THE OCEAN: A TURBULENT CONTROL SYSTEM FOR THE EARTH'S CLIMATE

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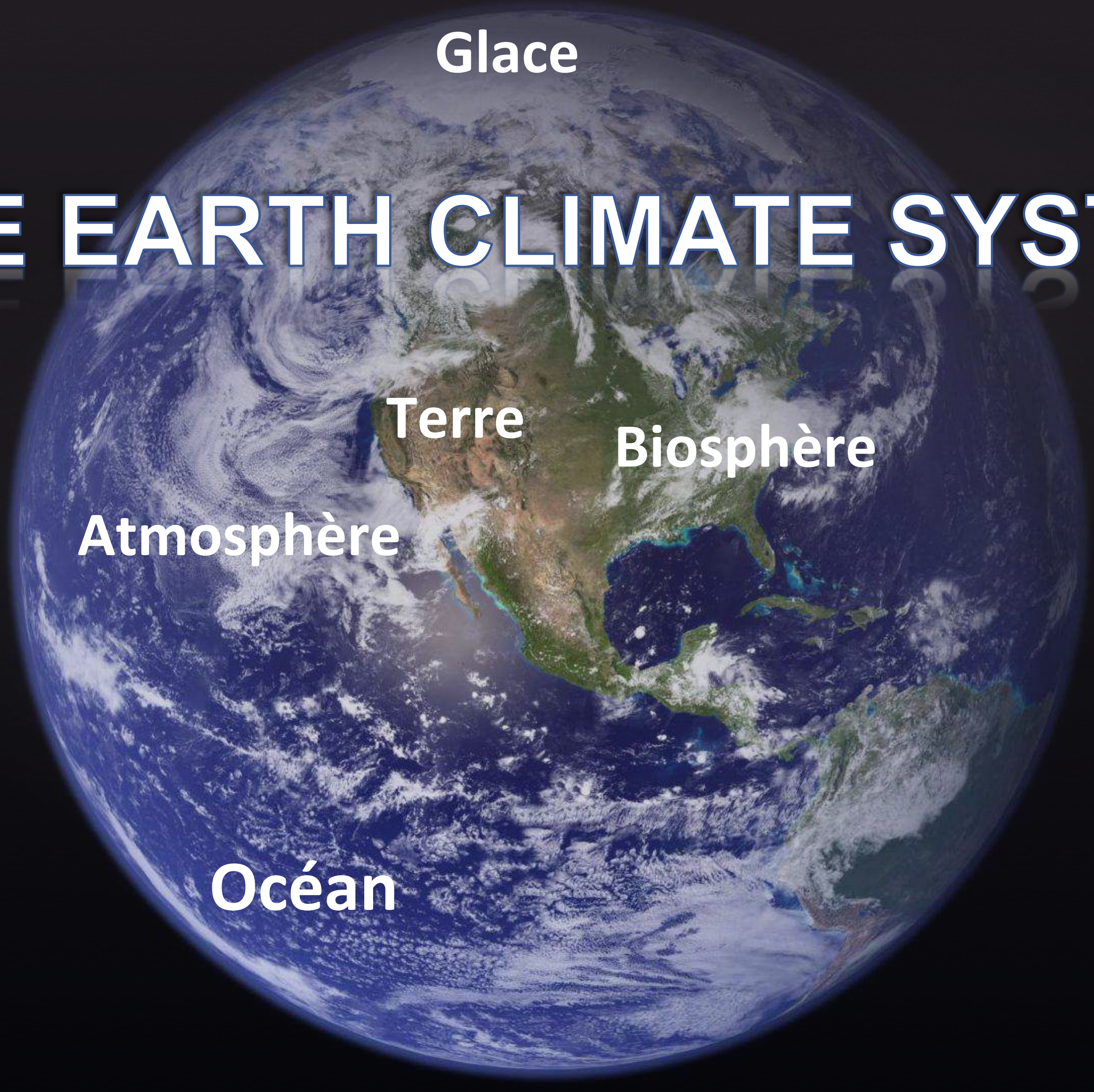
Lecture outline

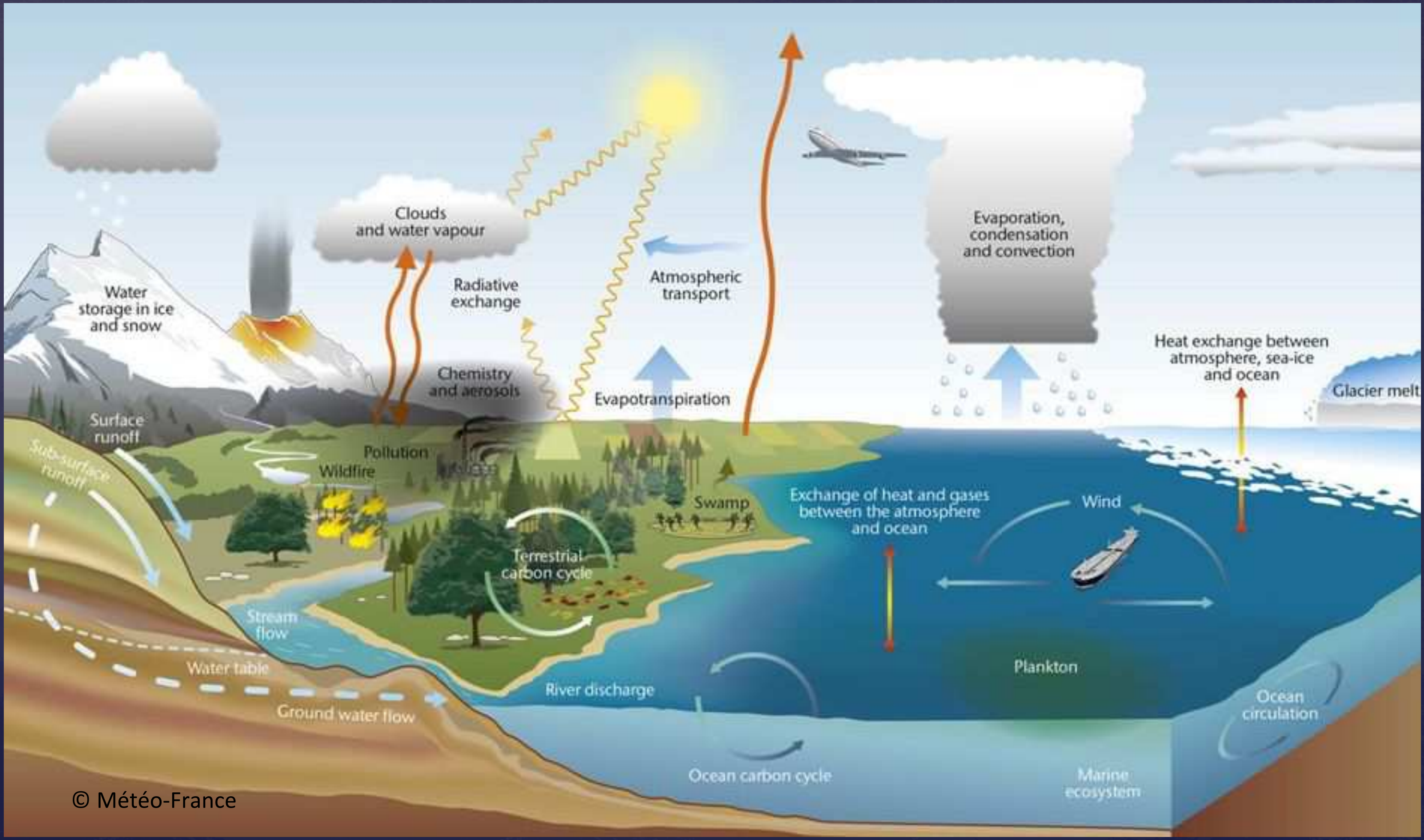
This lecture will give an overview of the principal mechanisms by which oceans influence climate, and climate influences the oceans.

We will consider the key differences between the content of mass, heat, and other (physical) properties in the atmosphere and the ocean, and use these to understand their behaviour.

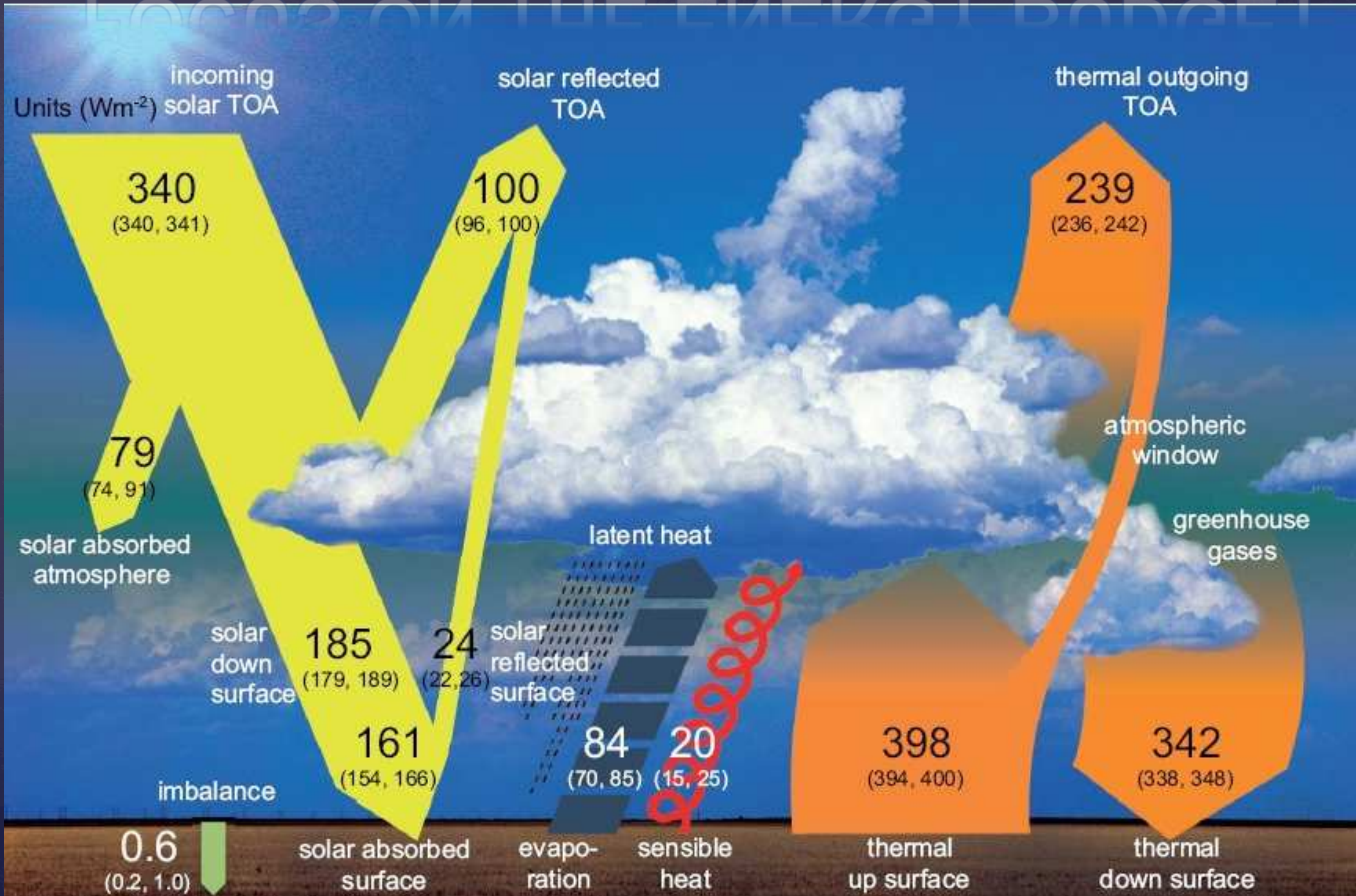
THE EARTH CLIMATE SYSTEM



The Earth Climate System is an extremely complex system with energy exchanges implying physical, chemical, and biological processes evolving continuously over a very wide spatio-temporal spectrum



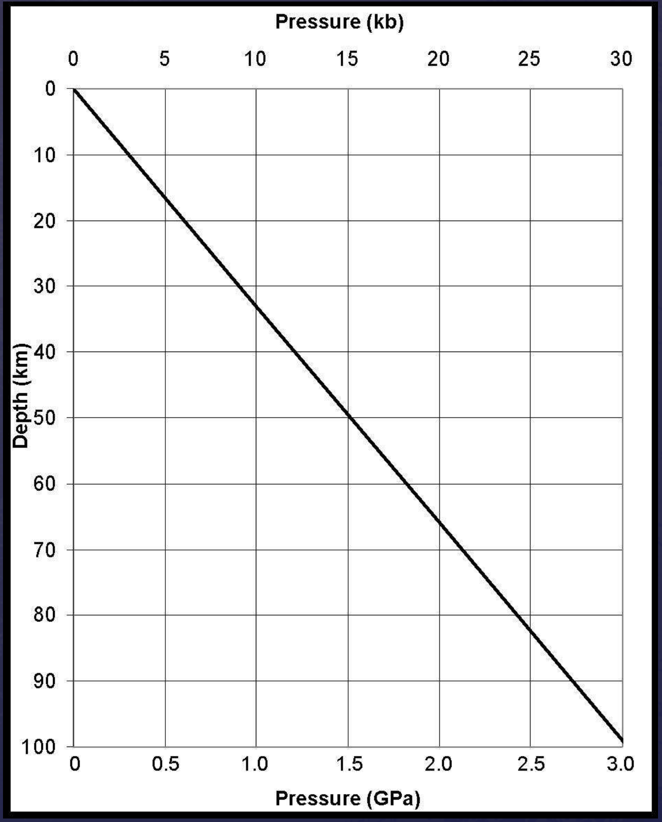
FOCUS ON THE ENERGY BUDGET



Relative mass of the ocean and atmosphere

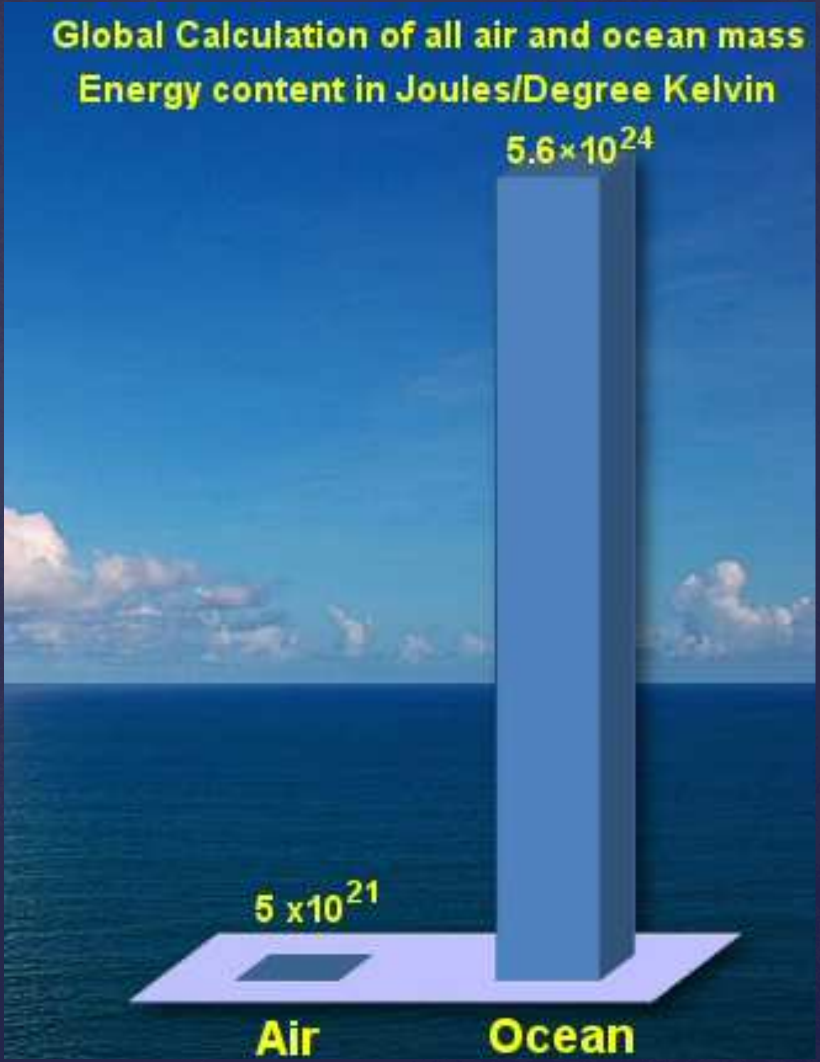
Pressure is proportional to the vertical integral of density in a hydrostatic fluid: $\mathbf{dp/dz = -\rho g}$, (g is gravitational acceleration). Therefore the overlying mass is $\boldsymbol{m = pA/g}$, where A is area.

10 metres (10 dbar) of water exerts as much pressure as the entire atmosphere (1 bar). The average depth of the ocean in nearly 4000 m, covering 70% of the surface area. Therefore the ocean is nearly 300 times as massive as the atmosphere (~1.4×10^{21} kg versus ~5×10^{18} kg).



Relative heat capacity of the ocean and atmosphere

MATERIAL	SPECIFIC HEAT (Joules/gram • °C)
Liquid water	4.18
Solid water (ice)	2.11
Water vapor	2.00
Dry air	1.01
Basalt	0.84
Granite	0.79
Iron	0.45
Copper	0.38
Lead	0.13



Relative heat capacity of the ocean and atmosphere

Heat capacity is the volume integral of density multiplied by specific heat capacity. Seawater has a specific heat capacity (~4000 J K^{-1} kg^{-1}) about four times that of the atmosphere, and 300 times the mass. Therefore the ocean has ~1000 times the heat capacity of the atmosphere (~$6x10^{24}$ J K^{-1} versus ~$5x10^{21}$ J K^{-1}).

A 2.5 m deep swimming pool has about the same heat capacity as the column of air through the entire atmosphere that overlies it.

Ocean and atmosphere reservoirs: Other properties

- Carbon dioxide is soluble in seawater, and reacts with ions in seawater do form bicarbonate and carbonate ions. Due principally to the large mass of the oceans, there is about 50 times as much carbon in the ocean than the atmosphere.

- Velocities are typically ~2 orders of magnitude greater in the atmosphere than the ocean; kinetic energy, $KE = \frac{1}{2} \int \rho u^2 \, dV$; *u* is velocity; *V* is volume). So despite the ocean's greater mass, the atmosphere has more kinetic energy.

Heat capacities per unit area – mixed layer ocean & atmosphere

- Ocean mixed layer is ~ 50m deep
- Deep ocean is ~ 4000m deep

Atmosphere:

$C_A = c_{p,A}\,\rho_A H_A = 10^3\ J\ kg^{-1}\ K^{-1} \times 1\ kg\ m^{-3} \times 10 \times 10^3\ m = \mathbf{10^7\ J\ m^{-2}\ K^{-1}}$

Ocean (mixed layer):

$C_O = c_{p,O}\,\rho_O H_O =$

$4 \times 10^3\ J\ kg^{-1}\ K^{-1} \times 10^3\ kg\ m^{-3} \times 50\ m = \mathbf{2 \times 10^8\ J\ m^{-2}\ K^{-1}}$

Consequences: Equilibration timescales

- Consider transient temperature for the atmosphere, mixed layer, deep ocean (*C* here is heat capacity; *B* is a restoring rate):

atmosphere (balance between tendency & restoring term):

$$C_a \frac{dT_a'}{dt} + BT_a' = 0 \Rightarrow \frac{dT_a'}{dt} + \frac{B}{C_a} T_a' = 0\ ;\ T_a' = a_1 \exp\left(-\lambda_a t\right) + a_2$$

$$\text{where } \lambda_a = B/C_a = 1/\tau_a \ \text{ i.e., } \tau_a = C_a/B$$

mixed layer (ditto atmosphere):

$$C_o \frac{dT_o'}{dt} + \lambda T_o' = 0 \Rightarrow \frac{dT_o'}{dt} + \frac{\lambda}{C_o} T_o' = 0\ ;\ T_o' = b_1 \exp\left(-\lambda_o t\right) + b_2$$

$$\text{where } \lambda_o = \lambda/C_o = 1/\tau_o \ \text{ i.e., } \tau_o = C_o/B$$

deep ocean - vertical diffusion equation:

$$\frac{\partial T}{\partial t} - k_v \frac{\partial^2 T}{\partial z^2} = 0 \ \rightarrow \text{scaling } (\partial z^2 \sim H^2) \text{ yields } \tau_d = \frac{H^2}{k_v}$$

Consequences: Equilibration timescales

- **Atmosphere (troposphere) : ~ two months**
  - w.r.t. thermal equilibration with space (via OLWR, for which B ≈ 2 $W\,m^{-2}\,K^{-1}$)

$$C_A / B \approx 10^7\ Ws\ m^{-2}\ K^{-1} / 2\ W\ m^{-2}\ K^{-1} \approx 5 \times 10^6\ s \approx 50\ days$$

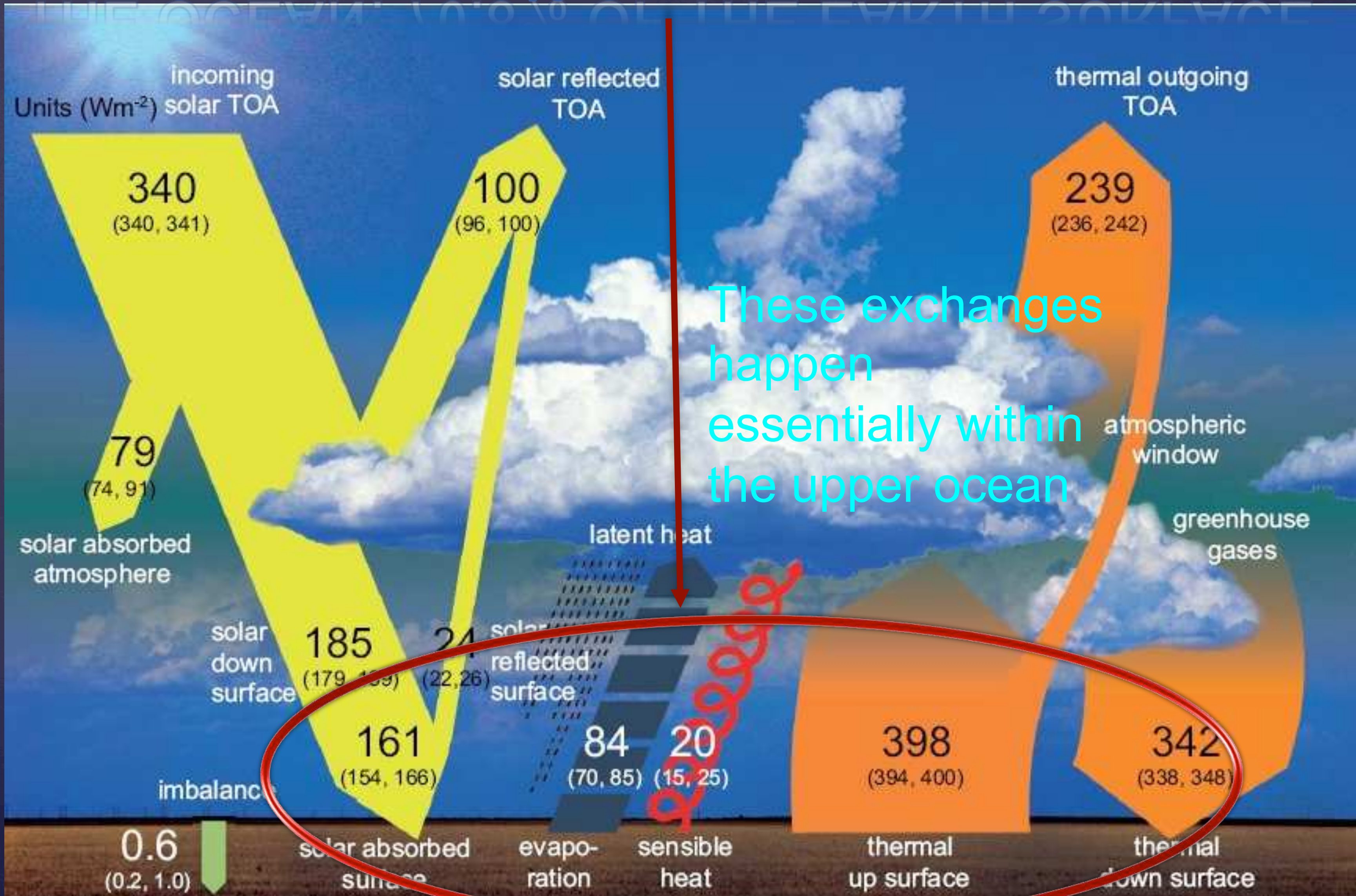
- **Ocean mixed layer : also two months**
  - w.r.t. thermal equilibration with atmosphere (via air-sea exchange, for which λ ≈ 35 $W\,m^{-2}\,K^{-1}$)

$$C_o / \lambda \approx 2 \times 10^8\ Ws\ m^{-2}\ K^{-1} / 35\ W\ m^{-2}\ K^{-1} \approx 6 \times 10^6\ s \approx 60\ days$$

- **Deep Ocean : ~ 1000 years**
  - w.r.t. diffusive mixing (with deep ocean depth scale, H = 2000 m; ocean vertical diffusivity, $k_v \approx 10^{-4}\ m^2\ s^{-1}$)

$$H^2 / k_v \approx 4 \times 10^6\ m^2 / 10^{-4}\ m^2\ s^{-1} \approx 4 \times 10^{10}\ s \approx 1300\ years$$

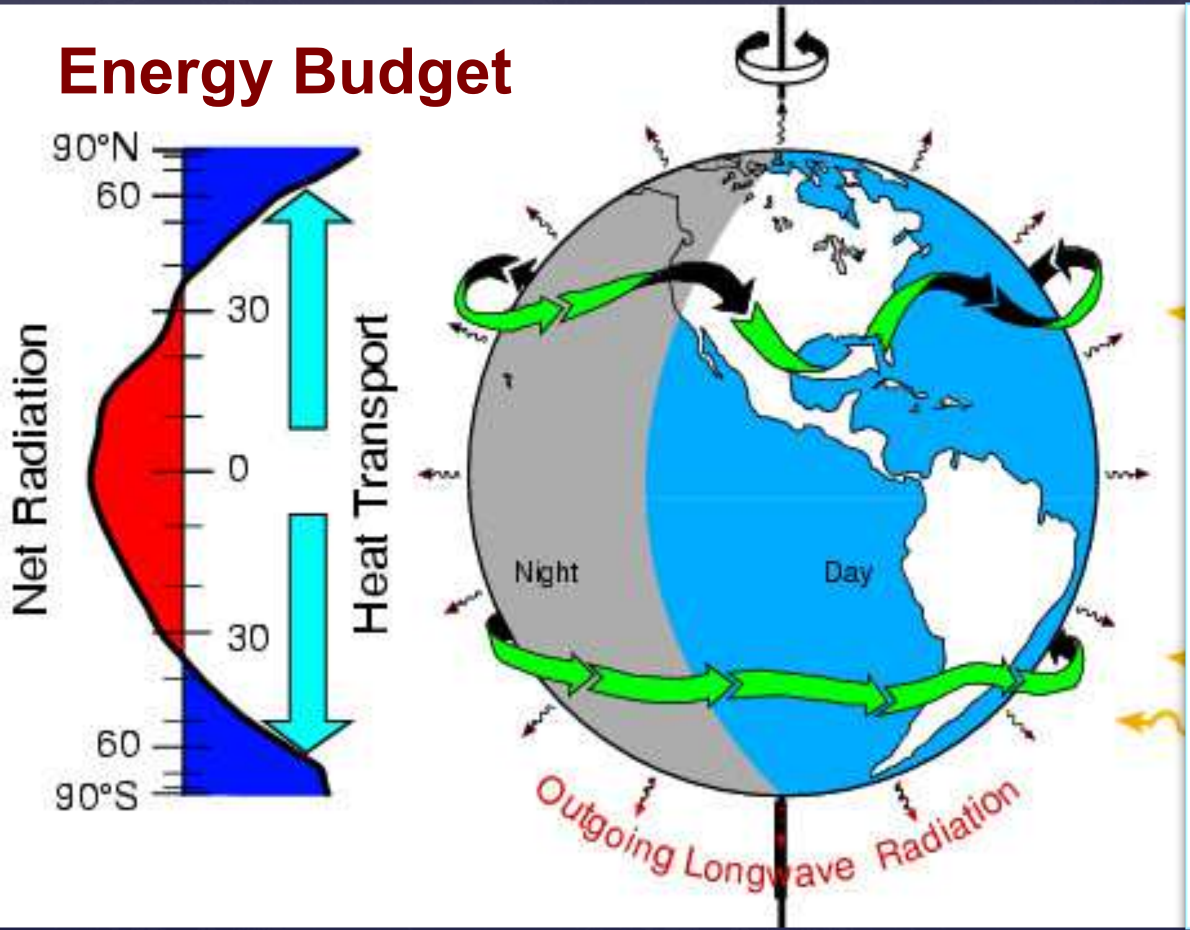
FOCUS ON THE ENERGY BUDGET & THE OCEAN: 70.8% OF THE EARTH SURFACE



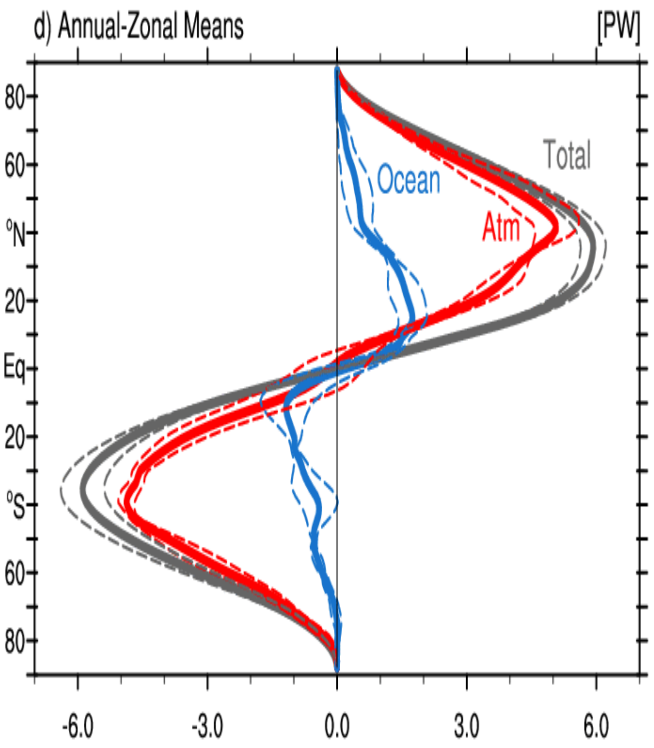
ENERGY ON EARTH

At equilibrium: Balance between the incoming and outgoing radiation

Energy Budget



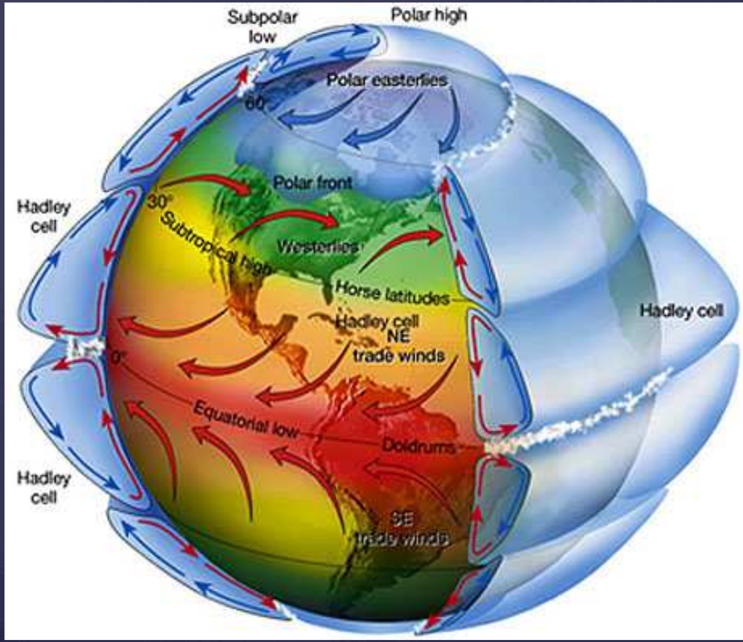
Energy Transport

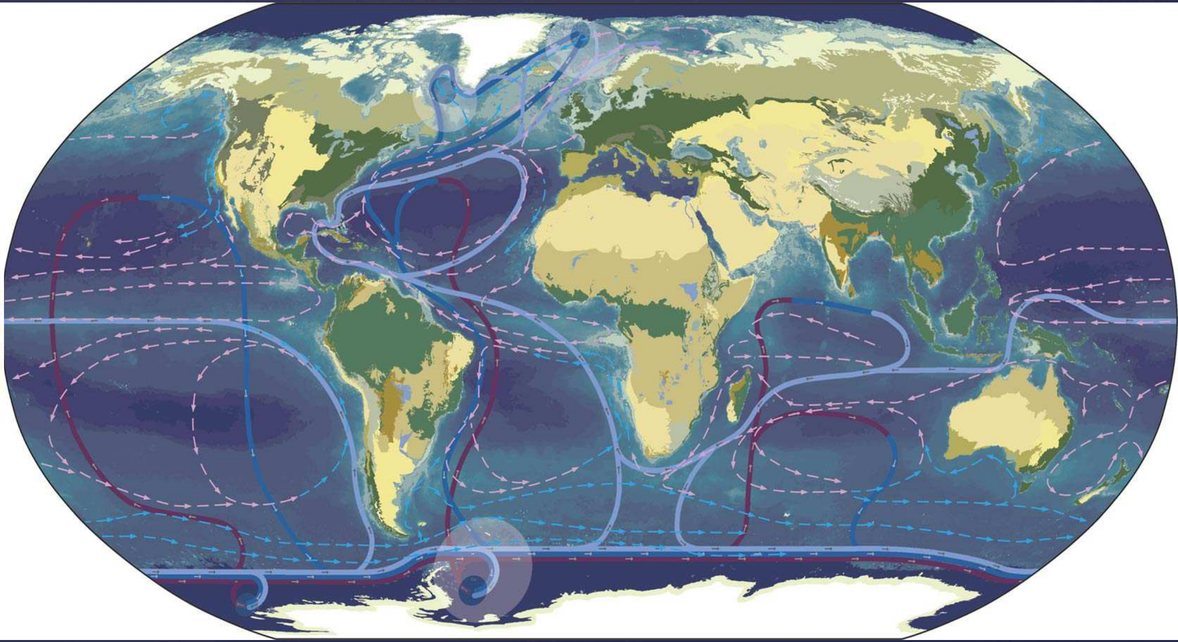


The Global Ocean Circulation

Forced by wind-stress and buoyancy fluxes (heat & fresh-water)

SCHEMATICS:

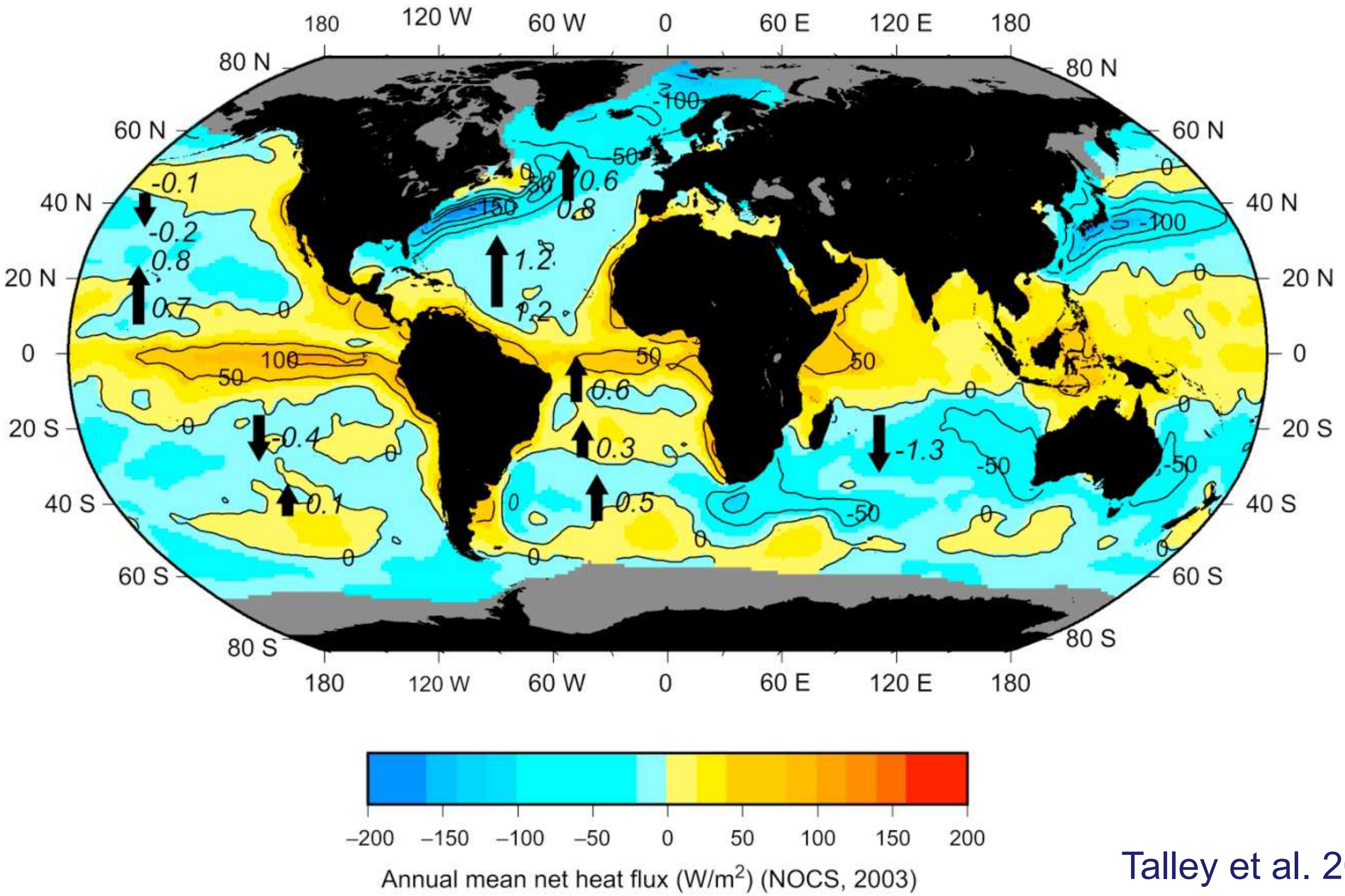




Atmosphere (Troposphere) circulation

Ocean circulation, surface and deep

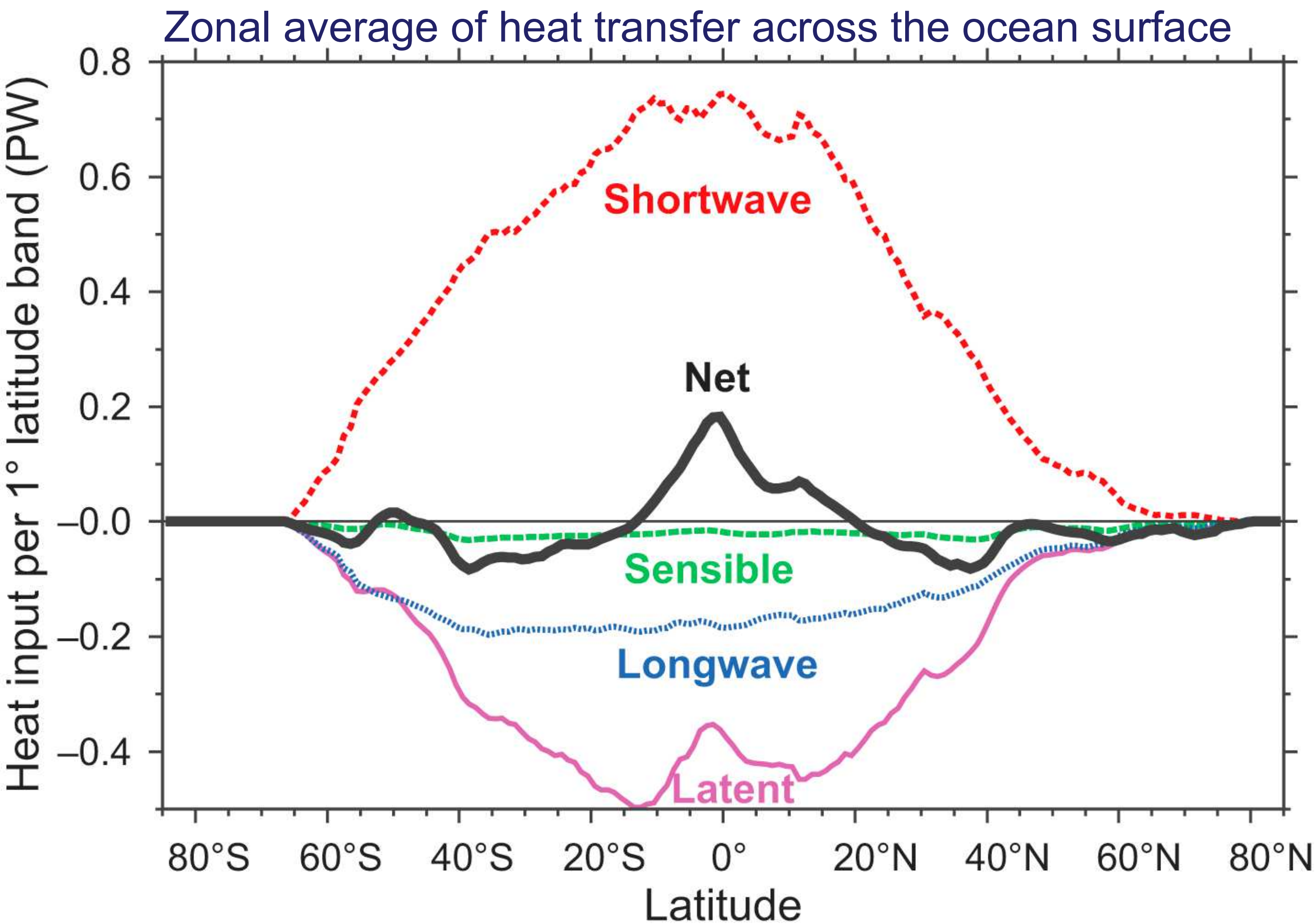
Net Ocean Surface Heat Flux



Talley et al. 2011

Heat flux $$\frac{DT}{Dt} = -\frac{1}{\rho c_p}\frac{\partial Q}{\partial z}$$ & Heat transport (Q_{adv})

Net Ocean Surface Heat Components



- The integral of the net heat flux should be zero in steady state.
- Imbalance at each latitude implies meridional ocean heat transport.

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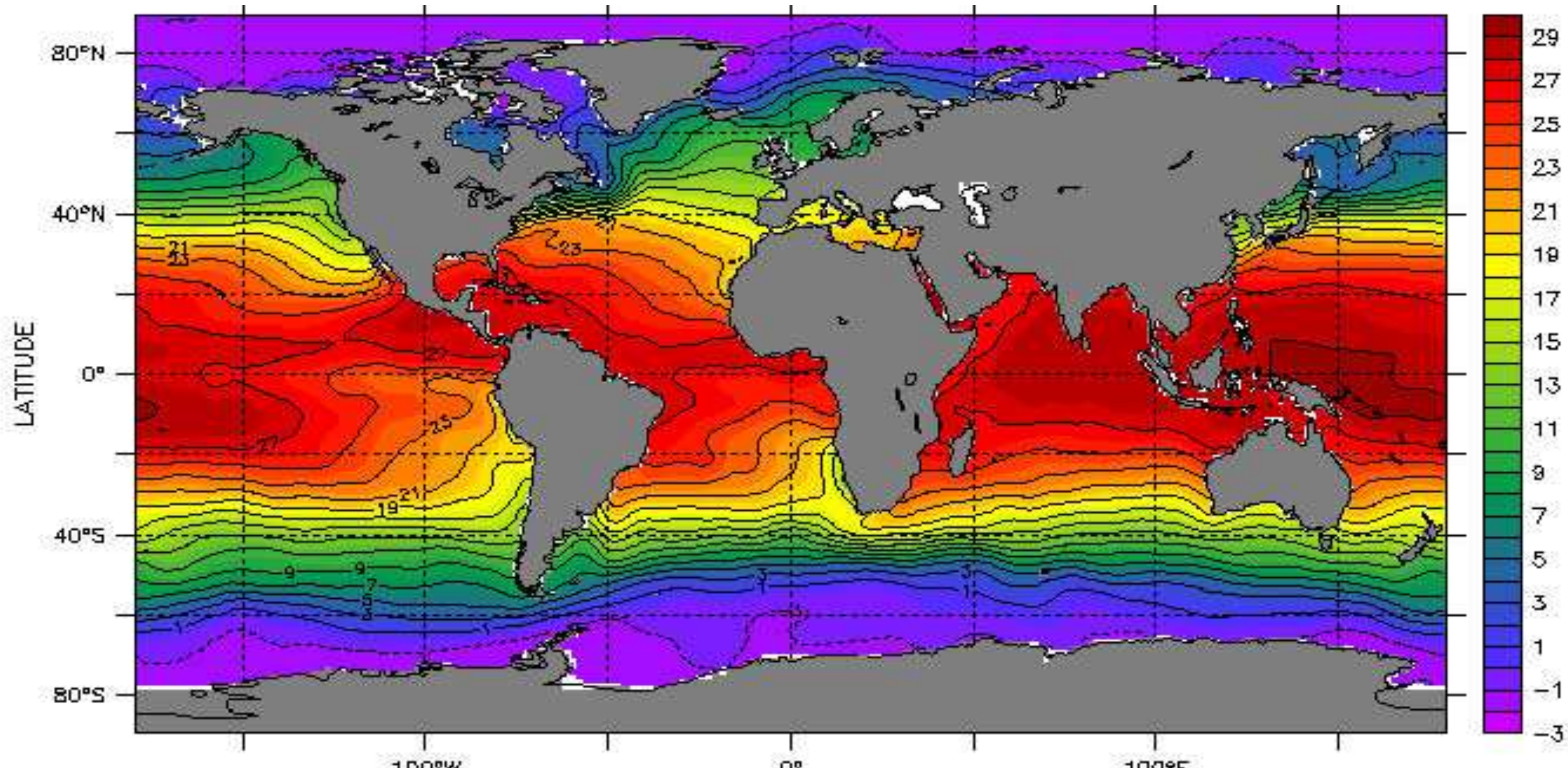
Sea Surface Temperature of the Ocean



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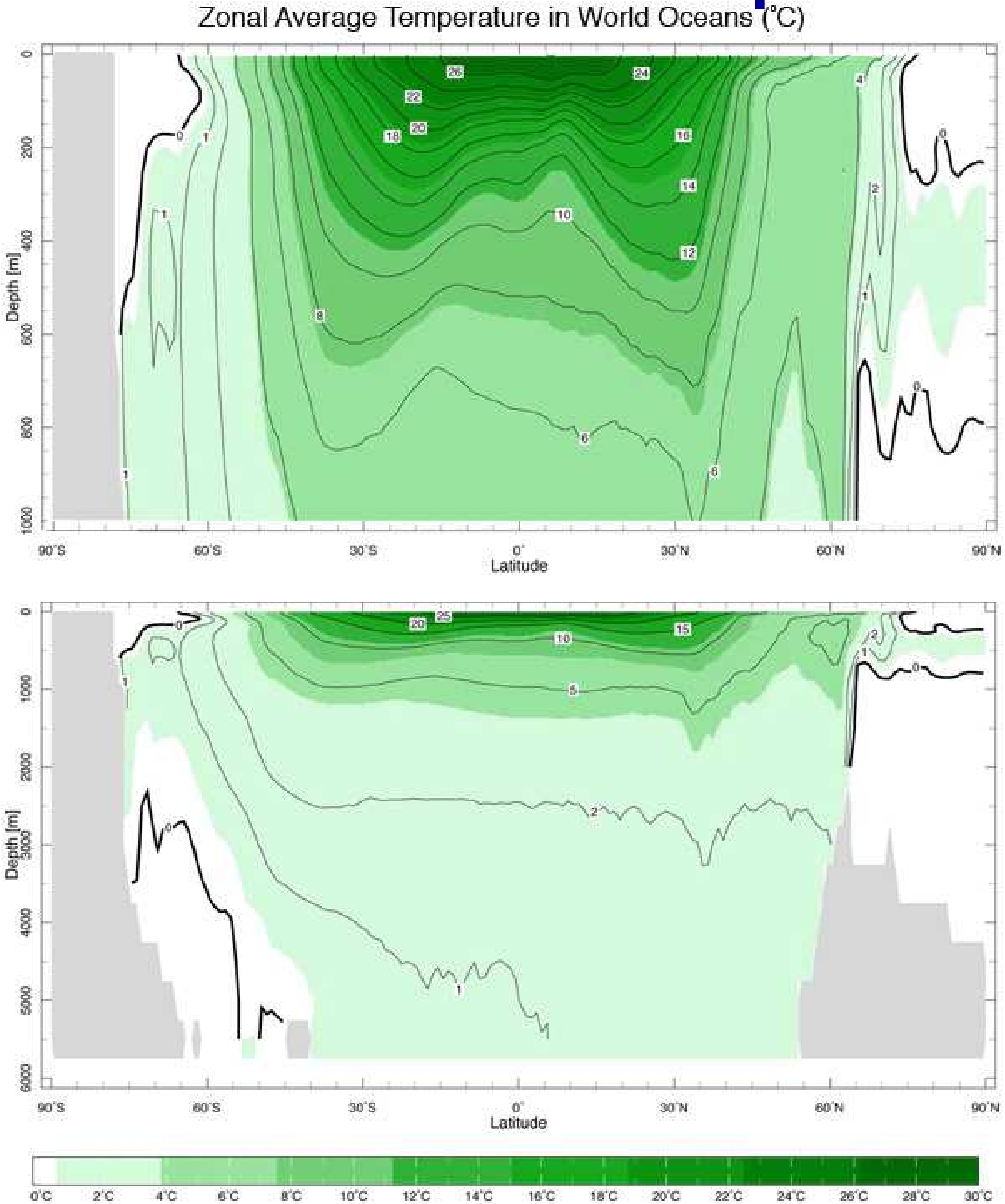
Ocean's Temperature at depth



Annual-mean cross-section of zonal-average salinity (in psu) in the world's oceans:

- Top : upper 1000 m
- Bottom : the whole water column.

Darker shading represents warmer water.

Data from the Levitus World Ocean Atlas 1994

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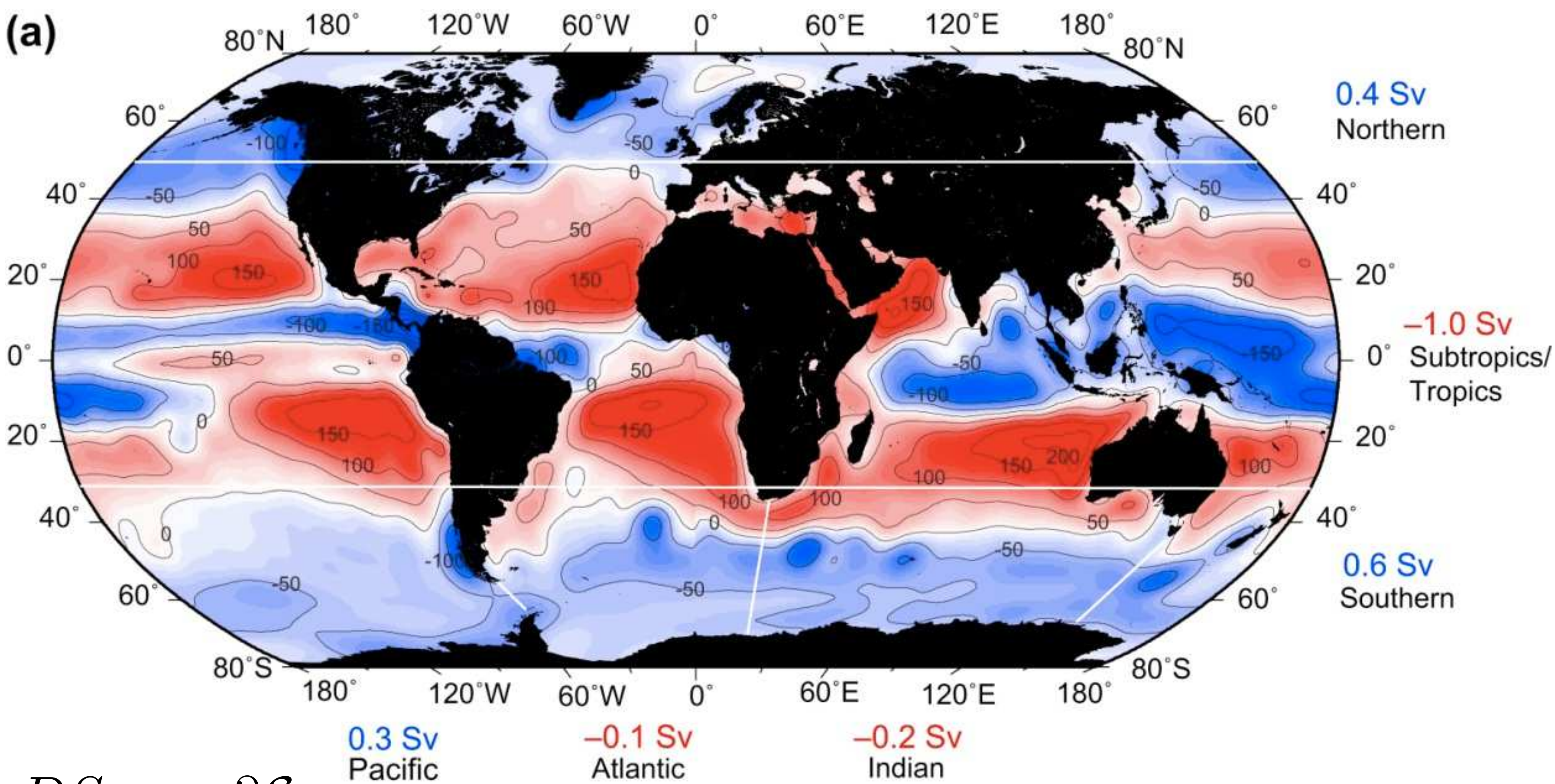
Surface Freshwater (E – P) flux

Data from National Centre for Environmental Prediction (NCEP)



$$\frac{DS}{Dt} = S\frac{\partial \mathcal{E}}{\partial z}$$

Freshwater flux

$\mathcal{E}$ is the turbulent vertical ux of freshwater and at the surface is equal to E – P.

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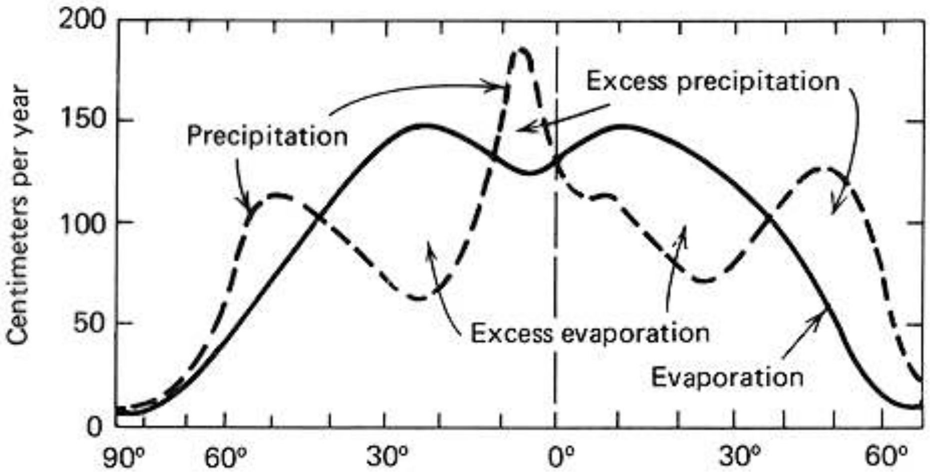
General Circulation of the Atmosphere & Climatic Regions

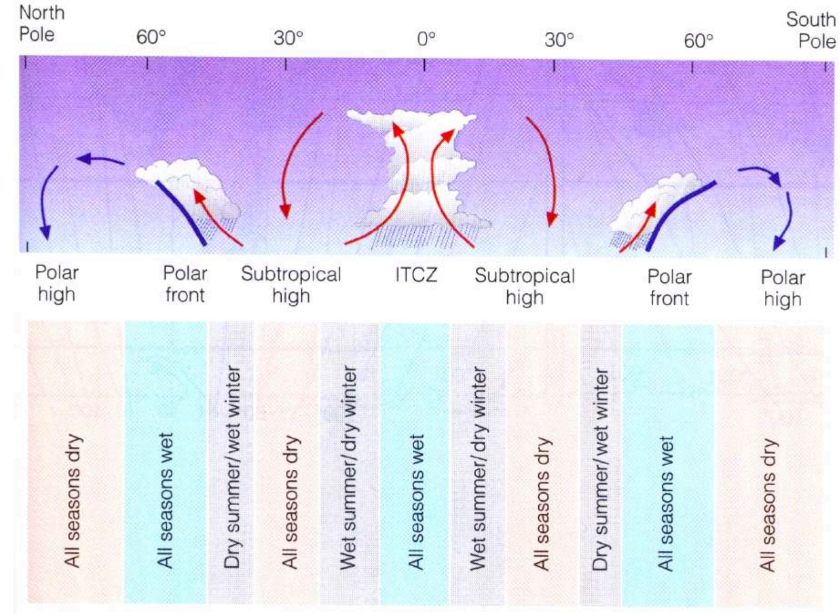
Evaporation

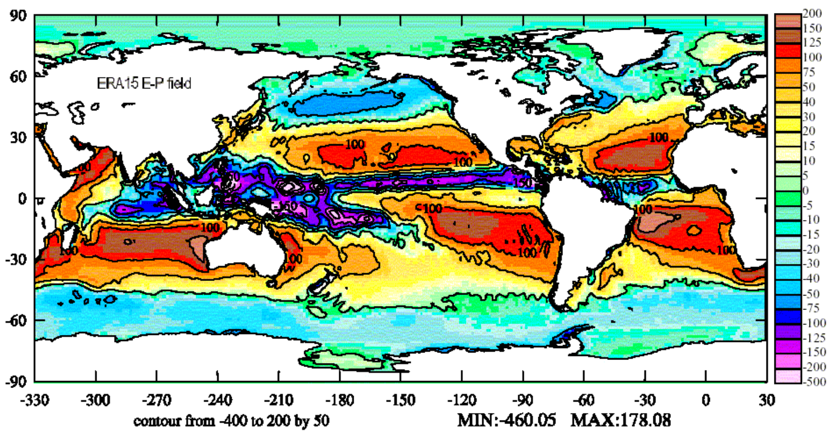
Where air subside

Precipitation

Where air rise in altitude







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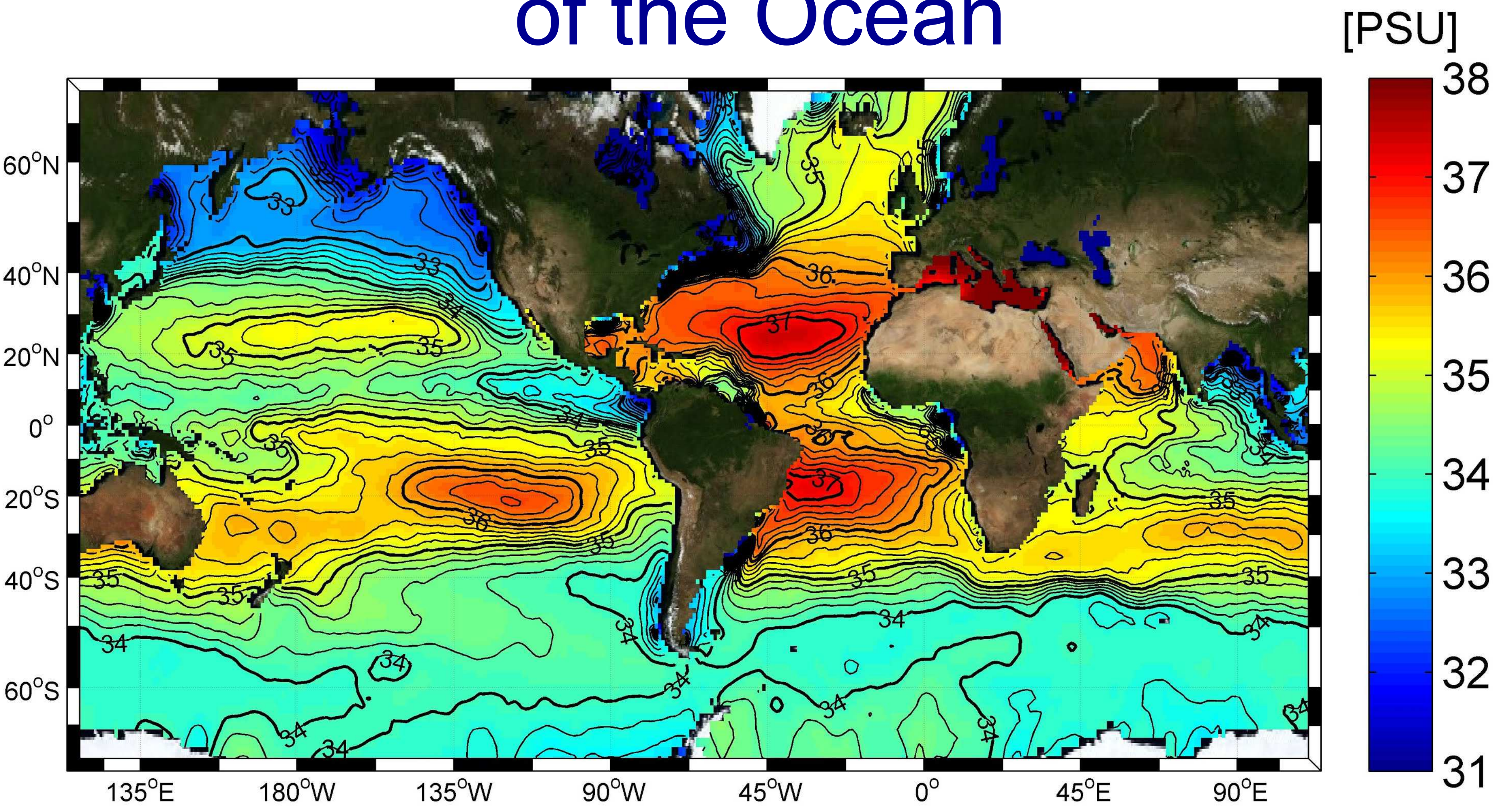
Sea Surface Salinity of the Ocean



Interpolated global ocean salinity at the surface based on all historical observations: red areas have high salinity (i.e., 36 PSU or higher) and blue areas have low salinity (i.e., 34 PSU or lower). *World Ocean Atlas 2009*

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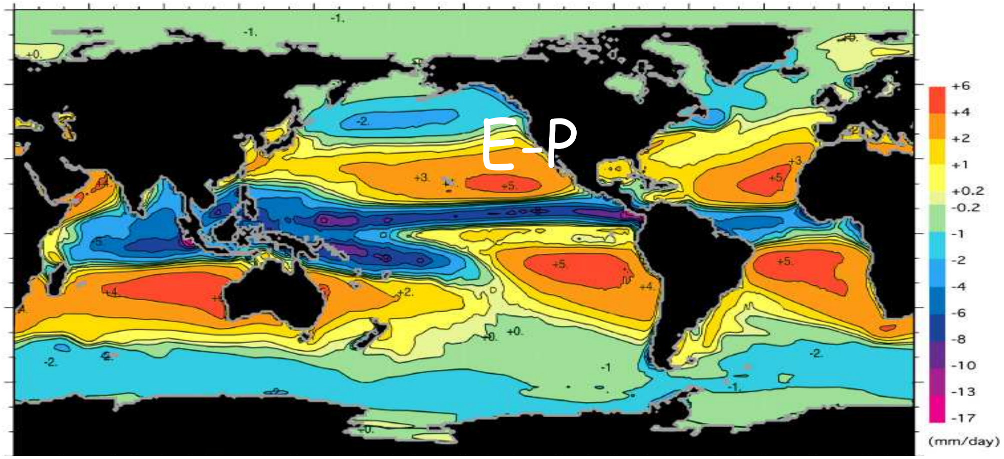
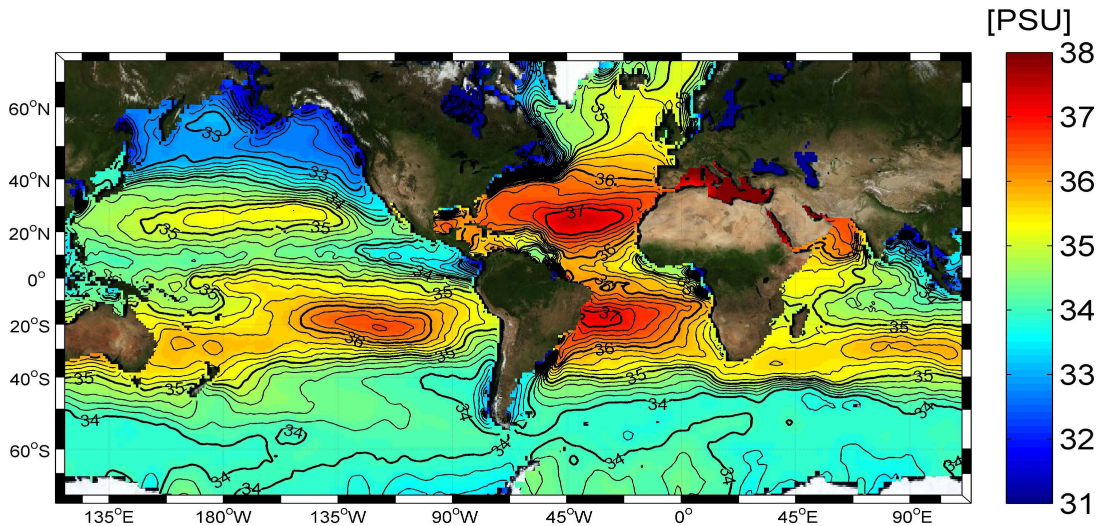
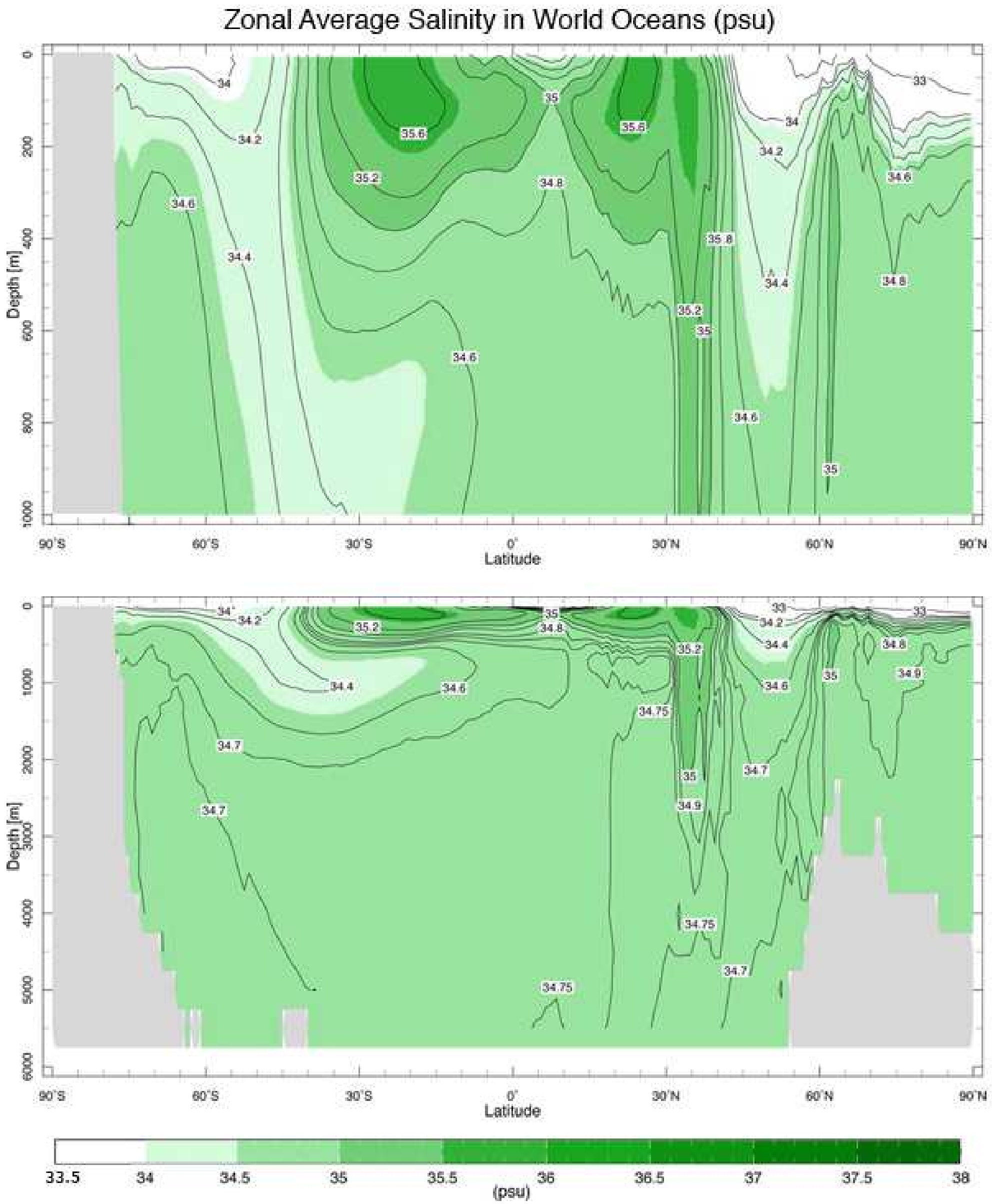
Relation between the fresh-water flux & Sea Surface Salinity (SSS)





Ocean's Salinity at depth



Annual-mean cross-section of zonal-average potential temperature (in °C) in the world's oceans:

- Top : upper 1000 m
- bottom : the whole water column.

Dark shading represents saltier water.

Note the variable contour interval in the bottom plot.

Data from the Levitus World Ocean Atlas 1994

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The Momentum Equations for a Rotating Fluid

Momentum Equations

Acceleration: Substantial Derivative $D\vec{u}/Dt$, Coriolis. Force/Mass: Pressure Gradient, Gravity.

$$\underbrace{\overbrace{\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}}^{\text{Substantial Derivative } D\vec{u}/Dt} \overbrace{- fv}^{\text{Coriolis}}}_{\text{Acceleration}} = \underbrace{\overbrace{-\frac{1}{\rho}\frac{\partial p}{\partial x}}^{\text{Pressure Gradient}} + \text{friction}}_{\text{Force/Mass}}$$

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

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial z} \overbrace{- g}^{\text{Gravity}} + \text{friction}$$

Friction terms all take a similar form. For the x equation we have

$$\frac{\partial}{\partial x}\left(A_H\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_H\frac{\partial u}{\partial y}\right) + \frac{\partial}{\partial z}\left(A_V\frac{\partial u}{\partial z}\right) + \nu\nabla^2 u.$$

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The Ekman transport

Recall the x-momentum equation

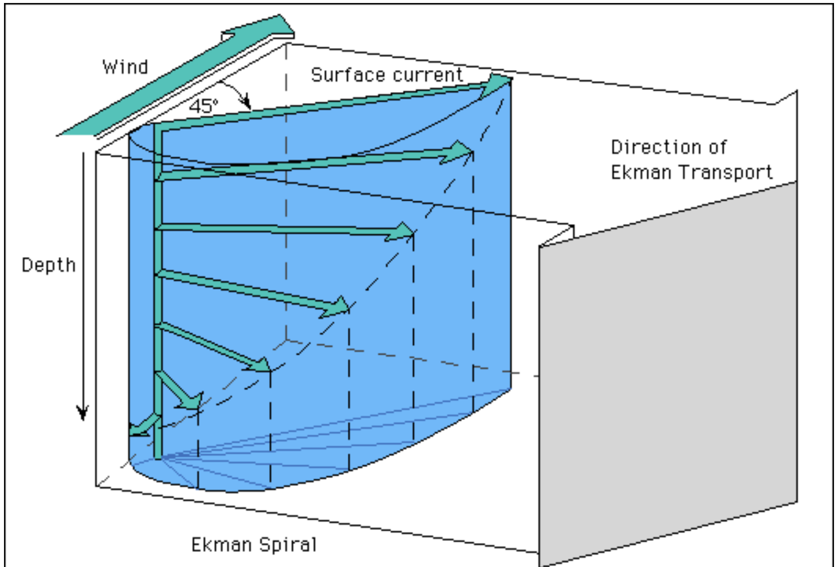
$$-fv = A_V \frac{d^2u}{dz^2} = \frac{1}{\rho}\frac{\partial \tau_x}{\partial z} \quad \Rightarrow \quad \rho v = -\frac{1}{f}\frac{\partial \tau_x}{\partial z}$$

The net mass transport (per unit width) in the y-direction is

$$M_y = \int_{-\infty}^{0} \rho v \, dz$$

$$= \int_{-\infty}^{0} \left(-\frac{1}{f}\frac{\partial \tau_x}{\partial z}\right) dz$$

$$= -\frac{1}{f}\left(\tau_x(0) - \tau_x(-\infty)\right) = -\frac{\tau_x}{f}$$



Adapted from Thurman, Harold V. **Essentials of Oceanography, 5th ed.** Prentice-Hall, Inc., 1996.

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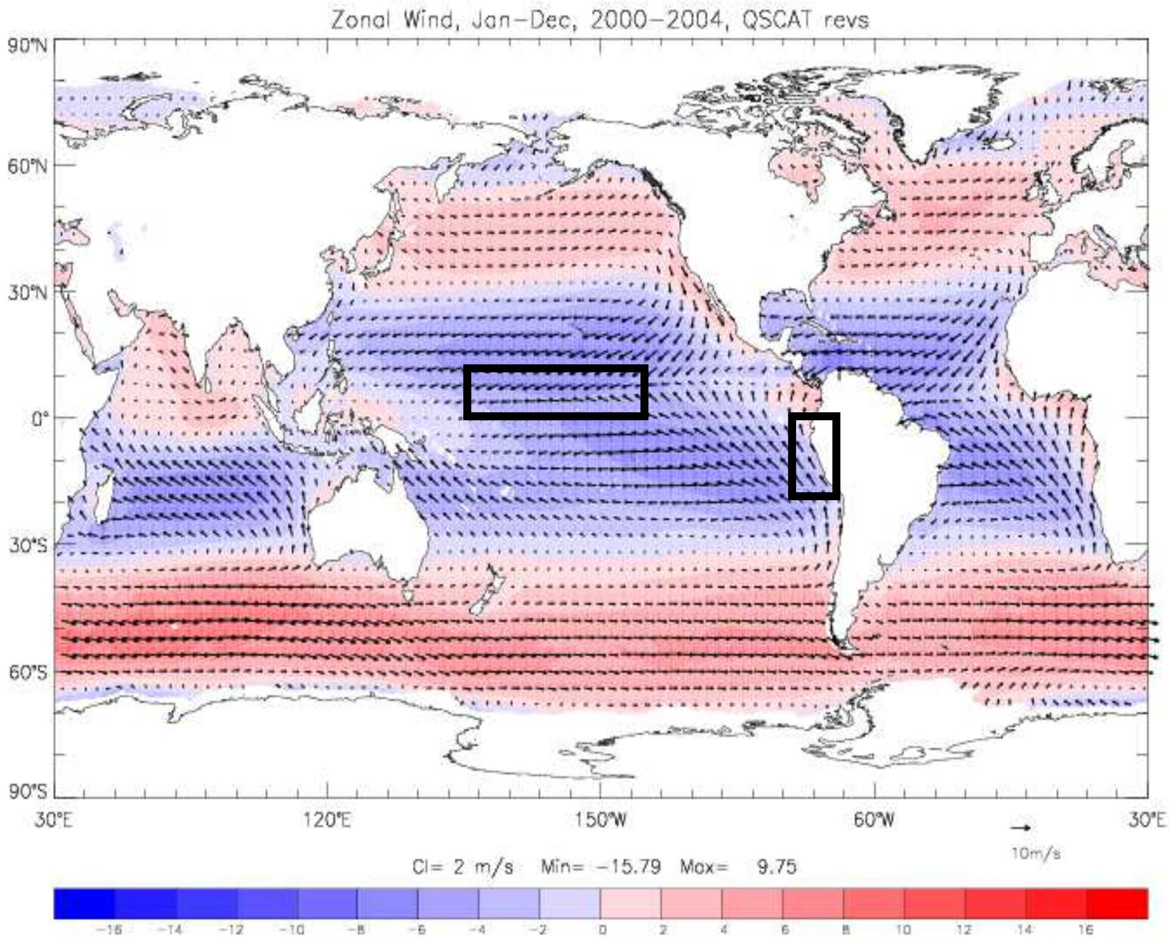
Global surface wind velocity



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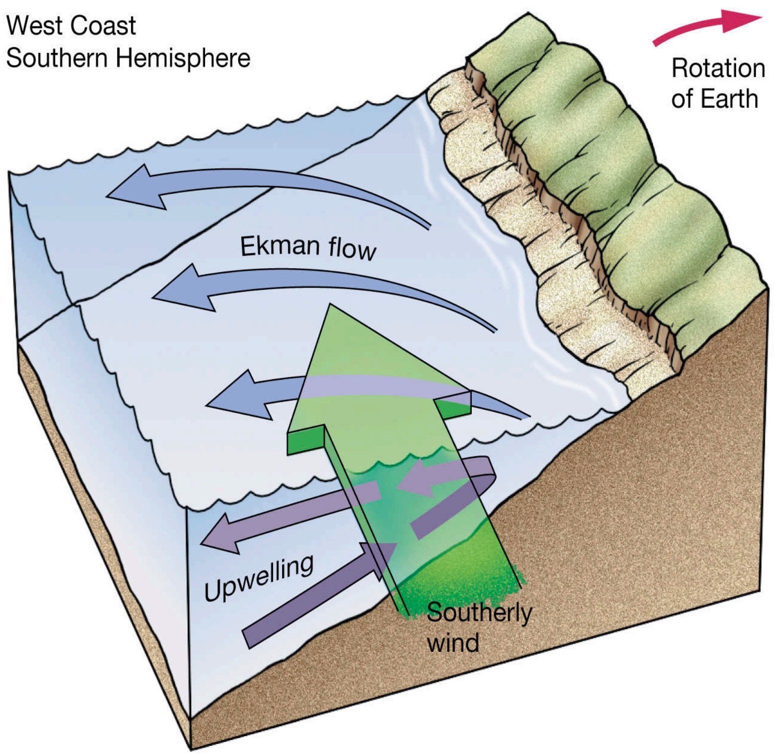
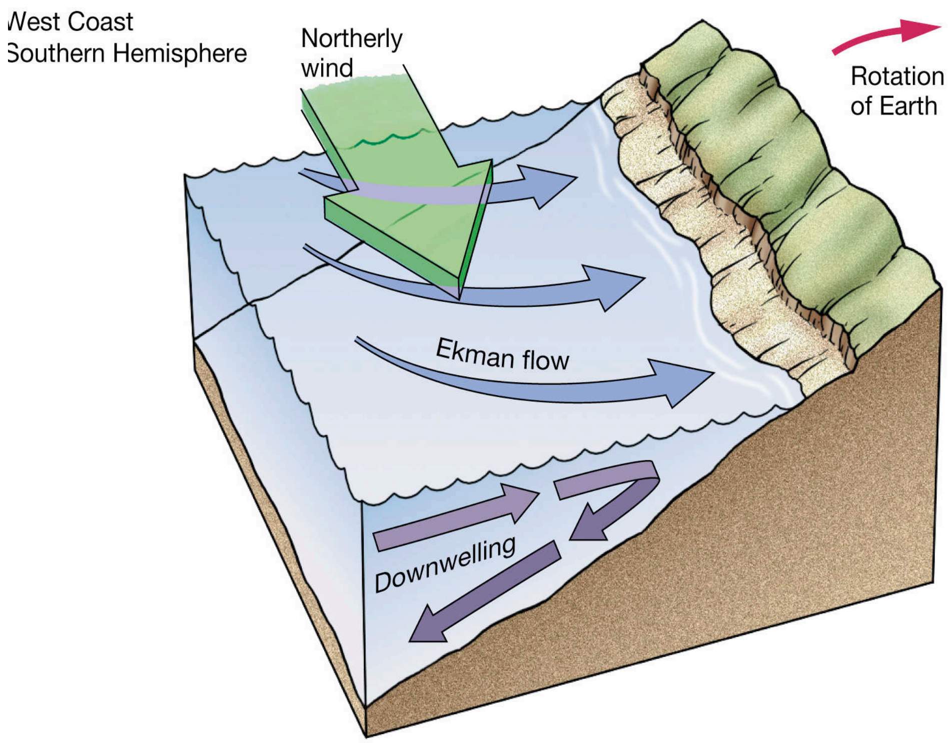
Ekman divergence (Ekman upwelling) at equator and at **land boundaries**

Example for the Southern Hemisphere (SH)

SH Coastal Upwelling



SH Coastal Downwelling



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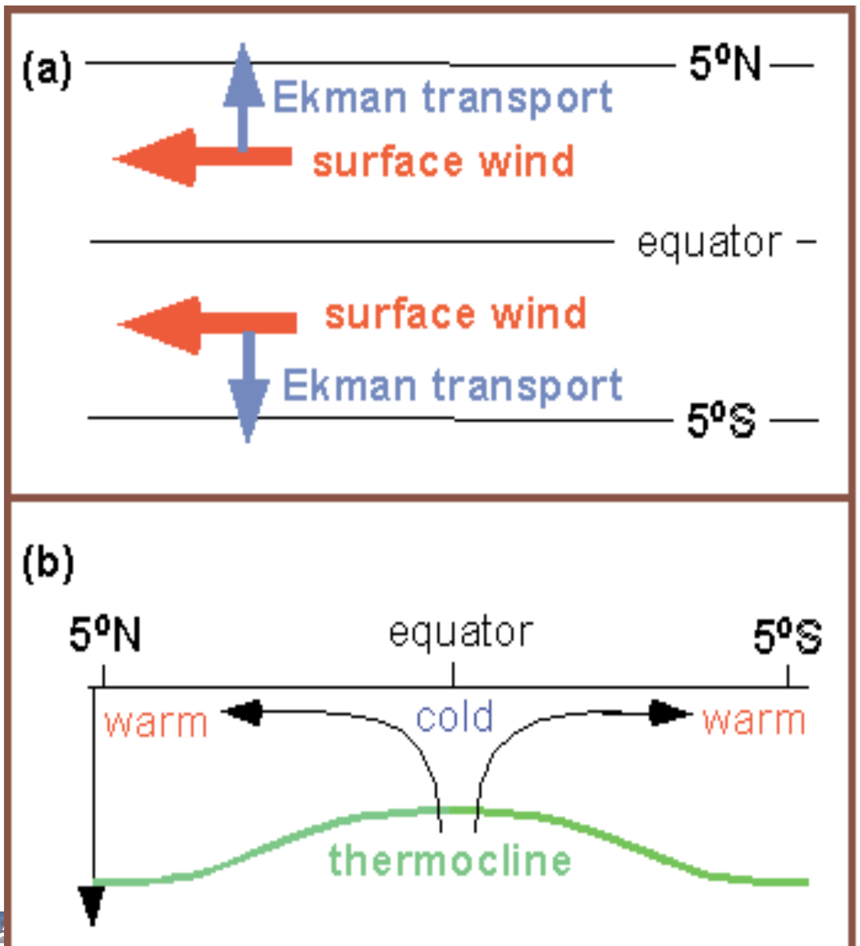
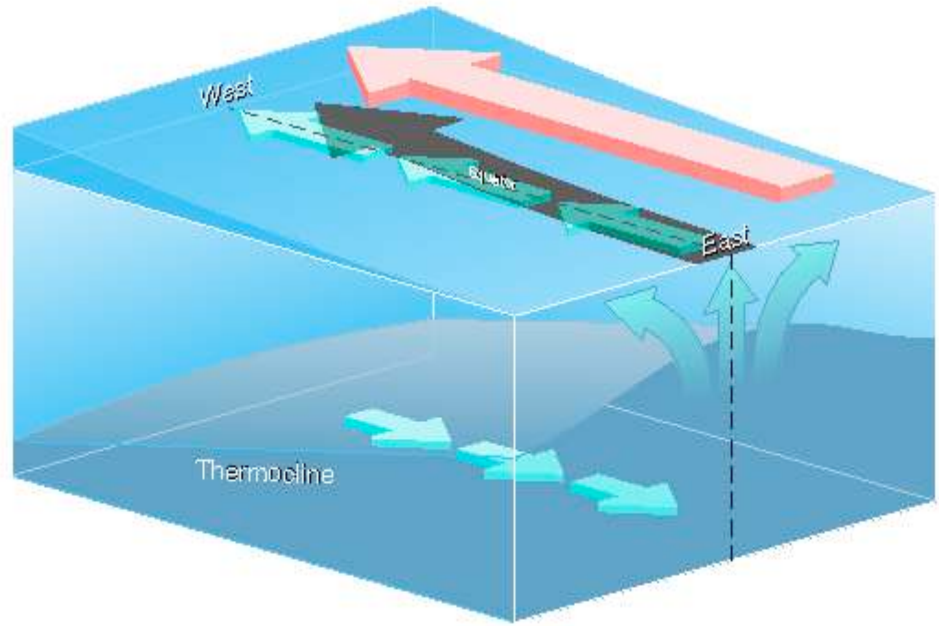
Ekman divergence (Ekman upwelling) **at the equator** and at land boundaries

Equatorial





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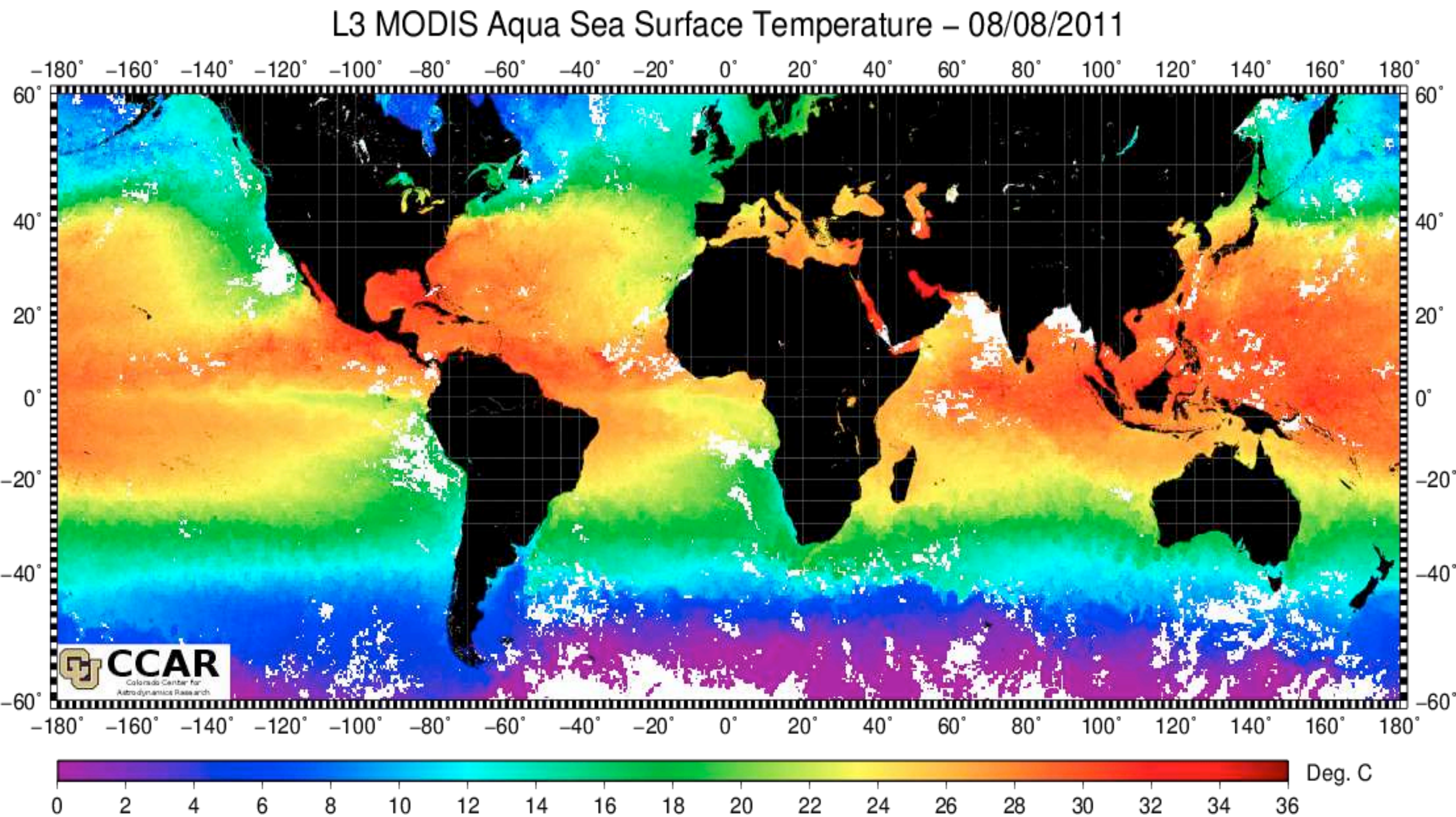
Ekman divergence (Ekman upwelling) **at the equator and at land boundaries**



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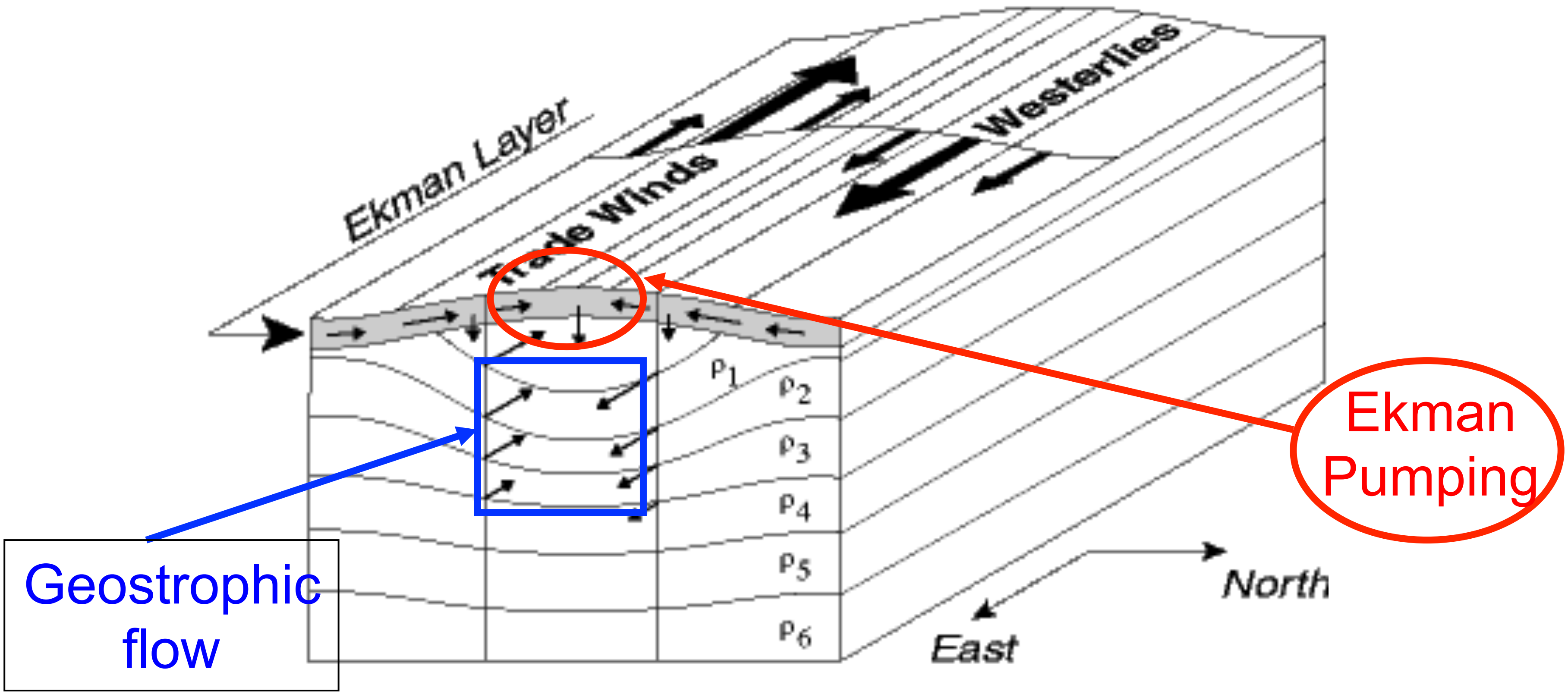
Ekman transport convergence and divergence



Vertical velocity at base of Ekman layer: order (10^{-4}cm/sec)

(Compare with typical horizontal velocities of 1-10 cm/sec)

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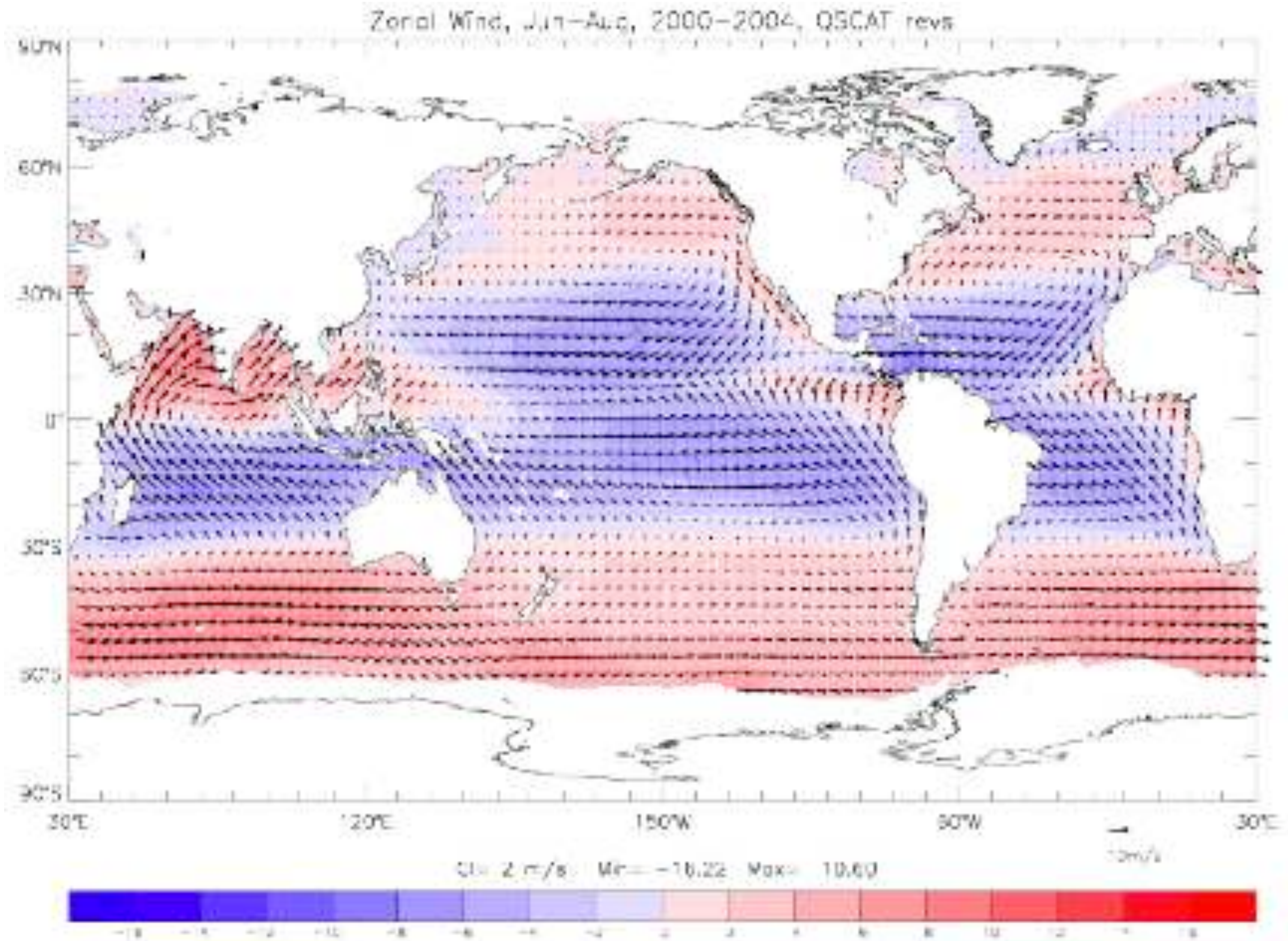
Global surface wind velocity



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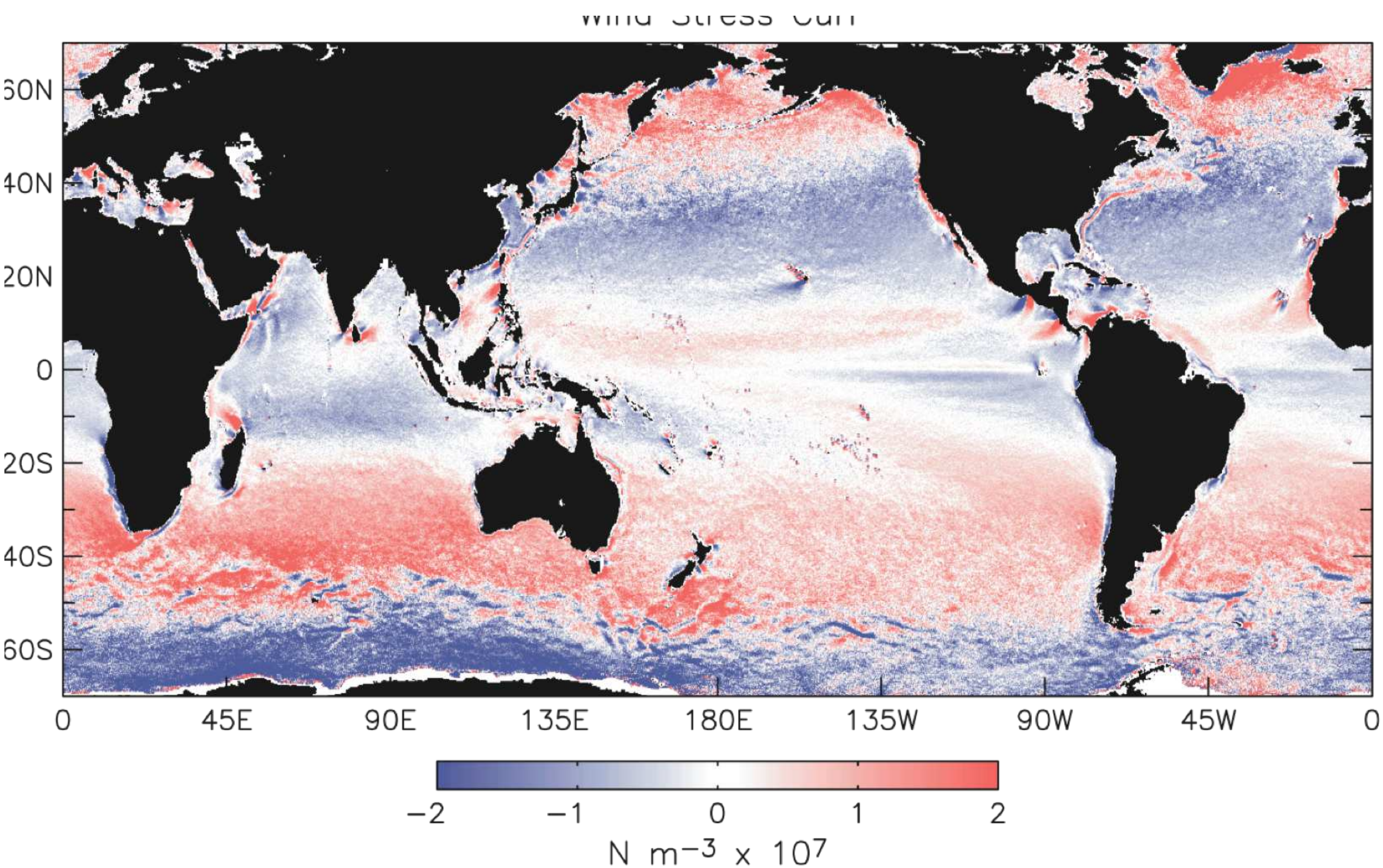
Global surface wind stress curl



NH:
Red = upwelling
Blue = downwelling

SH:
Red = downwelling
Blue = upwelling

Wind stress curl (related to Ekman transport convergence and divergence) (Chelton et al., 2004)

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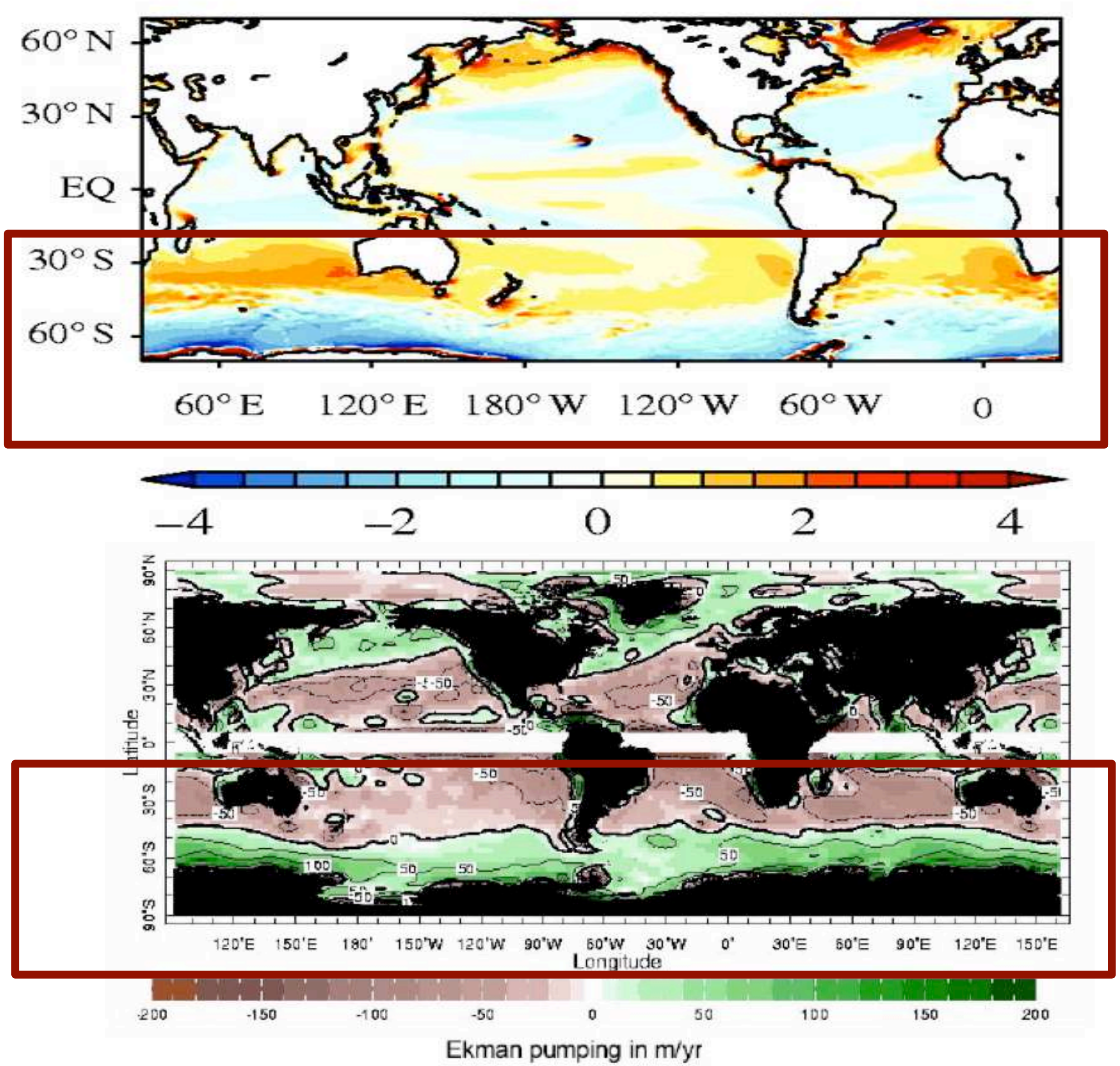
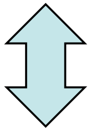
Wind driven circulation: Ekman Pumping



Wind Curl (climatology)

$$\nabla_h \times \boldsymbol{\tau}$$



Ekman pumping

$$w_e = \frac{1}{\rho f} \nabla_h \times \boldsymbol{\tau}$$

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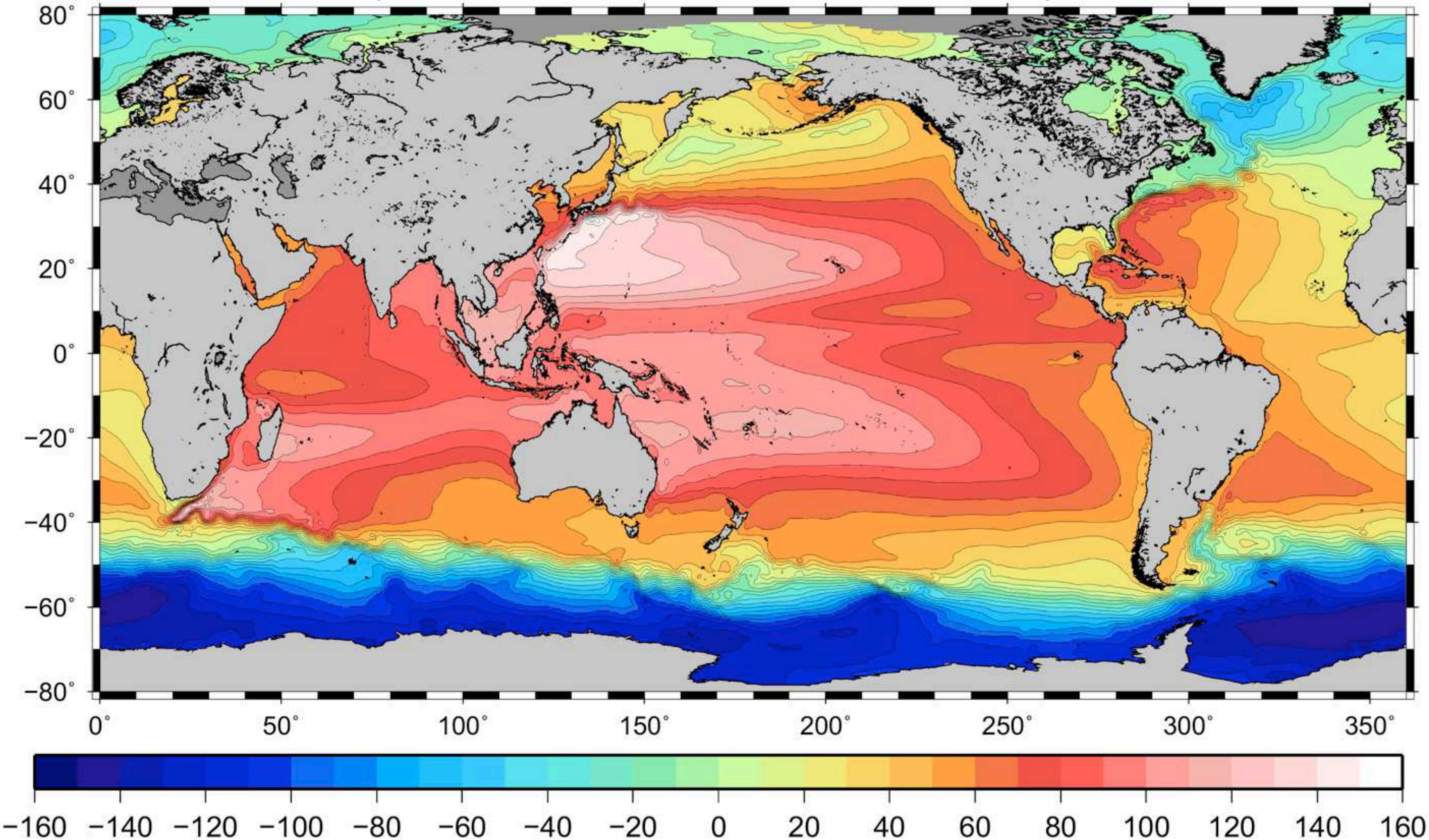
Sea Surface Height
(from satellite & in situ data)



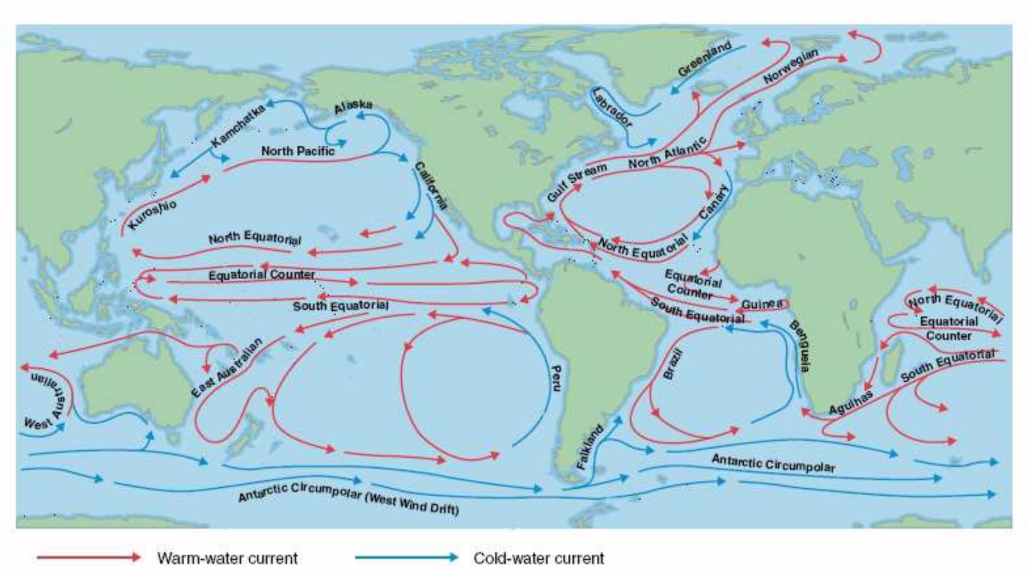
Mean dynamic topography in cm

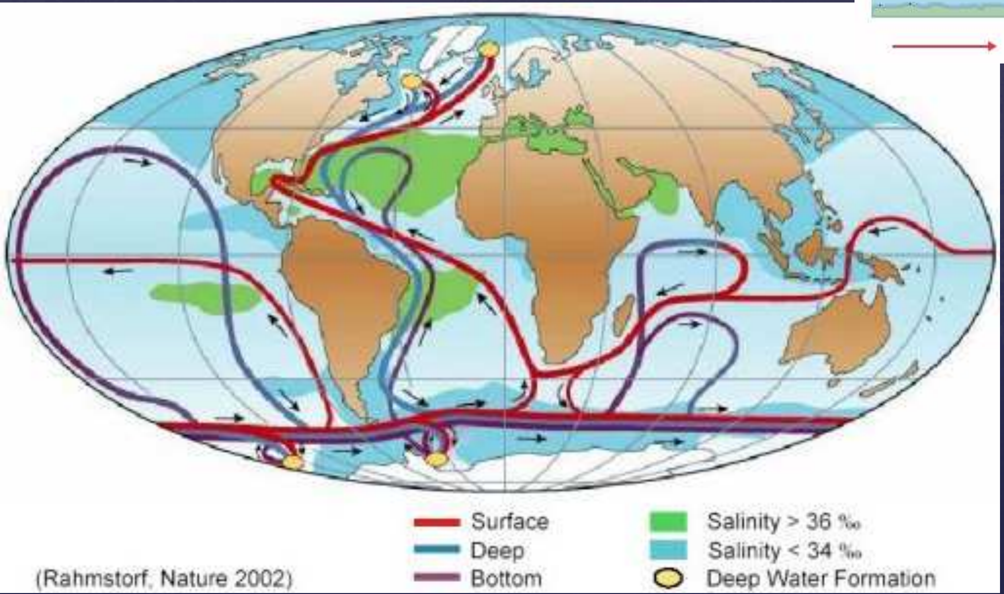
The Global Ocean Circulation

Forced by wind-stress and buoyancy fluxes (heat & fresh-water)

SCHEMATICS:

Upper ocean currents





3D global ocean circulation

Th… ns

Navier-S…
(cons. mon…

$\vec{\tau}$

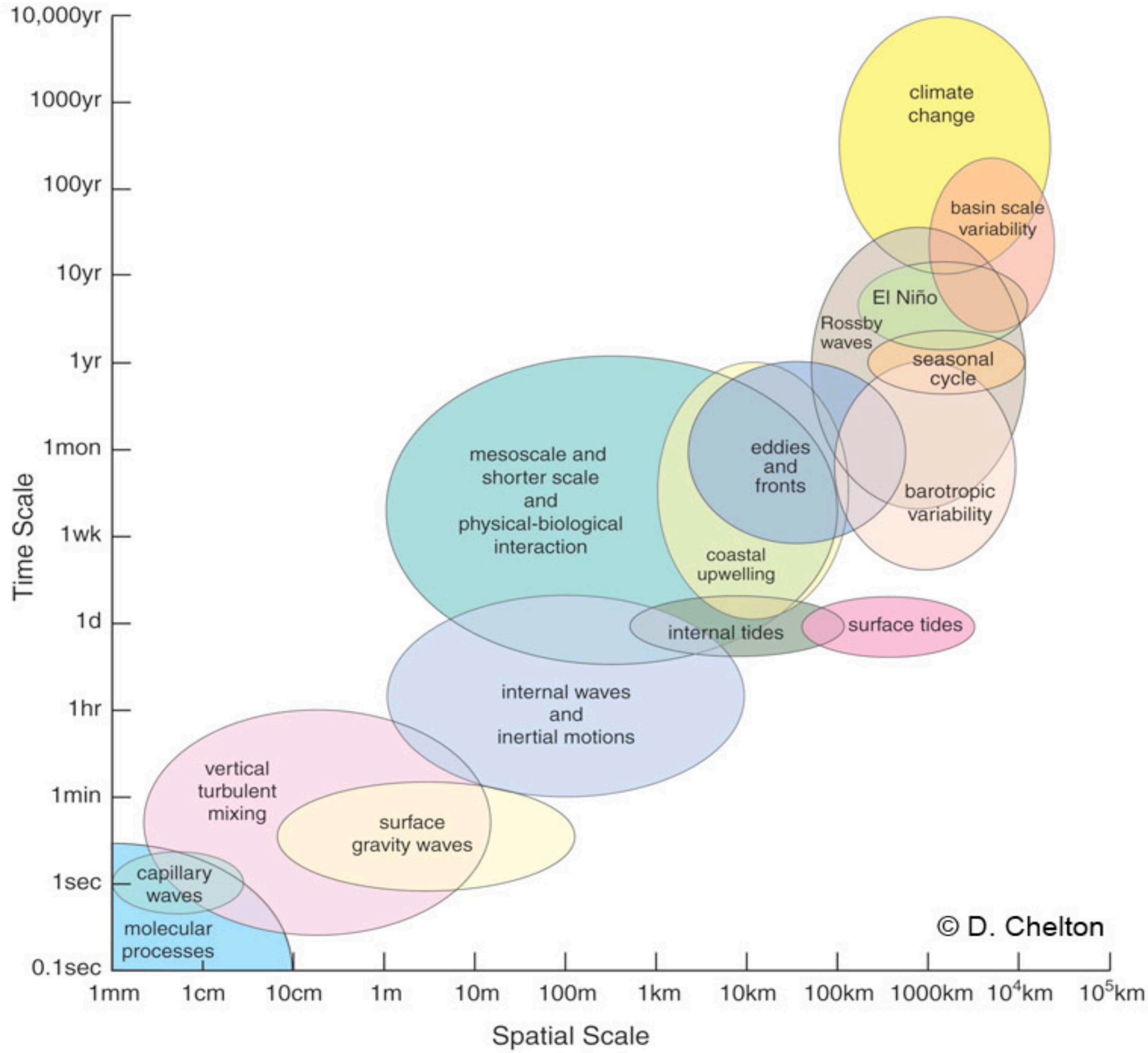
Conserva…
heat and

$\nabla \cdot \mathcal{F}_\theta$

Conserva…
mass

$, S, p)$

Ocean dynamics spatio-temporal scales



These … olve

Putting things on the sphere

- Geophysical fluids are particularly “thin”, gravity is very important

- A fluid parcel on the rotating earth “feels” a rotation rate of only 2Ω $\sin\varphi$ (= 2Ω resolved in the direction of gravity, rather than the full 2Ω)

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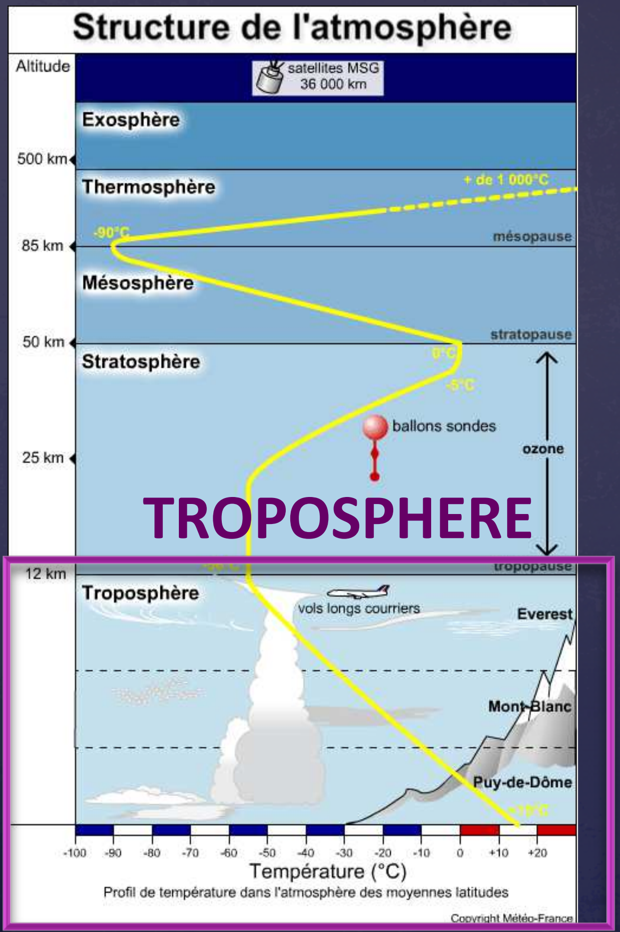
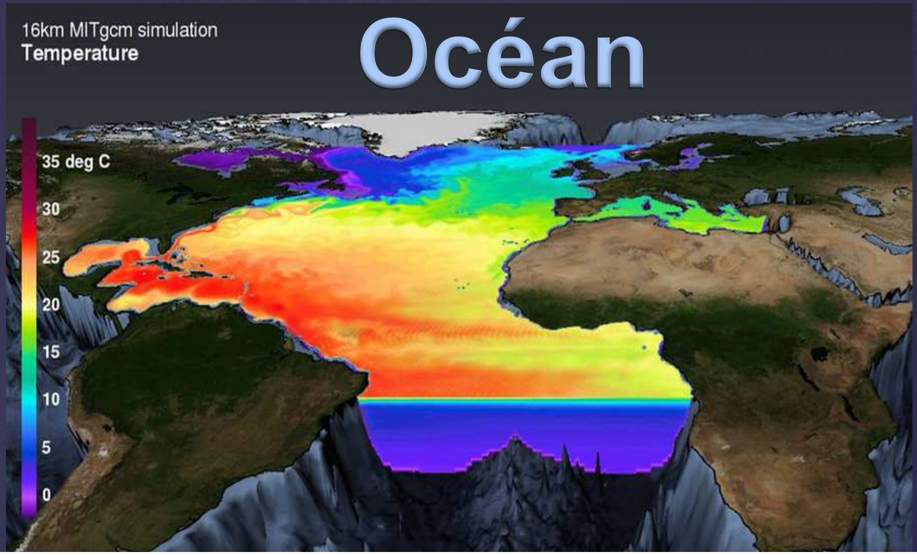
The ocean are rapidly rotating with the Earth and they are stratified

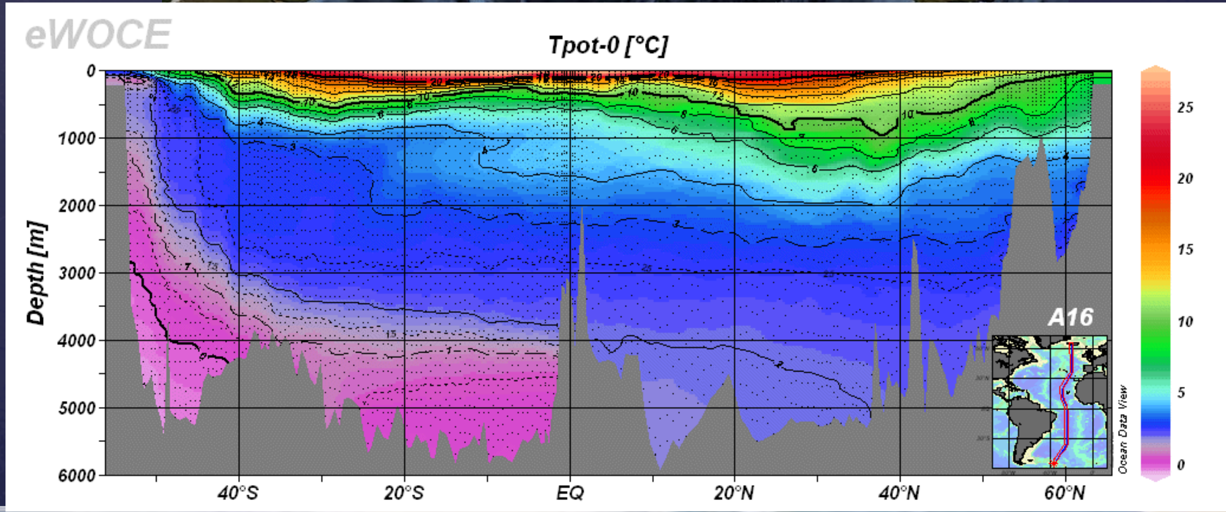
Vertical structure in temperature

Atmosphere

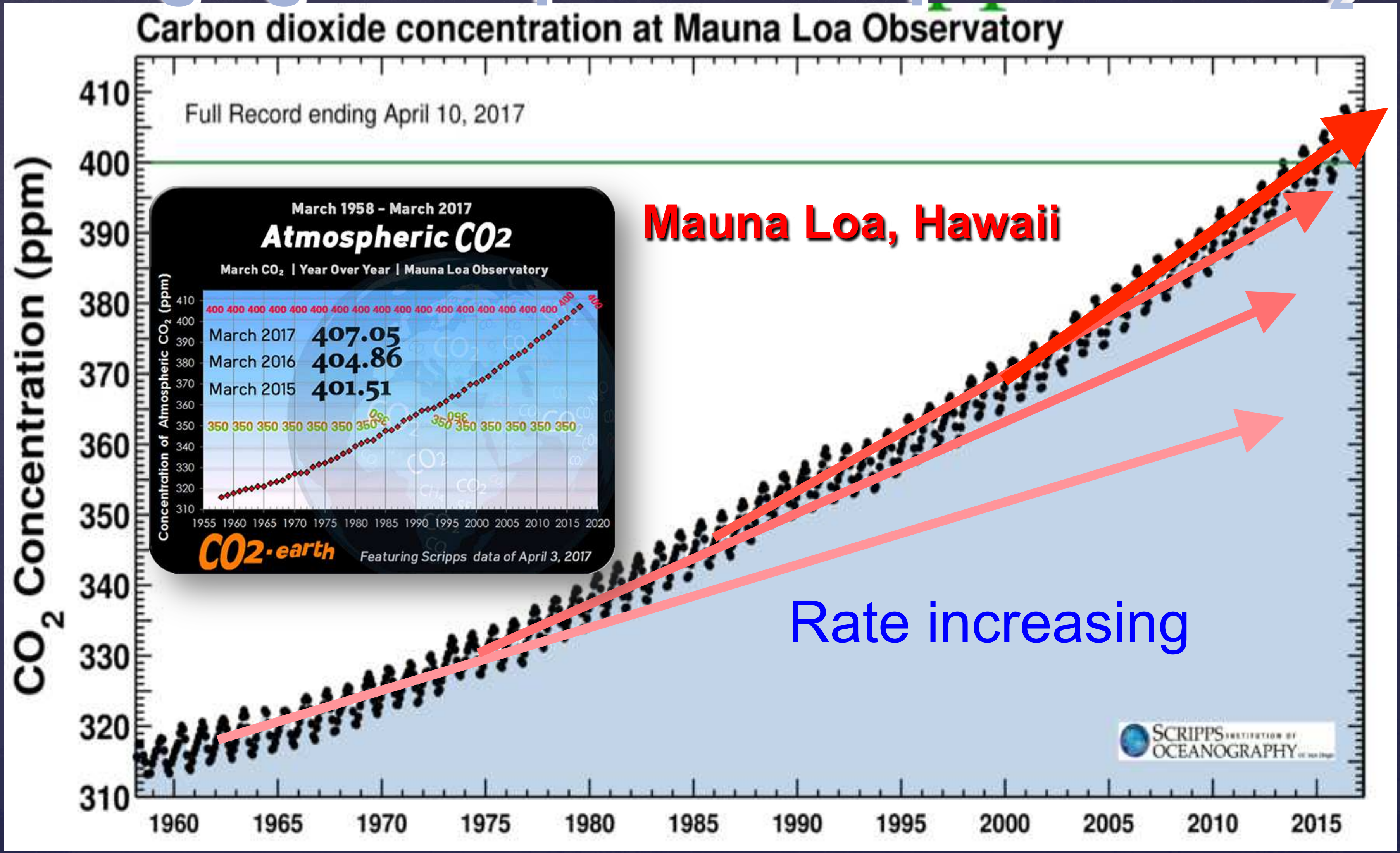


Océan



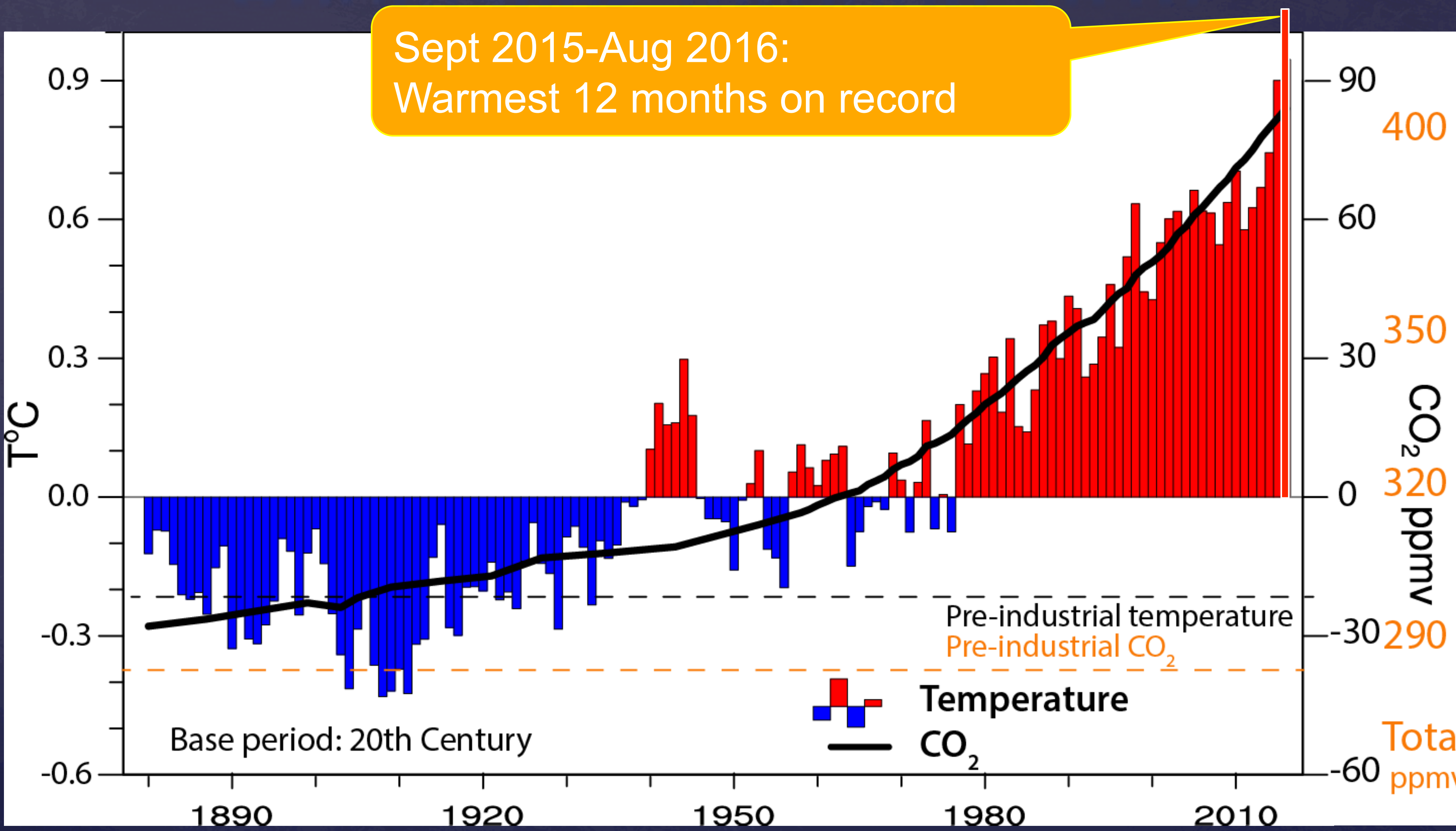


Changing atmospheric composition: CO_2



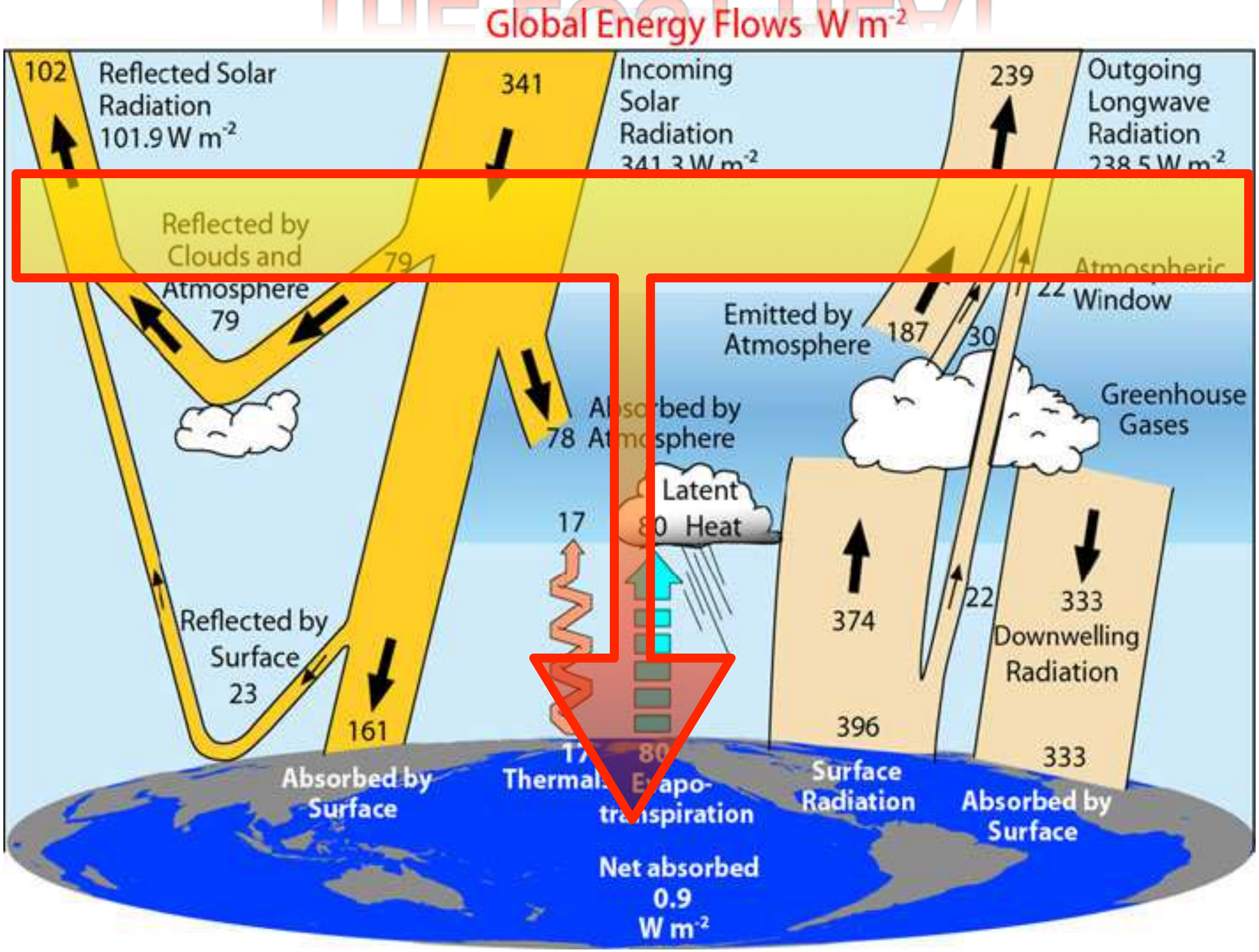
Data from Climate Monitoring and Diagnostics Lab., NOAA. Data prior to 1974 from C. Keeling, Scripps Inst. Oceanogr.

Global temperature and CO2: Anomalies through 2016



Base period 1900-99; data from NOAA

FOCUS ON THE ENERGY BUDGET & THE LOST HEAT



Trenberth & Fasullo 2011

sabrina.speich@ens.fr

Ocean observing
... by remote sensing (satellites)

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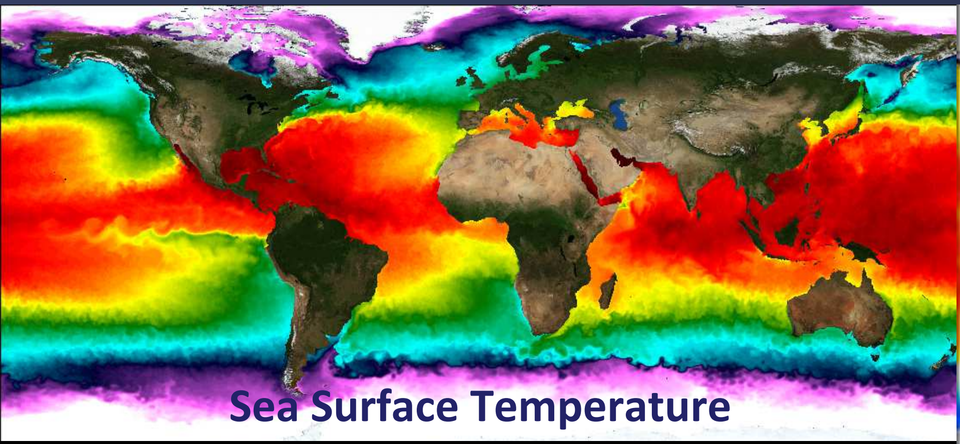
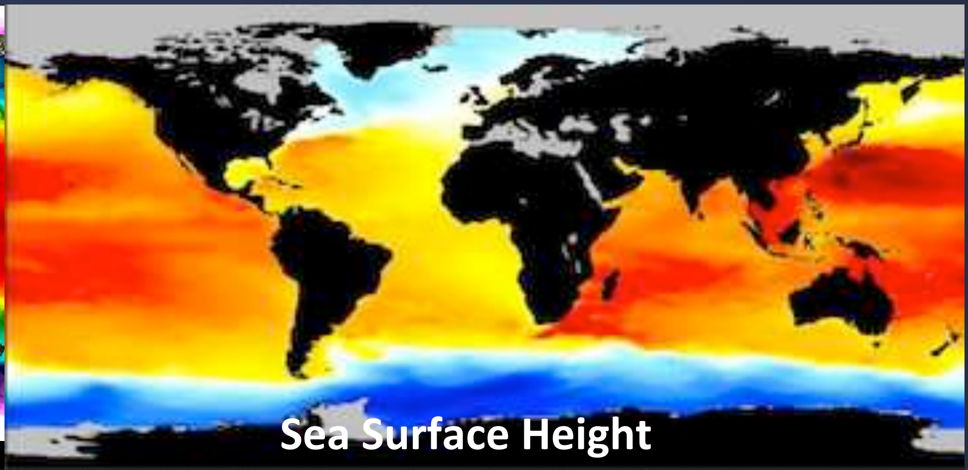
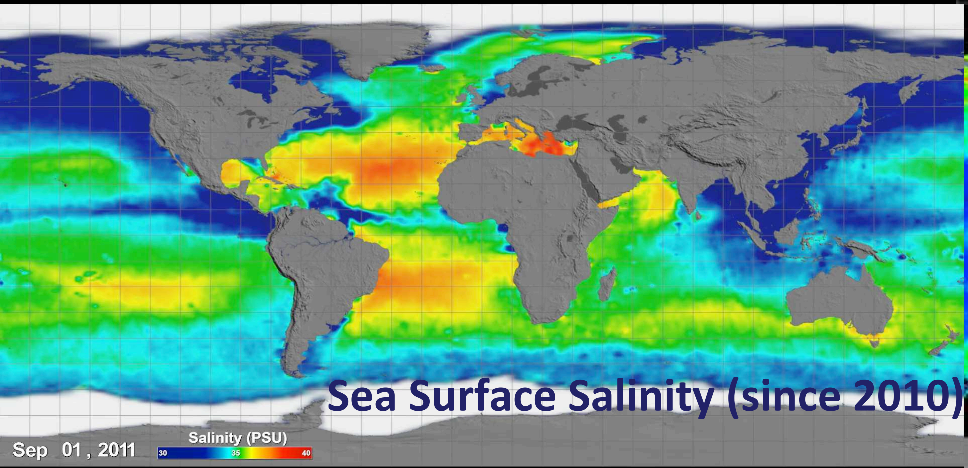
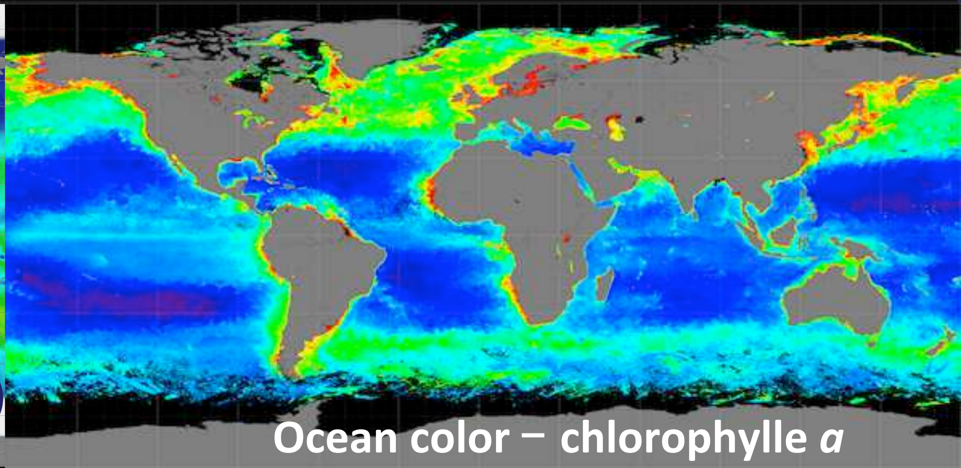
Ocean observing
… by remote sensing (satellites)









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Ocean observing

... but the ocean is opaque to EM radiation

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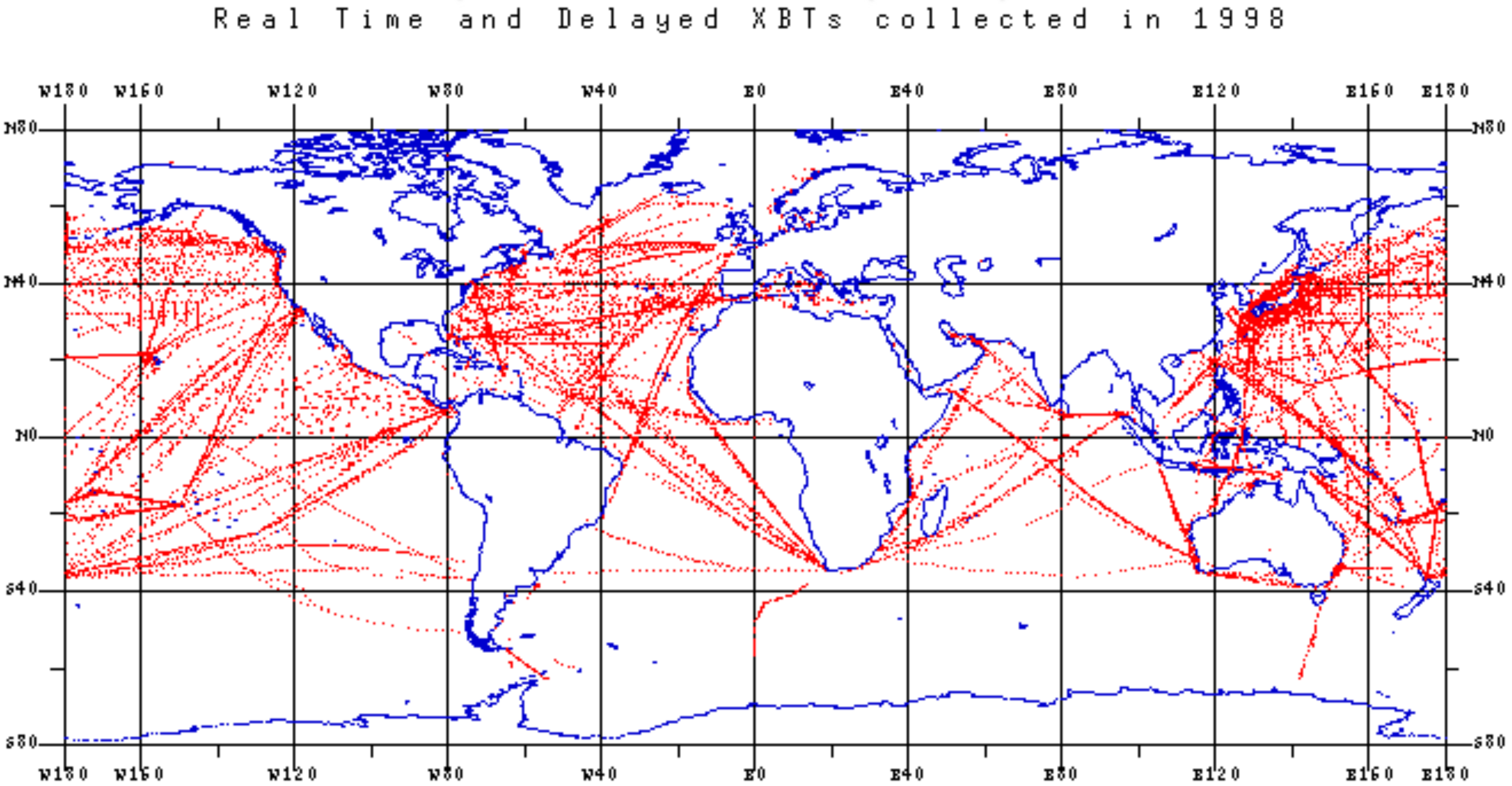
Ocean observing

... therefore, we need to acquire *in situ* measurements

sabrina.speich@ens.fr

In Situ Ocean Observing: Vertical Profiles Of Temperatures (0 – 700 M)

Expandable Bathymograph Temperature – XBTs (1998)



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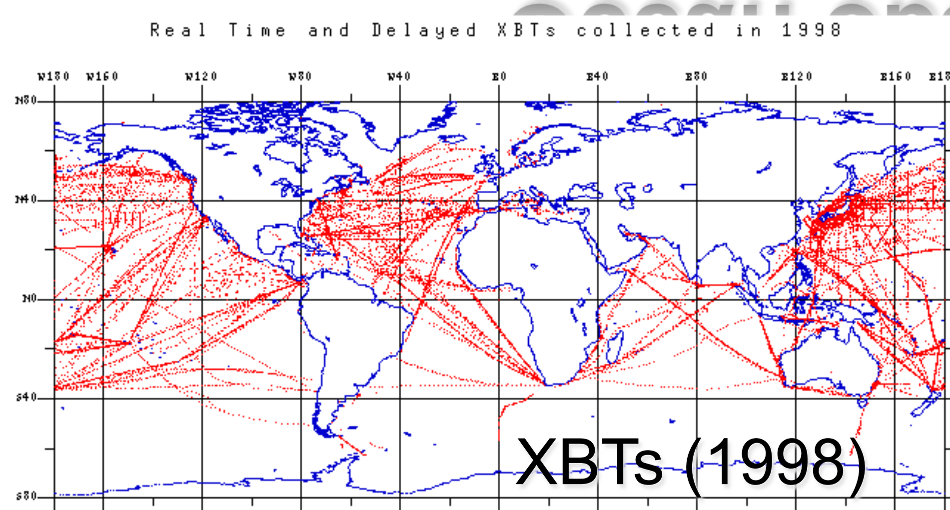
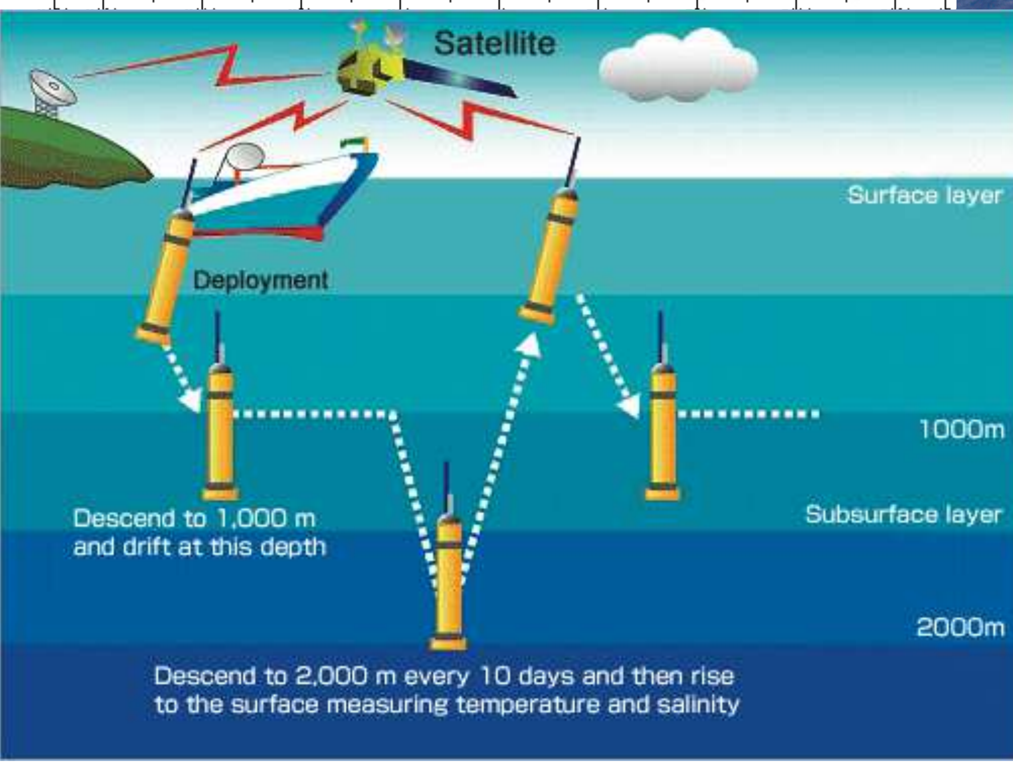
Ocean observing





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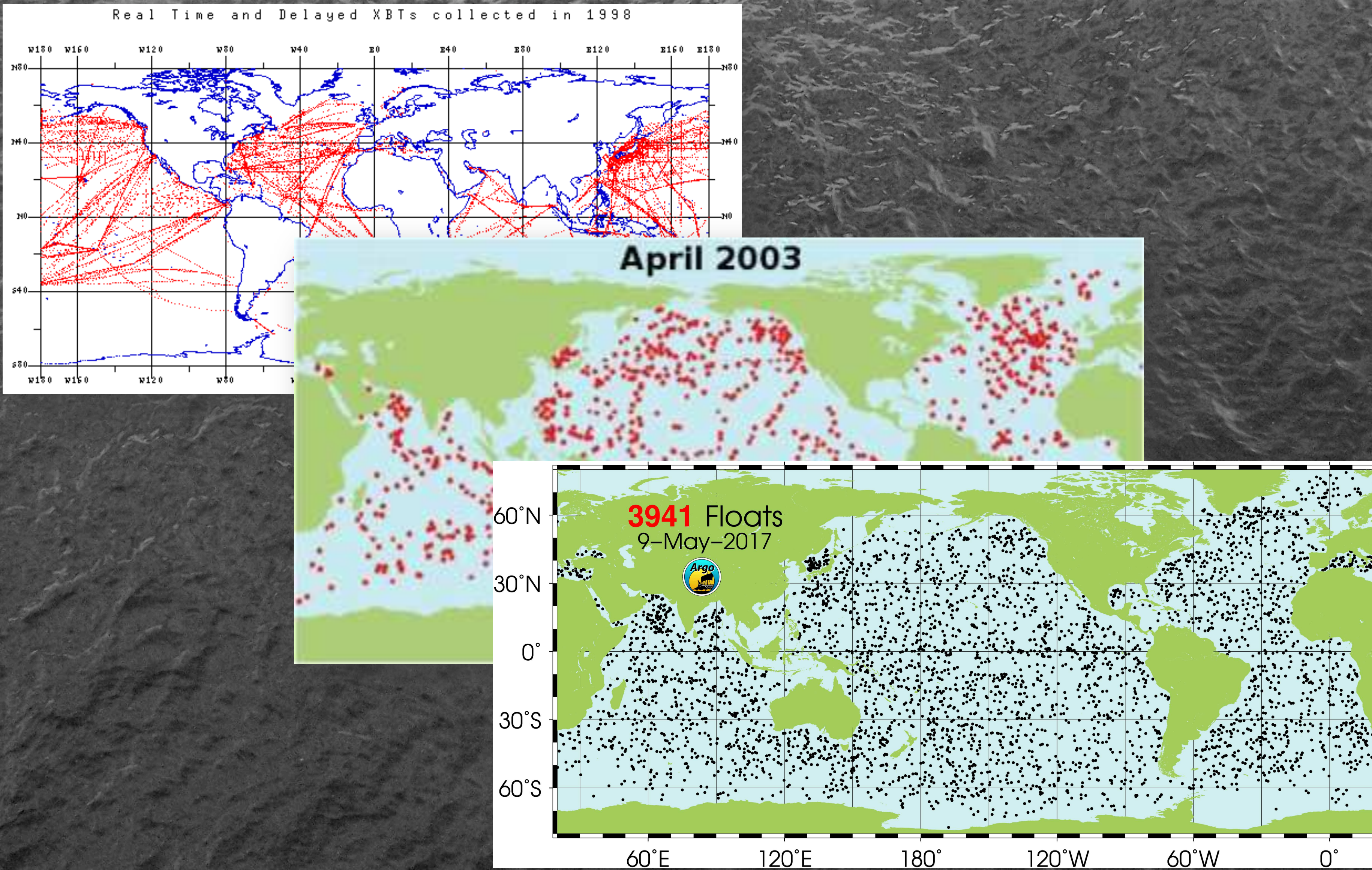
Ocean observing evolution: Argo floats



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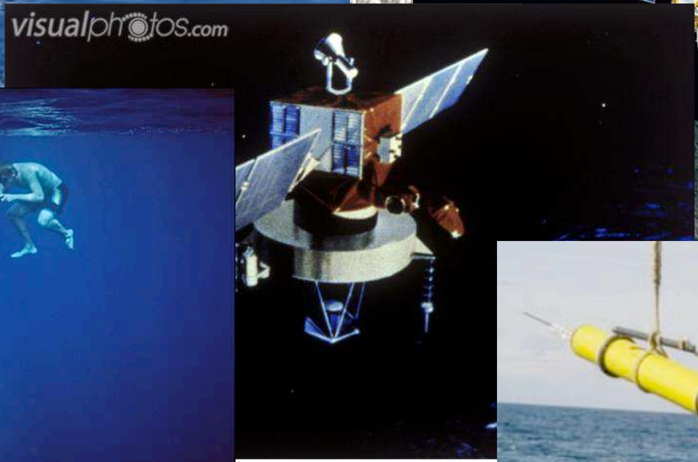
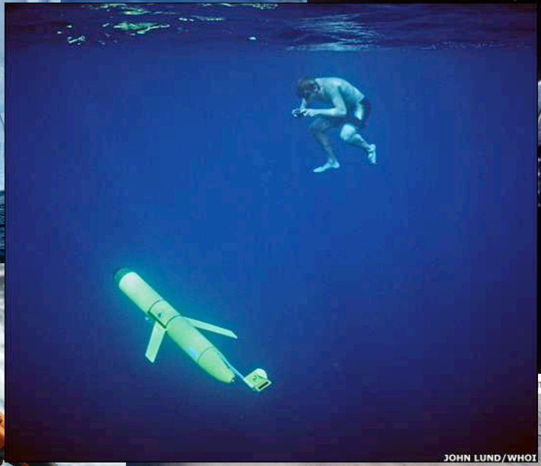
Ocean observing evolution: all together

From ocean cruises

… to the development of new instruments





Robotic observing

XBT

CTD

and … instrumented animals

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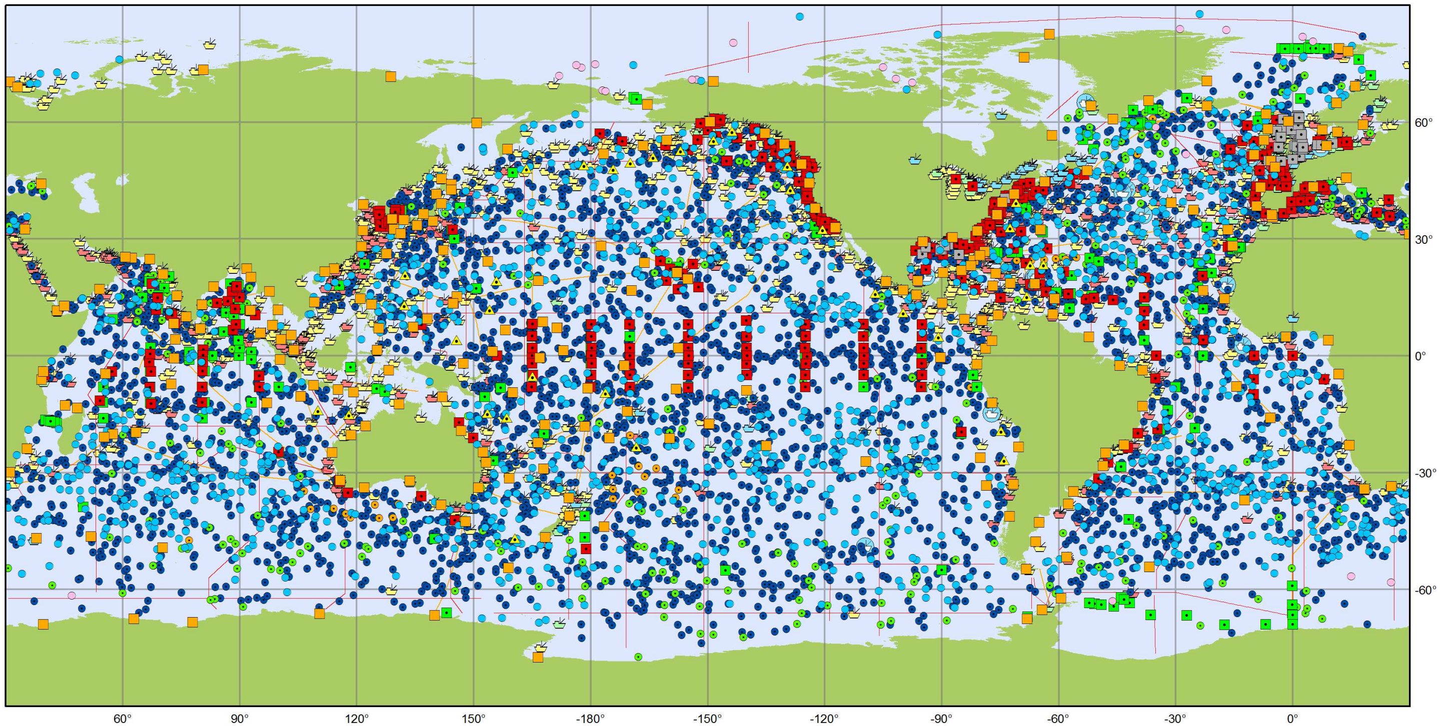
Ocean observing evolution: all together



Main in-situ Elements of the Global Ocean Observing System — **March 2017**

Argo
- Argo (3937)
- Deep-Argo (32)
- BGC-Argo (282)

DBCP
- Surface Drifters (1407)
- Fixed Platforms (103)
- Ice Buoys (22)
- Moored Buoys (394)
- Tsunameter (34)

OceanSITES
- Platforms (332)

GO-SHIP
- GO-SHIP (61)

GLOSS
- Tide Gauges (252)

SOT
- VOSClim-Automated (102)
- VOSClim-Manned (371)
- VOS-Automated (149)
- VOS-Manned (1188)
- ASAP Radiosondes (20)
- SOOP XBTs (37)

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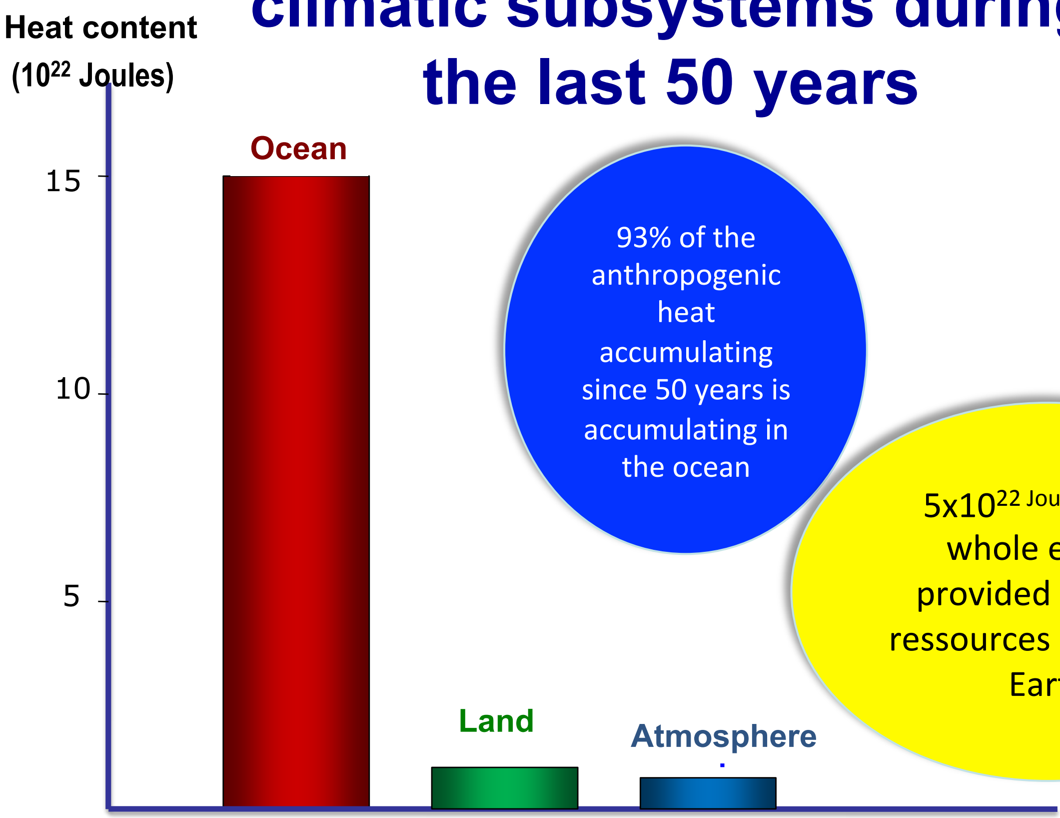
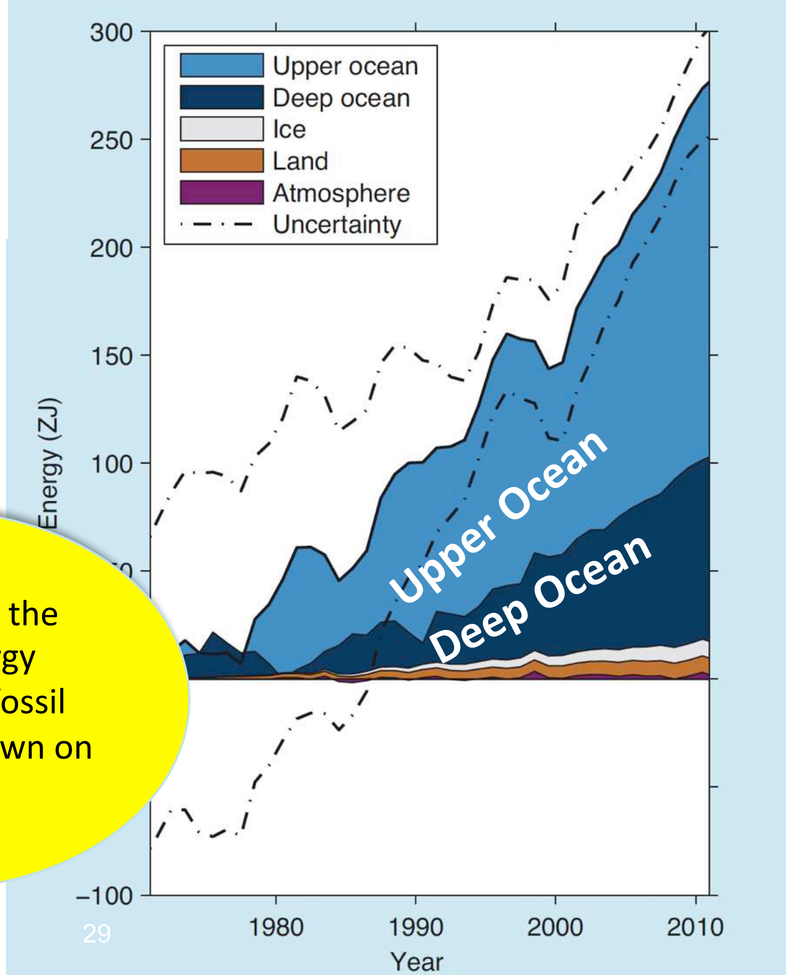
The Ocean :
The anthropogenic heat repository

Heat stored in the different climatic subsystems during the last 50 years



93% of the anthropogenic heat accumulating since 50 years is accumulating in the ocean

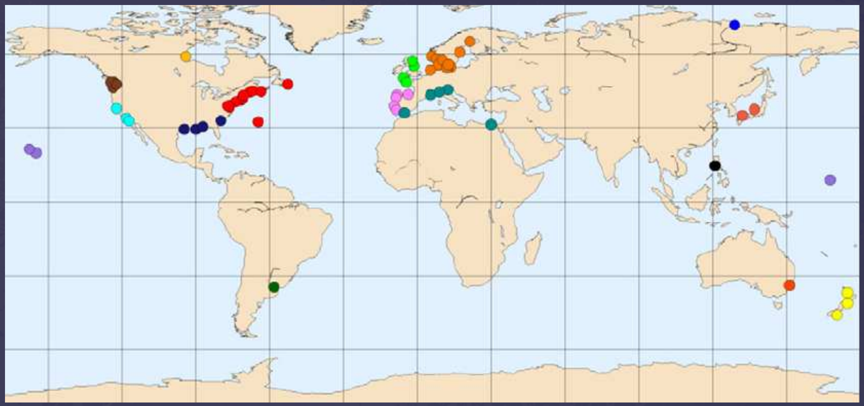
5×10^{22} Joules = the whole energy provided by fossil ressources known on Earth



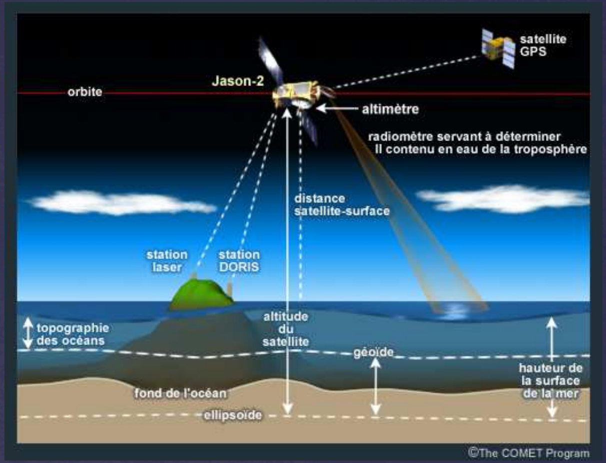
Rhein et al., 2013; IPCC AR5

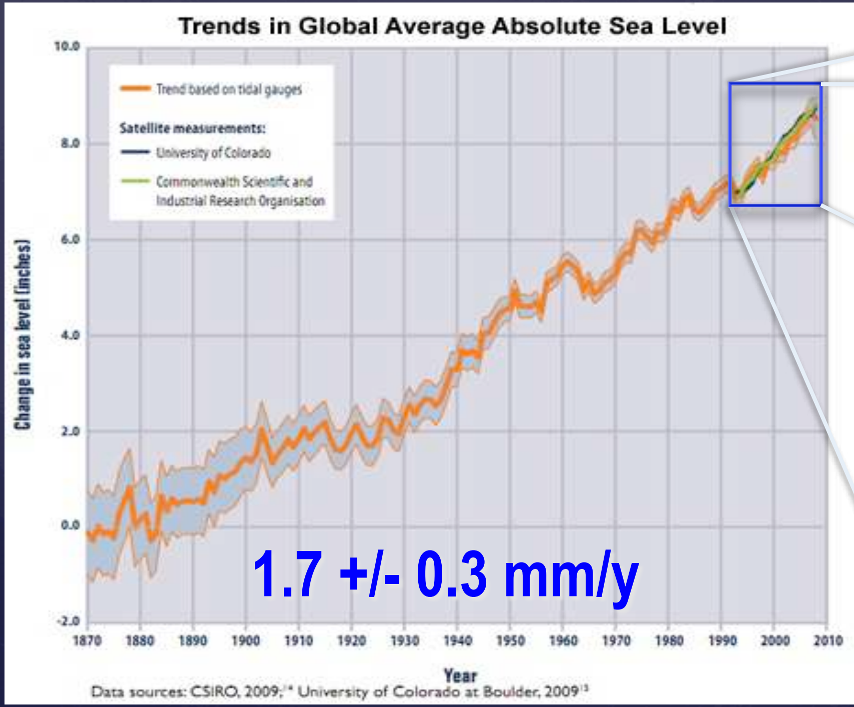
Sea level rise

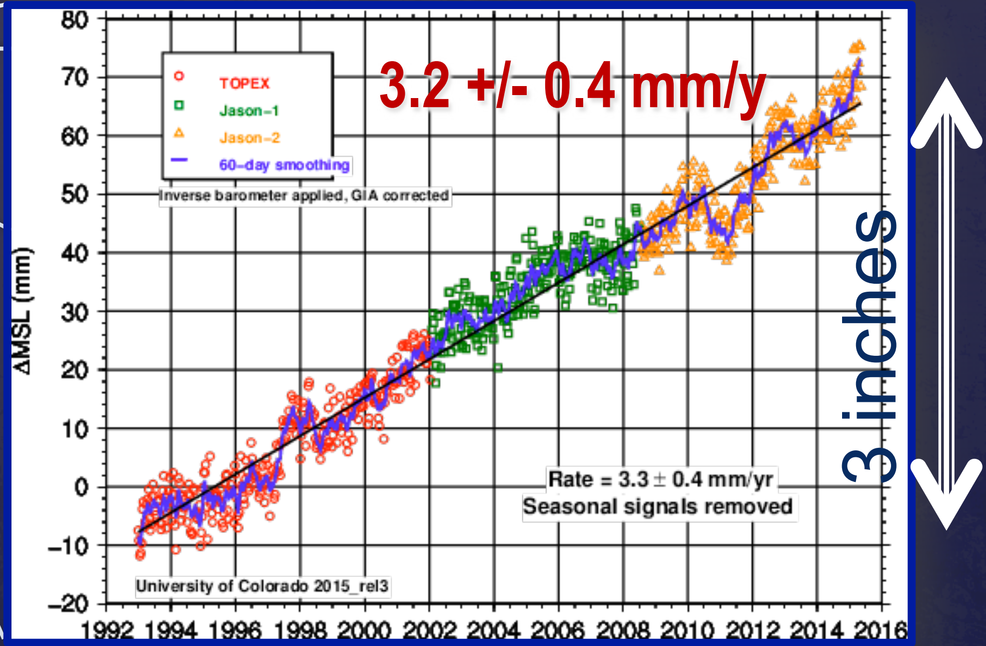
20^{th} century: tide gauges



Last 20 years: satellite altimetry

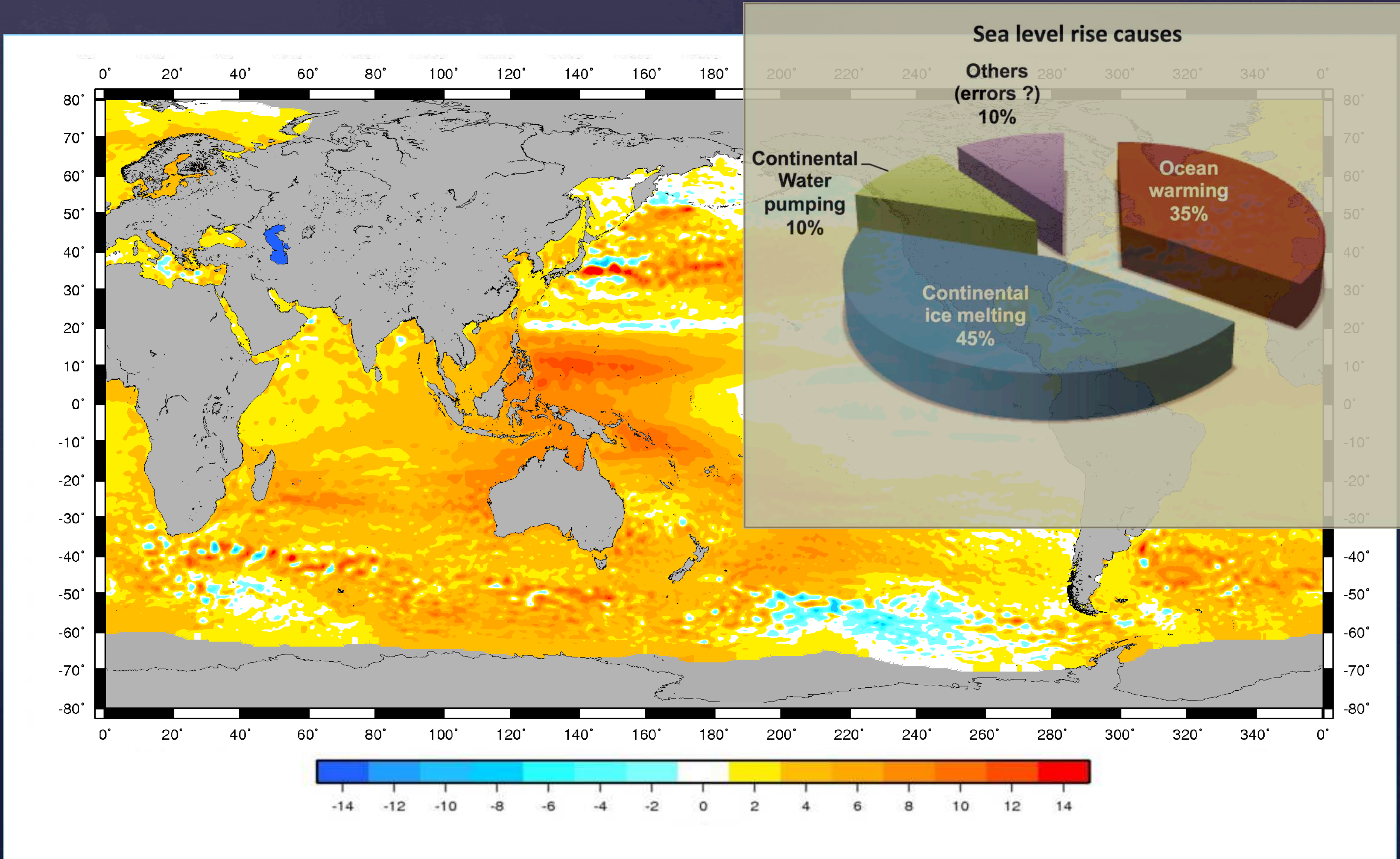




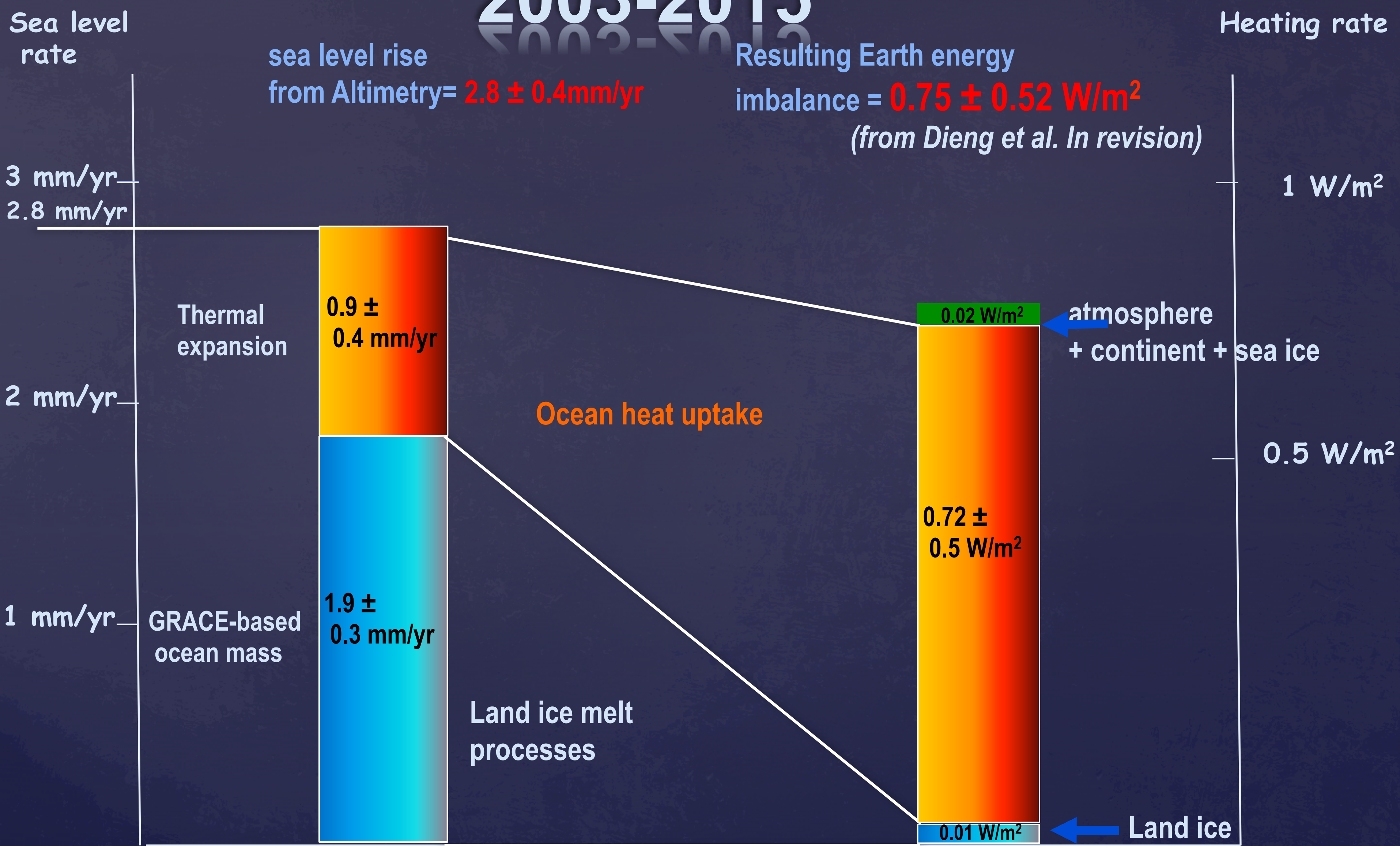


Sea level rise

Sea level does not rise uniformly!

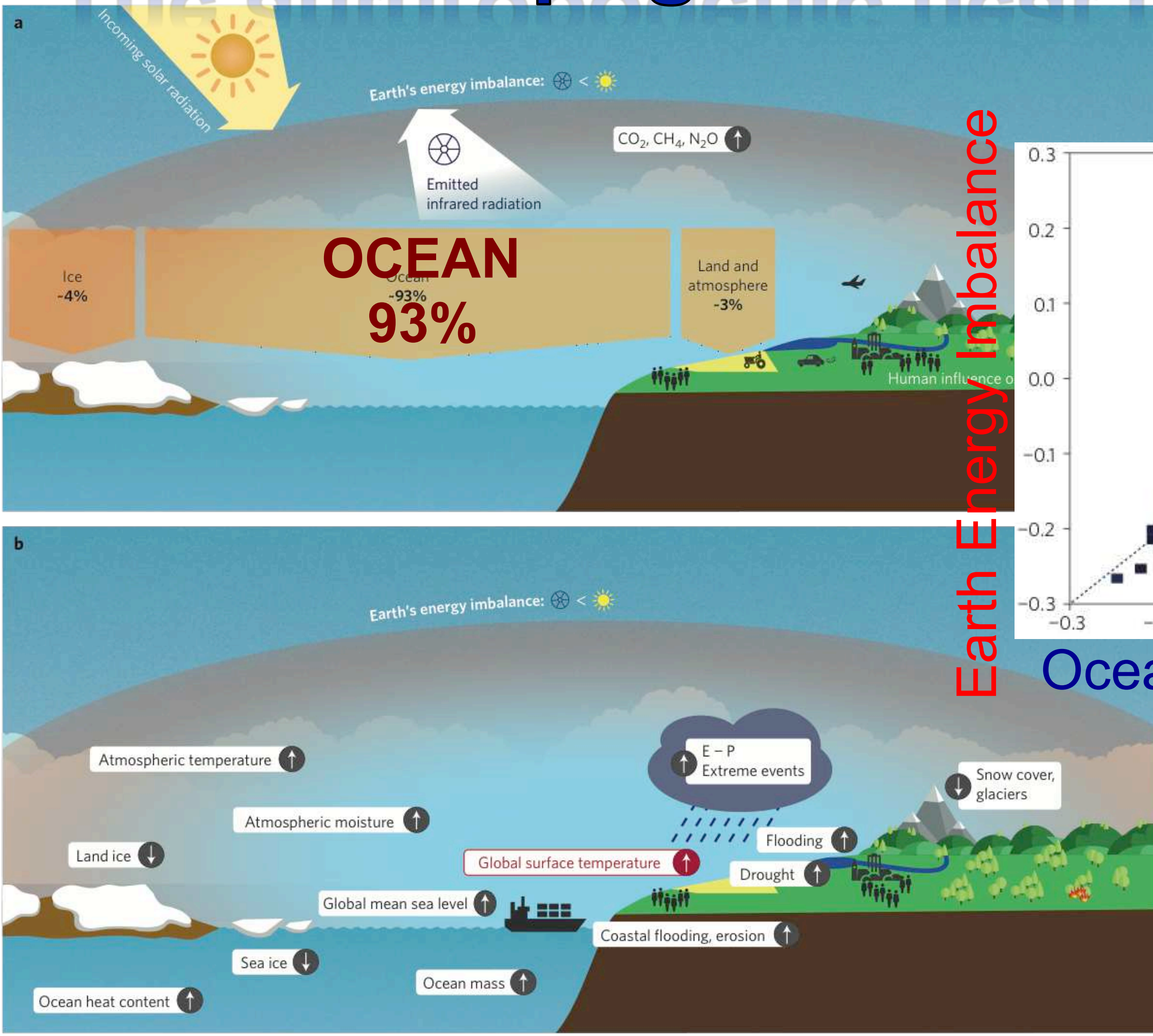


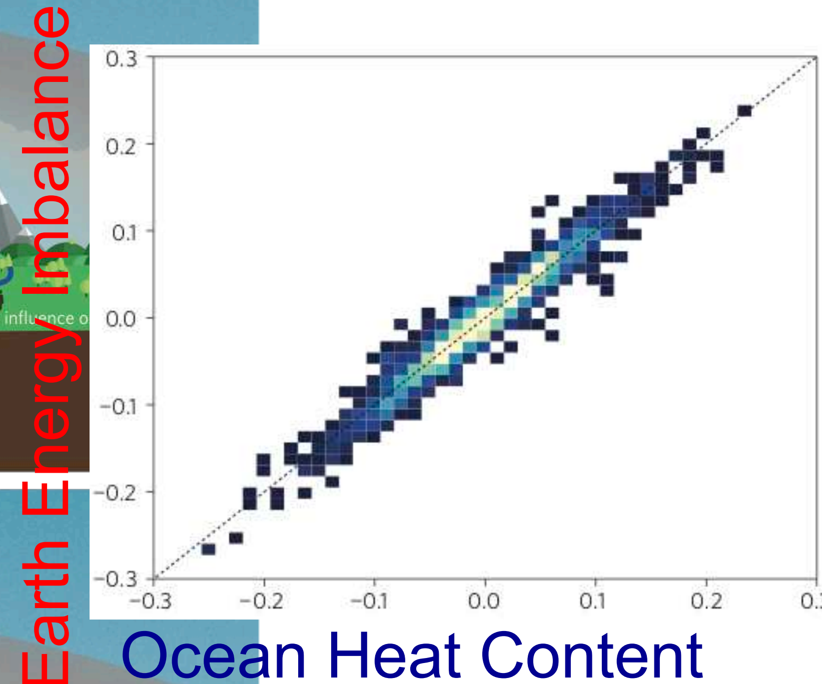
Sea level rise & Earth Energy Budget 2003-2015



Messignac et al. 2017

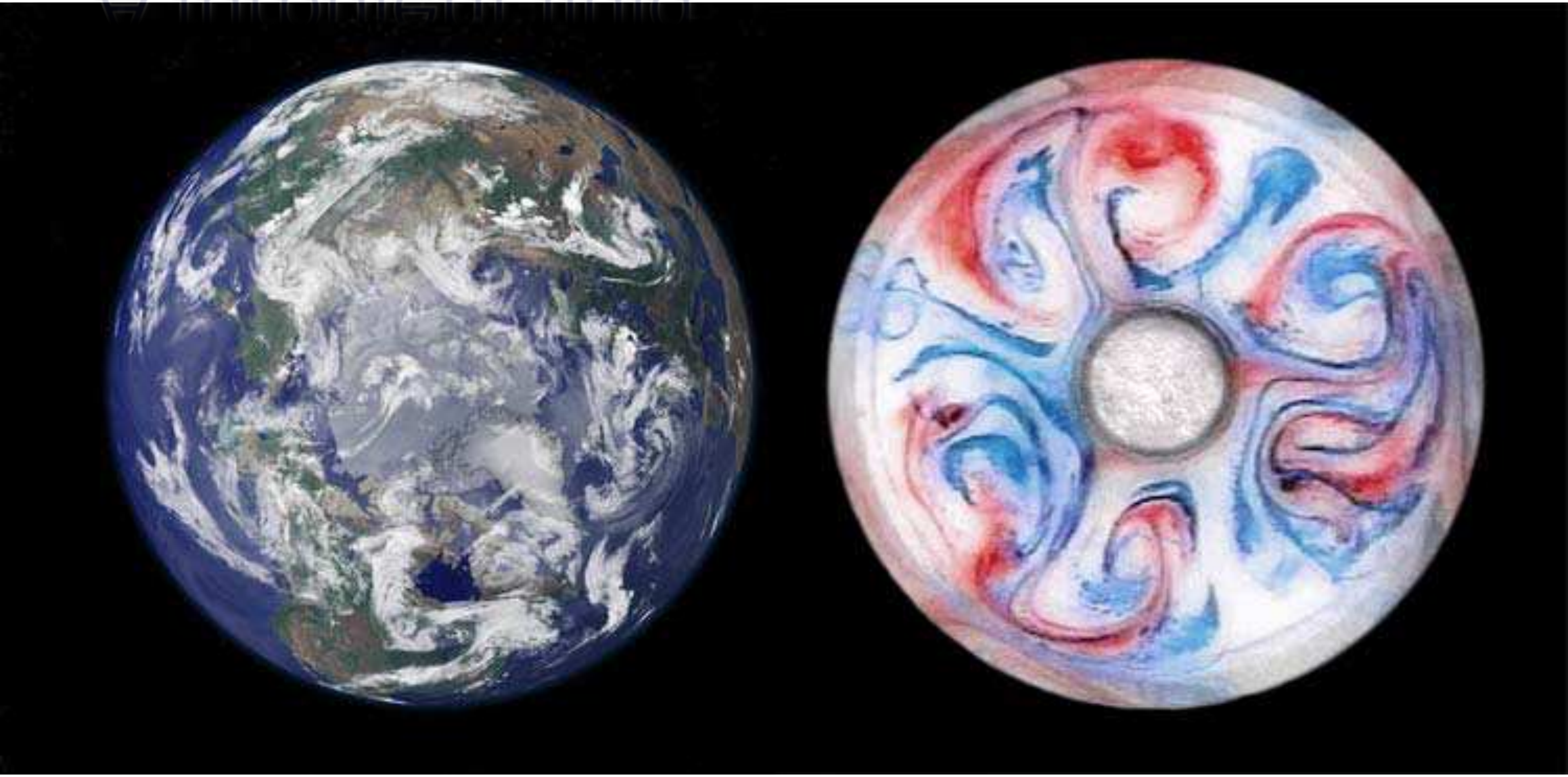
The Ocean :
The anthropogenic heat repository





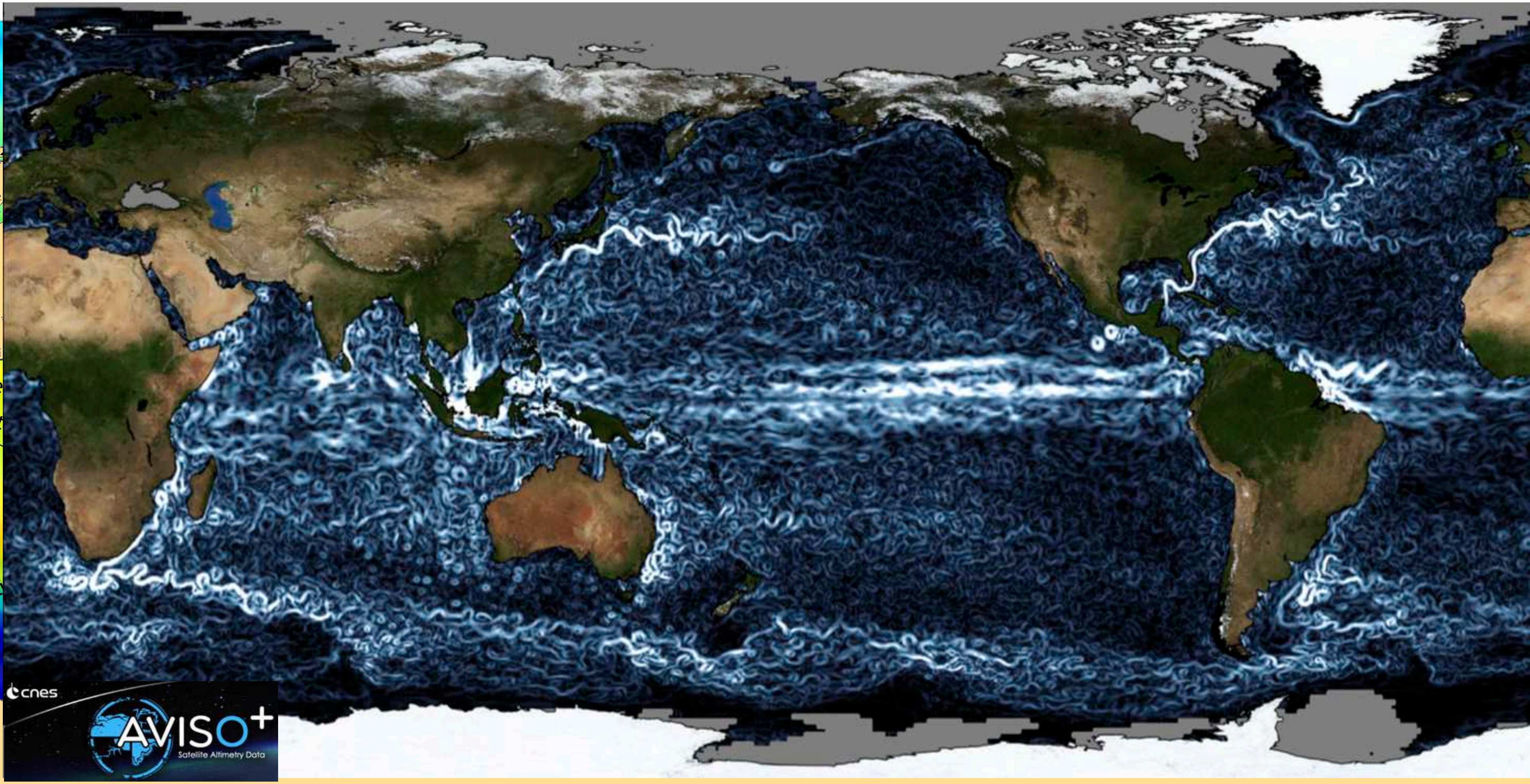
Von Schukmann et al. 2016

Fluid Dynamics on a sphere: A turbulent fluid



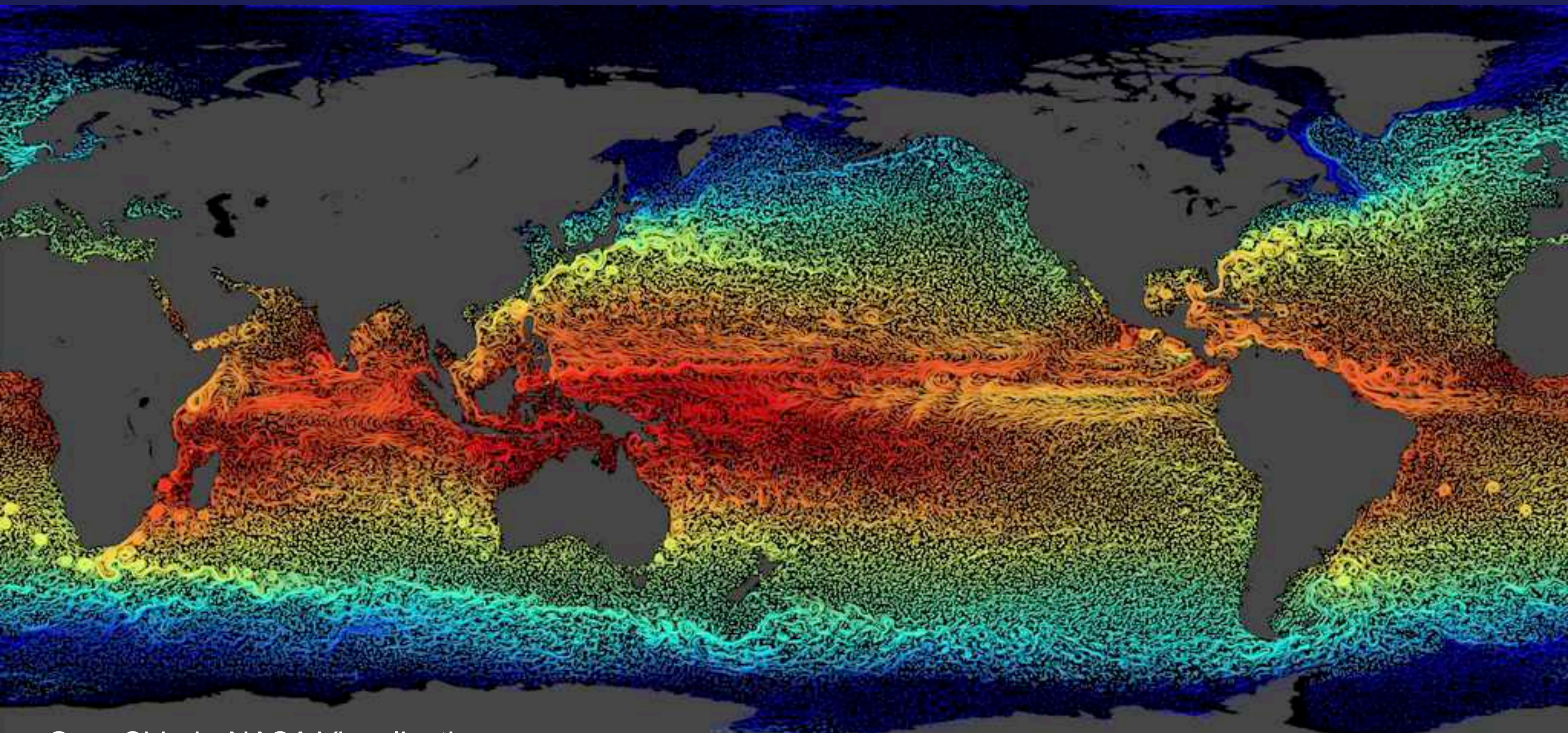
Ocean Dynamics:
A (very) turbulent fluid

Map of absolute geostrophic current



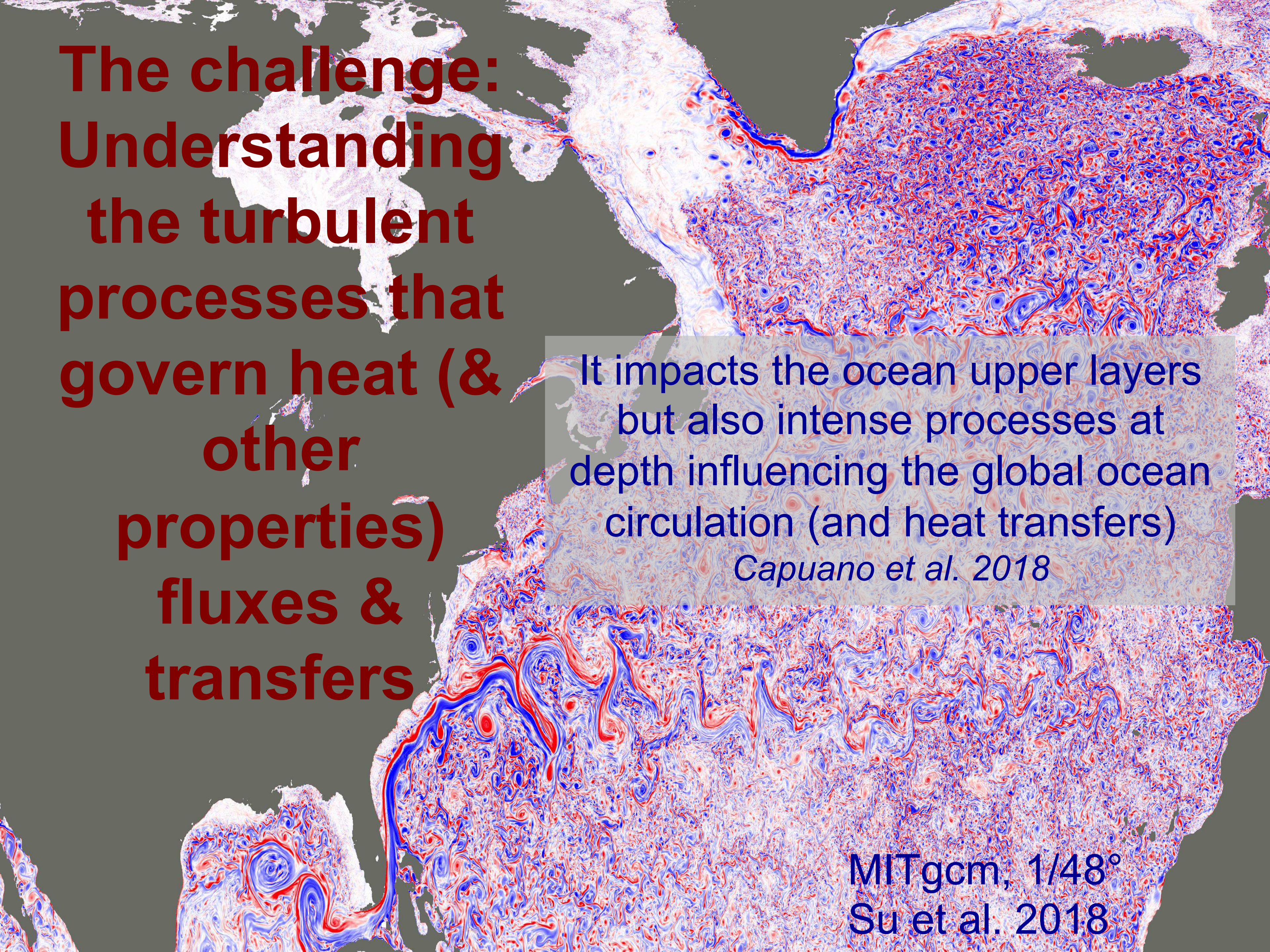
Ocean Dynamics a turbulent heat reservoir and source

Surface Ocean Currents & ocean surface temperature

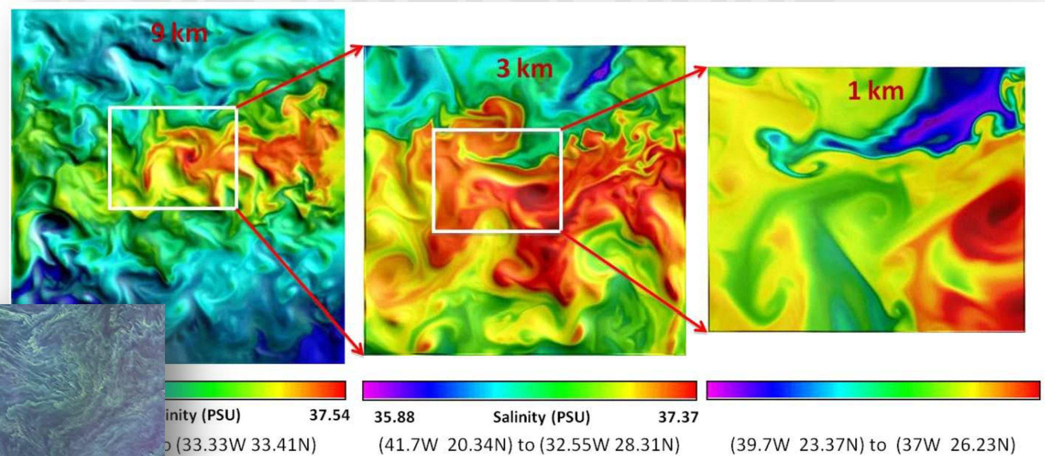


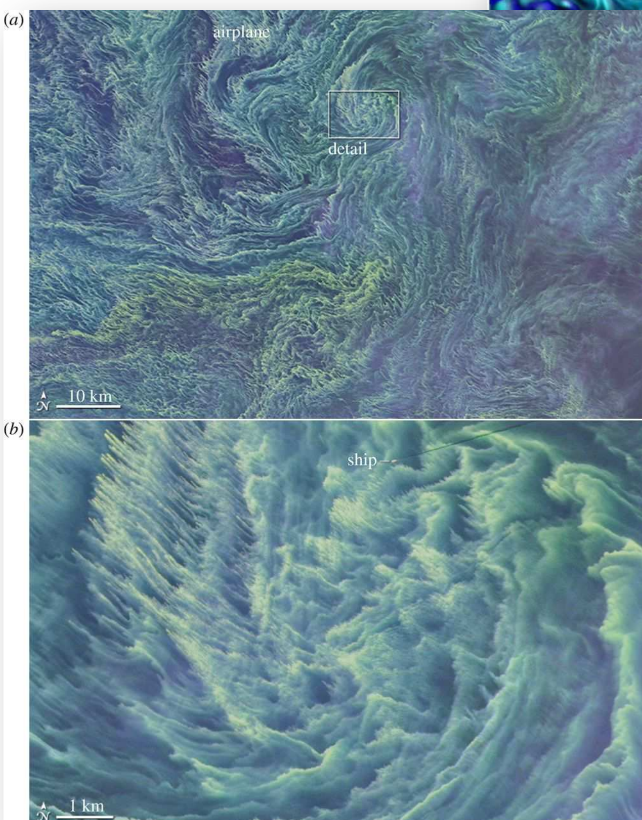
Greg Shirah, NASA Visualization

ECCO2 model and satellite SST


The challenge: Understanding the turbulent processes that govern heat (& other properties) fluxes & transfers
It impacts the ocean upper layers but also intense processes at depth influencing the global ocean circulation (and heat transfers)
Capuano et al. 2018
MITgcm, 1/48°
Su et al. 2018

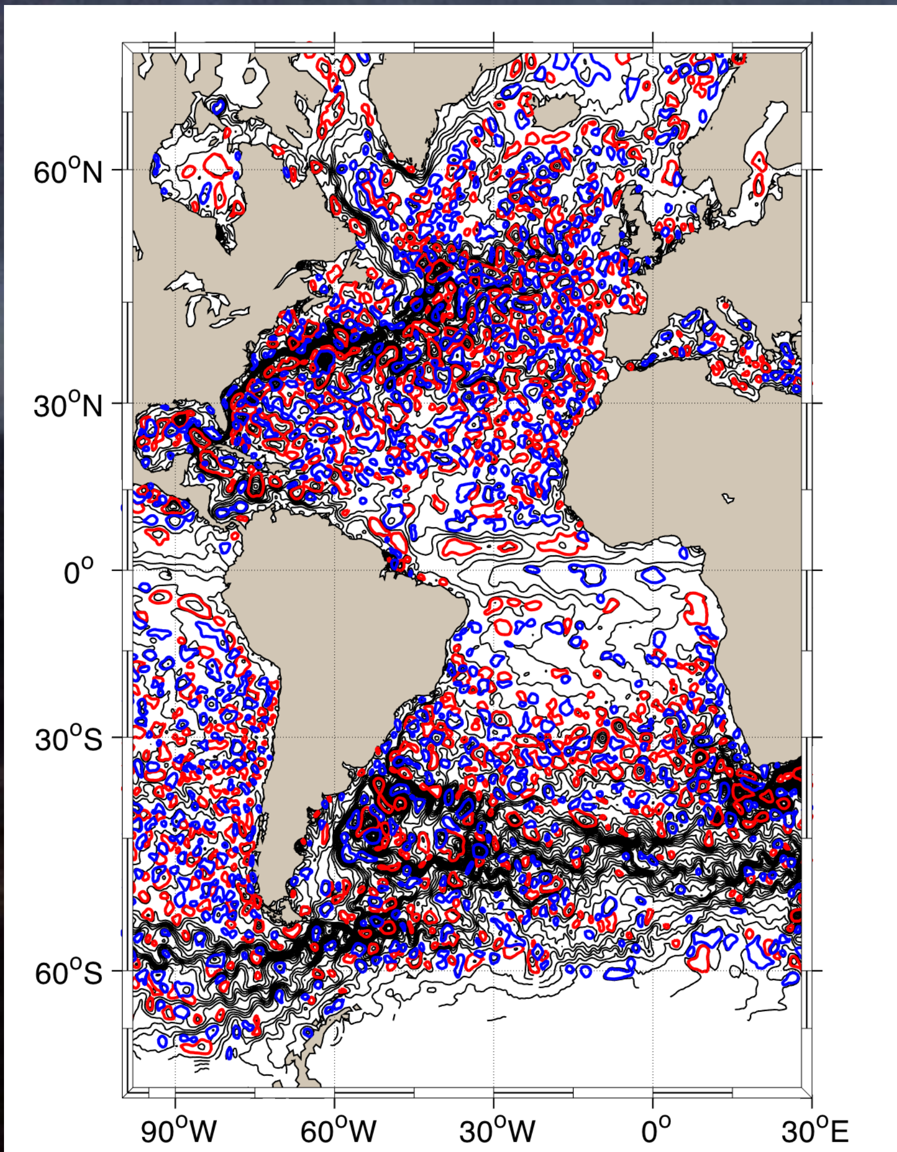
The ocean has a complex dynamics: Scale interactions





sabrina.speich@ens.fr

The ocean is a very turbulent fluid



Red = Anticyclones

Blue = Cyclones

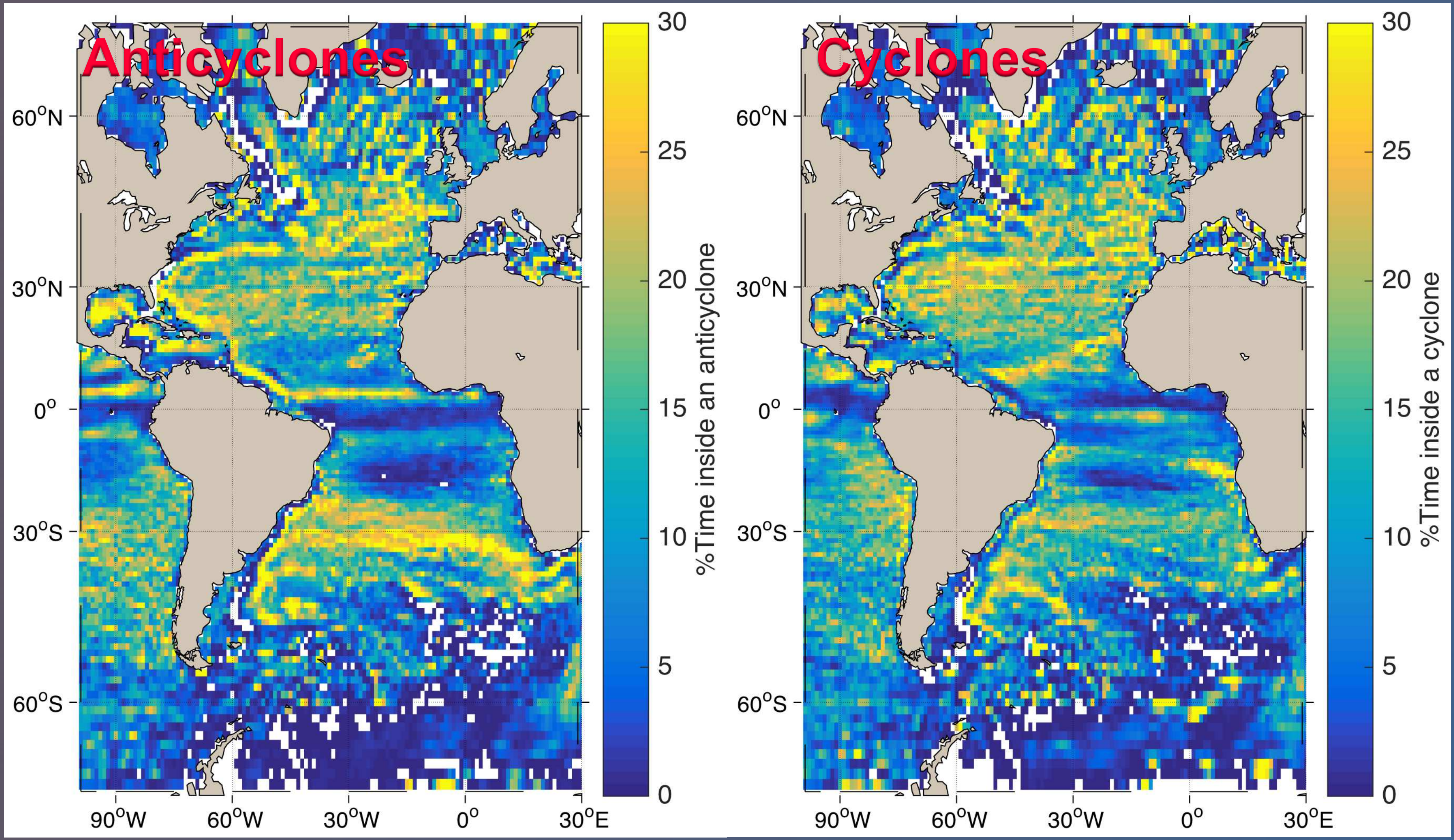
Eddy detection from satellite altimetry (2000-2015)
Laxenaire et al., 2017

[AVISO Ssalto-Duacs Daily multi-satellite Maps of Absolute Dynamic Topography; Ducet et al., 2000; Pascual et al. 2006]

Automatic detection and tracking of ocean eddies

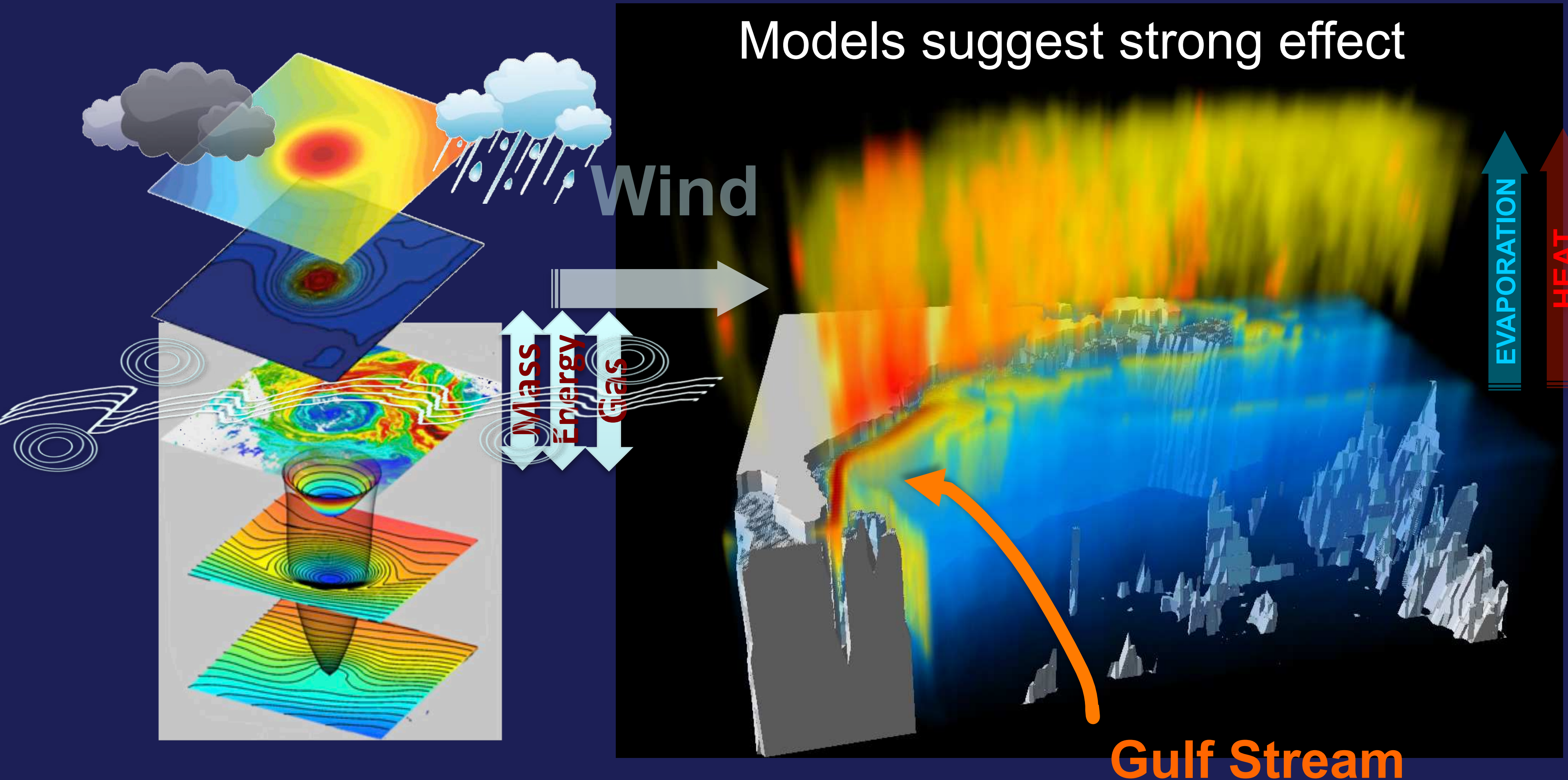
The Atlantic (surface) eddies global picture

% of eddies presence for each ¼°x¼° grid cell

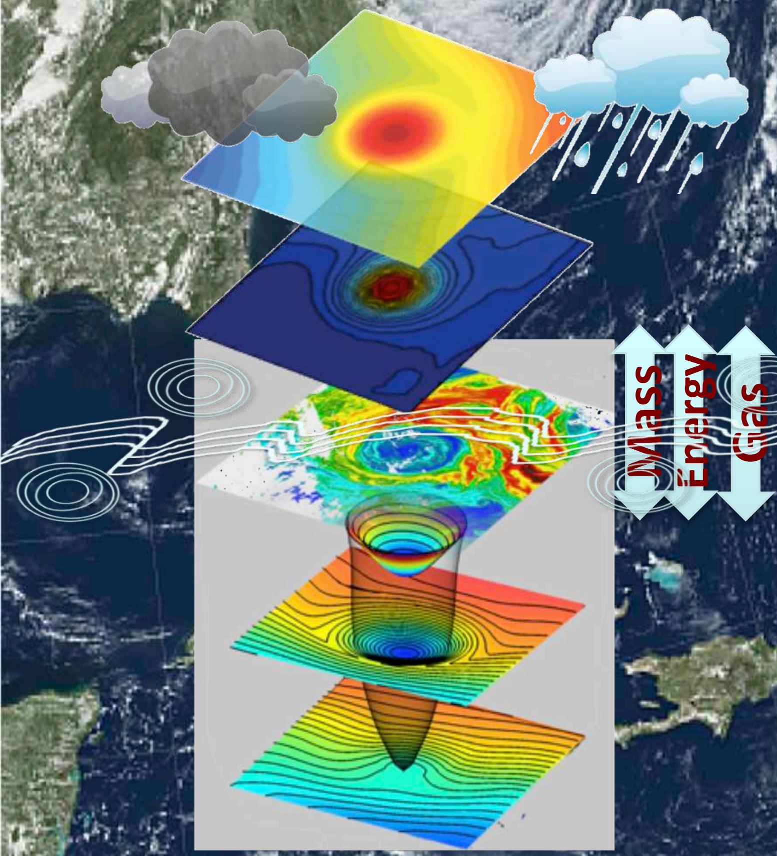


Laxenaire, 2015; Laxenaire et al. 2017

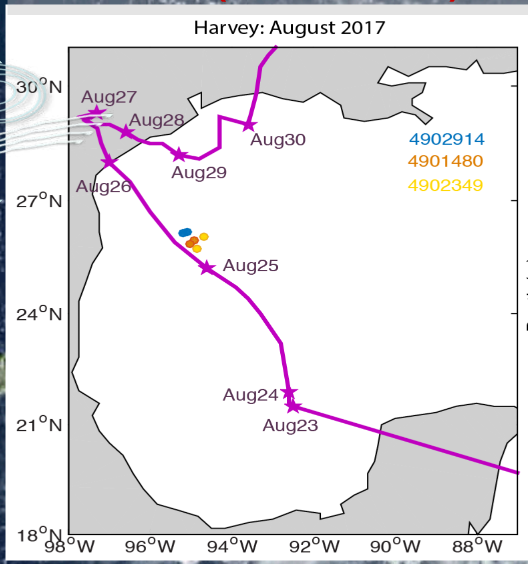
The Ocean: Air-Sea interactions at the ocean mesoscale

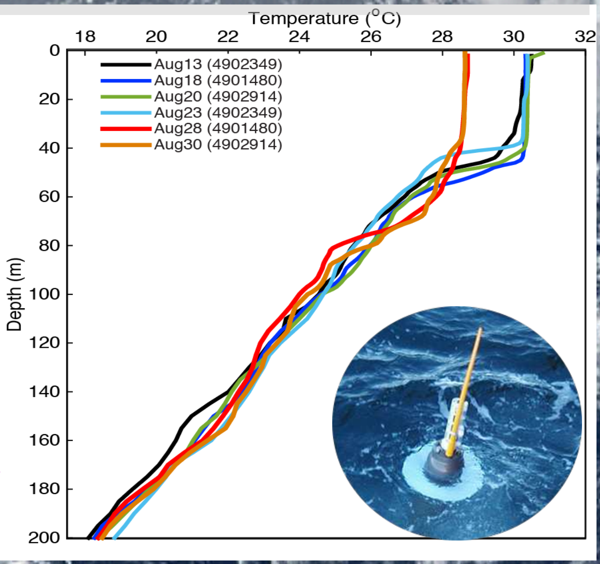


The Ocean: Air-Sea interactions at the ocean mesoscale



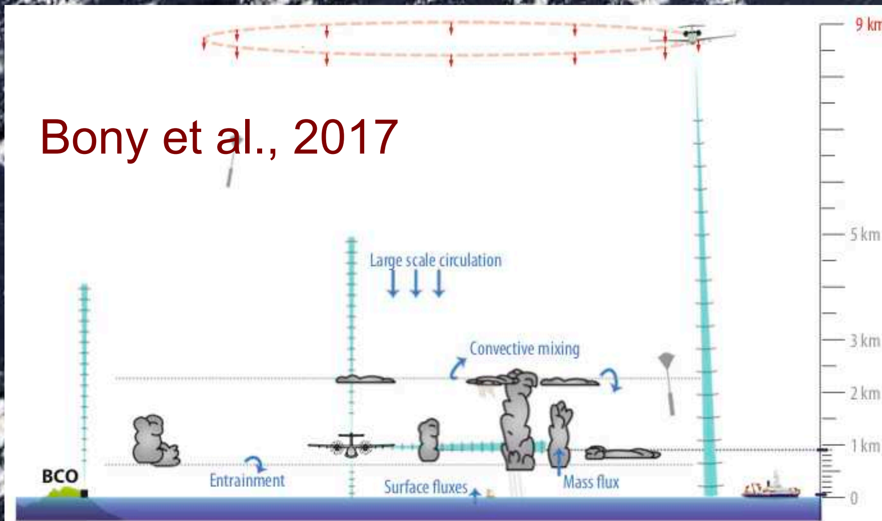
Observations:
Hurricane Harvey drawing heat (& water) from the ocean





The EURC^{4}A (EU) – ATOMIC (US) project

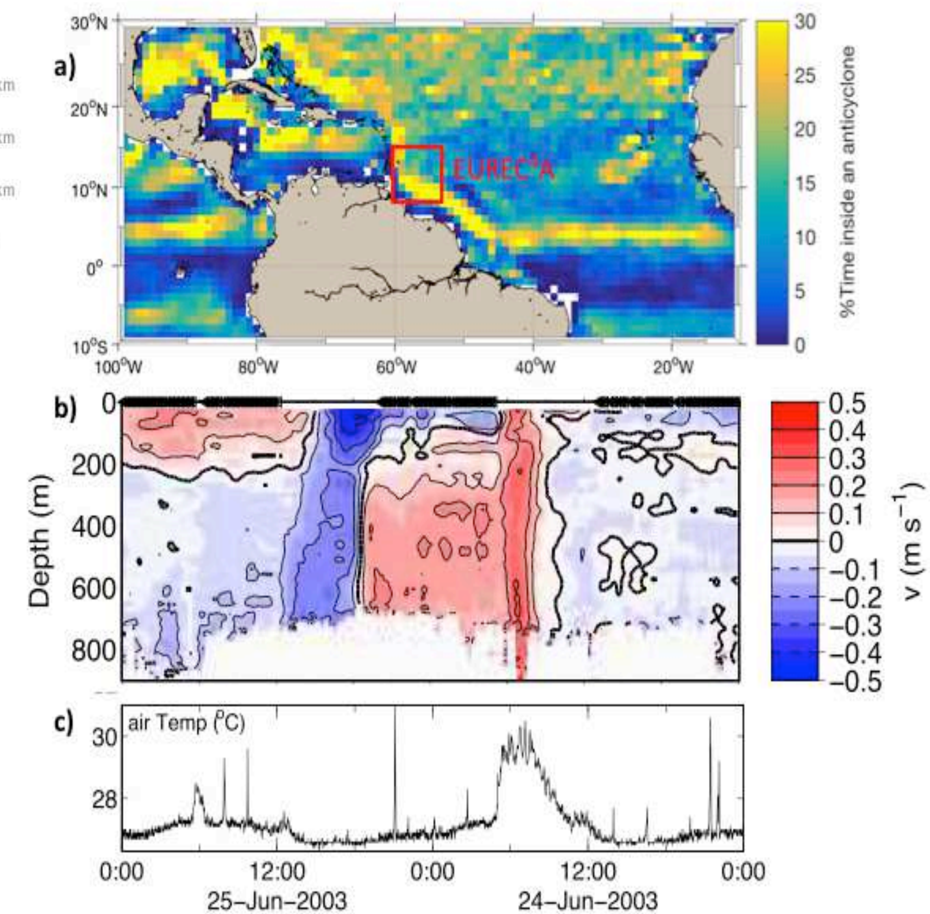
Shallow convection, clouds & air-sea exchanges

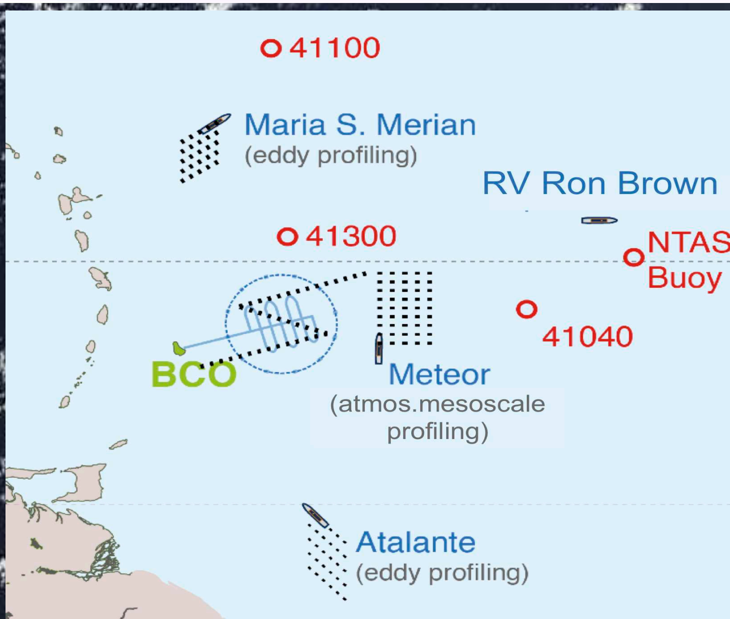


Intense observing period Jan.-Feb. 2020

WARM OCEAN EDDIES

1° x 1° % Time of eddies presence

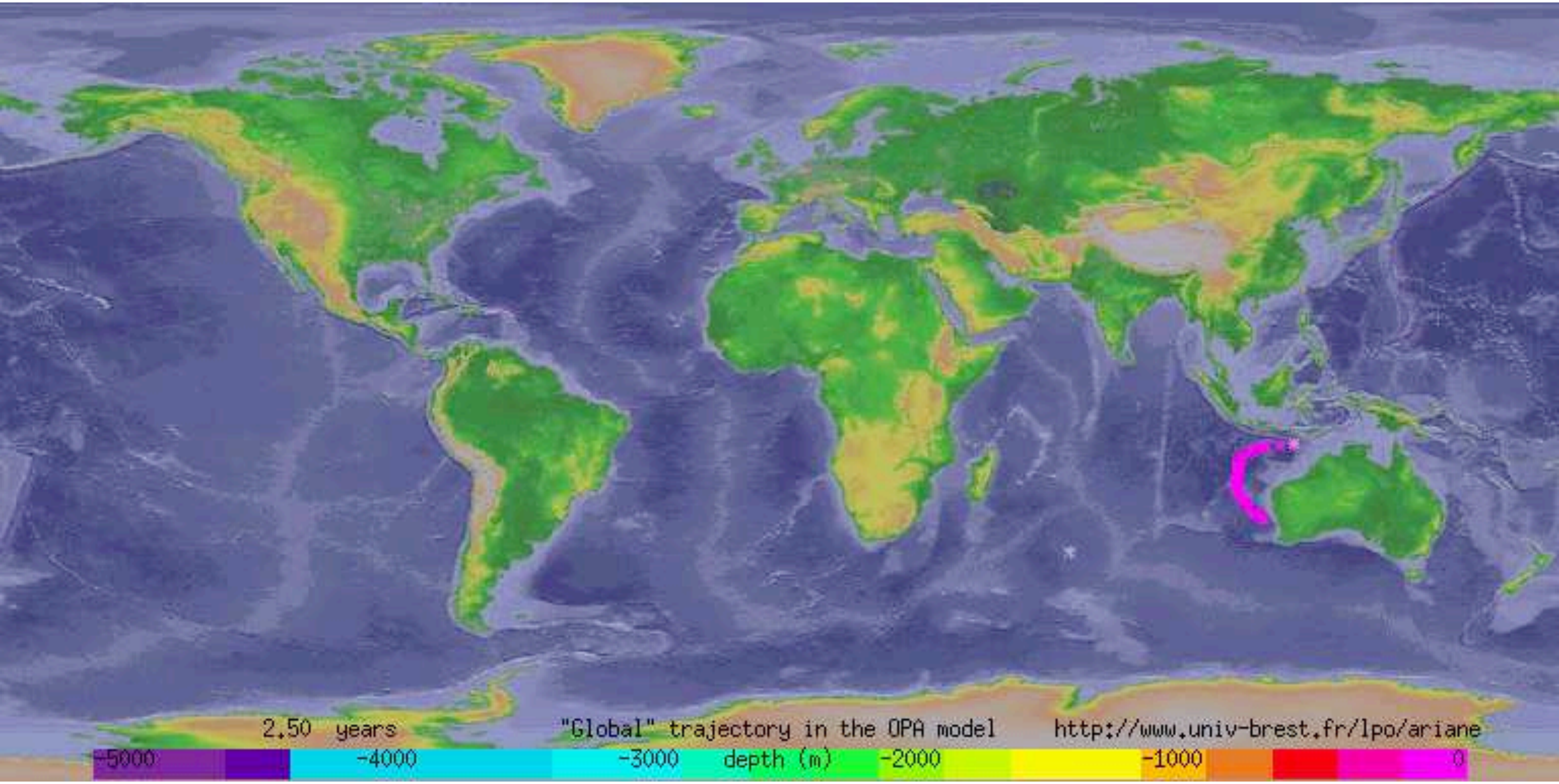




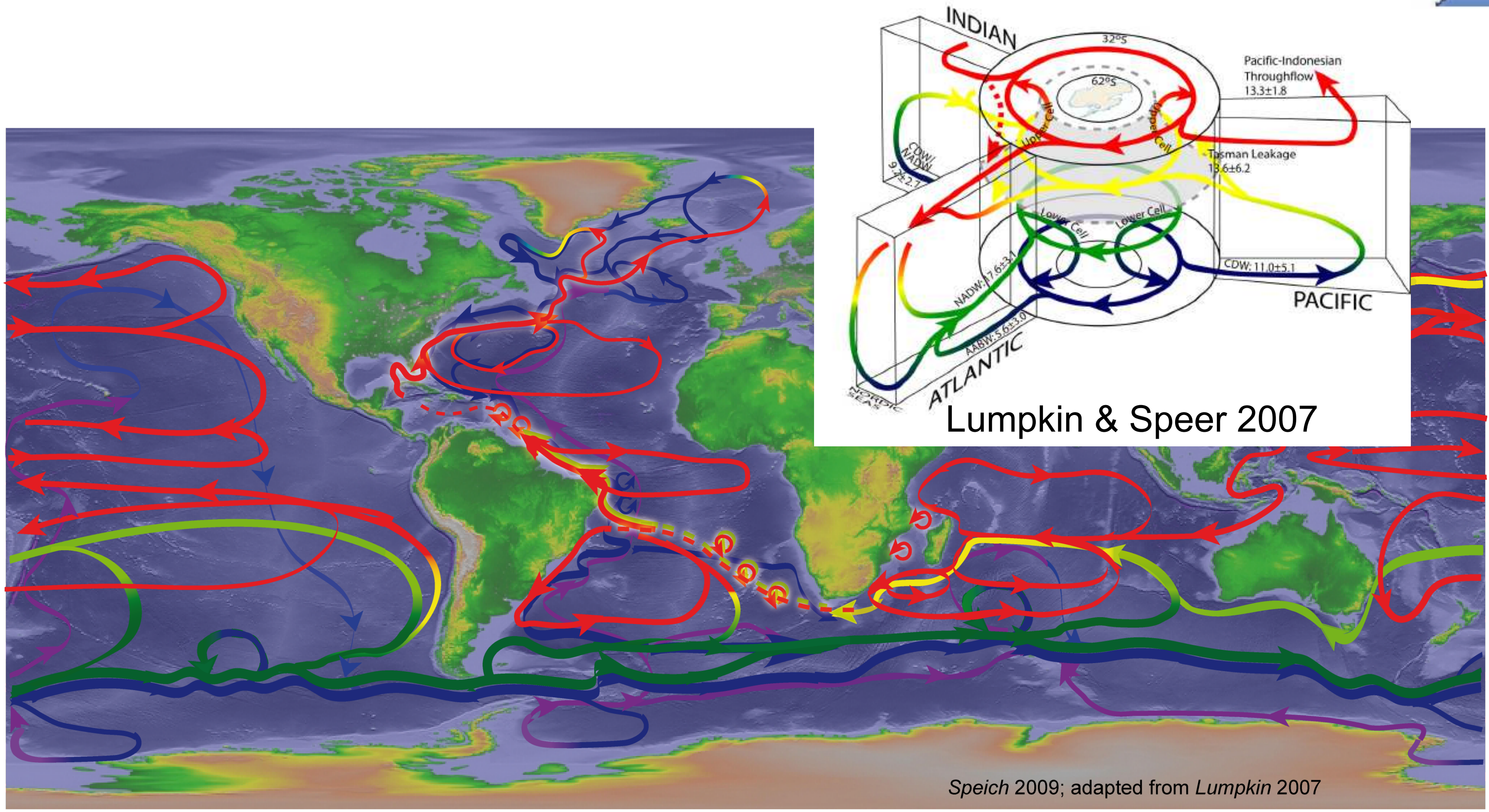
Speich et al. 2018

Circulation océanique globale

Meridional overturning circulation or Thermohaline circulation or Ocean Conevor Belt



FROM THE THERMOHALINE CIRCULATION TO THE GLOBAL OCEAN CIRCUMATION

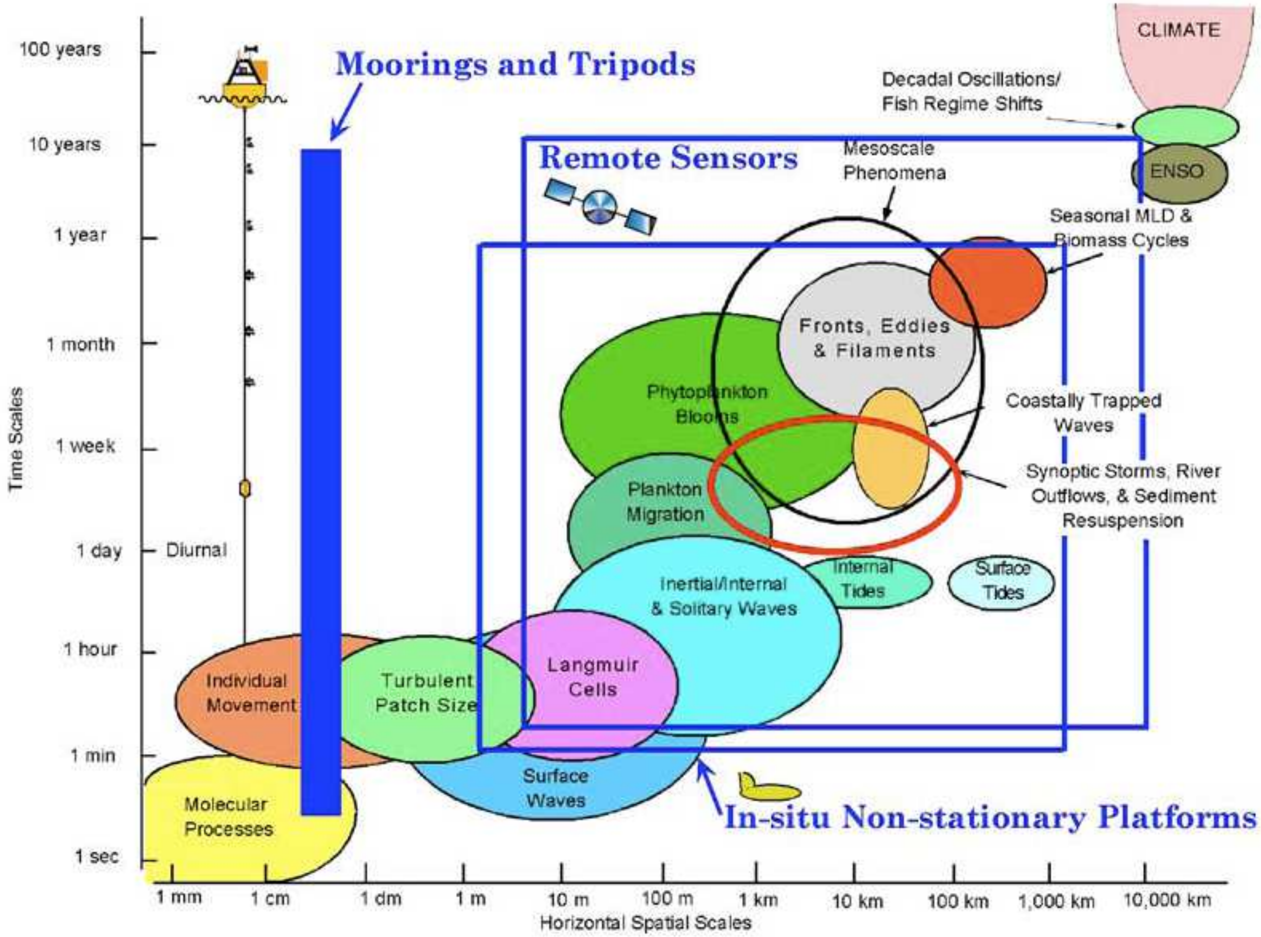


Lumpkin & Speer 2007

Speich 2009; adapted from *Lumpkin* 2007

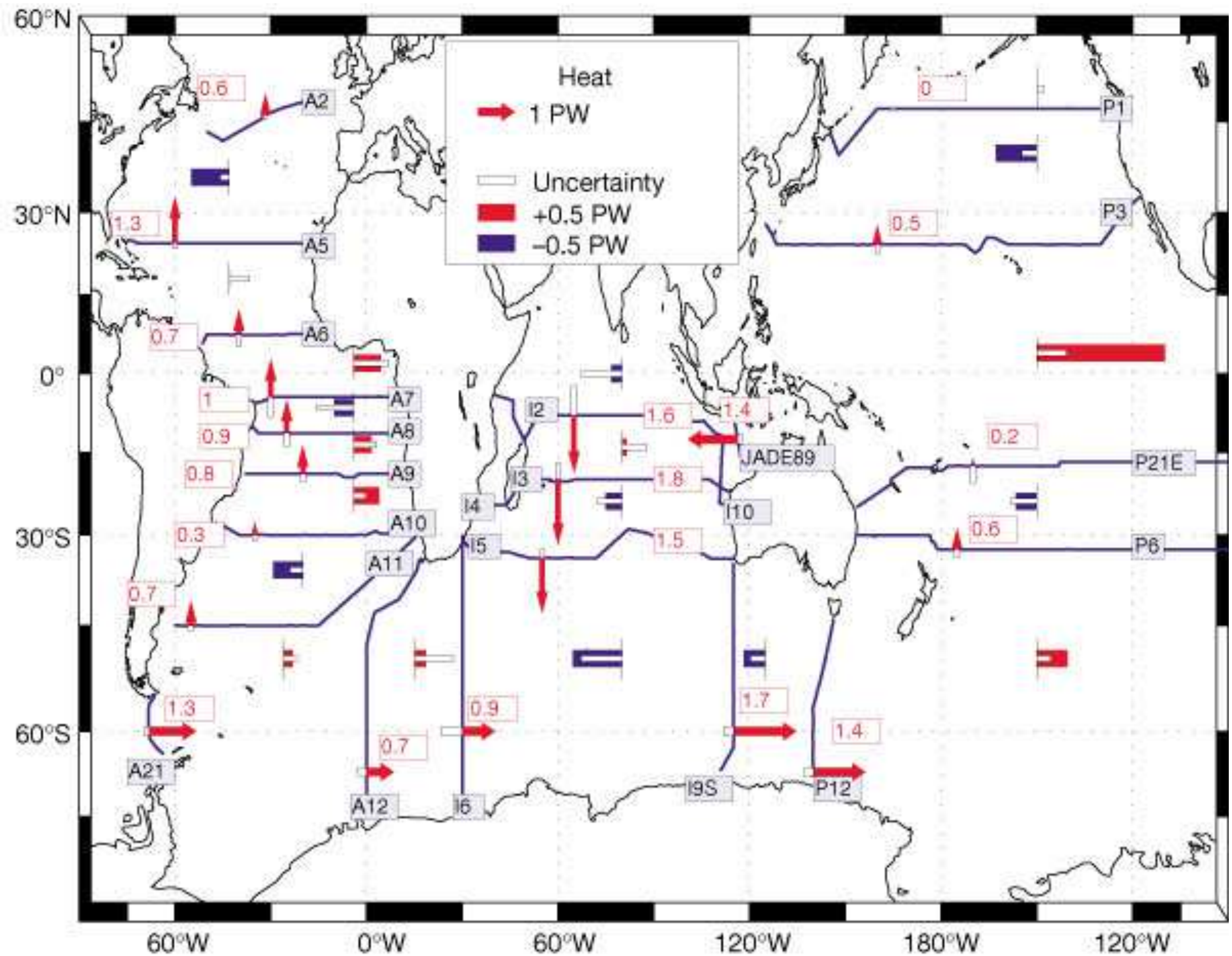
Ocean Dynamics resulting from multiscale processes interactions

Oceanic Measurements and Large-Scale Patterns

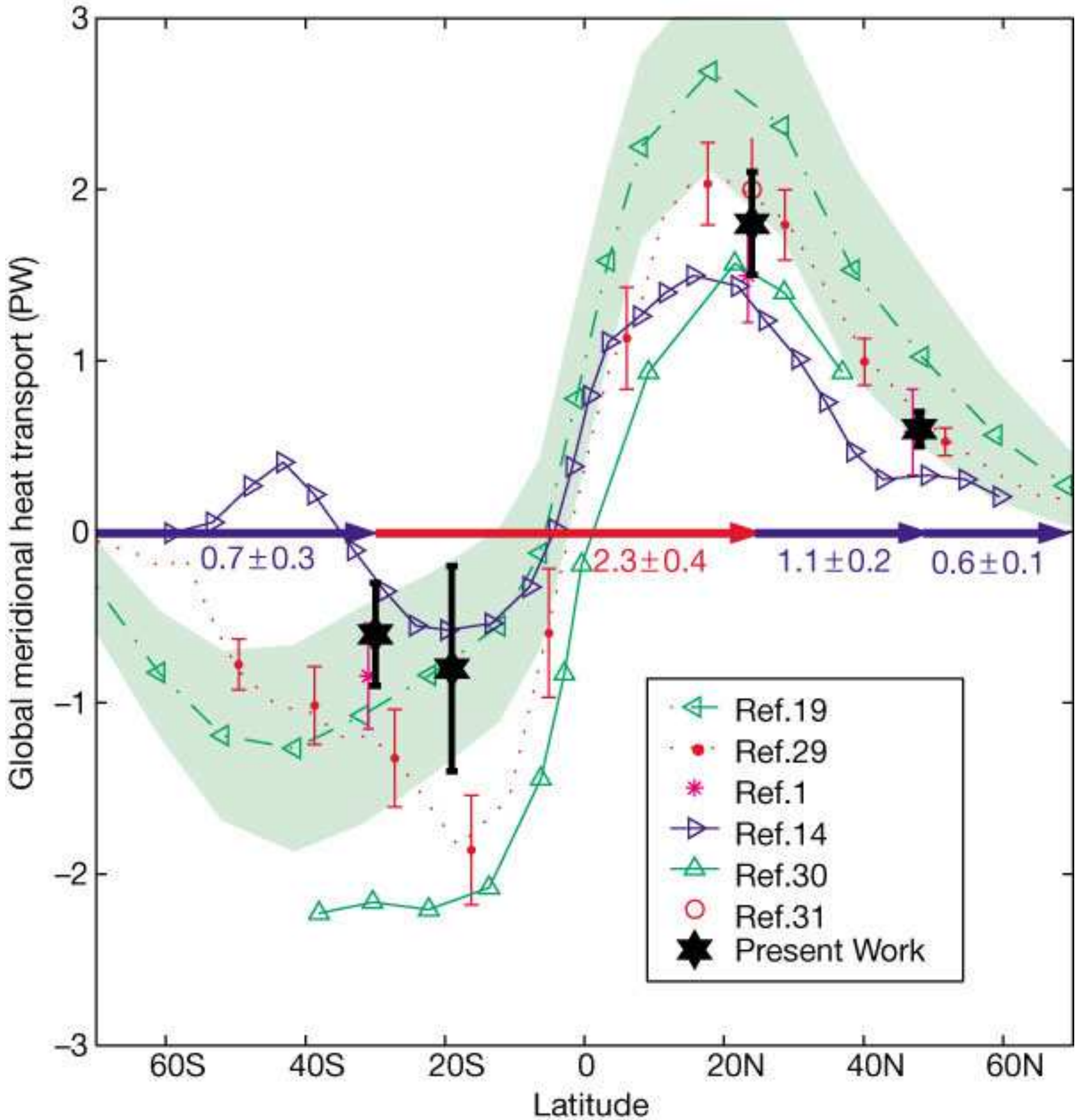


Global heat transport

(Ganachaud and Wunsch, 2000)



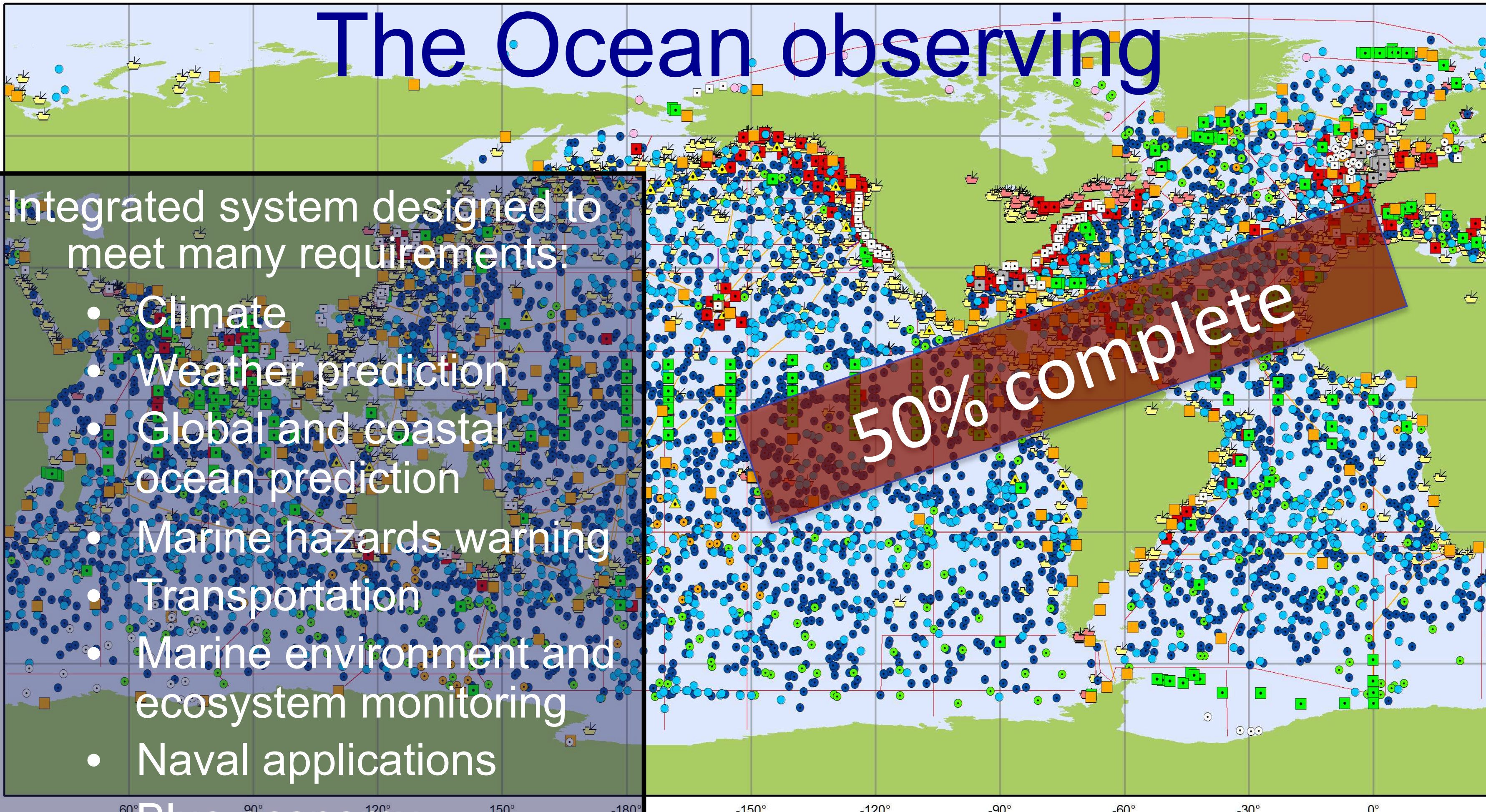
Global heat transport
(Ganachaud and Wunsch, 2000)



The Ocean observing

Integrated system designed to meet many requirements:

- Climate
- Weather prediction
- Global and coastal ocean prediction
- Marine hazards warning
- Transportation
- Marine environment and ecosystem monitoring
- Naval applications
- Blue economy
- 8 of 9 Societal Benefits



Main in situ Elements of the Global Ocean Observing System

April 2018

Profiling Floats (Argo)
- Core (3815)
- Deep (57)
- BioGeoChemical (305)

Data Buoys (DBCP)
- Surface Drifters (1408)
- Offshore Platforms (96)
- Ice Buoys (11)
- Moored Buoys (387)
- Tsunameters (32)

Timeseries (OceanSITES)
- Interdisciplinary Moorings (338)

Repeated Hydrography (GO-SHIP)
- Research Vessel Lines (61)

Sea Level (GLOSS)
- Tide Gauges (252)

Ship based Measurements (SOT)
- Automated Weather Stations (248)
- Manned Weather Stations (1767)
- Radiosondes (8)
- eXpendable BathyThermographs (37)

Other Networks
- HF Radars (270)
- Animal Borne Sensors (53)
- Ocean Gliders (31)

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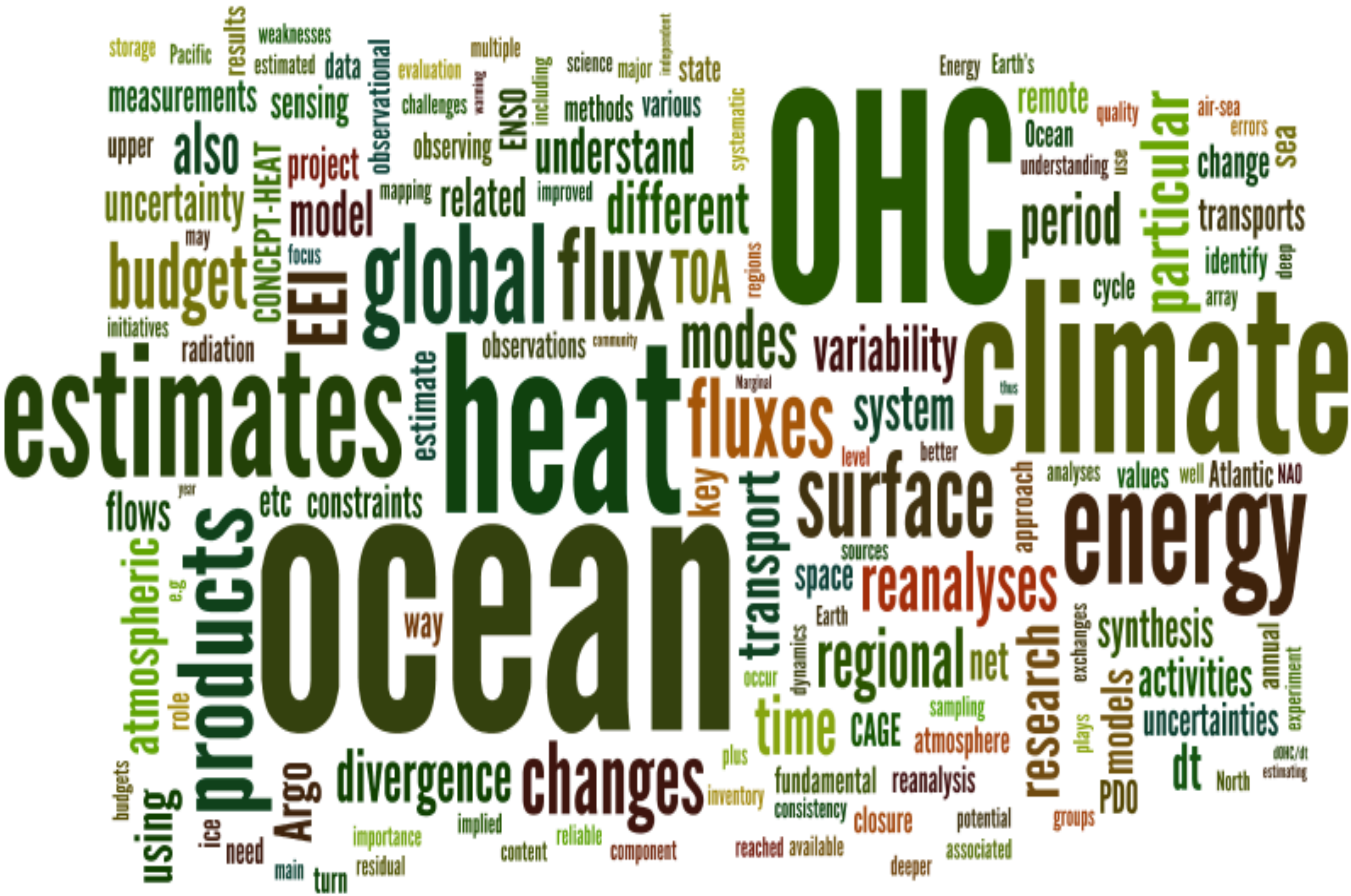
The Ocean Observing



ocean
heat
OHC
climate
estimates
energy
global
flux
surface
products
changes
fluxes
reanalyses
regional
budget
EEI
TOA
modes
variability
system
particular
period
different
understand
model
also
uncertainty
CONCEPT-HEAT
measurements
sensing
observational
project
related
transport
divergence
research
synthesis
activities
uncertainties
time
dt
models
atmospheric
Argo
using
constraints
flows
etc
estimate
observations
radiation
initiatives
key
space
net
CAGE
atmosphere
reanalysis
fundamental
closure
PDO
potential
consistency
inventory
plus
sampling
occur
dynamics
Earth
sources
approach
analyses
values
well
Atlantic
NAO
exchanges
annual
experiment
plays
groups
North
associated
deeper
available
reached
component
reliable
implied
content
importance
residual
main
turn
need
ice
budgets
role
way
level
better
Marginal
thus
community
year
e.g
may
focus
regions
cycle
array
deep
identify
transports
change
sea
errors
air-sea
quality
remote
Ocean
understanding
use
Energy
Earth's
state
major
science
multiple
evaluation
weaknesses
results
storage
Pacific
estimated
data
challenges
ENSO
including
methods
various
systematic
observing
mapping
improved
upper

Global warming and the ocean

Human activities have increased Green House Gases and Aerosols

- Energy fluxes across the system are not instantaneous
- This causes an Earth Energy Imbalance (EEI)
- The Ocean is the repository of this energy
- The ocean warms up, expands, provides more energy and water vapor to the atmosphere, affect marine ecosystems and society

Global warming and the ocean (2)

- The absolute value of EEI represents the most fundamental metric defining the status of global climate change (not global surface temperature).
- Sustained ocean observations are crucial to refining future estimates of EEI
- This will allow to assess the status of global climate change and testing the effectiveness of mitigation actions
- We need to better understand ocean and air-sea processes to improve weather and climate predictions, marine ecosystem and fisheries management and enable a more efficient adaptation
- Progress can only be achieved with a concerted international effort.