Lecture 2 : Open Ocean circulation and extreme events

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What physical processes influence the ocean mean sea level and sea level variations ?

What are the different space/time scales involved – are they observable with altimetry?

How do we process altimetric data to access the different signals?

Open ocean applications and extreme events

Satellite Altimetry mesures changes in **sea level**

Sea level responds to the **vertically integrated** changes in mass and density throughout the entire water column.

Altimetry is the **ONLY satellite measurement** that responds to internal ocean changes (e.g. changes in deep ocean currents, heating and cooling at depth, …)

Key observation in **constraining ocean models** via data assimilation

Sea level variations

The sea surface height (SSH) varies due to internal changes in the ocean pressure field, either from **internal density changes** or **mass transfers**.

Ocean density, ρ, varies as a function of temperature, salinity and pressure:

$$\rho = \rho\ (T, S, p)$$

The ocean pressure field is also related to density via the **hydrostatic relation**:

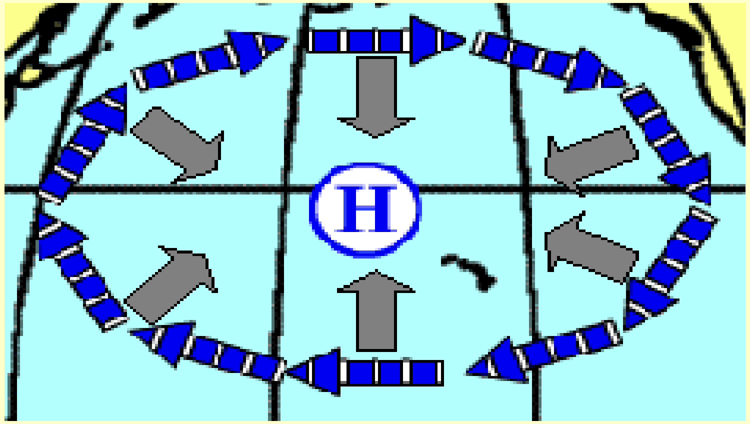
$$\delta\ p / \delta\ z = \rho g$$

=> vertically integrating the density field gives us part of the ocean pressure field.

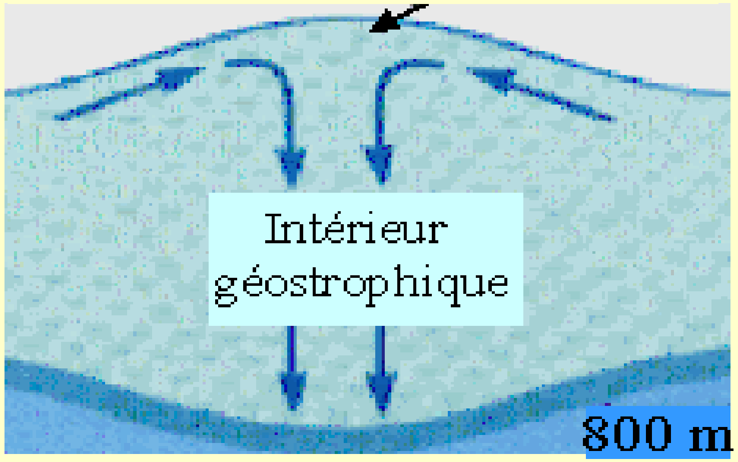
A **transfer of mass** (convergence or divergence of the water) can also modify the ocean pressure field.

Sea level can also change due to the **hydrological cycle** : E-P, river runoff, ice melt

1) Mass transfer - convergence

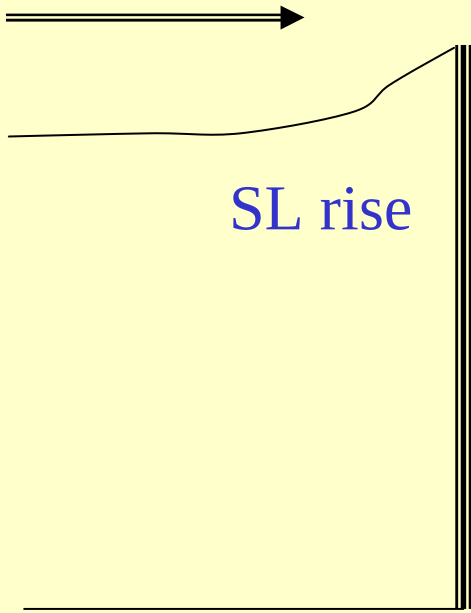


Ekman transport – upper layer convergence



SL rise

Wind forcing against a coast



2) Density changes : Steric Height

• *If a given quantity of water changes its salinity or temperature and thus its density, then its volume also changes.*

• *For example, increasing the temperature in the water column decreases its density and the volume of water expands, and therefore, the sea level rises.*

Steric height, *h*, represents the height difference between two surfaces of constant pressure :

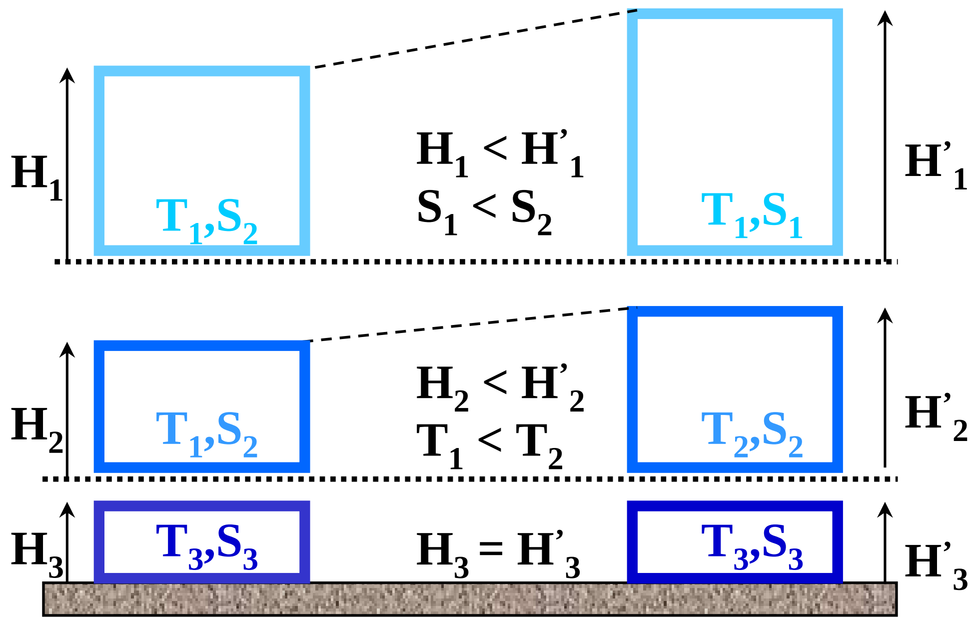
$$h\,(z1, z2) = \int \Delta\rho\,(T,S,p)\,/\rho_0(p)\,dz$$

Typically, h is 0(10-100) cm.

Dynamic height, is simply gravity multiplied by steric height : $D = gh$.

Pressure, P, and **steric height, h,** are linked **:**

Hydrostatic Pressure, $P = \rho g h$



Géostrophic Equations

x: $$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+fv+F_x$$

y : $$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial y}-fu+F_y$$

z : $$\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}-g+F_z$$

Horizontal Circulation in near geostrophic balance

Hydrostatic balance

In the ocean interior (away from surface and side boundaries), F_i -> 0.

For non-synoptic (> 3 jours) and large-scale movements (> 10 km).

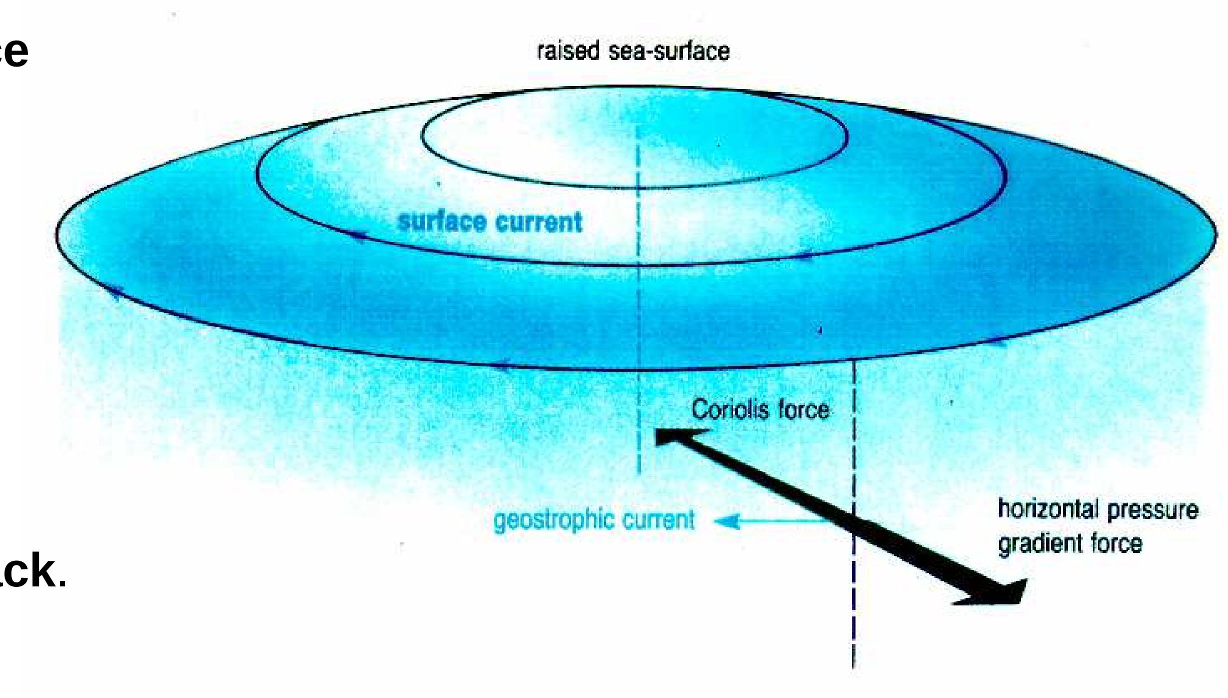
$$\frac{D\tilde{u}}{Dt}->0\ , \qquad \frac{\partial\tilde{u}}{\partial x}->0\ ,\ \frac{\partial\tilde{u}}{\partial y}->0\ ,\ \frac{\partial\tilde{u}}{\partial z}->0\ ,$$

Surface Currents from altimetry

If we consider the sea surface in terms of steric height, *h*, we can express the **geostrophic balance** as :

$$u = - g/f \; dh/dy$$

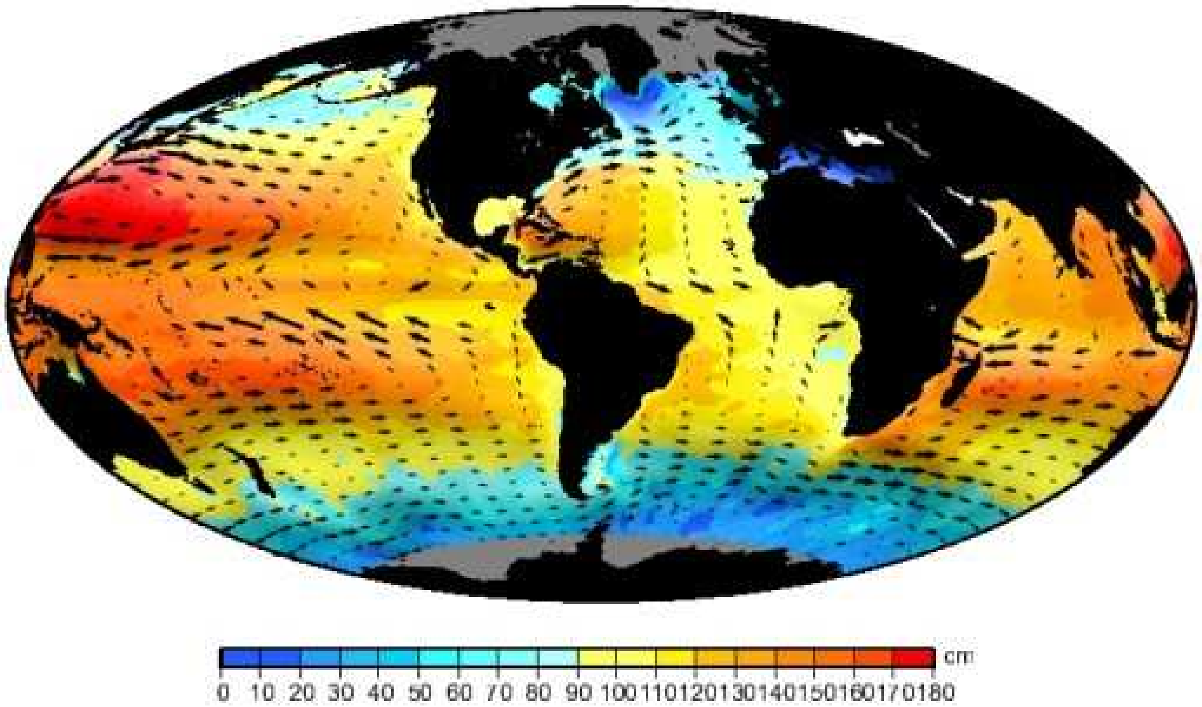
$$v = g/f \; dh/dx$$



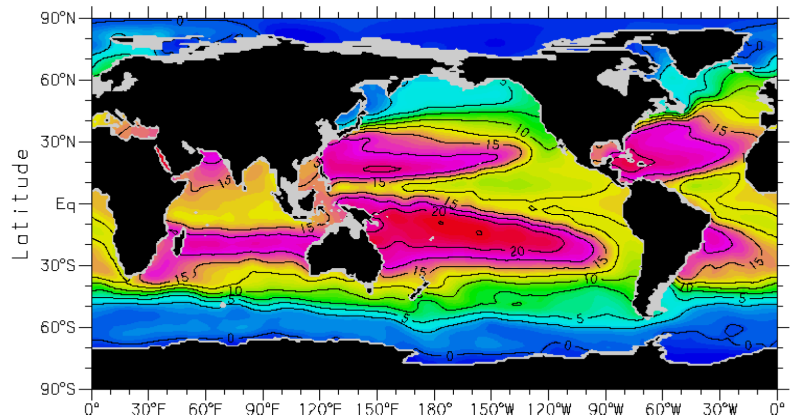
Geostrophic currents calculated from the alongtrack slope will be **perpendicular to the groundtrack**.

Mean Dynamic Height vs temperature and salinity structure

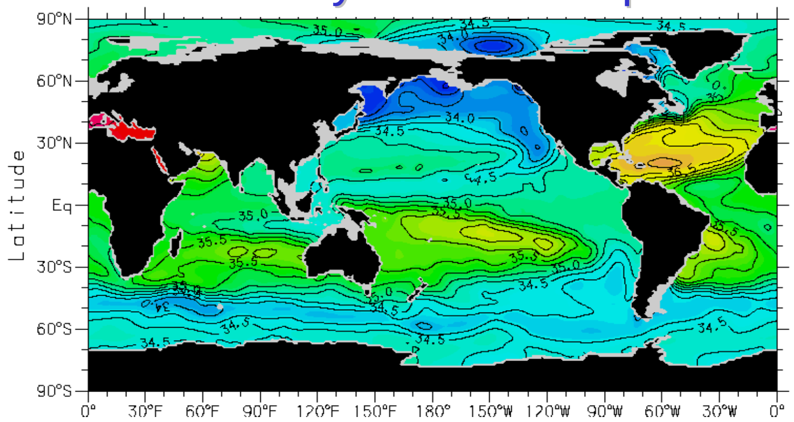
Surface Mean Dynamic height,
with mean geostrophic currents



Temperature at 200 m depth

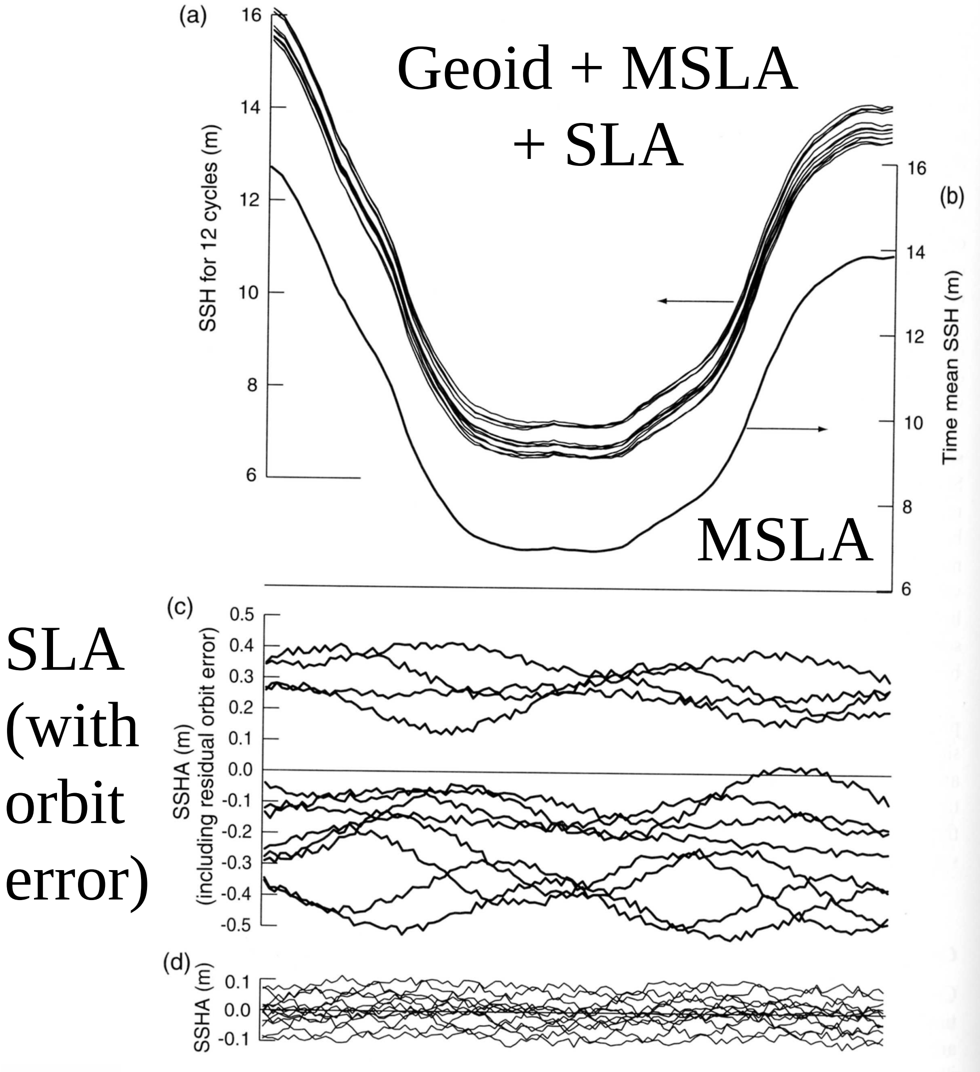


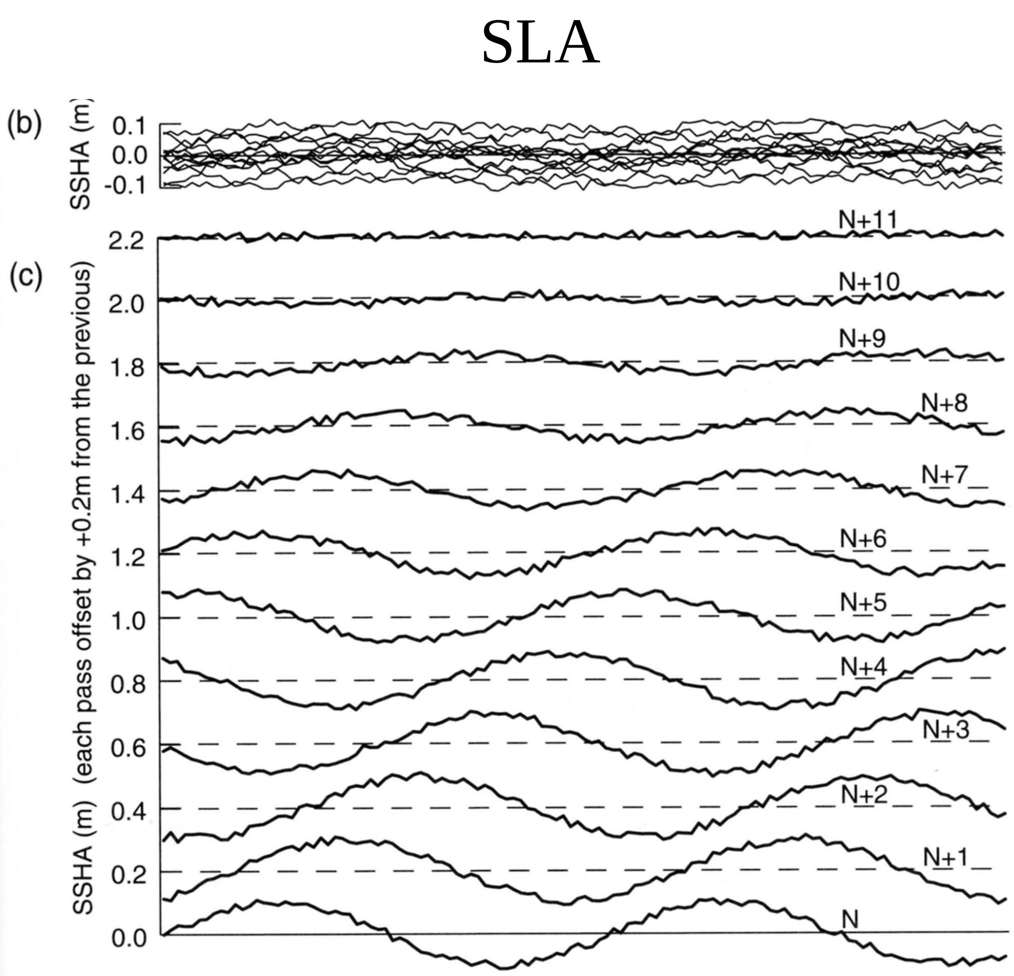
Salinity at 200 m depth



Standard Techniques for analysing altimeter data

Repeat-track analysis of sea level





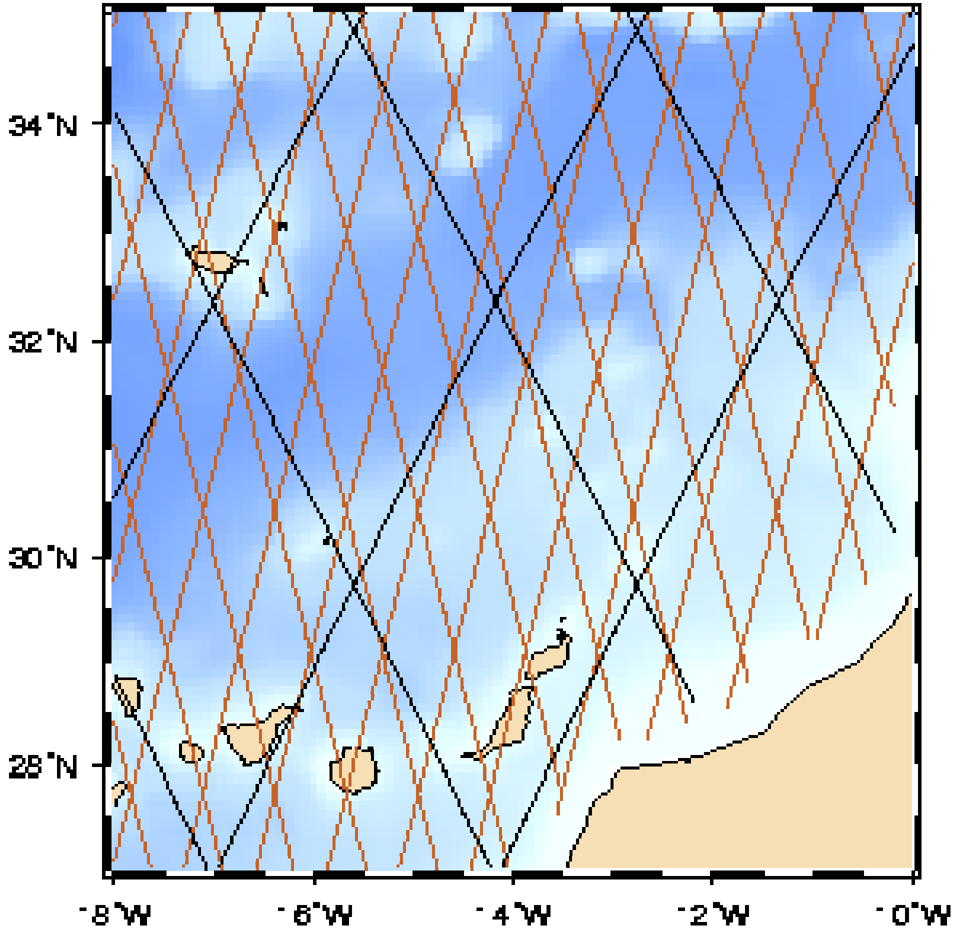
Mapping altimetry data

Mapping alongtrack data onto a regular grid

This Figure shows a 35-day coverage of T/P tracks (black) and ERS tracks (brown). During this time, there will be 3.5 T/P cycles and one single repeat of the ERS tracks.

For many oceanographic applications using time series analysis or spatial analysis, the data are easier to use on a regular grid.

Thus optimal mapping techniques are developed to transform alongtrack SSH measurements with irregular space and time distributions onto a regular grid.



Objective analysis for mapping altimetry data

Objective analysis mapping uses a **gaussian weighting scheme** to **map irregular data onto a regular grid**.

A gaussian space-time covariance model is used, e.g. :

$$F(r,dt) = [1 + br + 1/6(br)^2 - 1/6(br)^3]e^{-br}\, e^{-(dt/rct)^2}$$

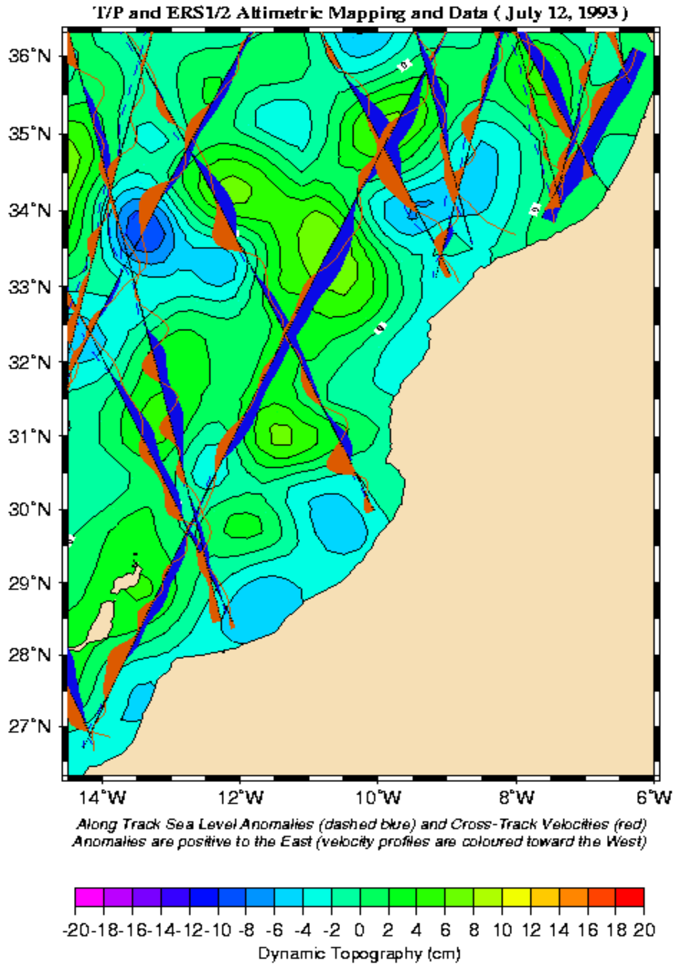
Here r is the non-dimensional radius :

$$r = \sqrt{(dx^2/rcx^2 + dy^2/rcy^2)}$$

This function uses different space lags (dx, dy) and time lags (dt).

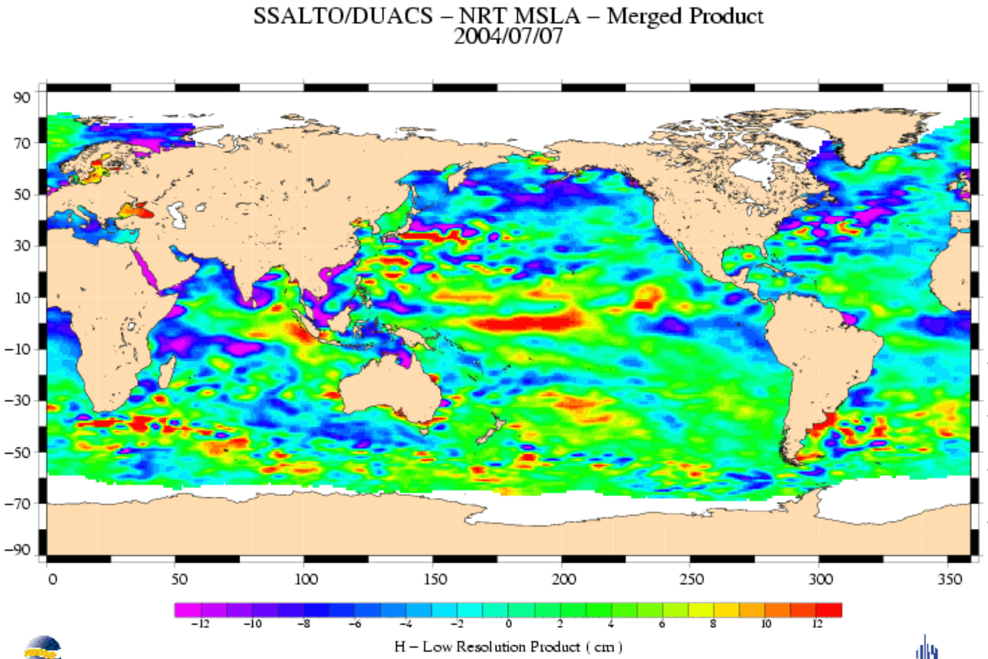
The choice of decorrelation space and time scales is a balance between resolving the mesoscale ocean signals and having enough data, taking into account the altimetry groundtrack separation and repeat period.

At mid-latitudes, **typical decorrelation space scales** are rcx = 200 km, rcy = 150 km, with **time scales**, rct = 15 days.



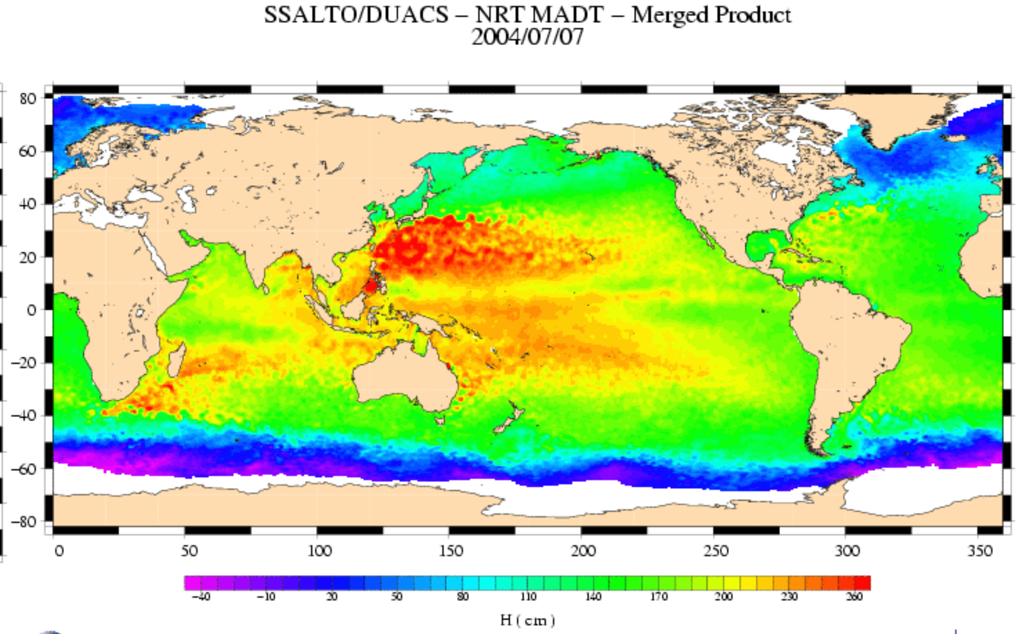
Along Track Sea Level Anomalies (dashed blue) and Cross-Track Velocities (red)
Anomalies are positive to the East (velocity profiles are coloured toward the West)

Example : AVISO Global Merged 7-day maps



Sea level anomalies 7 July 2004

T/P+Jason+GFO+ENVISAT



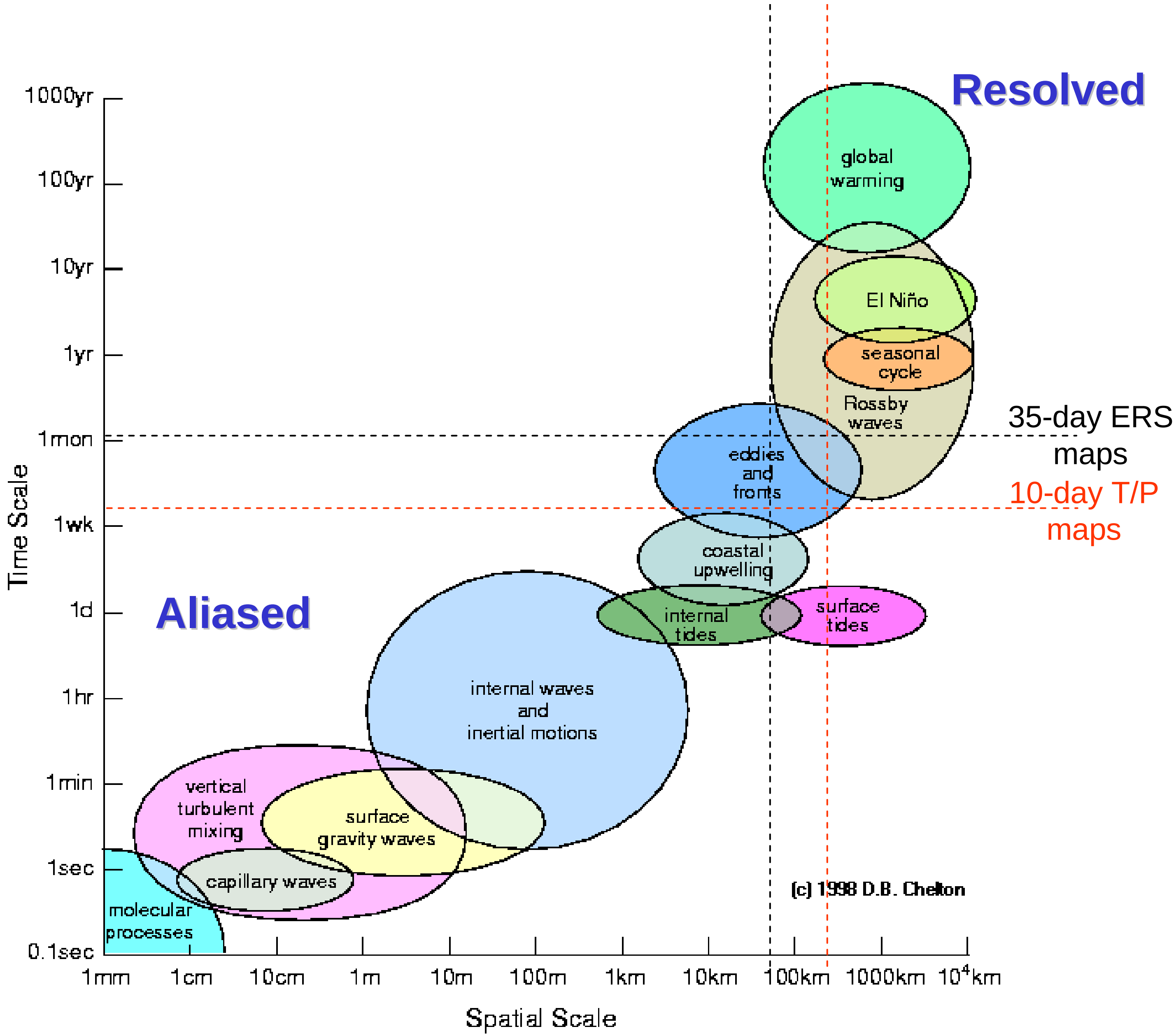
Dynamic Topography 7 July 2004

(SLA + Mean Dyn. Topo)

T/P+Jason+GFO+ENVISAT + mean sea surface

Applications

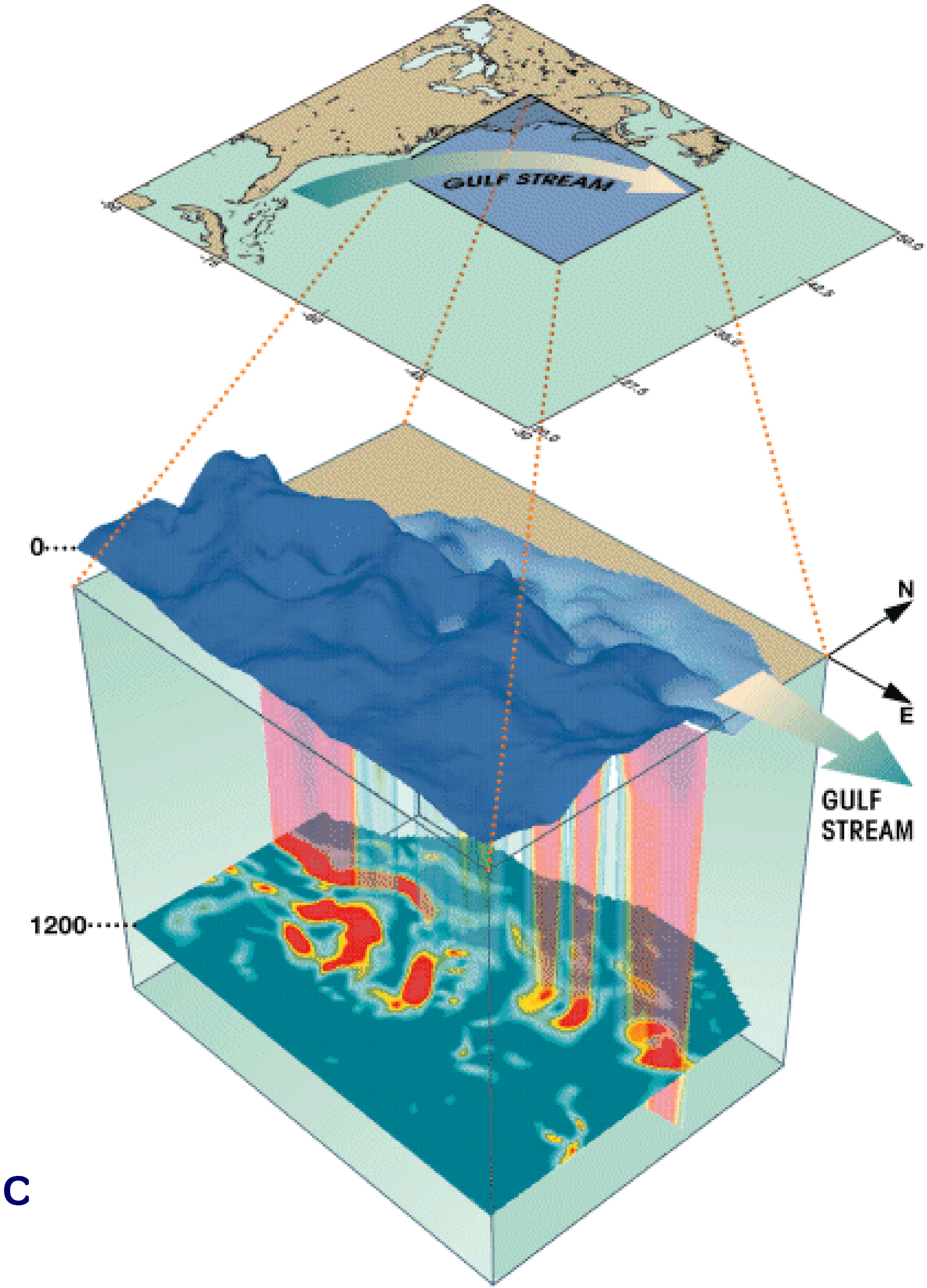
Space and Time scales resolved by altimetry



Mesoscale Eddy Field

The ocean currents can also become unstable, generating meanders which can pinch off to form mesoscale eddies. These eddies tend to drift westward at Rossby wave speeds unless they are advected by the mean flow.

This example is for the Gulf Stream, with alongtrack altimetric sea level anomalies (SLA) superimposed on the temperature field at 1200 m. Warm core eddies and meanders have high SLAs, cold –core rings and meanders have low SLAs.

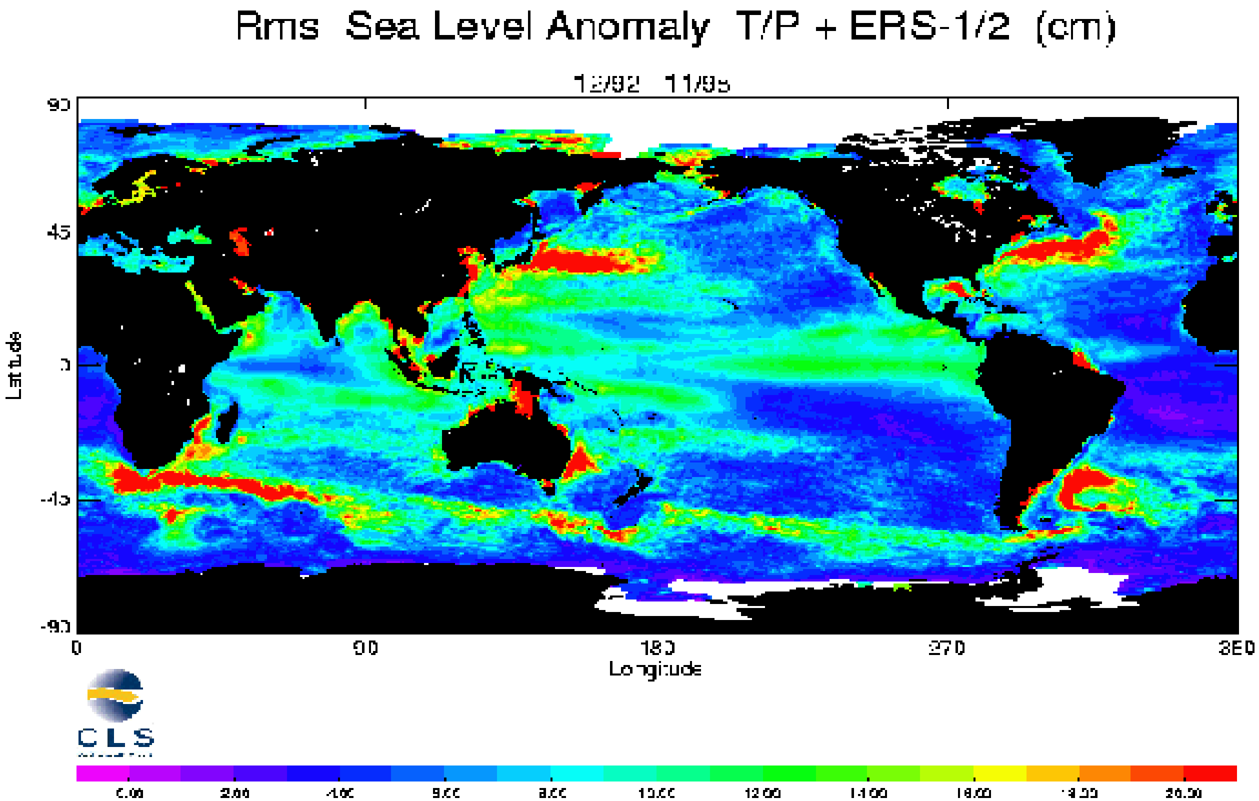


Calculating rms variability

At each alongtrack point, we now have a time series of sea surface level (SLA) anomalies, h'.

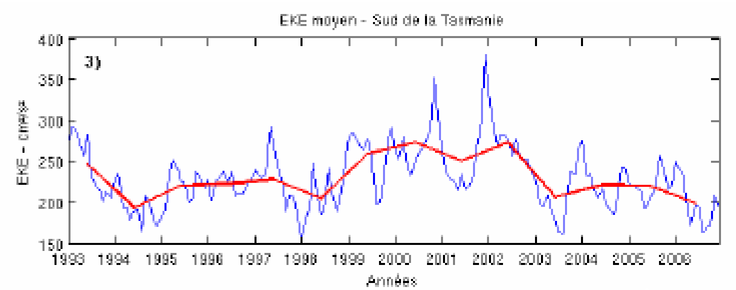
The rms variability over N cycles is simply :

Rms = $\sqrt{\sum h'^2} / N$



Eddy Statistics

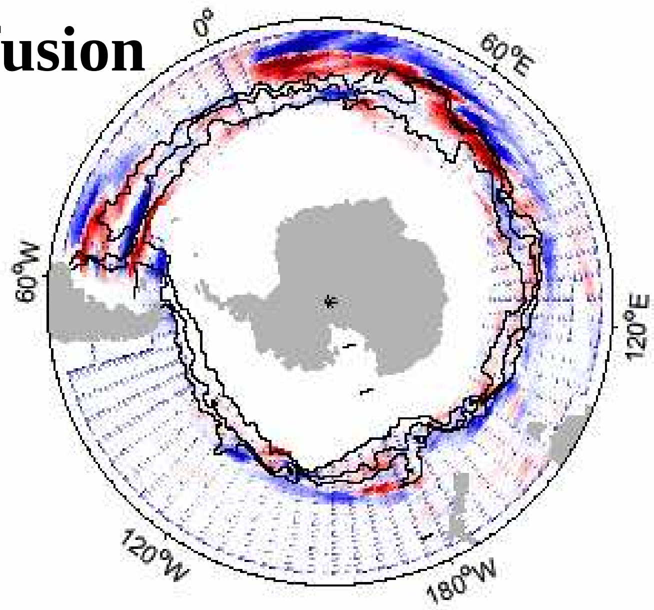
1) **Eddy Kinetic Energy (EKE)** in the Southern Ocean and its temporal variability



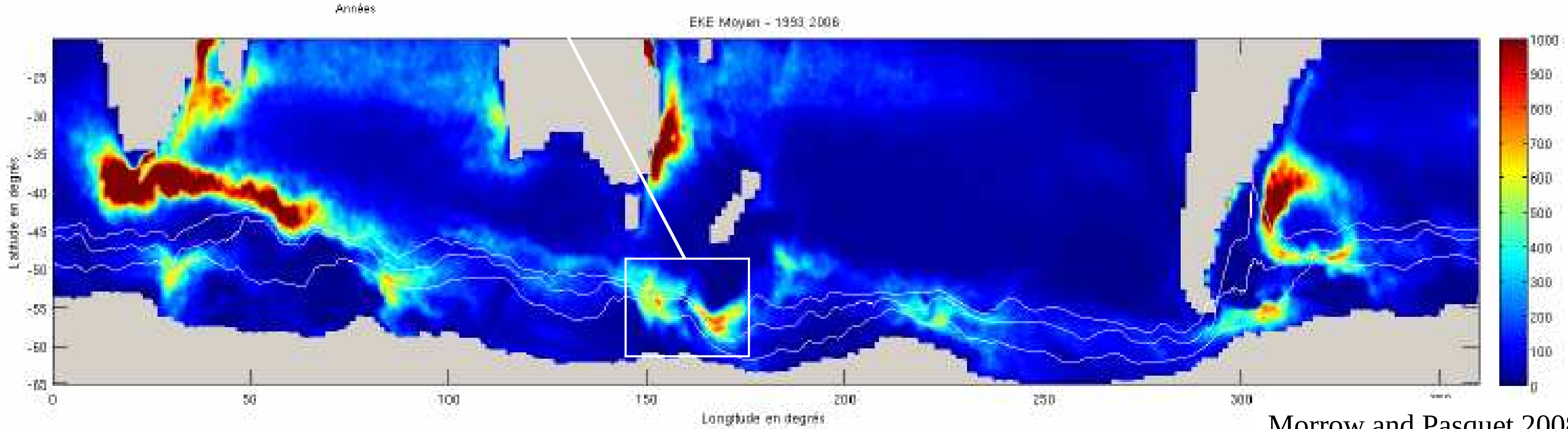
2) **Eddy heat diffusion**

$$\nabla(\kappa_h.\nabla T)$$

Eddy diffusion co-eff from altimetry, + satellite SST



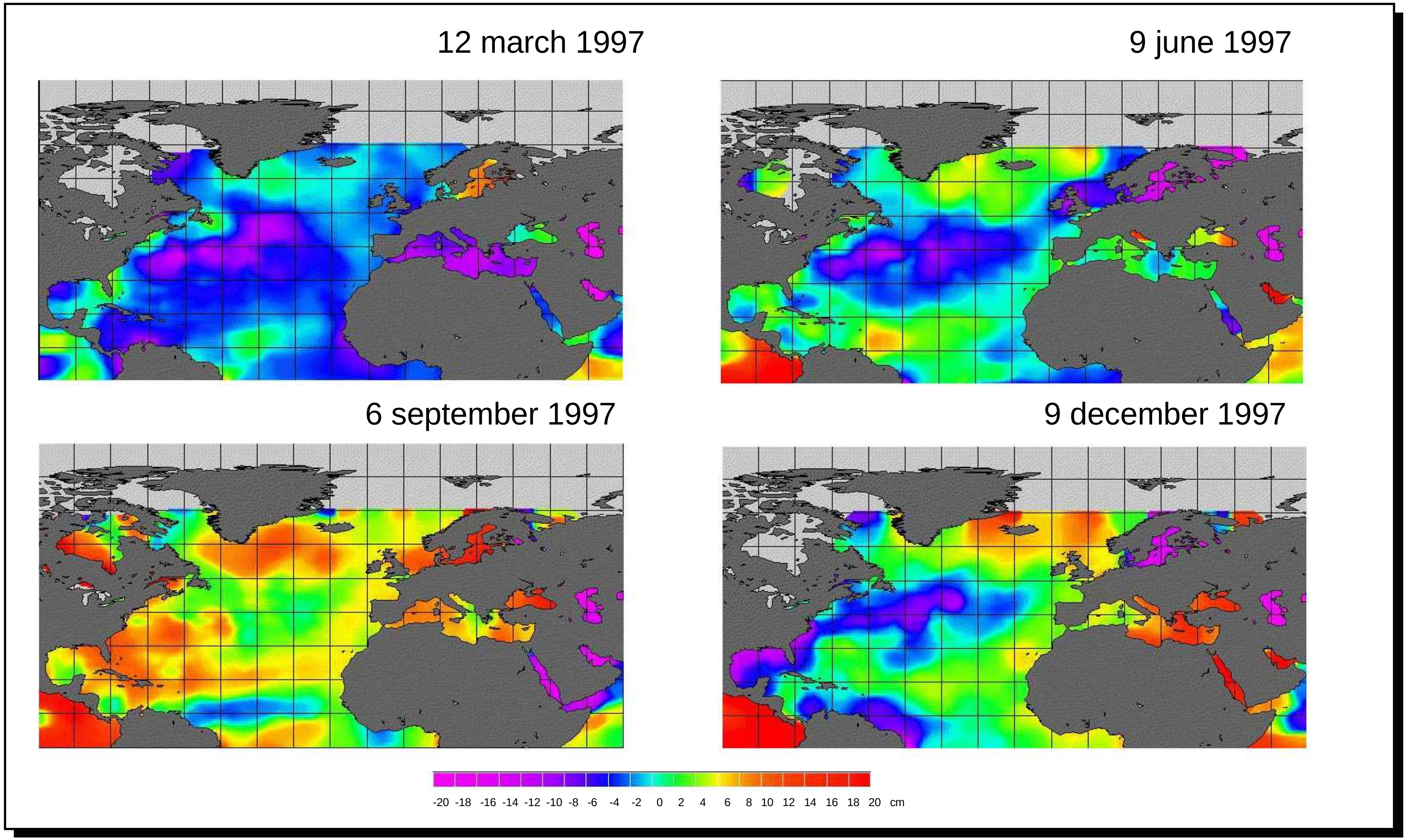
Sallee et al 2007



Morrow and Pasquet 2008

TOPEX-POSEIDON

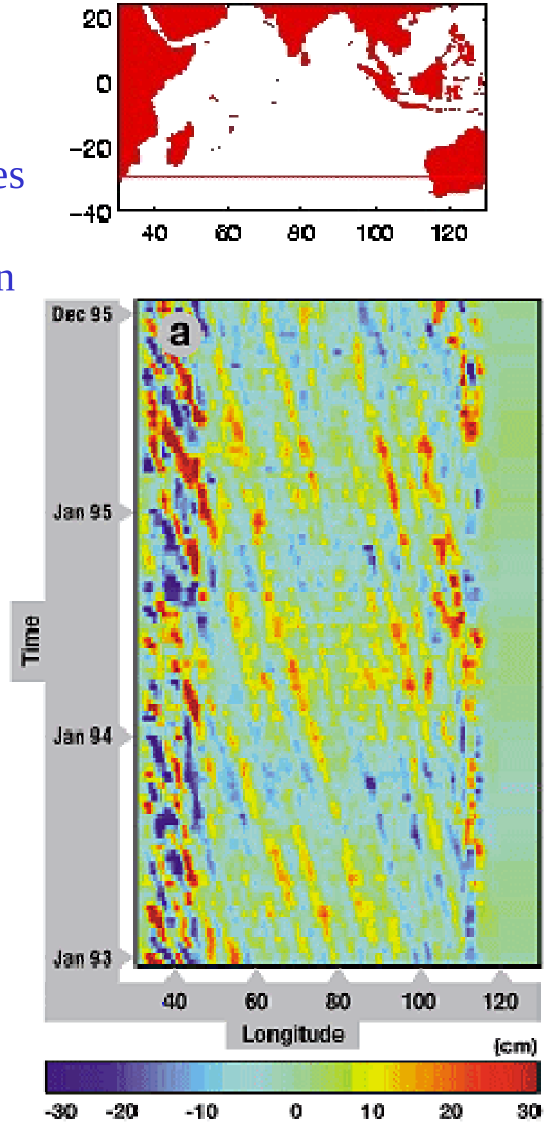
Oceanic Seasons



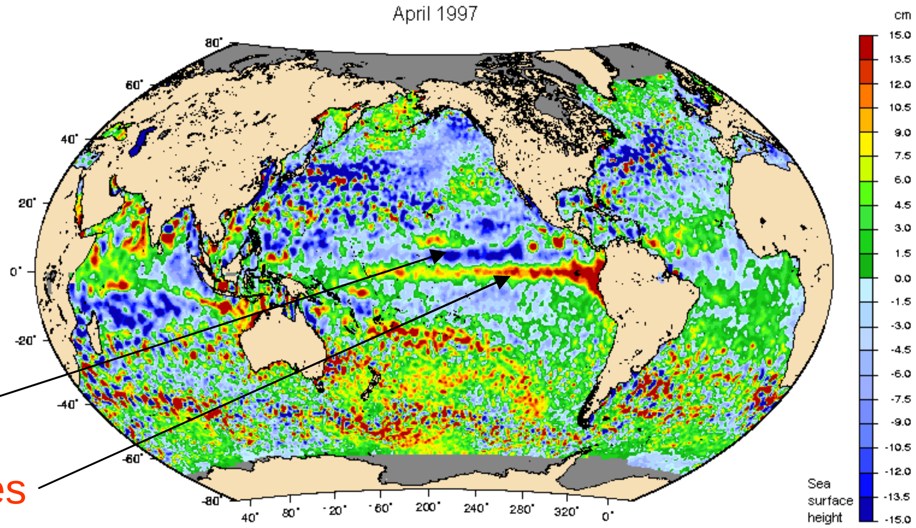
Planetary Waves

One of the major processus of ocean adjustment is via planetary waves : large-scale perturbations of the thermocline can generate Kelvin waves at the equator and along the basin edges, and westward propagating Rossby waves in the ocean interior. These perturbations are either wind-forced, forced by remote waves, or even by current instabilities.

Rossby Waves propagating along 30°S in the Indian Ocean.



In the Equatorial Pacific, planetary waves create a fast El Nino adjustment

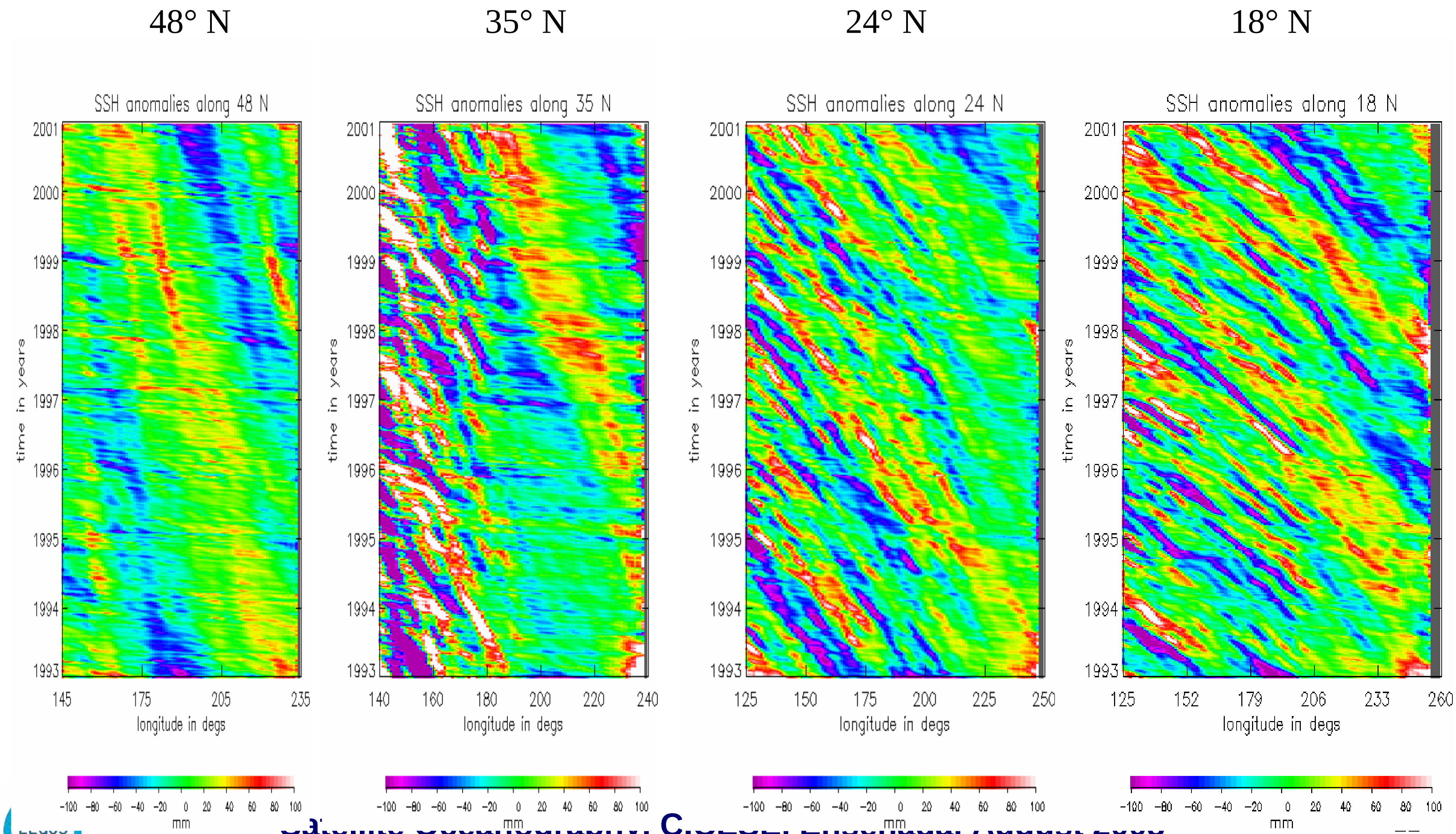


Rossby waves

Kelvin waves

Rossby Waves in the North Pacific

Low-frequency adjustment to wind forcing change

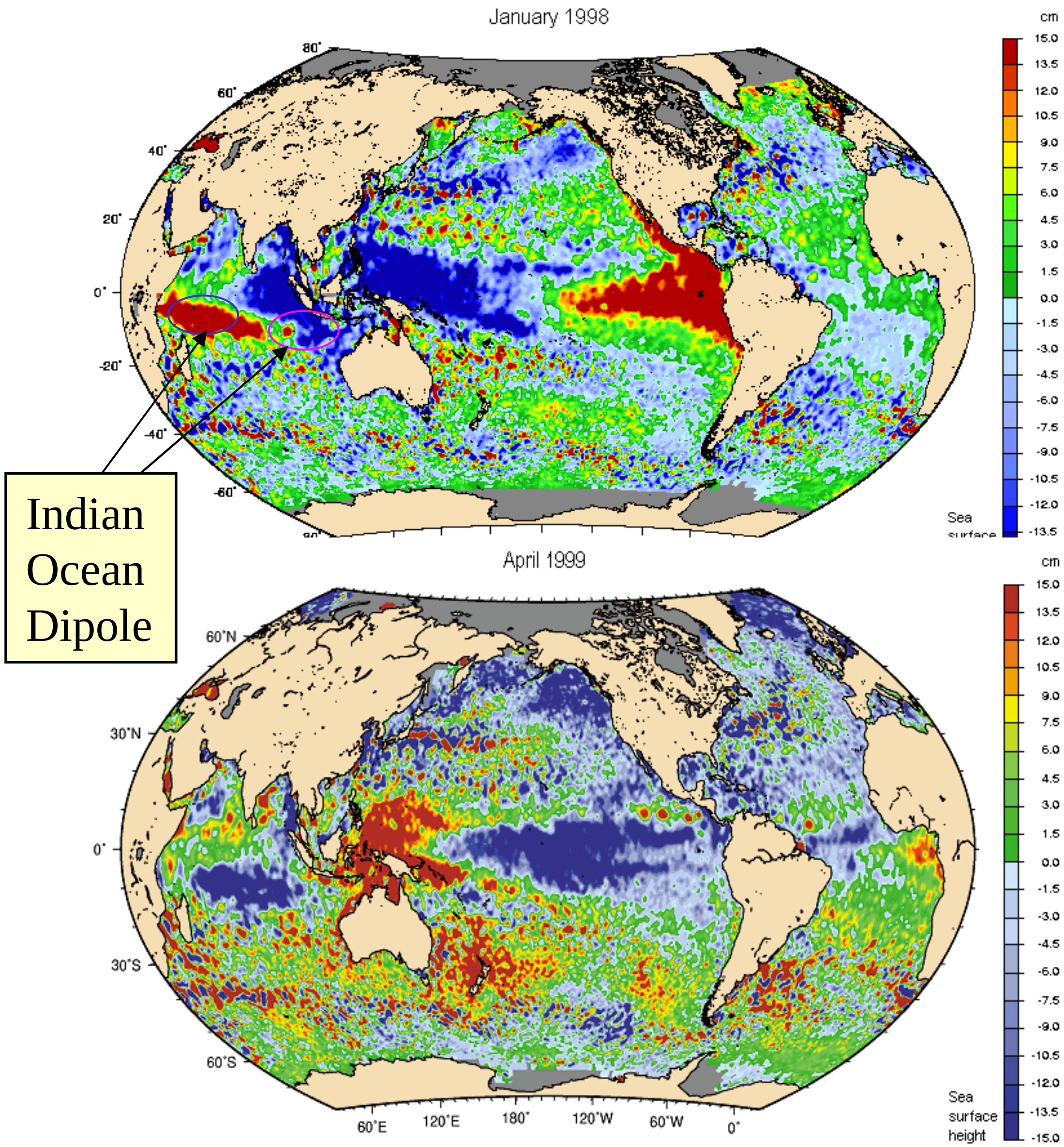


Fu and Chelton, 2001

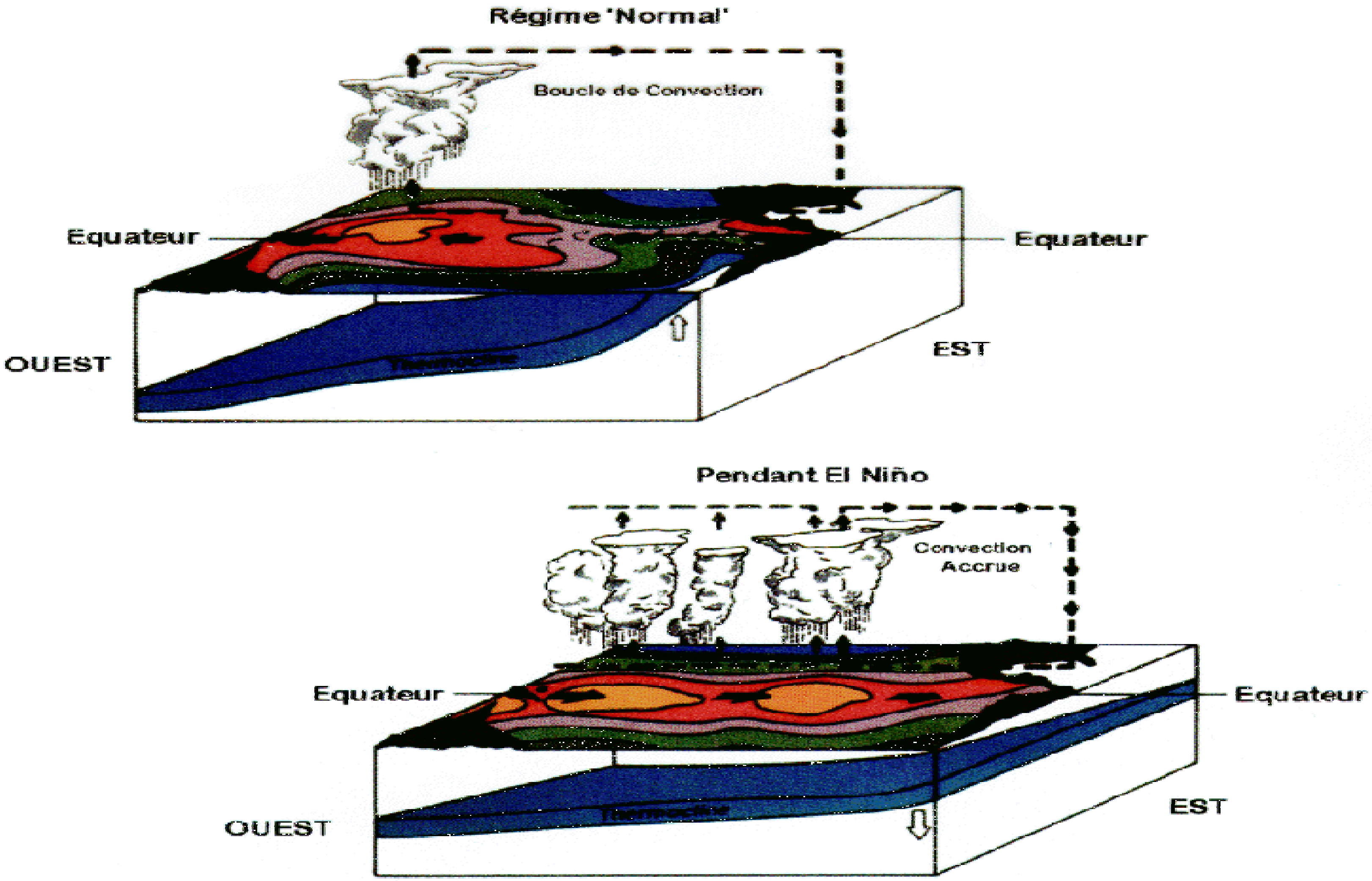
Internanual Variations

One of the largest interannual signals that has been closely monitored with altimetry is ENSO. The figure shows El Nino conditions in the Pacific in Jan 98 and La Nina conditions in Apr 99.

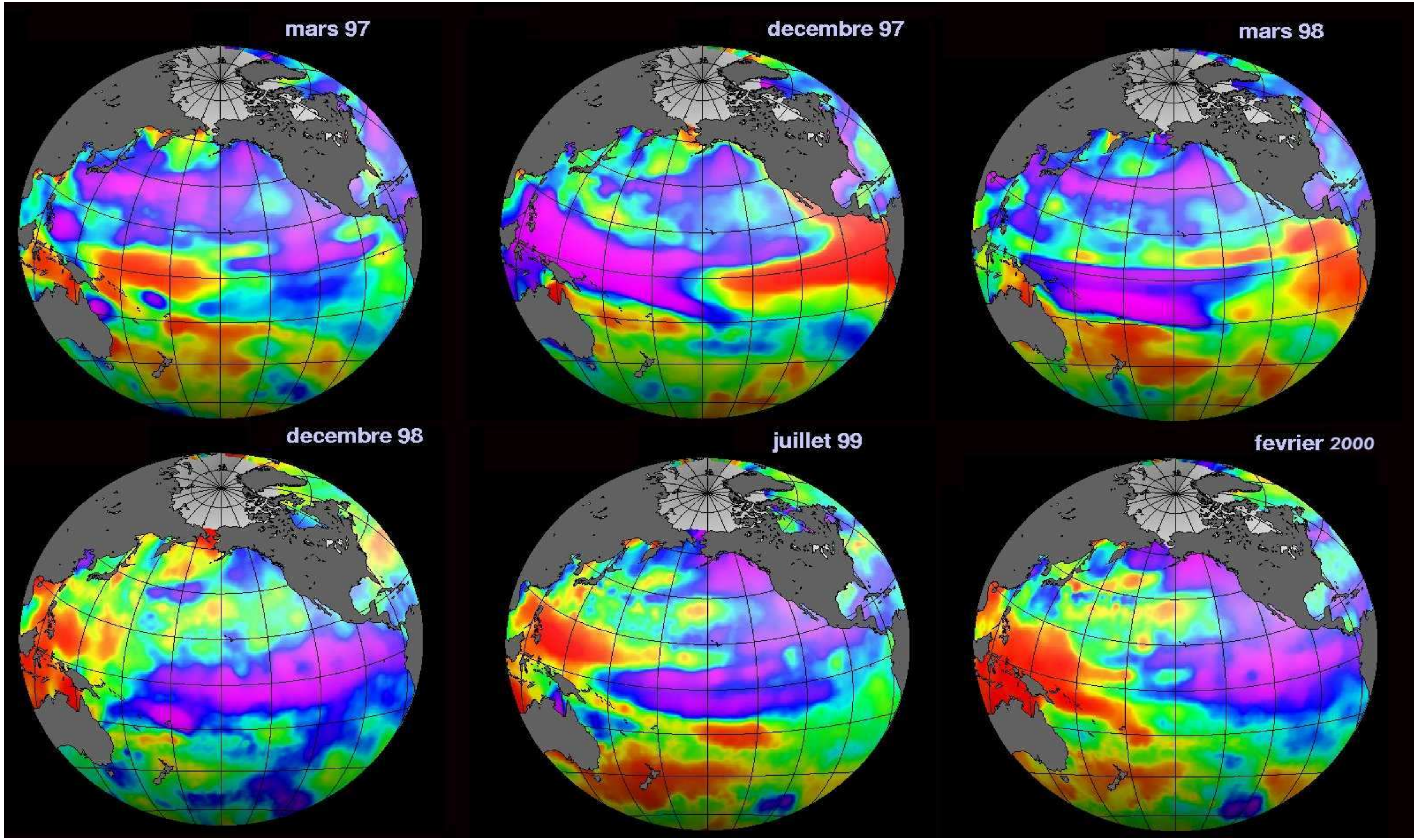
Altimetry has also revealed less well-known interannual signals in other oceans, e.g., the Indian Ocean Dipole which is in phase with El Nino in 1997/98, the North Atlantic Oscillation, and the Antarctic Circumpolar Wave.

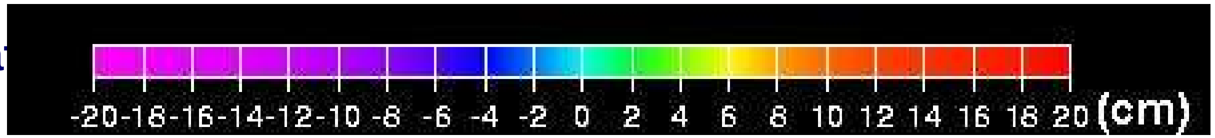


Ocean-atmosphere interaction : El Nino



TOPEX/POSEIDON El Niño/La Niña 97-99



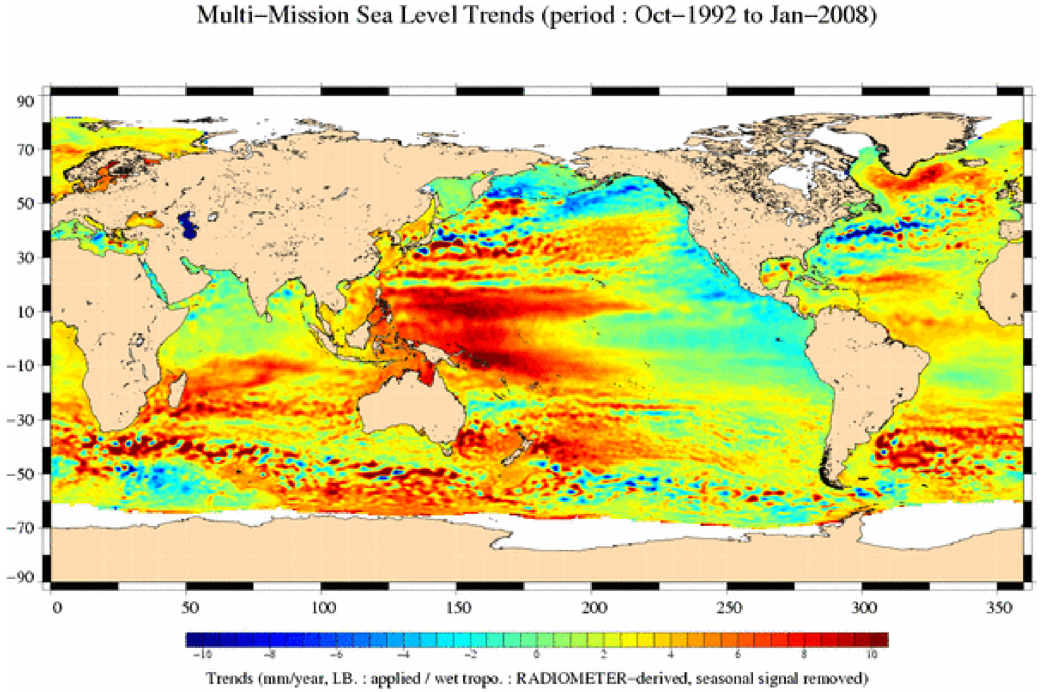


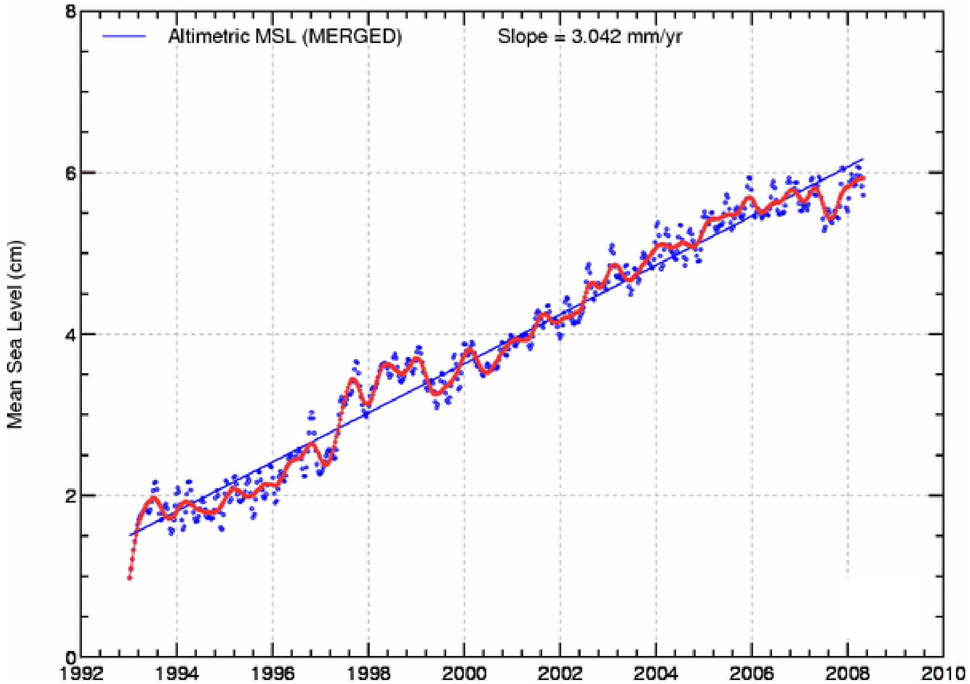
Sea level trend and global mean sea level changes

The trend shows us the spatial distribution of sea level rise over the period 1993-2001.

Although sea level has increased by 3 mm/yr globally in the 1990s, this increase is not evenly distributed.

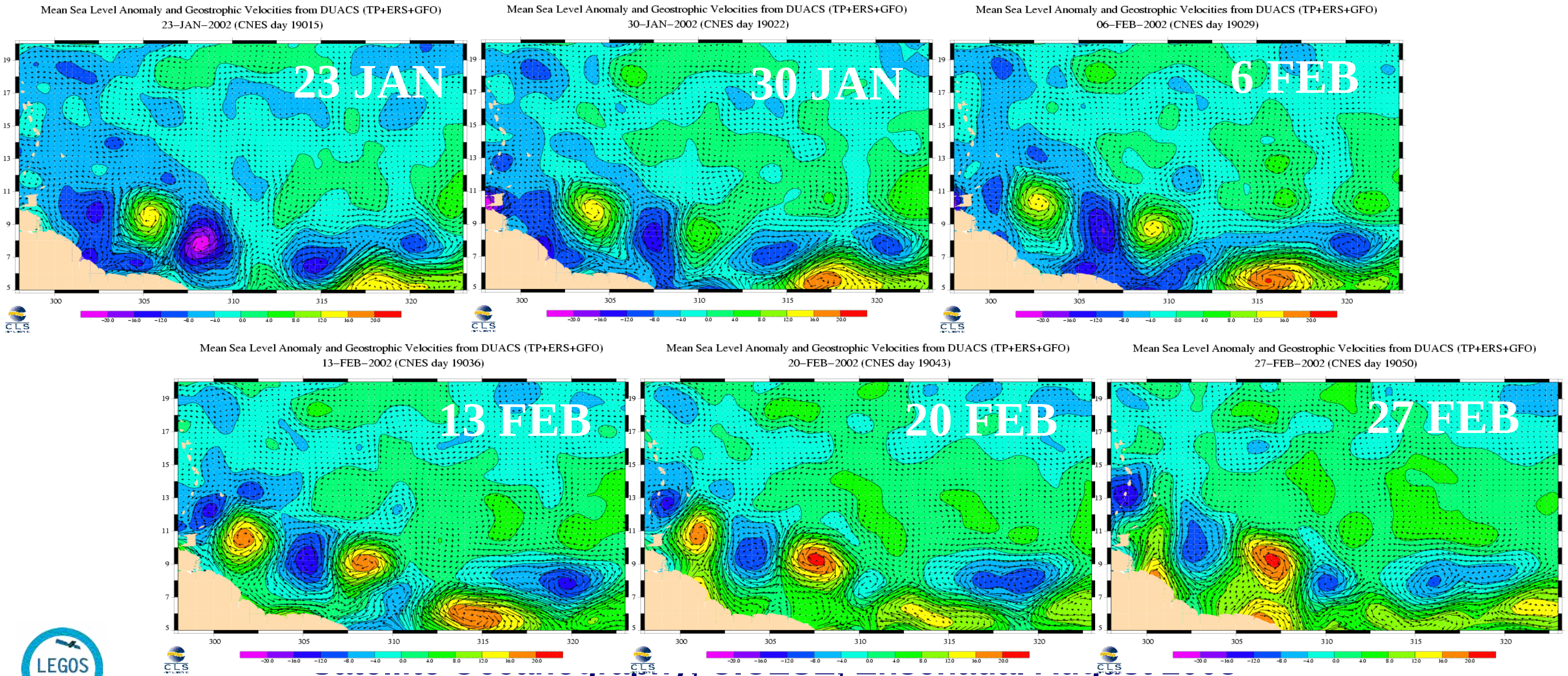
Sea level rise
using altimetry: 3.0 +/- 0.4 mm/yr





Real-time monitoring of North Brazil Current Rings

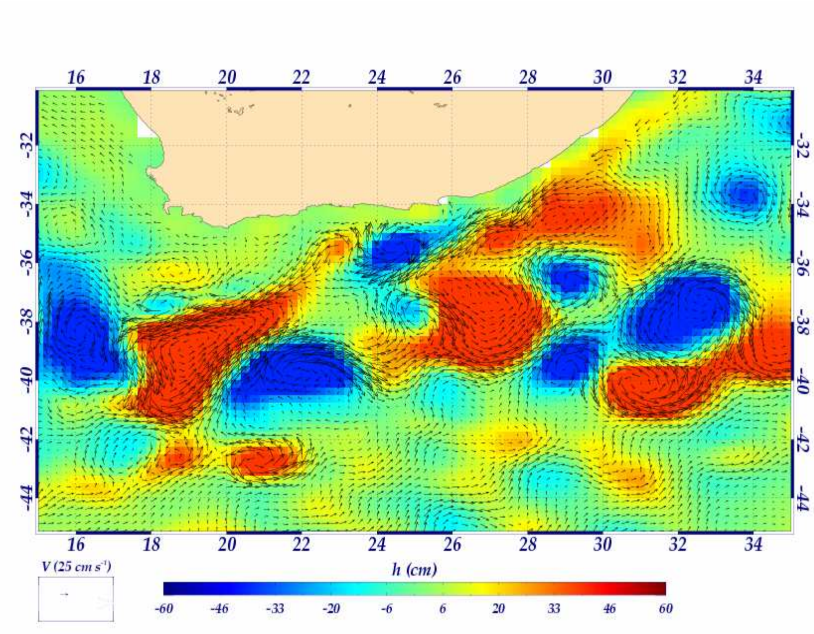
- Eddies visible with a map each 7 days
- Propagation westward

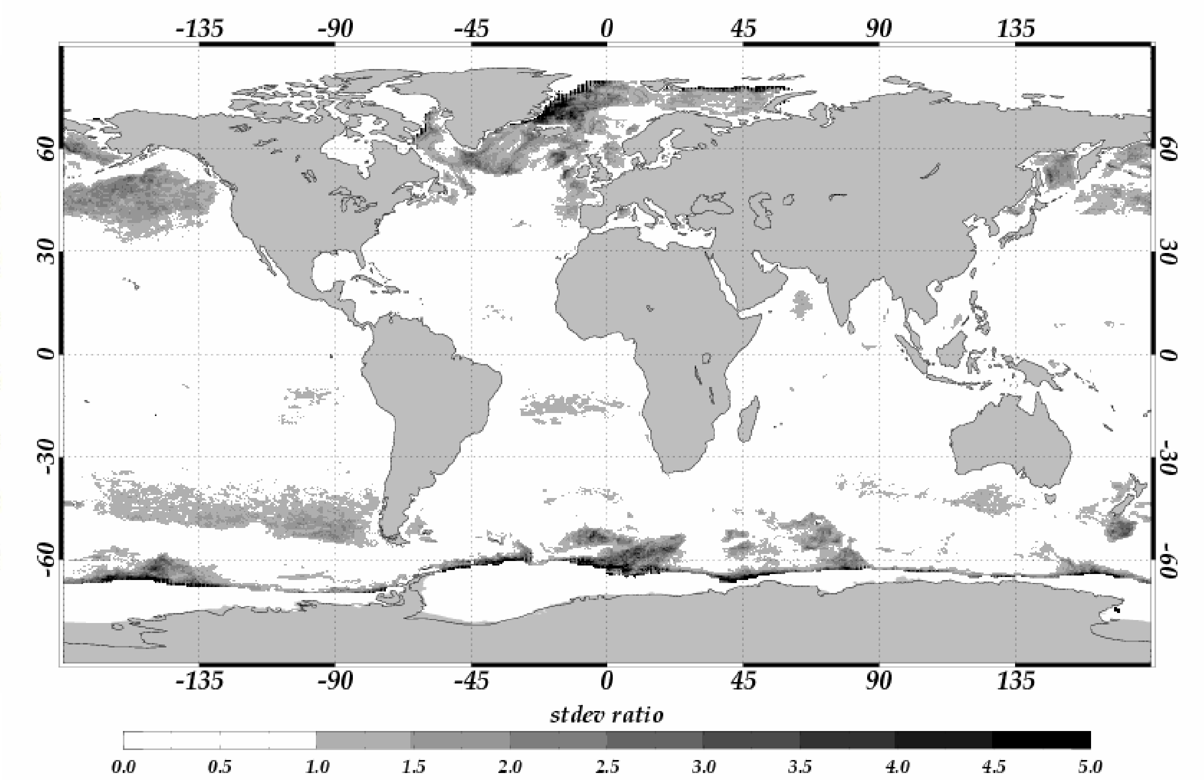


Satellite near-surface currents

- wind-driven Ekman currents from scatterometry

- geostrophic currents from altimetry www.legos.obs-mip.fr/ctoh





Altimetric SLA (colour) + total surface currents (vectors)

Regions where rms Ekman currents dominate rms geostrophic currents

Tracking ocean eddies with altimetry

Calculate the **Okubu-Weiss** parameter : the term *Q* measures the relative contribution of the flow **rotation** and its **deformation**.

$$Q = -\left(\frac{\partial u}{\partial x}\right)^2 - \left(\frac{\partial v}{\partial x}\right)\left(\frac{\partial u}{\partial y}\right) > 0,$$

For $Q > 0$, the rotation dominates the deformation.

Isern-Fontanet et al. [*2003*],

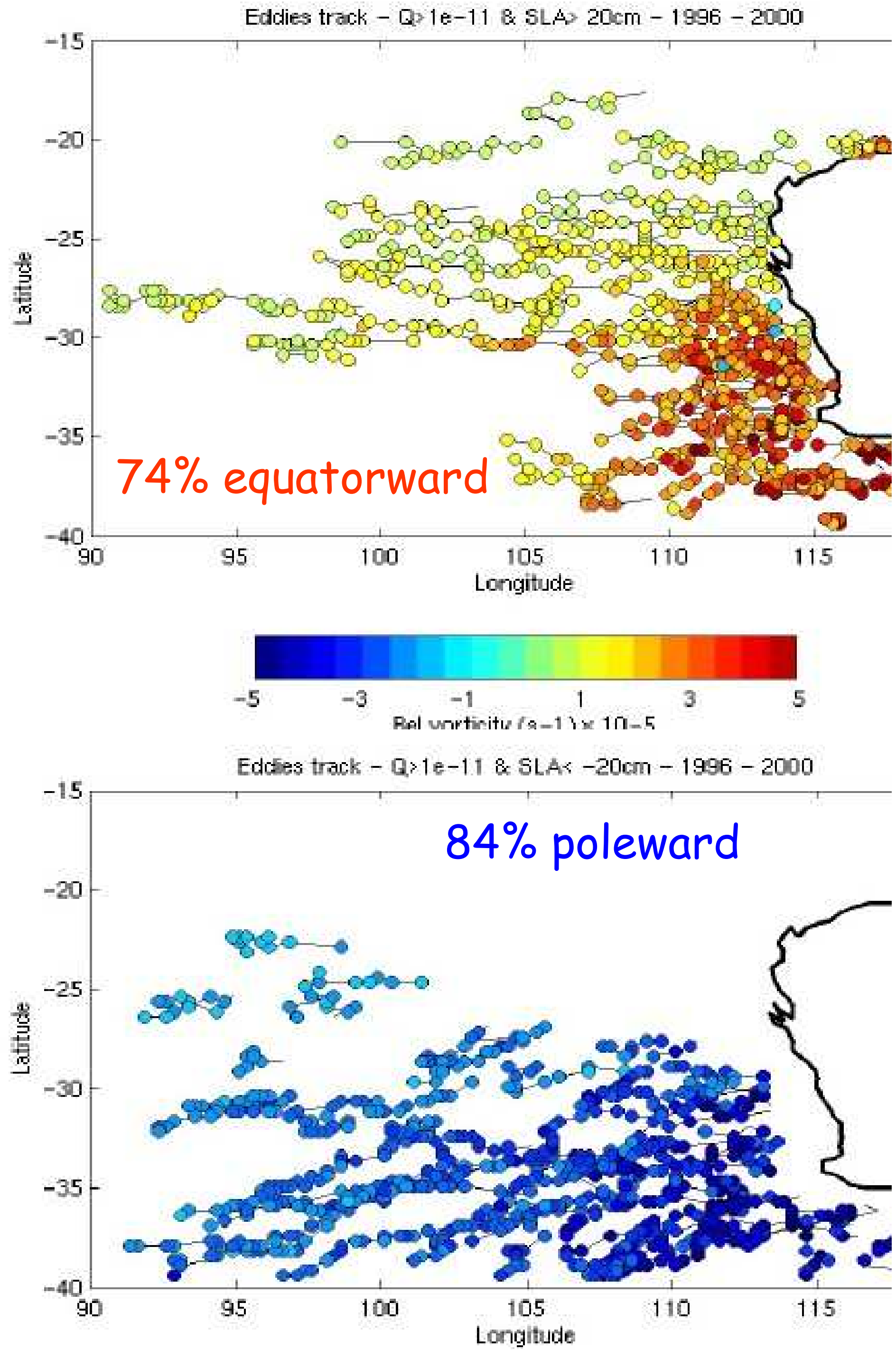
Cold and warm eddies propagate in different directions

Ocean eddies and Rossby waves tend to propagate westward

Away from strong currents and coasts :

• warm-core (anti-cyclonic) ocean eddies tend towards the equator

• cold (cyclonic) ocean eddies tend towards the poles



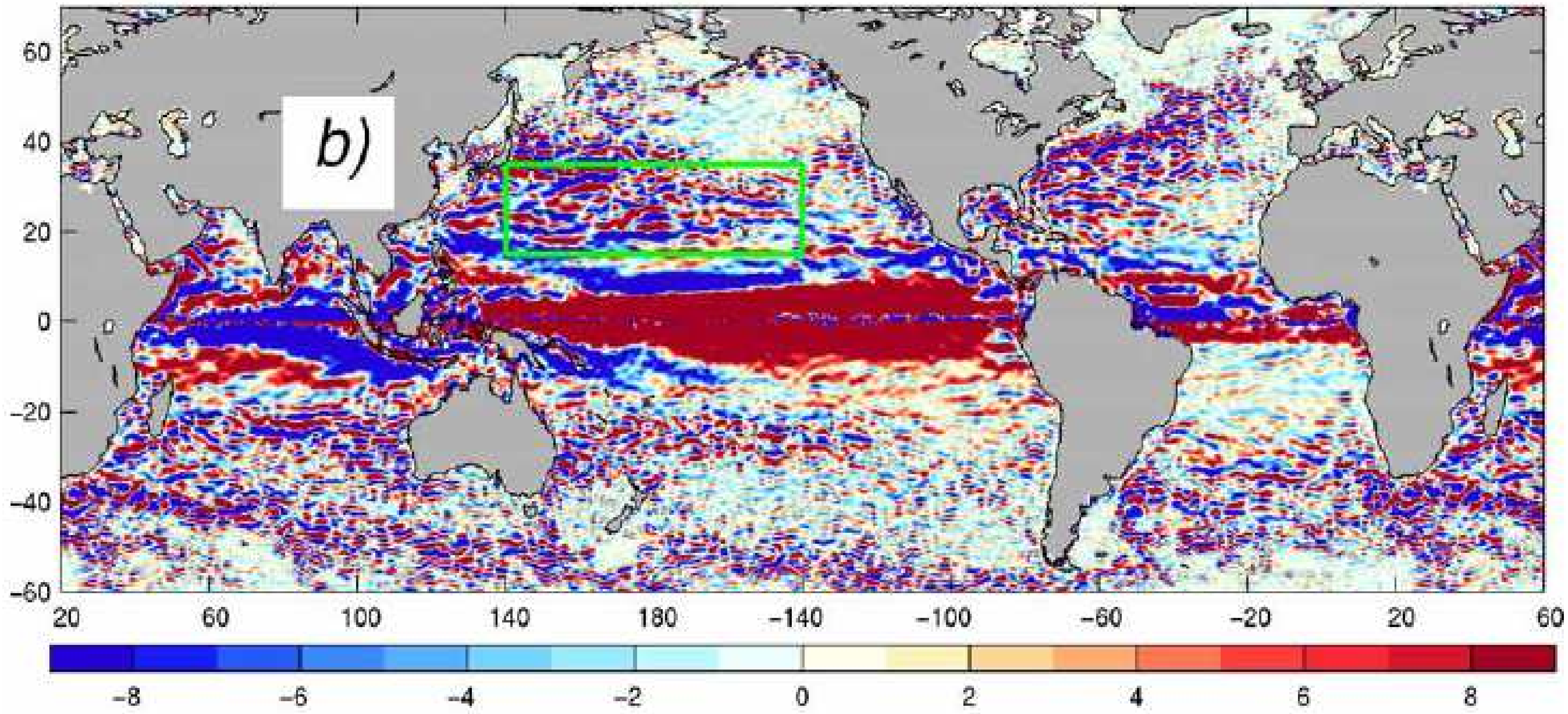
Impact on the net ocean heat transport

LEGOS

Satellite Oceanography, CICESE,

Fronts and Jets

Time-varying zonal jets populate all the oceans



b) : 18-week averages of geostrophic velocity U'.

Fronts and jets revealed from the velocity or vorticity field : ∇SLA

Models show they have high vertical coherence

Maximenko et al., GRL 2005.

Also Hughes and Ash, JGR, 2001

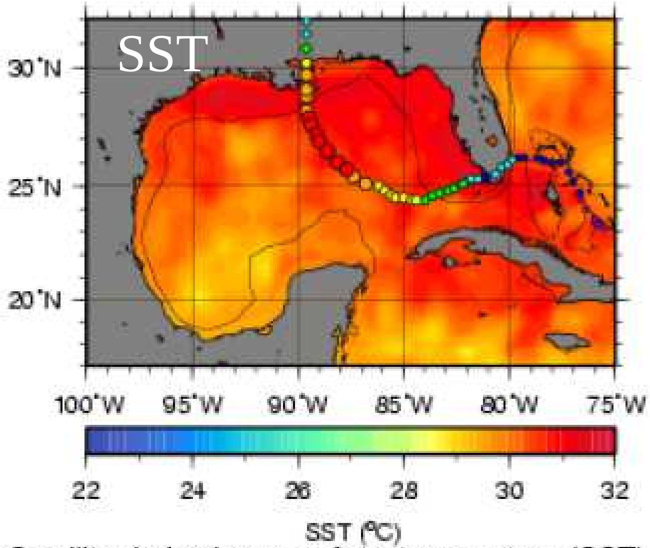
Open Ocean Extreme Events

1) Cyclone / hurricane / typhoon forecasts

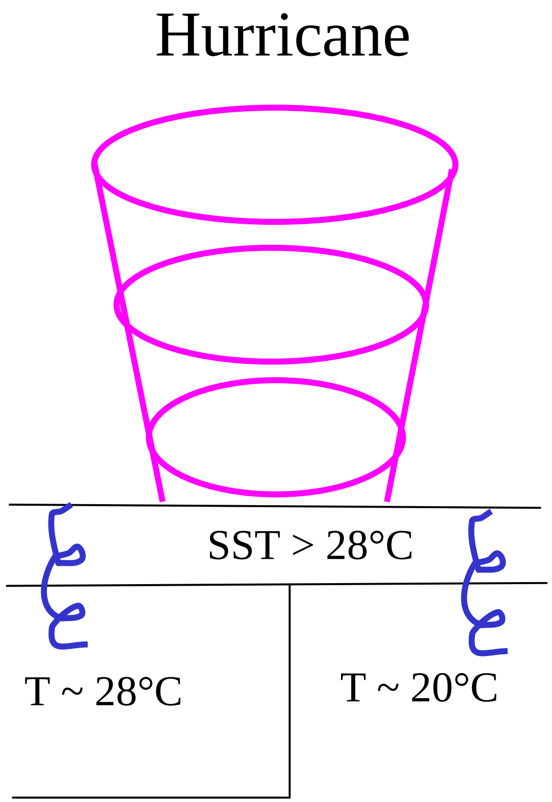
Katrina hurricane monitoring and forecasting

- Ocean **altimeter data** are used for seasonal forecasts of the number and strength of **hurricanes** expected in a given hurricane season, as well as short term forecasts of the strength of individual hurricanes.

- Why?

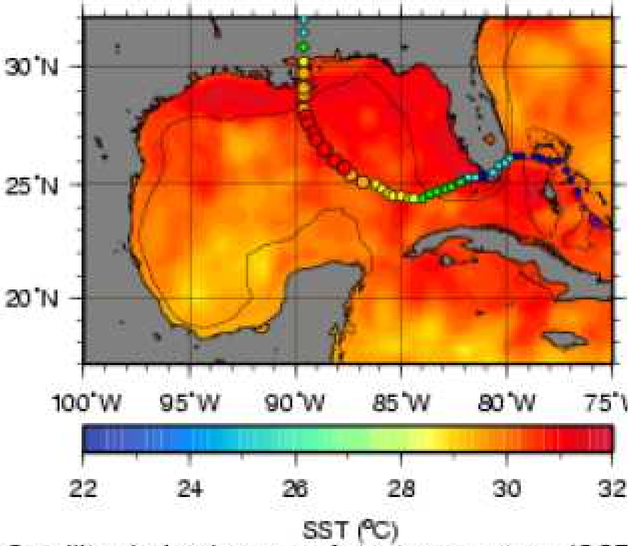


Satellite-derived sea surface temperature (SST) in the Gulf of Mexico on August 28, 2005. The circles of different colors indicate the track and intensity of Hurrican Katrina. The isobath of 200m is superimposed.



Strong winds induce strong ocean mixing

Before Katrina



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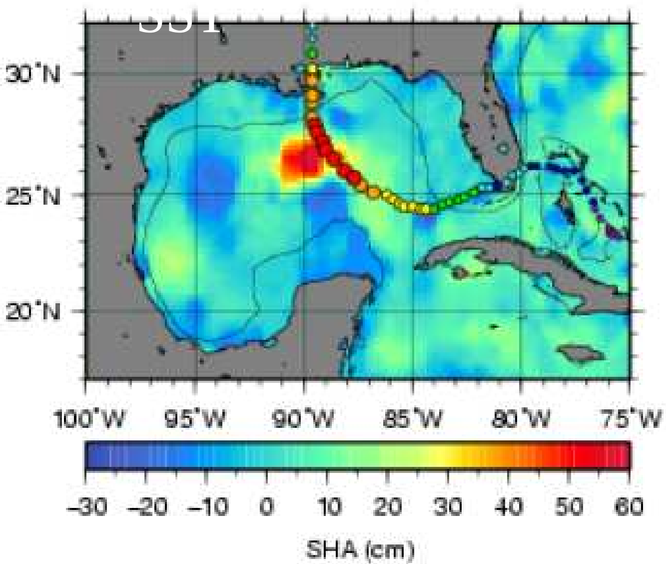
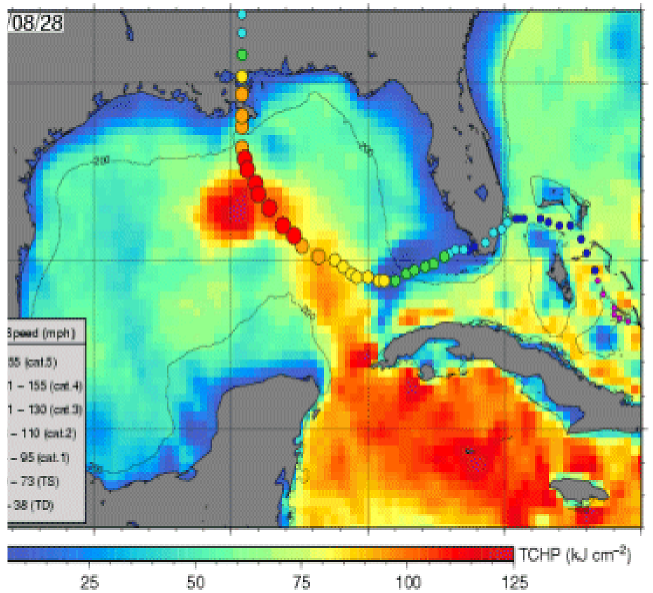
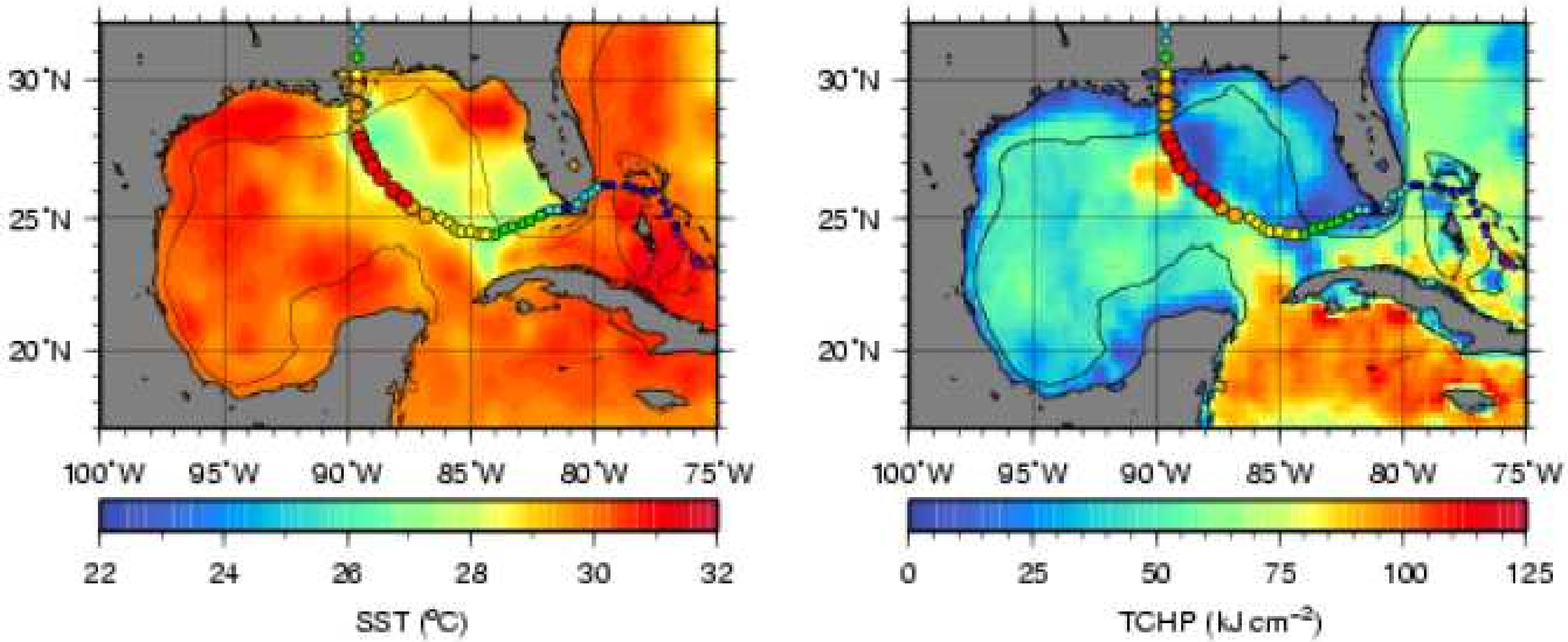


Satellite altimetry-derived field of sea height anomaly (SHA) on August 28, 2005, in the Gulf of Mexico. The large values (red) of SHA in the center of the Gulf are indicative of the presence of a warm anticyclonic ring. The circles of different colors indicate the track and intensity of Hurricane Katrina. The isobath of 200m is superimposed.



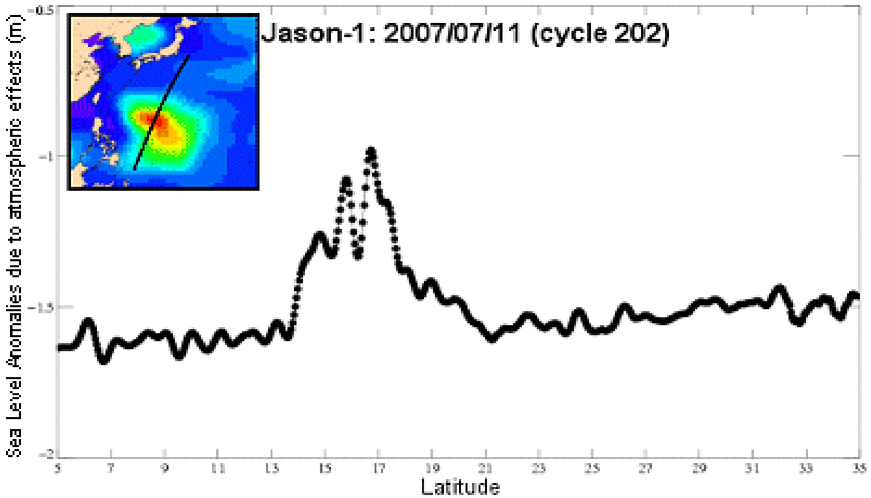
- These images from NOAA illustrate **altimetry** combined with sea surface temperature (**SST**) and a **two-layer model** to show ocean heat potential.

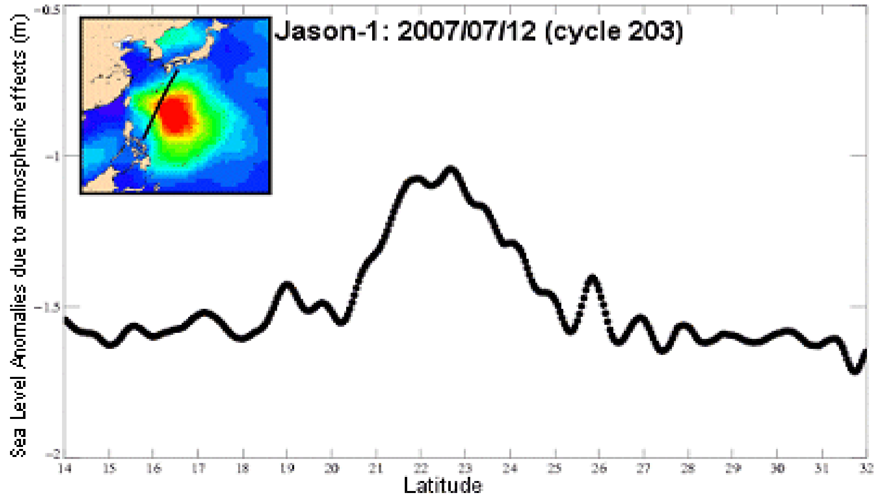
After the passage of hurricane Katrina



Sea surface temperature (SST) and Tropical Cyclone Heat Potential (TCHP) in the Gulf of Mexico on August 31, 2005. The cooling of the surface waters is observed in both maps. The circles of different colors indicate the track and intensity of Hurricane Katrina. The isobath of 200m is superimposed.

Typhoon Man-Yi (SLA)



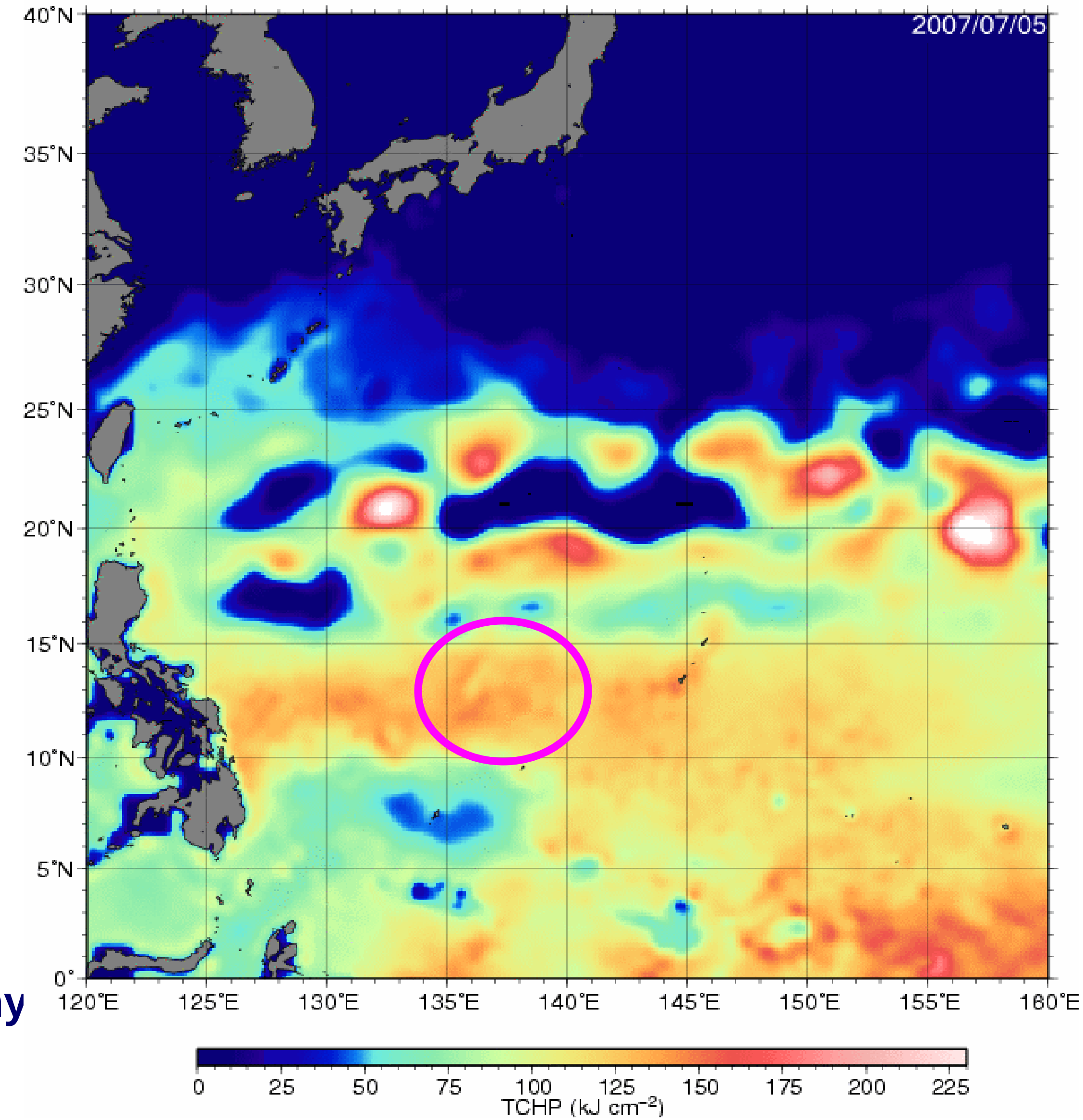


Sea level anomalies due to the effects of atmosphere on the sea surface, as measured by Jason-1 over the Man-Yi typhoon (top left, the plotted Jason-1 ground track overlaid on a significant wave height map at the same time). The typhoon causes a sea surface height increase of about 50 cm (ocean variability has been removed). Specific processing were applied in such extreme cases as cyclones.
(Credits CLS)

Typhoon Man-Yi (TCHP)

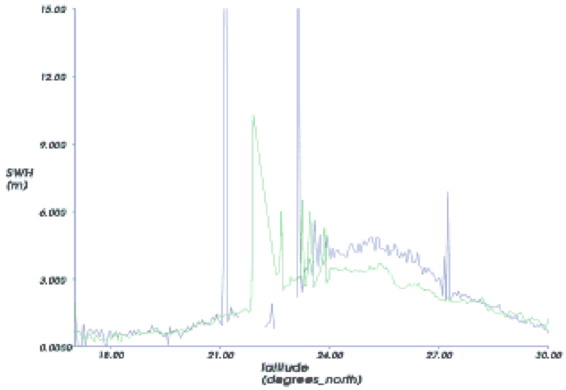
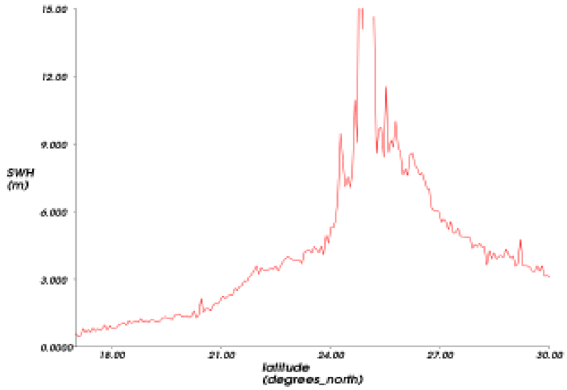
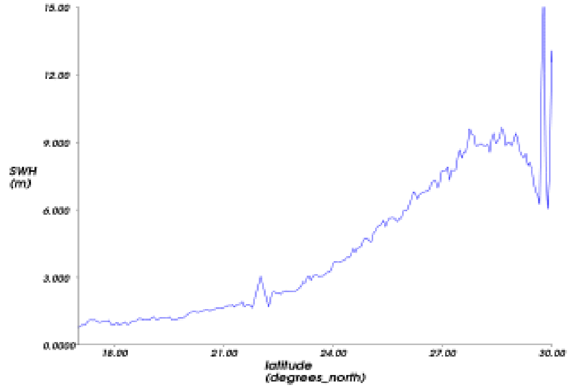
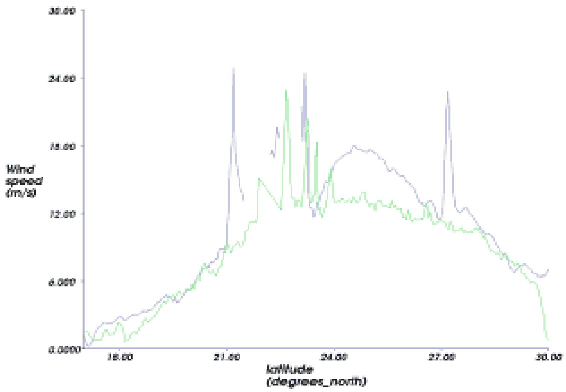
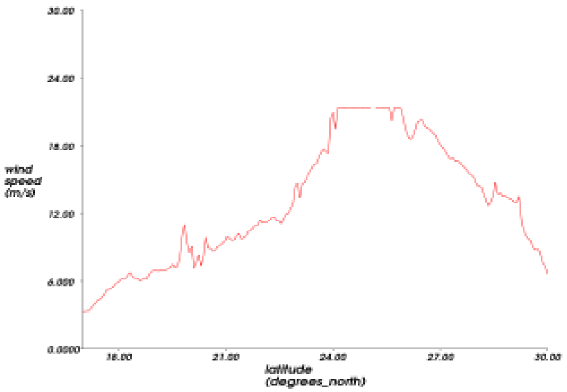
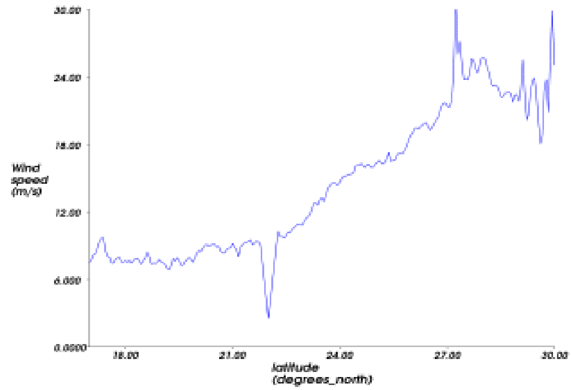
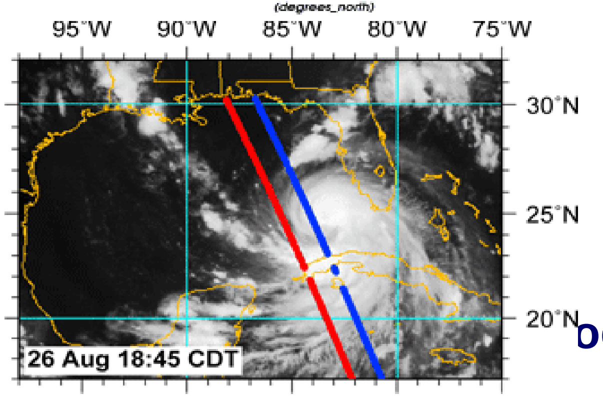
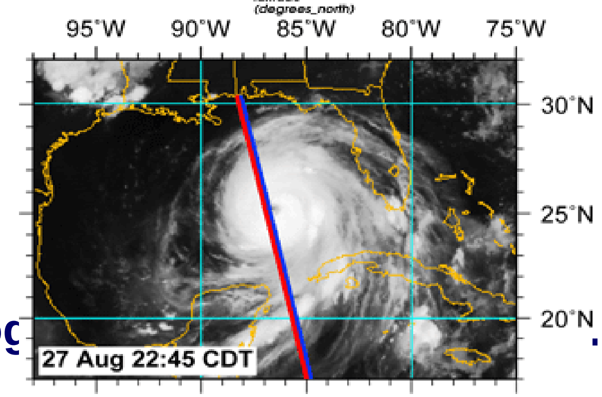
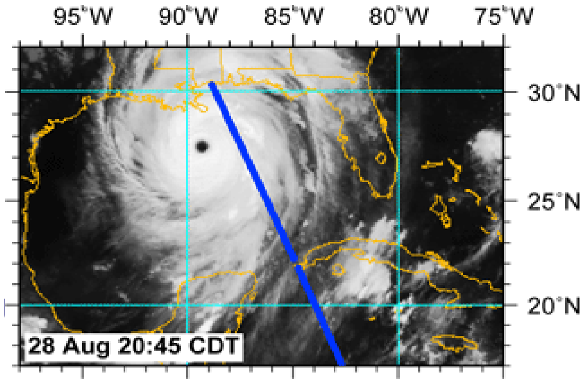
Tropical Cyclone Heat Potential (TCHP) animation between July 5 and 17, 2007 computed using satellite altimetry combined with sea surface temperature and hydrographic observations.

Typhoon Man-Yi appears to intensify in the region of high TCHP values.
(Credits Noaa/AOML)

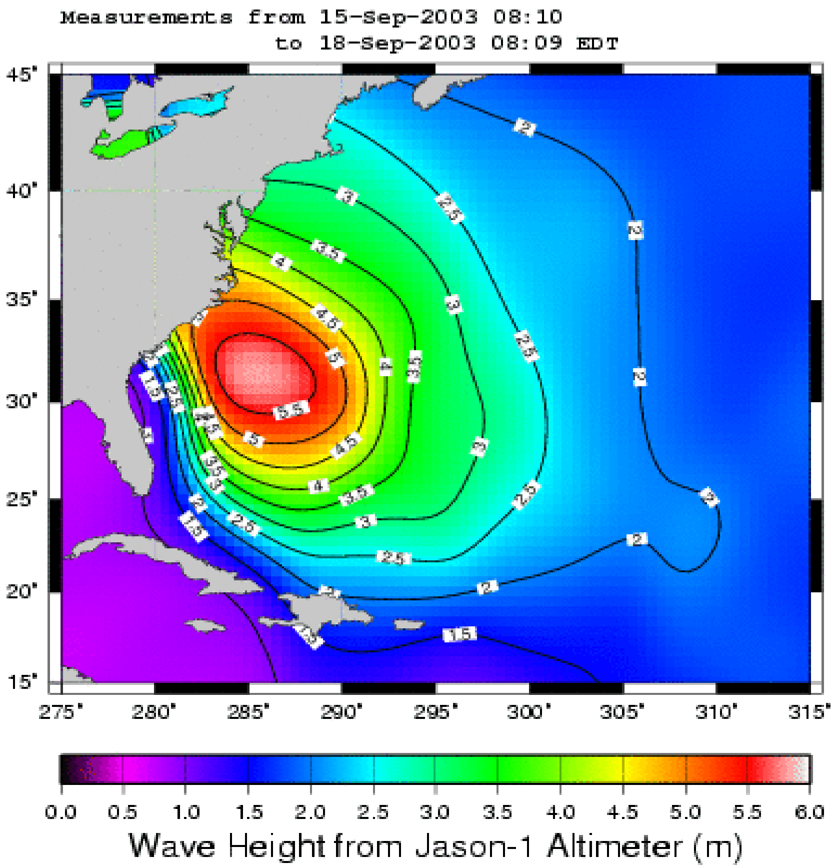


2) Extreme wave conditions under cyclones / hurricanes

Hurricane Katrina

	Jason-1 & T/P	*Envisat*	*GFO*
SWH			
Wind			
			

Jason-1 Real-time Significant waveheights during Hurricane Isabel

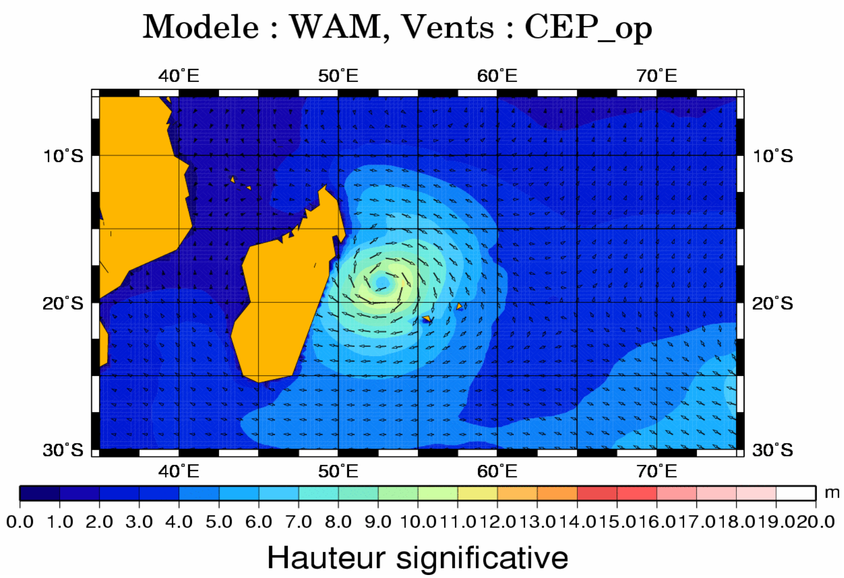


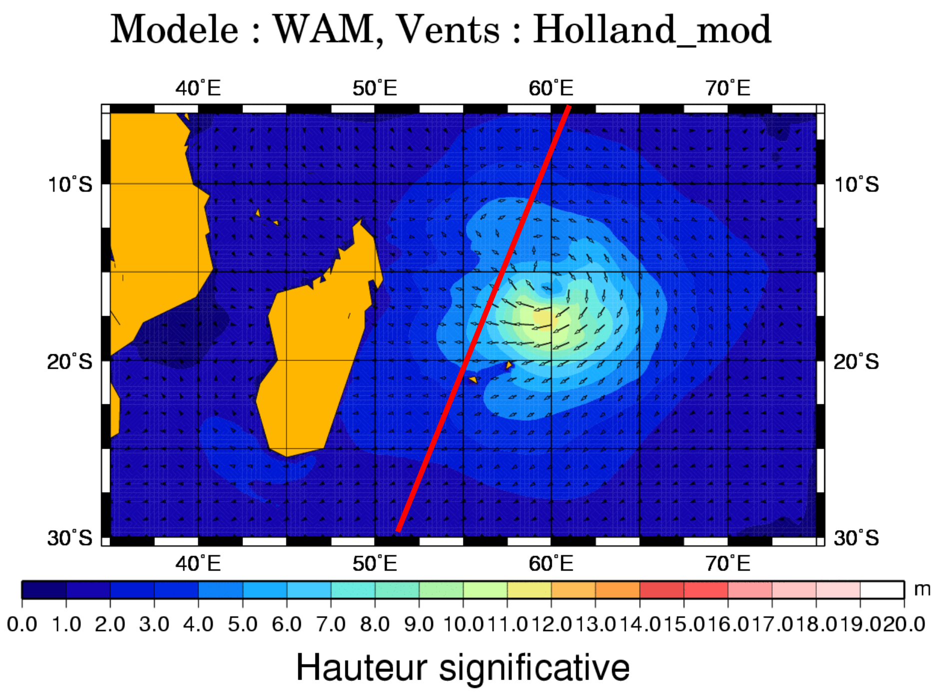
(Source: JPL)

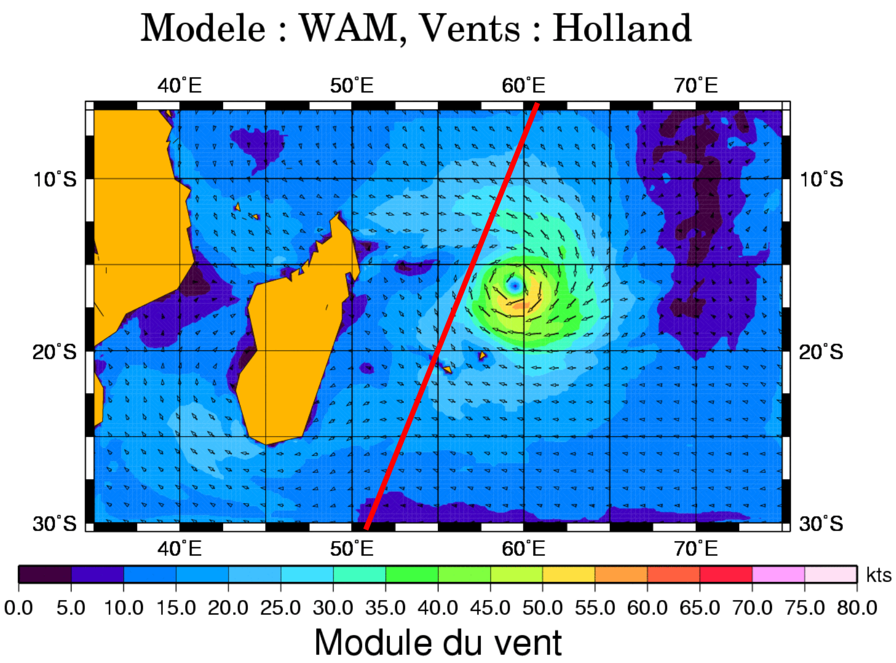
Operational models of surface waves under cyclones

- Study region : 6N-30S, 35-75E
- Period 22-28 Feb 2007
- Résolution 0.25°x0.25°
- Modèles VAG et WAM4.5 (+ DRAG FOAM)
- Forcing 6h
  - ECMWF 0.25
  - ARPTRO 0.25
  - ALADIN (version 2007)
  - ALADIN HOLLAND (version 2008)
  - ALADIN RANKIN
- Wave data : **ENVISAT et JASON**
- Buoy observations

METEO FRANCE
Toujours un temps d'avance



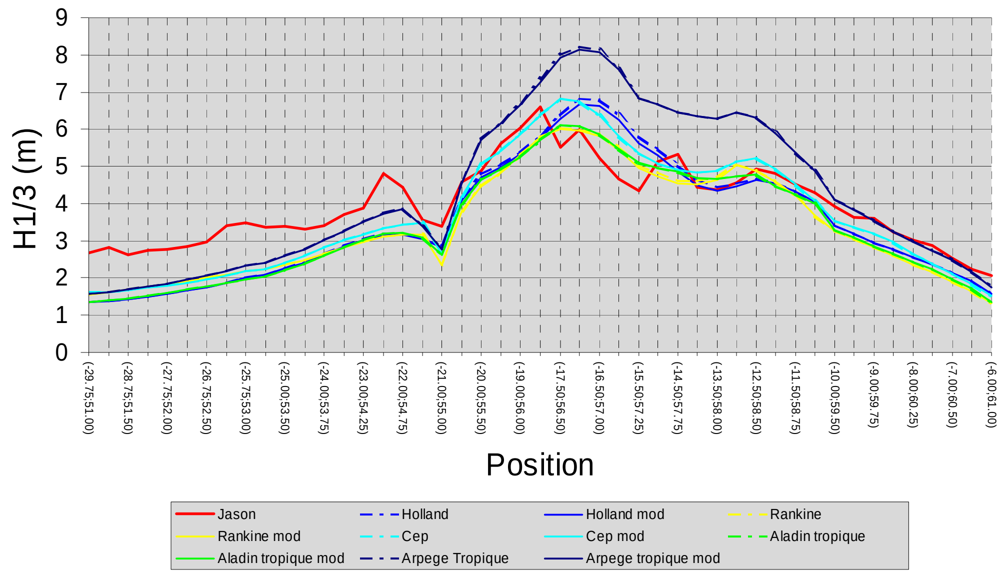




Using **altimetry** in **Operational wave forecast models** :

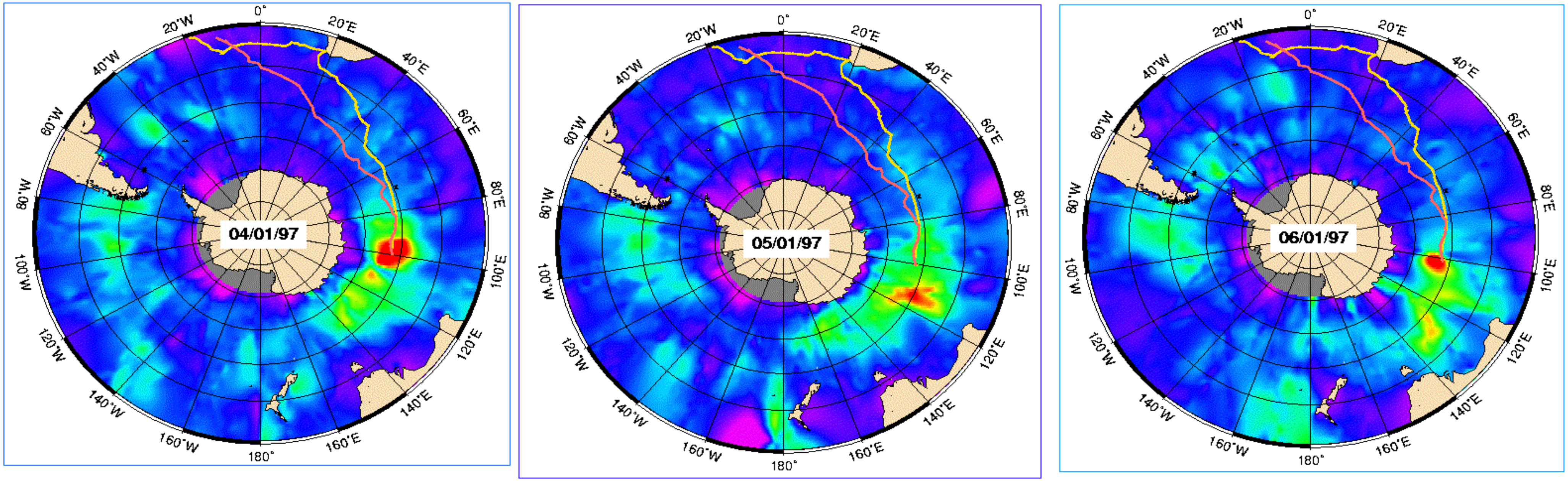
- validation
- assimilation

Cyclone Gamède (23/02 12h) : modèle WAM

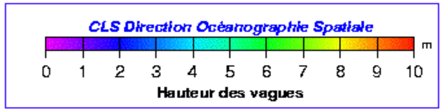


3) Extreme wave conditions

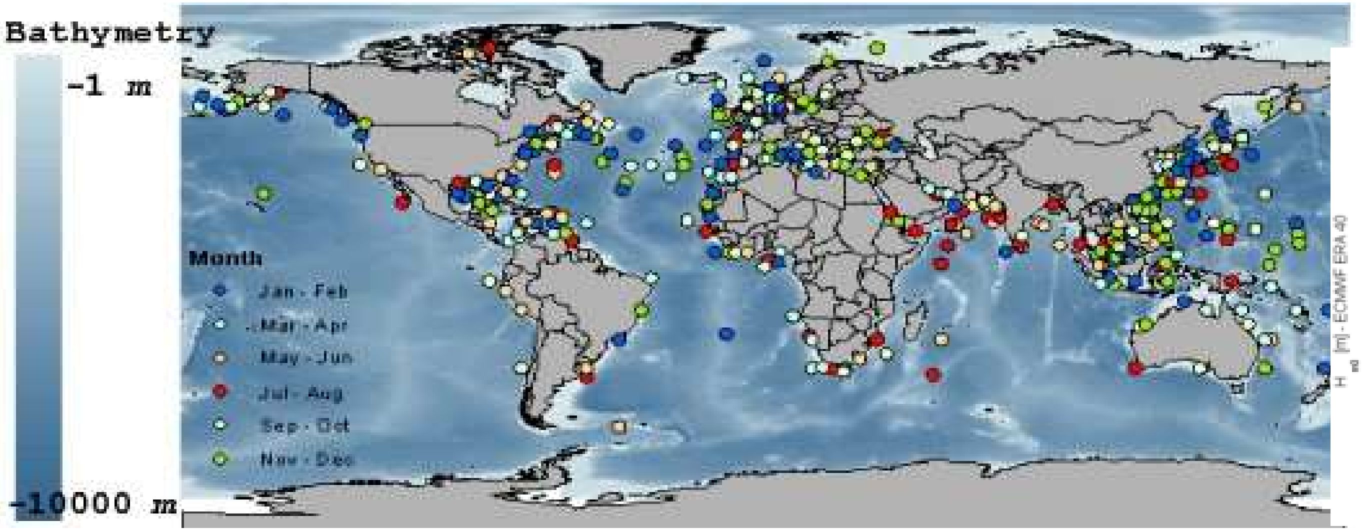
Wave forecasting for sea rescue
Vendée Globe 1996



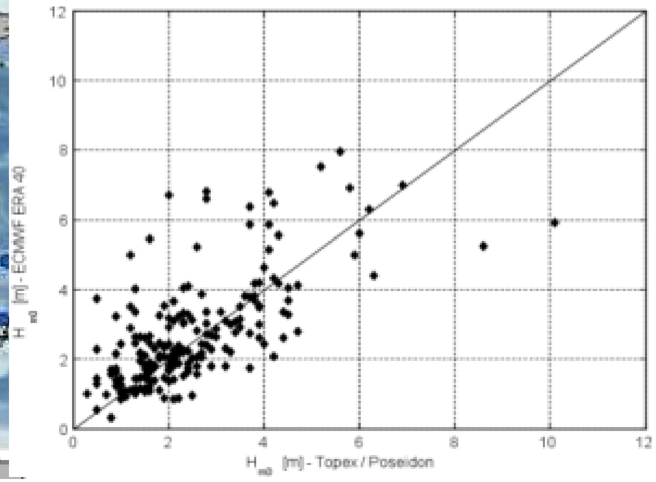
Trajectoires de T. Dubois (yellow) et T. Bullimore (red)



Rogue waves

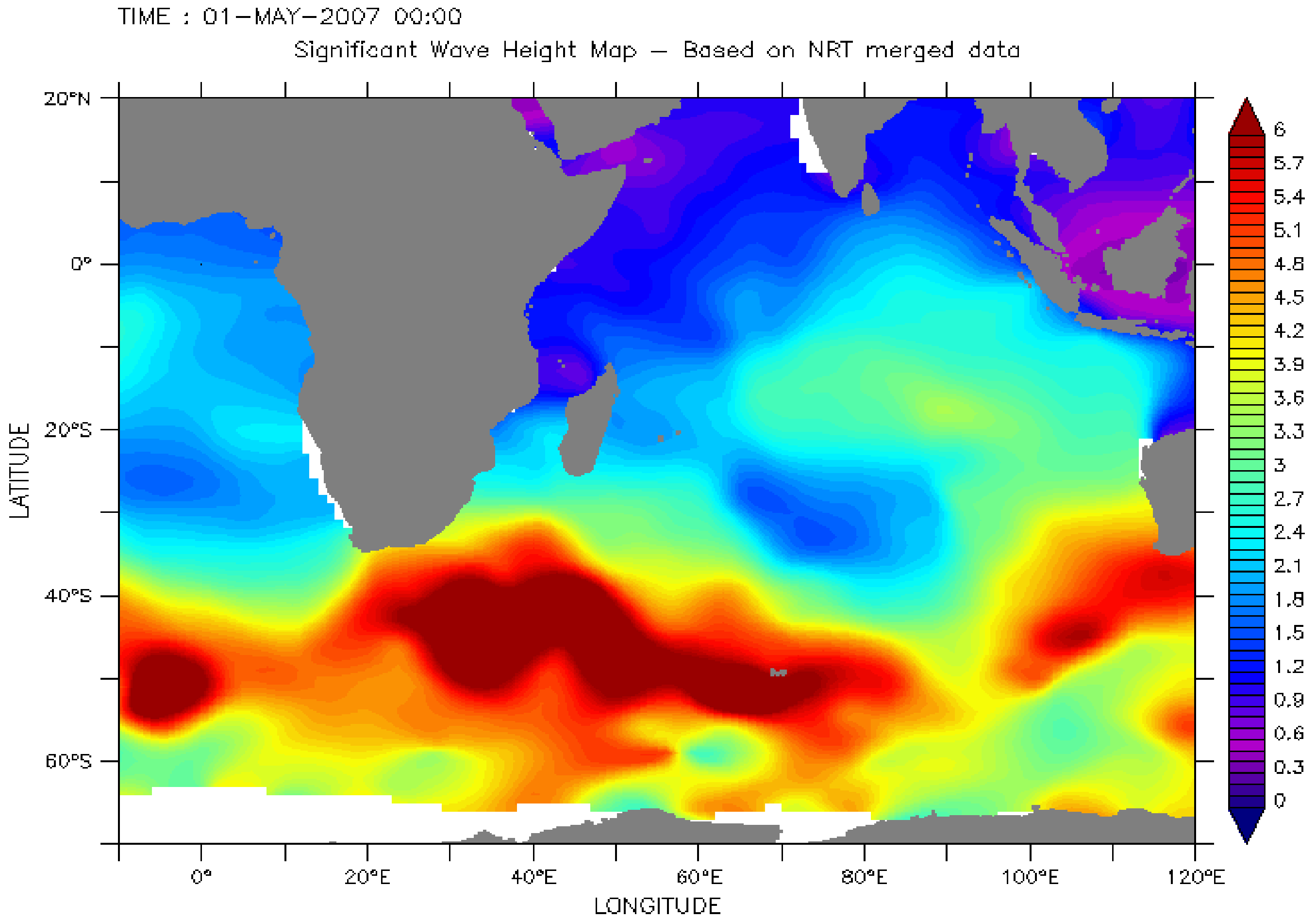


(Credits Lloyd's Marine Information Service)



Comparison between significant wave heights simulated by the ECMWF WAM model and actual wave heights measured by Topex/Poseidon (simulations from the ECMWF ERA40 reanalysis). Those data are used to validate numerical wave models. Jason-1 data (OSDR) are now used in real-time processing to correct the initial states of wave models in several meteorological centers

Southern swell, May 2007

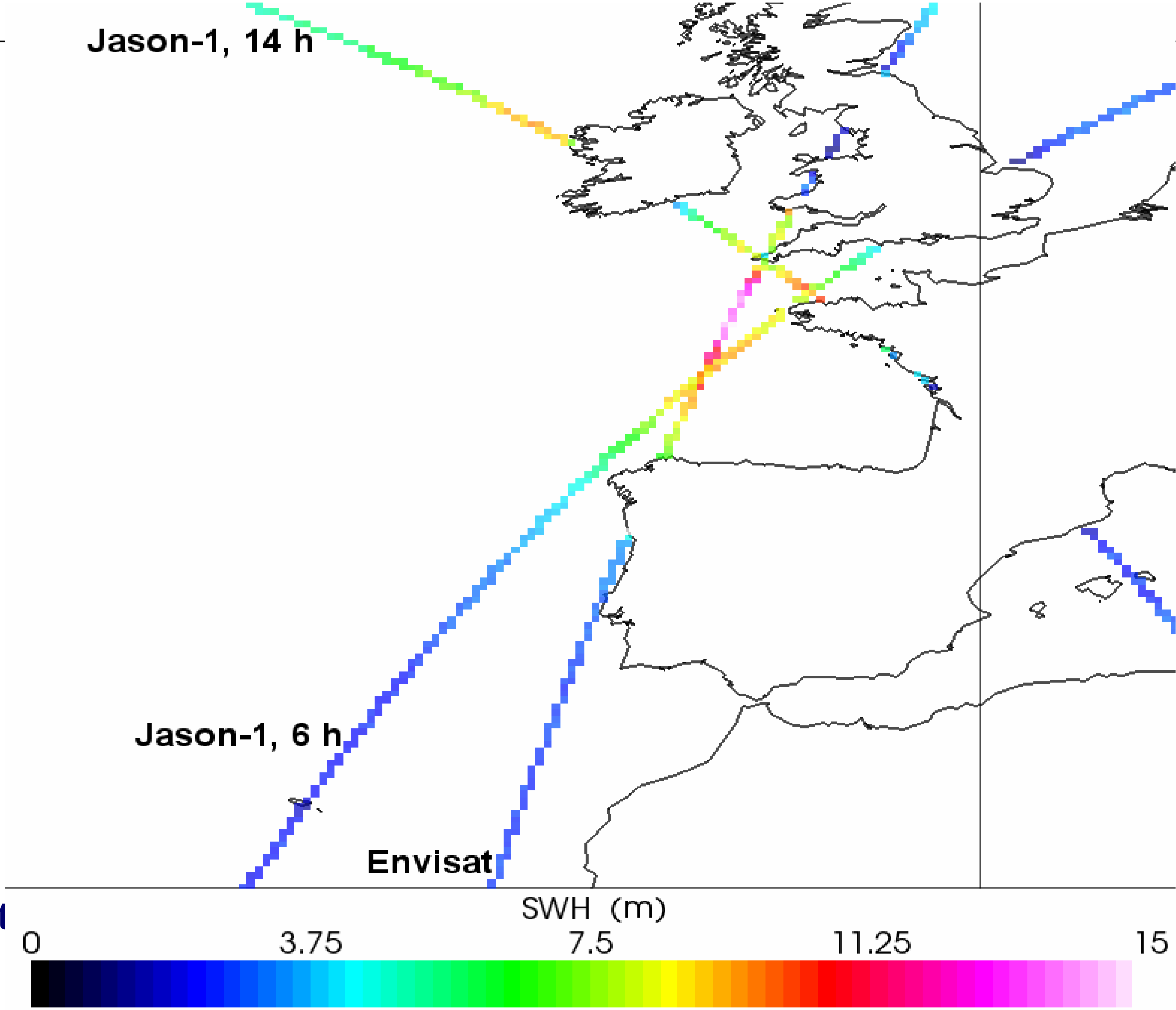


Significant Wave Height (m)

Significant wave height animation between May 1st and 25th in the whole Indian Ocean (data merging several altimeter measurements). The waves propagate in the whole ocean, reaching Indonesian coasts. (Credits CLS)

North Atlantic Storm (9 Dec. 2007)

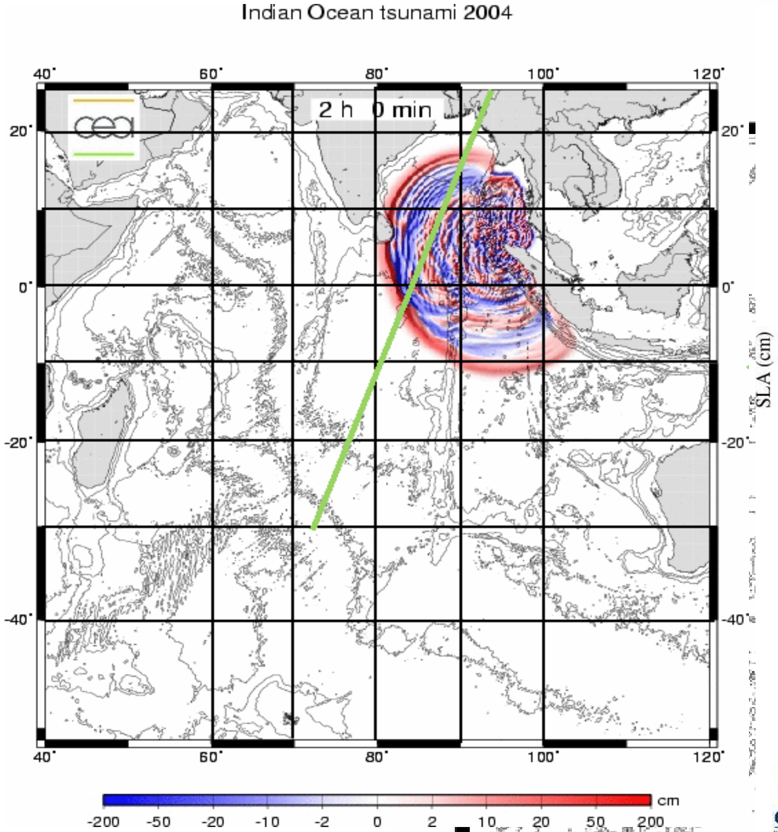
Significant wave heights along the tracks of Jason-1 and Envisat on December 9, 2007, during an especially strong storm (buoys measured SWH as high as 18 m near Ireland). (Credits CLS)

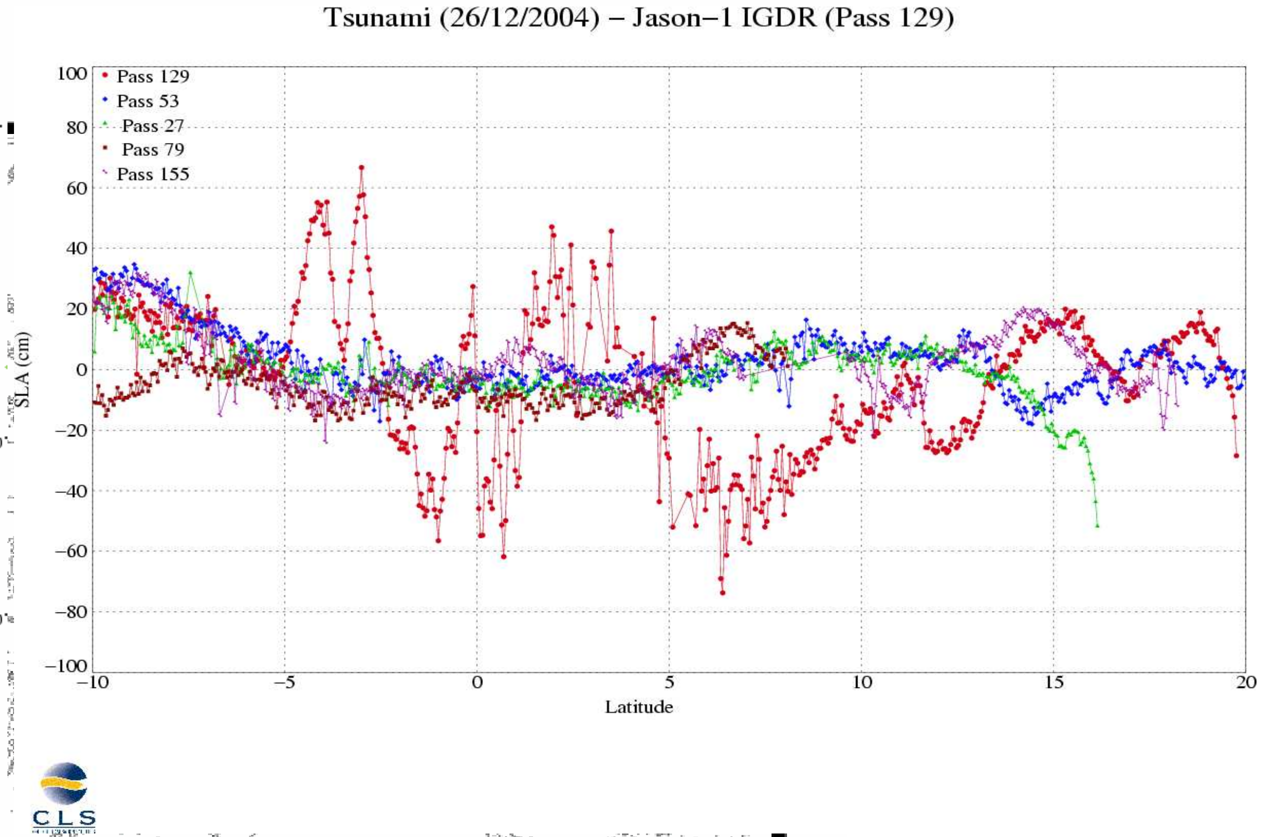


Satellit

4) Tsunamis

OBSERVATION DU TSUNAMI DU 26 décembre 2004





Left part Jason-1 ground track superimposed to the tsunami signals modeled by CEA (1h53 after earthquake)

Right part – in red : Sea Surface anomaly (+/- 50 cm) compared to usual signals

Conclusions

Altimetry necessary for long term climate studies – important for surface and deep ocean changes

Helps monitor upper ocean thermal conditions for forecasting extreme events (e.g. hurricanes)

Near real-time wind and wave observations used in operational forecasting of extreme wave events