OCEAN WAVES

INTRODUCTION

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- **Lesson 1 :**
  - Introduction about Ocean waves
  - Surface waves
  - Internal Waves (Introduction)
  - Internal Waves in the 2-layer shallow-water model

- **Lesson 2 :**
  - Internal Waves with a continuous stratification

- **Lesson 3 :**
  - Generation of internal waves

- **Lesson 4 :**
  - Dissipation and interaction of internal waves
  - Activities: Numerical simulation of internal waves

Presentations and material will be available at :

jgula.fr/Ondes/

Useful references

- *The course is largely based on:*
  - Gerkema- Zimmerman (2008). *An introduction to internal waves* https://www.jgula.fr/Ondes/gerkema.pdf

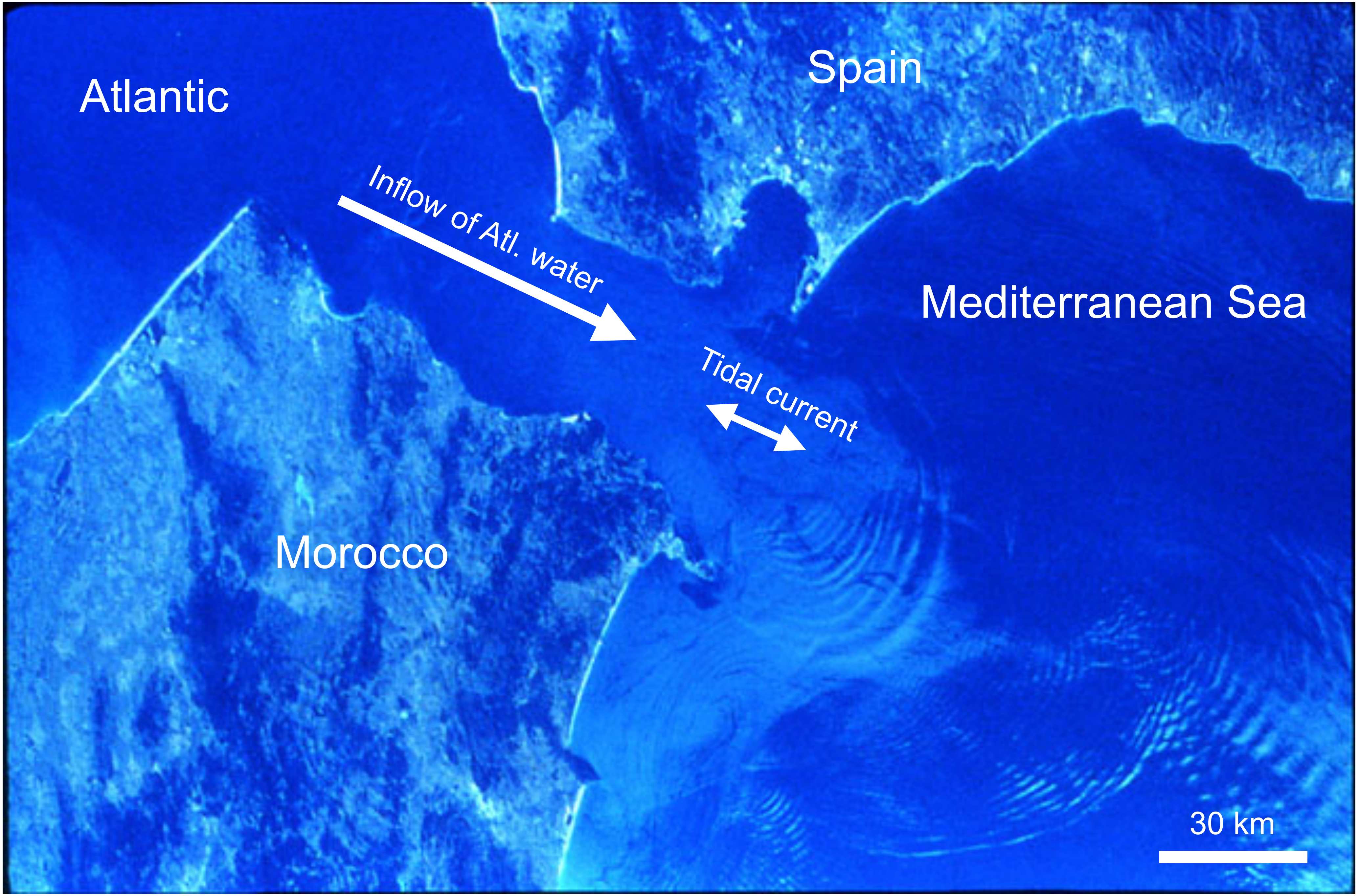
- *Other useful references are:*
  - Leblond-Mysak (1977) *: Waves in the ocean*
  - Whitham (1974) *: Linear and nonlinear waves*
  - Gill (1982) *: Atmosphère-Ocean Dynamics*
  - Kundu-Cohen (1987). *Fluid Mechanics. Third edition*
  - Cushman-Roisin. *Introduction to geophysical fluid Dynamics*

- ***Some important research articles and reviews are available here:*** **https://www.jgula.fr/Ondes/**

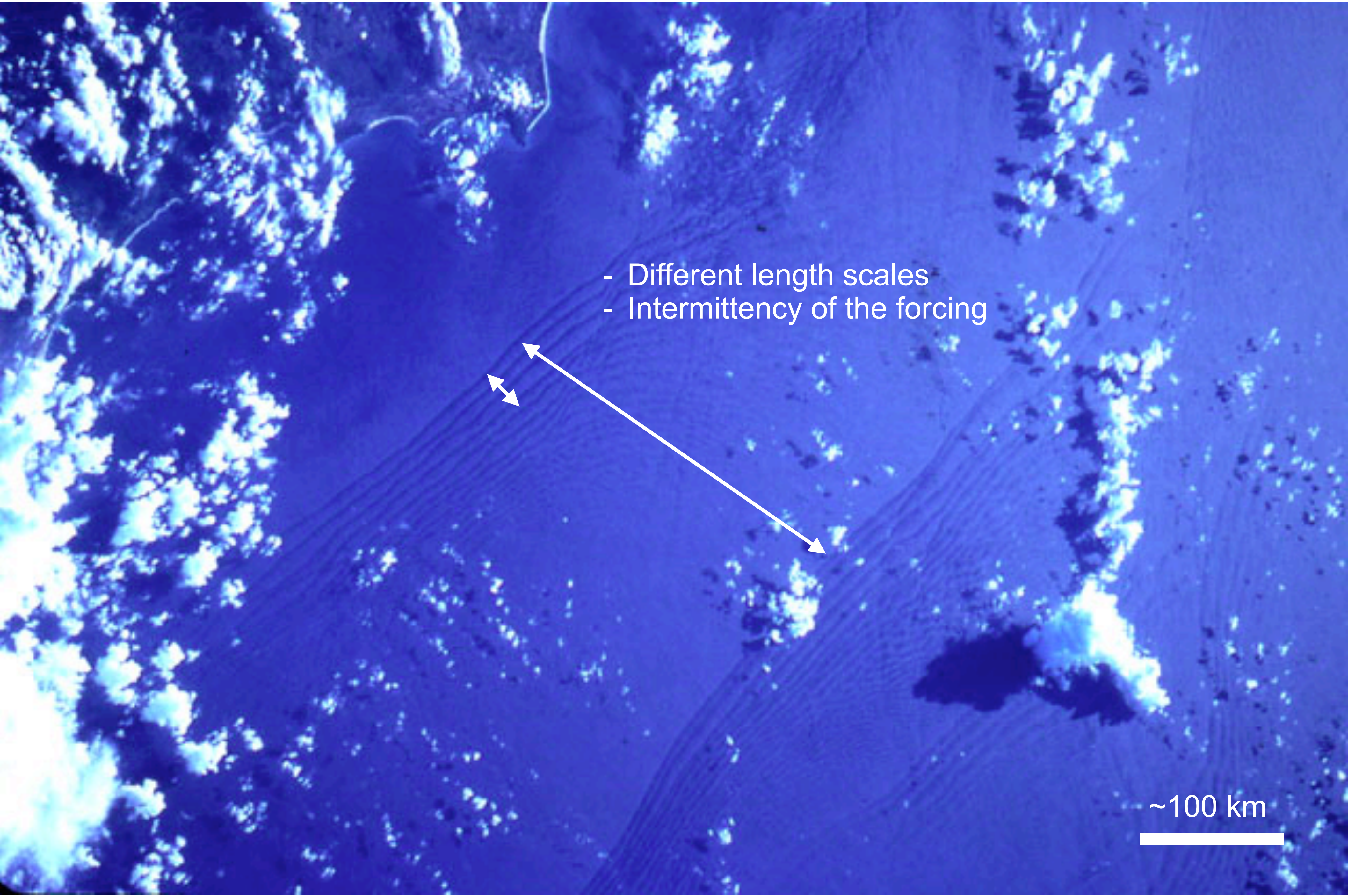
Space and time scales ?


Surface capillary wave
a few cm

Soliton in the Strait of Gibraltar

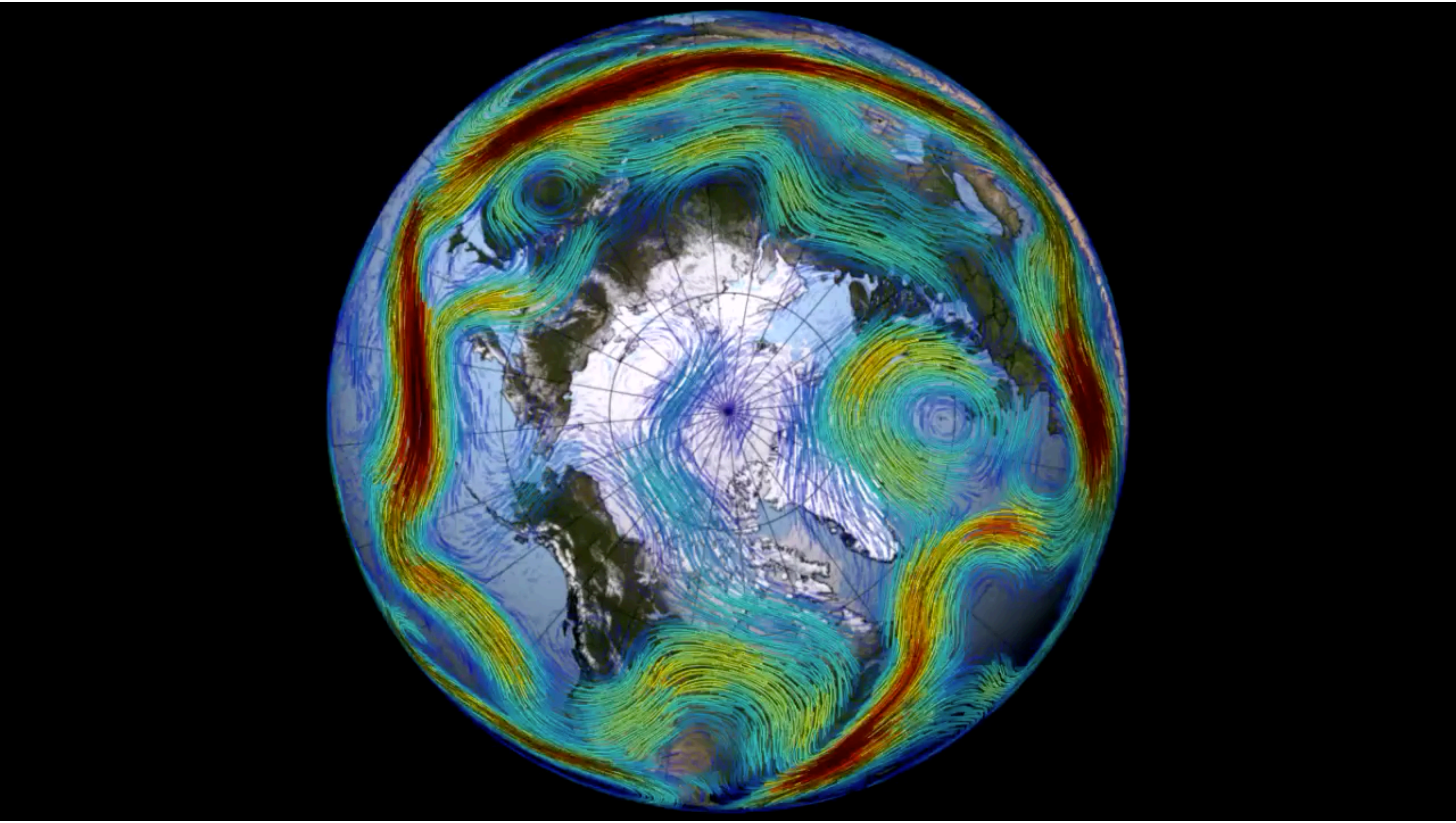


Wave packets in the South China Sea

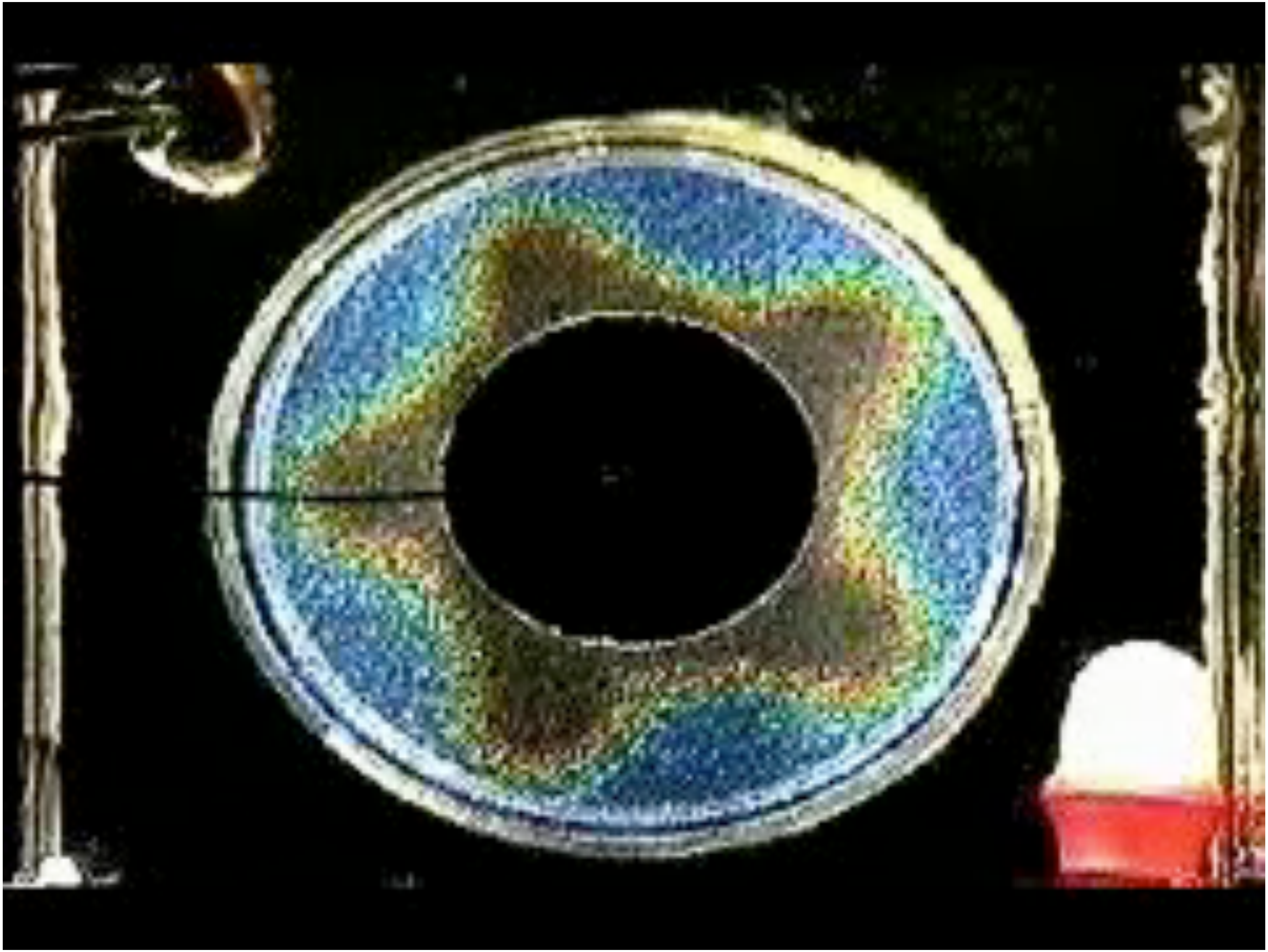


Standing waves generated leeward of a mountain summit

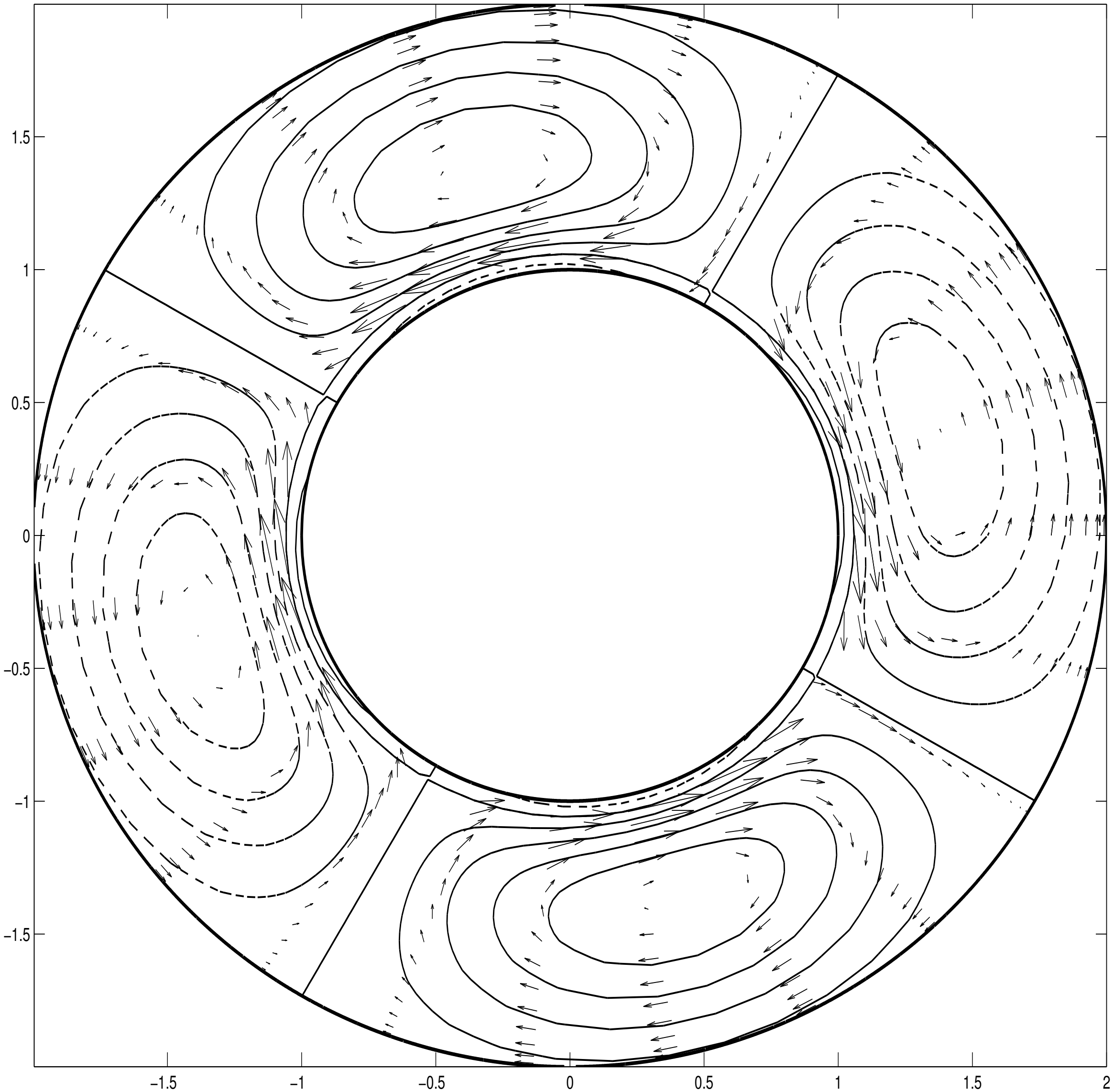
Planetary-scale waves

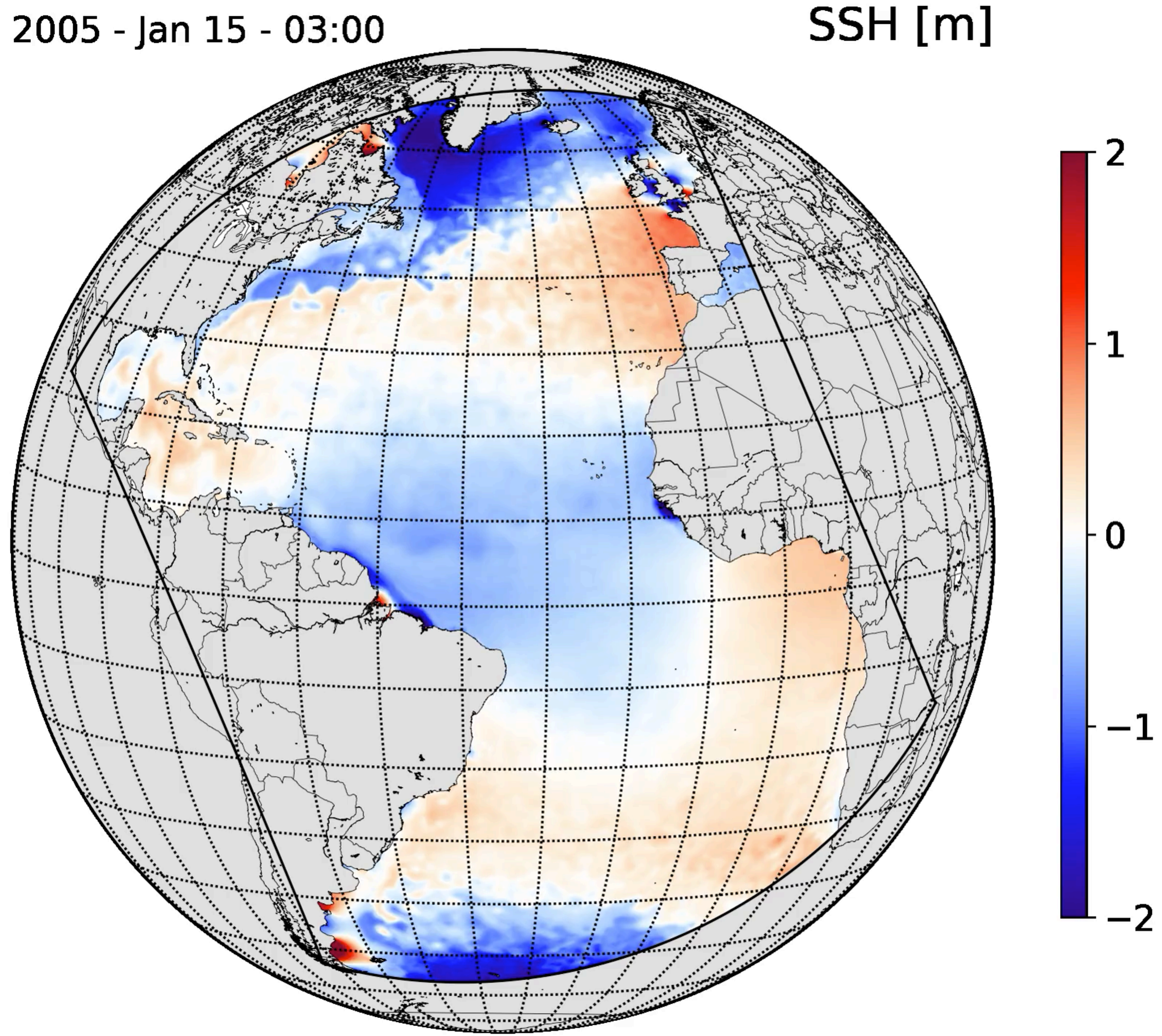


Replication of planetary waves in a rotating tank

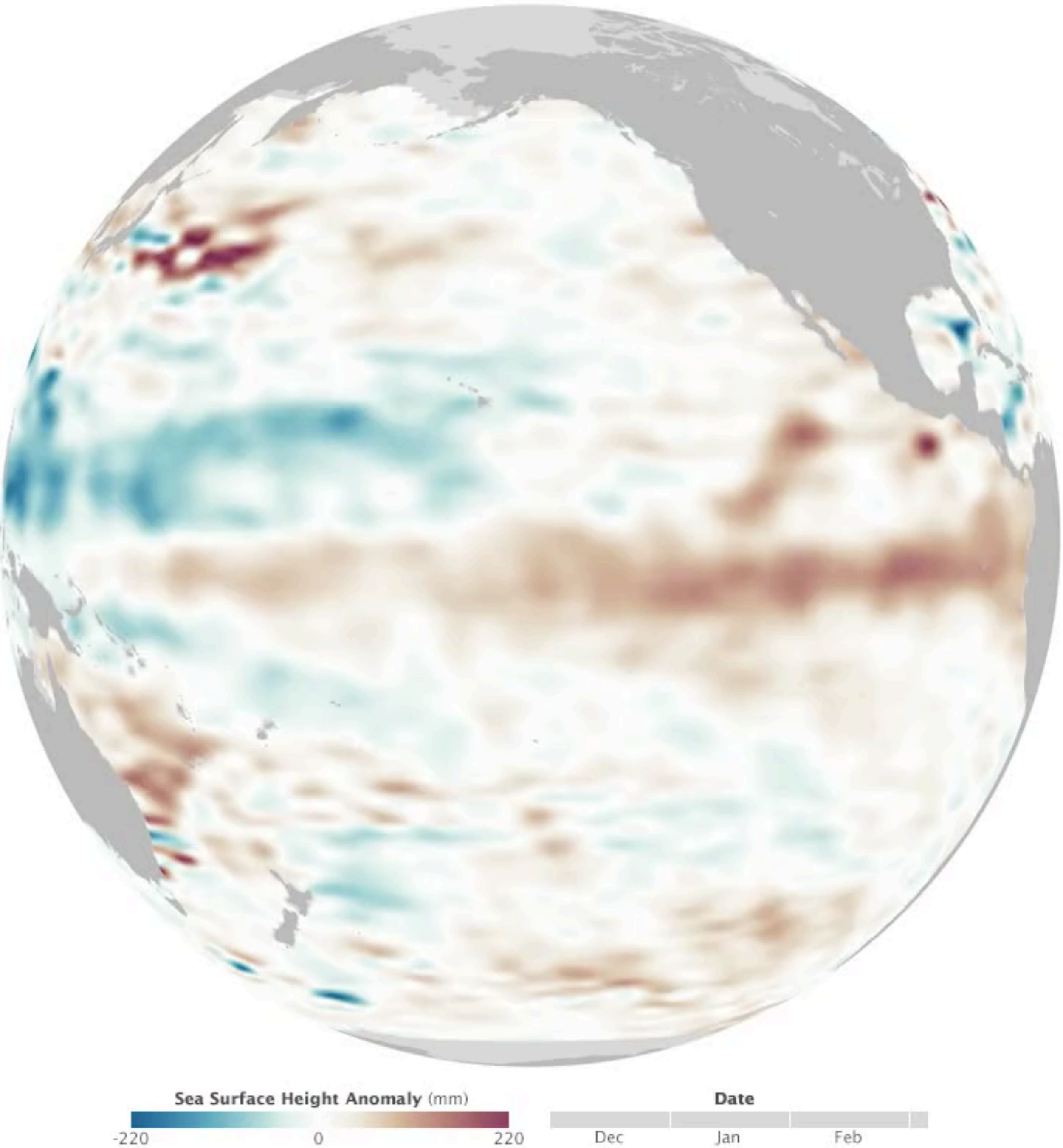


Theory of planetary waves




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

Equatorial Kelvin waves seen in sea surface height



Ocean Waves

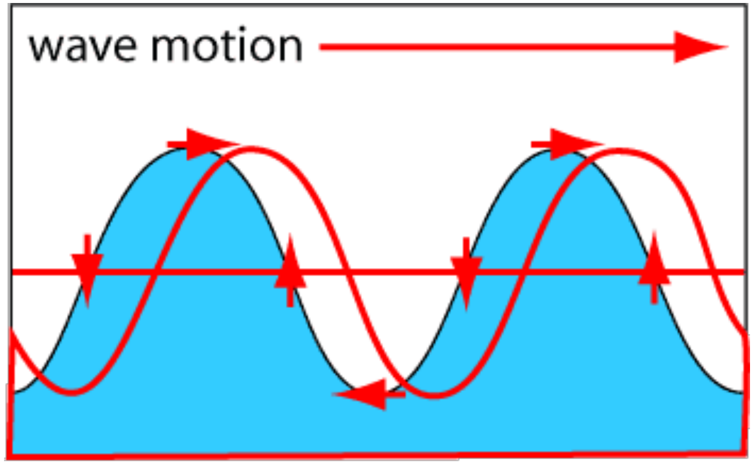
Definition of a wave:

- *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 »]

Ocean Waves

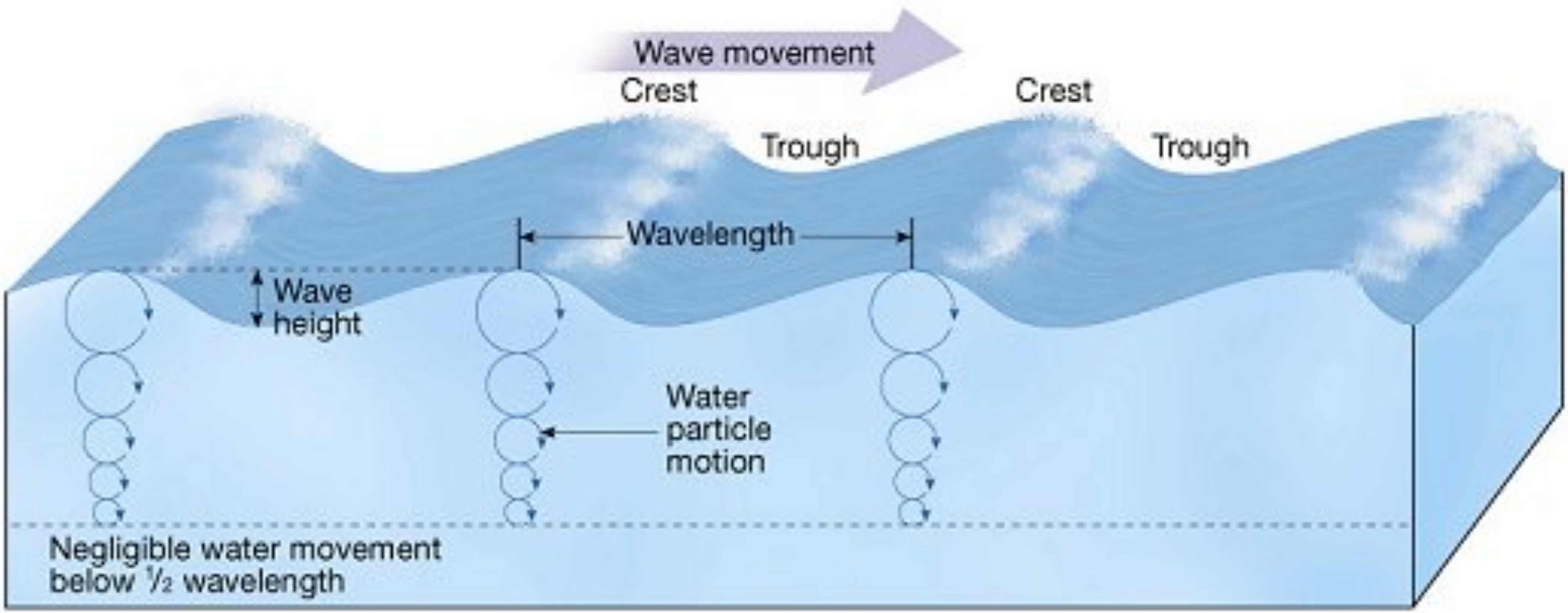
- A wave results when fluid is displaced from a position of equilibrium.

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



Ocean Waves

- Waves propagate energy but do not transport water



Ocean Waves

The different type of waves can be classified on the basis of:

- Restoring force
- Disturbing force
- Wavelength
- Free wave Vs forced wave

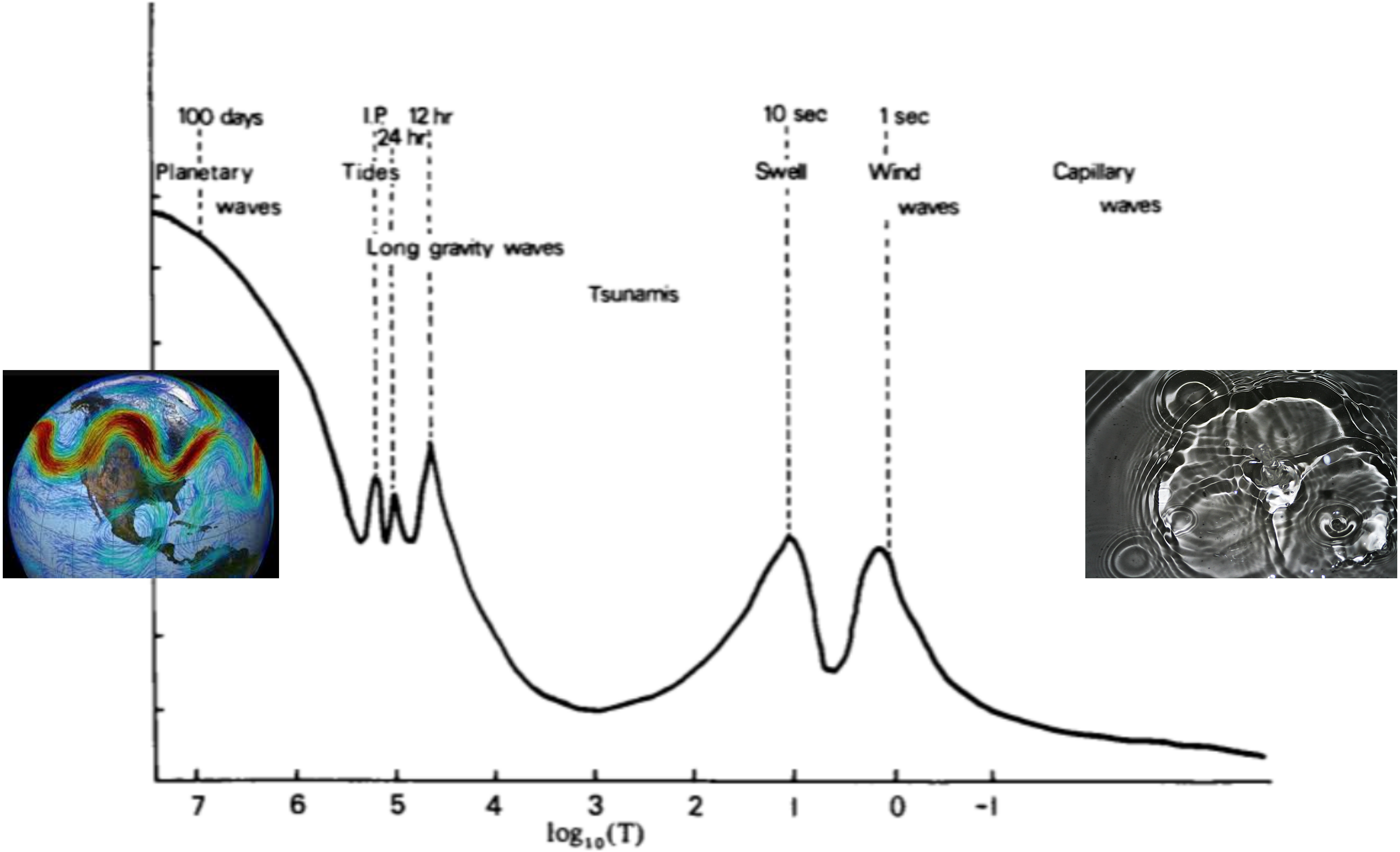
Ocean Waves

	Disturbing Force	Restoring Force	Wavelength	Periods

Ocean Waves

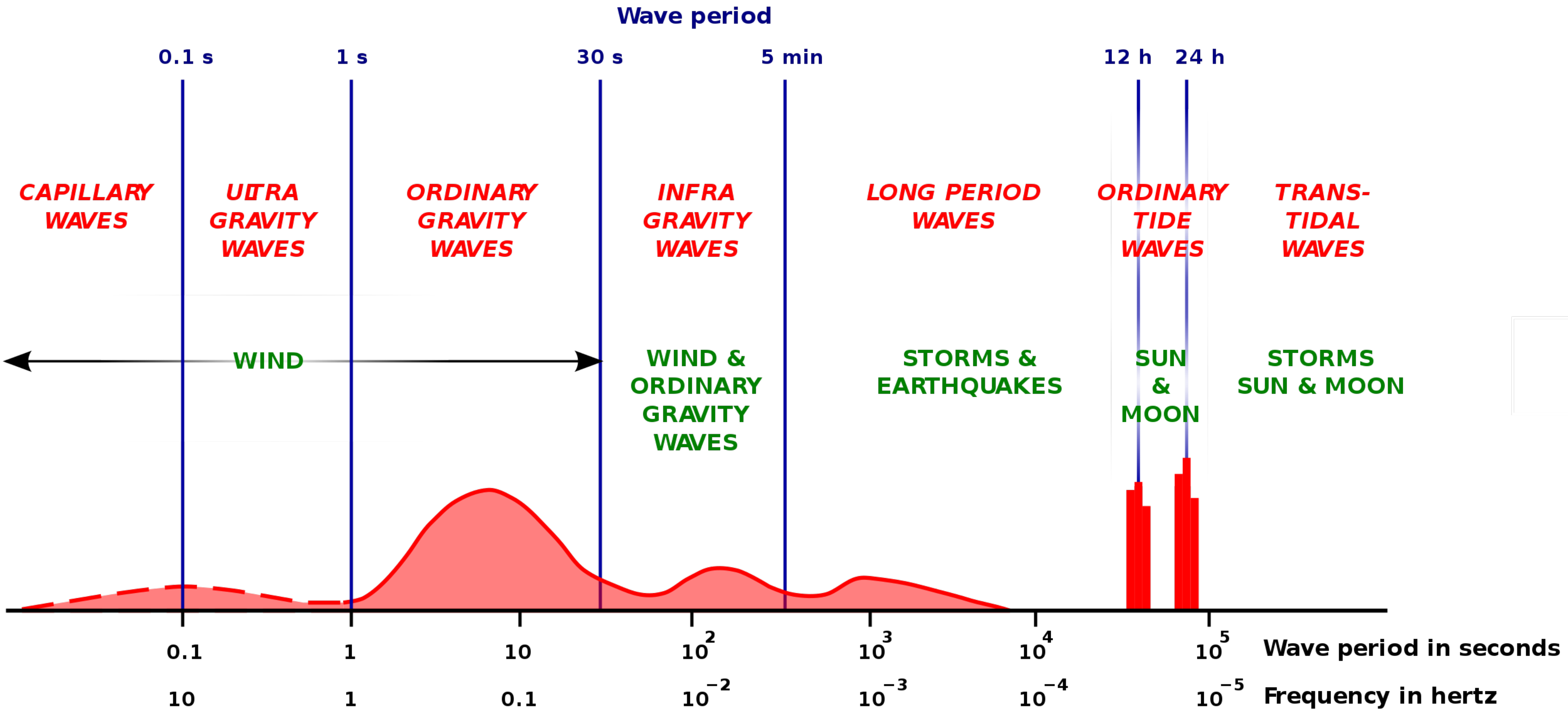
	Disturbing Force	Restoring Force	Wavelength	Periods
Acoustic waves		Pressure (compressibility)	1 mm - 10 km	< 1 s
Capillary waves		Suface tension	1 mm - 1 cm	< 1 s
Surface gravity waves	Wind, boat, earthquake, etc.	Gravity	1 cm - 100 km	1 s - 1 day
Internal waves	Tides, Wind, Topography, etc.	Gravity (stratification) + Coriolis	1 m - 100 km	1 s - 1 day
Rossby waves		PV (variation of Coriolis with latitude)	100 km - 1000 km	Days - Months
Kelvin wave		Pressure gradient + Coriolis	10 km - 100 km	Days - Months
Equatorial Waves		Pressure gradient + Coriolis	10 km - 1000 km	Days - Years

Ocean Waves

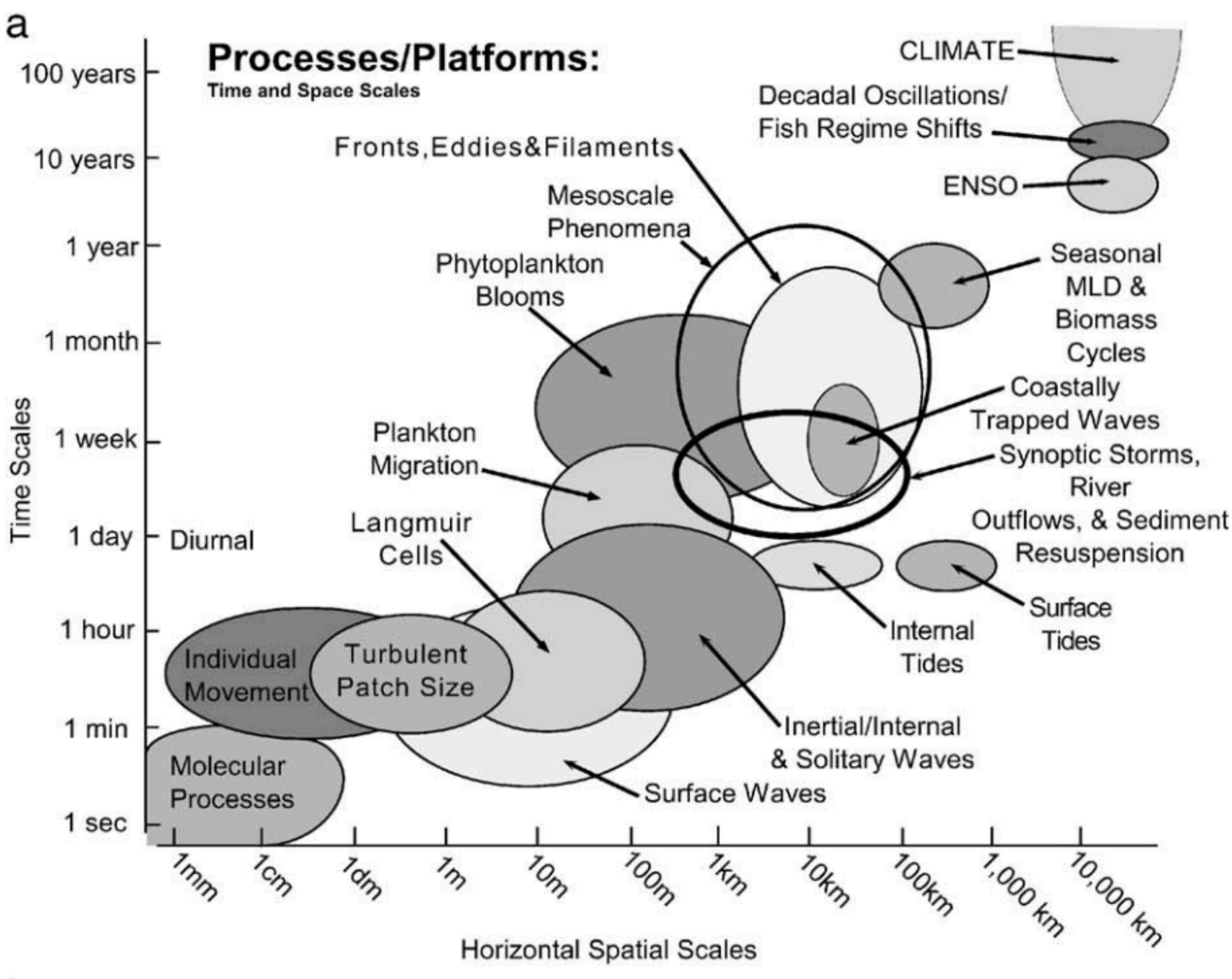


Schematic energy spectrum of ocean variability [Leblond & Mysak]

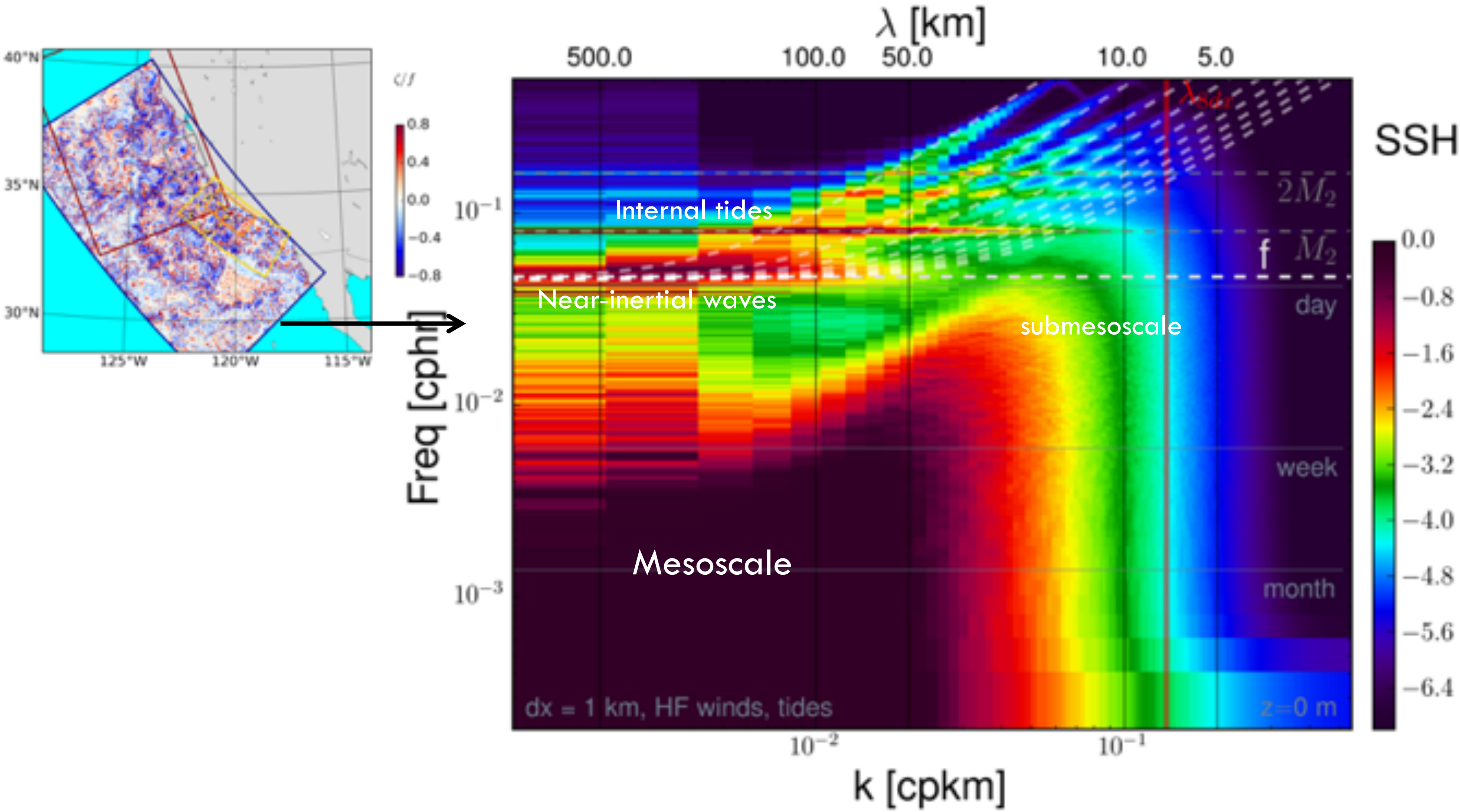
Surface gravity Waves



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

Ocean Waves



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

- 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

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

- With general solutions in the form:

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

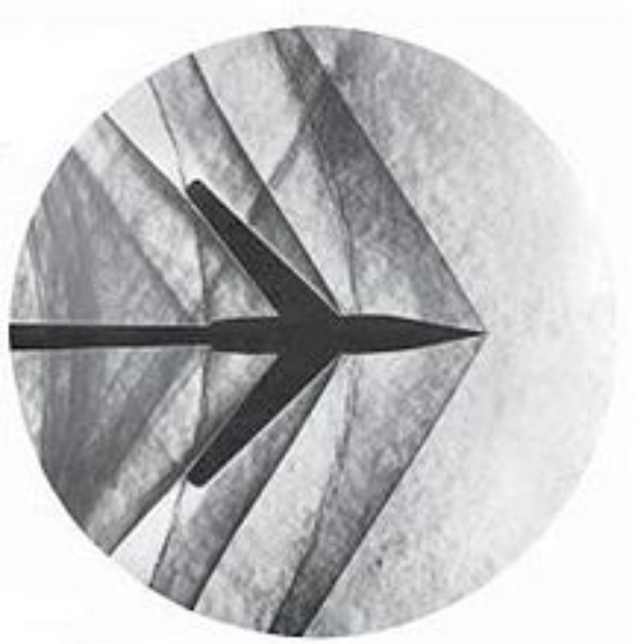
- Very frequent in acoustics, elasticity, electromagnetism, etc.

Hyperbolic waves

1. Examples of **Hyperbolic waves**

- Flood wave, tidal bores

- Shock wave



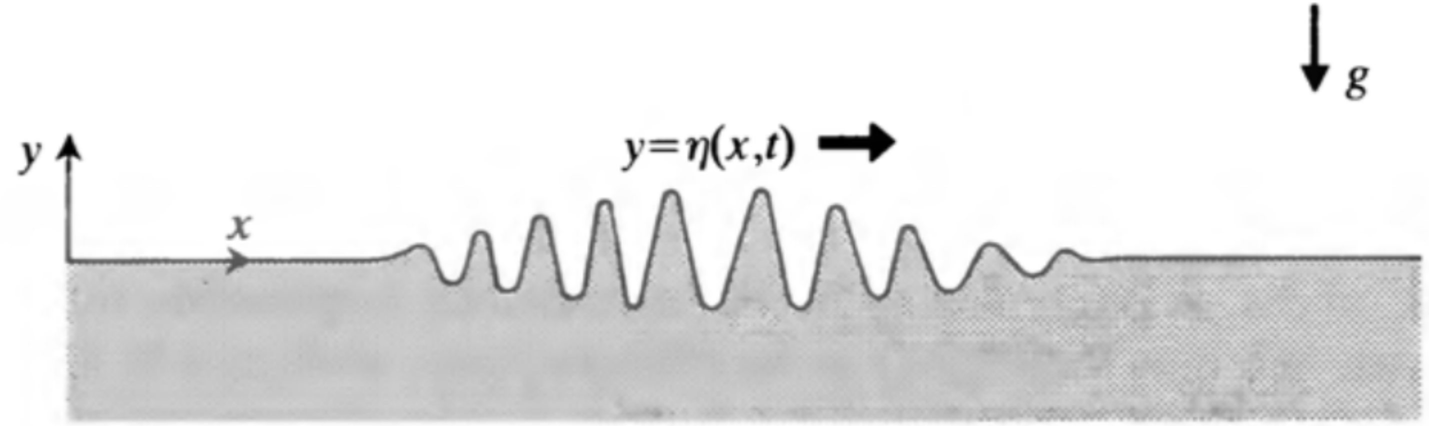
Dispersive waves

2. Dispersive waves come from a variety of partial differential equations, they are characterized principally by their dispersion relation:

$$\omega = f(k)$$

Connecting the frequency and the wave number.

They are visualized as a group of waves where the different Fourier components propagate at different speeds



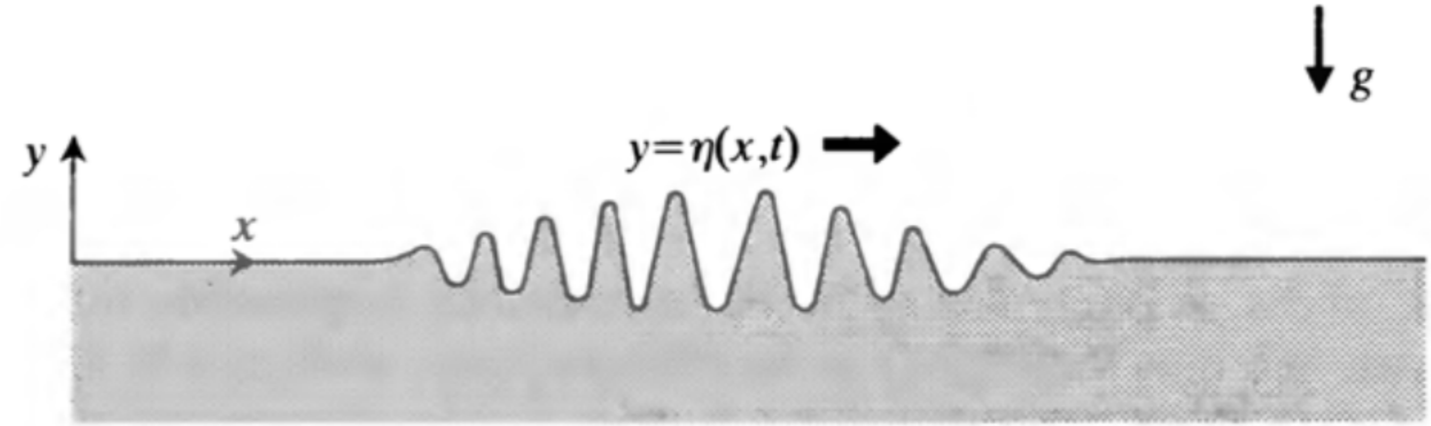
Dispersive waves

2. Dispersive waves:

$$\omega = f(k)$$

The wave speed is $$c = \frac{\omega}{k}$$

Energy propagates with the group velocity: $$c_g = \frac{\partial \omega}{\partial k}$$

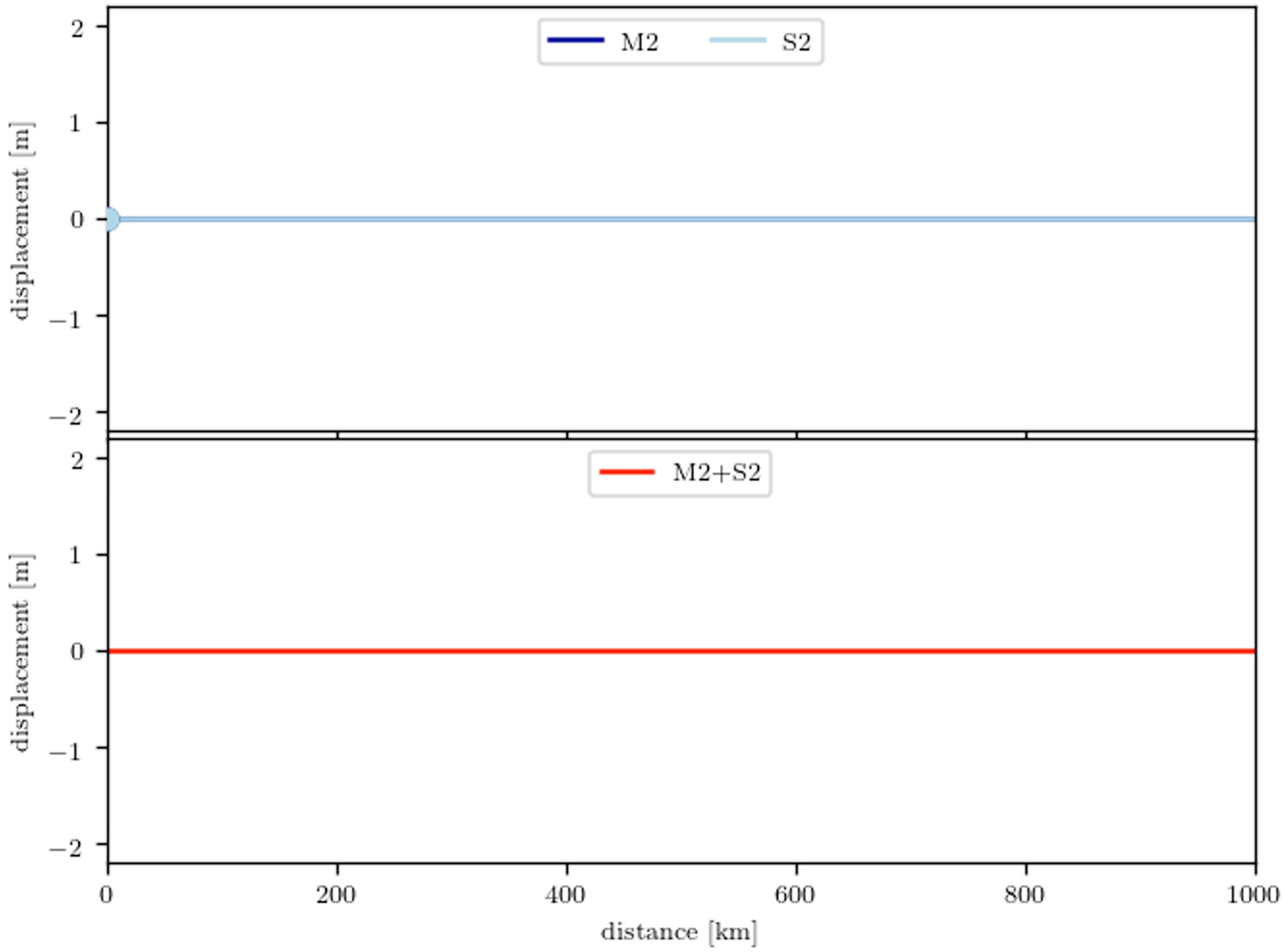


Dispersive waves

Example of the interaction of tidal waves :

- "M2 wave" (M=Moon) $f_{M2} = A_{M2} \exp\left(i(\omega_{M2}t - k_{M2}x)\right)$
- "S2 wave" (S=Sun). $f_{S2} = A_{S2} \exp\left(i(\omega_{S2}t - k_{S2}x)\right)$
- f can be the sea surface, current, displacement of isopycnals, etc.

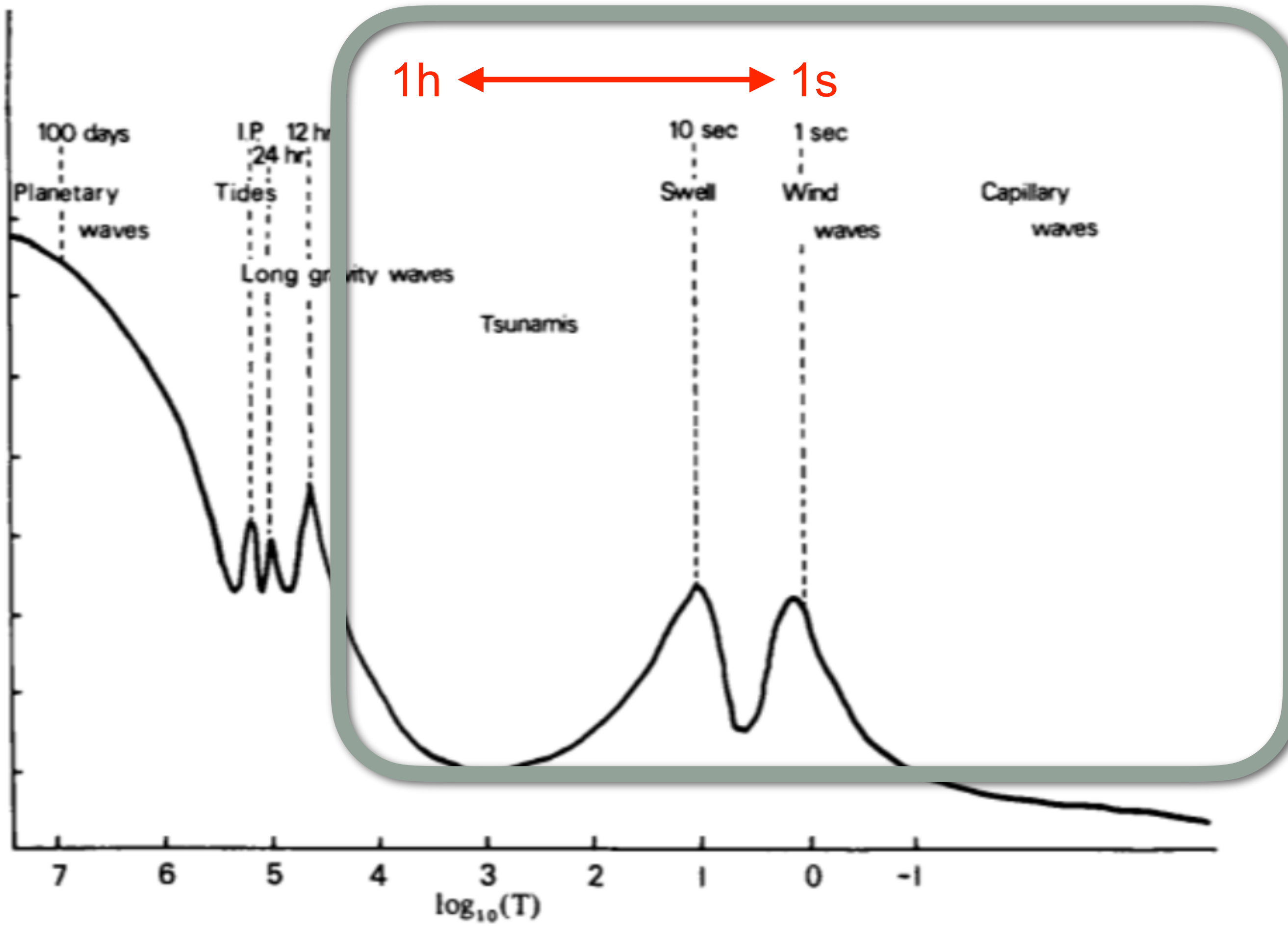
Dispersive waves



OCEAN WAVES

1. Surface waves [very brief reminder]
2. Internal waves
3. Long waves
   a. Rossby waves [Rossby, Poincare, etc.]
   b. Coastal trapped waves [Kelvin waves, etc.]
   c. Equatorial waves [Rossby, Kelvin, Yanai]

1. Surface waves



Schematic energy spectrum of ocean variability [Leblond & Mysak]

1. Surface waves

Solving the linearized incompressible Euler equations:

Incompressible Euler equations (*convective or Lagrangian form*)

$$\begin{cases} \dfrac{D\rho}{Dt} = 0 \\ \dfrac{D\mathbf{u}}{Dt} = -\dfrac{\nabla p}{\rho} + \mathbf{g} \\ \nabla \cdot \mathbf{u} = 0 \end{cases}$$

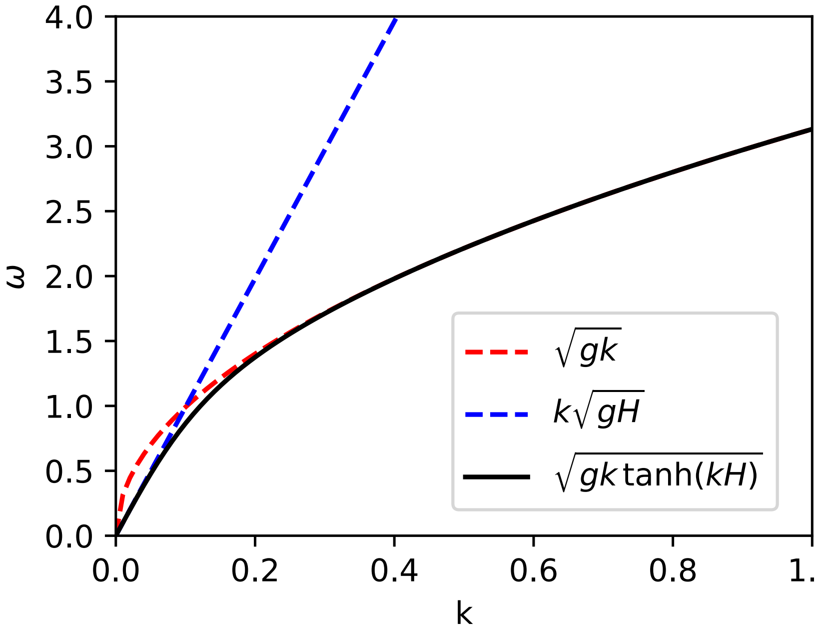
$$\begin{aligned} u_t &= -p_x \\ v_t &= -p_y \\ w_t &= -p_z - g \\ 0 &= u_x + v_y + w_z, \end{aligned}$$

Looking for a wave solution: $\Phi = F(z)e^{i(\vec{k}\cdot\vec{x}-\omega t)}$

We get the dispersion relation :

$\omega = \sqrt{gk\tanh(kH)}$ (black line)

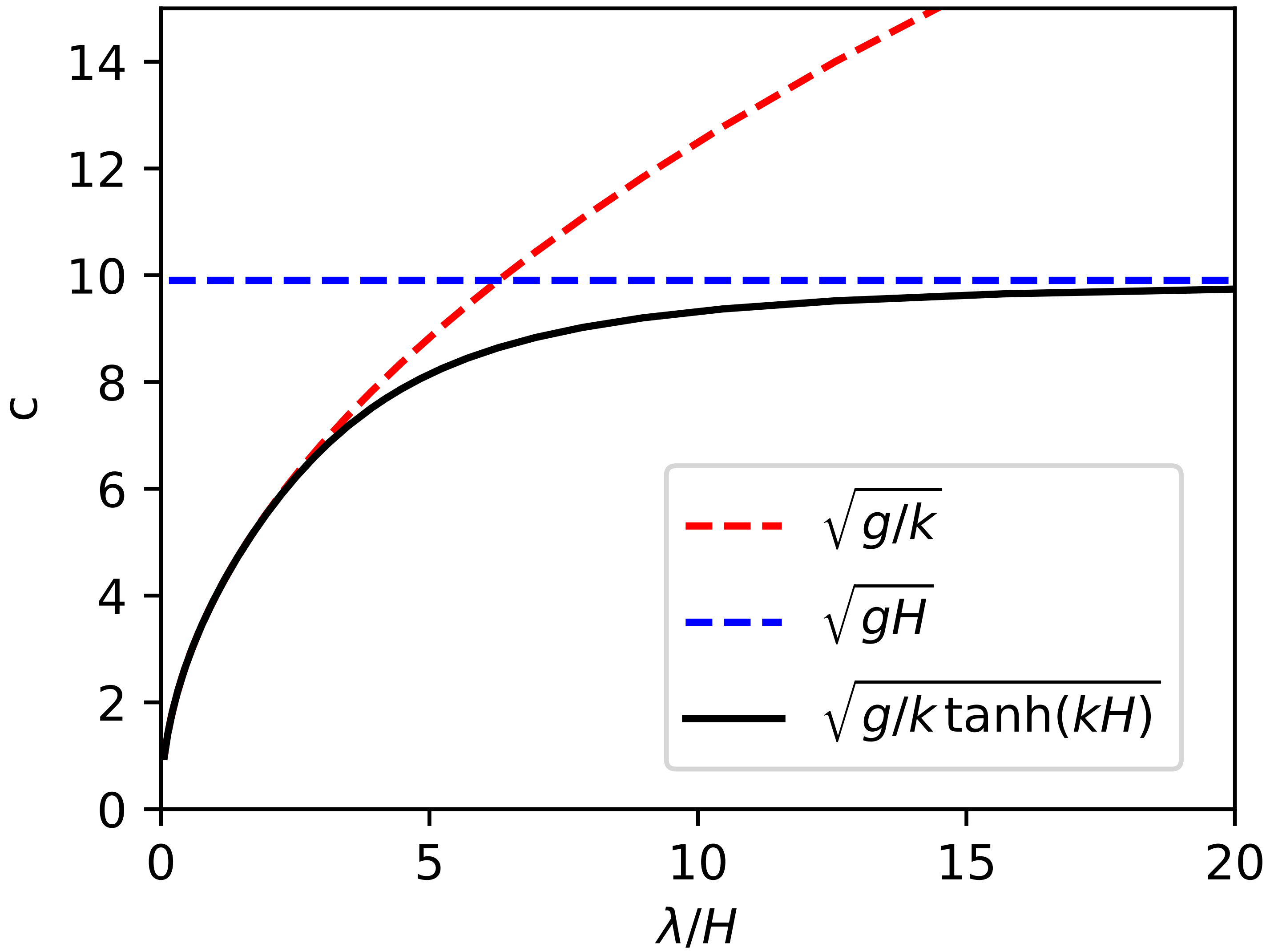
With H the water depth.



1. Surface waves

Phase speed:

$$c = \frac{\omega}{k}$$



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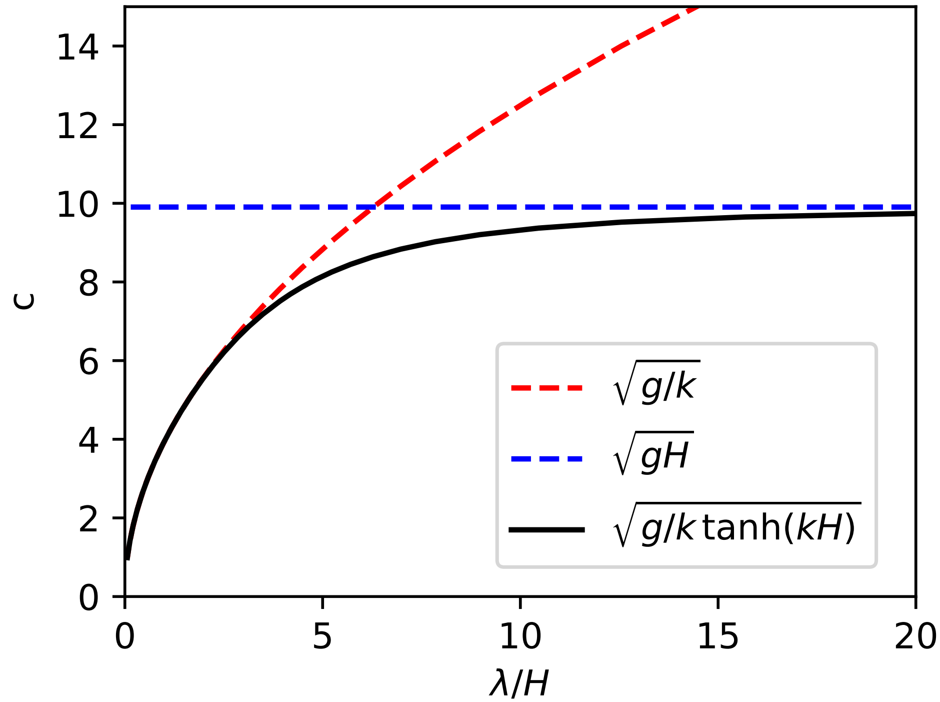
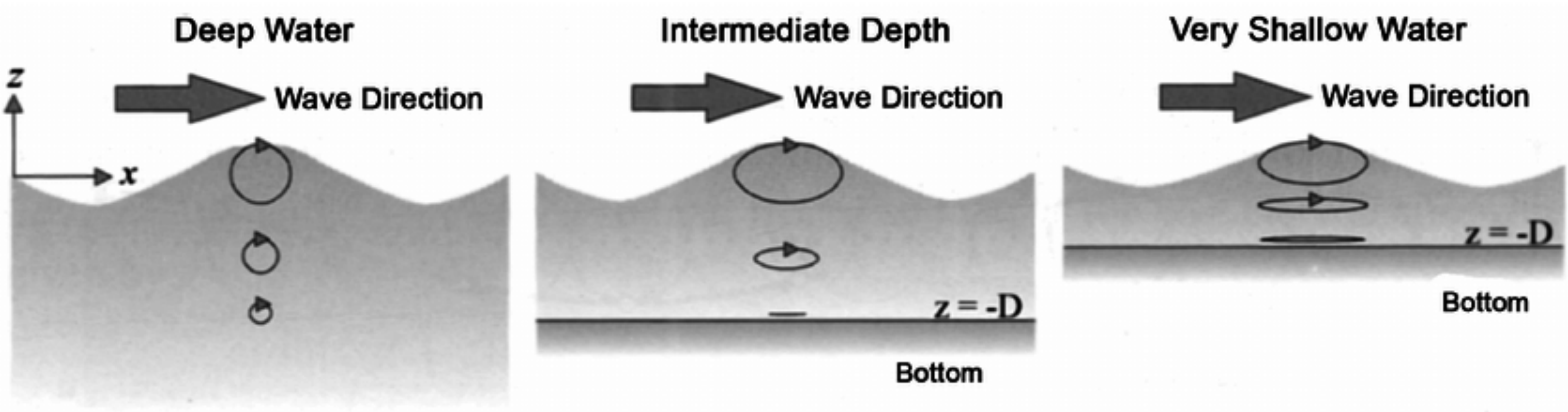
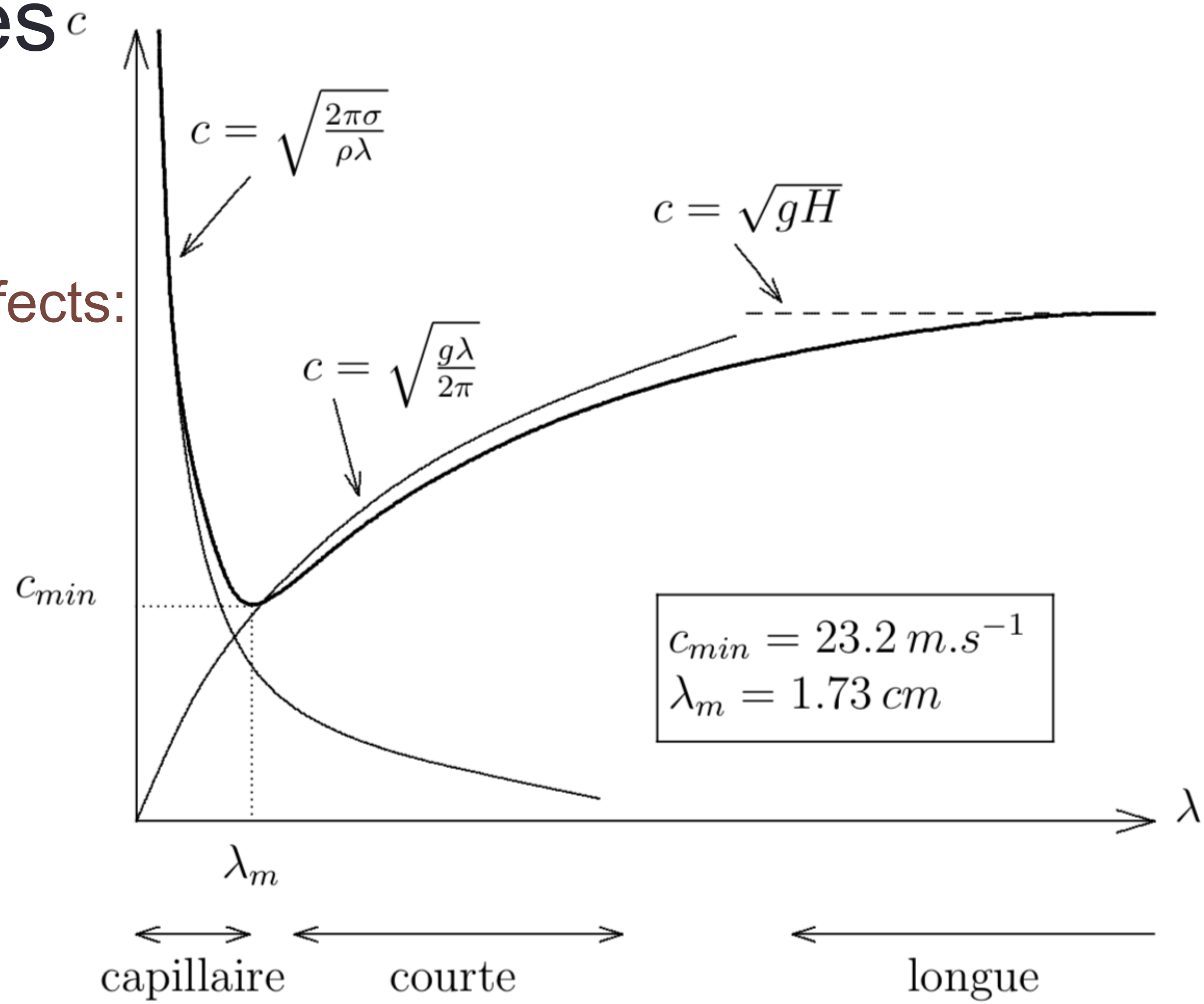




1. Surface waves

With surface tension effects:



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