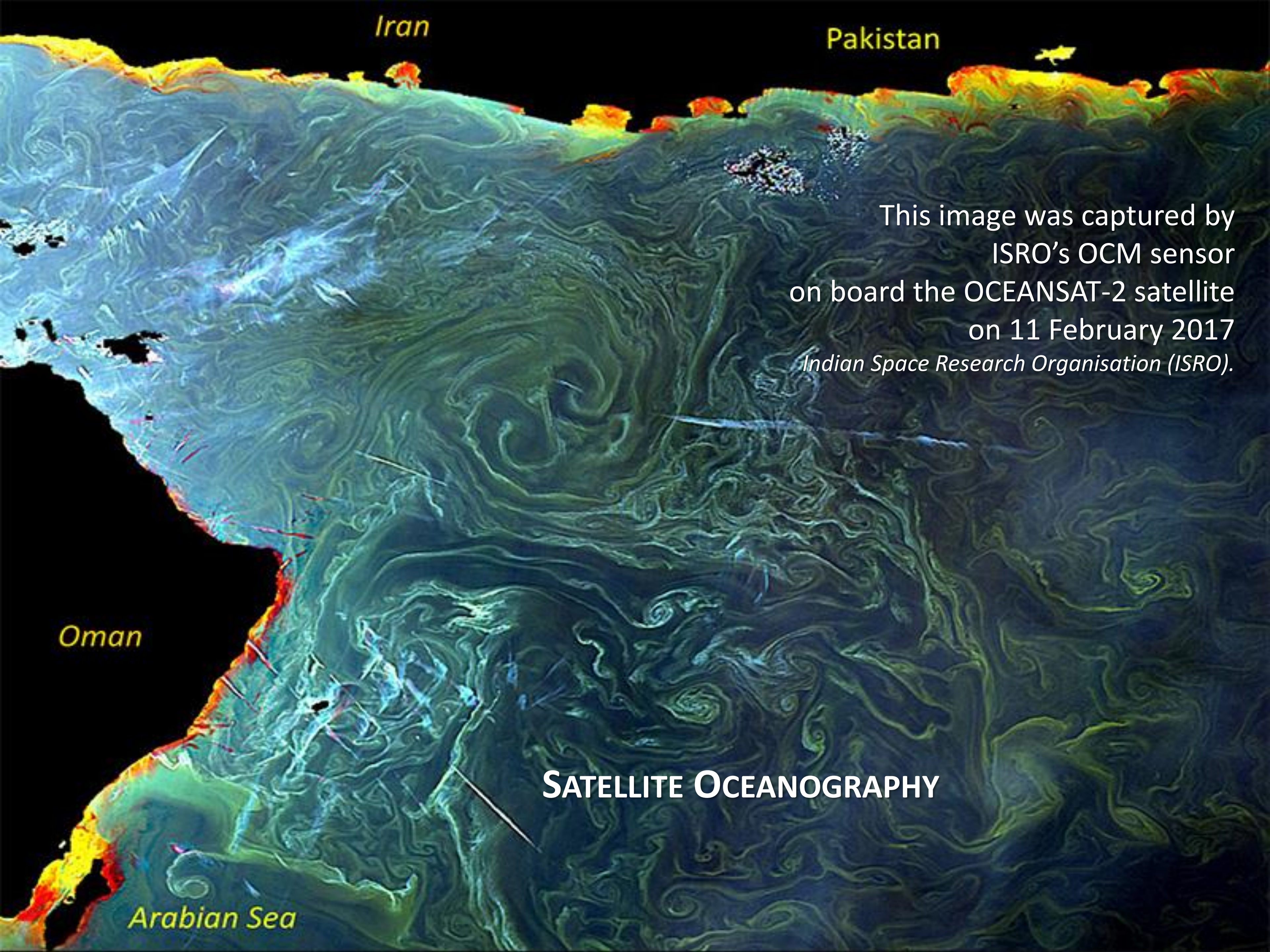
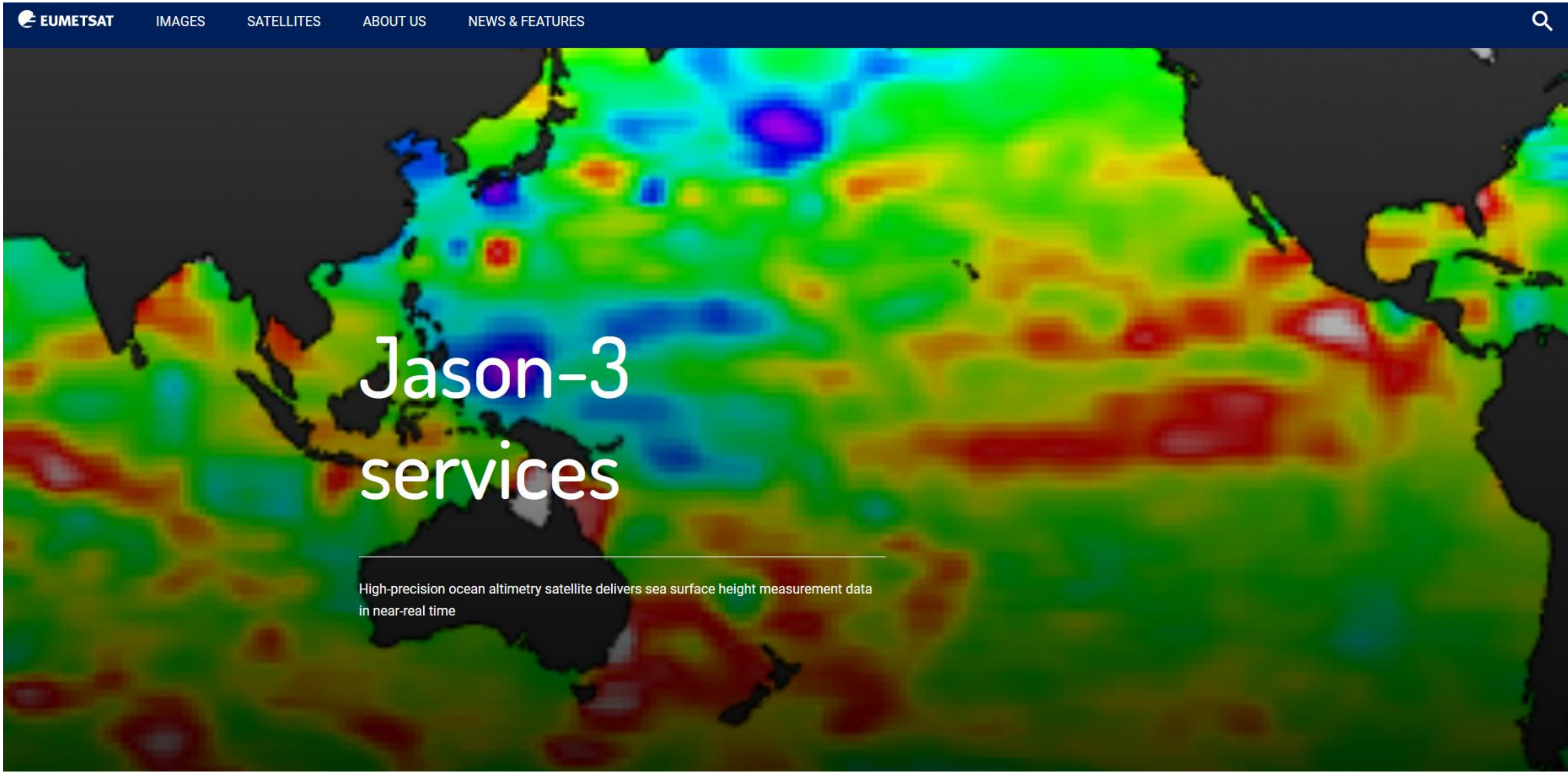

Iran
Pakistan
This image was captured by
ISRO's OCM sensor
on board the OCEANSAT-2 satellite
on 11 February 2017
Indian Space Research Organisation (ISRO).
Oman
SATELLITE OCEANOGRAPHY
Arabian Sea



Satellite Altimetry In Oceanography

Sea Surface Height / Slope

- Ocean Geoid
- Sea Floor Bathymetry
- Tides
- Geostrophic Surface Flow

Sea Surface Roughness

- Surface Wind
- Wave Height and Spectra
- Internal waves
- Surface Slicks

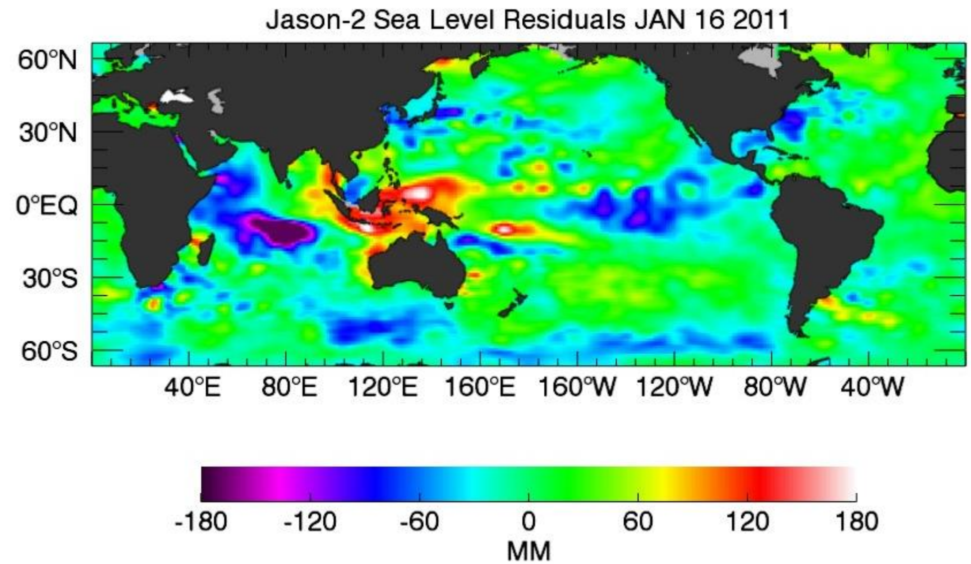
ENSO Indicators

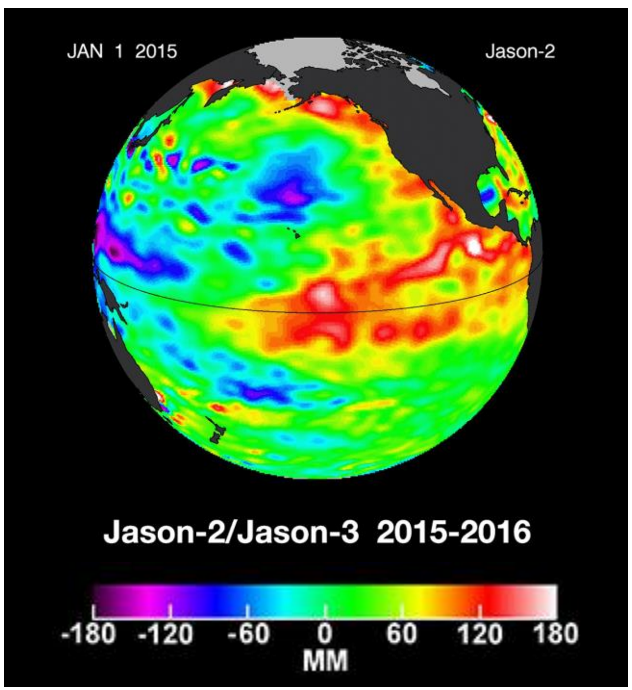
Southern Oscillation Index (SOI)
standardized index based on the observed sea level pressure differences between Tahiti and Darwin, Australia

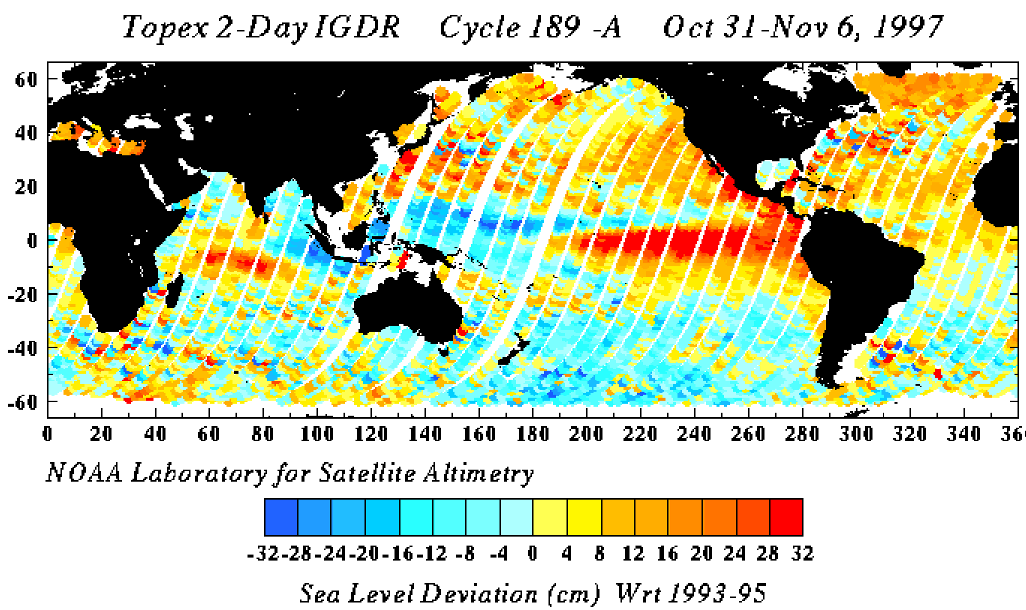
Oceanic Niño Index (ONI)
Sea Surface Temperatures (SST) anomalies for several commonly-known ENSO regions

Sea Level Anomalies
Sea surface height images from the Jason-3 satellite

Outgoing Longwave Radiation (OLR)
This OLR product is a proxy for convective precipitation in the western equatorial Pacific

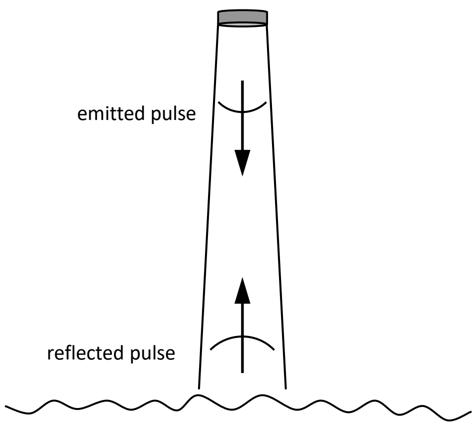


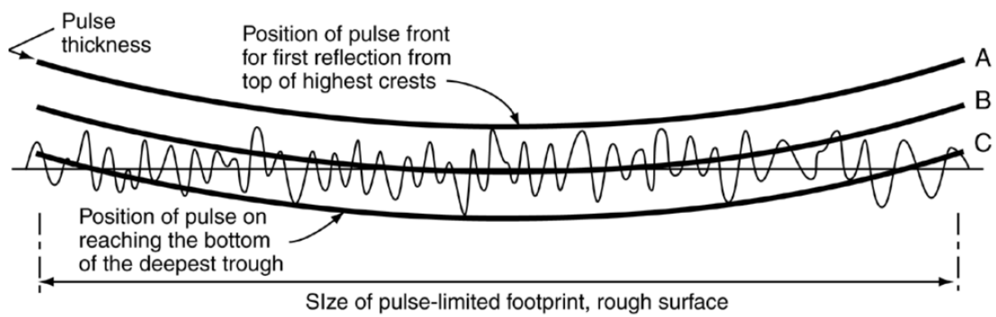




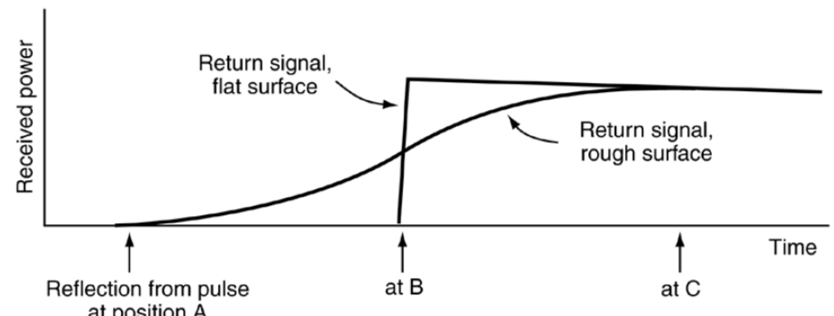
https://www.ncdc.noaa.gov/teleconnections/enso/

Satellite Altimetry – Surface Waves





(a)



(b)

Wave height - H

- *H related to time between 1. and last reflection from pulse-limited footprint*
- *average of ~1000 pulses*
- *pulse limited footprint ~3-10km*

Wave Period - T

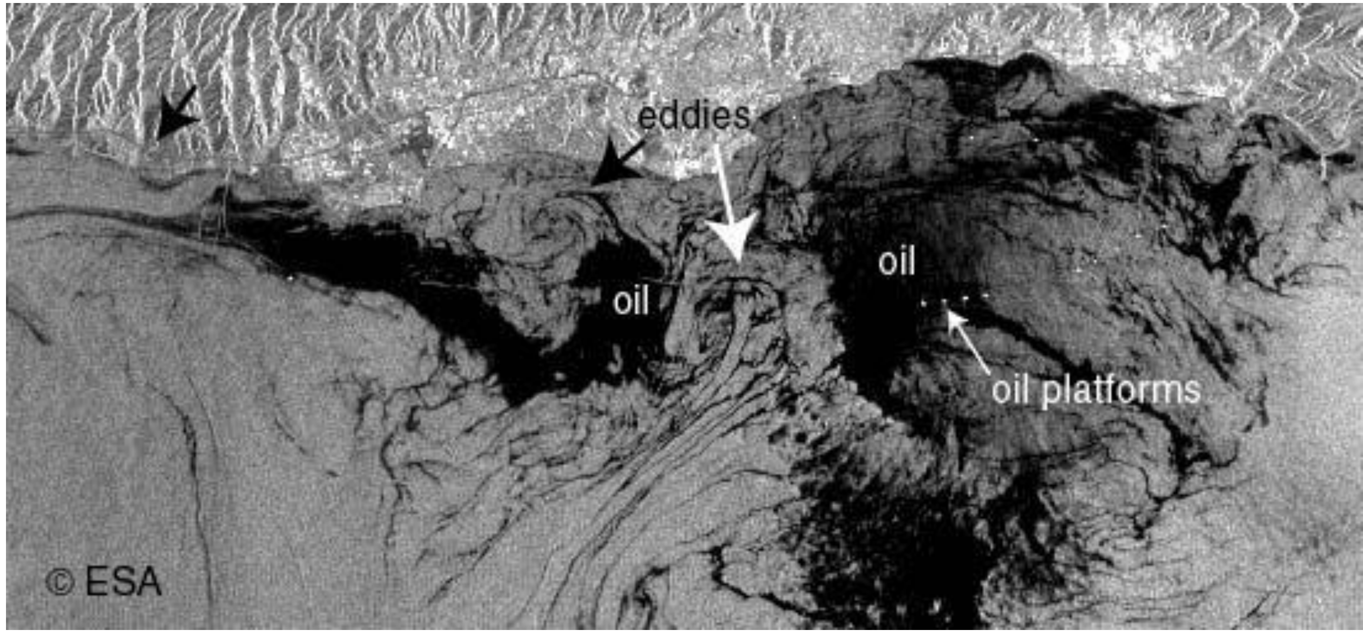
- *backscatter intensity related to steepness (Hs/λ)*
- *deep water: T related to λ*

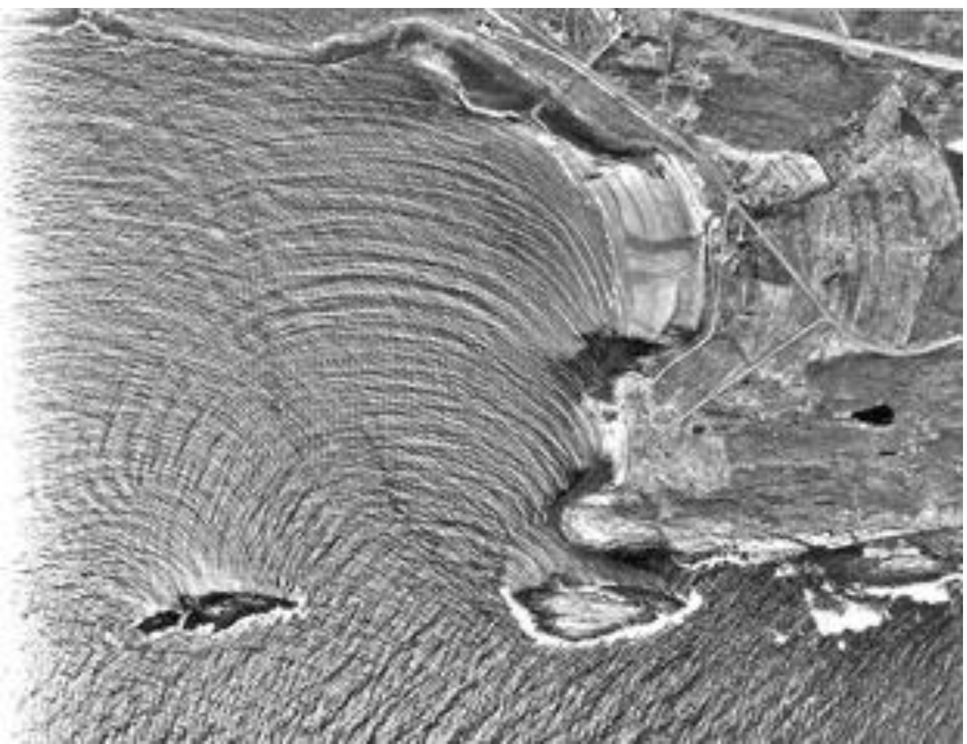
Other parameters:

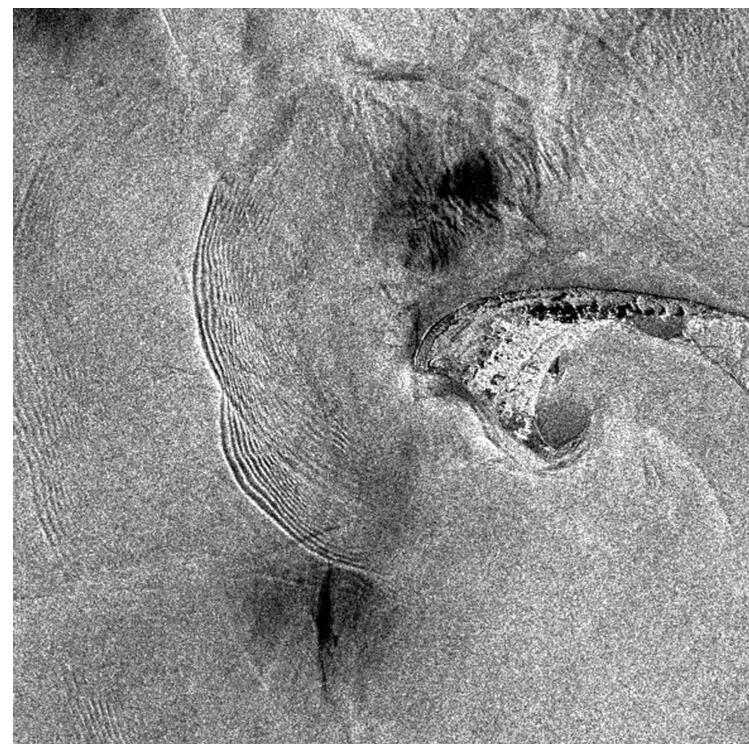
Wind
Internal waves
Surface slick

Other methods:
Wave detection also possible by Synthetic Aperture Radars (SAR)

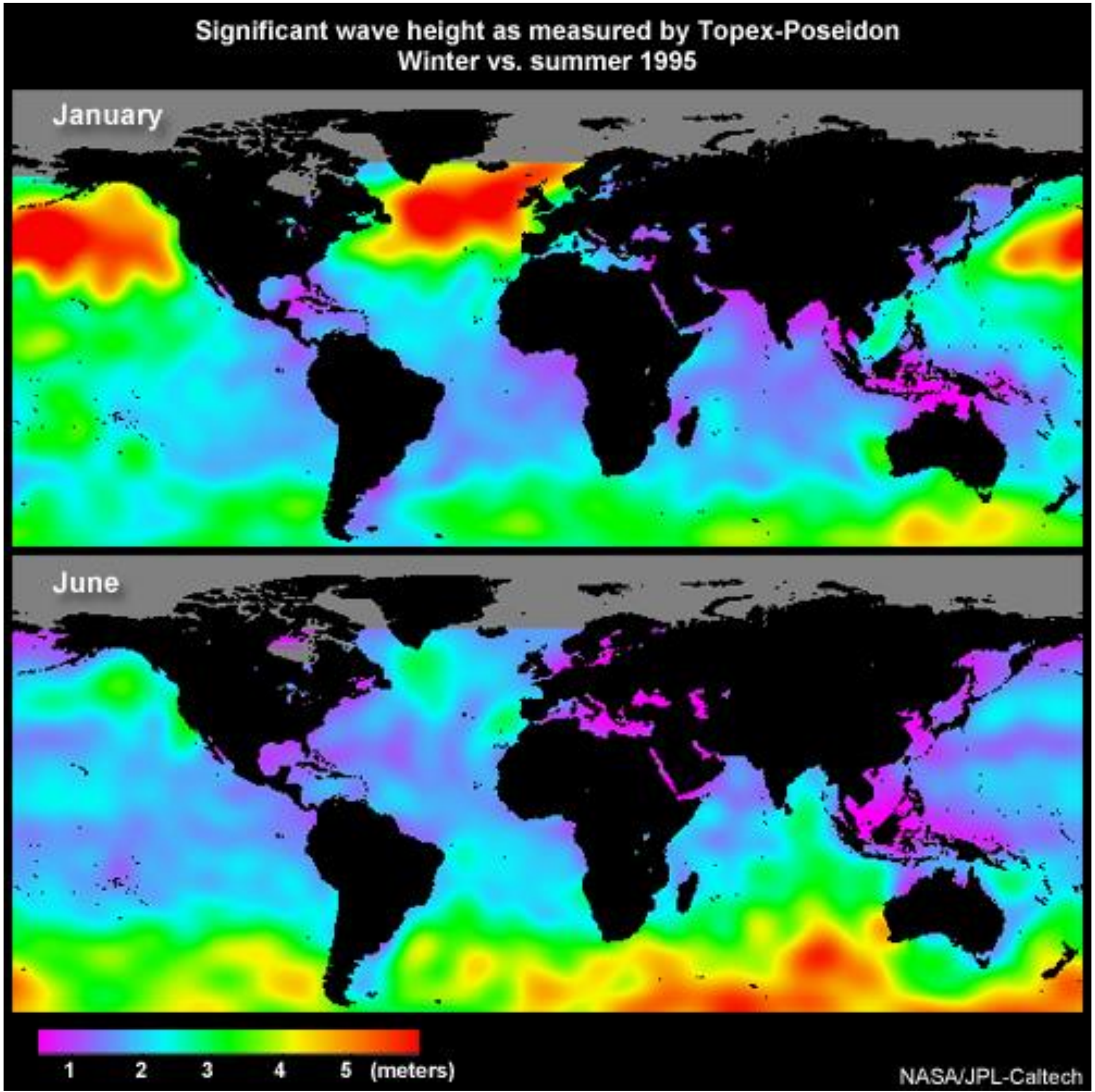
Radar Altimetry
Sea Surface
Roughness



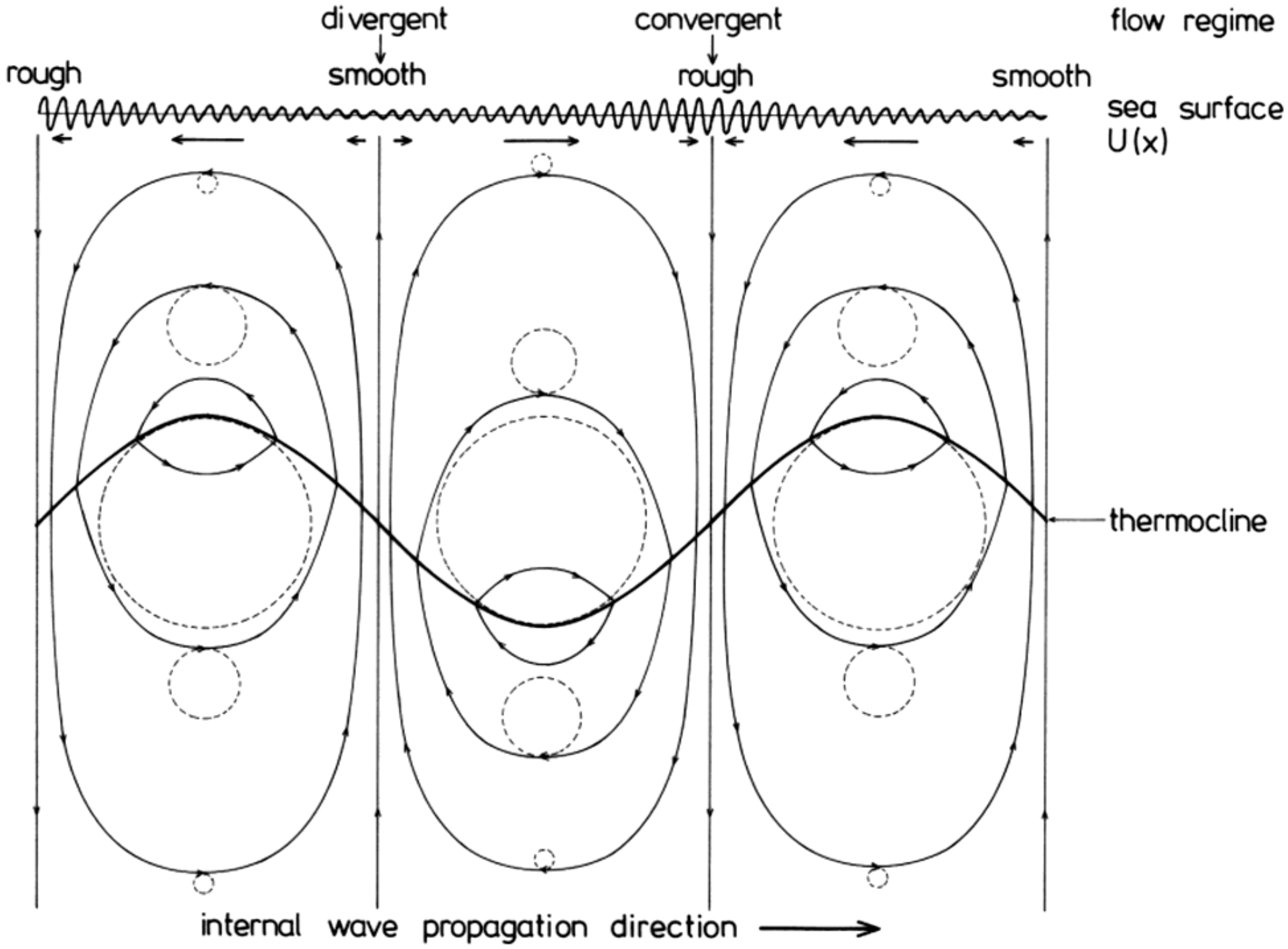




Global Waves

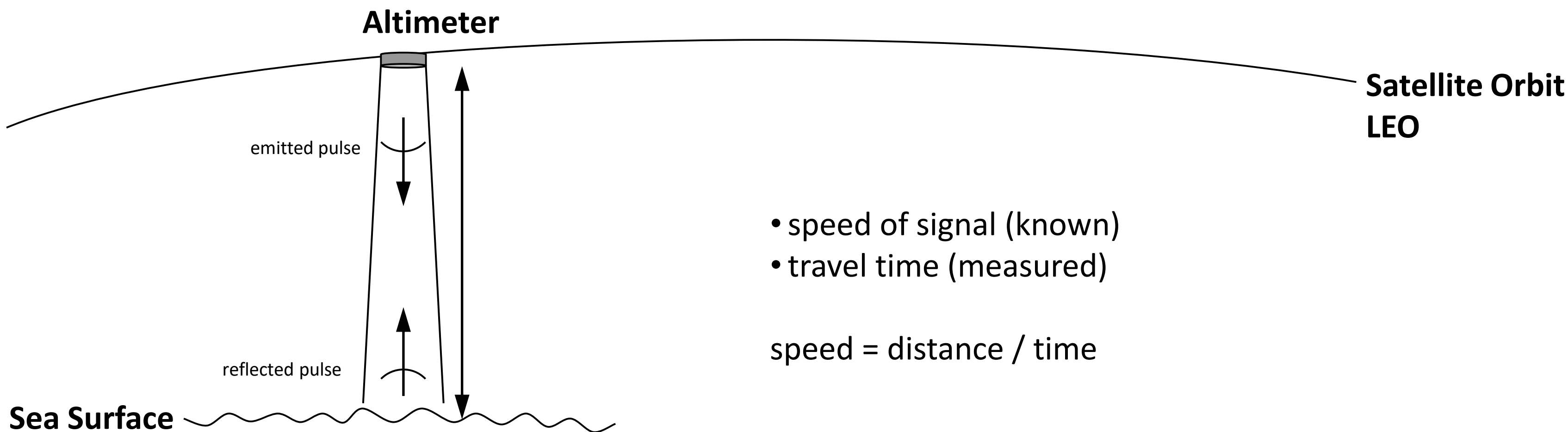


Satellite Altimetry Internal Waves



TerraSAR-X image dated July 4, 2008 of Cape Cod Bay, showing internal wave signatures as dark bands on a gray background (single-negative signature). The signature is typical in coastal zones in the presence of surface films.

Radar Altimetry

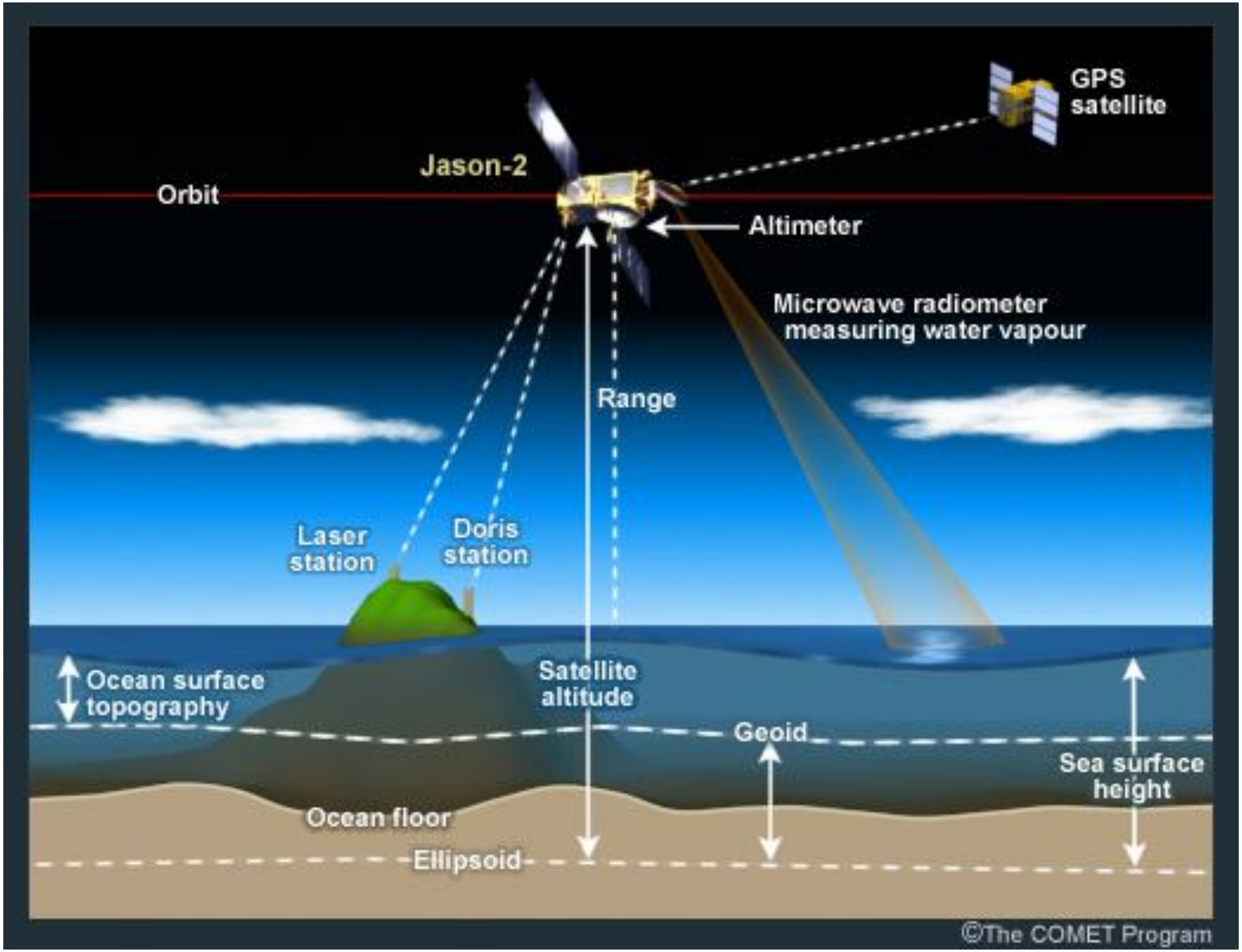


- speed of signal (known)
- travel time (measured)

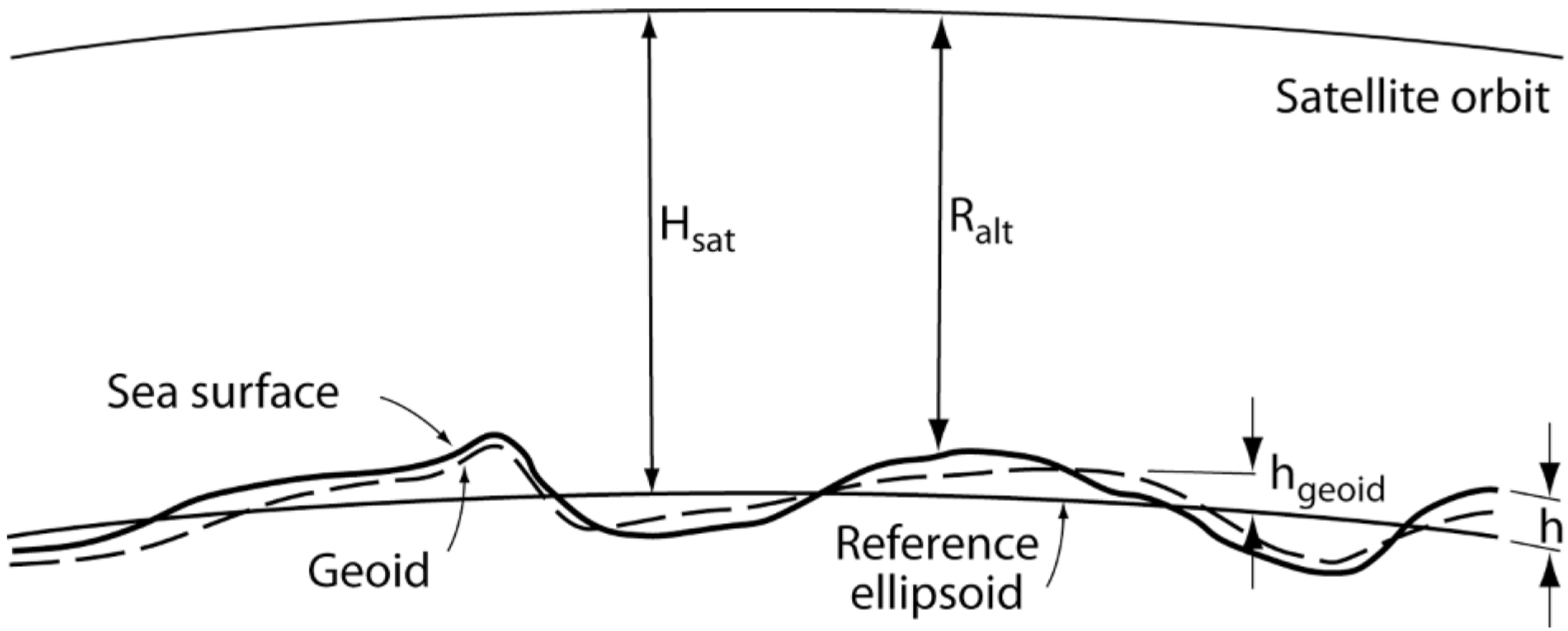
speed = distance / time

→ distance from radar to sea surface = c·t/2

Radar Altimetry – SS Height



Radar Altimetry – Geoid



H_{sat} (known): height of satellite orbit above reference ellipsoid
R_{alt} (measured): distance satellite ocean surface – satellite
h (computed): height of sea above reference level

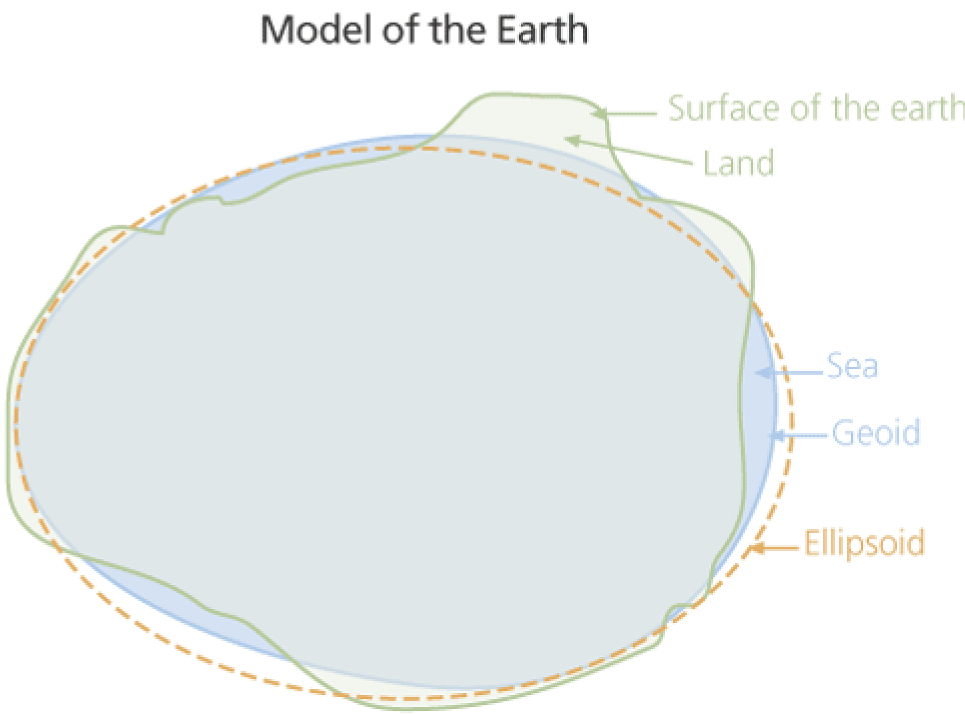
$$h = R_{alt} - H_{sat}$$

$$h = h_{geoid} + h_{dyn} + h_{tide} + h_{atm}$$

h_{geoid}: no change in short time = mean sea level

$h_{dyn} + h_{tide} + h_{atm}$: change in short time

Earth Geoid



All points on the geoid have the same gravity potential energy (the sum of gravitational potential energy and centrifugal potential energy).

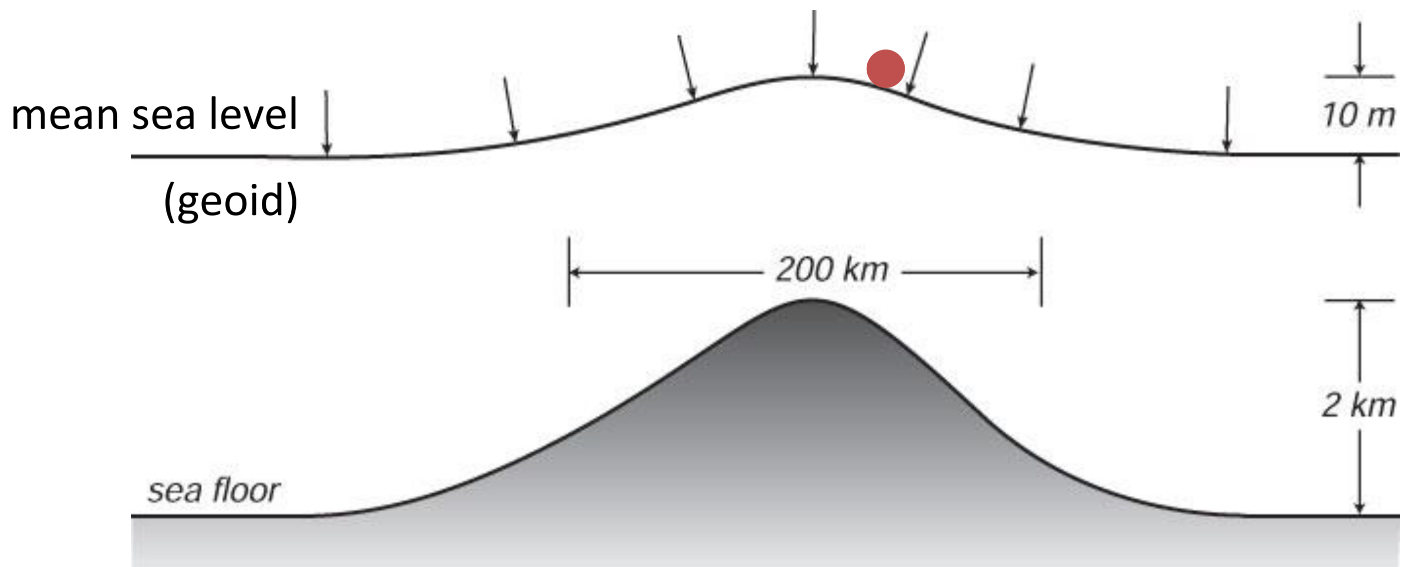
The geoid is the equipotential surface that would coincide with the mean ocean surface of Earth if the oceans and atmosphere were in equilibrium and at rest relative to the rotating Earth (no ocean currents winds or tides).

Sea Surface = geoid + *effects of*

- *ocean currents*
- *tides*
- *wind*
- *atm. pressure*

Sea Floor Topography from Sat. Altimetry

- Mapping of sea floor topography by space borne accurate radar altimeter
- Long-term- and in-situ data needed for correction and removal of dynamic sea surface features like waves, tides, eddies etc.

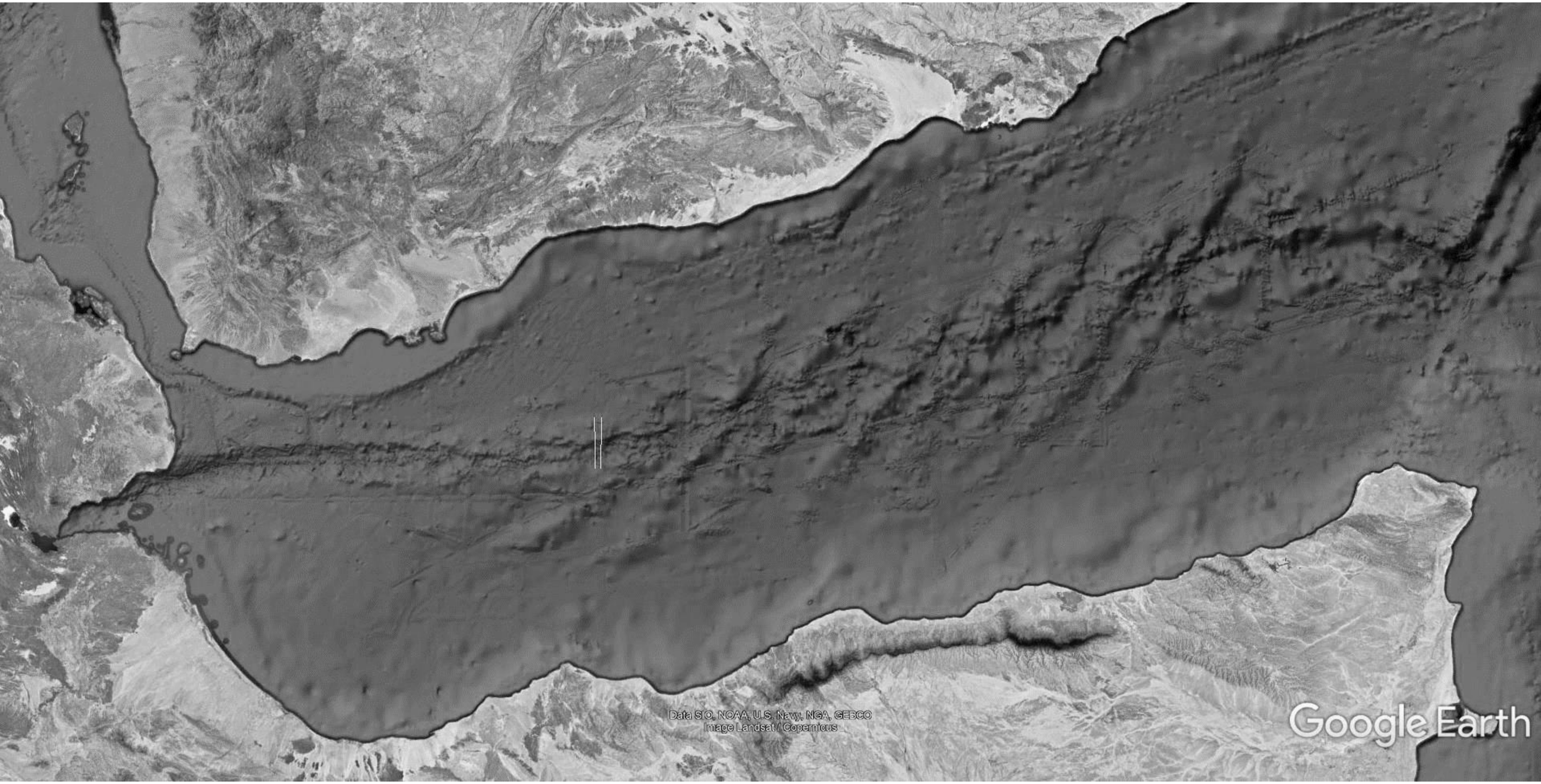


All points on the geoid have the same gravity potential

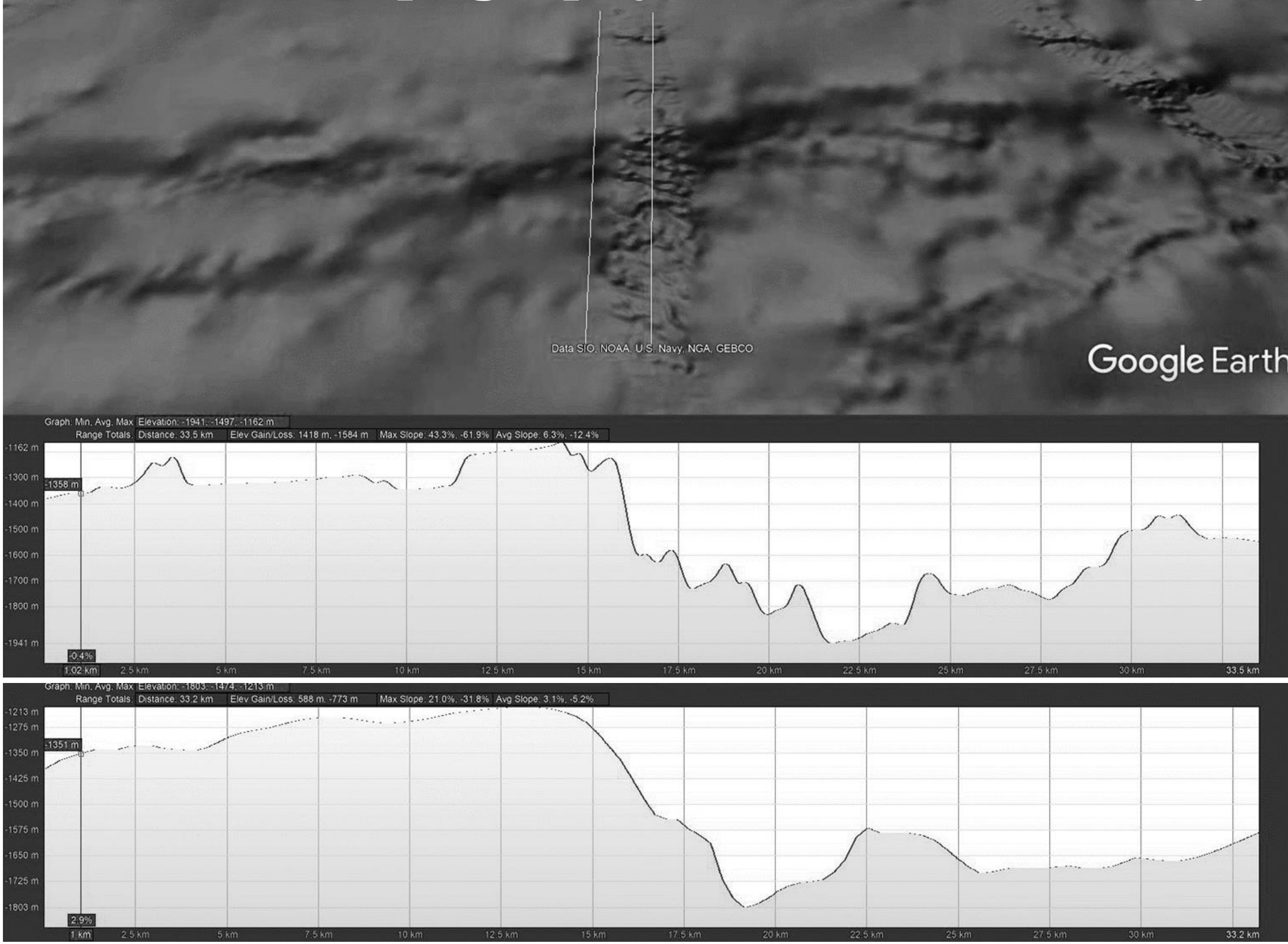
Gravity is determined by mass and distance

→ Sea floor topography can be seen in mean sea surface topography (geoid)

Sea Floor Topography from Sat. Altimetry



Sea Floor Topography from Sat. Altimetry



Radar Altimetry – Geoid

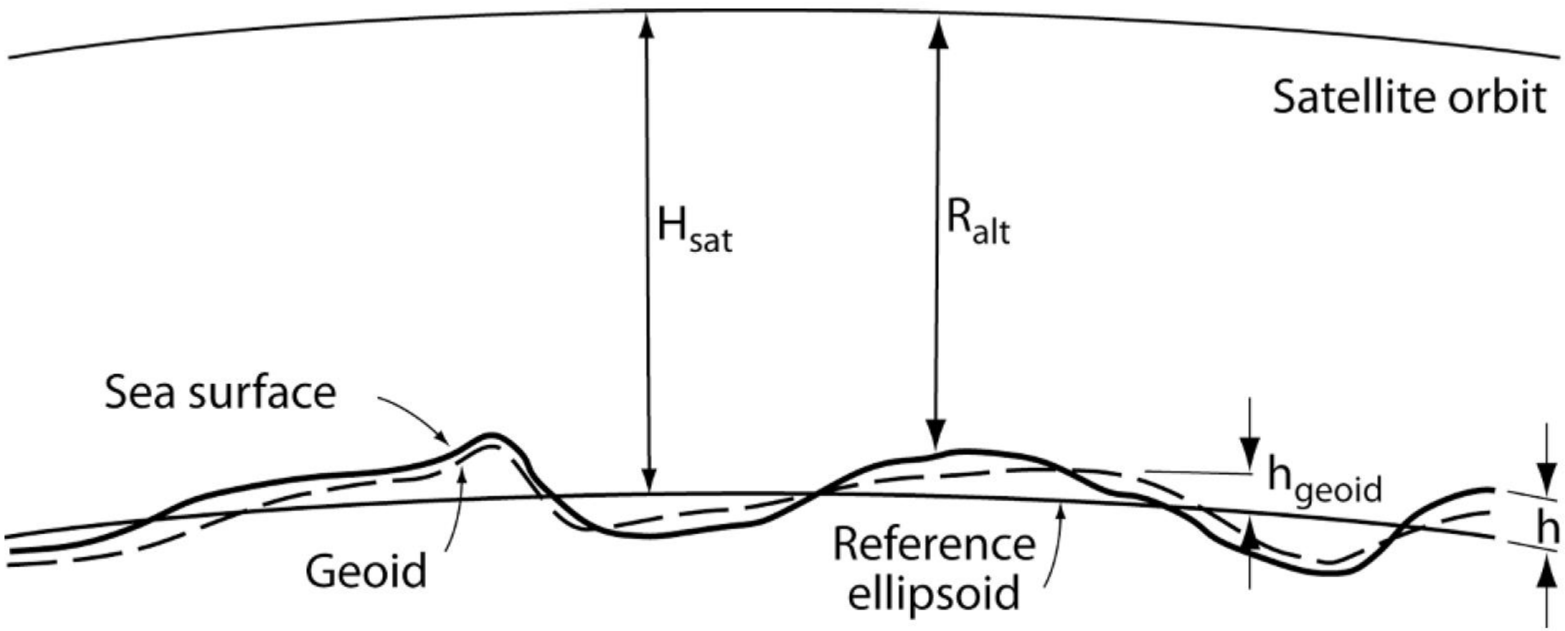


Figure 2.19. The relationship between different distance quantities used in altimetry.

H_{sat} (known): height of satellite orbit above reference ellipsoid
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$h_{dyn} + h_{tide} + h_{atm}$: change in short time

Tides

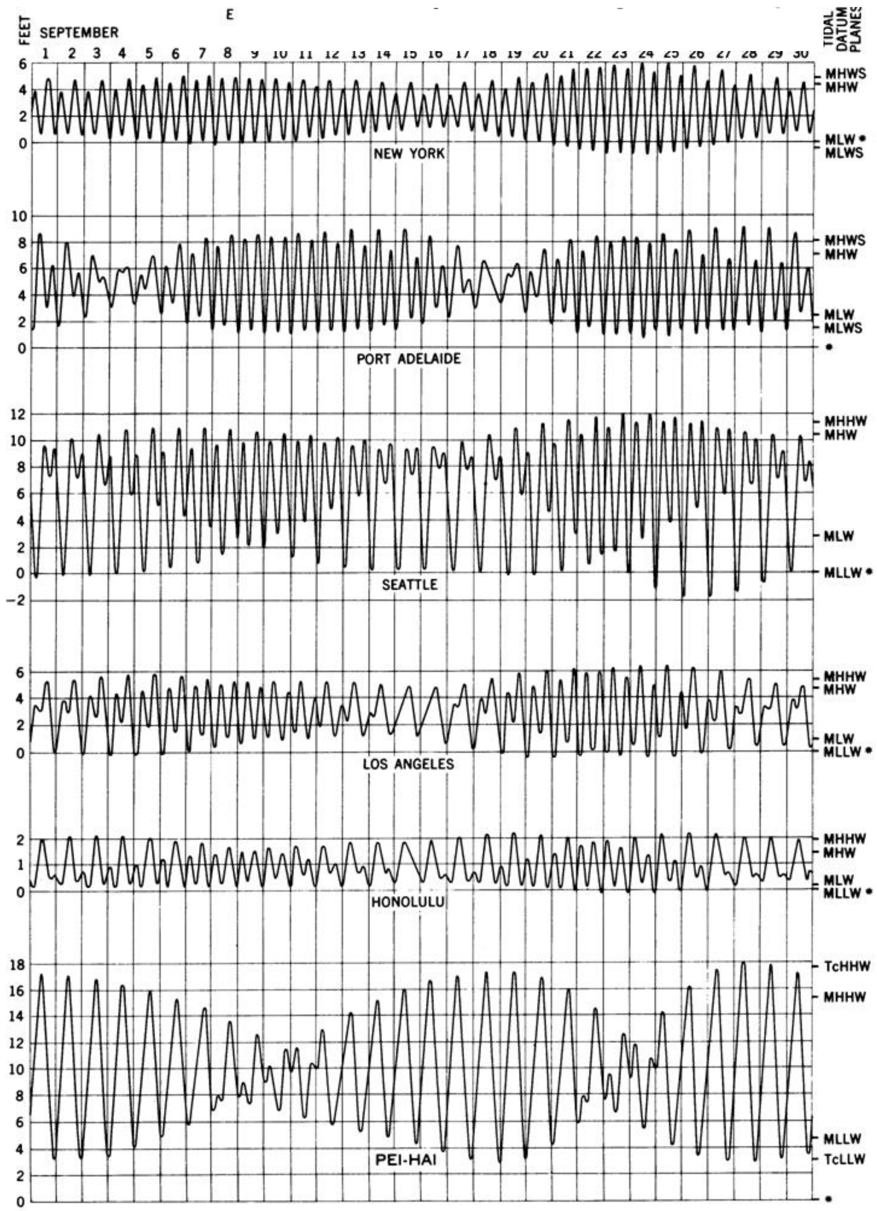
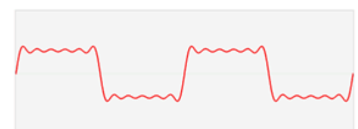
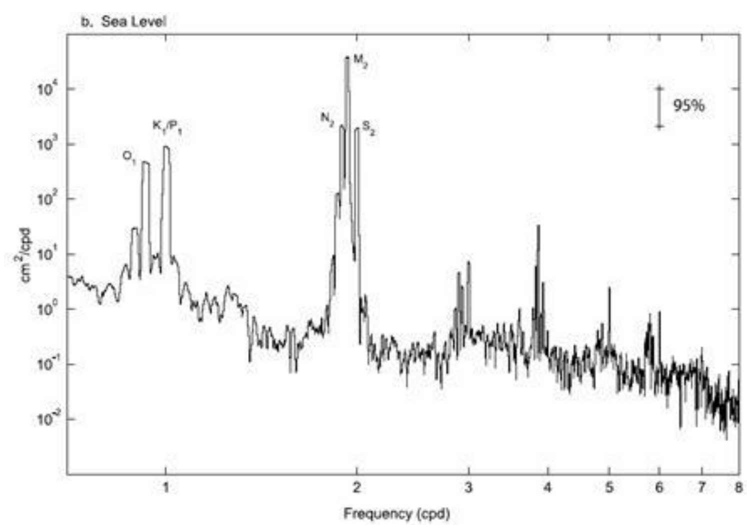


Table 2.1 Some principal tidal constituents. The coefficient ratio (column 4) is the ratio of the amplitude of the tidal component to that of M_2.

Name of tidal component	Symbol	Period in solar hours	Coefficient ratio ($M_2 = 100$)
Semi-diurnal:			
Principal lunar	M_2	12.42	100
Principal solar	S_2	12.00	46.6
Larger lunar elliptic	N_2	12.66	19.2
Luni-solar	K_2	11.97	12.7
Diurnal:			
Luni-solar	K_1	23.93	58.4
Principal lunar	O_1	25.82	41.5
Principal solar	P_1	24.07	19.4
Longer period:			
Lunar fortnightly	M_f	327.86	17.2
Lunar monthly	M_m	661.30	9.1

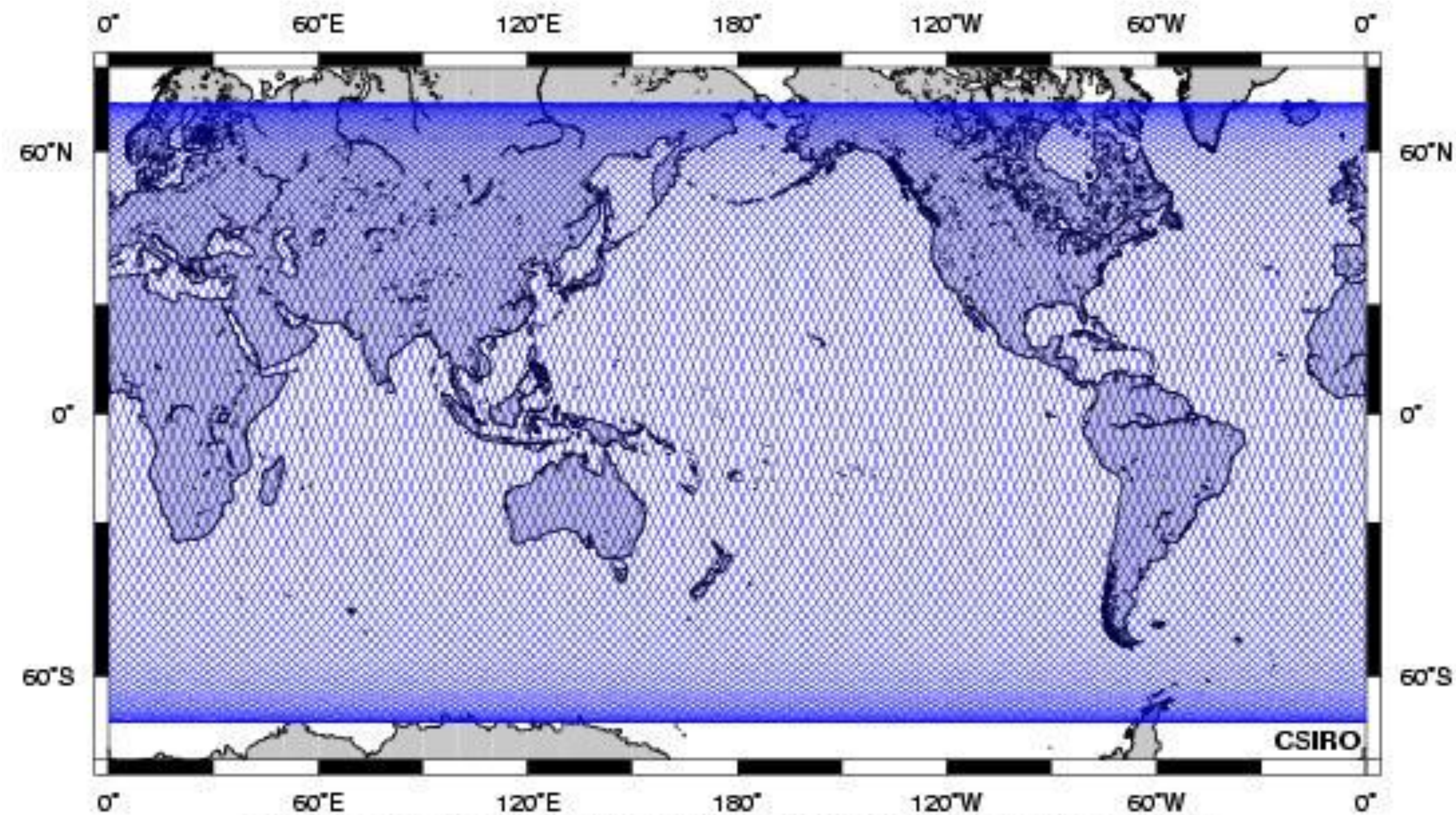




Satellite Altimetry - Tides

Long term record of SSH

→ Harmonic analysis
→ Global Tides

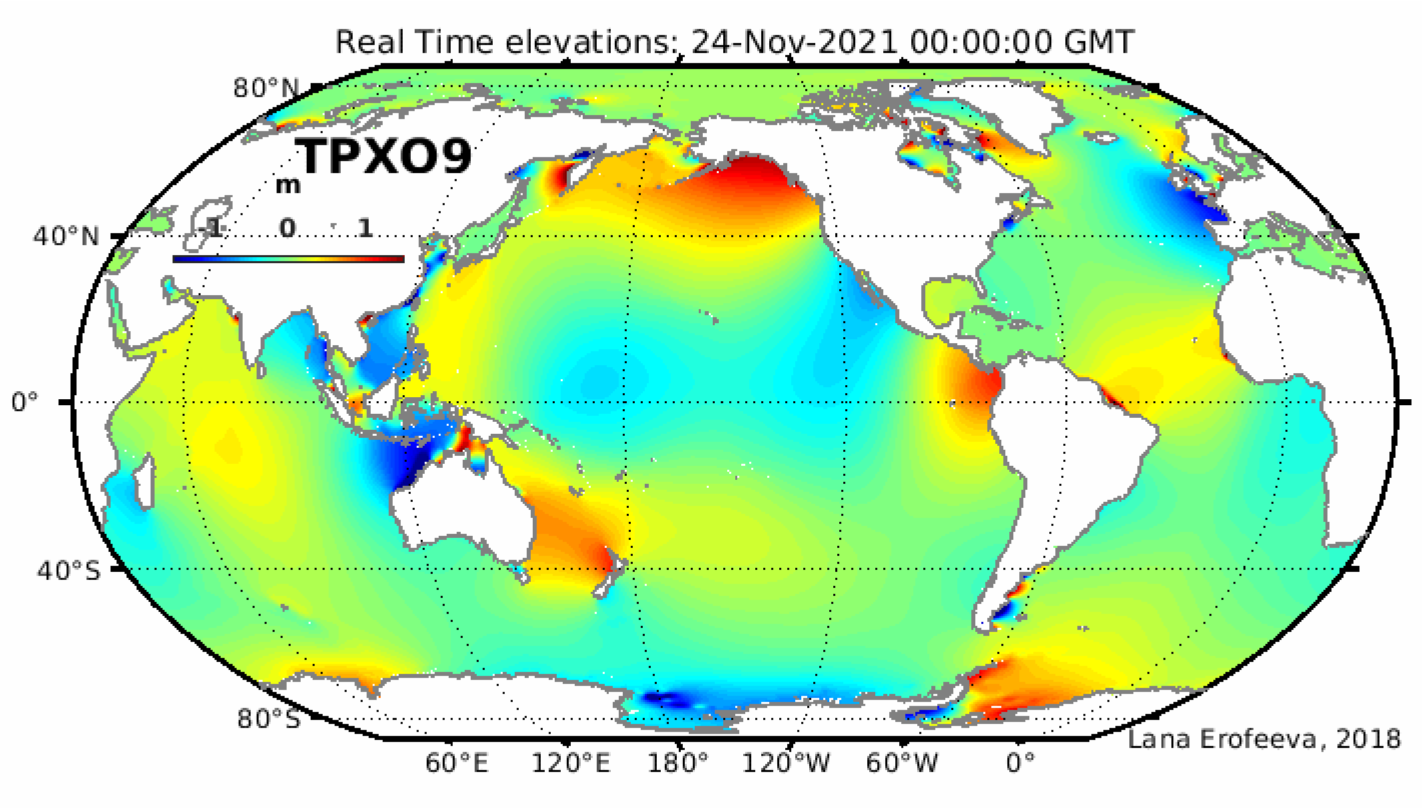


The ground track of one complete 10-day cycle of TOPEX/Poseidon

Tides

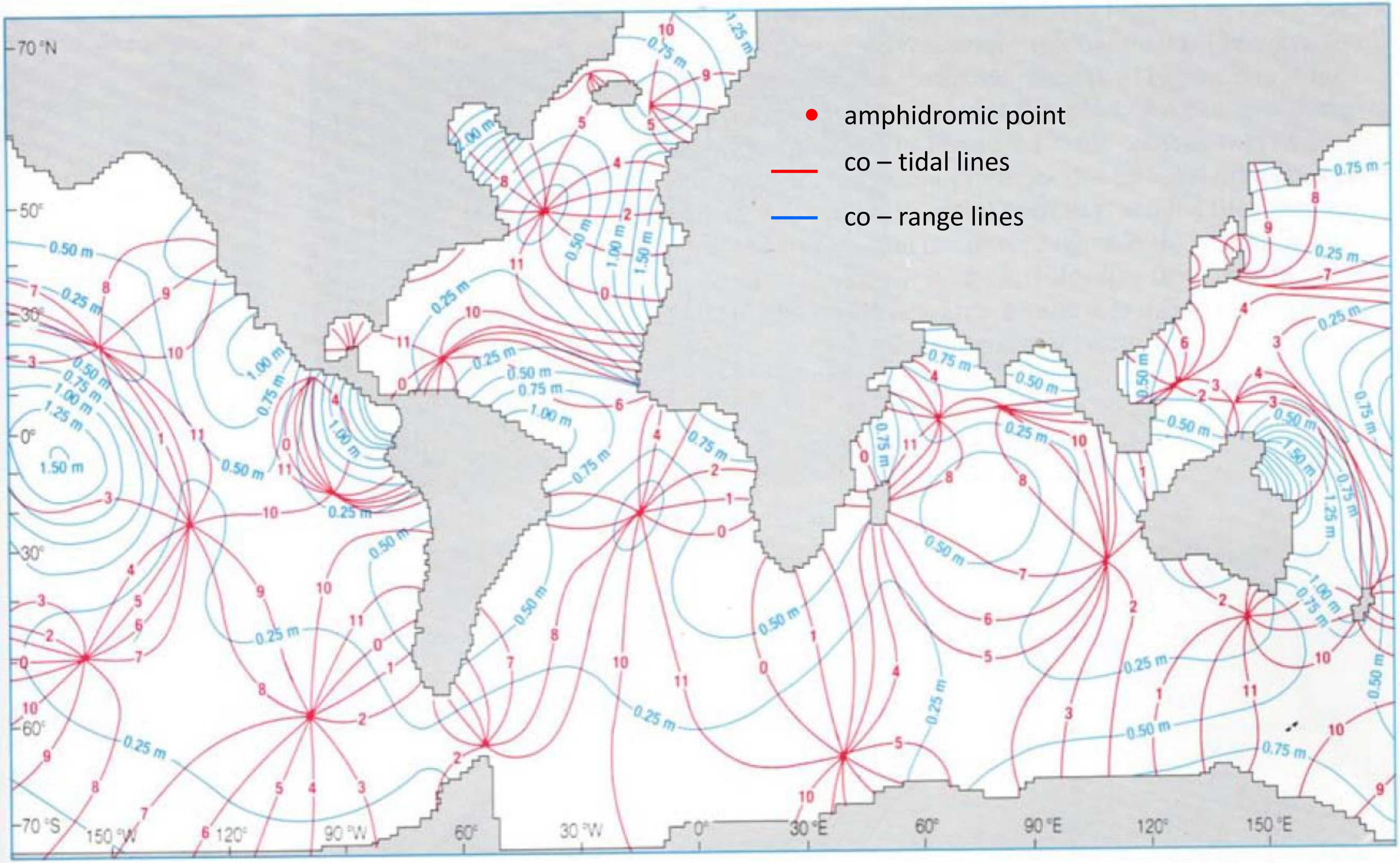
https://www.tpxo.net/home

TPXO is a global model of ocean tides, which best-fits, in a least-squares sense, the Laplace Tidal Equations and along track averaged data from TOPEX/Poseidon and Jason (Egbert&Erofeeva, 2002, 2010).



The tides are provided as complex amplitudes of earth-relative sea-surface elevation for eight primary (M2, S2, N2, K2, K1, O1, P1, Q1), two long period (Mf,Mm) and 3 non-linear (M4, MS4, MN4) harmonic constituents, on a 1440x721, 1/4 degree resolution full global grid (for versions 6.* and later).

Amphidromic Systems



Open Source Software
to work with TPXO data:

Fortran-90 OTPS
OSU Tidal Prediction Software

Matlab TMD
Tidal Model Driver

Harmonica
Aquaveo Python API

OTPS2FRC
ROMS tidal forcing

https://tpxows.azurewebsites.net/

YOUR PERSONAL INFO:

First name:

Last name:

E-mail:

YOUR TPXO9 FORECAST PARAMETERS

SSH(m): u,v(m/s):

Latitude:

Longitude:

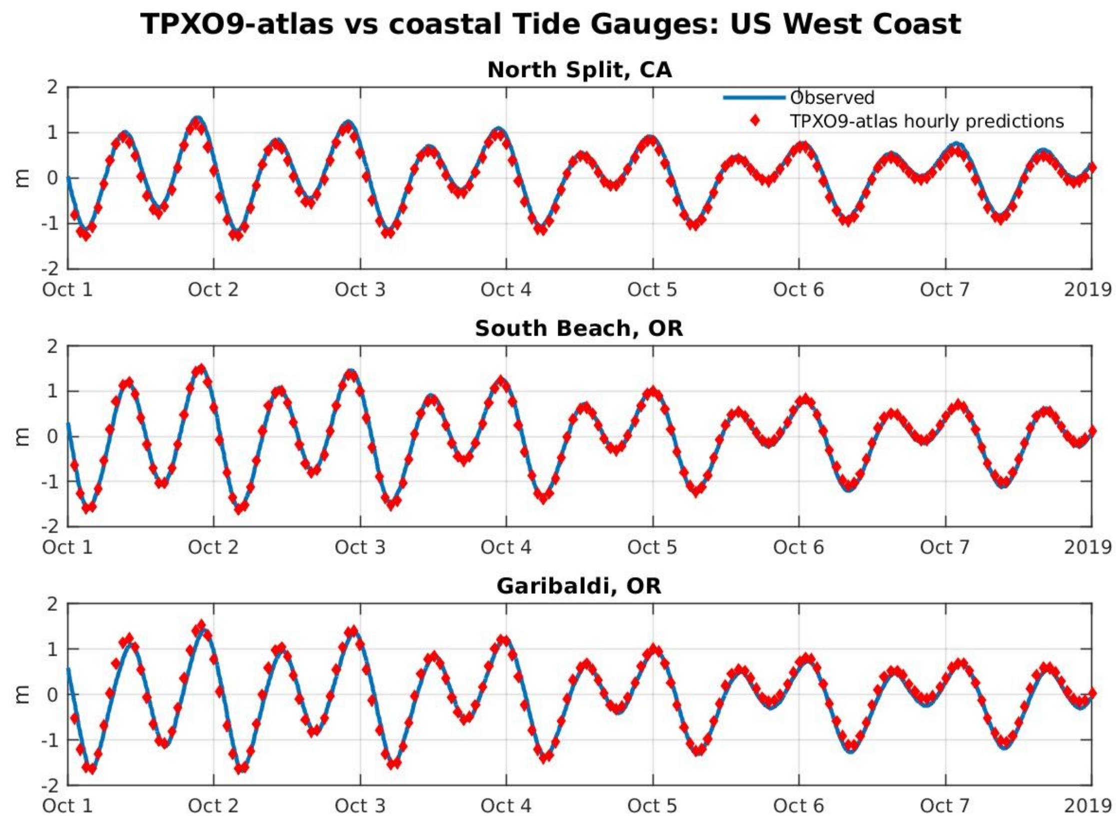
Starting Date mm / dd / yyyy

Starting Time GMT -- : -- --

For: 1 days

Submit Reset

Please fill out and submit the form.



Radar Altimetry – Geoid

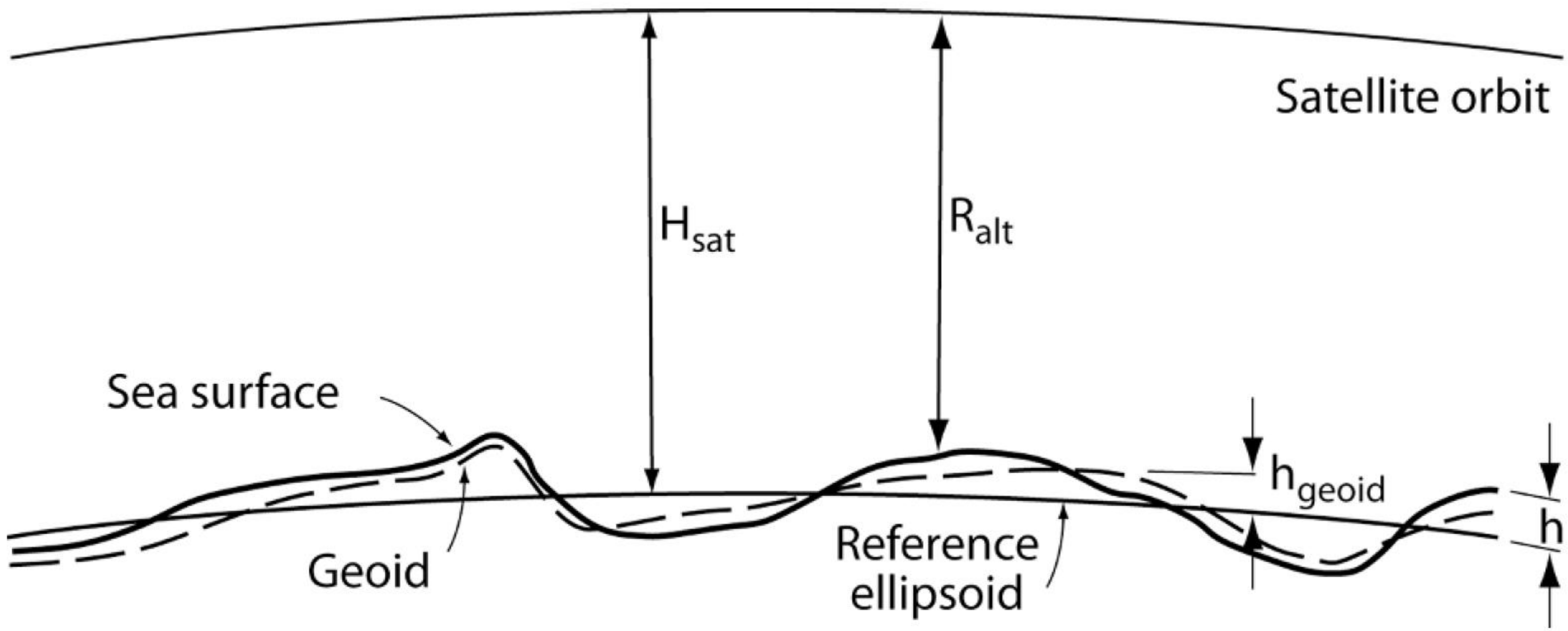


Figure 2.19. The relationship between different distance quantities used in altimetry.

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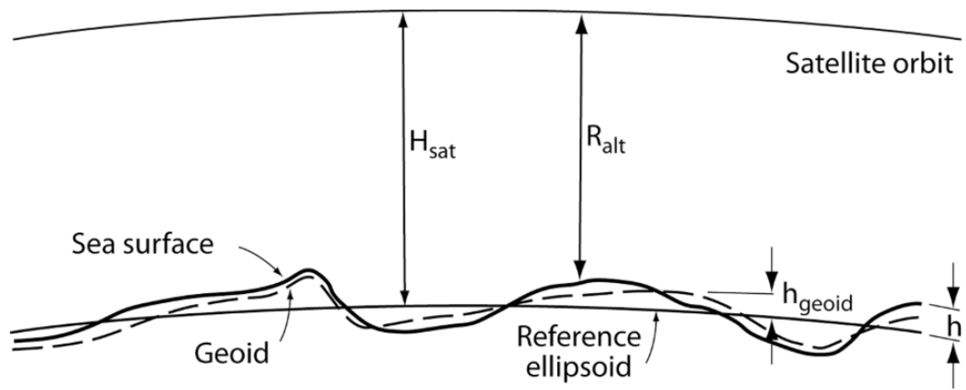
SSH Anomaly

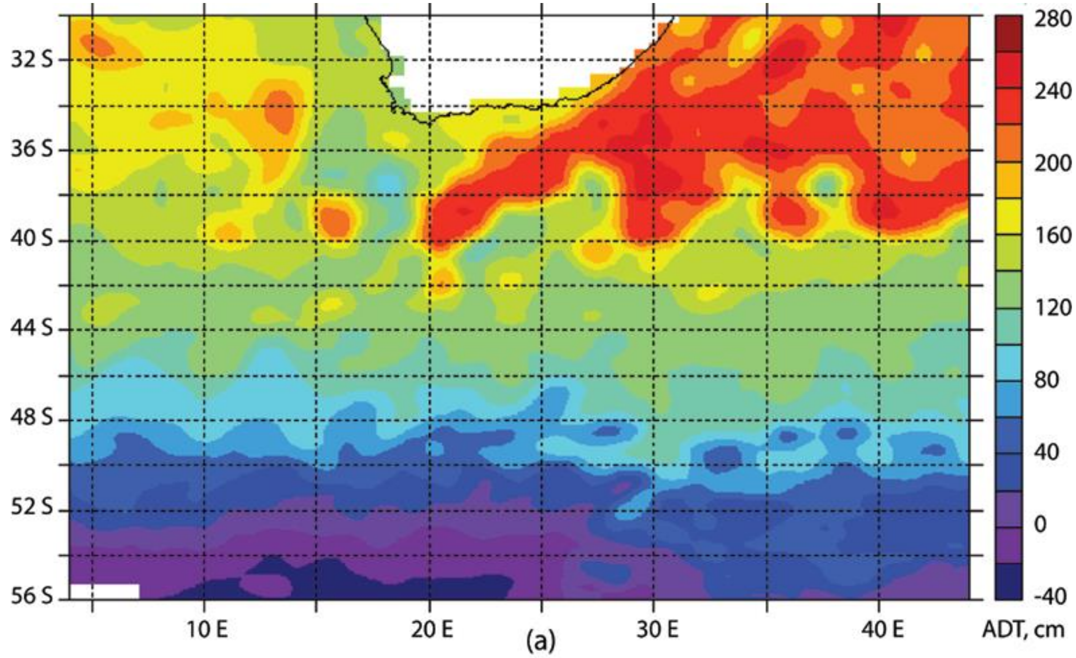


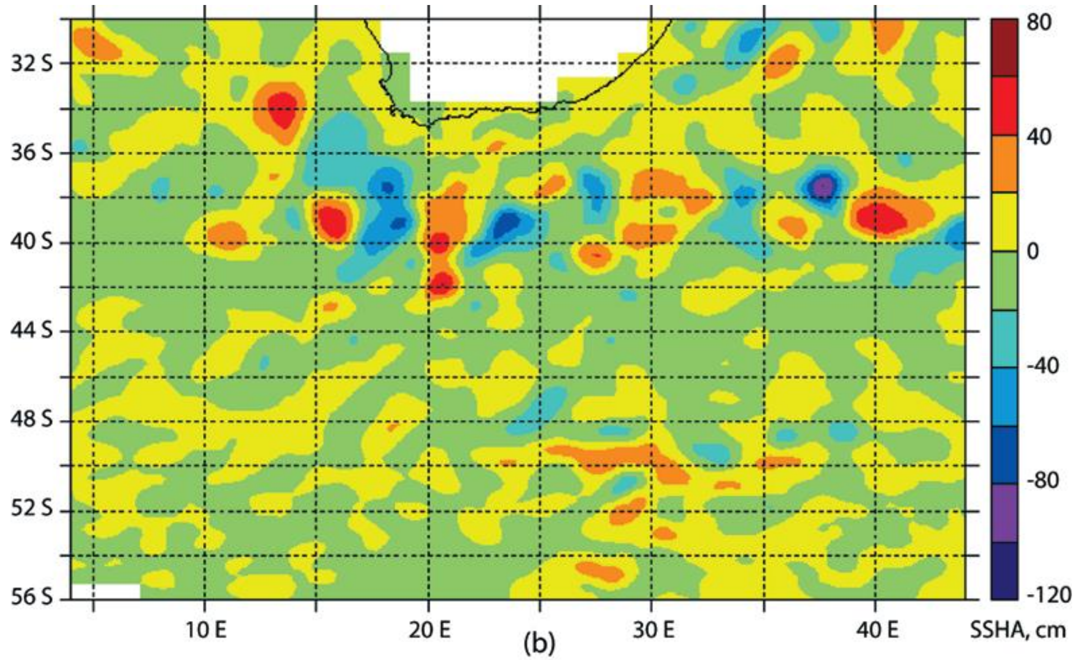
SSHA from - radar altimetry

- along-track record of surface height
- corrected at each sampled point along the given orbit track
  - removal of:
    - long-term mean height
    - tidal height signal (estimated from tidal analysis of the long-term altimeter record)
    - instantaneous effect of barometric pressure
    - wind influence
  - Requirement - mature altimetric program (TOPEX/Poseidon (T/P) plus Jason)

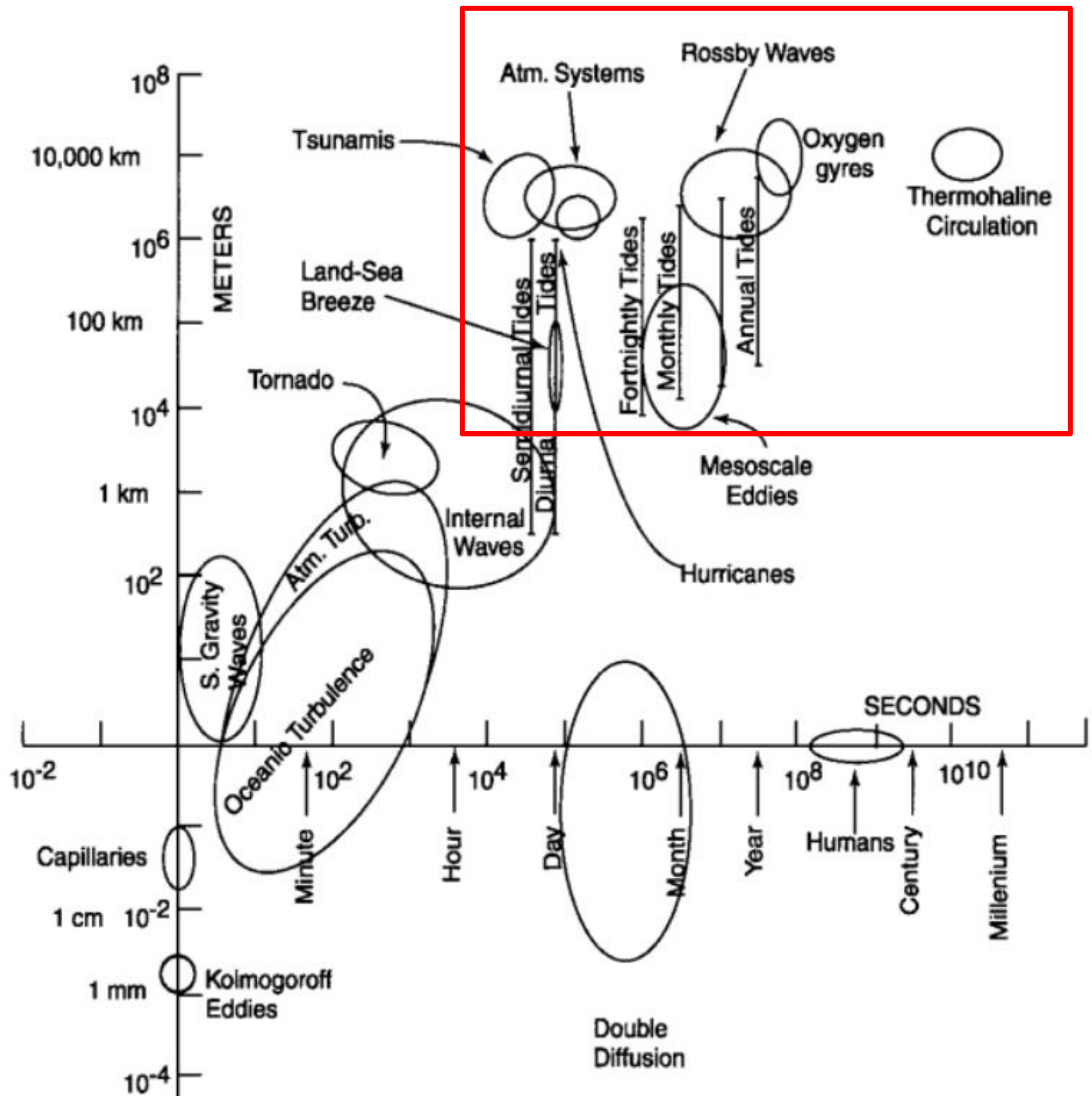
SSH Anomaly

Sea surface altimetry data products for the Southern Ocean off South Africa on August 25, 1993, produced as a SSALTO/DUACS merged product from all available altimetry records at the time, mapped onto a 1/3 grid. (a) Approximate absolute dynamic topography (ADT). (b) Sea surface height anomaly (SSHA) (from the AVISO website).





Scales in the Ocean and Atmosphere



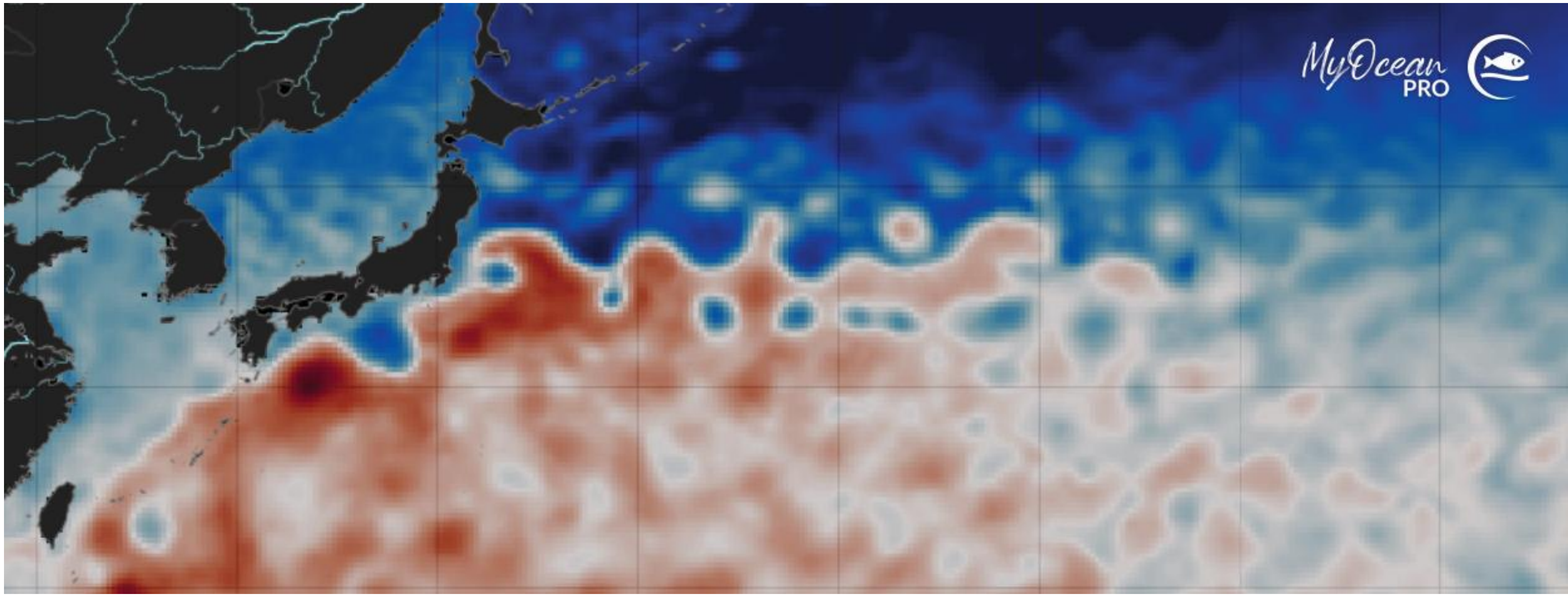
Scales in the Ocean and Atmosphere

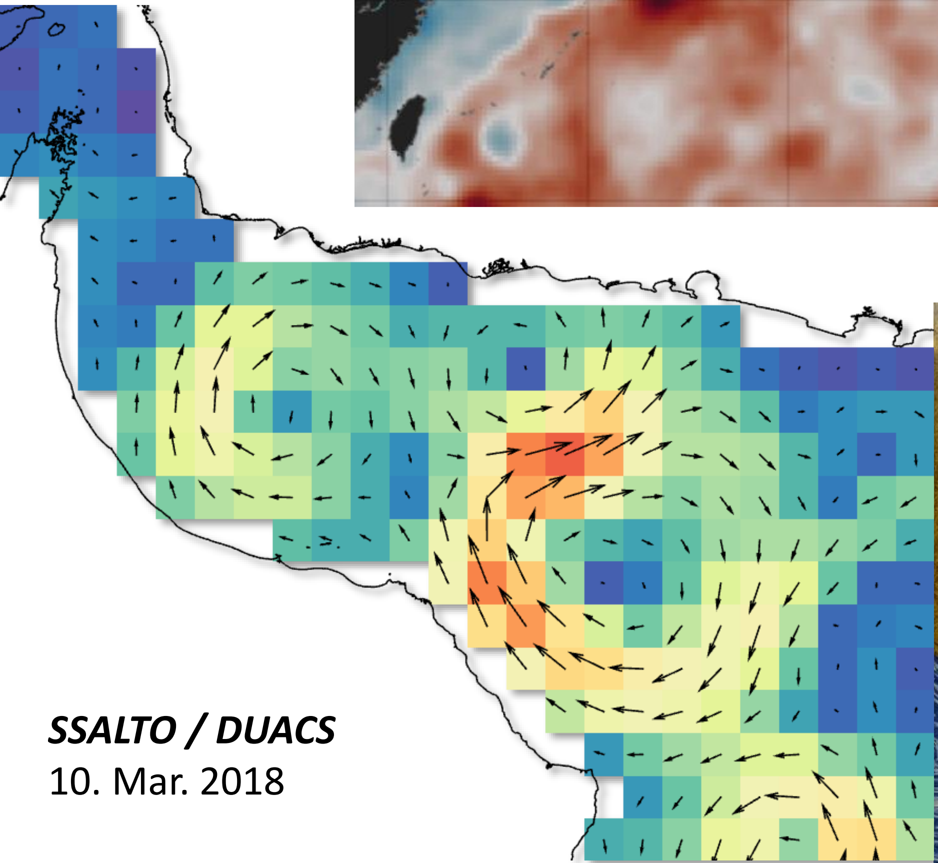
$$Ro = \frac{U}{L \cdot f}$$

Phenomena

Process	Length scale	Timescale	Rossby number
Dissipative scales	1–2 mm	~1 s	$\sim 10^4$
Vertical mixing (ocean)	1–100 m	several minutes	$\sim 10^2$
Vertical mixing (atm)	1–1000 m	several minutes	$\sim 10^2$–10^3
Surface waves	1–100	several seconds	~ 10–10^2
Internal waves	1–10 km	mins–hrs	$\sim 10^{-1}$–1
Double diffusion	1 cm–10 m	days–weeks	~10
Coastal upwelling	10–20 km	days	$\sim 10^{-1}$–1
Mesoscale eddies	10–400 km	weeks–months	$\sim 10^{-1}$
Atm. weather patterns	100–5000 km	days–weeks	$\sim 10^{-1}$–1
Ocean fronts	5–50 km	weeks	$\sim 10^{-1}$
Boundary currents	50–100 km	months	$\sim 10^{-1}$
Basin gyres	2000–15000 km	years	$\sim 10^{-2}$
Ocean tides	100–1000 km	1/2, 1 day, ...	$\sim 10^{-4}$–10^{-2}
Tornadoes	few km	<1 hr	$\sim 10^3$
Hurricanes	500–2000 km	days	~10
Rossby waves	1000 km	months–years	$\sim 10^{-3}$
Tsunamis	100 km	day	$\sim 10^2$
Land–sea breeze	10–50 km	1/2 day	~1

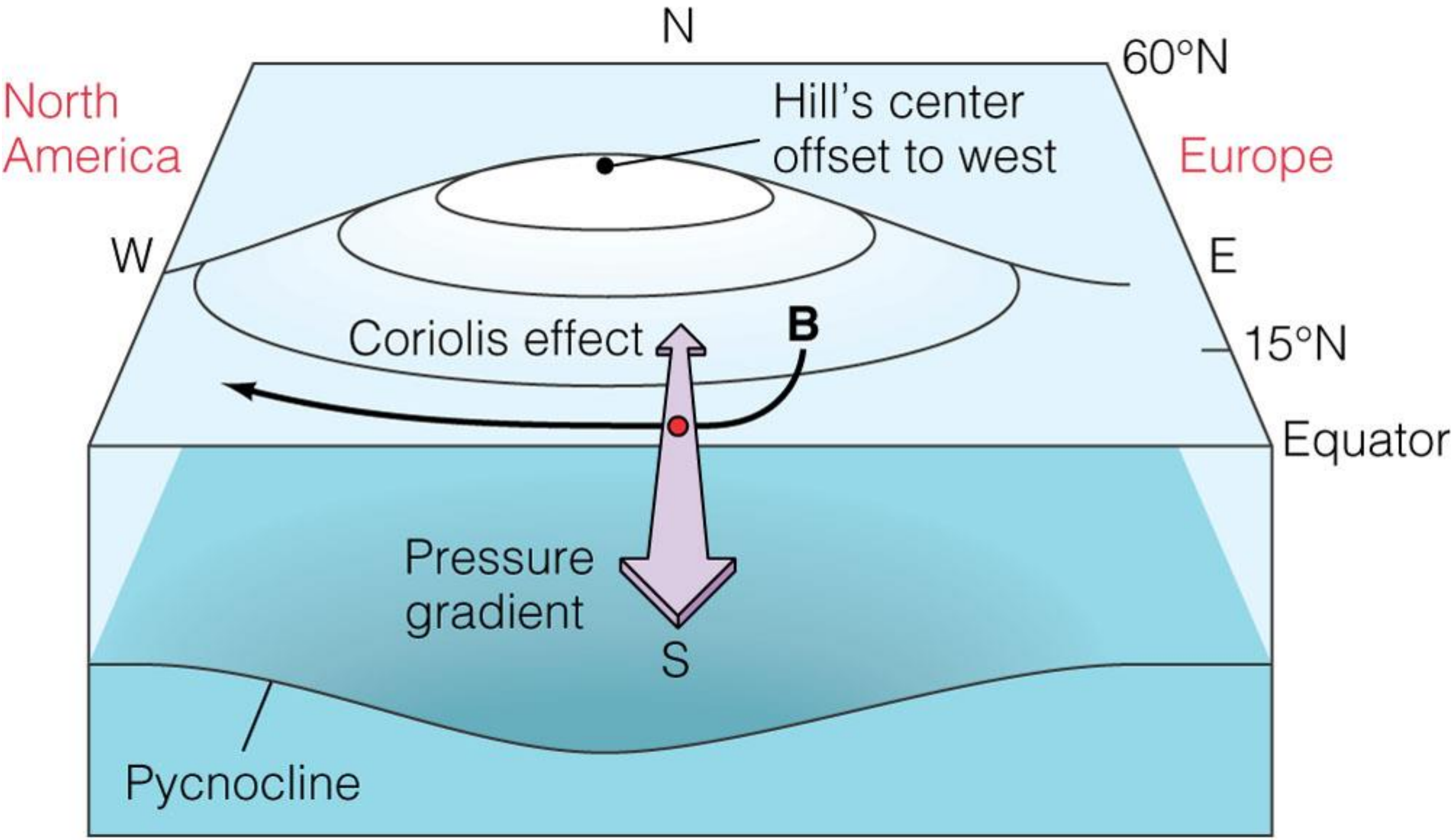
Mesoscale Variability in the Ocean





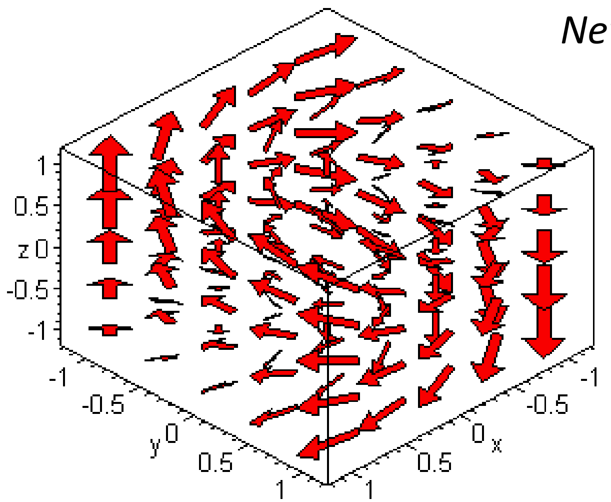
SSALTO / DUACS
10. Mar. 2018

Eddies



N
60°N
North America
Hill's center offset to west
Europe
W
E
B
Coriolis effect
15°N
Equator
Pressure gradient
S
Pycnocline

Geostrophic Flow



Equation of Motion

Newton / Euler / Navier Stokes

$$m\frac{dv}{dt} = F$$

Earth Rotation

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

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

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

Pressure Gradients

Friction

Gravity

Assumptions: Acceleration = 0
Friction is small

$$fv = -\frac{1}{\rho}\frac{\partial p}{\partial x}; \quad fu = -\frac{1}{\rho}\frac{\partial p}{\partial y}; \quad g\rho = -\frac{\partial p}{\partial z}$$

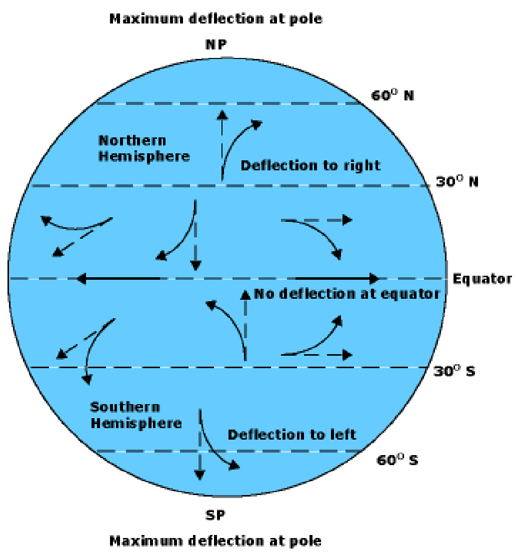
$$f = 2\cdot\Omega\cdot\sin\Phi$$

Rotation of the Earth

Gaspard-Gustave Coriolis, 1835

$$f = 2 \cdot \Omega \cdot \sin \Phi$$

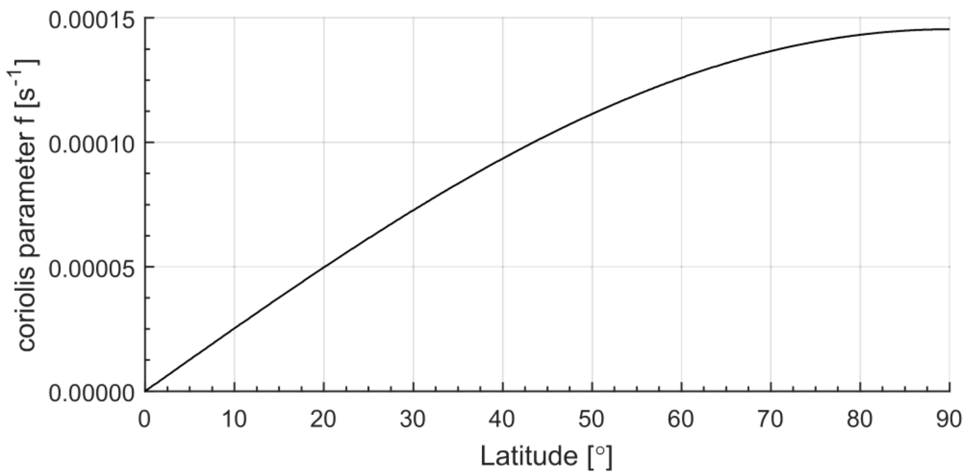
$$\Omega = \frac{360°}{24h} = 15 \,{}^{\circ}\!/_{h}$$

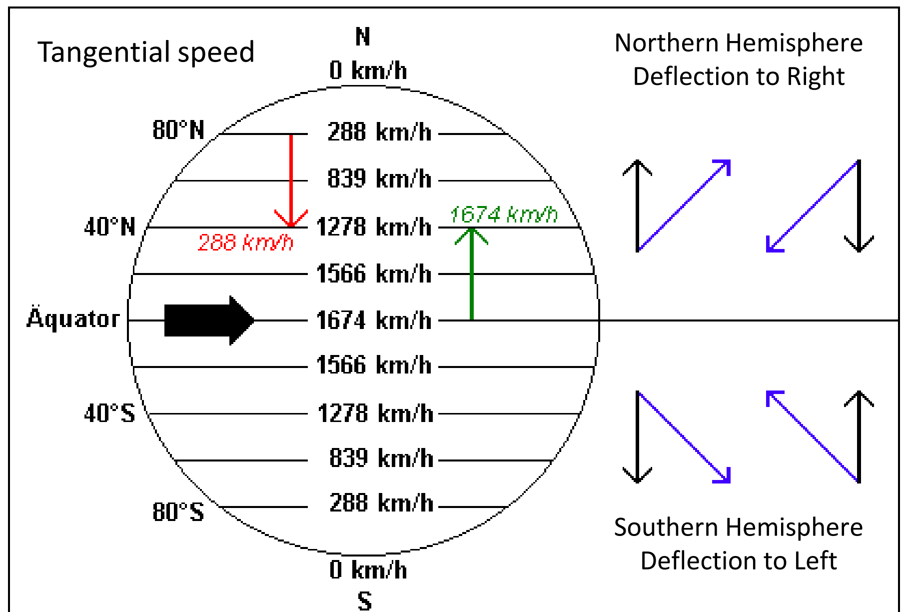


Carl-Gustaf Rossby

$$Ro = \frac{U}{L \cdot f}$$

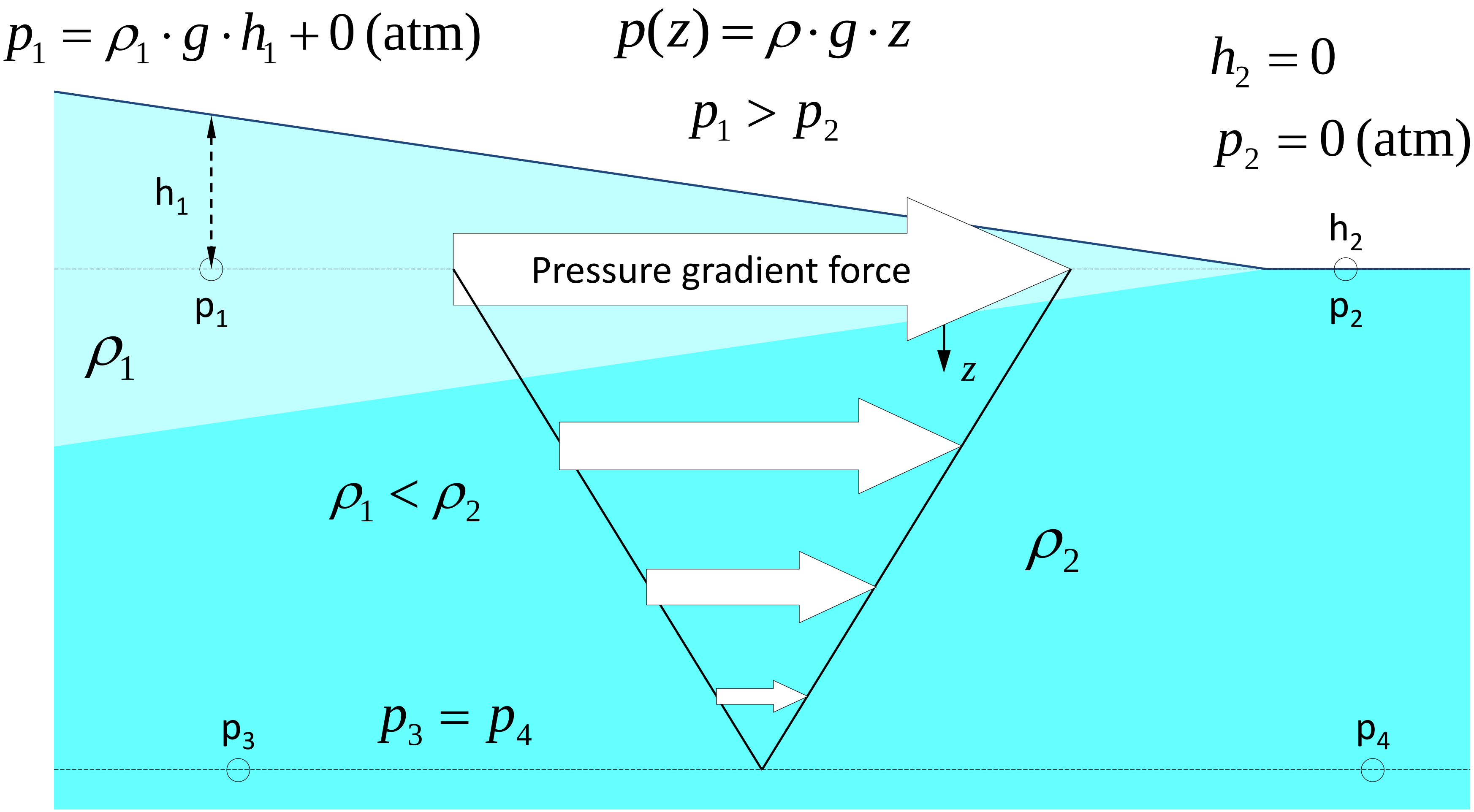
http://www.dartmouth.edu/~ears5/handouts/Coriolis.html





Coriolis Force

Horizontal Pressure Gradient Force



Horizontal Pressure Gradient

→ *Ocean Circulation: Section 3.3.1*

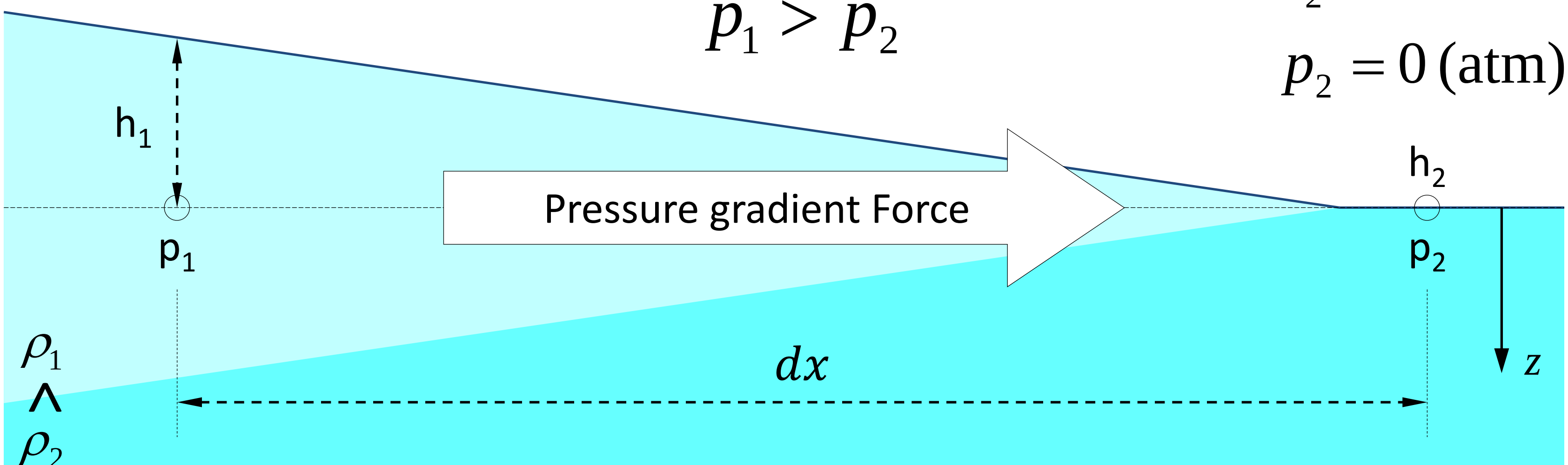
$$p(z) = \rho \cdot g \cdot z$$

$$p_1 = \rho_1 \cdot g \cdot h_1 + 0\,(\text{atm})$$

$$h_2 = 0$$

$$p_1 > p_2$$

$$p_2 = 0\,(\text{atm})$$



$$\frac{F_{hpg}}{mass} = \frac{1}{\rho}\frac{dp}{dx}$$

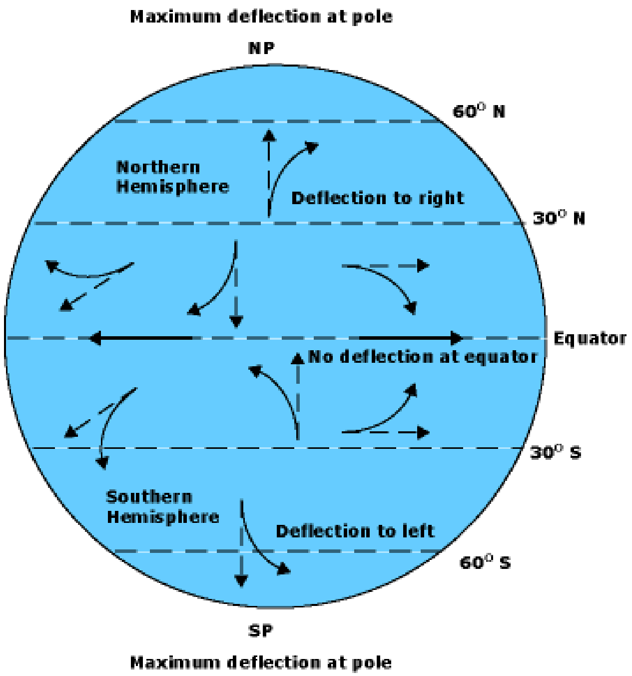
$$fv = -\frac{1}{\rho}\frac{\partial p}{\partial x}; \quad fu = -\frac{1}{\rho}\frac{\partial p}{\partial y}; \quad g\rho = -\frac{\partial p}{\partial z}$$

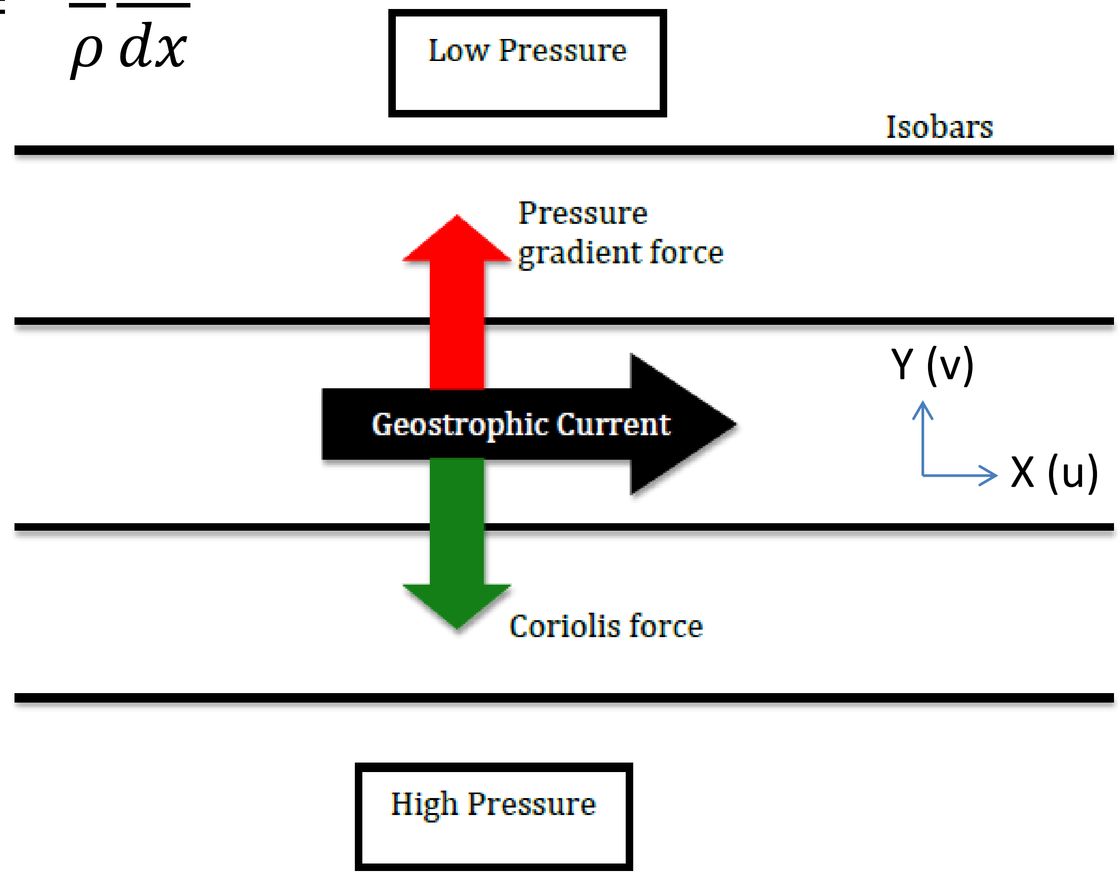
Geostrophic Flow

Coriolis Force = Horizontal Pressure Gradient Force

$$f \cdot u = -\frac{1}{\rho}\frac{dp}{dy}$$

$$f \cdot v = \frac{1}{\rho}\frac{dp}{dx}$$





Geostrophic Flow + Eddies

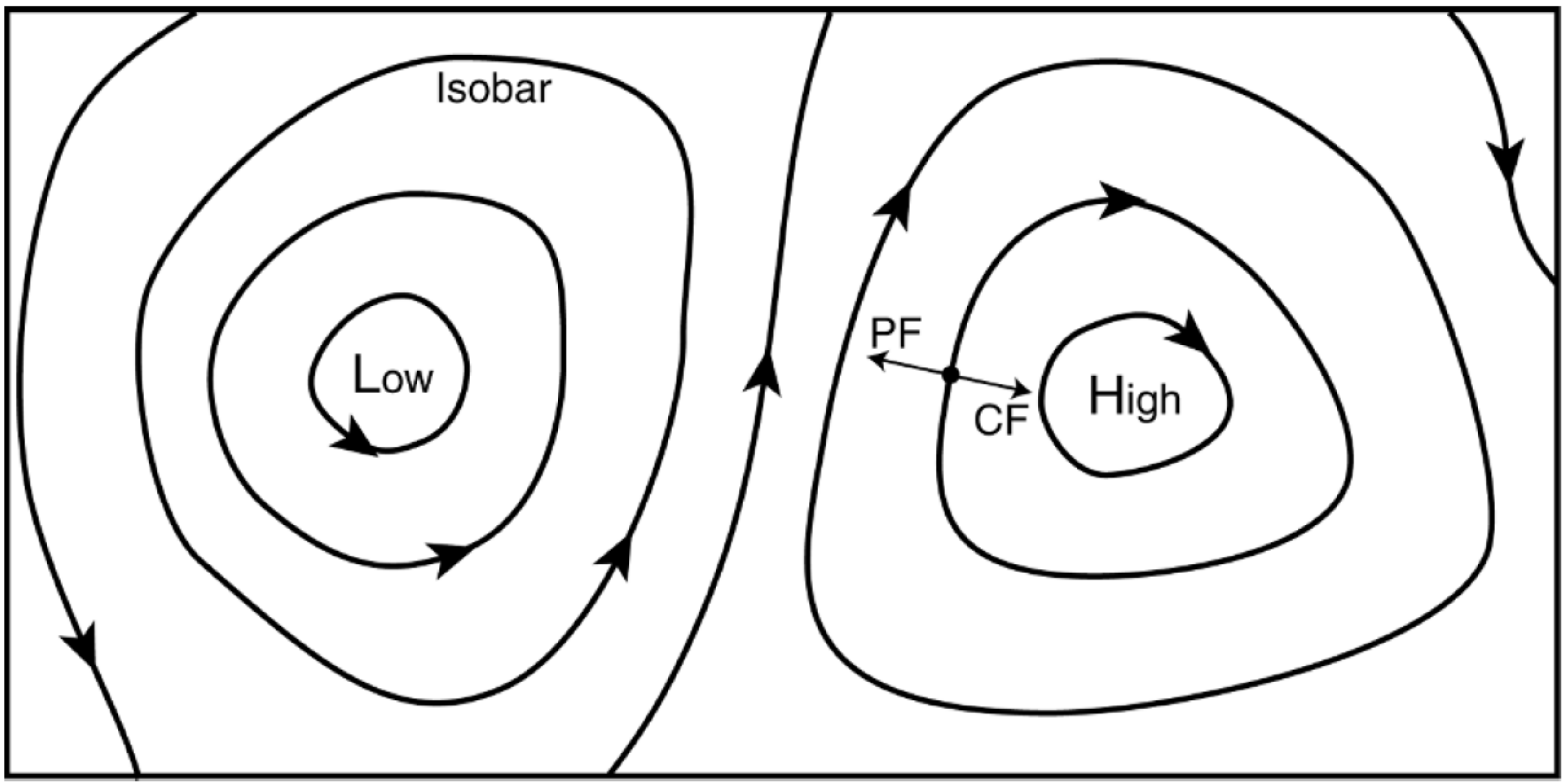


Figure 3.5. Part of a geostrophic flow field with steady flow along isobars (northern hemisphere).

Eddies

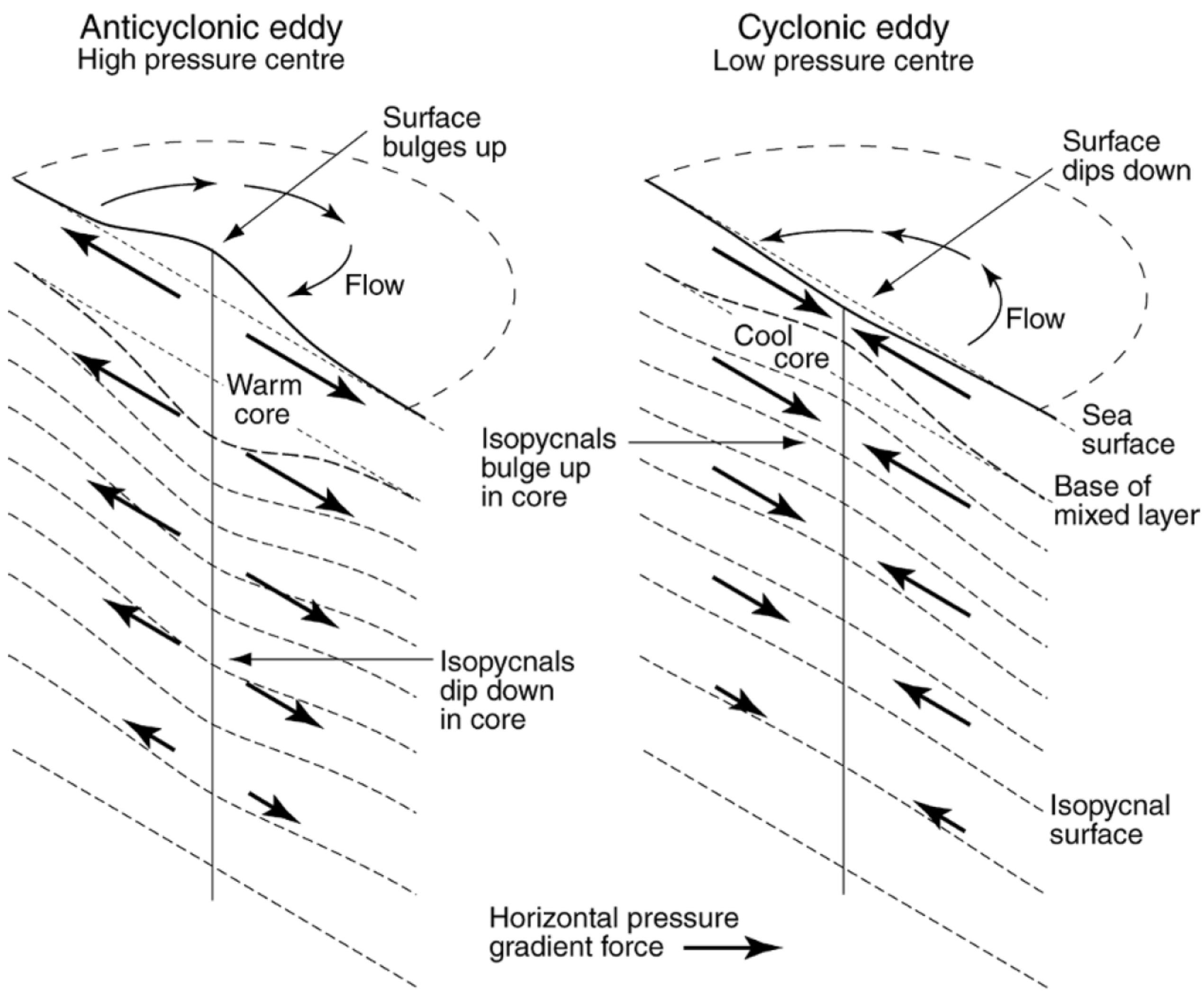
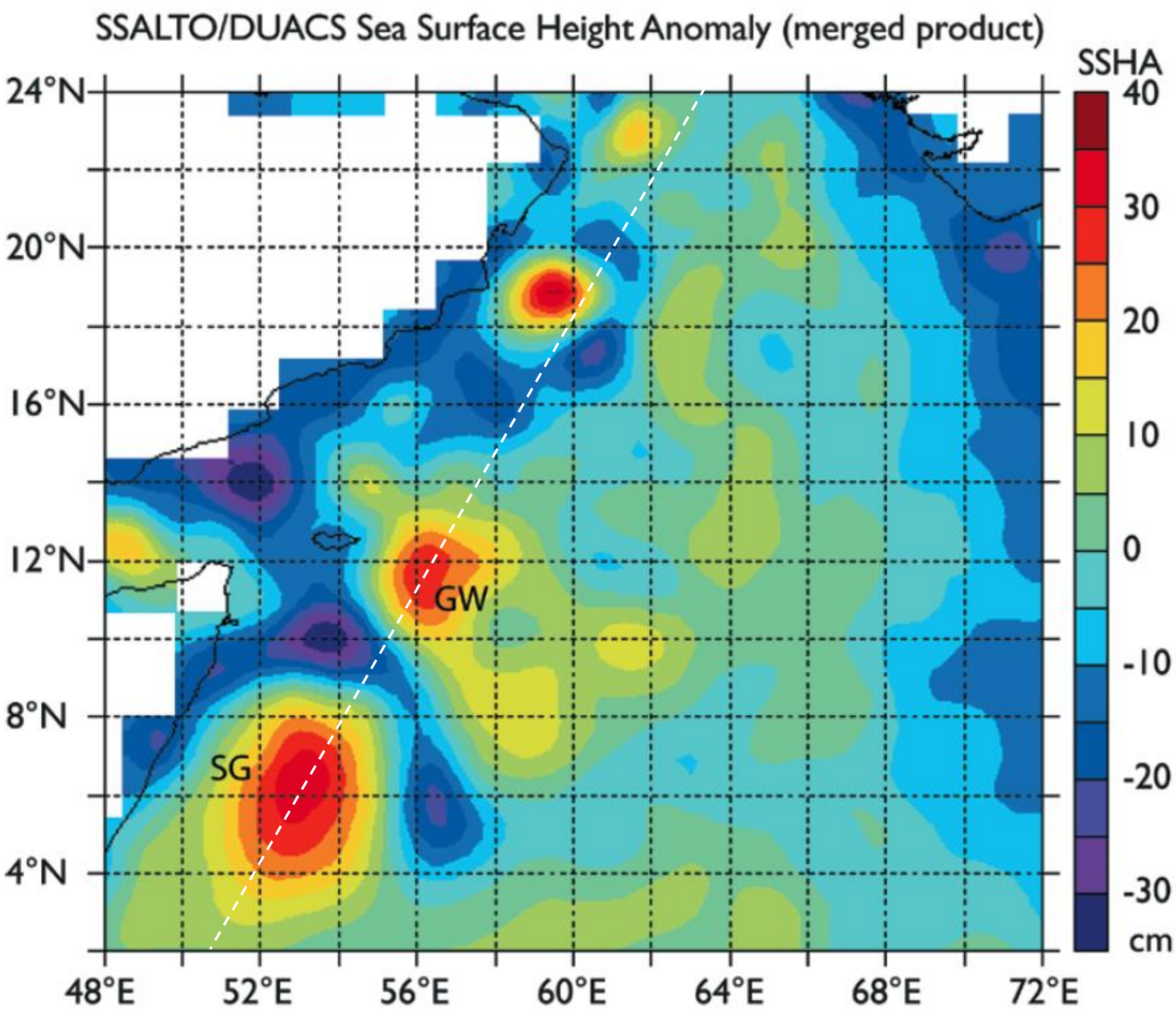


Figure 3.7. Schematic of the basic structure of a simple eddy in the northern hemisphere. On the left is an anticyclonic eddy (warm core) and on the right is a cyclonic eddy (cold core).

Sea Surface Height Anomaly

Geostrophic surface currents follow SSHA contours



Geostrophic flow from SSHA

Measurement of SSHA

→ Calculation of geostrophic currents

$$fv = \frac{1}{\rho}\frac{\partial p}{\partial x} = g\,\frac{\partial h_{SSHA}}{\partial x}$$

$$fu = -\frac{1}{\rho}\frac{\partial p}{\partial y} = g\,\frac{\partial h_{SSHA}}{\partial y}$$

Eddy Kinetic Energy

$$EKE = \frac{1}{2}\left(u^2 + v^2\right)$$

Okubo Weiss Parameter

$$OW = S_n^2 + S_n^2 - \omega^2$$

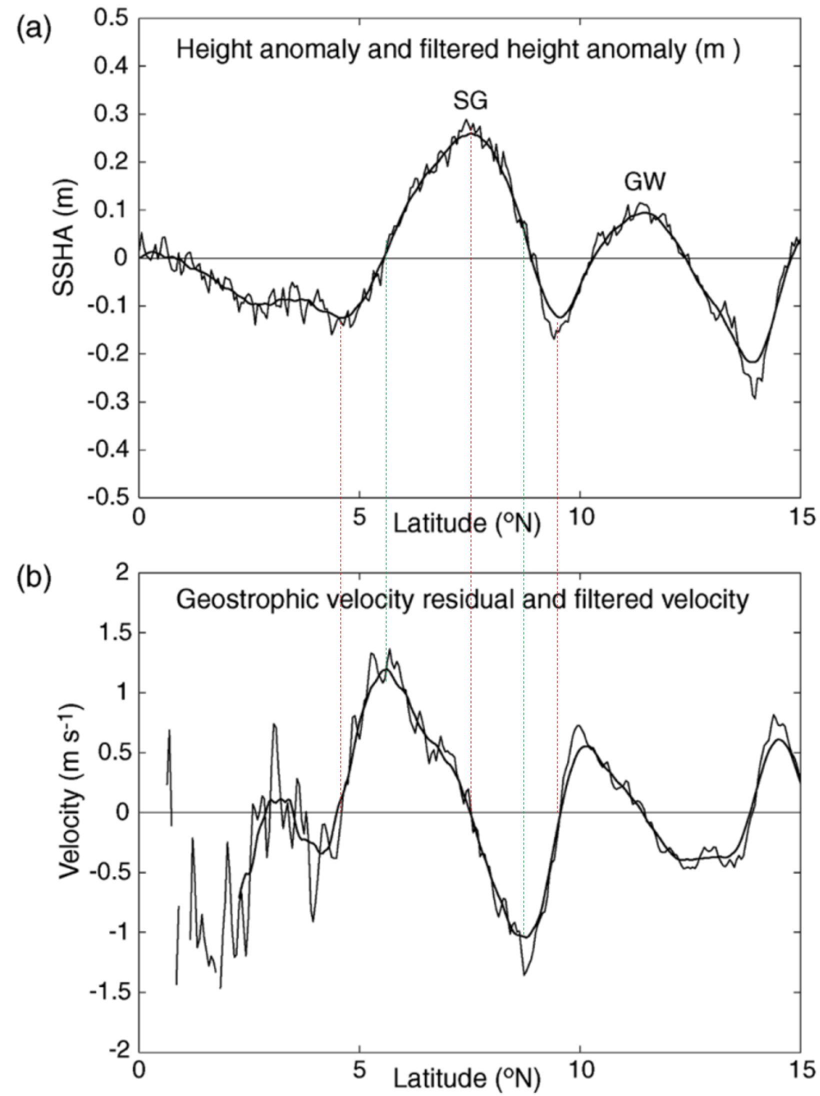


Figure 3.8. Along-track altimeter records from TOPEX/Poseidon, showing a portion of Track 233 over the Arabian Sea during Cycle 36 in August 1993. (a) Sea surface height anomaly. SG is the Southern Gyre eddy and GW the Great Whirl eddy. (b) Derived geostrophic velocity (data courtesy of B. Subrahmanyam).

Lagrangian flow analysis

Okubo Weiss Parameter

$$OW = S_n^2 + S_n^2 - \omega^2$$

Lagrangian Coherent Structures (FTLE)

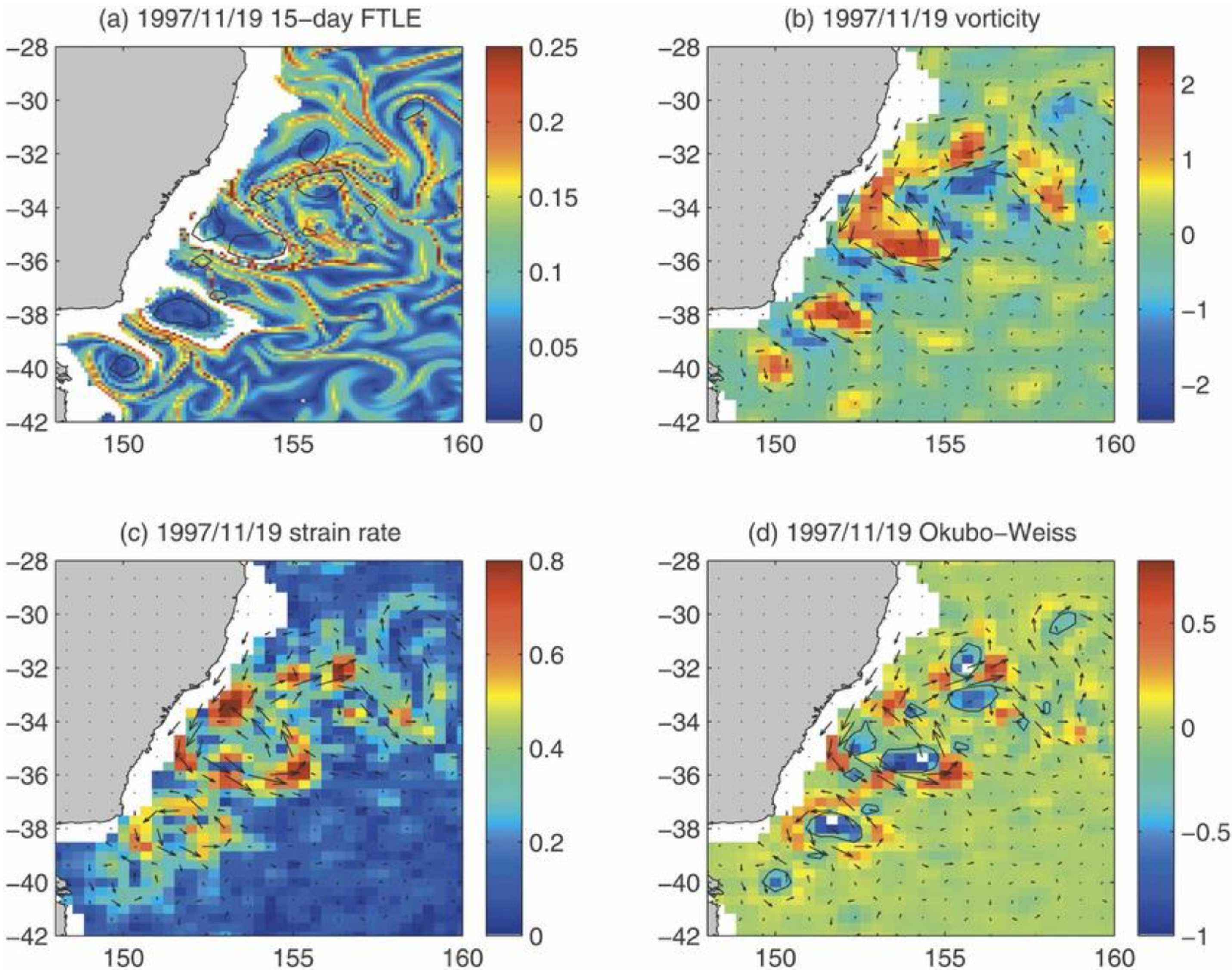
$$x \rightarrow D\phi_t^{t+T}(x)$$

$$\Delta = [D\phi_t^{t+T}(x)]' D\phi_t^{t+T}(x)$$

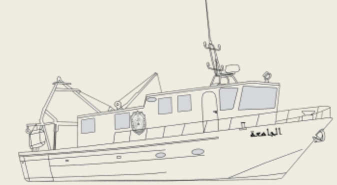
$$\sigma_T(x,t) = \frac{1}{2|T|} \ln \lambda_{max}(\Delta)$$

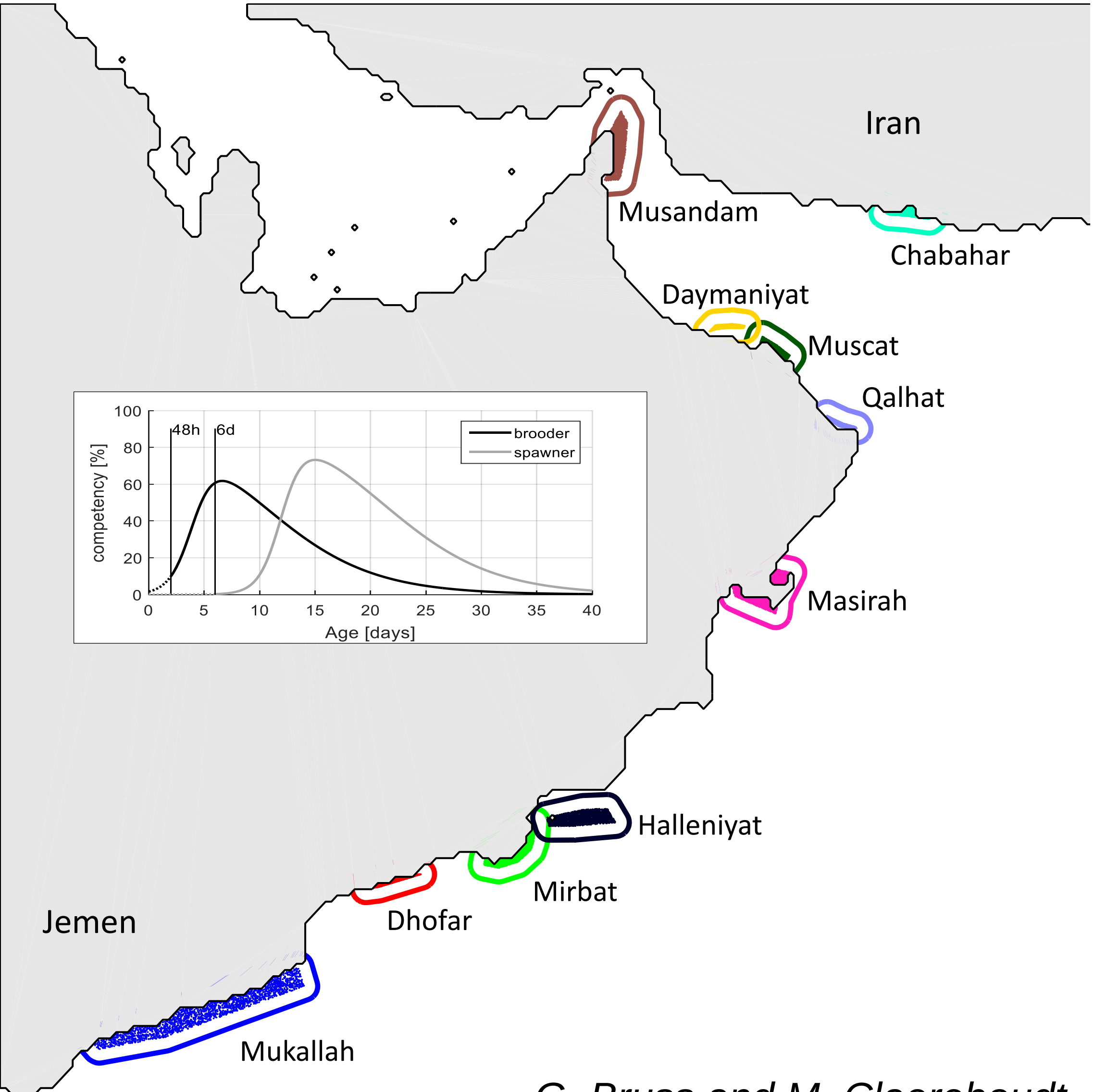
Lagrangian Transport Modelling

$$v = v_i + r\sqrt{2\,\varepsilon^{1/3} l^{4/3} / \Delta t}$$



Lagrangian Transport Modelling
applied to study connectivity of coral communities





Background

- resilience, species distribution and biogeography of coral reefs is determined by larval connectivity
- larval connectivity relies on the potential of coral larvae to disperse in the environment following ocean currents

Research Question

How are coral communities around Oman (AS and SO) connected?

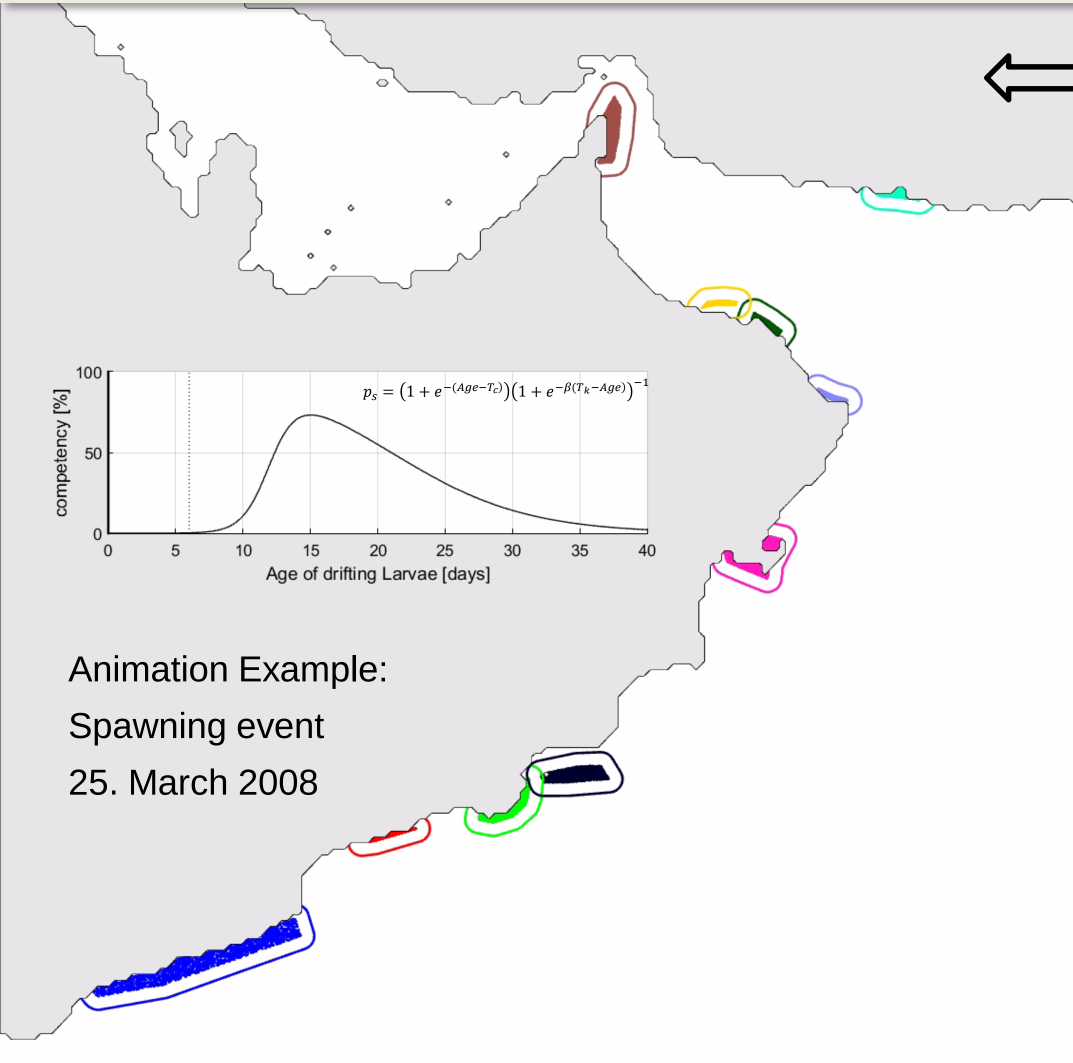
Method

Modelling of Lagrangian Larvae Transport

G. Bruss and M. Claereboudt

Lagrangian Transport Modelling

applied to study connectivity of coral communities



Animation Example:

Spawning event

25. March 2008

Lagrangian Transport Modelling

$$v = v_i + r\sqrt{2\,\varepsilon^{1/3} l^{4/3}/\Delta t}$$

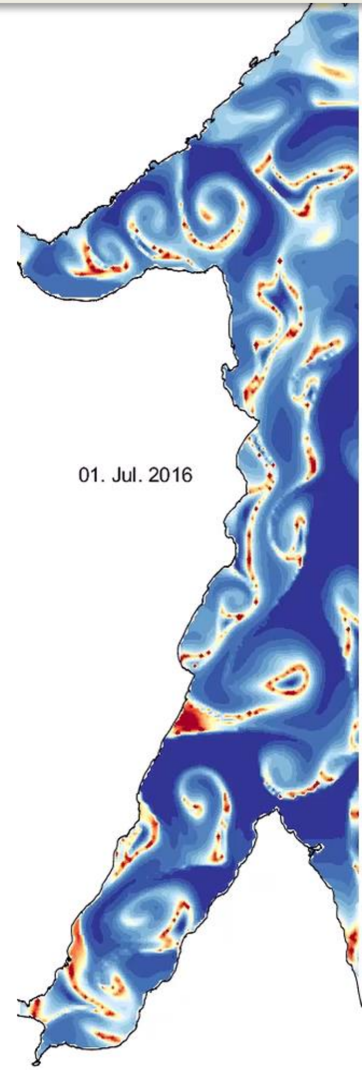
$$e = 10^{-9} m^{-2} s^{-3}$$
$$\Delta t = 1h$$
$$l = 25km$$

- flow fields *DUACS / HYCOM*
- 10 reefs
- 24 scenarios
- 1000 Larvae / km^2
- drift length 40 days
- settling f(age, type)

Lagrangian Coherent Structures (FTLE)

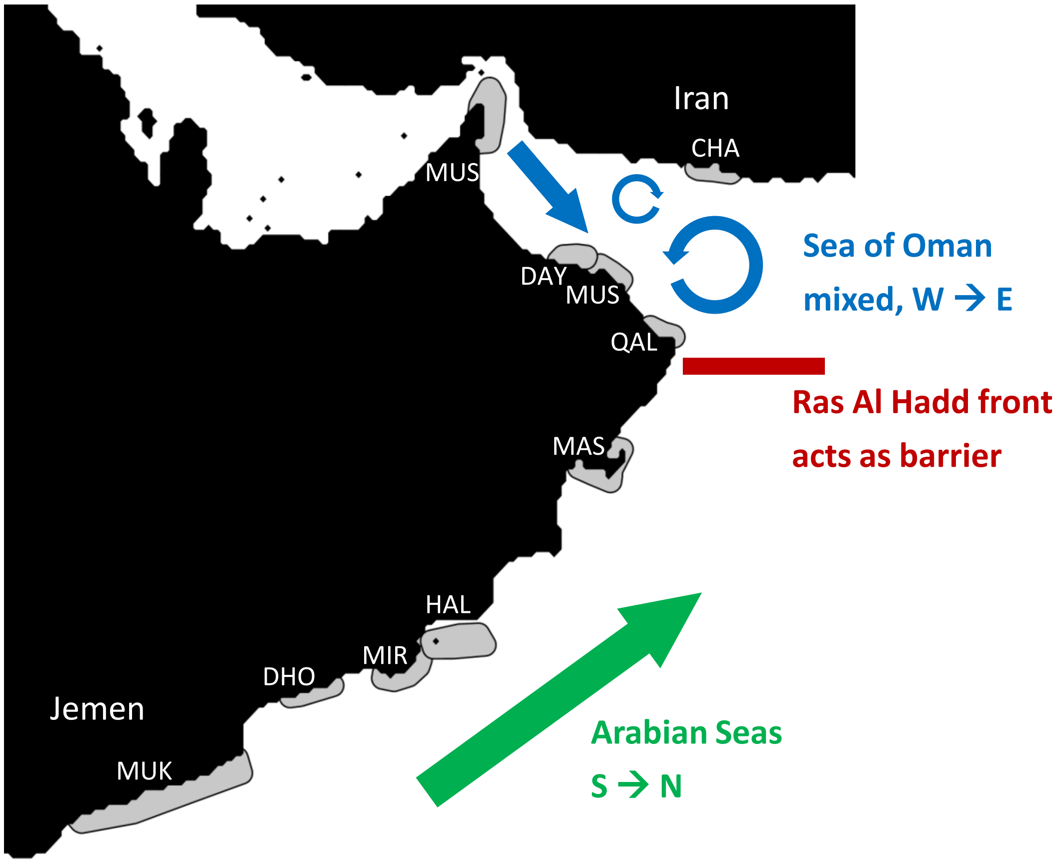
$$x \rightarrow D\phi_t^{t+T}(x)$$
$$\Delta = [D\phi_t^{t+T}(x)]' D\phi_t^{t+T}(x)$$
$$\sigma_T(x,t) = \frac{1}{2|T|} \ln \lambda_{max}(\Delta)$$

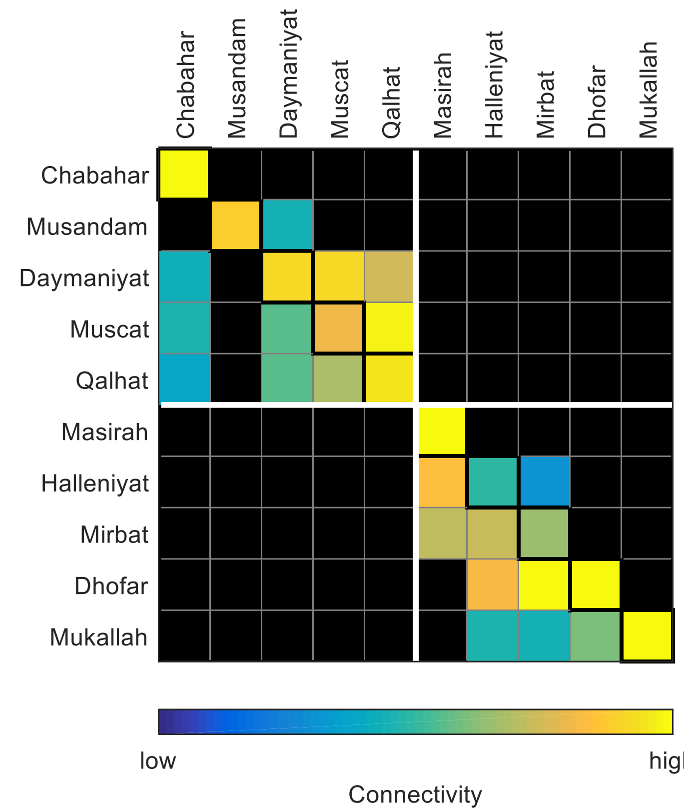
- flow fields DUACS
- 15 years



Lagrangian Transport Modelling

applied to study connectivity of coral communities





Eddies from Satellite Altimetry

Limitations

- Accuracy of radar altimetry in the range of few cm
- Altimeter is better at detecting variability at the larger end of the mesoscale range than at the smaller end defined by the baroclinic Rossby radius
- Beware of the (hor.) 2d effect – only velocities at 90deg to along track direction can be computed

Surface Signature

- Sea Surface Height
- Sea Surface Temperature
- Advection of Tracers (Ocean Color)
- Sea Surface Roughness

Eddies from Satellites – SST

Large mesoscale features

- Flow approx along smoothed contours

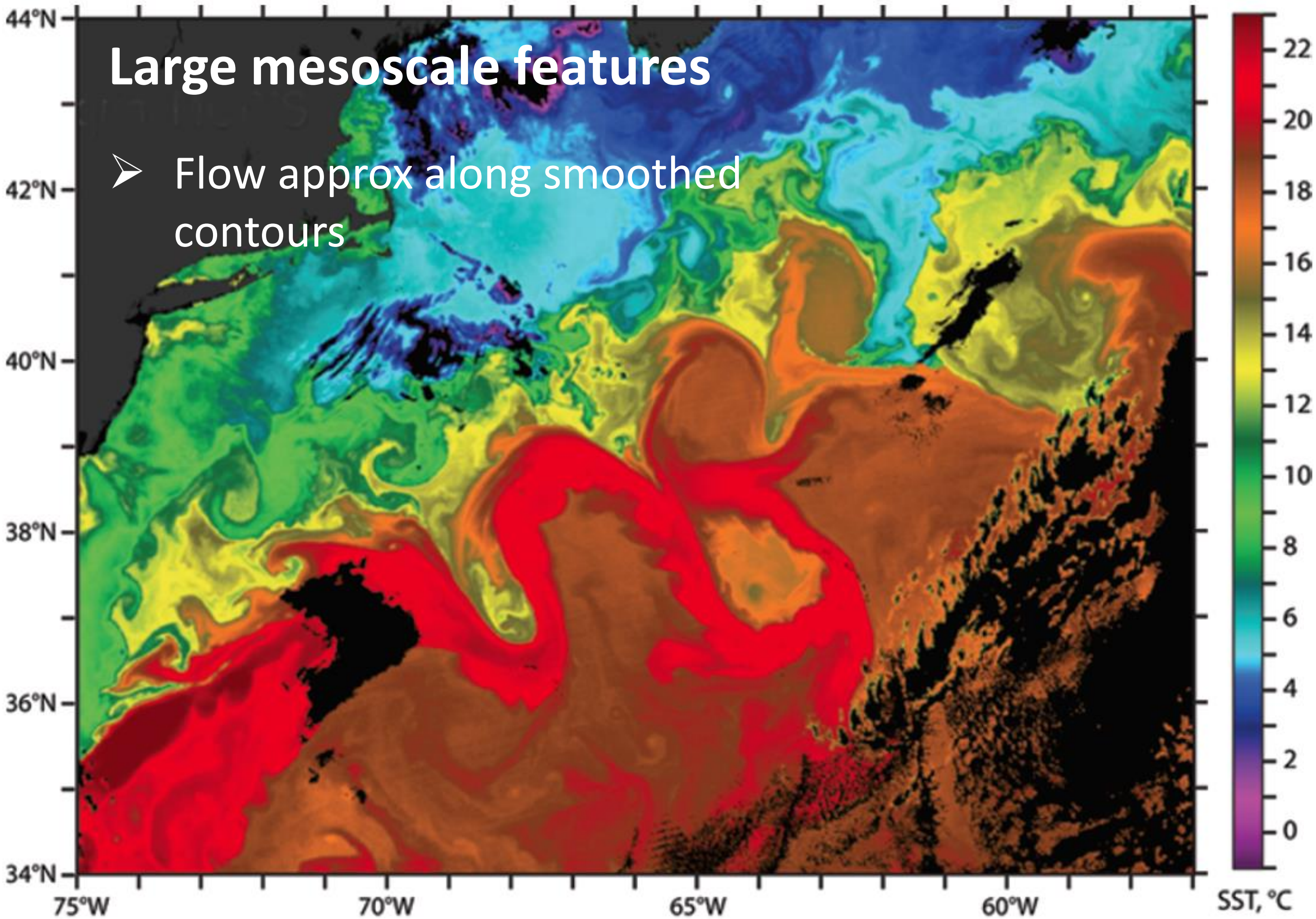


Figure 3.16. Sea surface temperature field derived by MODIS on Aqua, April 18, 2005, showing the meanders of the Gulf Stream (from NASA Ocean Color website at *http://oceancolor.gsfc.nasa.gov/*).

Eddies from Satellites – SST

Smaller mesoscale features

- Flow not directly linked to temperature contours

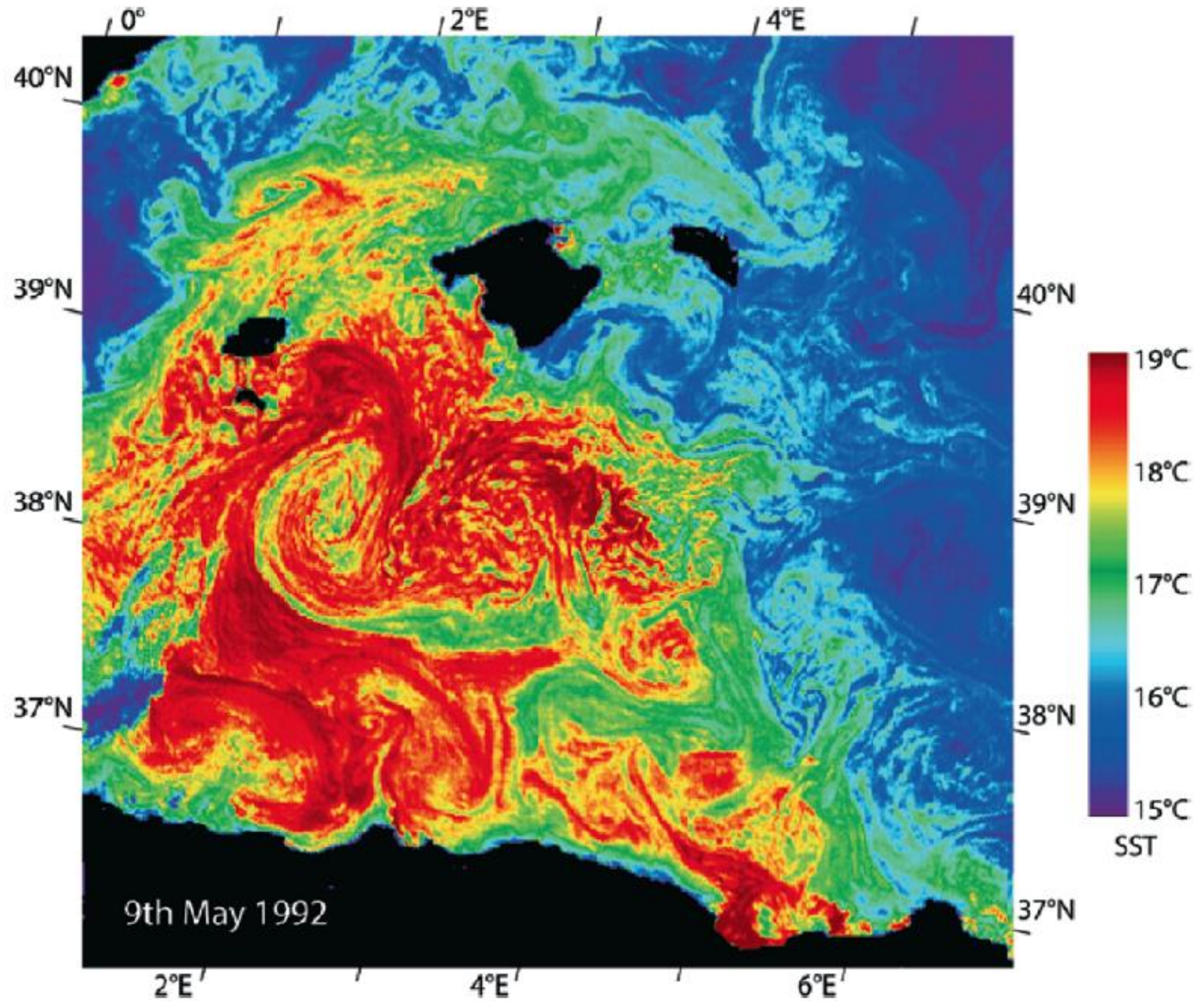


Figure 3.17. Map of level 2 SST data from ATSR nighttime image on May 9, 1992 over the Balearic Islands in the western Mediterranean Sea, showing fine-scale thermal structures viewed using a spatial resolution of 1 km. This image is 500 km across.

Eddies from Satellites – Ocean colour

- transported substances act as tracers
- can resolve smaller scale turbulence
- short timespan before dispersion
- natural decay time

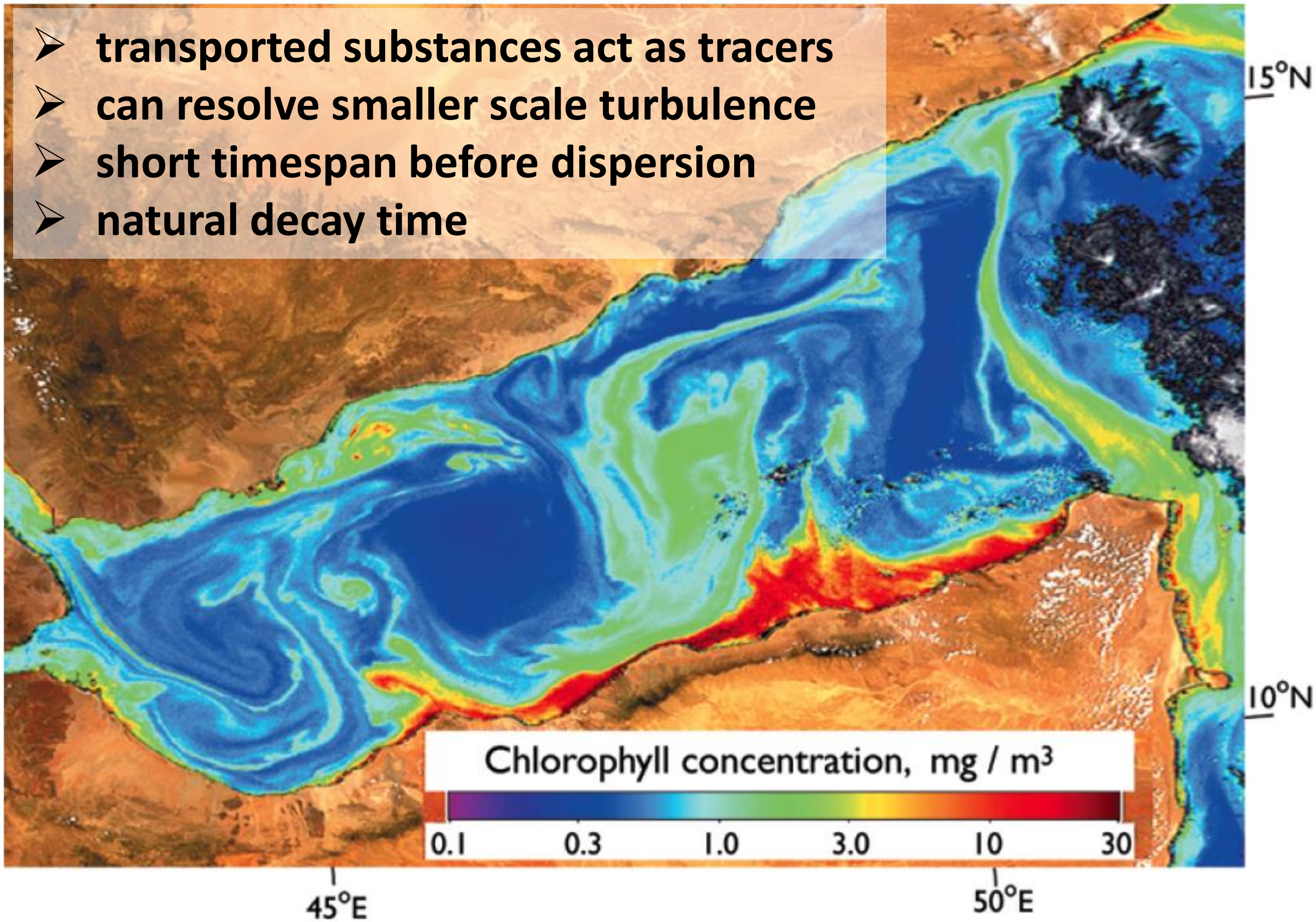
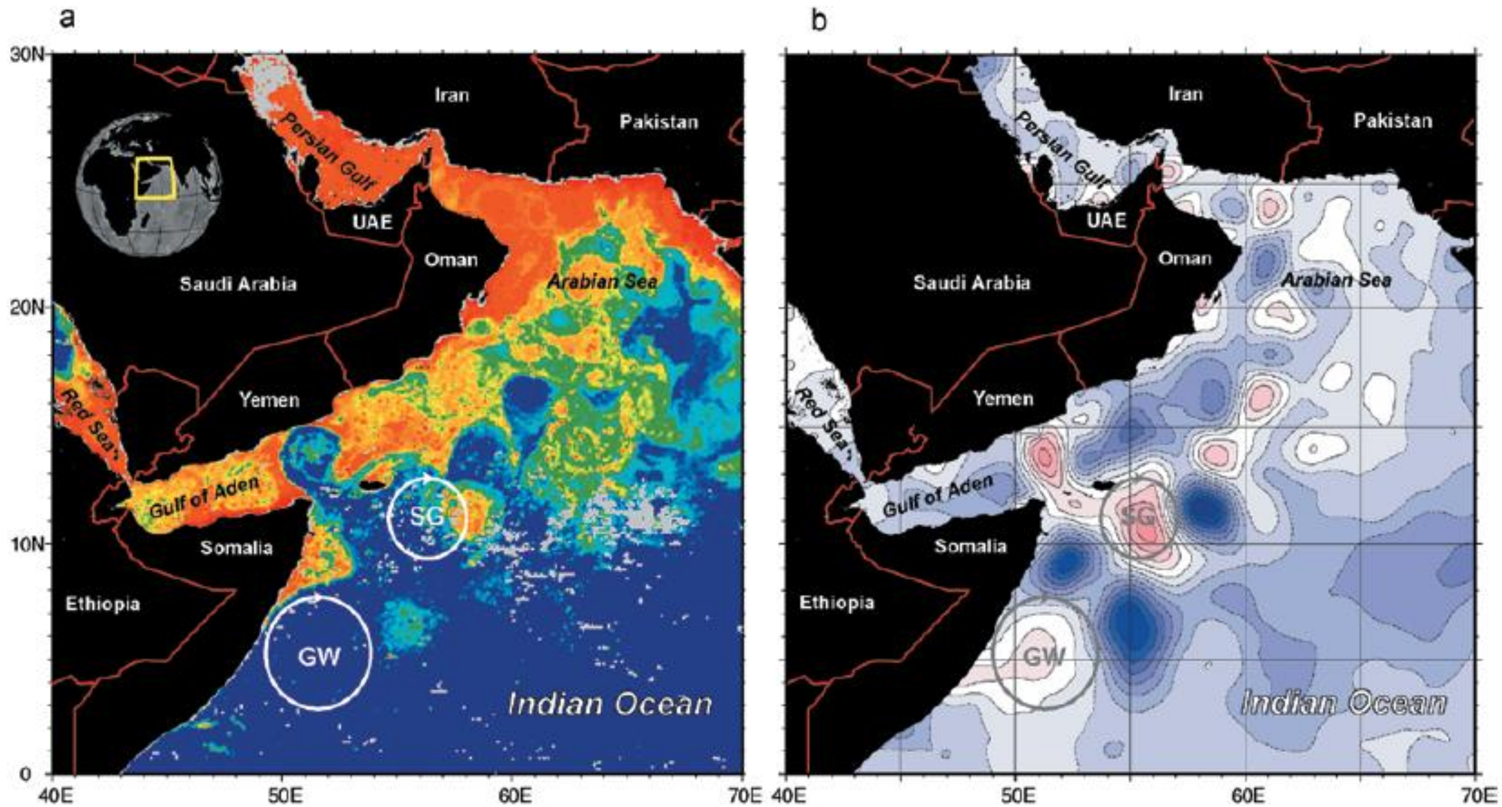


Figure 3.21. Map of chlorophyll concentration derived from the SeaWiFS overpass of the Gulf of Aden, between the Indian Ocean and the Red Sea, on November 1, 2003.

Eddies from Satellites – Ocean color

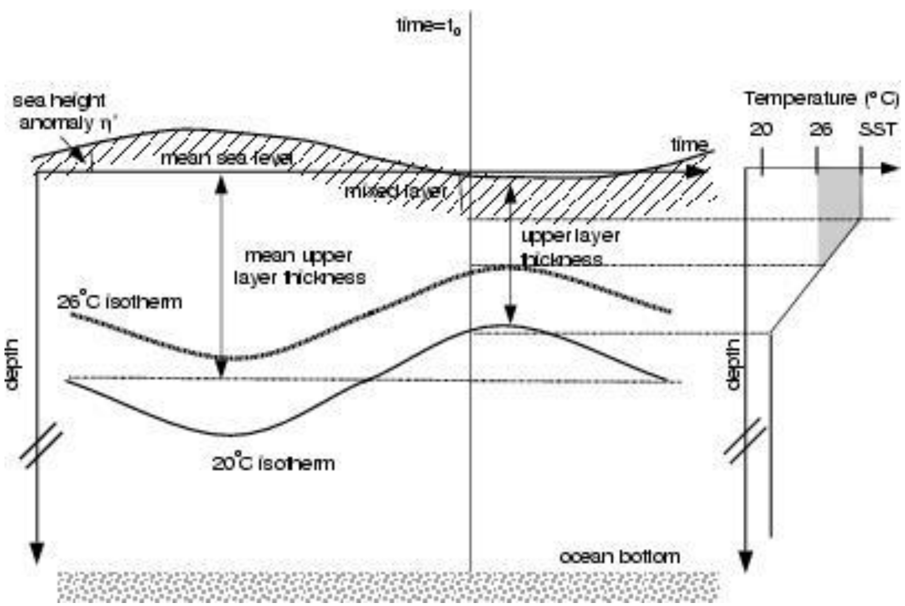


- Sometimes weak linkage between color ocean and ssh
- Caution in interpreting circular patch of high chlorophyll as evidence of the simultaneous core of an eddy

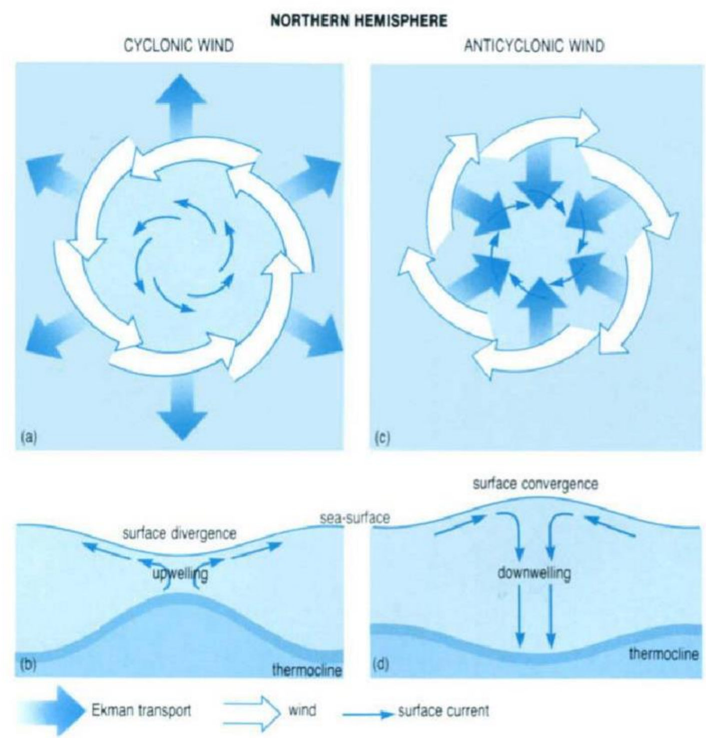
Tropical Cyclones and SSH

- TC Intensification
- TC effects on long-term ocean warming

Tropical Cyclone Heat Potential



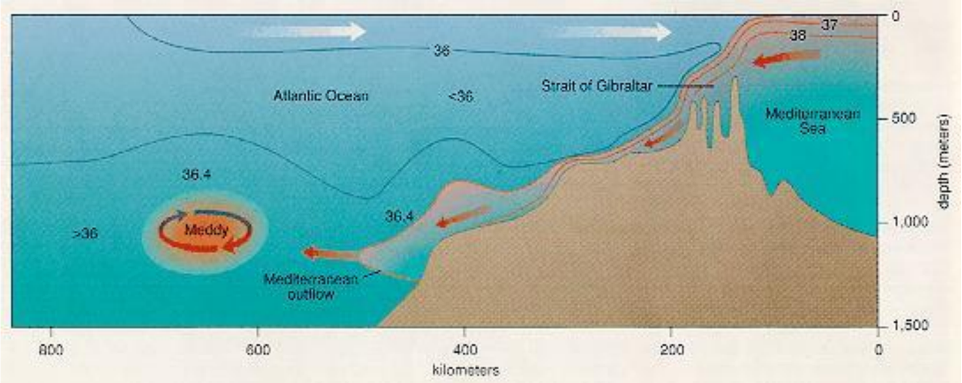
Ekman Pumping

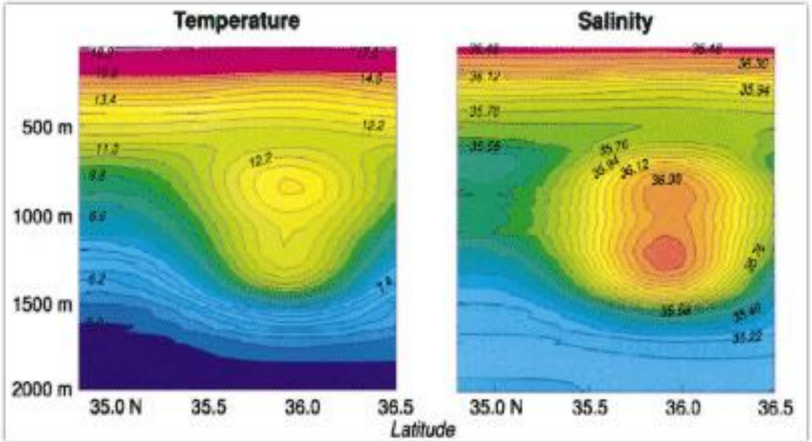


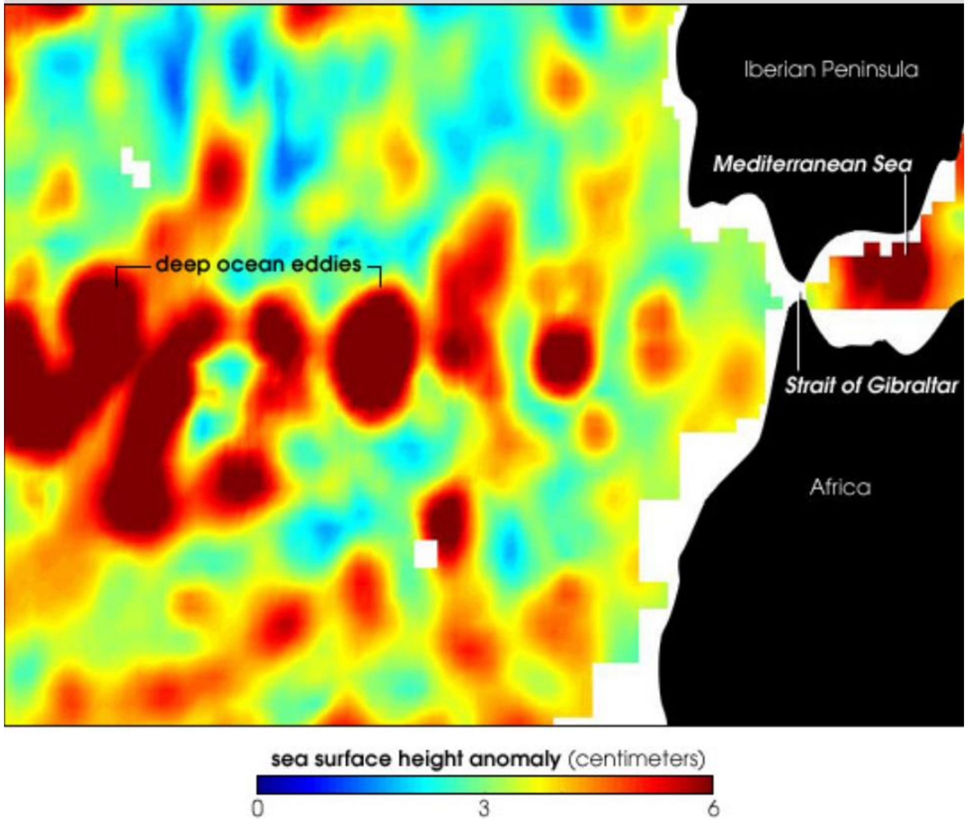
Eddies from Satellites

Meddies

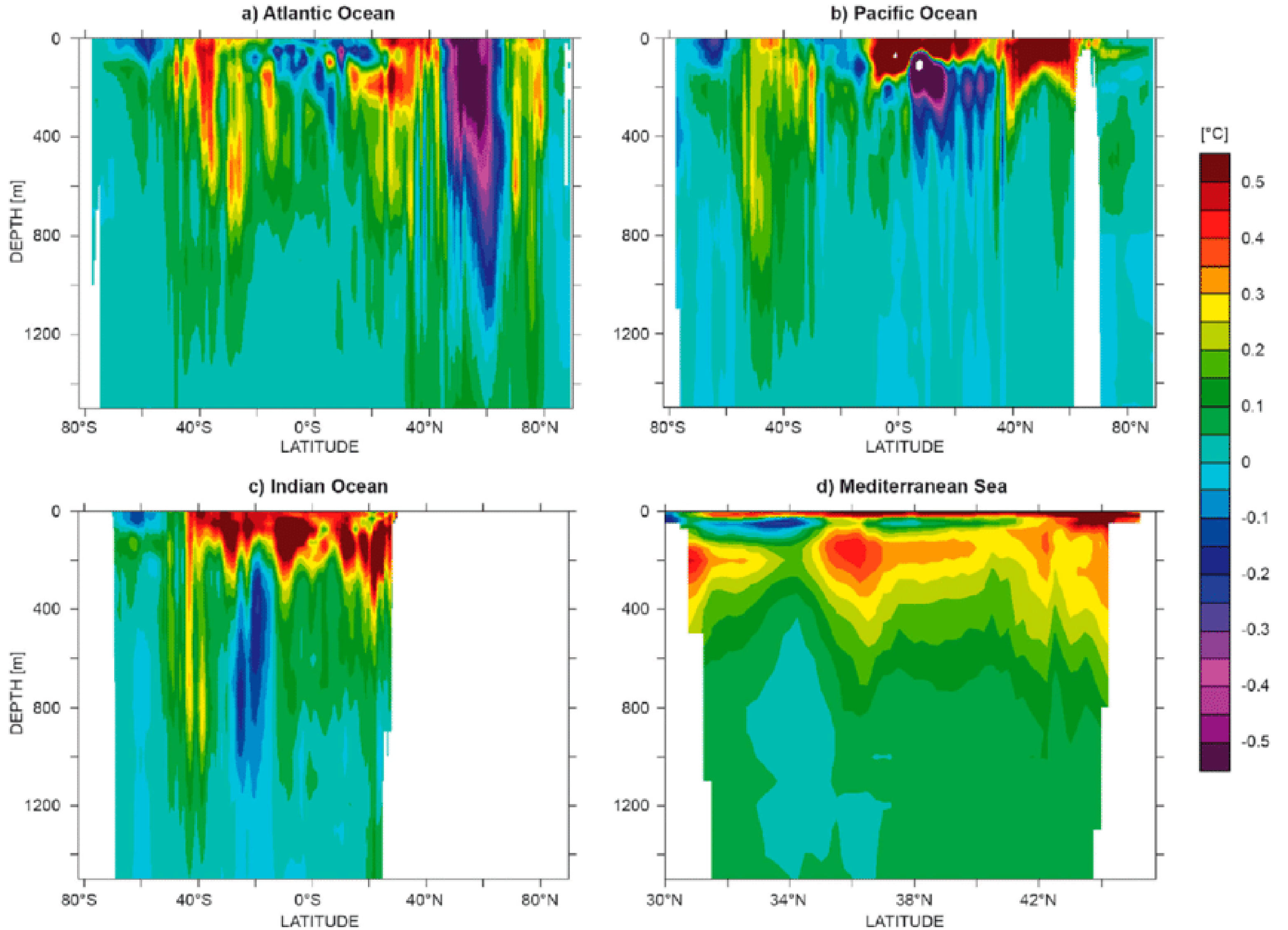
- only observable in SSHA
- no SST signature







Subsurface temperature anomalies

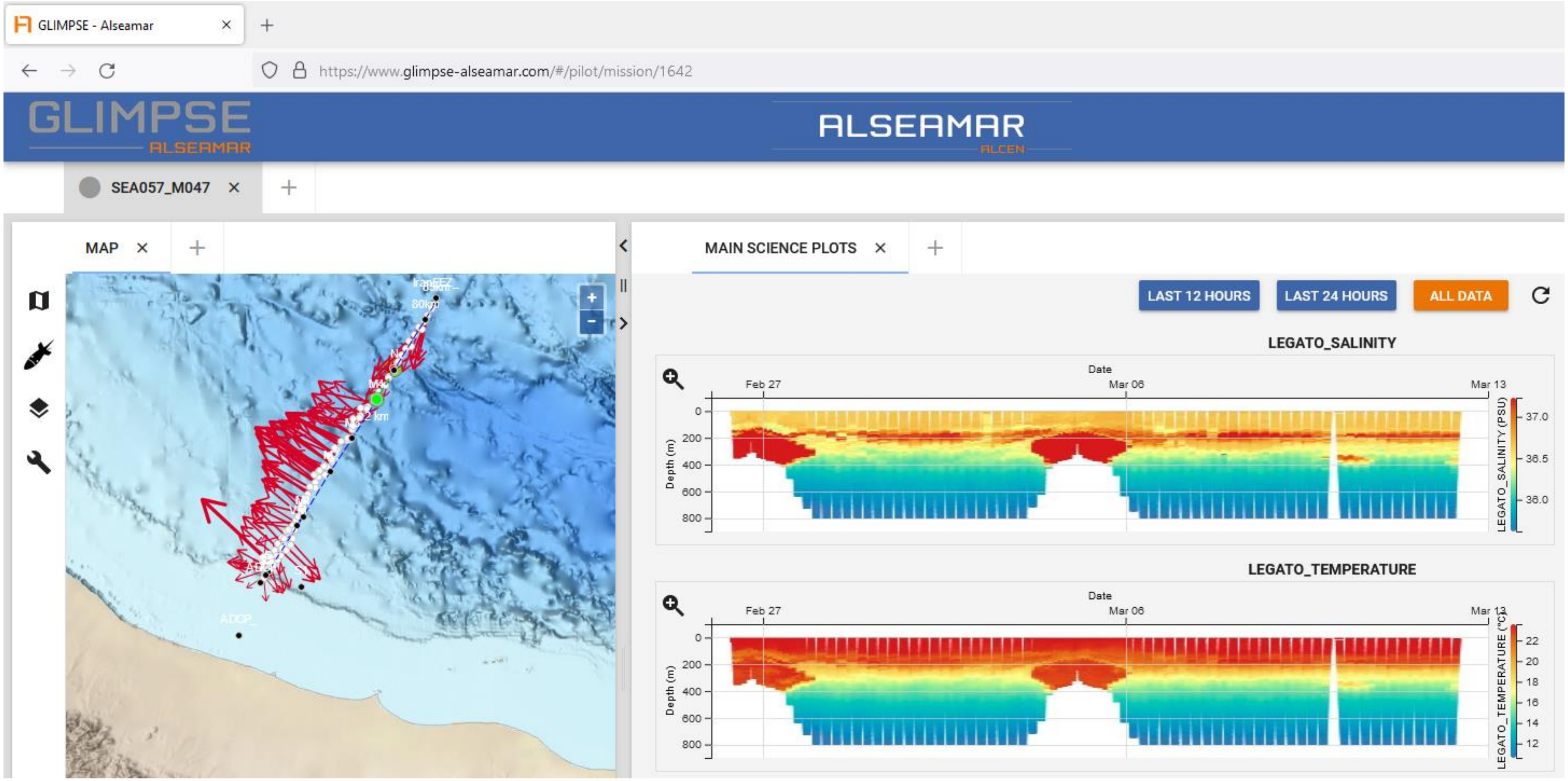


Schuckmann, Karina & Traon, Pierre-Yves & Alvarez Fanjul, Enrique & Axell, Lars & Balmaseda, Magdalena & Breivik, L. & Brewin, Bob & Bricaud, Clément & Drevillon, Marie & Drillet, Y. & Dubois, C. & Embury, Owen & Etienne, Helene & Sotillo, Marcos & Garric, Gilles & Gasparin, Florent & Elodie, Gutknecht & Guinehut, S. & Hernandez, Fabrice & Verbrugge, Nathalie. (2016). The Copernicus Marine Environment Monitoring Service Ocean state report.

Subsurface temperature anomalies

- only observable in SSHA
- no SST signature

P/AGW



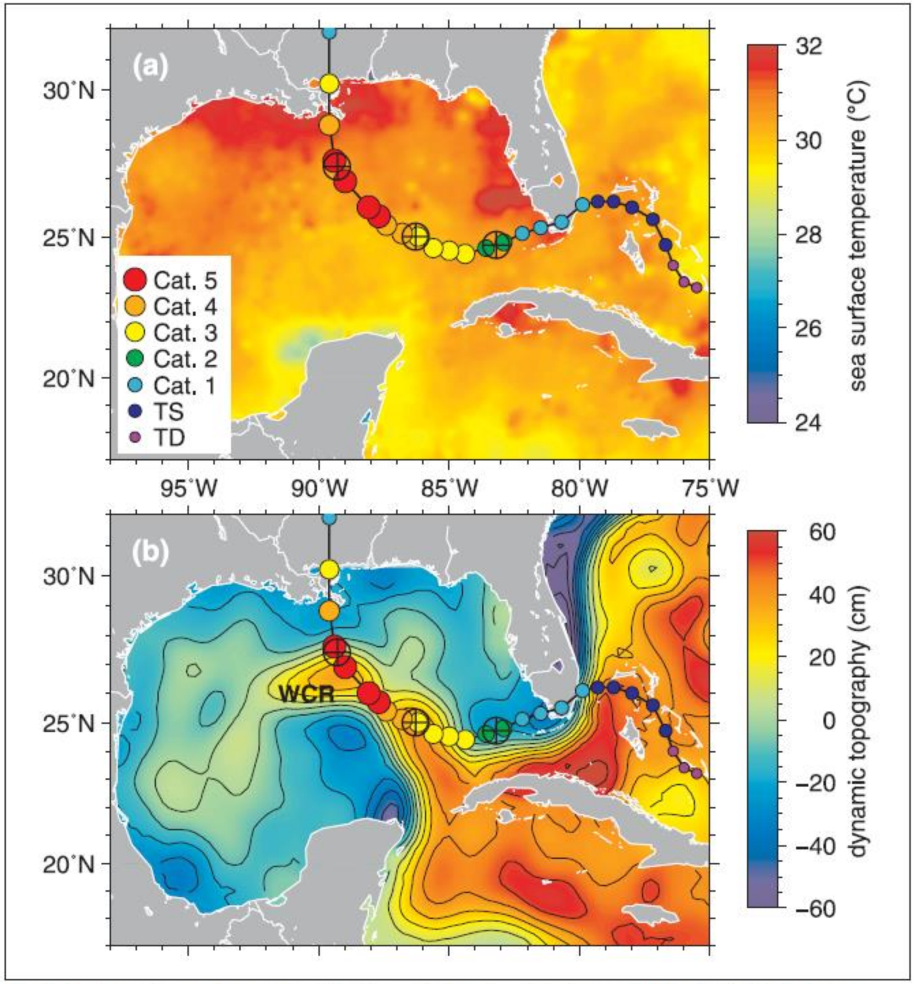
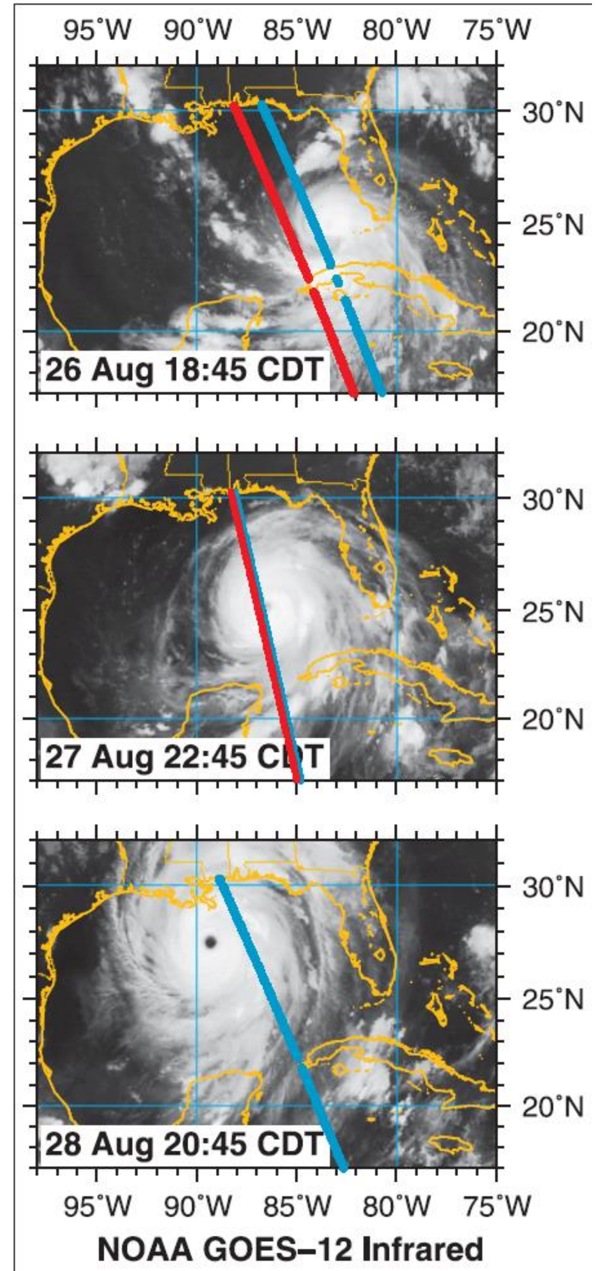
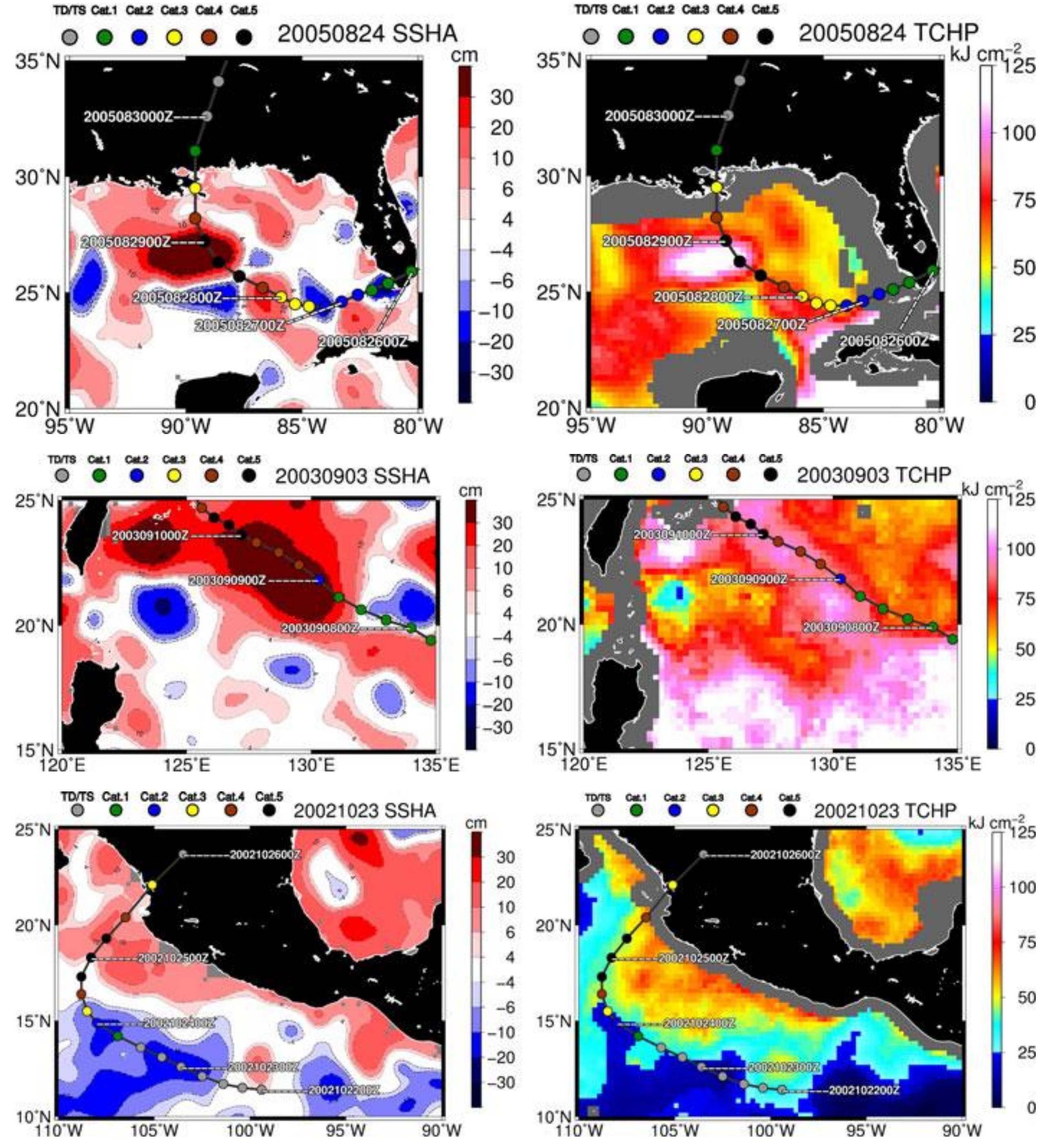


Fig. 2. The location and intensity of Katrina at intervals of six hours (circles indicate data from National Hurricane Center advisories) show two intensification events. (a) Intensification is not correlated with sea surface temperature (from POES high-resolution infrared data). (b) In contrast, the intensifications correlate well with highs in the ocean dynamic topography (from Jason 1, TOPEX, Envisat, and GFO sea surface height data). The Loop Current can be seen entering the Gulf south of Cuba and exiting south of Florida; the warm-core ring (WCR) is the prominent high shedding from the Loop Current in the center of the Gulf. The crosshair symbols on the storm tracks show the storm position at the times of the three rows of panels in Figure 1.



Scharroo, Remko & Smith, Walter & Lillibridge, John. (2005). Satellite Altimetry and the Intensification of Hurricane Katrina. Eos, Transactions American Geophysical Union. 86. 10.1029/2005EO400004.

Lin, I-I & Goni, Gustavo & Knaff, John & Forbes, Cristina & Ali, MM. (2012). Ocean heat content for tropical cyclone intensity forecasting and its impact on storm surge. Natural Hazards. 66. 10.1007/s11069-012-0214-5.



Sea surface height evidence for long-term warming effects of tropical cyclones on the ocean

Jishi Zhang, Yanluan Lin, Zhanhong Ma, Footprint of Tropical Cyclone Cold Wakes on Top-of-Atmosphere Radiation, Geophysical Research Letters, 10.1029/2021GL094705, 48, 19, (2021).

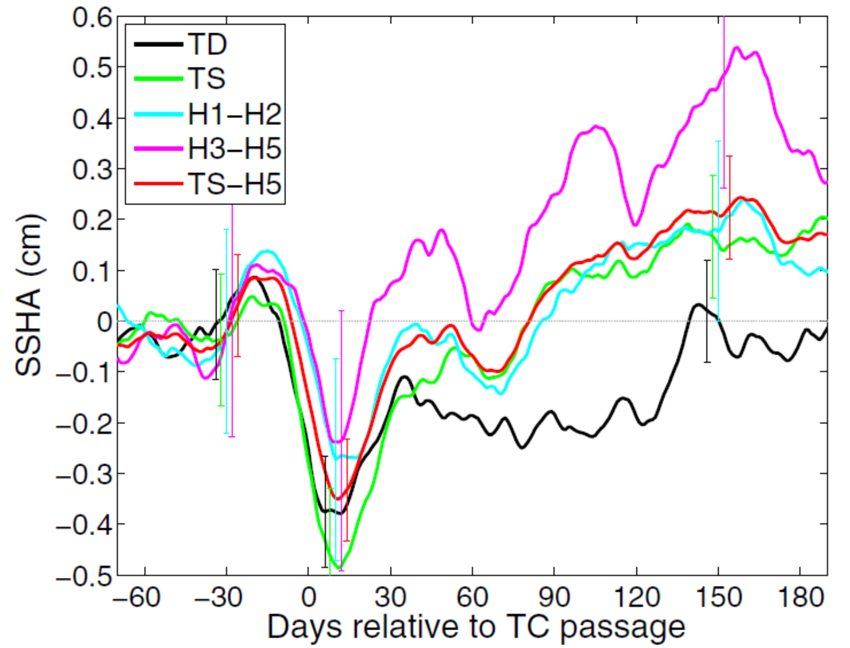


Fig. 2. Temporal evolution of area-averaged composite SSHA associated with the passage of TCs of different intensity in the Northern Hemisphere: tropical depressions (black), tropical storms (green), category-1 to -2 hurricanes (light blue), category-3 to -5 hurricanes (magenta), and all cyclones of tropical storm intensity and above (red). Error bars are calculated as the SD

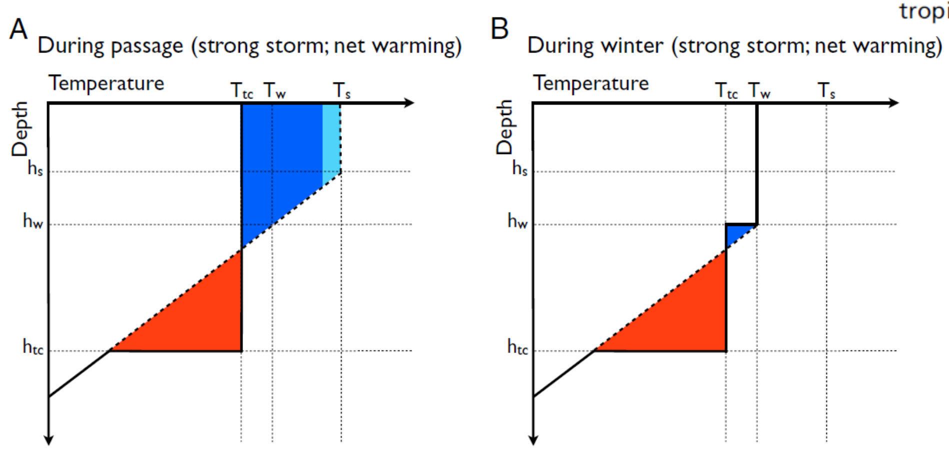


Fig. 4. (*A* and *B*) Schematic diagram for the change in the vertical temperature profile for the case of strong storms with net warming: (*A*) immediately after the TC passage and (*B*) after the winter season. Dashed lines show the climatological condition, and solid lines show the situation with the effect of the TC. Red and blue colors indicate, respectively, warming and cooling with respect to climatological conditions. Light blue shows the heat extracted from the ocean during the passage of the storm. h_s, climatological mixed-layer depth during the summer season; h_{tc}, TC-induced mixing-layer depth; h_w, climatological mixed-layer depth during the winter season; T_s, climatological SST during the summer season; T_{tc}, minimum SST after the TC passage; T_w, climatological SST during the winter season. (See *SI Appendix*, Fig. S6 for the cases with weak storms that lead to either net cooling or no effect.)

Satellite Altimetry and tsunamis

Hébert, H., Occhipinti, G., Schindelé, F. et al. Contributions of Space Missions to Better Tsunami Science: Observations, Models and Warnings. Surv Geophys ***41,*** *1535–1581 (2020). https://doi.org/10.1007/s10712-020-09616-2*

This observation still remains exceptional, and the 2011 tsunami could not be recorded at such an early stage of the propagation, not necessarily because of smaller amplitudes, but due to satellite tracks not properly crossing the tsunami front waves in their temporal distribution. The available maximal amplitudes, from 20 to 60 cm, were available on Envisat, Jason 1 and Jason 2, from 5:20 to 8:25 h after the earthquake (Song et al. 2012), and were not as useful as in 2004 to retrieve any information on the source processes. It should also be kept in mind that the altimetry profiles give a picture of the tsunami propagation along tracks, crossing the area by chance. Even though almost static compared to the tsunami propagation time scale, they do not provide full insight into the accurate description of the waveforms. The full temporal description of amplitudes and phases are usually more efficiently recovered throug

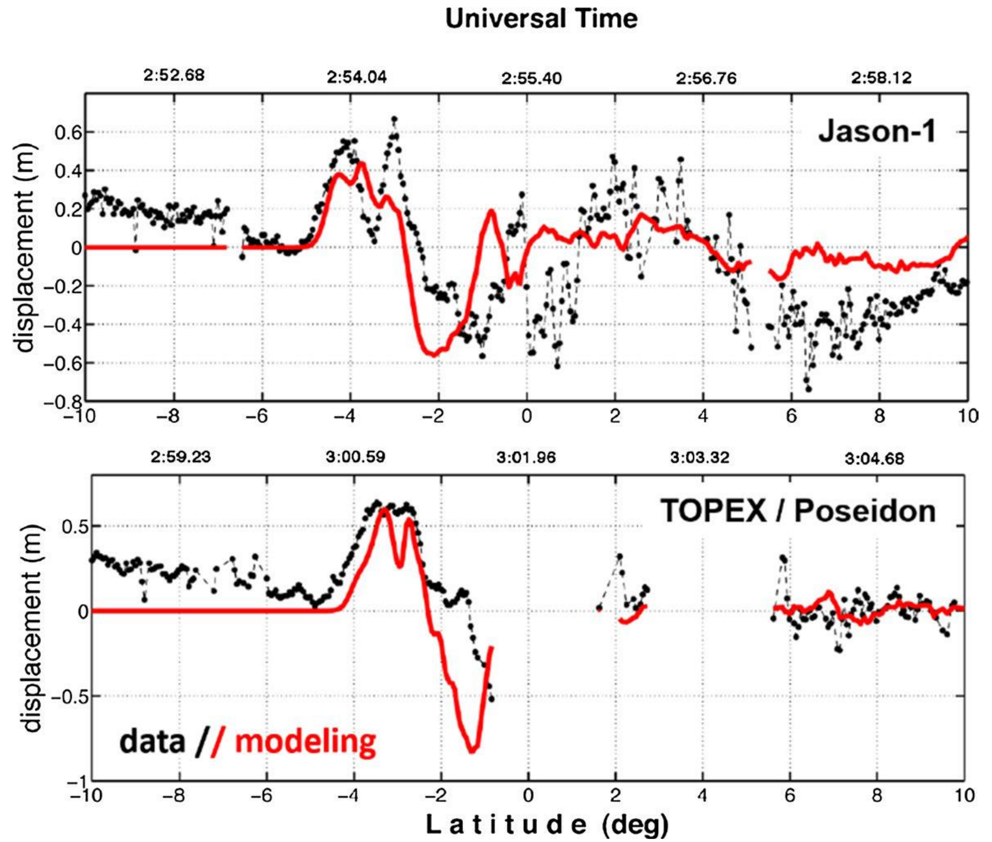
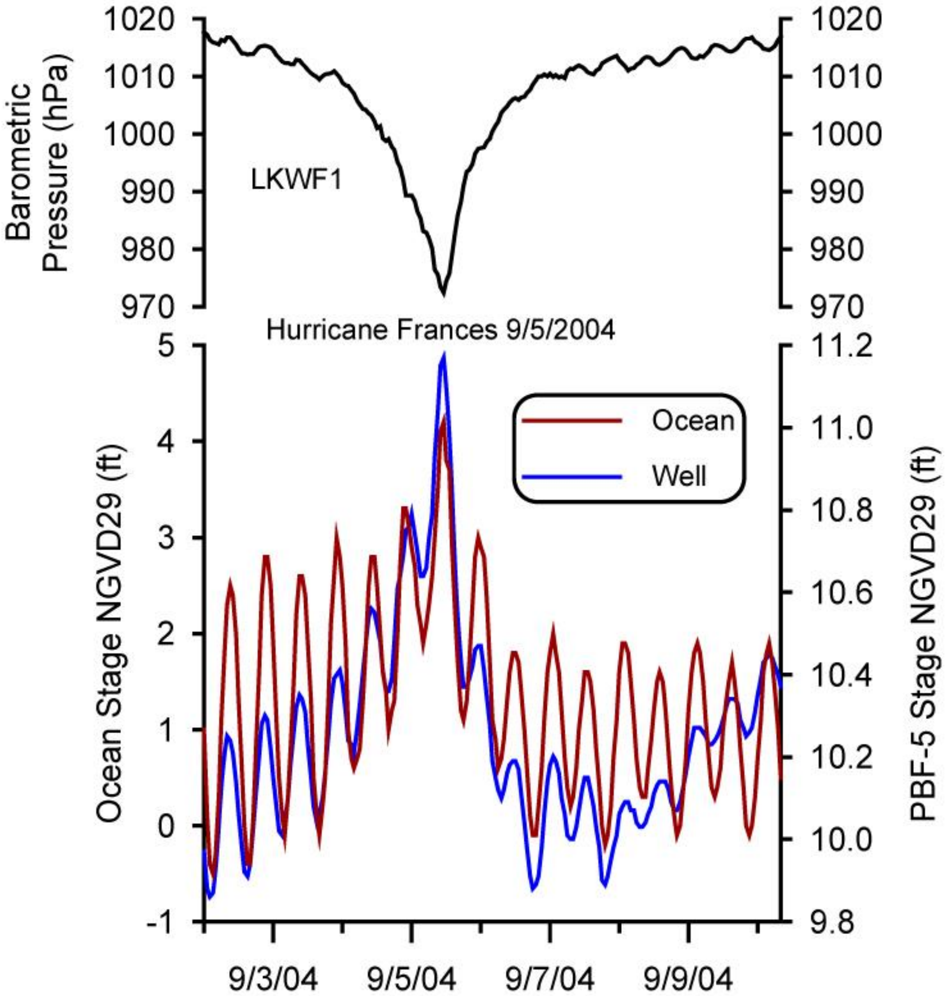
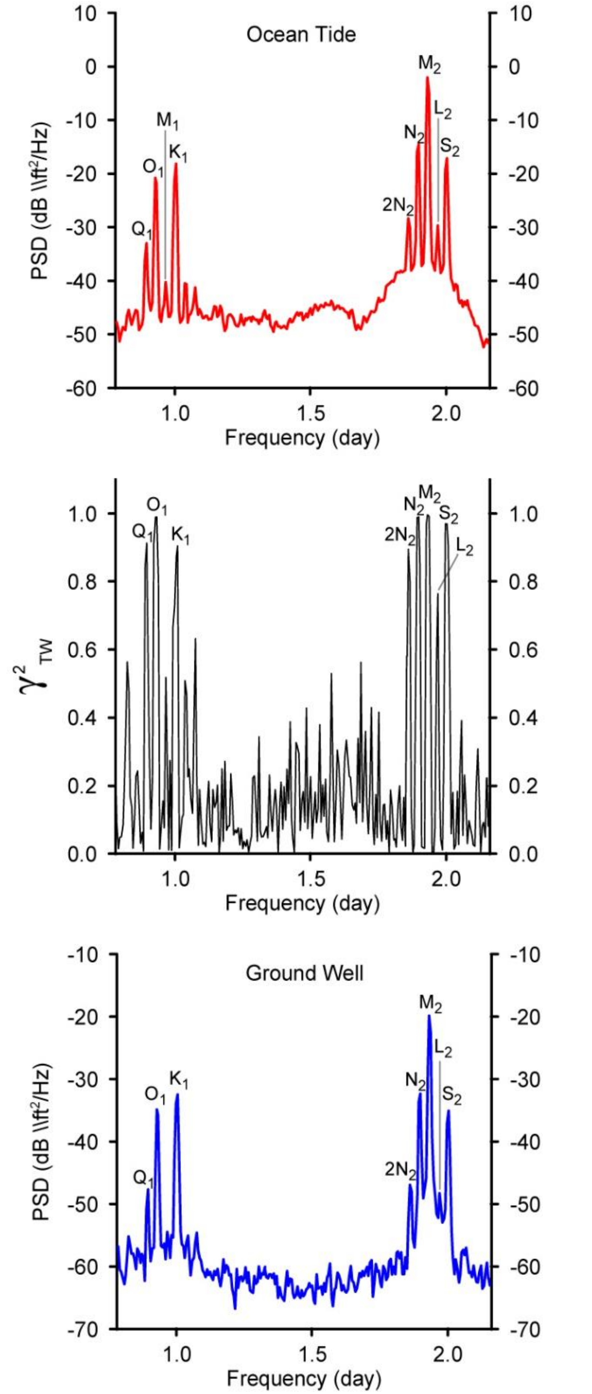


Fig. 7 Altimetry signatures of the 2004 Sumatra tsunami, with measurements of the ocean surface (black) for the Jason-1 (top) and Topex/Poseidon (bottom). The synthetic ocean isplacements are shown in red (Figure from Occhipinti et al. 2006)

Groundwater and ADT / SSHA





https://en.wikipedia.org/wiki/Coherence_(signal_processing)