A short course on Altimetry

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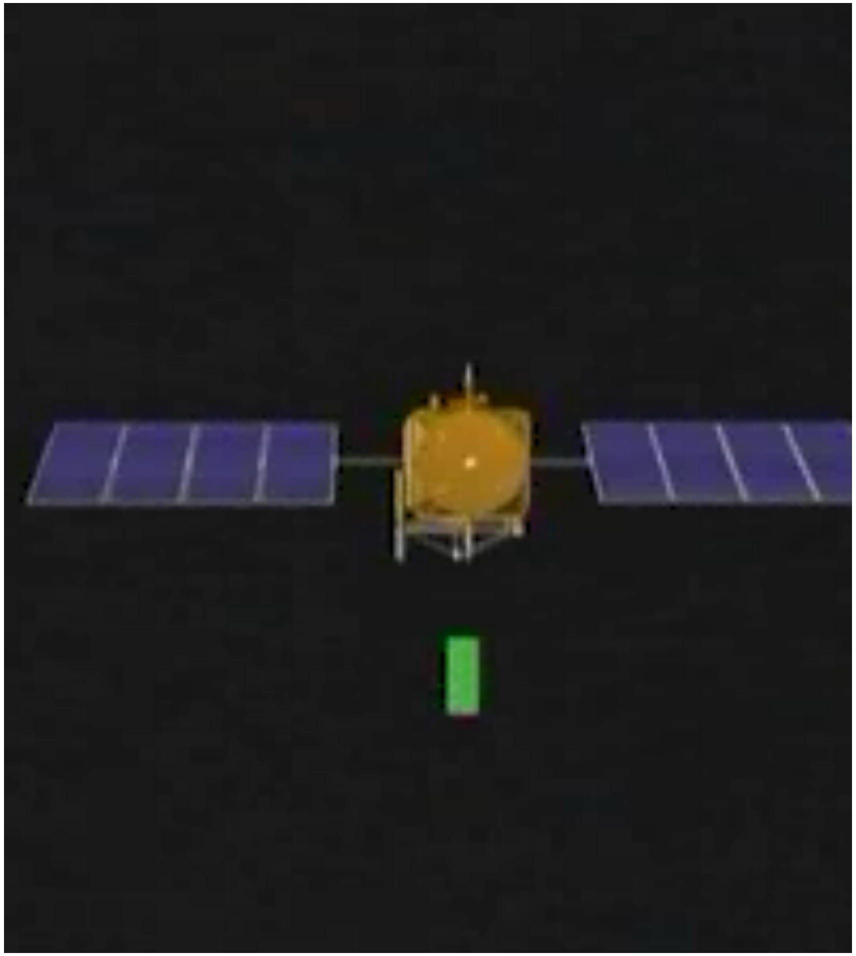
with contributions by Peter Challenor, Paolo Cipollini, Ian Robinson, R. Keith Raney + some other friends…

Outline

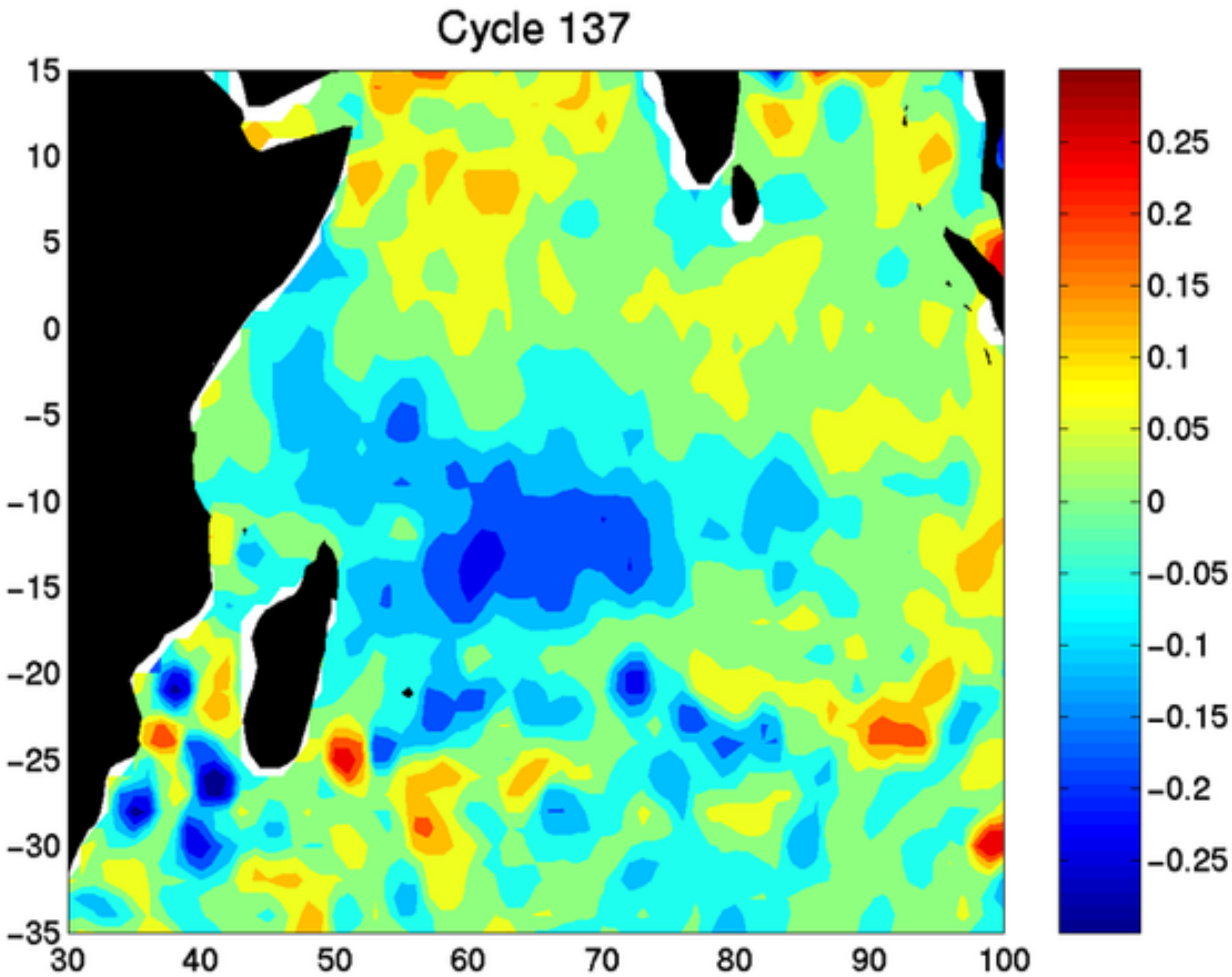
- Rationale
  – why we need altimetry
- Principles of altimetry
  – how it works in principle
  – New techniques
- Altimeter Data Processing
  – From satellite height to surface height: corrections
  – (or how it is made accurate)
- Geophysical parameters and applications
  – what quantities we measure
  – how we use them!

Rationale for Radar Altimetry over the oceans

- Climate change
  - oceans are a very important component of the climate system
- Altimeters monitor **currents / ocean circulation**…
- …that can be used to estimate **heat** storage and transport
- … and to assess the interaction between **ocean and atmosphere**
- We also get interesting by-products: **wind/waves, rain**



The sea is not flat….

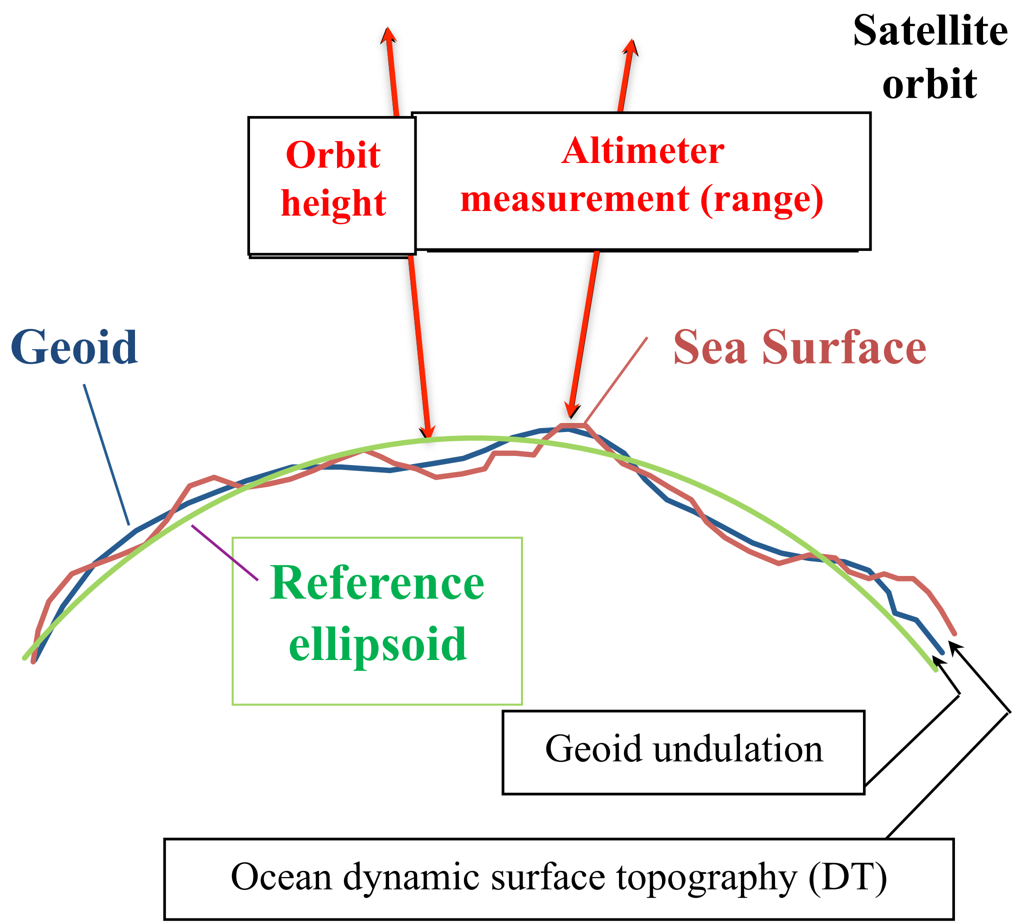


Surface dynamical features of height = **tens of cm** over lengths = **hundreds of kms**

Principles and instruments

Basic Principles

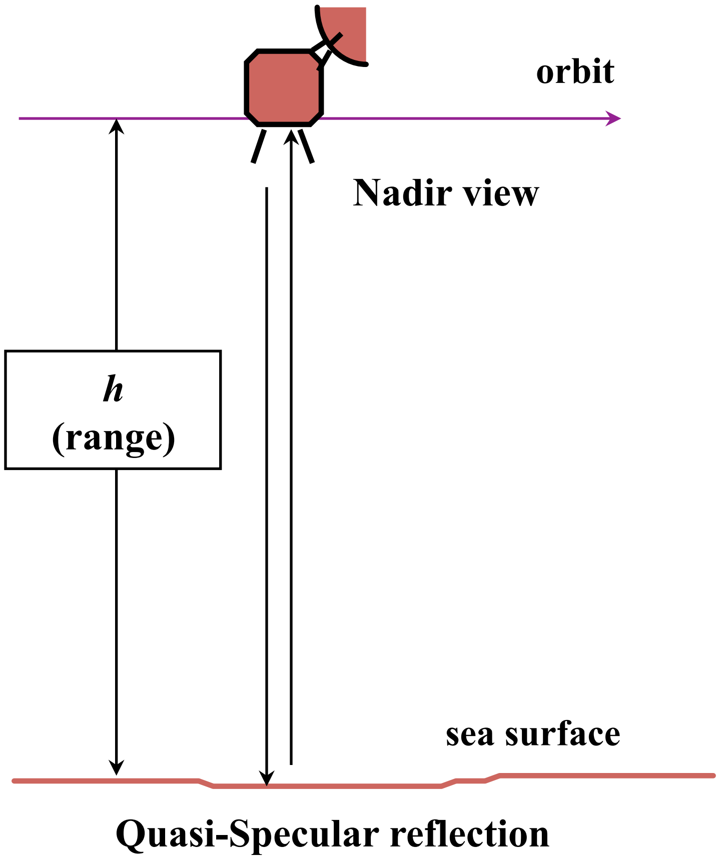
- The altimeter is a radar at vertical incidence
- The signal returning to the satellite is from quasi-specular reflection
- Measure distance between satellite and sea (**range**)
- Determine position of satellite (precise **orbit**)
- Hence determine **height** of sea surface
- Oceanographers require height relative to **geoid**



DT= Orbit - Range - Geoid

Measuring ocean topography with radar

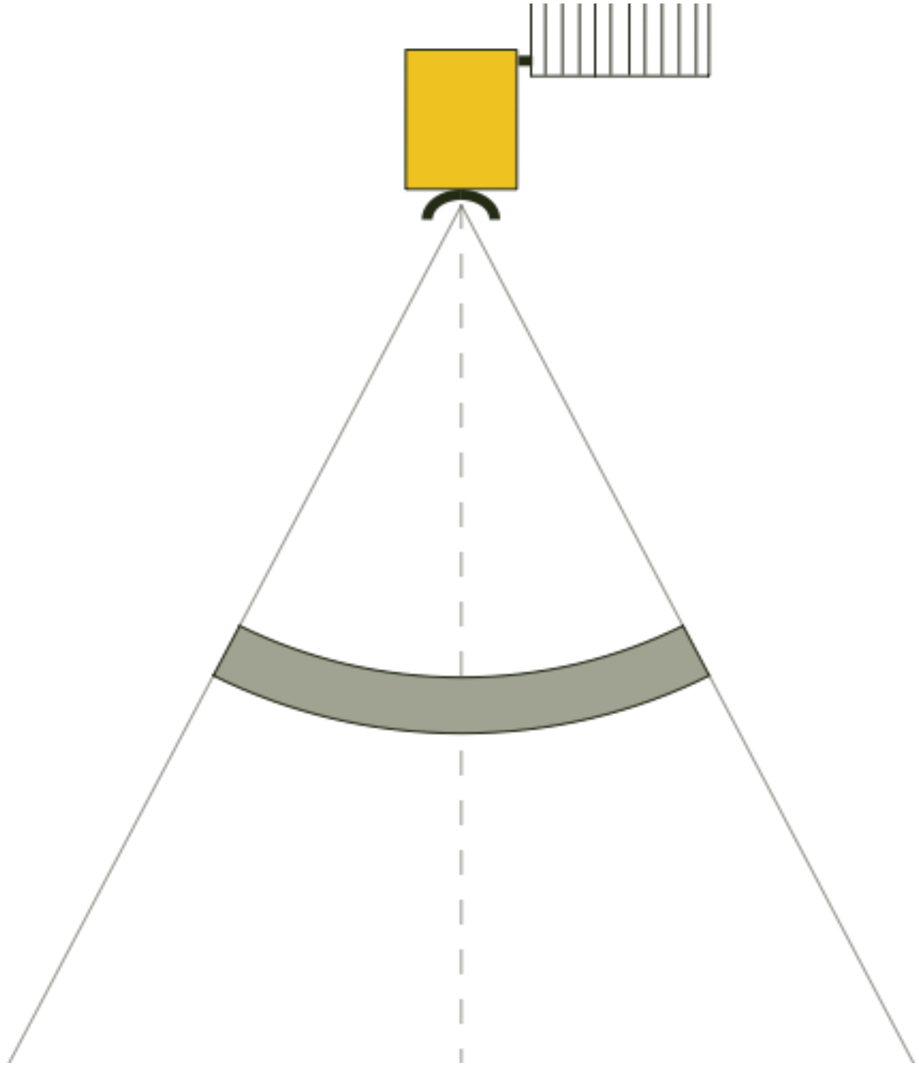
- Measure travel time, 2T, from emit to return
- $h = T \times c$ ($c \approx 3x10^8$ m/s)
- **Resolution to ~1cm** would need a pulse of $3x10^{-10}$s (0.3 nanoseconds)



0.3ns…
That would be a pulse bandwidth of >3 GHz…
Impossible!

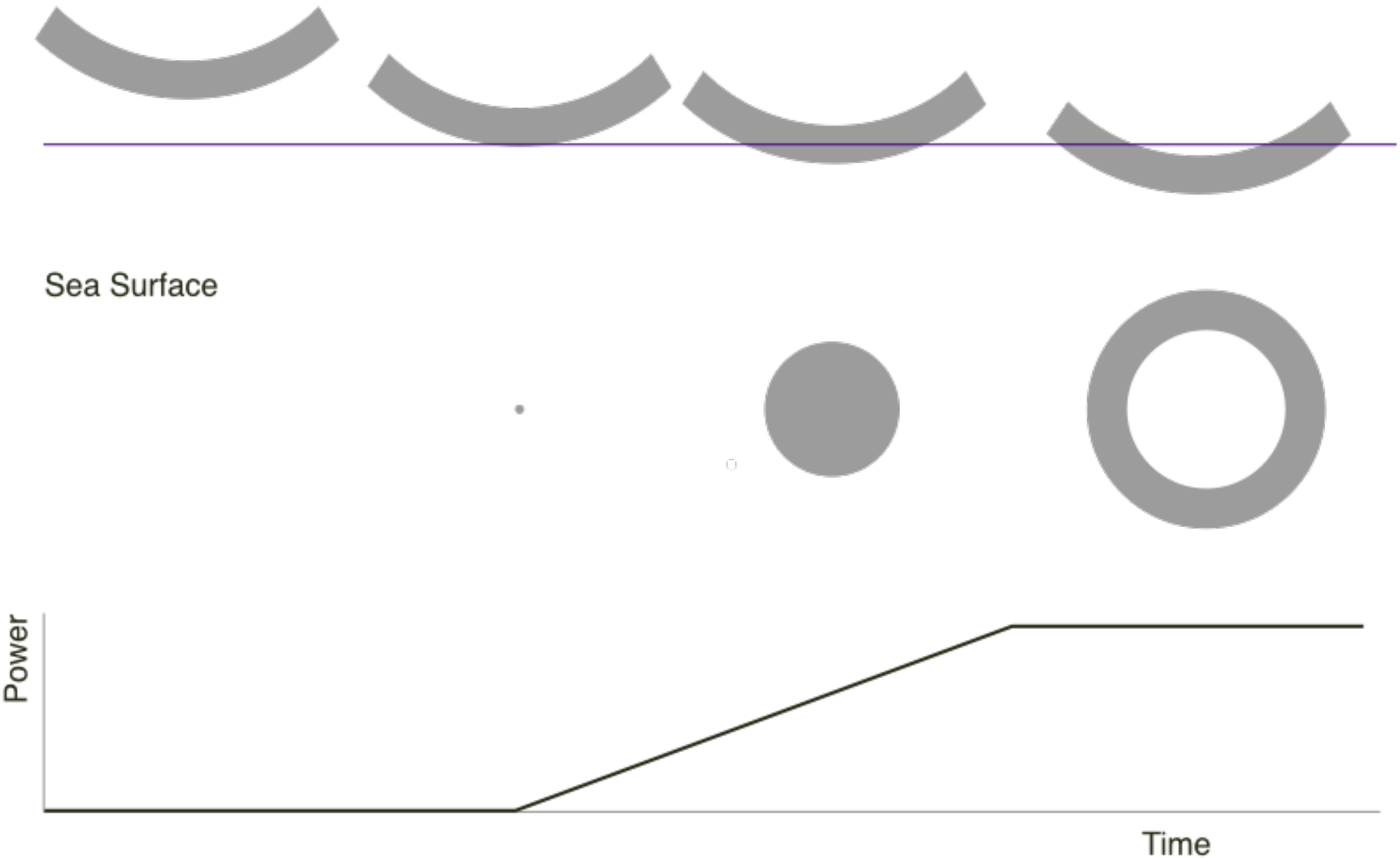
Pulse Limited Altimeter

- In a pulse limited altimeter the shape of the return is dictated by the length (width) of the pulse

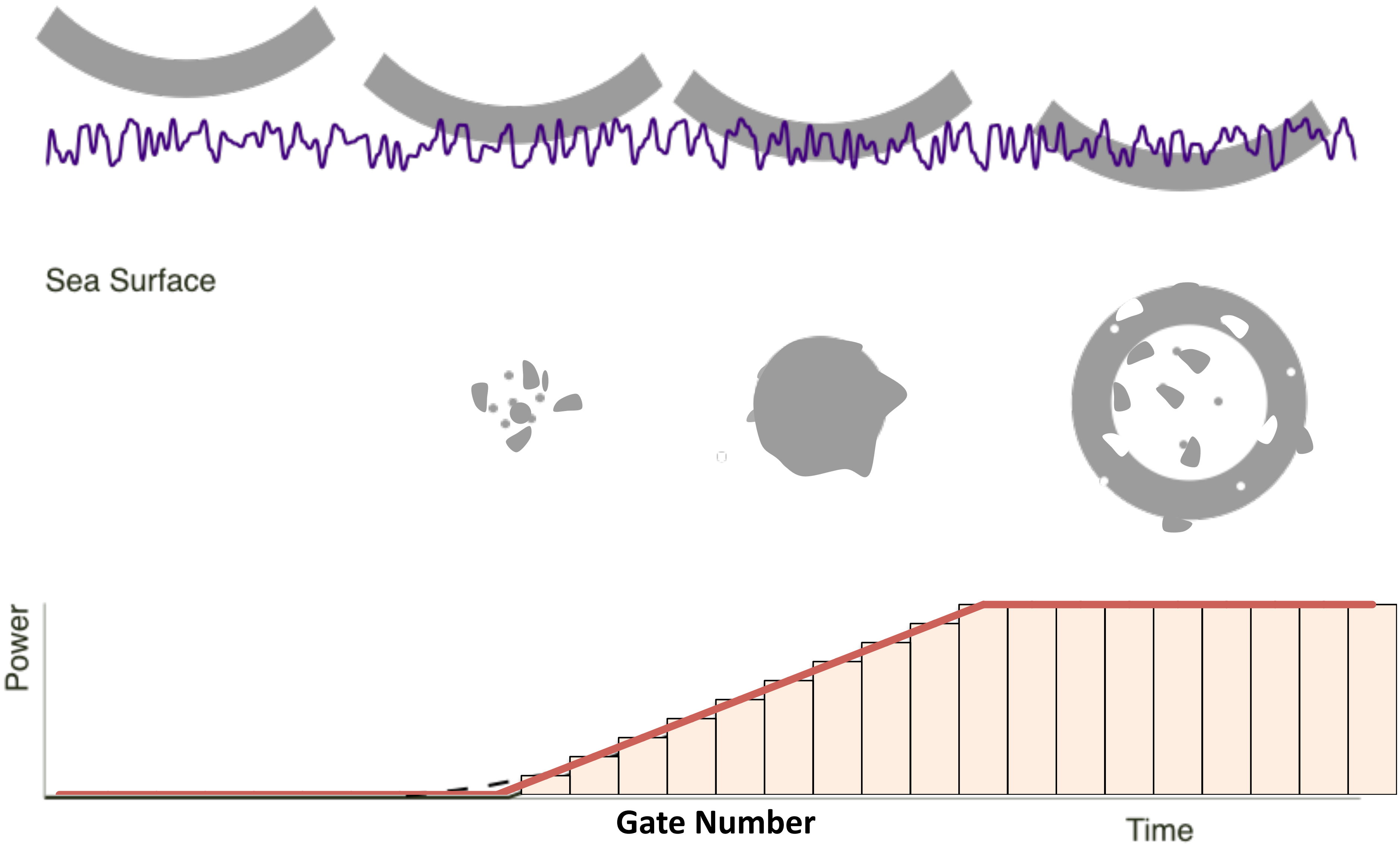


Basics of Pulse-limited Altimeter Theory

- We send out a thin shell of radar energy which is reflected back from the sea surface
- The power in the returned signal is detected by a number of gates (bins) each at a slightly different time


Sea Surface
Power
Time

If we add waves …



The area illuminated or 'effective footprint'

- The total area illuminated is related to the significant wave height noted as SWH [or Hs] (SWH ≈ 4 × std of the height distribution)
- The formula is

$$\frac{\pi R_0 \left(c\tau + 2H_s \right)}{1 + R_0 / R_E}$$

Where

c is the speed of light

τ is the pulse length

H_s significant wave height

R_0 the altitude of the satellite

R_E the radius of the Earth

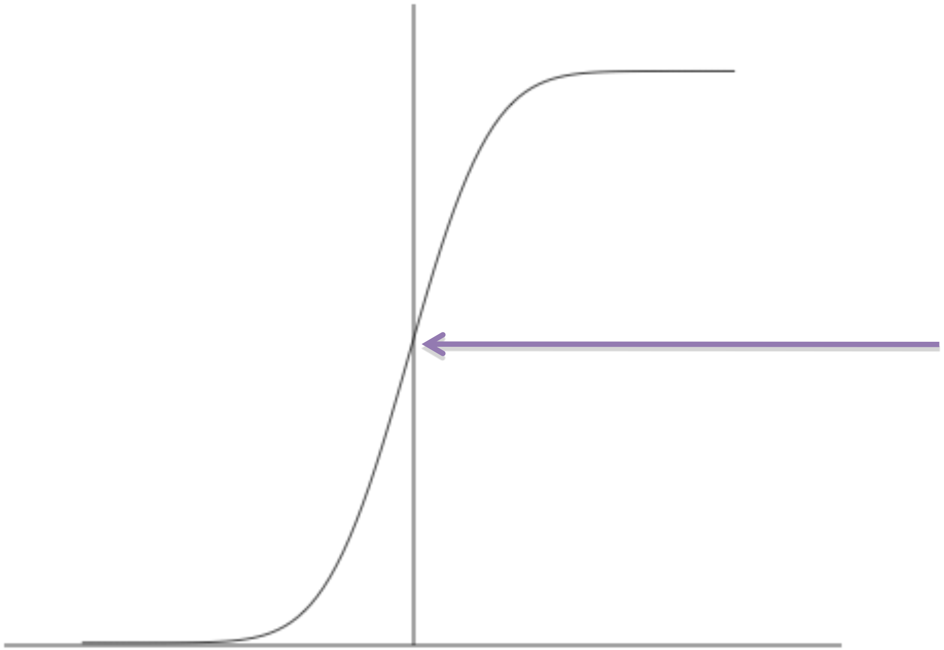
DIAMETERS of the effective footprint

H_s (m)	ERS-2/1, ENVISAT Effective footprint (km) (800 km altitude)	TOPEX, Jason-1/2 Effective footprint (km) (1335 km altitude)
0	1.6	2.0
1	2.9	3.6
3	4.4	5.5
5	5.6	6.9
10	7.7	9.6
15	9.4	11.7
20	10.8	13.4

From Chelton et al (1989)

The shape of the return signal

- A plot of return power versus time for a pulse limited altimeter looks like the *integral* of the heights of the specular points, i.e. the cumulative distribution function (cdf) of the specular scatterers

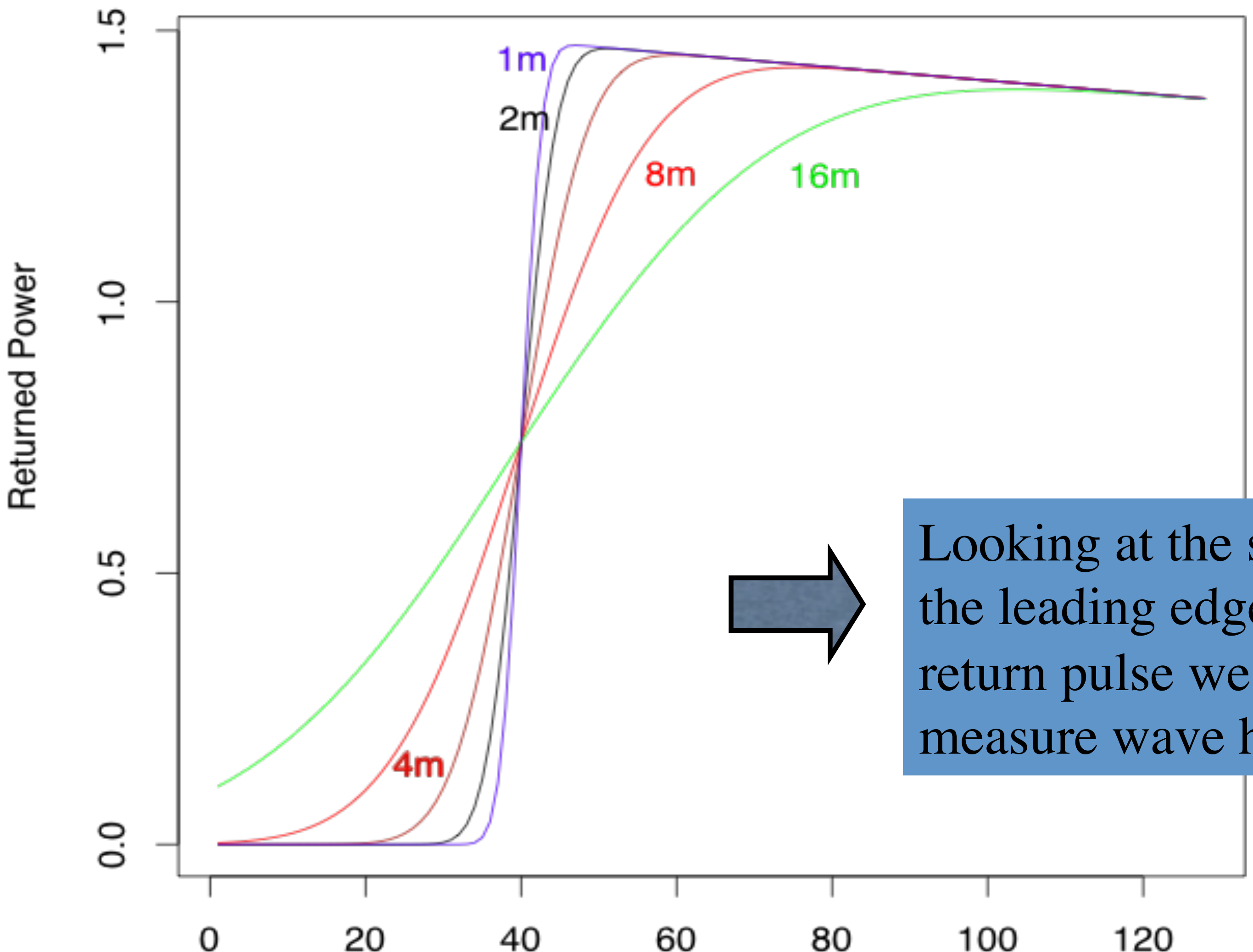


The tracking point is the half power point of the curve

What are we measuring?

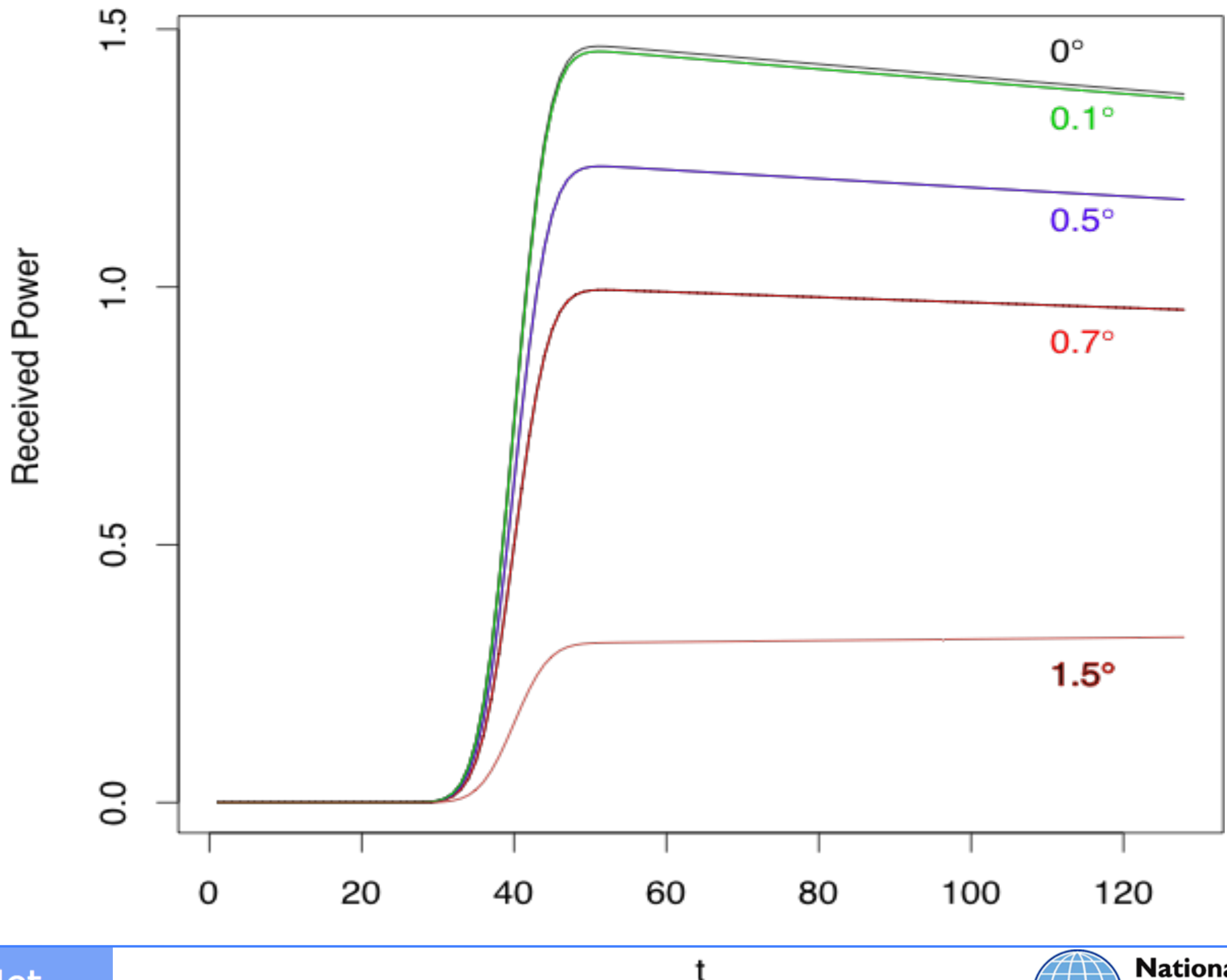
- *SWH* - **significant wave height**
- t_0 - the **time** for the radar signal to reach the Earth and return to the satellite
  - we then convert into **range** and finally into **height** – see in the next slides
- σ^0 - the **radar backscatter coefficient**
  - note this is set by the **roughness** at **scales comparable with radar wavelength**, i.e. cm, therefore it is (in some way) related to wind

Some theoretical waveforms

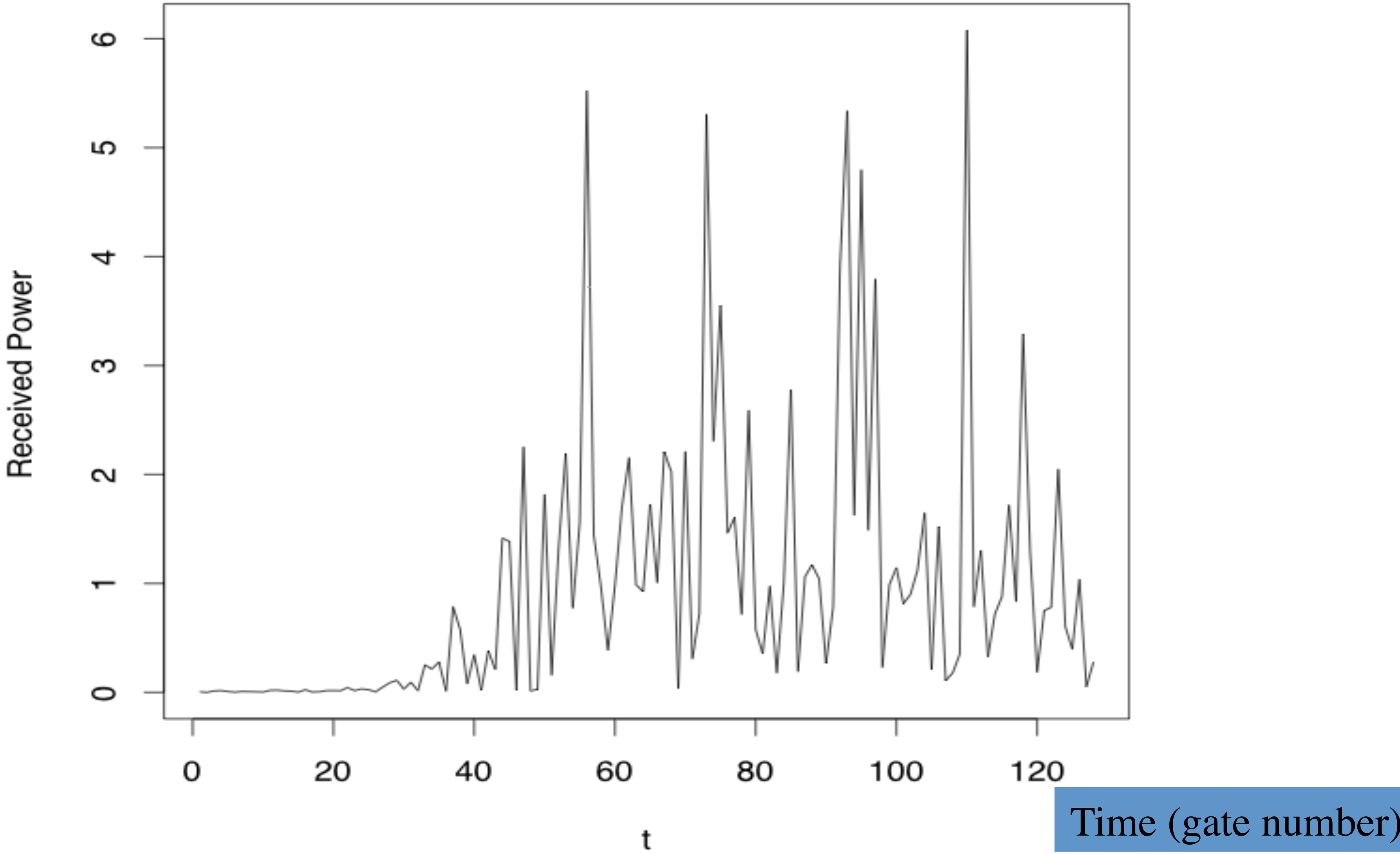


Looking at the slope of the leading edge of the return pulse we can measure wave height!

The effect of mispointing



A single pulse

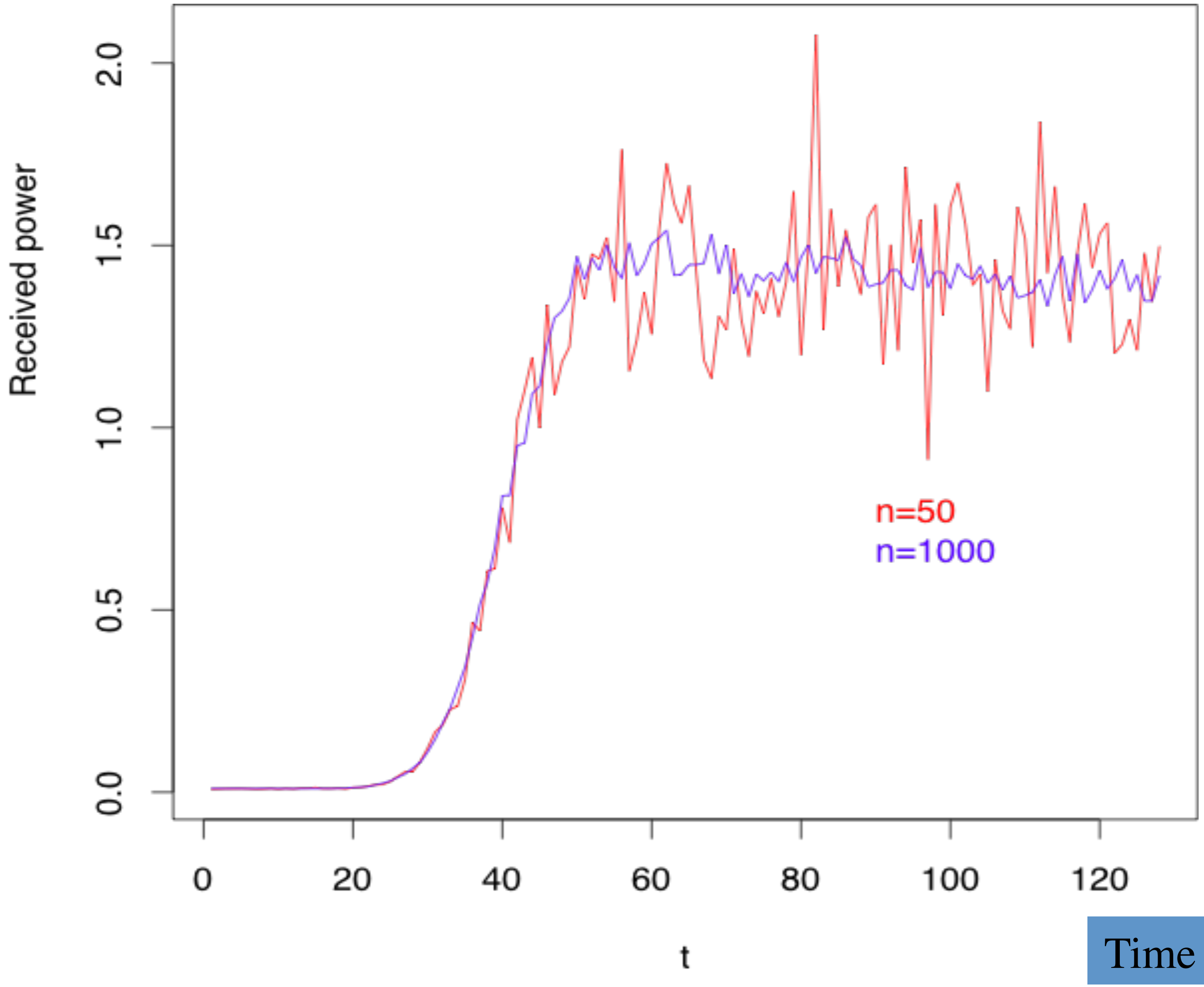


Averaging to reduce noise

- Individual altimeter pulses pulses are very noisy

⇨ **We need a lot of averaging to achieve good Signal to Noise Ratio**

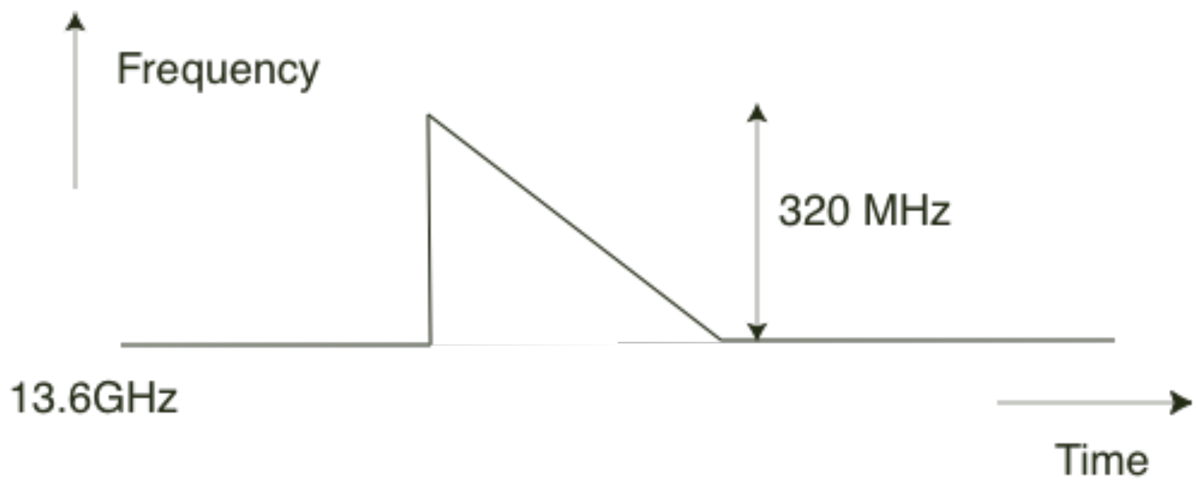
- The pulse repetition frequency is thousands per second
  - 1020 for ERS-1/2, 1800 for Jason & Envisat, 4500 for Topex
- Usually data are transmitted to the ground at ~20Hz and then averaged to ~1 Hz



Time (gate number

How altimeters really work

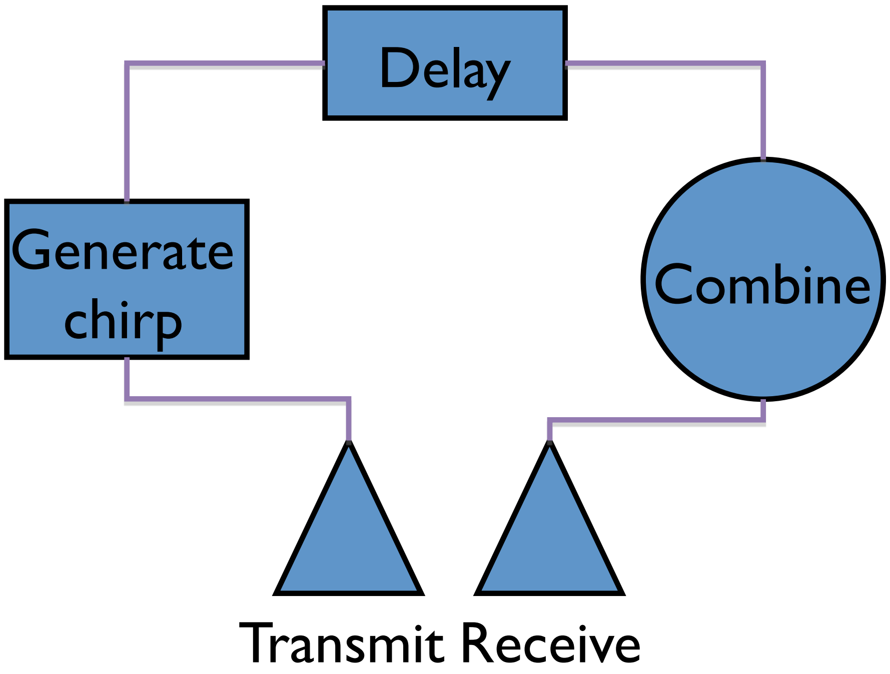
- It is very difficult (if not impossible) to generate a single-frequency pulse of length 3 ns
- It **is** possible to do something very similar in the frequency domain using a chirp: modulating the frequency of the carrier wave in a linear way



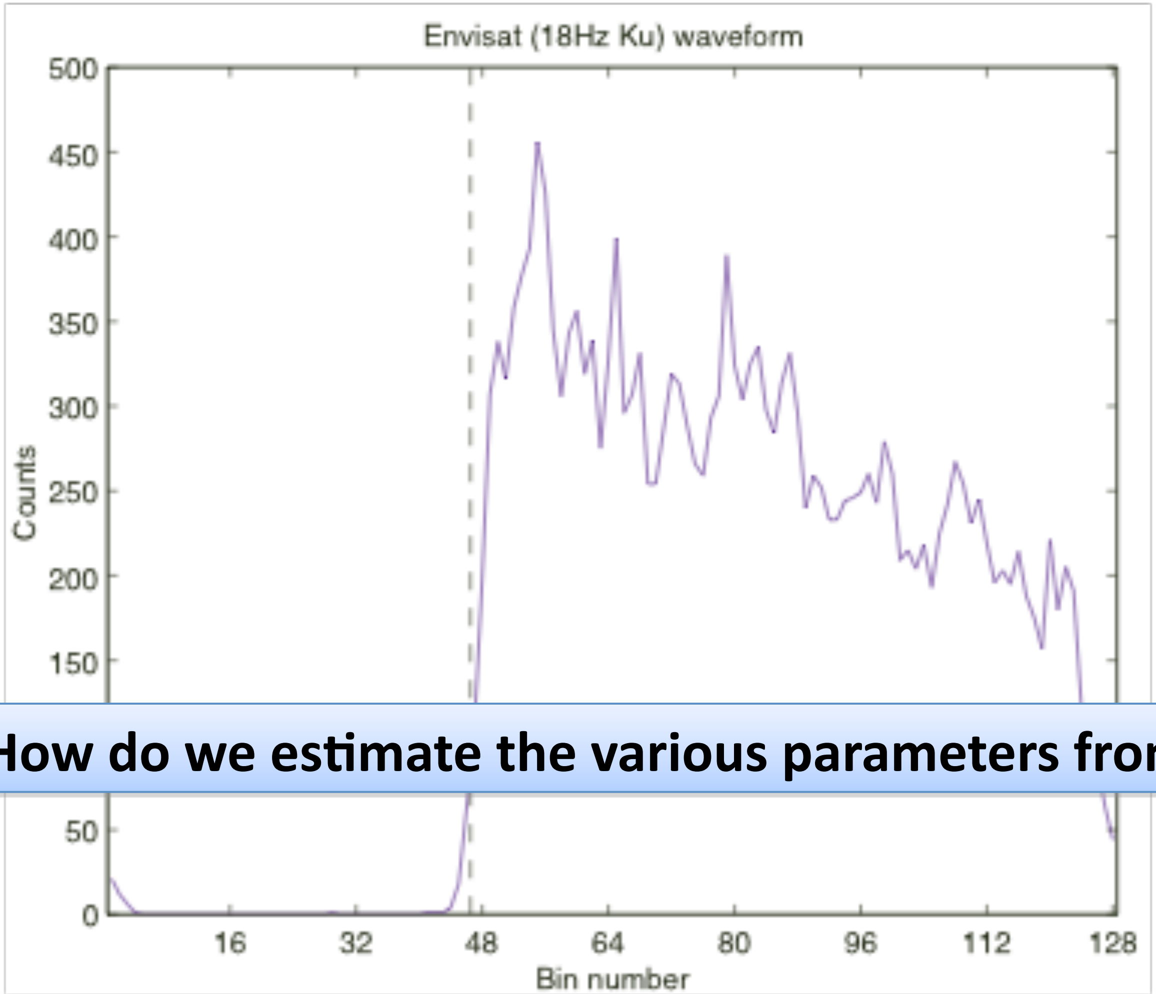
- The equivalent pulse width = 1/chirp bandwidth

Full chirp deramp

- A chirp is generated
- Two copies are taken
- The first is transmitted
- The second is delayed so it can be matched with the reflected pulse
- The two chirps are mixed
- A point above the sea surface gives returns at frequency lower expected and vice versa



A real waveform
- from the RA-2 altimeter on ESA's Envisat



How do we estimate the various parameters from this?

Ku band, 13.5 Ghz, 2.1 cm

"Retracking" of the waveforms

= fitting the waveforms with a waveform model to estimate the parameters

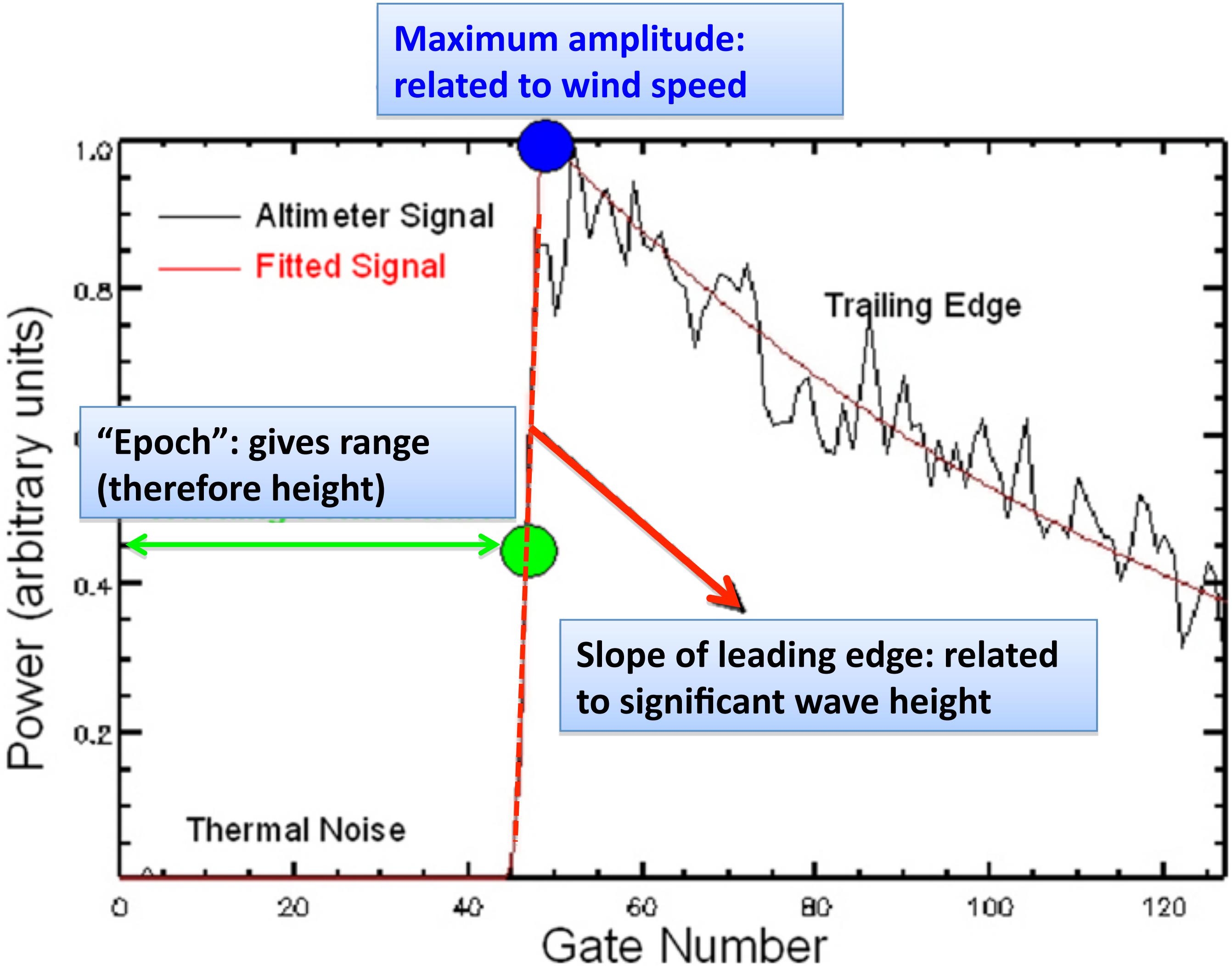
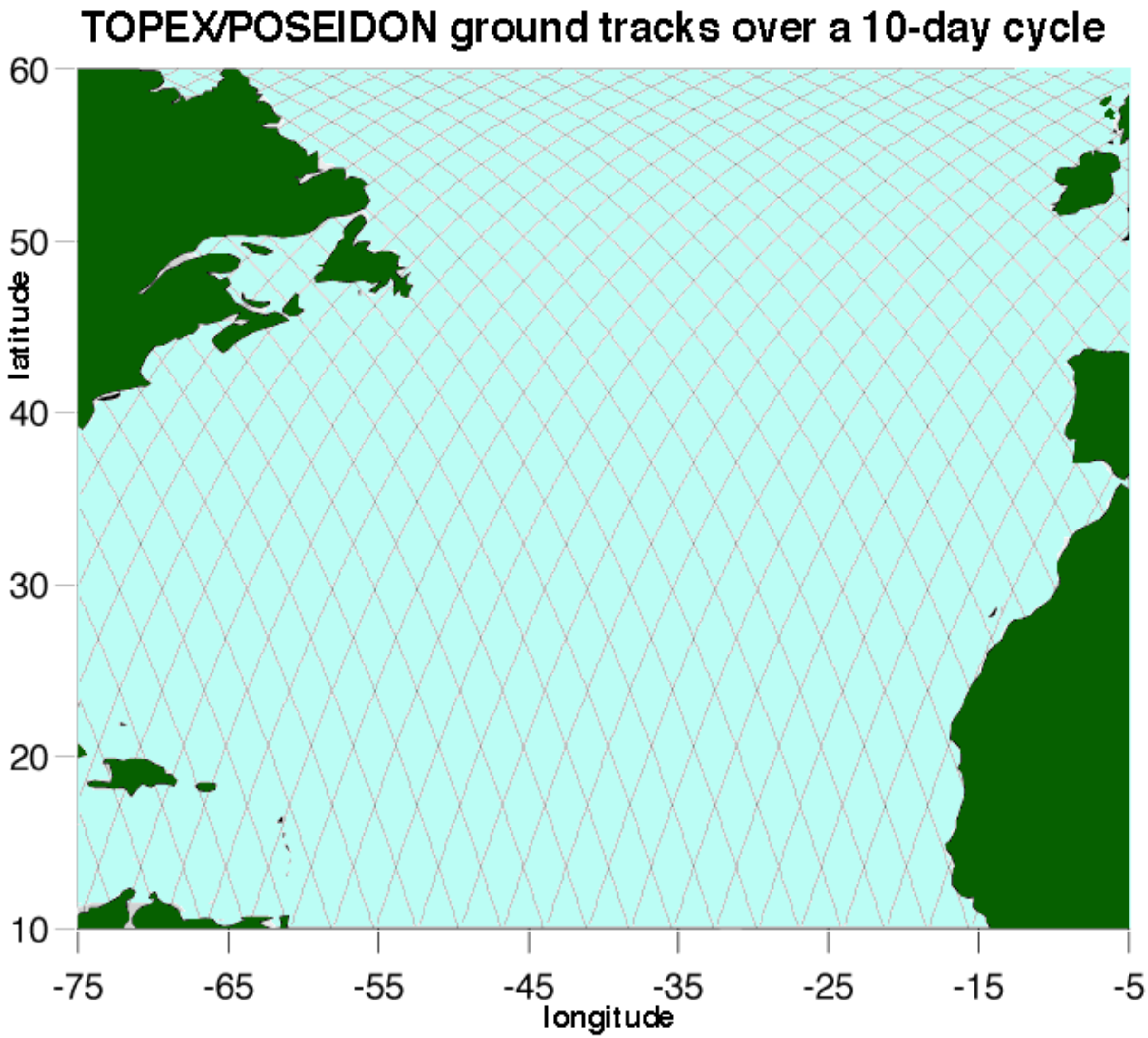
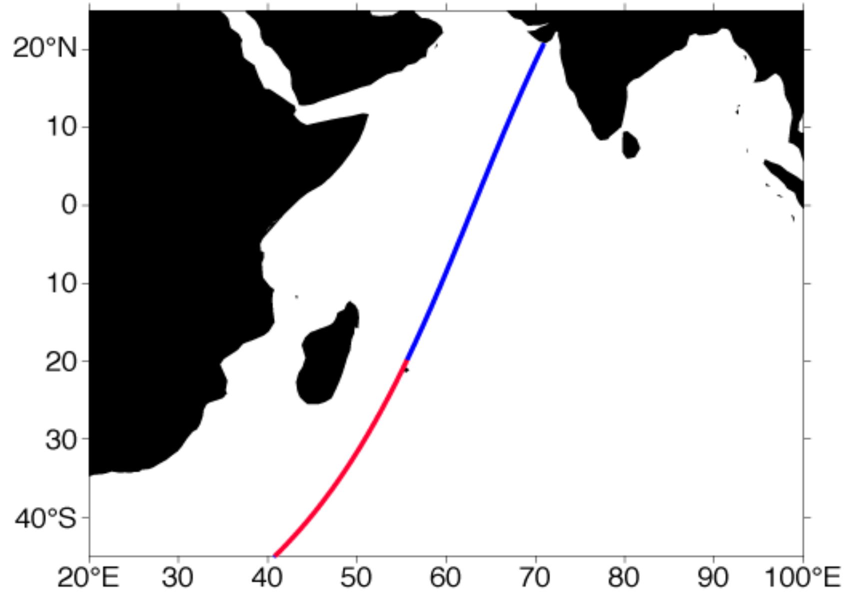


Figure from J Gomez-Enri et al. (2009)

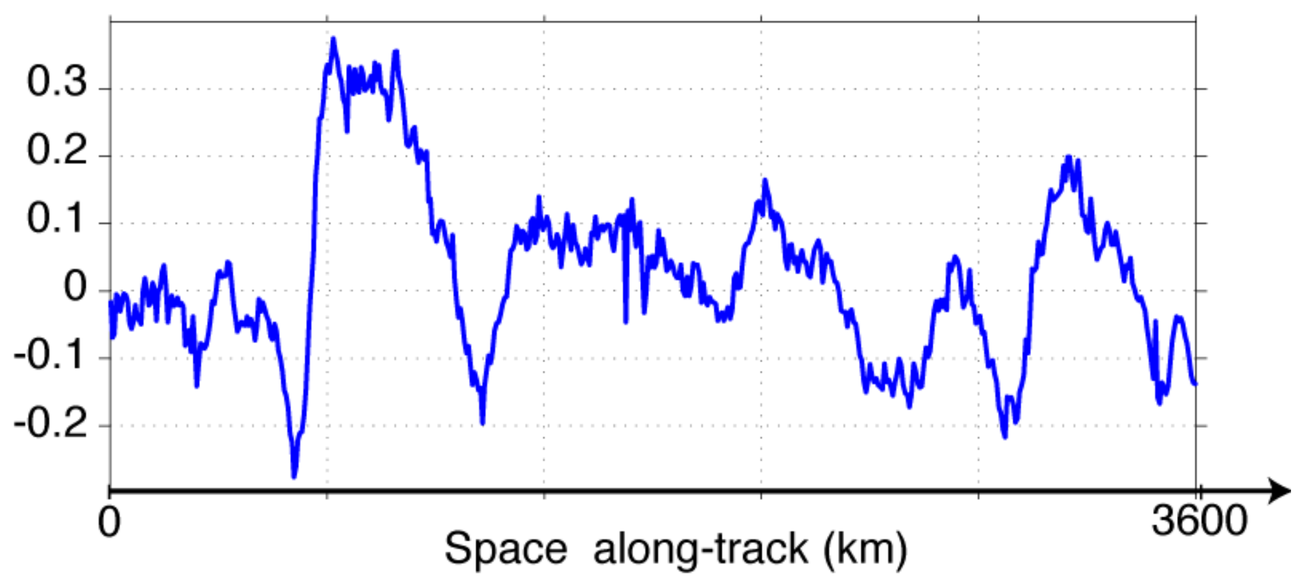
1-D (along-track) measurement



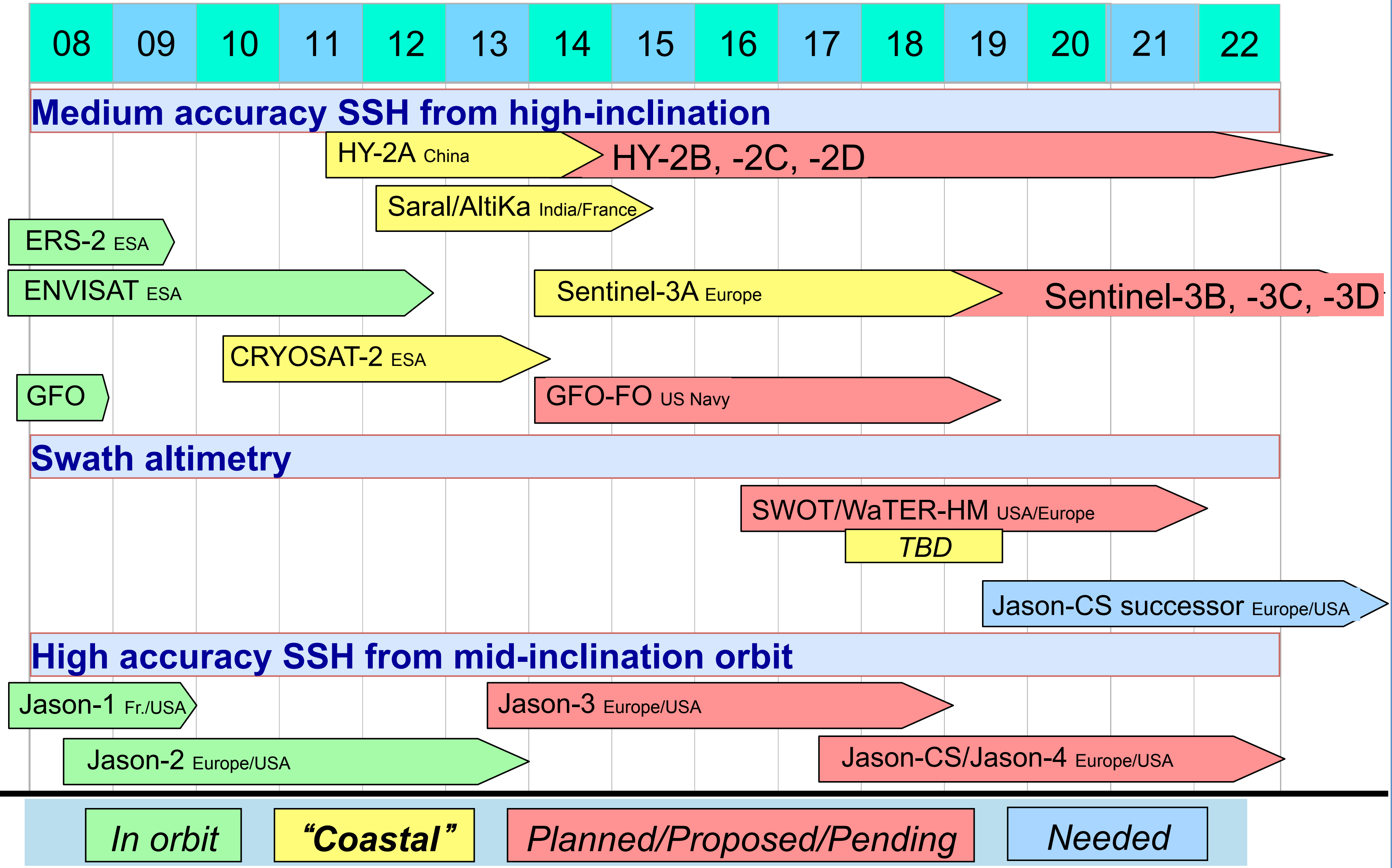
Example: Sea Surface Height along the ground track of a satellite altimeter



SSHA (m) along TOPEX/POSEIDON cycle 350 pass 29 16/03/02



Radar Altimeters: Now and Then

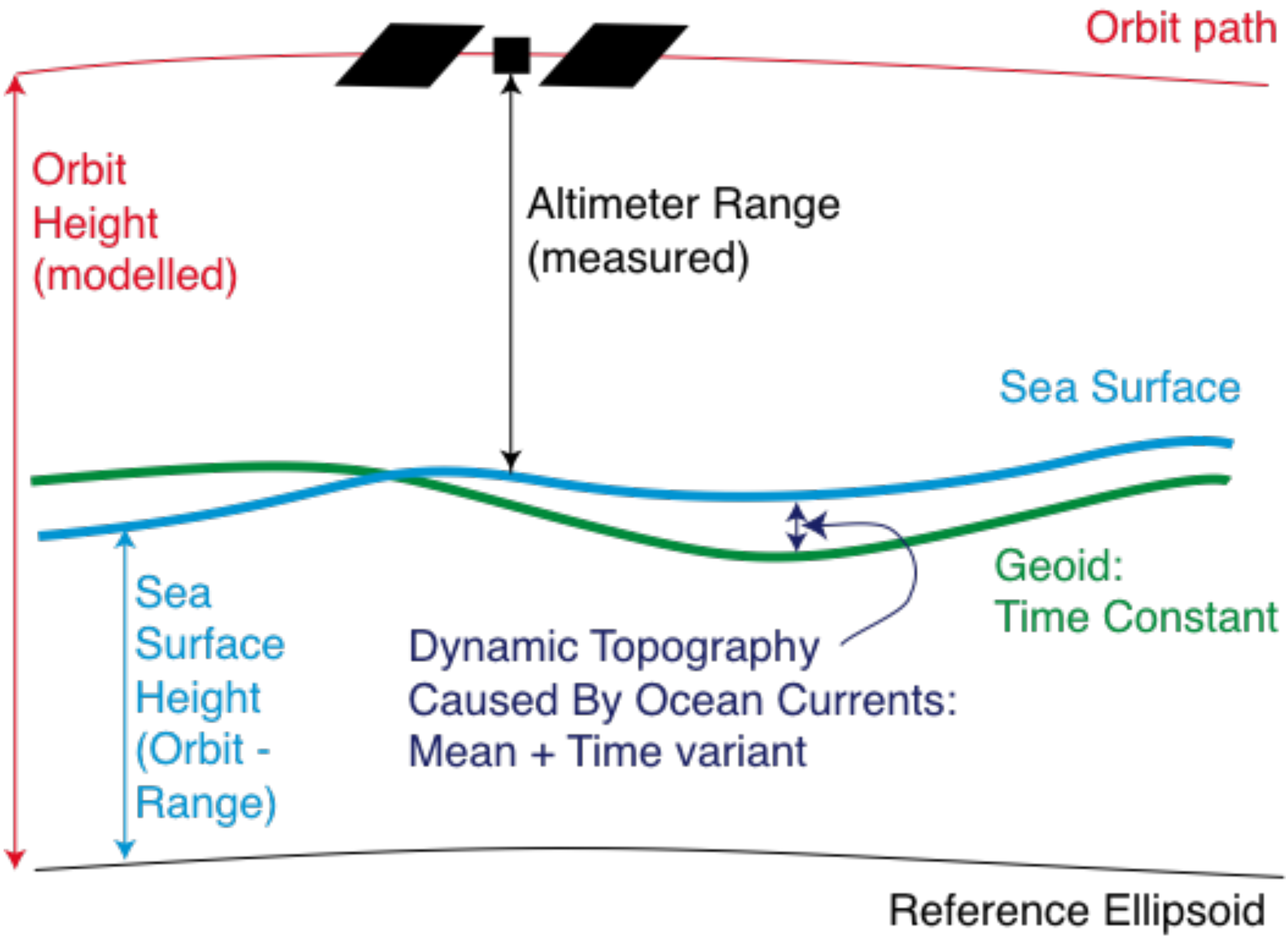


Adapted from CNES, 2009, with acknowledgement

From satellite height to sea surface height

satellite height to sea surface height

- The altimeter measures the altitude of the satellite above the earth surface
- The oceanographer wants a measurement of sea level
- Steps that need to be taken
  - Instrument corrections
  - Platform corrections
  - Orbit determination
  - The effect of refraction: ionospheric, wet/dry tropospheric
  - Sea surface effects


Orbit path
Orbit
Height
(modelled)
Altimeter Range
(measured)
Sea Surface
Sea
Surface
Height
(Orbit -
Range)
Dynamic Topography
Caused By Ocean Currents:
Mean + Time variant
Geoid:
Time Constant
Reference Ellipsoid

Altimeter Corrections & Orbits

- **Platform Corrections** - due to instrument geometry and other effects on the satellite
- **Orbits** - must be known as accurately as possible
- Correction for **atmospheric** delay effects
- Correction for **surface effects**
- Correction for **barometric effects**
- Estimating/Removing the **geoid**
- Estimating/Removing **tides**

Platform corrections

- The Earth is not round.
  - The true shape of the earth is the geoid
  - As the satellite orbits the Earth it moves closer and further away responding to changes in gravity

⇨ Satellite is moving towards and away from the earth

⇨ A Doppler correction applied to range

- Other platform corrections are applied to range and need not worry the scientist…
  - Eg correction for the distance between the centre of gravity of the spacecraft and the altimeter antenna
- …unless something goes wrong
  - eg the USO (Ultra Stable Oscillator) range correction for RA-2 on board Envisat

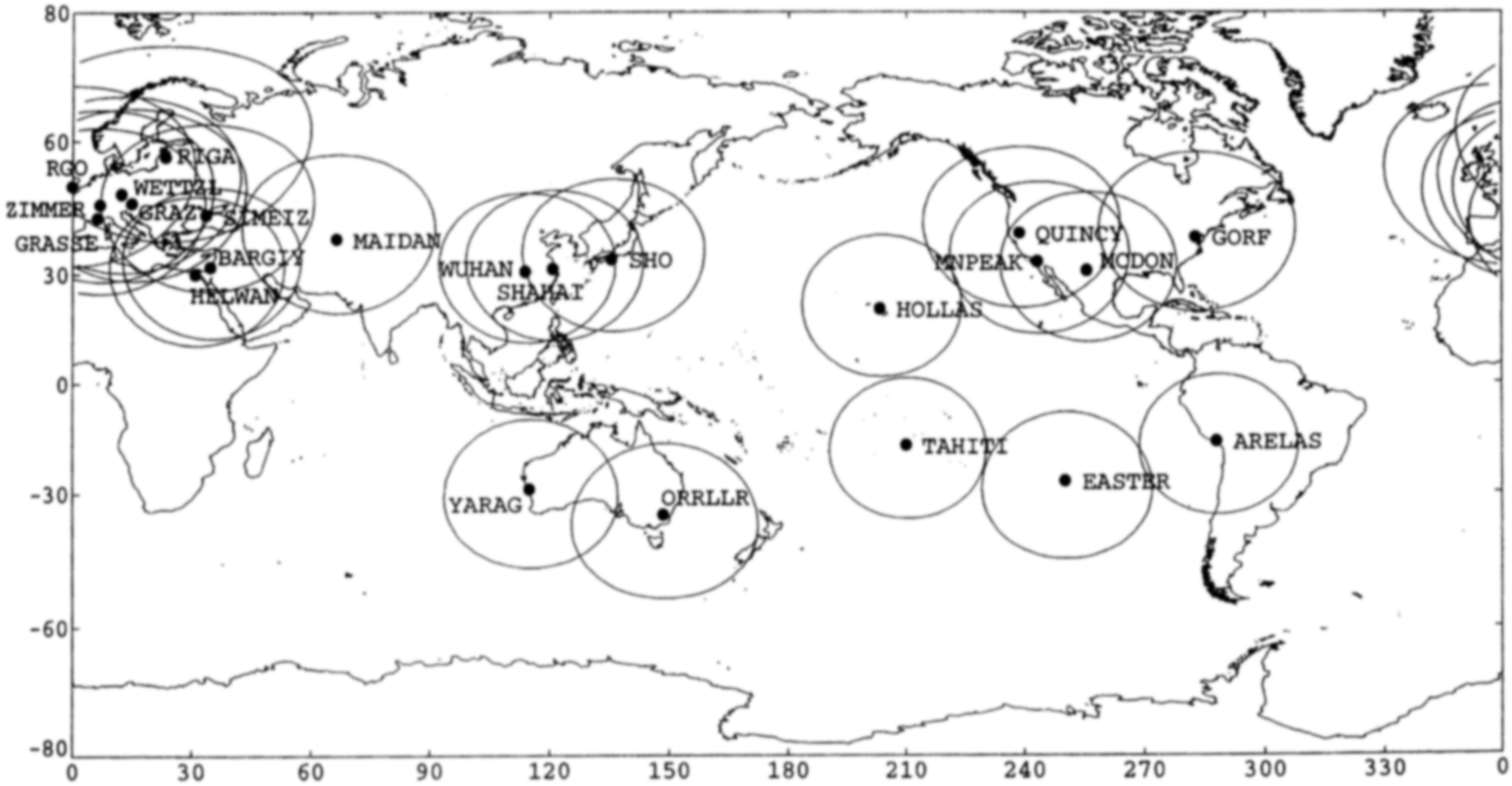
Orbits

- From the altimeter measurement we know the height of the satellite above the sea surface
- We want to know the height of the sea surface above a reference (the geoid or an ellipsoid)
- Therefore we need to know the satellite orbit, to a few cm or less, relative to the same reference
- This is done through a combination of satellite tracking and dynamical modelling.
- A dynamical model is fitted through the tracking data. Solutions cover a few days at a time.
- The tracking information comes from DORIS, GPS and Satellite Laser ranging (SLR)

DORIS

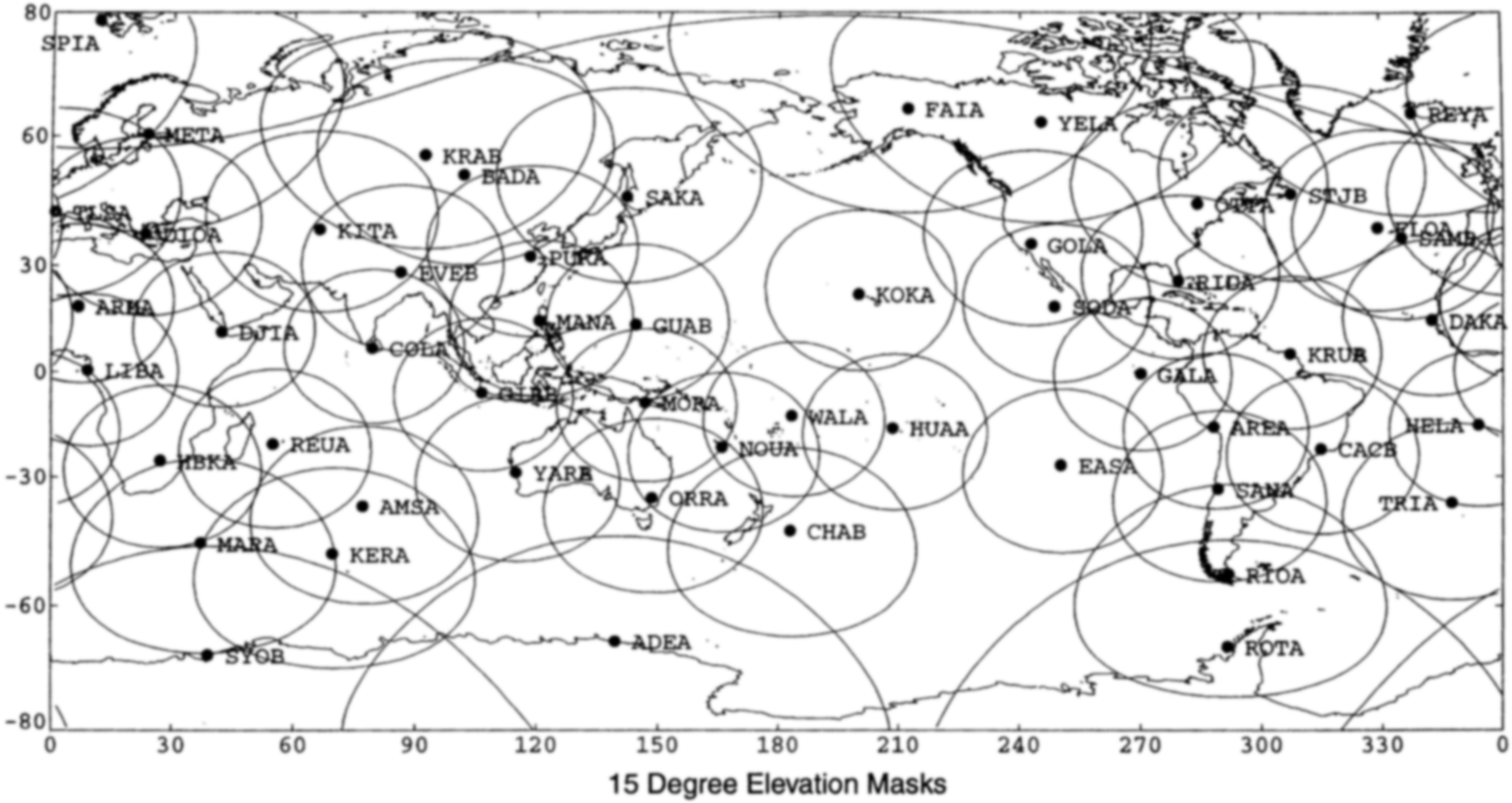
SLR

SLR Stations



20 Degree Elevation Masks

DORIS stations



Quality of orbits

- The quality of orbits are measured by the reduction of crossover differences and by comparison to SLR stations
- TOPEX/Poseidon and Jason orbits are now good to the **~2-cm** level
- ERS-2 and ENVISAT: **~3 cm**
  - more affected by drag, as in lower orbit, and much larger, than T/P and Jason

Topex/Poseidon Orbit Error Budget

- Size of observed error in orbit model, by parameter
  - Gravity, 2.0 cm
  - Radiation pressure, 2.0cm
  - Atmospheric drag, 1.0 cm
  - Geoid model, 1.0 cm
  - Solid earth and ocean tide, 1.0 cm
  - Troposphere, < 1 cm
  - Station location, 1.0 cm
- ⇨ **Total radial orbit error, 3.5 cm**
  - Mission design specification, 12.8 cm
- **With latest, state-of-art models, the above total orbit error decreases to ~2.0 cm**

Atmospheric Corrections

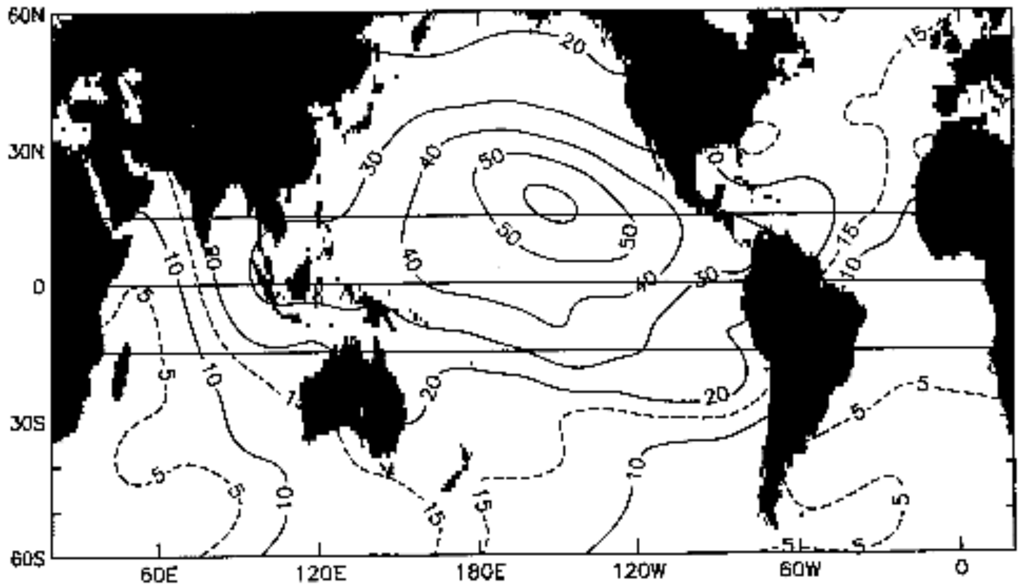
- As the radar signal travels through the atmosphere it is slowed down w.r.t. speed of light in the vacuum
- Since we need speed to estimate range, we must correct for this effect.
- There are three parts of the atmosphere that must be taken into account
  - Ionosphere
  - Dry troposphere
  - Wet troposphere

Ionospheric correction

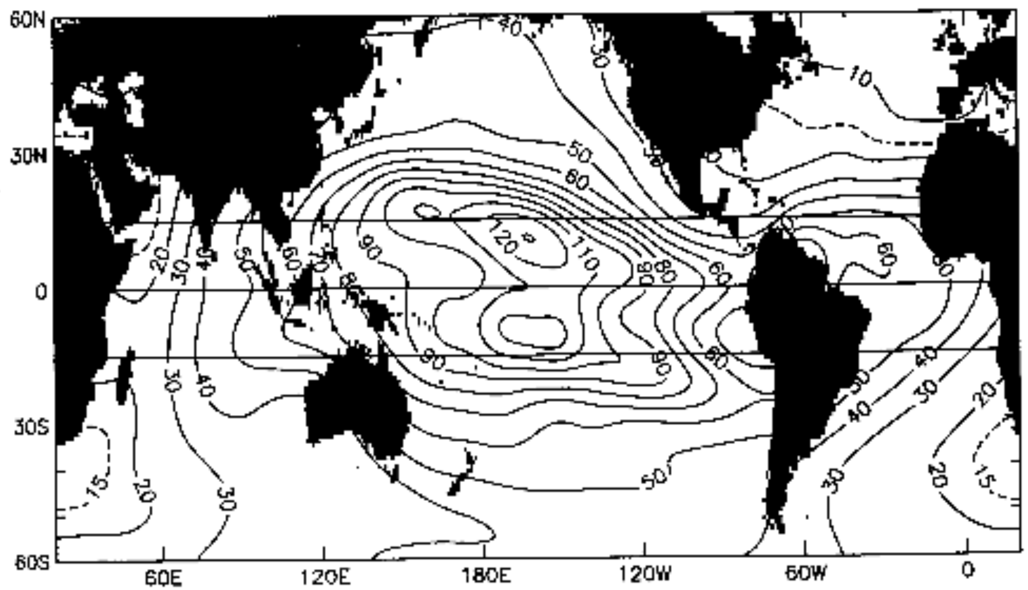
- Caused by free electrons in the ionosphere
- Frequency dependent so it can be measured with a dual frequency altimeter:

ERS-1/2 × Topex ✔ Jason-1/2 ✔ Envisat ✔ (only up to 17/01/08)
GFO × Cryosat ×

- Otherwise use a model or other observations from another dual frequency radar system (GPS, DORIS)
- Average value 45mm, s.d. 35mm
- Depends on solar cycle and time of day
- GIM (based on GPS, produced by JPL) is a good product to use for single-frequency altimeters



Low solar activity



High solar activity

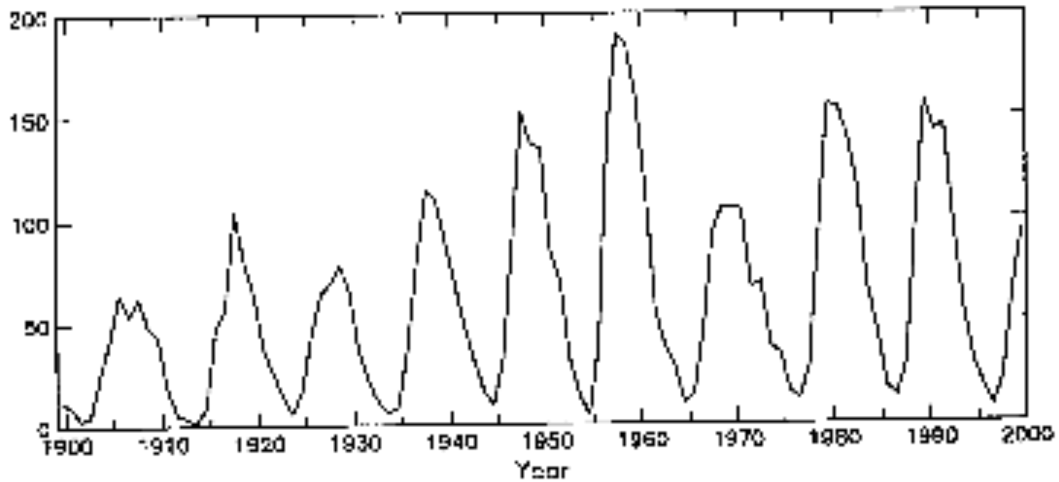


FIGURE 31 Annual average number of sunspots over the time period 1900–1999.

Annual sunspot numbers

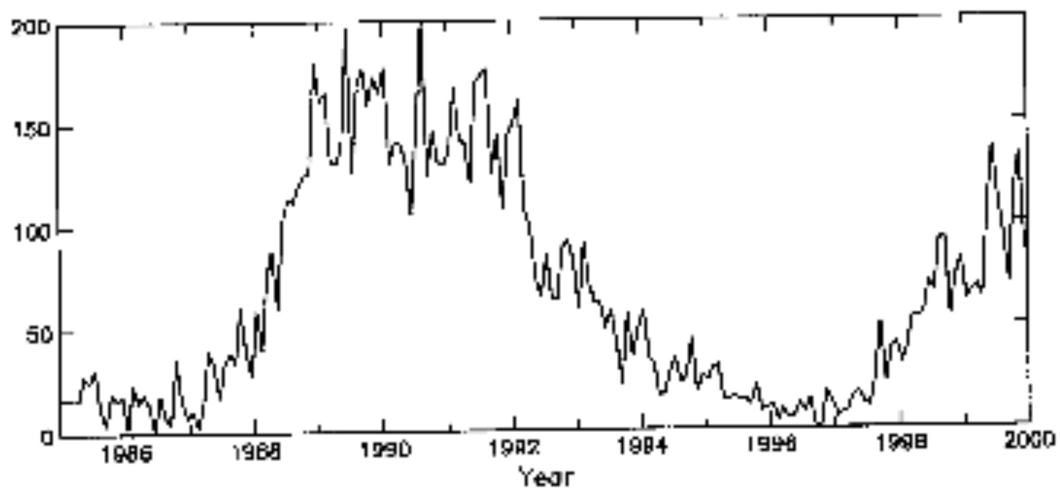


FIGURE 32 Monthly average number of sunspots over the time period 1985–1999.

Monthly sunspot numbers

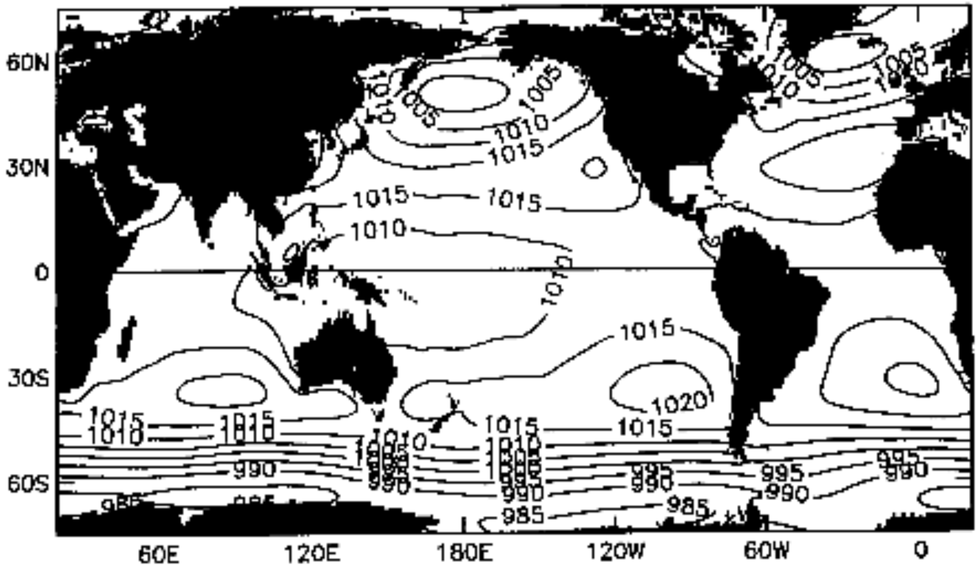
Dry Tropospheric Correction

- Due to O_2 molecules in the atmosphere
- Derived from atmospheric pressure (from met models) by:

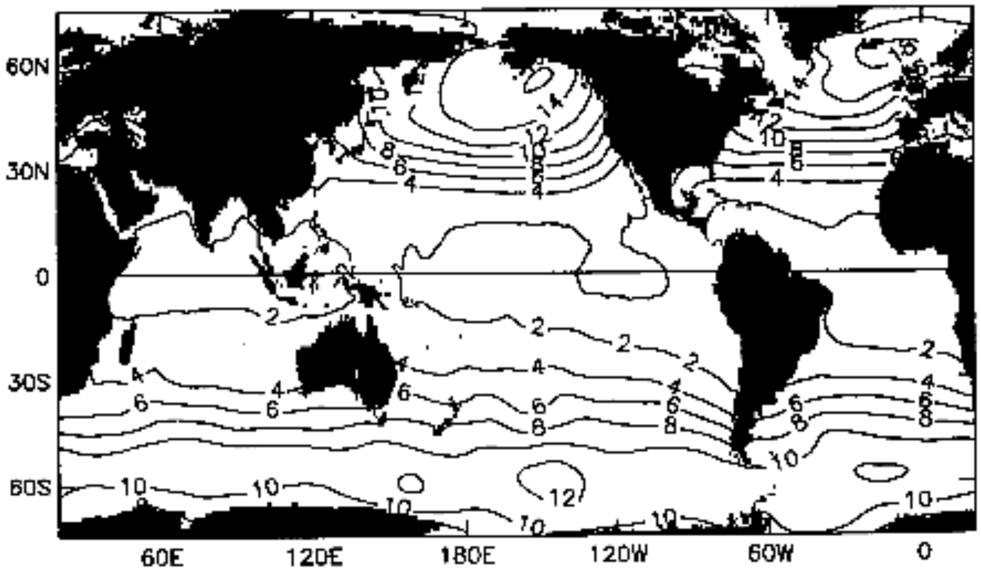
  Dry_trop = 2.277 p (1 + 0.0026 cos(2×latitude))

  (mm) (hPa)

- Average value 2300 mm, s.d. 30 mm

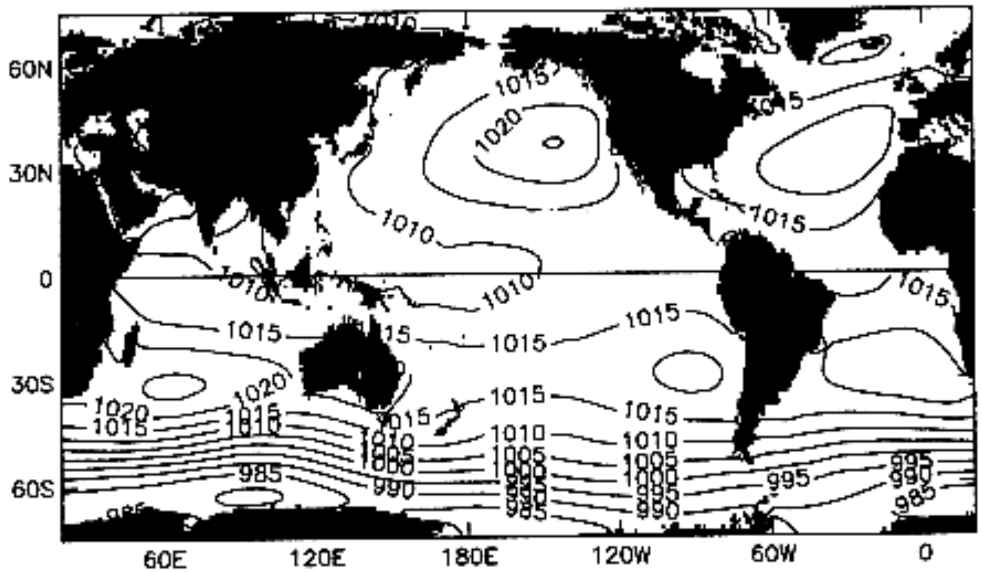


Winter DJF Air Pressure Mean (hPa)

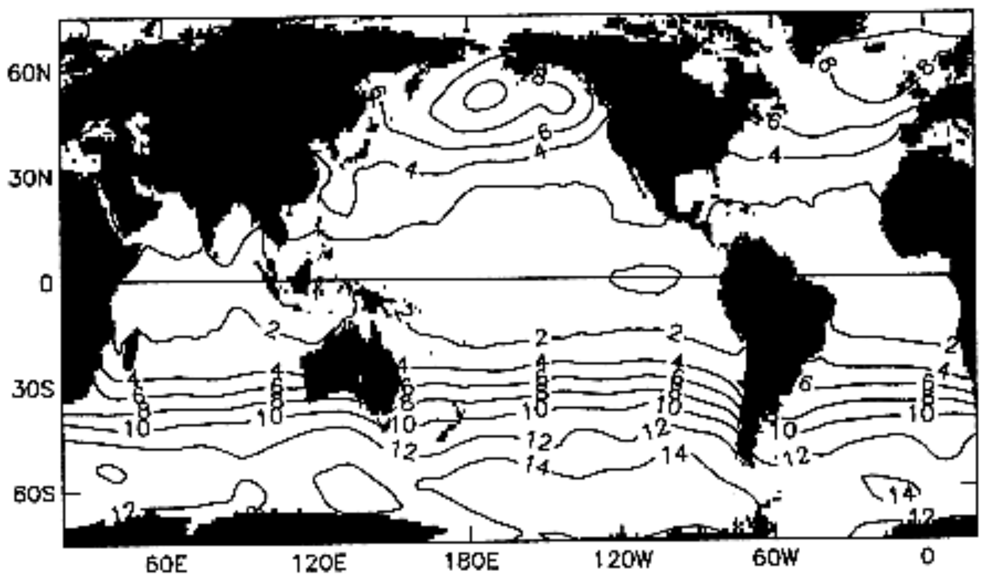


Standard deviation

Summer JJA Atmospheric Pressure Mean (hPa)



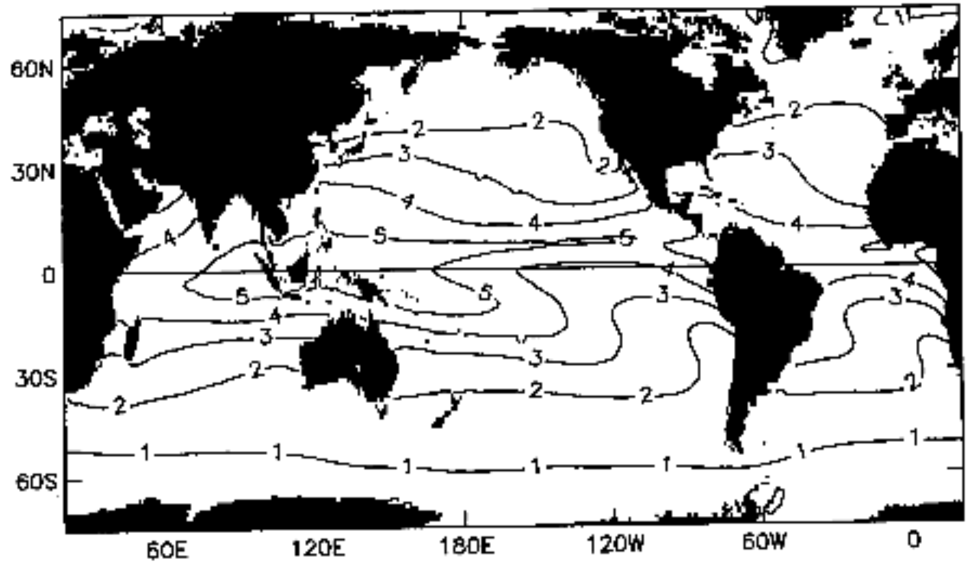
Standard Deviation



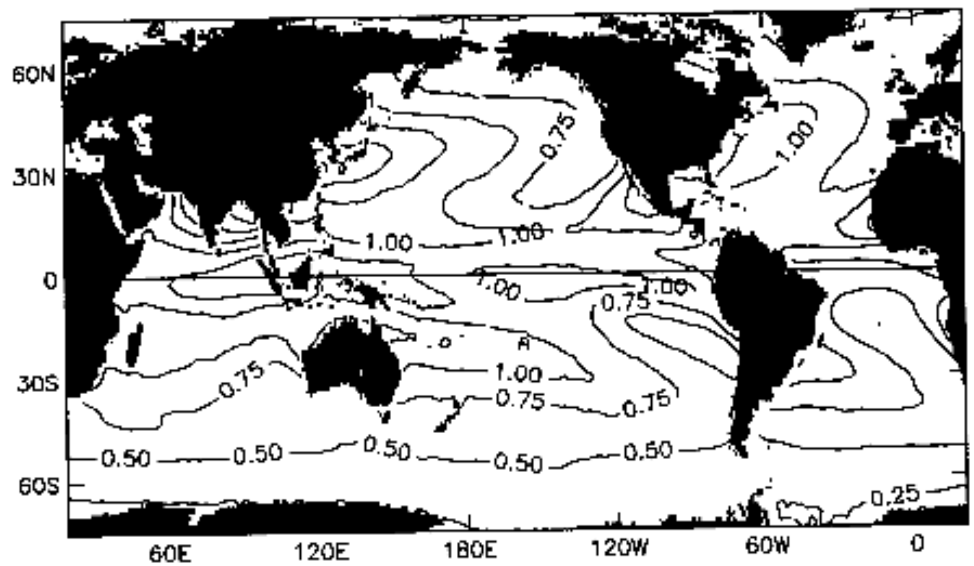
Wet Tropospheric Correction

- Caused by water vapour in the atmosphere
- Obtained by microwave radiometer on satellite
  - two frequency on ERS-1/2 and Envisat
  - three frequency on T/P and Jason-1/2
- Or from weather forecasting models (ECMWF)
- Or (new!) from GPS measurements
- This is a difficult correction due to the high temporal and spatial variability of water vapour
- Average value 150 mm, s.d. ~50 mm

Tropospheric water vapour from SSM/I Mean (g/m^2)



Standard deviation

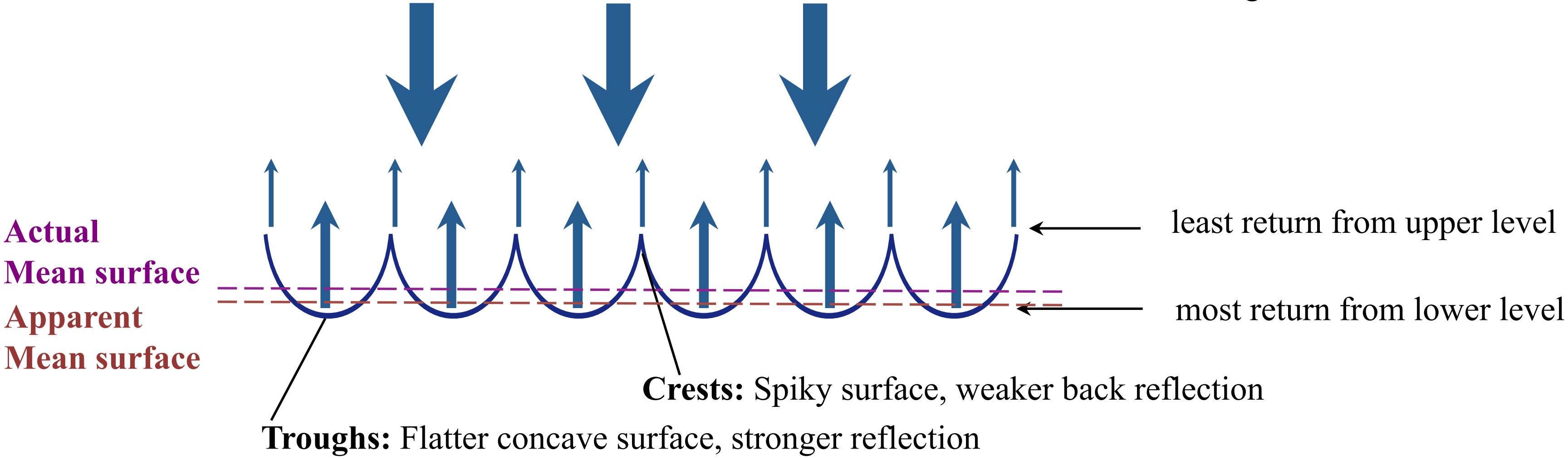


Atmospheric corrections - summary

- Ionospheric correction: 2-20 cm [+/- 3 cm]
  - Caused by presence of free electrons in the ionosphere
  - Use model or measure using dual frequency altimeter
- Dry tropospheric correction: 2.3 m [+/- 1-2 cm]
  - Caused by oxygen molecules
  - Model the correction accurately using surface atmospheric pressure
- Wet tropospheric correction: 5-35 cm [+/- 3-6 cm]
  - Caused by clouds and rain (variable)
  - Measure H_2O with microwave radiometer
  - Or use weather model predictions

Sea State Bias Corrections

- Tracker bias
  - Problem with "tracking" the pulse when the sea is rough
- Electromagnetic Bias
  - Radar return from the troughs is stronger than from the crests
- First approx: empirical correction based on H_s (~5%)



State of the art in sea state bias

- There is as yet no **theoretical method** for estimating the sea state bias.
- We are therefore forced to use **empirical methods**
- We find the function of H_s (and U_{10} - that is wind) that minimises the altimeter crossover differences or the differences w.r.t in situ observation (from wave buoys)

Parametric vs non-parametric

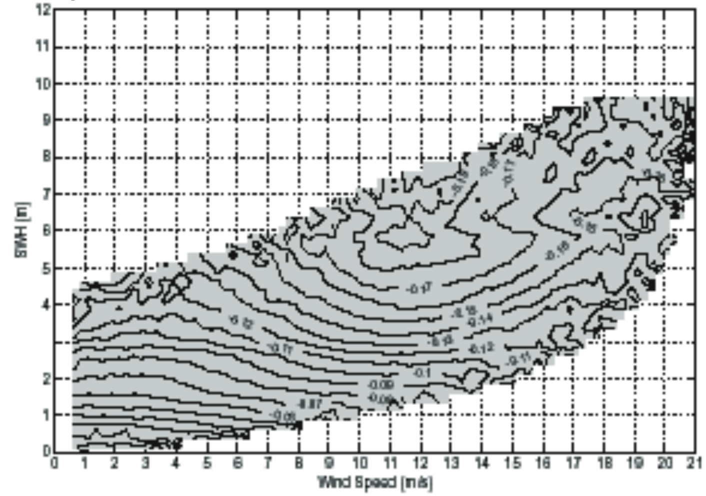
- With parametric methods we have a specified function for the SSB and estimate the parameters of this function, e.g. the BM4 model used for TOPEX

  ➔Then we use the fitted function

- With non-parametric methods we compile statistics and smooth the resulting 2-d histogram

  ➔Then we use the histogram as look-up table

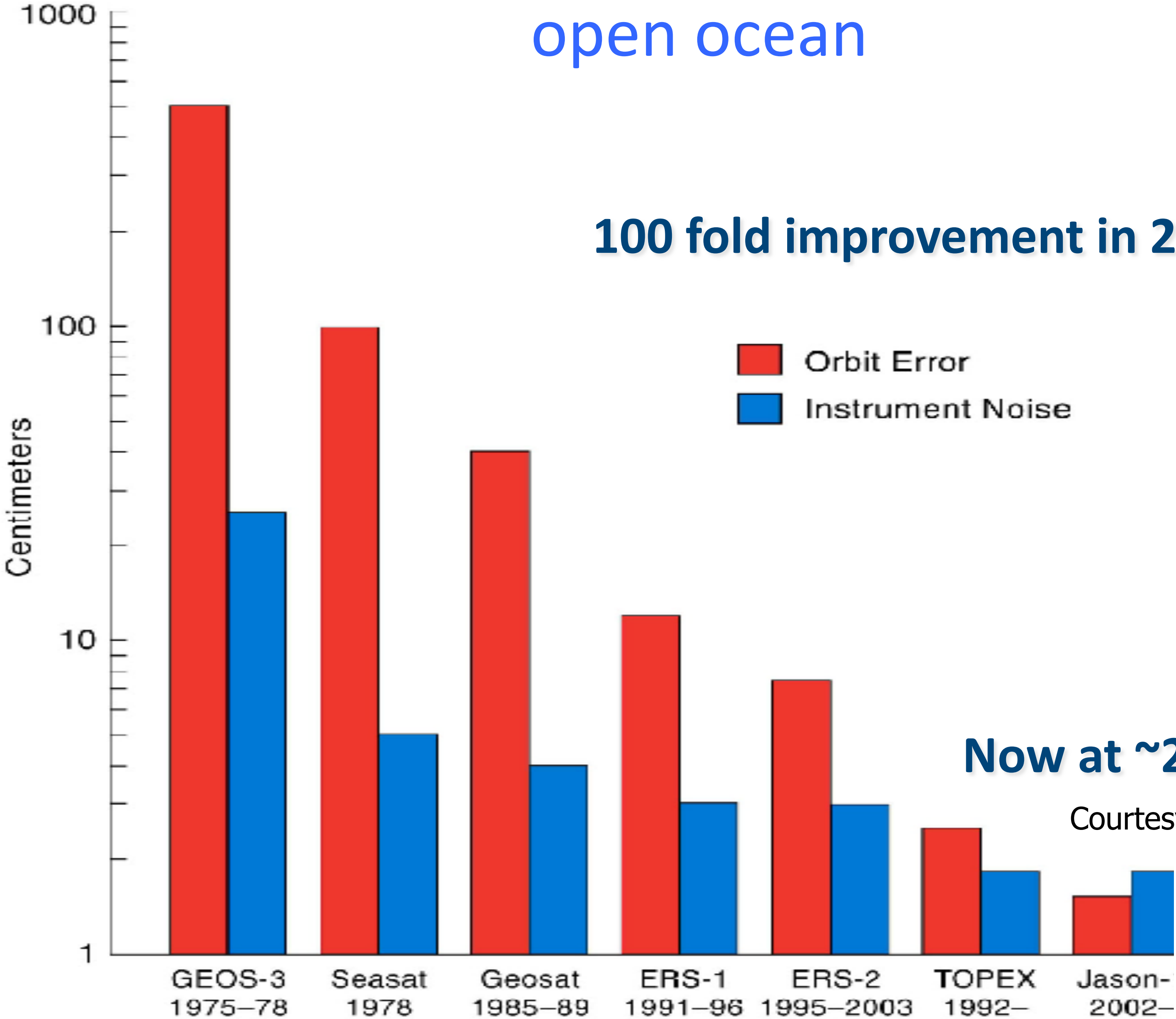
An example non-parametric SSB



Example of TOPEX Error Budget for 1-Hz measurement (from Chelton et al 2001)

Source	Error
Instrument Noise	1.7cm
Ionosphere	0.5cm
EM Bias	2.0cm
Skewness	1.2cm
Dry Troposphere	0.7cm
Wet Troposphere	1.1cm
Orbit	2.5cm
Total	**4.1cm**

History of satellite altimetry accuracy in open ocean

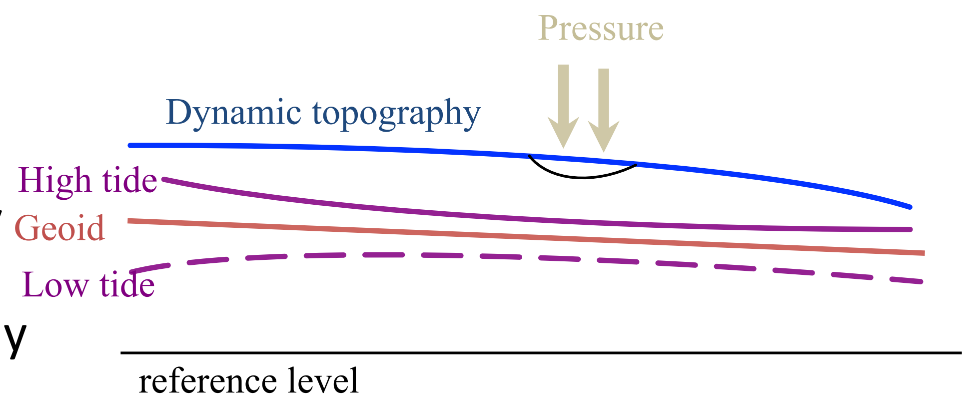


100 fold improvement in 25 years !

Now at ~2 cm level!!

Courtesy of Lee-Lueng Fu., NASA

Interpreting Ocean Surface Topography



Geoid (~100 m)

- Time invariant
- Not known to sufficient accuracy at short length-scales
- Must be measured independently (eg gravity survey)

Tides (~1-2 m)

- Apply a tidal prediction
- New tidal models derived from altimetry
- Choose orbit to avoid tidal aliasing

Atmospheric pressure (~0.5 m)

- Apply inverse barometer correction (1mbar ~ 1 cm)

Dynamic topography (~1 m)

- The intended measurement

Some of these we want to correct for – or not, depending on the application!!!

Atmospheric pressure (the "Inverse Barometer" Correction)

- When air pressure changes the ocean acts like a barometer (in reverse). High air pressure depresses the sea surface, low air pressure raises it.
- 1 mbar (hPa) change in air pressure is approximately equal to a 1cm change in the sea surface
- Good approximation in mid and high latitudes but not in Tropics
- Also, not very accurate in enclosed basins (like the Mediterranean)

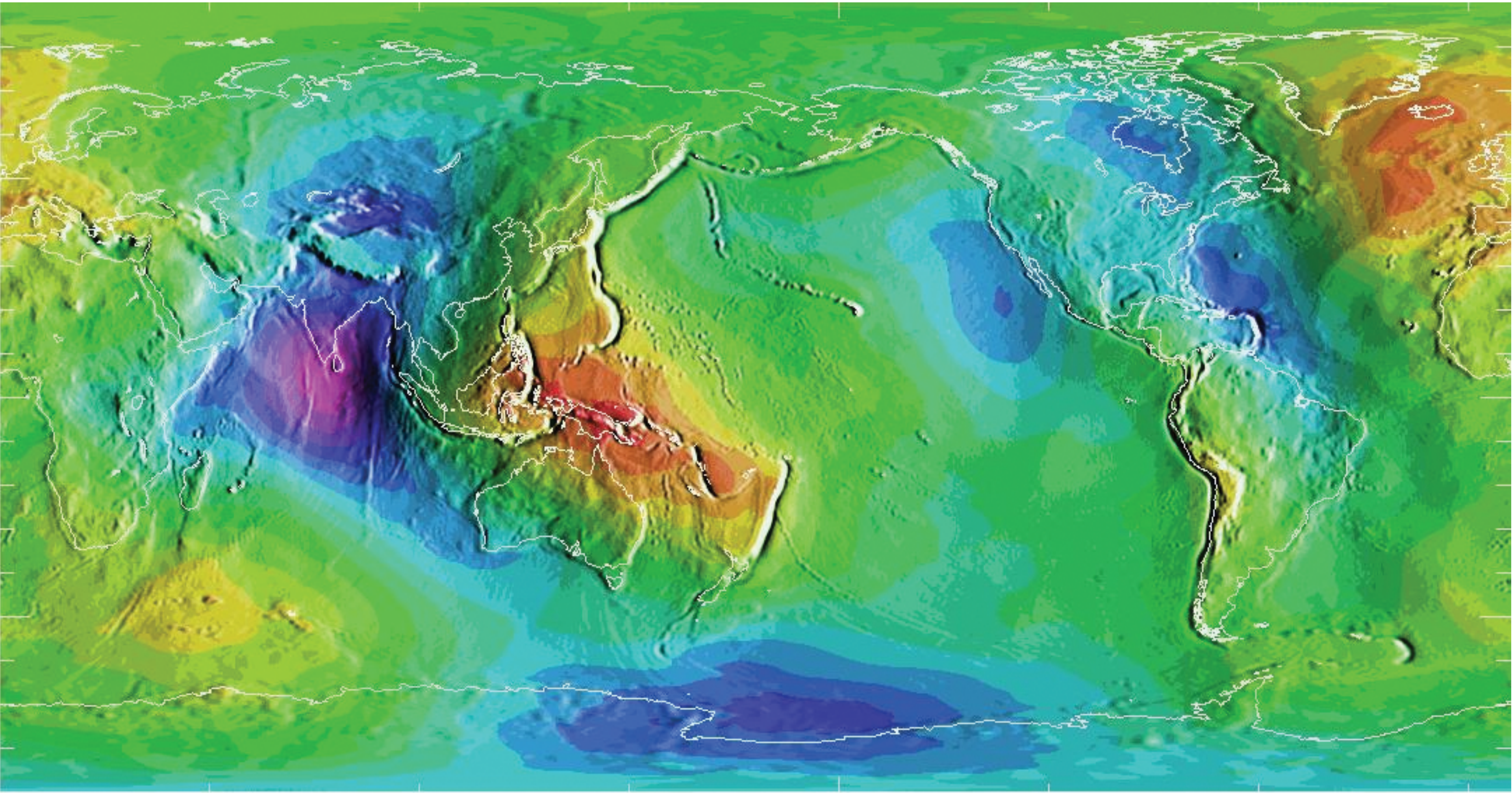
Barotropic Models

- An alternative to an IB correction is to use a correction from a barotropic model of the ocean
- Barotropic (non-depth dependent) motions move very quickly and can be aliased by the altimeter ground tracks
- Barotropic models are quick to run but have proved hard to validate

The problem of the Geoid

- The geoid is the surface of equal gravity potential on the Earth's surface (the shape of the Earth)
- The ellipsoid is an approximation to the shape of the Earth
- We know the ellipsoid - we do not know the geoid with the accuracy we would like!!!

The Geoid



Scale: magenta (-107 m) to red (84.5 m)

The Geoid

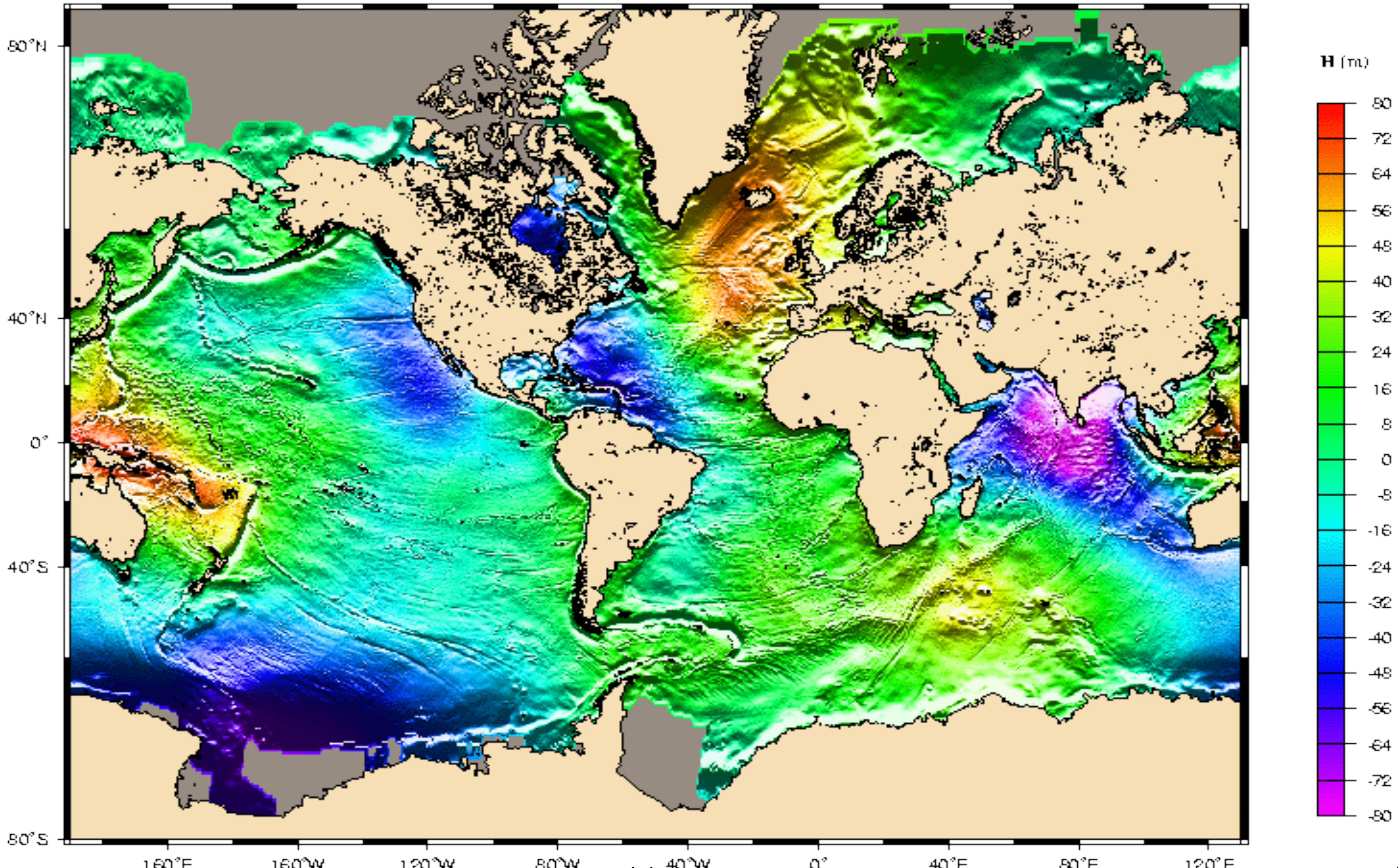
- The geoid is usually expressed in terms of spherical harmonics (sine curves on the sphere). These have degree and order
  - Degree and order 360 is a resolution of approx. 1°
- Sea surface pressure and hence geostrophic currents are in terms of sea surface height relative to the geoid
- We measure sea surface height (and hence slopes) relative to the ellipsoid.

Removing the Geoid

- The geoid is time invariant (approximately)
- So if we subtract a mean sea surface we will remove the geoid
- But we lose ...

... the mean circulation

Mean sea surface



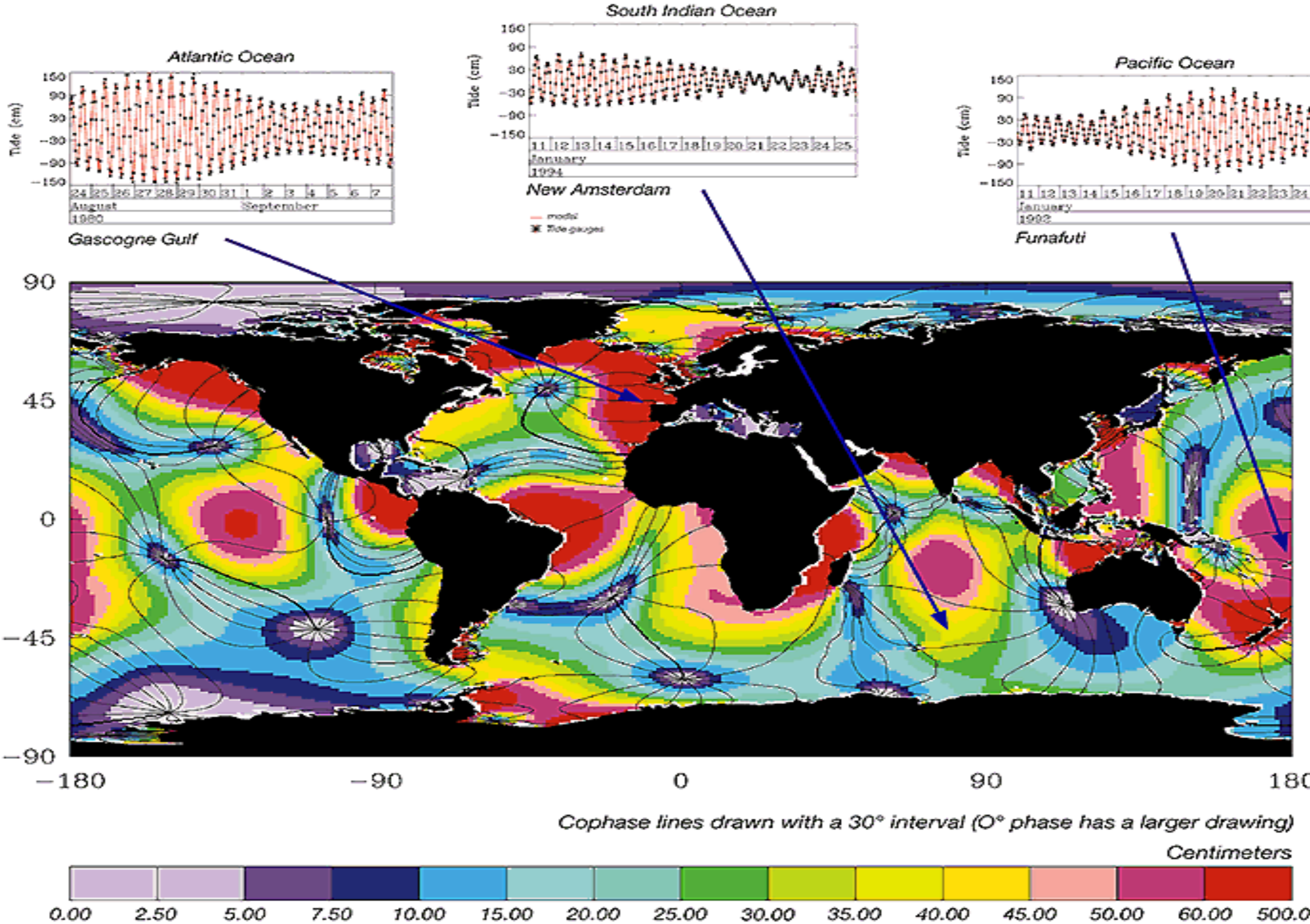
SSH residuals

- The sea surface height residual (or Sea Surface Height Anomaly - SSHA) is what remains after removing the mean in each location (Mean Sea Surface)
- Any constant dynamic topography (from steady currents) will have been removed!
- Contains only the **time-varying** dynamic topography
- May still contain time varying errors
  - Un-removed tidal or barometric signal
  - Orbit error
- With new independent accurate geoid models (from GRACE and the new ESA GOCE mission) we are starting to be able to subtract the geoid and work with **absolute dynamic topography** (much better for oceanographers!)

Tides (1)

- If we are going to use altimetry for studies of ocean currents we need to remove the effect of the tides
- Alternatively we could use the altimeter to estimate the tides - tidal models have improved dramatically since the advent of altimetry!
- In general we use global tidal models to make predictions and subtract them from the signal

The up and down of the ocean tides



Source : IMG/LEGI, Grenoble 1995

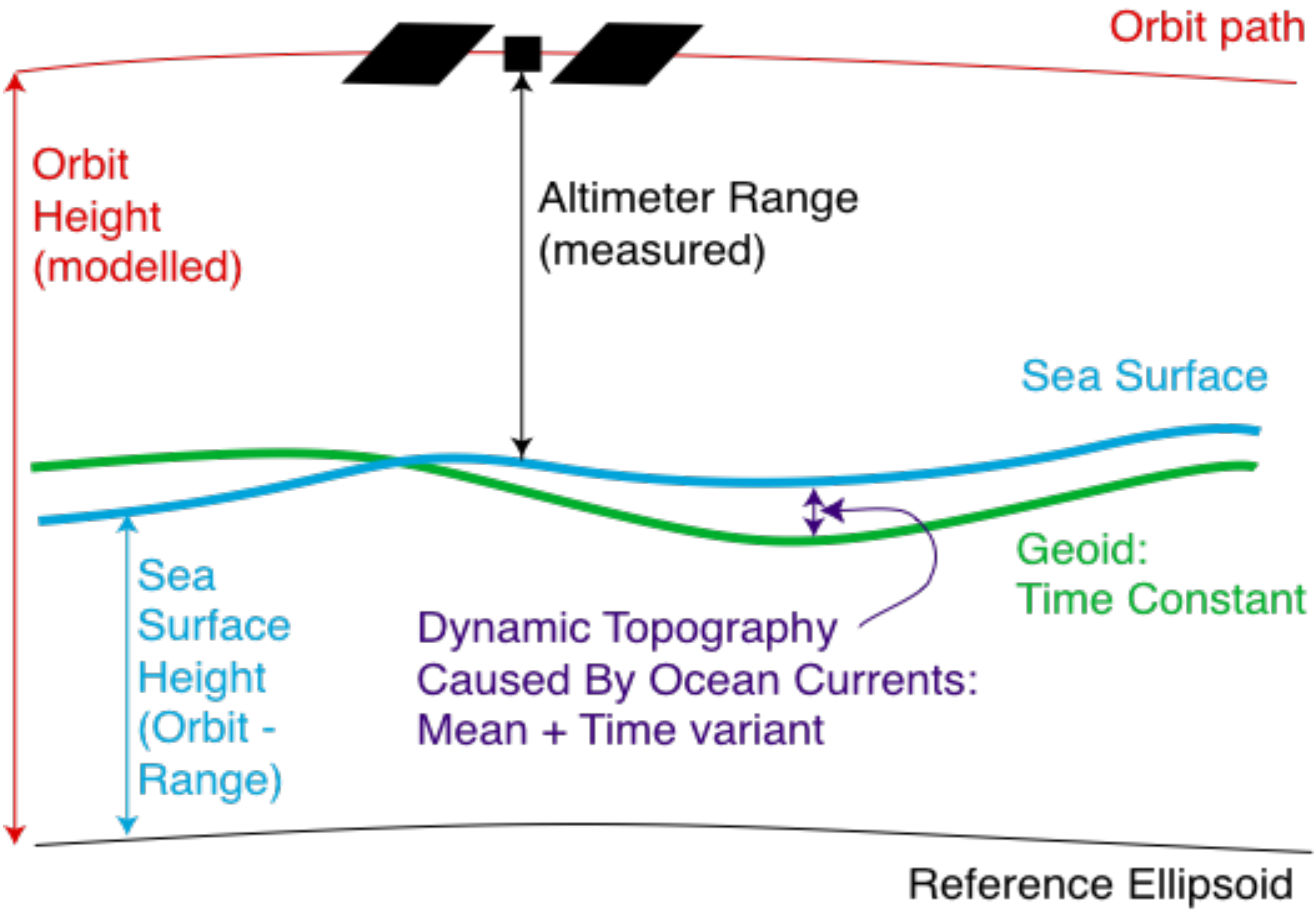
Tides (2)

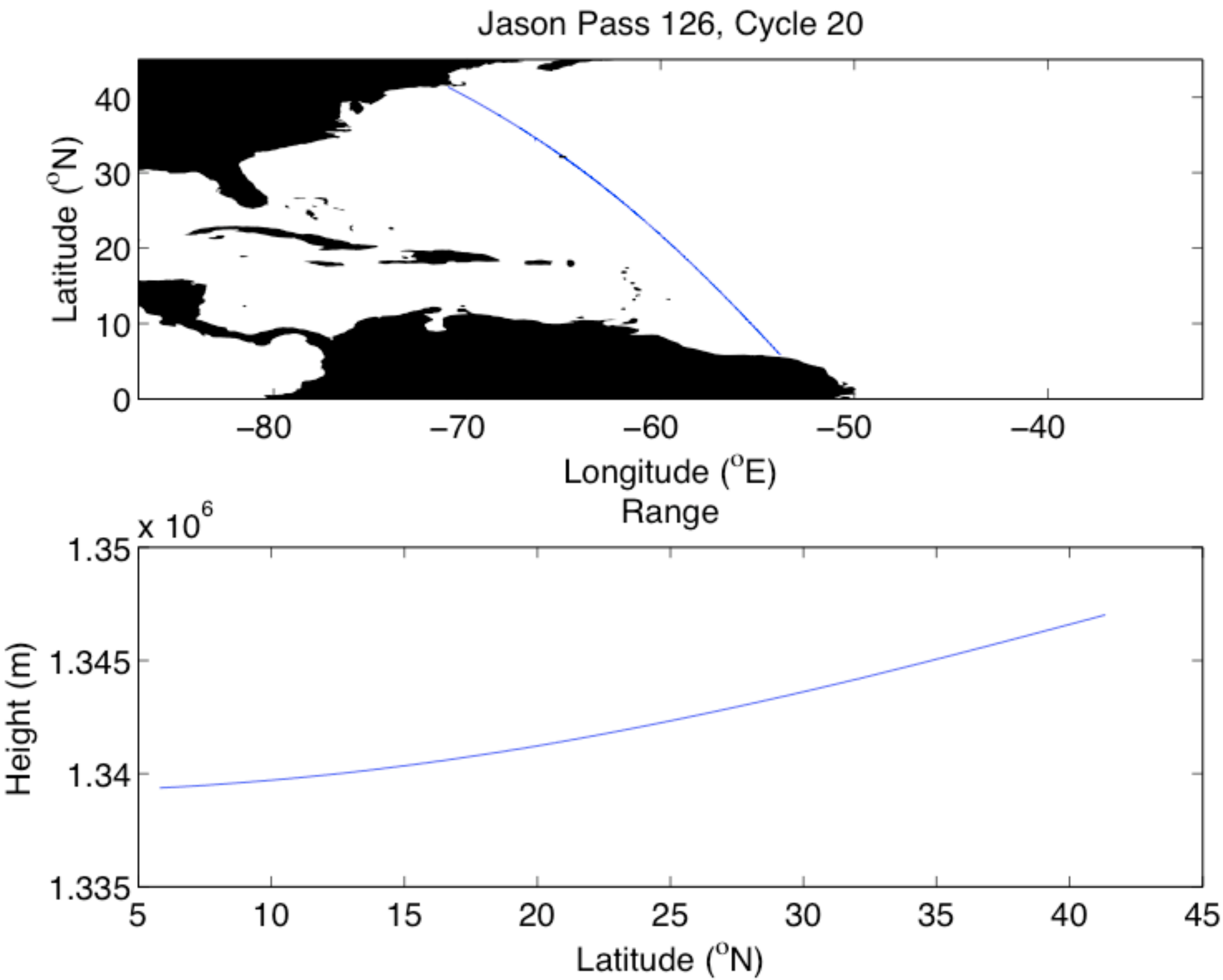
- As well as the ocean tide we have to consider
  - the loading tide (the effect of the weight of water). This is sometimes included in the ocean tide
  - the solid earth tide
  - the polar tide
- On continental shelves the global models are not very accurate and local models are needed
- Any residual tidal error is going to be aliased by the sampling pattern of the altimeter

Aliasing Periods

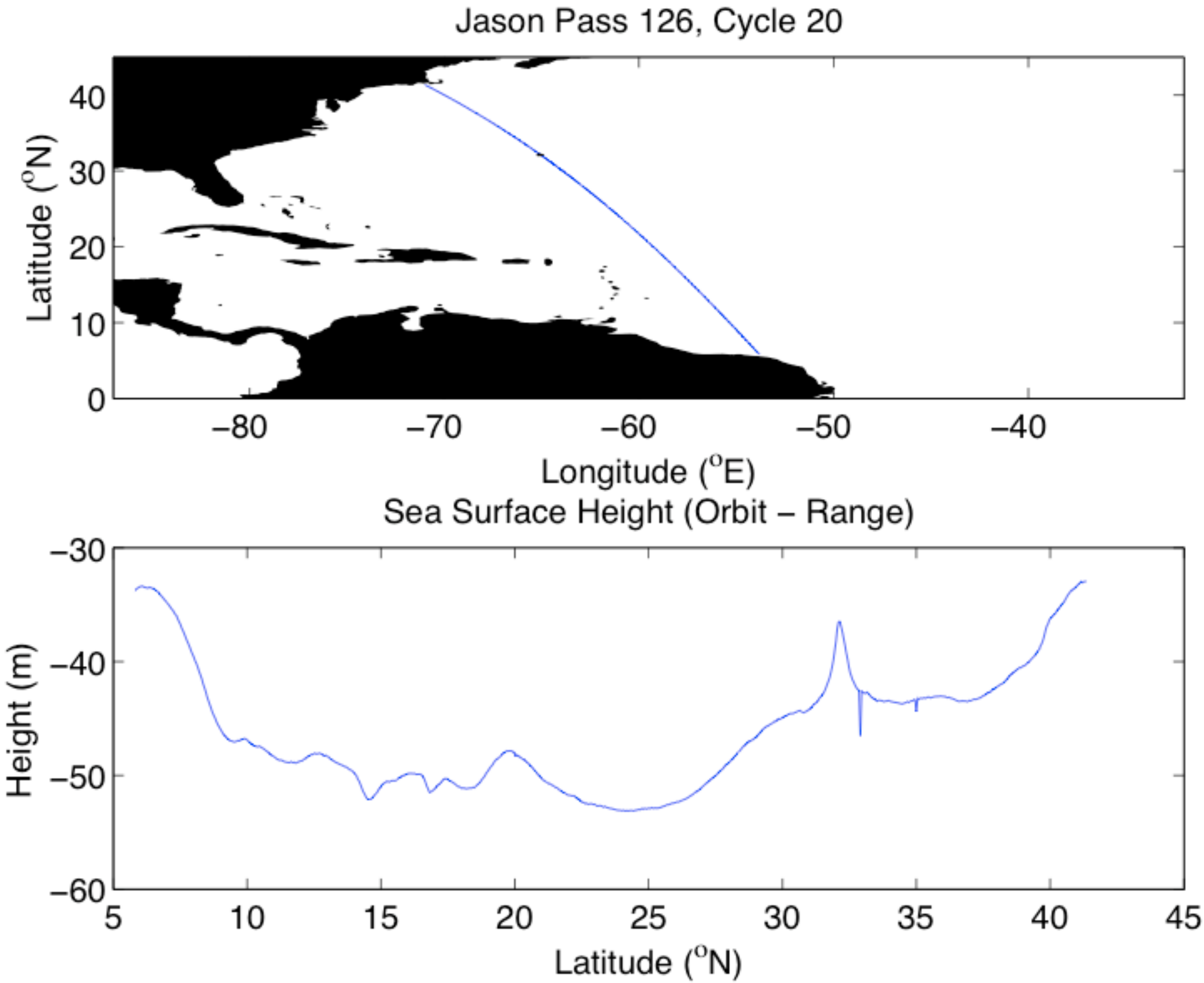
		T/P		ERS	
Tide	Period (h)	Alias (days)	wave length (°)	Alias (days)	wave length (°)
M2	12.42	62	9E	95	9E
S2	12	59	180W	0	∞
N2	12.65	50	9W	97	4W
K1	23.93	173	360W	365	360E
O1	25.82	46	9.23E	75	9E
P1	24.07	89	360W	365	360W

Example over a pass

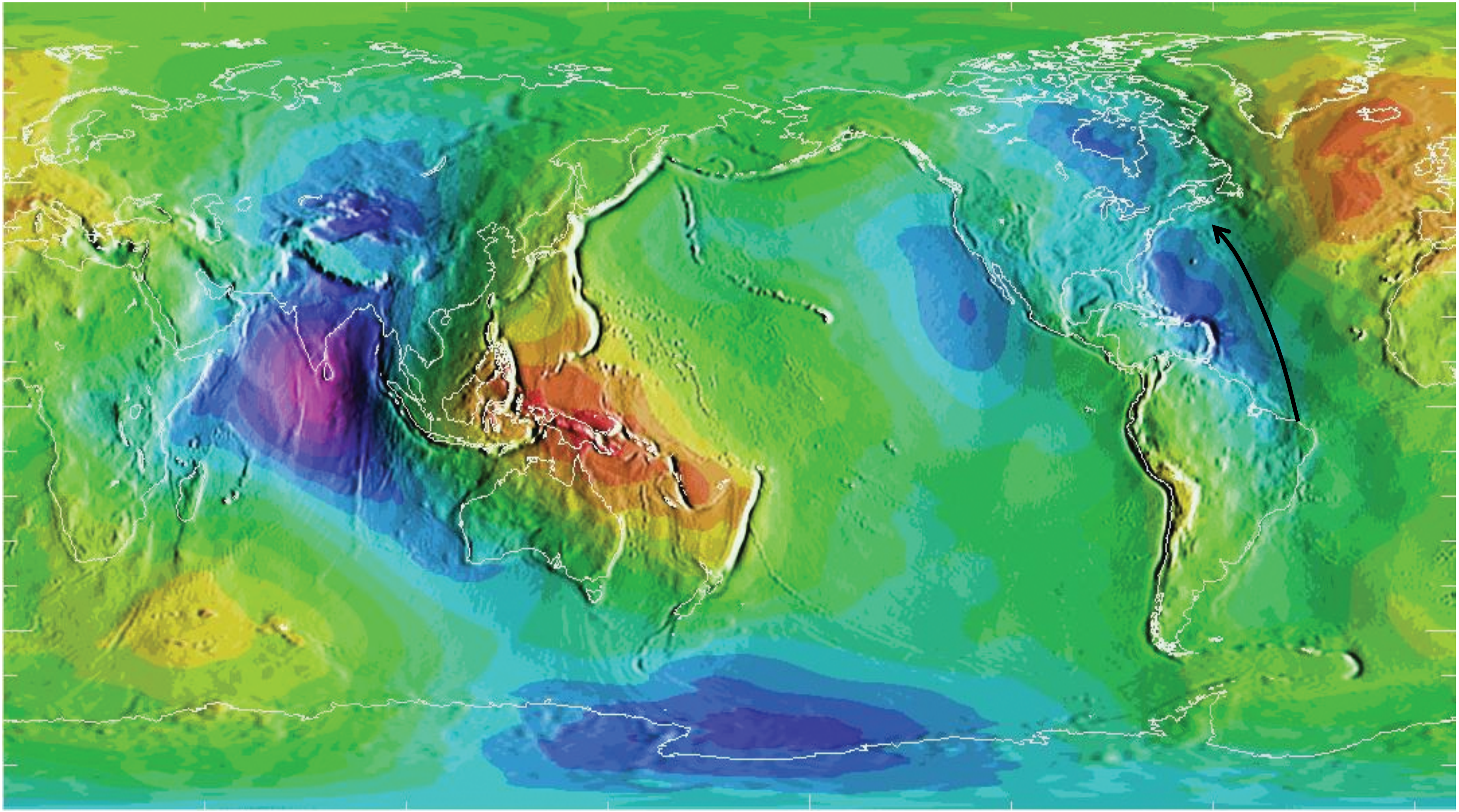




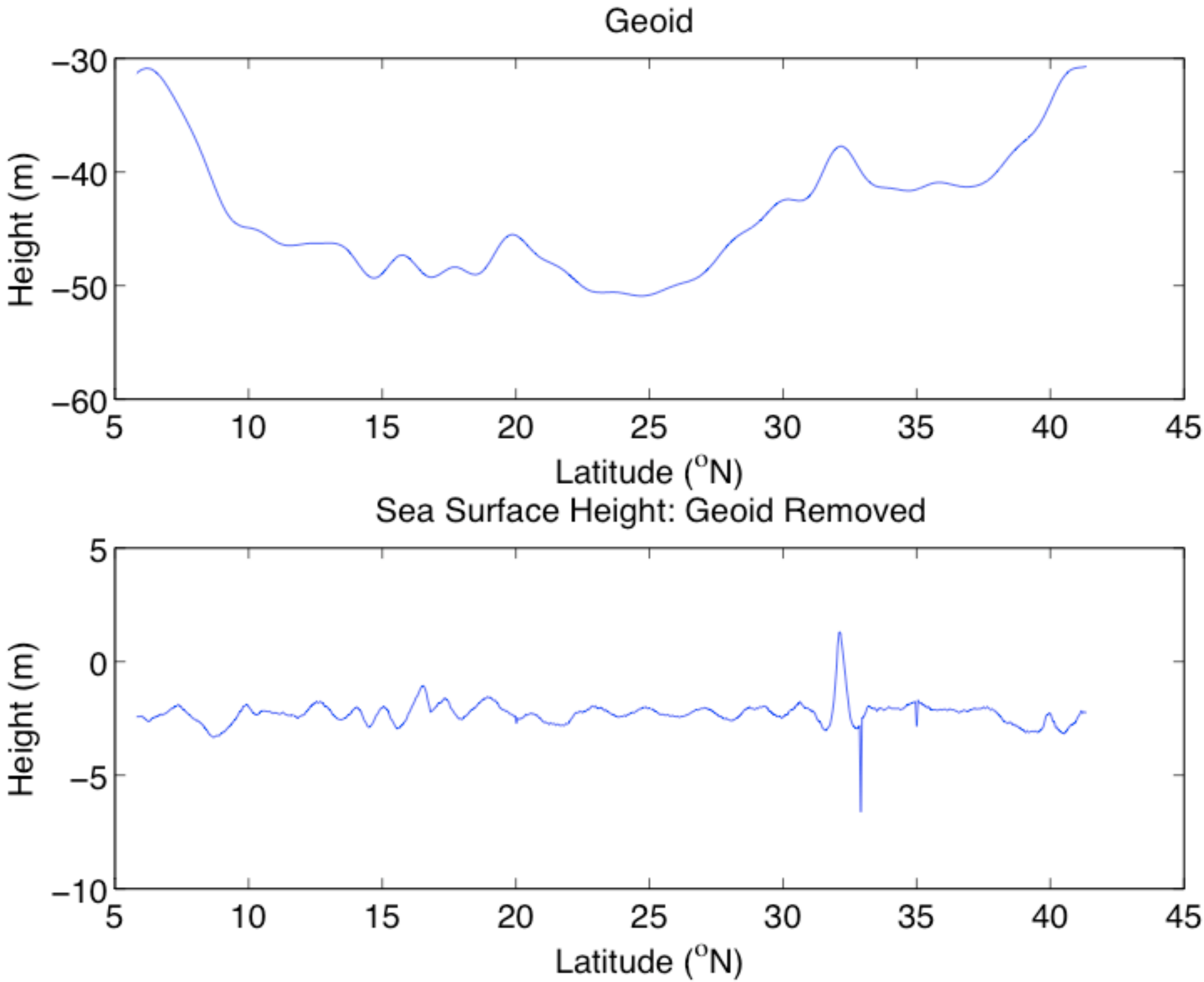
Jason Pass 126, Cycle 20
Latitude (°N)
40
30
20
10
0
−80
−70
−60
−50
−40
Longitude (°E)
Range
x 10^6
1.35
1.345
1.34
1.335
Height (m)
5
10
15
20
25
30
35
40
45
Latitude (°N)

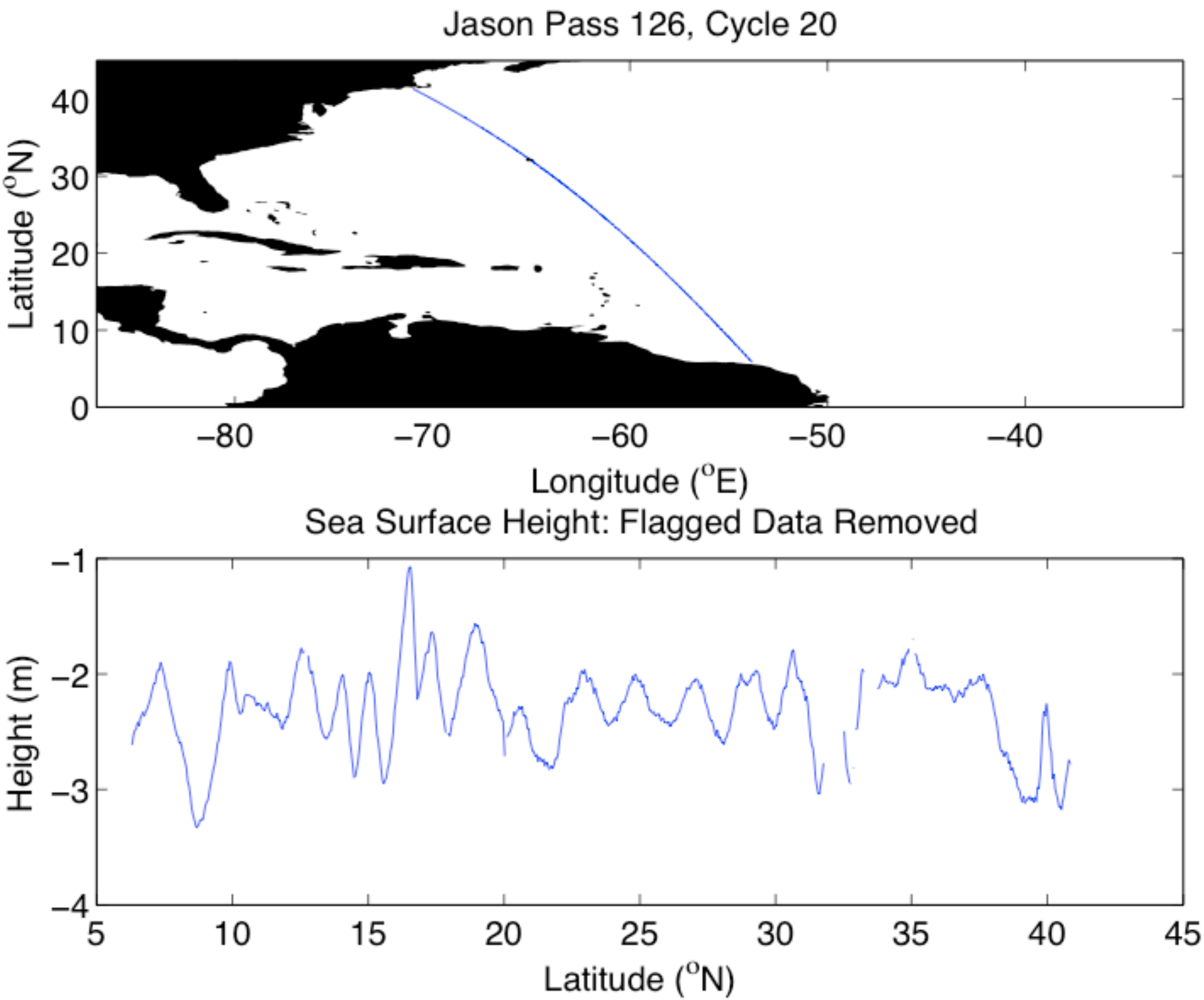

Jason Pass 126, Cycle 20
Latitude (°N)
40
30
20
10
0
−80
−70
−60
−50
−40
Longitude (°E)
Sea Surface Height (Orbit − Range)
Height (m)
−30
−40
−50
−60
5
10
15
20
25
30
35
40
45
Latitude (°N)

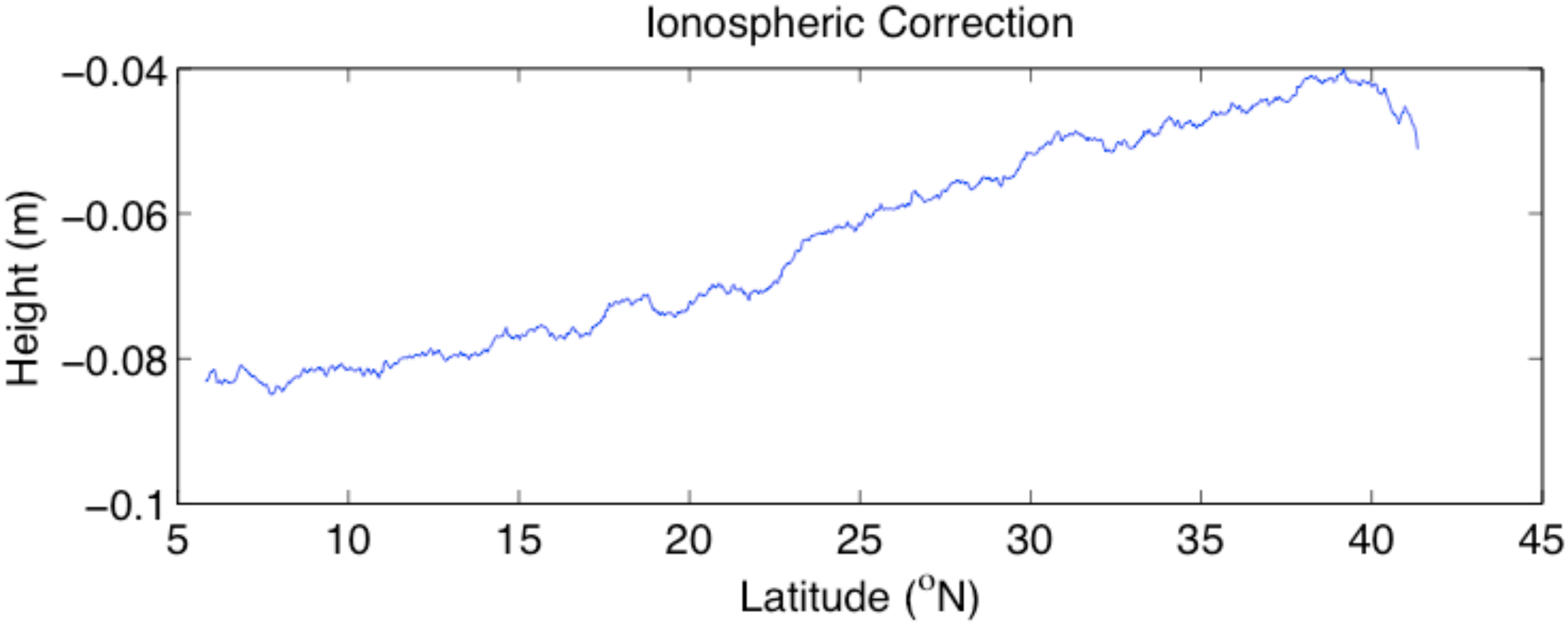
The Geoid



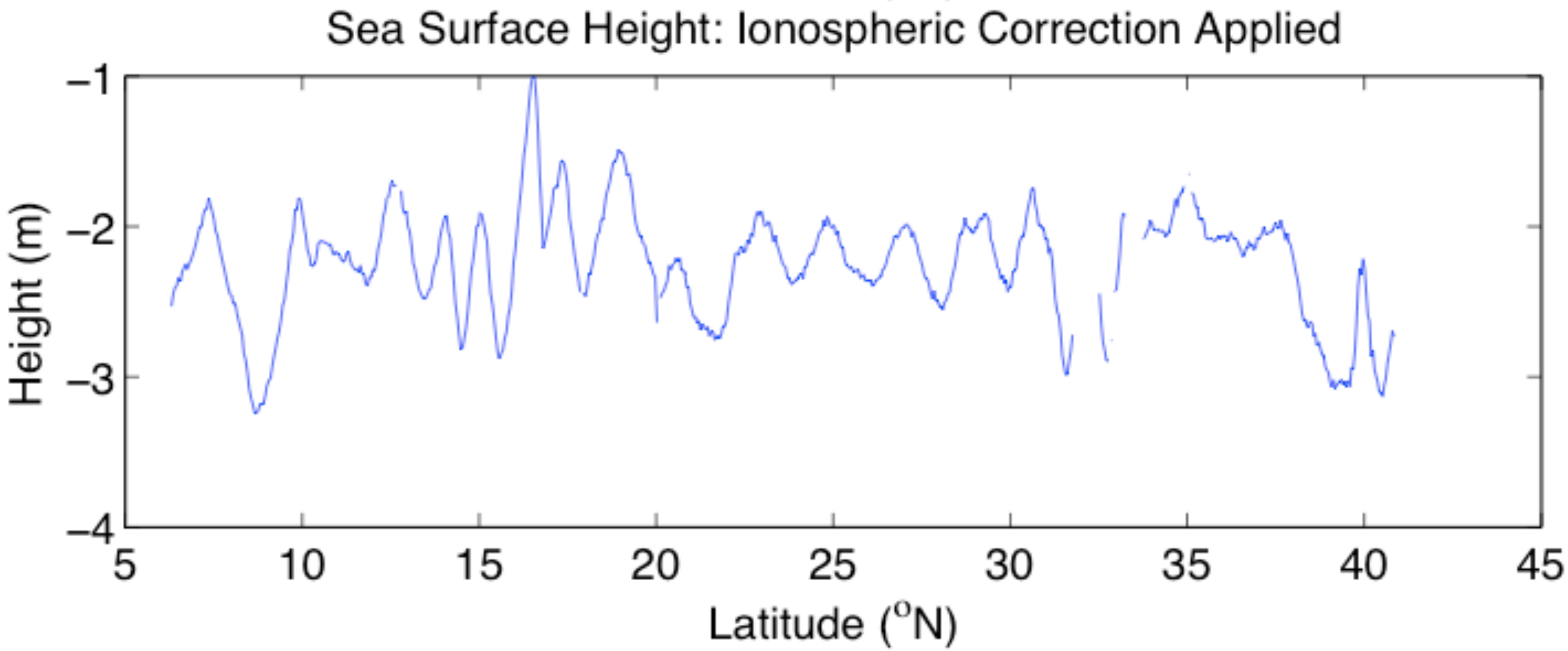
Scale: magenta (-107m) to red (84.5m)


Geoid
Height (m)
Latitude (°N)
Sea Surface Height: Geoid Removed
Height (m)
Latitude (°N)

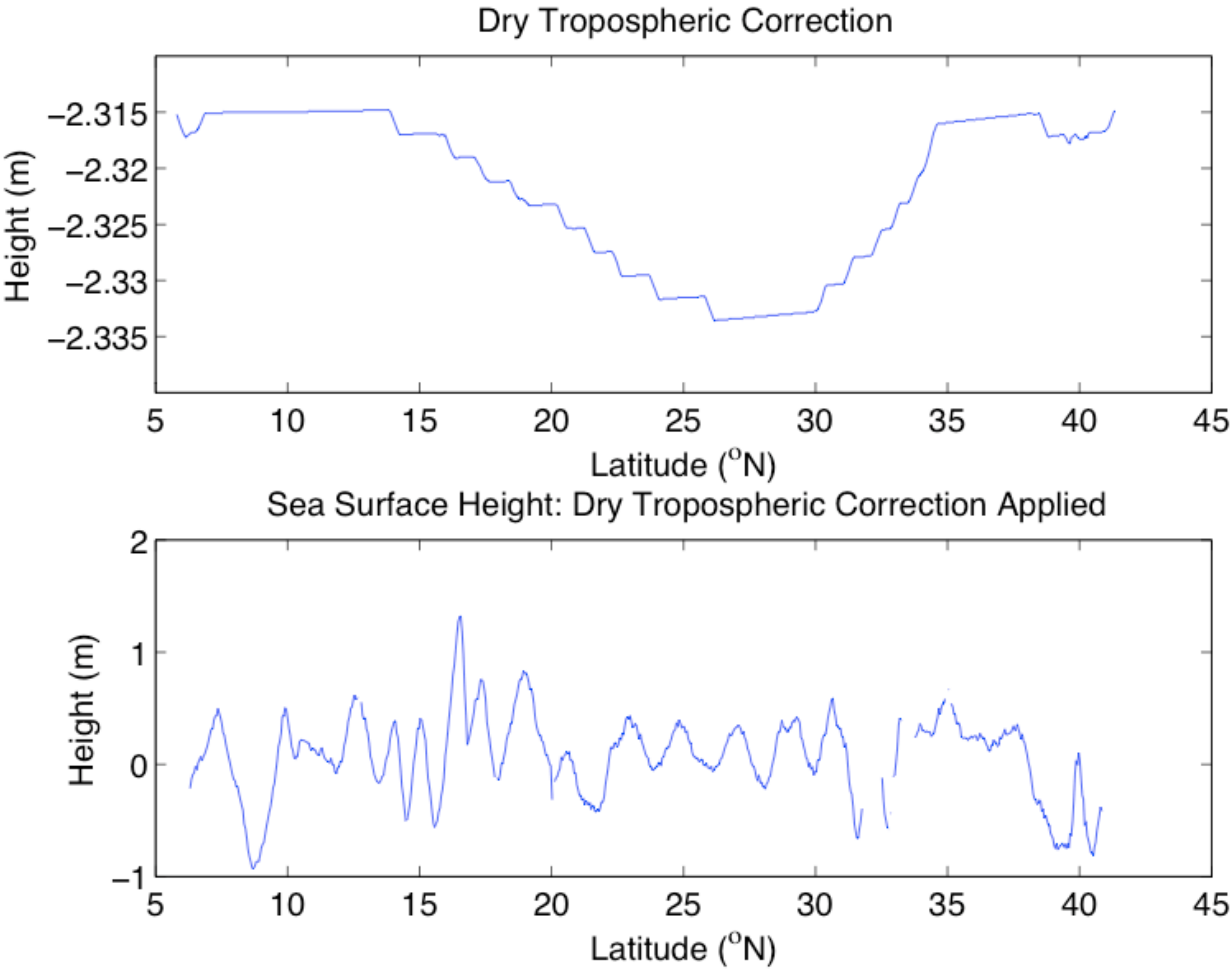

Jason Pass 126, Cycle 20
Latitude (oN)
40
30
20
10
0
−80
−70
−60
−50
−40
Longitude (oE)
Sea Surface Height: Flagged Data Removed
Height (m)
−1
−2
−3
−4
5
10
15
20
25
30
35
40
45
Latitude (oN)

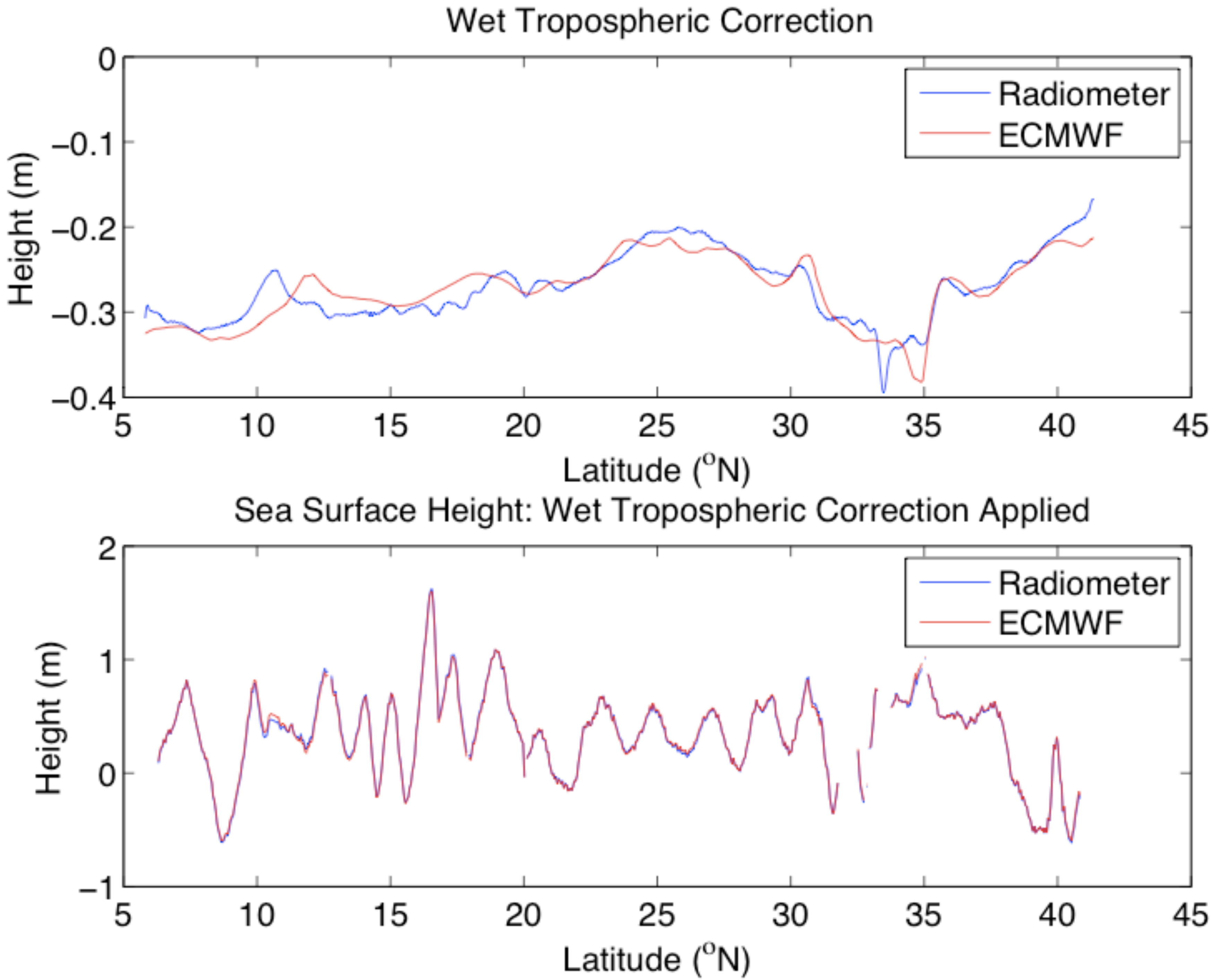


Ionospheric Correction
−0.04
−0.06
−0.08
−0.1
Height (m)
5
10
15
20
25
30
35
40
45
Latitude (°N)

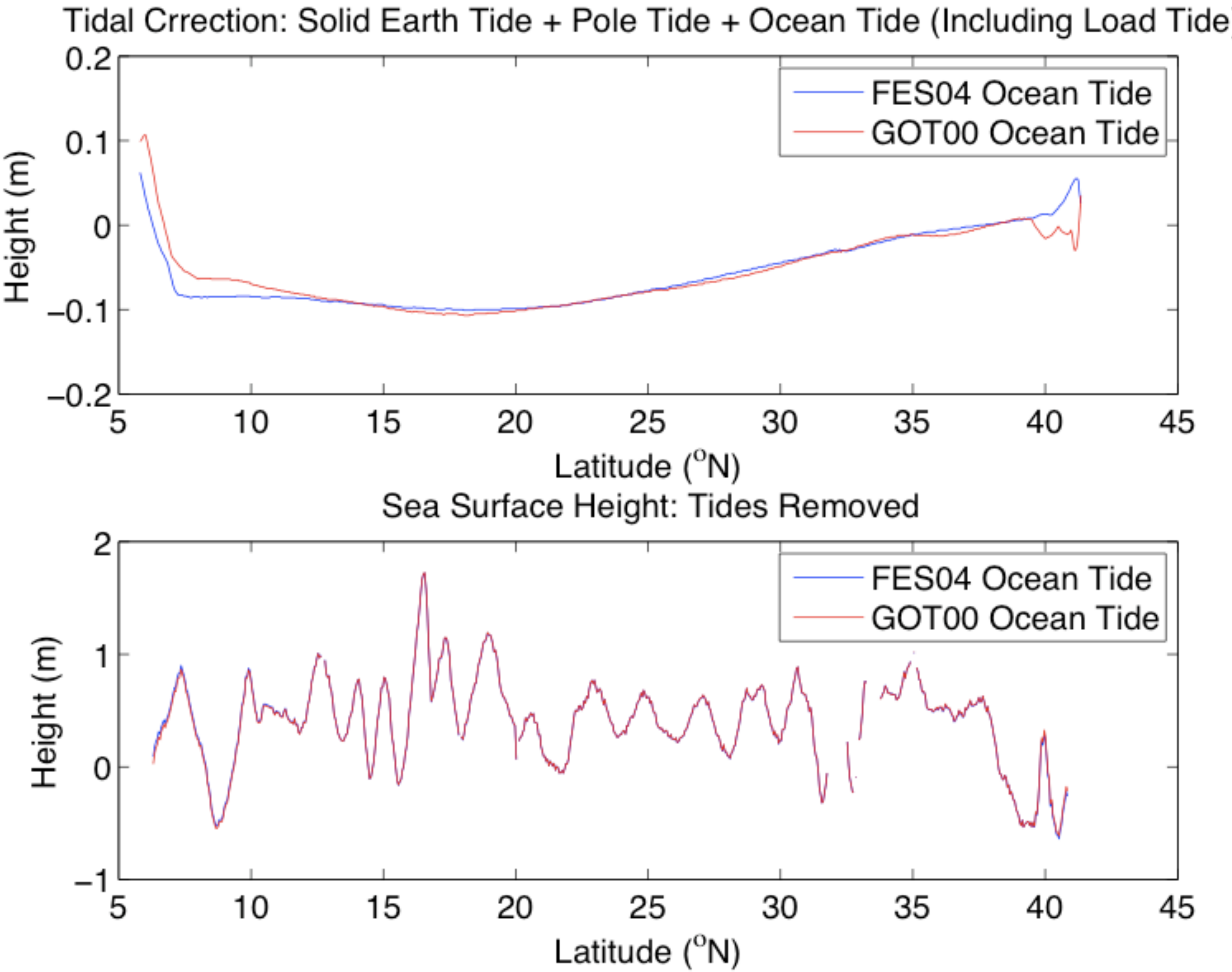


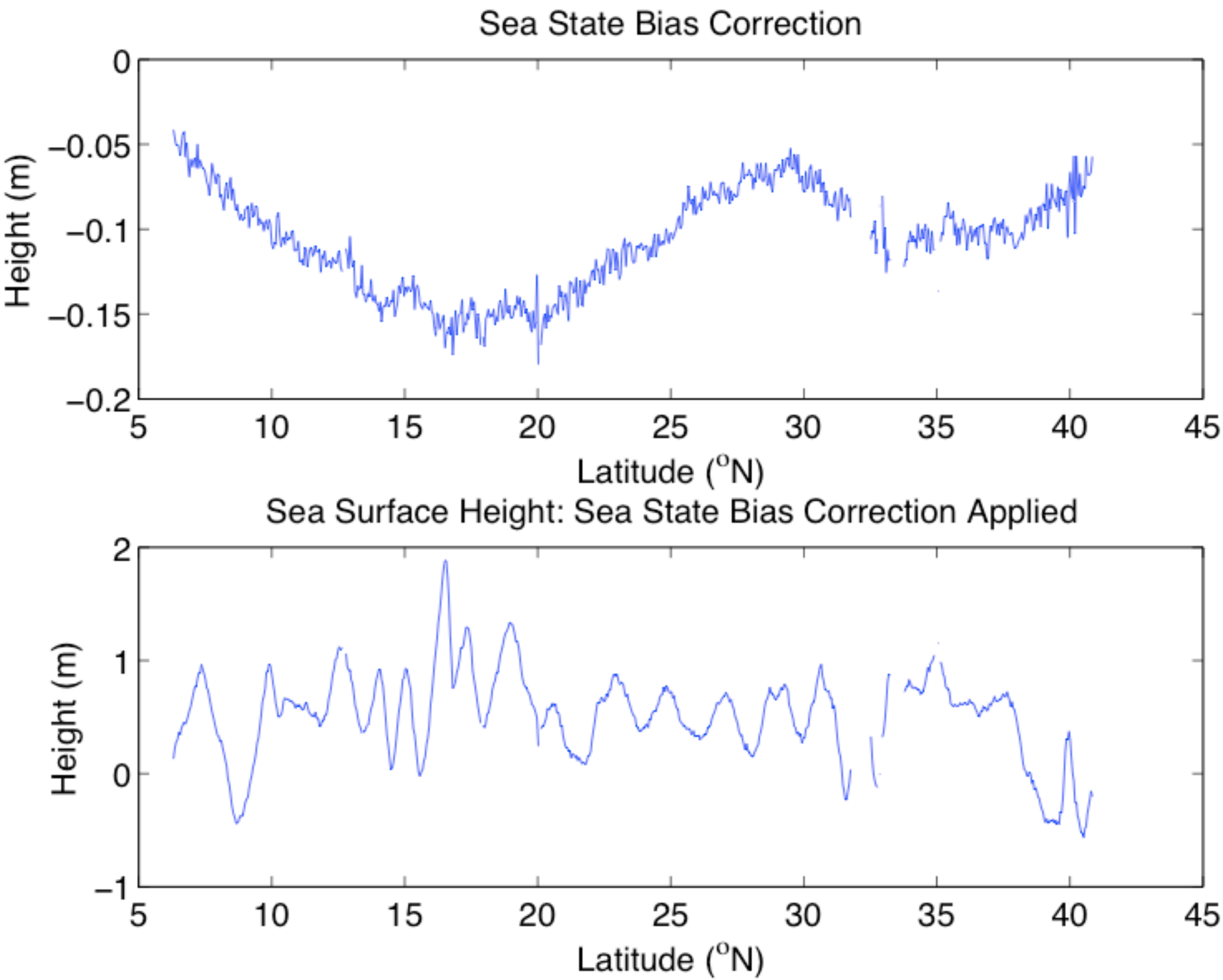
Sea Surface Height: Ionospheric Correction Applied
−1
−2
−3
−4
Height (m)
5
10
15
20
25
30
35
40
45
Latitude (°N)

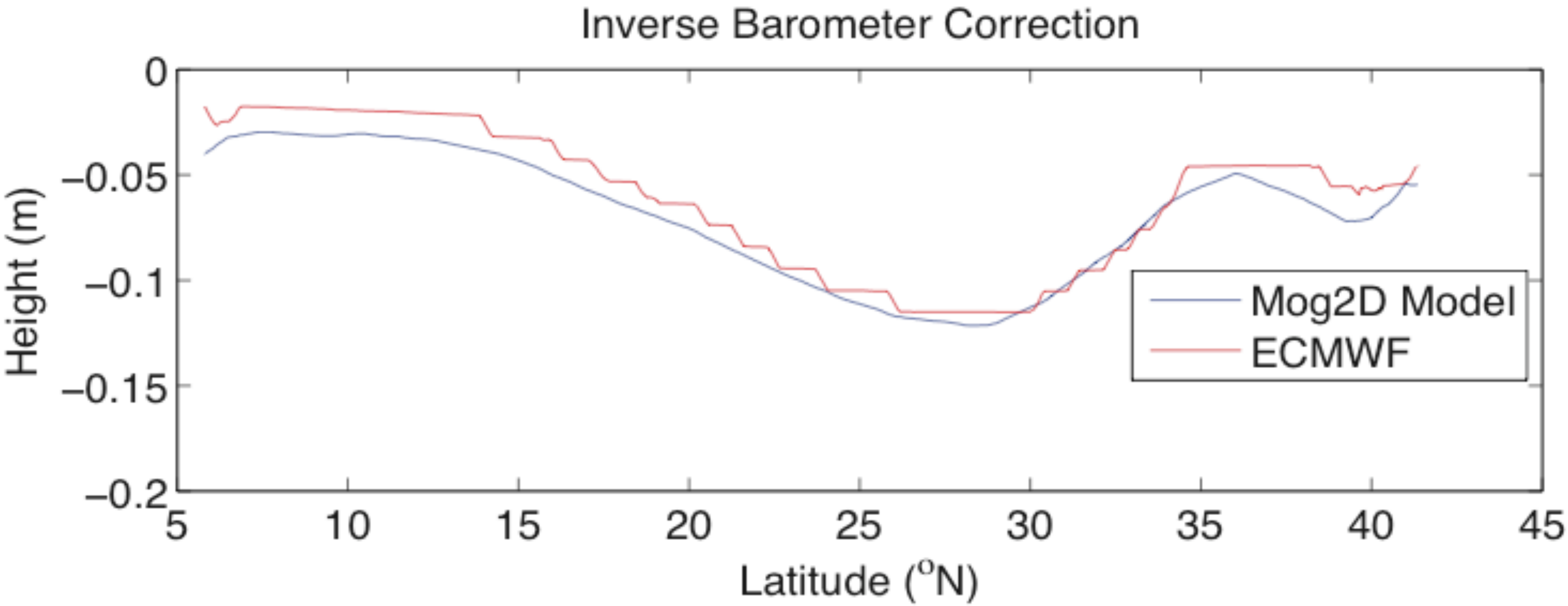

Dry Tropospheric Correction
Height (m)
−2.315
−2.32
−2.325
−2.33
−2.335
5
10
15
20
25
30
35
40
45
Latitude (°N)
Sea Surface Height: Dry Tropospheric Correction Applied
Height (m)
2
1
0
−1
5
10
15
20
25
30
35
40
45
Latitude (°N)

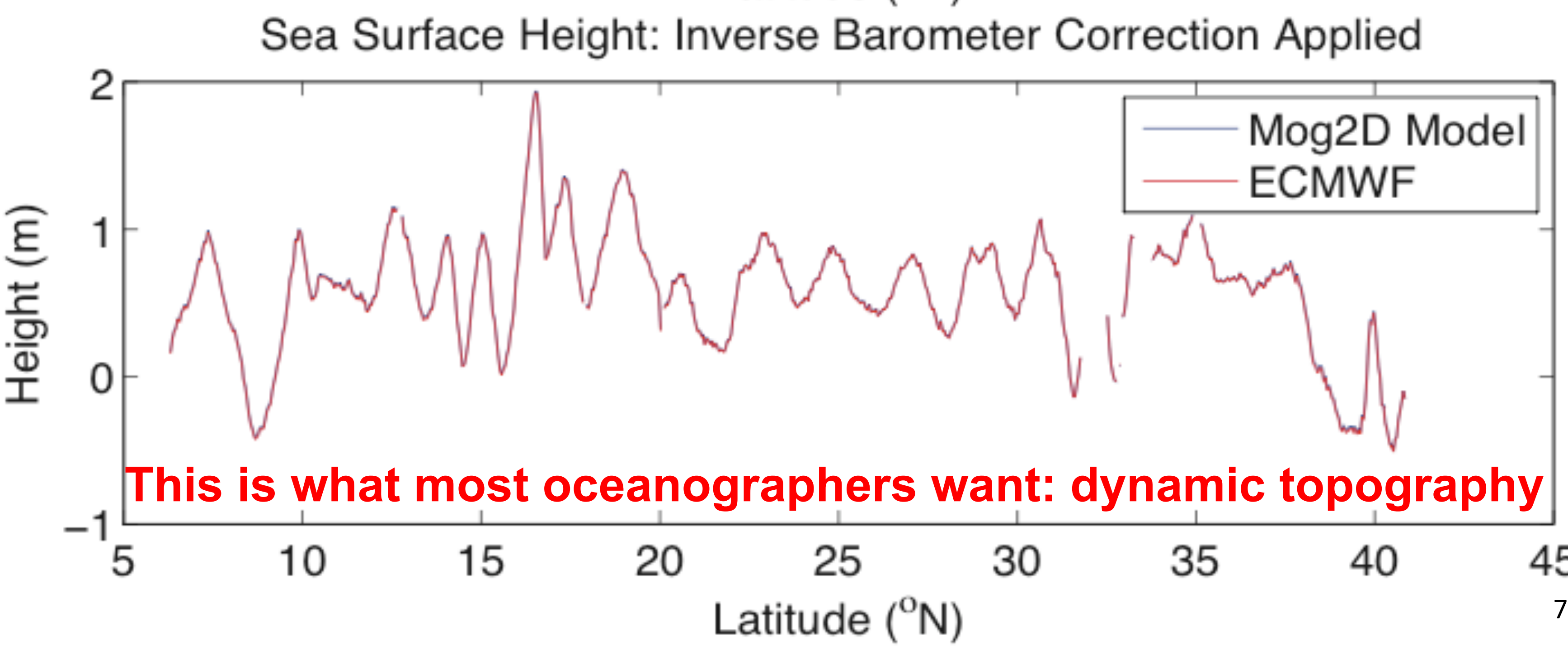


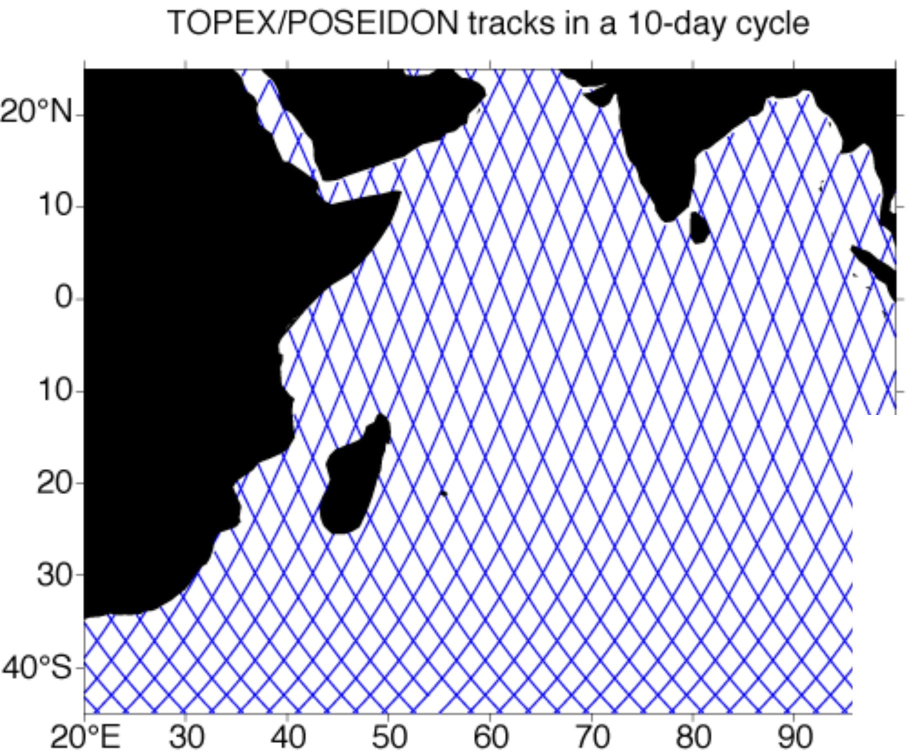
Wet Tropospheric Correction
Sea Surface Height: Wet Tropospheric Correction Applied
Radiometer
ECMWF
Height (m)
Latitude (°N)


Tidal Crrection: Solid Earth Tide + Pole Tide + Ocean Tide (Including Load Tide)
FES04 Ocean Tide
GOT00 Ocean Tide
Height (m)
0.2
0.1
0
−0.1
−0.2
5
10
15
20
25
30
35
40
45
Latitude (°N)
Sea Surface Height: Tides Removed
FES04 Ocean Tide
GOT00 Ocean Tide
Height (m)
2
1
0
−1
5
10
15
20
25
30
35
40
45
Latitude (°N)

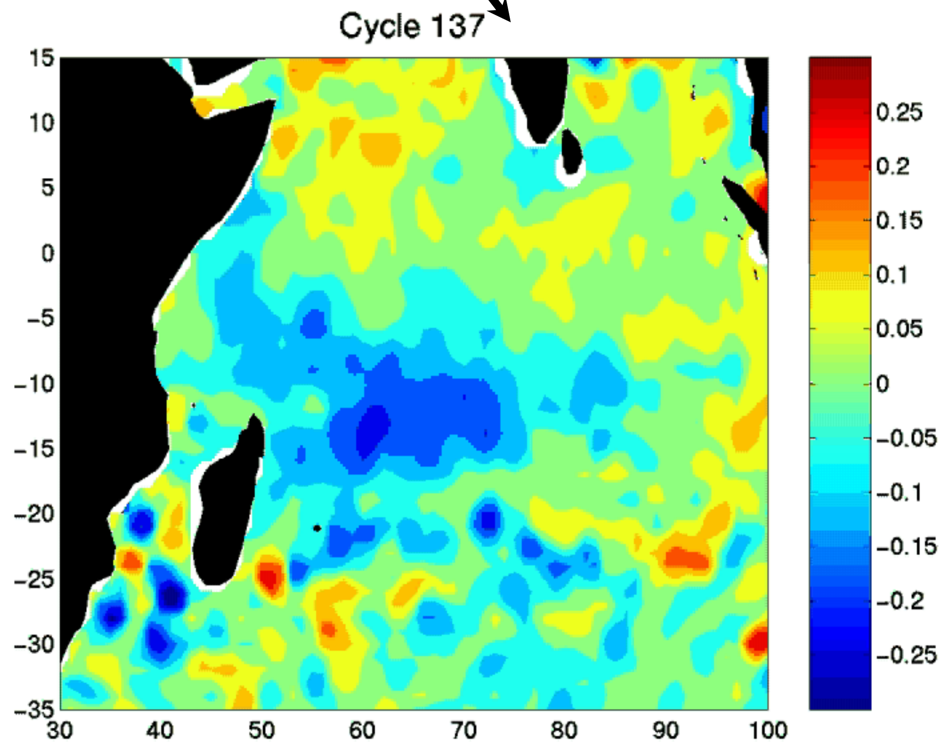

Sea State Bias Correction
Height (m)
0
−0.05
−0.1
−0.15
−0.2
5
10
15
20
25
30
35
40
45
Latitude (°N)
Sea Surface Height: Sea State Bias Correction Applied
Height (m)
2
1
0
−1
5
10
15
20
25
30
35
40
45
Latitude (°N)


Inverse Barometer Correction
Height (m)
Latitude (°N)
Mog2D Model
ECMWF
0
−0.05
−0.1
−0.15
−0.2
5
10
15
20
25
30
35
40
45


Sea Surface Height: Inverse Barometer Correction Applied
Height (m)
Latitude (°N)
Mog2D Model
ECMWF
2
1
0
−1
5
10
15
20
25
30
35
40
45
This is what most oceanographers want: dynamic topography



“Interpolation”
“Gridding”



Example of interpolated data and data in space and time

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
- Recently, with more accurate geoid, or using 'synthetic' mean sea surface: absolute SSH
  - ➪ Absolute currents
- From shape of return: wave height
- From radar backscattering σ0: 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)

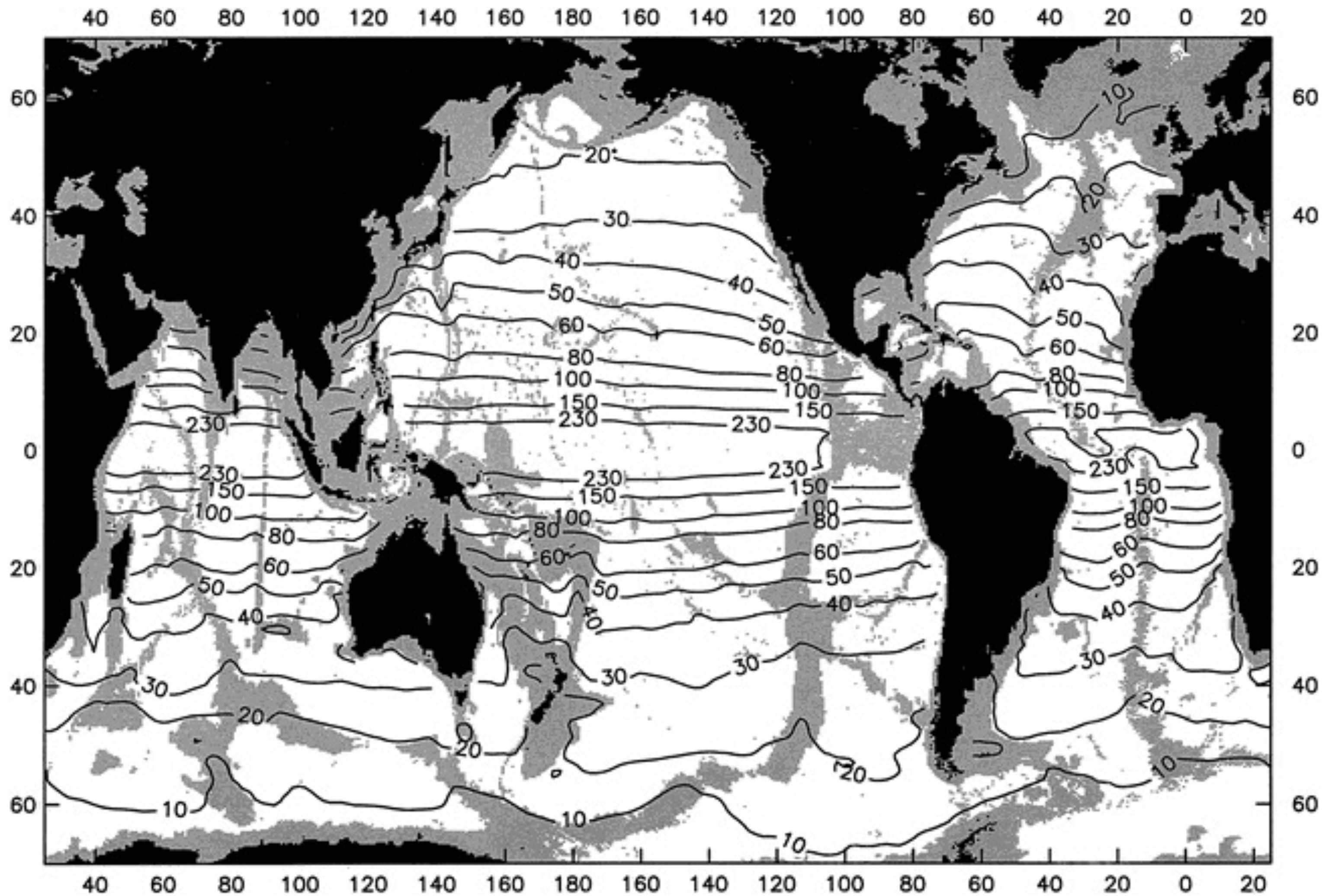
$$\boldsymbol{v = \frac{g}{f}\frac{\partial H}{\partial x}}$$

- 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 at low latitudes)
- At smaller scales, other (ageostrophic) components, such as those due to the local wind, will be present.
- With SSHprofiles 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 ageostrophic 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, 998)

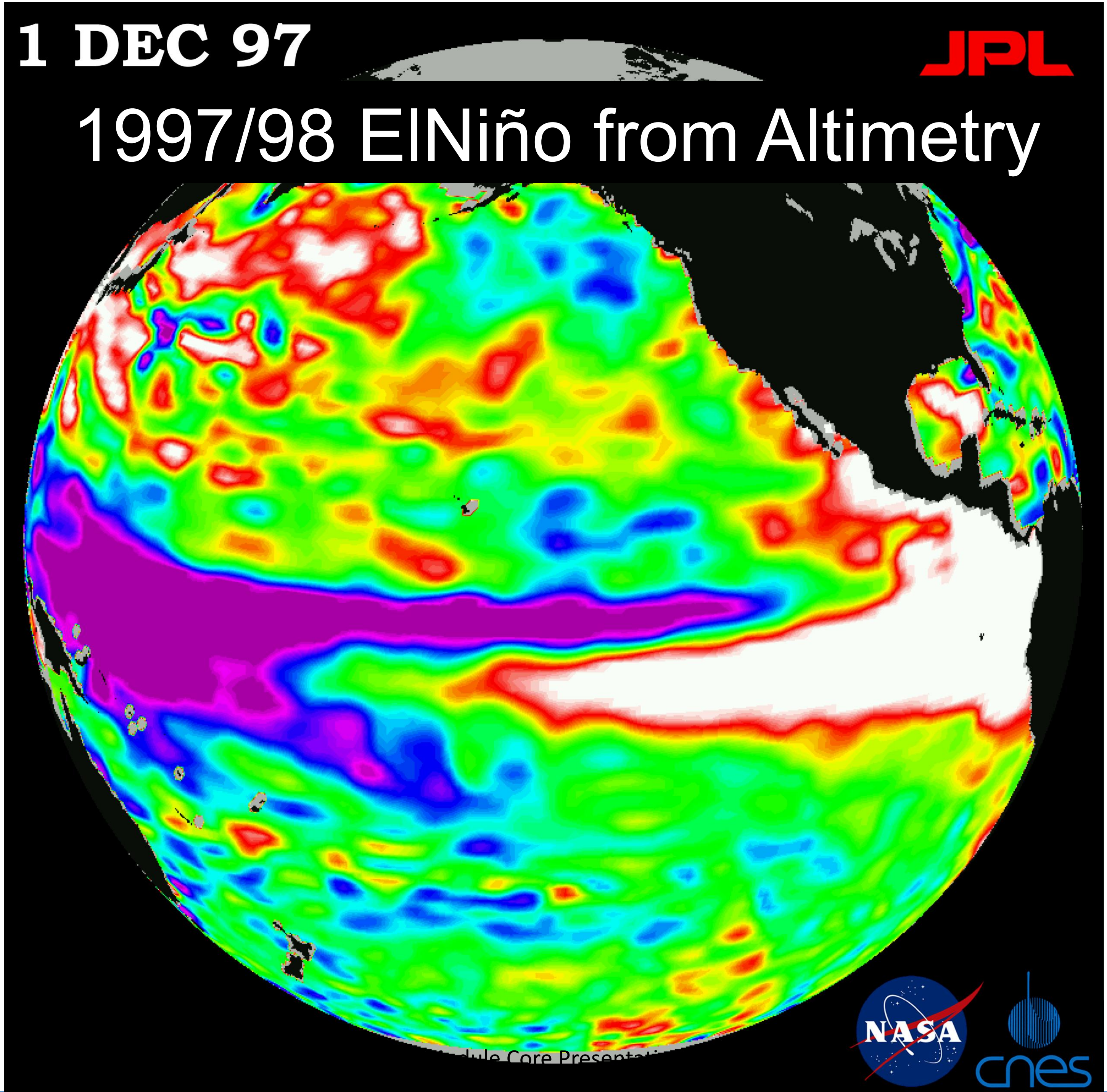
…BUT very important

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

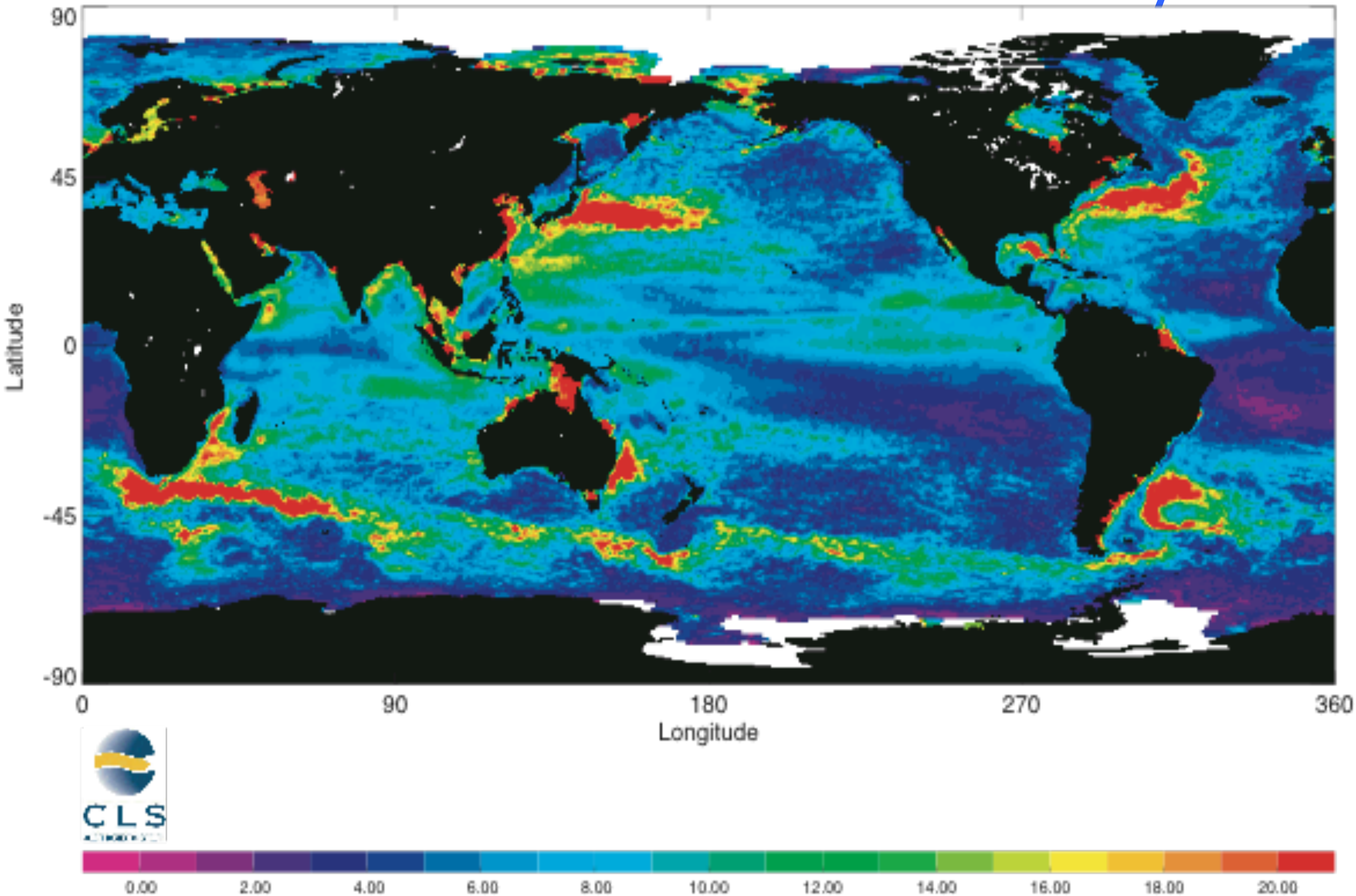
Ocean dynamics & climate studies

- 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

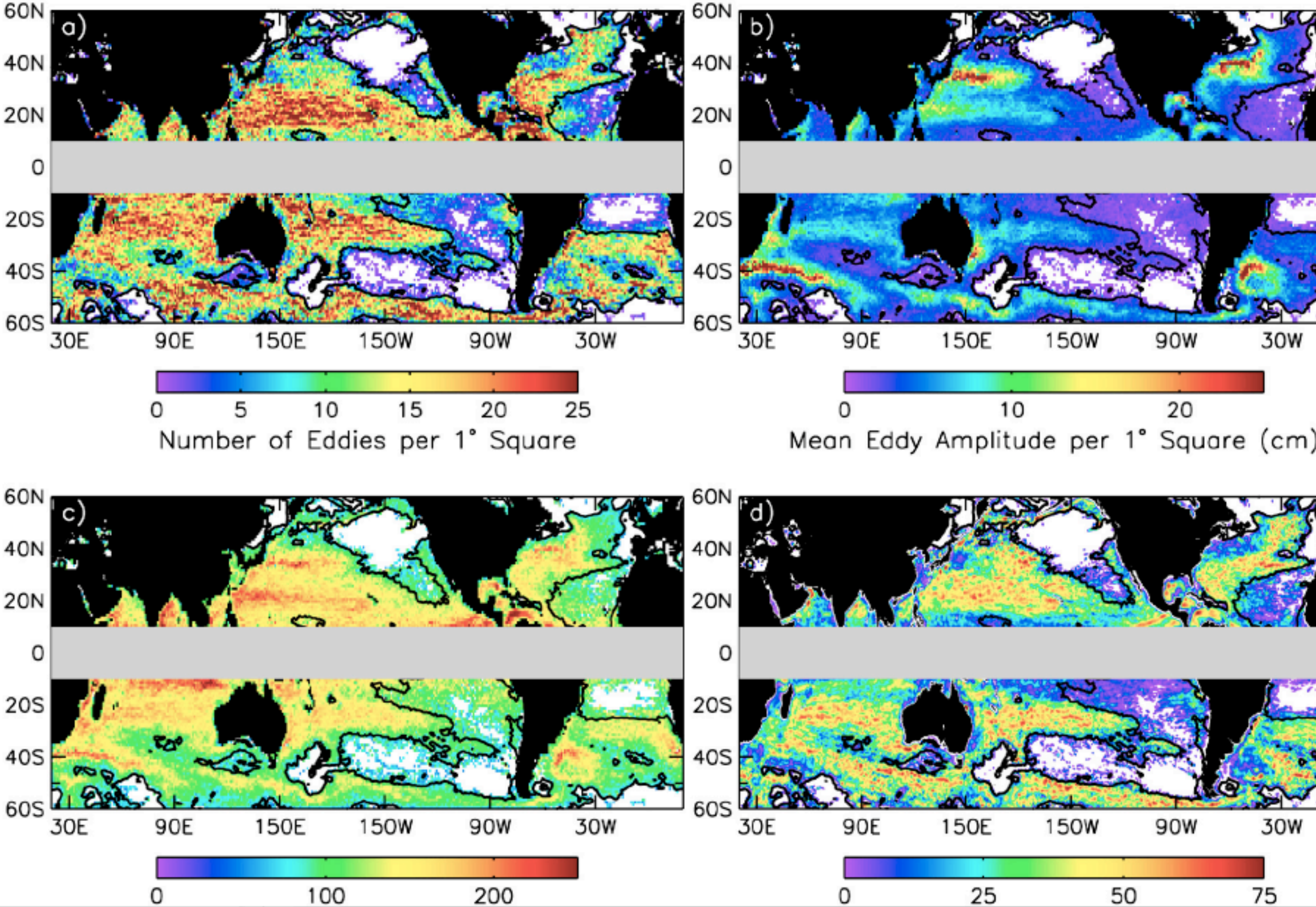


Ocean meso-scale variability



Global Eddy Statistics

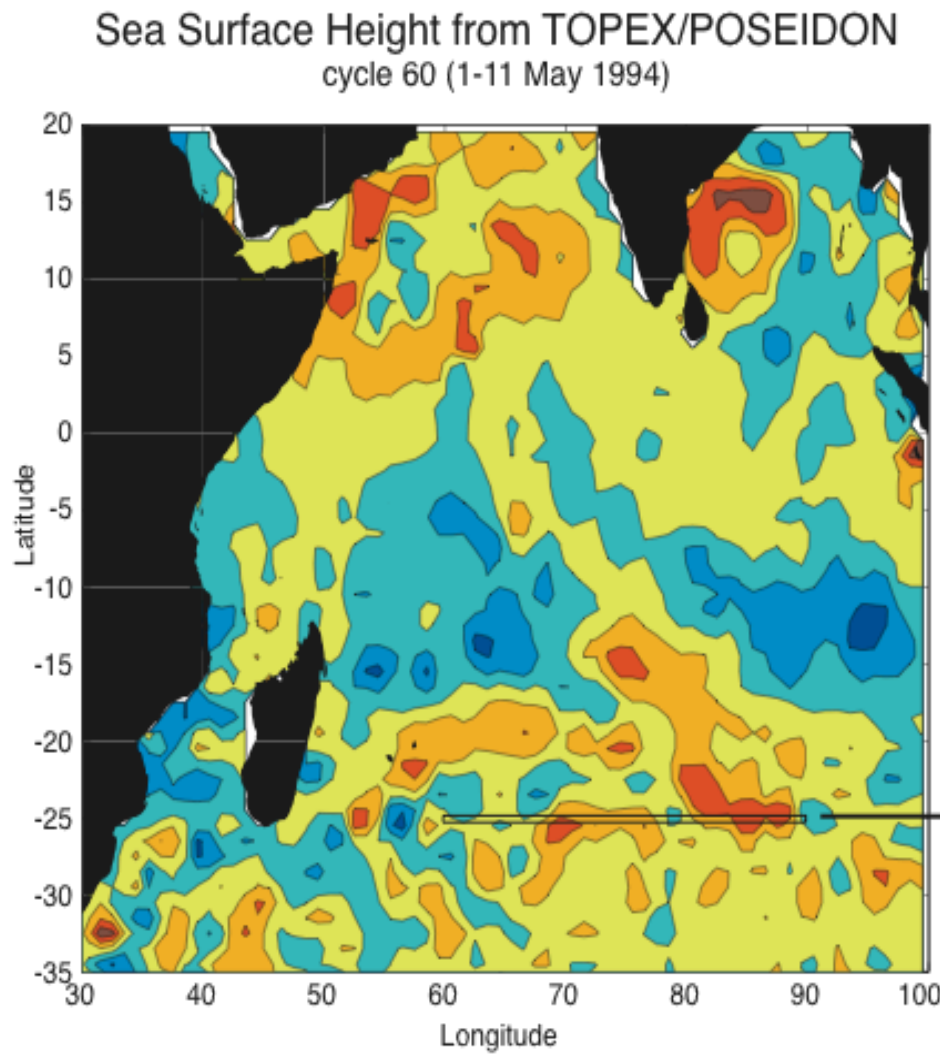
Chelton et al 2007 (GRL)



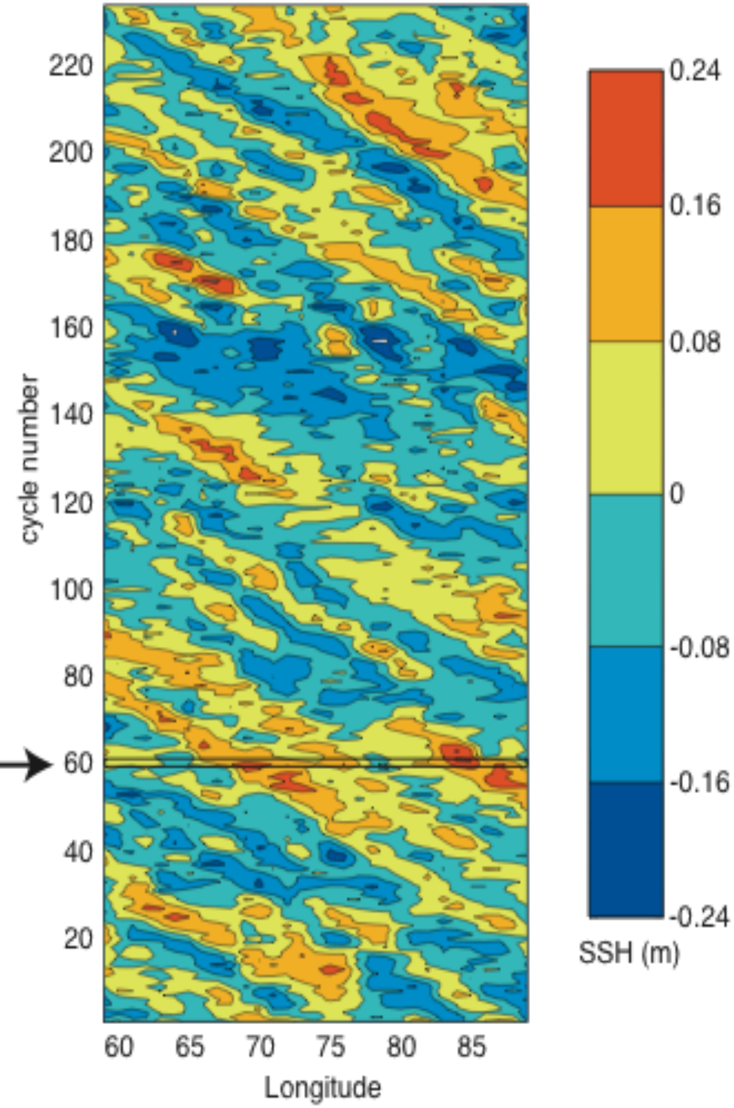
Mean eddy diameter (km)

Percentage of SSH variance explained

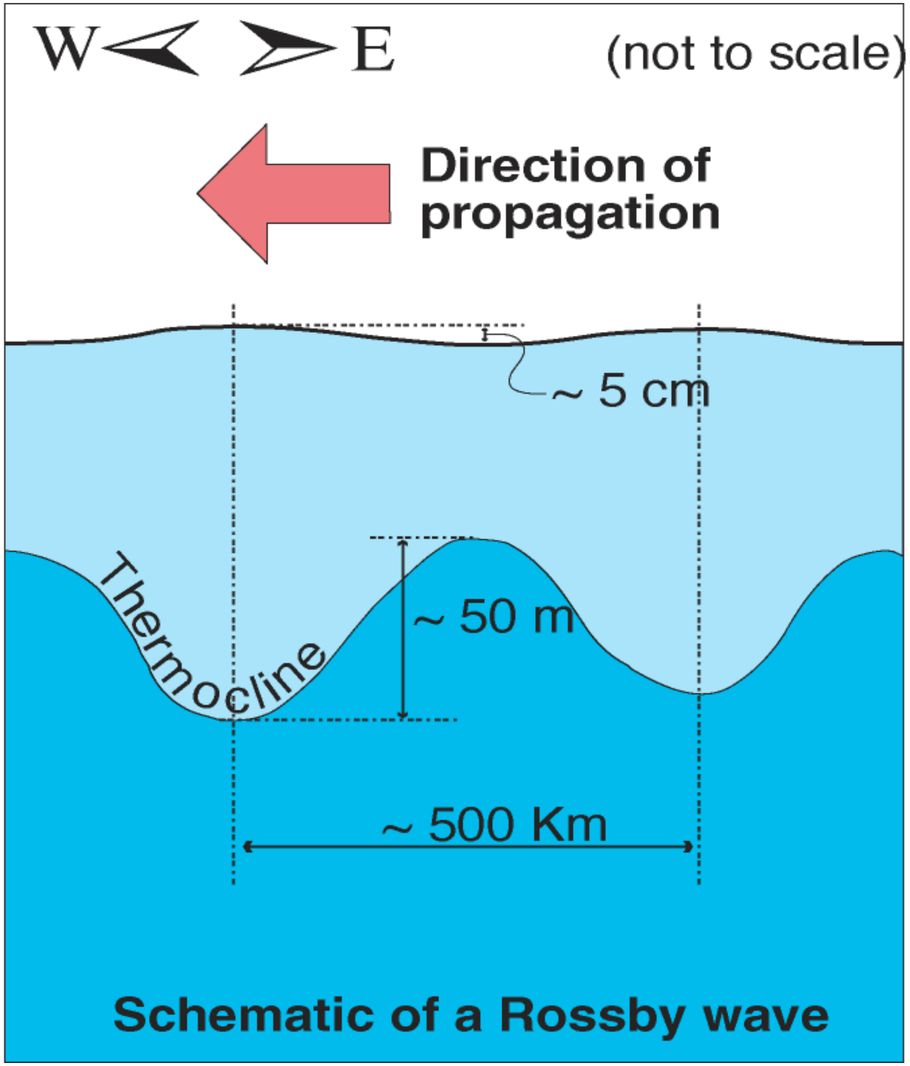
Eddies and Planetary (Rossby) Waves



Hovmüller diagram at 25˚S

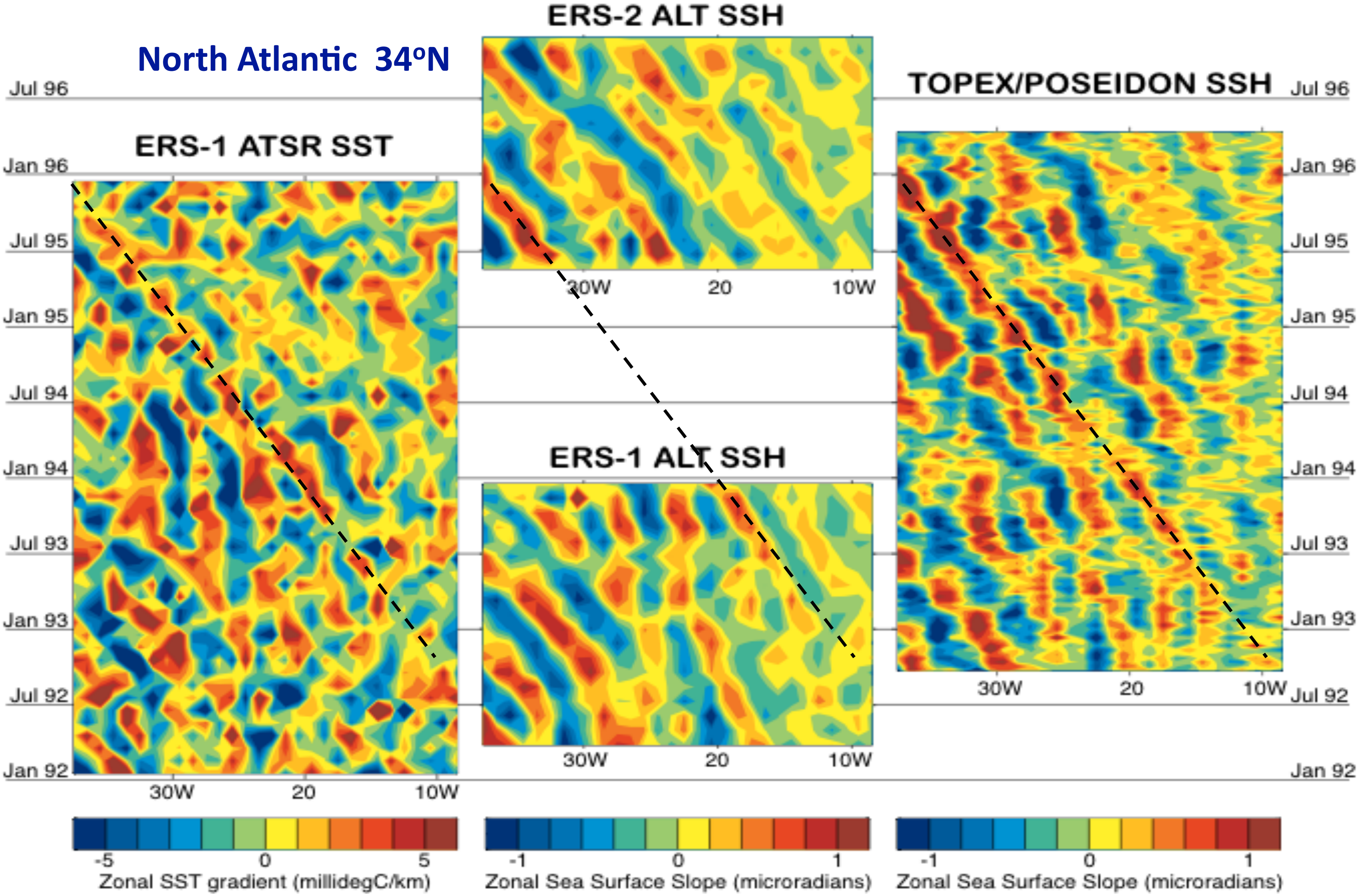


Planetary waves in the oceans



- 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)

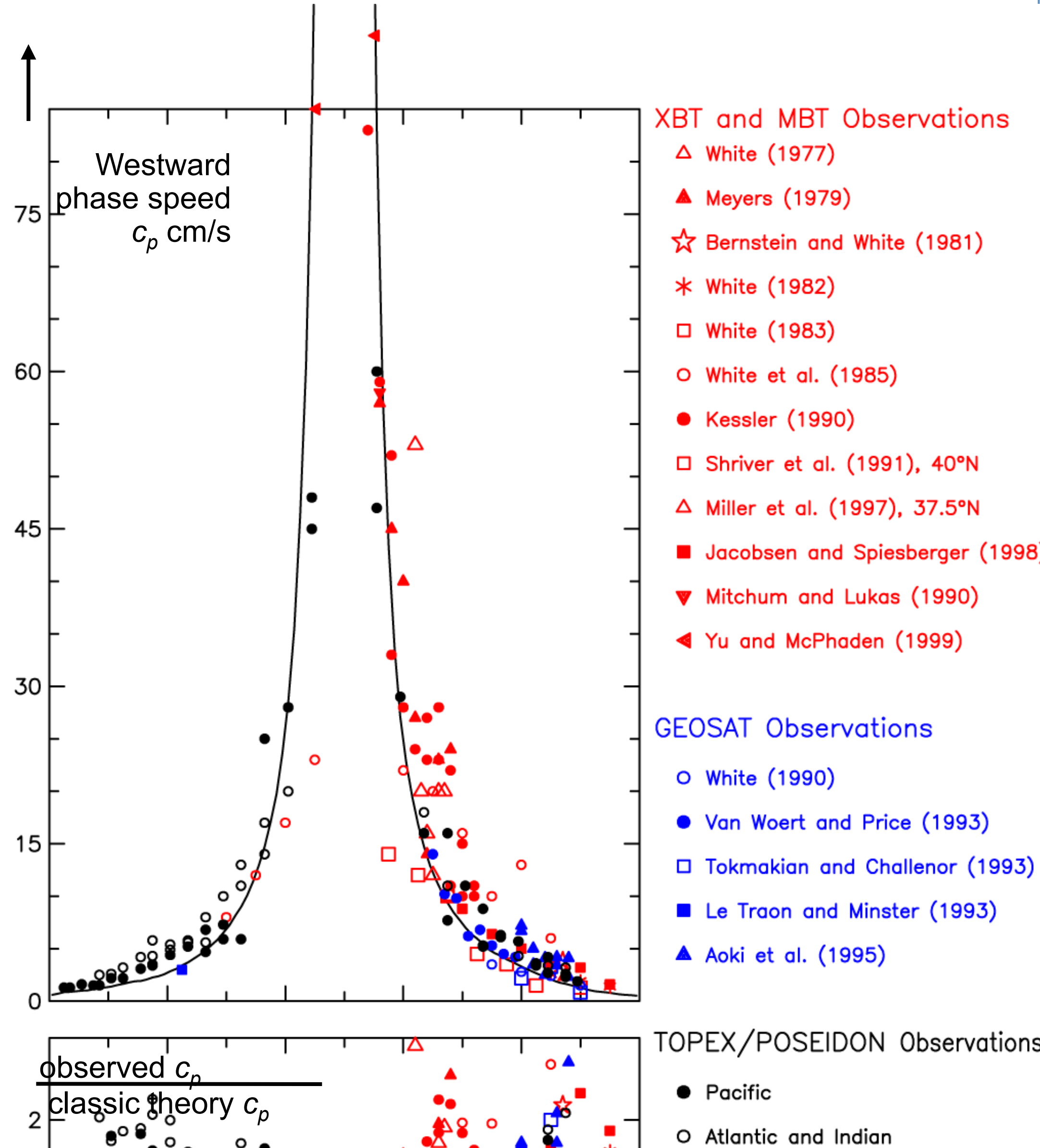
ERS-based observations



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

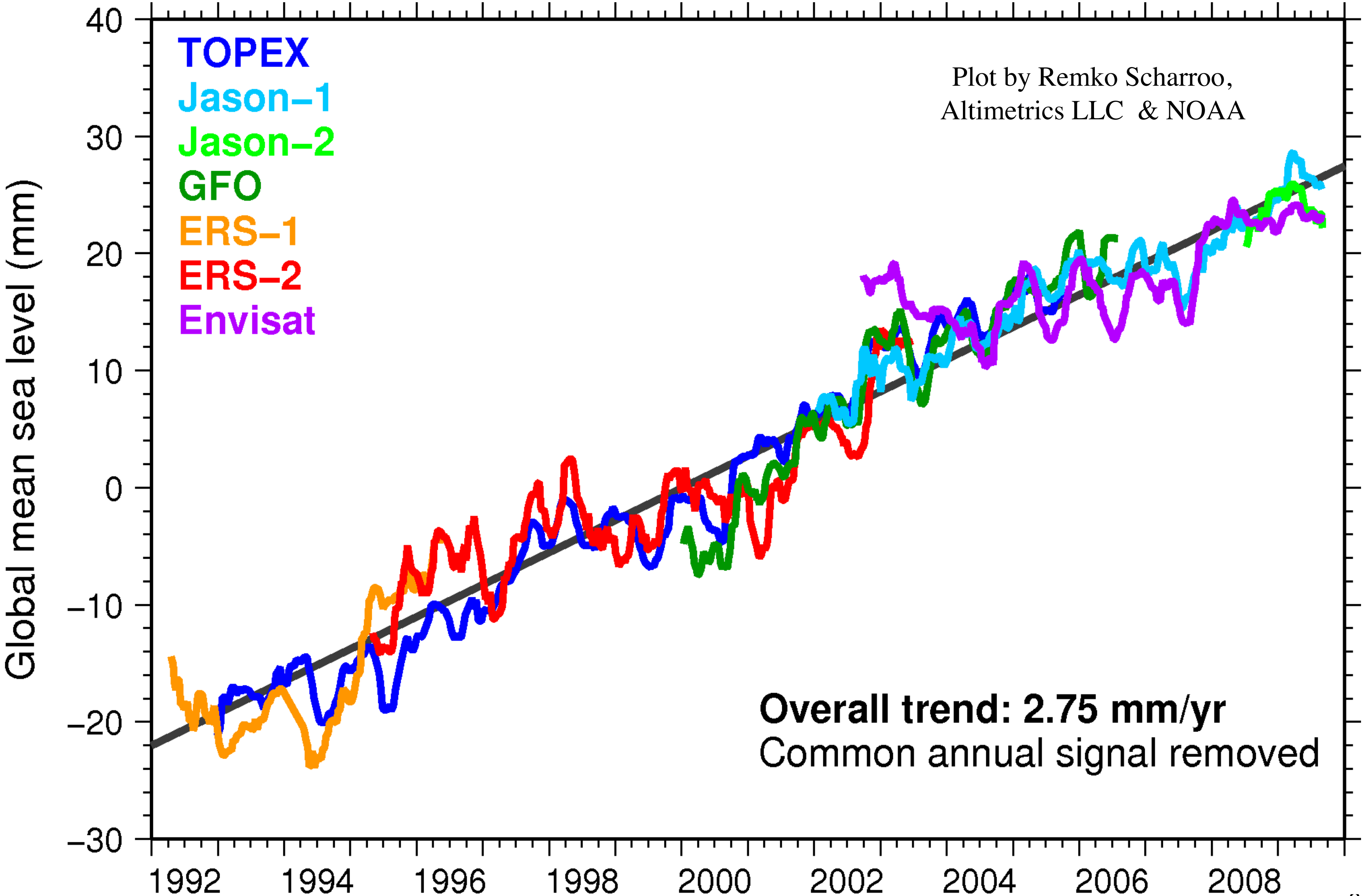
Planetary wave speeds in merged T/P+ERS data

- 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

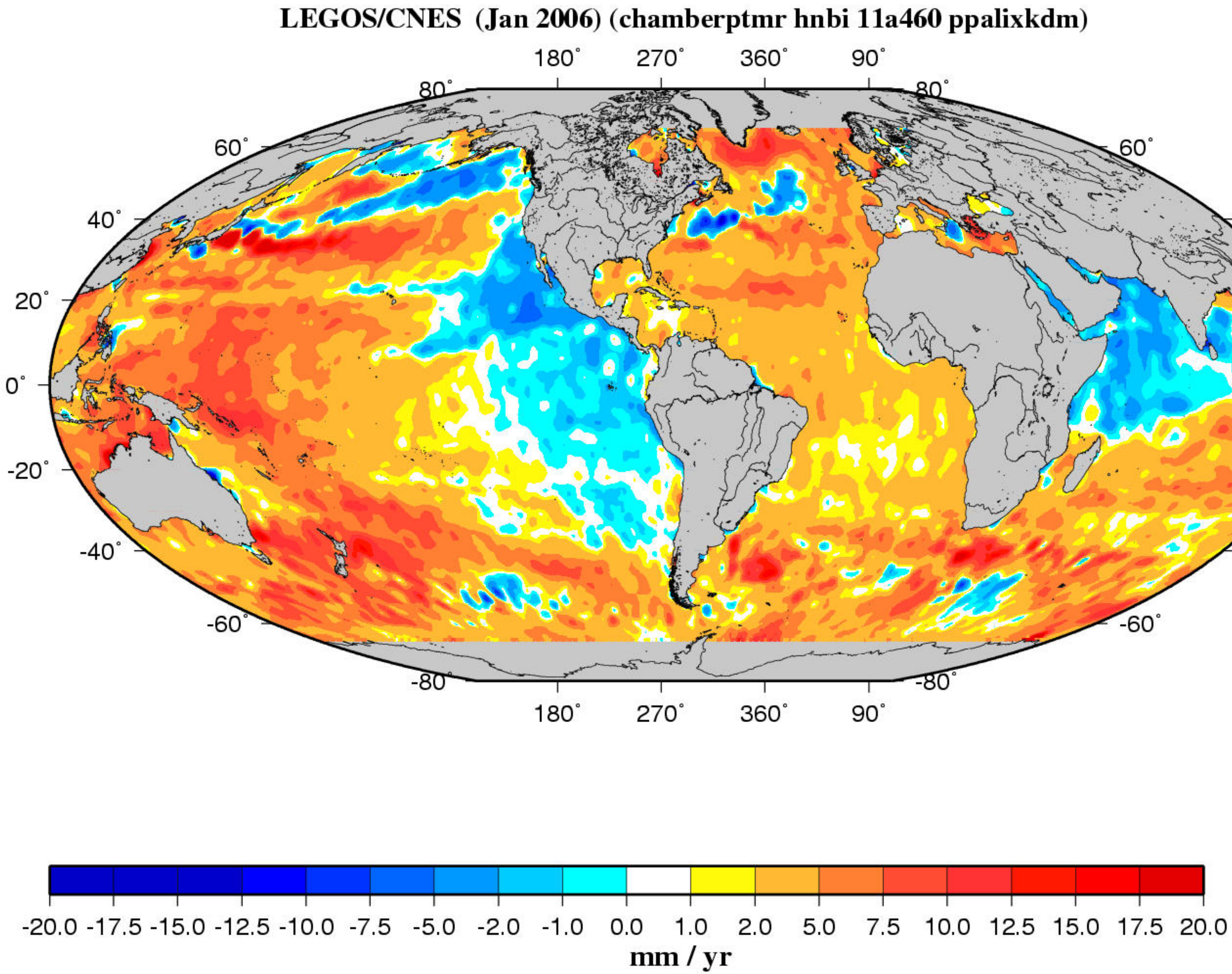


Theory had to be extended to account for the 'faster' speeds (see work by P. Killworth and collaborators)

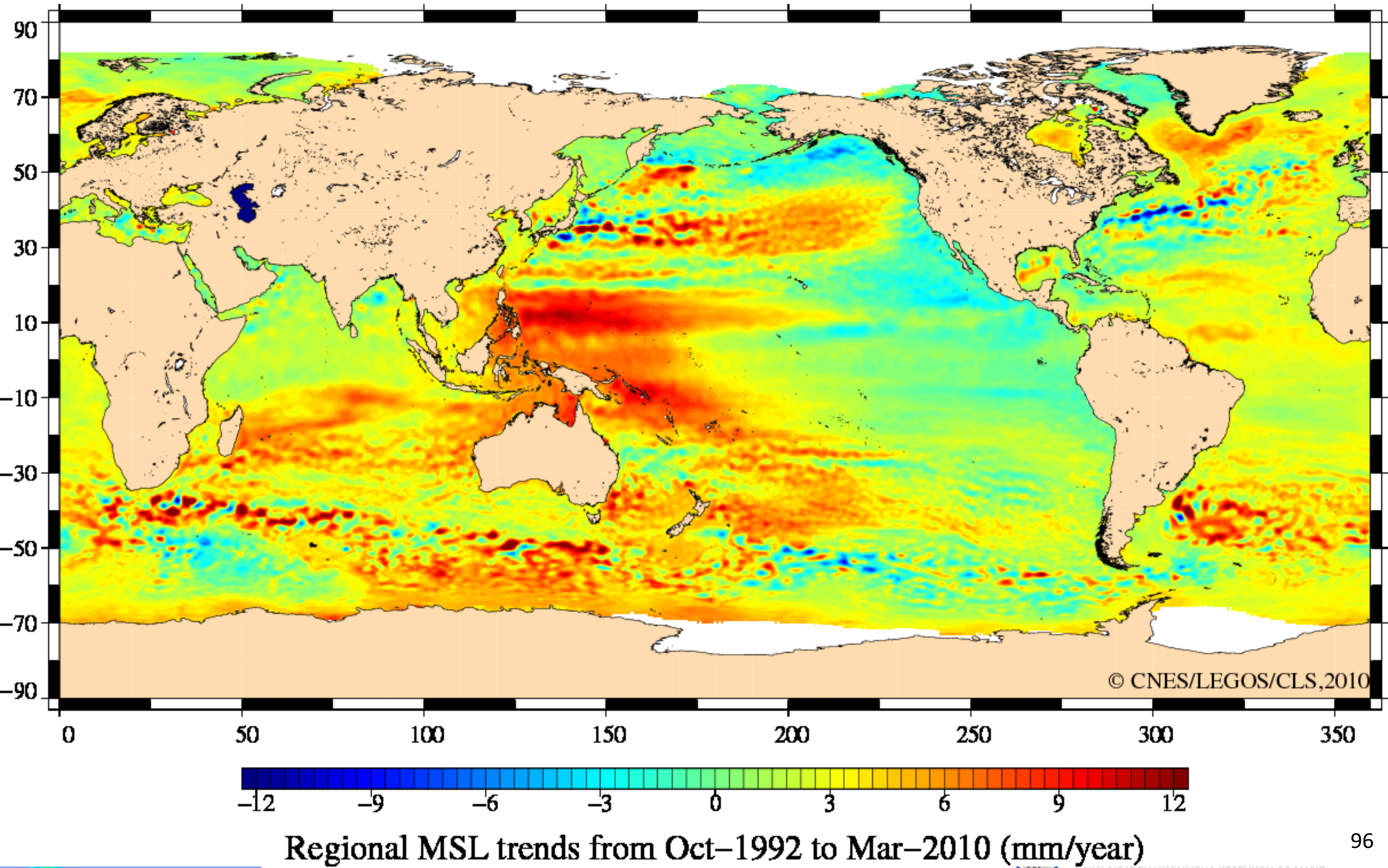
Global Sea Level Rise



Sea level trends from Topex-Poseidon (1993-2005)



Regional trends in Sea Level



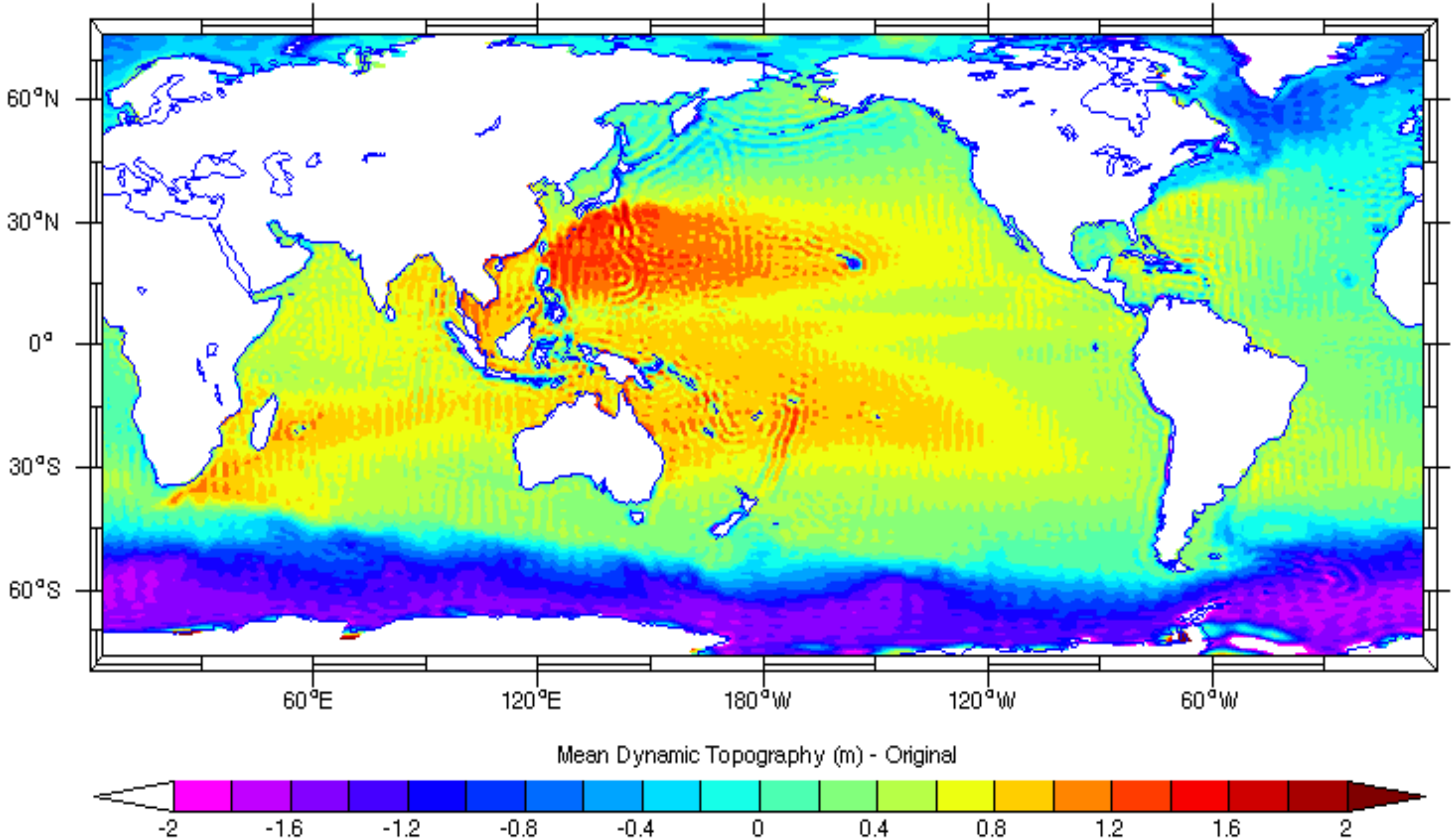
Absolute Dynamic Topography

- From Altimetry we have the surface height variability – relative to a mean field
- Absolute Dynamic Topography
  = Mean + variability
- We need a Mean Dynamic Topography (MDT)
  - Generate a Synthetic MDT using in situ and / or model data
  - Generate a 'satellite only' MDT
    = Mean Sea Surface Height - Geoid

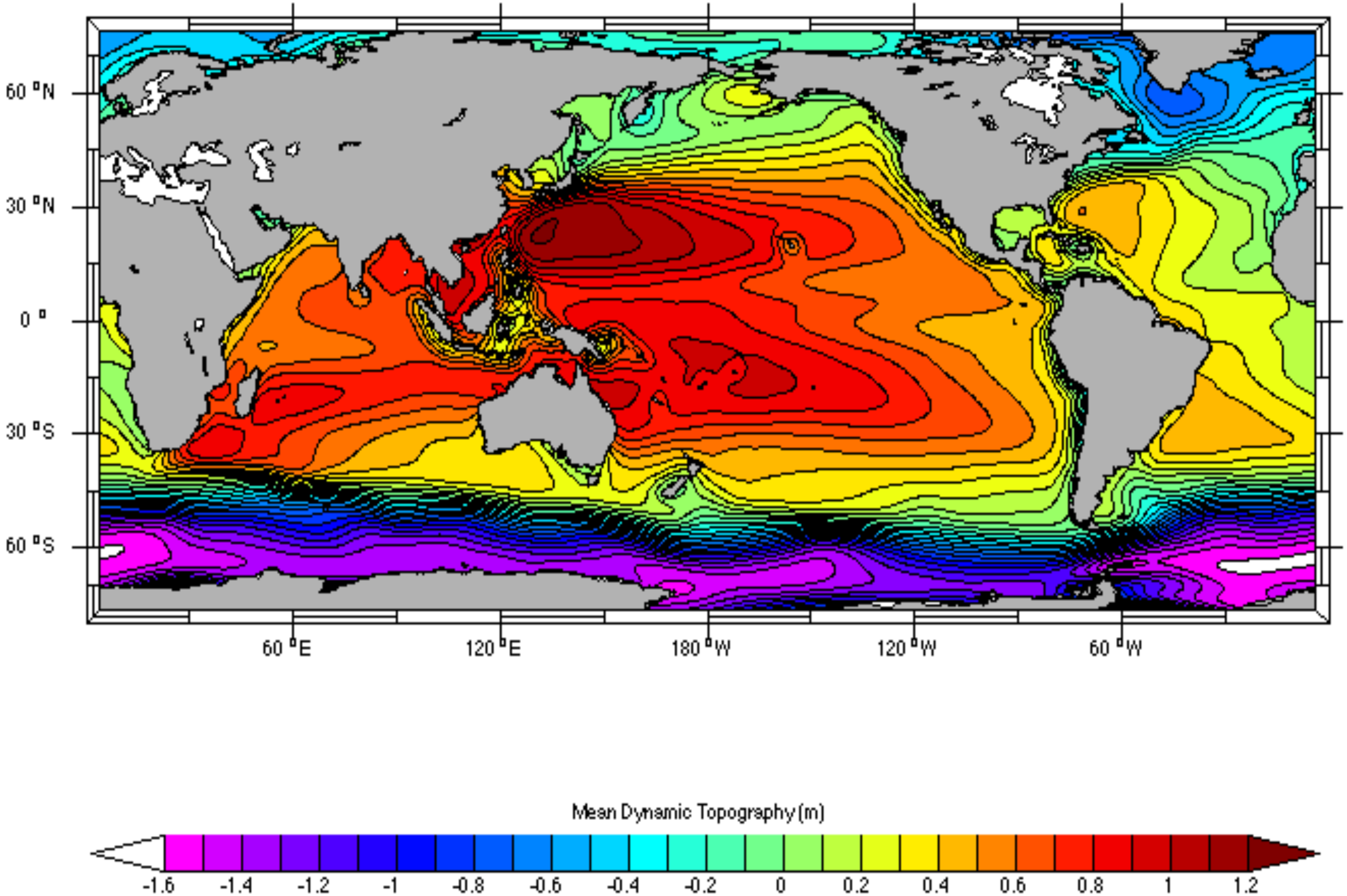
Generate MDT

- Mean Sea Surface Height
  - Contain information at all scales
  - Field is dominated by large scale geoid changes
  - Ocean Dynamic Topography is order of magnitude smaller
- Geoid Models
  - Information limited by resolution of model (provided in Spherical Harmonics (SH)
  - Dominated by larger spatial scales
- Merging Data
  - **Vital** we match the spatial scales of data

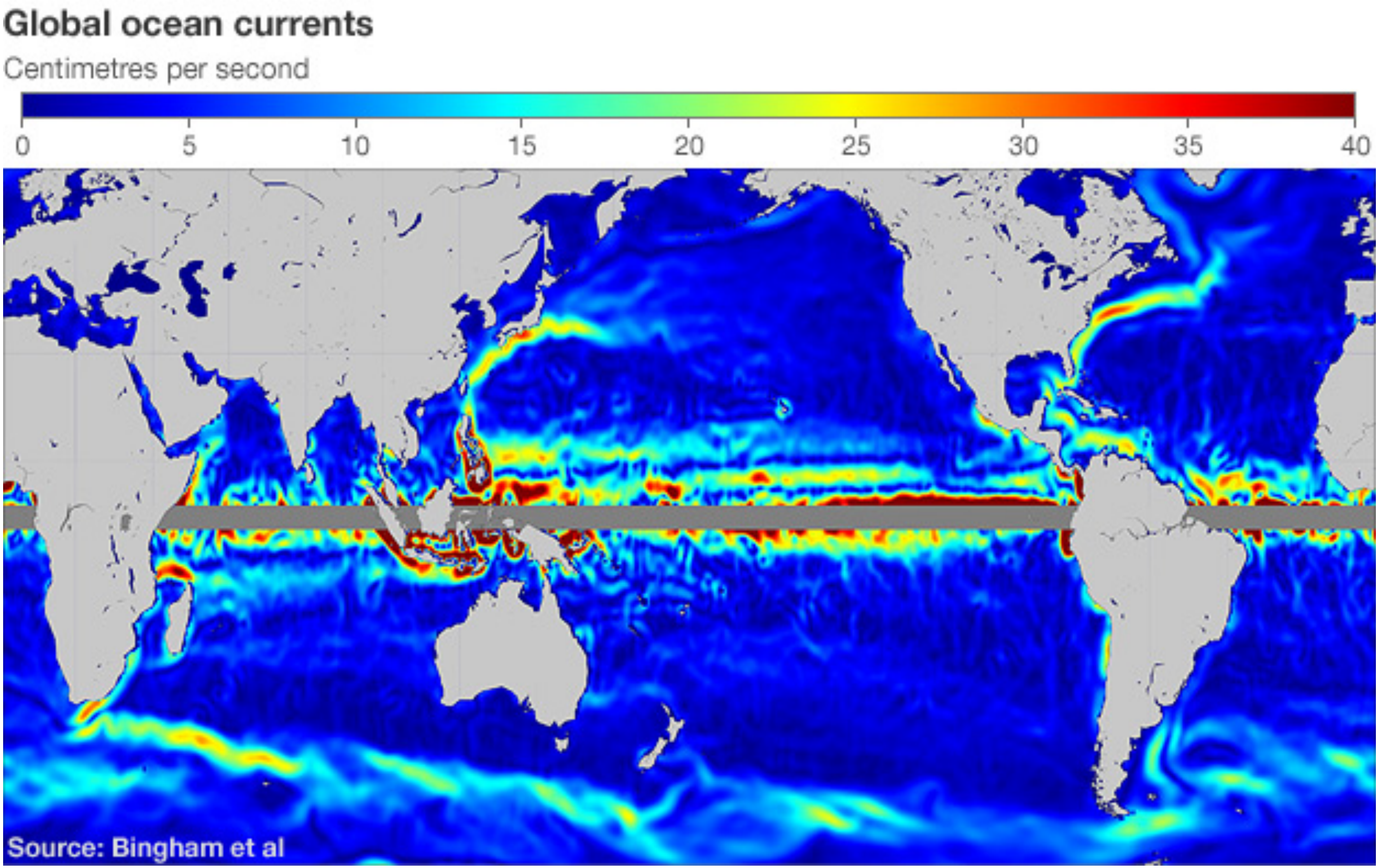
Mean Sea Surface - Geoid



Apply Filtering



Absolute Geostrophic Currents



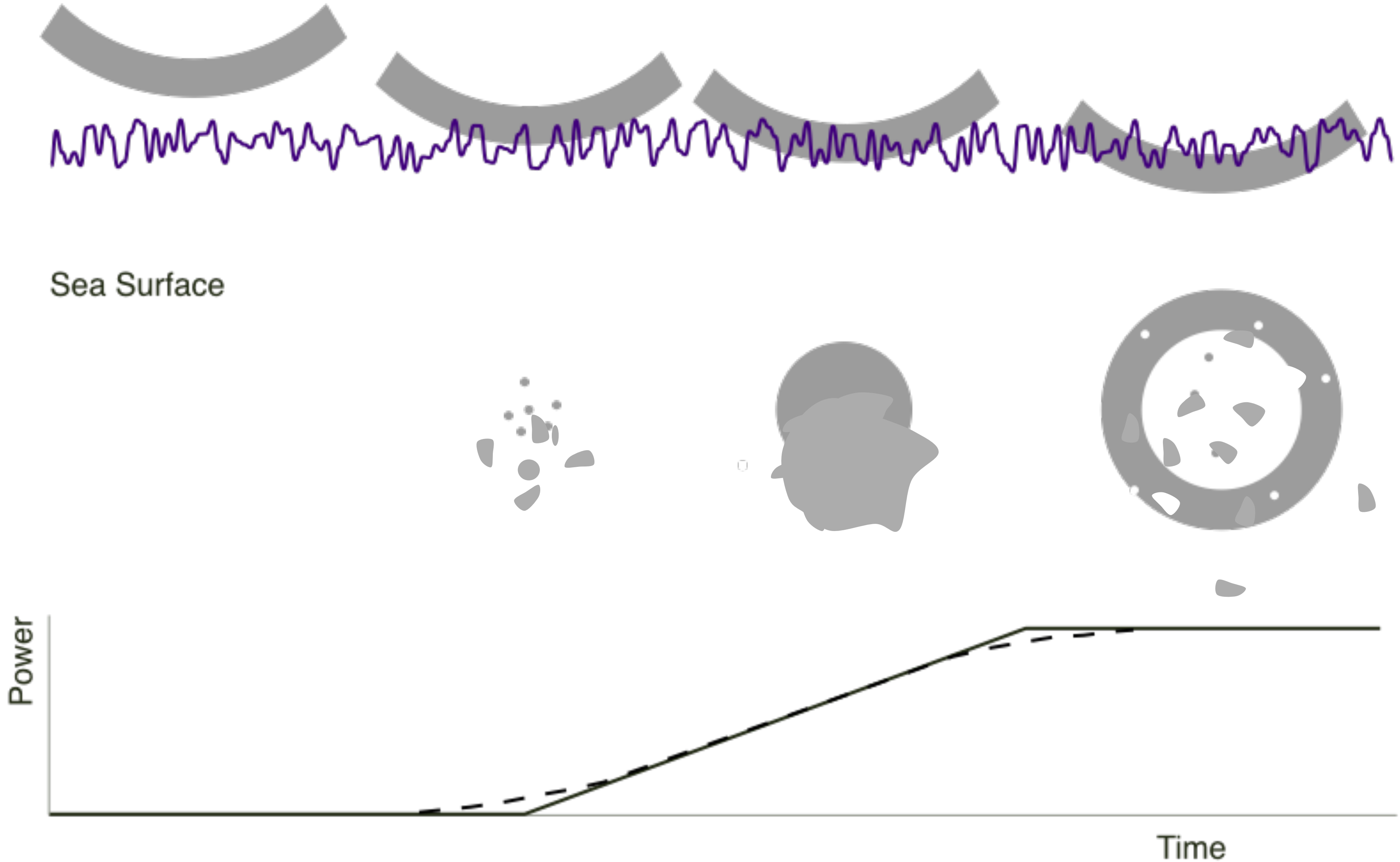
Waves, winds and other parameters

- Significant wave height
- Altimeter winds
- Calibration/validation
- Wave climate

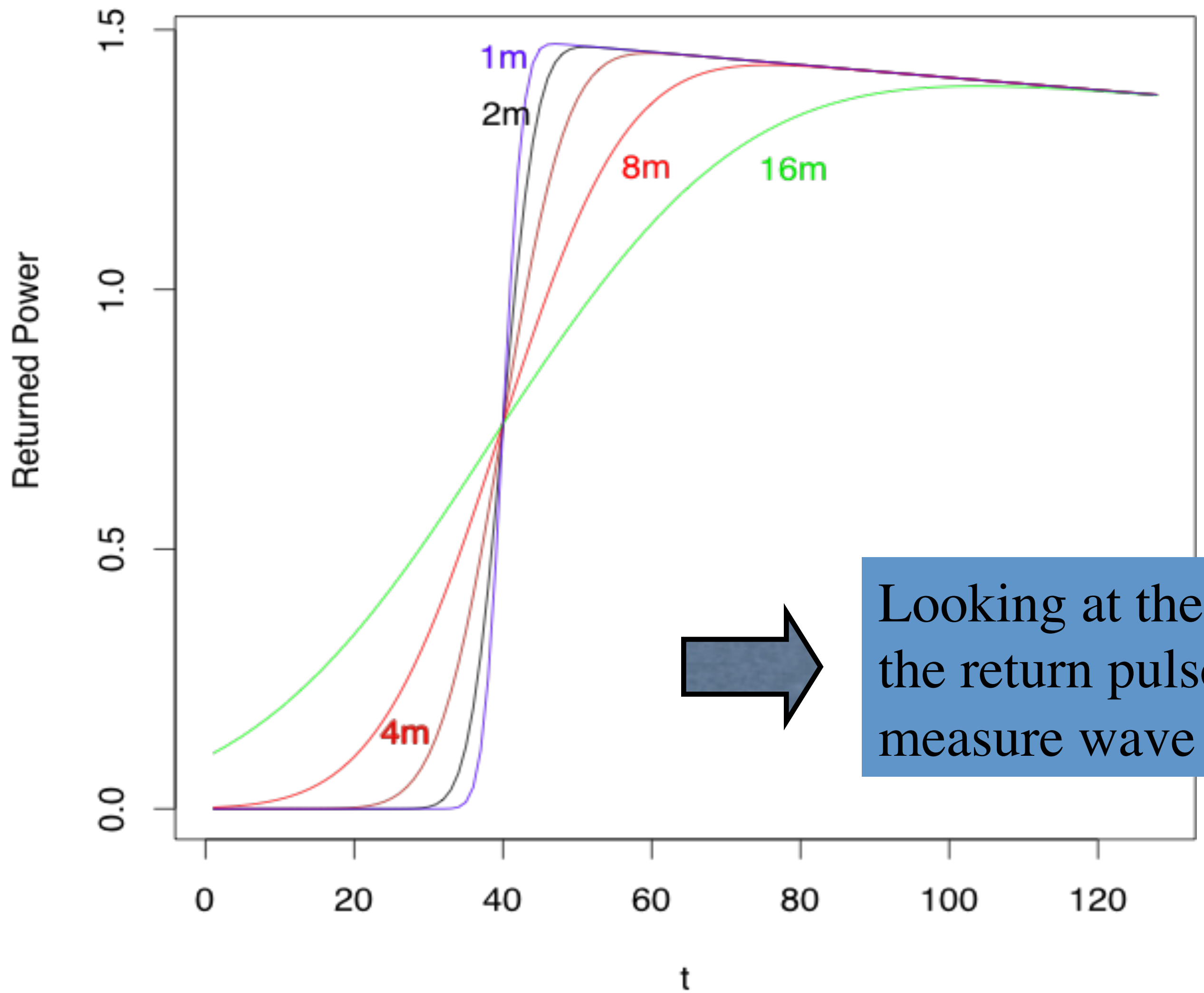
What is significant wave height?

- H_s (or SWH) is defined by
  H_s = 4 s.d.(sea surface elevation)
- Used to be defined (H1/3) as
  Mean height (highest third of the waves)
- ≈ visual estimate of wave height

How an altimeter measures Hs

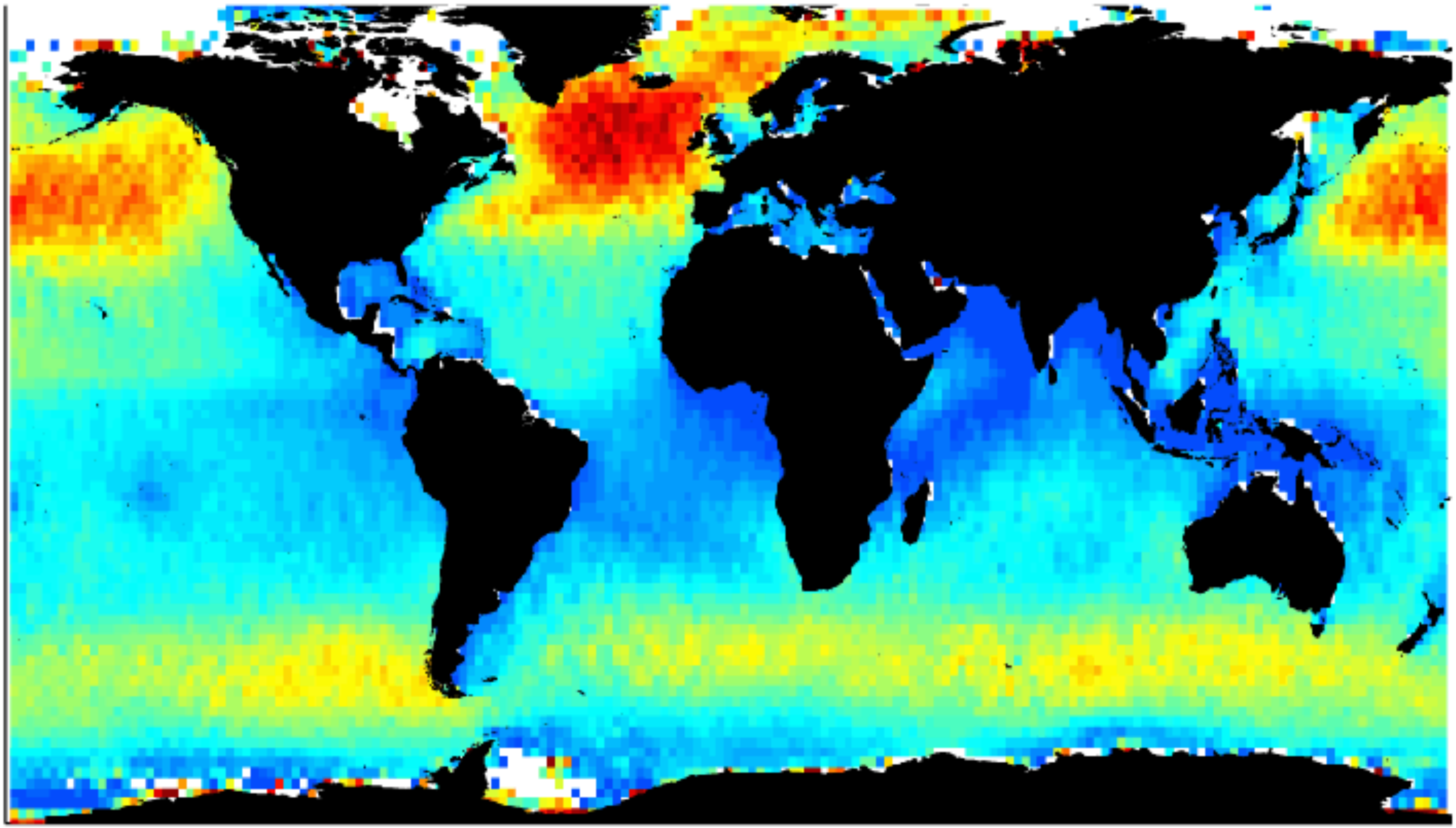


Effect of SWH on altimeter return

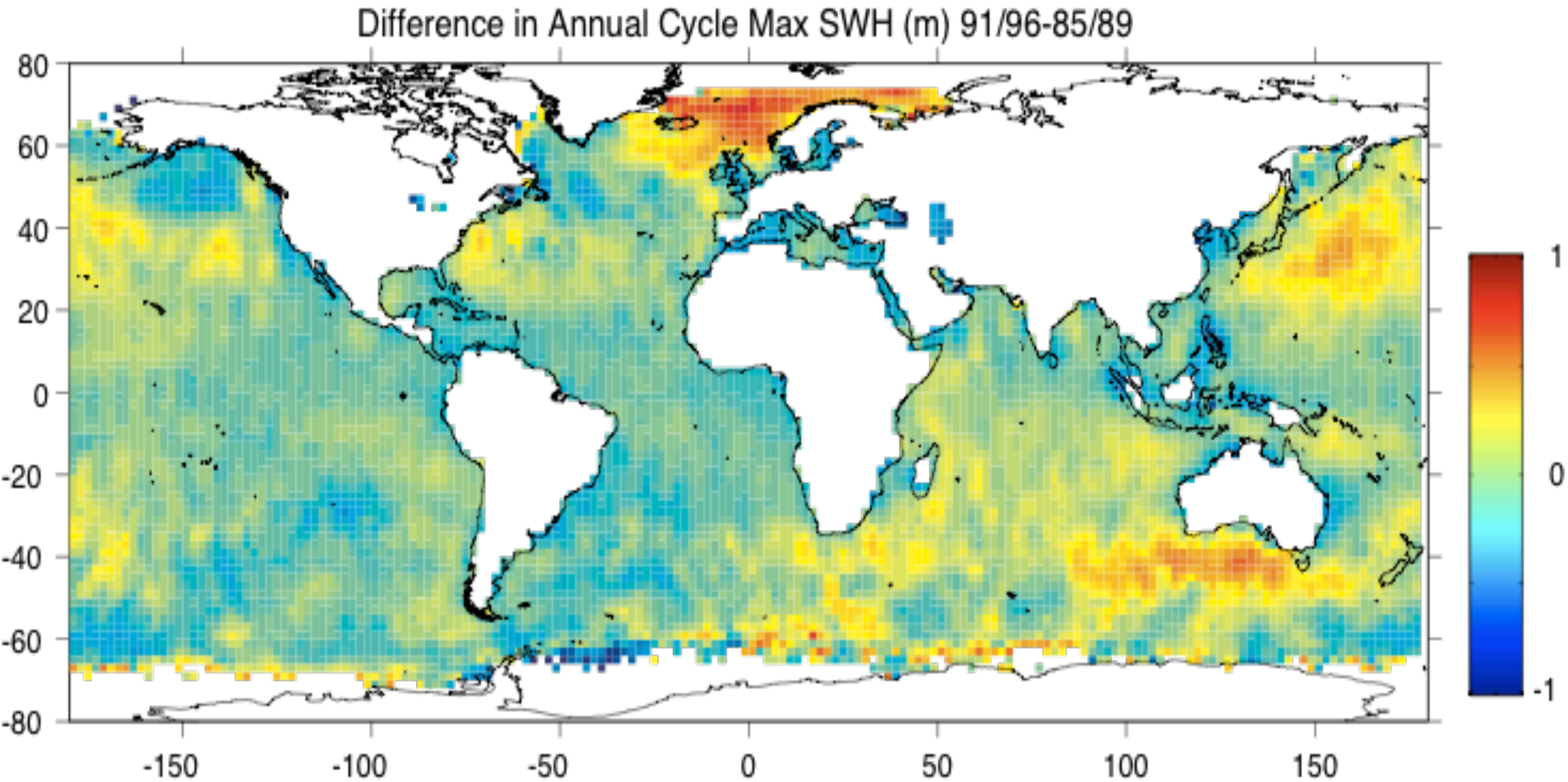


Looking at the shape of the return pulse we can measure wave height

Wave Height , Month 1

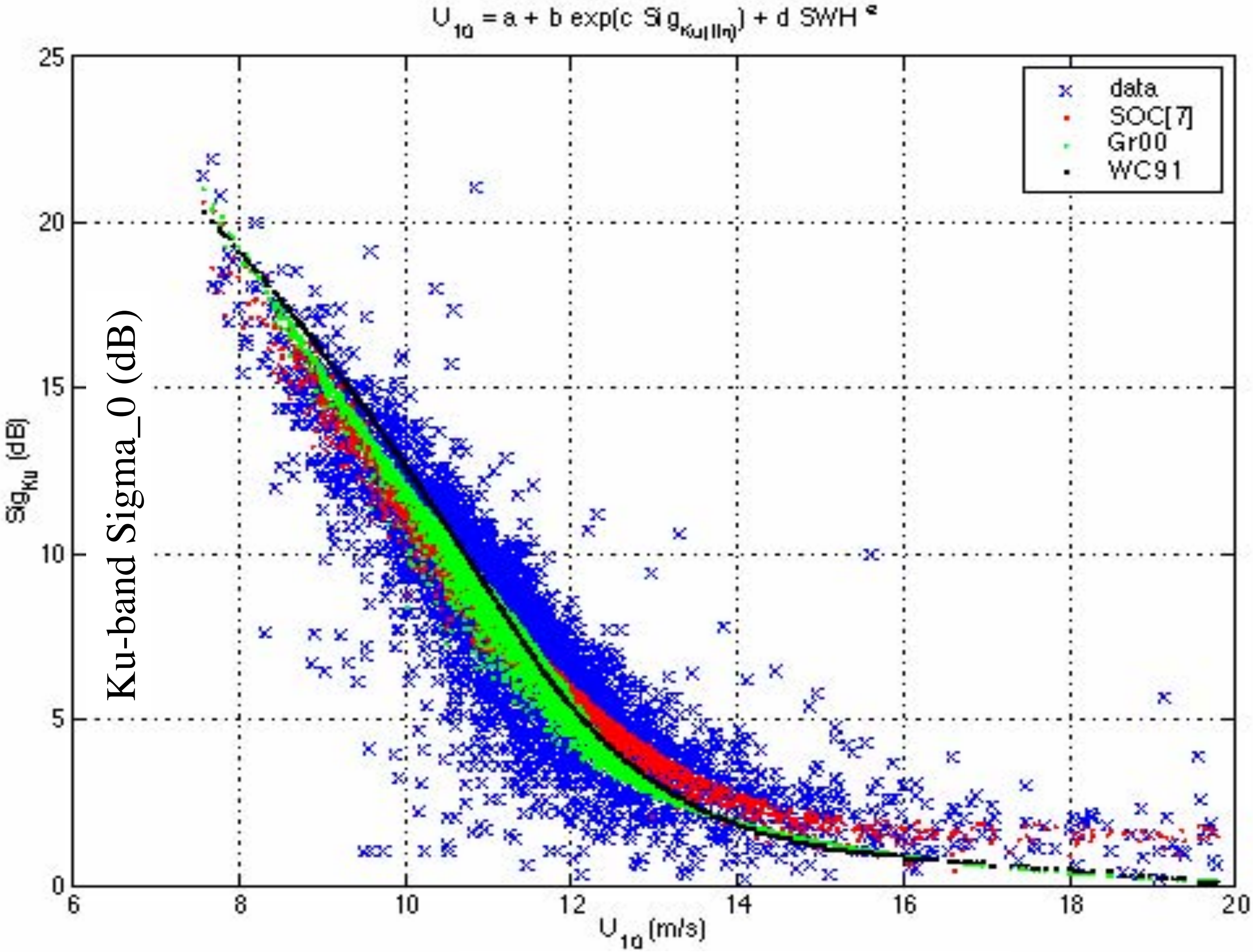


Climate changes



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})



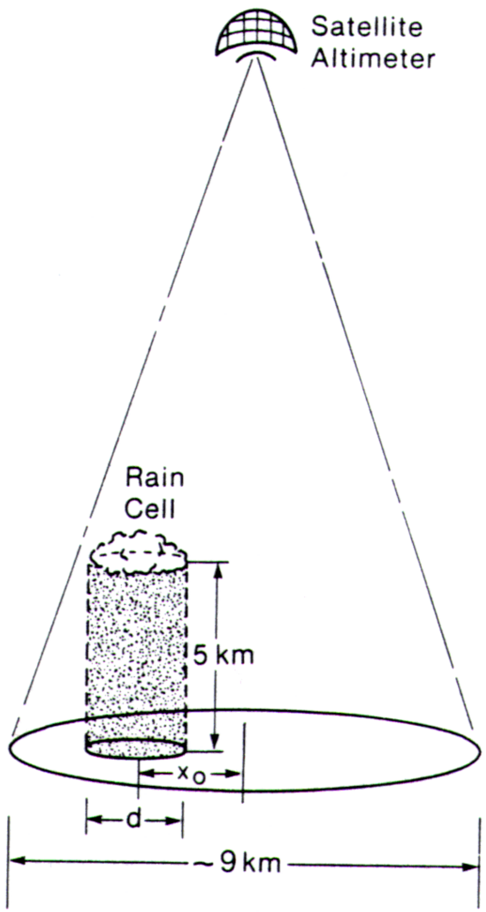
U_{10} (m/s) in situ measurements

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)

Rain effects in altimeter data

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



G. Quartly, NOCS

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!!