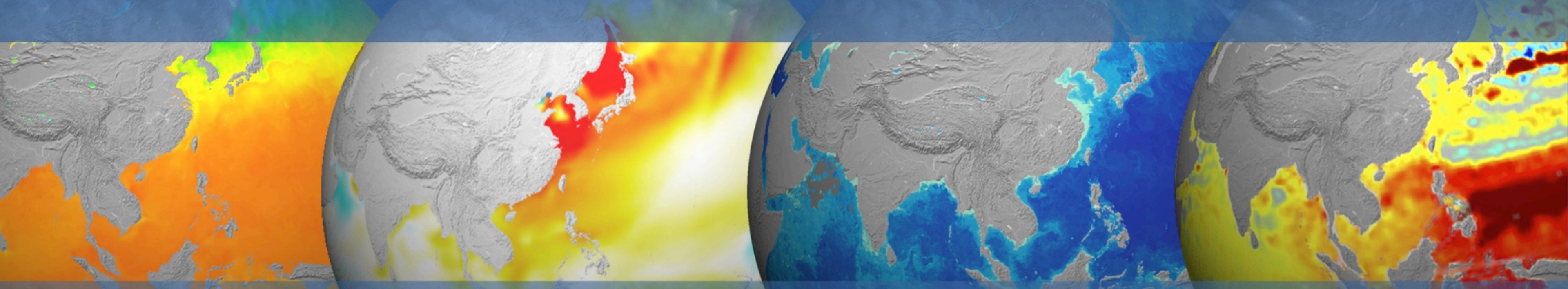
ESA–MOST China Dragon 4 Cooperation

→ ADVANCED TRAINING COURSE IN OCEAN AND COASTAL REMOTE SENSING



12 to 17 November 2018 | Shenzhen University | P.R. China

From Altimeter Sea Level Anomalies to ocean surface currents *by* M.-H. Rio

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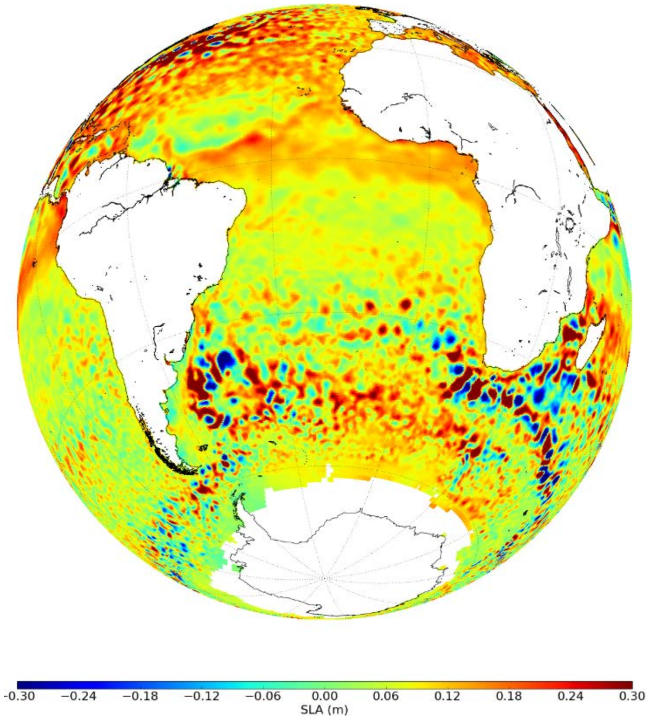
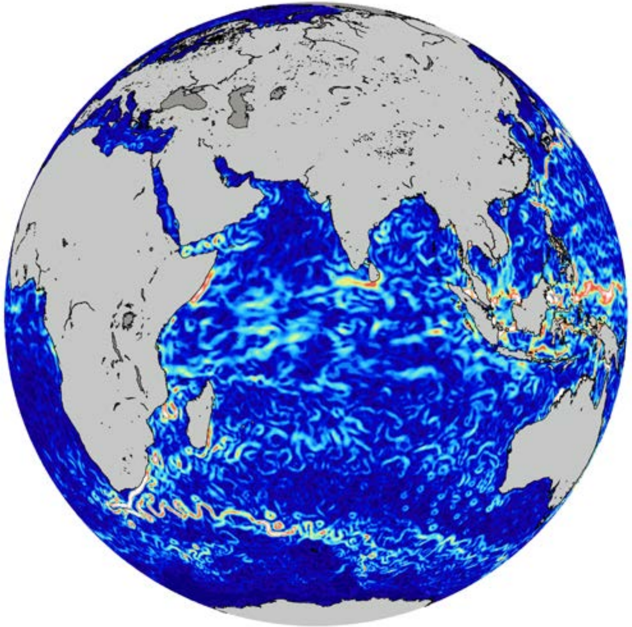

-0.30 −0.24 −0.18 −0.12 −0.06 0.00 0.06 0.12 0.18 0.24 0.30
SLA (m)



Space gravity AND Altimetry synergy for ocean current retrieval

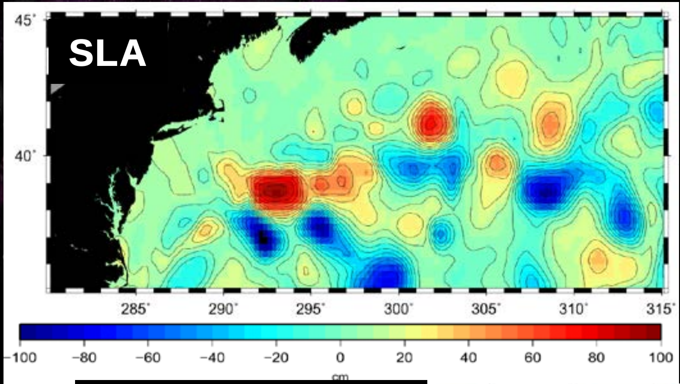
Some very simple equations

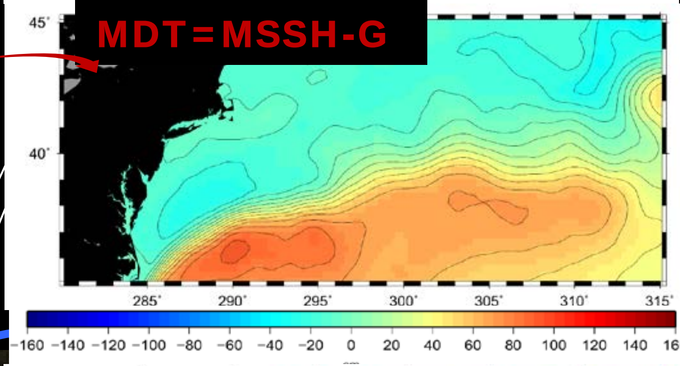
$$SSH = h + G \leftrightarrow h = SSH - G$$

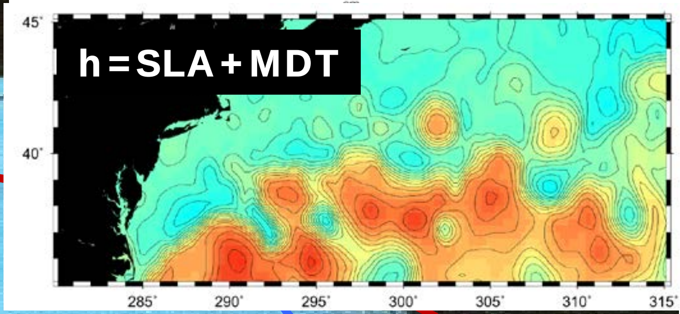
$$MSSH = MDT + G \leftrightarrow MDT = MSSH - G$$

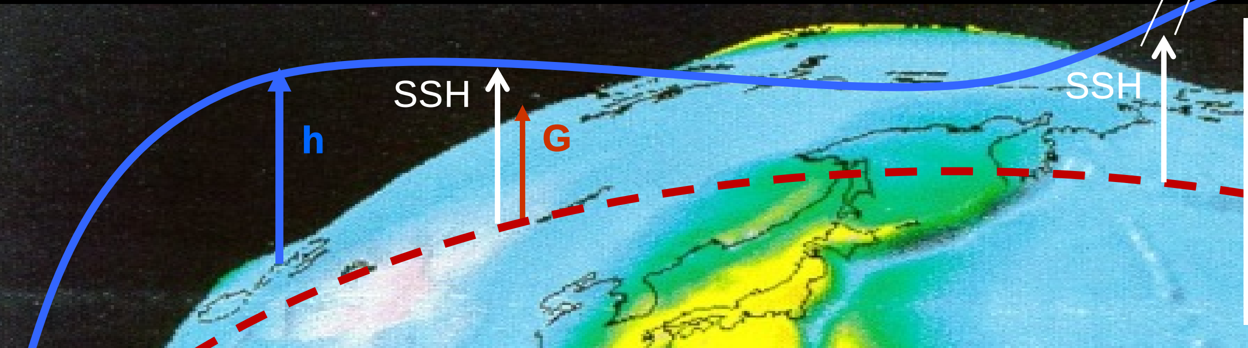
$$SSH - MSSH = h - MDT = SLA$$

$$\mathbf{h = SLA + MDT}$$

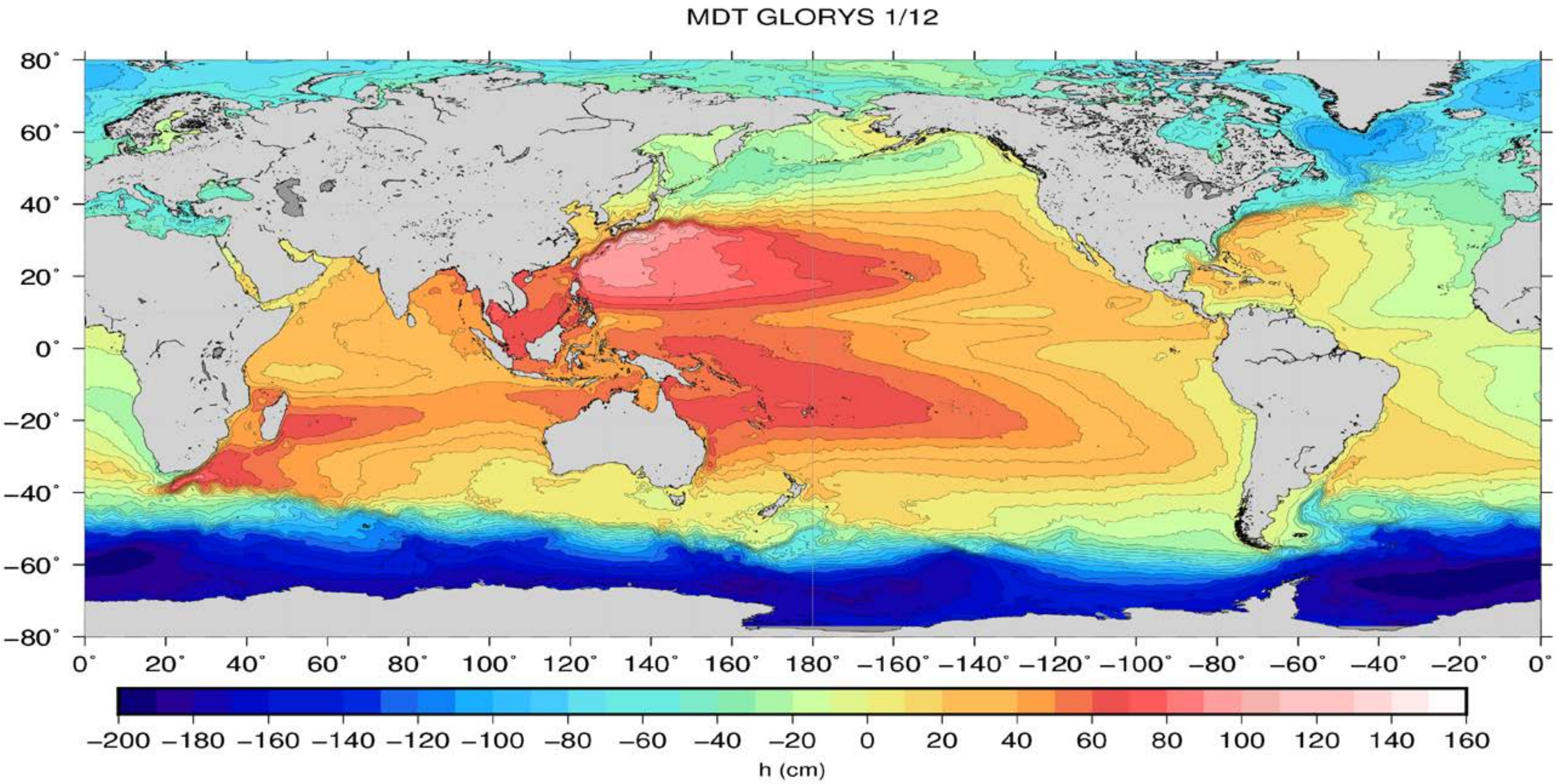




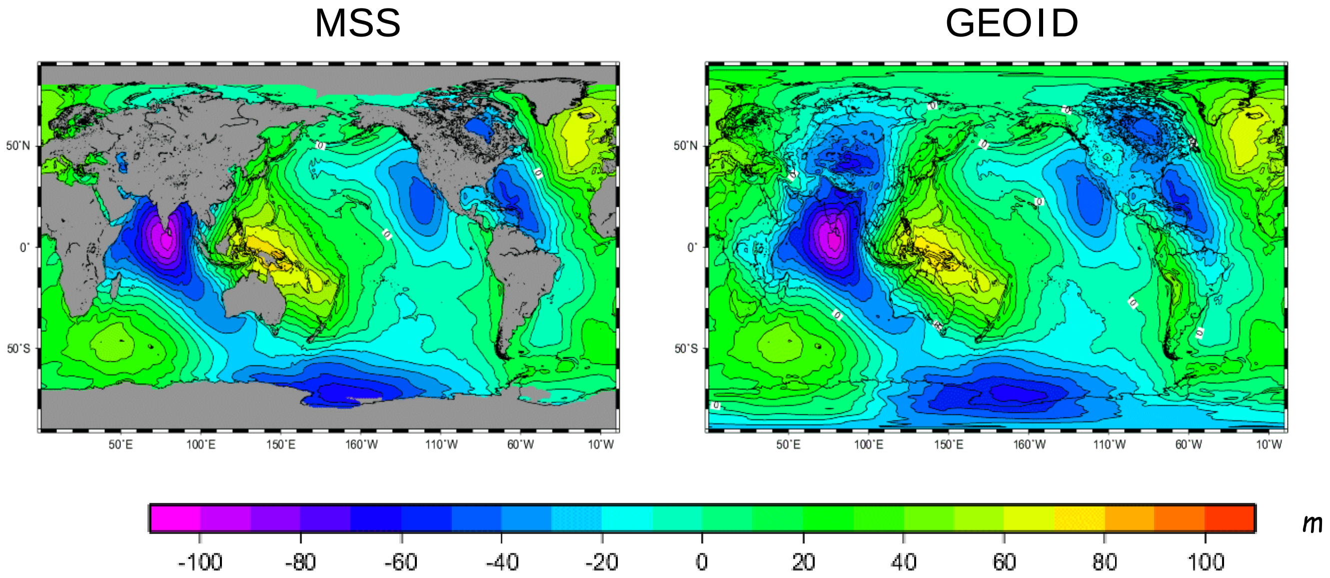




Mean Dynamic Topography from a high resolution (1/12°) ocean numerical model

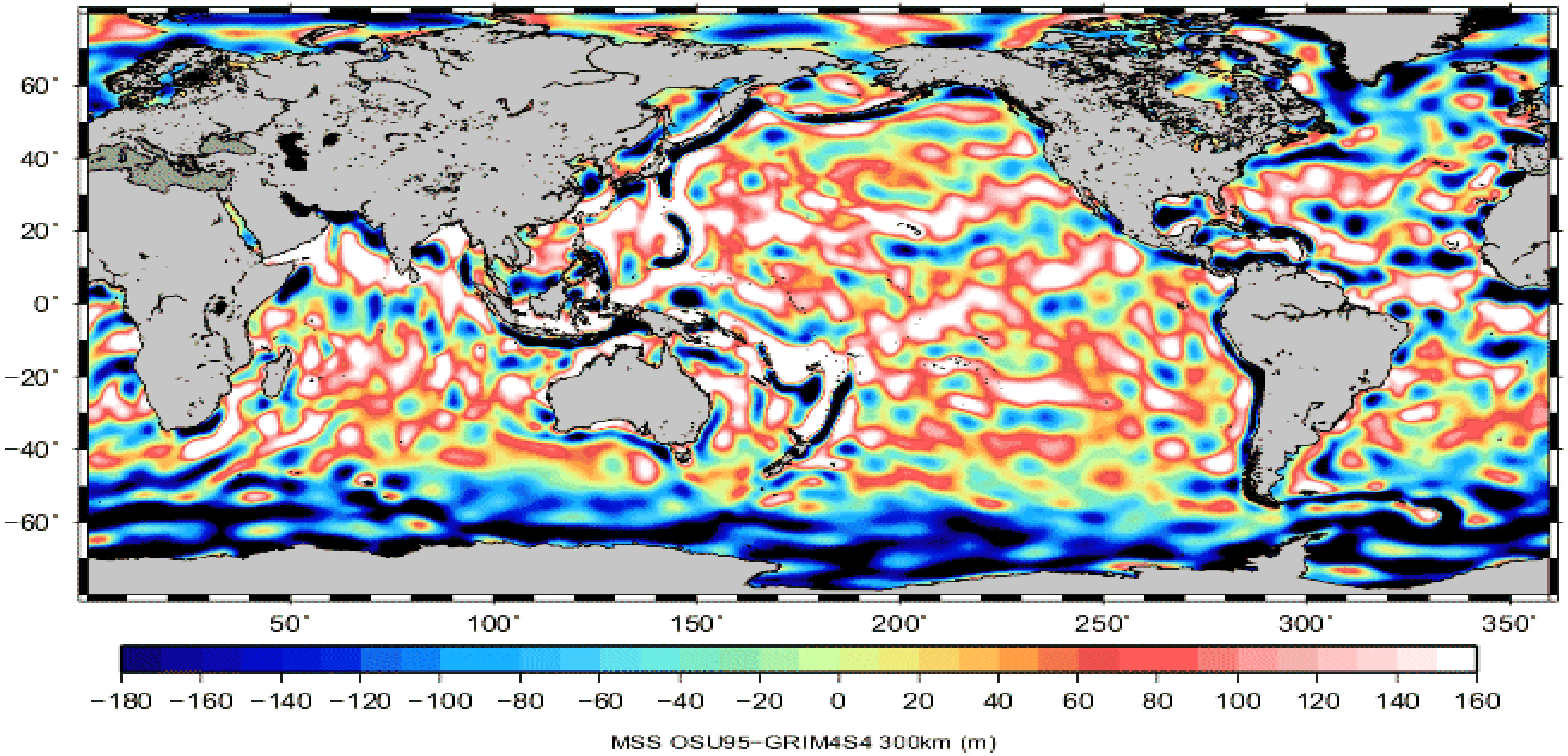


MDT = MSS – GEOID



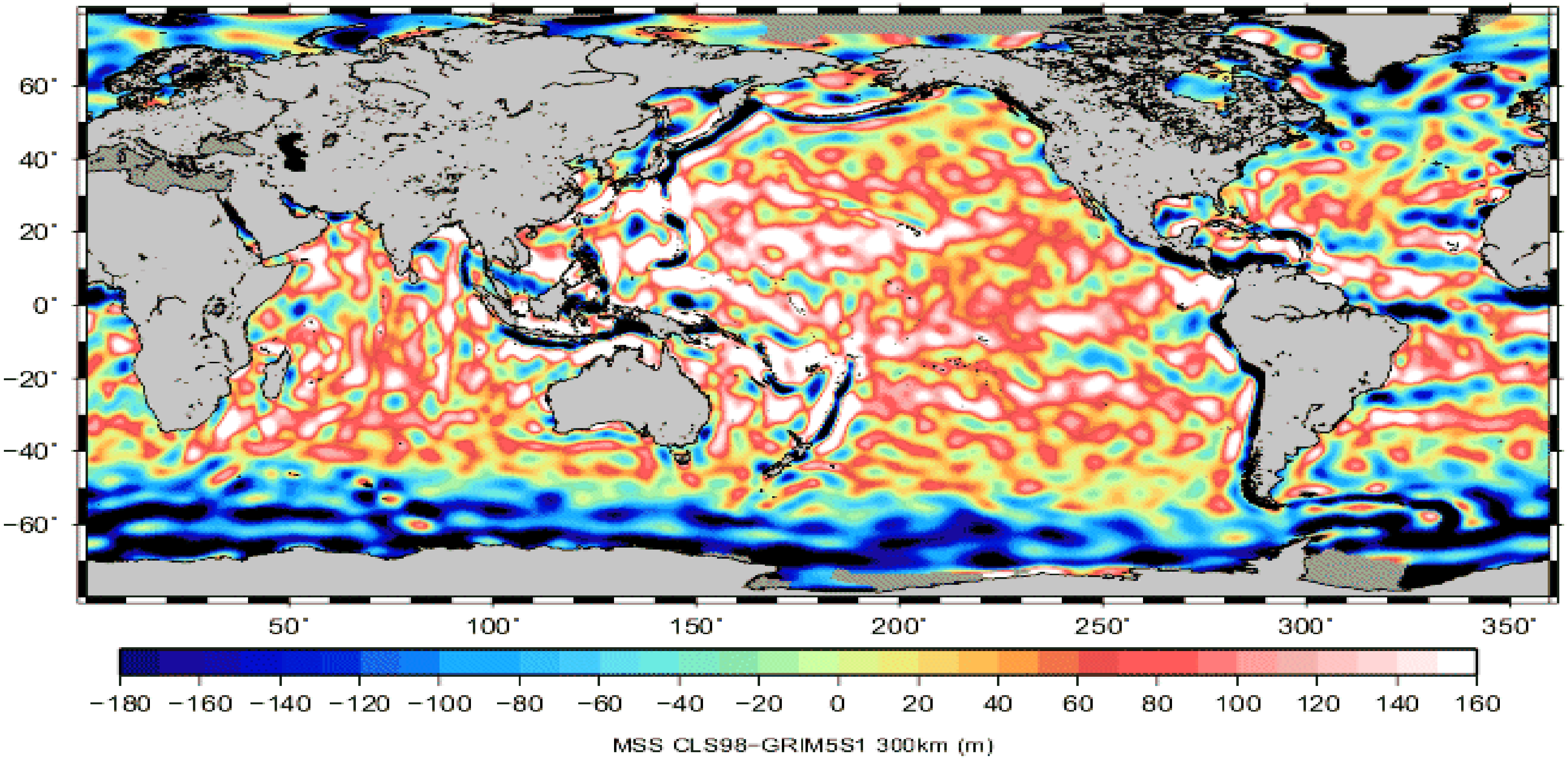
Mean Dynamic Topography estimation
25 YEARS OF IMPROVEMENTS

1995



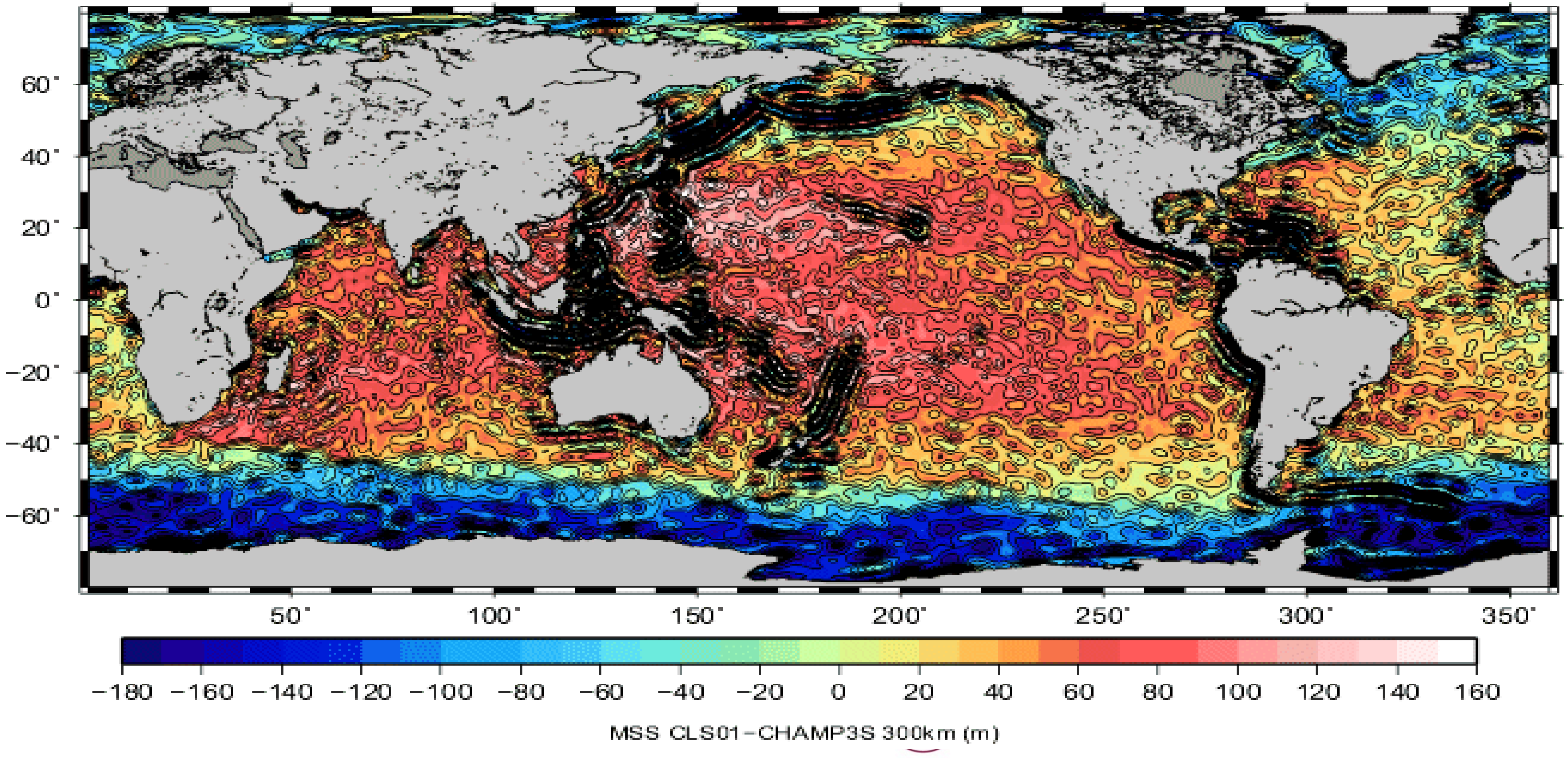
Mean Dynamic Topography estimation
25 YEARS OF IMPROVEMENTS

1999



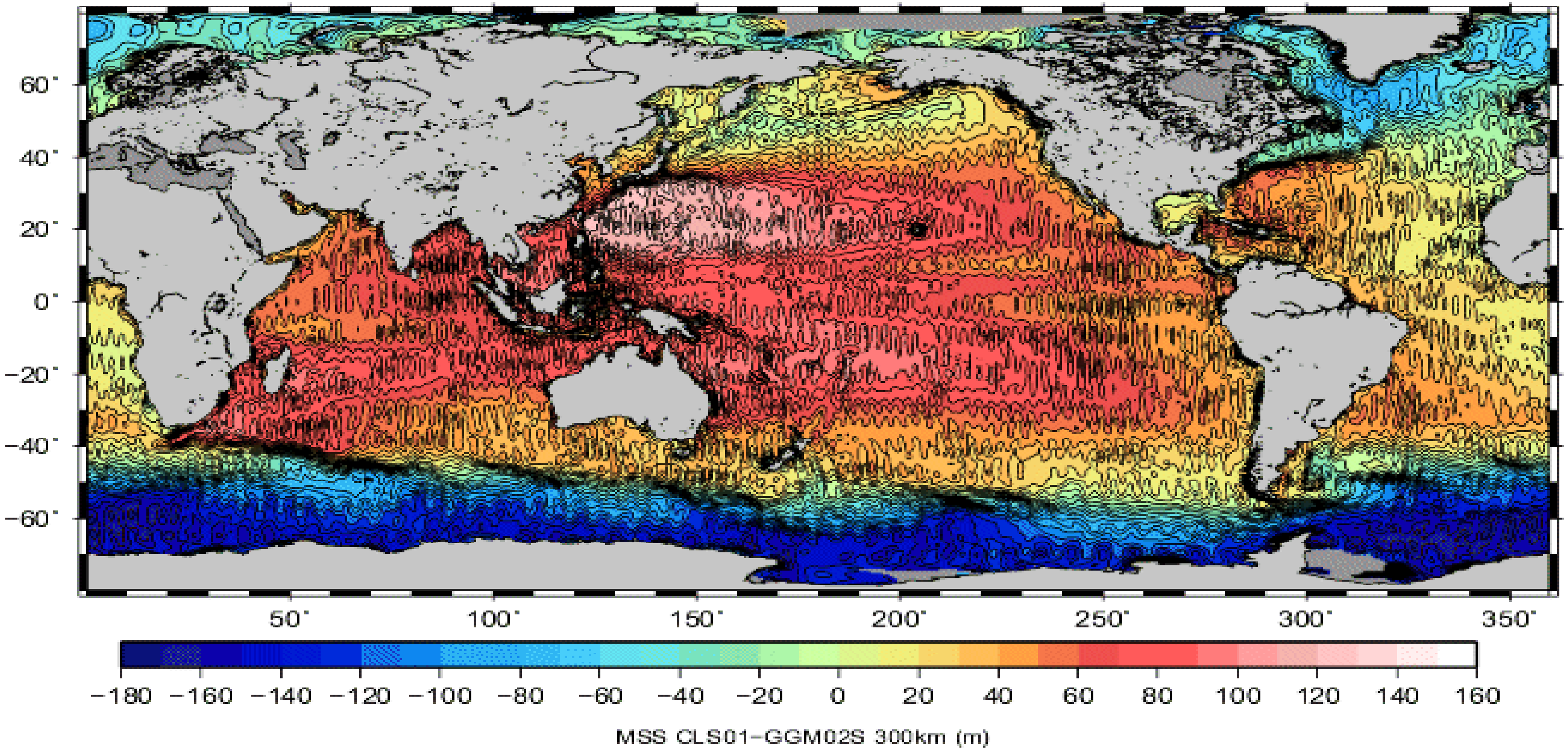
Mean Dynamic Topography estimation
25 YEARS OF IMPROVEMENTS

2003



Mean Dynamic Topography estimation
25 YEARS OF IMPROVEMENTS

2005



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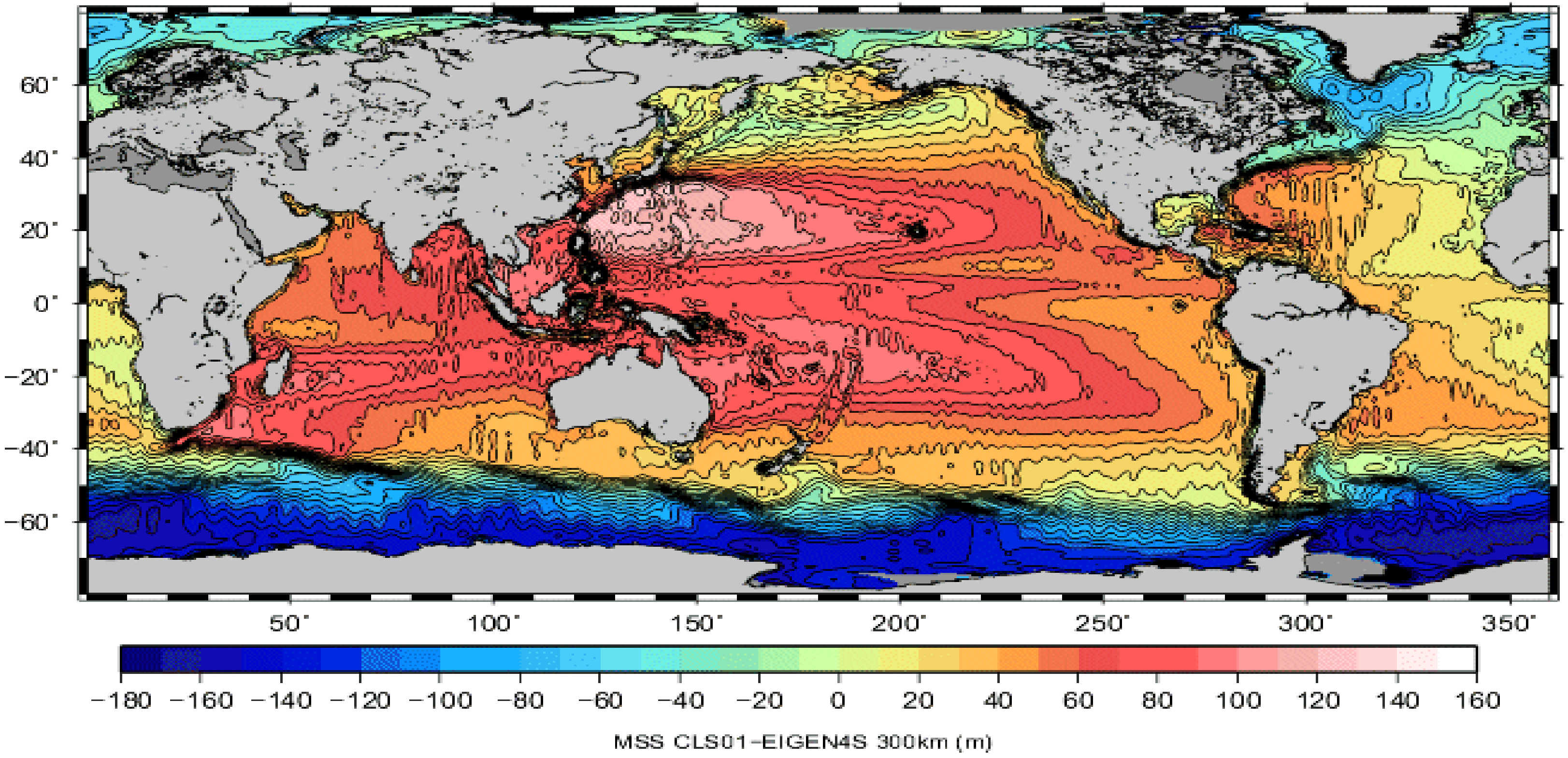
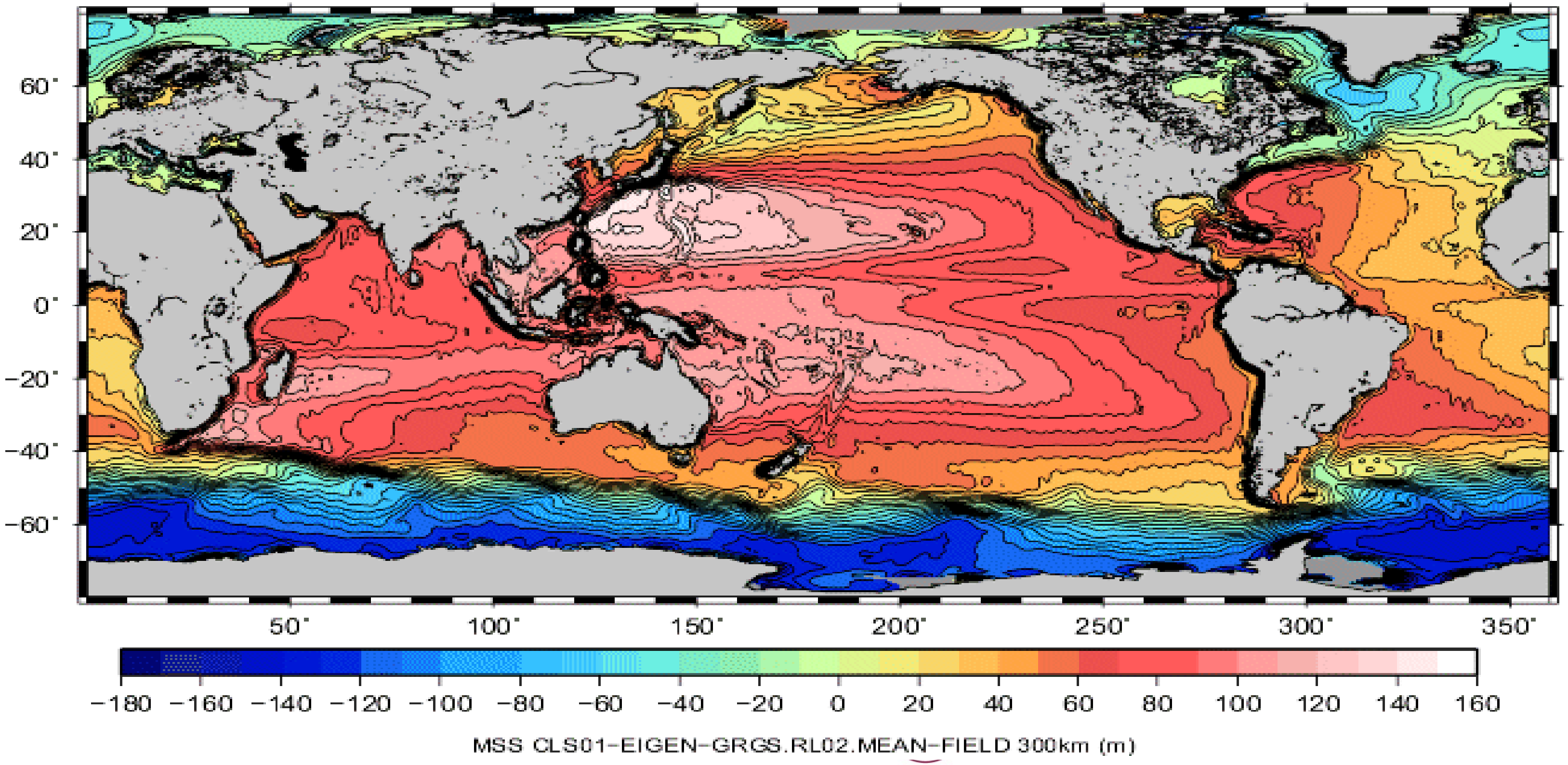
Mean Dynamic Topography estimation
25 YEARS OF IMPROVEMENTS

2006



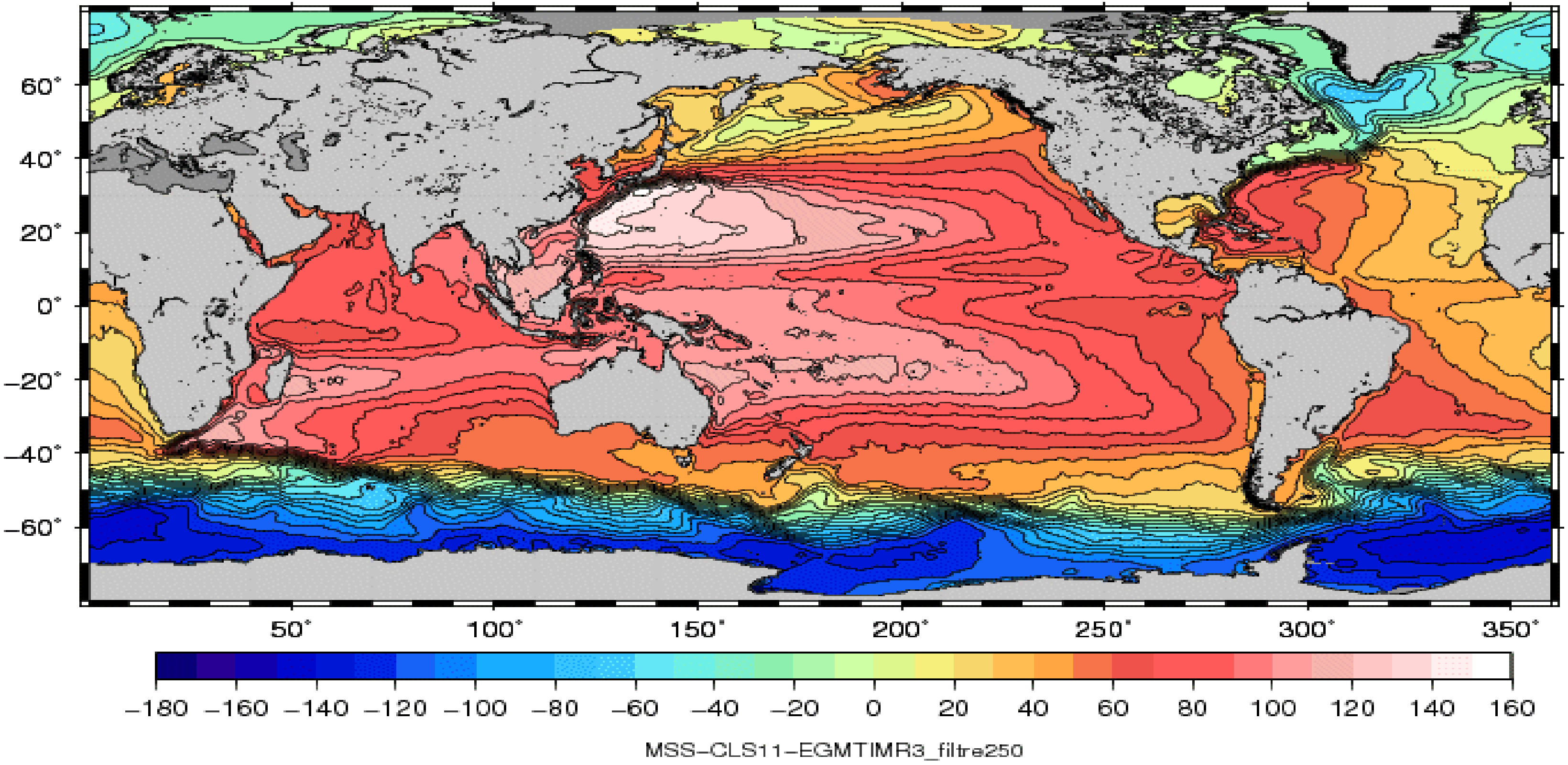
Mean Dynamic Topography estimation
25 YEARS OF IMPROVEMENTS

2009



Mean Dynamic Topography estimation
25 YEARS OF IMPROVEMENTS

2012



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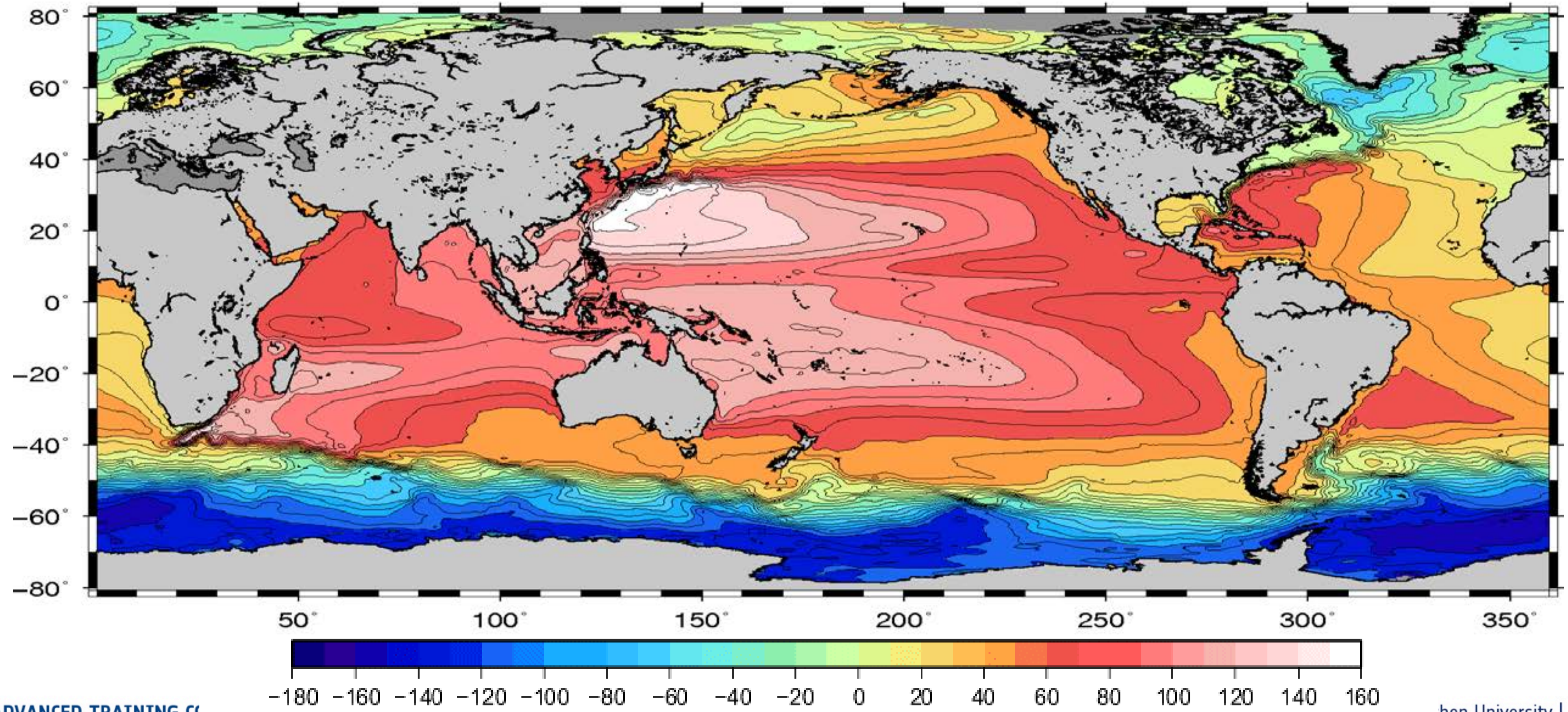
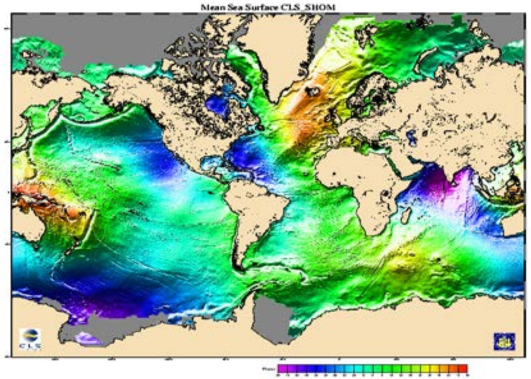
Mean Dynamic Topography estimation
25 YEARS OF IMPROVEMENTS

2015

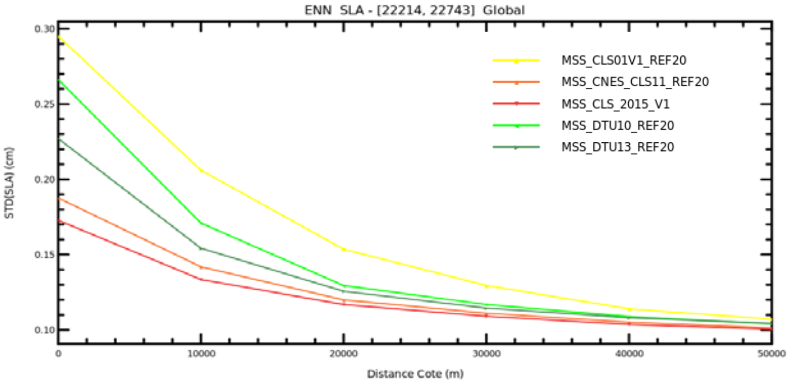


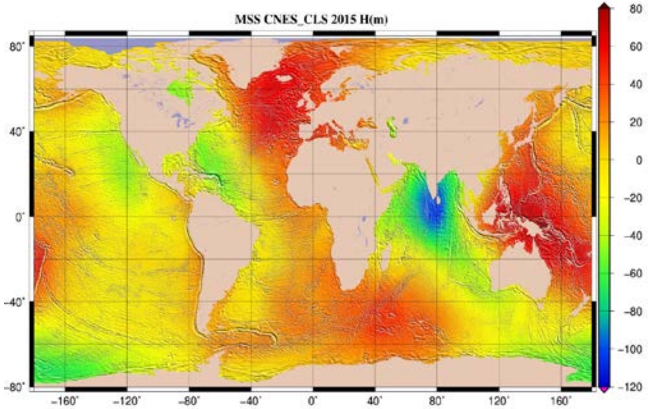
Mean Sea Surface estimation:
25 YEARS IMPROVEMENTS



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





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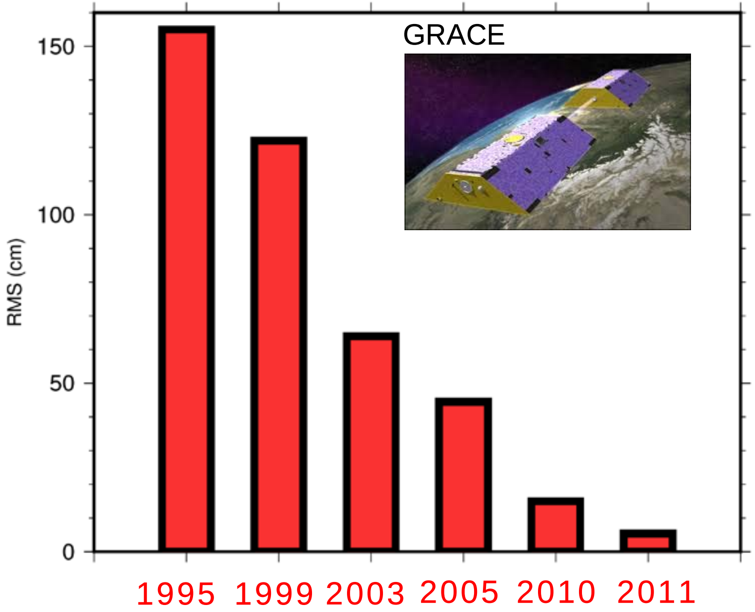
Geoid estimation:
25 YEARS IMPROVEMENTS

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)



The geostrophic approximation

E<10^{-3} R_0<10^{-3} and w<<u,v

Away from the boundary layers and away from the equator, over large (> 50-100 km) spatial and long (>2-10 days) temporal scales ocean is to the first order in geostrophic balance.

The largest terms in the equations of motion reduce to the Coriolis force and the pressure gradient.

$$0 = -\frac{1}{\rho}\frac{\partial p}{\partial x} + fv$$

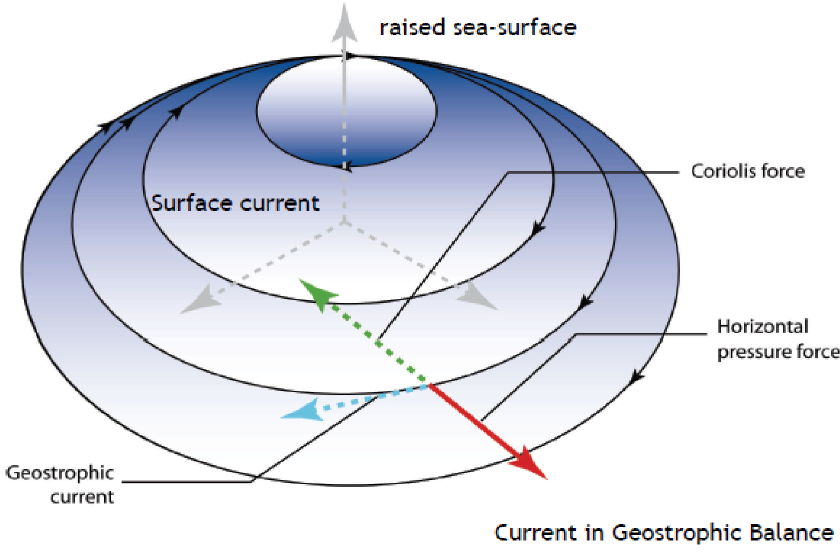
$$0 = -\frac{1}{\rho}\frac{\partial p}{\partial y} - fu$$

+ *Hydrostatic equation*

$$0 = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g$$

$$u_{geo} = -\frac{g}{f}\frac{\partial h}{\partial y}$$

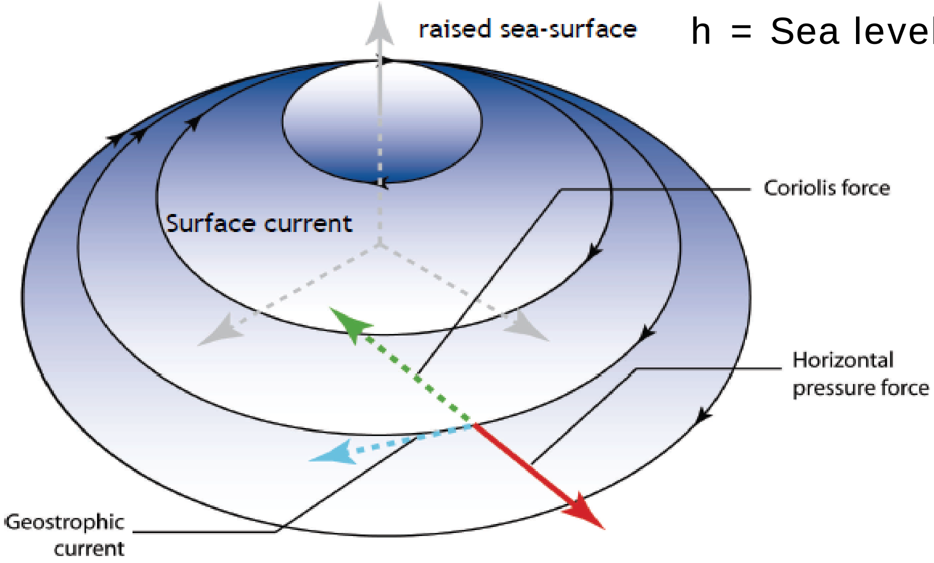
$$v_{geo} = \frac{g}{f}\frac{\partial h}{\partial x}$$



The ocean surface velocity field (u,v) can be readily obtained from the gradients of h, the sea level above the geoid h.

The geostrophic approximation

h = Sea level above geoid



Current in Geostrophic Balance

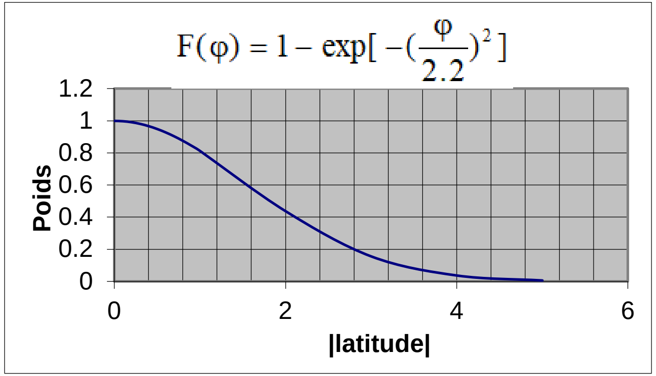
$$u_{geo} = -\frac{g}{f}\frac{\partial h}{\partial y} \qquad v_{geo} = \frac{g}{f}\frac{\partial h}{\partial x}$$

At the equator f=0, a β-plane approximation is used

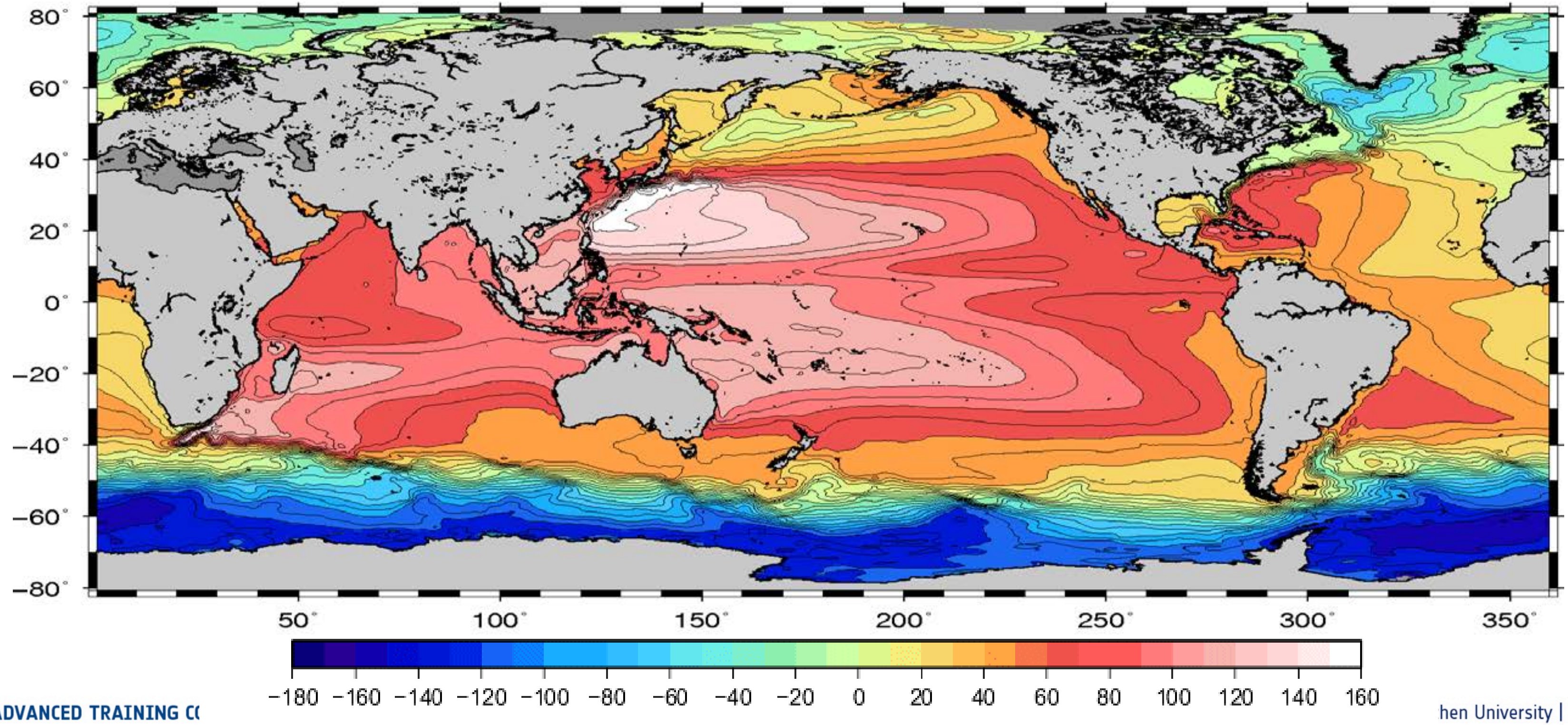
$$u = -F(\varphi)\frac{g}{f}\frac{\partial h}{\partial y} - [1-F(\varphi)]\frac{g}{\beta}\frac{\partial^2 h}{\partial y^2}$$

$$v = F(\varphi)\frac{g}{f}\frac{\partial h}{\partial x} + [1-F(\varphi)]\frac{g}{\beta}\frac{\partial^2 h}{\partial x \partial y}$$

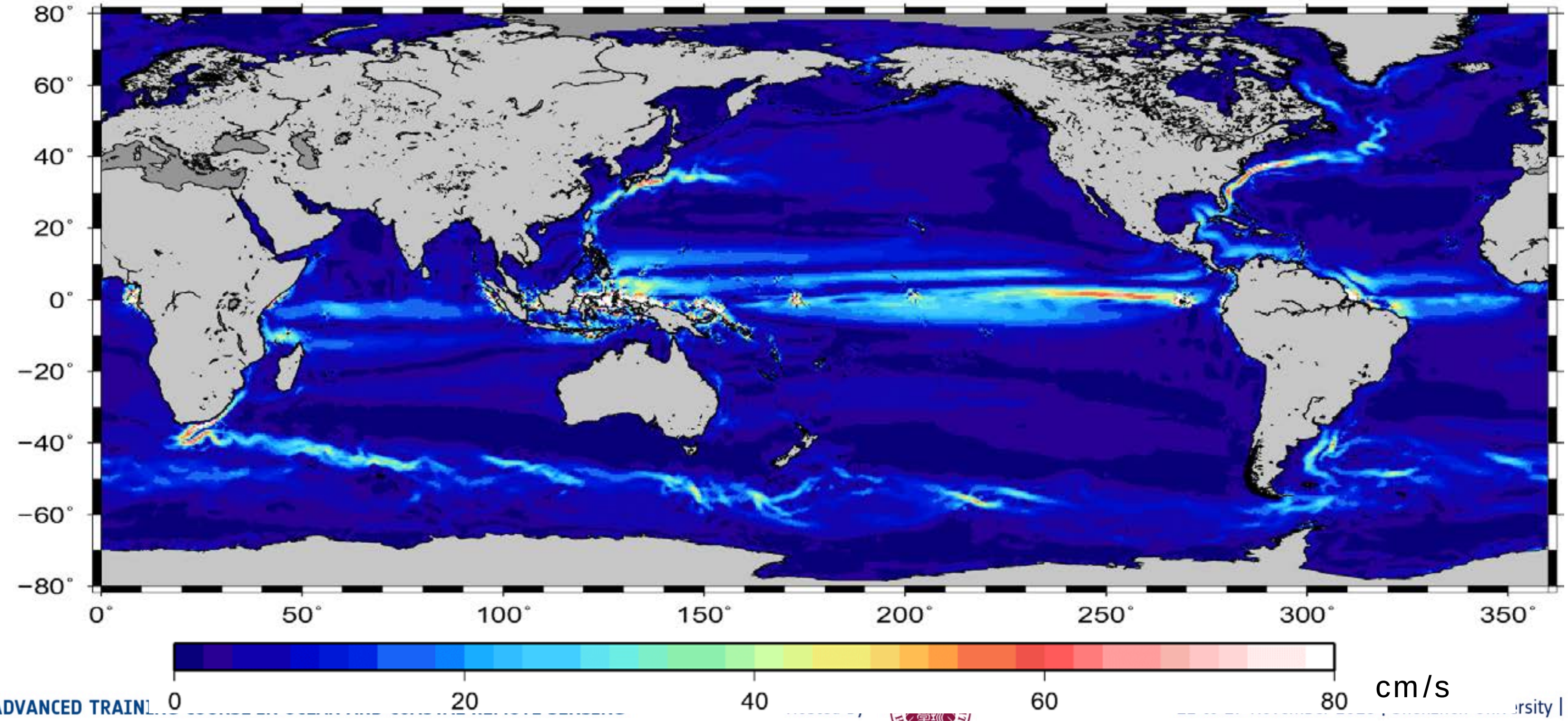
$$\beta = \frac{2\Omega}{R_T}\cos\varphi$$



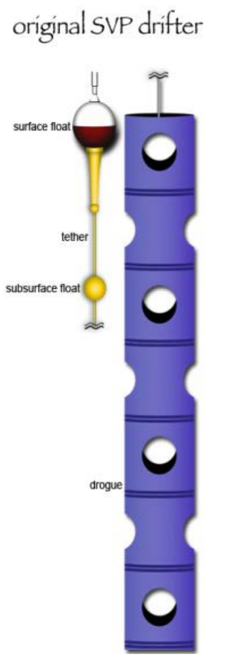
Mean Dynamic Topography



Mean geostrophic currents from the GOCE only MDT

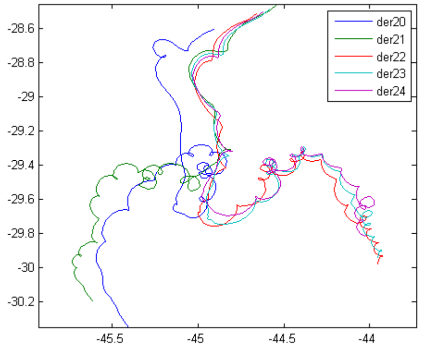


In-Situ measurements: drifting buoys

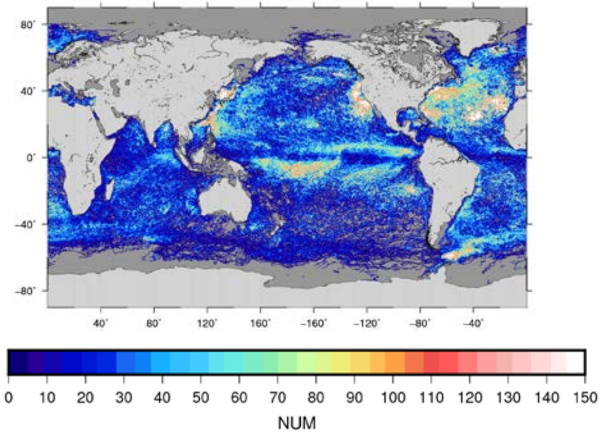


SVP (Surface Velocity Program) type

- Buoy position localized by Argos/Iridium
- Have been designed to minimize the direct wind slippage (less than 0.7 cm/s in 10 m/s winds)
- Holey-Sock drogue centered at 15 m depth -> advected by 15m depth currents
- Drogue loss detection sensor
- After quality control and position processing, regularly sampled velocities are estimated along the buoy trajectory.
- Time sampling: 1 hour, 6 hours
- Life time: ~400 days

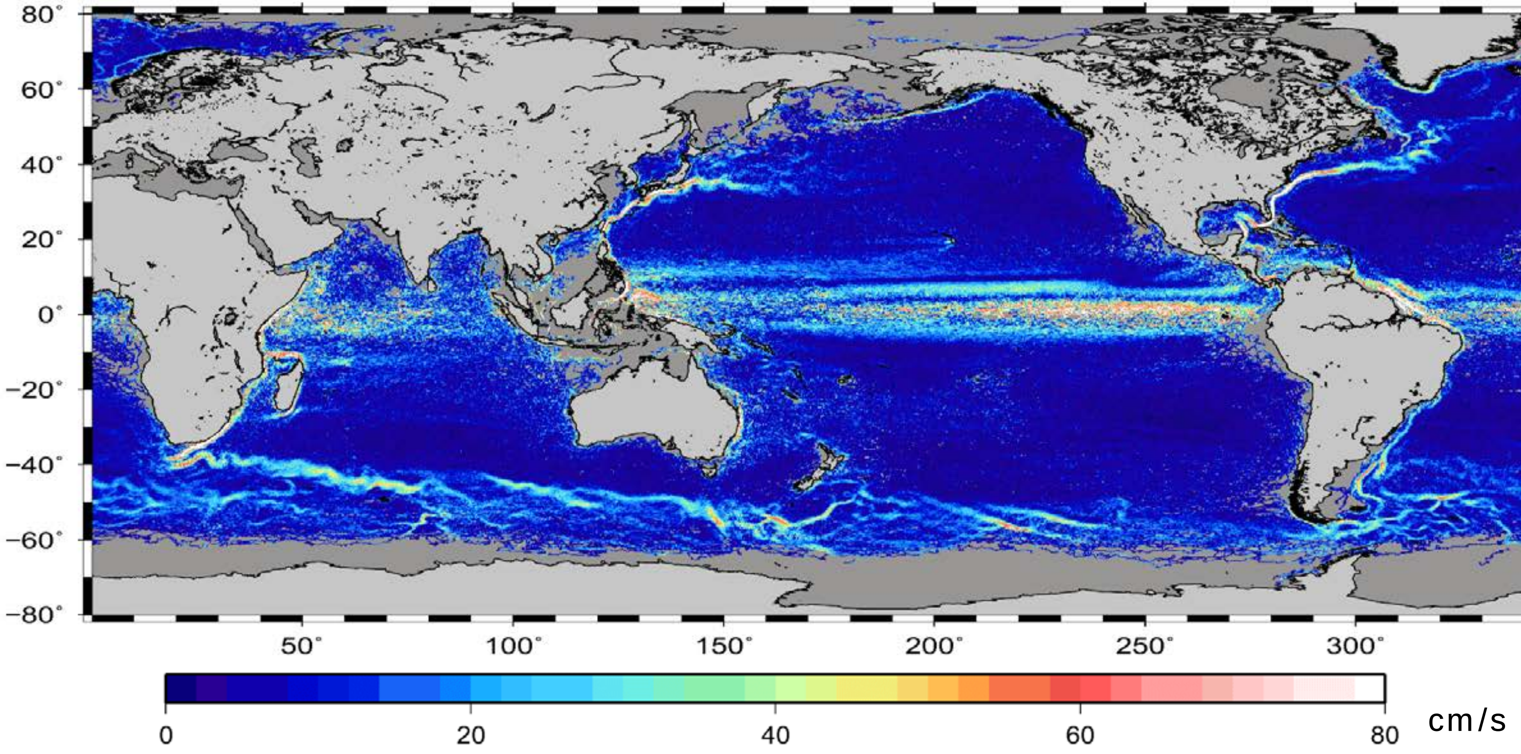


Number of obs (1993-2016)

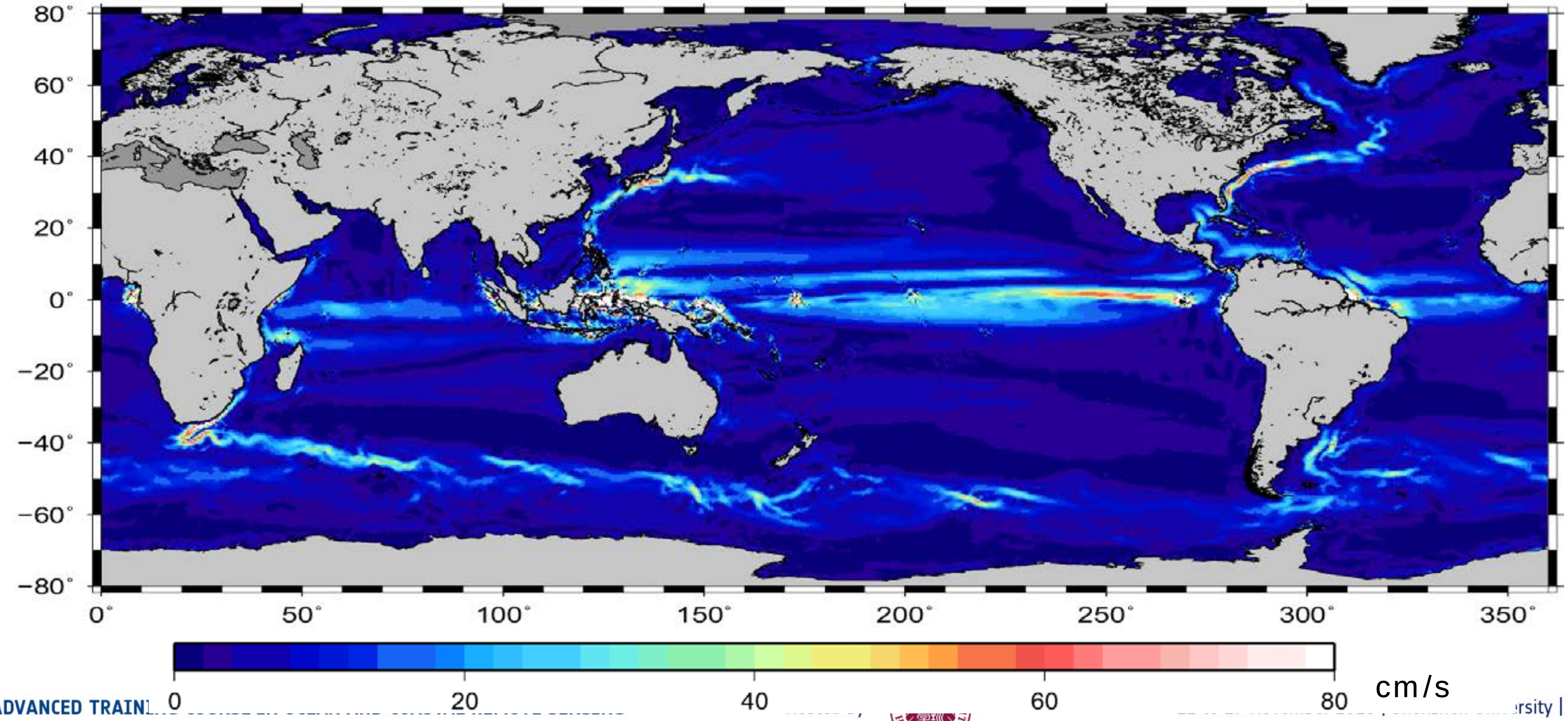


$$U_{buoy} = U_{geost} + U_{ekman} + U_{tides} + U_{inertial} + U_{stokes} + U_{ageost\_hf}$$

Mean geostrophic currents from in-situ measurements



Mean geostrophic currents from the GOCE only MDT



Comparison of mean MSSH-GOCE velocities to in-situ mean velocities

MDT=MSS-Geoid

Filtering of the MDT with a gaussian filter

Computation of the mean geostrophic currents

Computation of **synthetic estimate of mean geostrophic velocities** from in-situ oceanographic measurements and altimetry

MDT=MSS – EGM_DIR_R1

100 km (DO 200)

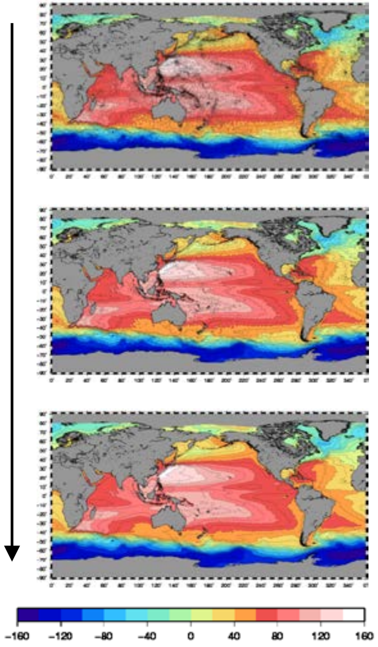
125 km (DO 160)

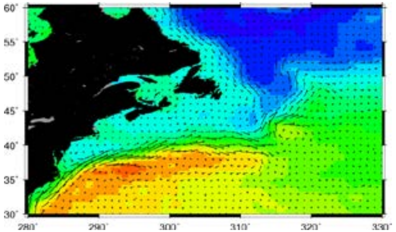
150 km (DO 133)

200 km (DO 100)

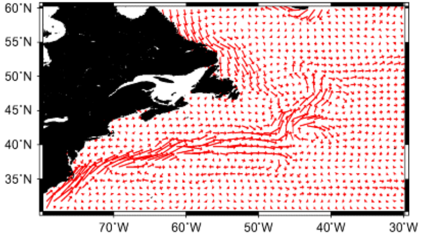
250 km (DO 80)

350 km (DO 60)



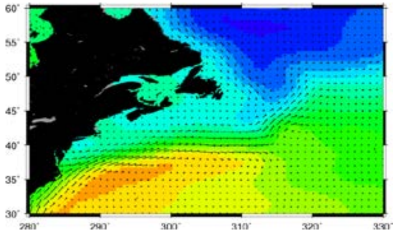


100 km

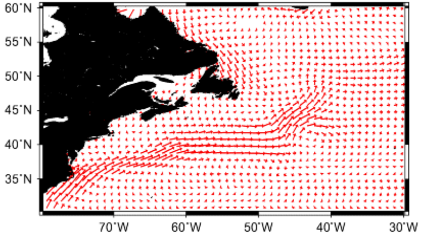


Comparison with independent data

over the global ocean



200 km



$$\sigma_1^2 = \varepsilon_{synth_f}^2 + \varepsilon_{MSS_f}^2 + \varepsilon_{Geoid_f}^2 + \varepsilon_s^2$$

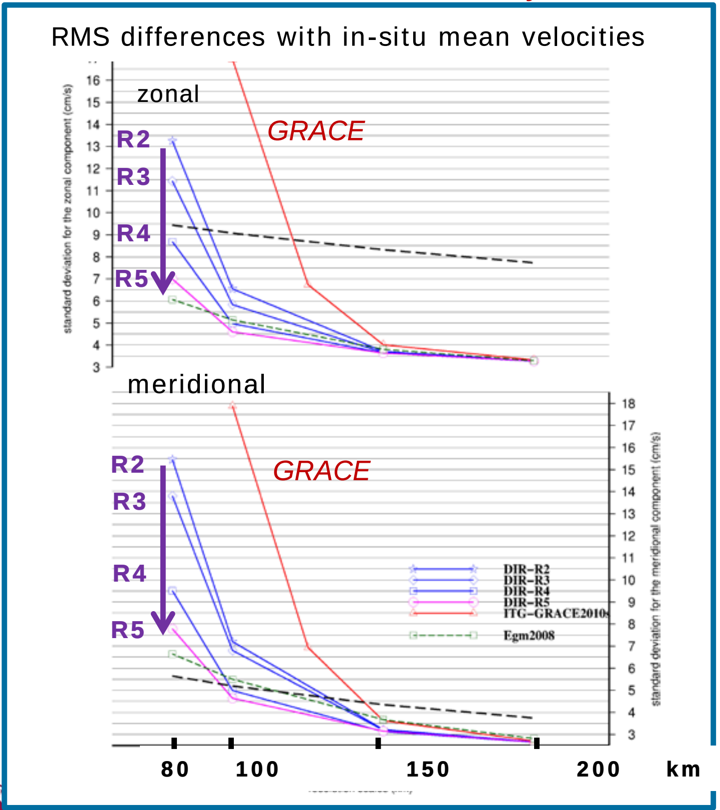
Geodetic MDT validation using independent drifting buoy velocities

Model	Year	Max DO	Data
ITG-GRACE2010s	2010	180	7 years of GRACE
GOCE	2009-2013	200-250	2 months (R1) 6 months (R2) 1 year (R3) 2 years (R4) 4 years=Full mission (R5)

GOCE orbit was lowered 4 times during the last 14 months of the mission

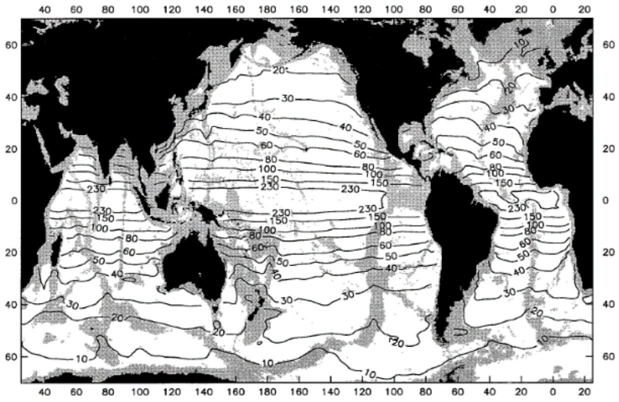
The following accuracy is obtained for GOCE R5:
4 cm/s error on mean circulation at 100km
7 cm/s error on mean circulation at 80km
Significant impact of orbit lowering (from R4 to R5): RMS differences to observations at 80 km resolution reduced by 4 % for both components

Courtesy, S. Mulet



- 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

$$\lambda = \frac{1}{|f|m\pi}\int_{-H}^{0} N(z)dz$$

High latitudes

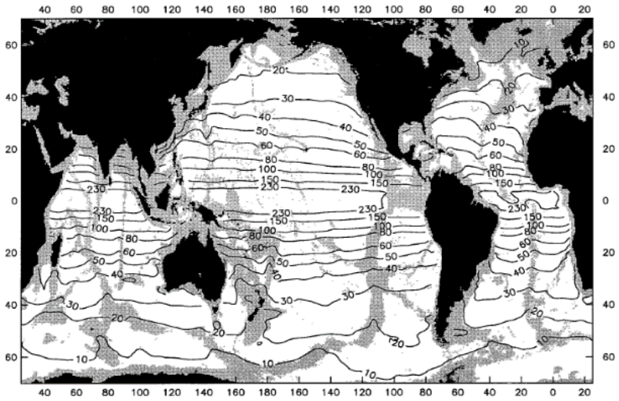
Shallow waters
Coastal areas

Highly stratified areas

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

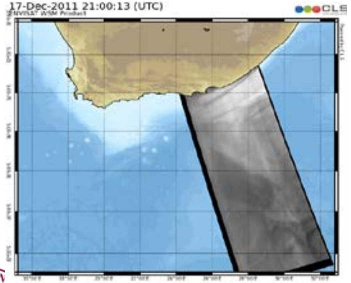
- *Global Ocean*

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*

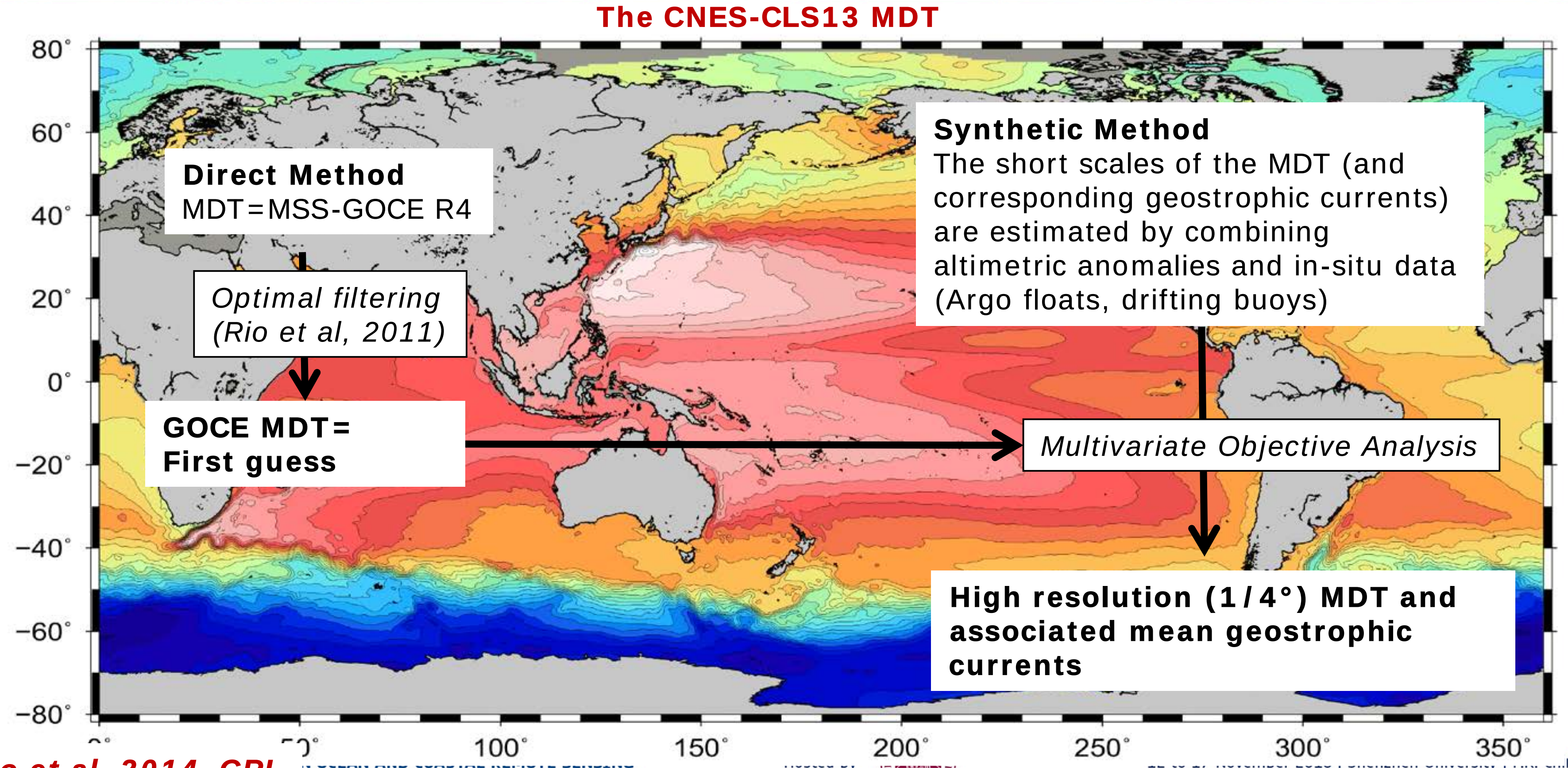
HF radar system (coastal)
Typical resolution: 1-10 km, hourly
SAR Doppler radial velocities
Typical resolution: 4-8 km, every 2-4 days

SAR



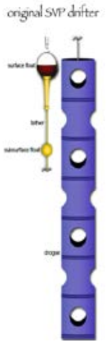
Drifters

Beyond GOCE resolution: Synergy with in-situ data

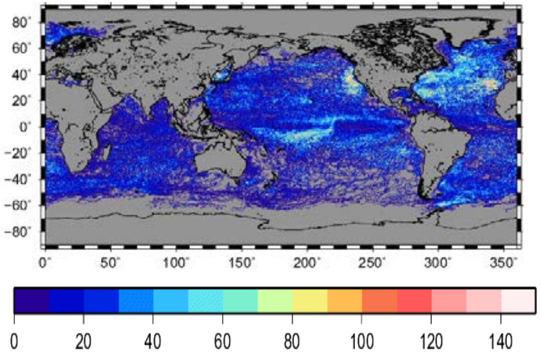


Rio et al, 2014, GRL

Beyond GOCE resolution: Synergy with in-situ data

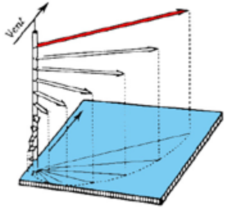


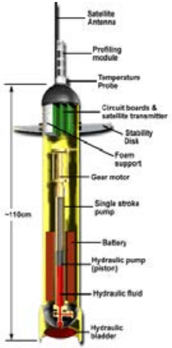
Number of SVP-type velocities (15m depth)



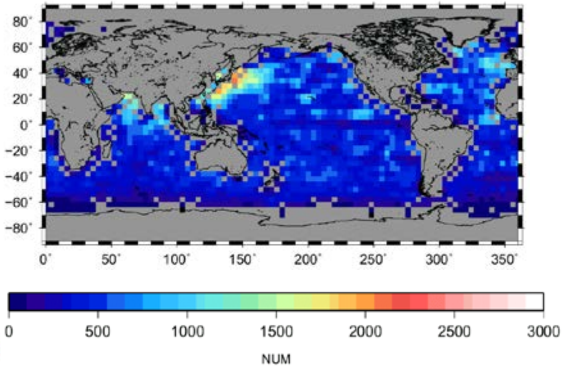
$$U_{buoy} = U_{geost} + U_{ekman} + U_{tides} + U_{inertial} + U_{stokes} + U_{ageost\_hf}$$

- ➢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

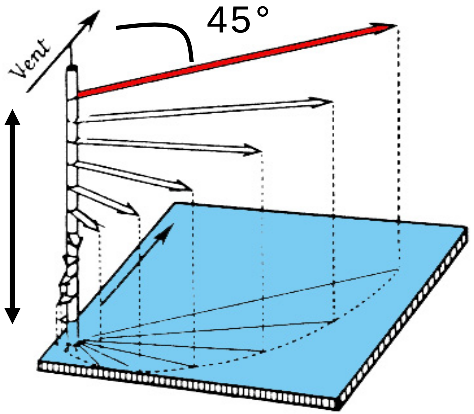
The wind-driven Ekman+Stokes currents

Wind-driven Ekman

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

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

β θ



Model

Rio et al, 2003, 2014

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

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

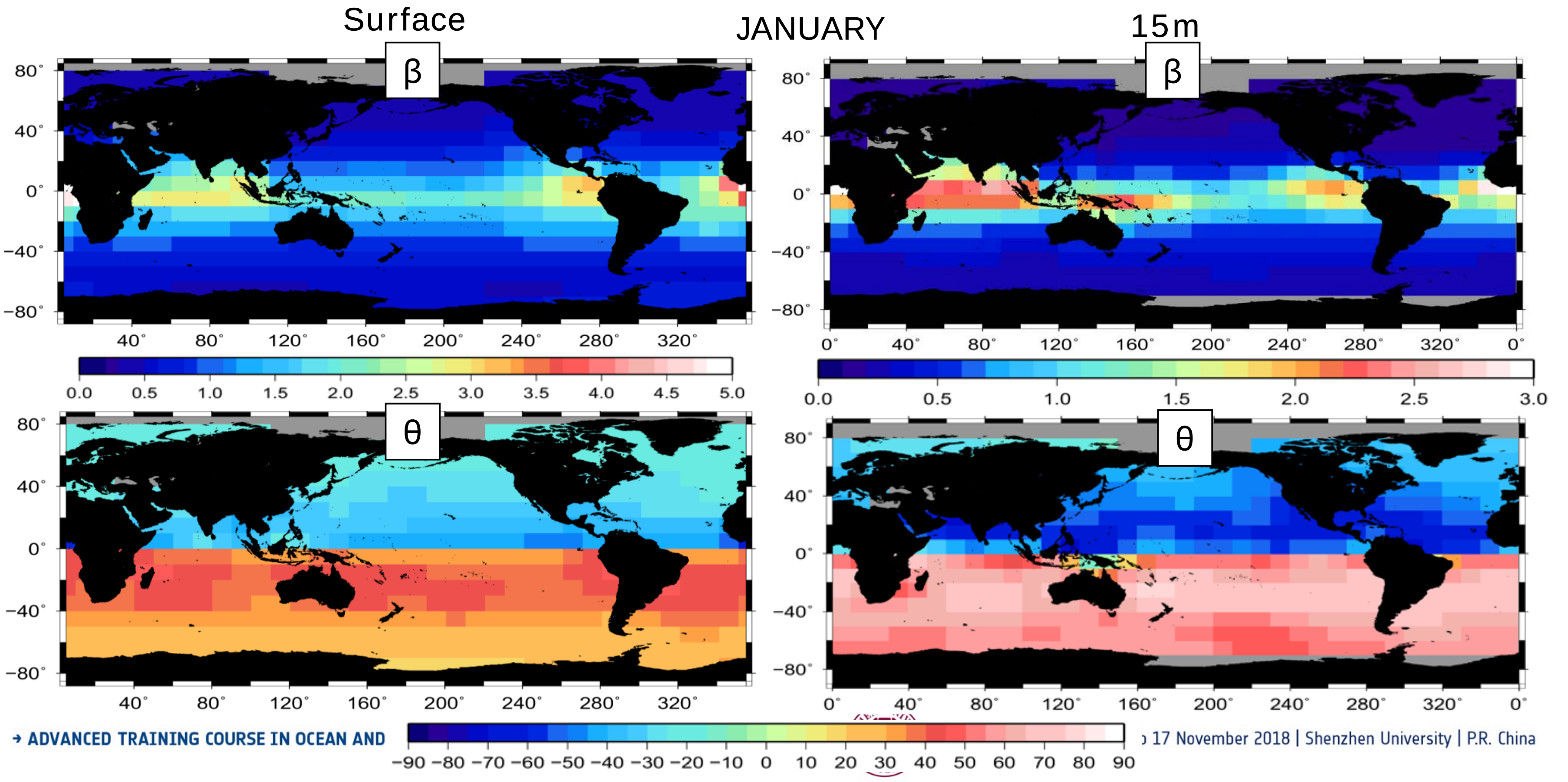
ERA INTERIM Wind stress

τ_e= Effective Wind Stress
D_e= Ekman depth
f= planetary vorticity
w=local vorticity

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

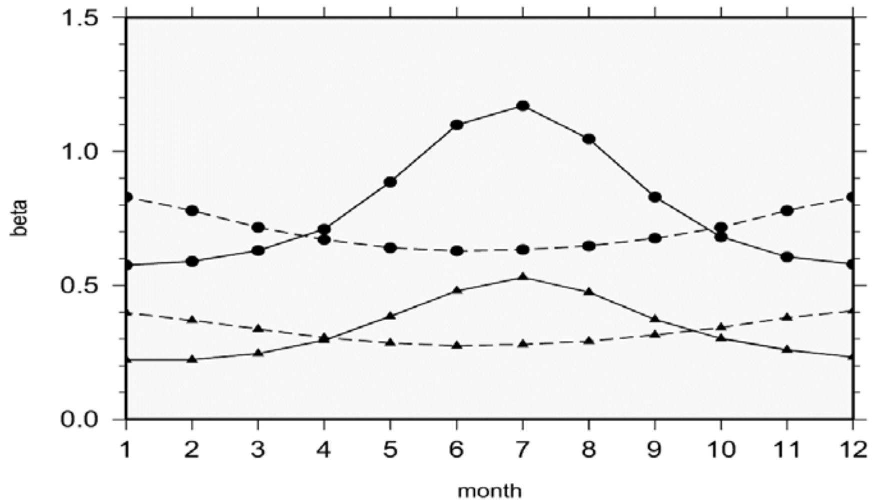
β and θ are estimated through least square fit by month and 4° boxes. At the surface using the Argo float surface velocity dataset **from YoMAHA. At 15m** depth using SVP Drifting buoys **flagged as DROGUED by the SD-DAC**

The wind-driven Ekman+Stokes currents

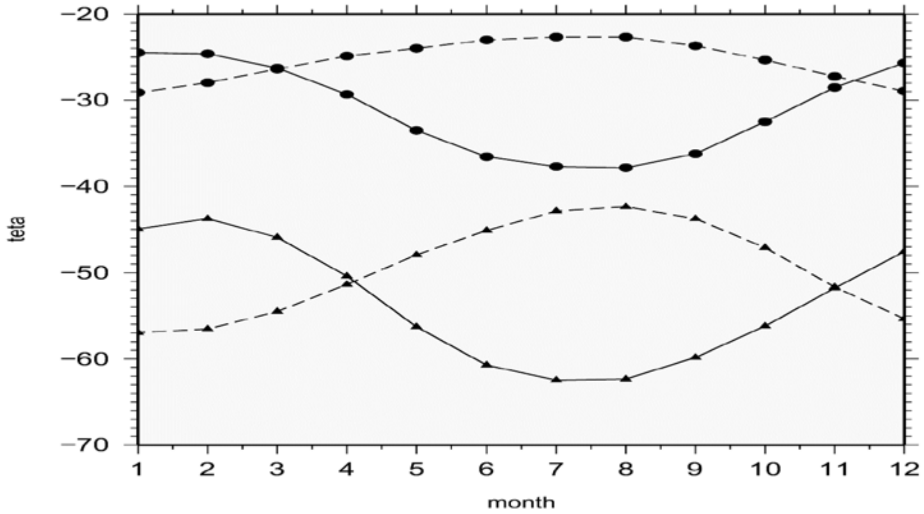


The wind-driven Ekman+Stokes currents

β (m^2s/kg)



θ (°C)



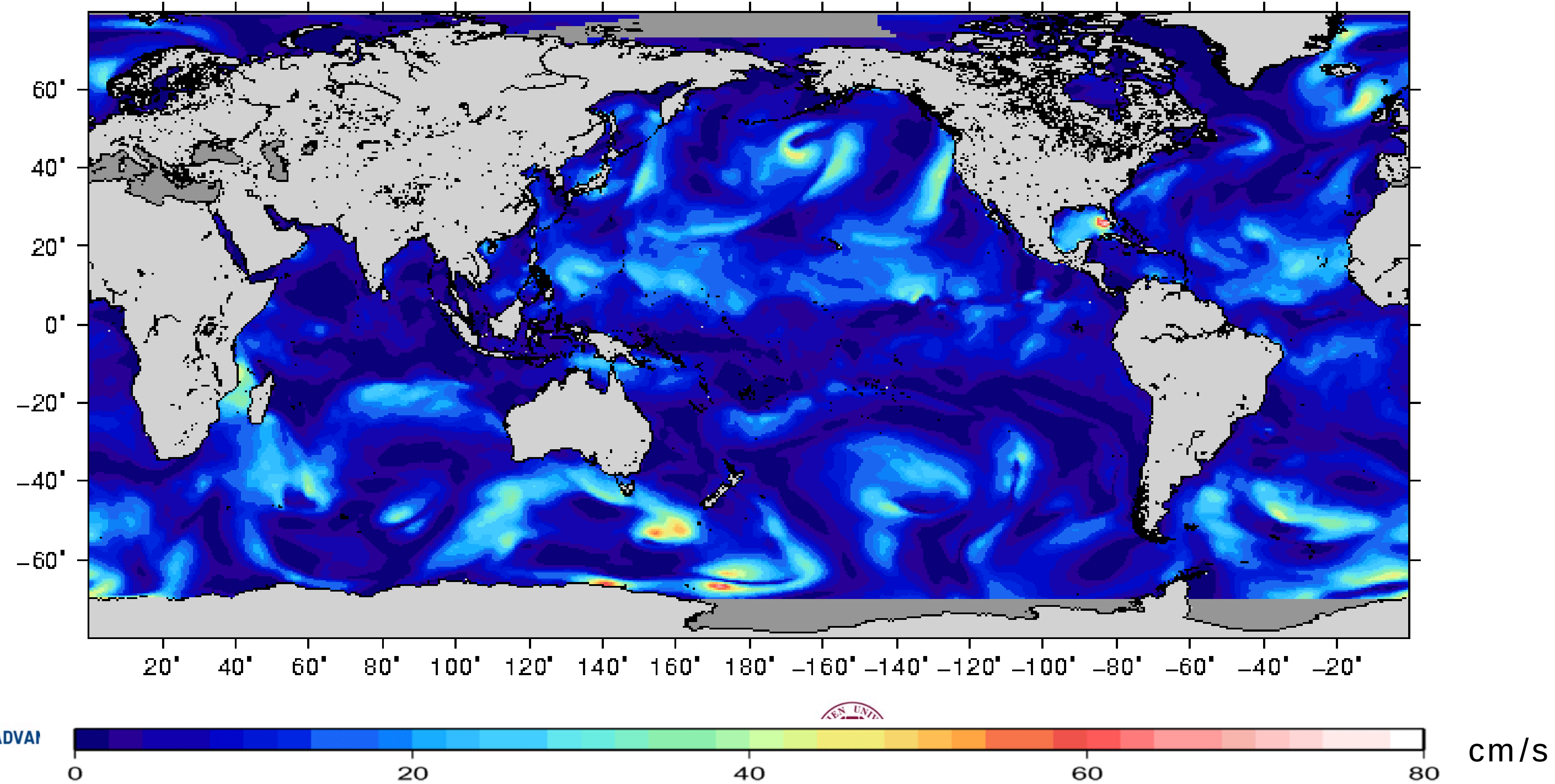
Northern Hemisphere: solid line
Southern Hemisphere: dashed line
Surface: circles
15m depth: triangles

In Summer stratification increases => De decreases

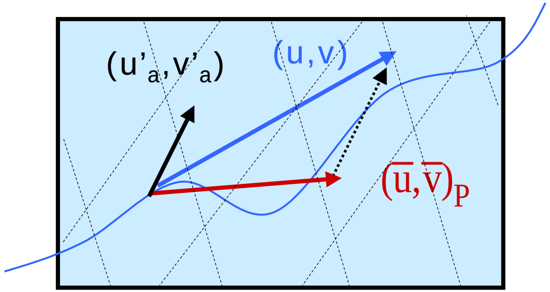
$$\beta = \frac{\pi\sqrt{2}}{\rho f D_E} e^{\frac{\pi}{D_E} z}$$ increases

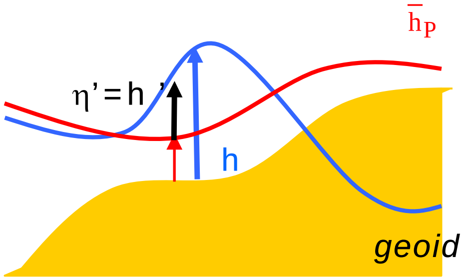
$$|\theta| = \left(\frac{\pi}{4} + \frac{15}{D_e}\right)$$ increases

The wind drivenEkman+Stokes current
May, 5th 2016



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.

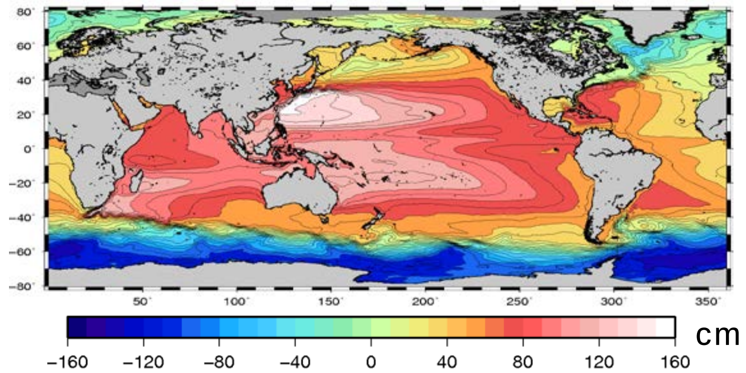
- the altimetric height/velocity anomaly is interpolated to the position/date of the in-situ data.

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

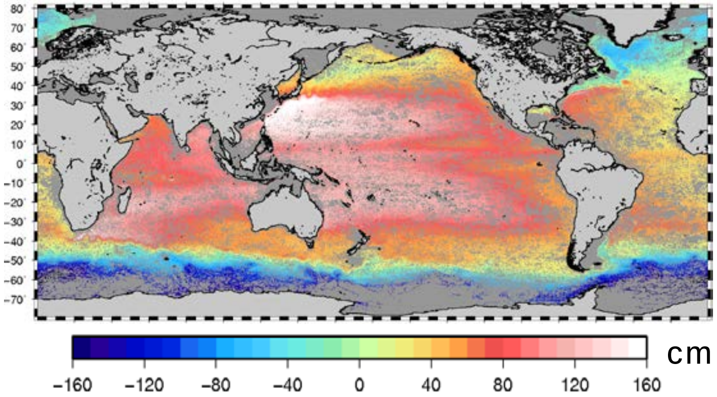
$$\bar{h}_P = h_{insitu} - h'_P \qquad \bar{u}_P = u_{insitu} - u'_P \qquad \bar{v}_P = v_{insitu} - v'_P$$

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

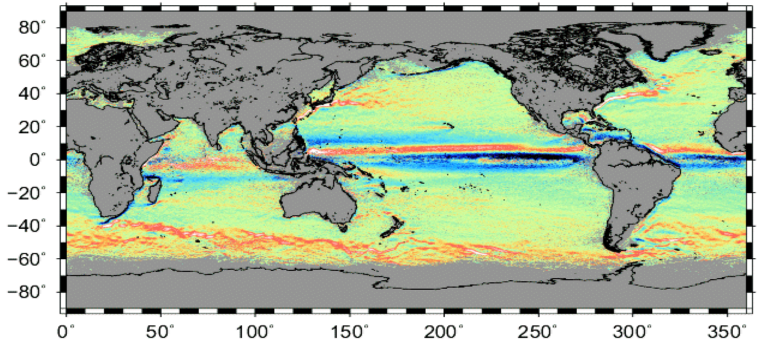
First Guess = MSS – Geoid   OPTIMALLY FILTERED



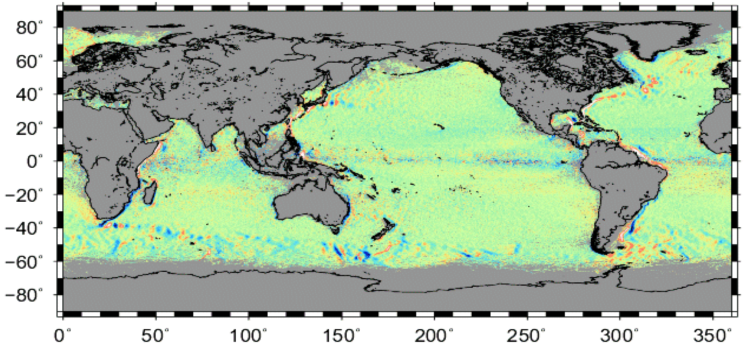
Synthetic Mean Heights (1/4° box means)

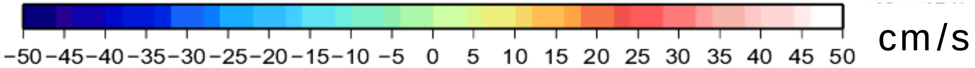


Synthetic Mean Zonal Velocity (1/4° box means)

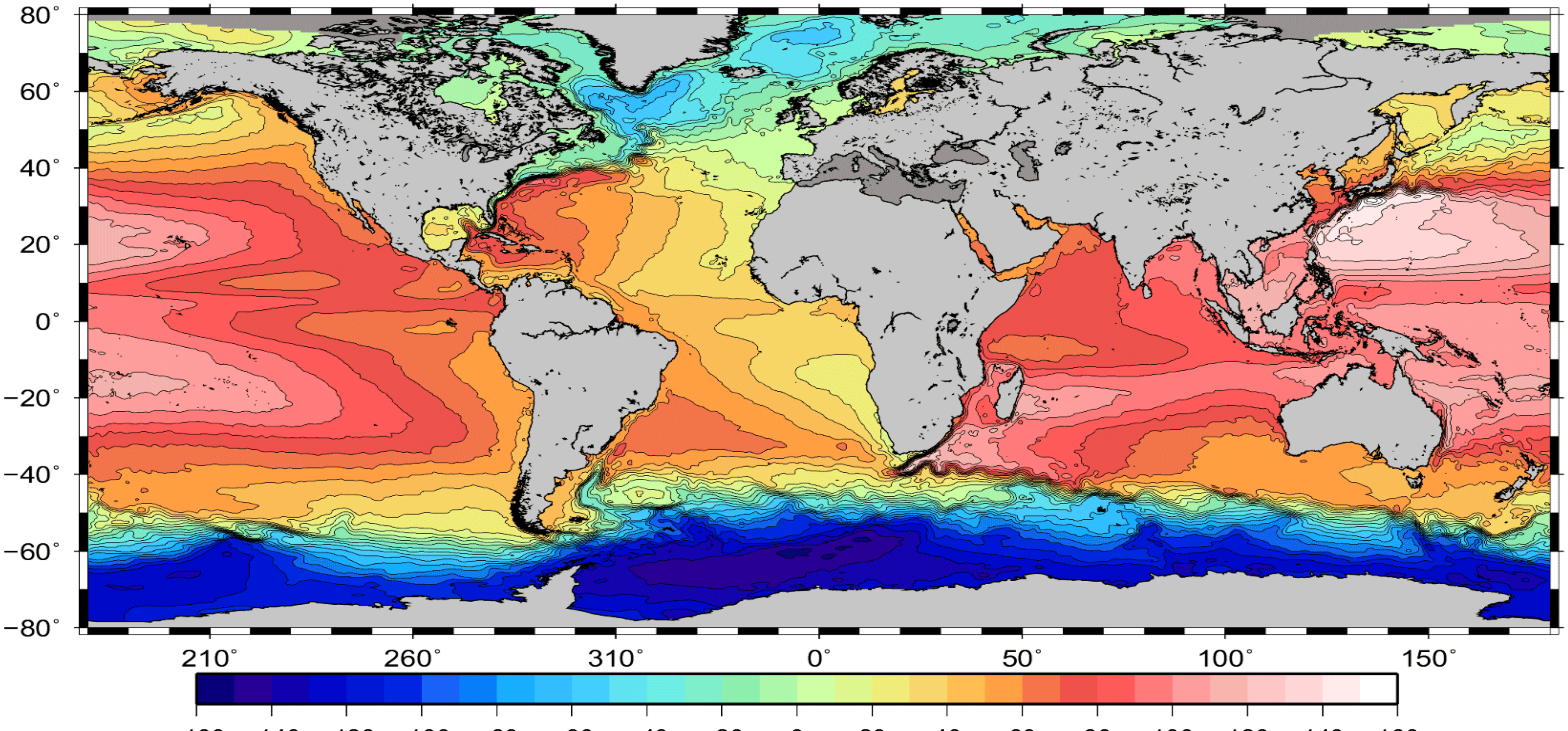


Synthetic Mean Meridional Velocity (1/4° box means)

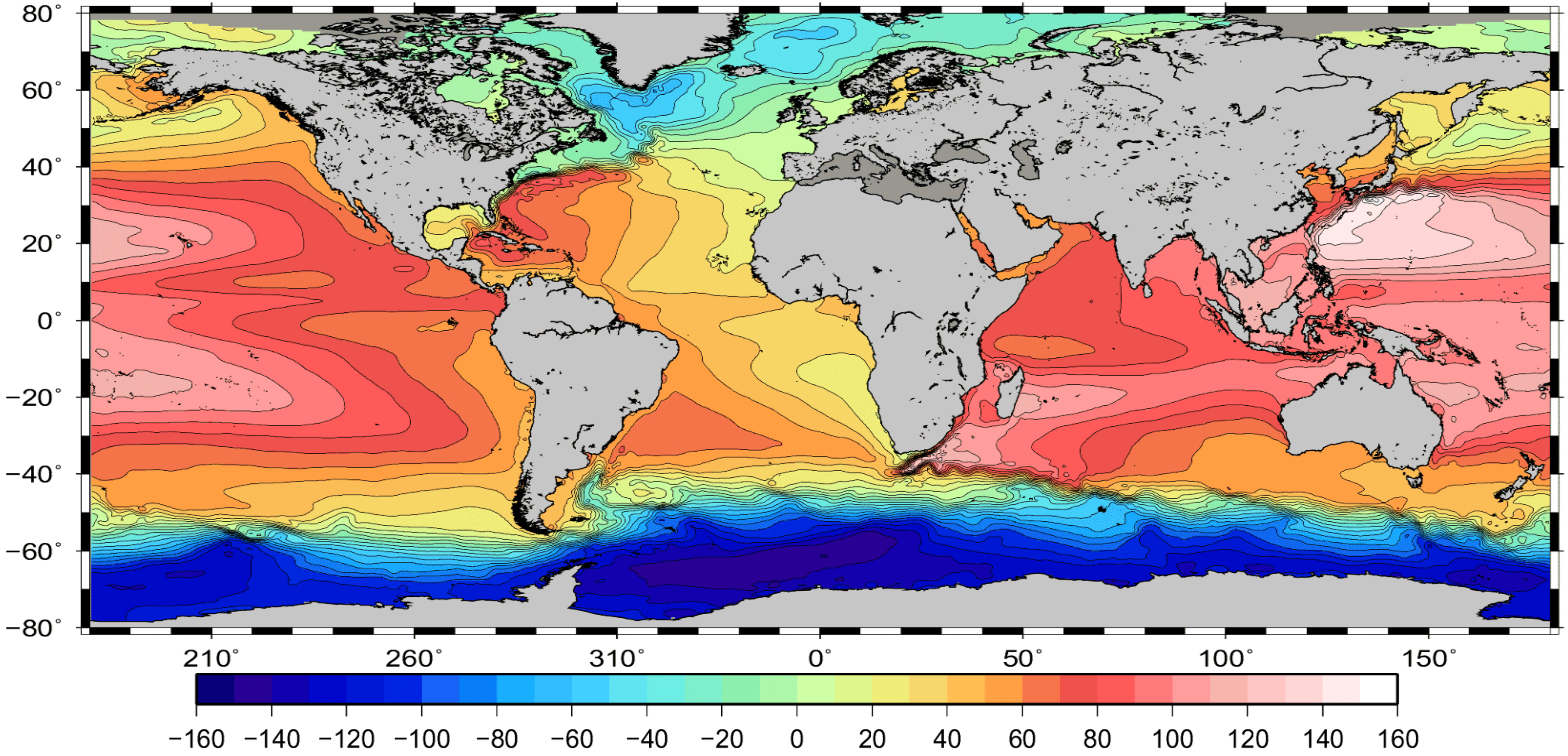




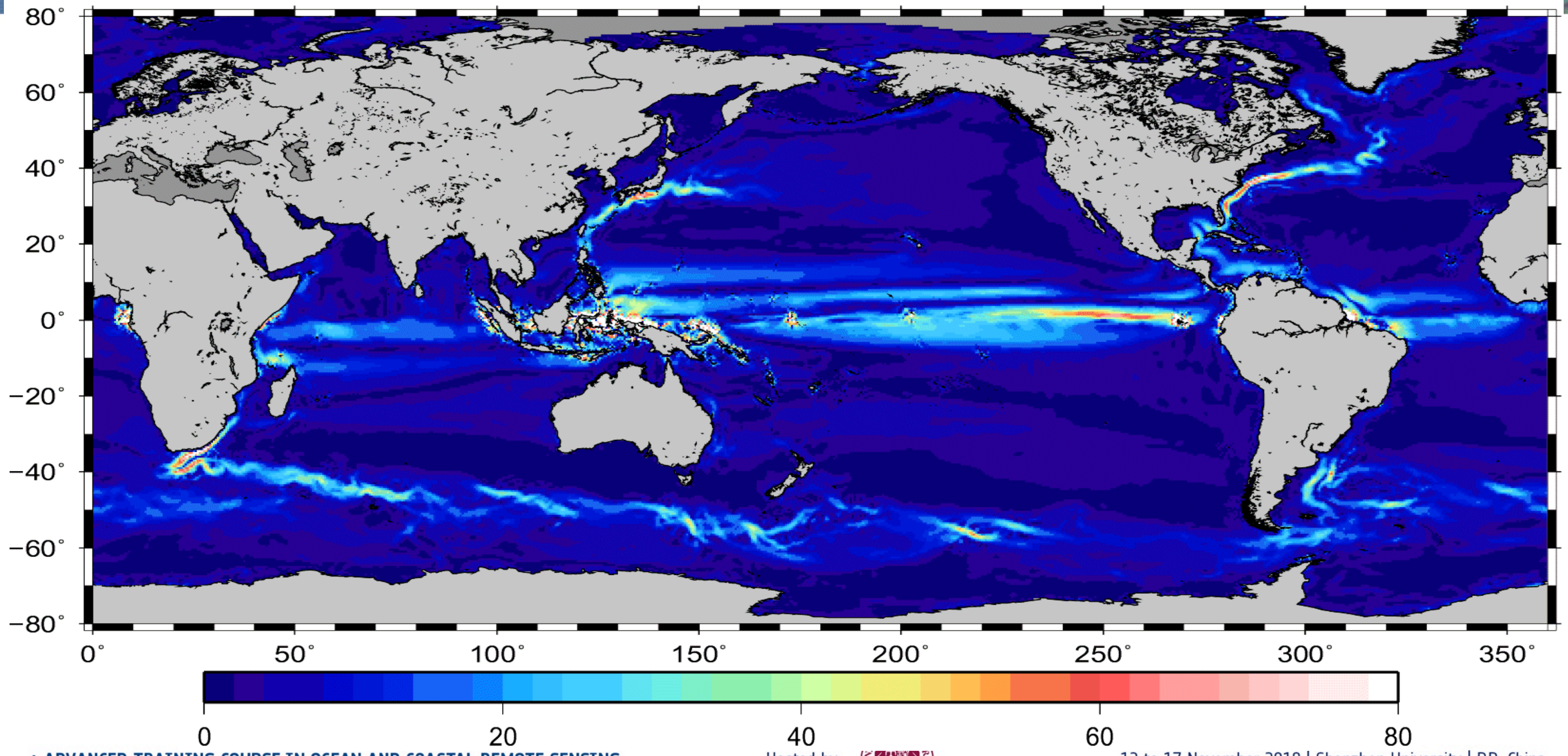
The CNES-CLS13 MDT



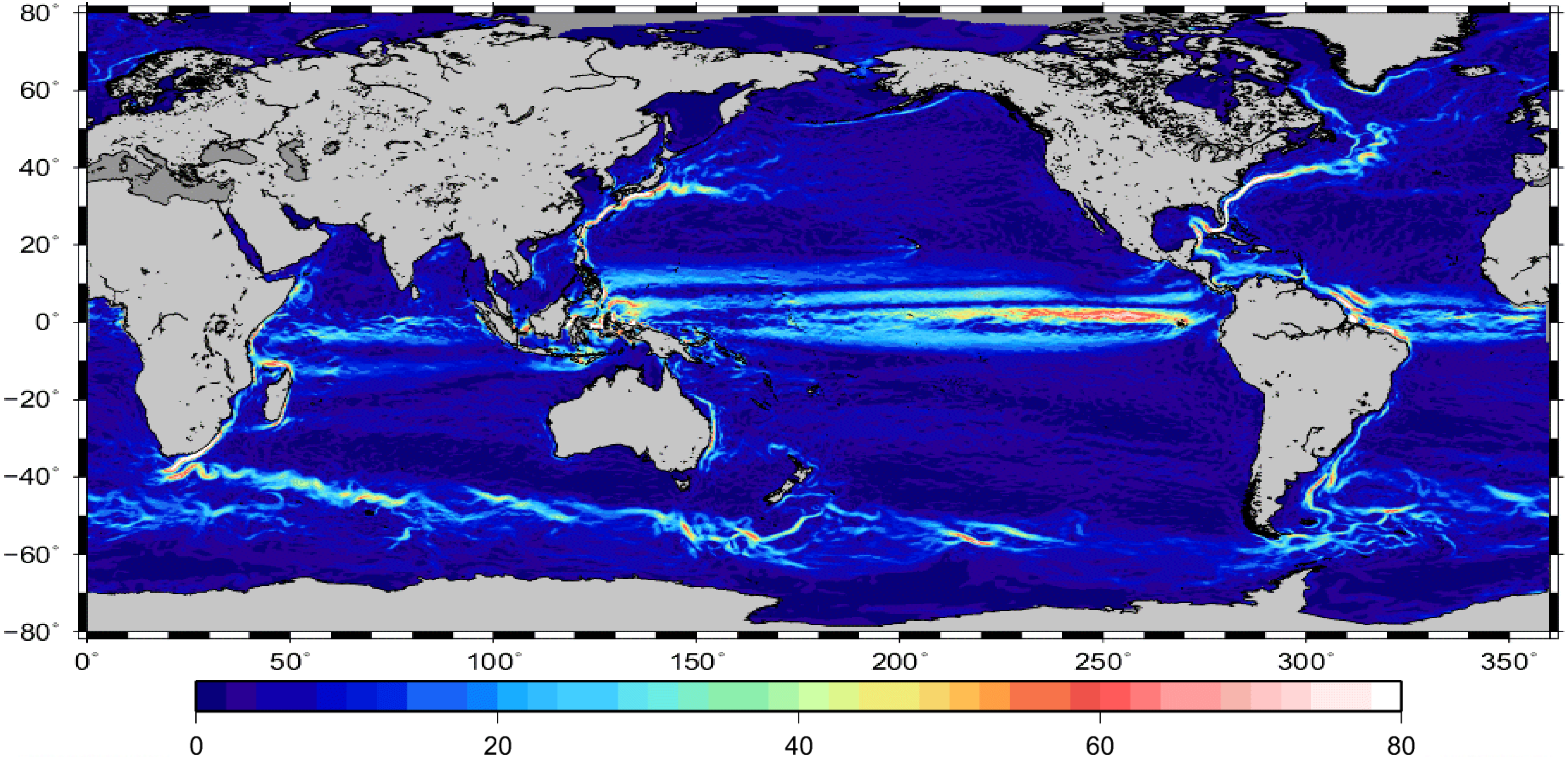
The GOCE only MDT (First Guess)



The GOCE only MDT (First Guess)



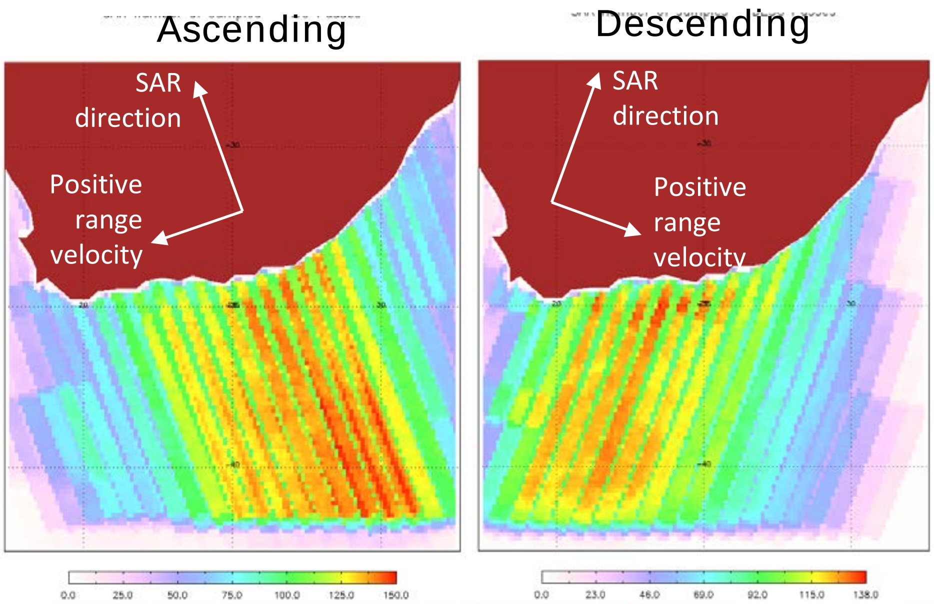
The CNES-CLS13 MDT



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.

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

Refinement in the Agulhas current using SAR Doppler velocities

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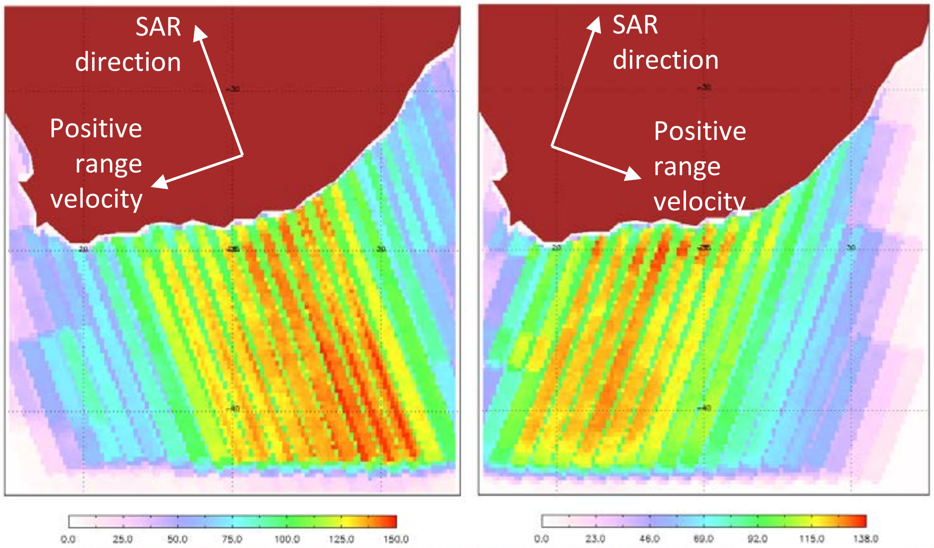
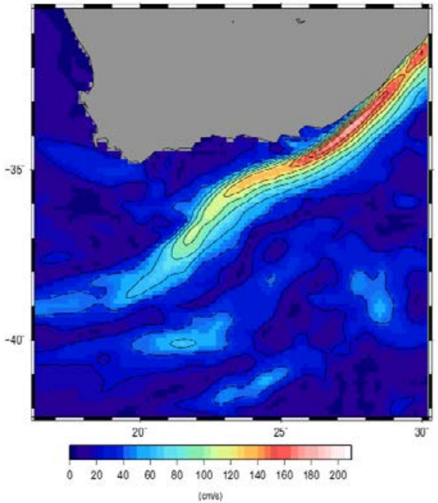
SAR number of samples

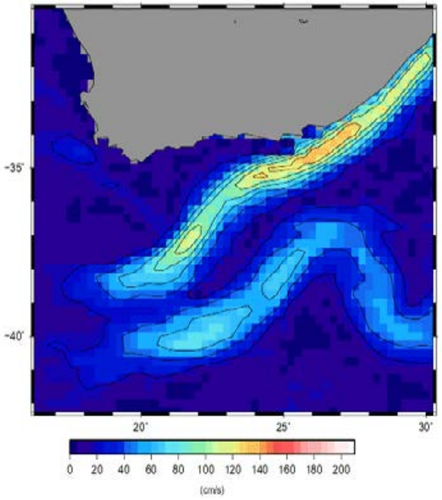
Ascending | Descending



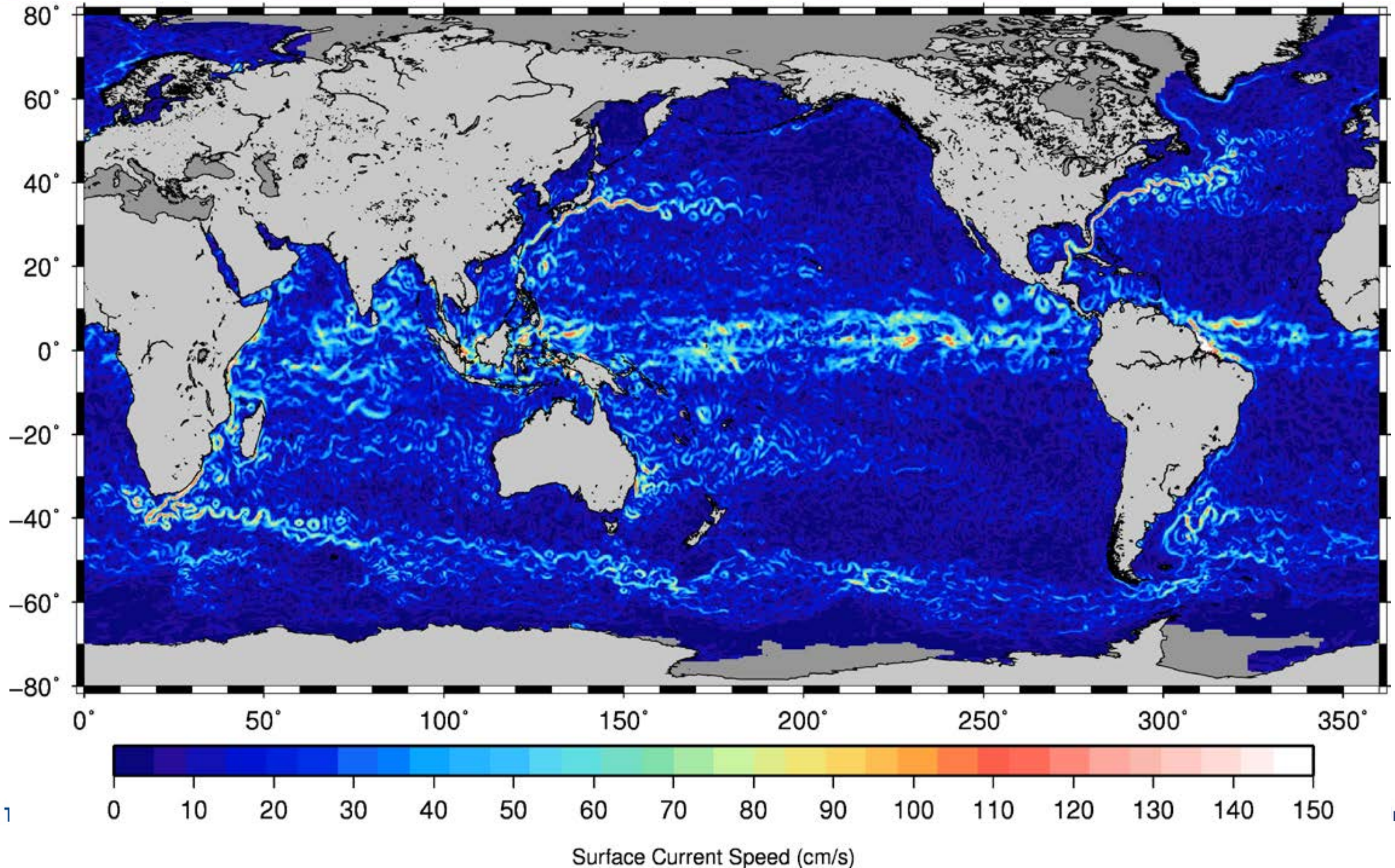
SAR MDT



CNES-CLS13 MDT



25 Years of geostrophic ocean currents



Simplified decomposition of Ocean Surface Currents (OSC)

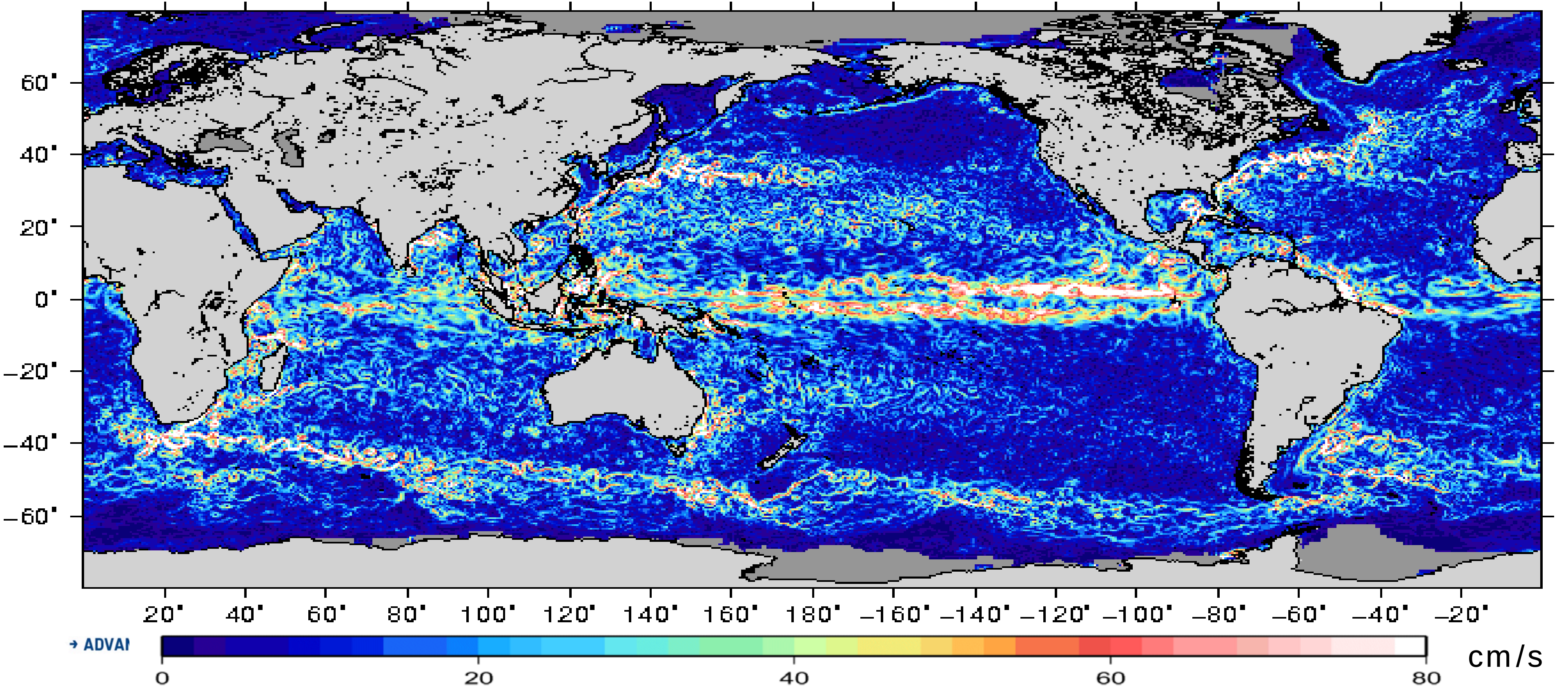
$$U_{osc} = u + \frac{\sqrt{2}}{\rho_0(f+\omega)\delta} e^{z/\delta} \left[\tau_e^x \cos\left(\frac{z}{\delta} - \frac{\pi}{4}\right) - \tau_e^y \sin\left(\frac{z}{\delta} - \frac{\pi}{4}\right) \right]$$

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

underlying flow → U_{geo}, V_{geo}

upper wind stress driven flow → U_{ekman}, V_{ekman}

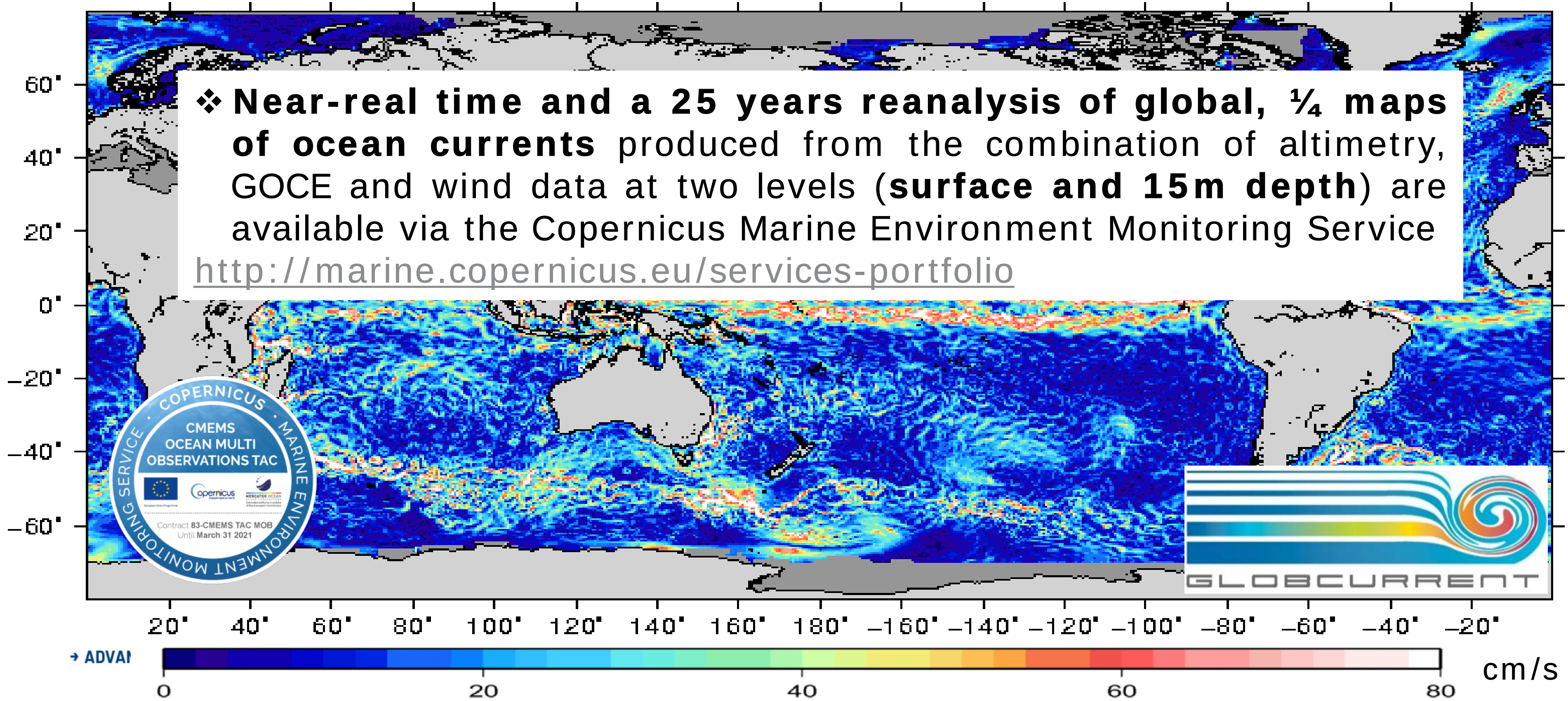
The Geostrophic current May, 5th 2016



Ocean Surface Current from Gravity+Altimetry+Wind

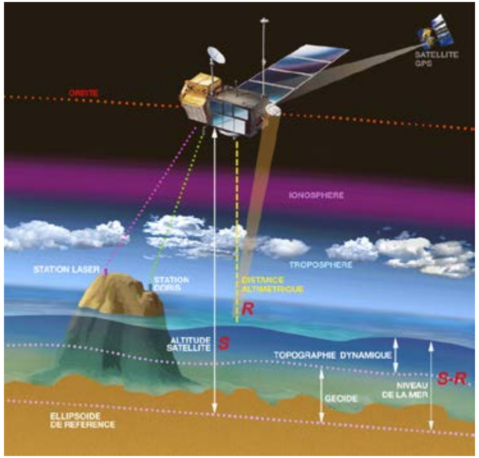
❖ **Near-real time and a 25 years reanalysis of global, ¼ maps of ocean currents** produced from the combination of altimetry, GOCE and wind data at two levels (**surface and 15m depth**) are available via the Copernicus Marine Environment Monitoring Service

http://marine.copernicus.eu/services-portfolio



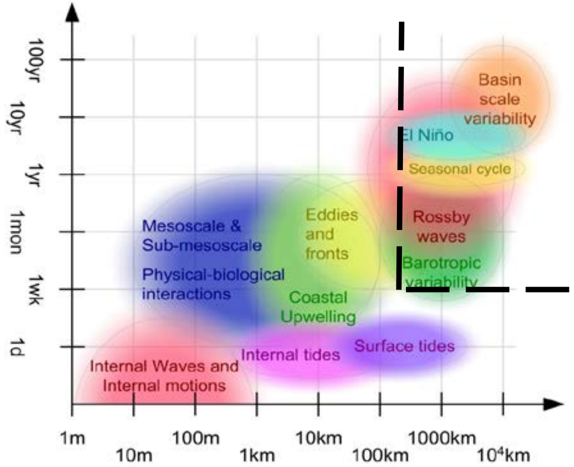
Extra slides on SSH/SST synergy

➢Limitations of the altimetry system for ocean current estimation



$$u = -\frac{g}{f}\frac{\partial h}{\partial y}$$

$$v = \frac{g}{f}\frac{\partial h}{\partial x}$$

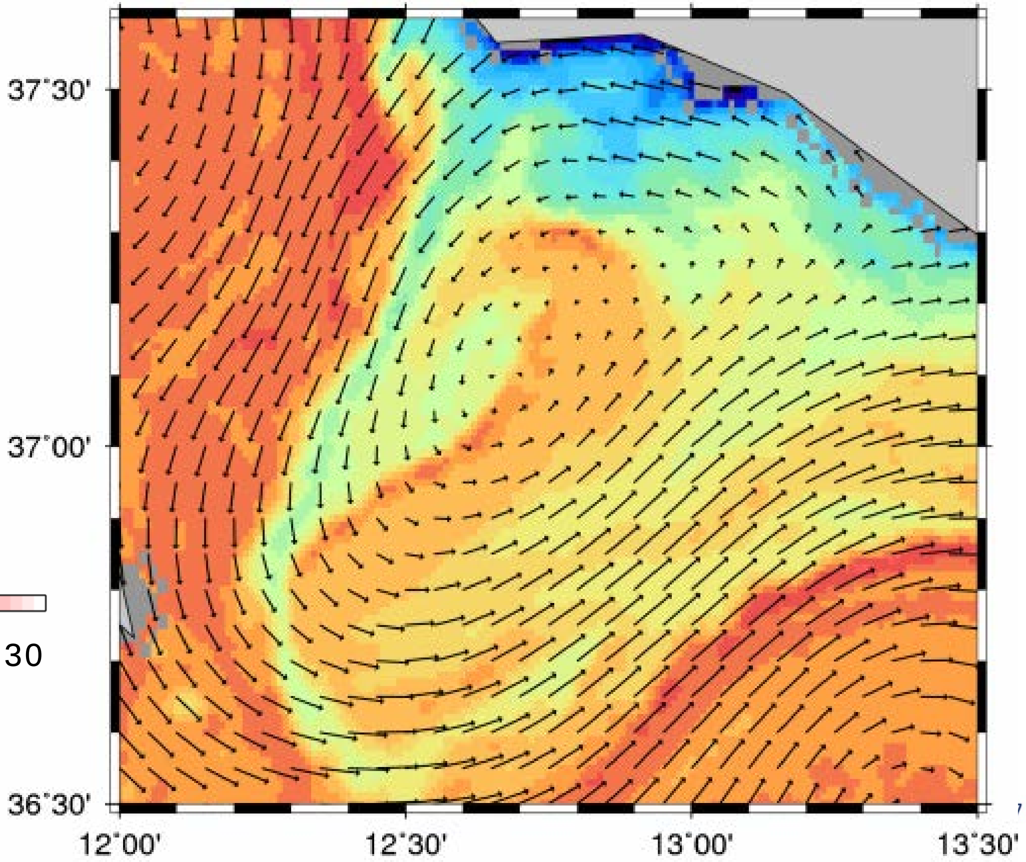


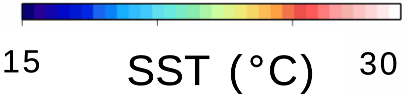
❖Only the **geostrophic component of the surface current** is obtained

❖For a **limited part of the spatio-temporal spectra**

In order to go beyond the altimeter system limitations, **new sensors and new methodologies must be explored**

Sentinel-3 data on July, 28th 2016





SSH / SST combination method for velocity calculation

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**.

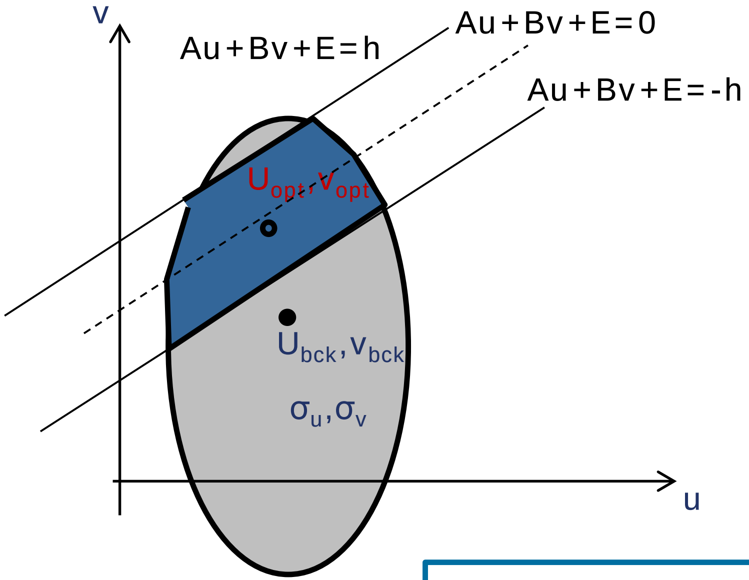
Synergy : Following an approach proposed by Piterbarg et al (2009), the method is used on successive SST images using the altimeter geostrophic velocities as background so as to obtain an optimized 'blended' velocity (u_{opt}, v_{opt}).
Rio et al, 2016, 2018

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

Temporal SST variations

Forcing term estimates

Forcing term error

Background velocity error

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

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

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

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

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

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

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

Global implementation over 2014-2016

DATA USED

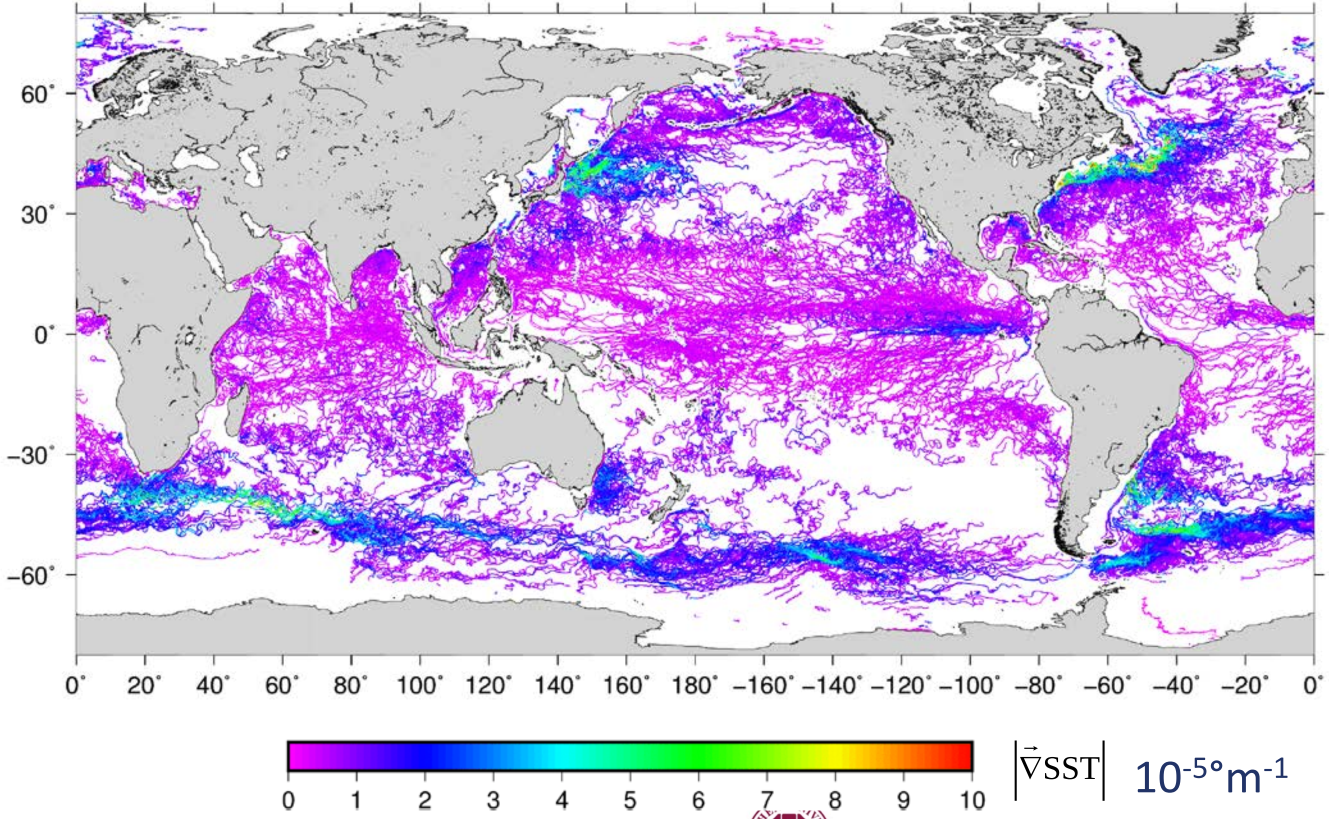
- Background velocities: CMEMS L4 altimeter gridded geostrophic velocity products:
  « twosat » (2 satellites configuration) - resolution ~250 km
  « allsat » (5 satellites configuraton) - resolution ~100km

- 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

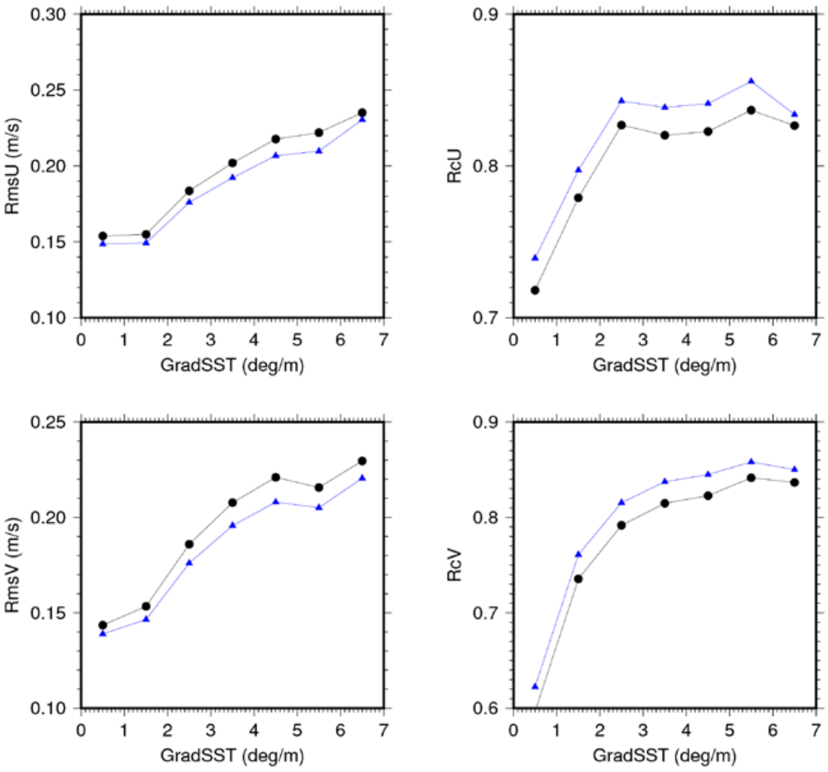
→ Three years (2014-2016) of global combined « twosat » SSH + MW SST and « allsat » SSH + MW-IR SST has been produced.

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

Global implementation over 2014-2016



$\left|\vec{\nabla}\mathrm{SST}\right|$ $10^{-5}°m^{-1}$

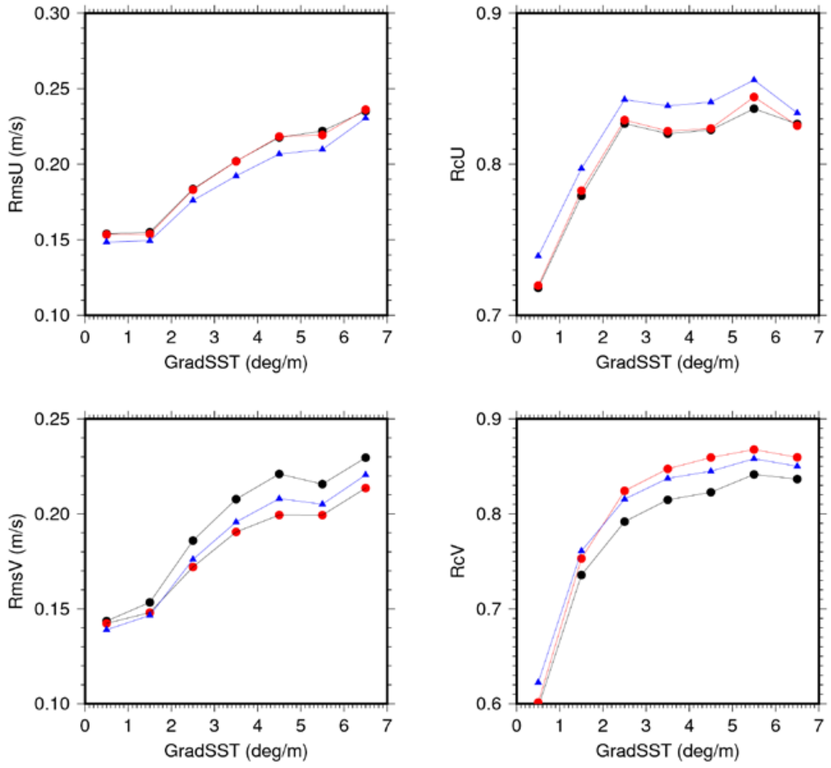


Alti « twosat »

Alti « allsat »

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

Rio and Santoleri, 2018

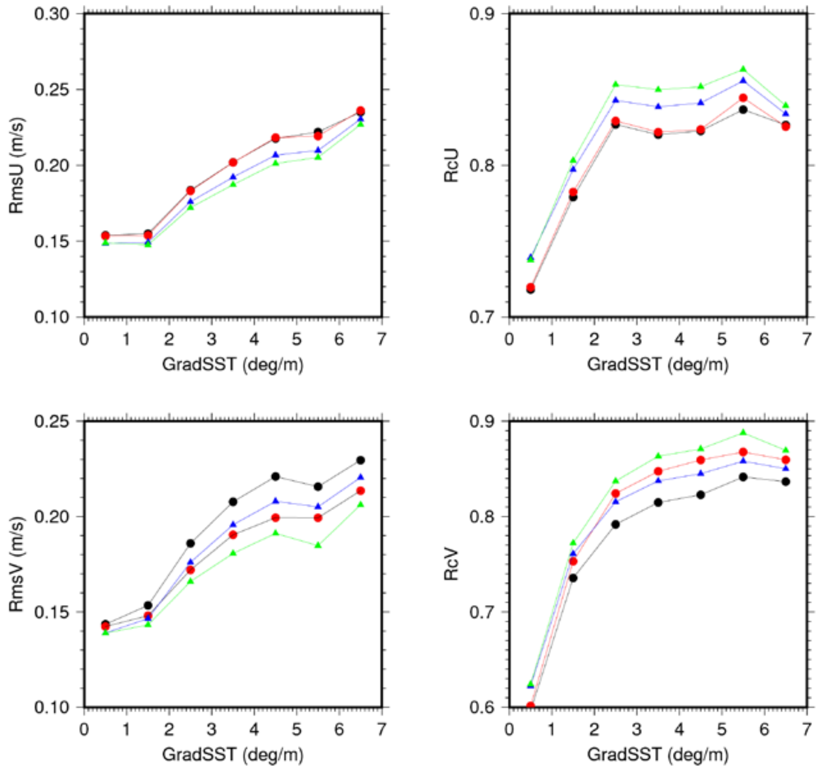


Alti « twosat »

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 »



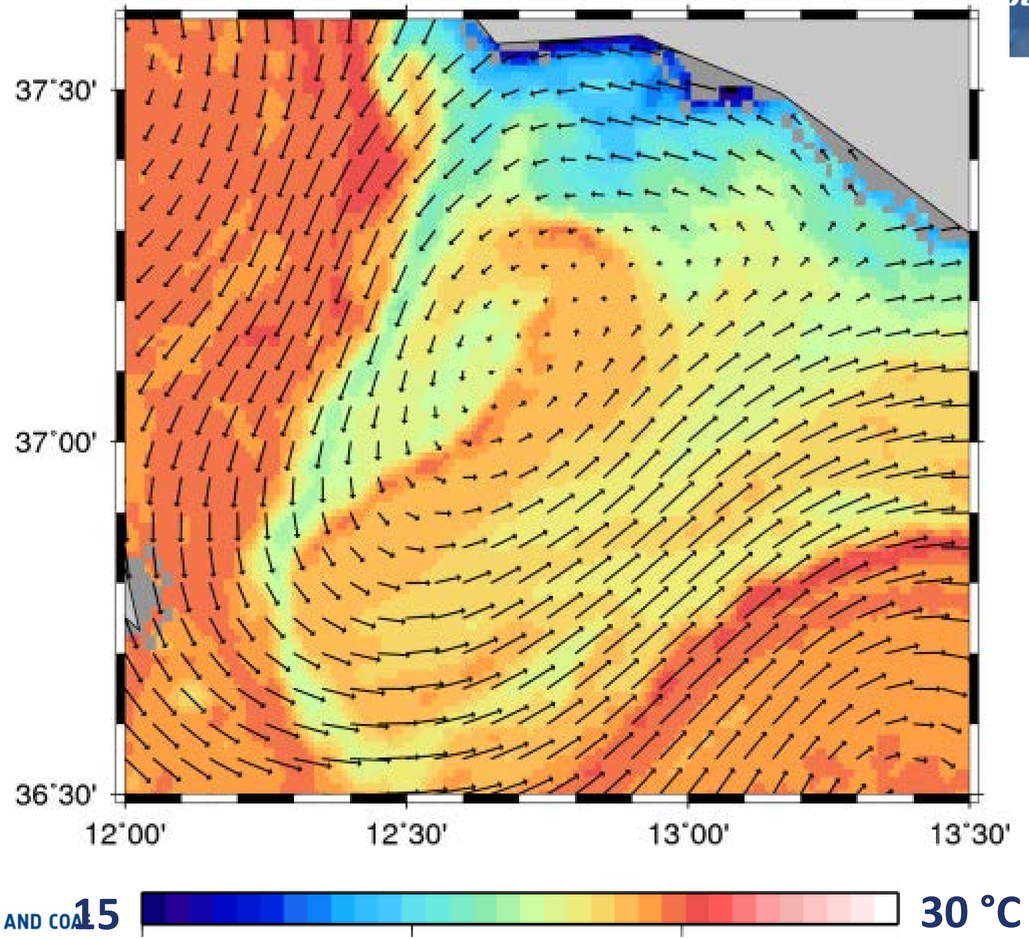
Alti « twosat »
Alti « twosat » + SST MW
Alti « allsat »
Alti « allsat »+SST MWIR

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

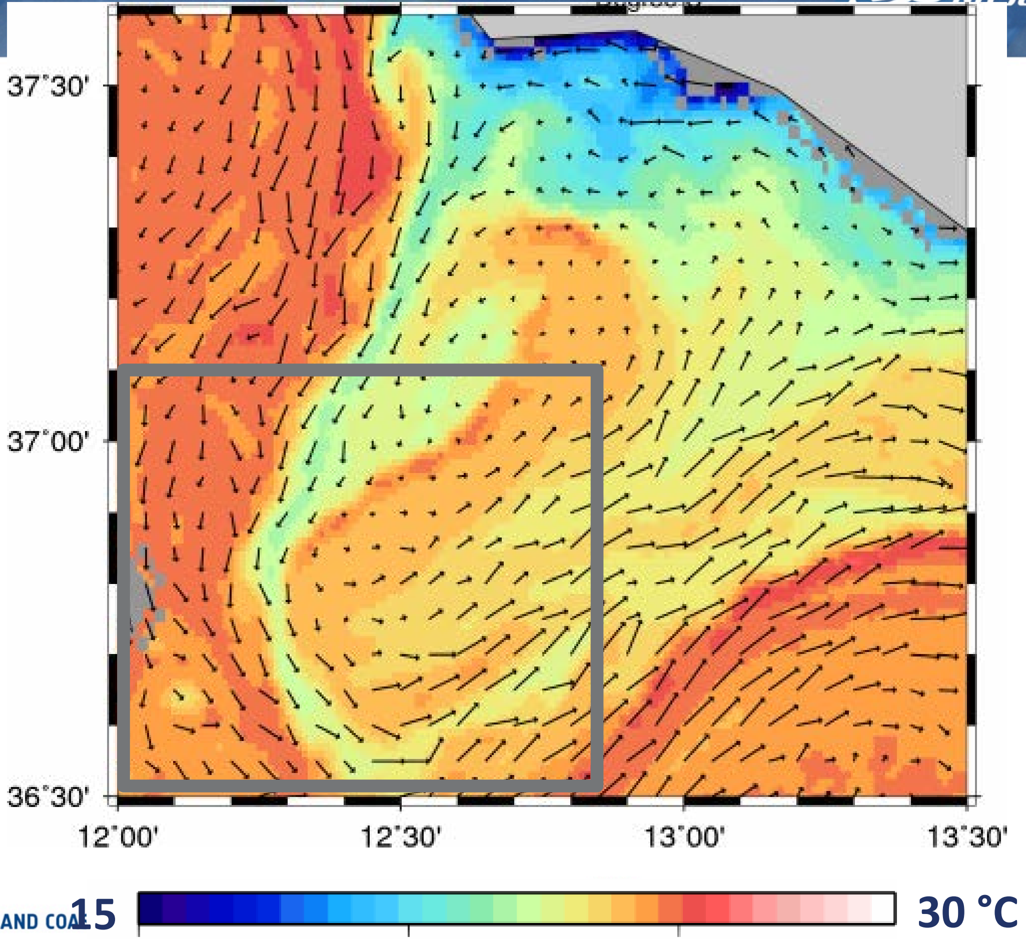
- Strong improvement for the meridional component of the velocity in areas where SST gradients greater then 10^{-5}°/m
- « twosat »+ MW SST better than « allsat »

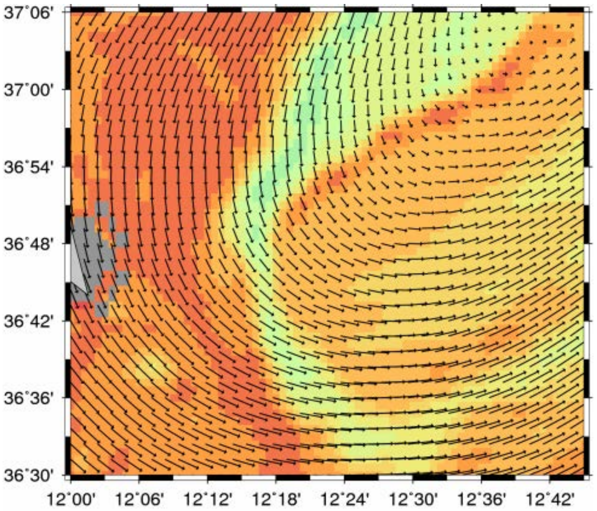
- Further improvement with « allsat »+MWIR SST (also on the zonal component)

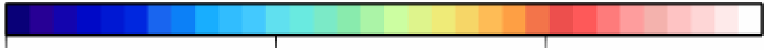
Sentinel-3 data on July, 28th 2016



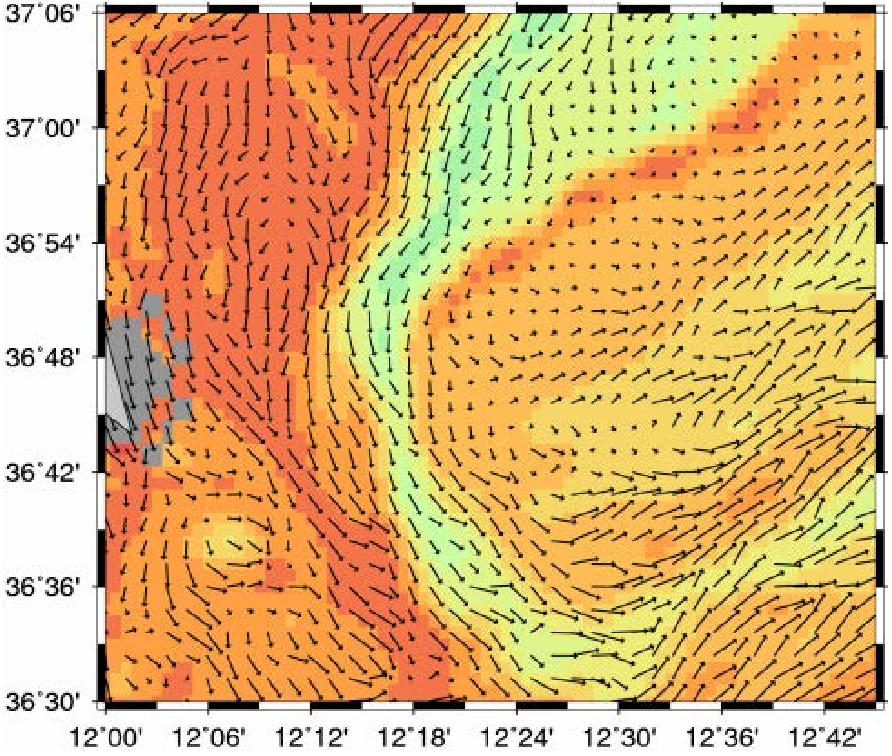
Sentinel-3 data on July, 28th 2016

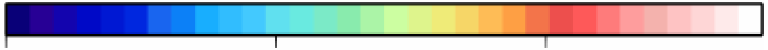



37°06'
37°00'
36°54'
36°48'
36°42'
36°36'
36°30'
12°00'
12°06'
12°12'
12°18'
12°24'
12°30'
12°36'
12°42'

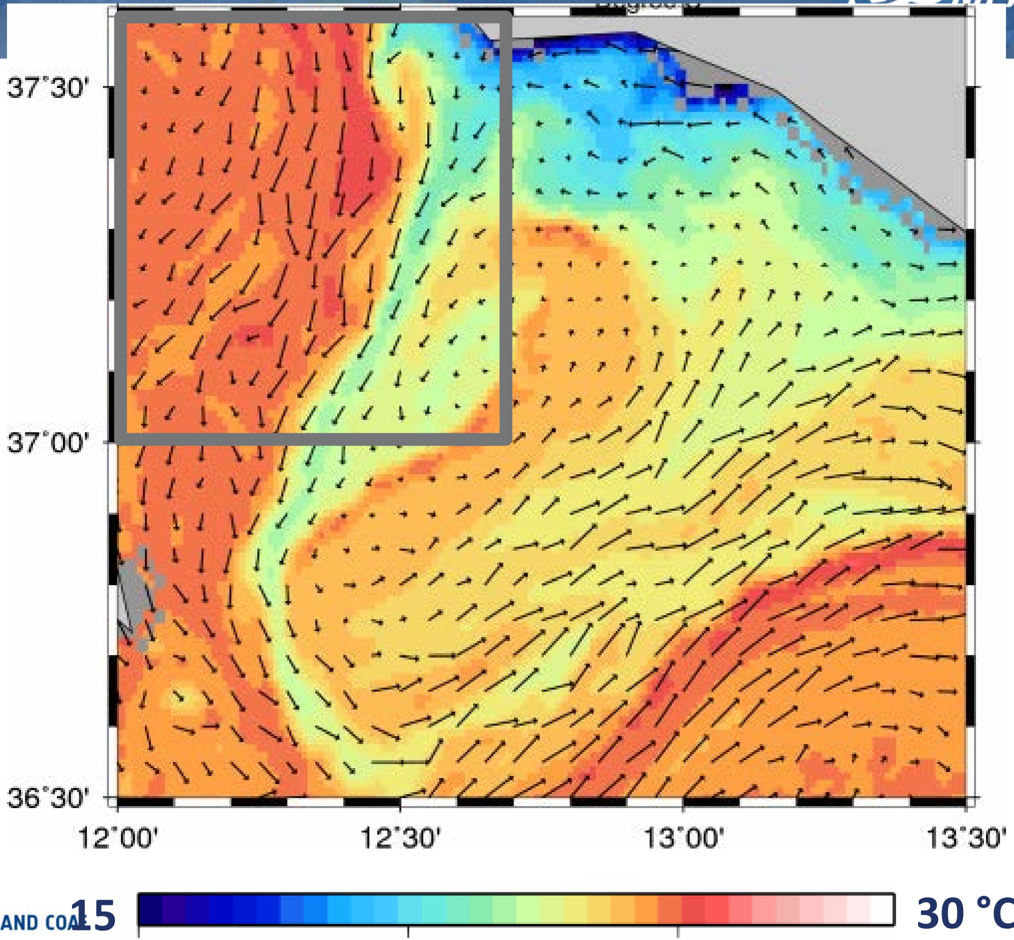

15
30 °C

Sentinel-3 data on July, 28th 2016

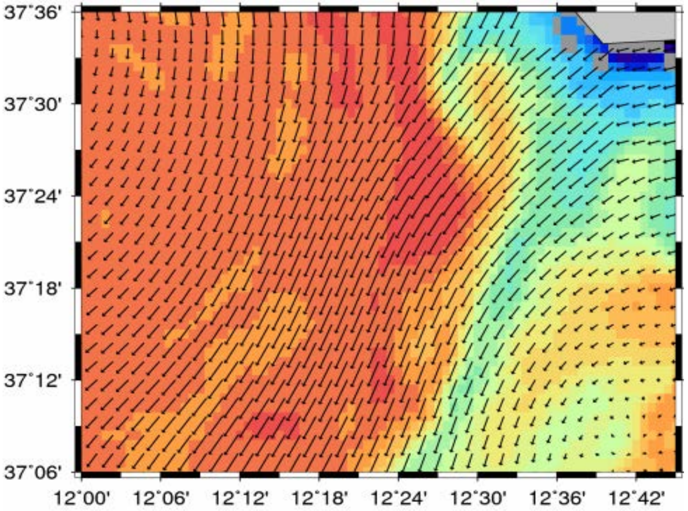


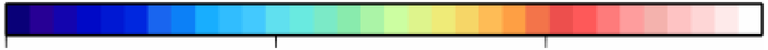


Sentinel-3 data on July, 28th 2016



Sentinel-3 data on July, 28th 2016





Sentinel-3 data on July, 28th 2016