esa

→ EARTH OBSERVATION SUMMER SCHOOL

Earth System Monitoring & Modelling

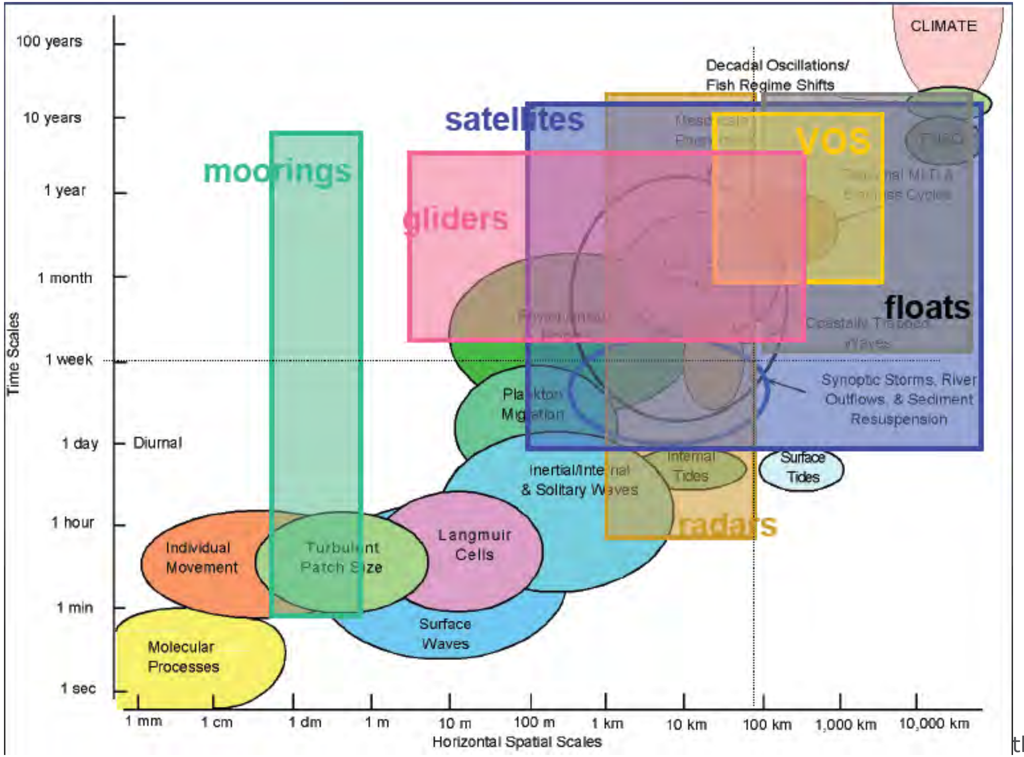
30 July–10 August 2018 | ESA–ESRIN | Frascati (Rome) Italy

OCEAN CIRCULATION II

Marie-Hélène RIO

Space and in-situ data synergy for a better retrieval of the ocean circulation

Complementarity of space and in-situ observations



Space and in-situ Observation network

Space data

GOCE, GRACE

Geoid

ERS, ENVISAT,CRYOSAT, SENTINEL-3
TOPEX, JASON

Sea Surface Height

ENVISAT, Sentinel-1

SAR doppler velocity

In-situ data

SVP drifting buoys

Surface/sub-surface velocities

Argo floats

Temperature, salinity profiles

ENVISAT, Sentinel-3

Sea Surface Temperature

ASCAT, QuickScat

Wind speed

Space and in-situ data synergy for a better retrieval of the ocean circulation

- Geostrophic currents from Altimetry, space Gravity, in-situ measurements of T,S, surface drifter velocities
- Ekman currents from in-situ drifting buoy velocities, altimetry, wind
- SST/SSH synergy for higher resolution surface currents

Space and in-situ data synergy for a better retrieval of the ocean circulation

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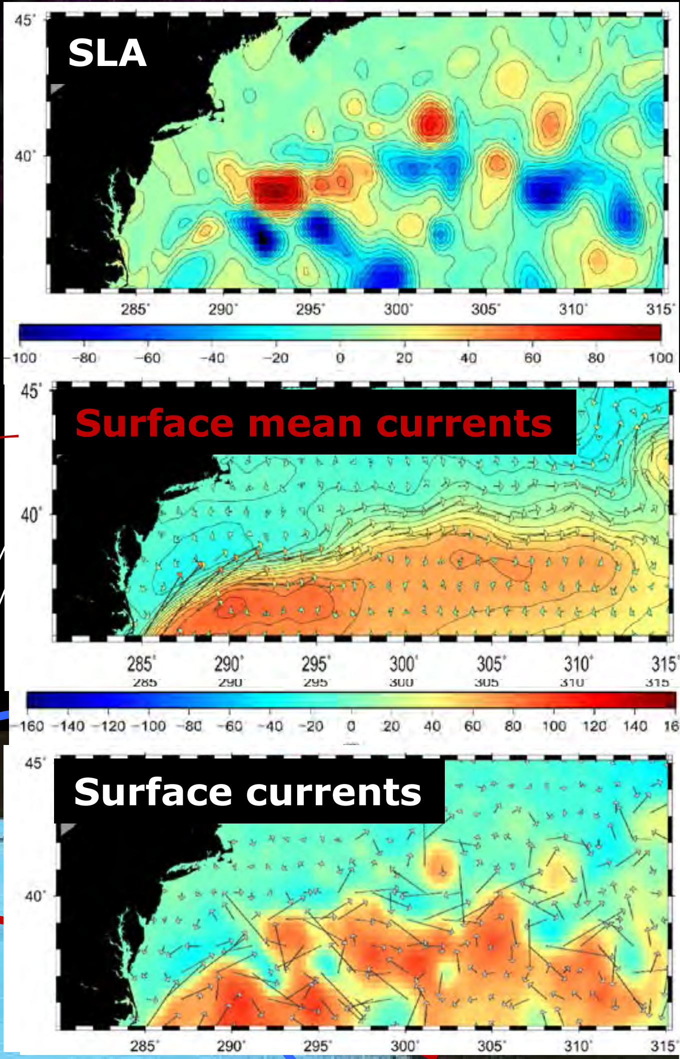
Space gravity AND Altimetry synergy for ocean current retrieval



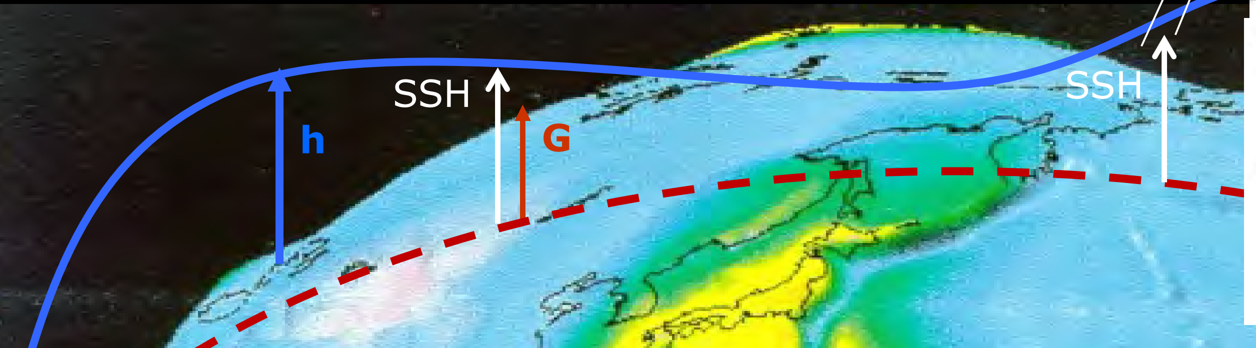
Some very simple equations

SSH=h+G ↔ h=SSH-G

MSSH=MDT+G ↔ MDT=MSSH-G

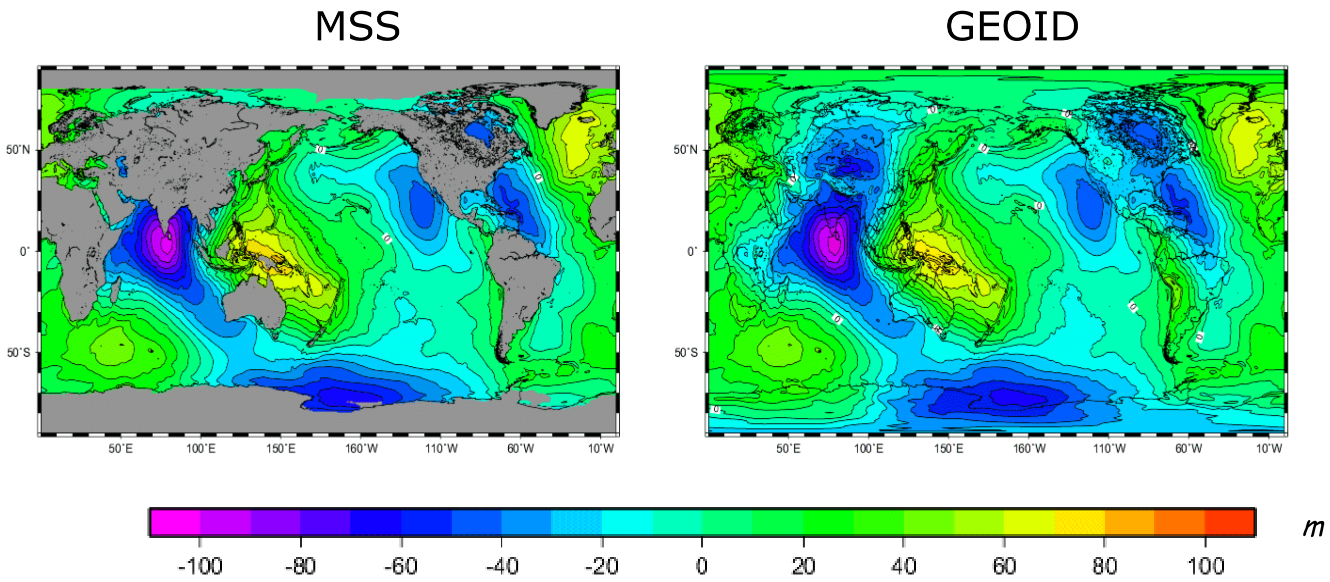
SSH-MSSH=h-MDT=SLA

h=SLA+MDT

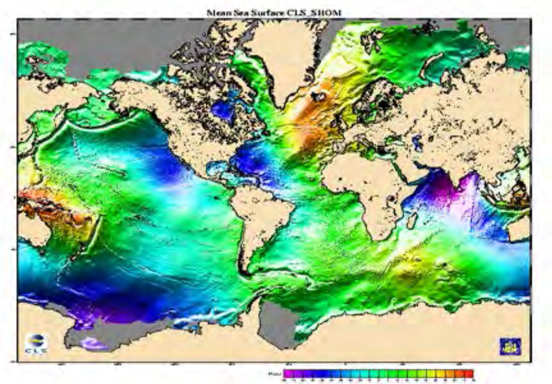


Computation of the « geodetic » MDT

MDT=MSS –GEOID



Mean Sea Surface estimation: 25 YEARS IMPROVEMENTS



MSS OSU 95

MSS CLS_SHOM98

MSS CLS01

MSS DNSC08

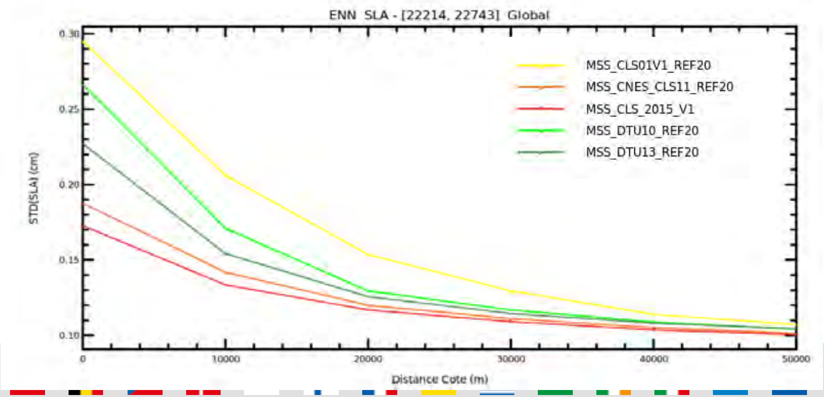
MSS DTU10

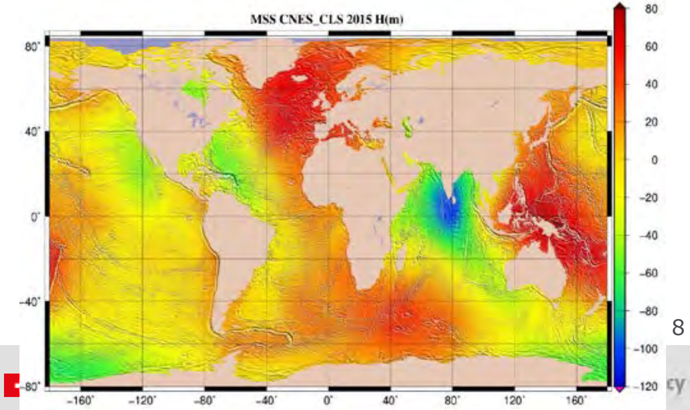
MSS CNES_CLS_2011

MSS DTU15

MSS CNES_CLS_2015

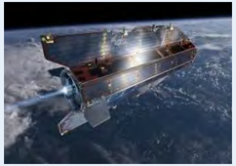
Standard Deviation of Envisat New orbit (ENN) SLA as a function of coastal distance when using different MSS solutions



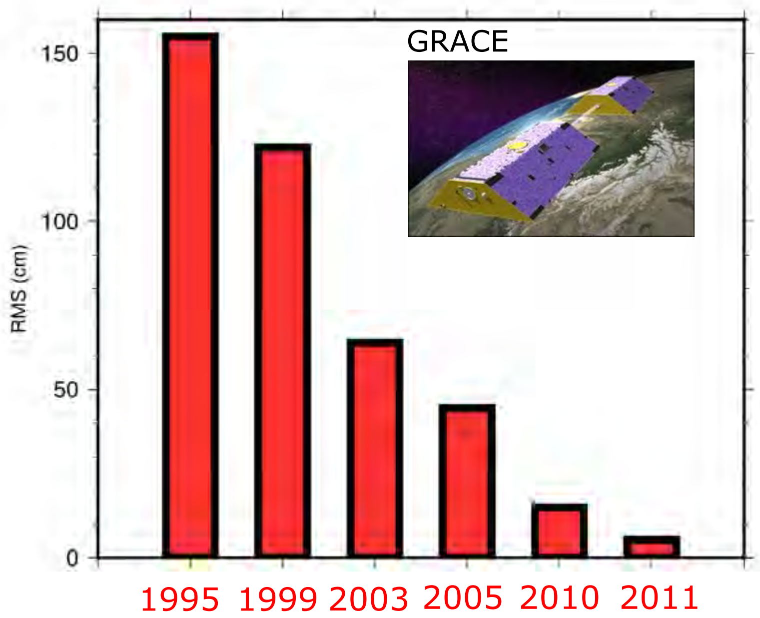


Geoid estimation: 25 YEARS IMPROVEMENTS

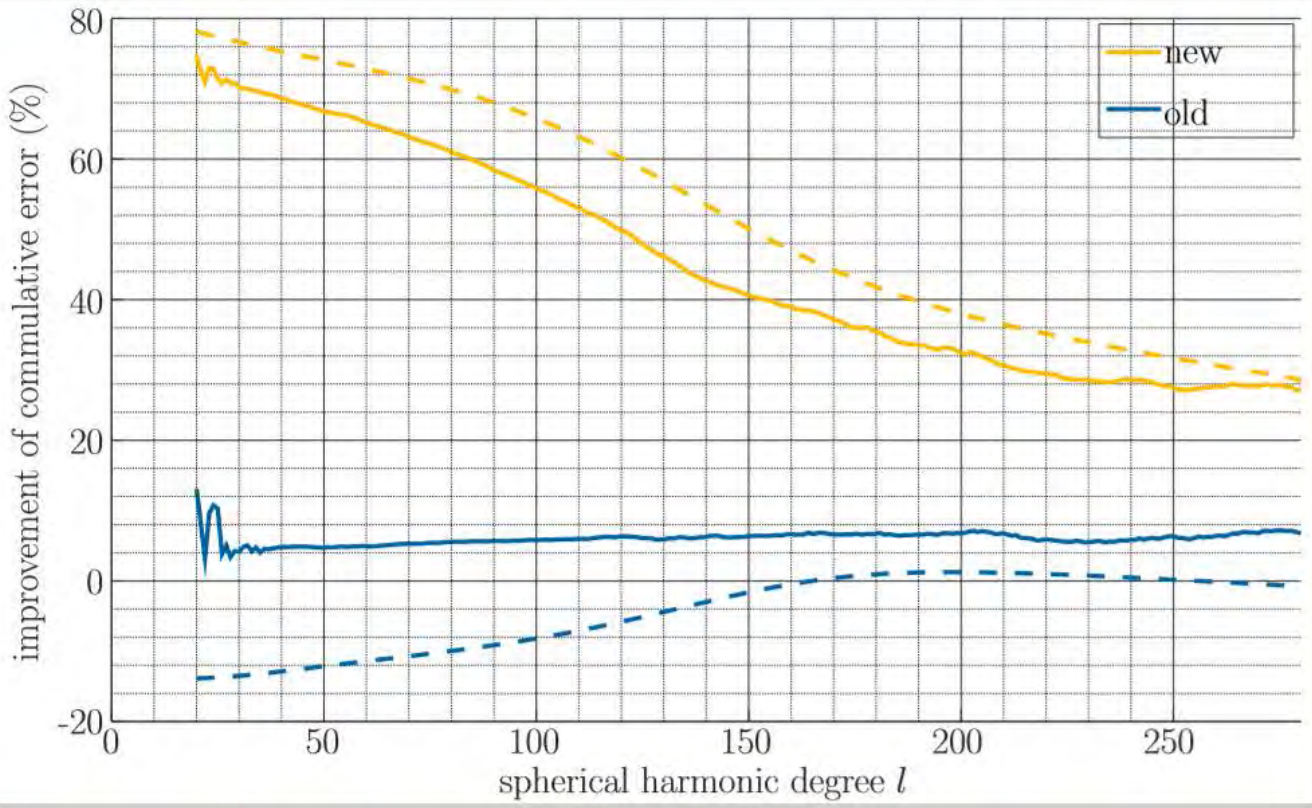
Satellite-only geoid models

Model	Year	Max DO	Data
GRIM4S4	1995	70	Geodetic satellites
GRIM5S1	1999	99	Geodetic satellites
CHAMP3S	2003	140	33 months of CHAMP
GGM02S/ EIGEN3S	2005	150	2 years of GRACE
ITG-GRACE2010s	2010	180	7 years of GRACE
GOCE 	2009-2013	200-250	2 months (R1) 6 months (R2) 1 year (R3) Full mission (R5)

RMS differences (in cm) between geoid models and GOCE-DIR-R5 filtered at 100km (on oceans)



Improvements Cumulative Errors XGMvsTIM

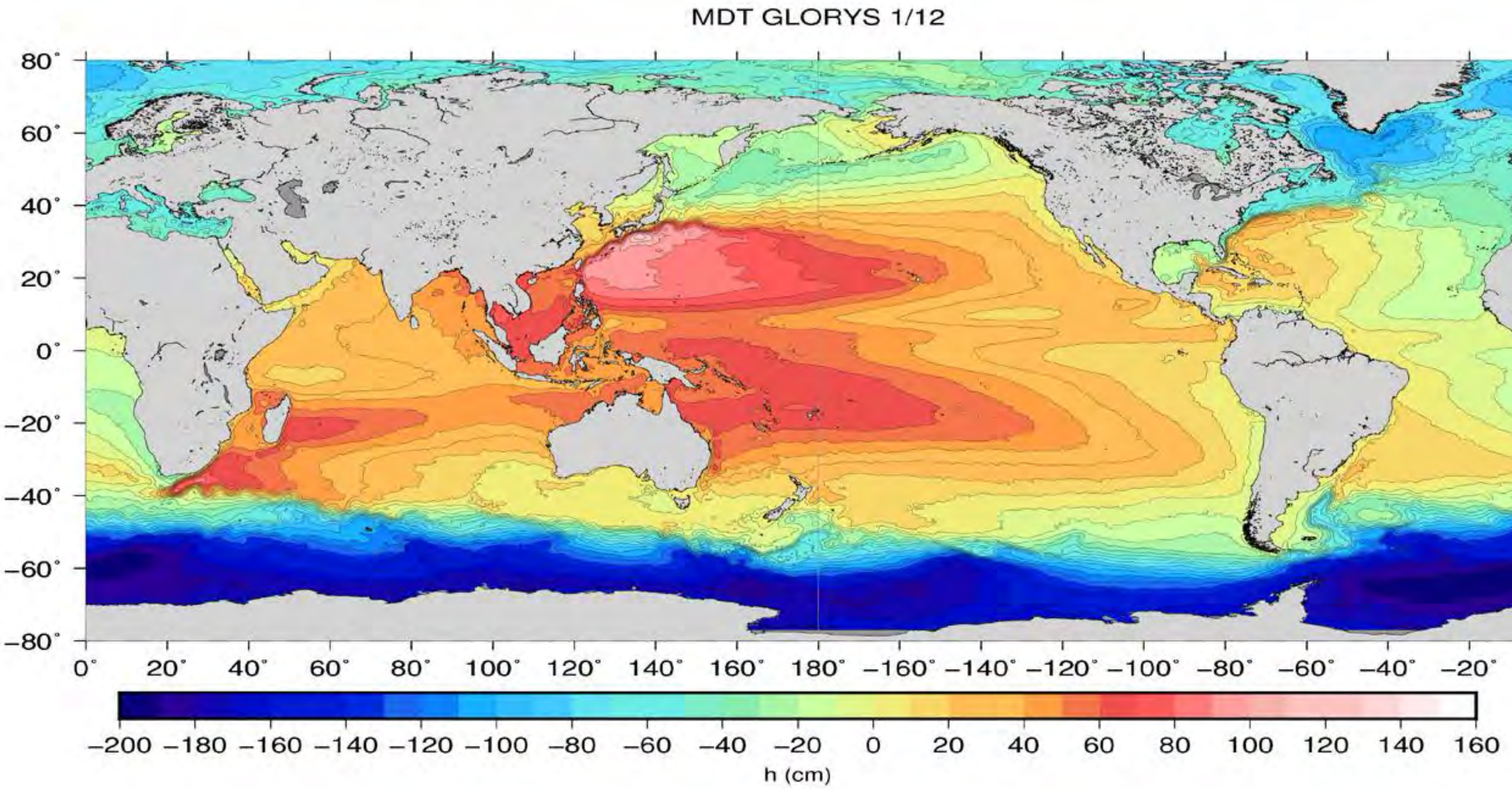


period: 2
improvement w.r.t. rl5 solution

Courtesy from
Jan Martin Brockman
University of Bonn

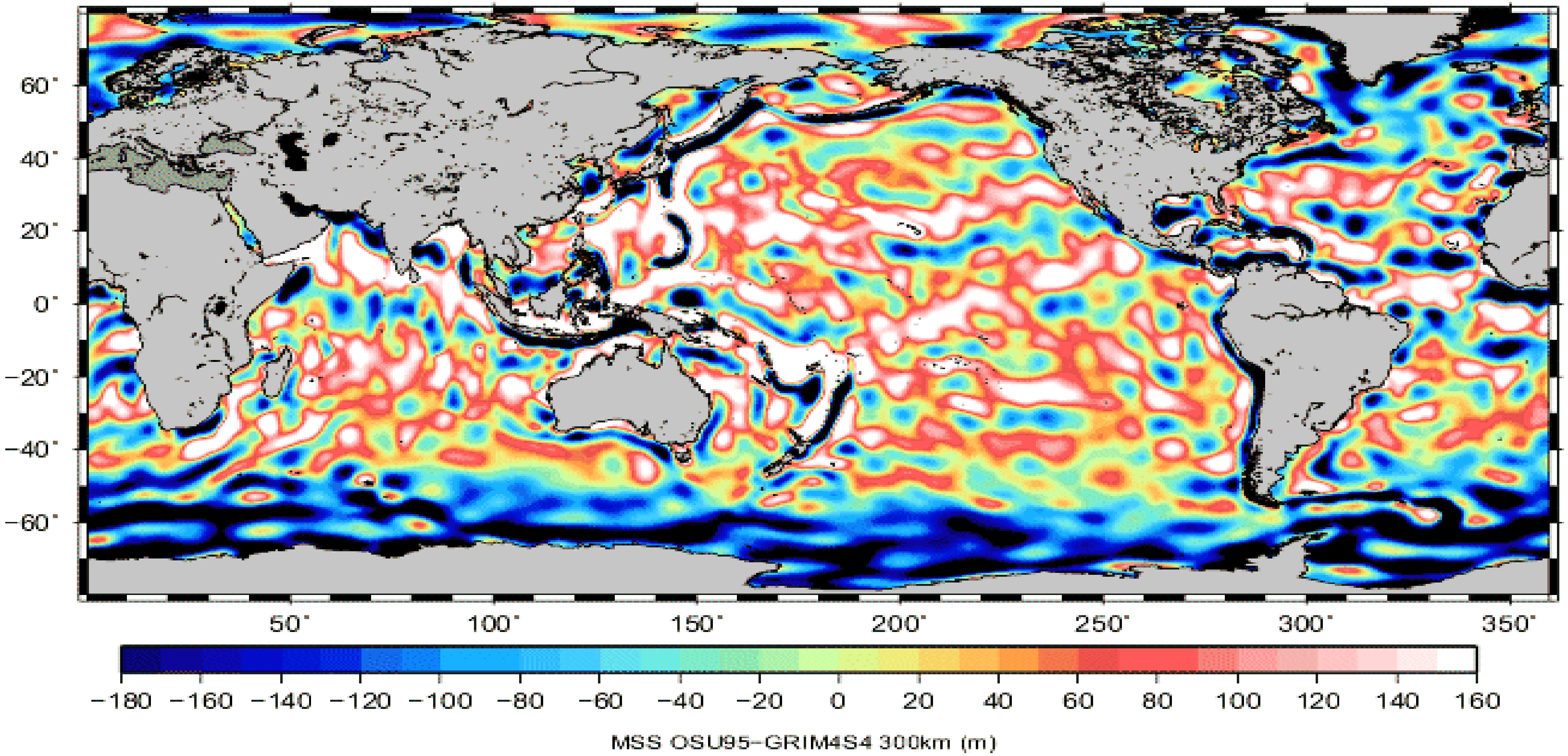
solid: empirical from difference to EGM_TIM_RL05, dashed: formal from covariance matrix

Mean Dynamic Topography from a high resolution (1/12°) ocean numerical model



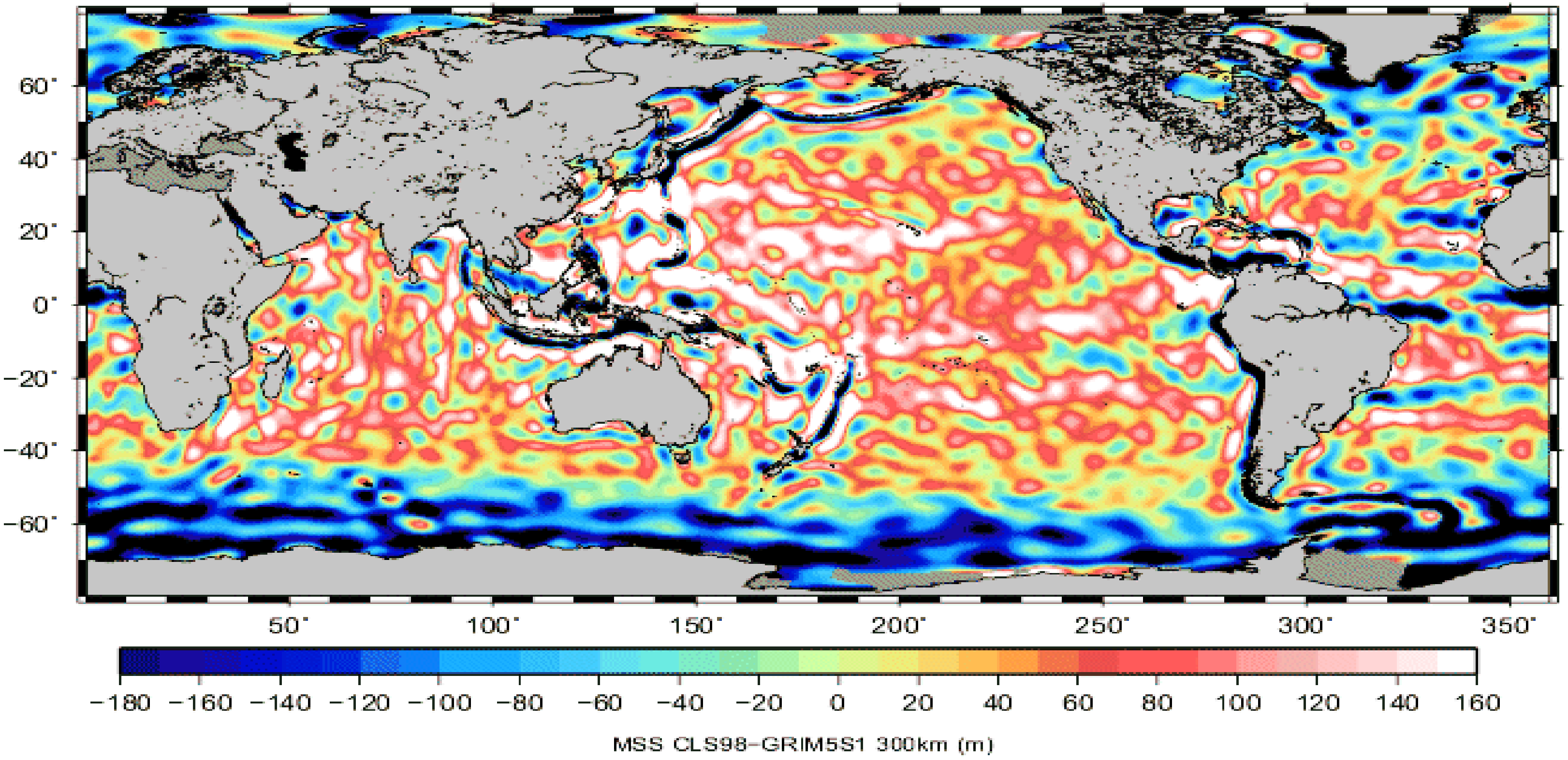
Mean Dynamic Topography estimation
25 YEARS OF IMPROVEMENTS

1995



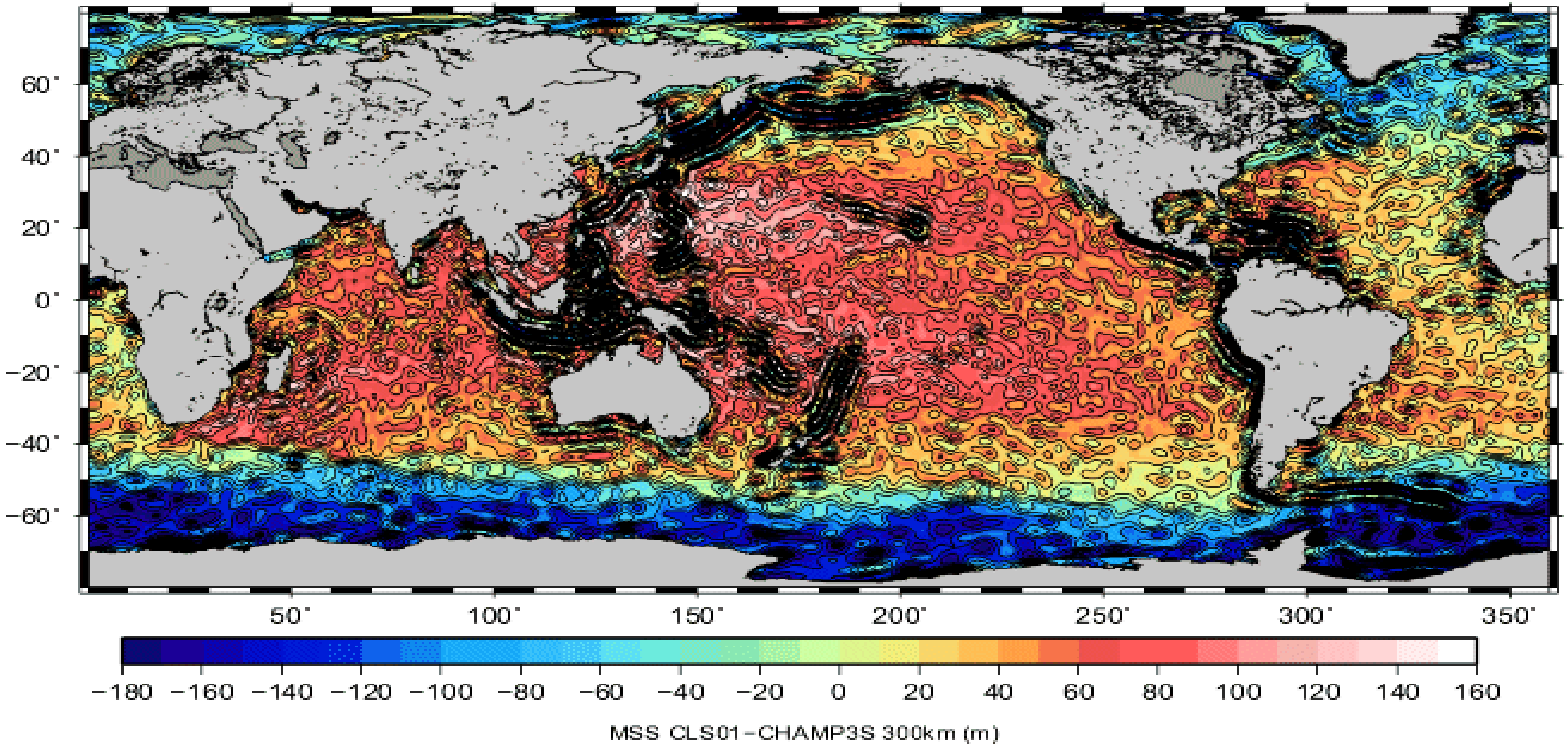
Mean Dynamic Topography estimation
25 YEARS OF IMPROVEMENTS

1999



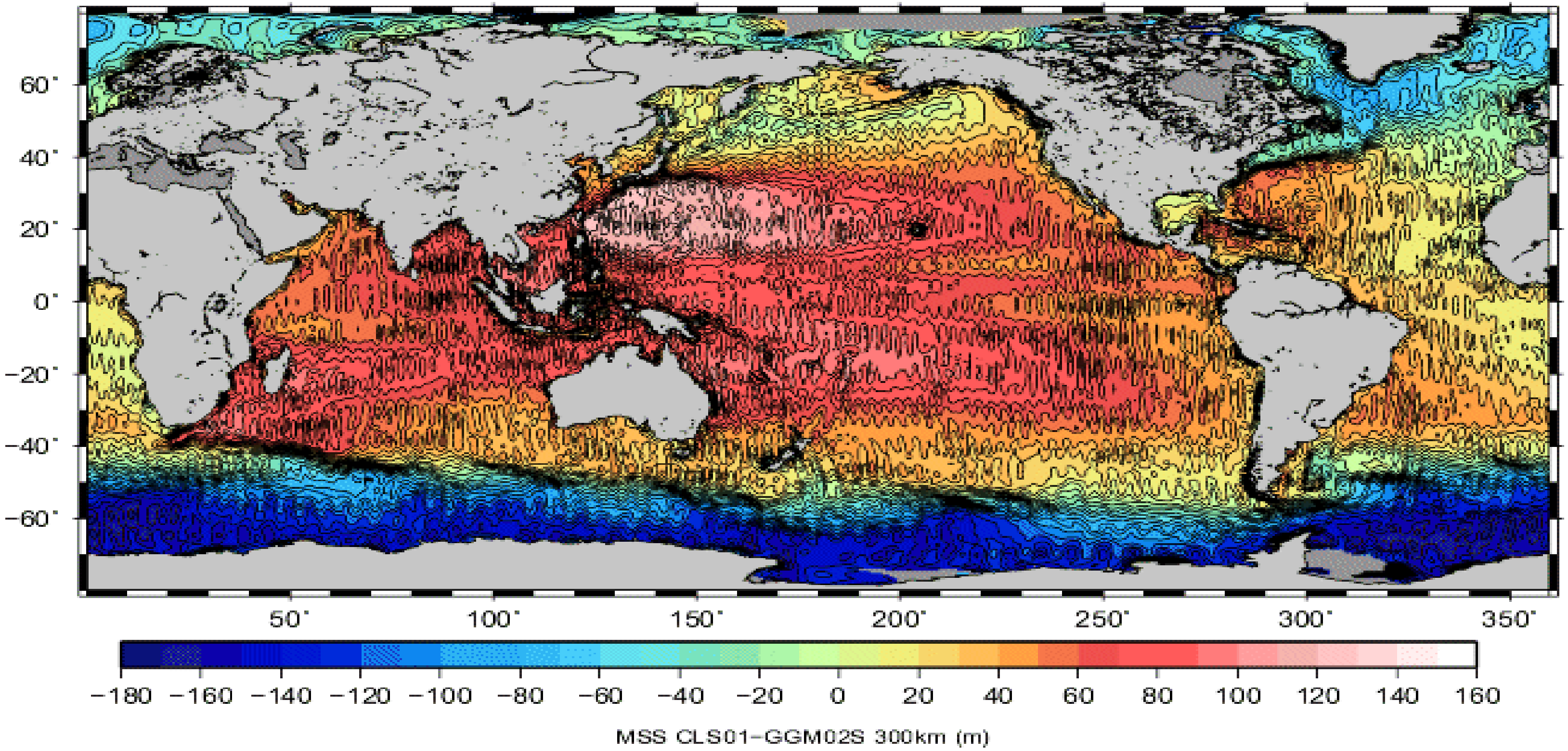
Mean Dynamic Topography estimation
25 YEARS OF IMPROVEMENTS

2003



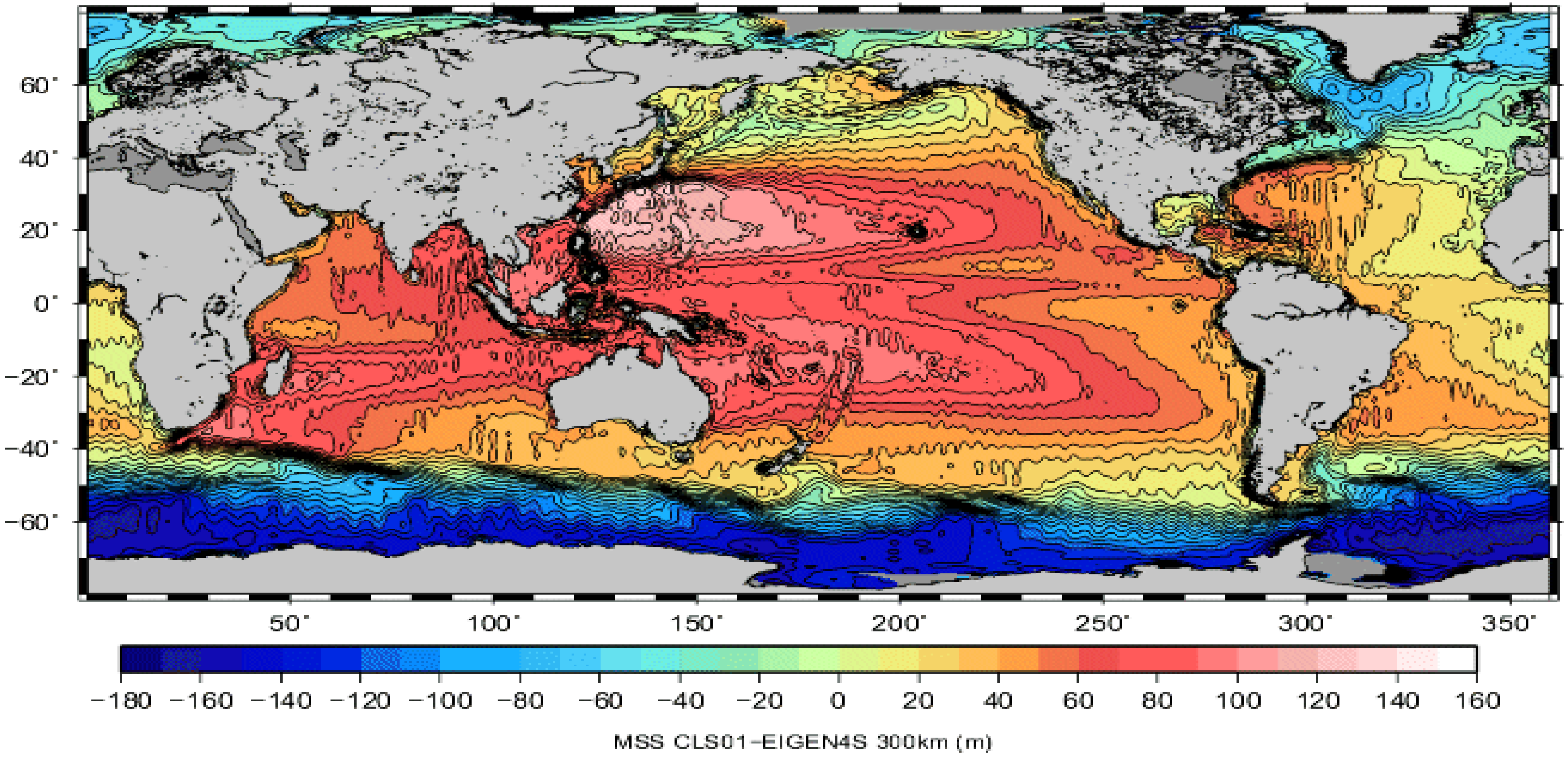
Mean Dynamic Topography estimation
25 YEARS OF IMPROVEMENTS

2005



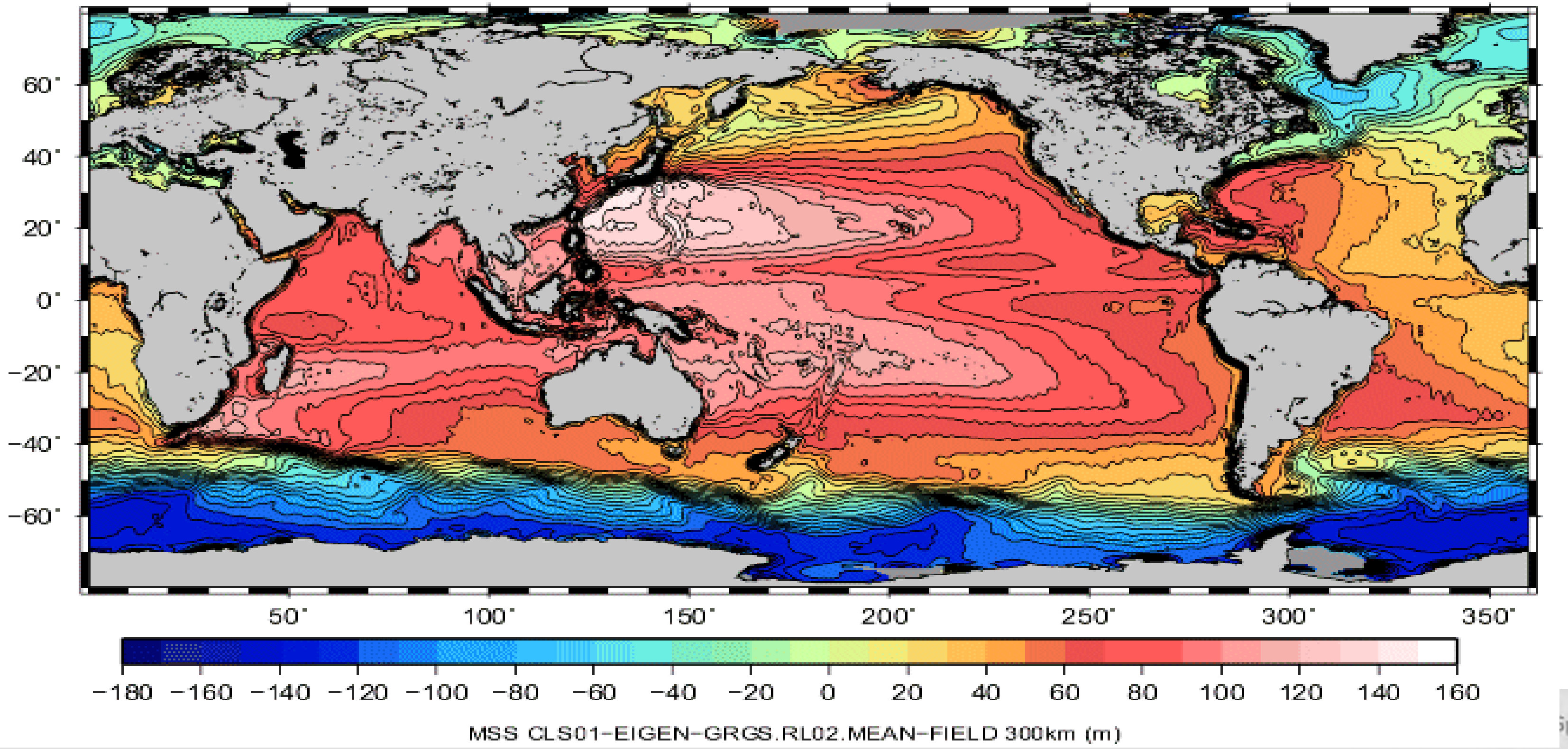
Mean Dynamic Topography estimation
25 YEARS OF IMPROVEMENTS

2006



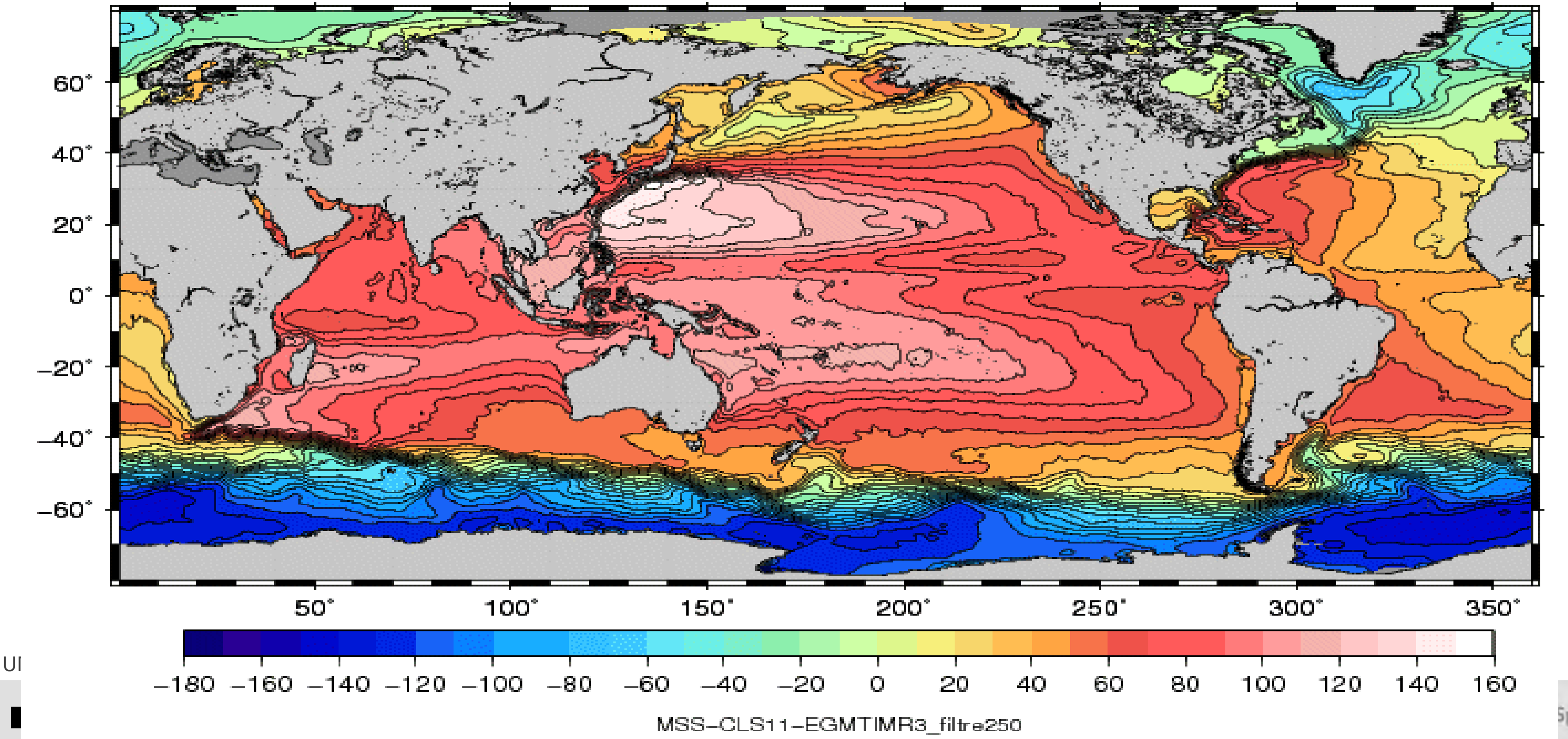
Mean Dynamic Topography estimation
25 YEARS OF IMPROVEMENTS

2009



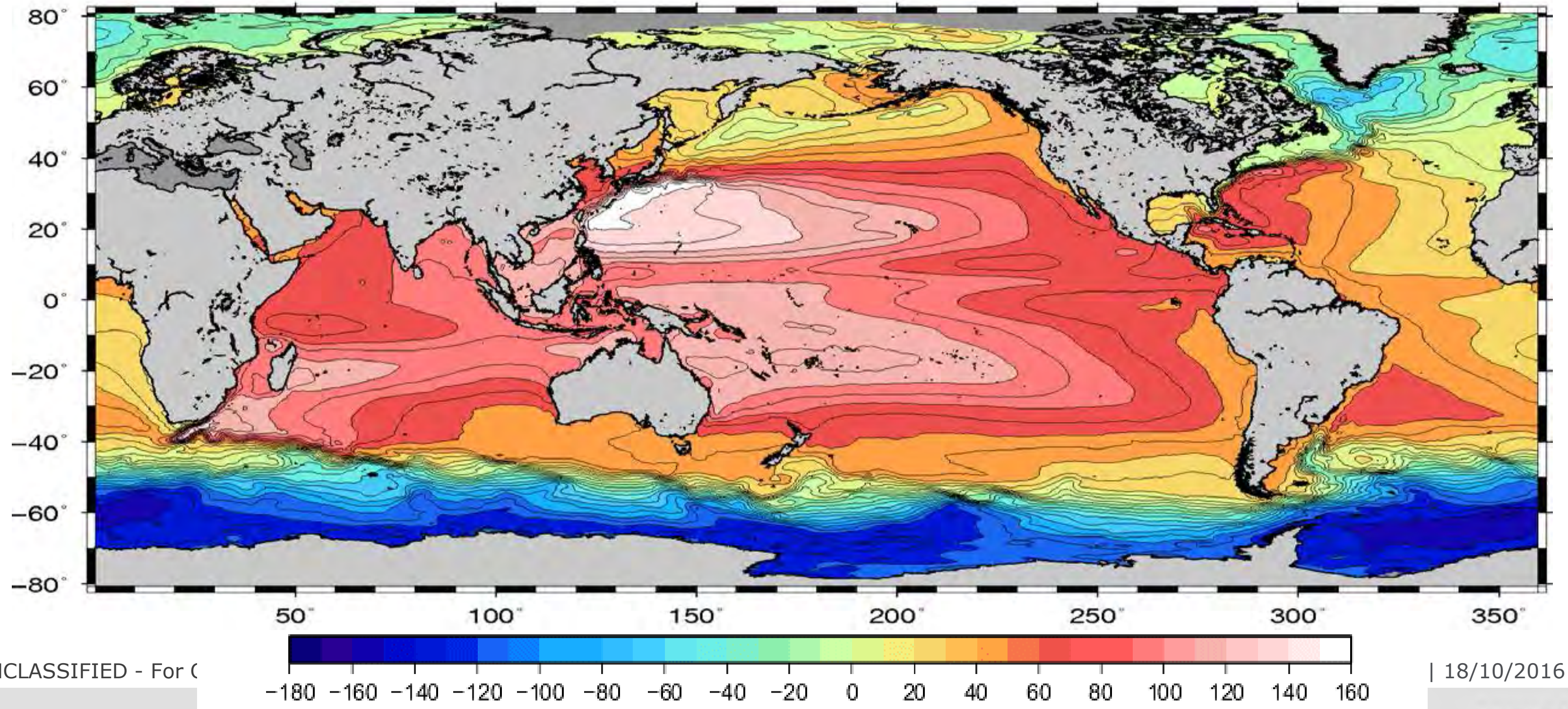
Mean Dynamic Topography estimation
25 YEARS OF IMPROVEMENTS

2012

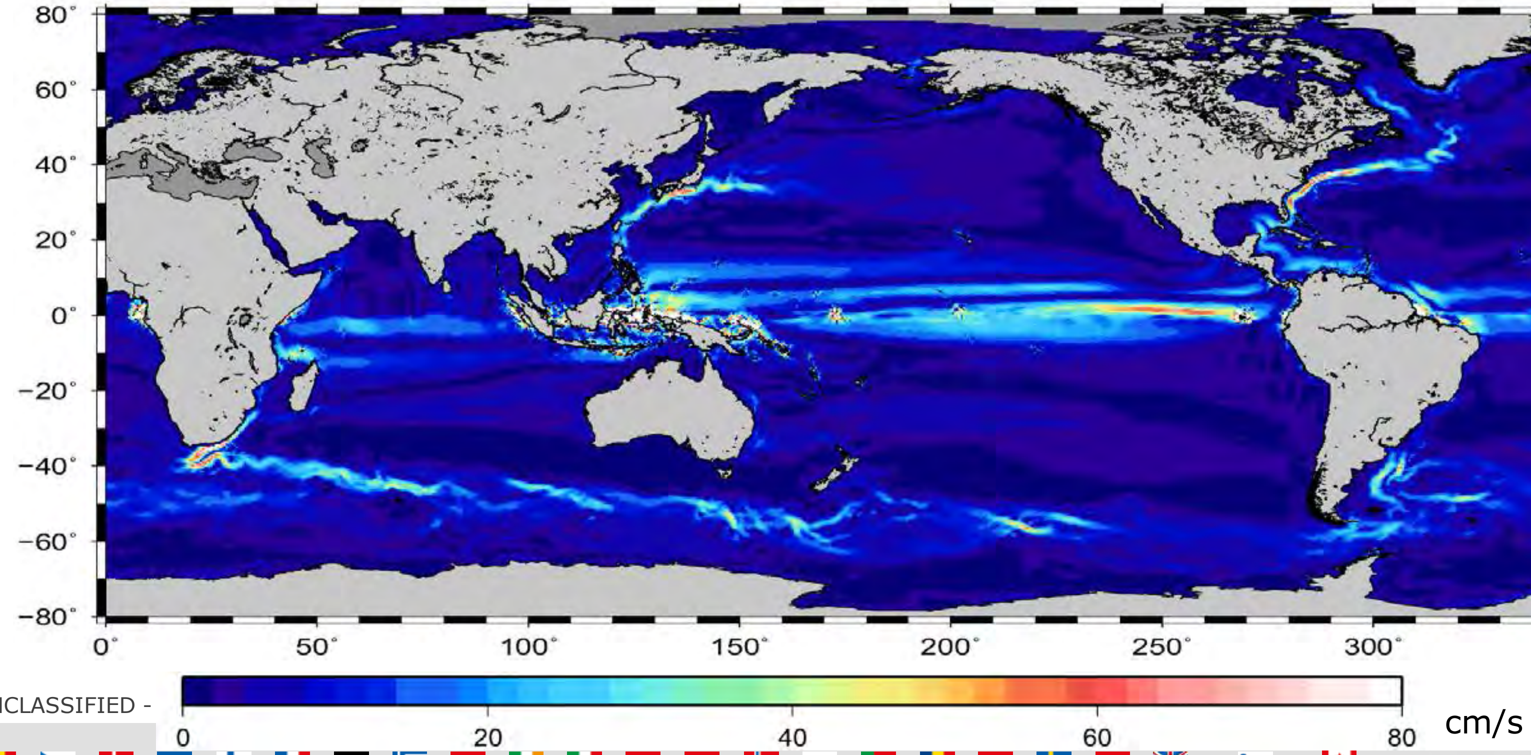


Mean Dynamic Topography estimation
25 YEARS OF IMPROVEMENTS

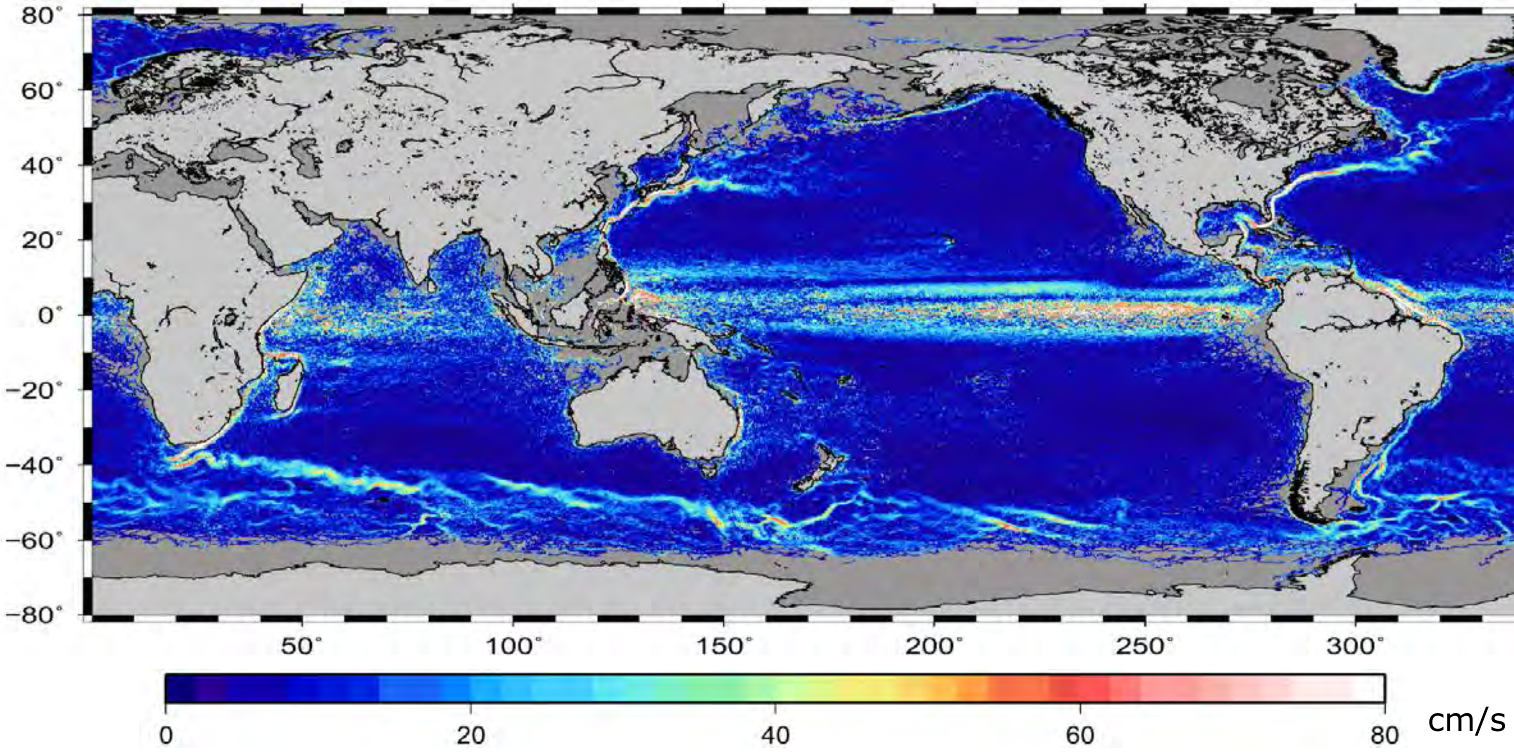
2015



Mean geostrophic currents from the GOCE only MDT



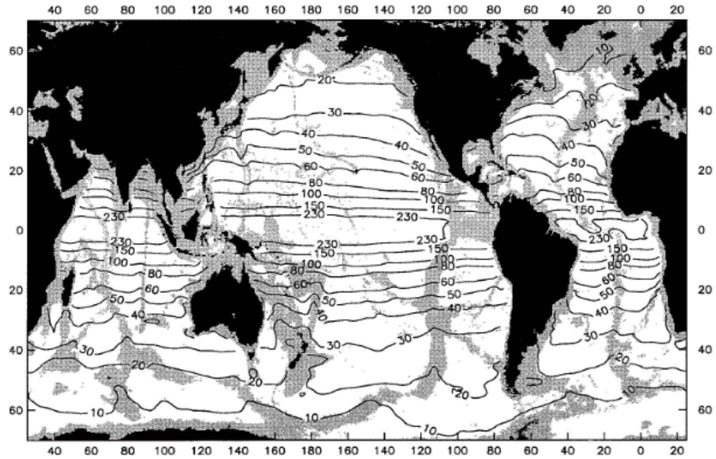
Mean geostrophic currents from in-situ measurements



Beyond GOCE resolution: Synergy with space-borne and in-situ data

- MDT spatial scales are expected to be lower than 100 km.

First baroclinic Rossby radius of deformation length scale at which the geostrophic balance will become important



from Chelton et al, 1998

- In order to go beyond GOCE resolution, synergy with other observations is needed

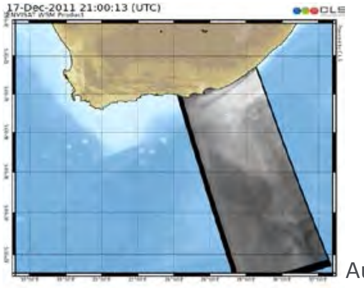
- *Global Ocean*

Drifting buoy velocities: One velocity measurement every 6 hours along the buoy trajectory => 2,16 km in 10 cm/s currents, 21.6 km in 1 m/s currents

- *Regionally*

HF radar system (coastal)
Typical resolution: 1-10 km, hourly
SAR Doppler radial velocities
Typical resolution: 4-8 km, every 2-4 days

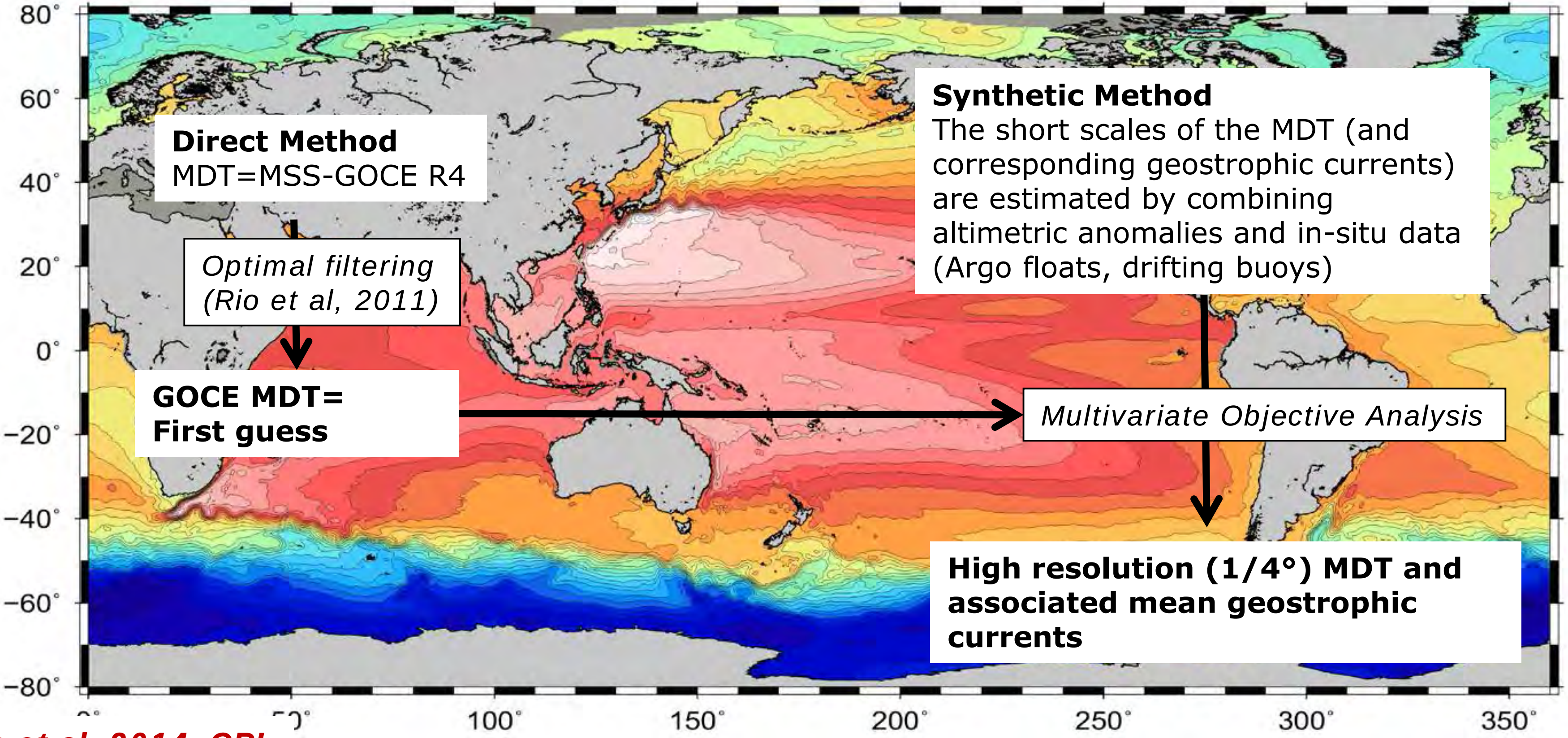
SAR



Drifters

Beyond GOCE resolution: Synergy with in-situ data

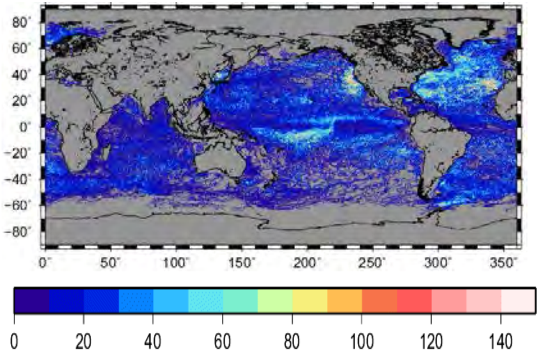
The CNES-CLS13 MDT



Rio et al, 2014, GRL

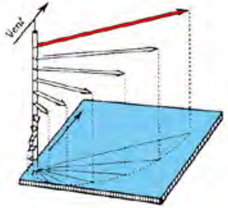
Beyond GOCE resolution: Synergy with in-situ data

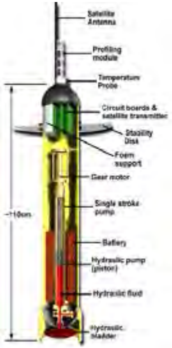
Number of SVP-type velocities (15m depth)



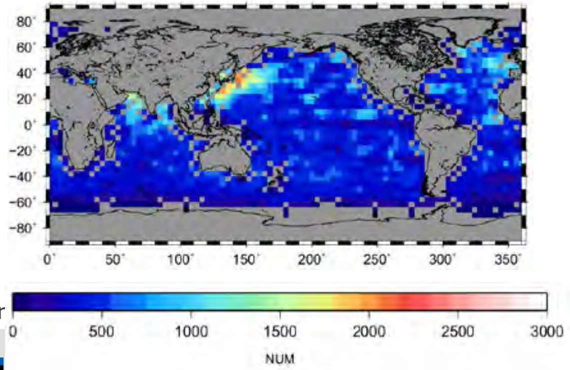
$$U_{buoy} = \boxed{U_{geost}} + U_{ekman} + U_{tides} + U_{inertial} + U_{stokes} + U_{ageost\_hf}$$

- ➢Modelization of Ekman/Stokes currents
- ➢Low pass filtering





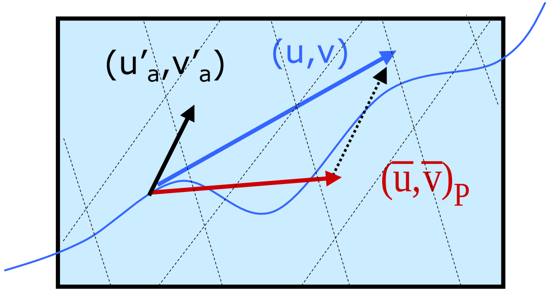
Number of Argo floats (T/S profiles and surface velocities)

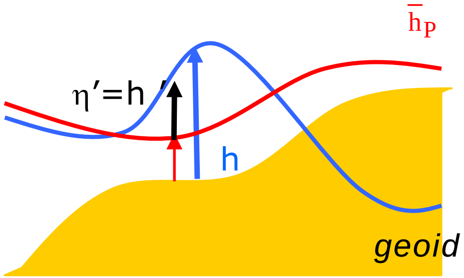


Dynamic Height relative to a reference depth Pref -> baroclinic component of the geostrophic current

➢Processing is needed to add the missing barotropic and deep baroclinic component

Computation of mean heights and mean geostrophic velocities





At each position r and time t for which an oceanographic in-situ measurement is available:
dynamic height h (r,t) or surface velocity u(r,t),v(r,t)

- the in-situ data is processed to match the physical content of the altimetric measurement.

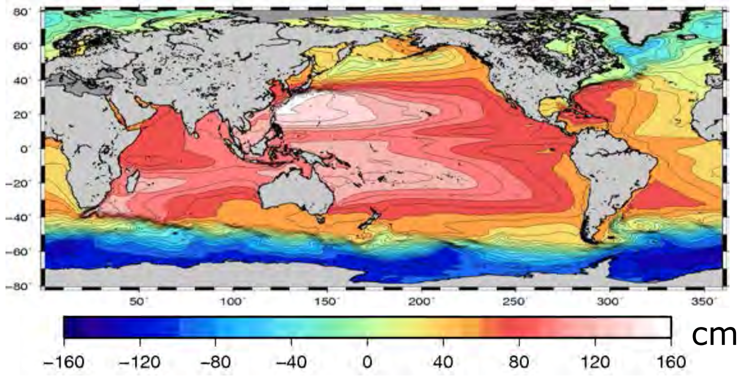
- the altimetric height/velocity anomaly is interpolated to the position/date of the in-situ data.

- the altimetric anomaly is subtracted from the in-situ height/velocity

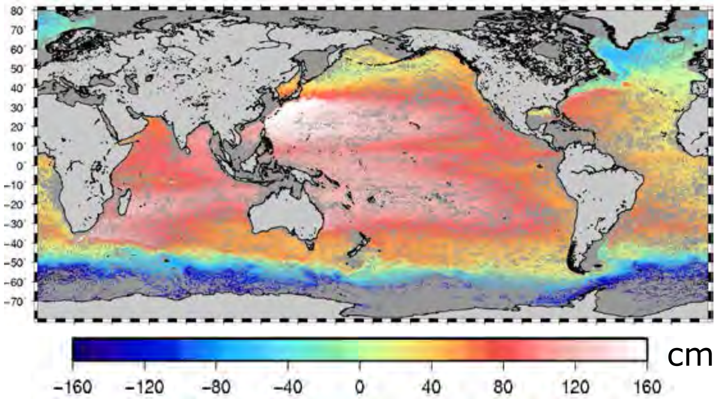
$$\bar{h}_P = h_{insitu} - h'_P \qquad \bar{u}_P = u_{insitu} - u'_P \qquad \bar{v}_P = v_{insitu} - v'_P$$

The CNES-CLS13 MDT (Rio et al, 2014)

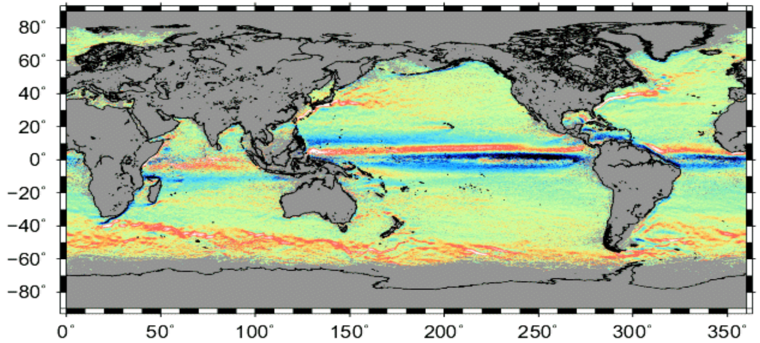
First Guess = MSS – Geoid   OPTIMALLY FILTERED



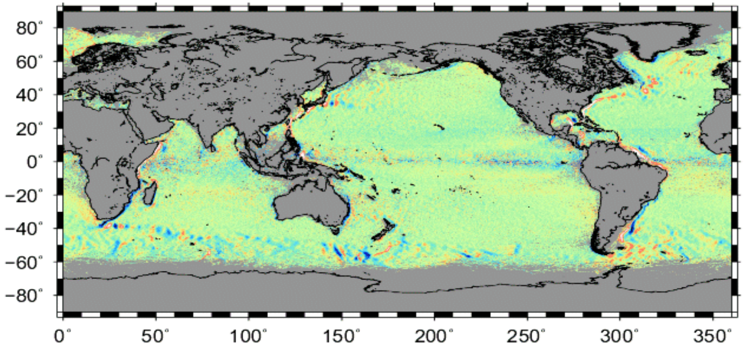
Synthetic Mean Heights (1/4° box means)

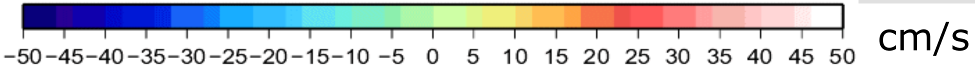


Synthetic Mean Zonal Velocity (1/4° box means)

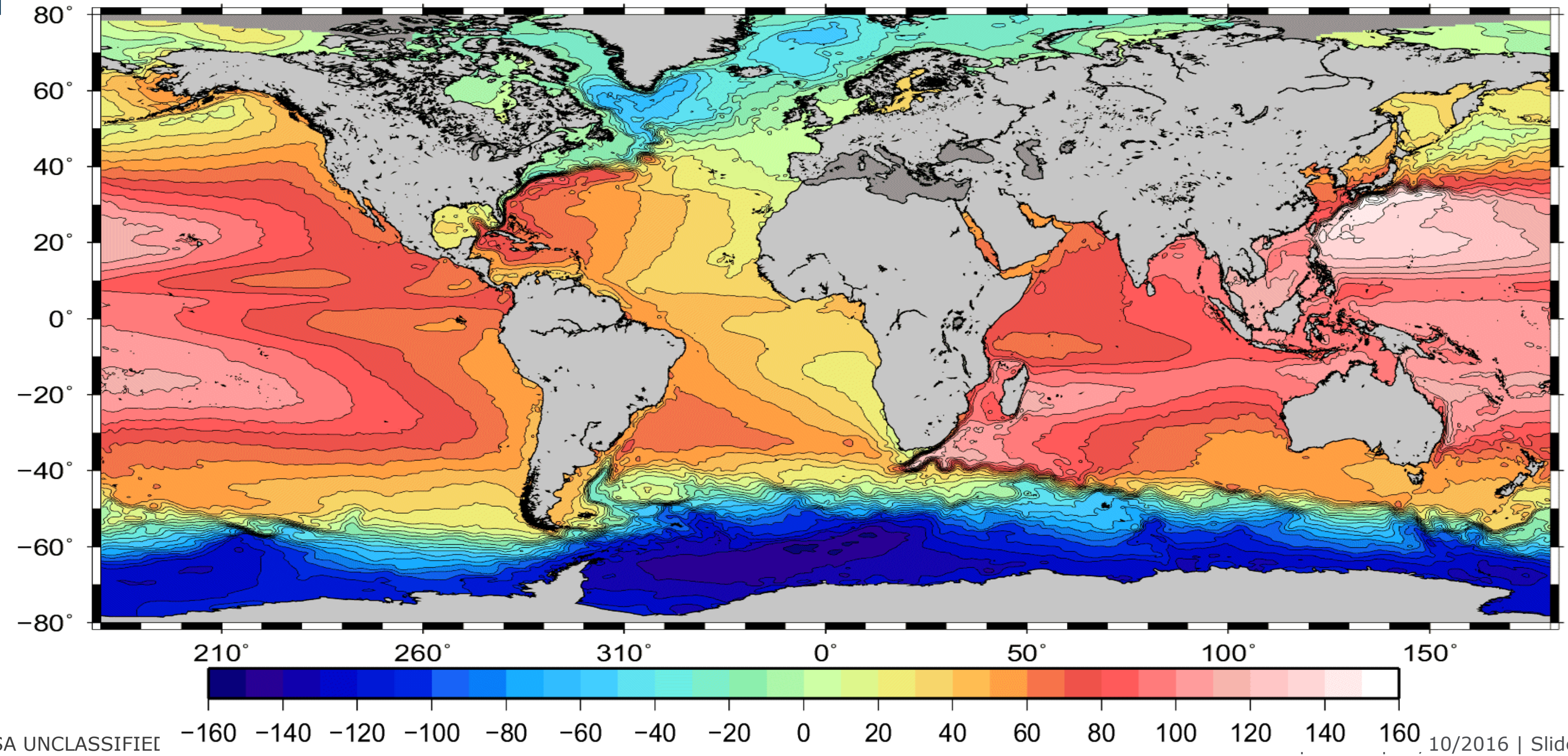


Synthetic Mean Meridional Velocity (1/4° box means)

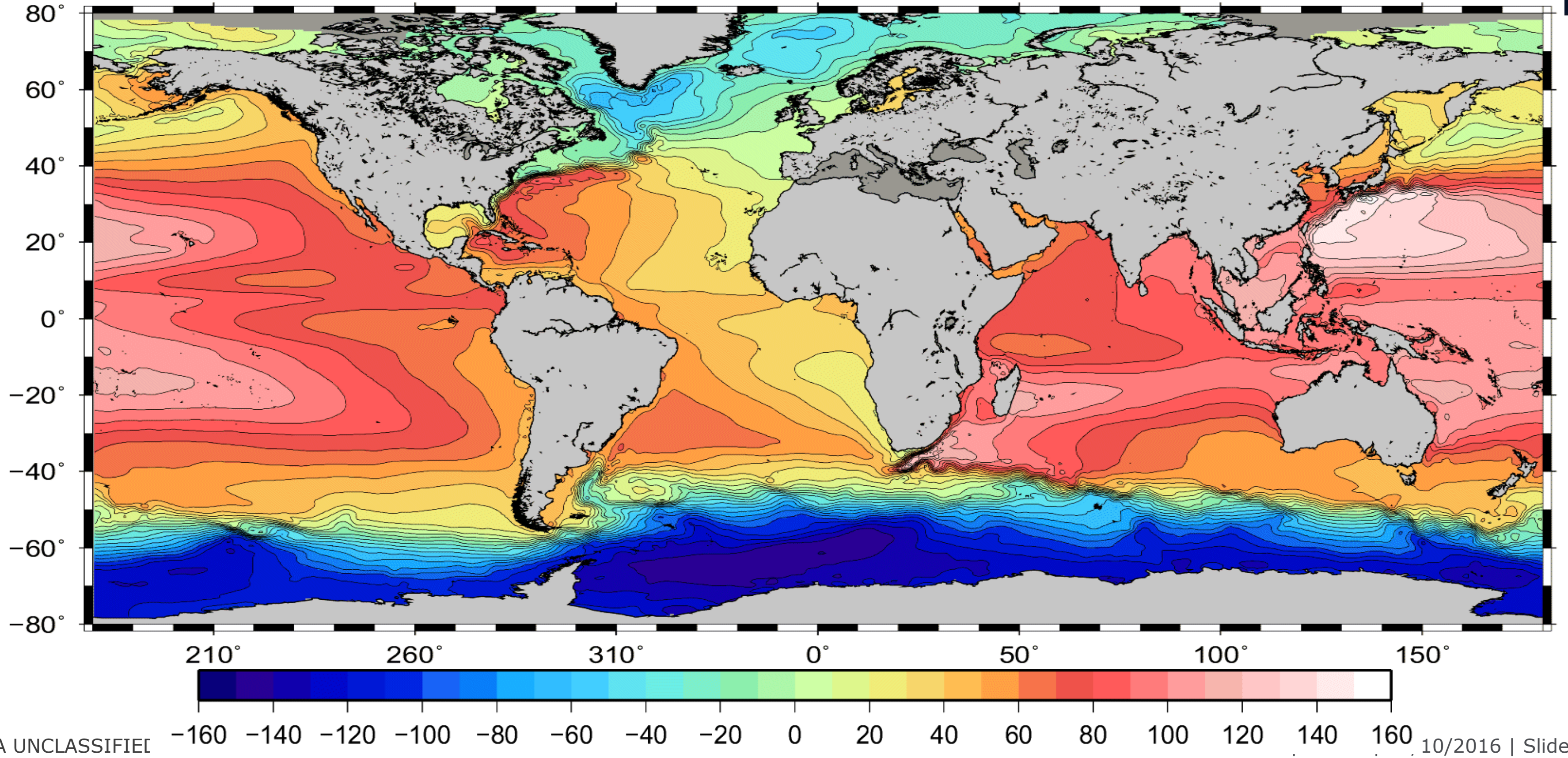




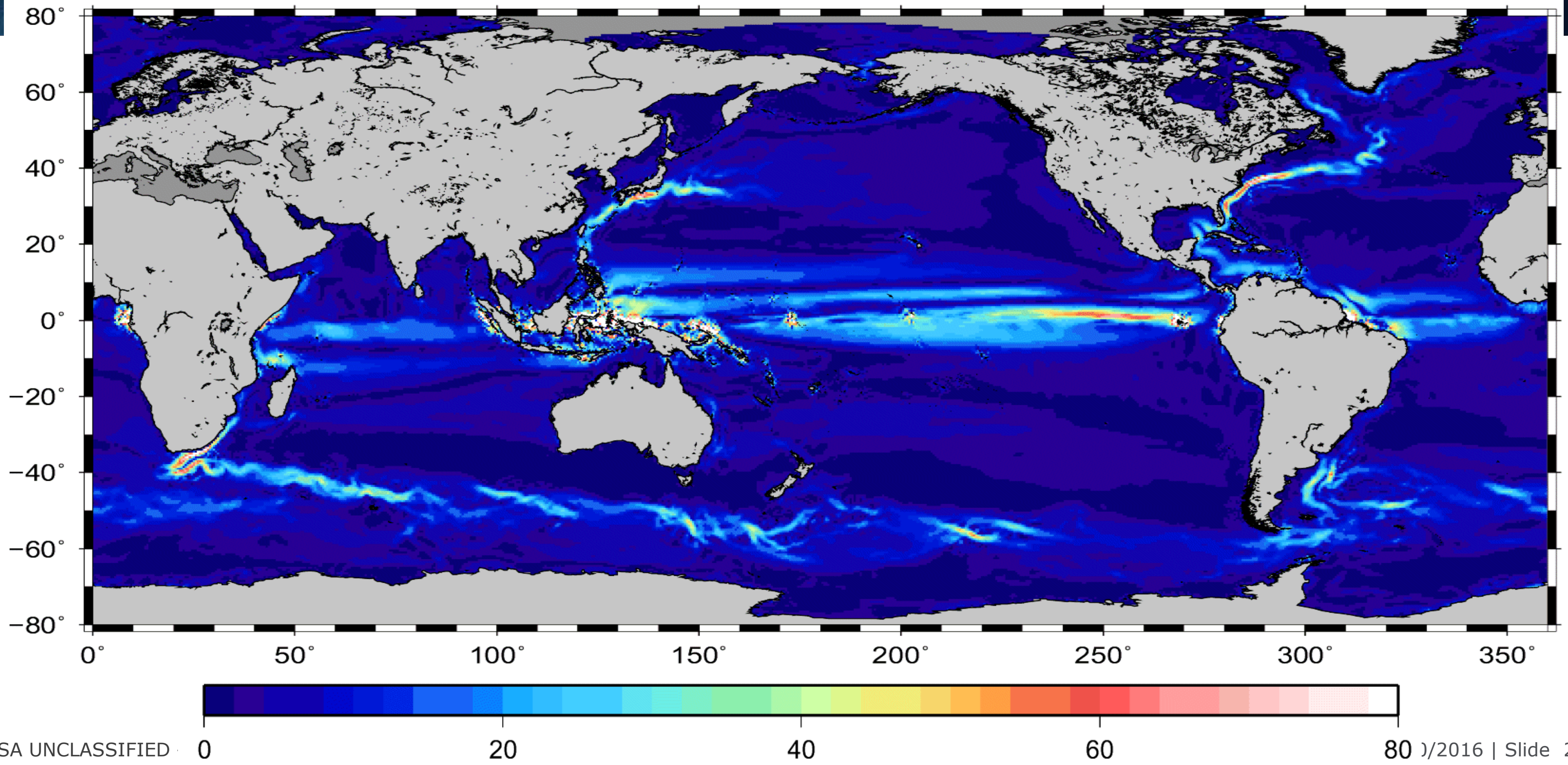
The CNES-CLS13 MDT



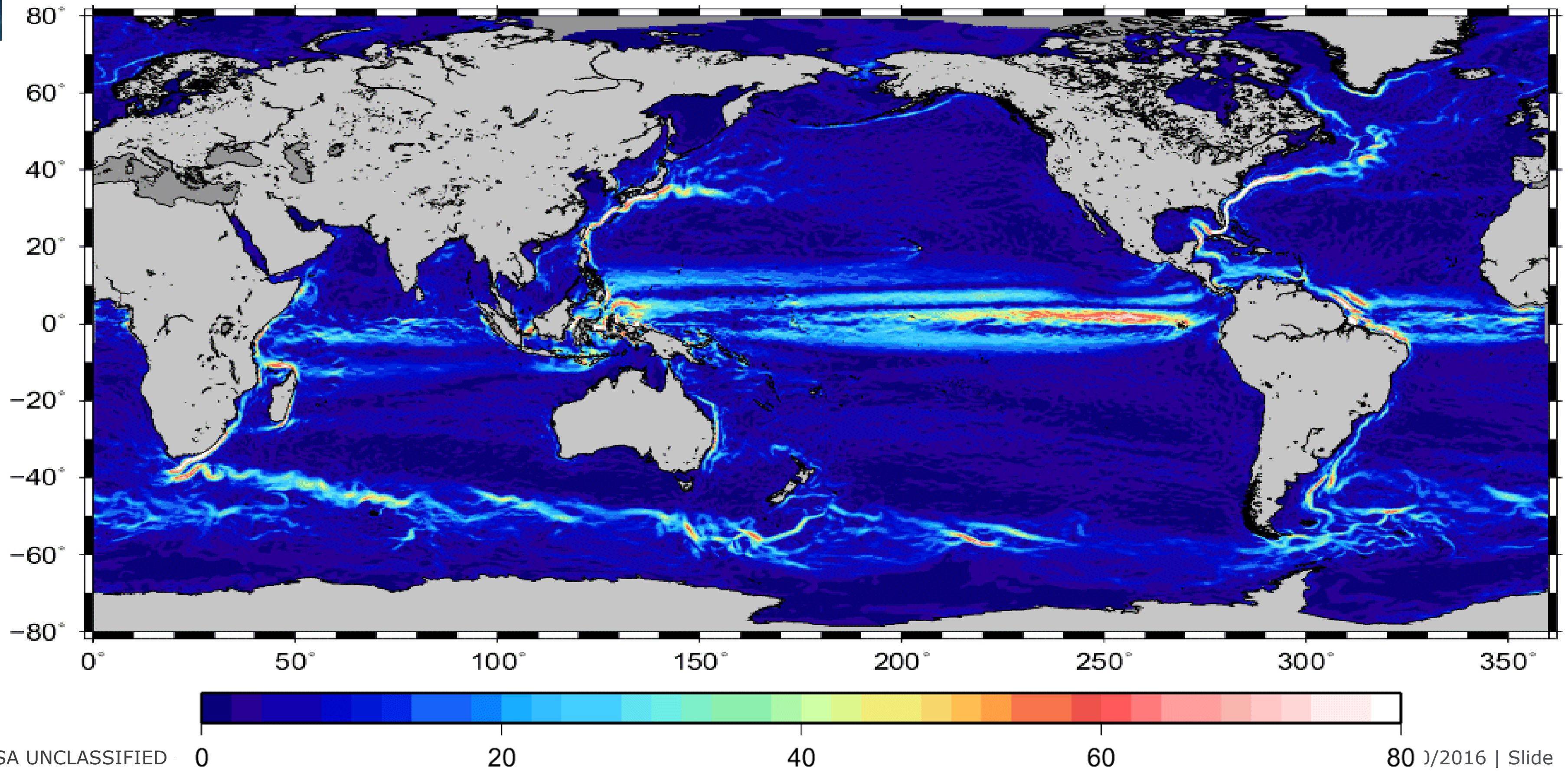
The GOCE only MDT (First Guess)



The GOCE only MDT (First Guess)



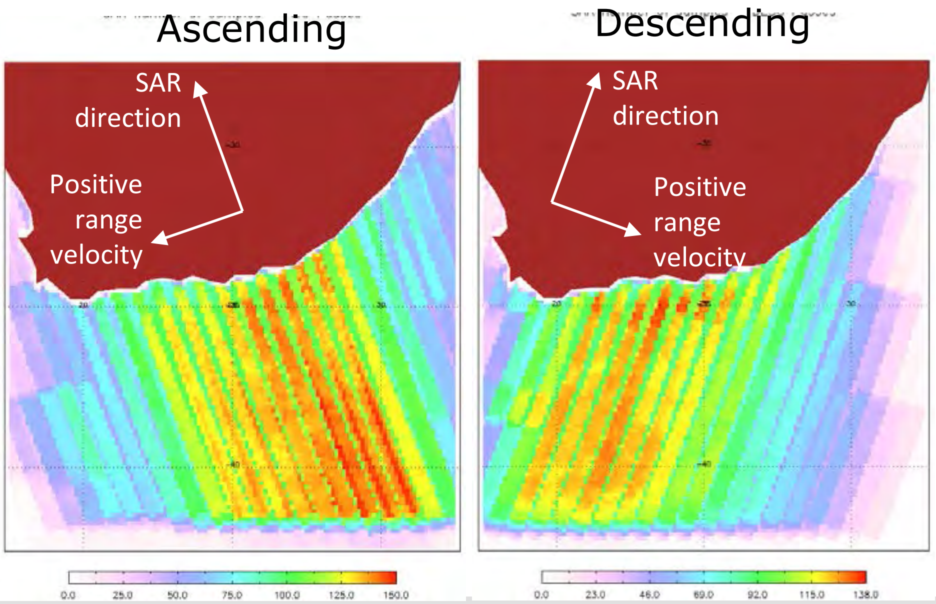
The CNES-CLS13 MDT



Refinement in the Agulhas current using SAR Doppler velocities

- radial velocities from the ENVISAT ASAR images acquired over the Agulhas Current region (lon/lat coordinates [13°, 36°], [-45°, -23°]) from 2007 to 2012 and processed on a systematic basis by (Collard et al., 2008; Johannessen et al., 2008)
- The 2 components velocity vectors are reconstructed using the altimeter-derived current direction information:

SAR number of samples



V_a^{SAR} and V_d^{SAR} SAR-derived range velocities in ascending and descending passes.

β_a and β_d angle between the SAR range direction and the altimeter-derived current direction for ascending and descending passes.

$$\overset{*}{V}_a = \frac{V_a^{SAR}}{\cos(\beta_a)} \qquad \overset{*}{V}_d = \frac{V_d^{SAR}}{\cos(\beta_d)}$$

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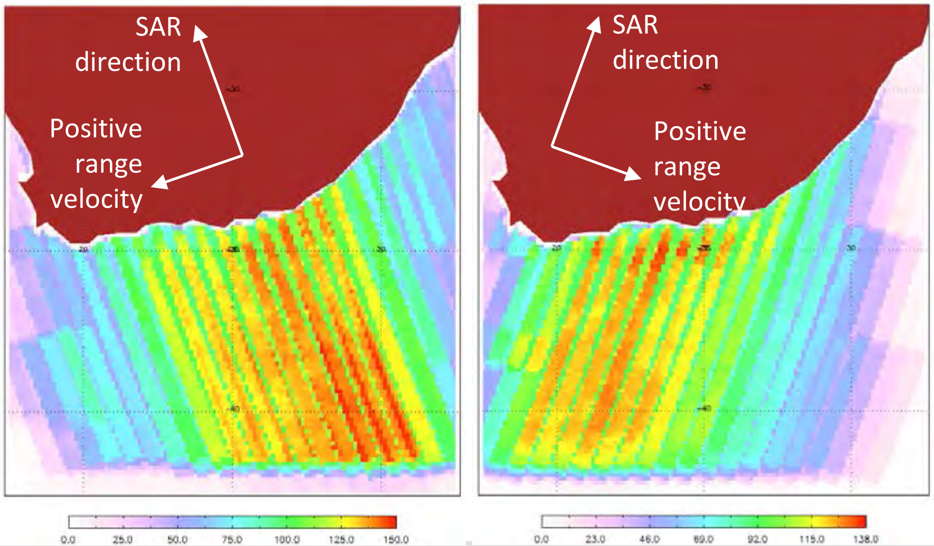
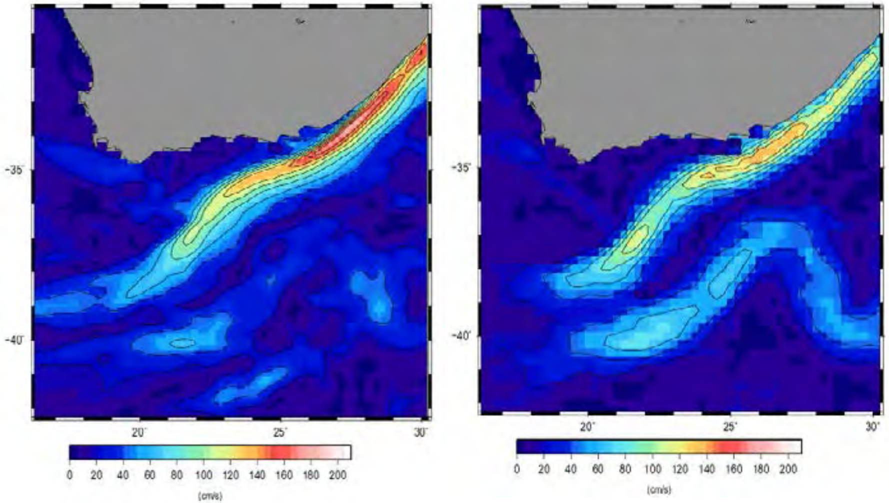
SAR number of samples

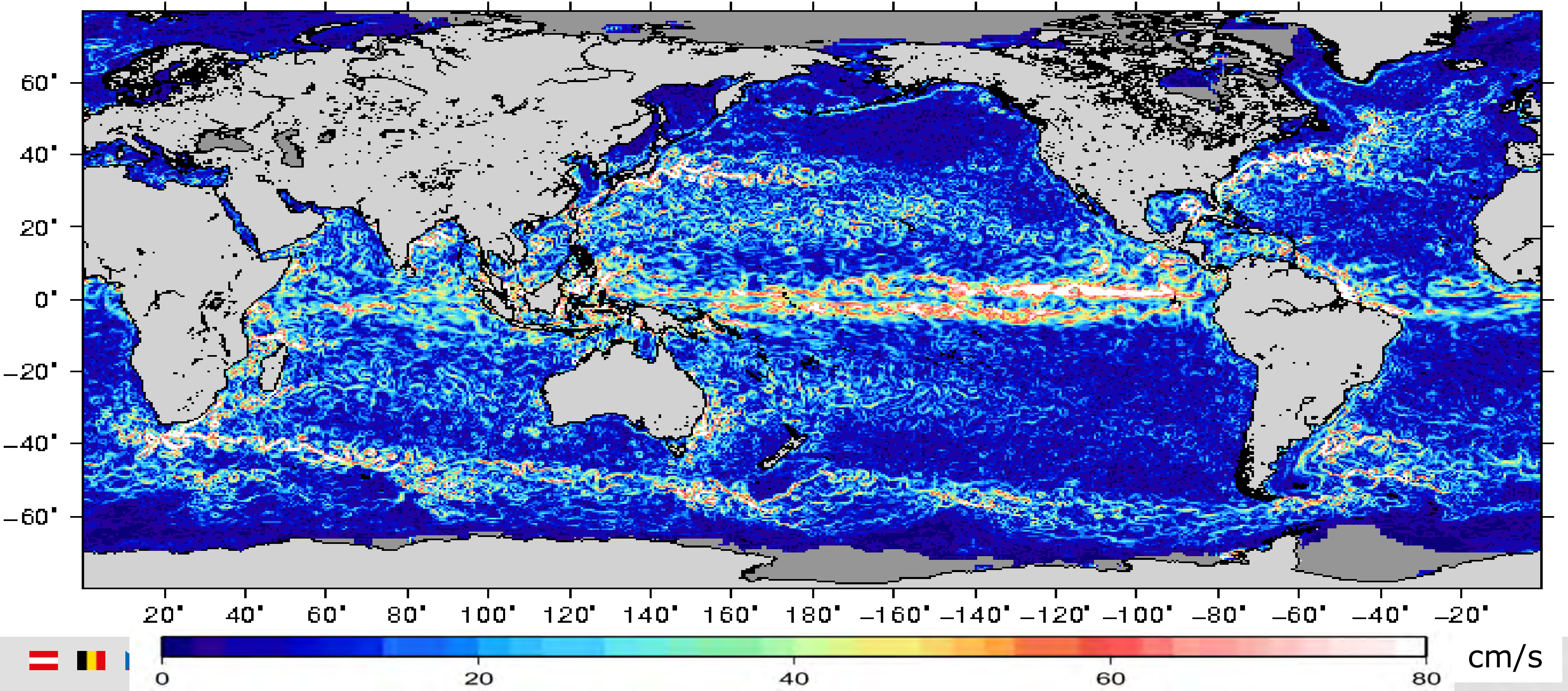
Ascending | Descending



SAR MDT | CNES-CLS13 MDT



The Geostrophic current May, 5th 2016



Space and in-situ data synergy for a better retrieval of the ocean circulation

- Geostrophic currents from Altimetry, space Gravity, in-situ measurements of T,S, surface drifter velocities
- **Ekman currents from in-situ drifting buoy velocities, altimetry, wind**
- SST/SSH synergy for higher resolution surface currents

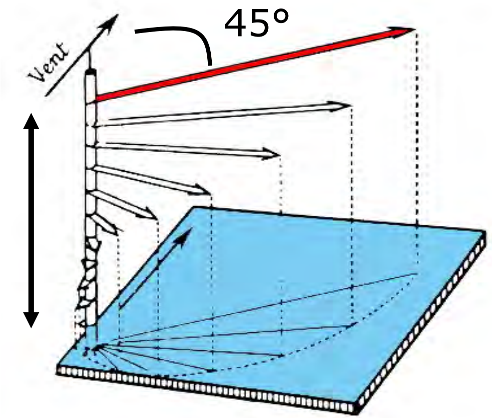
The wind-driven Ekman+Stokes currents

Wind-driven Ekman

$$u_e = \pm \boxed{\frac{\pi\sqrt{2}}{\rho(f+w)D_e} e^{\frac{\pi}{D_e}z}} * \tau_e * \cos\boxed{\left(\frac{\pi}{4} + \frac{\pi}{D_e}z\right)}$$

$$v_e = \boxed{\frac{\pi\sqrt{2}}{\rho(f+w)D_e} e^{\frac{\pi}{D_e}z}} * \tau_e * \sin\boxed{\left(\frac{\pi}{4} + \frac{\pi}{D_e}z\right)}$$

β θ



Model

Rio et al, 2003, 2014

$$\vec{u}_e = \beta \vec{\tau} e^{i\theta}$$

$$\vec{u}_{buoy} - \vec{u}_{alti}$$

ERA INTERIM Wind stress

β and θ are estimated through least square fit by month and 4° boxes. At the surface using the Argo float surface velocity dataset **from YoMAHA. At 15m** depth using SVP Drifting buoys **flagged as DROGUED by the SD-DAC**

τ_e= Effective Wind Stress

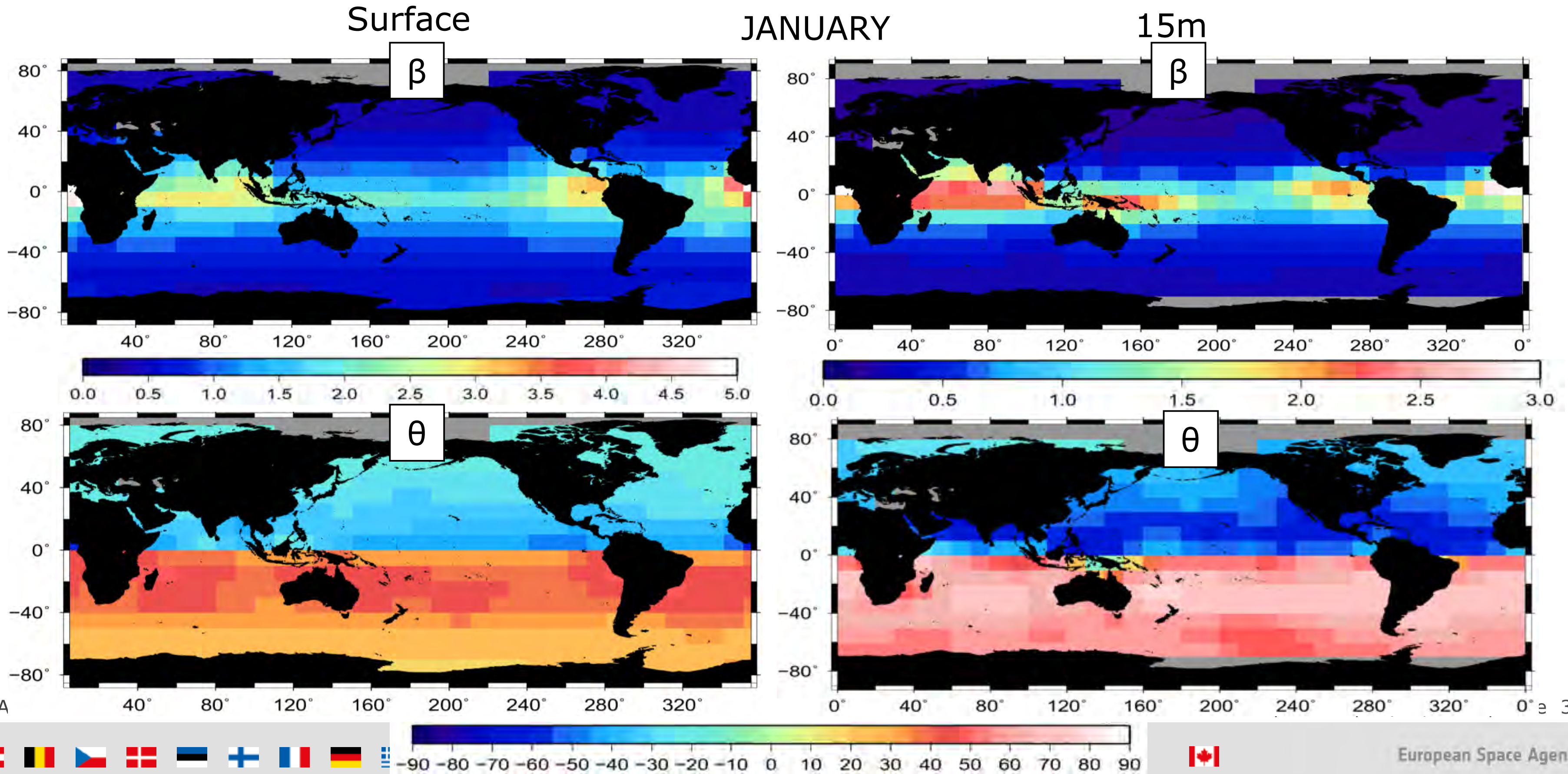
D_e= Ekman depth

f= planetary vorticity

w=local vorticity

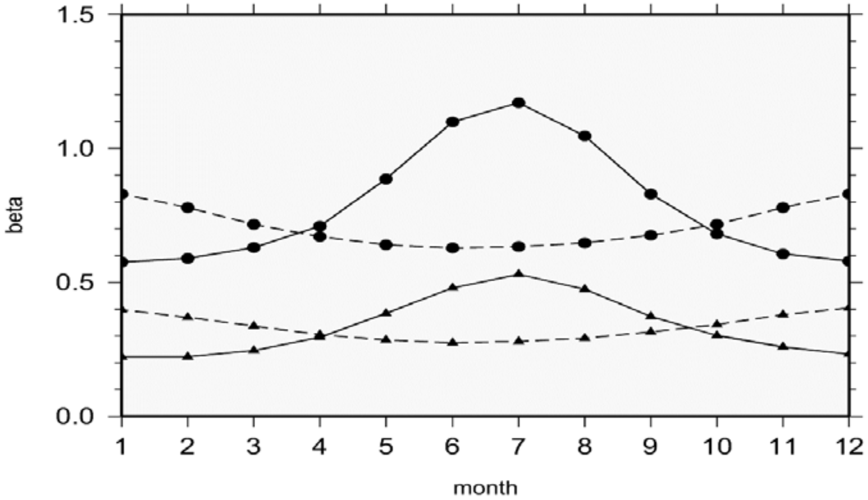
$$2\omega = \partial_x vgeost - \partial_y ugeost$$

The wind-driven Ekman+Stokes currents

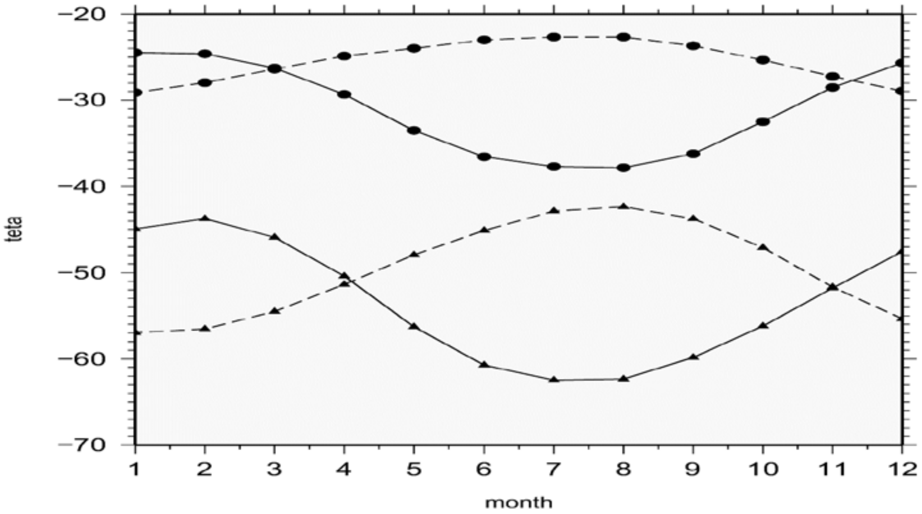


The wind-driven Ekman+Stokes currents

β (m^2s/kg)



θ (°C)



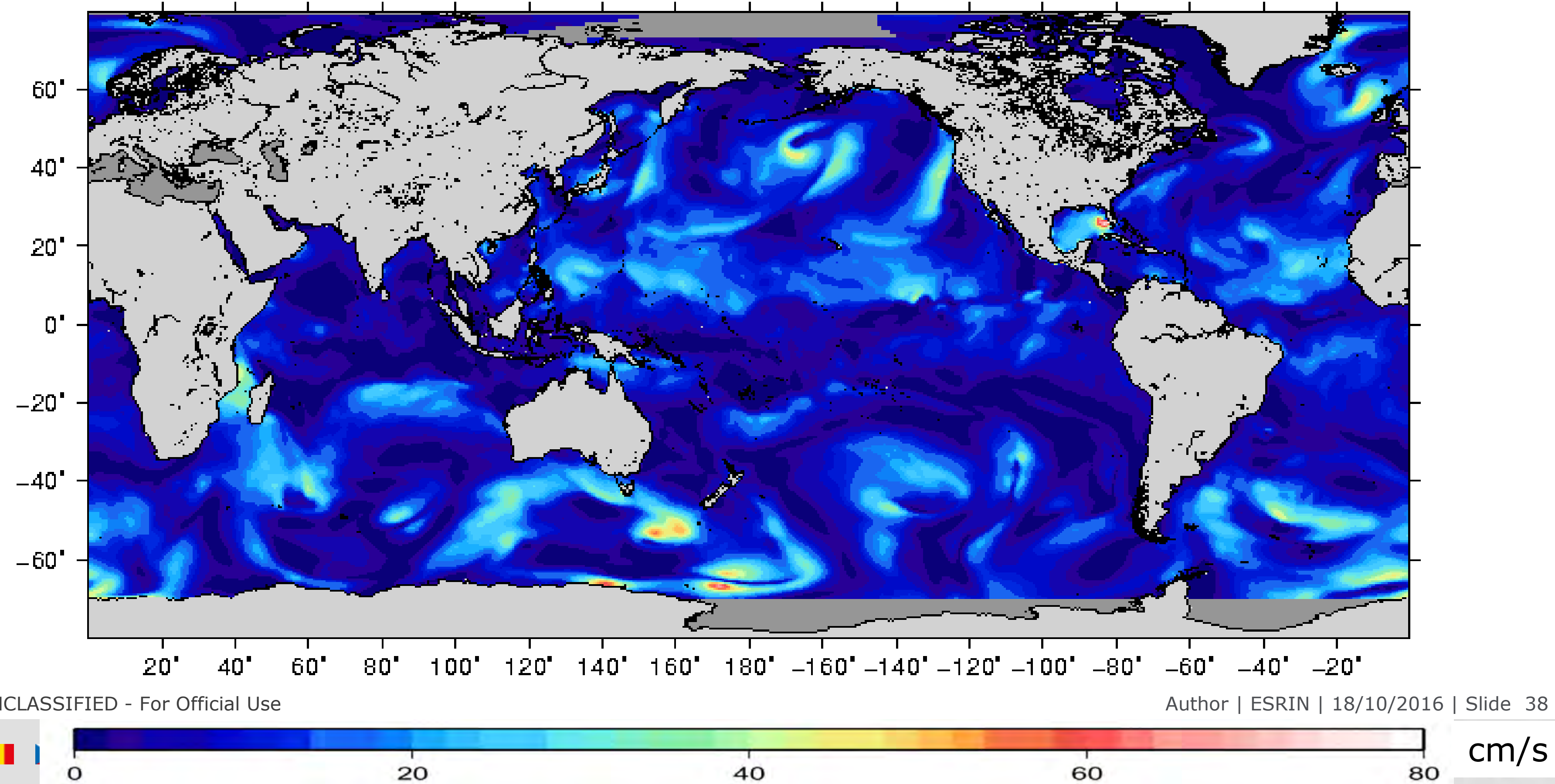
Northern Hemisphere: solid line
Southern Hemisphere: dashed line
Surface: circles
15m depth: triangles

In Summer stratification increases => De decreases

$$\beta = \frac{\pi\sqrt{2}}{\rho f D_E} e^{\frac{\pi}{D_E} z}$$ increases

$$|\theta| = \left(\frac{\pi}{4} + \frac{15}{D_e}\right)$$ increases

The wind drivenEkman+Stokes current
May, 5th 2016



Ocean Surface Current from Gravity+Altimetry+Wind

The Globcurrent products (http://www.globcurrent .org)

Now accessible via the Copernicus Marine Service (CMEMS) http://www/copernicus.cmems.eu)

Simplified decomposition of Ocean Surface Currents (OSC)

$$U_{osc} = u + \boxed{\frac{\sqrt{2}}{\rho_0 (f+\omega)\delta} e^{z/\delta} \left[\tau_e^x \cos\left(\frac{z}{\delta} - \frac{\pi}{4}\right) - \tau_e^y \sin\left(\frac{z}{\delta} - \frac{\pi}{4}\right) \right]}$$

$$V_{osc} = v + \boxed{\frac{\sqrt{2}}{\rho_0 (f+\omega)\delta} e^{z/\delta} \left[\tau_e^x \sin\left(\frac{z}{\delta} - \frac{\pi}{4}\right) + \tau_e^y \cos\left(\frac{z}{\delta} - \frac{\pi}{4}\right) \right]}$$

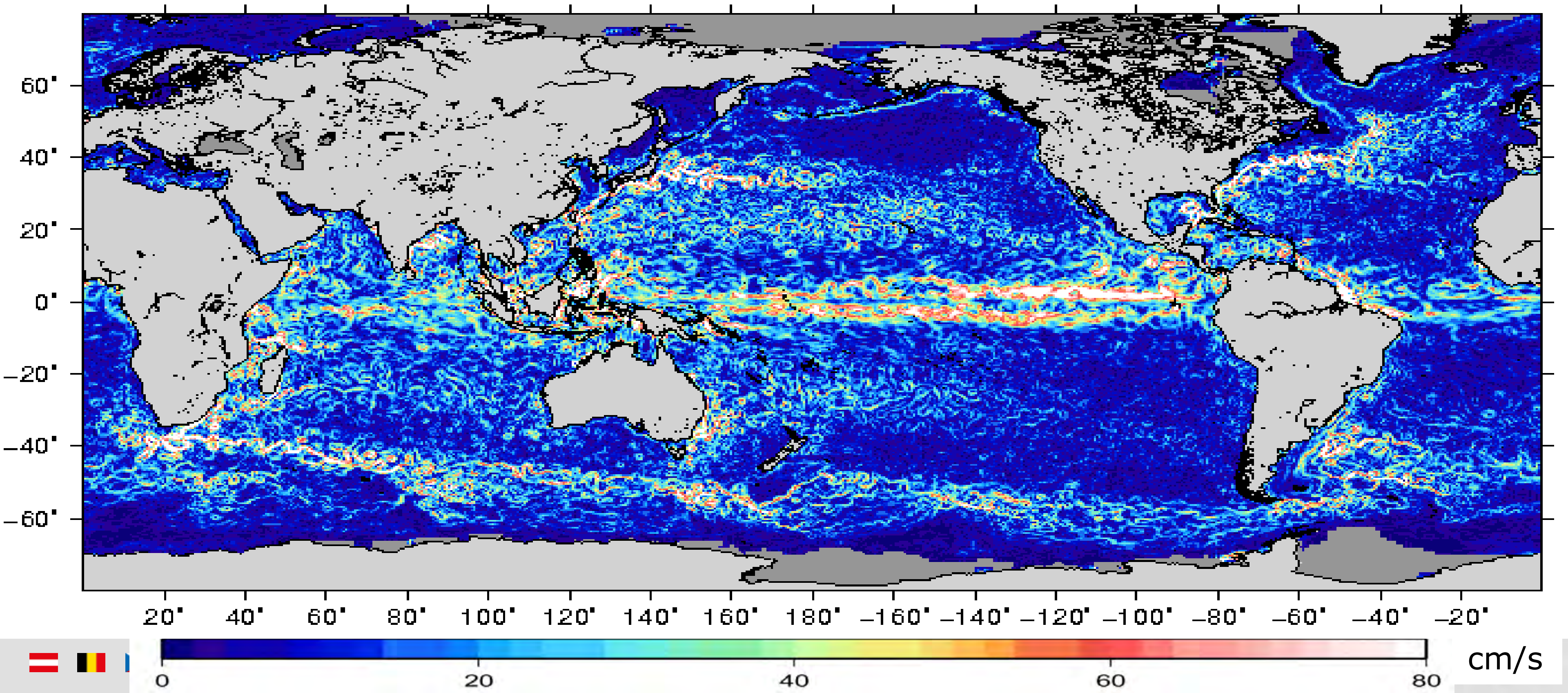
underlying flow

upper wind stress driven flow

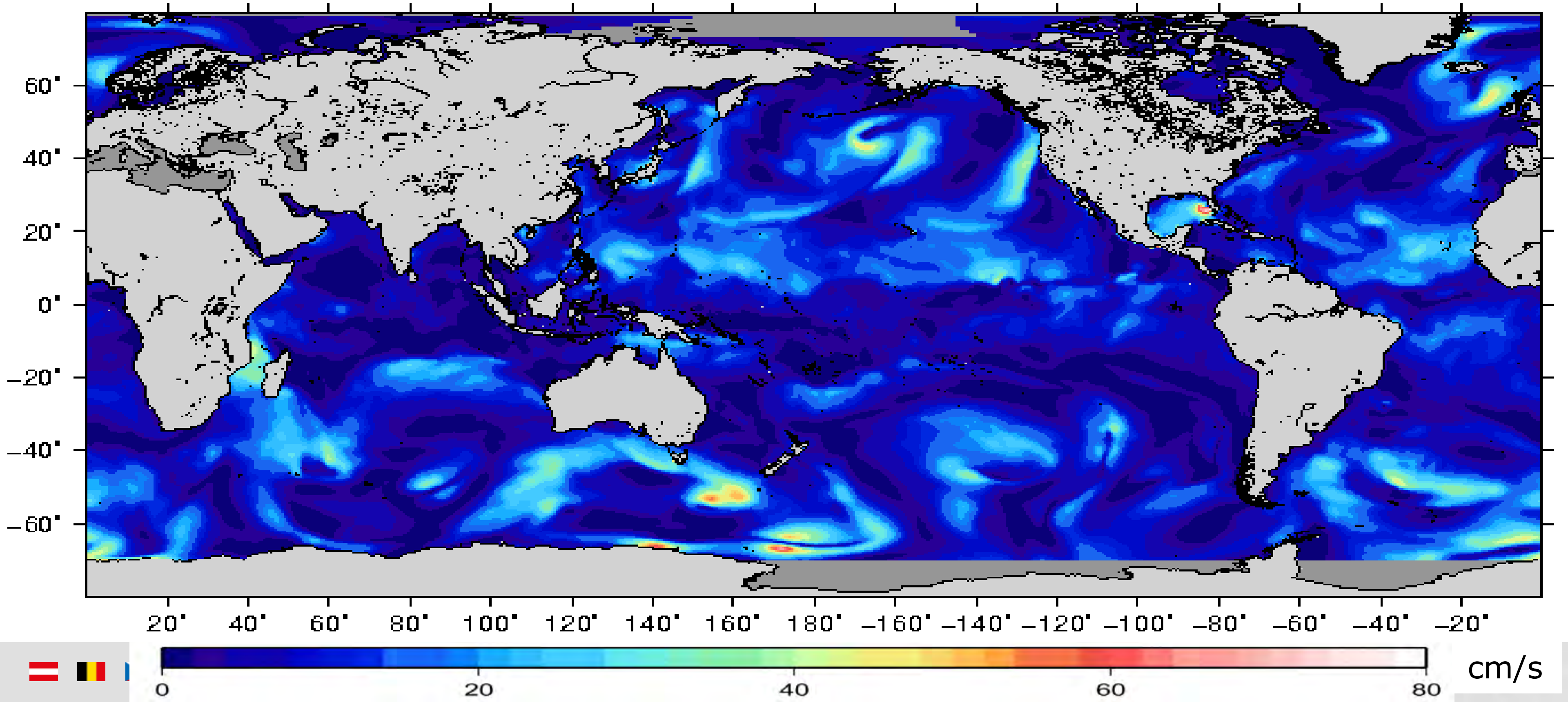
U_{geo}, V_{geo}

U_{ekman}, V_{ekman}

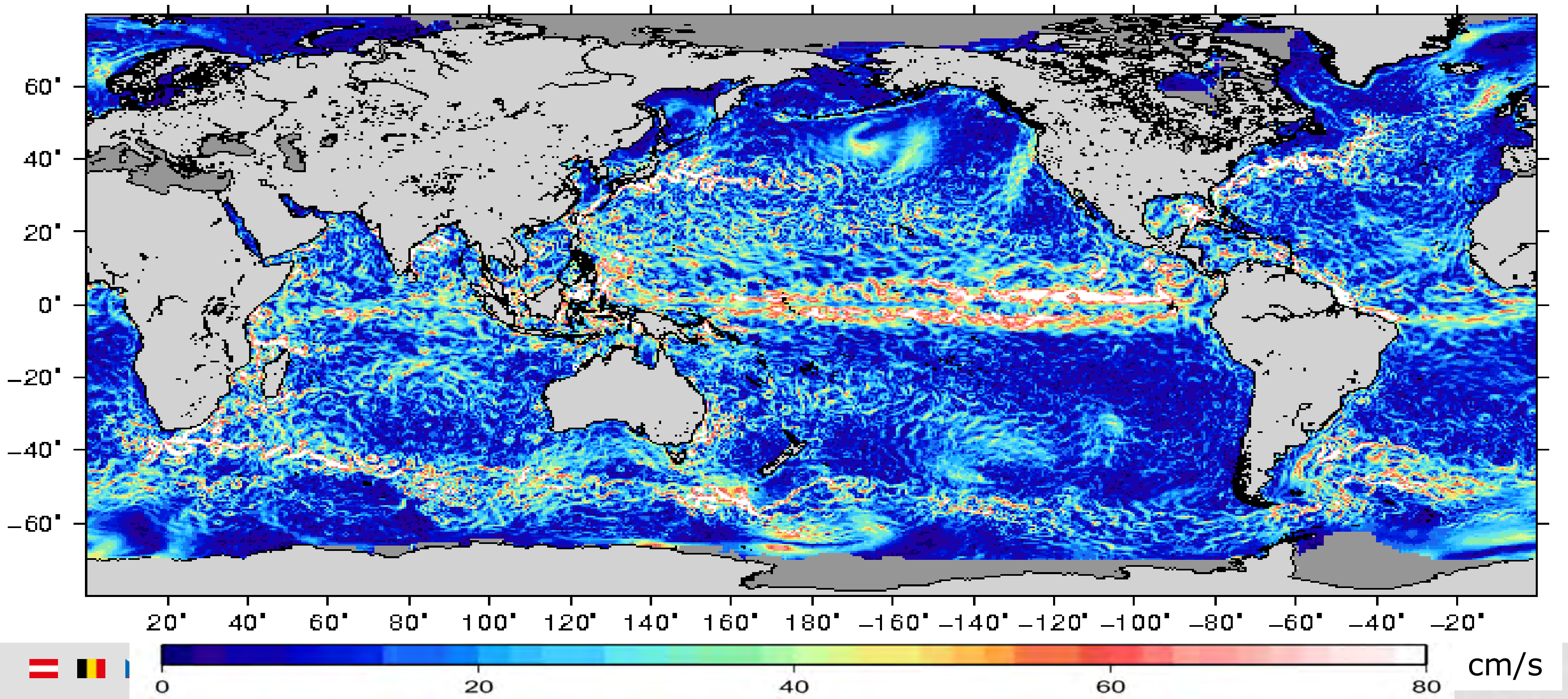
The Geostrophic current May, 5th 2016



The wind drivenEkman+Stokes current
May, 5th 2016



Ocean Surface Current from Gravity+Altimetry+Wind

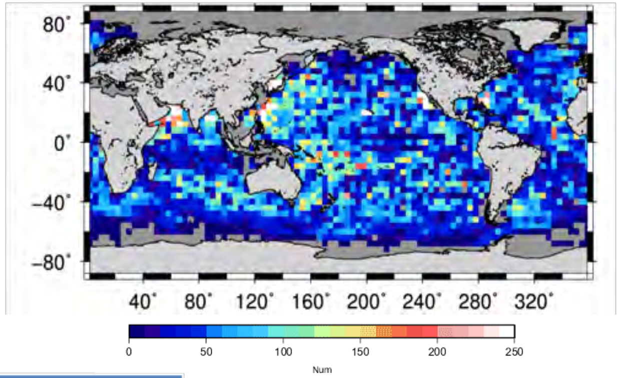


Validation of the GlobCurrent 0m currents: Comparison to independent data

✓Comparison to Argo surface velocities for the year 2015 (Not used for the MDT calculation nor the Ekman model estimation)

✓**The Mercator-Ocean surface velocities** first level (0.5m) from the 1/4° GLORYS2V4 reanalysis (with assimilation)

Number of Argo float data



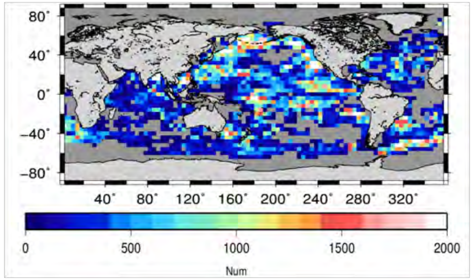
Year 2015: 105349 (100379) velocities*	RMS (cm/s) Bracket: |lat|>3	
	U	V
DRIFTER	27.6 (26.4)	22.8 (22.6)
DRIFTER-GC Geostrophic	20.2 (19.1)	18.2 (17.7)
DRIFTER-**GC Geostrophic + Ekman**	**17.0 (15.8)**	**16.6 (16.0)**
DRIFTER-Mercator (1/4°)	19.3 (18.6)	18.7 (18.6)

***Unfiltered velocities: contain Geos, Ekman, Stokes, inertial oscillations, tidal current…**

Validation of the GlobCurrent 0m currents: Comparison to independent data

✓**Comparison to SVP drogued velocities for the year 2015** (Not used for the MDT calculation nor the Ekman model estimation)
✓**The Mercator-Ocean surface velocities** ninth level (13.99m) from the 1/4° GLORYS2V4 reanalysis
✓**The OSCAR (Ocean Surface Current Analysis Real-Time) NOAA product (see K. Dohan's talk on Thursday)**
-Geostrophic currents based on AVISO data (with the old CNES-CLS09 MDT)
- Ekman current using variable eddy viscosity and NCEP winds -5 days mean, 1/3°
-averaged value over the top 30 m of the solution

Number of SVP data



Year 2015: 722657 (695020) velocities *	RMS (cm/s) Bracket: |lat|>3	
	U	V
DRIFTER	23.0	18.8
DRIFTER-GC Geostrophic	14.8 (13.6)	14.2 (13.6)
DRIFTER-**GC Geostrophic + Ekman**	**13.7 (12.5)**	**13.4 (12.8)**
DRIFTER-OSCAR	14.1 (13.4)	13.8 (13.0)
DRIFTER-Mercator (1/4°)	15.9 (15.3)	15.2 (15.2)

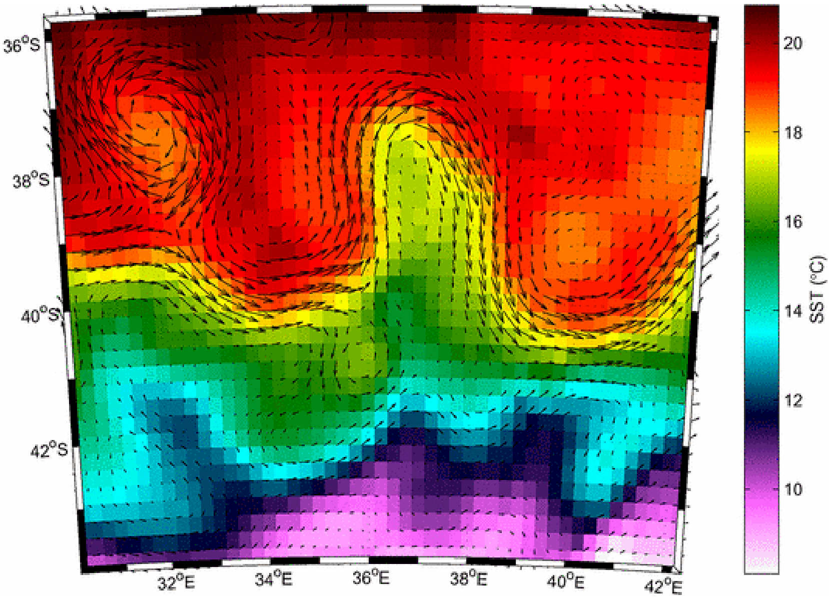
***Unfiltered velocities: contain Geos, Ekman, Stokes, inertial oscillations, tidal current…**

Space and in-situ data synergy for a better retrieval of the ocean circulation

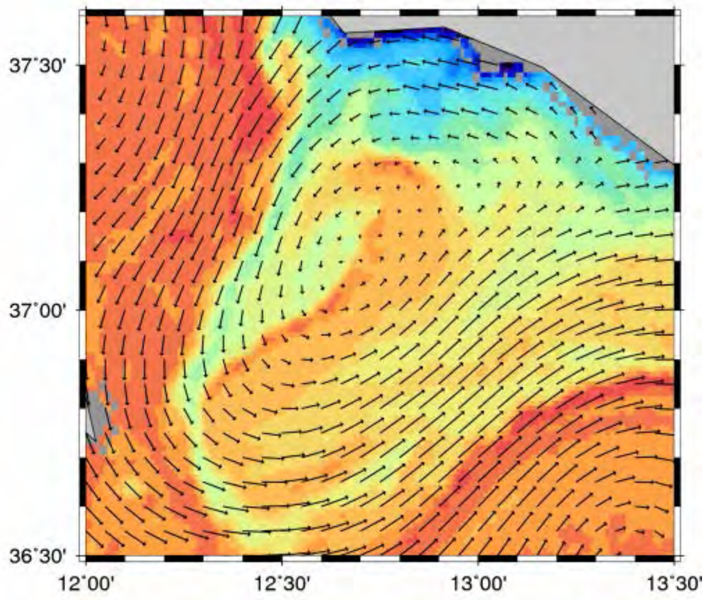
- Geostrophic currents from Altimetry, space Gravity, in-situ measurements of T,S, surface drifter velocities
- Ekman currents from in-situ drifting buoy velocities, altimetry, wind
- **SST/SSH synergy for higher resolution surface currents**

SSH/SST synergy for higher resolution surface currents

January, 1st 2004
Microwave SST product
Altimeter geostrophic velocities



Sentinel-3 data on July, 28th 2016
SRAL and SLSTR



Effective Surface Quasi Geostrophy (E-SQG) Method

Under favourable environmental conditions, the streamfunction ψ from which geostrophic velocities are derived, can be calculated from surface density values:

Lapeyre et al, 2006; Klein et al., 2008

Inversion of the Quasi Geostrophic Potentiel Vorticity conservation equation in the horizontal Fourier transform domain (valid for space scales of 10-200km)

$$\frac{\partial}{\partial y}\psi_{sqg} = -u \qquad \frac{\partial}{\partial x}\psi_{sqg} = v$$

Currents

$$\psi_{sqg}(\widehat{\vec{k}, z}) = \frac{f}{N_{eff}\rho_0 k}\widehat{\rho'_s(\vec{k})}.e^{\left(\frac{N_{eff}kz}{f_0}\right)}$$

Streamfunction

Surface Density Anomalies

$$\rho'_S = -\alpha \cdot T_S' - \beta S_S' = -\alpha' T_S'$$

SST anomaly

N_{eff} is the effective Brunt-Vaisala frequency (constant stratification assumed)

$\alpha' N_{eff}^{-1}$ is a free parameter that needs to be set up to account both interior PV and the partial compensation of salinity and temperature.

$$\hat{\psi}(\vec{k}) = F_T(k)\hat{T}_s(\vec{k}),$$

$F_T(k)$ is the transfer fonction is to be determined using independent observations.

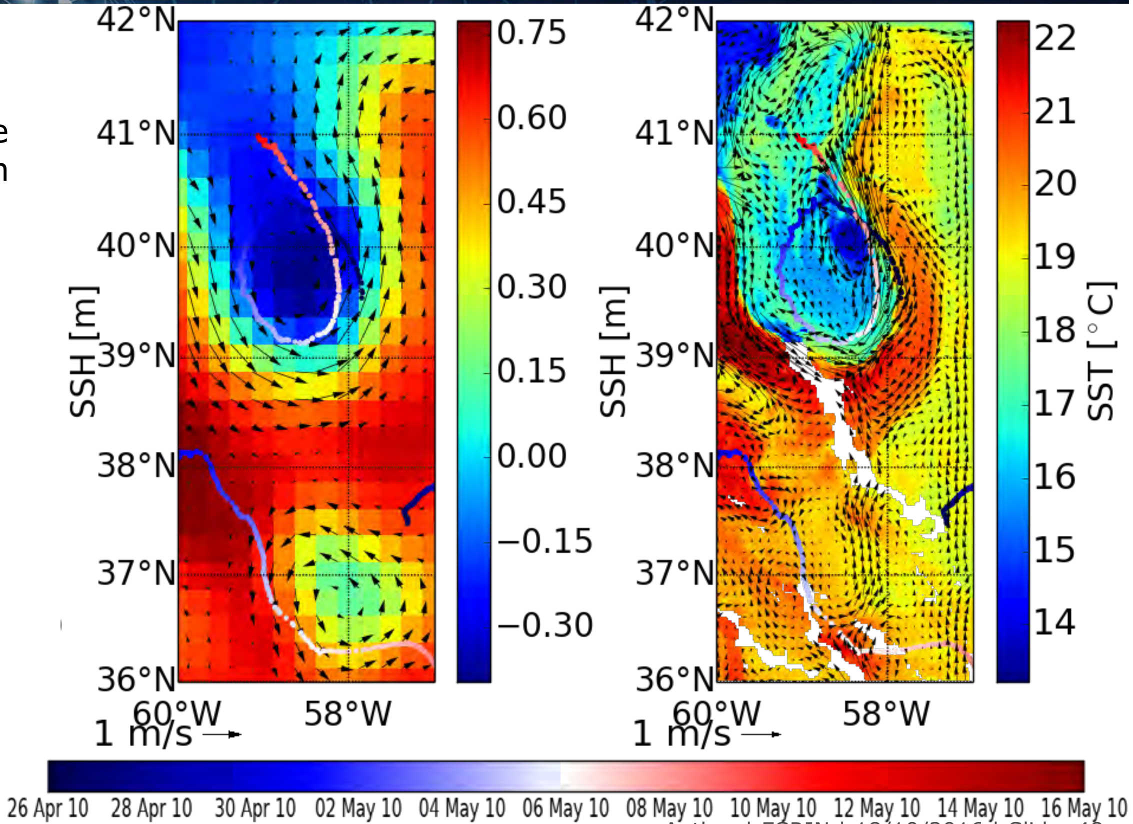
Isern-Fontanet et al. [2014]: the geostrophic streamfunction at the ocean surface is proportional to the SSH (η).

$$\psi(\mathbf{x}) = \frac{g}{f_0}\eta(\mathbf{x}).$$

So that the transfer fonction can write:

$$F_T(k) = \frac{g}{f_0}\frac{\langle|\hat{\eta}|\rangle_k}{\langle|\hat{T}_s|\rangle_k},$$

Combination of the phase of SST measurements and the amplitude of SSH measurements.



« Optical flow » methods: inversion of a tracer conservation equation

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

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

c represents the concentration of any tracer as Sea Surface Temperature, Sea Surface Salinity, Chl-a concentration,

F(x,y,t) represents the source and sink terms

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

Synergy : Following an approach proposed by Piterbarg et al (2009), the method is used on successive SST images using the altimeter geostrophic velocities as background so as to obtain an optimized 'blended' velocity (u_{opt}, v_{opt}).

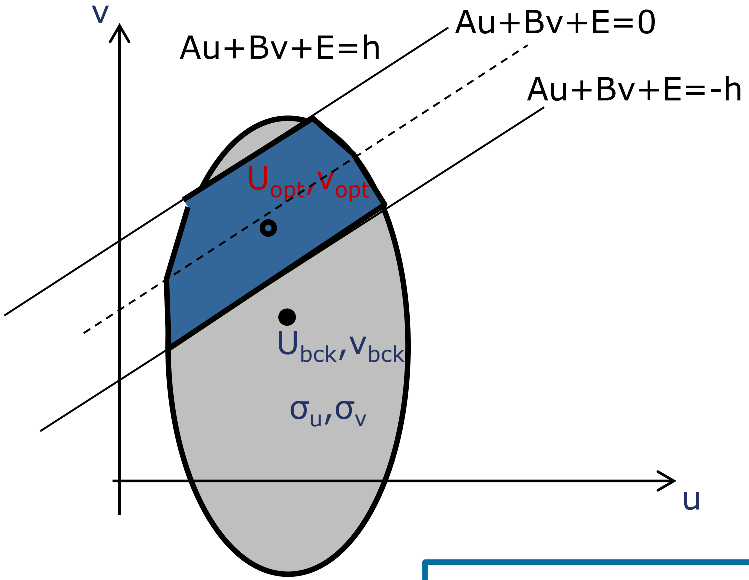
Rio et al, 2016, 2018

METHOD

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

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

$|F-F_{bck}|<h$



Spatial SST variations

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

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

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

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

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

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

Temporal SST variations
Forcing term estimates

Forcing term error

Background velocity error

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

Piterbarg et al, 2009

Global implementation over 2014-2016

DATA USED

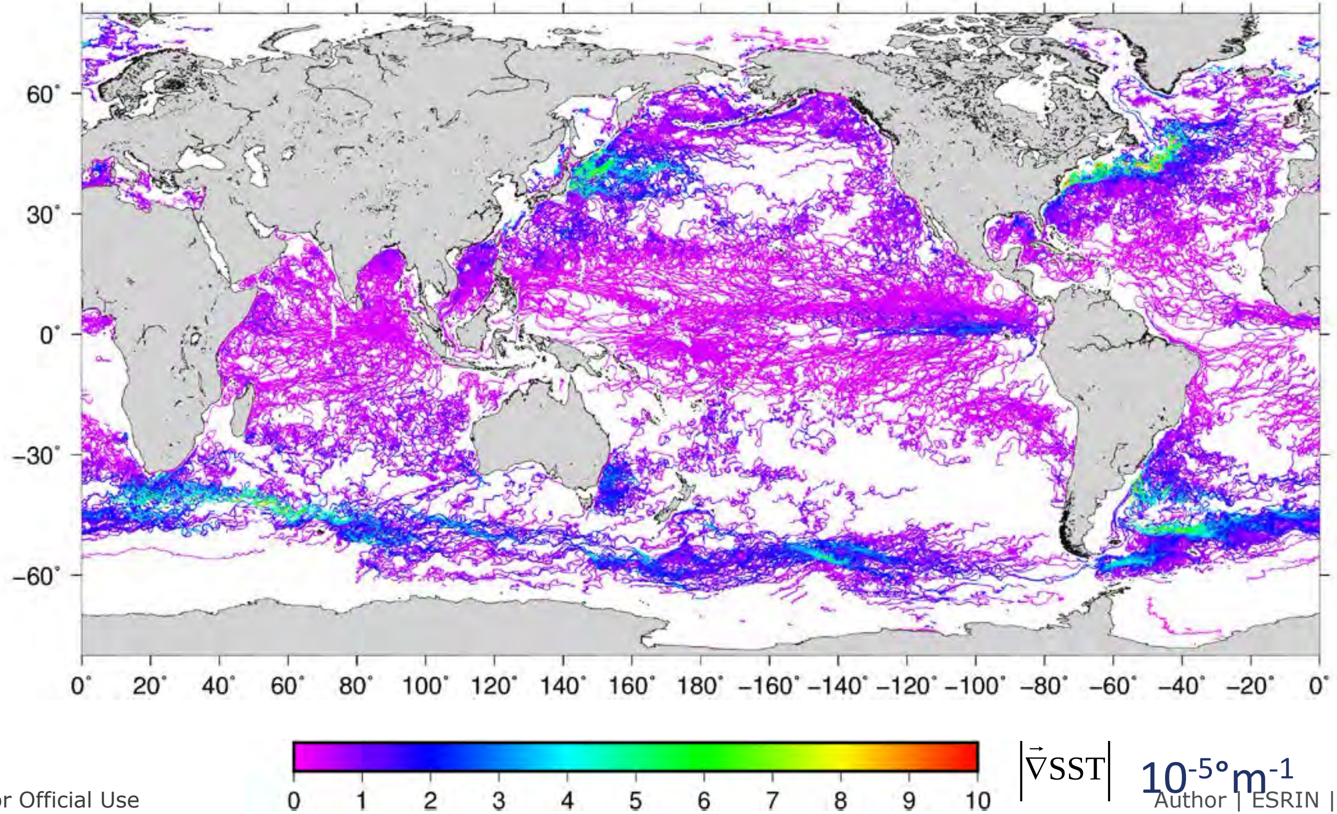
- Background velocities: CMEMS L4 altimeter gridded geostrophic velocity products:
  - « twosat » (2 satellites configuration) - resolution ~250 km
  - « allsat » (5 satellites configuraton) - resolution ~100km

- Sea Surface temperature: L4 OI (100km, 4 days) daily maps from REMSS
  - MW: microwave sensors only - resolution ¼°
  - MW_IR: microwave and infrared sensors - resolution ~9 km

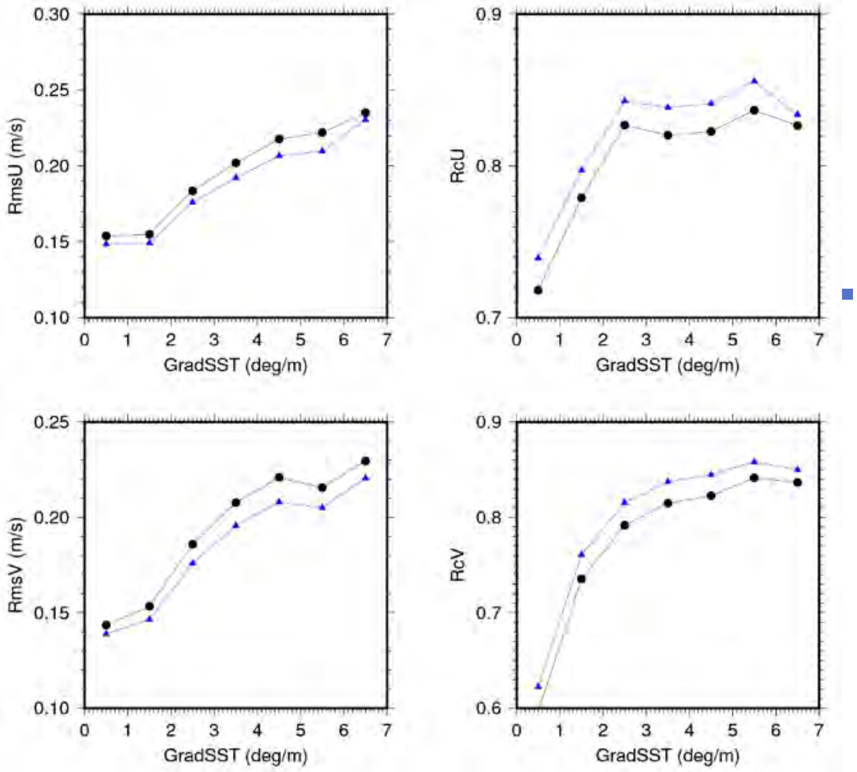
→ Three years (2014-2016) of global combined « twosat » SSH + MW SST and « allsat » SSH + MW-IR SST has been produced.

- Validation dataset: Drifting buoy velocities, SVP 15m drogued, 6 hourly resolution along the buoy trajectory

Global implementation over 2014-2016



$|\vec{\nabla}SST|$ $10^{-5}{}^{\circ}m^{-1}$



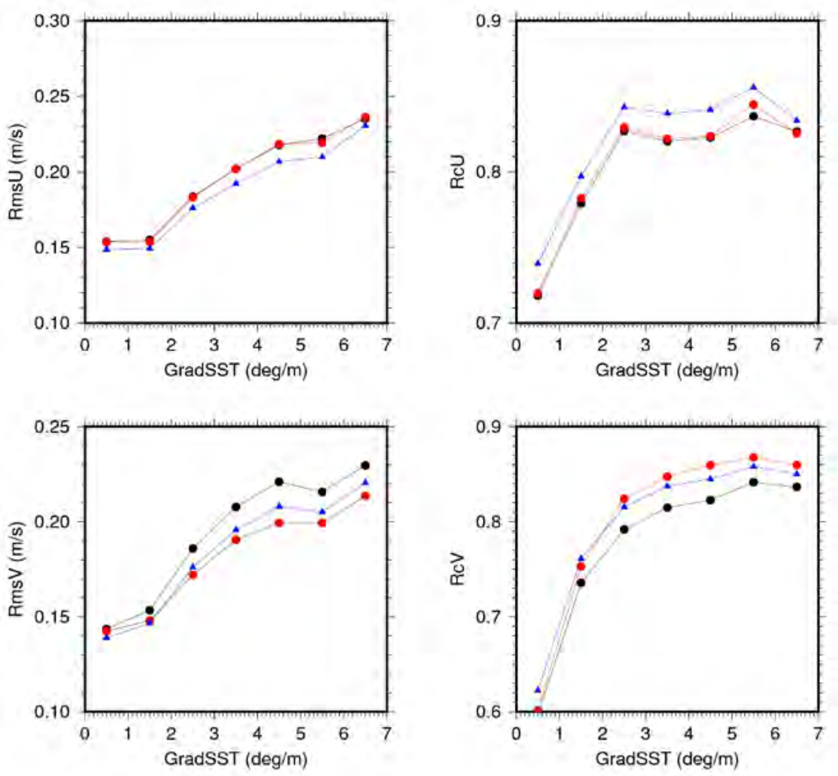
Alti « twosat »

Alti « allsat »

- « allsat » velocities closer to in-situ velocities than « twosat » velocities everywhere

Rio and Santoleri, 2018

VALIDATION 2014-2016



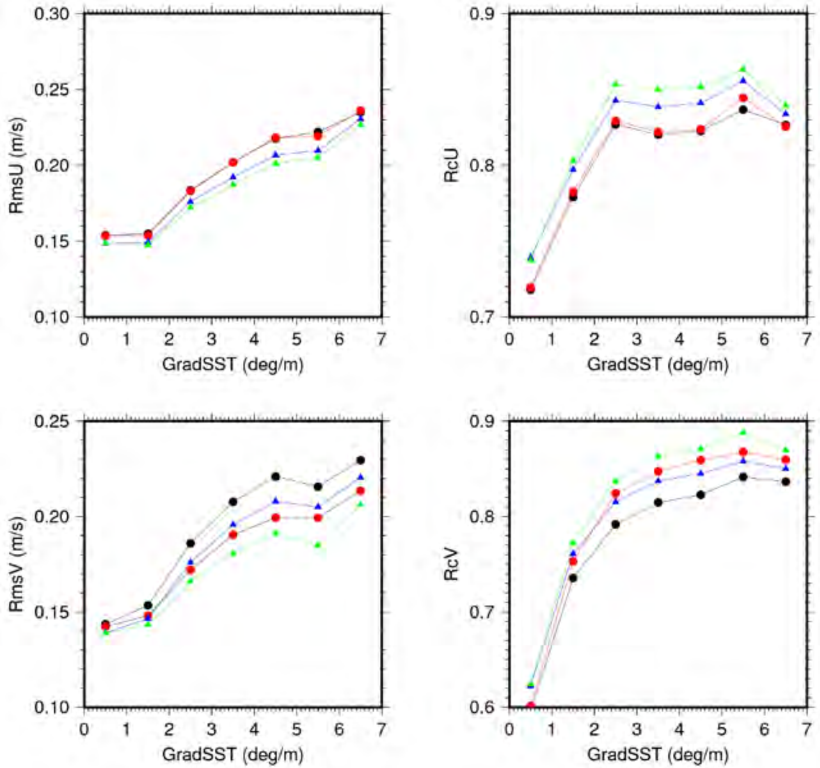
Alti « twosat »

Alti « twosat » + SST MW

Alti « allsat »

- « allsat » velocities closer to in-situ velocities than « twosat » velocities everywhere
- Strong improvement for the meridional component of the velocity in areas where SST gradients greater then 10^{-5}°/m
- « twosat »+ MW SST better than « allsat »

VALIDATION 2014-2016



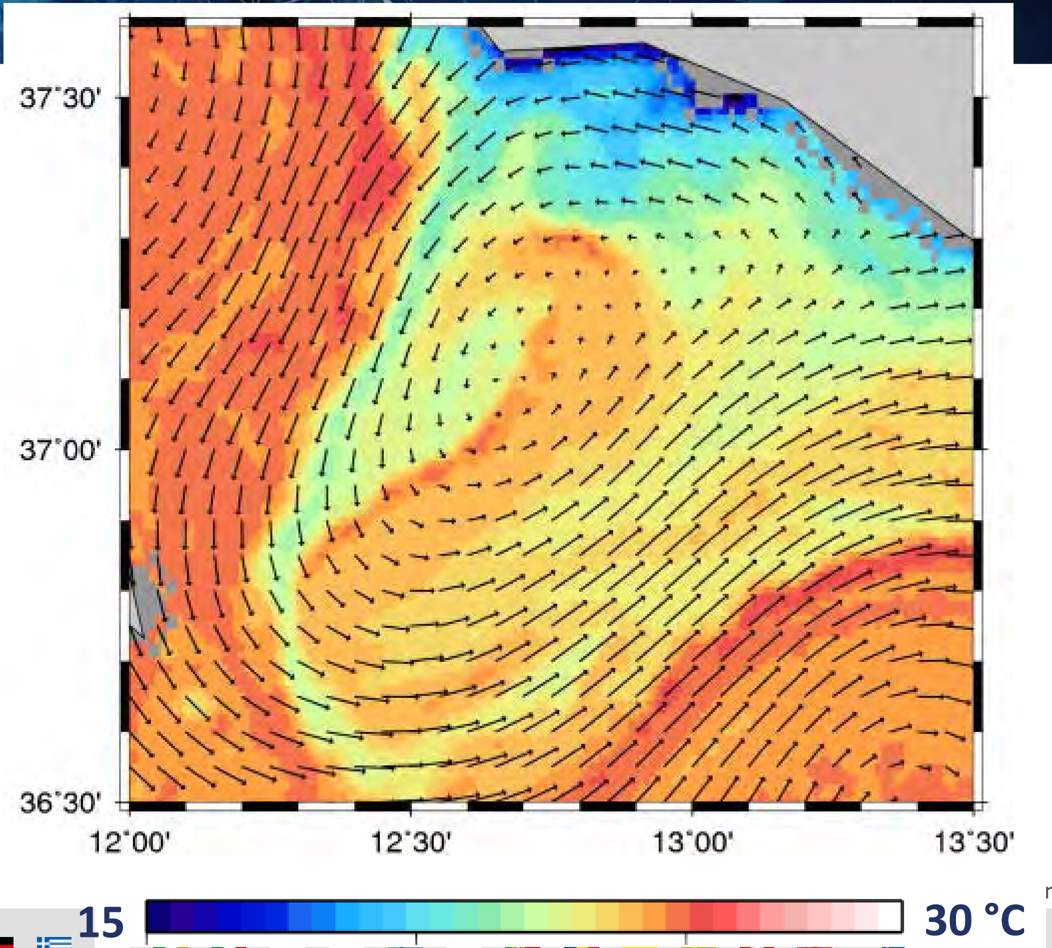
Alti « twosat »
Alti « twosat » + SST MW
Alti « allsat »
Alti « allsat »+SST MWIR

- « allsat » velocities closer to in-situ velocities than « twosat » velocities everywhere

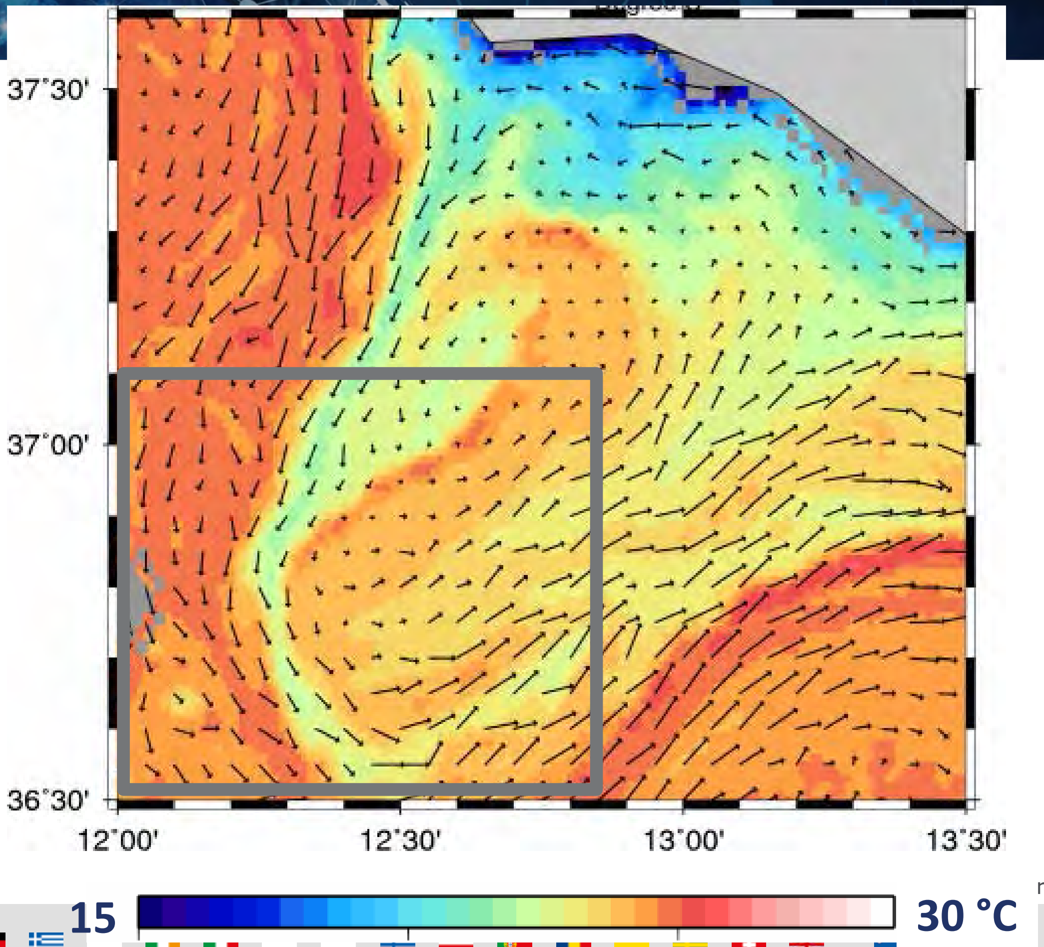
- Strong improvement for the meridional component of the velocity in areas where SST gradients greater then 10^{-5}°/m
- « twosat »+ MW SST better than « allsat »

- Further improvement with « allsat »+MWIR SST (also on the zonal component)

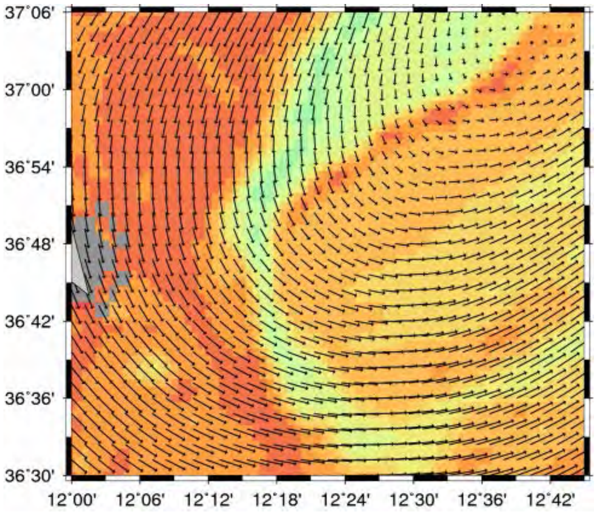
Sentinel-3 data on July, 28th 2016



Sentinel-3 data on July, 28th 2016

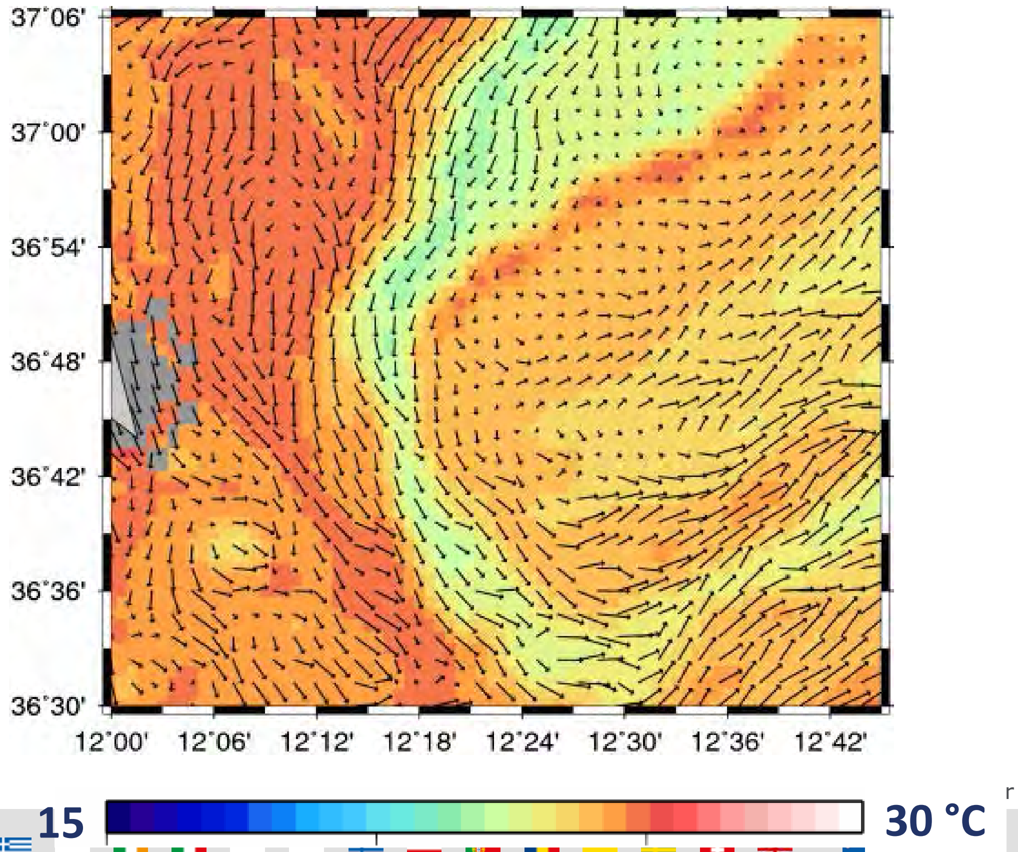


Sentinel-3 data on July, 28th 2016

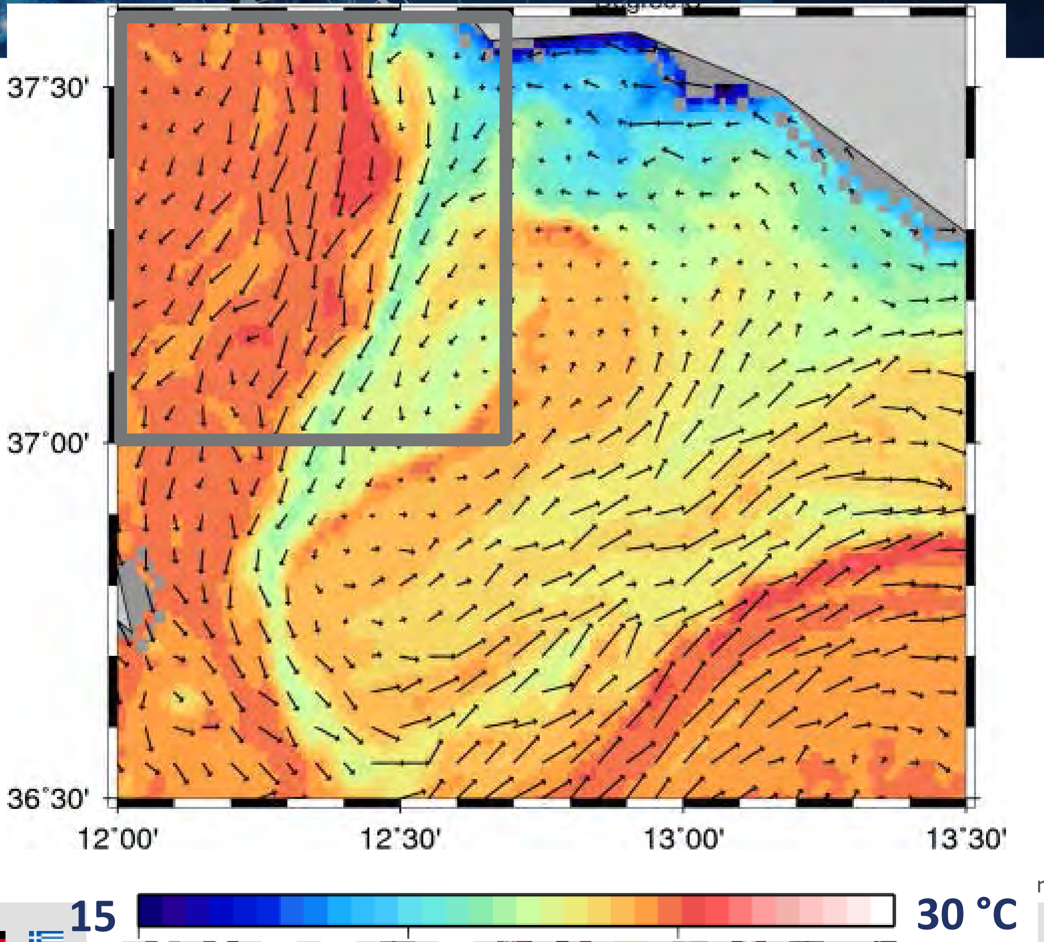


15

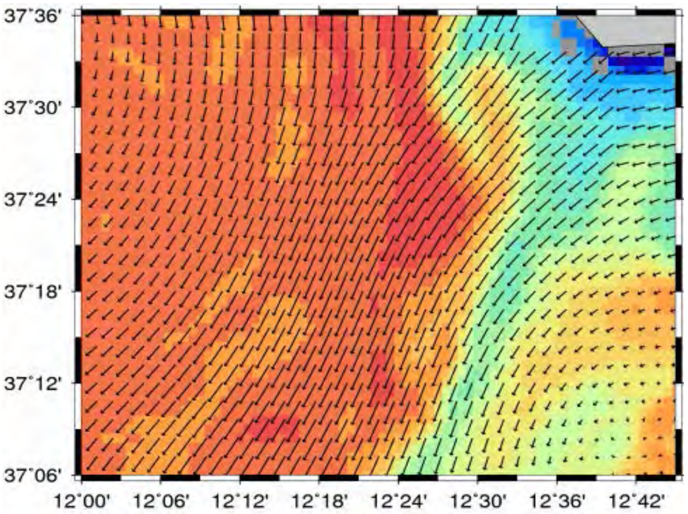
30 °C

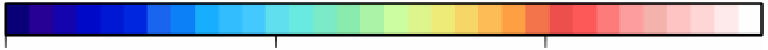

37°06'
37°00'
36°54'
36°48'
36°42'
36°36'
36°30'
12°00'
12°06'
12°12'
12°18'
12°24'
12°30'
12°36'
12°42'
15
30 °C

Sentinel-3 data on July, 28th 2016

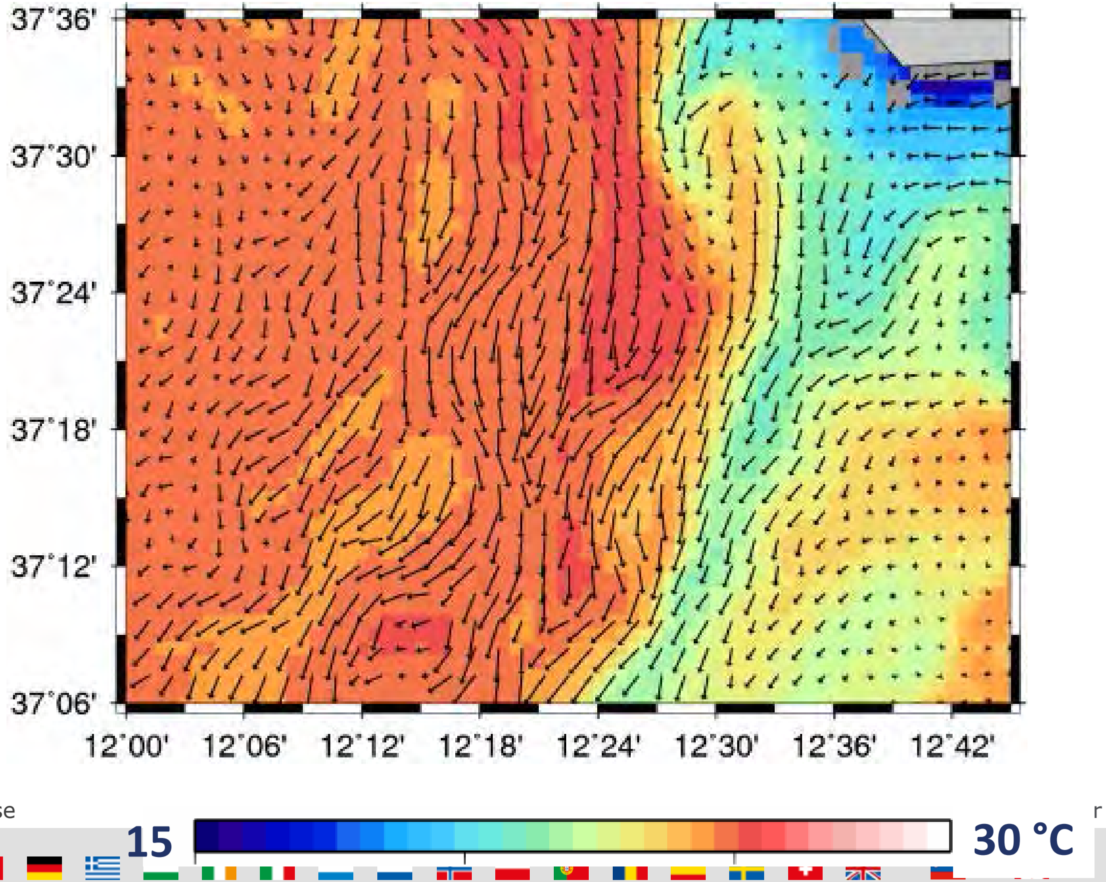


Sentinel-3 data on July, 28th 2016





Sentinel-3 data on July, 28th 2016



SSH/SST merging for ocean circulation estimation

- Promising combination results are obtained
- The quality of the merged velocities strongly depends on the quality of the SST product
- The spatio-temporal resolution of the merged product is the spatio temporal resolution of the SST product

- Today: MW 25 km, daily, all weather
- IR on geostationary satellites: few km, hourly, cloud sensitive

- Tomorrow? CIMR (Copernicus Imaging Microwave Radiometer) Phase A/B1

Sub-daily measurements of SST at 15km, all weather

Strong impact for global ocean currents retrieval from SSH/SST merging

Thanks!