P. Cipollini, H. Snaith - A short course on Altimetry

Altimetry 3 –
Geophysical parameters and applications

What can we get from Altimetry?

- Sea Surface Height Anomaly
  - ➪ Varying part of ocean circulation, eddies, gyres, tides, long waves, El Nino, etc
  - ➪ Variable currents
  - ➪ Sea Level Change
- In near future (with accurate geoid), or using ‘synthetic’ mean sea surface: absolute SSH
  - ➪ Absolute currents
- From shape of return: wave height
- From radar backscattering σ_0: wind

Geostrophic currents from Altimetry

- Assume geostrophic balance
  - geostrophy: balance between pressure gradient and Coriolis force

for unit mass:

$$g\frac{\partial H}{\partial x} = fv$$

Pressure gradient = **Coriolis force**

$f = 2\Omega\sin(latitude)$ "Coriolis parameter" in s^{-1}
(Ω is the Earth rotation rate)

g = gravity acceleration (m/s^2) v = current velocity (m/s)

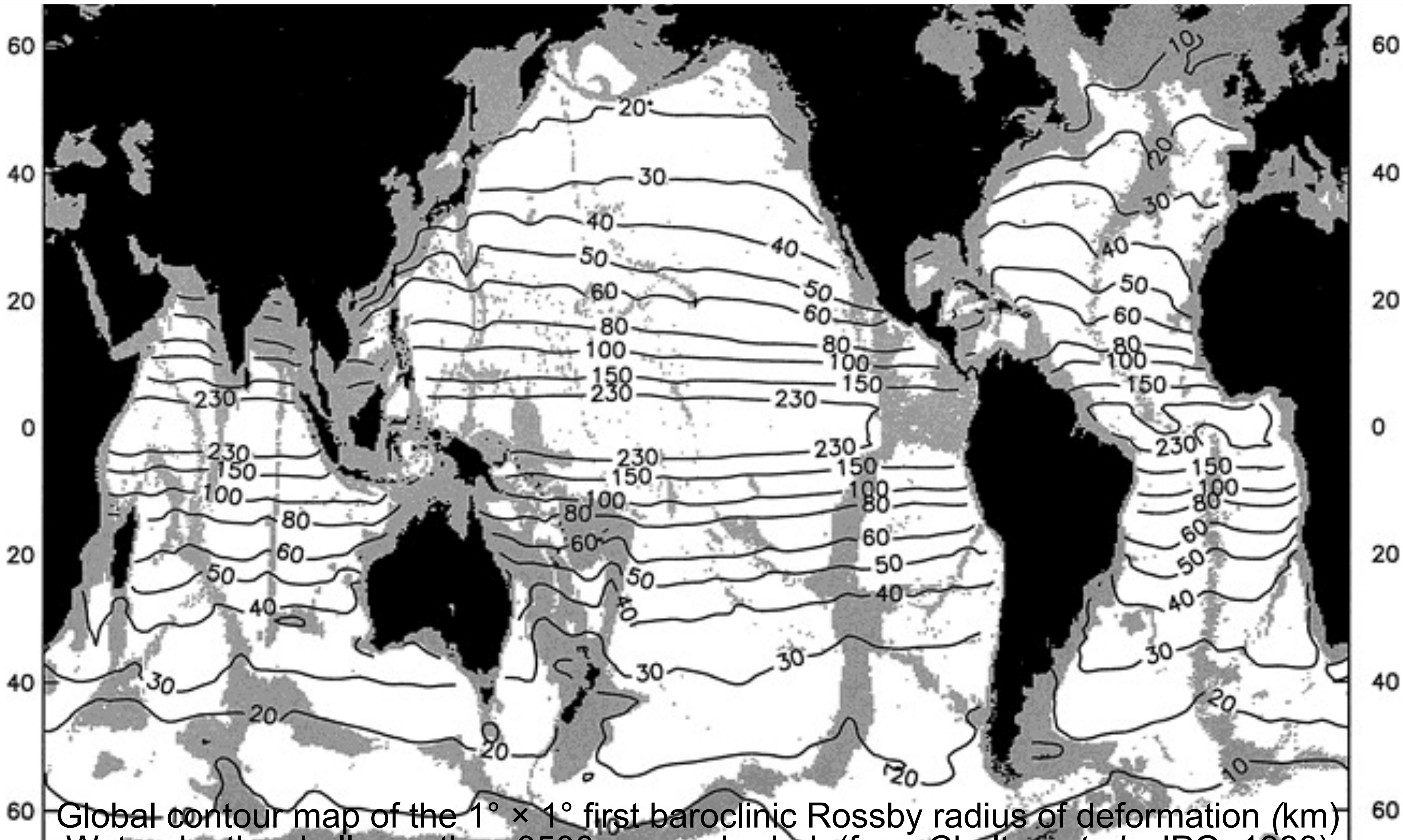
$$\Rightarrow \boldsymbol{v} = \frac{\boldsymbol{g}}{\boldsymbol{f}}\frac{\partial \boldsymbol{H}}{\partial \boldsymbol{x}}$$

- Unavoidable limitations
  - Measures only cross-track component of current
  - Cannot recover currents near the equator (geostrophy does not hold there)
  - Only variable (non-steady) currents are detectable

Geostrophy: not the whole story…

- Geostrophy only affects scales larger than the ‘**Rossby Radius of Deformation**’
  - a typical length scale in the ocean
  - ranges from ~10 Km in polar seas to ~200Km near)
- At smaller scales, other (ageostrophic) components, such as due to the local wind, will be present.
- With ssh profiles from altimetry we can estimate the geostrophic currents and subtract them from local total current measurements (for instance from a current meter) – and estimate the ageostropic component

Rossby radius of deformation



Global contour map of the 1° × 1° first baroclinic Rossby radius of deformation (km)
Water depths shallower than 3500 m are shaded. (from Chelton *et al.*, JPO, 1998)

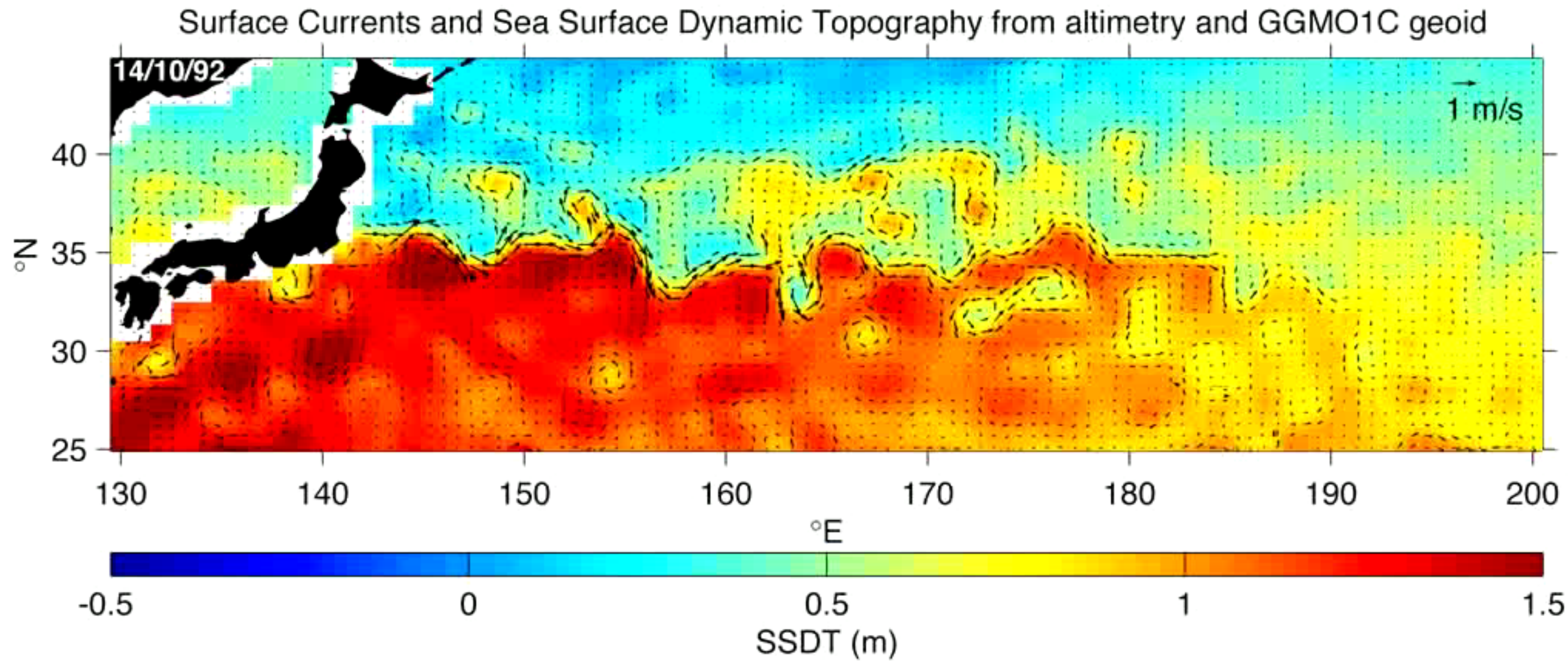
…BUT very important

- Geostrophy **dominates** the meso- and large scale ocean circulation
  - eddies and major current systems are essentially geostrophic

Absolute currents / absolute topography - an example

- Kuroshio Current - important current system in North Pacific
- We will see a model animation first, in SST
  - Model data from OCCAM model at NOCS, courtesy of Andrew Coward
- Then we will see the combination of all Altimeter mission available subtracting a geoid derived from the GRACE mission
  - Courtesy of Doug McNeall, NOCS (now at MetOffice)

Kuroshio current from Altimetry: a movie



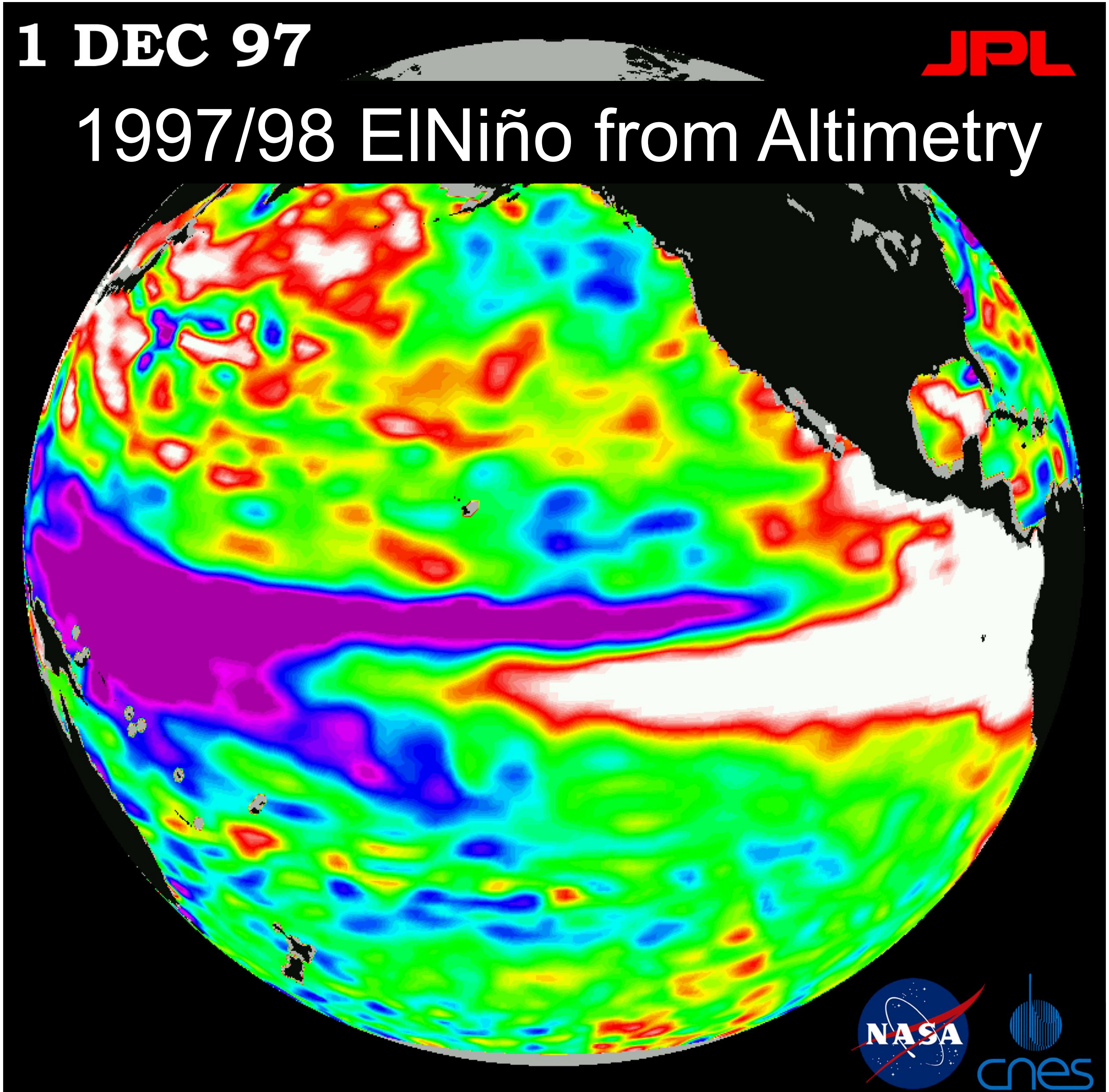
1 full map every 7 days, from a combination of all available satellite altimeters

Movie by Doug McNeall, NOC (now UK MetOffice)

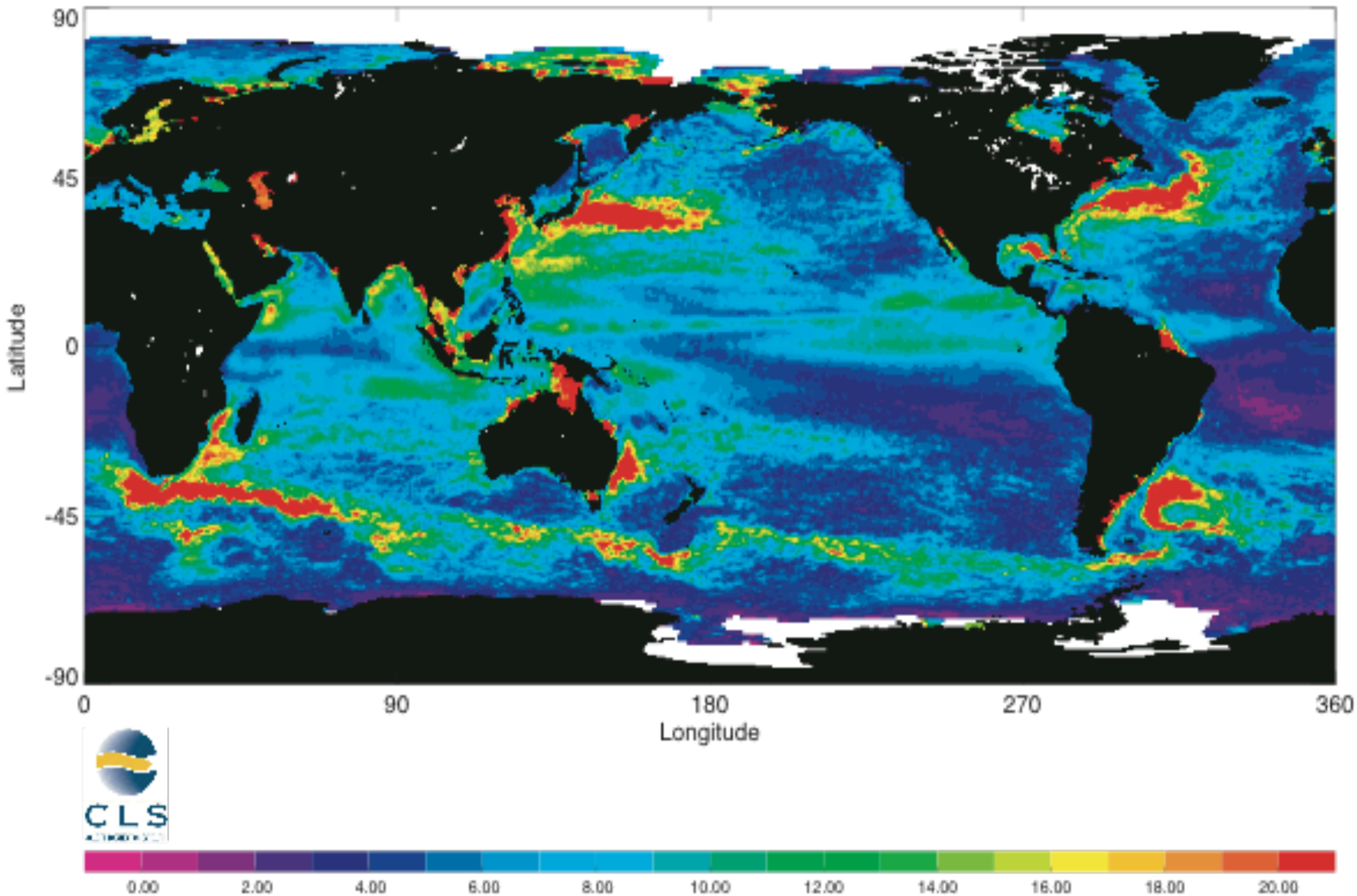
Ocean dynamics & climate studies

- Detect large scale SSH anomalies
  - e.g. El Niño, Antarctic Circumpolar Wave, etc.
  - Identify global connections
- Isolate seasonal current variability
  - e.g. Monsoon dynamics
- Detect and follow mesoscale (50-200 Km) eddies
  - Use transect time series
- Identify planetary waves
  - Use longitude/time (Hovmüller) plots
  - Measure phase speed from gradients of wave signatures
- Global and regional Sea Level Rise

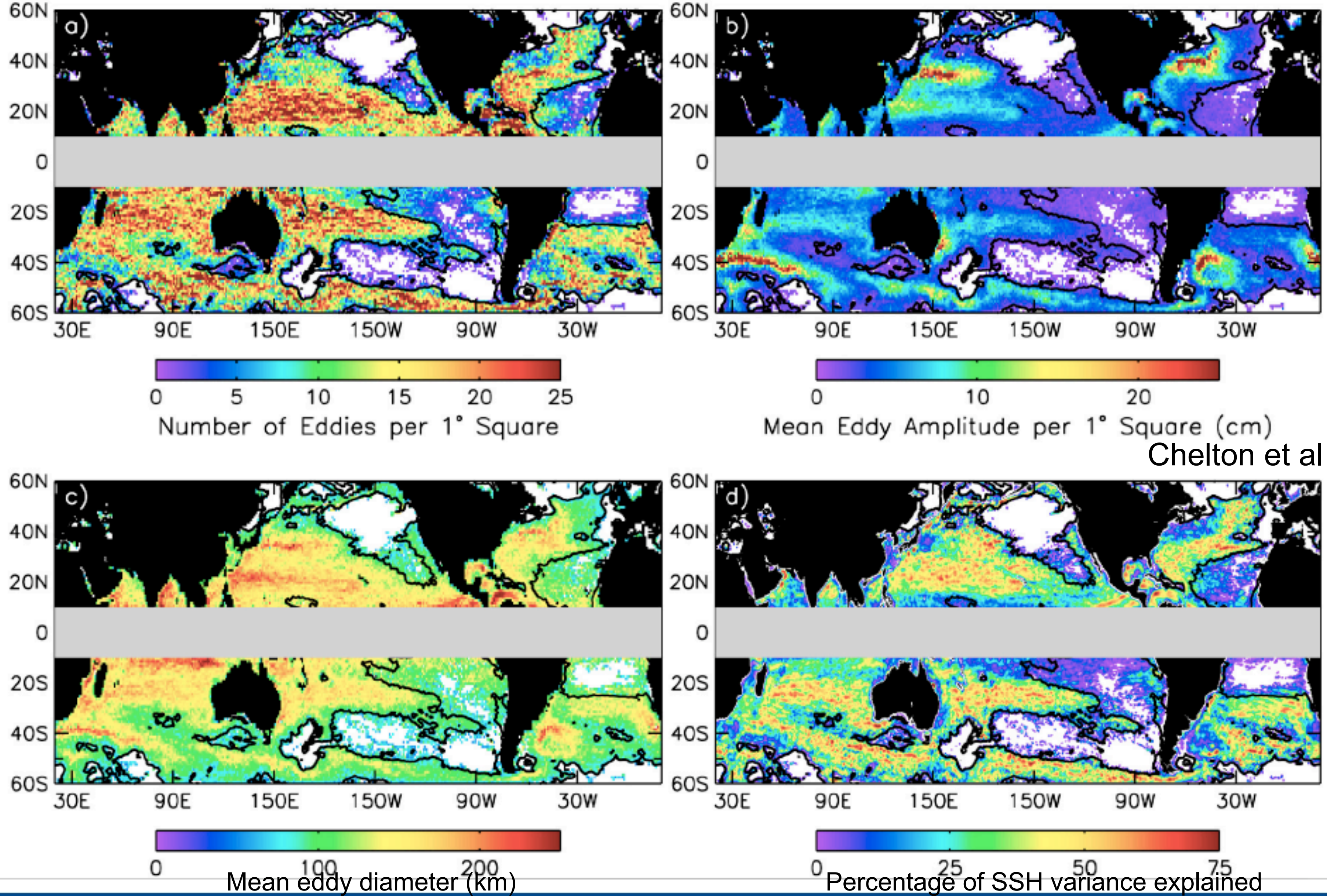
1997/98 ElNiño from Altimetry



Ocean meso-scale variability

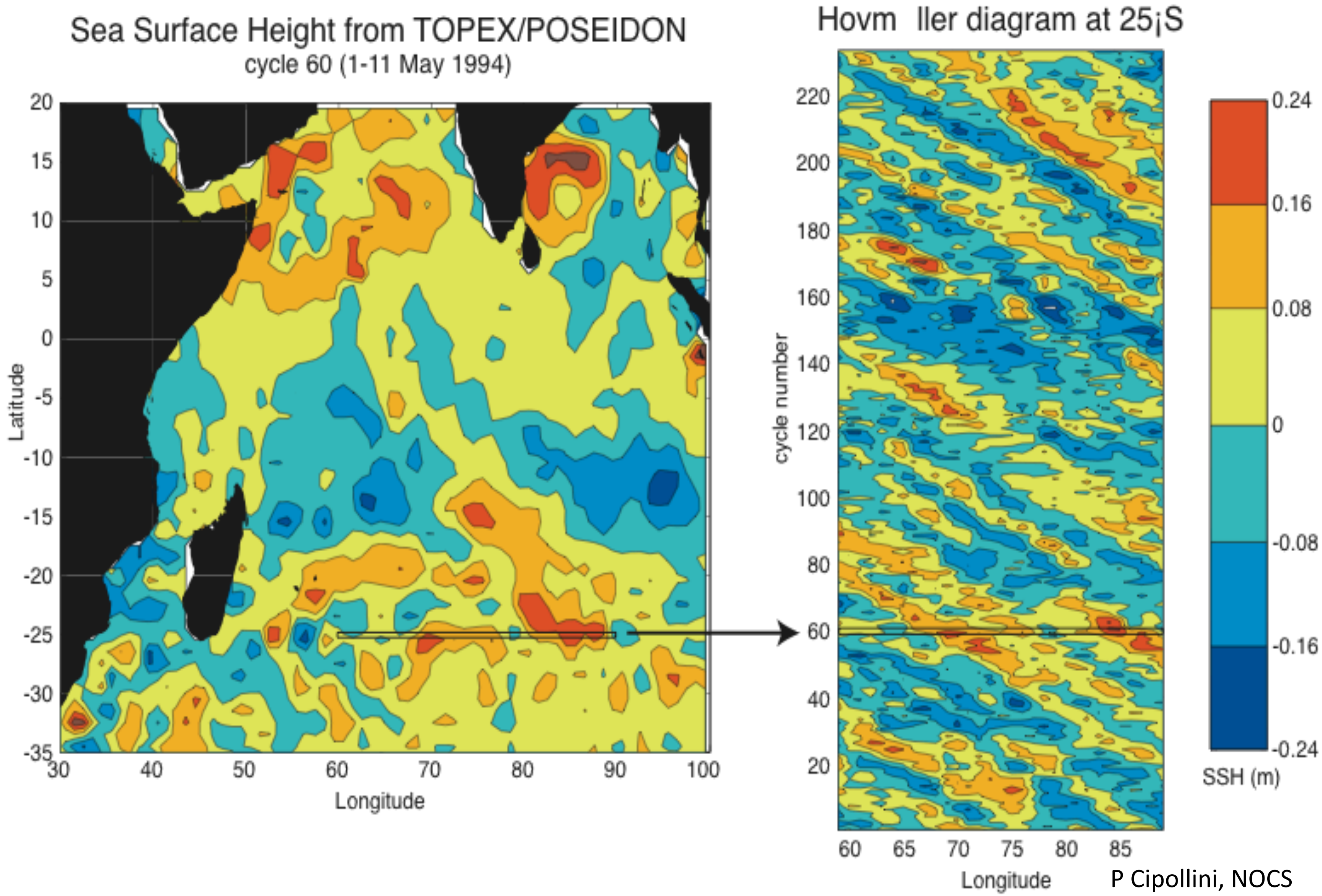


Global Eddy Statistics



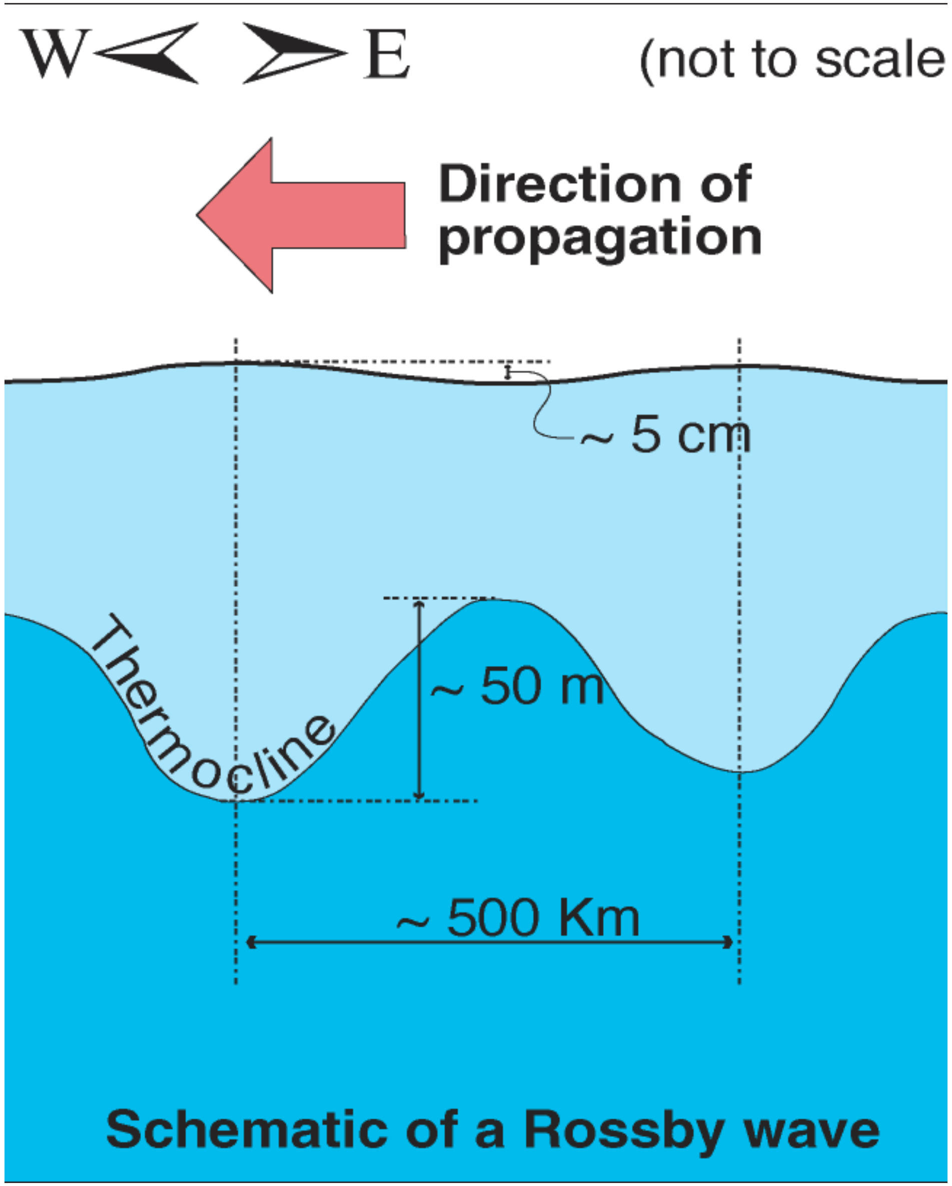
Chelton et al 2007,2011

Eddies and Planetary (Rossby) Waves

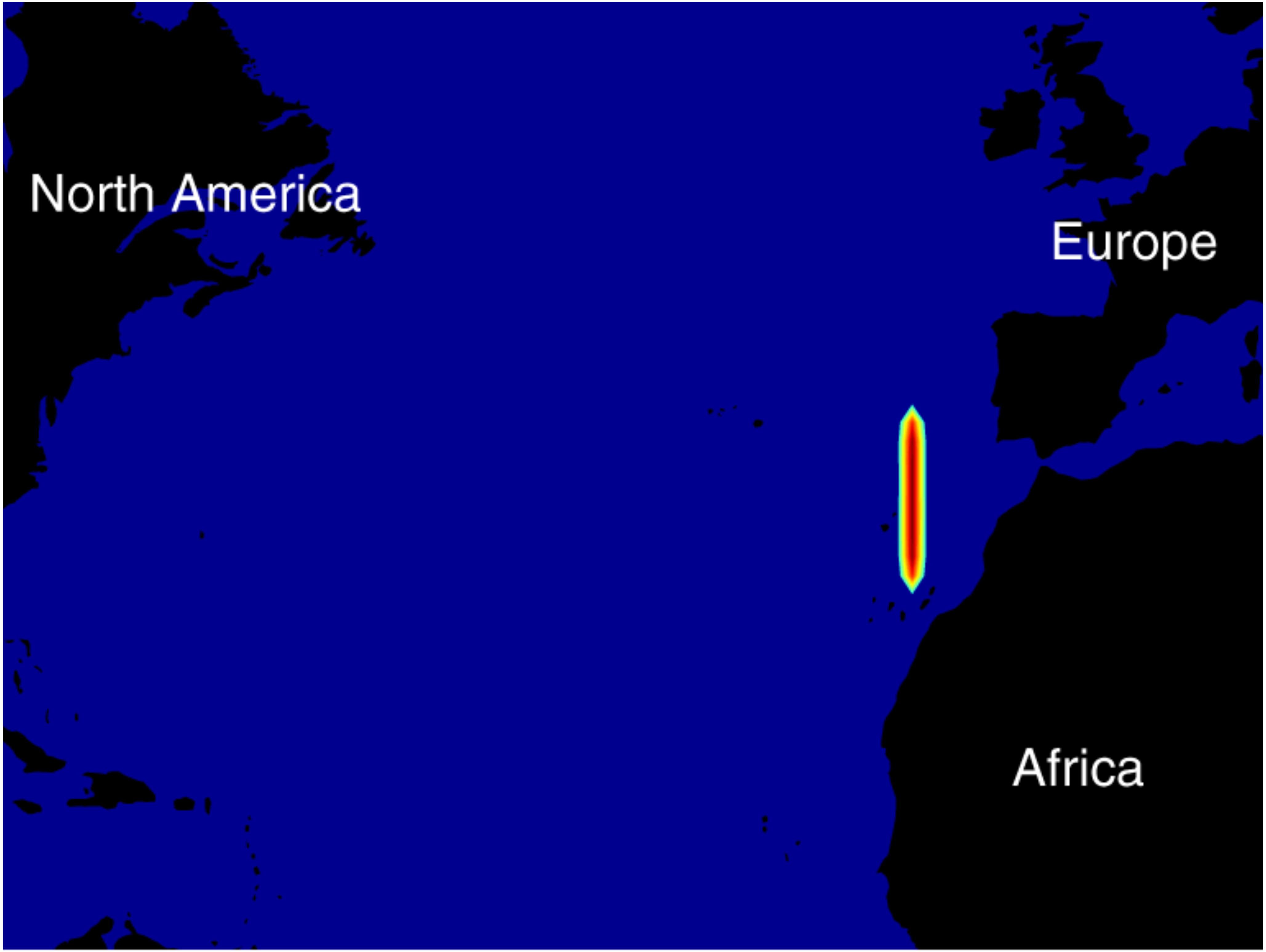


P Cipollini, NOCS

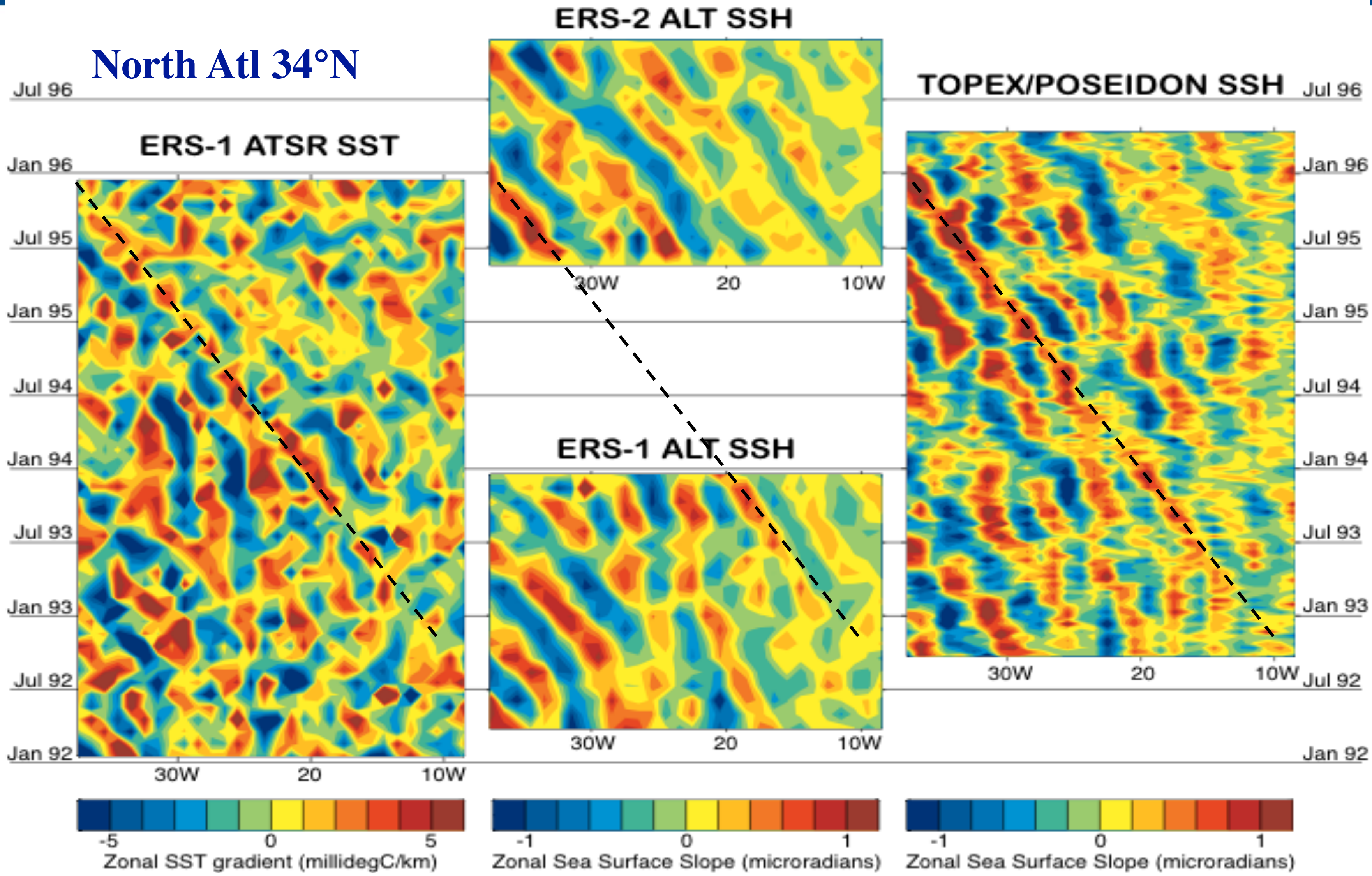
Planetary waves in the oceans



- Large-scale internal waves with small surface signature
- Due to shape and rotation of earth
- Travel E to W at speeds of 1 to 20 cm/s
- Main mechanism of ocean adjustment to forcing
- Maintain western boundary currents
- Transmit information across ocean basins, on multi-annual time scales
- Also known as Rossby waves (after C.-G. Rossby)

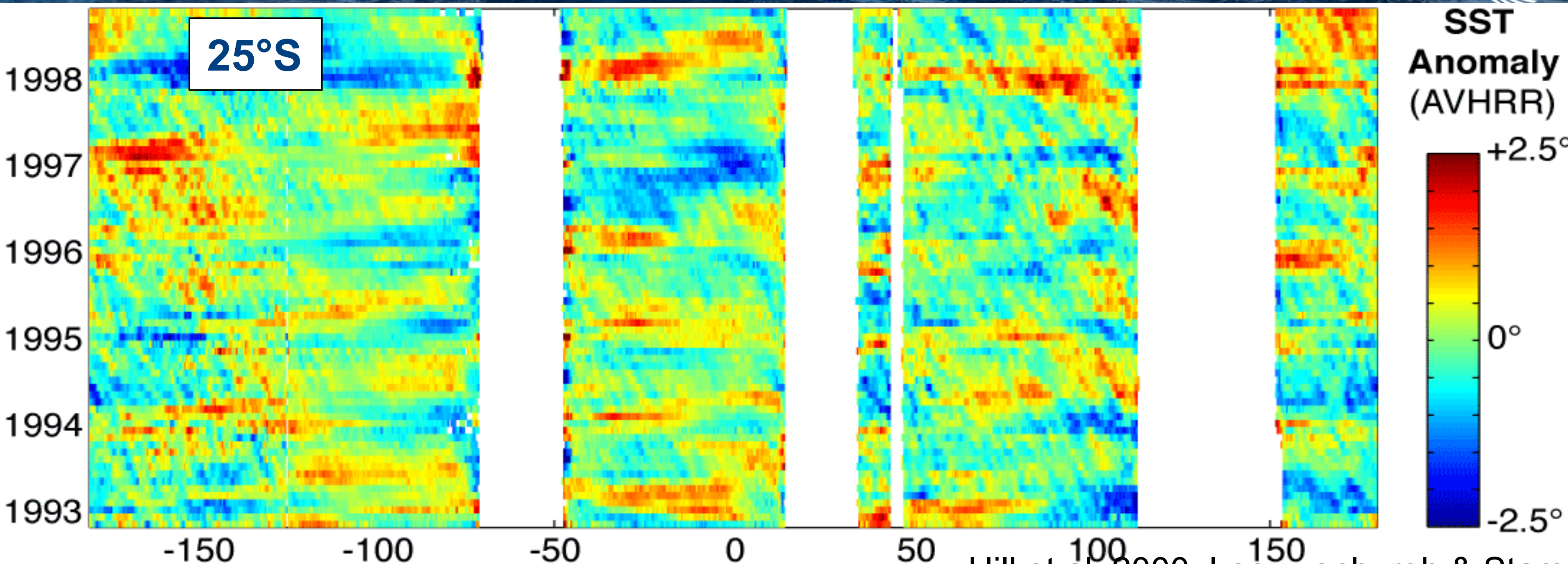

North America
Europe
Africa

ERS-based observations

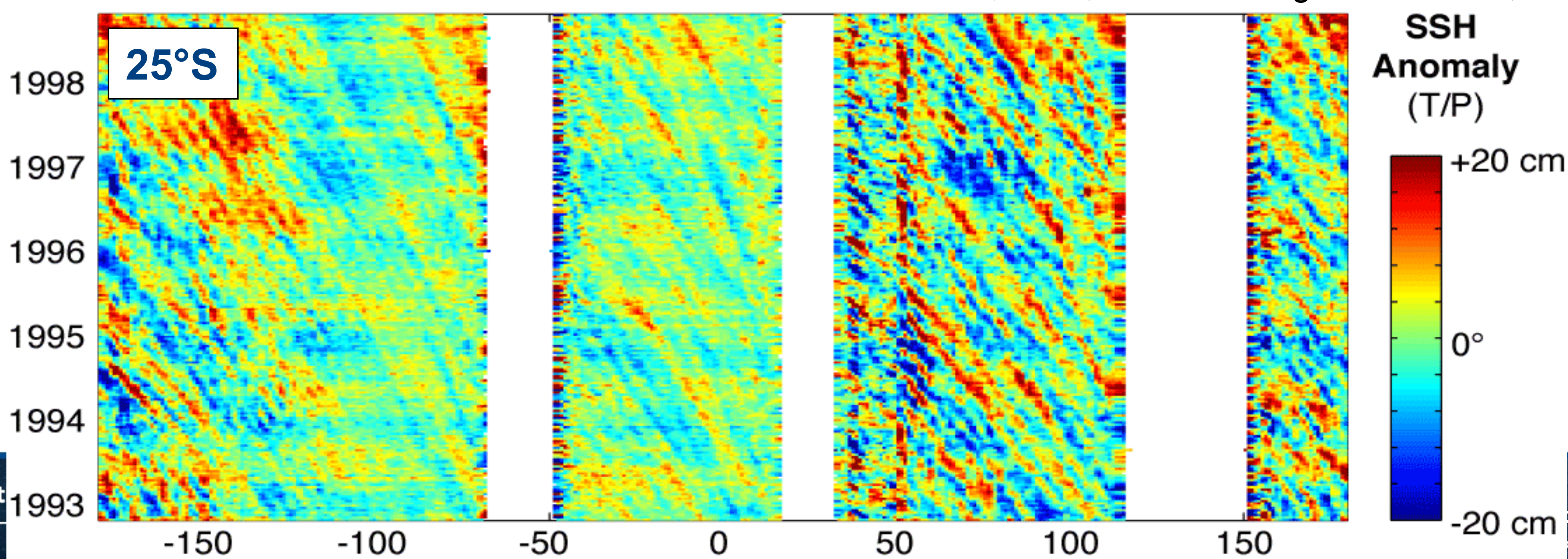


Cipollini et al 1997 (North Atlantic): Hughes et al 1998 (Southern Ocean)

Global observations in SST



Hill et al, 2000; Leeuwenburgh & Stammer, 2001

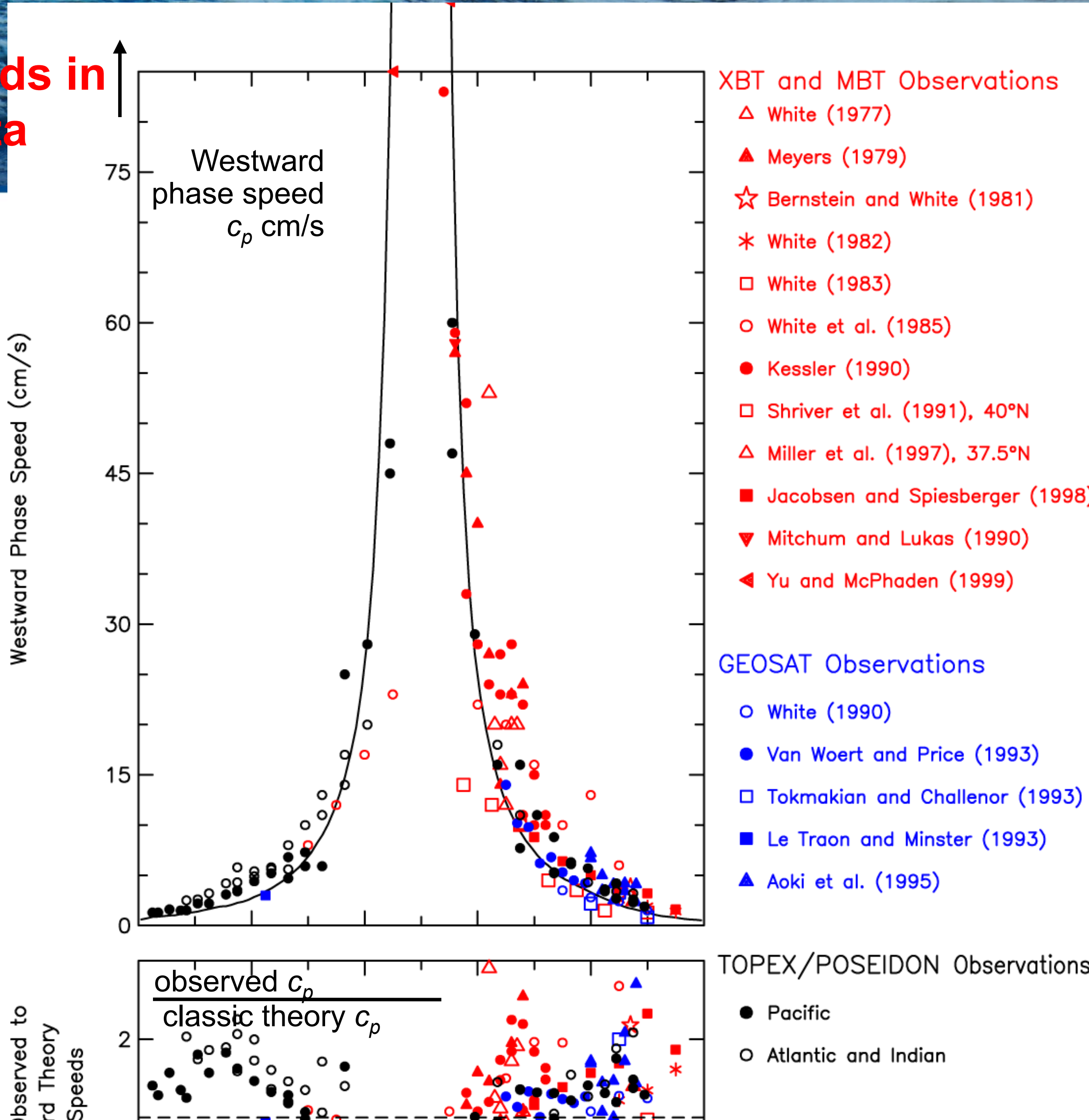


Planetary wave speeds in merged T/P+ERS data

Used in global westward propagation study by Chelton et al 2007

Made possible by both remarkable improvement in ERS orbits (Scharroo et al 1998, 2000), and careful intercalibration + optimal interpolation techniques (Le Traon et al 1998, Ducet et al 2000)

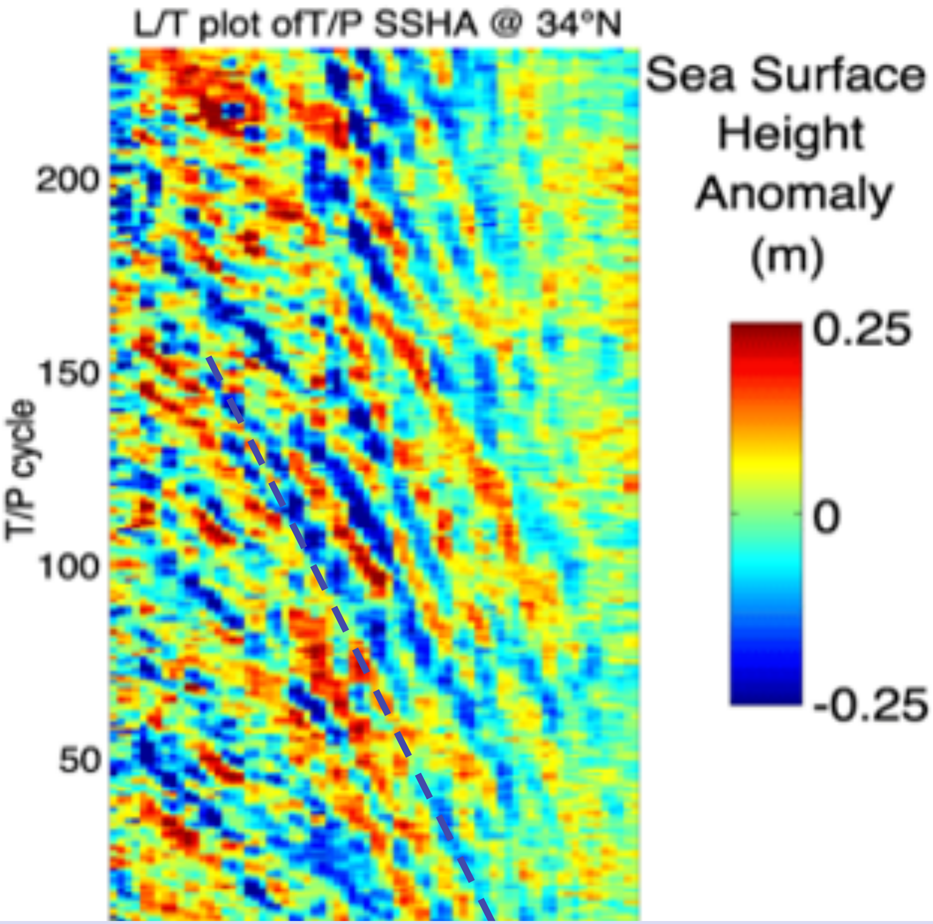
Good example of synergy between different altimetric missions



Theory had to be extended to account for the ‘faster’ speeds (see work by P. Killworth and collaborators)

Looking for Lines…

- Sometimes in our images we are looking for lines, that is alignments of high values or low values
- One typical example is a longitude/time plot of SSHA data where diagonal alignments may indicate planetary waves

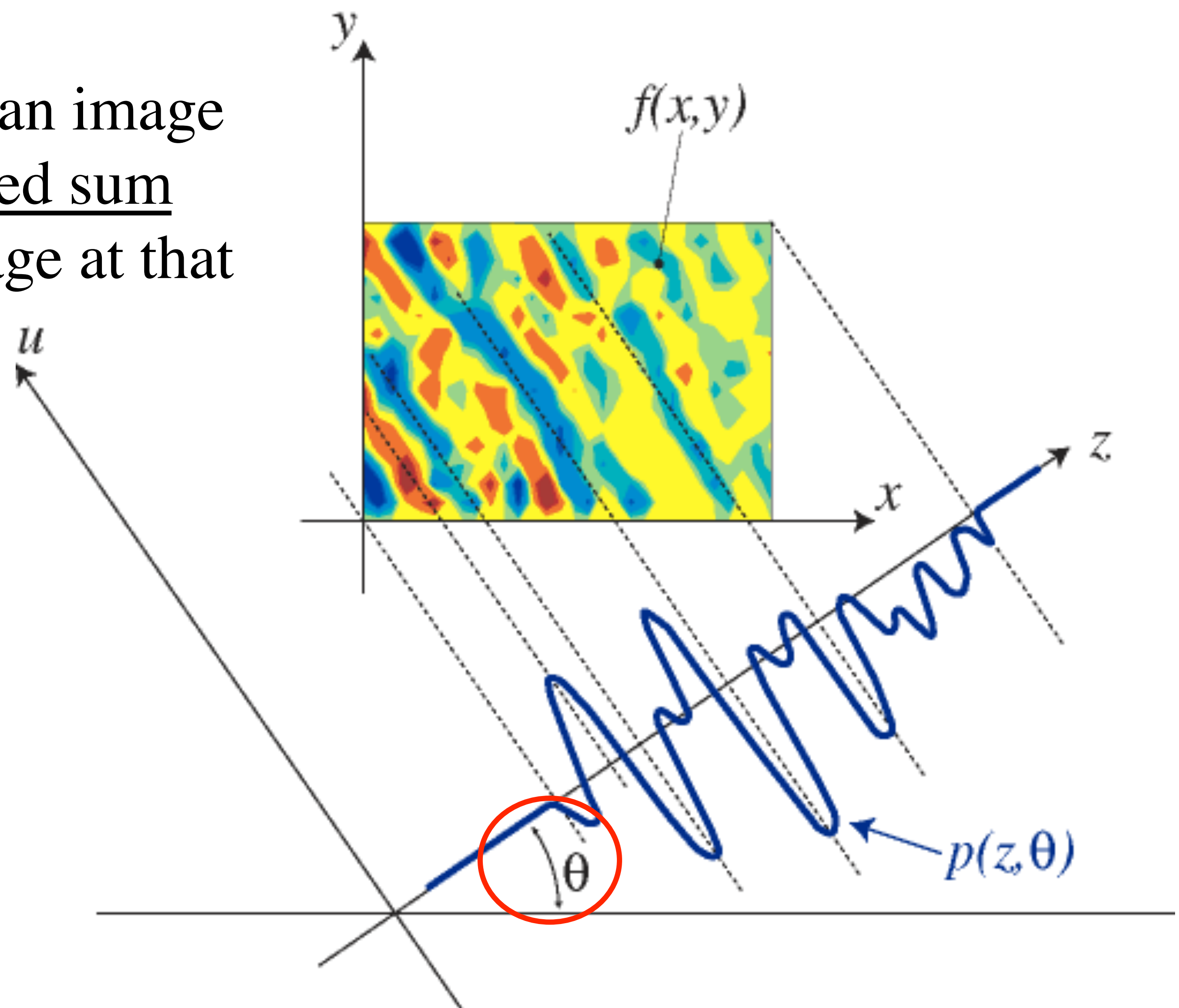


The slope of the line is inversely proportional to the wave propagation speed, so we would like to measure it!

..and measuring their speed

- One intuitive method to measure slope would be to take a ruler and try to visually match the alignments by moving it over the image, then measure the angle - but this is not very objective!
- A nice, objective method to find lines in an image and measure their angle is the **Radon Transform**

Radon Transform of an image at an angle θ = projected sum (or integral) of the image at that angle

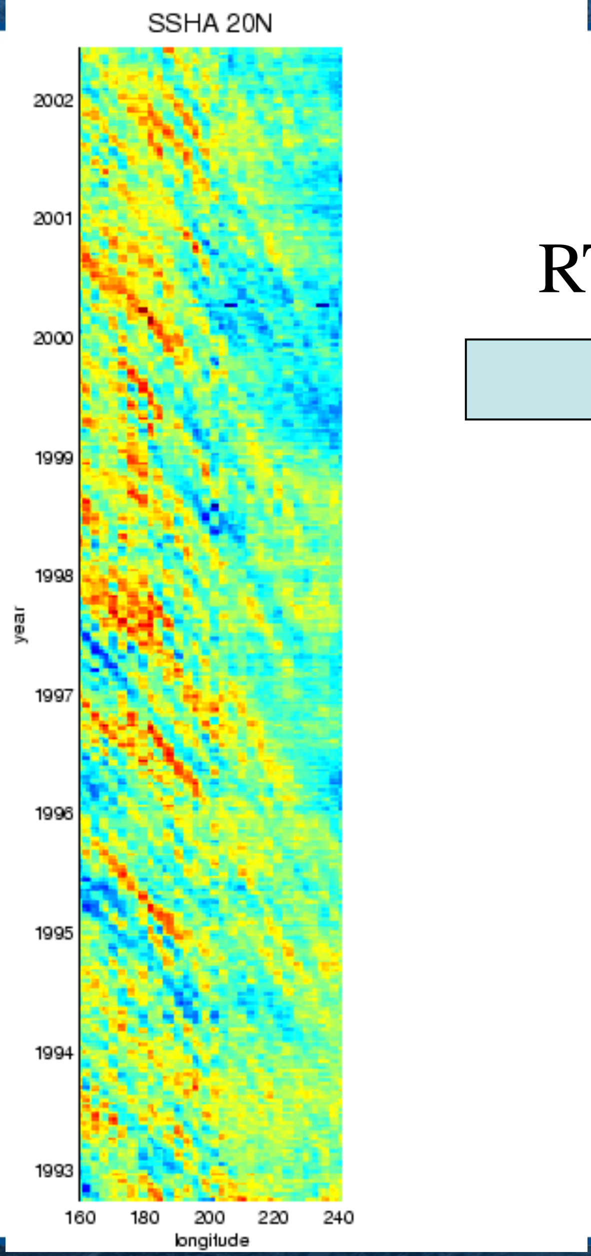


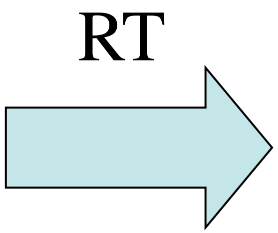
RT definition formula

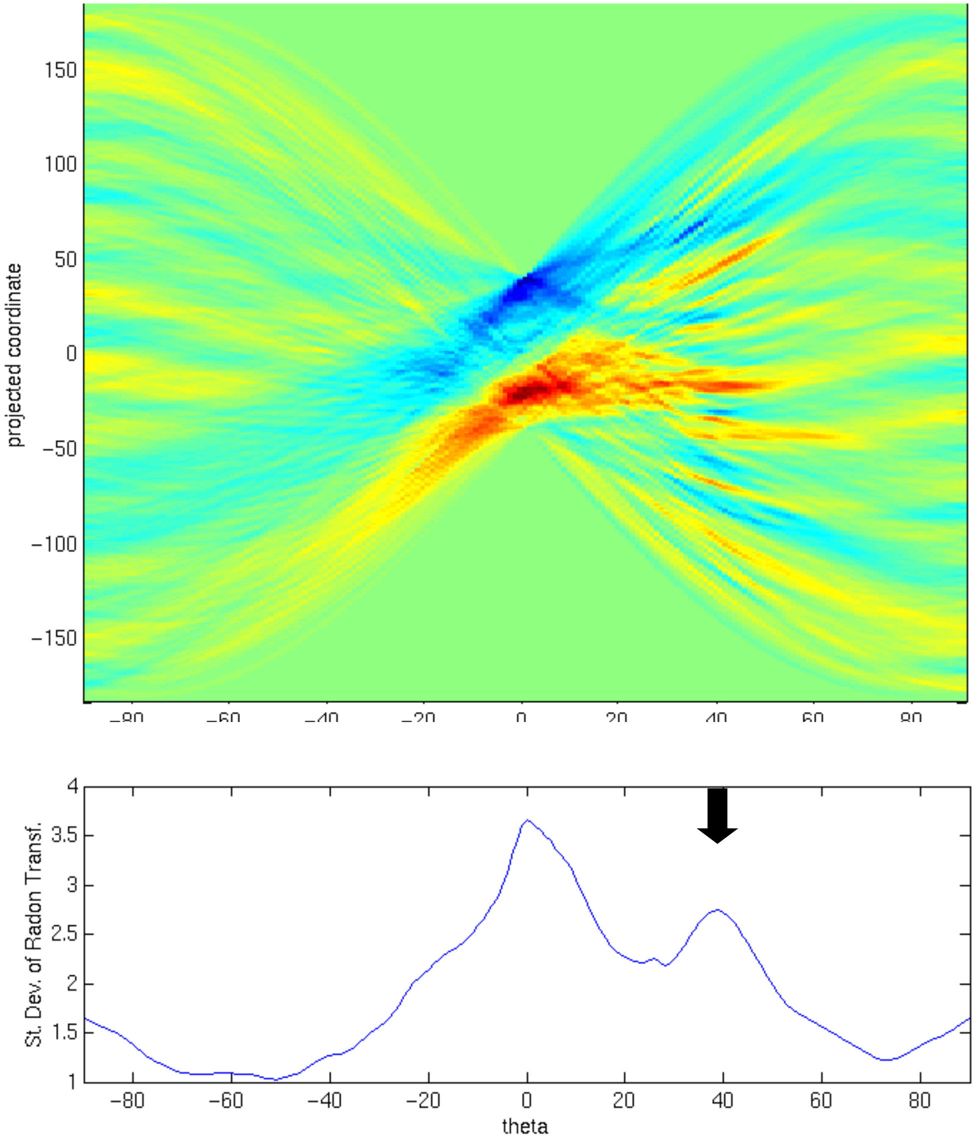
$$p(z,\theta) = \int_u f(x,y)\Big|_{\substack{x = z\cos\theta - u\sin\theta \\ y = z\sin\theta + u\cos\theta}} du$$

in MATLAB: **radon**

RT of a longitude/time plot

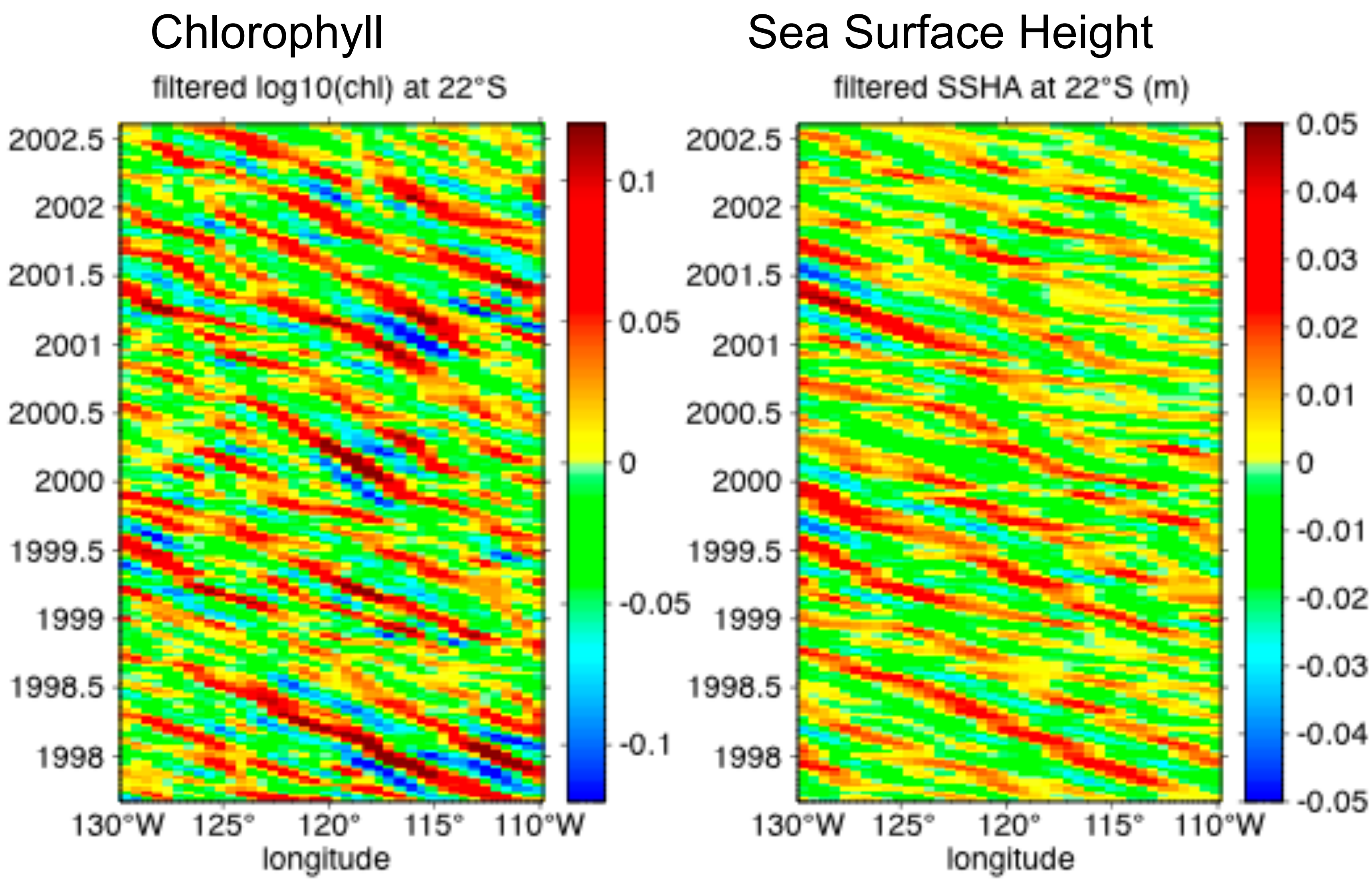






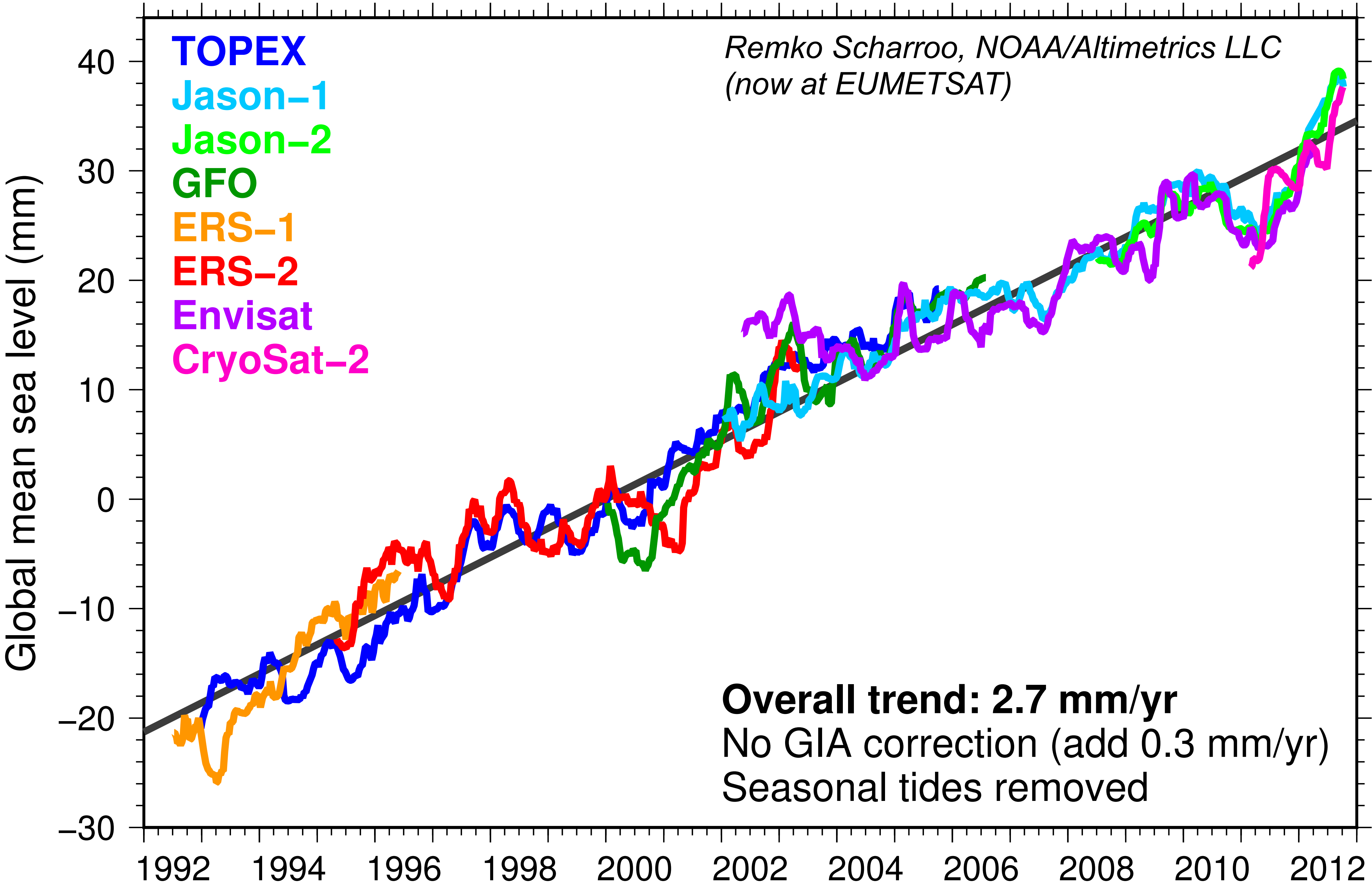
ROSSBY WAVES AND EDDIES

Cipollini et al, 2001; Uz et al, 2001; Siegel, 2001; Charria et al., 2003; Killworth et al, 2004; Dandonneau et al., 2004; Charria et al, 2006, various papers by Chelton and co-authors



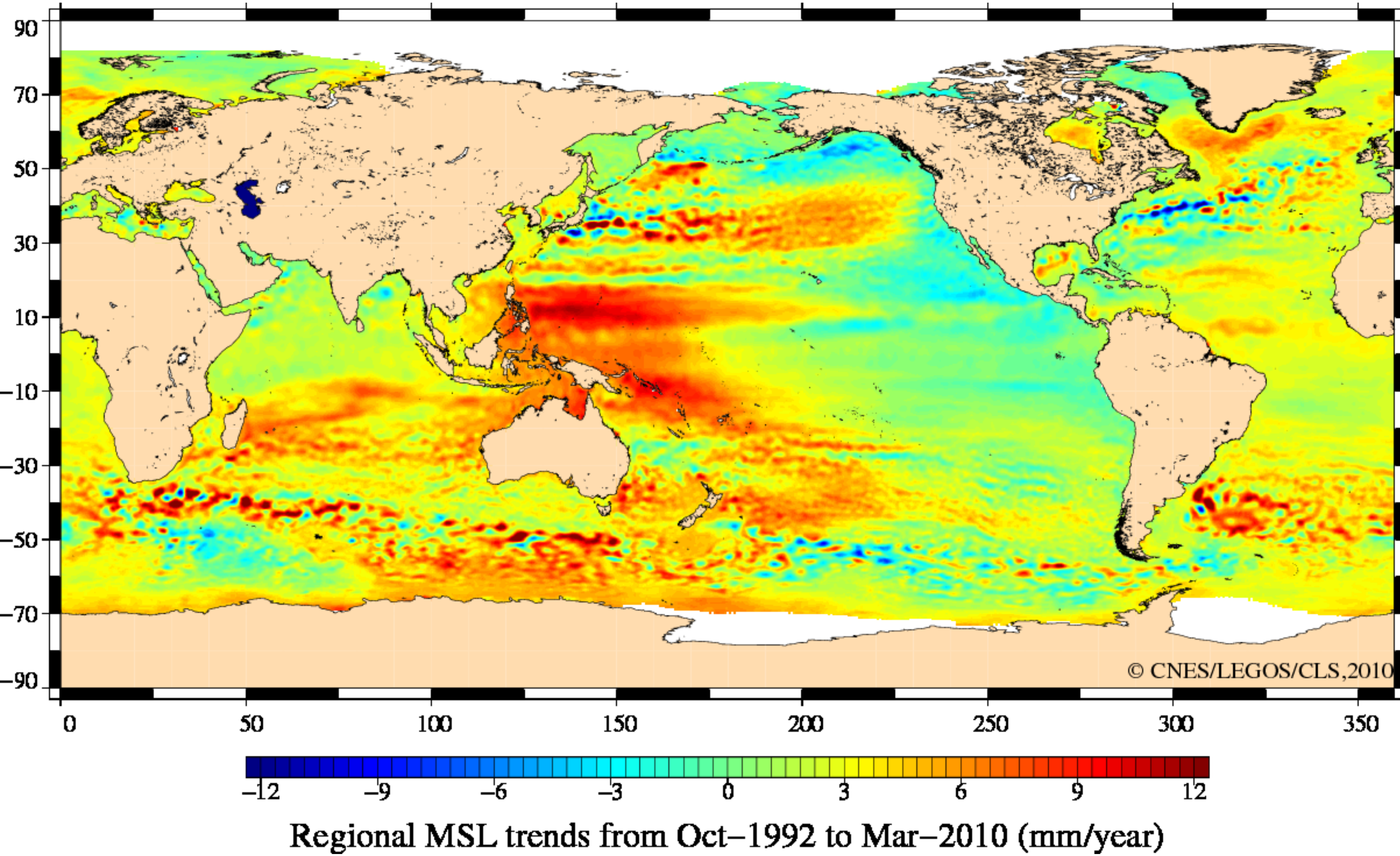
Great synergy possible in all studies of bio-phys interactions when altimetry is combined with SST, ocean colour

SEA LEVEL RISE - global



SEA LEVEL TRENDS - regional

→ Sea Level component on dedicated ESA programme, the "Climate Change Initiative"

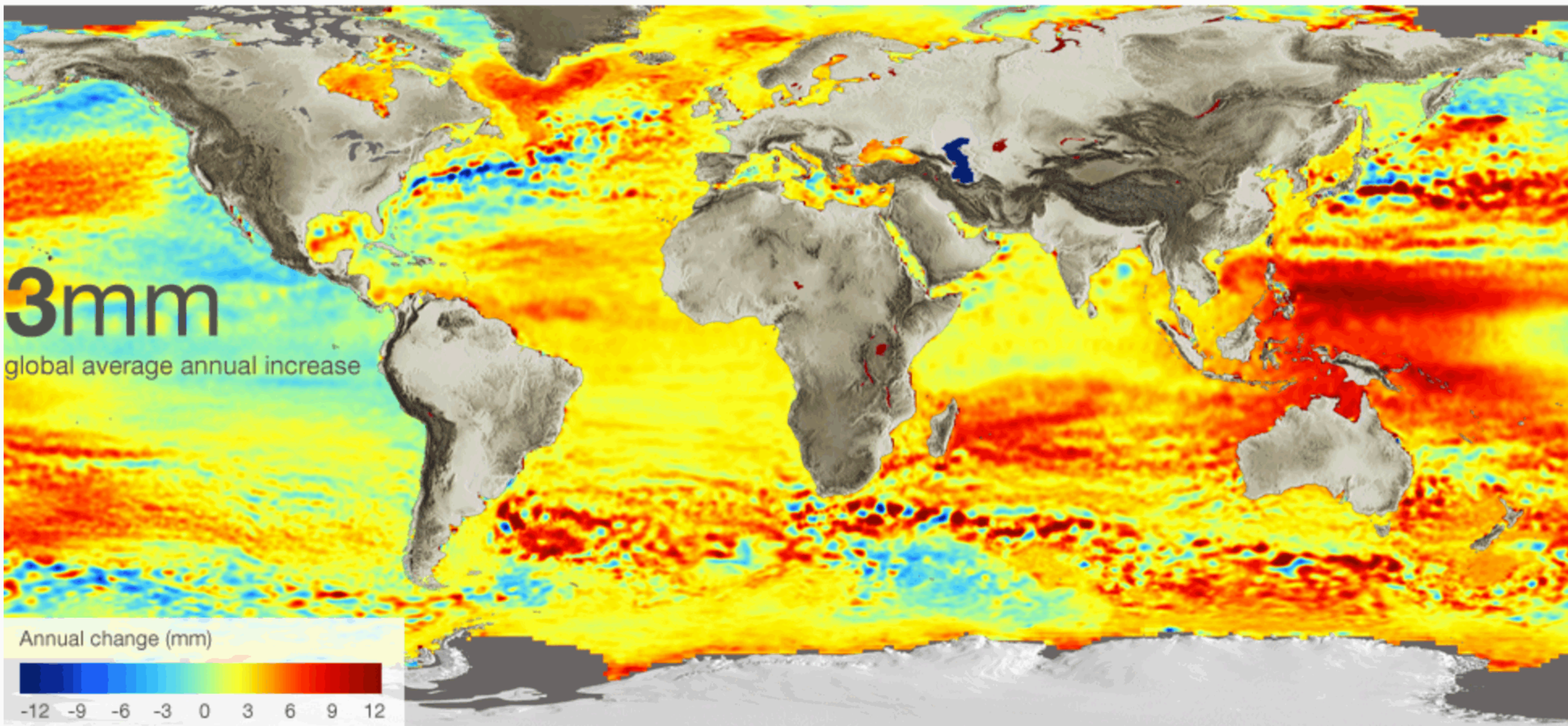


24 September 2012 Last updated at 17:19

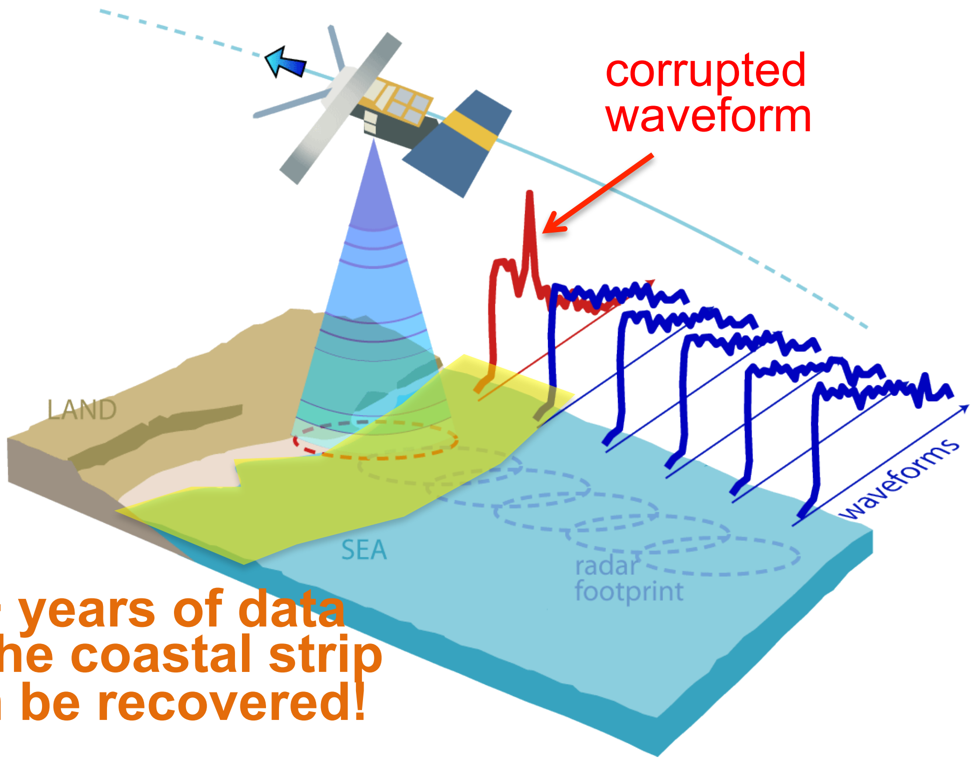
Satellites trace sea level change

Scientists have reviewed almost two decades of satellite data to build a new map showing the trend in sea levels. Globally, the oceans are rising, but there have been major regional differences over the period.

Annual average sea-level rise, 1993-2010



Coastal Altimetry



20+ years of data in the coastal strip can be recovered!

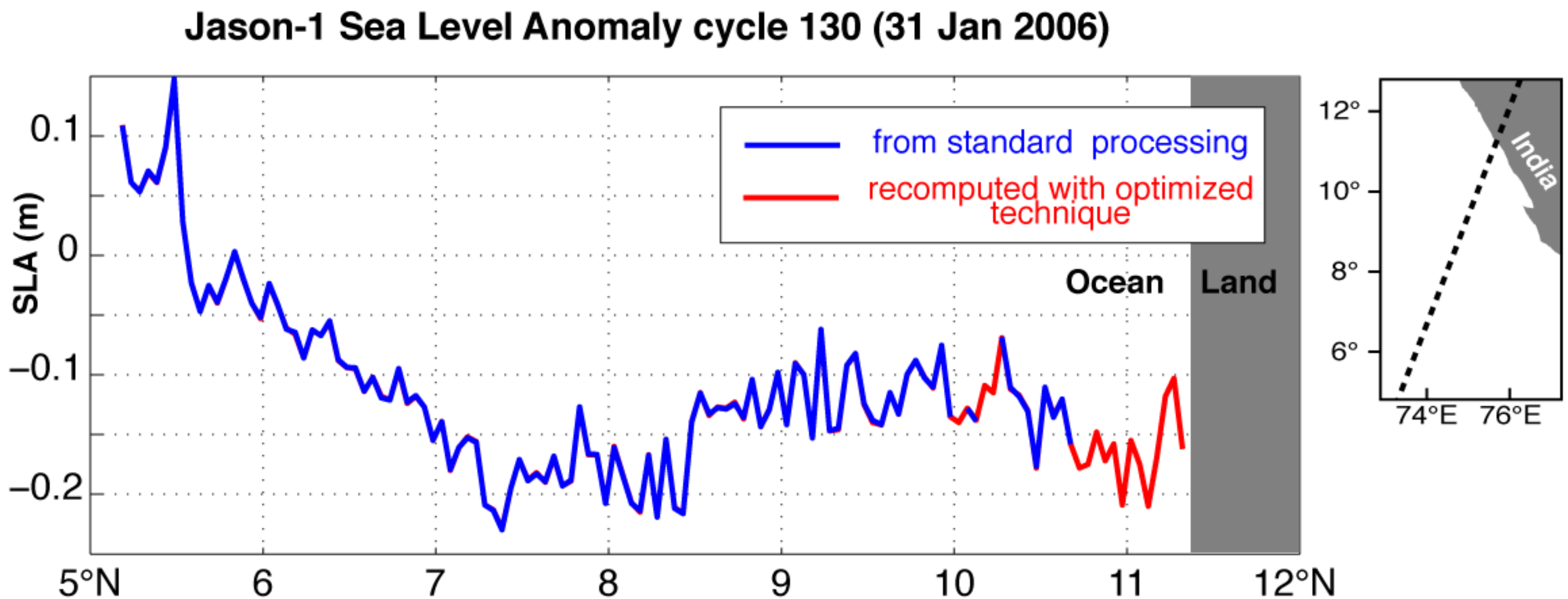
Standard altimetry does not quite go all the way to the coast!

Traditionally, data in the **coastal zone** are flagged as bad and left unused

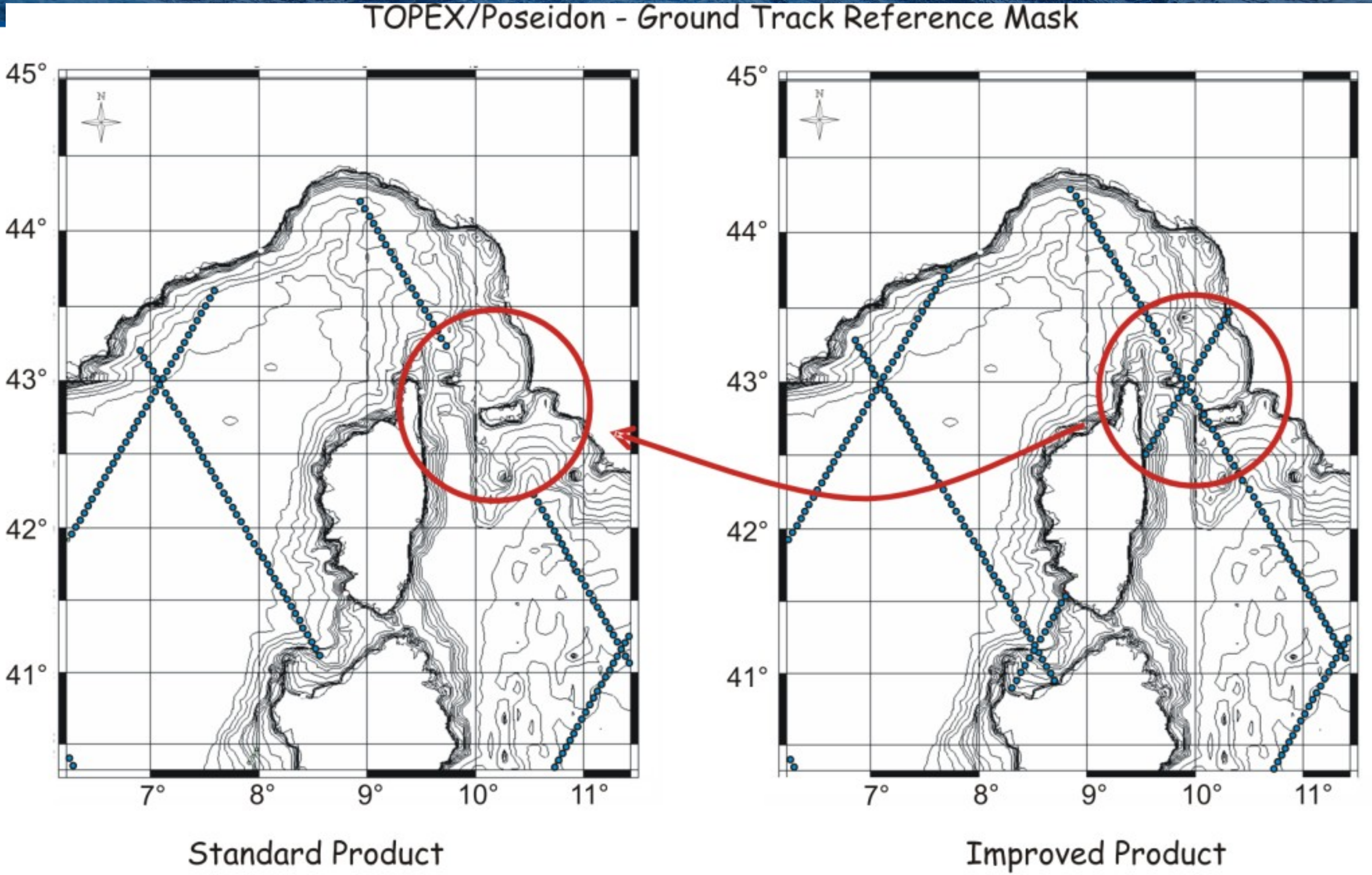
(coastal zone: as a rule of thumb 0-50 km from coastline, but in practice, **any place where standard altimetry gets into trouble** as radar waveforms are non-standard and/or corrections become inaccurate)

In recent years a vibrant community of researchers has started to believe that **most of those coastal data can be recovered** and that coastal altimetry can be **a legitimate component of coastal observing systems!**

Example of coastal altimetry



Can we recover these?



We believe so, with dedicated reprocessing and corrections.

Ifremer

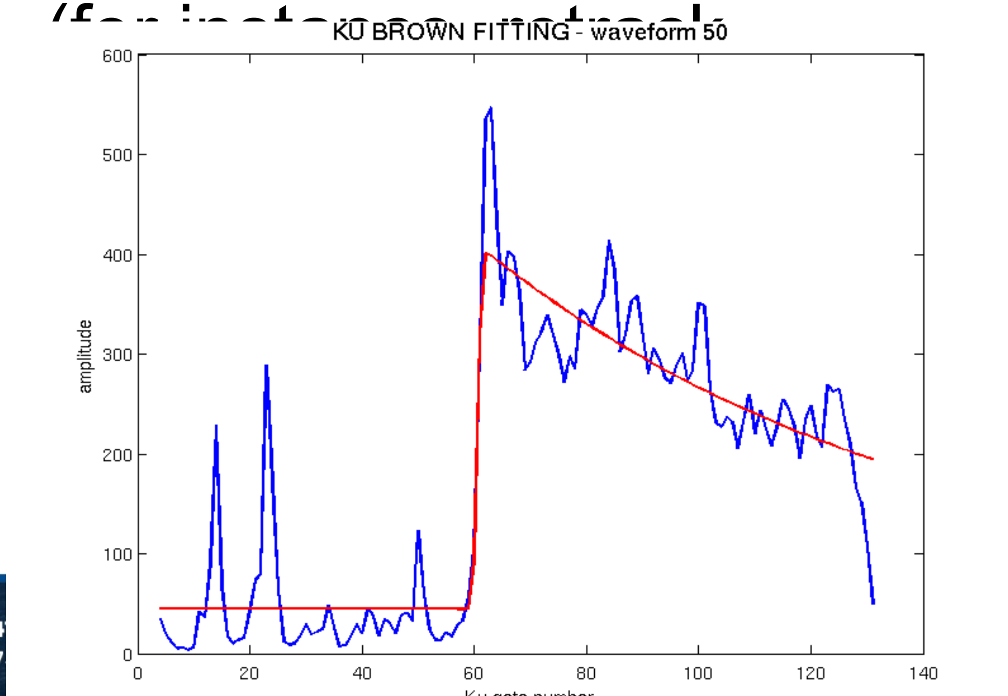
How we recover more data

esa

0-10 km

A. Specialized **retracking**

- Use new waveform models, accounting for change of shape in coastal environment
- Use specialized retracking techniques



0-50 km

B. Improved **Corrections**

- Most crucial is the correction of path delay due to **water vapour** ("wet tropospheric" correction)
- Some applications require correction of **tidal** and **high-frequency** signals, which are also difficult

Both validation and applications require **exploitation of coastal models & in situ measurements**

…the history bit…

- **Some early studies**
  - Manzella et al. 1997 – custom wet tropospheric correction
  - Crout 1998 - could recover data when coastal topography is flat
  - Anzenhofer et al. 1999 – retracking coastal waveforms
  - Vignudelli et al. 2000 - Signal recovered consistent with in situ data

ALBICOCCA
France-Italy-UK 2001/04
Feasibility

ALTICORE-EU
EU/INTAS 2006/08
Capacity building

ALTICORE-India
ALTICORE-Africa

MAP/XTRACK/MARINA
CNES/LEGOS/**CTOH**, ongoing
Integrated approach to data editing, filtering, multimission, dissemination

DATA available

PRODUCT DEVELOPMENT STUDIES INCLUDING WAVEFORM RETRACKING

PISTACH
CNES 2007-present
For Jason-2

COASTALT
ESA 2008-2011
For Envisat

→ following with **eSurge** (*multimission, 2011-2015*)

…plus several OSTST Projects funded by NASA and CNES

"Retracking" of the waveforms

= fitting the waveforms with a waveform model, therefore estimating the parameters

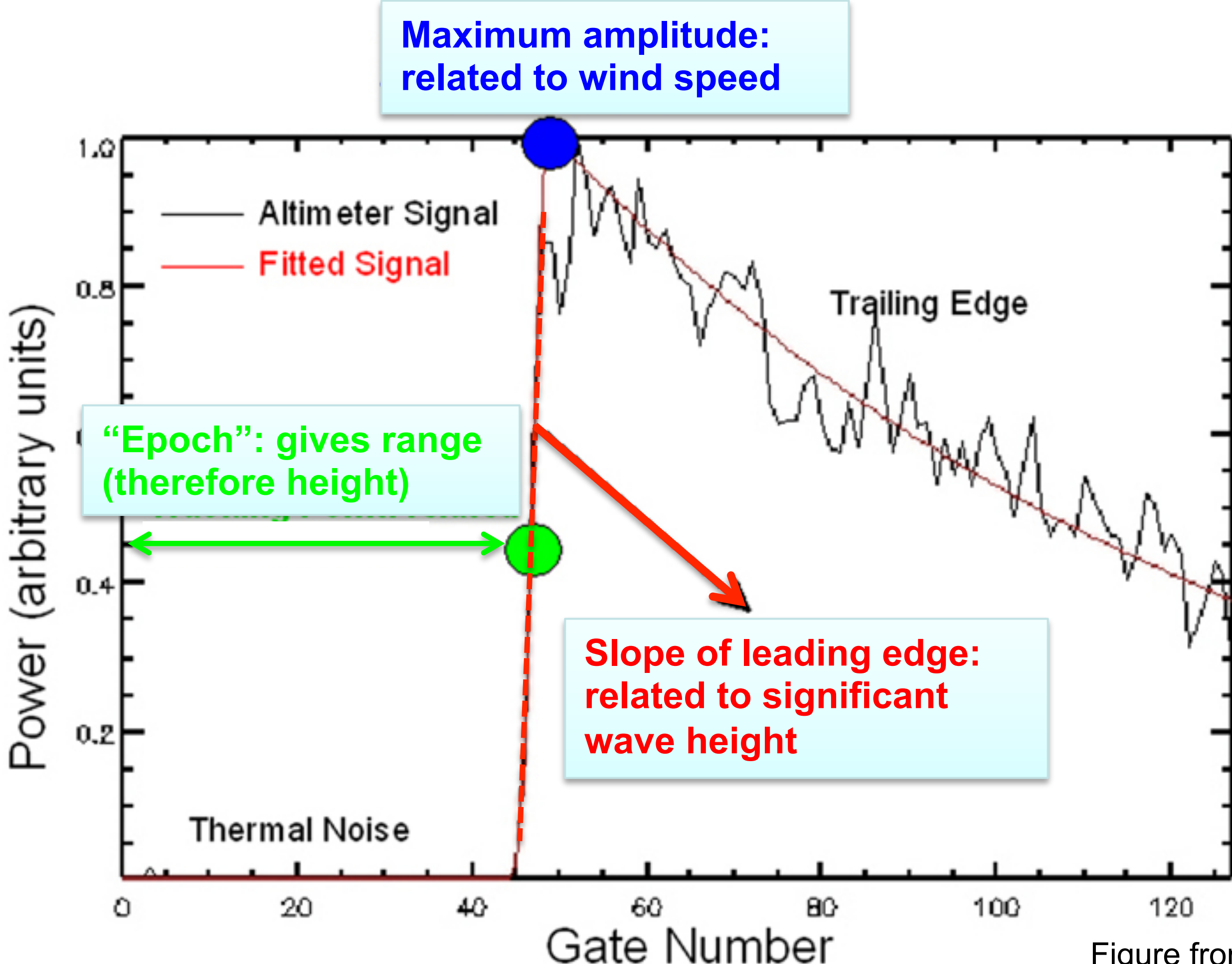


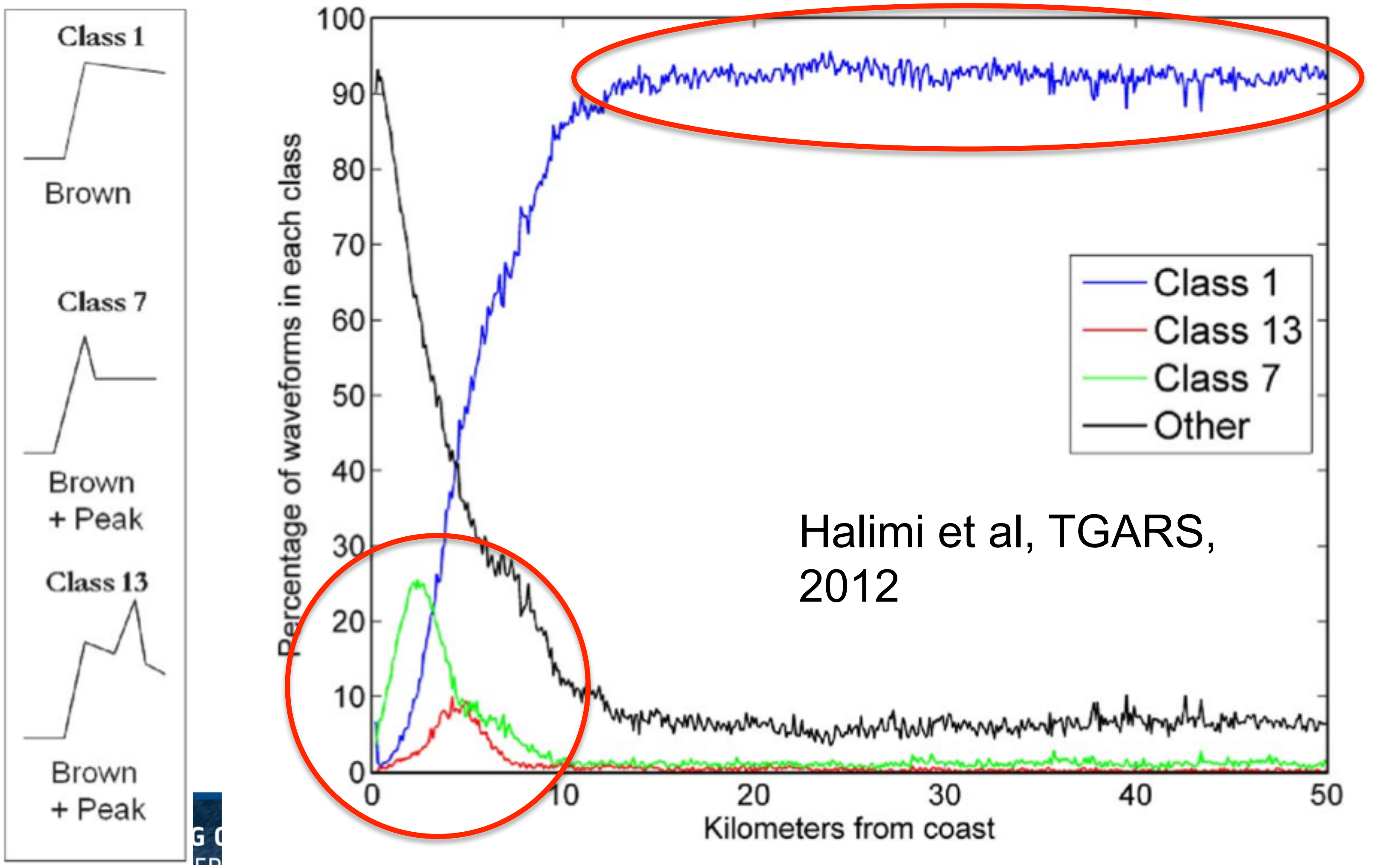
Figure from J Gomez-Enri et al. (2009)

Retracking – Coastal waveforms

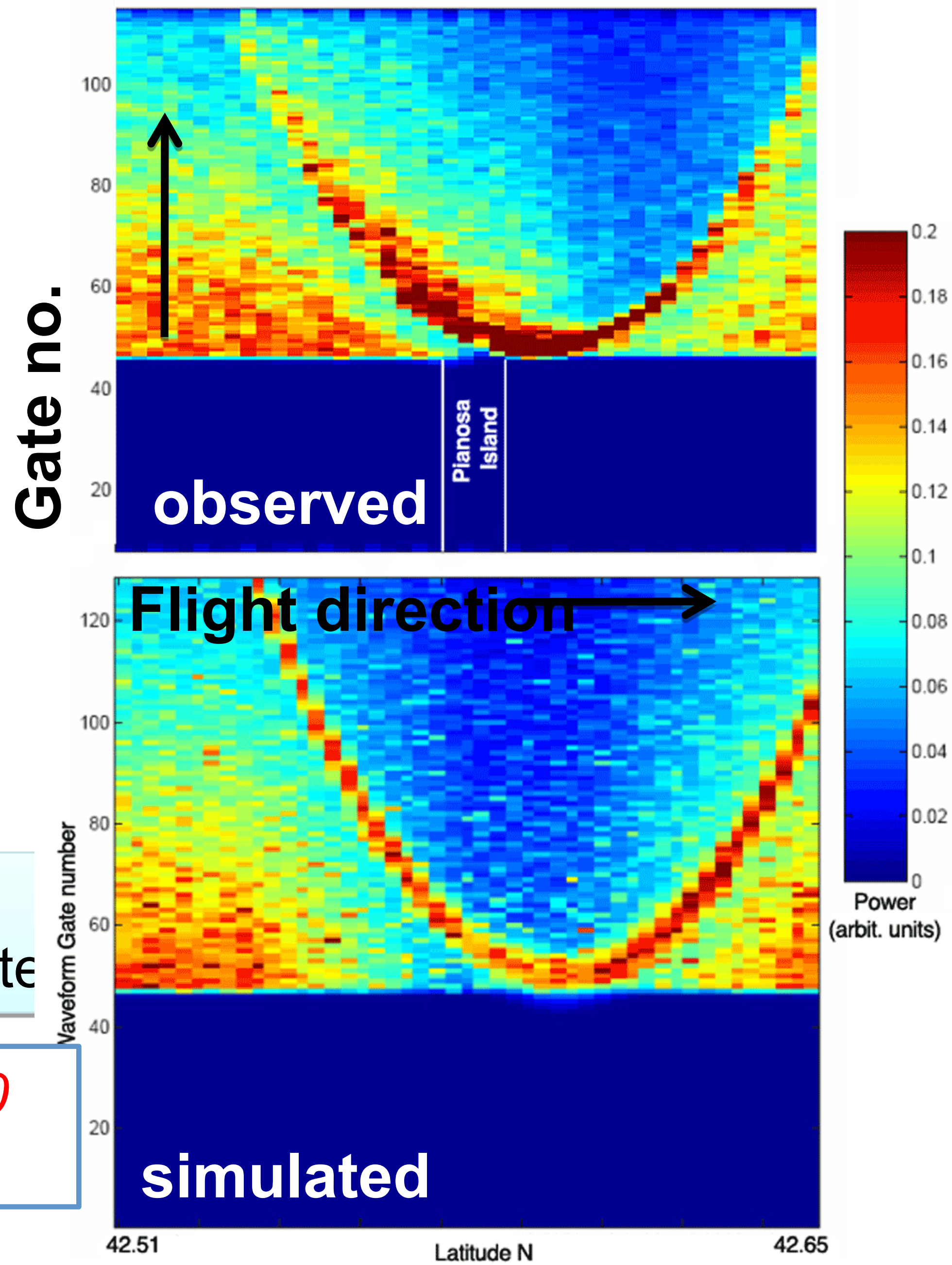
- waveforms in coastal zone and island passes have been extensively studied
- **effects of land** and **effects of calm waters** in the coastal strip are observed
  - Land normally gives ‘dark’ features (less signal)
  - Calm water cause quasi-specular reflections → bright features or **“bright targets”**
  - These features migrate in the waveform/gate number space following hyperbolae (a parabolic shape is usually a good approximation)
- Features are reproduced by a simple model of the land/ ocean/calm waters response
  - The idea is that this should allow removal of the land/calm waters contamination prior to retracking

Classification of coastal waveforms

- Standard ‘open-ocean’ model (Brown 1977)
- modified models: “reduced waveform”, Brown+peaks



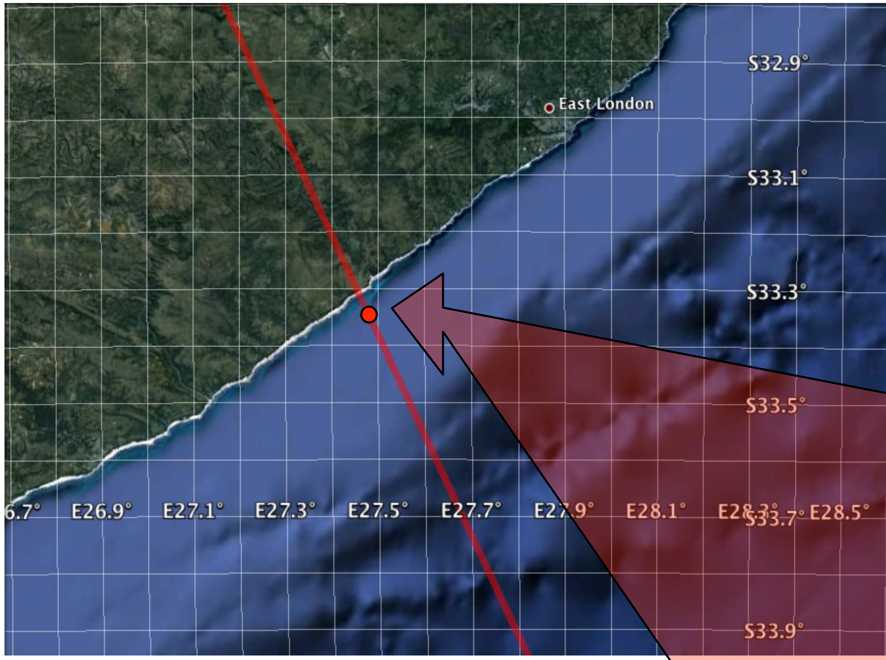
Example – Pianosa Island



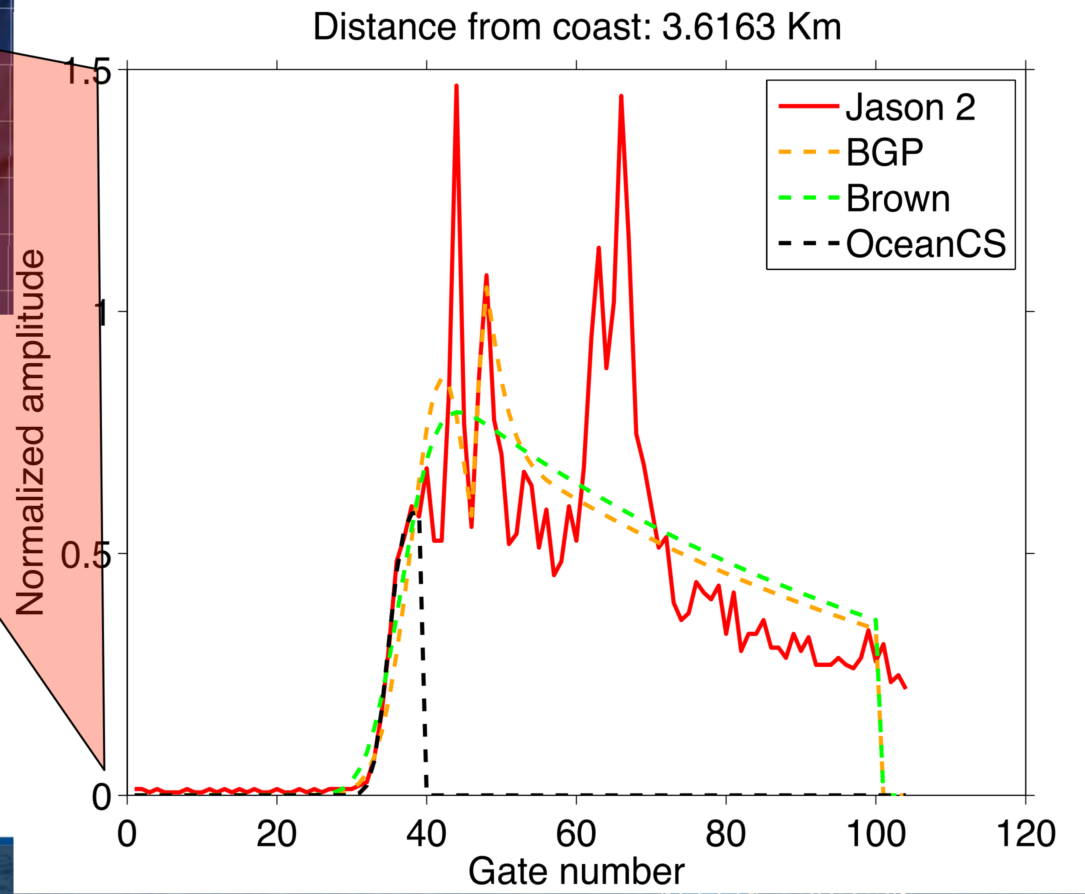
In cycle 49, bright target due to wave sheltering in NW bay (Golfo della Botte

J. Gómez-Enri et al., IEEE GRSL 2010
A. Scozzari et al, GRL, 2012

Coastal Retracking – an example



Jason-2 Example

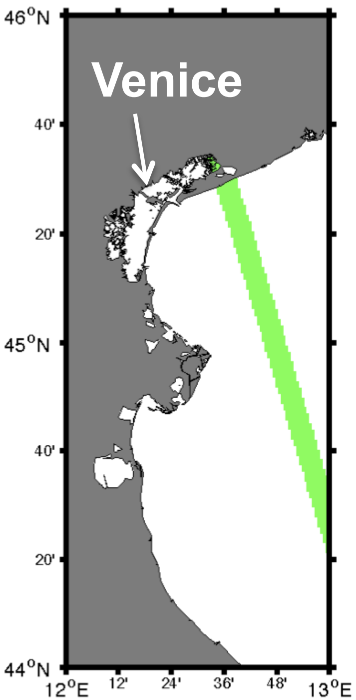


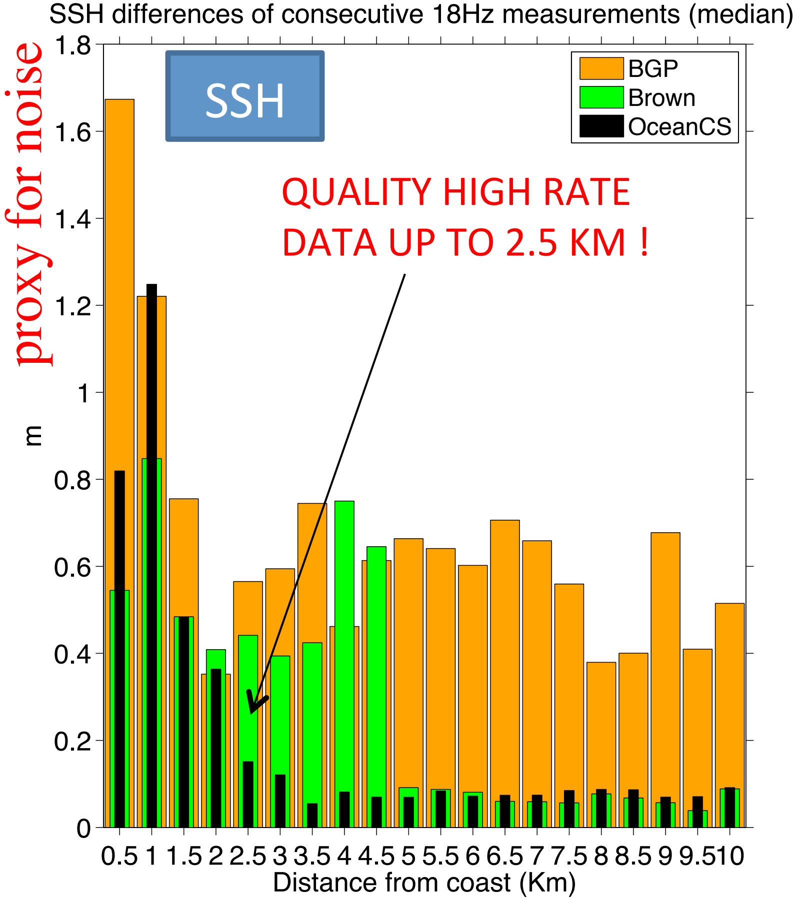
Jason-2 pass 096 over the coast of South Africa and example of **coastal waveform** for cycle 83 and its retracking with various models: **BGP (Halimi et al., 2013)**, **Brown (1977)**, **OceanCS (Yang et al., 2012)**

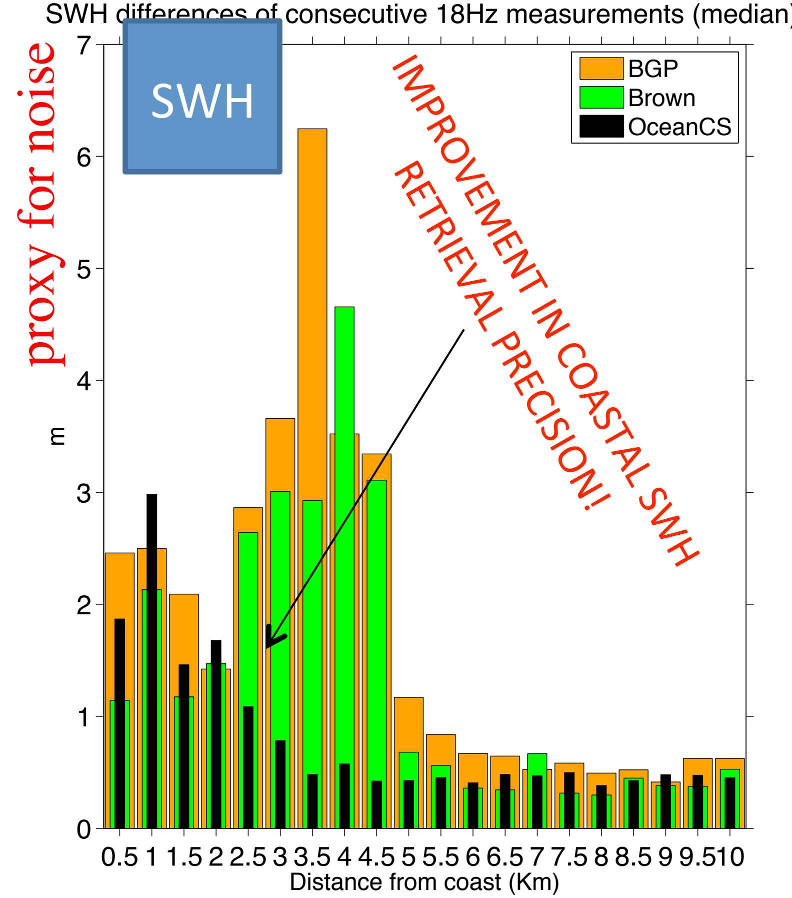
M. Passaro, NOC

With specialized retrackers we get much closer to the coast!

Envisat example, 20 cycles of pass 0543 over Northern Adriatic







The specialized coastal retrackers display encouraging performance – with several **pros:**

BGP: Better trailing edge fitting (useful to retrieve sigma0 or mispointing with greater precision)

OceanCS: "Open ocean" precision in SSH and SWH UP TO 2.5 KM FROM THE COAST; Precise leading edge fitting, better than classic schemes also far from the coast

LATEST DEVELOPMENT: ALES retracker (Passaro et al. 2014) – a sub-waveform retracker that works well both over open ocean and coastal zone → can be applied everywhere

Passaro et al 2014

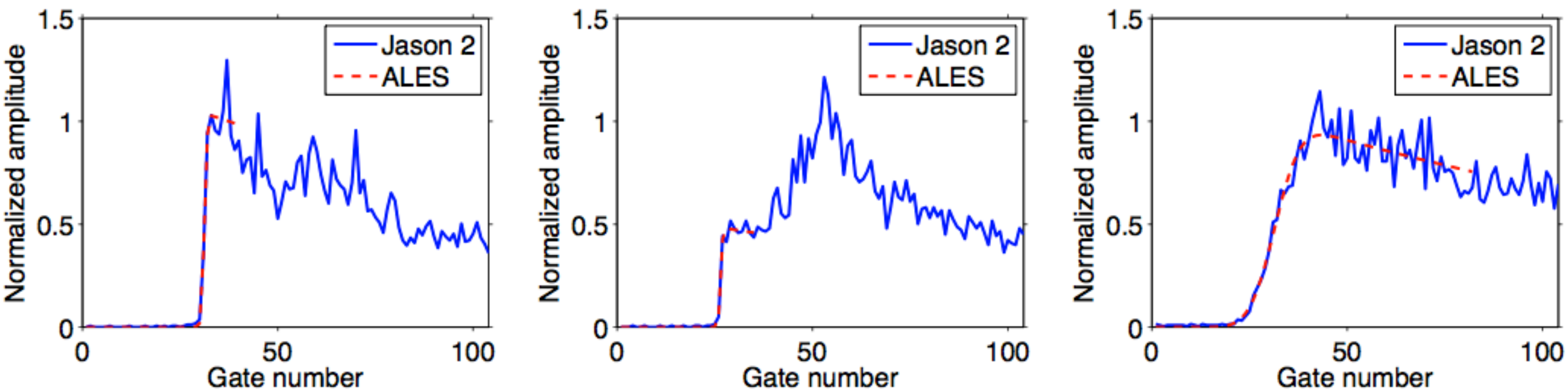
Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

ALES: A multi-mission adaptive subwaveform retracker for coastal and open ocean altimetry

Marcello Passaro [a,*], Paolo Cipollini [b], Stefano Vignudelli [c], Graham D. Quartly [d], Helen M. Snaith [e]



OPEN OCEAN, SWH=0.75 m

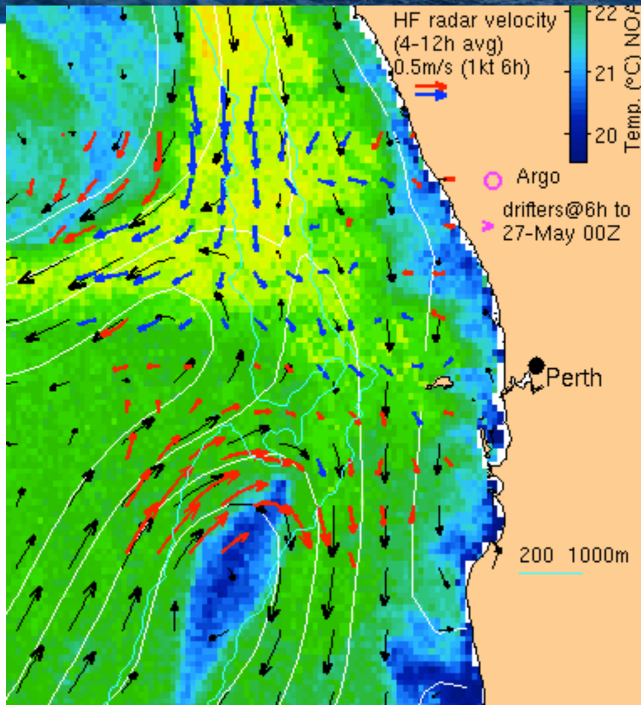
COASTAL OCEAN, SWH=1.65 m

OPEN OCEAN, SWH=9.48 m

Recent improvements - corrections

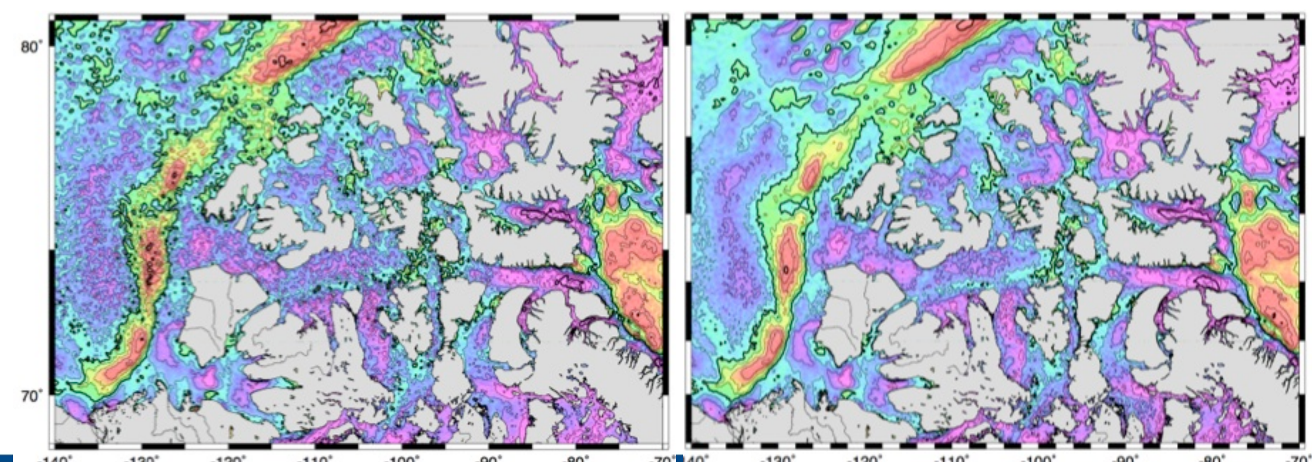
- Water Vapour path delay ('wet tropospheric' correction): crucial correction in coastal zone, now much improved
  - **Mixed-Pixel Algorithm** (S. Brown)
  - **Land Proportion Algorithm** (PISTACH group)
  - **GPD**: GNSS-derived Path Delay (J. Fernandes for COASTALT)
  - **CNN** – Coastal Neural Network wet tropo for Envisat (CLS), from $T_{brightness}$, Land Proportion and sigma0
- Better global and regional tidal models

Applications



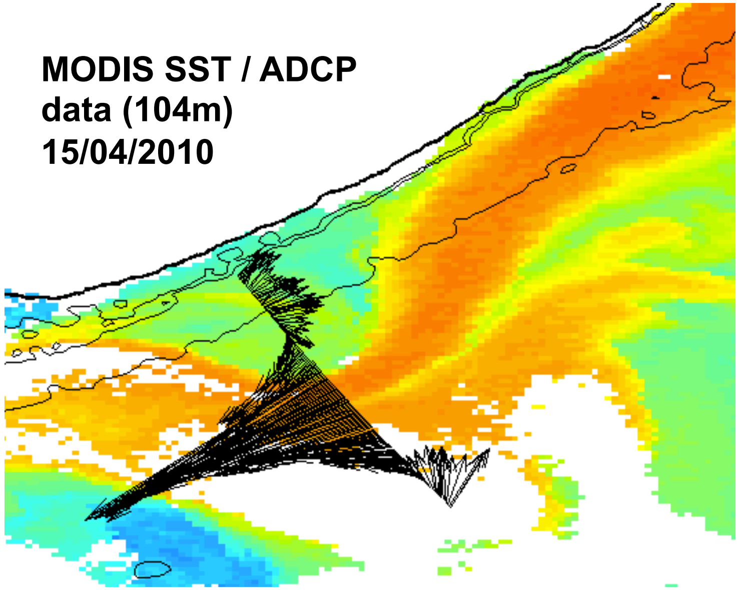
Comparison of Cryosat with Sub-mesoscale currents from HF-radar (D. Griffin)

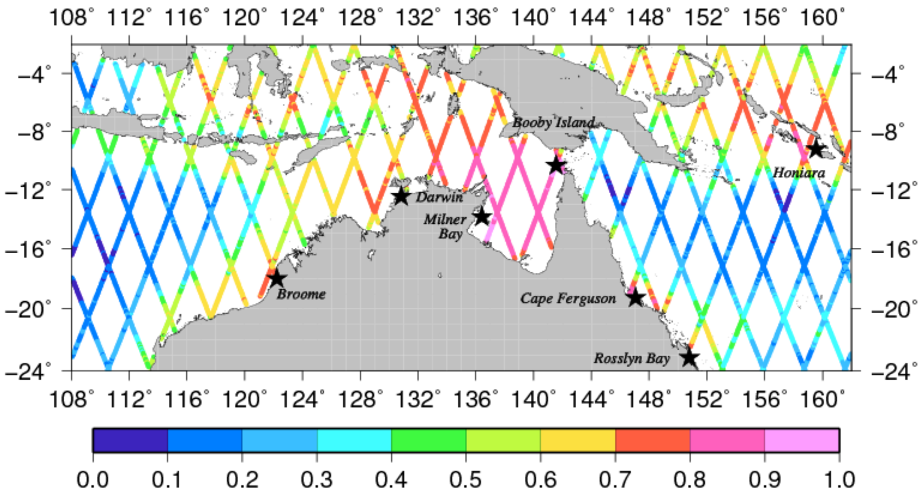
J-1 geodetic and Cryosat novel gravity data → improved gravity maps (O. Andersen)

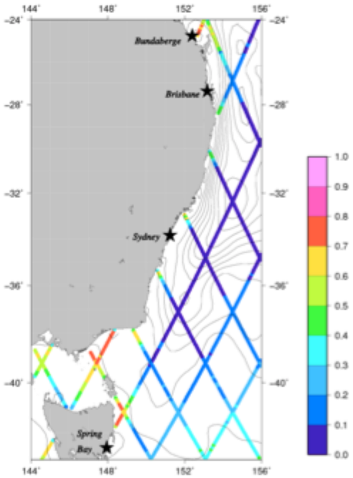


Applications

Successful identification of sub-mesoscale Natal pulses in comparison PISTACH 5Hz velocity vs in situ (from ACT campaign) (M. Cancet)



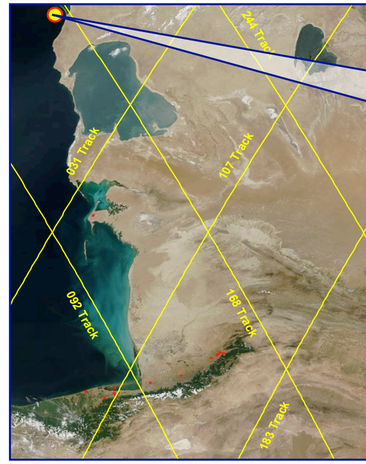


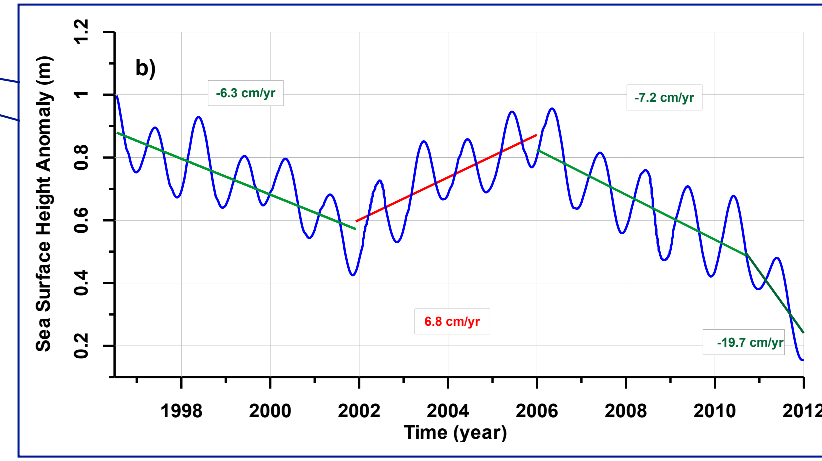


Statistical regression model to predict coastal sea level extreme events (X. Deng)

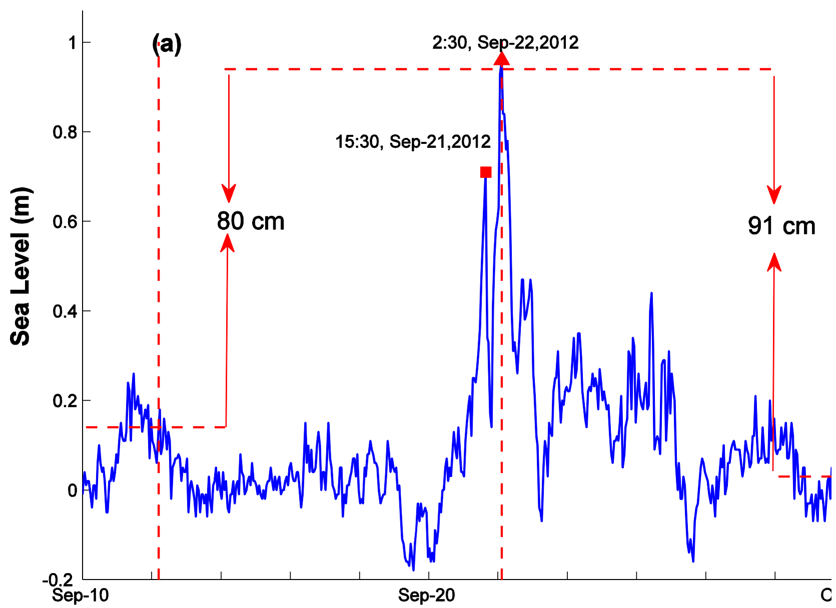
Applications

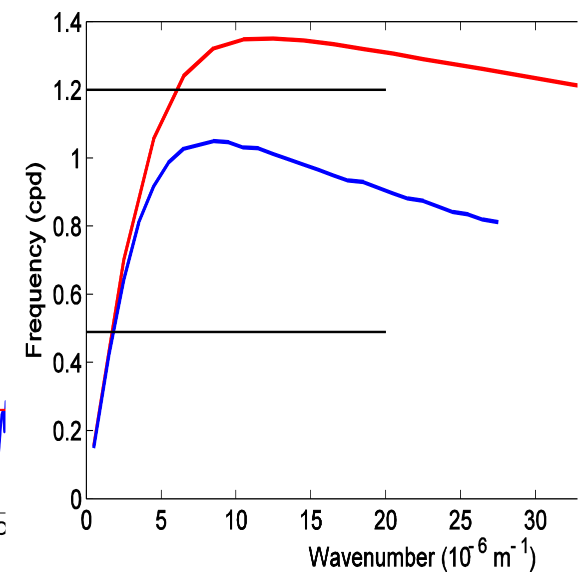
Inter-annual, seasonal variability in Caspian Sea, bay and lake levels (A. Kostianoy)





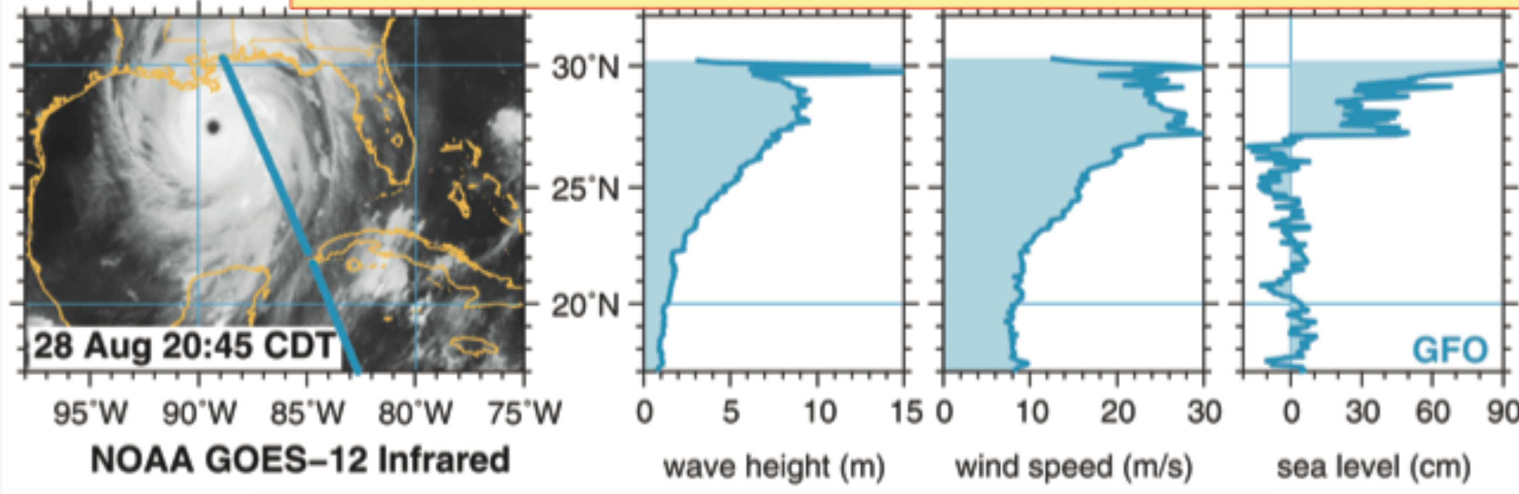
Storm Surges: Hurricane Igor storm surge and ensuing free Coastally Trapped Waves; propagation and dispersion agree with CTW theory

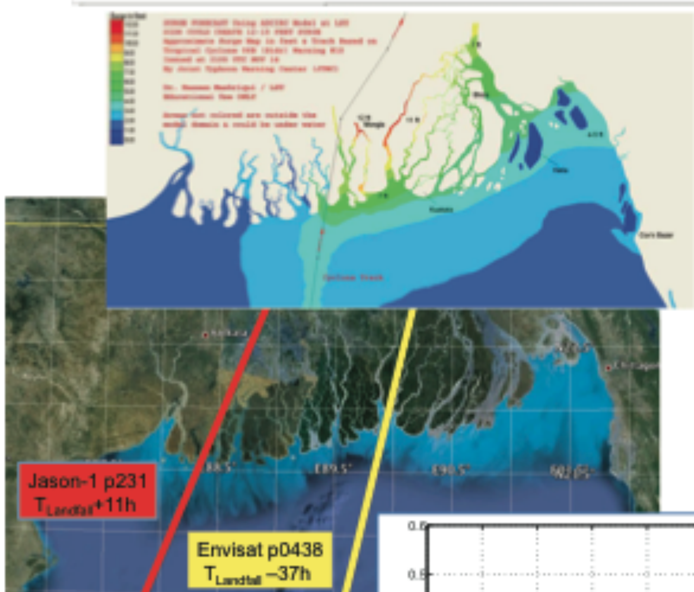


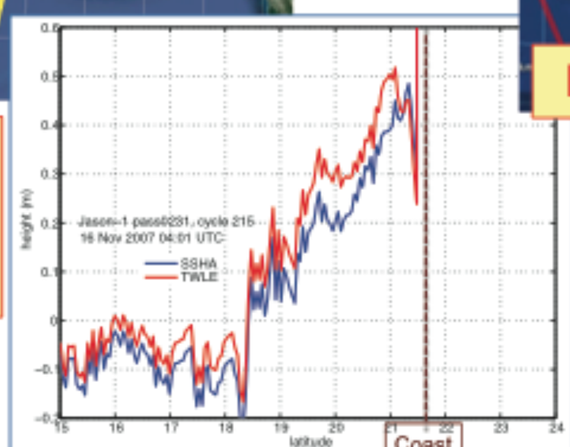


Examples of storm surges captured by altimetry:

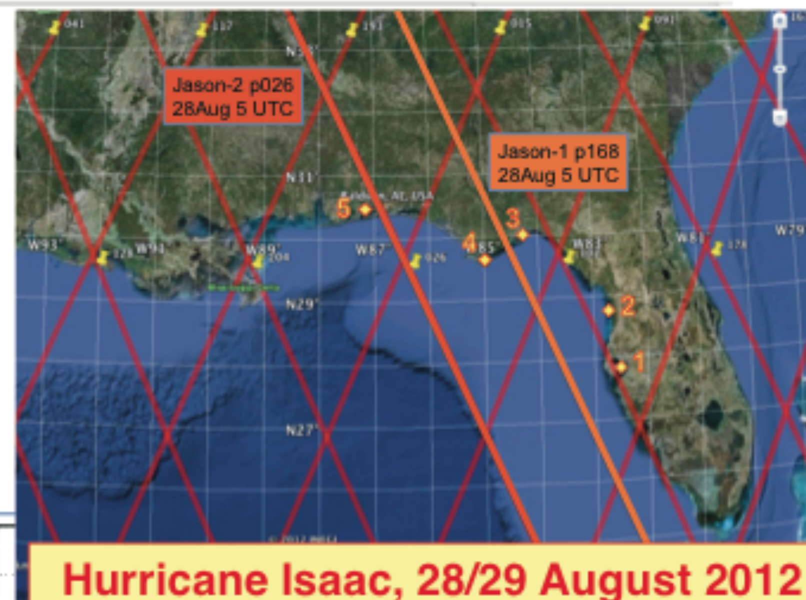
Katrina seen by Geosat follow-on (Scharroo et al., EOS 2005)



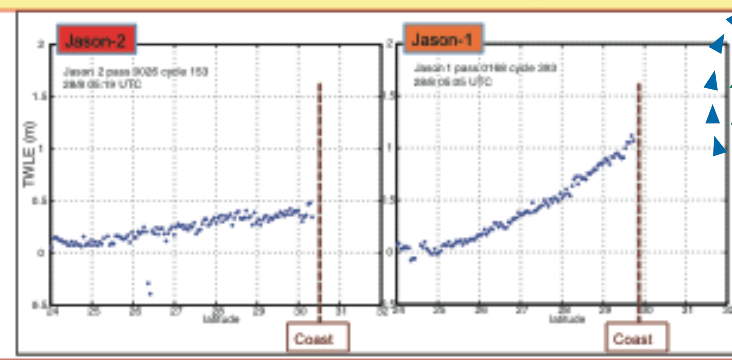




Cyclone Sidr Bay of Bengal 15 Nov 2007

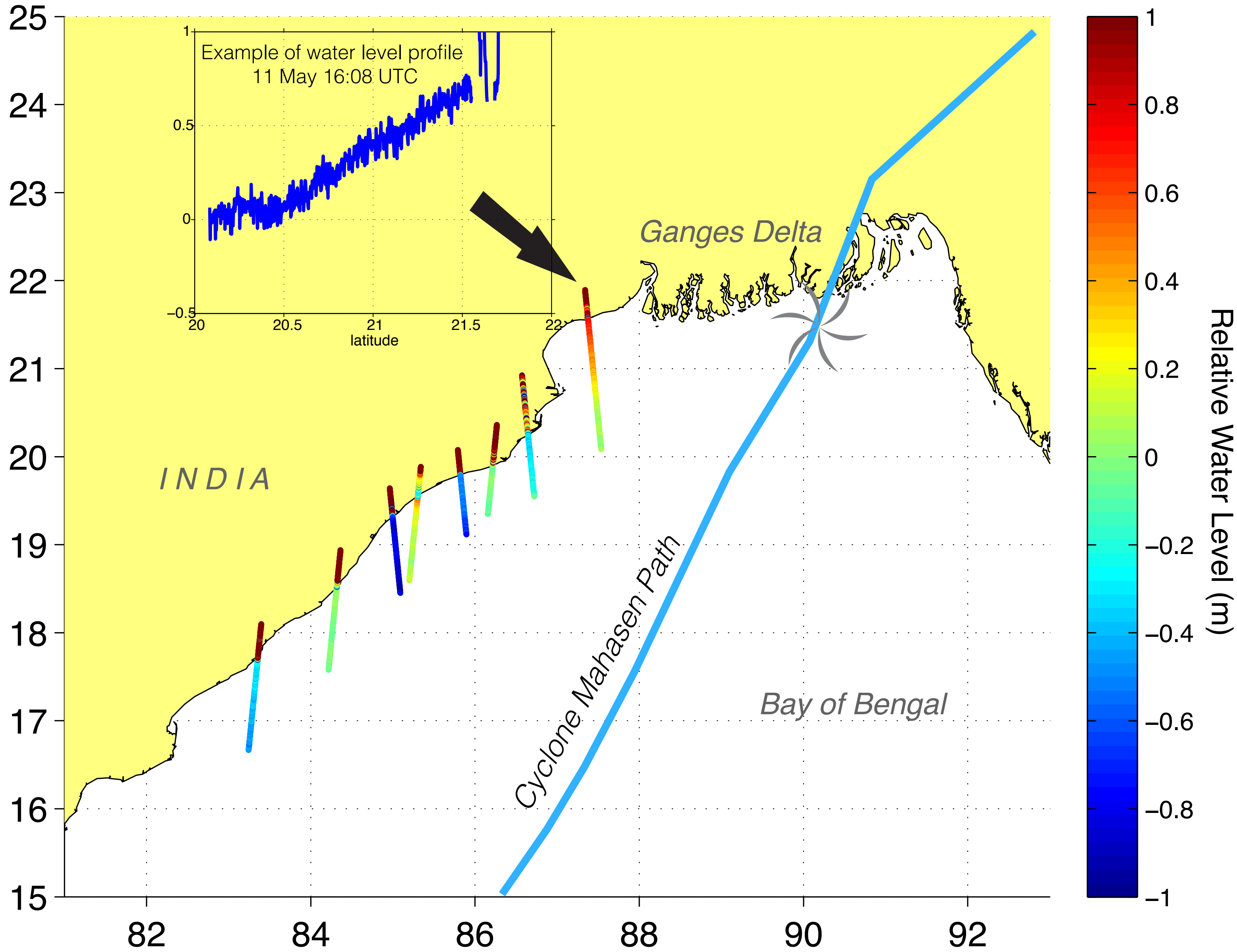


Hurricane Isaac, 28/29 August 2012



eSurge

Cryosat-2 measures coastal water levels 10-17 May 2013



Waves, winds and other parameters

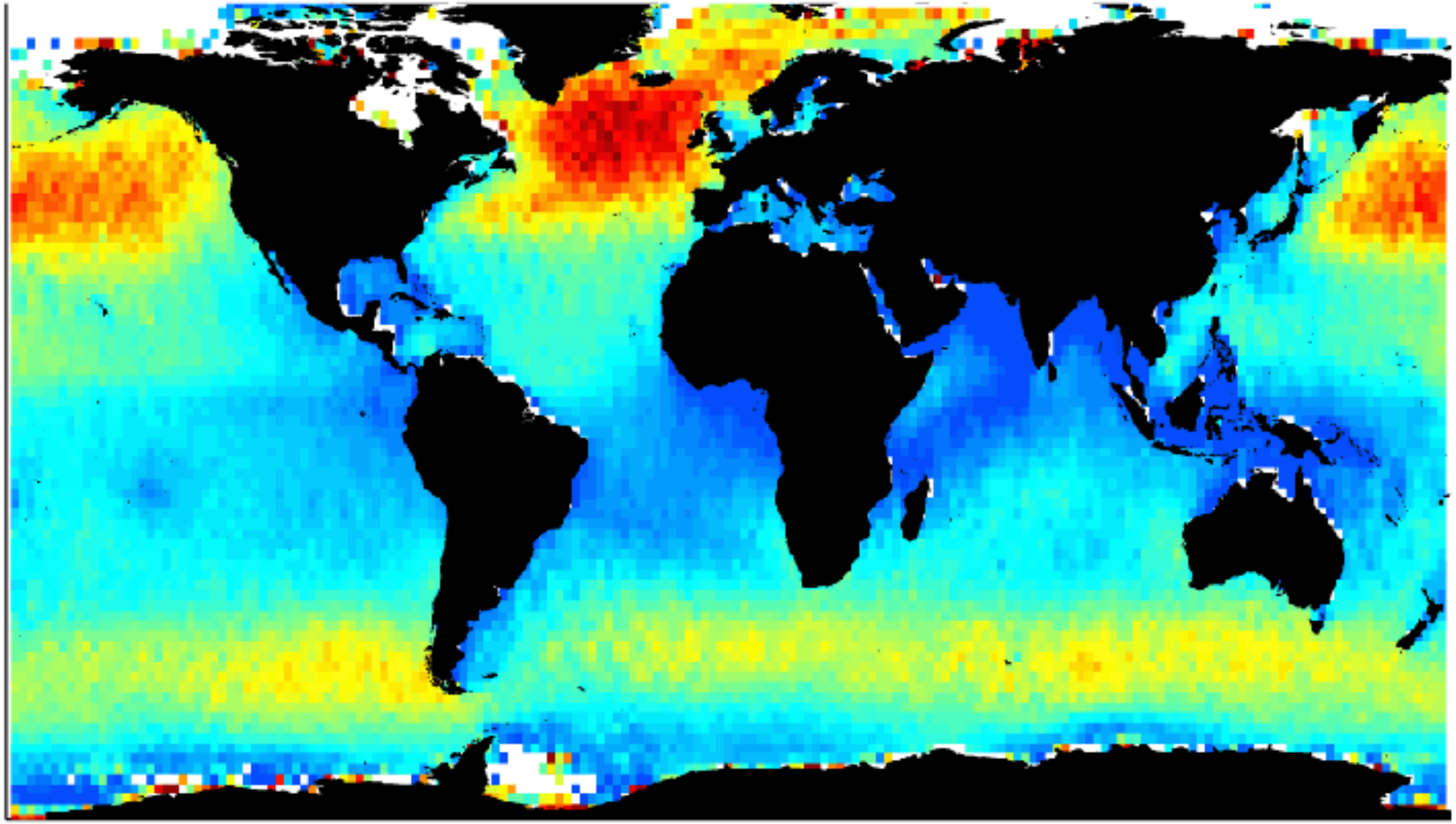
- Significant wave height
- Altimeter winds
- Calibration/validation
- Wave climate
- Sea Ice
- Rain

Ifremer

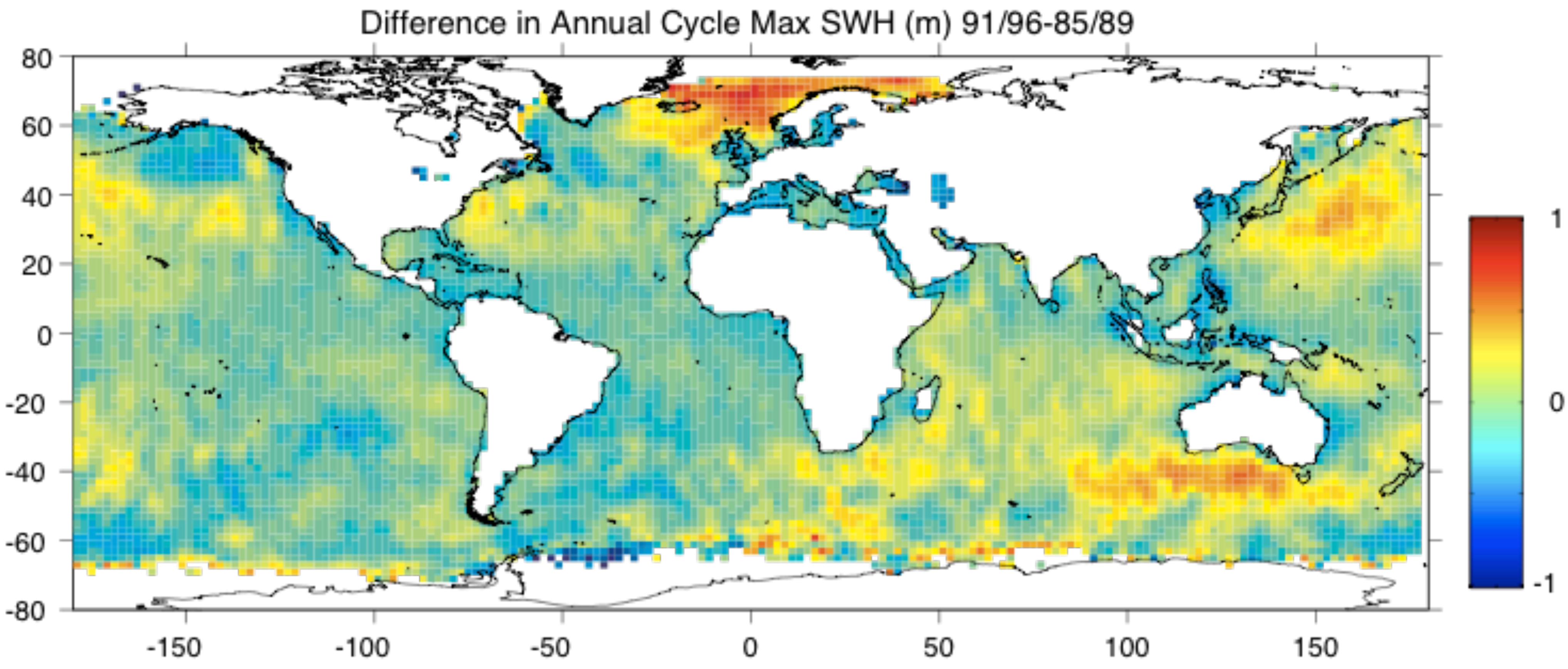
esa

P. Challenor/D. Cotton

Wave Height , Month 1



Climate changes



Altimeter wind speeds

- The radar backscatter coefficient can be related theoretically to the mean square slope of the sea surface **at wavelengths comparable with that of the radar**
- Ku band is ~2 cm, so it will depend on capillary waves
- …these, in turn, depend on the wind!!
- Empirically we relate this to wind speed (U_{10})

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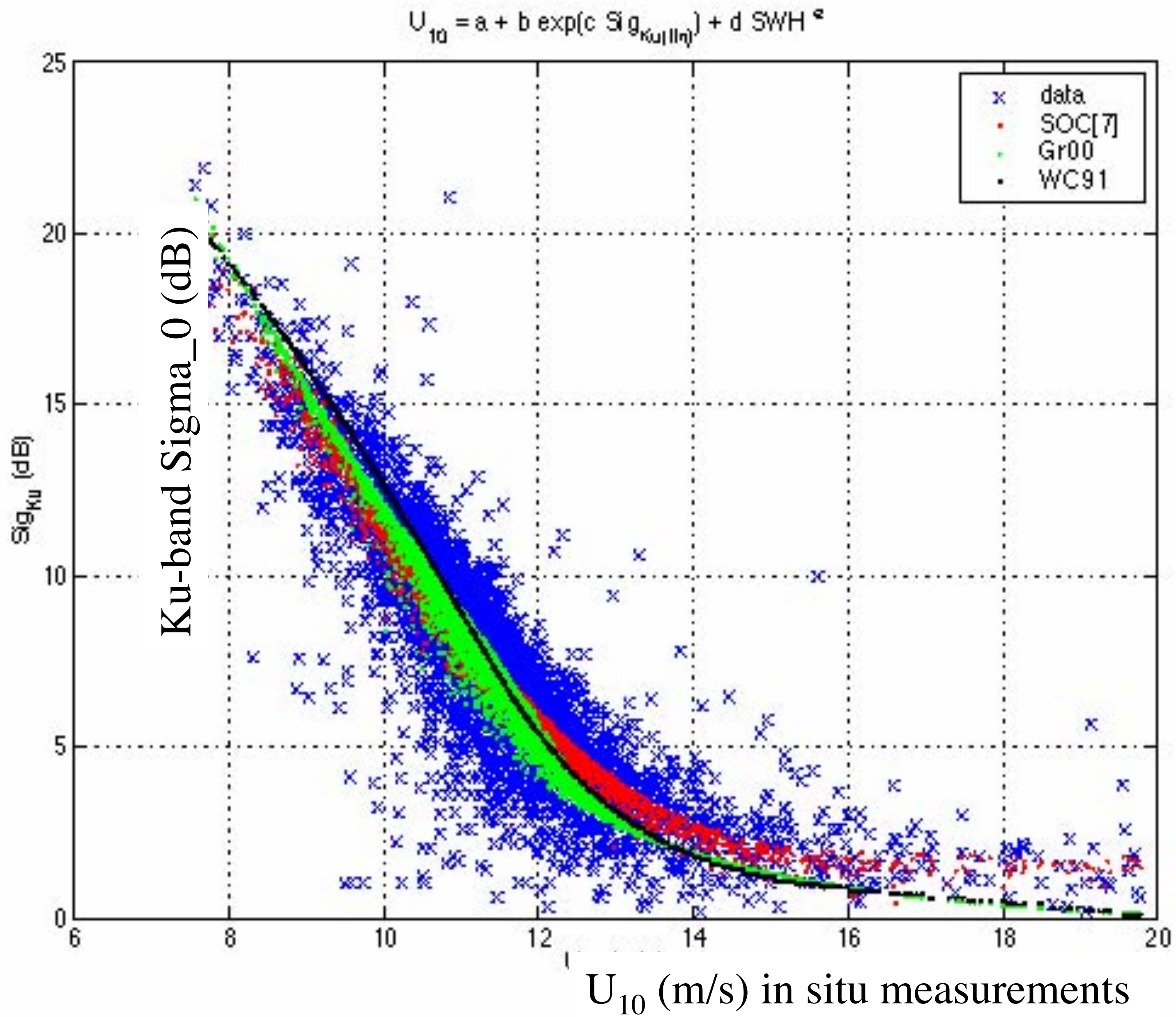

U10 = a + b exp(c Sig Ku(lin)) + d SWH e
25
20
15
10
5
0
6
8
10
12
14
16
18
20
Sig Ku (dB)
Ku-band Sigma_0 (dB)
data
SOC[7]
Gr00
WC91
U10 (m/s) in situ measurements

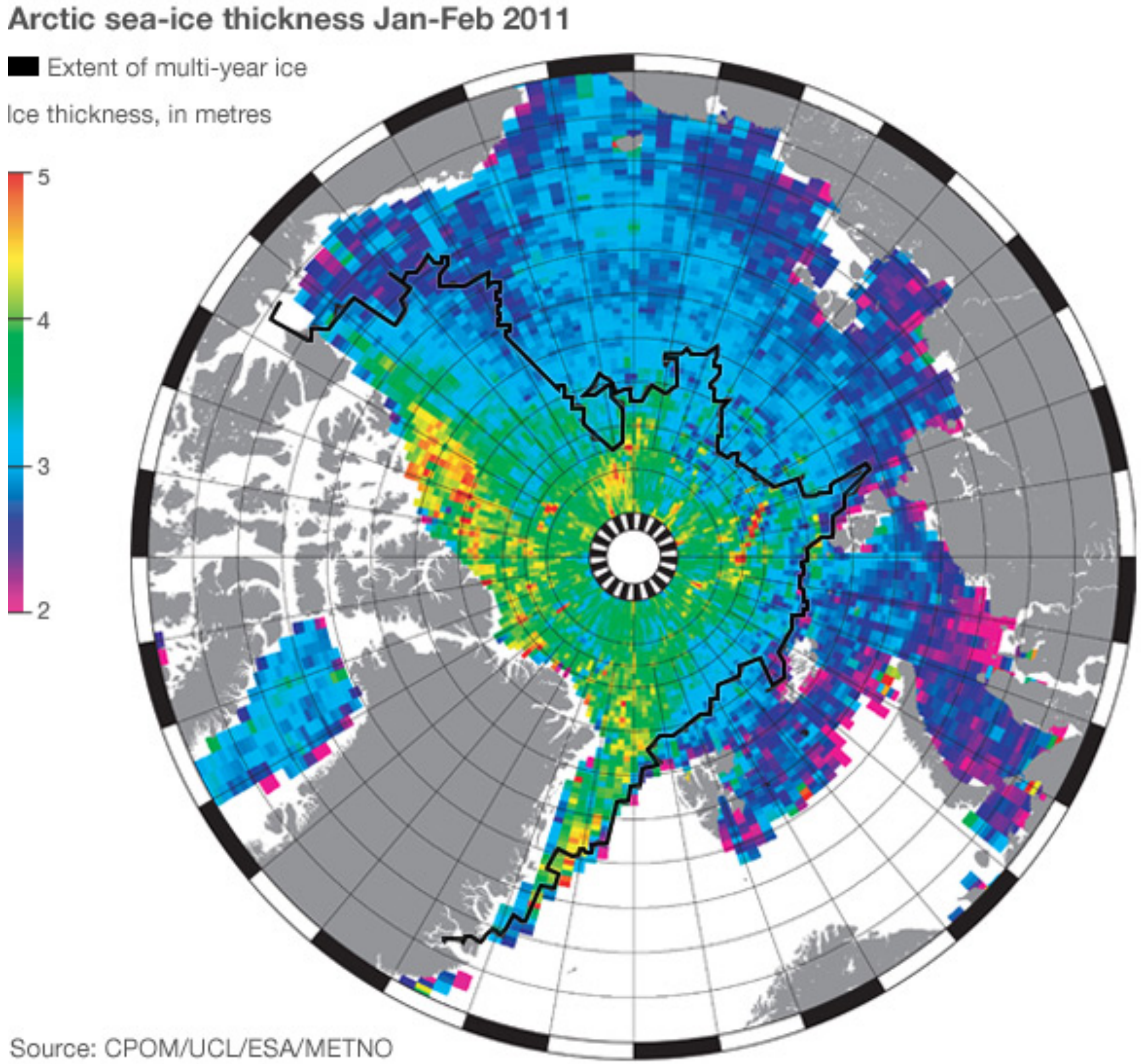
Why altimeter wind speeds?

- Scatterometers measure wind velocity over wide swaths
- Passive microwave measures wind speed over wide swaths
- Altimeters give us wind speed on a v. narrow swath
- Wind speed information coincident with wave height and sea surface height (e.g. sea state bias)

Sea Ice

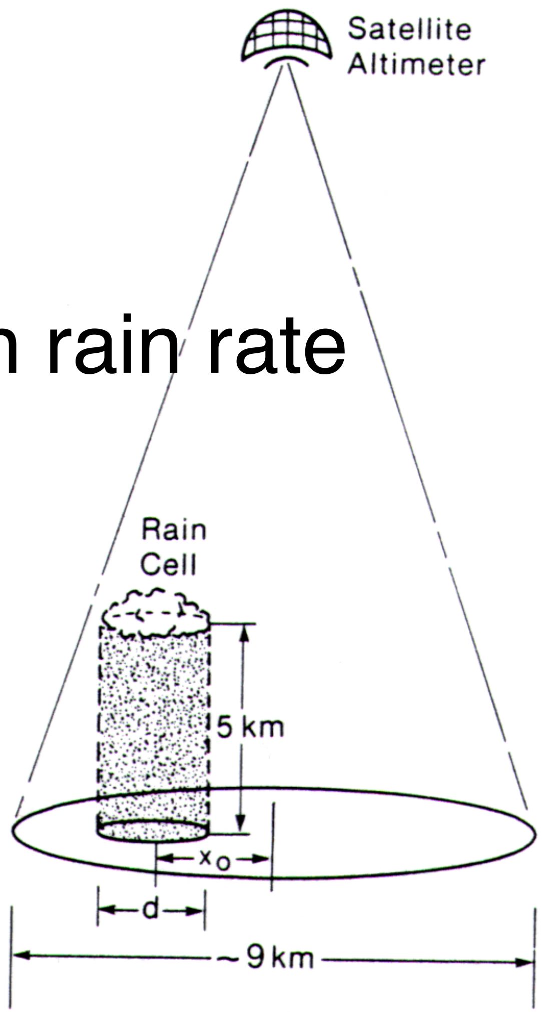
- Ice edge can be detected by a change in σ_0
- Re-tracking of the altimeter pulses over sea-ice can give
  - Sea surface topography in ice covered regions
  - Sea ice thickness!
    - the trick is that sea ice develops narrow cracks or ‘leads’, where we can observe the surface of the liquid water- by analysing both returns from the ice and from the leads we compute the ‘freeboard’ (the height of the ice surface above the water surface) which allows computation of the thickness.

Arctic Sea Ice Thickness from Cryosat



Rain effects in altimeter data

- Dual frequency altimeter (C and Ku band)
- Ku band attenuated
- C band is not
- Ku/C difference gives information on rain rate



G. Quartly

Altimetry, in summary

- Conceptually simple, but challenged by accuracy requirements
- Observes directly the dynamics of the ocean
- Therefore: El Niño, currents, eddies, planetary waves – but also wind waves and wind!!
- One of the most successful remote sensing techniques ever…
- …but still with plenty of room (new applications/ new instruments) for exciting improvements!!

Thanks for your interest & attention!

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