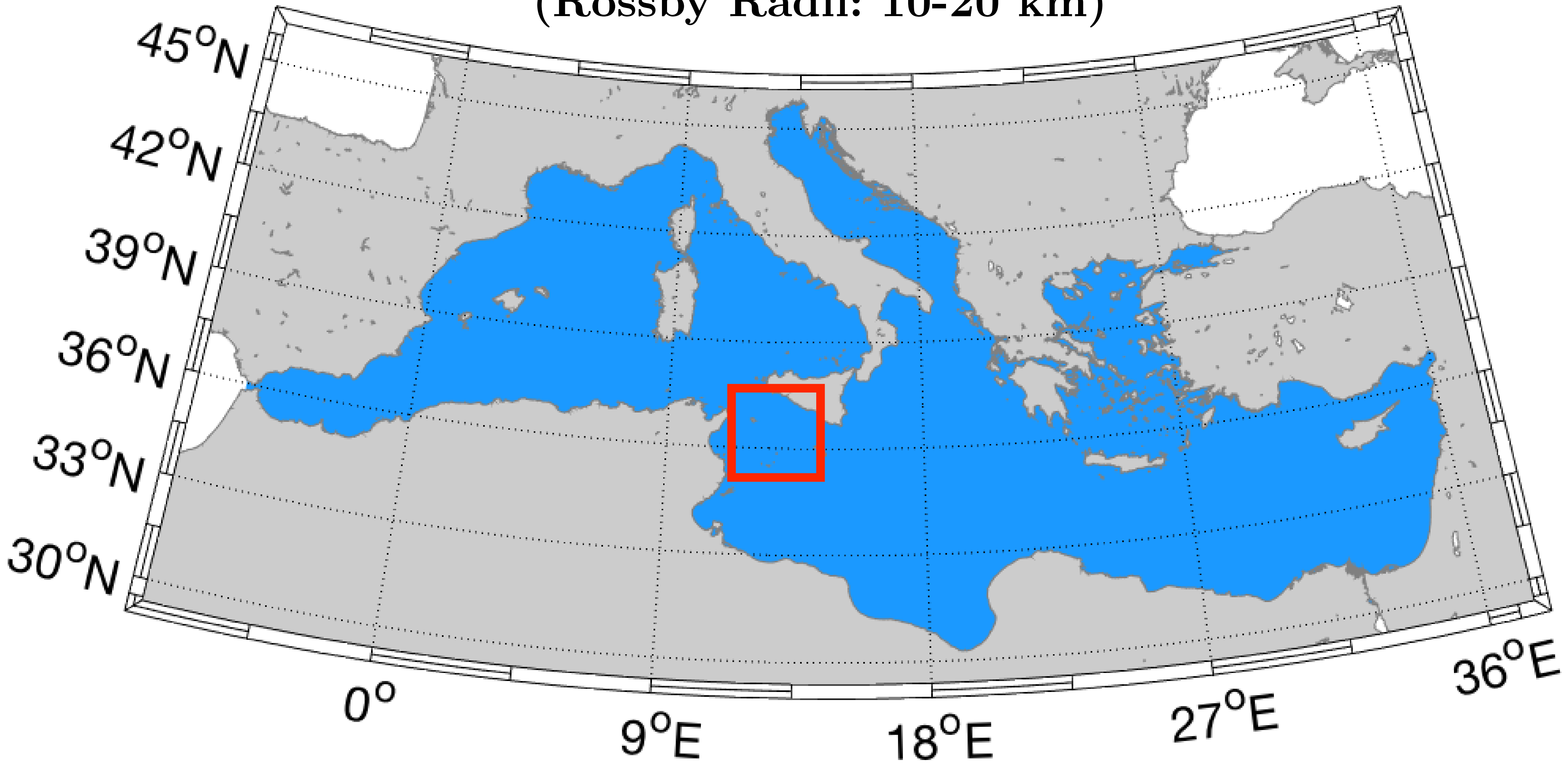
Satellite Altimetry: present-day synoptic monitoring of the sea-surface currents

Altimeter estimations in ageostrophic conditions





Only the geostrophic component of the surface current is obtained: not satisfactory for the Mediterranean Basin (Rossby Radii: 10-20 km)



The Altimeter-derived circulation cannot entirely describe the surface motion in the Mediterranean Basin, like suggested by the SST pattern

We aim at improving the currents retrieval merging the altimetric and the thermal (SST) observations

Outline

- **Materials and Methods: Improvement of the Altimeter-Derived Currents**
- **Results: comparisons with Satellite, Model and In-situ derived data**
- **Conclusions and perspectives**

Materials and Methods

Improvement of the Altimeter-derived currents

Require the velocity field (u,v) to obey to the SST evolution equation

$$\frac{\partial \mathrm{SST}}{\partial \mathrm{t}} + u\frac{\partial \mathrm{SST}}{\partial \mathrm{x}} + v\frac{\partial \mathrm{SST}}{\partial \mathrm{y}} = F$$

$F(x,y,t)$ = source and sink terms (solar input, net infrared radiation, latent and sensible heat fluxes)

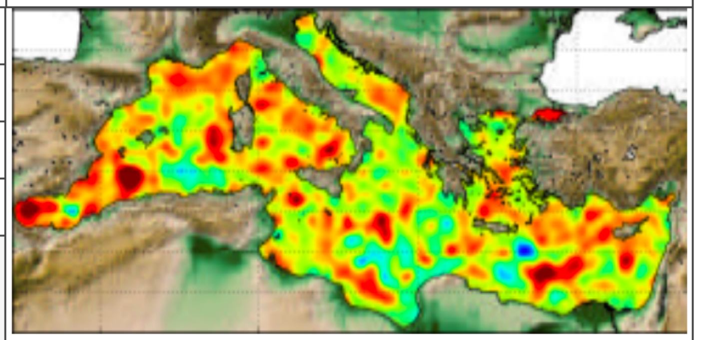
ISSUE: **only along-gradient velocity** information can be retrieved from the tracer distribution at subsequent times in **strong gradients areas**.

SOLUTION: **Piterbarg et al, 2009; Mercatini et al, 2010 :** Use a **background velocity** information (u_{bck}, v_{bck}) so that the satellite tracer information is used to obtain an **optimized merged velocity** (u_{opt}, v_{opt})

We applied the methodology to successive SST images using the low resolution, geostrophic altimeter velocities as background velocities (CMEMS Data: daily)

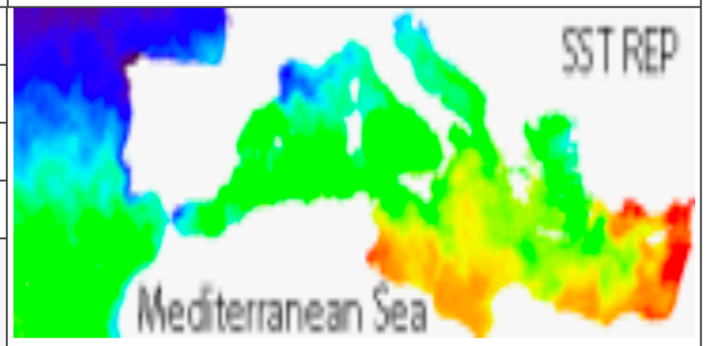
Background (SSALTO/DUACS)

SEALEVEL_MED_PHY_L4_REP_OBSERVATIONS_008_051		
MEDITERRANEAN SEA GRIDDED L4 SEA SURFACE HEIGHTS AND DERIVED VARIABLES REPROCESSED (1993-ONGOING)		
OBSERVATION	L4	MED
SSH UV		
0.125 degree x 0.125 degree (Surface only)		
From 1993-01-01 to 2017-05-15		
irregular		

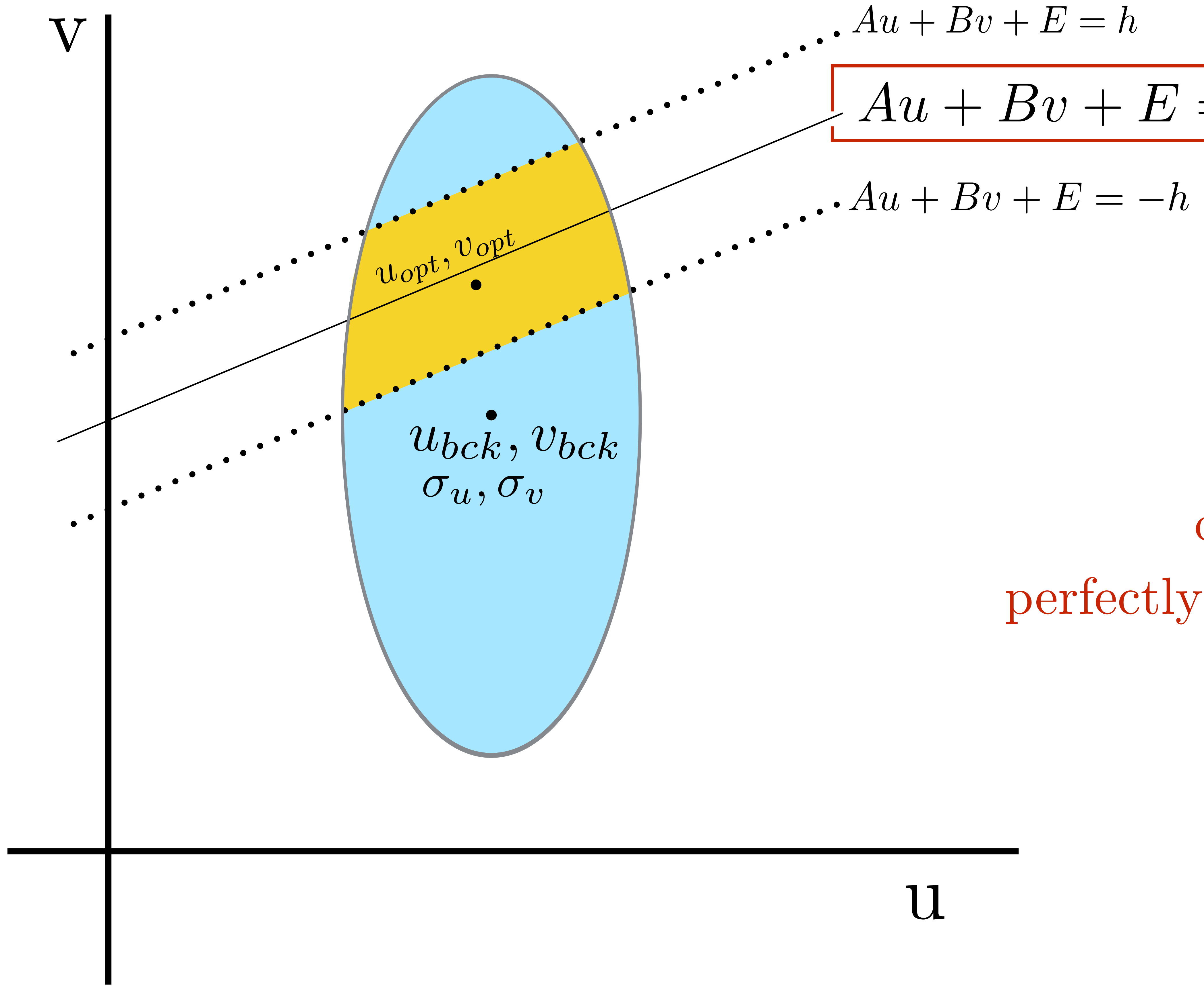


SST (CNR)

SST_MED_SST_L4_REP_OBSERVATIONS_010_021		
MEDITERRANEAN SEA - HIGH RESOLUTION L4 SEA SURFACE TEMPERATURE REPROCESSED		
OBSERVATION	L4	MED
SST		
0.04 degree x 0.04 degree (Surface only)		
From 1981-11-01 to 2016-12-31		
daily-mean		



$$\frac{\partial \mathrm{SST}}{\partial \mathrm{t}} + u\frac{\partial \mathrm{SST}}{\partial \mathrm{x}} + v\frac{\partial \mathrm{SST}}{\partial \mathrm{y}} = F$$



$\boxed{Au + Bv + E = 0}$

only for
perfectly known forcings

Method Inputs

$A = \partial_x SST;\ B = \partial_y SST$

$E = \partial_t SST - F;\ F = forcing$

$(\sigma_u, \sigma_v) =$ Bck ERROR

$h =$ F ERROR

$$v_{opt} = v_{bck} + u_0 sin\phi + v_0 cos\phi$$
$$u_{opt} = u_{bck} - u_0 cos\phi + v_0 sin\phi$$

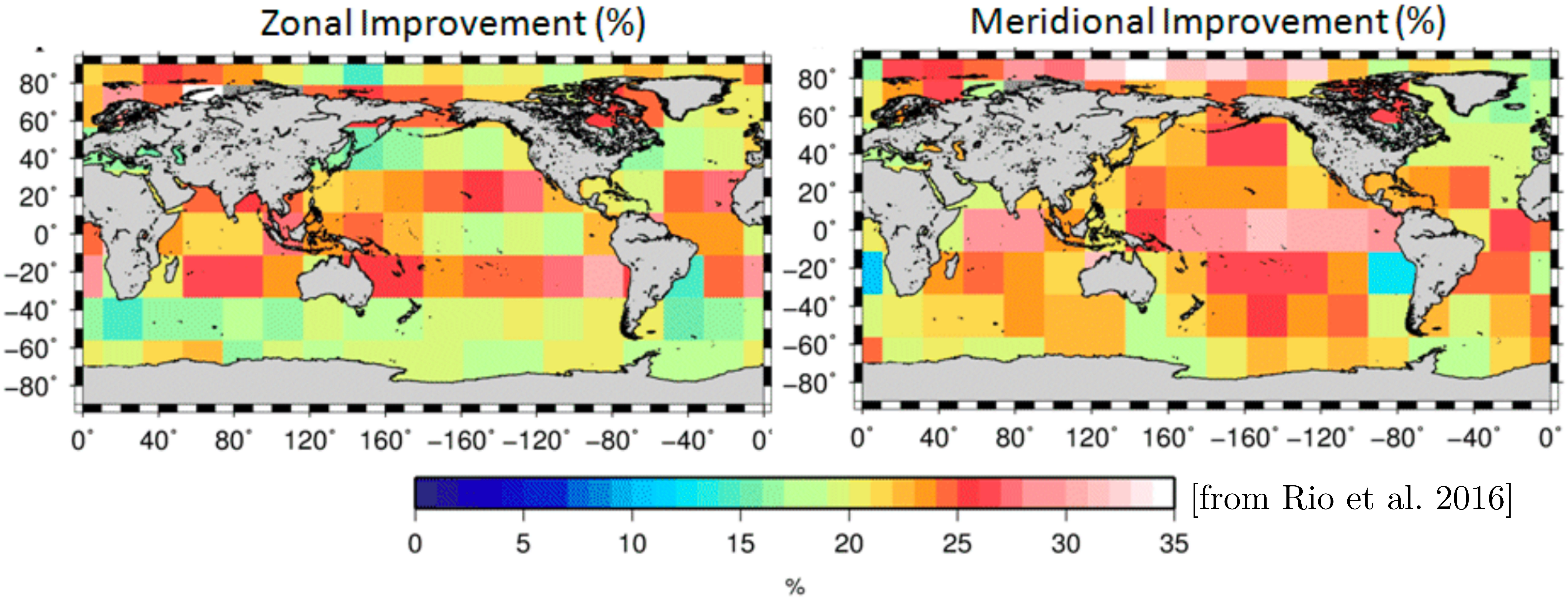
$$\phi = f(A, B)$$
$$u_0 = f(A, B, \overline{u}_{bck}, \sigma_u, \sigma_v, h, \partial_t SST, \phi)$$
$$v_0 = u_0 \cdot f(\phi, \sigma_u, \sigma_v)$$

Piterbarg et al, 2009

Materials and Methods

Improvement of the Altimeter-derived currents

In the framework of a global-scale Observing System Simulation Experiment, the Altimeter-derived currents were improved up to 35% (Rio et al. 2016)

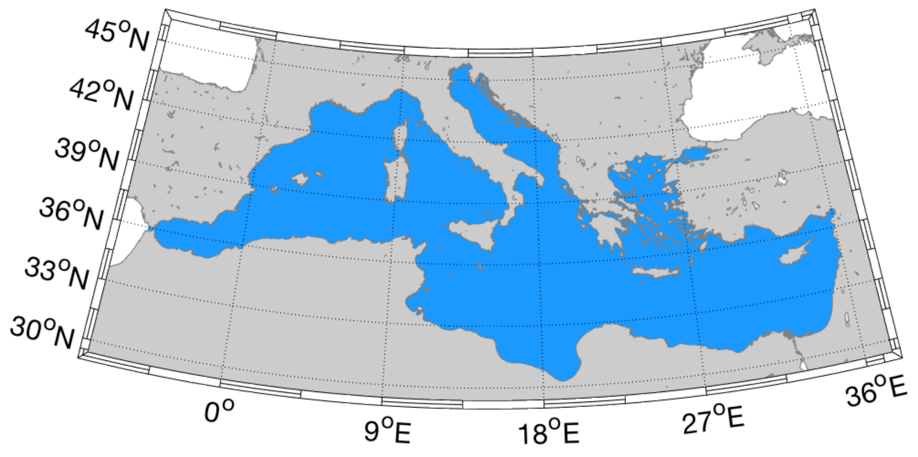


[from Rio et al. 2016]

The method has recently been applied to real oceanographic datasets at global scale (Rio et al. 2018, under revision for RSE)

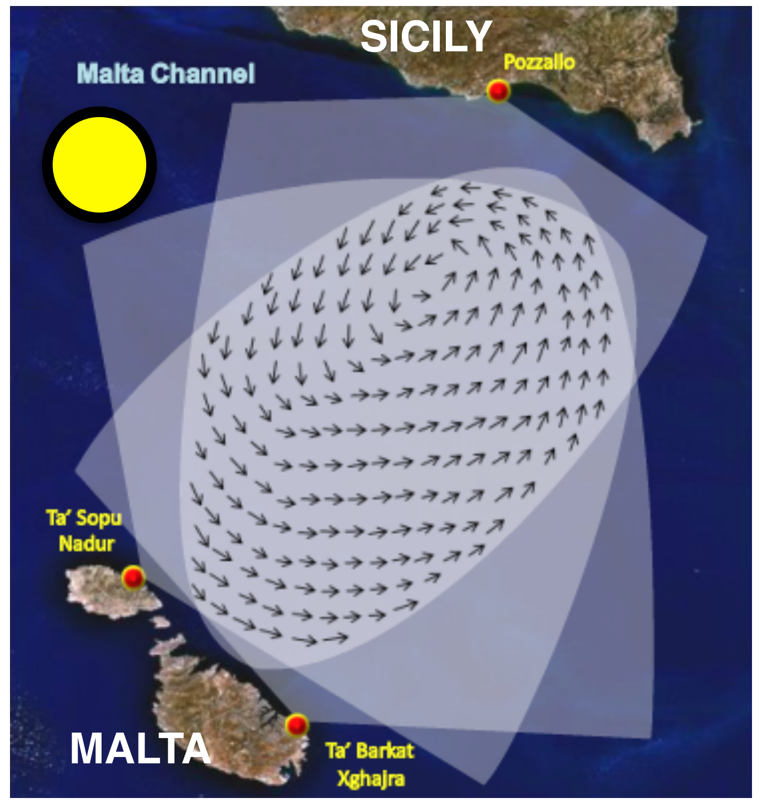
Materials and Methods

Improvement of the Altimeter-derived currents



1.**SSALTO/DUACS surface currents (regional, Mediterranean Sea)**
daily fields (DT, ALLSAT MERGED) dx=1/8°

2.**MERCATOR global operational model**
daily fields (near-surface level=-0.49m), dx=1/12°



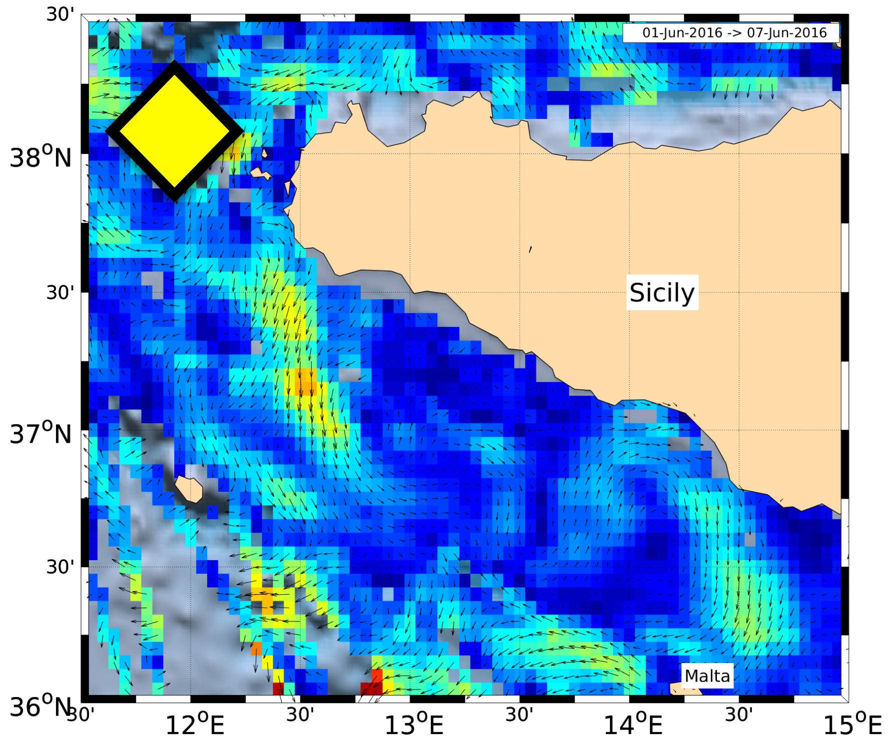
3.**Mediterranean Forecasting System (MFS - regional, Mediterranean Sea)**
daily fields (near-surface level = -1.47m), dx=1/24°

4.**CNR SST L4, (regional, Mediterranean Sea)**
daily fields, dx=1/16°

Copernicus

(L4 - gap filled fields)

5.**OPTIMAL currents** (Synergy 1+4 based on Rio et al. 2016, Piterbarg et al. 2009)
daily fields (sea-surface), dx=1/16° (higher spatial and temporal resolutions: underway) (L4 - gap filled fields)



6.**Drifting Buoys derived surface currents (Mediterranean Sea, OGS, Trieste, Italy)**

7.**HF RADAR - CALYPSO Project (University of Malta) - (Malta-Sicily Channel)**
hourly fields (sea-surface), dx=1/37°

8.**AIS-Ship-derived surface currents (e-Odyn, Brest, France)**
7-days mean fields, dx=1/20°

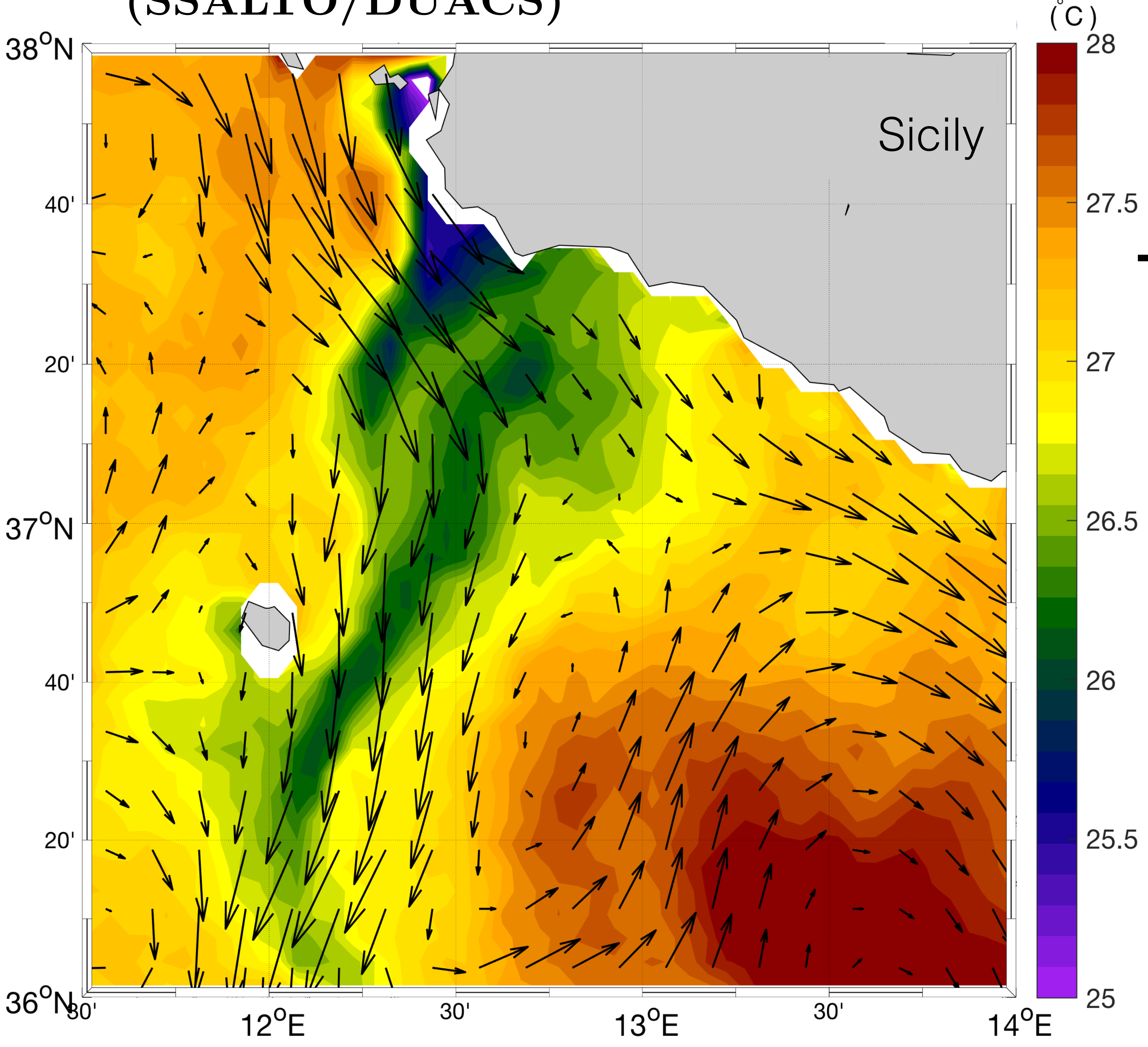
Outline

- Materials and Methods: Improvement of the Altimeter-Derived Currents
- **Results: comparisons with Satellite, Model and In-situ derived data**
- Conclusions and perspectives

Results

Improvement of the Altimeter-derived currents: a first example

BACKGROUND (SSALTO/DUACS) (u_{bck}, v_{bck})



SYNERGY OF
-**SSALTO/DUACS** surface currents
-**CNR daily SST**, dx=1/16°
(CMEMS products)

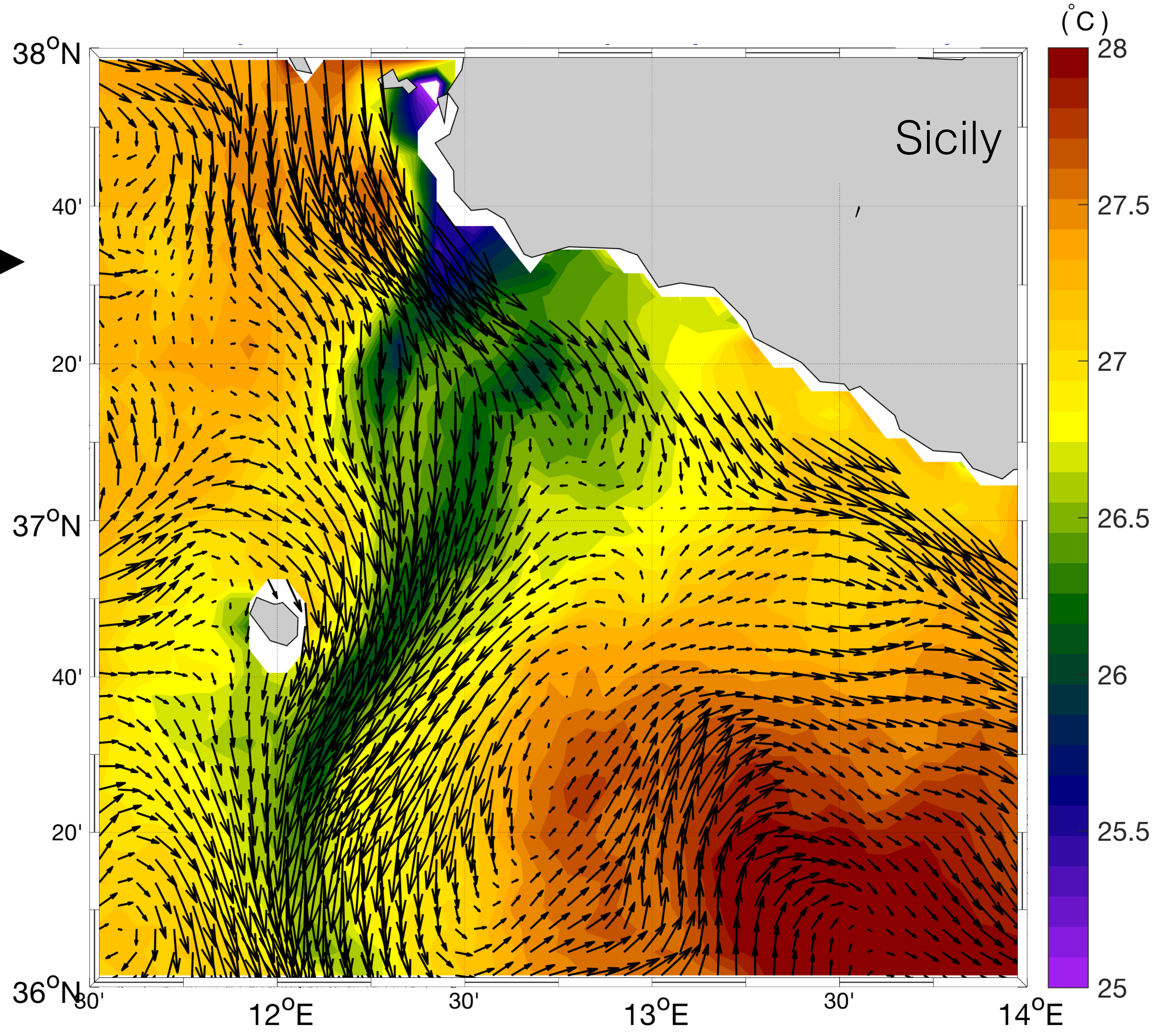
$$v_{opt} = v_{bck} + u_0 sin\phi + v_0 cos\phi$$
$$u_{opt} = u_{bck} - u_0 cos\phi + v_0 sin\phi$$

$$\phi = f(A, B)$$
$$u_0 = f(A, B, \overline{u}_{bck}, \sigma_u, \sigma_v, h, \partial_t SST, \phi)$$
$$v_0 = u_0 \cdot f(\phi, \sigma_u, \sigma_v)$$

$A = \partial_x SST;\ B = \partial_y SST$
$E = \partial_t SST - F;\ F = forcing$
$(\sigma_u, \sigma_v) =$ Bck ERROR
$h =$ F ERROR

Piterbarg et al, 2009

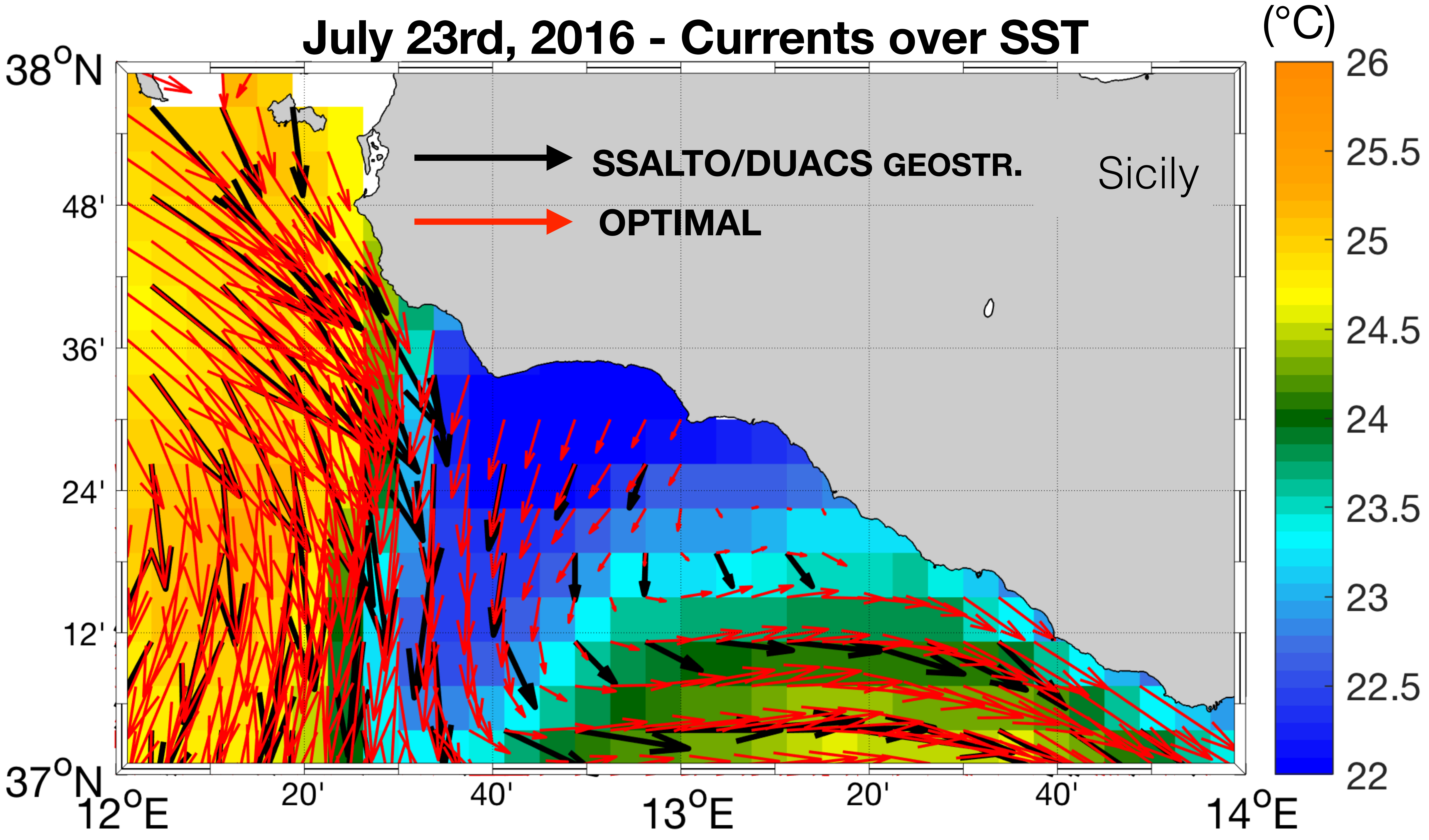
OPTIMAL (u_{opt}, v_{opt})

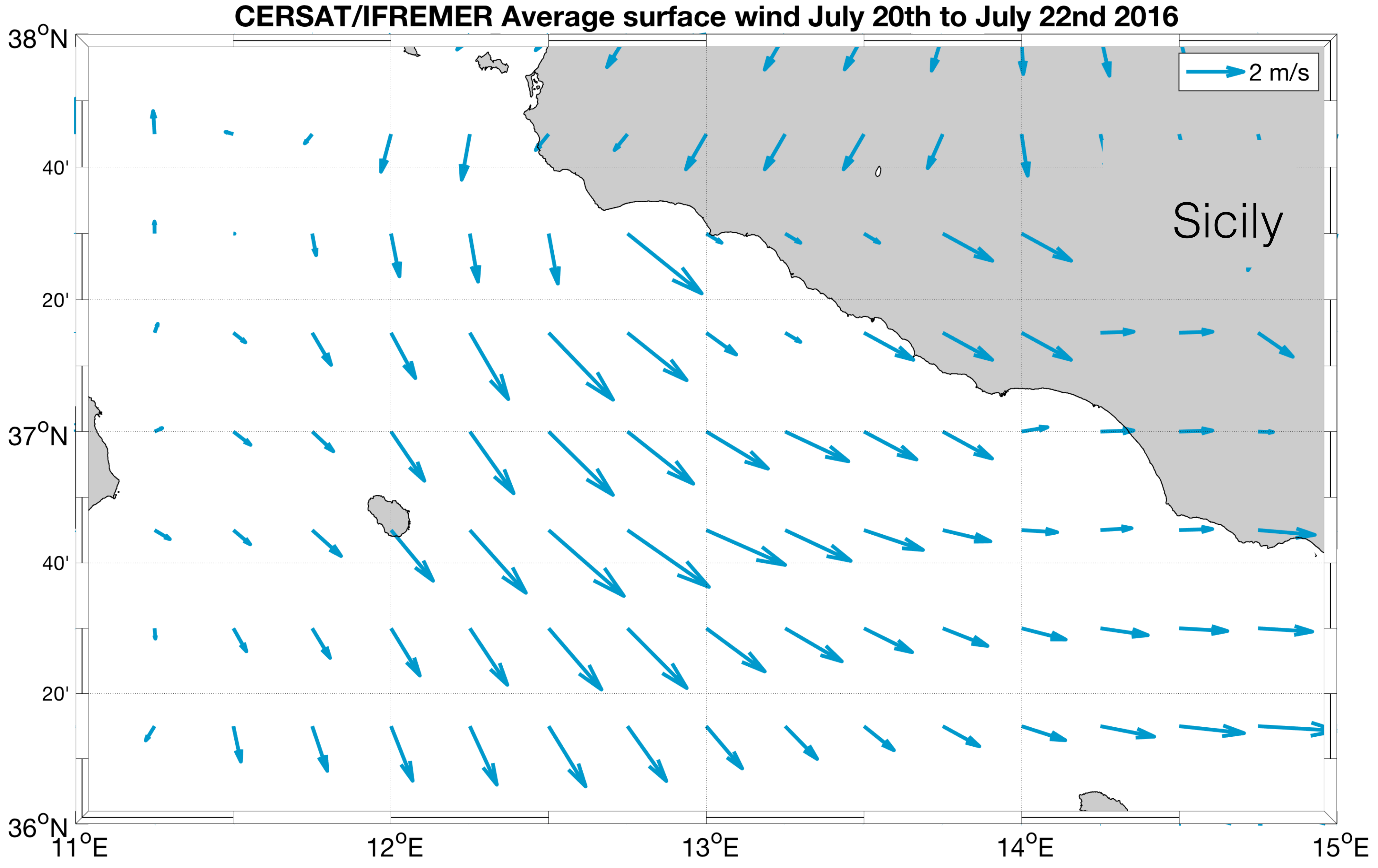


Results

Improvement of the Altimeter-derived currents: ageostrophic circulation

A focus on the year 2016 - Sicily Channel



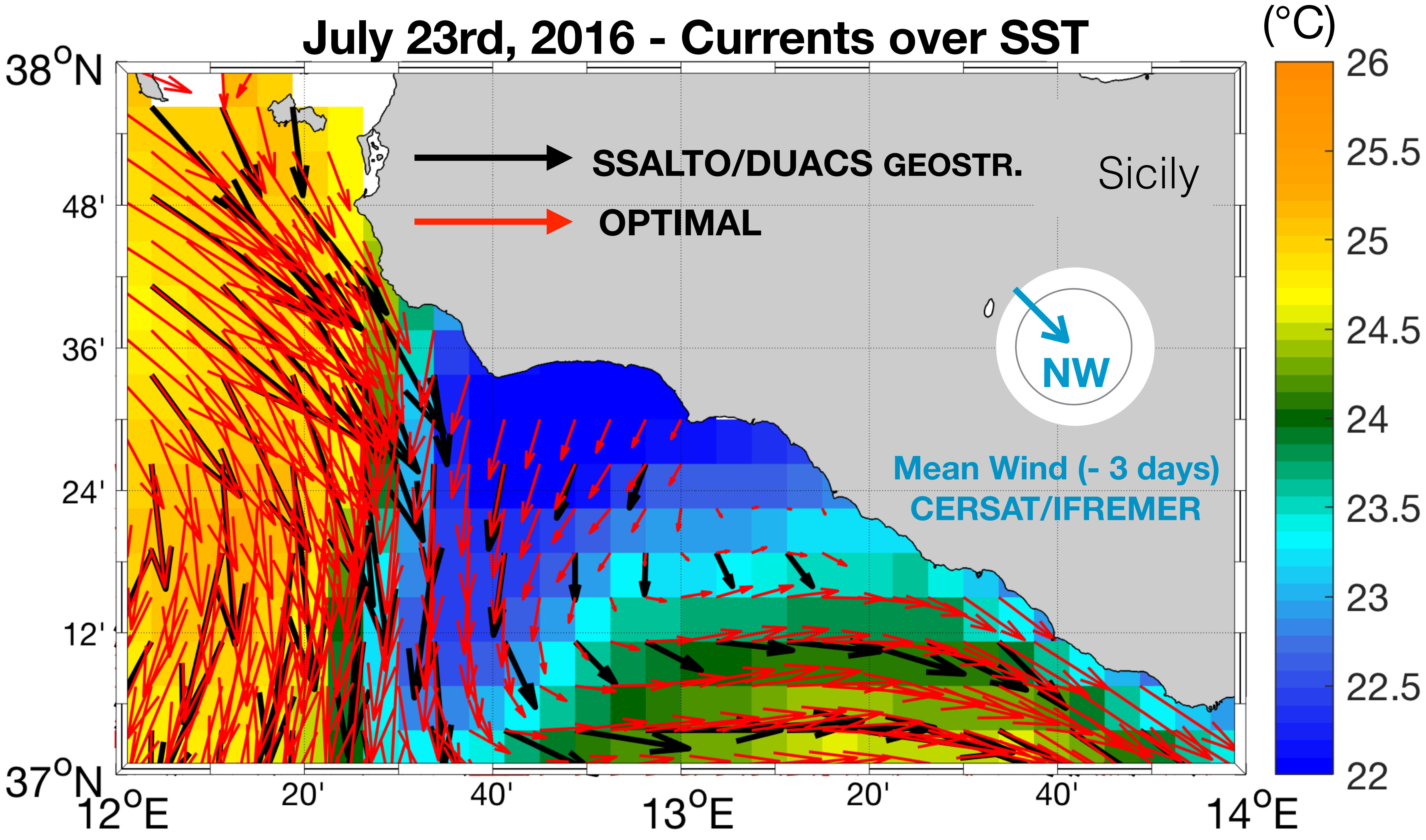


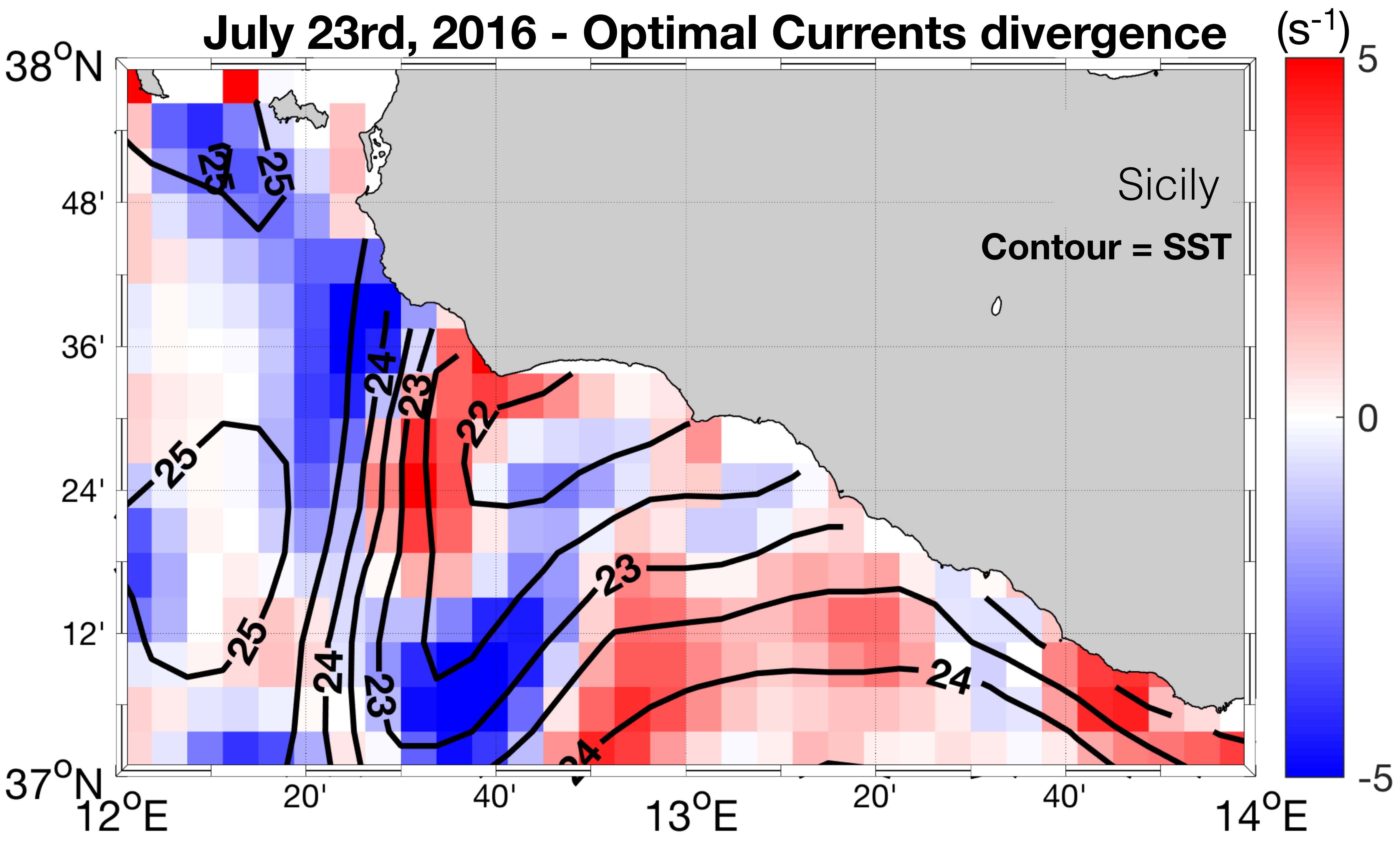
The upwelling is consistent with the NW surface surface winds during the previous three days [Piccioni et al. 1988]

Results

Improvement of the Altimeter-derived currents: ageostrophic circulation

A focus on the year 2016 - Sicily Channel



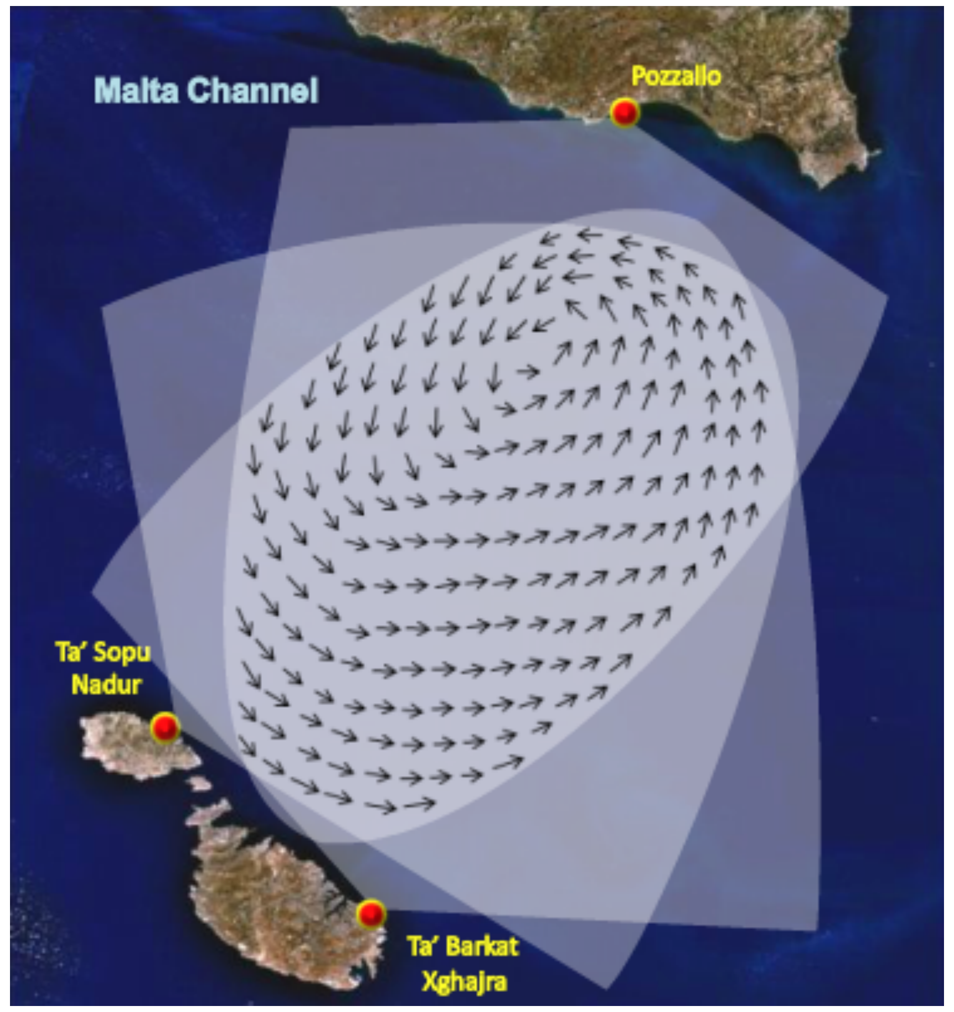


We obtain a divergent field, with values closer to a total surface current field ($\sim \pm 1.5\ \mathrm{s}^{-1}$)

Results

Comparisons with HF Radar in the Malta-Sicily Channel (2016)

Radar Calypso Project

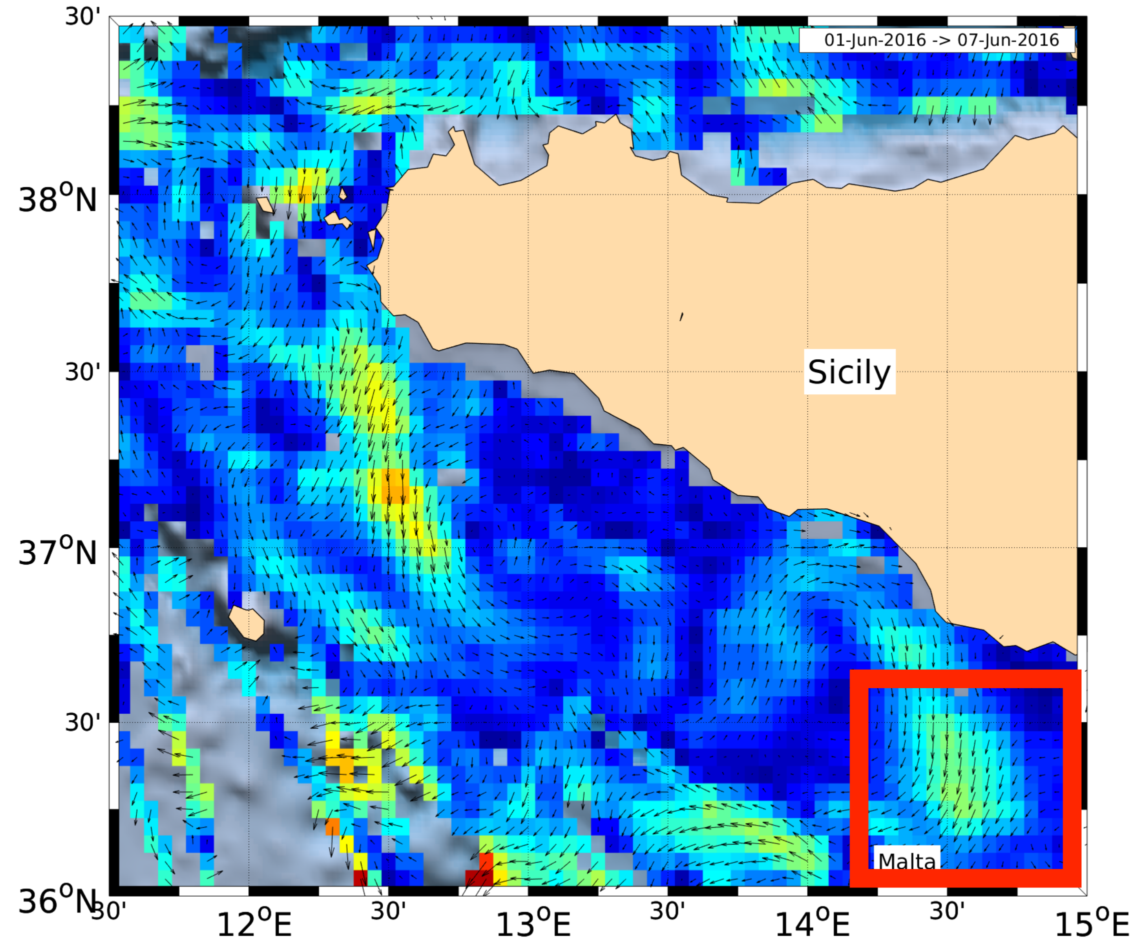


2016	RMS (cm/s) U	RMS (cm/s) V	BIAS (cm/s) U	BIAS (cm/s) V
OPTIMAL	10.12	9.00	3.60	1.40
SSALTO DUACS	11.23	9.12	4.39	1.30
MERCATOR	12.50	12.65	5.30	2.83
MFS	12.70	13.23	3.10	3.19

OPTIMAL CURRENTS

Lowest RMS. BIAS in line with Altimetry

AIS e-Odyn



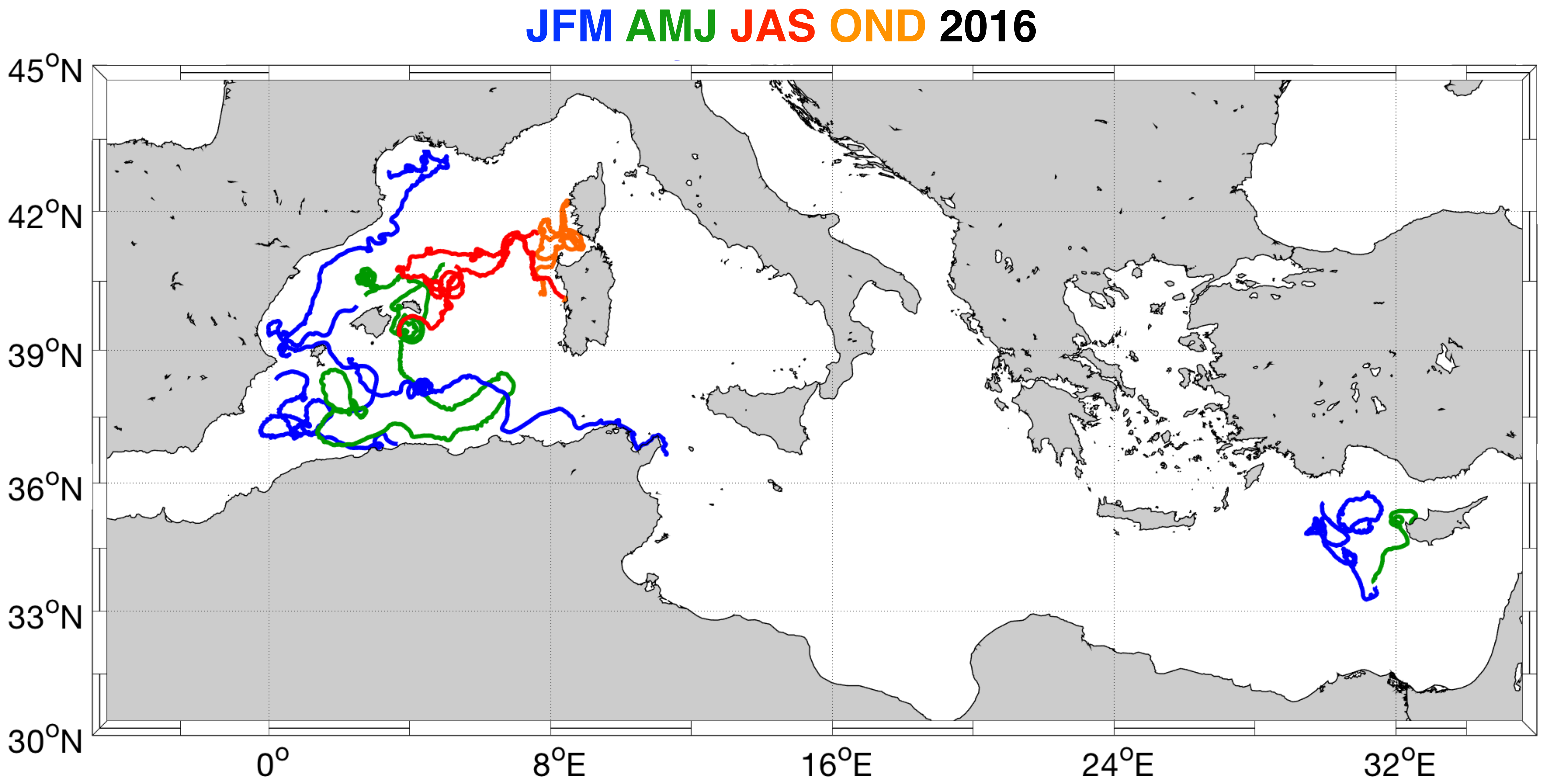
June/July 2016	RMS (cm/s) U	RMS (cm/s) V	BIAS (cm/s) U	BIAS (cm/s) V
OPTIMAL	11.00	10.01	7.50	5.10
SSALTO DUACS	12.00	10.03	7.61	5.15
MERCATOR	12.10	13.20	7.20	6.01
MFS	12.13	13.60	7.00	5.51
AIS	10.86	10.84	-6.20	5.02

AIS SHIP-DERIVED CURRENTS

Satisfactory RMS and BIAS (V component)

Results

Comparisons with drifters-derived surface currents (**OPTIMAL vs SSALTO/DUACS**)



Courtesy of M. Menna & P.M. Poulain (OGS, Trieste, Italy)

IMPROVEMENT

	RMS (cm/s) U	RMS (cm/s) V	BIAS (cm/s) U	BIAS (cm/s) V	RMS (cm/s) U	RMS (cm/s) V	BIAS (cm/s) U	BIAS (cm/s) V	RMS (cm/s) U	RMS (cm/s) V	BIAS (cm/s) U	BIAS (cm/s) V	RMS (cm/s) U	RMS (cm/s) V	BIAS (cm/s) U	BIAS (cm/s) V
OPT	19.41	19.72	5.96	-1.45	16.78	16.77	0.61	0.97	12.80	11.94	1.14	-0.77	17.66	15.70	-4.10	2.80
DUACS	19.43	20.21	7.70	-1.38	16.97	16.64	1.01	0.75	13.70	12.00	1.27	-0.91	18.20	15.70	-4.12	3.3

Optimal Currents: Overall Improvement with respect to Satellite Altimetry

Outline

- Materials and Methods: Improvement of the Altimeter-Derived Currents
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- **Conclusions and perspectives**

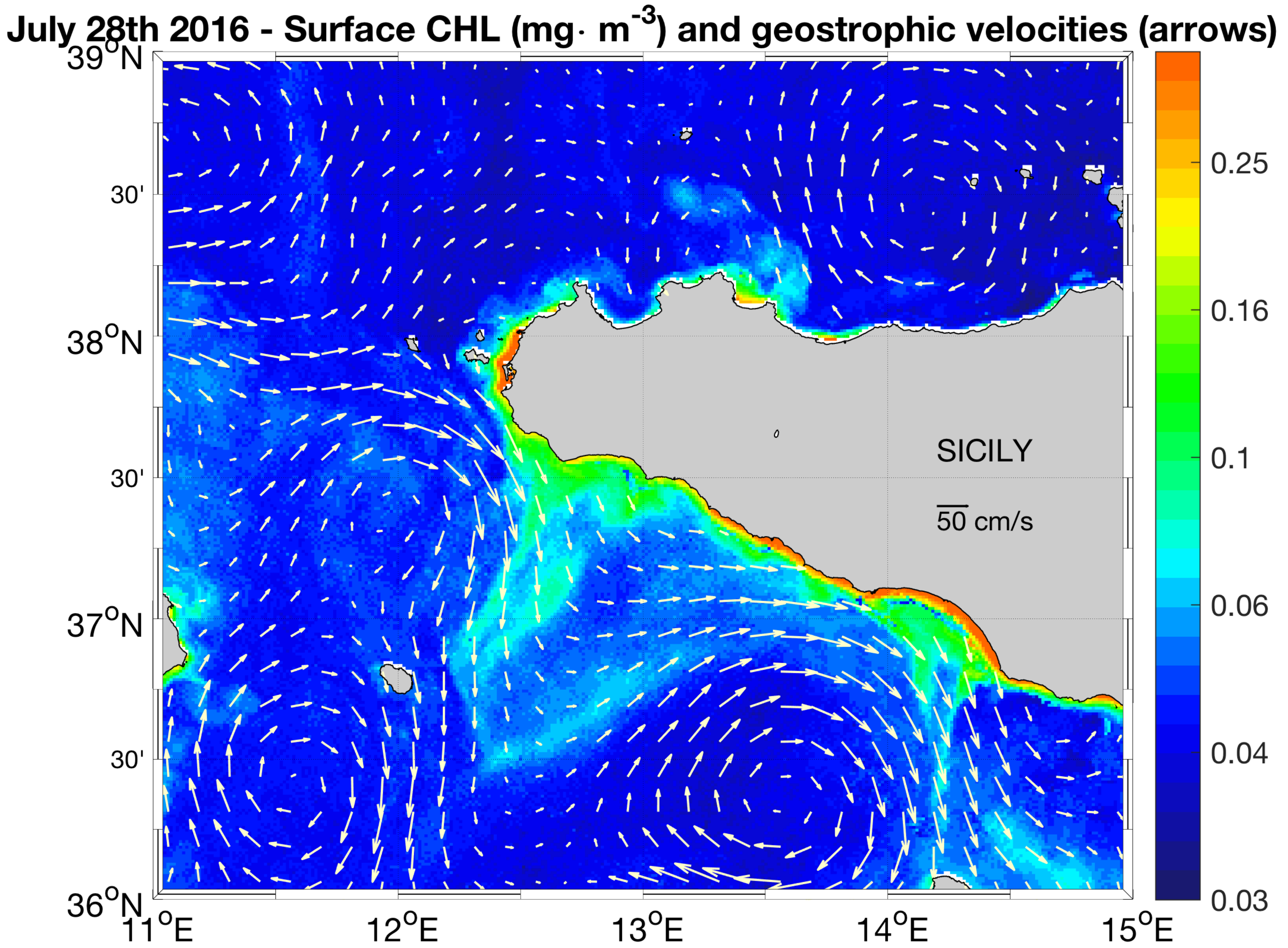
Conclusions and Perspectives

- **Merging the Altimeter-derived currents with satellite tracer observations (SST) in the Mediterranean Sea, we could improve the currents retrieval compared to Altimetry:**
  Overall improvement of the RMS and BIAS with respect to Drifting Buoys, lowest RMS with respect to HF RADAR currents in the Malta-Sicily Channel

- **Retrieval of small scale geostrophic and ageostrophic motions**

- **Satisfactory performance of the AIS ship-derived currents in the Sicily channel:**
  RMS with respect to HF RADAR comparable to Optimal Currents and Altimetry, though negative bias in the retrieval of the zonal component of the surface circulation

- Compute the Optimal currents at higher spatial (1 km) and temporal (1 h) resolutions
- Extend the Optimal Current validation period to the period (1993-2016). Computation of RMS, BIAS and Correlation Coefficients —> **larger HF RADAR currents time series**
- Evaluate the possibility of merging the Altimeter-derived currents with other oceanic tracers (e.g. CHLa)



Research Project submitted to the European Space Agency (ESA Living Planet Fellowship)

Thank you!

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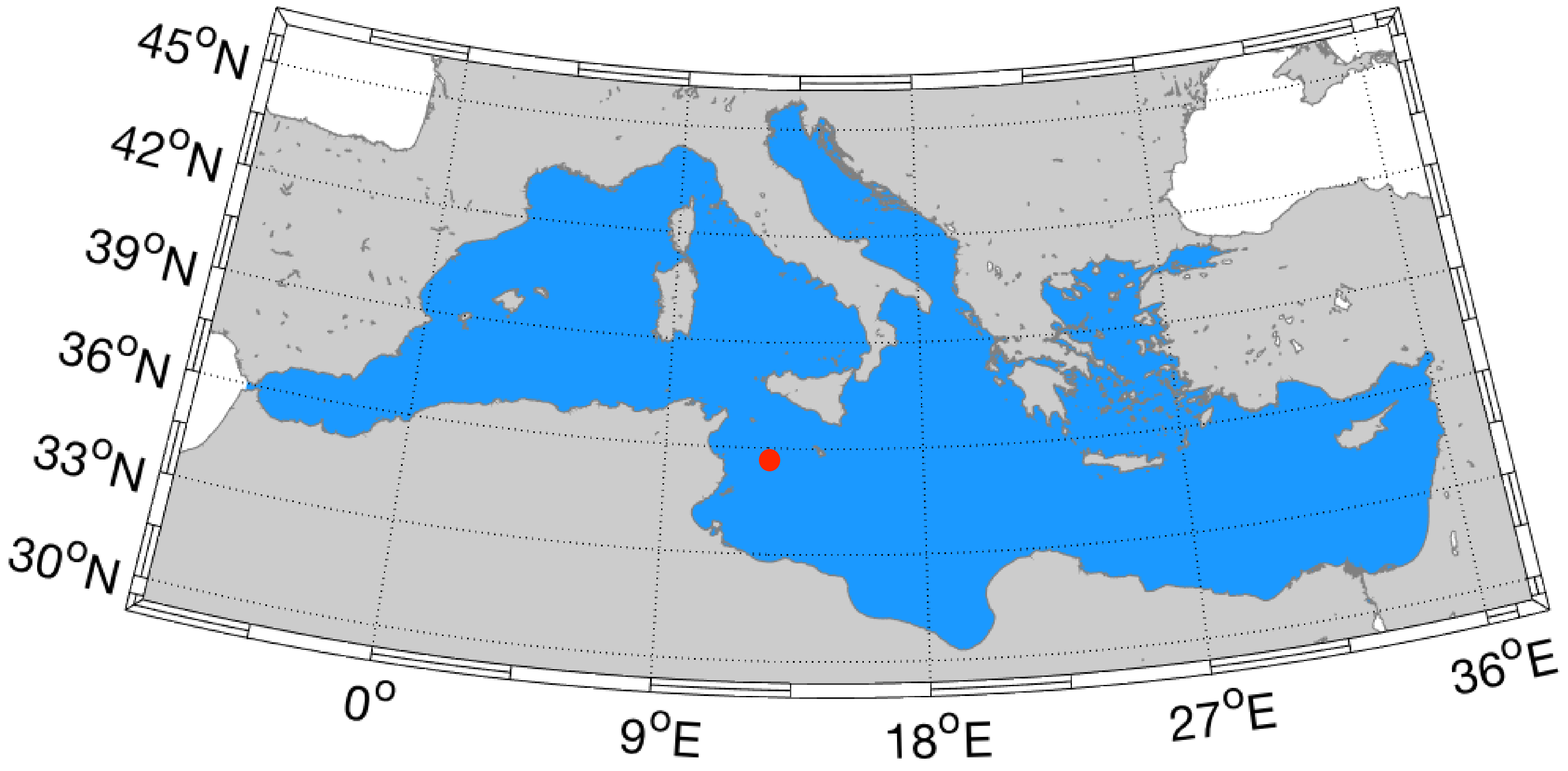
The Lampedusa Laboratory and CAL/VAL Site



The ENEA Laboratory

Instruments

- Meteorological station [air pressure, temperature, humidity, wind direction and velocity, precipitation (Vaisala); solar irradiance (Kipp and Zonen)] – since 1999.
- Non–dispersive Infra–red (NDIR) analyzer [atmospheric CO_2 concentration (the system includes a Siemens 5E analyzer)] – weekly samples, since 1992; continuous, since 1998.
- Gaschromatograph [atmospheric concentration of CH_4, N_2O, CFC–11 and CFC–12 (HP 6890)] – weekly samples, since 1997; continuous, since 2006.
- Cavity ring–down spectroscopy analyzer [atmospheric CO_2, CO, CH_4 (Picarro G2401)] – since 2012.
- Brewer MK III spectrophotometer (total ozone, spectral UV irradiance, aerosol optical depth) – since 1998.
- Aerosol lidar [together with University of Rome; aerosol backscattering and depolarization profiles] – since 1999.
- Visible Multi Filter Rotating Shadowband Radiometer [MFRSR; aerosol optical depth at several wavelengths, diffuse–to–direct irradiance ratio, column water vapor, aerosol single scattering albedo (Yankee Environmental Systems MFR–7)]; since 2001.
- Ultraviolet Multi Filter Rotating Shadowband Radiometer [UV–MFRSR; aerosol optical depth at several wavelengths, diffuse–to–direct irradiance ratio (Yankee Environmental Systems UV–MFR–7)]; 2004–2006, restarted in 2010.
- Cimel CE–318 sun–photometer [jointly with Univ. of Modena and Reggio Emilia; part of AERONET] – 2000–2005, restarted in 2010.
- Middleton 4–channel sun–photometer, wide field of view [aerosol optical depth, column water vapour] – since 2013.
- Middleton 4–channel sun–photometer, narrow field of view [aerosol optical depth, column water vapour] – since 2013.
- PM–10 aerosol sampler [Tecora Skypost, daily chemical analyses performed at the University of Florence; FAI Hydra, University of Florence] – since 2004.
- PM–10 aerosol sampler for EC/OC [Tecora Echo PM; daily chemical analyses performed at the University of Florence] – started in 2010.
- Particle soot/absorption photometer [PSAP; aerosol absorption coefficient; LSCE/IPSL] – starting in 2010.
- Precision Spectral Pyranometer [downward shortwave irradiance (Eppley)] – since 2003.
- Precision Infrared Radiometer [downward longwave irradiance (Eppley)] – since 2003.
- Shaded CGR4 pyrgeometer [downward longwave irradiance (Kipp and Zonen)] – since 2007.
- Shaded Precision Spectral Pyranometer [diffuse downward shortwave irradiance (Eppley)] – since 2006.
- CHP1 pyrheliometer [direct normal irradiance (Kippa and Zonen)] – since 2011.
- Photosynthetic radiation radiometer [downward photosynthetically active radiation (Li–cor)] – since 2004.
- Actinic radiation spectrometer [actinic radiation spectra, photodissociation rates (Metcon GmbH)] – since 2004.
- UV–Vis–near IR spectrometer [global spectral irradiance (Satlantic HyperOCR)] – since 2013.
- UV–Vis–near IR spectrometer [diffuse spectral irradiance (Satlantic HyperOCR)] – since 2013.
- CARAGA aerosol sampler [dust/aerosol total deposition; LISA] – started in 2011.
- Total sky imager [cloud cover (Yankee Environmental Systems TSI 440)] – since 2003.
- Water vapor Raman lidar [day/nighttime vertical profiles of water vapor, aerosol extinction (jointly with University of Rome)] – since 2009.
- Vaisala radiosonde [temperature, pressure, humidity, wind (Vaisala Digicora III)] – since 2004.
- SODAR [wind vertical profiles, three components, RSE] – 2006–2010.
- RPG Hat–Pro Microwave radiometer [temperature, water vapour, clouds vertical profiles] – 2009; restarted in 2010.
- IR camera [IR radiance in the atmospheric window (Heitronics)] – 2009; restarted in 2010.
- Ozone analyzer [surface ozone mixing ratio; Province of Agrigento] – 2003, 2006–2007, 2010–2013.
- Ozone analyzer [surface ozone mixing ratio; ISAC/CNR] – since 2014.
- ENEA gas sampling unit [weekly analyses of CFC–113, HCFC–22, HCFC–141b, HCFC–142b, HFC–134a, SF_6, CH_3Cl, CH_3Br, CH_2Cl_2, CCl_4, CH_3CCl_3, Halon–1211, Halon–1301, CH_2Br_2, CH_3I, $CHCl_3$, made at ENEA, Rome] – since 2004.
- NOAA gas sampling unit [weekly analyses of CO_2, CH_4, SF_6, CO, ^{13}C, H_2, ^{18}O, made at NOAA] – weekly analyses since 2006.

The CNR Cal/Val Site

Operational sensors:

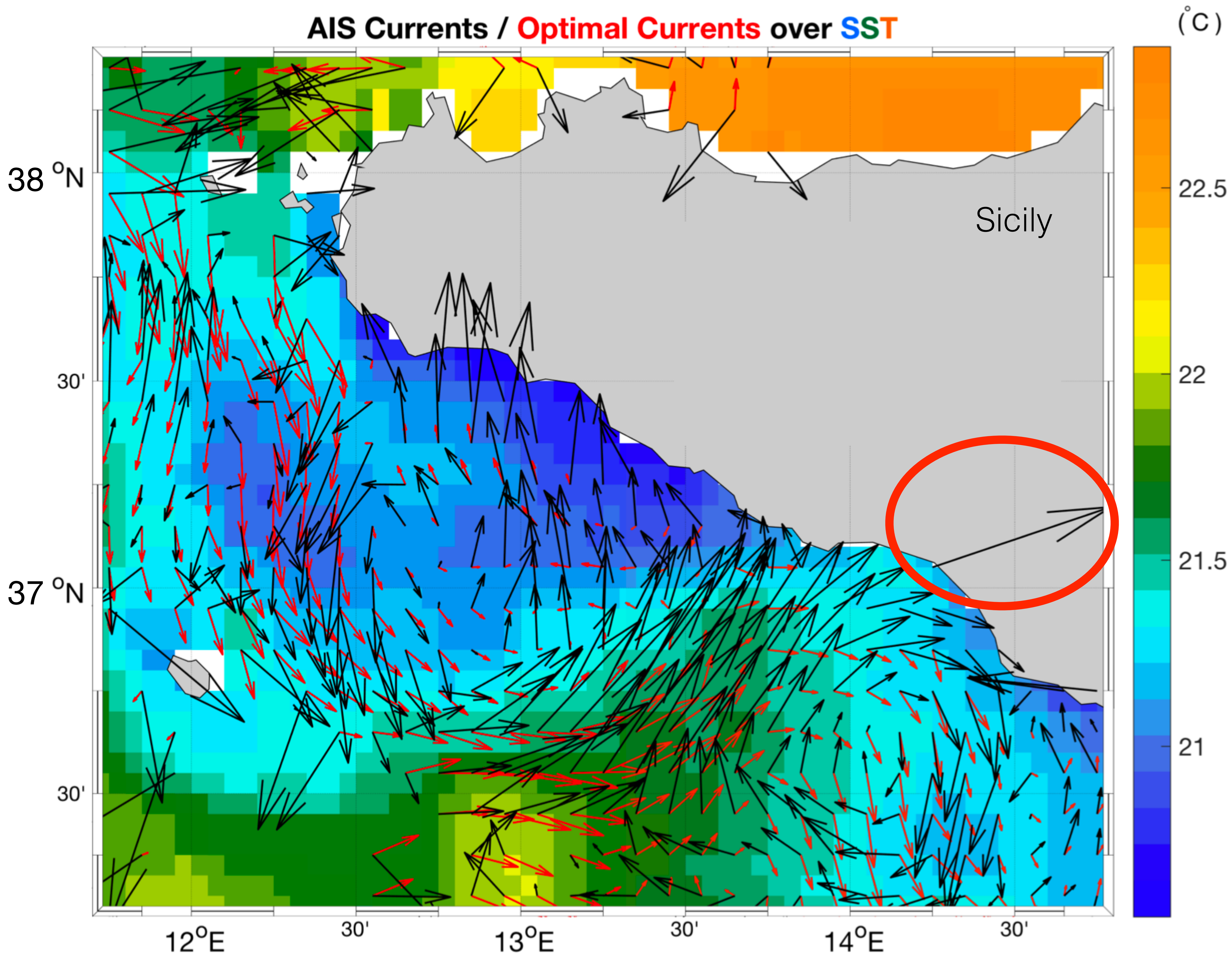
- **Vaisala MAWS401 meteorological station;**
- **Kipp and Zonen CMP21 and CGR4 radiometers for shortwave (SW) and longwave (LW) irradiances;**
- **two Seabird SBE 39 sensors at 1 and 2 m depth, acquired every minute;**
- **a Seabird SBE 37-ODO CTD for temperature, salinity, and dissolved oxygen at 18 m depth**; (foundation)
- 6 Satlantic OCR507 radiometers for up- and down-welling radiances/irradiances at 2.5 and 6 m depth.
- Additional sensors for upwelling shortwave and longwave irradiances, down- and upwelling spectral solar radiation, and downwelling irradiance in 7 bands.

for data access please contact: simone.colella@cnr.it

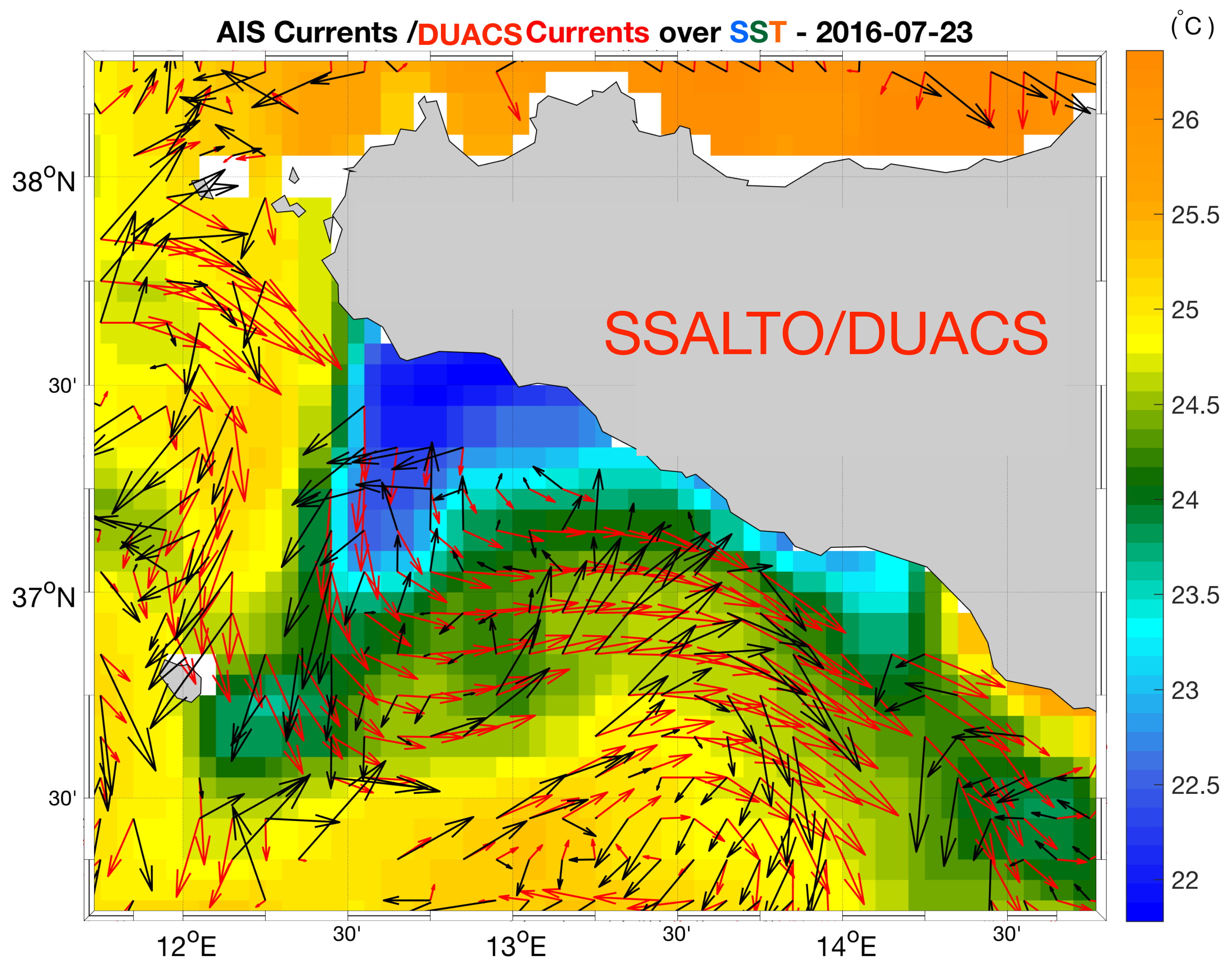
salvatore.marullo@enea.it

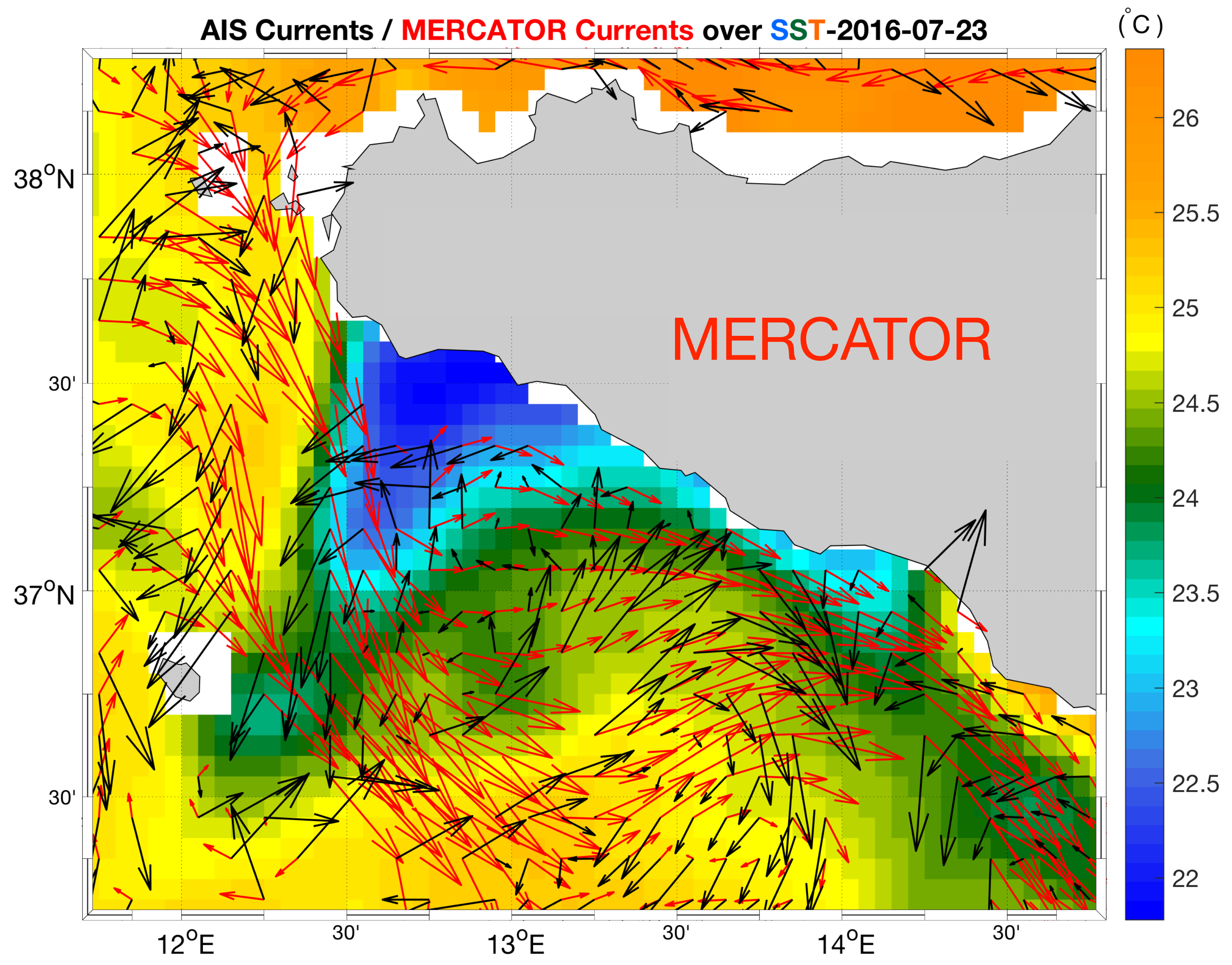
Qualitative Results

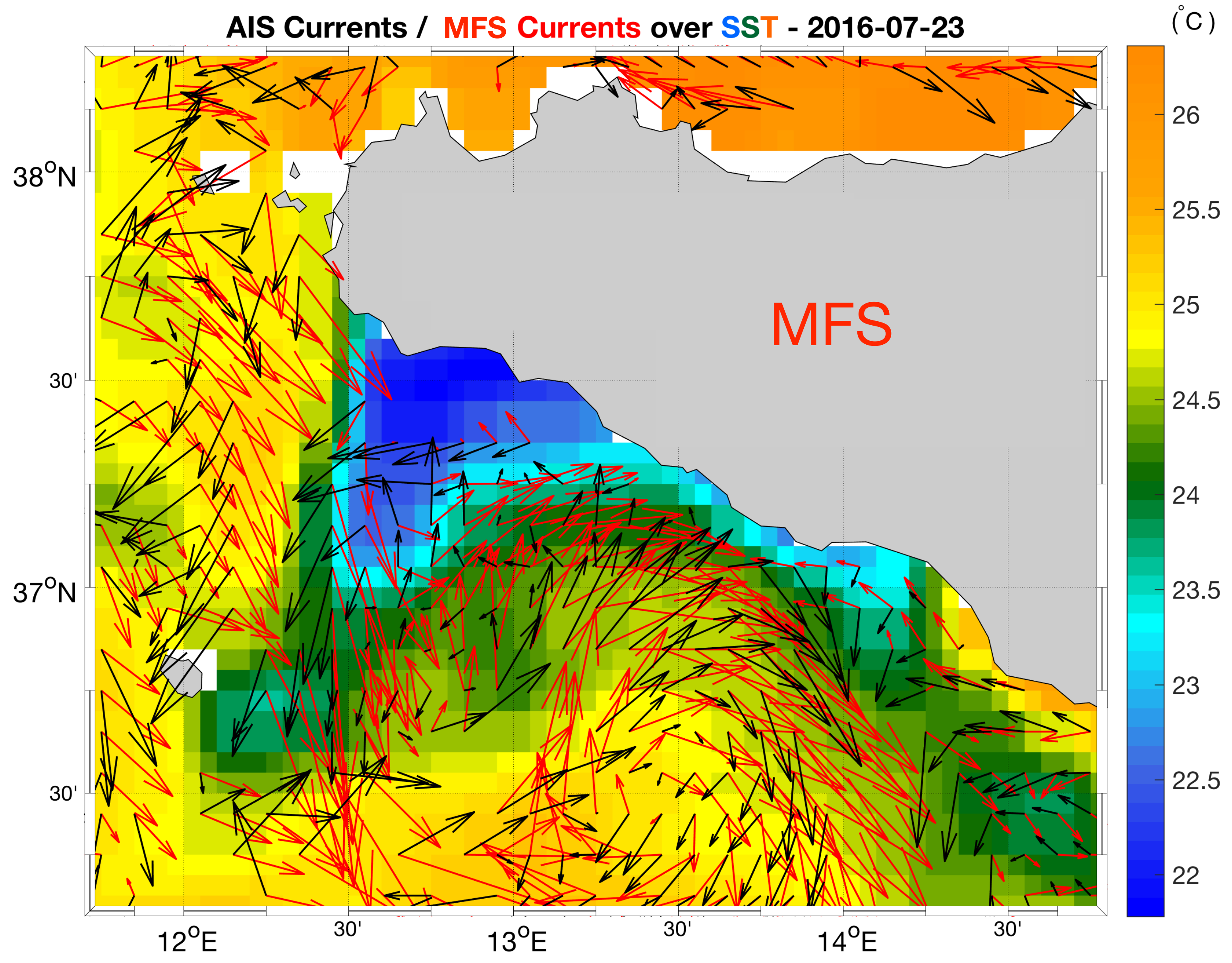
AIS: large inshore currents (up to 40 cm/s) - **discarded**

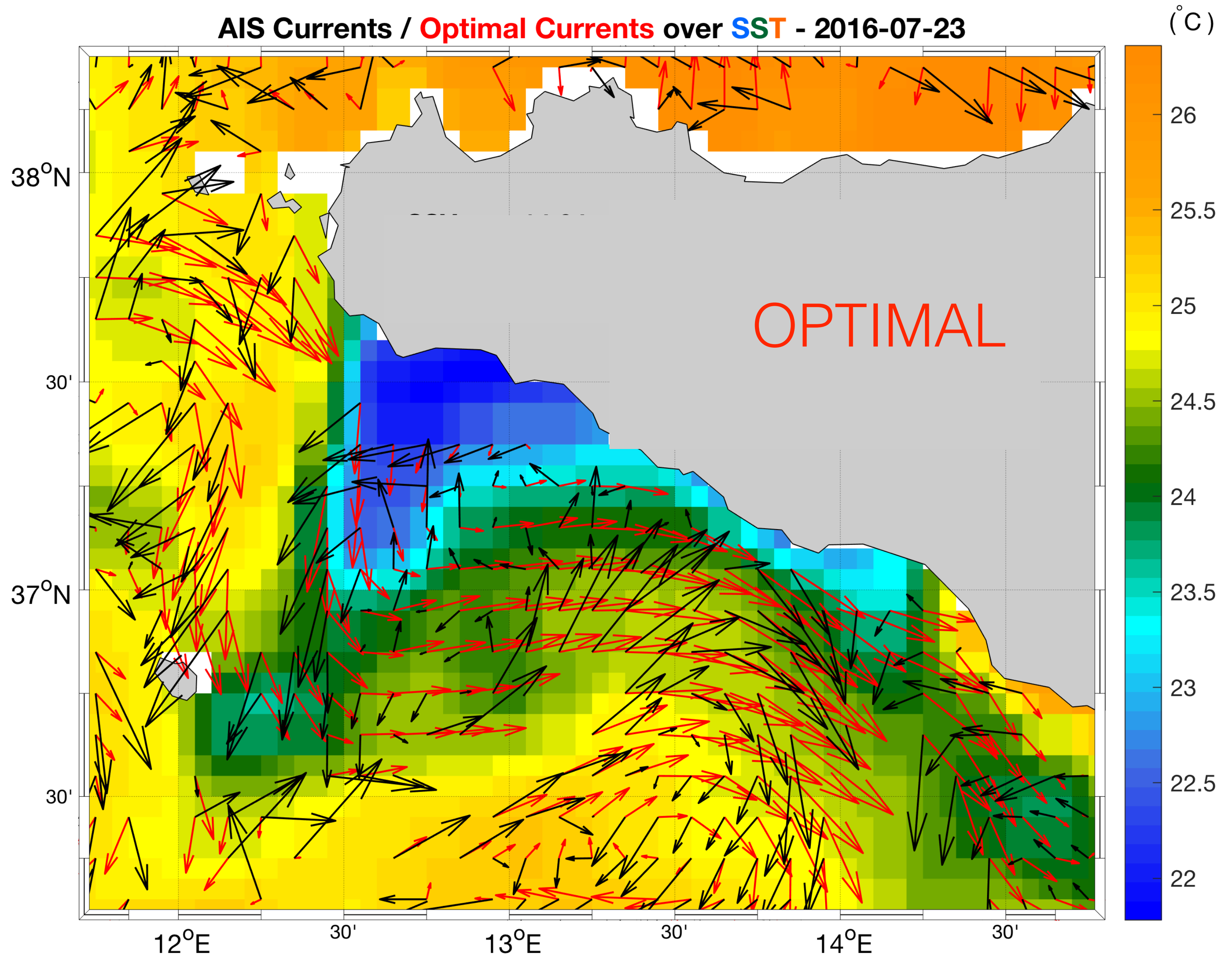


Qualitative Results (vs AIS currents)

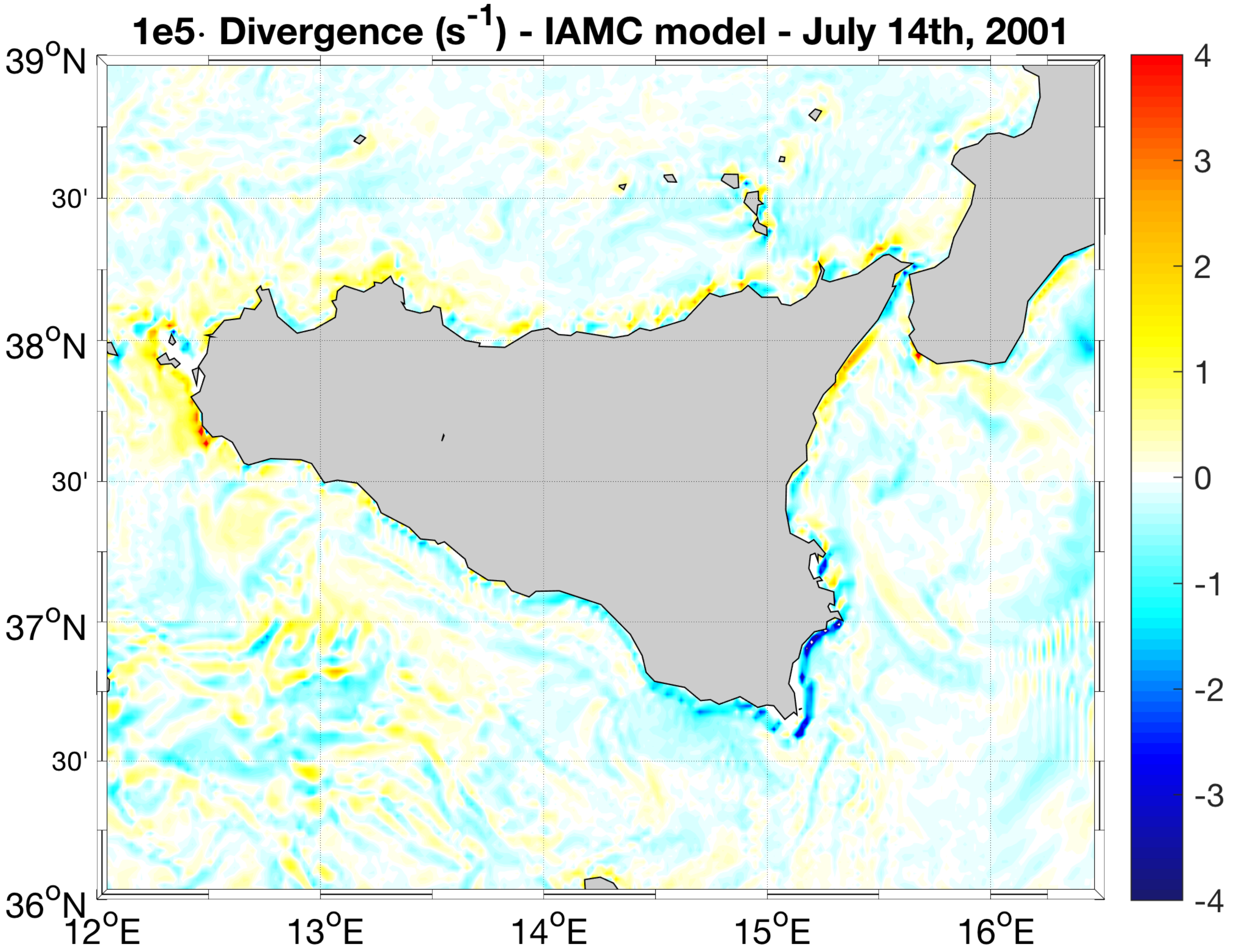








Divergences of the U,V fields derived from a model $\mathcal{O}(10^{-5})$



http://www.seaforecast.cnr.it/en/scrm.php

OPTIMAL CURRENTS

Require the velocity field (u,v) to obey the SST evolution equation and inverse it for the velocity vector:

$$\frac{\partial SST}{\partial t} + u\frac{\partial SST}{\partial x} + v\frac{\partial SST}{\partial y} = F(x, y, t)$$

F(x,y,t) represents the source and sink terms (insolation, net infrared radiation, latent and sensible heat fluxes)

The Heat conservation Equation

$$\frac{\partial SST}{\partial t} + u\frac{\partial SST}{\partial x} + v\frac{\partial SST}{\partial y} = F$$

The source and sink terms F

$$F = \frac{1}{H}\int_{z=0}^{z=H} -w(z)\frac{\partial T(z)}{\partial z}dz + \underbrace{\frac{\kappa_x}{H}\int_{z=0}^{H}\frac{\partial^2 T(z)}{\partial x^2}dz + \frac{\kappa_y}{H}\int_{z=0}^{H}\frac{\partial^2 T(z)}{\partial y^2}dz + \frac{\kappa_z}{H}\int_{z=0}^{H}\frac{\partial^2 T(z)}{\partial z^2}dz}_{\text{Diffusion}} + \frac{Q(H)}{\rho C_p H} - \frac{w_e}{H}(T_m - T_b)$$

Vertical advection

~0

Diffusion

~0

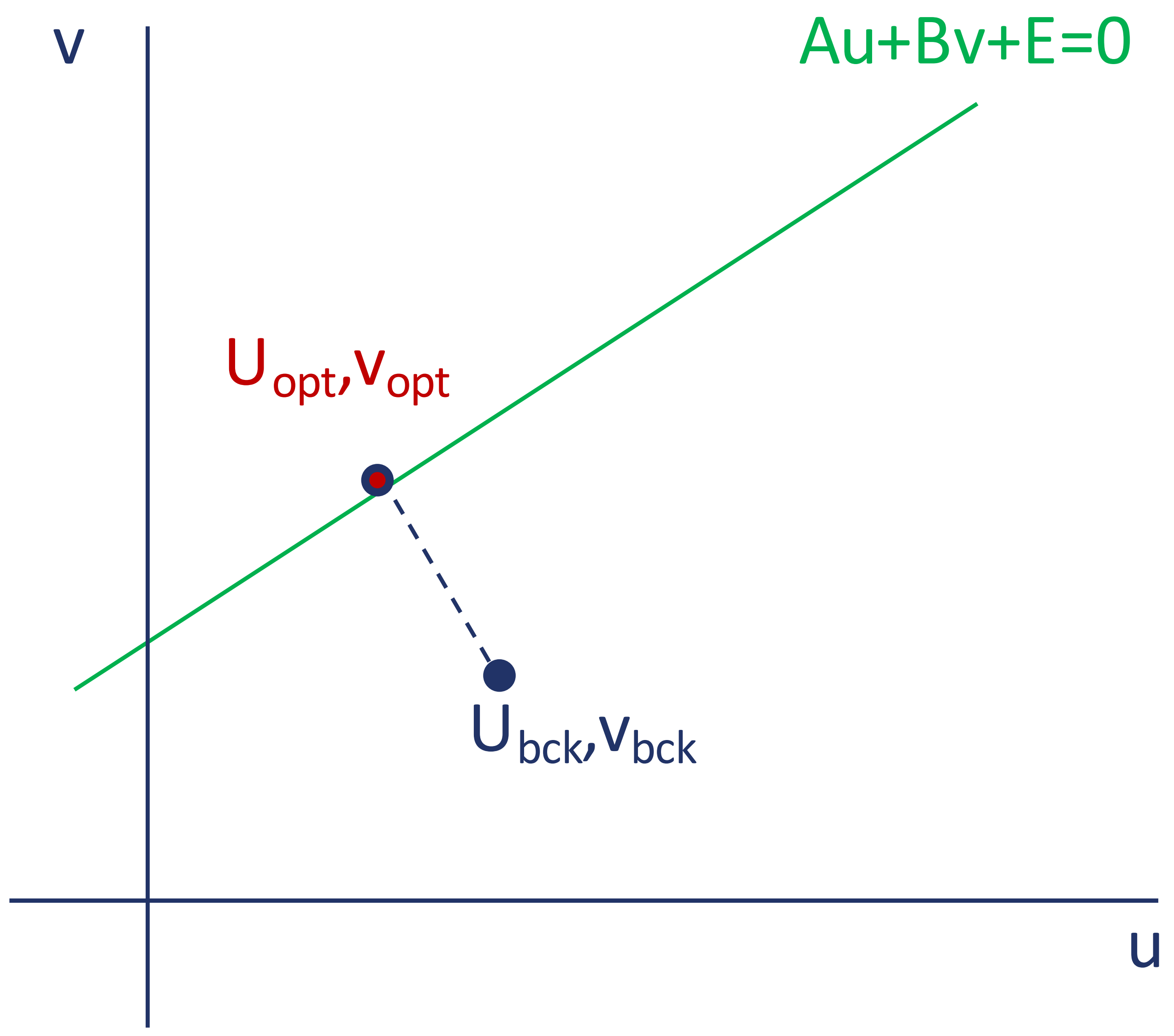
Heat fluxes

Large spatial scale of $\frac{\partial SST}{\partial t}$ $=F_{bck}$

Entrainment velocity (0 in case of shoaling)

Rio et al. 2016

OPTIMAL CURRENTS
perfectly known forcing



$$A = \frac{\partial SST}{\partial x} \qquad B = \frac{\partial SST}{\partial y} \qquad E = \frac{\partial SST}{\partial t} - F$$

$$\Downarrow$$

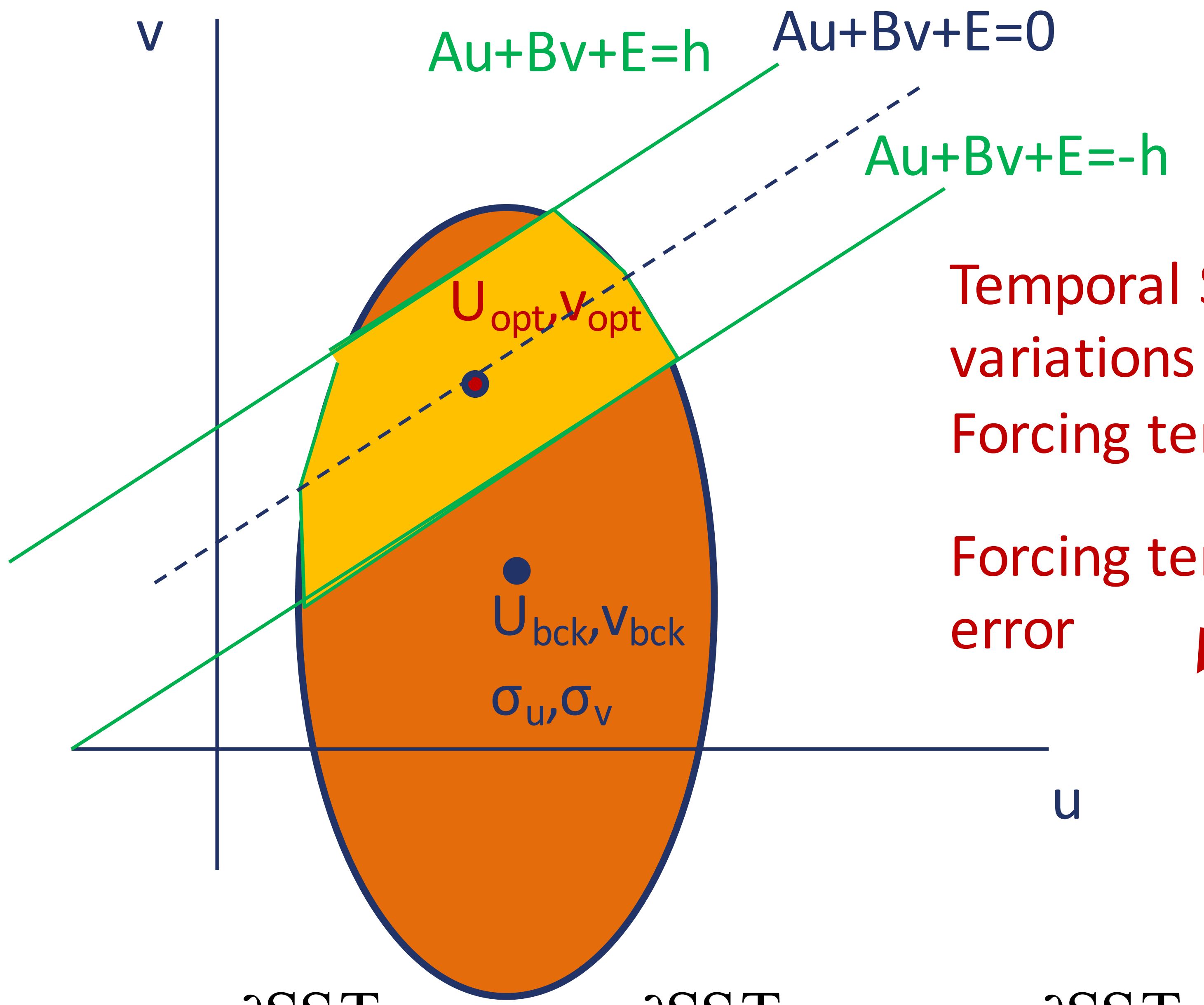
Au+Bv+E=0

$$u_{opt} = u_{bck} - \frac{A(Au_{bck} + Bv_{bck} + E)}{A^2 + B^2}$$

$$v_{opt} = v_{bck} - \frac{B(Au_{bck} + Bv_{bck} + E)}{A^2 + B^2}$$

Piterbarg et al., 2009

OPTIMAL CURRENTS (with ERROR)



Spatial SST variations

Temporal SST variations

Forcing term

Forcing term error

Background velocity error

$$q=\sqrt{\left(\sigma_u^2\sin^2\varphi+\sigma_v^2\cos^2\varphi\right)}\qquad \varphi=\operatorname{Arctan}\left(-\frac{A}{B}\right)$$

$$\alpha=\frac{Au_{bck}+Bv_{bck}+E-h}{\sqrt{A^2+B^2}}\qquad \beta=\frac{Au_{bck}+Bv_{bck}+E+h}{\sqrt{A^2+B^2}}$$

$$d=\frac{\left|Au_{bck}+Bv_{bck}+E\right|}{\sqrt{A^2+B^2}}\qquad p=\frac{\sin\varphi\cos\varphi\left(\sigma_v^2-\sigma_u^2\right)}{q^2}$$

$$u_0=\frac{F(\min(\beta,q))-F(\max(\alpha,-q))}{G(\min(\beta,q))-G(\max(\alpha,-q))}\qquad v_0=pu_0$$

$$F(x)=-\frac{2\left(q^2-x^2\right)^{3/2}}{3}$$

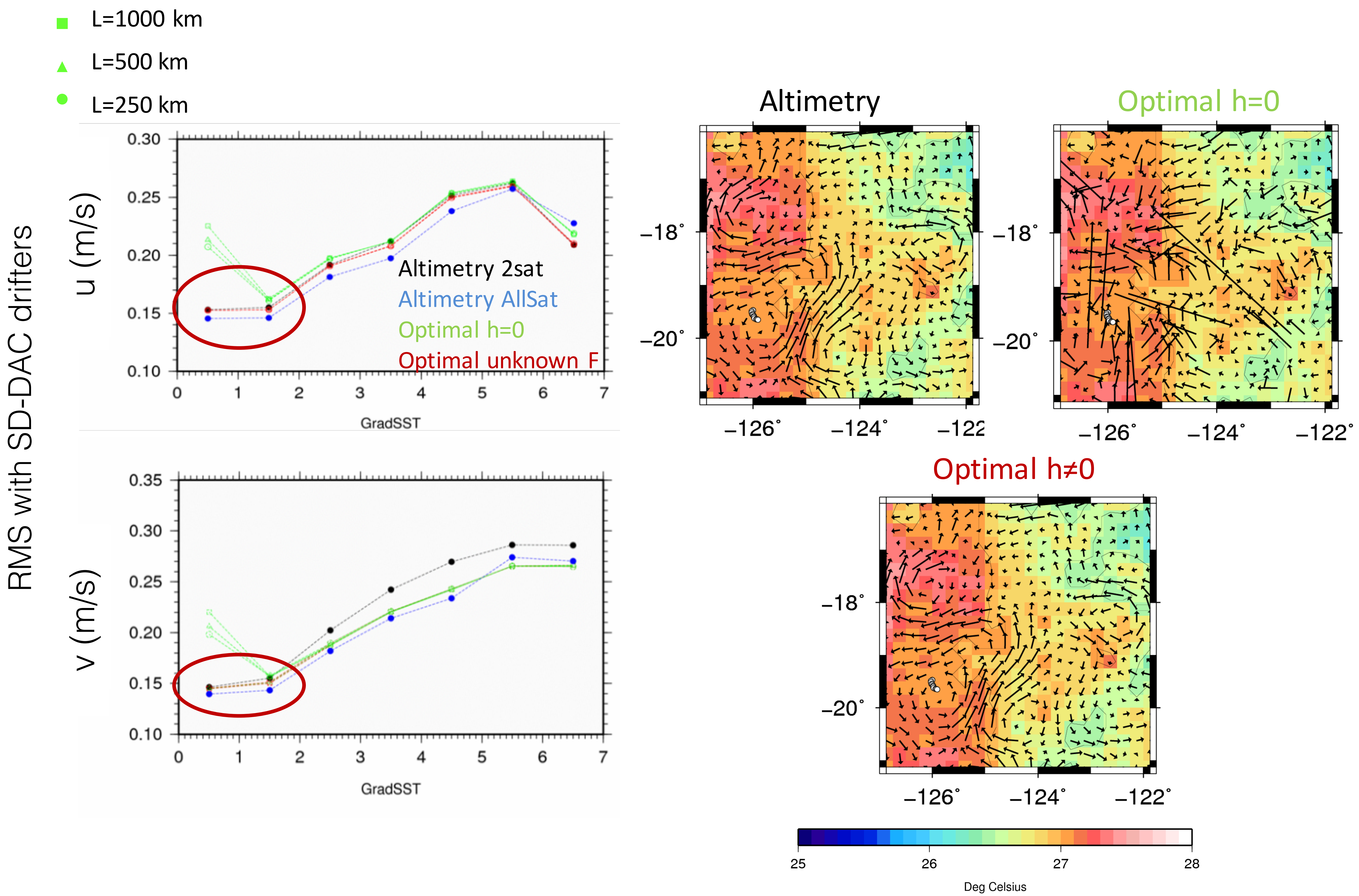
$$G(x)=x\left(q^2-x^2\right)^{1/2}+q^2\sin^{-1}(x/q)$$

$$A=\frac{\partial SST}{\partial x}\qquad B=\frac{\partial SST}{\partial y}\qquad E=\frac{\partial SST}{\partial t}-F_{bck}$$

$u_{opt}=u_{bck}+u_0\sin\varphi+v_0\cos\varphi$ $\qquad$ $v_{opt}=v_{bck}-u_0\cos\varphi+v_0\sin\varphi$

Piterbarg et al., 2009

OPTIMAL CURRENTS (with ERROR)

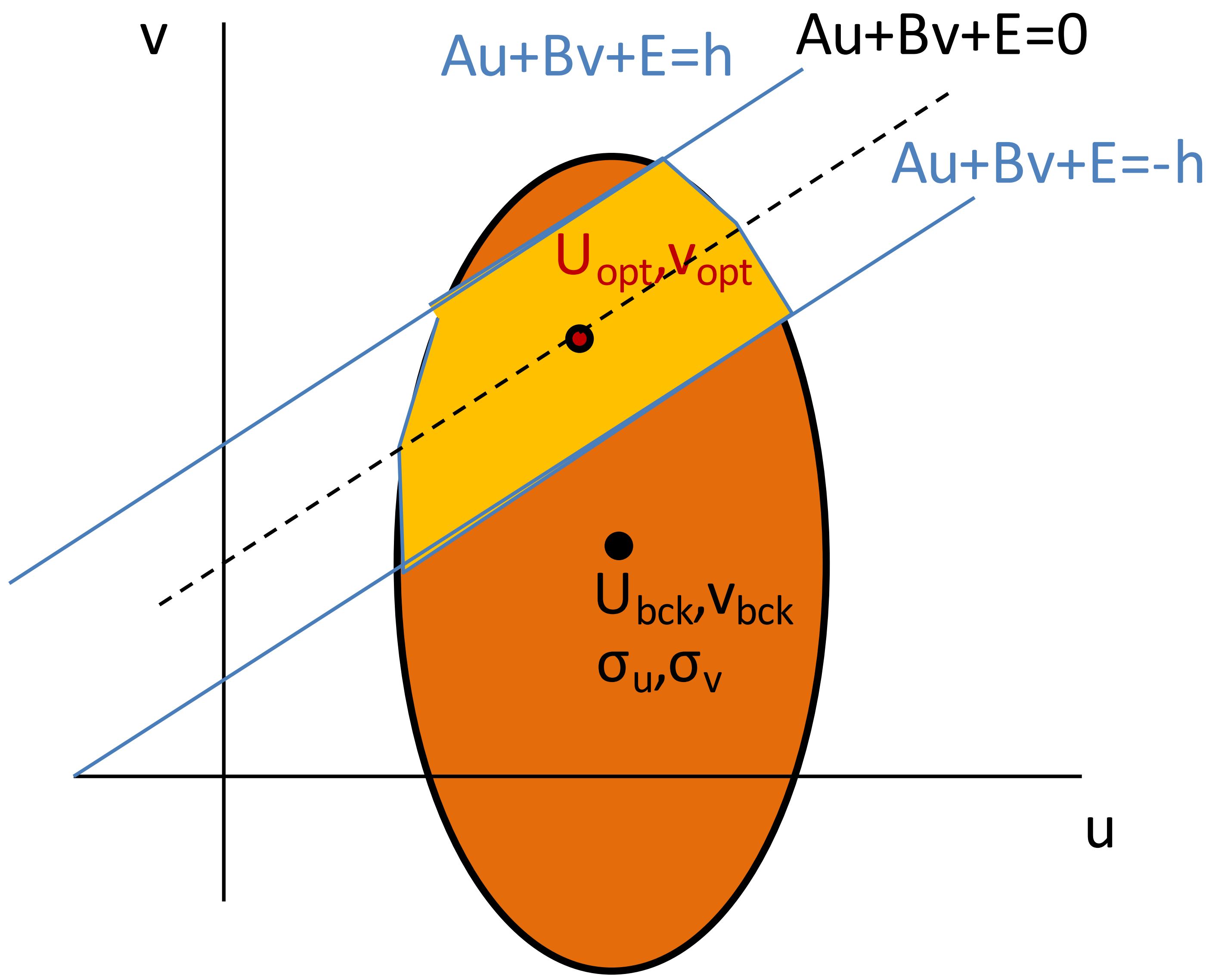


Rio et al., 2017 (submitted)

OPTIMAL CURRENTS (with ERROR)

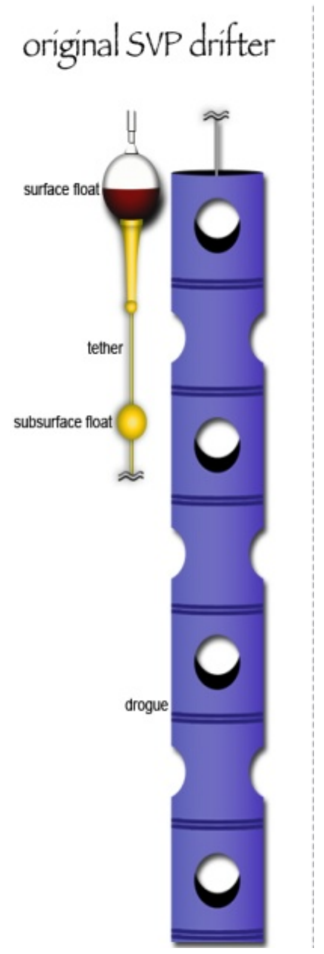
Taking into account the error on the background field (altimetry) and on the forcing term F is essential, in particular in low SST gradients areas.

However, if $h \gg \sigma_u, \sigma_v$ Optimal velocity -> Background velocity



Rio et al., 2016

OPTIMAL CURRENTS (with ERROR) - Background velocity error

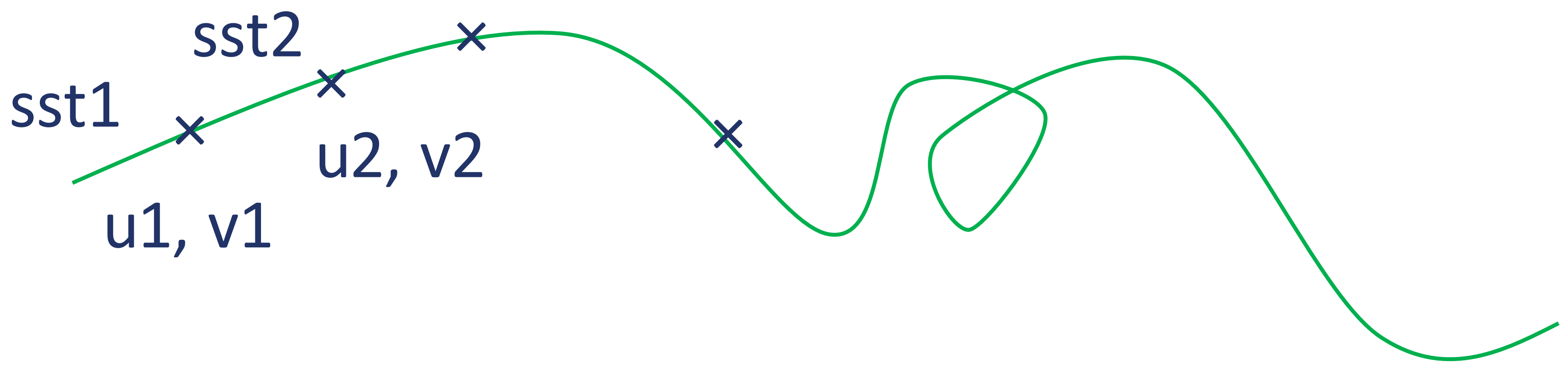


OGS drifting buoys

Med-Sea

In-situ u,v,sst

From 1993 to 2016



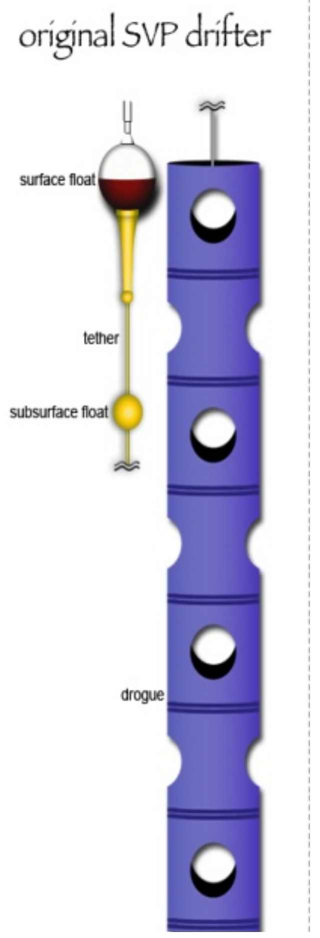
RMS differences

between the background velocities

(DUACS)

and the drifter velocities (OGS) in 1°x1° BOXES

OPTIMAL CURRENTS (with ERROR) - Background velocity error

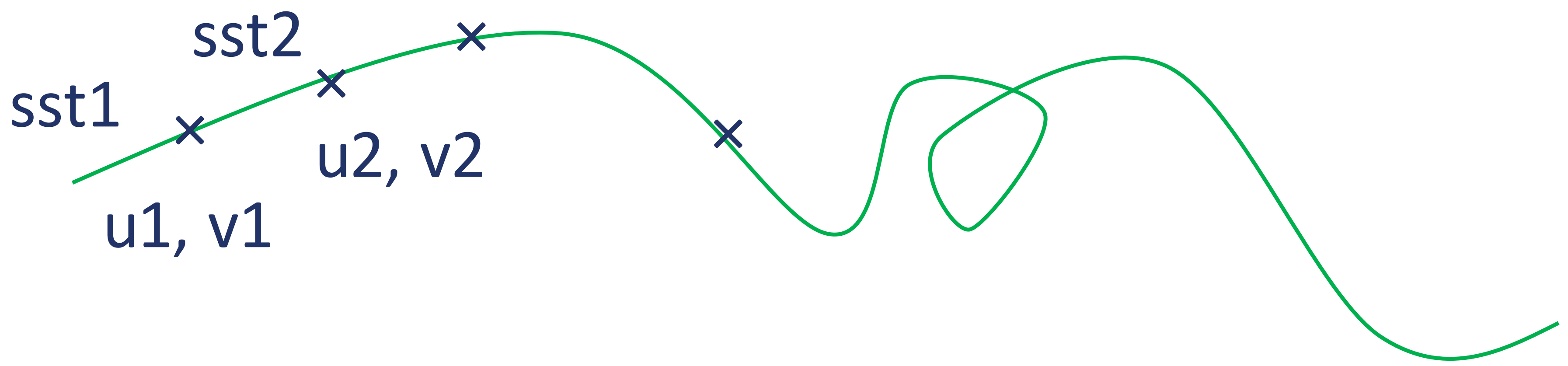


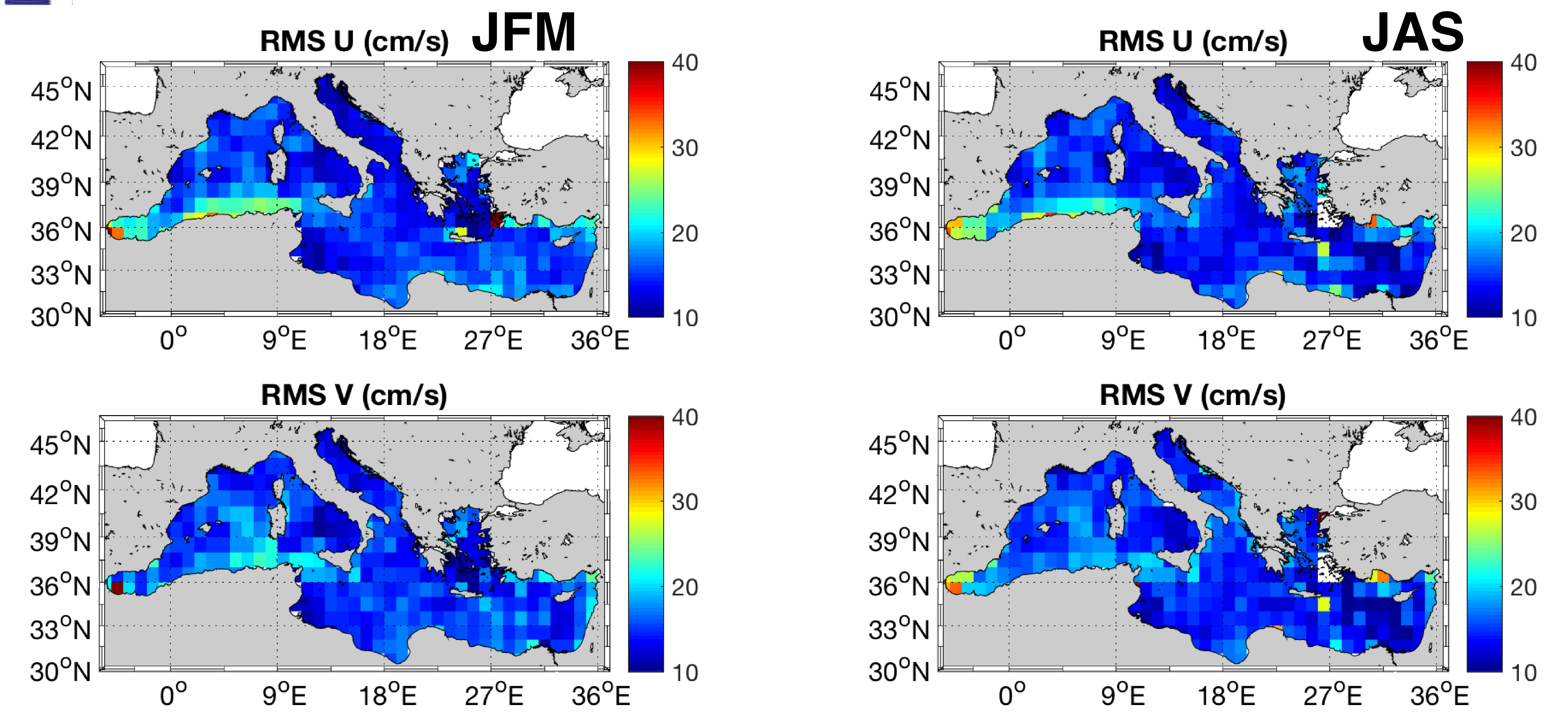
OGS drifting buoys

Med-Sea

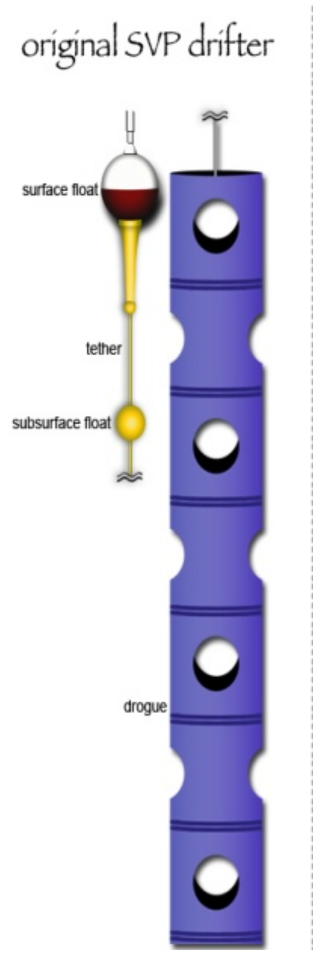
In-situ u,v,sst

From 1993 to 2016

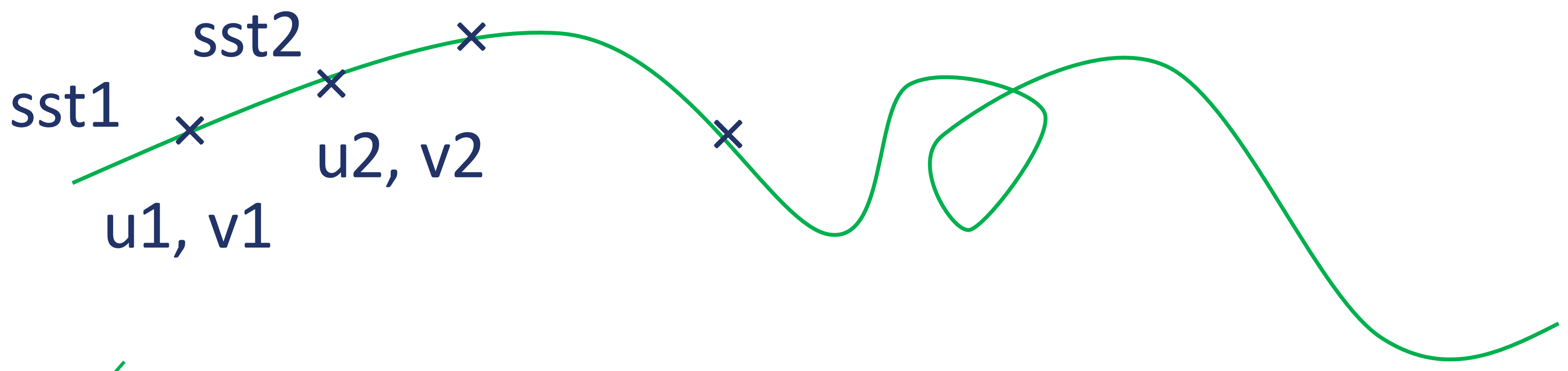




OPTIMAL CURRENTS (with ERROR) - Forcing error



OGS drifting buoys
Med-Sea
In-situ u,v,sst
From 1991 to 2017



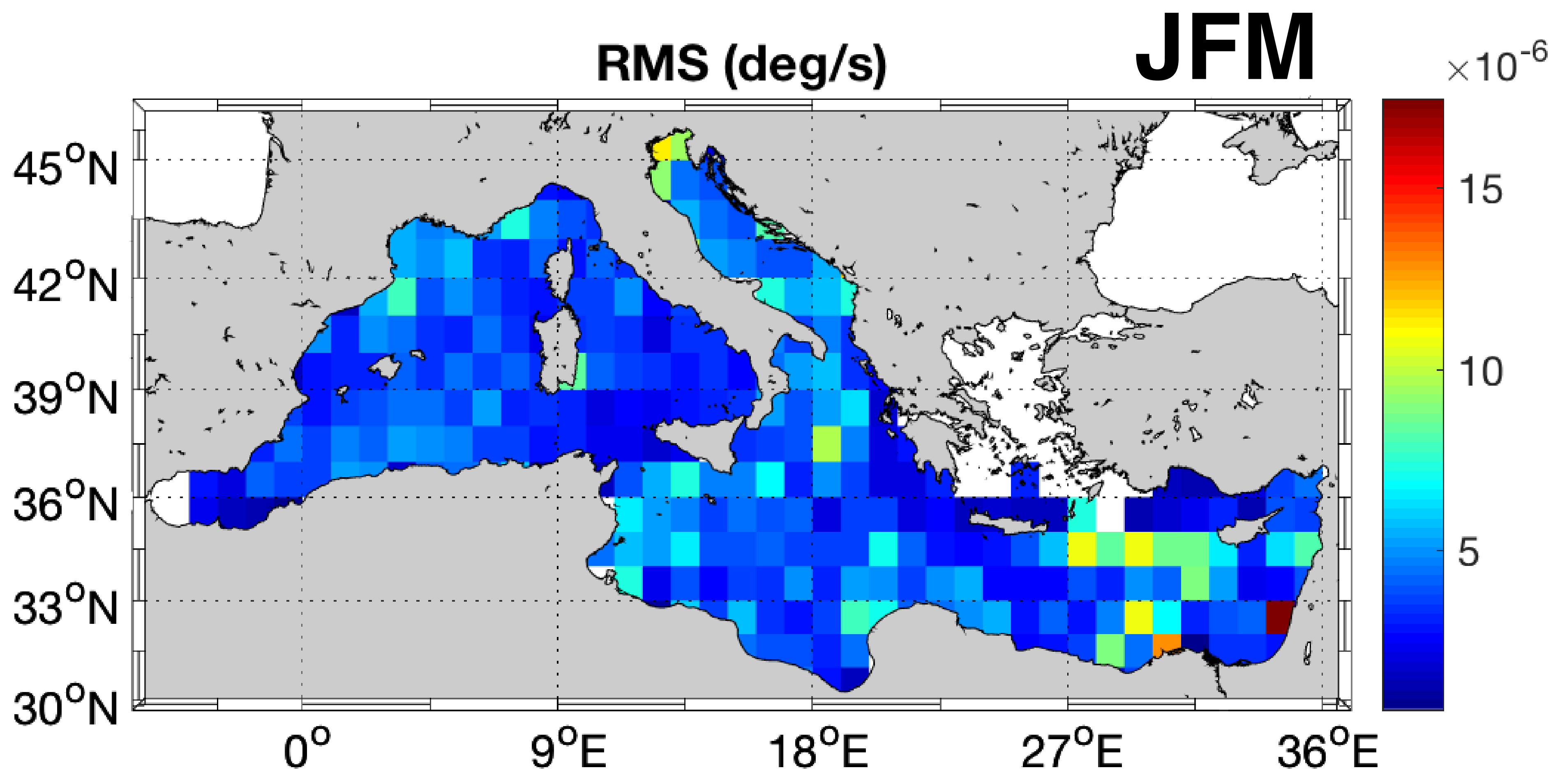
$$\mathrm{sst1} - \mathrm{sst2} = \frac{d\,\mathrm{sst}}{dt} = \underbrace{\frac{\partial\,\mathrm{sst}}{\partial t} + u\frac{\partial\,\mathrm{sst}}{\partial x} + v\frac{\partial\,\mathrm{sst}}{\partial y}}_{F_{obs}} + \cancel{w\frac{\partial\,\mathrm{sst}}{\partial z}}$$

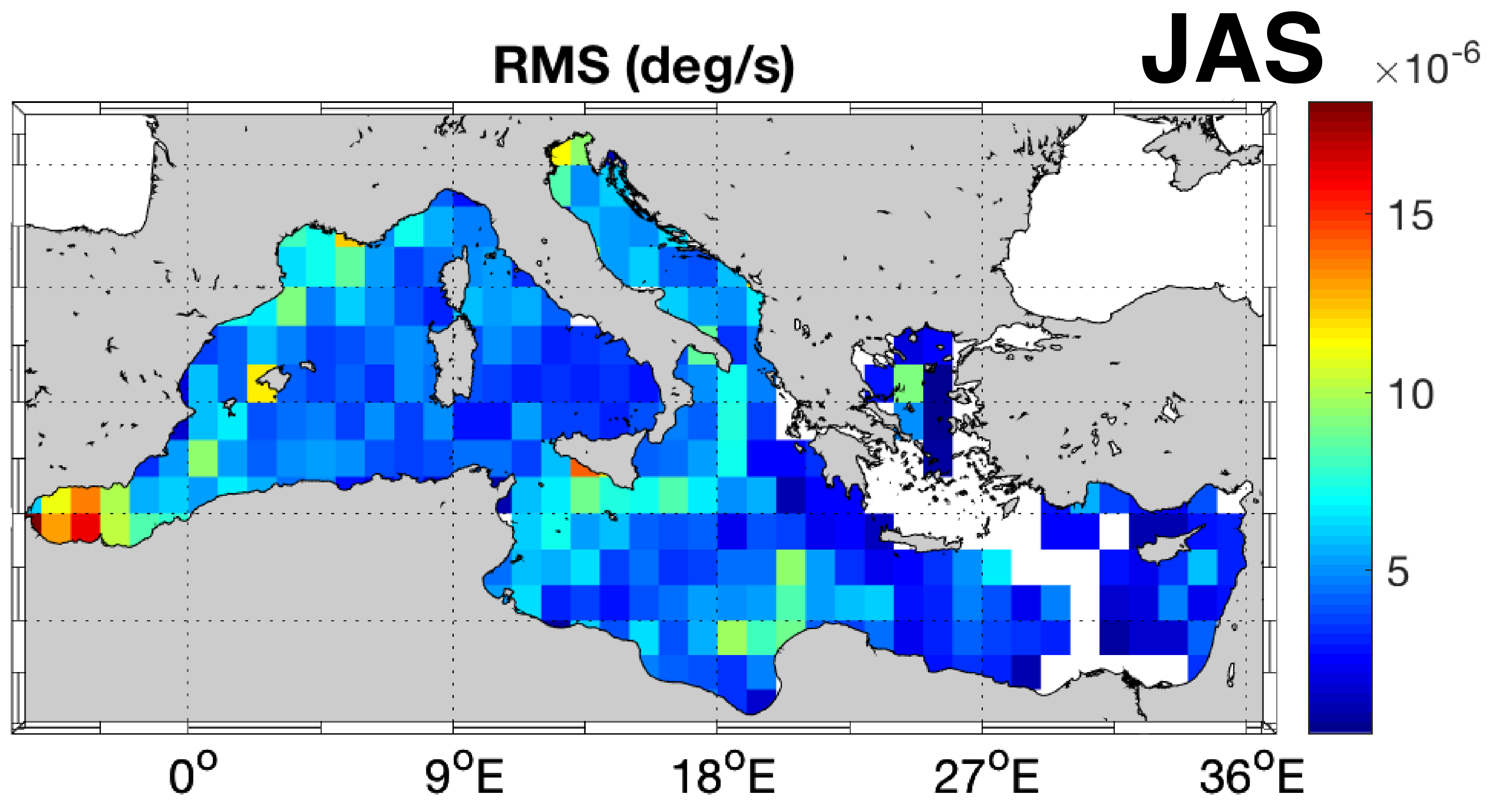
$$F_{obs} \Longleftrightarrow F_{bck} = \left(\frac{\partial\,\mathrm{SST}}{\partial t}\right)_{> 100\ \mathrm{km}}$$

sst=in-situ sensor
SST=space borne sensor

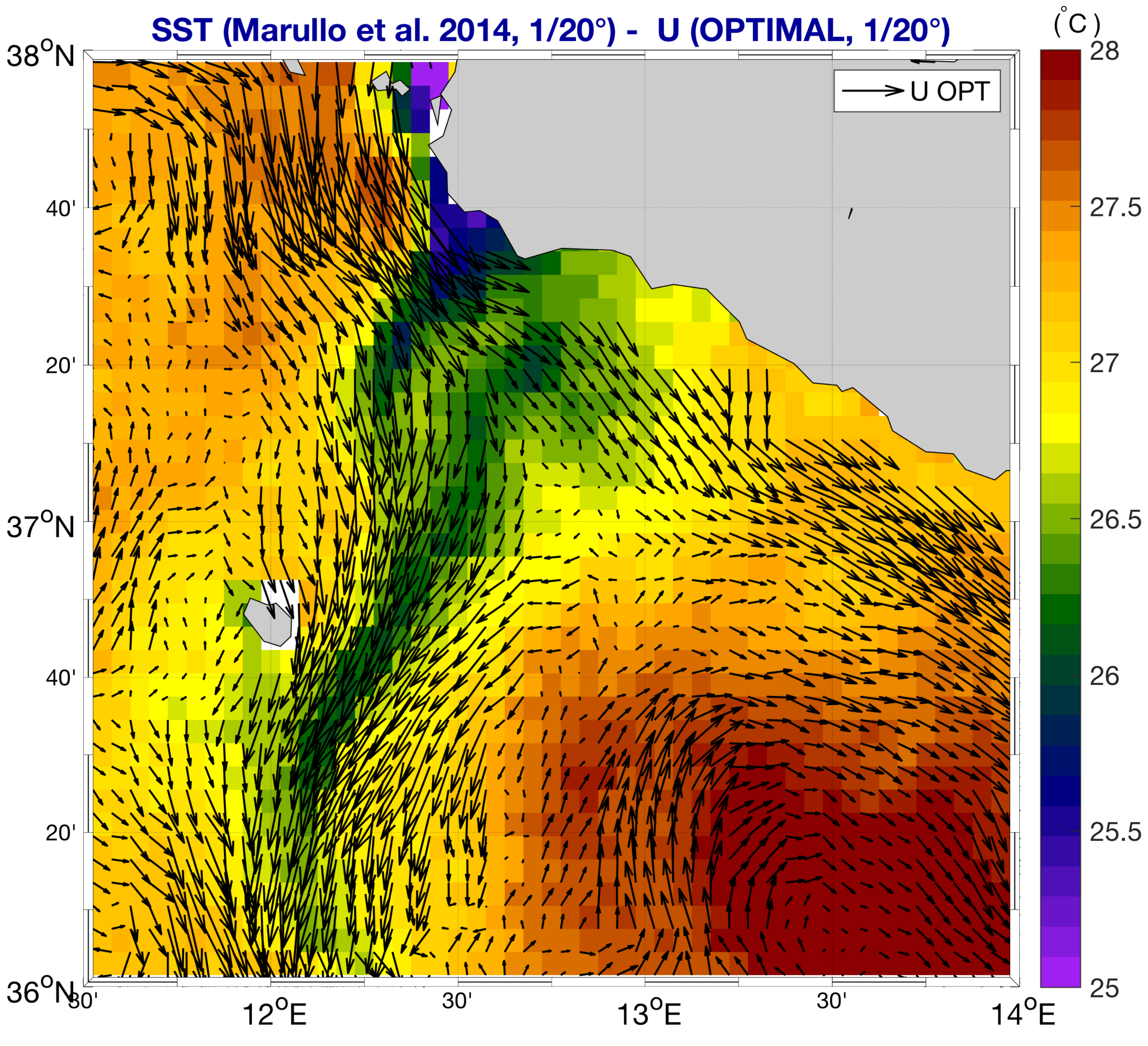
Along the buoy trajectory:

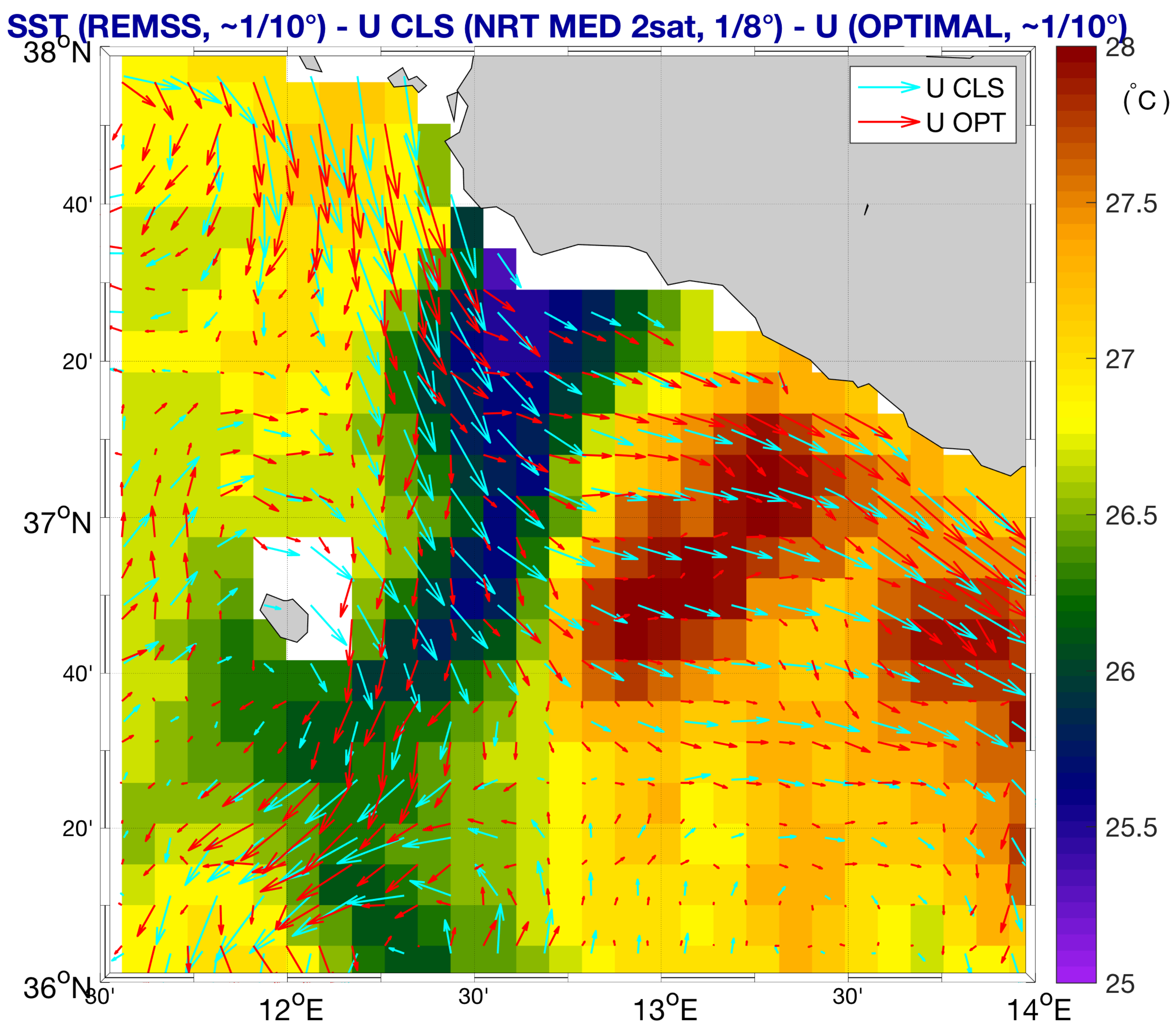
$$h_{buoy}(t) = \mathrm{sst}(t+12h) - \mathrm{sst}(t-12h) - \left(\mathrm{SST}(t+12h) - \mathrm{SST}(t-12h)\right)_{> 100\ \mathrm{km}}$$





NEED FOR AN HR SST INPUT





Better performances for the CMEMS CNR L4 SST compared to the REMSS SST