COASTAL DYNAMICS

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- **Outline:**

1. Introduction
2. General equations
3. Waves
    - 3.1.Surface gravity waves
    - 3.2.Inertia-gravity Waves
    - 3.3.Coastal waves
    - 3.4.Internal Waves
4. Tides
5. Coastal circulation and responses to meteorological forcing
6. Bottom and surface boundary layers
7. Frontal dynamics
8. Estuary plumes and regimes

Presentations and material will be available at :

jgula.fr/Coastal/

Cosatal Dynamics

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Evaluation

- The evaluation will be based on a sitting exam on **Oct. 9**

1. INTRODUCTION

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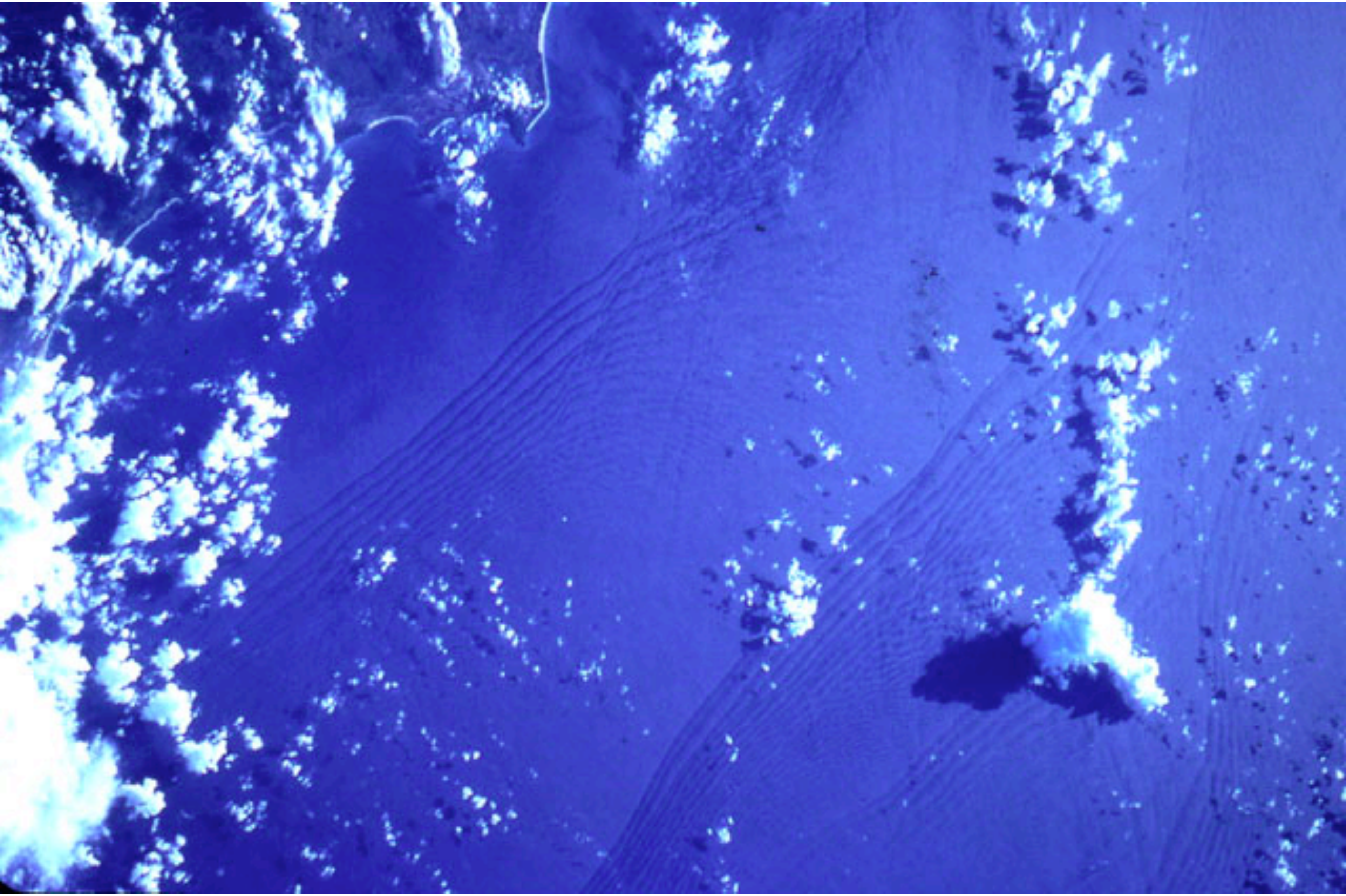
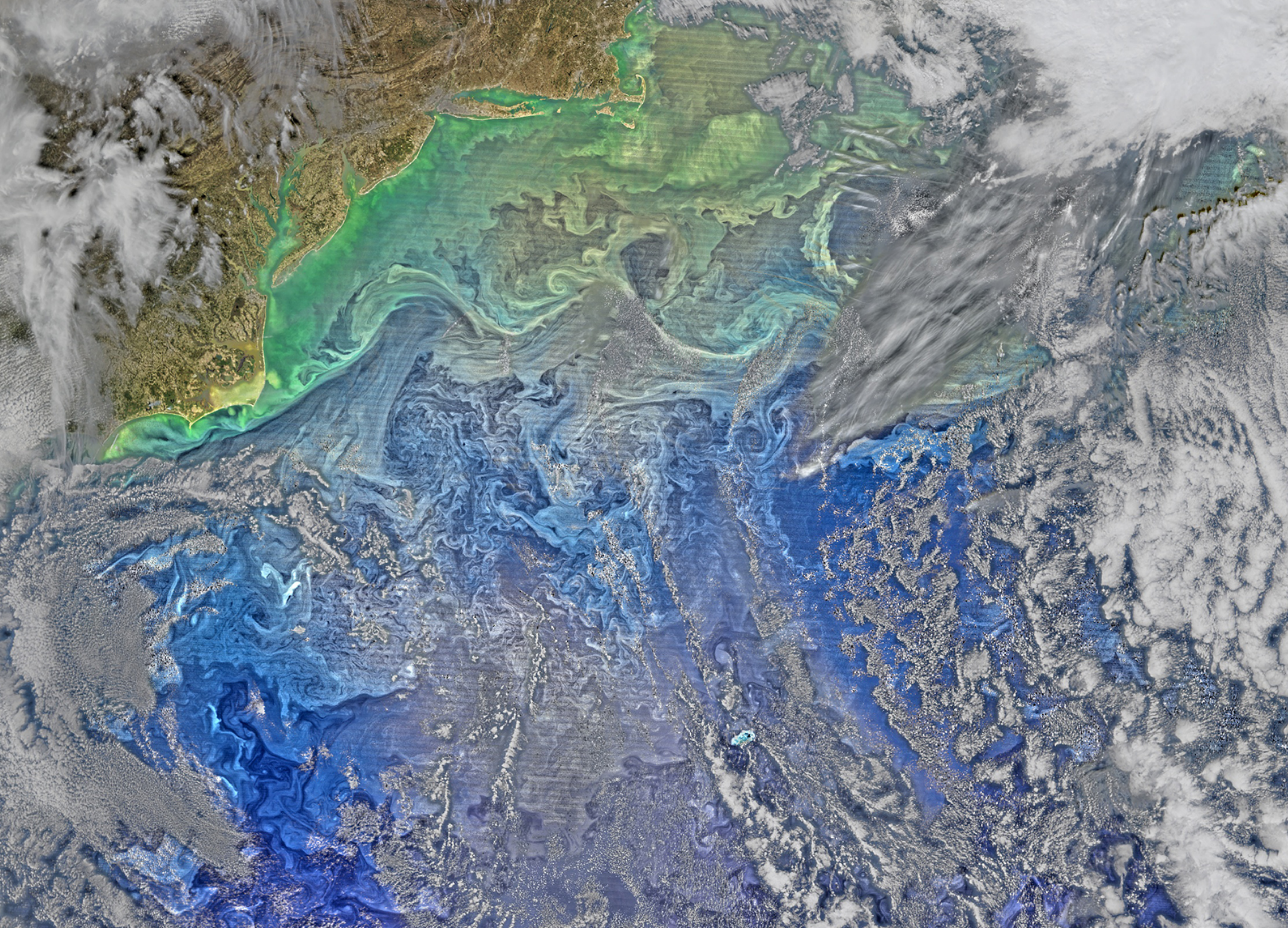
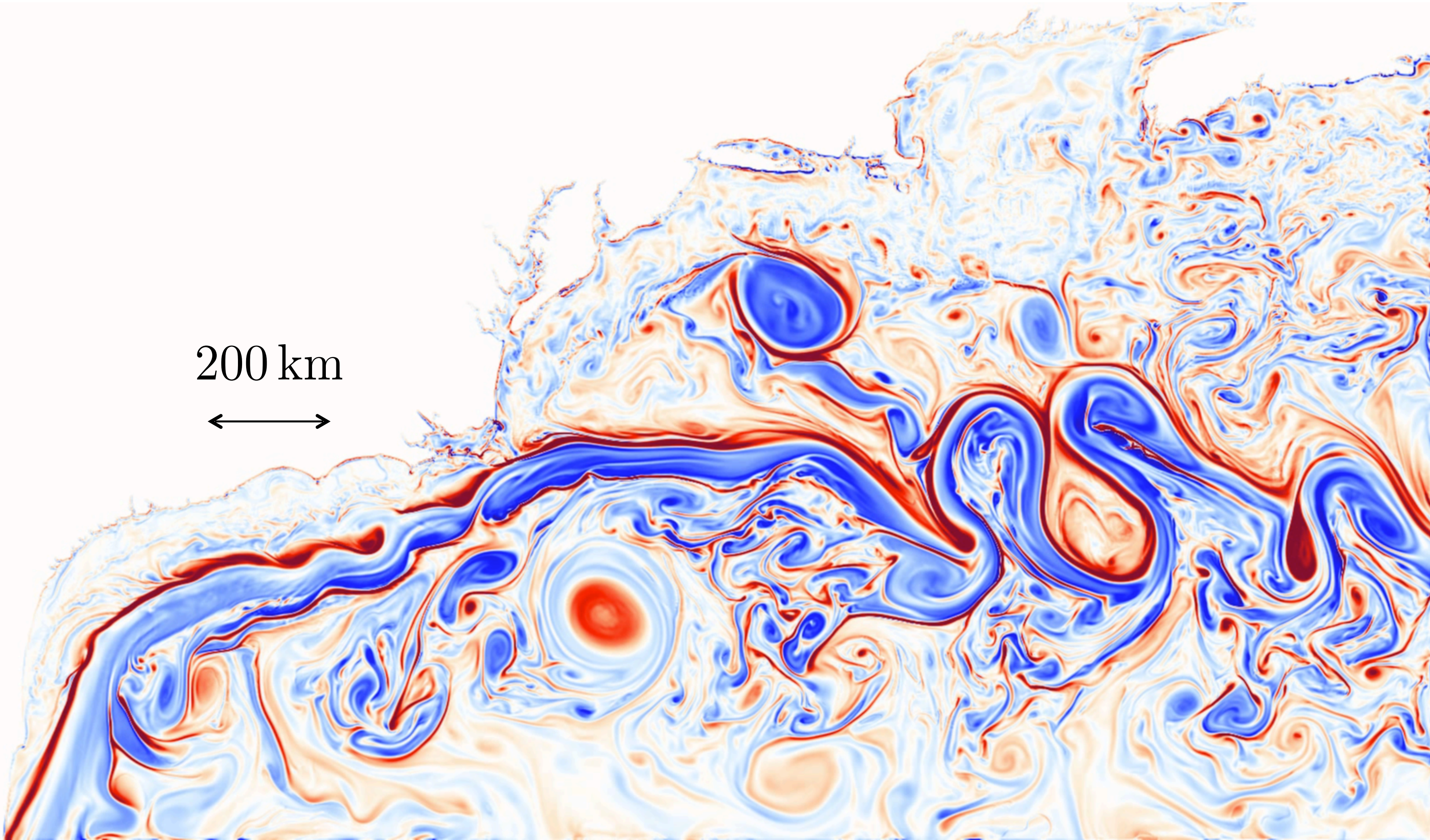
ENEOS
龍泉洞
Ryusendo Cave
51Km
三王岩
Sannoiwa Rocks
20Km
浄土ヶ浜
Jodogahama Beach
4Km
シートピアなあど
Seatopia Naado
1Km

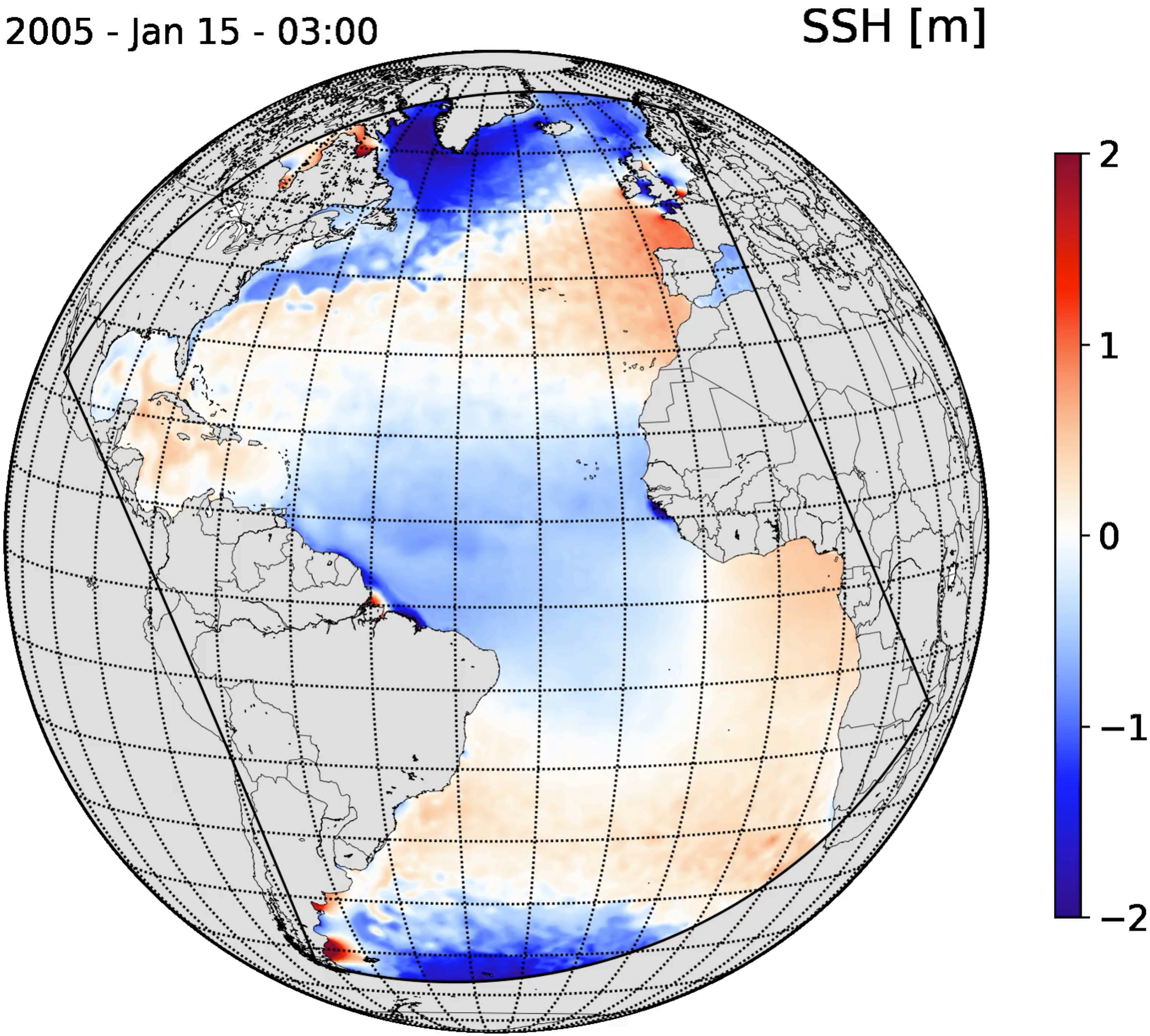




Surface relative vorticity

$\Delta x = 1.5\,\mathrm{km}$

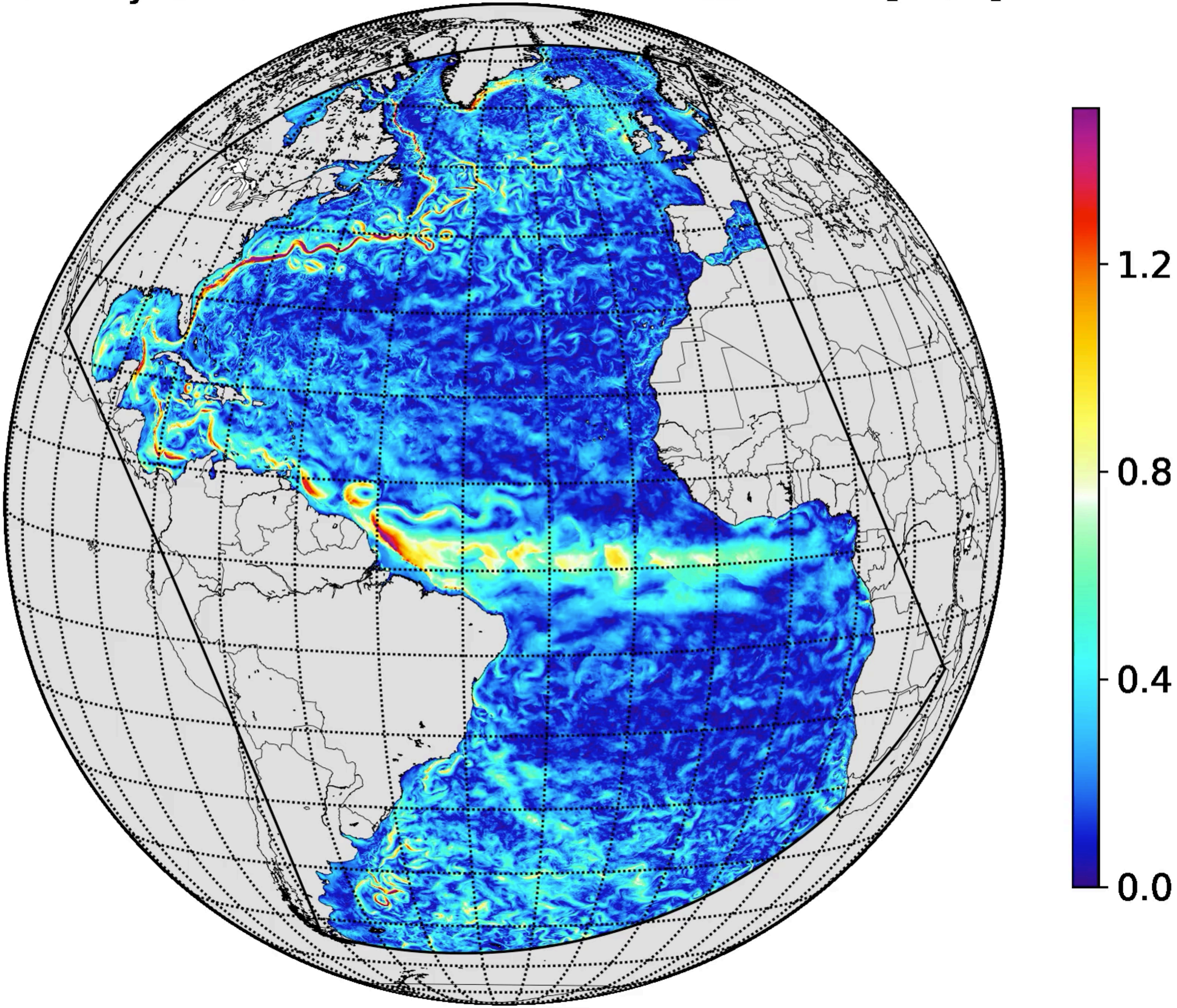


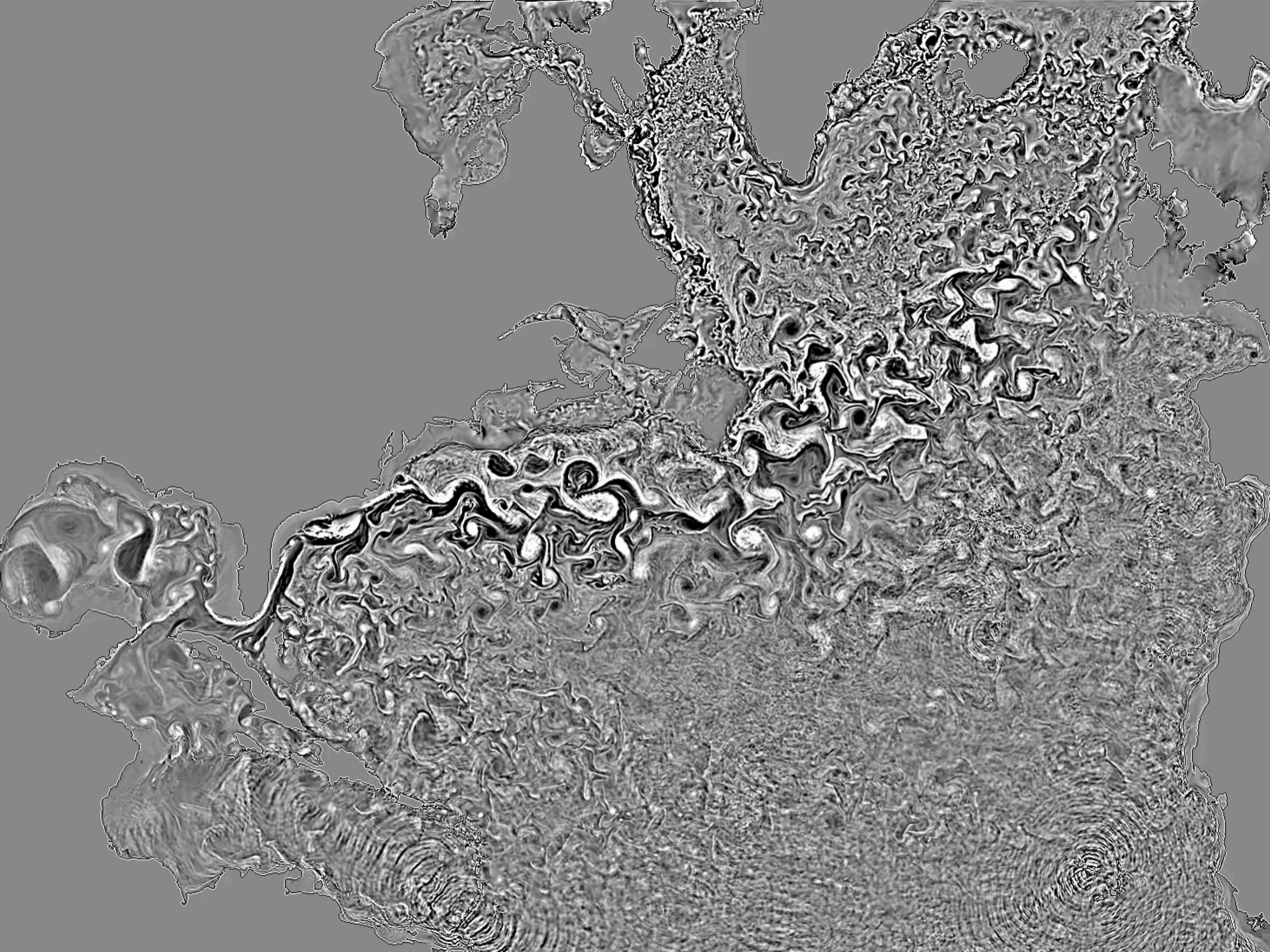


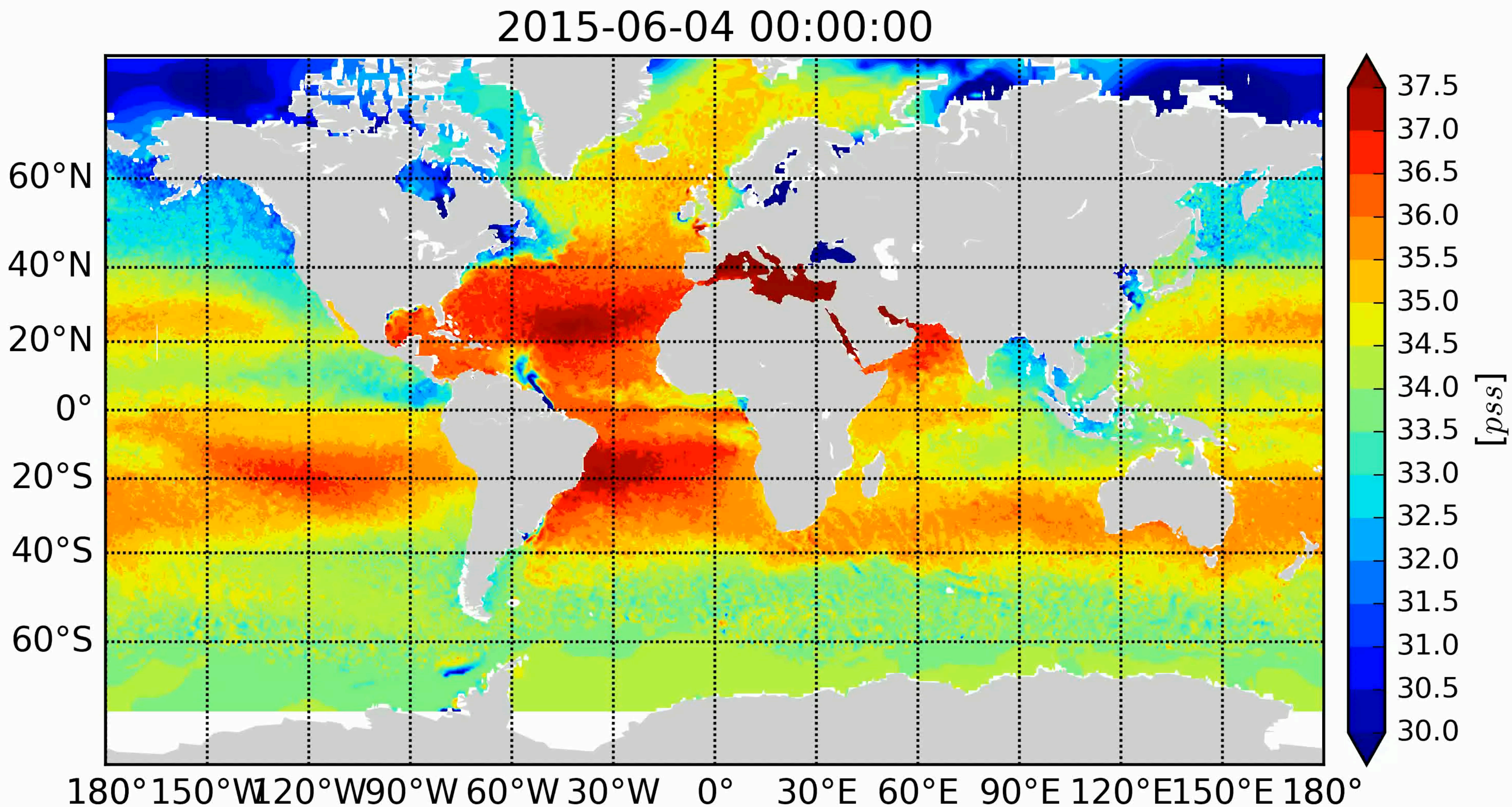
2005 - Jan 15 - 03:00
SSH [m]
2
1
0
−1
−2

2005 - Jan 14 - 00:00

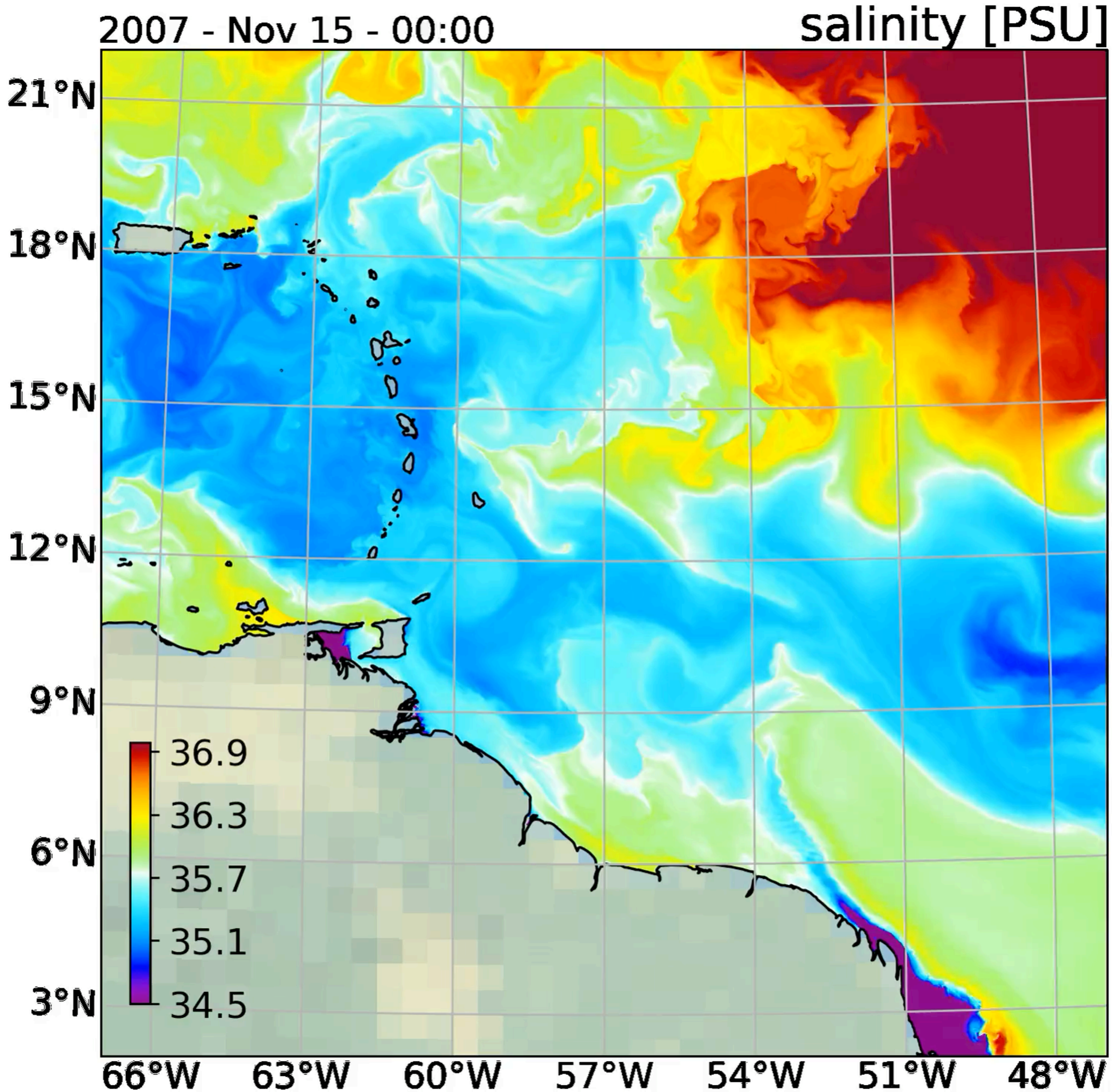
currents [m/s]

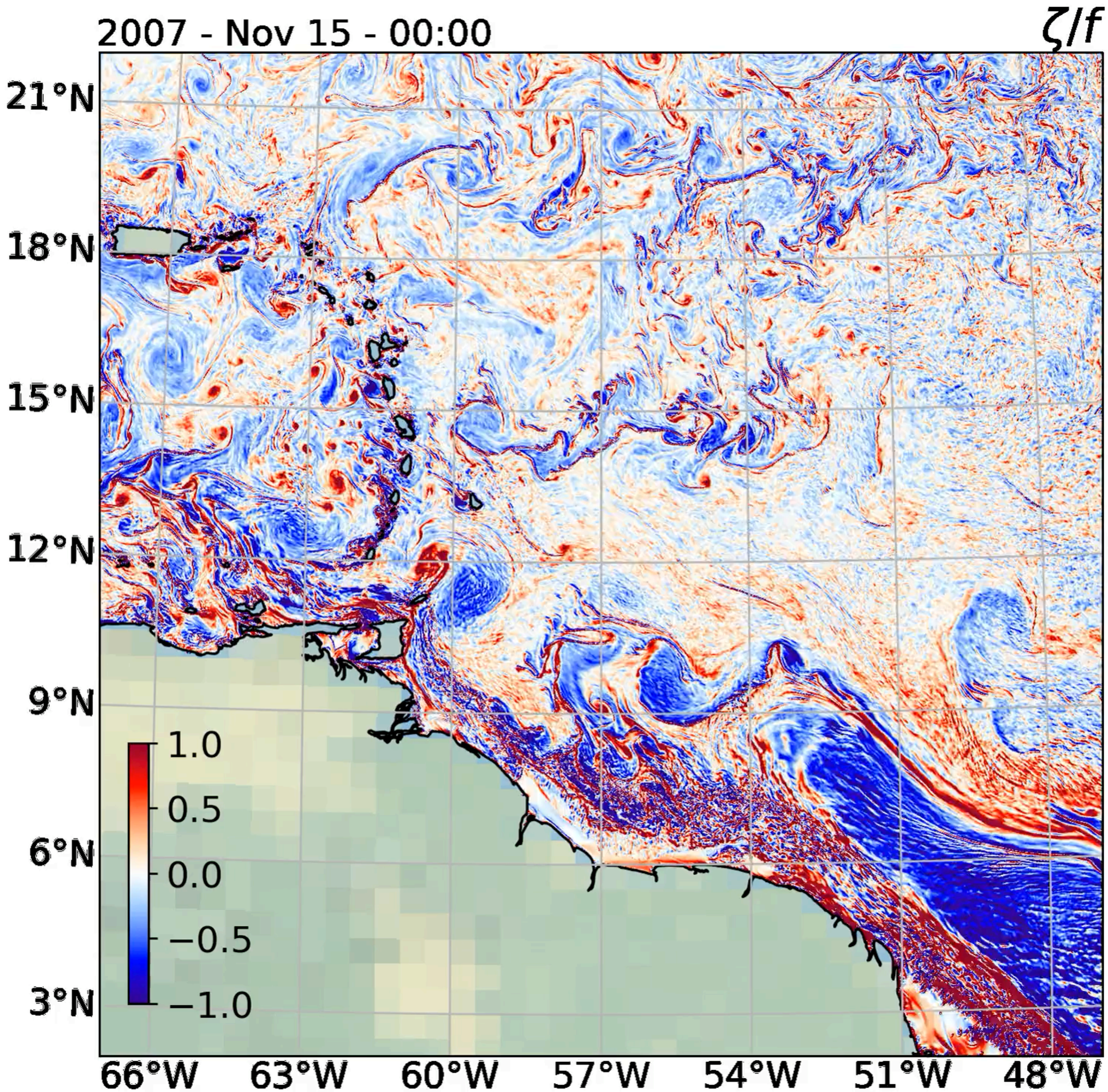




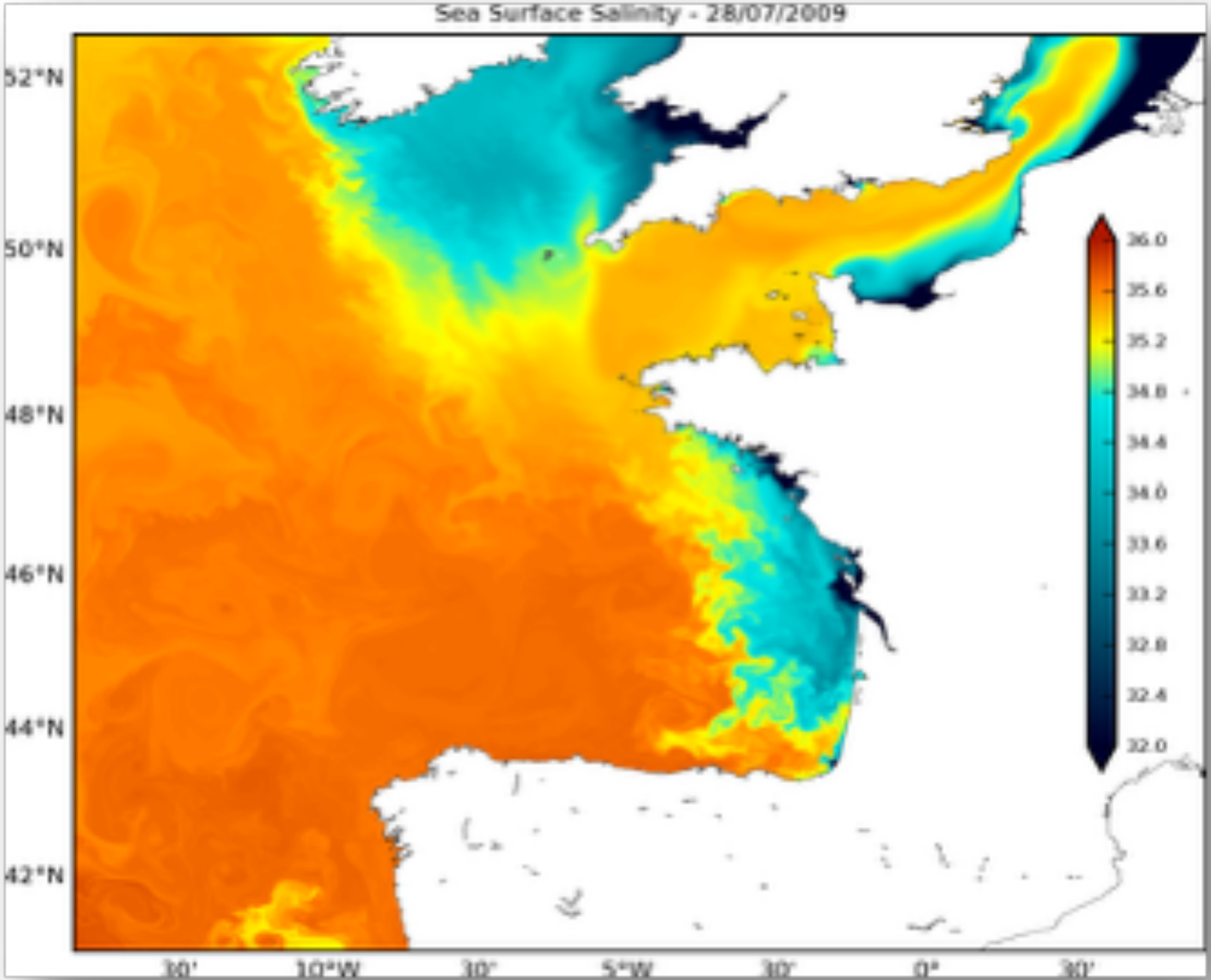


2015-06-04 00:00:00
60°N
40°N
20°N
0°
20°S
40°S
60°S
180° 150°W 120°W 90°W 60°W 30°W 0° 30°E 60°E 90°E 120°E 150°E 180°
37.5
37.0
36.5
36.0
35.5
35.0
34.5
34.0
33.5
33.0
32.5
32.0
31.5
31.0
30.5
30.0
[pss]


2007 - Nov 15 - 00:00
salinity [PSU]
21°N
18°N
15°N
12°N
9°N
6°N
3°N
66°W
63°W
60°W
57°W
54°W
51°W
48°W
36.9
36.3
35.7
35.1
34.5

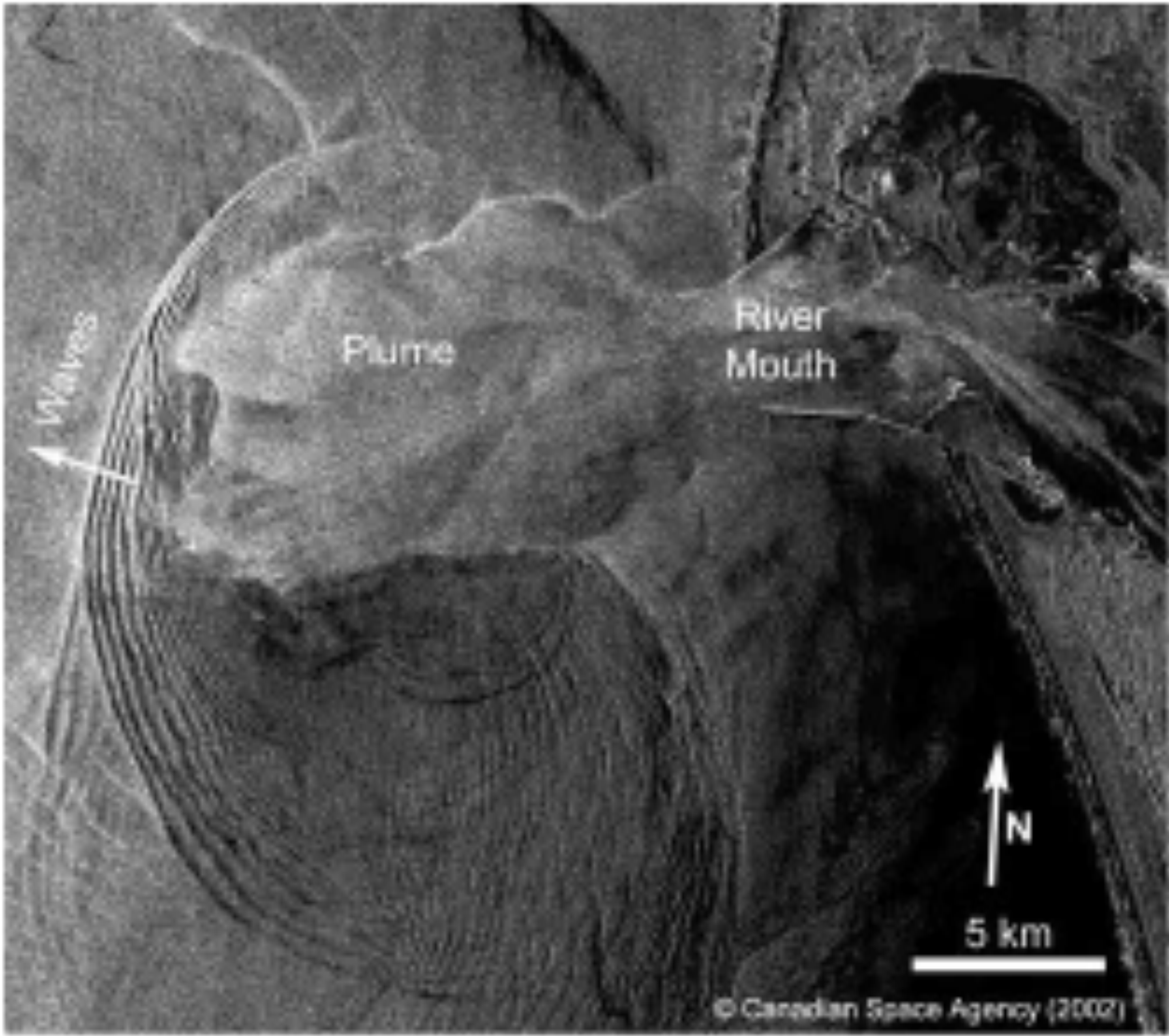


2007 - Nov 15 - 00:00
ζ/f
21°N
18°N
15°N
12°N
9°N
6°N
3°N
66°W
63°W
60°W
57°W
54°W
51°W
48°W
1.0
0.5
0.0
−0.5
−1.0

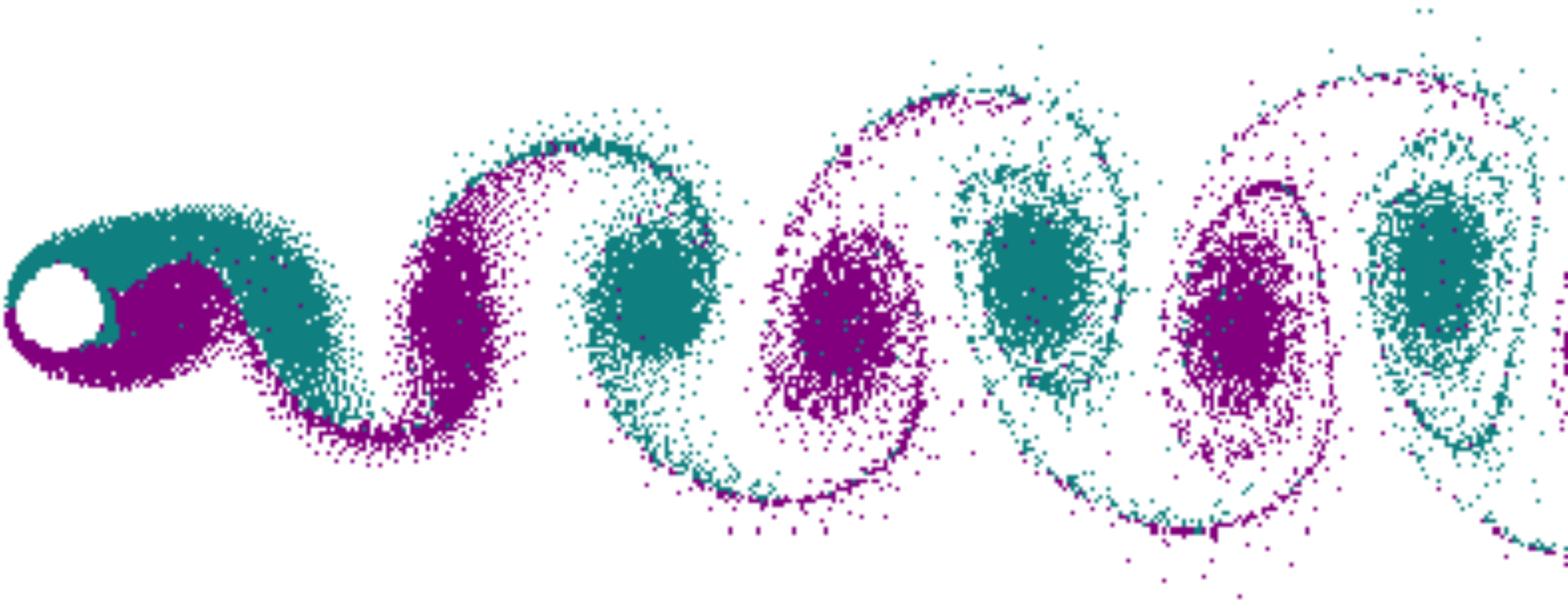


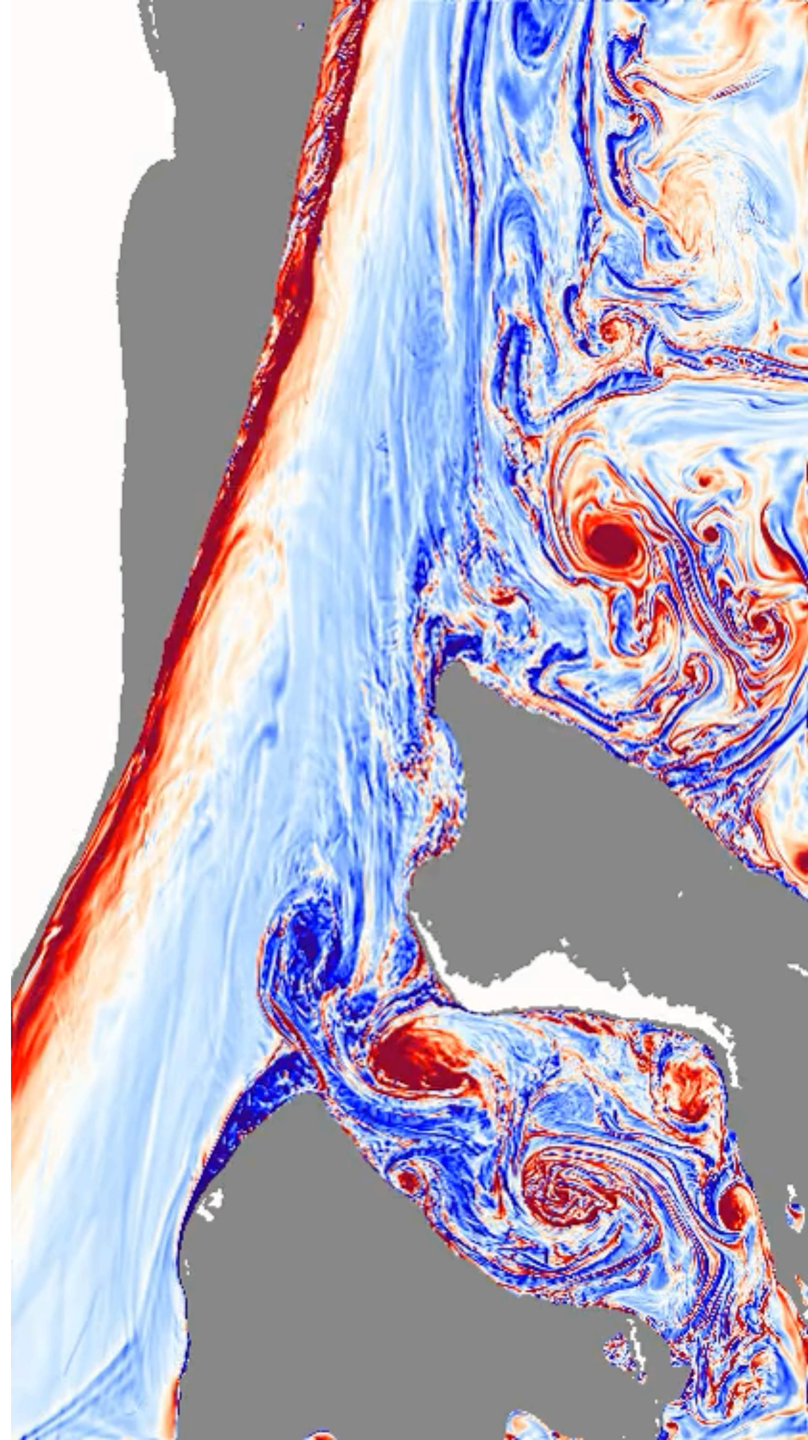
Sea Surface Salinity - 28/07/2009
52°N
50°N
48°N
46°N
44°N
42°N
30'
10°W
30'
5°W
30'
0°
30'
36.0
35.6
35.2
34.8
34.4
34.0
33.6
33.2
32.8
32.4
32.0


Roorda Aerial

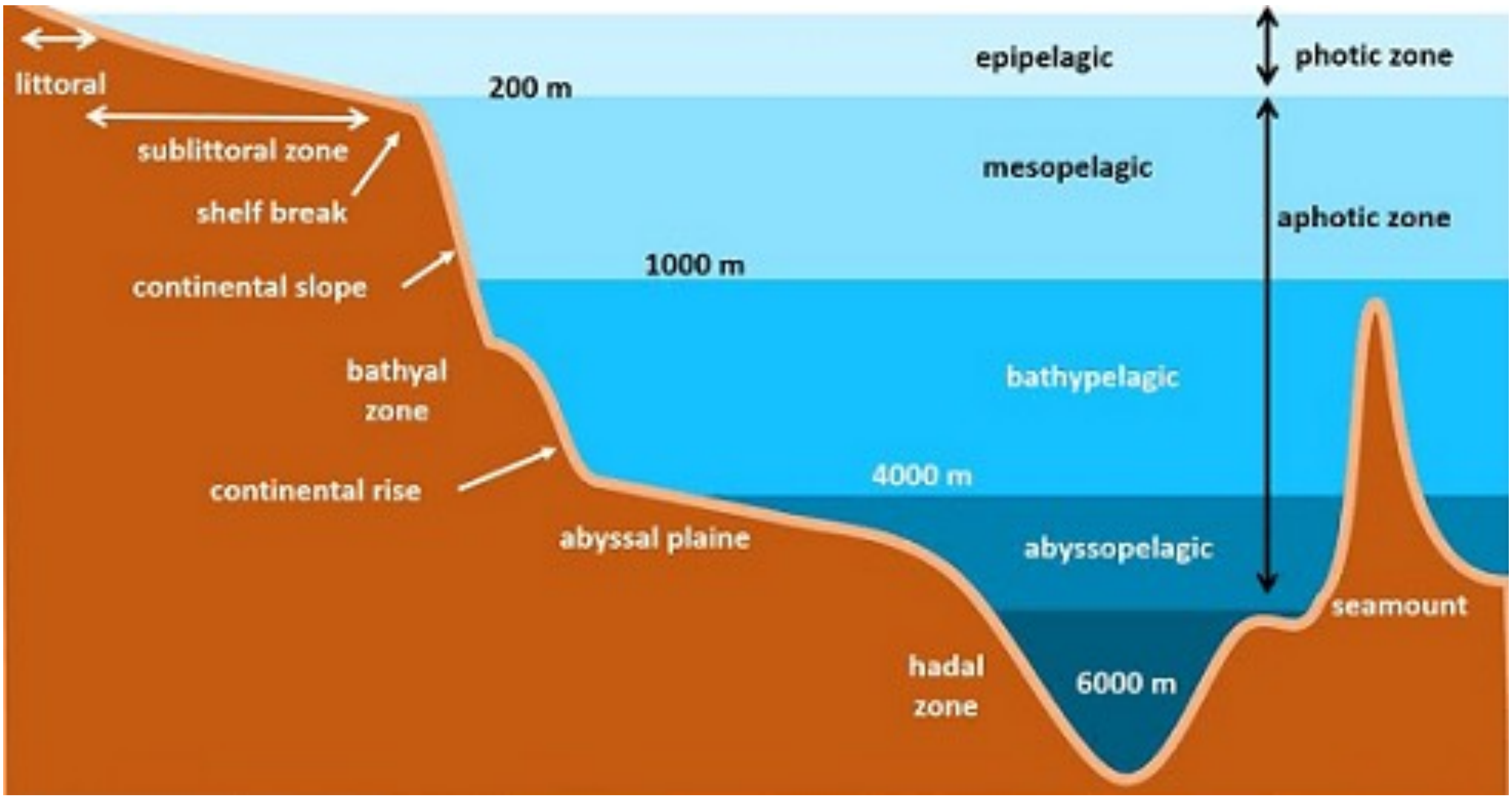


Waves
Plume
River
Mouth
N
5 km
© Canadian Space Agency (2002)

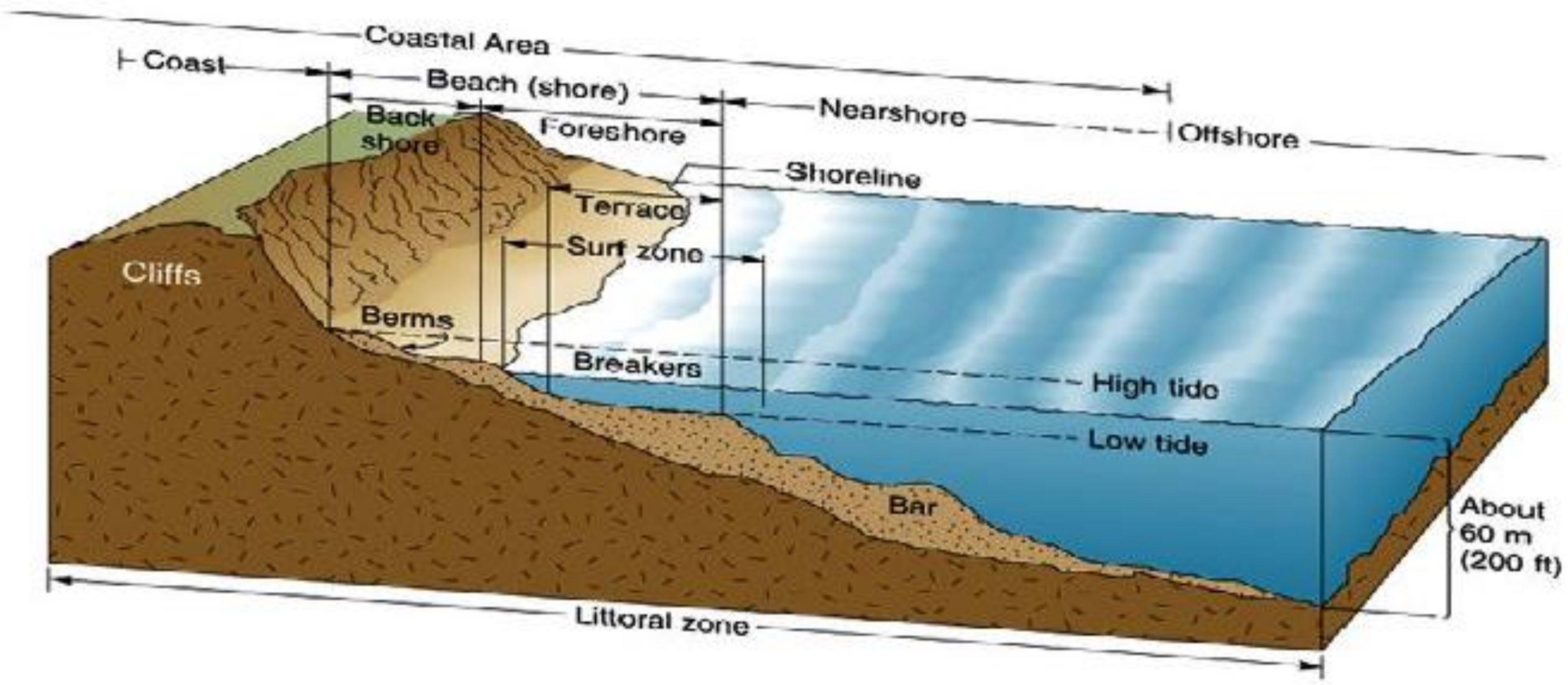




Coastal ocean



Littoral ocean



2. GENERAL EQUATIONS

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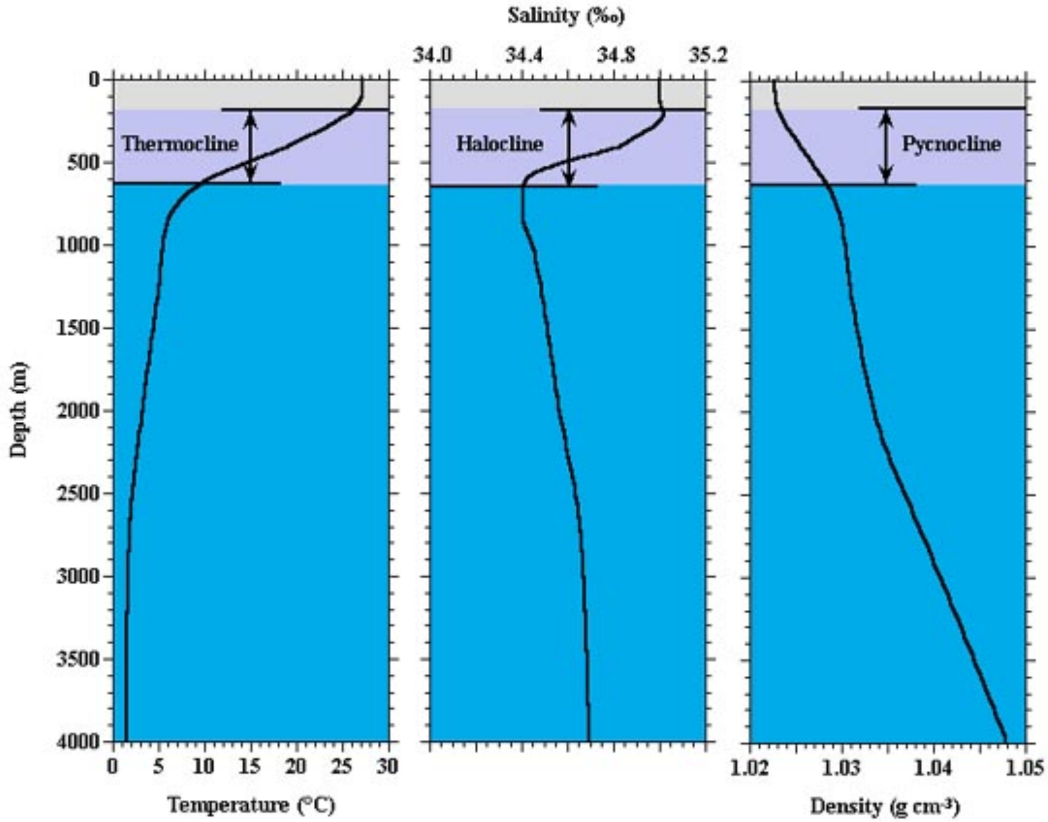
- Kundu-Cohen (1987). *Fluid Mechanics. Third edition*
- Cushman-Roisin*. Introduction to geophysical fluid Dynamics*
- Carton*. Elements de GFD*

Ingredients of GFD

2 important ingredients in Geophysical Fluid Dynamics (GFD): **rotation + stratification**

Ingredients of GFD

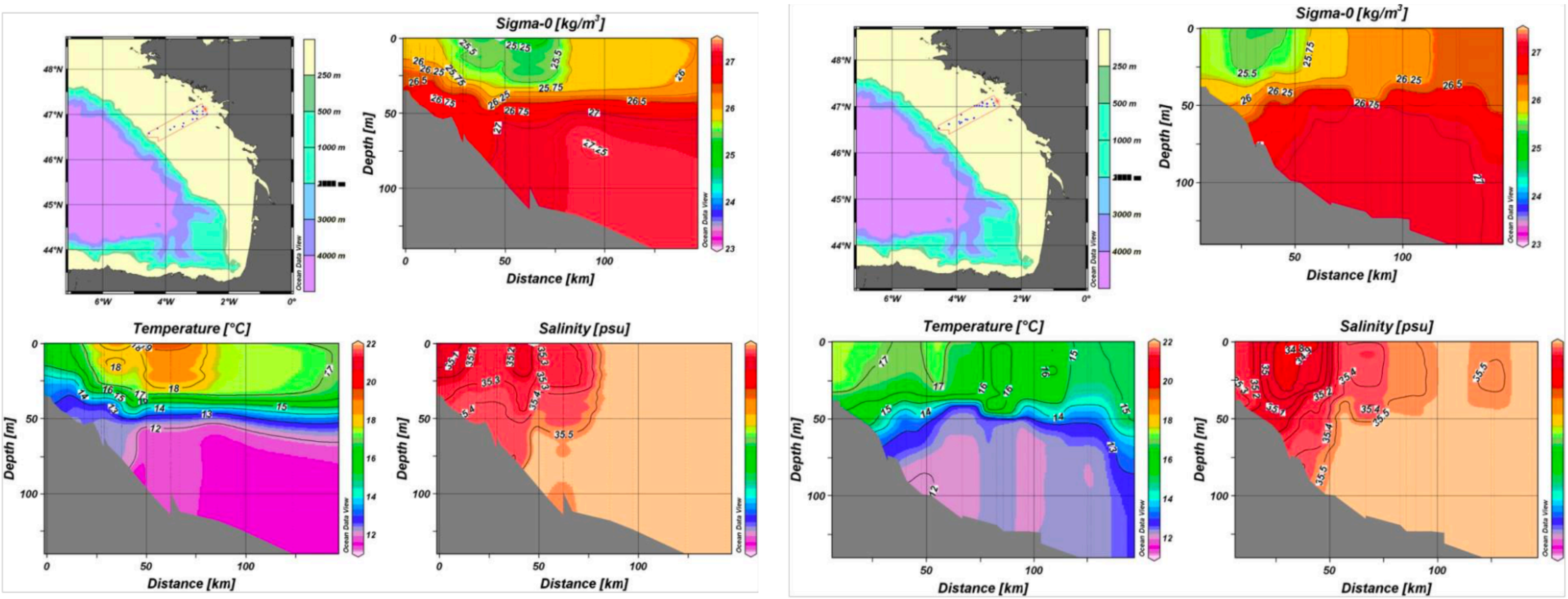
Stratification of the ocean:



with Equation of state : $\rho = \rho(T, S, p)$

Ingredients of GFD

Stratification of the ocean:

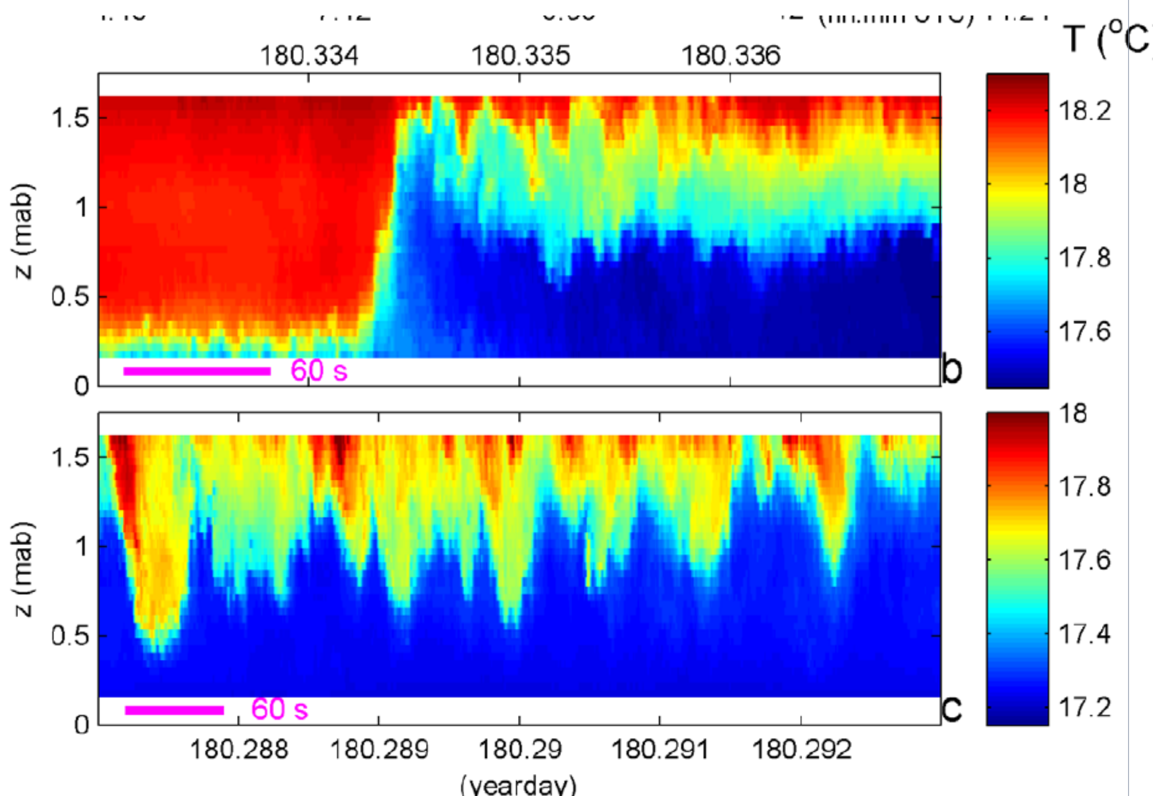


Example for the Bay of Biscay in summer/winter

Ingredients of GFD

Stratification of the ocean:

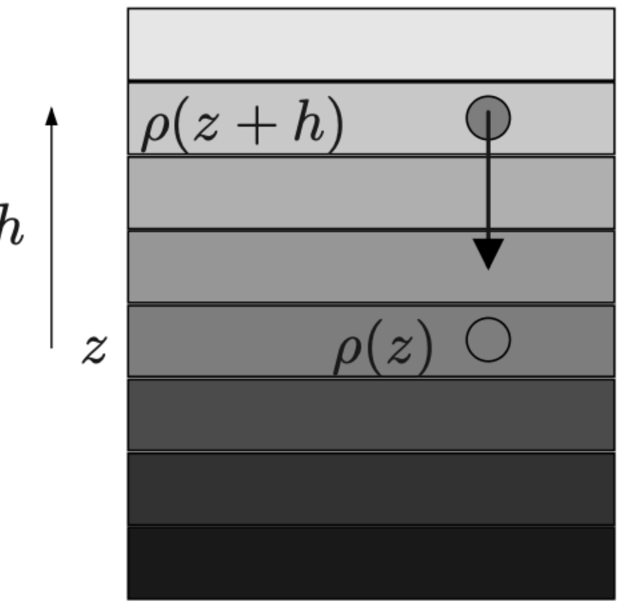
•



van Haren H, Gostiaux L, Laan M, van Haren M, van Haren E, Gerringa LJA (**2012**) Internal Wave Turbulence Near a Texel Beach. *PLoS ONE* 7(3): e32535. doi:10.1371/journal.pone.0032535

Ingredients of GFD

Stratification of the ocean:



An incompressible fluid parcel, displaced vertically, feels a buoyancy force:

$$g\left[\rho(z+h) - \rho(z)\right] V,$$

Newton's law then yields:

$$\rho(z)\, V \,\frac{d^2 h}{dt^2} = g\left[\rho(z+h) - \rho(z)\right] V.$$

with approx:

$$\rho(z+h) - \rho(z) \simeq \frac{d\rho}{dz}\, h.$$

$$\rho = \rho_0 + \rho'(x,\, y,\, z,\, t) \quad \text{with} \quad |\rho'| \ll \rho_0,$$

So

$$\frac{d^2 h}{dt^2} - \frac{g}{\rho_0}\frac{d\rho}{dz}\, h = 0,$$

with the Brunt-Vaisala frequency :

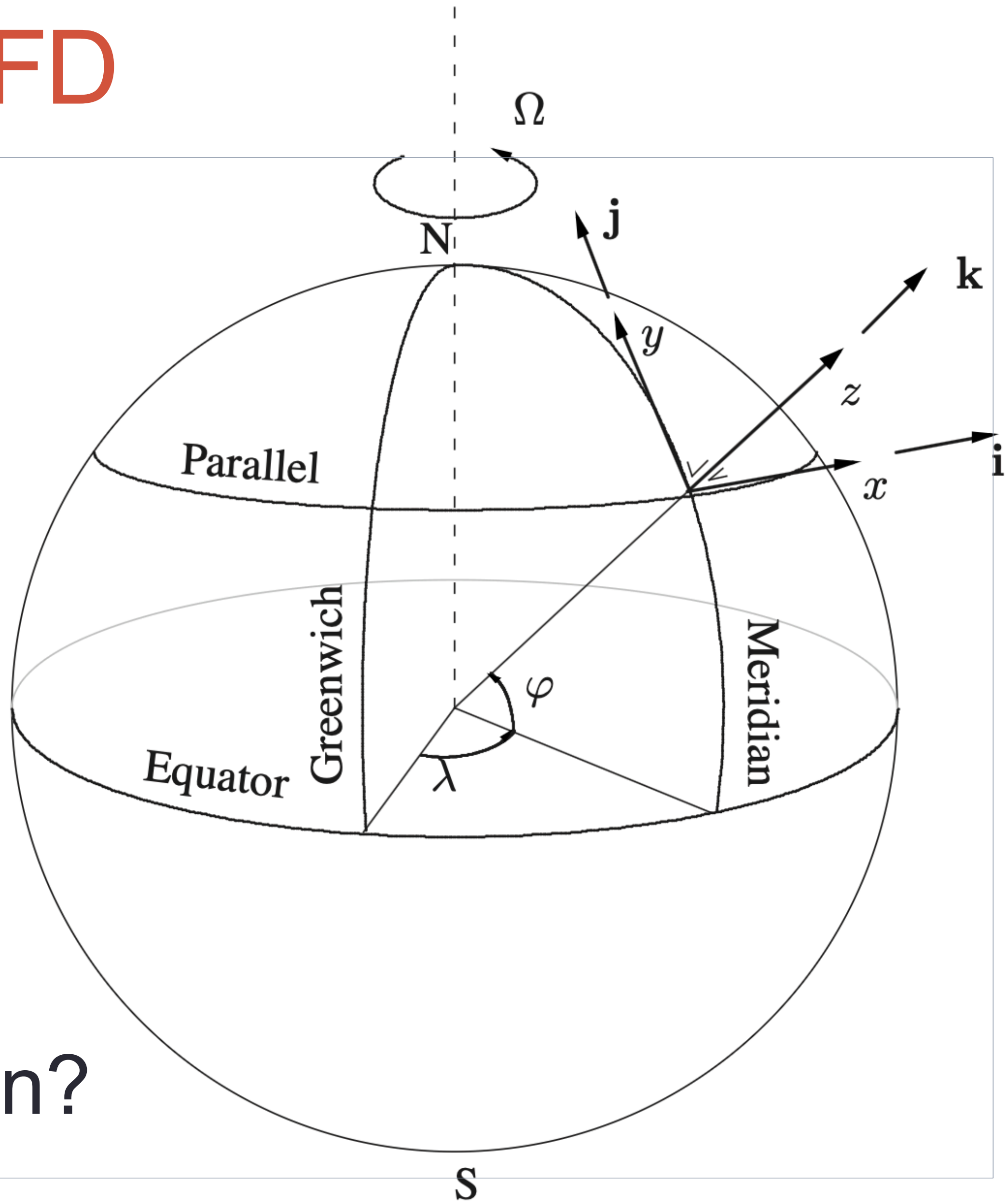
$$N^2 = -\frac{g}{\rho_0}\frac{d\rho}{dz},$$

Ingredients of GFD

For some processes, stratification can be neglected (e.g. coastal processes with well-mixed water) = **Shallow water model**

Ingredients of GFD

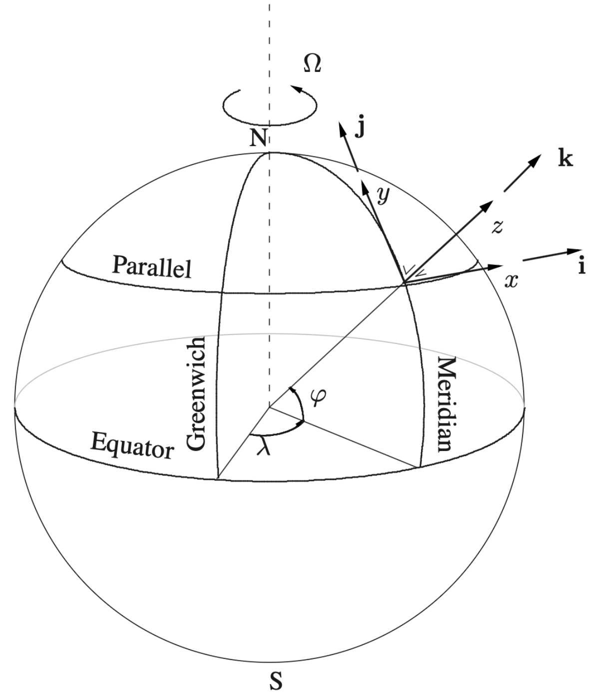
Rotation:



- Coriolis acceleration?

Ingredients of GFD

Rotation:



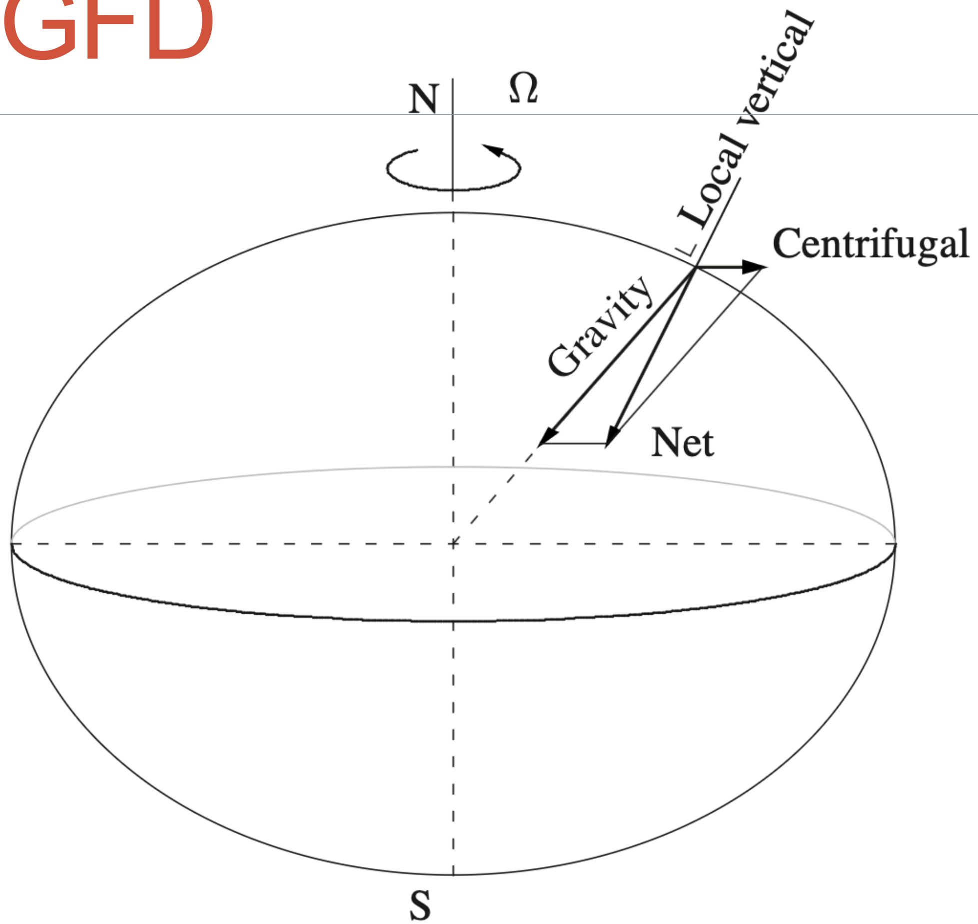
- Coriolis acceleration (or force): $2\overrightarrow{\Omega} \times \overrightarrow{v_r}$

- with the Coriolis parameter
- and the reciprocal Coriolis parameter

$$\begin{aligned} f &= 2\Omega \sin\varphi \\ f_* &= 2\Omega \cos\varphi. \end{aligned}$$

Ingredients of GFD

Rotation:



- Centrifugal force included in local gravity

Ingredients of GFD

Rotation can be neglected if $T << \frac{1}{2\Omega} = \frac{T_E}{4\pi}$ with $\frac{L}{U} = T$

So scales in which rotation effects are important :

$L = 1$ m	$U \leq 0.012$ mm/s
$L = 10$ m	$U \leq 0.12$ mm/s
$L = 100$ m	$U \leq 1.2$ mm/s
$L = 1$ km	$U \leq 1.2$ cm/s
$L = 10$ km	$U \leq 12$ cm/s
$L = 100$ km	$U \leq 1.2$ m/s
$L = 1000$ km	$U \leq 12$ m/s
$L =$ Earth radius $= 6371$ km	$U \leq 74$ m/s

Ingredients of GFD

Phenomenon	Length Scale L	Velocity Scale U	Time Scale T
Microturbulence	1–100 cm	1–10 cm/s	10–100 s
Internal waves	1–20 km	0.05–0.5 m/s	Minutes to hours
Tides	Basin scale	1–100 m/s	Hours
Coastal upwelling	1–10 km	0.1–1 m/s	Several days
Fronts	1–20 km	0.5–5 m/s	Few days
Eddies	5–100 km	0.1–1 m/s	Days to weeks
Major currents	50–500 km	0.5–2 m/s	Weeks to seasons
Large-scale gyres	Basin scale	0.01–0.1 m/s	Decades and beyond

Which Equations?

- Momentum equations (3d) $$\frac{D\vec{u}}{Dt} = \ldots$$
- Conservation of mass $$\frac{D\rho}{Dt} = \mathcal{S}_\rho$$
- Conservation of heat $$\frac{DT}{Dt} = \mathcal{S}_T$$
- Conservation of salinity $$\frac{DS}{Dt} = \mathcal{S}_S$$
- Equation of state : $$\rho = \rho(T, S, p)$$

[7 equations for the 7 variables: u,v,w,p,T,S,ρ]

Which Equations?

- Momentum equations (3d) $$\frac{D\vec{u}}{Dt} = \dots$$
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- Equation of state : $$\rho = \rho(T, S, p)$$

[7 equations for the 7 variables: u,v,w,p,T,S,ρ]

Equations for momentum/mass?

- Navier-Stokes Equations (NS)
- Non-hydrostatic Primitive Equations (NH)
- Hydrostatic Primitive Equations (PE)
- Shallow-water (SW)
- Quasi-geostrophic (QG)
- 2D Euler equations
- Etc.

Type of models

- DNS = Direct Numerical Simulation
- LES = Large Eddy Simulation
- PE = Primitive Equations models
- SW = Shallow-Water models
- SQG = Surface Quasi-Geostrophic models
- QG = Quasi-Geostrophic models
- Etc.

Navier Stokes

PE

SW

SQG

QG

CFD

Process studies

Ocean Circulation Models

Idealized models

Equations for momentum/mass?

Navier-Stokes Equations (with rotation + forcings):

$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \overrightarrow{\nabla} \vec{u} + 2\overrightarrow{\Omega} \times \vec{u} + g\vec{k} = -\frac{\overrightarrow{\nabla} P}{\rho} + \nu \nabla^2 \vec{u} + \overrightarrow{\mathscr{F}}$$

Momentum equations

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot \rho \vec{u} = 0$$

Mass conservation
(no source/sink)

Equations for momentum/mass?

Navier-Stokes Equations (with rotation + forcings):

$$\boxed{\frac{\partial \vec{u}}{\partial t}} + \boxed{\vec{u} \cdot \vec{\nabla} \vec{u}} + \boxed{2\vec{\Omega} \times \vec{u}} + \boxed{g\vec{k}} = \boxed{-\frac{\vec{\nabla} P}{\rho}} + \boxed{\nu \nabla^2 \vec{u}} + \boxed{\vec{\mathcal{F}}}$$

Time variation | Advection (inertia) | Rotation | Gravity | Pressure gradient | Viscosity | Forcings

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot \rho \vec{u} = 0$$

Mass conservation
(no source/sink)

Equations for momentum/mass?

Boussinesq Approximation:

Density perturbations small compared to mean background value:

$$\rho = \rho_0 + \rho' \qquad\qquad \rho' << \rho_0$$

Linearize all terms involving a product with density,

except the gravity term which is already linear:

$$\begin{aligned} \rho\vec{u} \quad &\rightarrow \quad \rho_0\vec{u} \\ \rho g \quad &\rightarrow \quad \rho g \end{aligned}$$

Equations for momentum/mass?

Boussinesq Approximation :

[+ incompressibility or adiabatic]

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot \rho \vec{u} = 0$$

$$\Big\downarrow \quad \text{Continuity equation}$$

$$\vec{\nabla} \cdot \vec{u} = 0$$

Equations for momentum/mass?

Non hydrostatic boussinesq (NH):

$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \overrightarrow{\nabla} \vec{u} + 2\overrightarrow{\Omega} \times \vec{u} + \frac{\rho}{\rho_0} g\vec{k} = -\frac{\overrightarrow{\nabla} P}{\rho_0} + \nu \nabla^2 \vec{u} + \overrightarrow{\mathscr{F}}$$

$$\vec{\nabla} \cdot \vec{u} = 0$$

Easier to solve than Navier-Stokes, but still requires to invert a 3d elliptic equation for P (computationally expansive)

Equations for momentum/mass?

Hydrostatic balance:

The vertical component of the Boussinesq momentum equations is

$$\frac{\partial w}{\partial t} + \vec{u} \cdot \vec{\nabla} w - 2\Omega cos\phi u + \boxed{\frac{\rho}{\rho_0} g = -\frac{\partial_z P}{\rho_0}} + \nu \nabla^2 w + \mathscr{F}_w$$

For long horizontal motions (L >> H) the dominant balance is

H ~10 m
L ~ 1 km

$$\frac{\partial P}{\partial z} = -\rho g$$

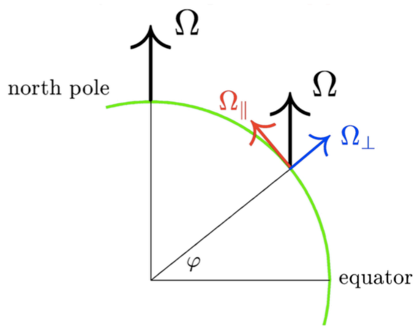
Such that pressure is just a vertical integral:

$$P = \int_z^\eta g \rho dz$$

Equations for momentum/mass?

Traditional approximation

= neglect horizontal Coriolis term



$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \vec{\nabla} \vec{u} + 2\overrightarrow{\Omega} \times \vec{u} + g\vec{k} = -\frac{\vec{\nabla} P}{\rho} + \nu \nabla^2 \vec{u} + \overrightarrow{\mathscr{F}}$$

$$\downarrow$$

$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \vec{\nabla} \vec{u} + f\vec{k} \times \vec{u} + g\vec{k} = -\frac{\vec{\nabla} P}{\rho} + \nu \nabla^2 \vec{u} + \overrightarrow{\mathscr{F}}$$

Equations for momentum/mass?

Hydrostatic Primitive Equations (PE)

- 2d momentum with Boussinesq approximation:

$$\frac{\partial u}{\partial t} + \vec{u} \cdot \vec{\nabla} u - fv = -\frac{\partial_x P}{\rho_0} + \nu \nabla^2 u + \mathscr{F}_u$$

$$\frac{\partial v}{\partial t} + \vec{u} \cdot \vec{\nabla} v + fu = -\frac{\partial_y P}{\rho} + \nu \nabla^2 v + \mathscr{F}_v$$

- Hydrostatic: $$\frac{\partial P}{\partial z} = -\rho g$$

- Continuity equation for an incompressible fluid: $\vec{\nabla} \cdot \vec{u} = 0$

Equations for PE Ocean Models

Hydrostatic Primitive Equations (PE)

- 2d momentum with Boussinesq approximation:

$$\frac{\partial u}{\partial t} + \vec{u} \cdot \vec{\nabla} u - fv = -\frac{\partial_x P}{\rho_0} + \nu \nabla^2 u + \mathscr{F}_u$$

$$\frac{\partial v}{\partial t} + \vec{u} \cdot \vec{\nabla} v + fu = -\frac{\partial_y P}{\rho} + \nu \nabla^2 v + \mathscr{F}_v$$

- Hydrostatic: $\frac{\partial P}{\partial z} = -\rho g$
- Continuity equation for an incompressible fluid: $\vec{\nabla} \cdot \vec{u} = 0$
- Conservation of heat and salinity $\frac{DT}{Dt} = \mathcal{S}_T \qquad \frac{DS}{Dt} = \mathcal{S}_S$
- Equation of state : $\rho = \rho(T, S, z)$

Ex: Geostrophic balance

$$
\begin{aligned}
\cancel{\frac{\partial u}{\partial t} + \vec{u} \cdot \vec{\nabla} u} \boxed{- f v = - \frac{\partial_x P}{\rho_0}} \cancel{+ \nu \nabla^2 u + \mathscr{F}_u} \\
\cancel{\frac{\partial v}{\partial t} + \vec{u} \cdot \vec{\nabla} v} \boxed{+ f u = - \frac{\partial_y P}{\rho}} \cancel{+ \nu \nabla^2 v + \mathscr{F}_v}
\end{aligned}
$$

Ex: Linear Gravity waves

$$\frac{\partial u}{\partial t} + \vec{u} \cdot \vec{\nabla} u - f v = -\frac{\partial_x P}{\rho_0} + \nu \nabla^2 u + \mathscr{F}_u$$

$$\frac{\partial v}{\partial t} + \vec{u} \cdot \vec{\nabla} v + f u = -\frac{\partial_y P}{\rho} + \nu \nabla^2 v + \mathscr{F}_v$$

Ex: Linear Inertia-Gravity waves

$$\frac{\partial u}{\partial t} + \cancel{\vec{u} \cdot \vec{\nabla} u} - fv = -\frac{\partial_x P}{\rho_0} + \cancel{\nu \nabla^2 u + \mathscr{F}_u}$$

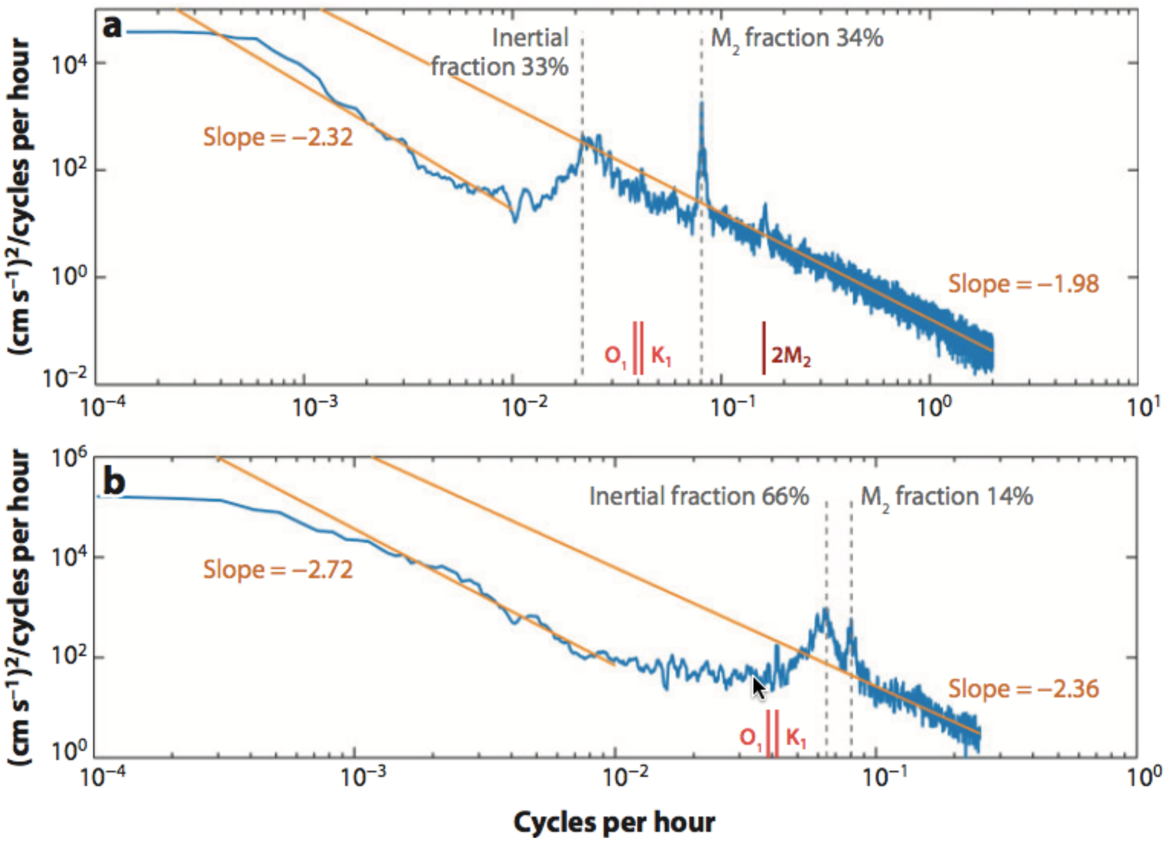
$$\frac{\partial v}{\partial t} + \cancel{\vec{u} \cdot \vec{\nabla} v} + fu = -\frac{\partial_y P}{\rho} + \cancel{\nu \nabla^2 v + \mathscr{F}_v}$$

Ex: Inertial motions and NIW

$$\frac{\partial u}{\partial t} + \vec{u} \cdot \vec{\nabla} u - fv = -\frac{\partial_x P}{\rho_0} + \nu \nabla^2 u + \mathscr{F}_u$$

$$\frac{\partial v}{\partial t} + \vec{u} \cdot \vec{\nabla} v + fu = -\frac{\partial_y P}{\rho} + \nu \nabla^2 v + \mathscr{F}_v$$

Ex: Inertial motions and NIW



(*a*) Kinetic energy estimate for an instrument in the western North Atlantic near 15◦N at 500 m. (*b*) Power density spectral estimate from a record at 1000 m at 50.7◦S, 143◦W, south of Tasmania in the Southern Ocean

From Mackinnon 2013

Ex: Inertial motions and NIW

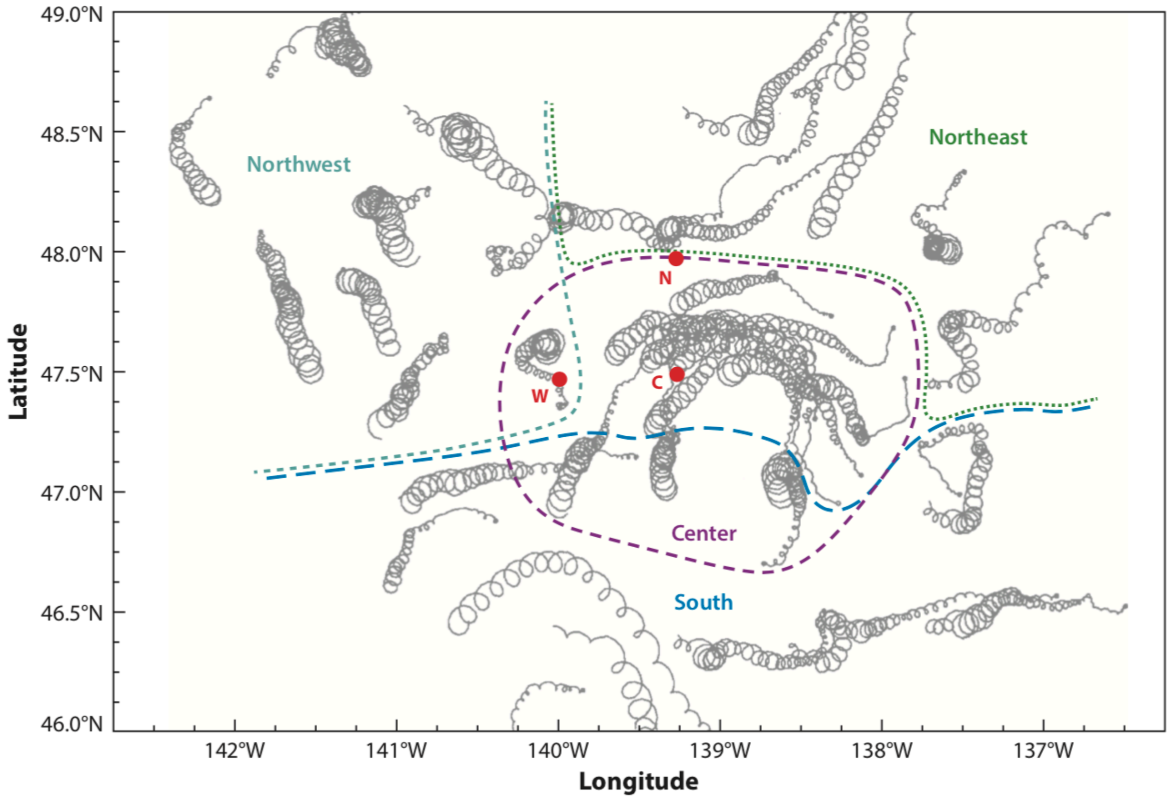
- Near-inertial frequencies are associated primarily with atmospheric forcing.

- The ocean selects near-inertial frequencies for amplification because the aspect ratio of the forcing is exceedingly small.
  - Storms tends to have horizontal scales of O(100-1000 km)
  - The ocean mixed layer is typically no deeper than 100 m
  - Storms move rapidly so that the ocean does not have time to adjust

-

Ex: Inertial motions and NIW

- NIW are recognizable by their characteristic circularly polarized velocities



3. WAVES

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3. WAVES

- 3.1. Introduction
  - 3.1.1. General properties of Wave
  - 3.1.2. Different types of ocean waves
- 3.2. Surface Gravity Waves
  - 3.2.1. Long waves
  - 3.2.2. Short waves
- 3.3. Inertia-gravity Waves
- 3.4. Coastal waves
- 3.5. Internal Waves

Bibliography

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- Whitham (1974) *: Linear and nonlinear waves*
- Cushman-Roisin*. Introduction to geophysical fluid Dynamics*
- Ardhuin (2024) *Waves in Geosciences*
- Gerkema- Zimmerman (2008). *An introduction to internal waves*
  - *http://stockage.univ-brest.fr/~gula/Ondes/gerkema.pdf*

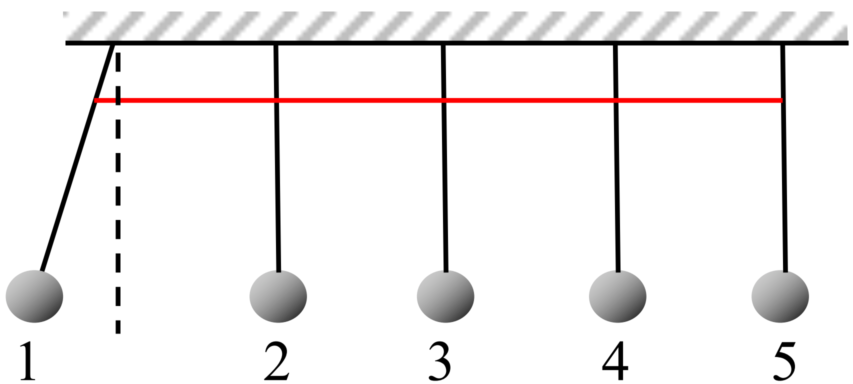
3.1.1. General properties

Definition of a wave:

- *A wave is a recognizable signal that is transferred from one part of the medium to another with a recognizable velocity of propagation. The signal may be any feature of the disturbance, such as a maximum or an abrupt change in some quantity, provided that it can be clearly recognized and its location at any time can be determined*. [Whitham: « Linear and nonlinear waves »]
-

Definition of a wave:

- *Restoring force and a continuous medium to transport oscillation*



Definition of a wave:

- *Restoring force and a continuous medium to transport oscillation*

3.1.1 General properties

- Mathematically two main classes of waves:

Hyperbolic waves and **dispersive waves**

Hyperbolic waves

1. Hyperbolic waves are formulated in terms of hyperbolic partial differential equations, for example:

$$\eta_t + c\nabla\eta = 0 \qquad\qquad \eta_{tt} - c^2\nabla^2\eta = 0$$

Hyperbolic waves

1. Hyperbolic waves are formulated in terms of hyperbolic partial differential equations, for example:

$$\eta_t + c\nabla\eta = 0 \qquad\qquad \eta_{tt} - c^2\nabla^2\eta = 0$$

- With general solutions in the form:

$$\eta = f(x - ct) \qquad\qquad \eta = f(x - ct) + g(x + ct)$$

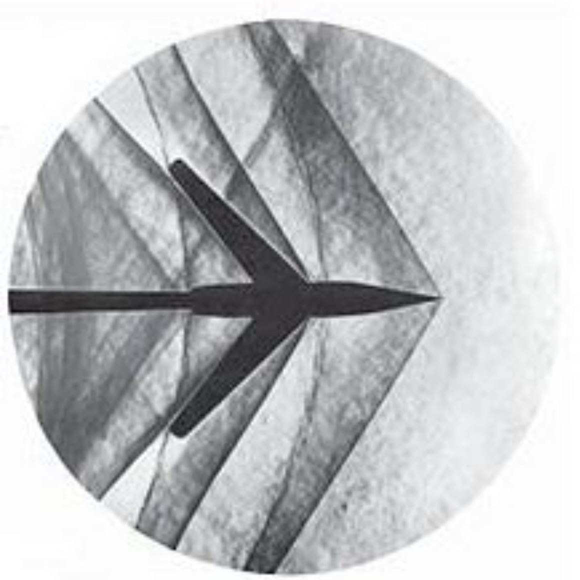
- Very frequent in acoustics, elasticity, electromagnetism, etc.

Hyperbolic waves

1. Examples of **Hyperbolic waves**

- Flood wave, tidal bores

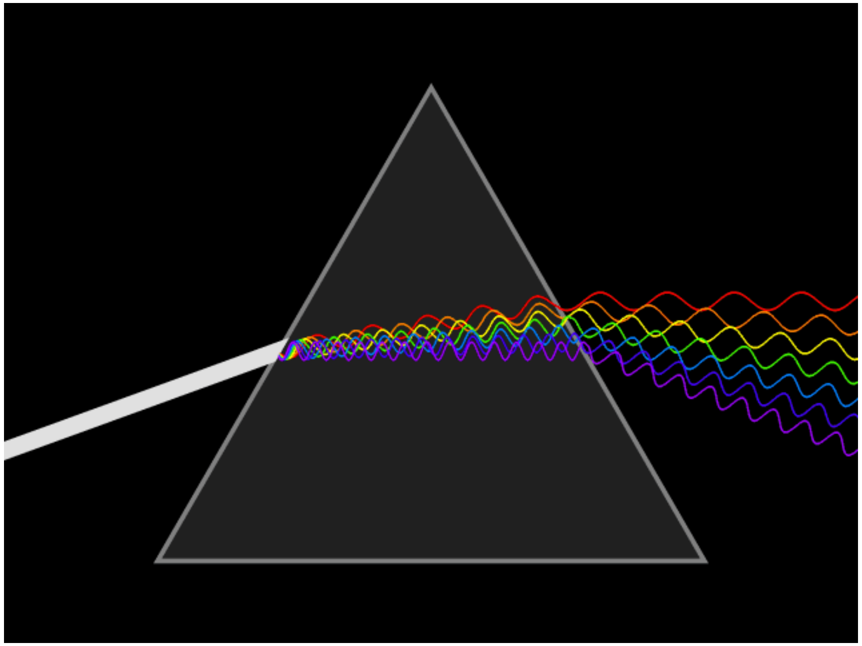
- Shock wave



Dispersive waves

- **Dispersive waves** come from a variety of PDEs and are characterised by their dispersion relation $\omega = f(k, \text{environment})$, with ω their frequency and k their wavenumber. They are observed as the superposition of waves where the Fourier components (corresponding to specific ω) propagate at different speeds.

The wave (phase) speed is $c_\phi = \dfrac{\omega}{k}$ and the group speed is $c_g = \dfrac{\partial \omega}{\partial k}$.



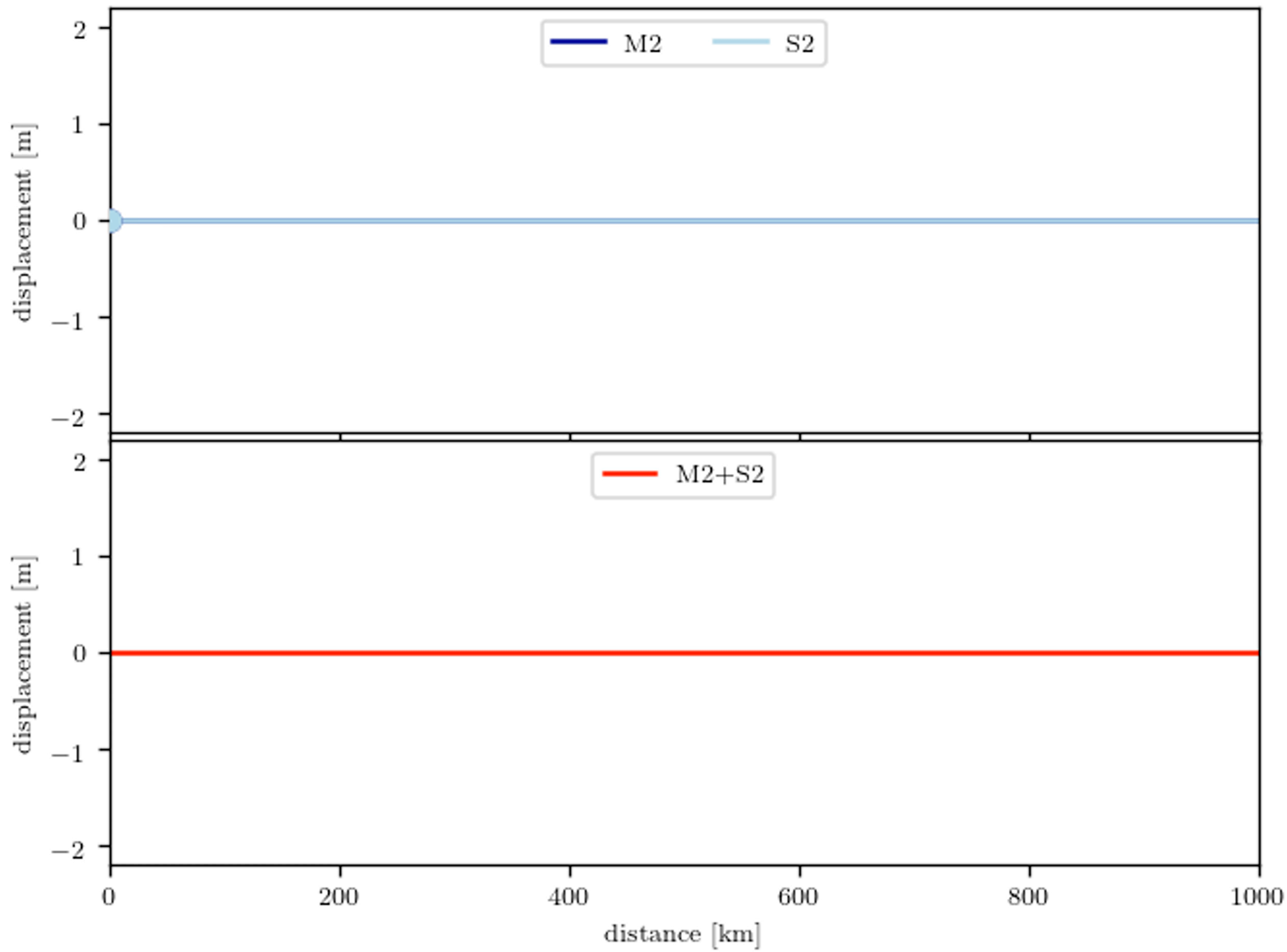
Dispersive waves

- **Dispersive waves** in the ocean: superposition of tidal waves,

  "M2 wave" (M=Moon): $\eta_{M2} = A_{M2} \exp\left(i(\omega_{M2}t - k_{M2}x)\right)$

  "S2 wave" (S=Sun): $\eta_{S2} = A_{S2} \exp\left(i(\omega_{S2}t - k_{S2}x)\right)$

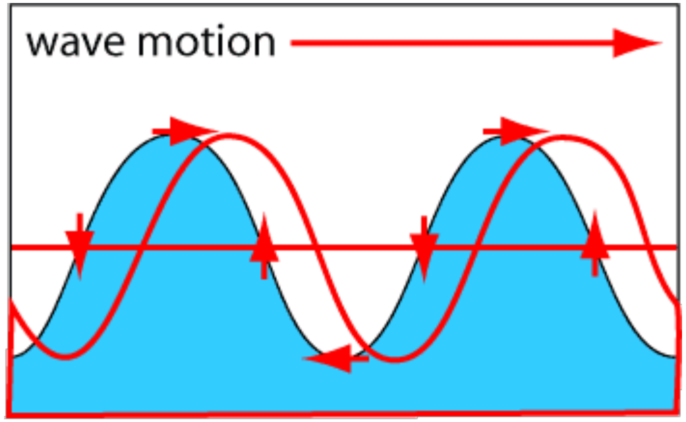
3.1.1 General properties



Ocean Waves

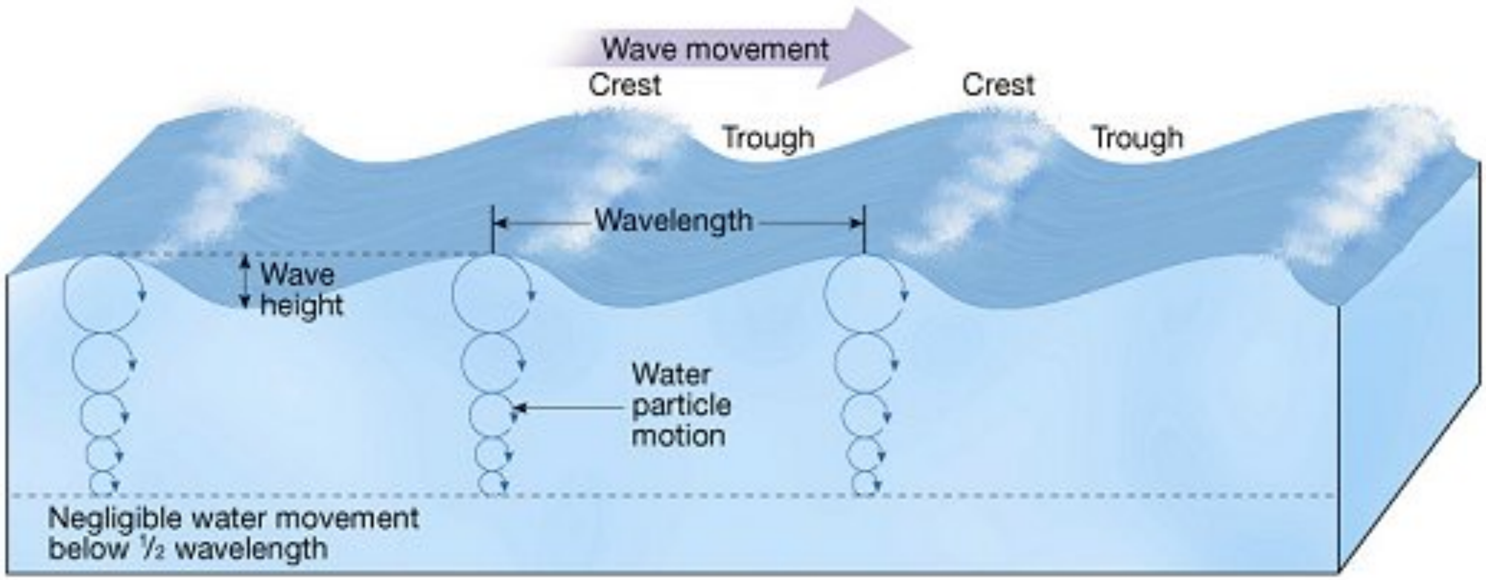
- A wave results when fluid is displaced from a position of equilibrium.

- The restoration of the fluid to equilibrium will produce a movement of the fluid back and forth, called a wave orbit.

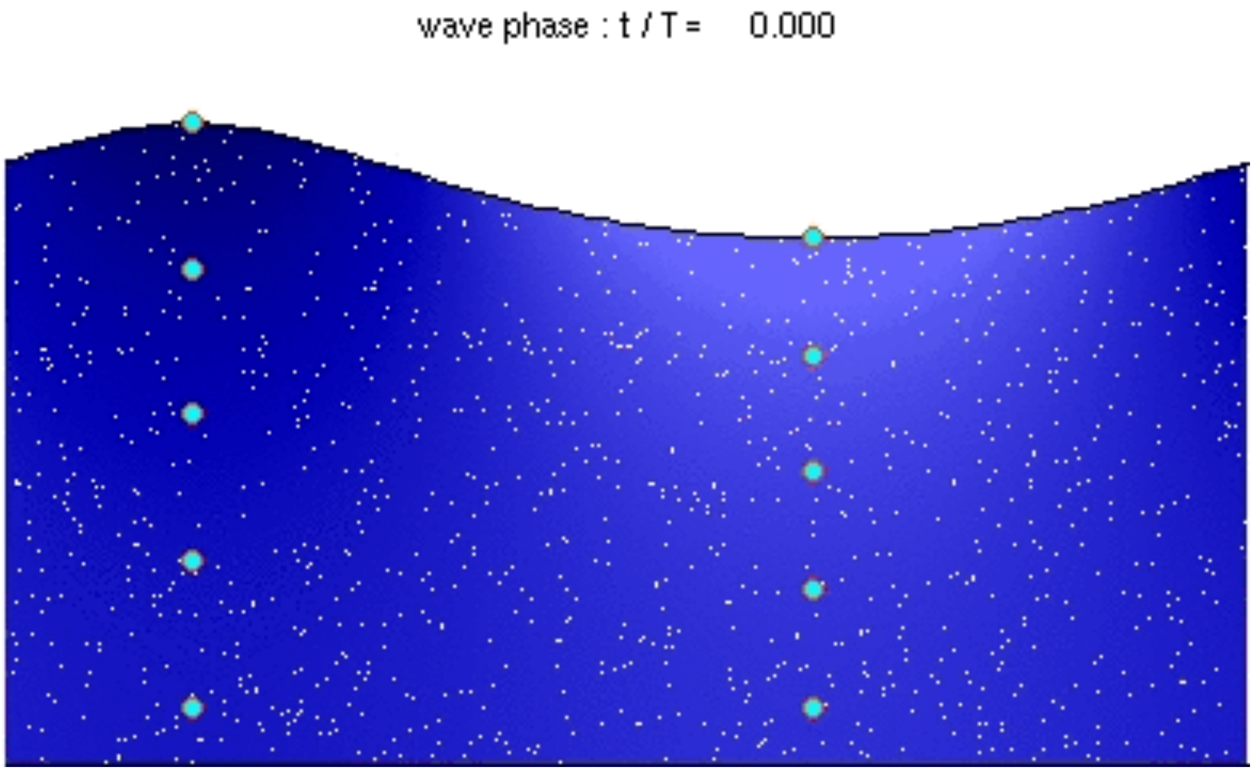


Ocean Waves

- Waves propagates energy but do not transport water



Ocean Waves



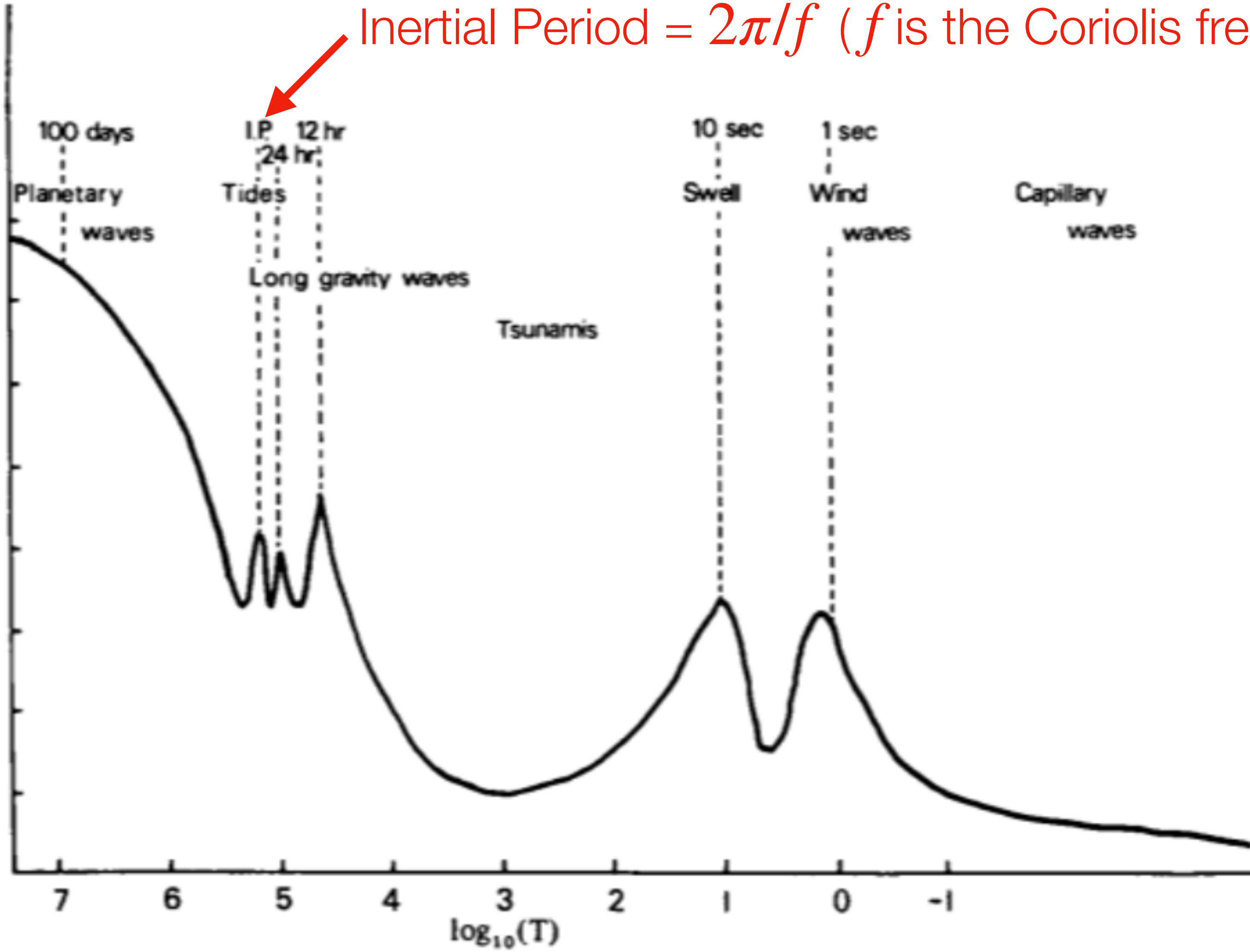
A **nonlinear wave** also carries energy and can lead to a net transport of material (for example, Stokes drift at the ocean surface)

Animation from https://en.wikipedia.org/wiki/Wind_wave

3.1.2 Ocean Waves

Ocean Waves

Inertial Period = $2\pi/f$ (f is the Coriolis frequency)



Schematic energy spectrum of ocean variability [Leblond & Mysak]

Ocean Waves

Different type of waves are classified on the basis of:

- Disturbing force
- Restoring force
- Properties: wavelength, frequency, amplitude, …
- Freely propagating vs forced wave

3.1.2 Ocean Waves

Type of waves	Disturbing force	Restoring force	Horizontal wavelength	Period
Acoustic wave				
Capillary wave				
Surface gravity wave				
Rossby wave				
Kelvin wave				
Internal wave				

3.1.2 Ocean Waves

Type of waves	Disturbing force	Restoring force	Horizontal wavelength	Period
Acoustic wave	Any motion	Pressure (compressibility)	1 mm - 10 km	< 1 s
Capillary wave				
Surface gravity wave				
Rossby wave				
Kelvin wave				
Internal wave				

3.1.2 Ocean Waves

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Surface gravity wave				
Rossby wave				
Kelvin wave				
Internal wave				

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Surface gravity wave	Wind, boat, earthquake, …	Gravity	1 cm - 100 km	1 s - 1 day
Rossby wave				
Kelvin wave				
Internal wave				

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Kelvin wave				
Internal wave				

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Kelvin wave	Atmospheric forcing	Pressure gradient + Coriolis	10 km - 100 km	Days - months
Internal wave				

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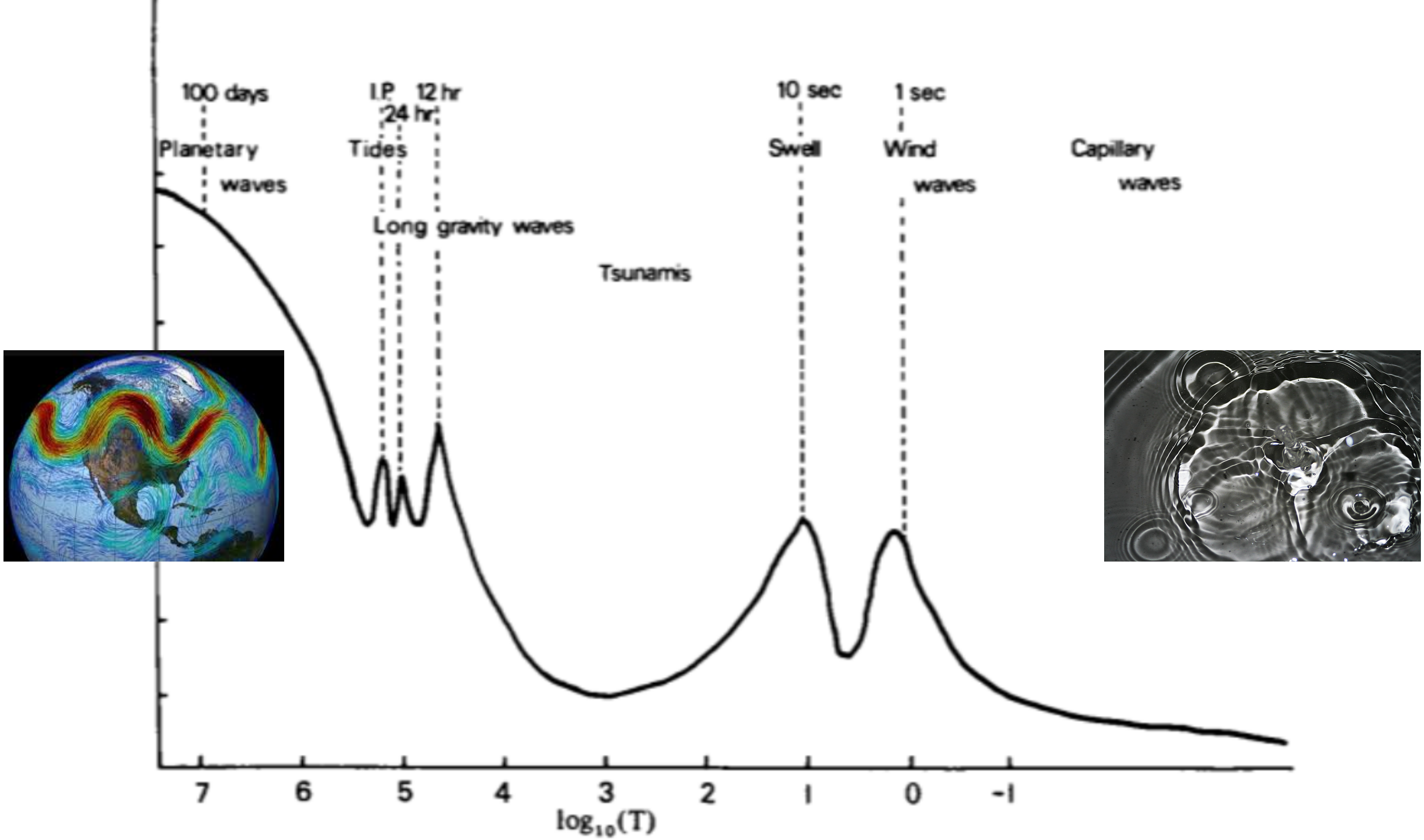
Kelvin wave	Atmospheric forcing	Pressure gradient + Coriolis	10 km - 100 km	Days - months
Internal wave	Tides, winds, current instability, …	Gravity (stratification) + Coriolis	1 m - 100 km	10 s - 1 day

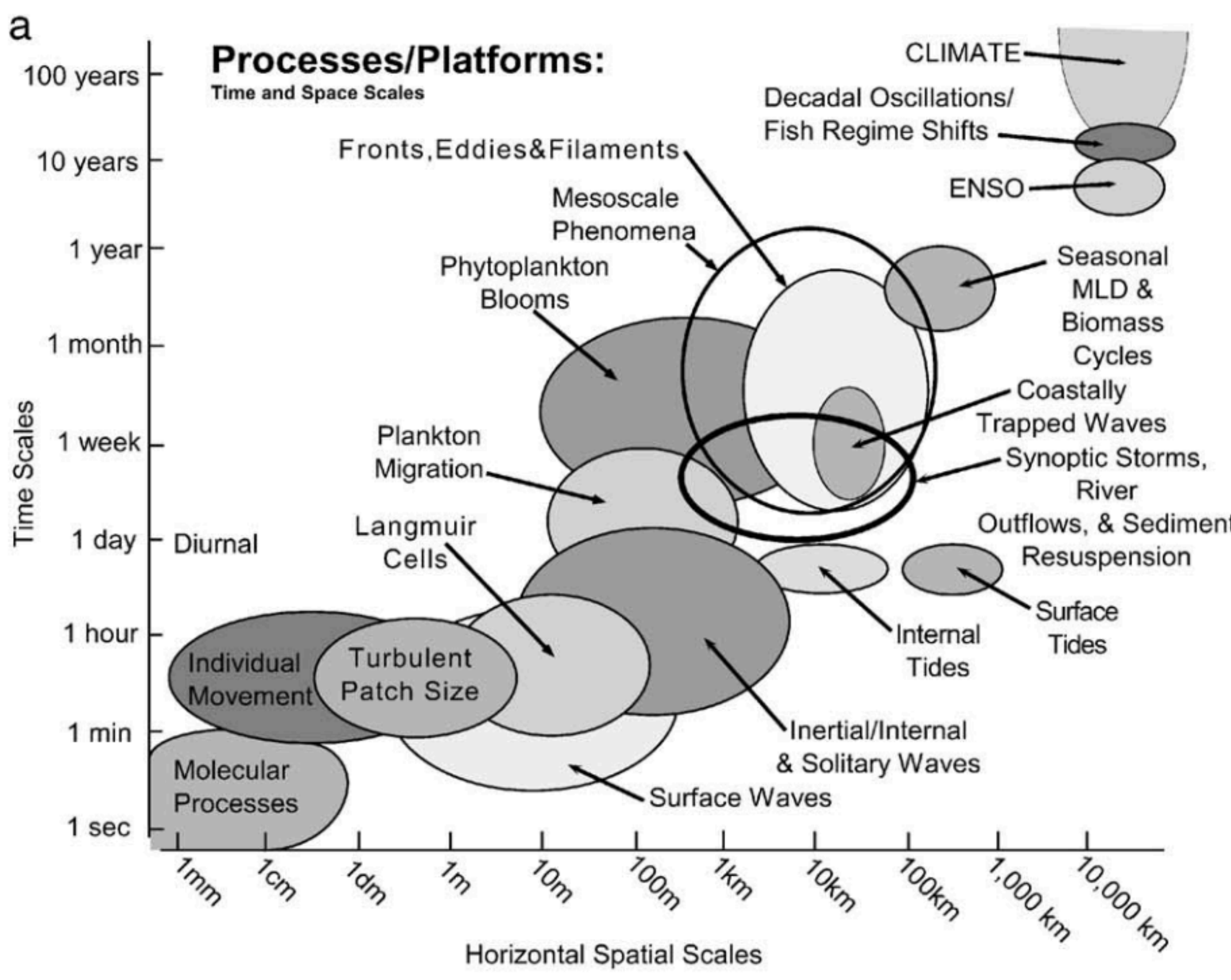
3.1.2 Ocean Waves

Ocean Waves



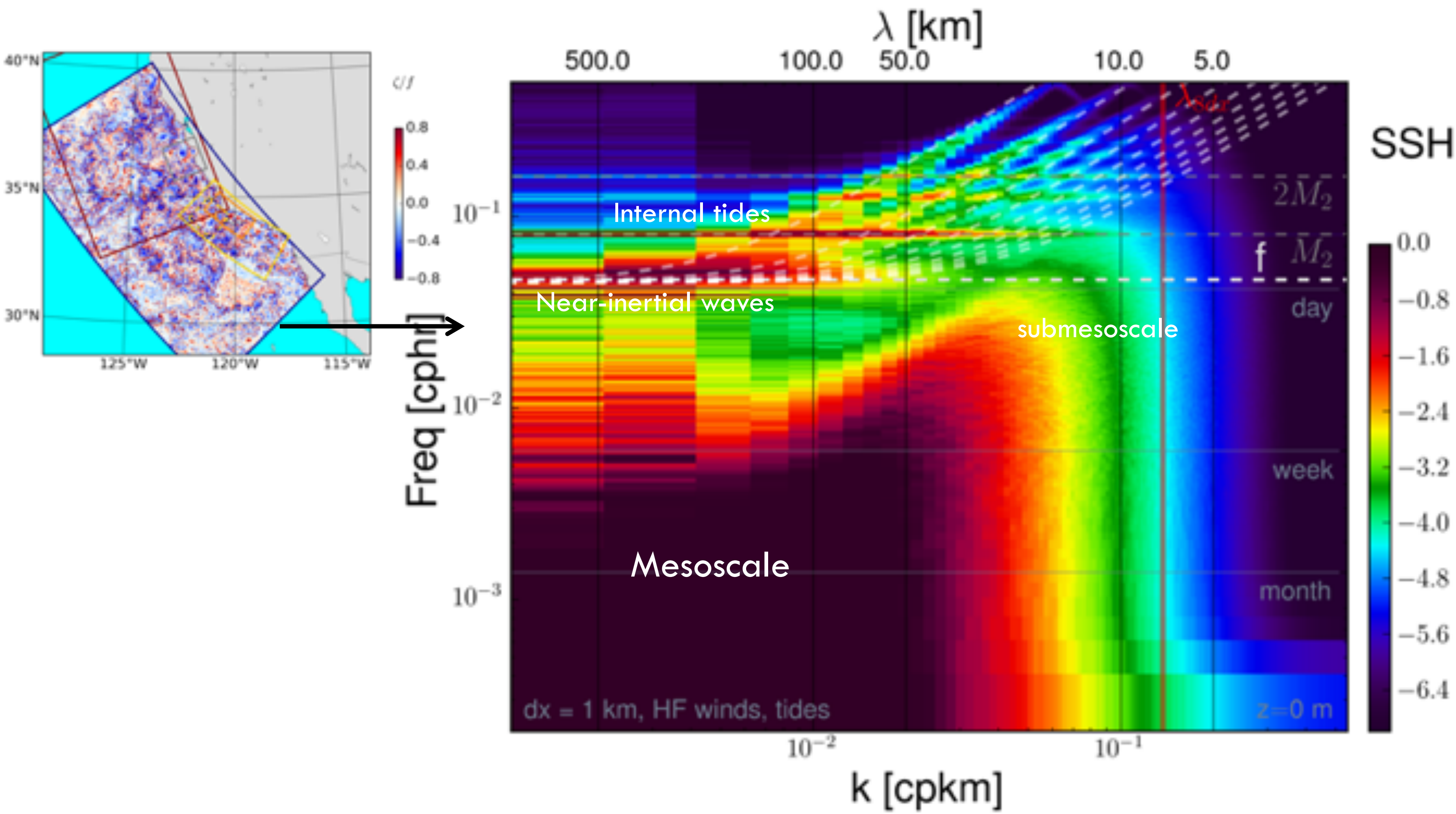
Schematic energy spectrum of ocean variability [Leblond & Mysak]

Ocean Waves


a
Processes/Platforms:
Time and Space Scales
100 years
10 years
1 year
1 month
1 week
1 day
1 hour
1 min
1 sec
Time Scales
Diurnal
CLIMATE
Decadal Oscillations/
Fish Regime Shifts
ENSO
Fronts, Eddies & Filaments
Mesoscale
Phenomena
Phytoplankton
Blooms
Seasonal
MLD &
Biomass
Cycles
Coastally
Trapped Waves
Synoptic Storms,
River
Outflows, & Sediment
Resuspension
Plankton
Migration
Langmuir
Cells
Internal
Tides
Surface
Tides
Individual
Movement
Turbulent
Patch Size
Inertial/Internal
& Solitary Waves
Molecular
Processes
Surface Waves
1mm
1cm
1dm
1m
10m
100m
1km
10km
100km
1,000 km
10,000 km
Horizontal Spatial Scales

3.1.2 Ocean Waves

Ocean Waves



Azimuthally-averaged 2D frequency-wavenumber spectra for SSH in California Current

3. WAVES

3.1. Introduction

3.1.1. General properties of Wave

3.1.2. Different types of ocean waves

3.2. Surface Gravity Waves

3.2.1. Long waves

3.2.2. Short waves

3.3. Inertia-gravity Waves

3.4. Coastal waves

3.5. Internal Waves

3.2 Surface Gravity Waves

3.2 Surface Gravity Waves

3.2 Surface Gravity Waves

Short waves

Long waves

Type	Period	Wavelength	Main Forcing
Capillary–Gravity	< 0.1 s	~cm	Wind, surface tension
Wind waves	1–10 s	m–100 m	Local wind
Swell	10–30 s	100–500 m	Remote wind
Infragravity	30–300 s	100s m–km	Wave–wave interaction
Seiche	minutes–hours	Basin-scale	Resonance
Tsunami	10 min–hours	100–200 km	Seismic, landslides
Storm surge	hours–days	Basin-scale	Wind + pressure
Tide	12–24 h	Ocean-basin	Moon & Sun gravity

3.2 Surface Gravity Waves

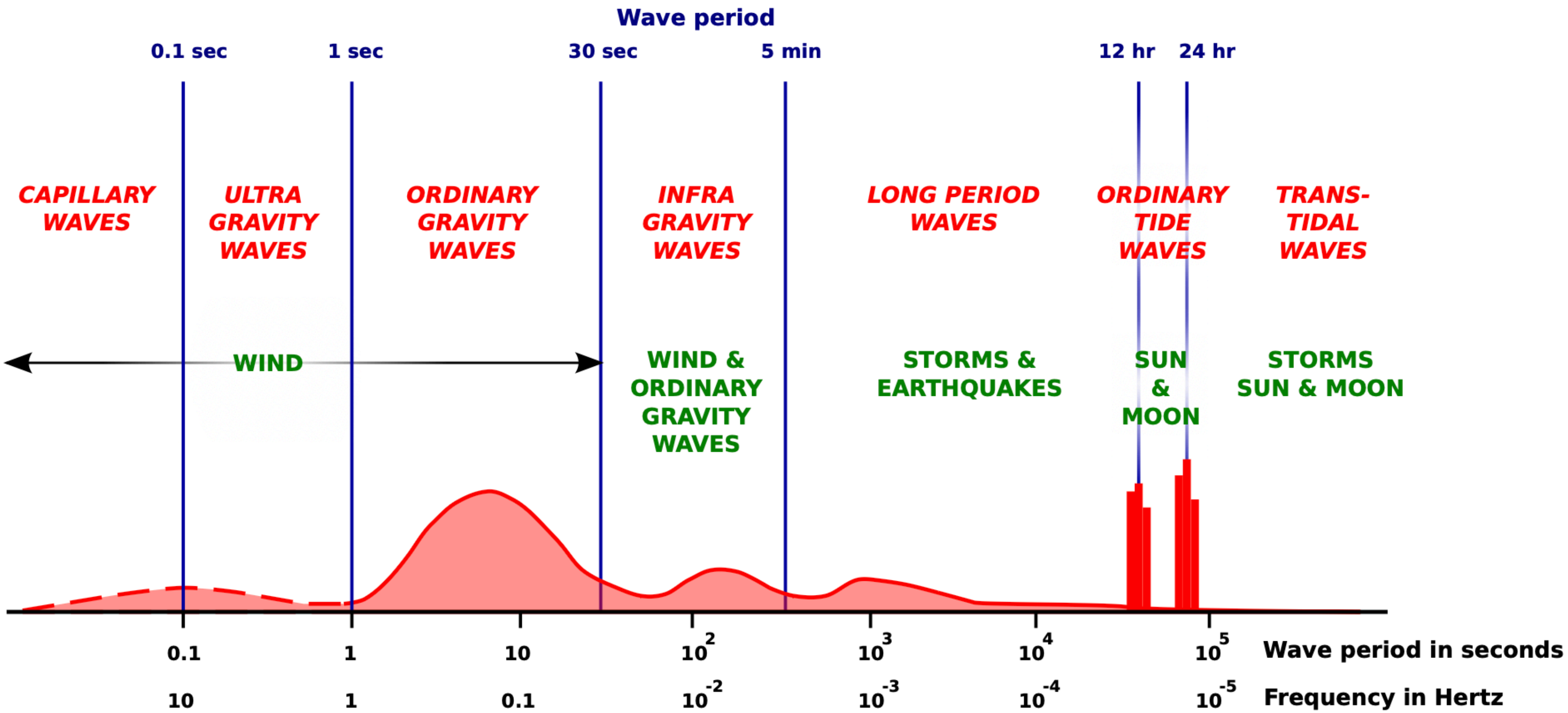


Figure 1.1: Classification of ocean surface waves with usual names in red, as a function of wave periods (x-axis), with dominant forcing mechanisms in green. Adapted from Munk (1950).

3. WAVES

- 3.1. Introduction
  - 3.1.1. General properties of Wave
  - 3.1.2. Different types of ocean waves
- 3.2. Surface Gravity Waves
  - **3.2.1. Long waves**
  - 3.2.2. Short waves
- 3.3. Inertia-gravity Waves
- 3.4. Coastal waves
- 3.5. Internal Waves

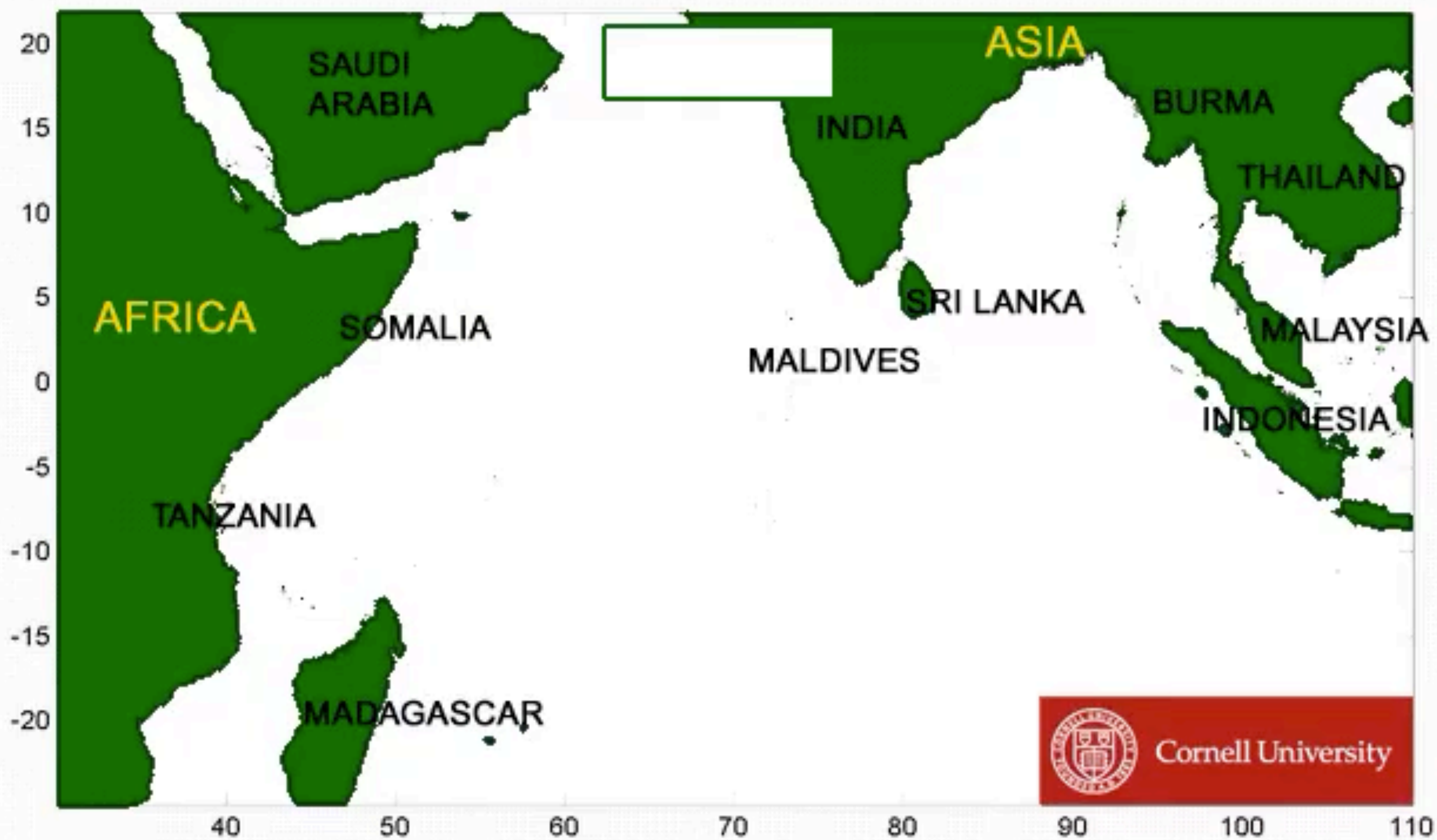
3.2.1 Long waves

3.2.1 Long waves

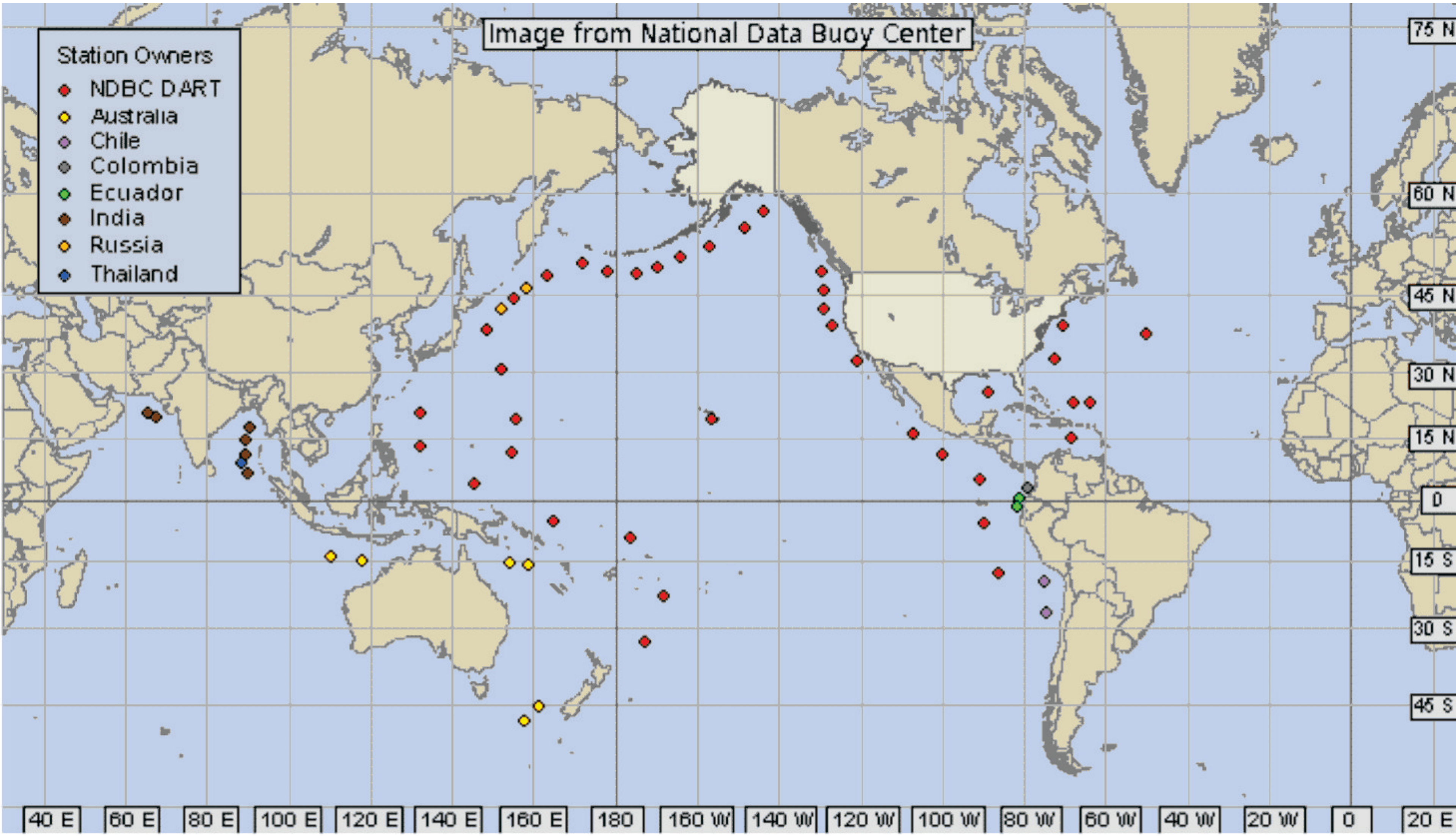
Example of long waves:

- **Tsunamis**
- **Tidal bores**

3.2.1 Long waves

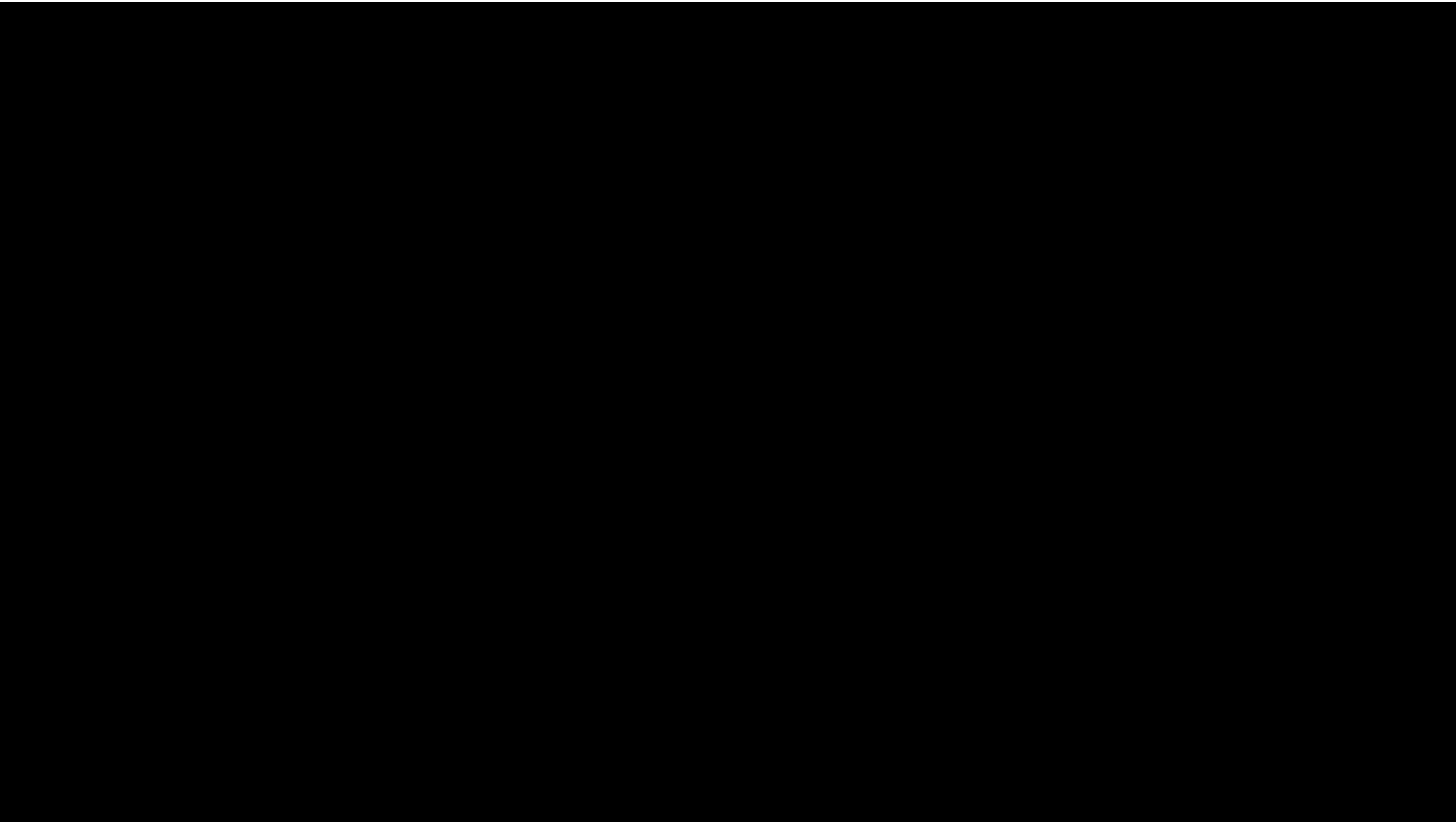


3.2.1 Long waves



Tsunami detection buoys have been placed around many tectonically active locations. M
Map is from NOAA Tsunami Detection website http://www.ndbc.noaa.gov/dart.shtml

3.2.1 Long waves



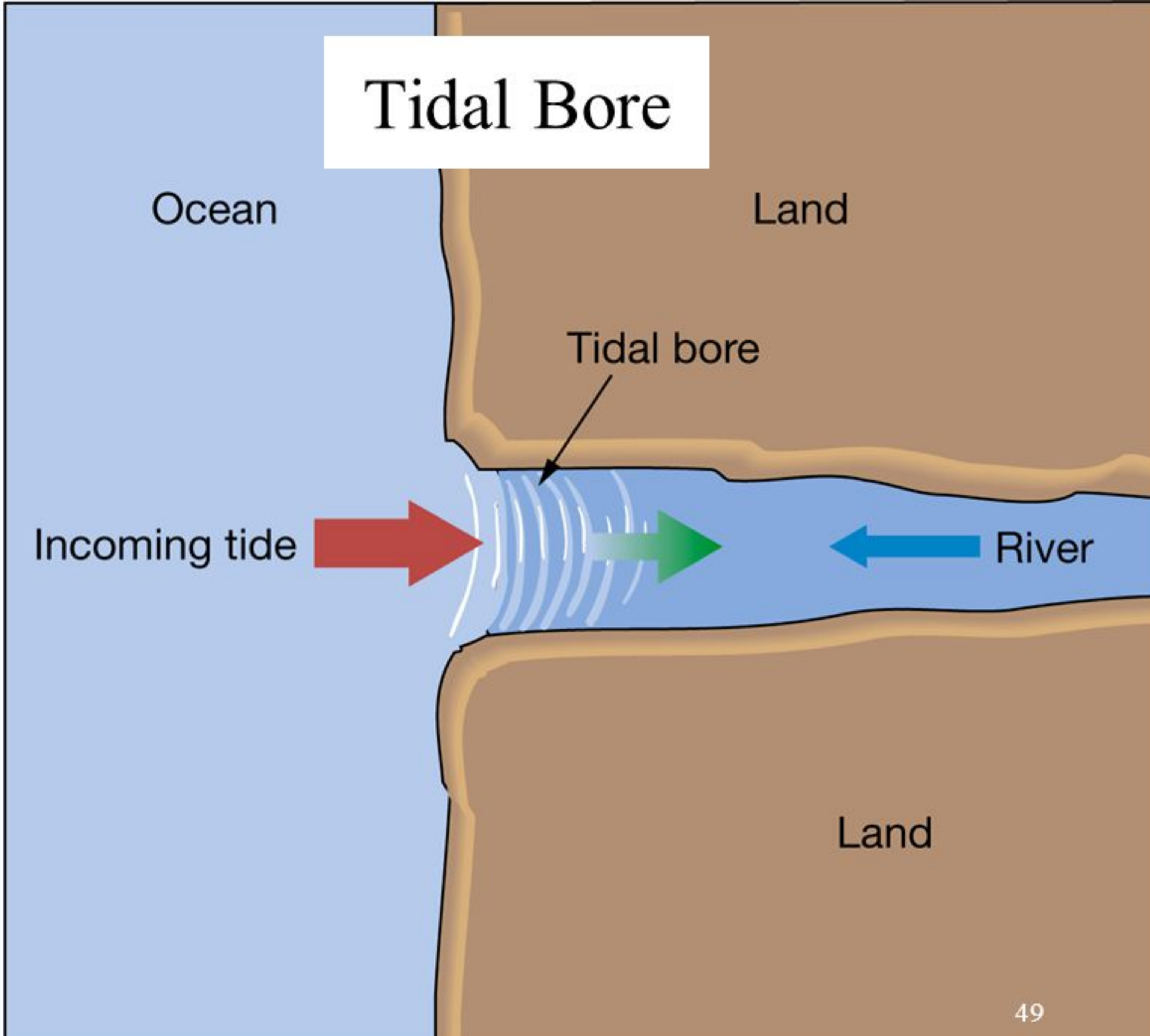
3.2.1 Long waves

Example of long waves:

- **Tsunamis**
- **Tidal bores**

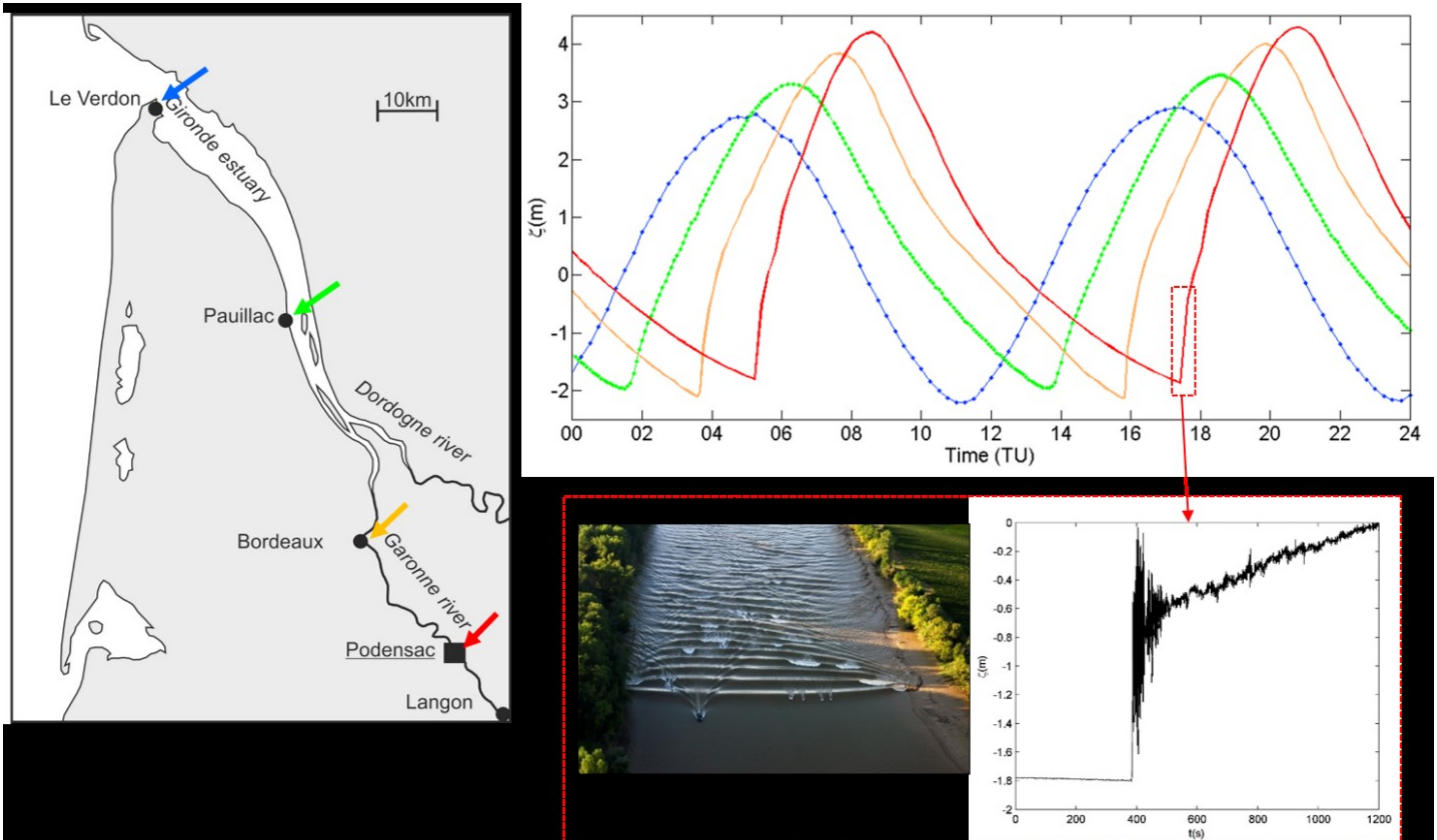
A tidal bore is a wall of water that surges upriver with the advancing high tide.

Tidal Bore



3.2.1 Long waves

Tidal bores

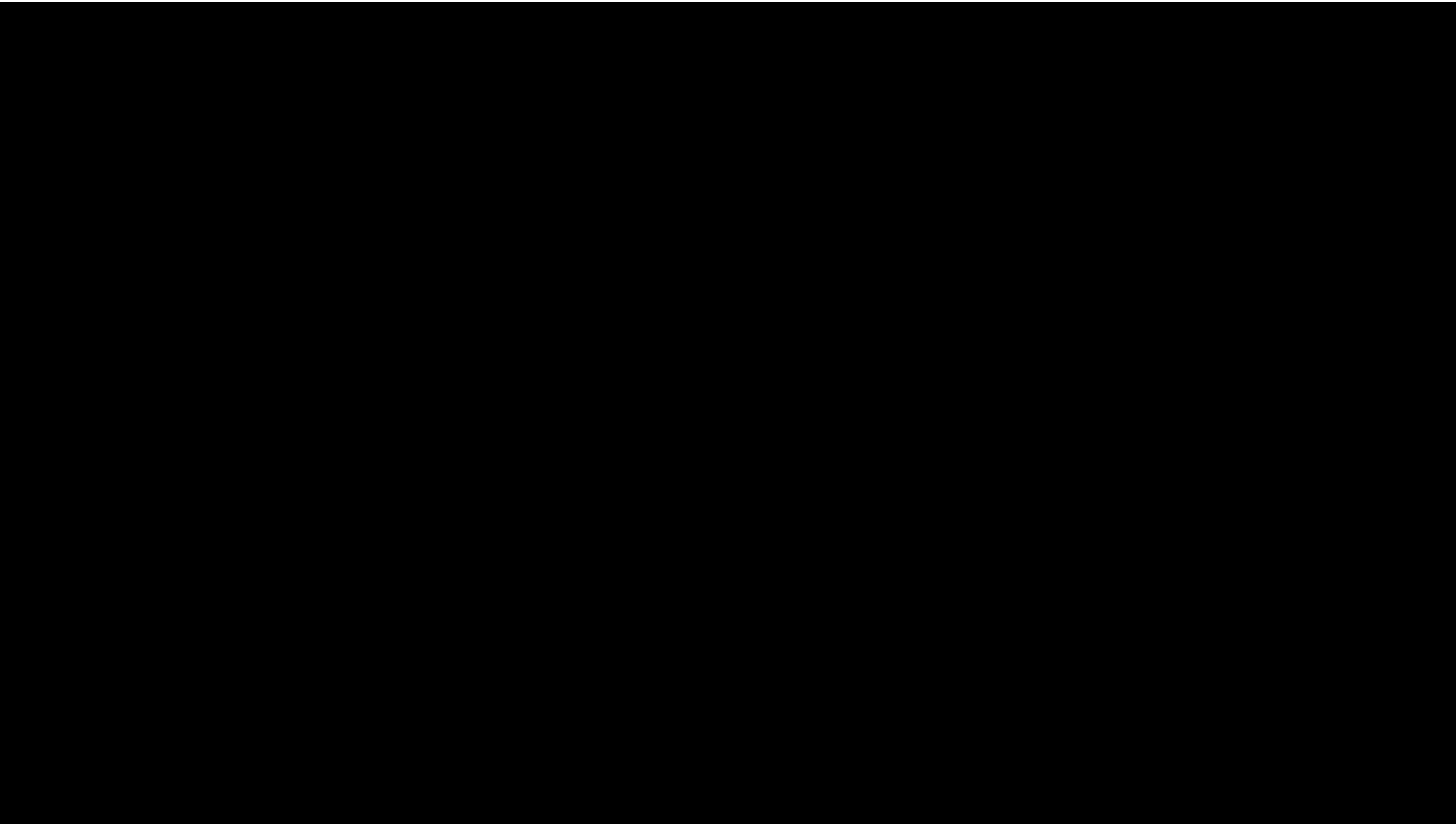


3.2.1 Long waves

3.2.1 Long waves

A group of surfers ride the bore tide at Alaska's Turnagain Arm in July 2014. Alaska's most famous bore tide occurs here in the lower arm of the Cook Inlet where waves can reach 6 to 10 feet (1.8 to 3 meters) tall and move at 10 to 15 mph (16 to 24 kph).

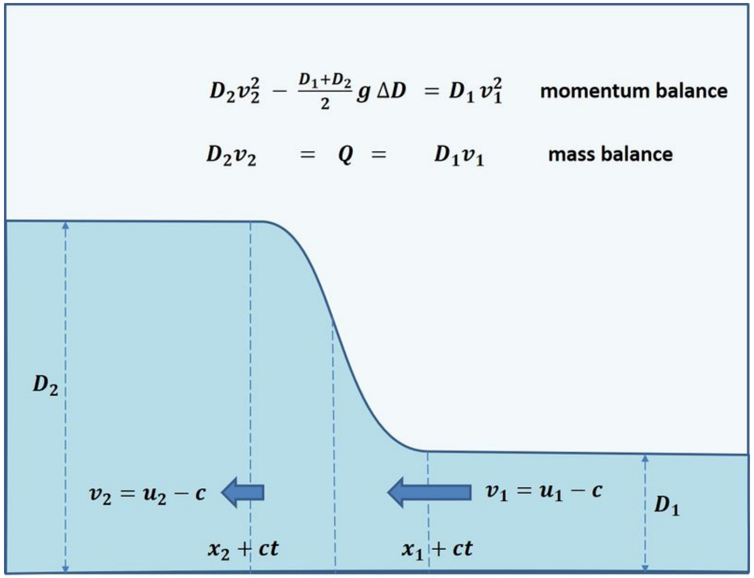
3.2.1 Long waves



3.2.1 Long waves

Tidal bores

Tidal bores are non-linear and require non linear shallow water equations.



Solutions of the propagation of a bore/solution can described by a Korteweg-deVries (KdV) type equation:

$$\partial_t u + \partial_x^3 u + 6u\partial_x u = 0$$