IMPERIAL

The turbulent ocean that shapes our future

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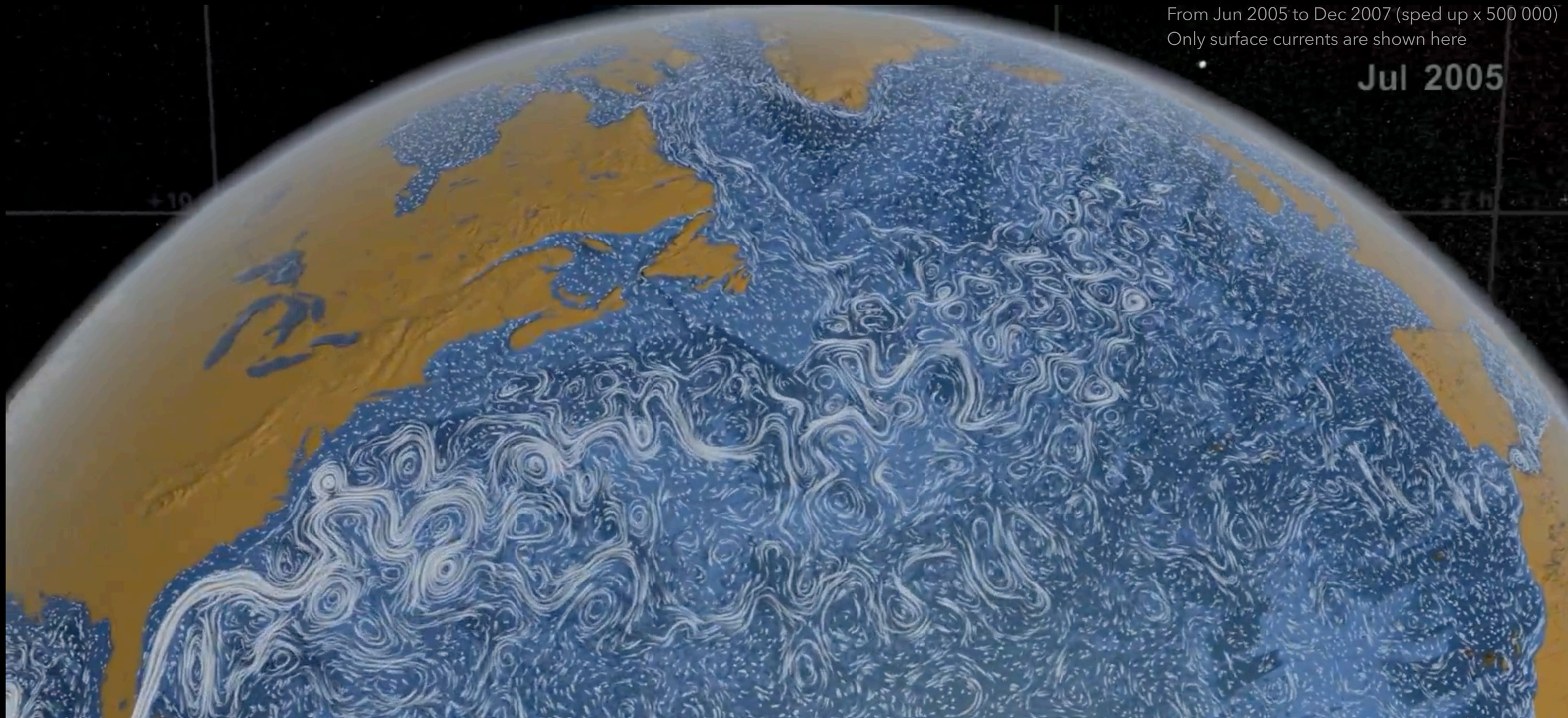

Ocean circulation computer model (NASA)
From Jun 2005 to Dec 2007 (sped up x 500 000)
Only surface currents are shown here

Goal: Overview of the role and practice of physical modelling of the ocean

1. Introduction: The ocean circulation and importance of turbulence and mixing

2. Case study: focus on estuaries with an example of latest research

3. Zooming out: applications of environmental modelling

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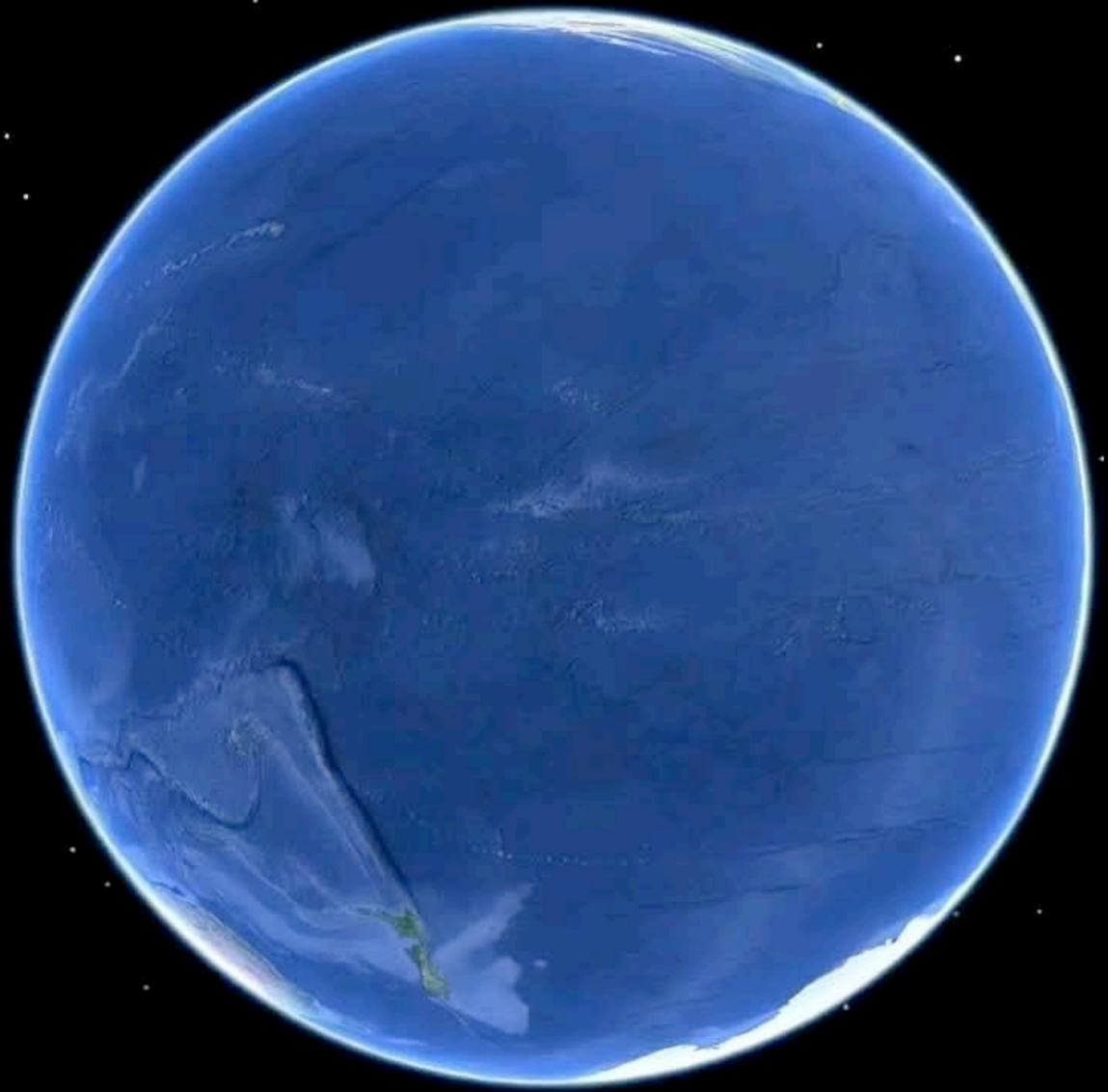
We live on land, but the OCEAN is the main engine of the climate system

The “Earth”



Follow the energy…

Heat capacity of the oceans

= 1000 x that of the atmoshpere

We live on land, but the OCEAN is the main engine of the climate system

Oceans store

91% of excess heat

28% of excess CO_2

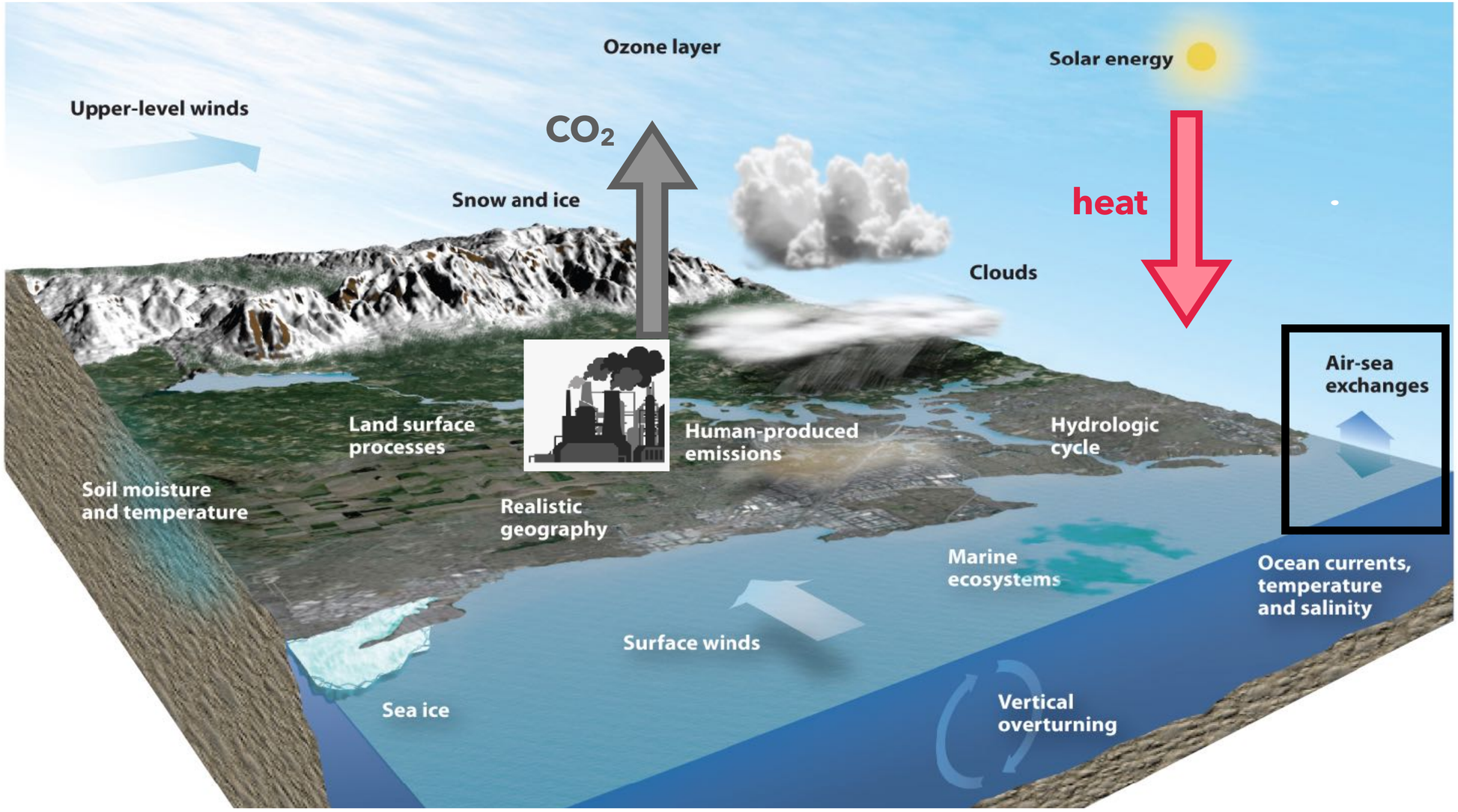
Consequences of ocean warming and acidification:

Biodiversity loss
(coral reefs, fish stocks)

More extreme rainfall
(including tropical cyclones)

Ice sheet melting
Sea-level rise, coastal flooding

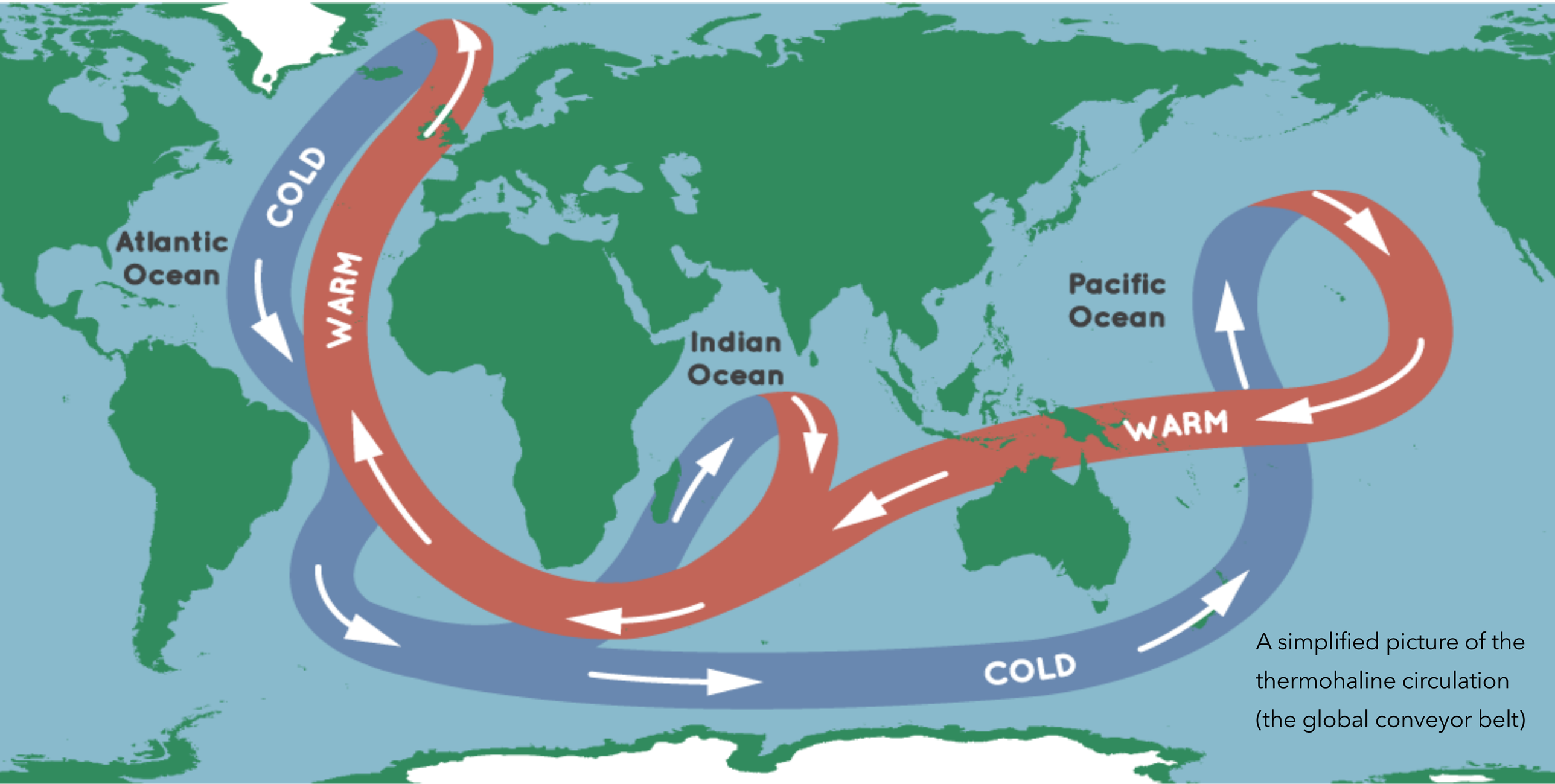
Long-term carbon and heat storage and feedback with the atmosphere



90% of global warming is happening **underwater**

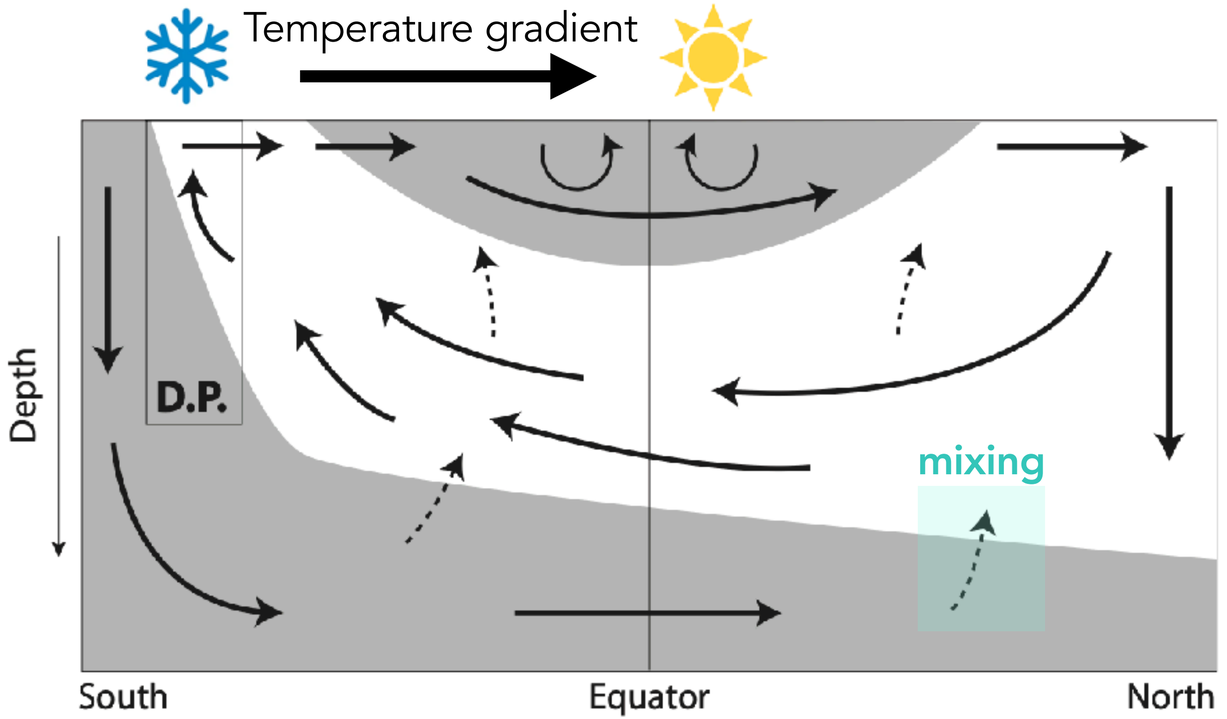
Understanding heat transport in the oceans is key to mitigate and adapt to climate change

The **ocean circulation transports heat and carbon** over the planet and across centuries



A simplified picture of the thermohaline circulation (the global conveyor belt)

Turbulent mixing is key to the ocean circulation because it controls the rate of meridional heat transport, carbon sequestration, nutrient fluxes…



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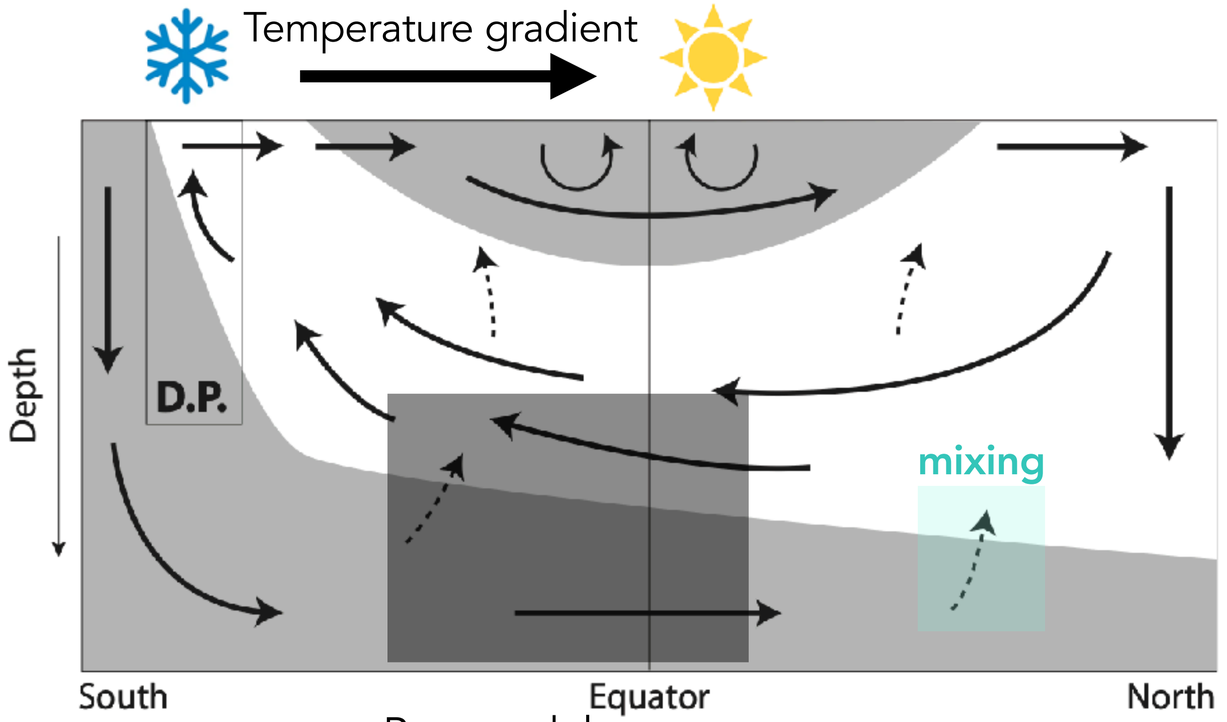
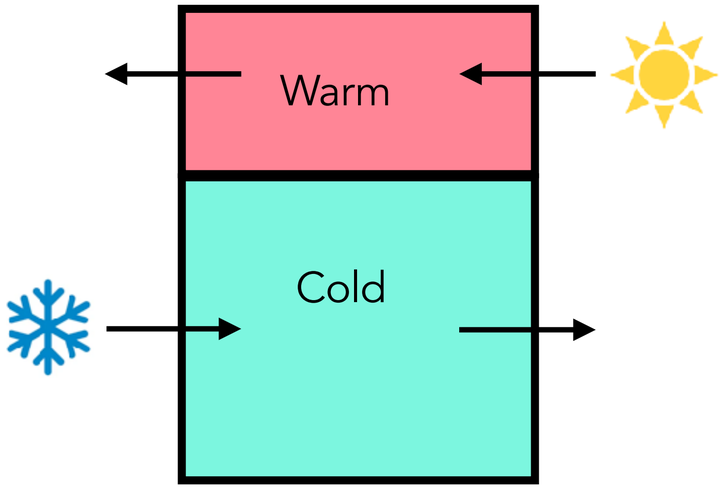


Box model



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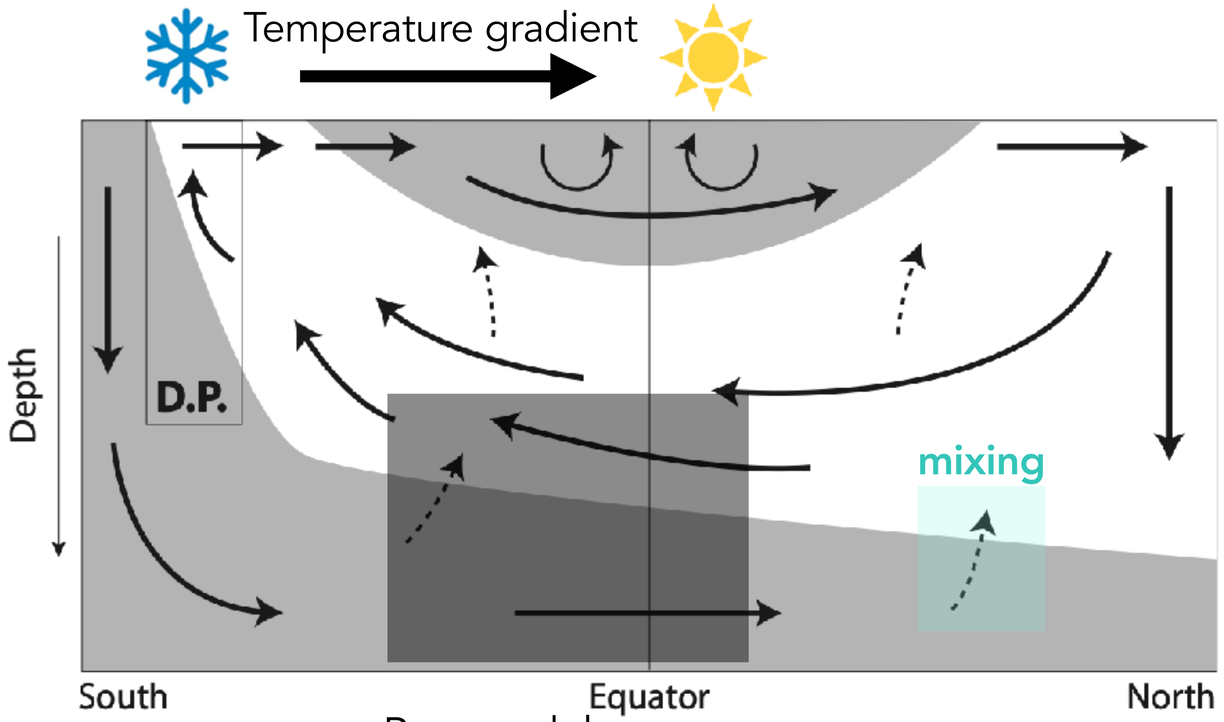

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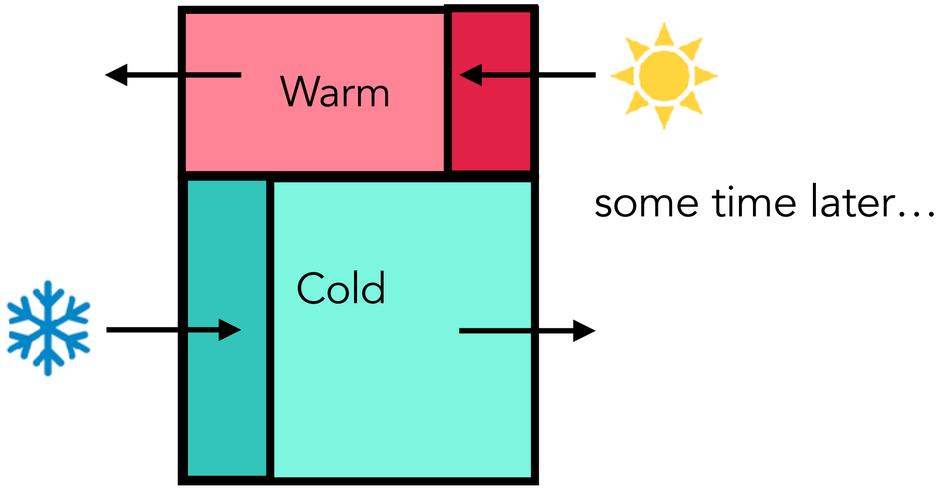

some time later…

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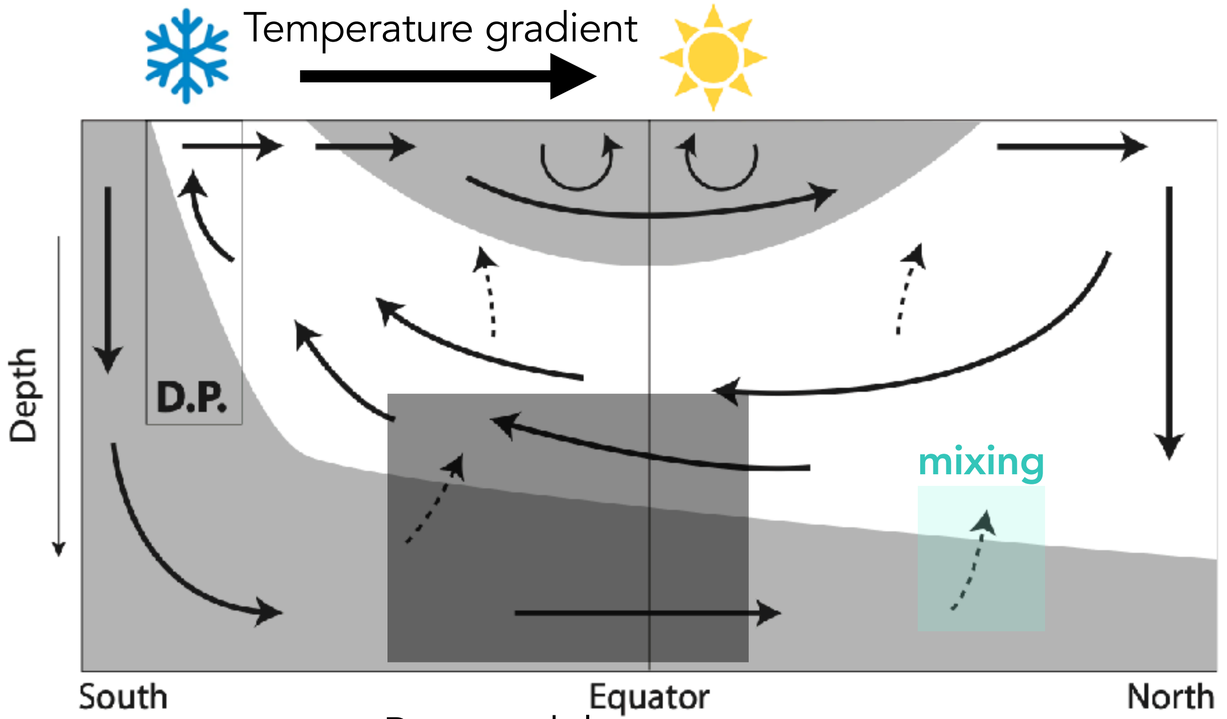

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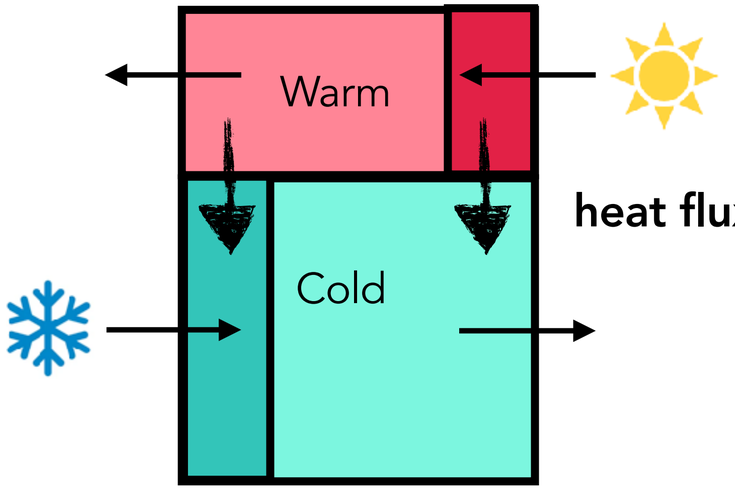
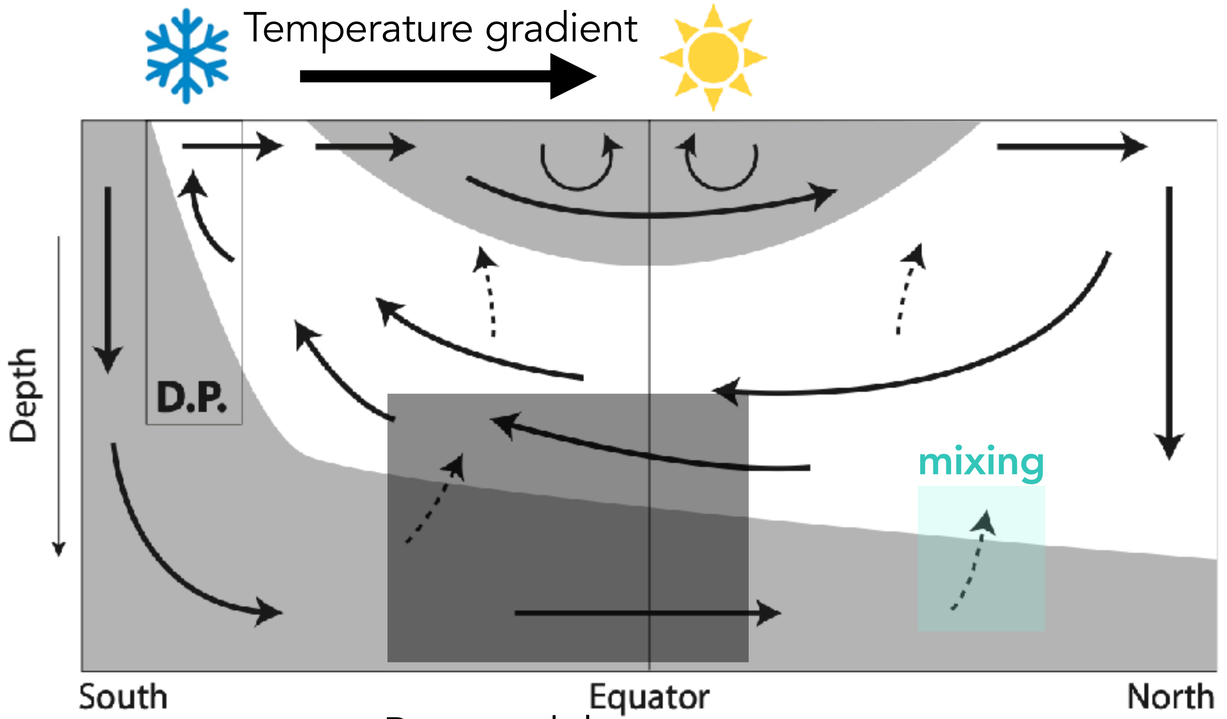


In the presence of a **horizontal gradient**, the persistence of this circulation requires constant **mixing**

heat flux must destroy the extra variance

Turbulent mixing is key to the ocean circulation because it controls the rate of meridional heat transport, carbon sequestration, nutrient fluxes…



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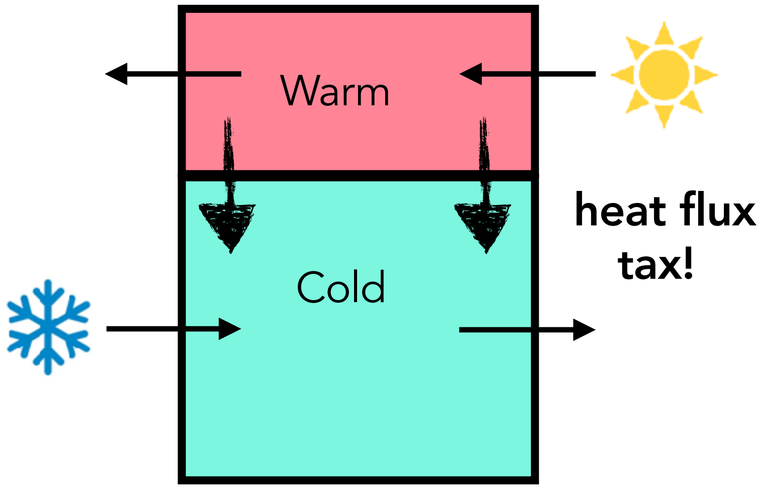

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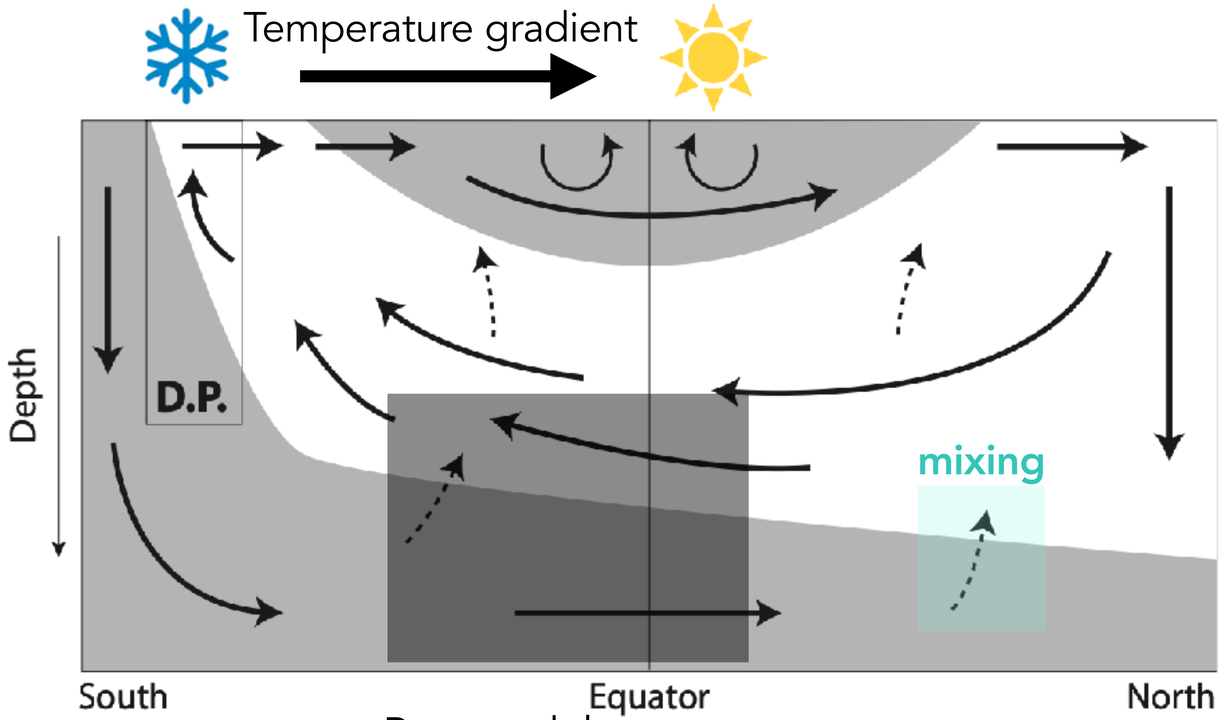

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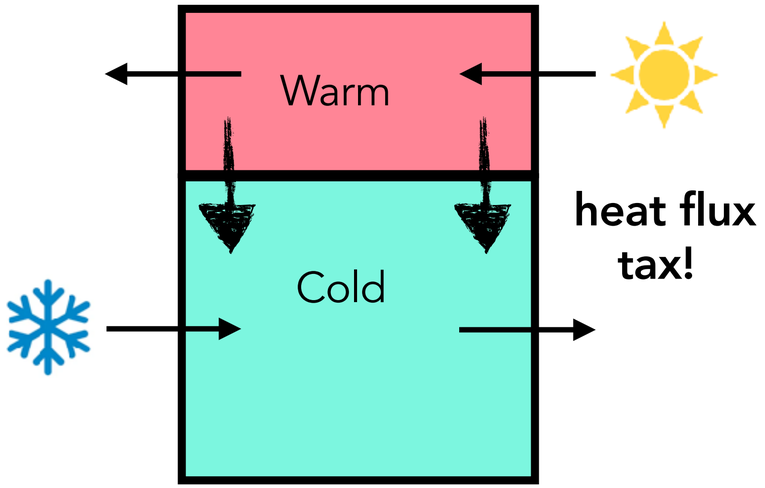


In the presence of a **horizontal gradient**, the persistence of this circulation requires constant **mixing**

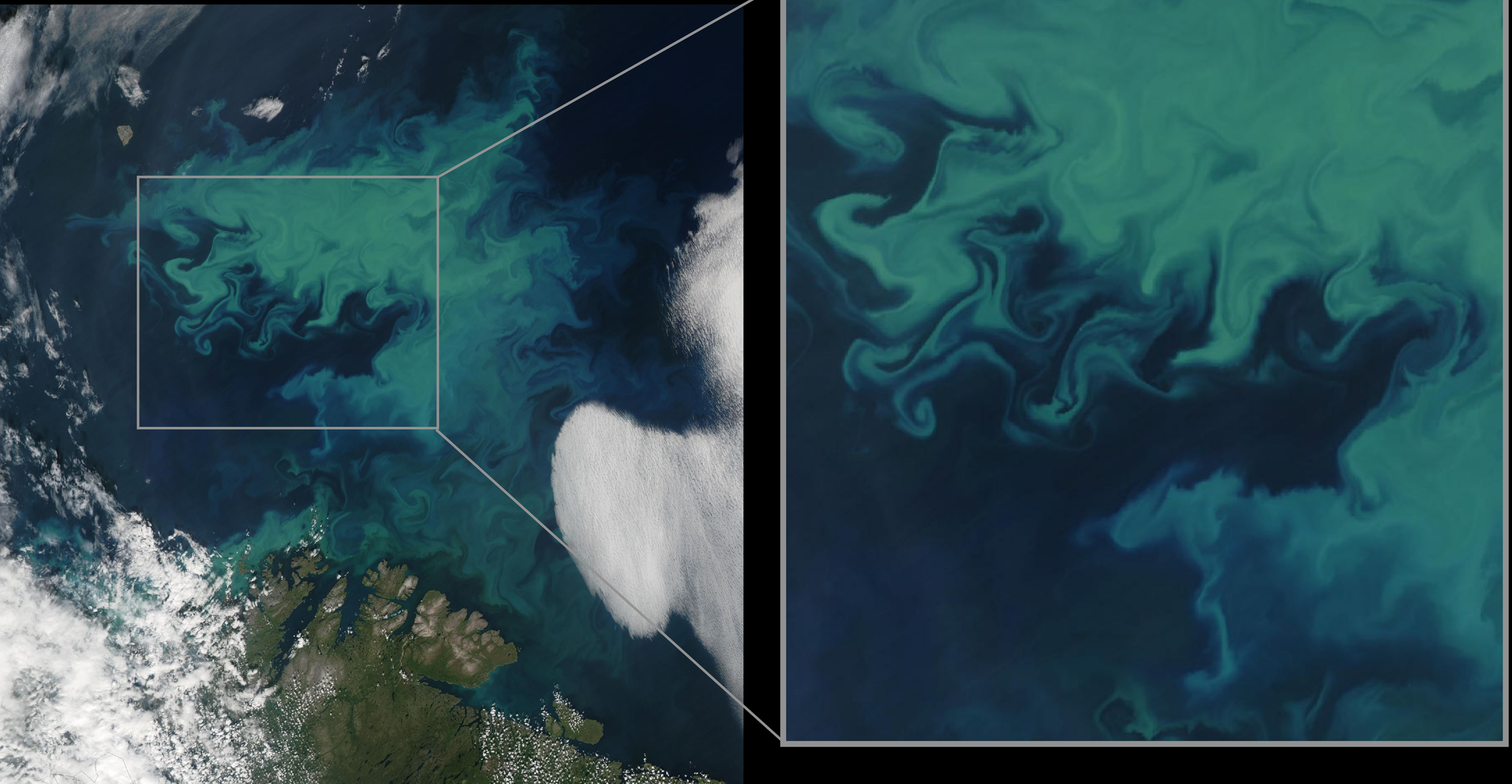
Demonstration

Science questions:

- How strong is the ocean circulation?
- How much mixing sustains it?
- Where does the energy come from?
- Efficiency of this mixing (tax rate)?
- Type of mixing?

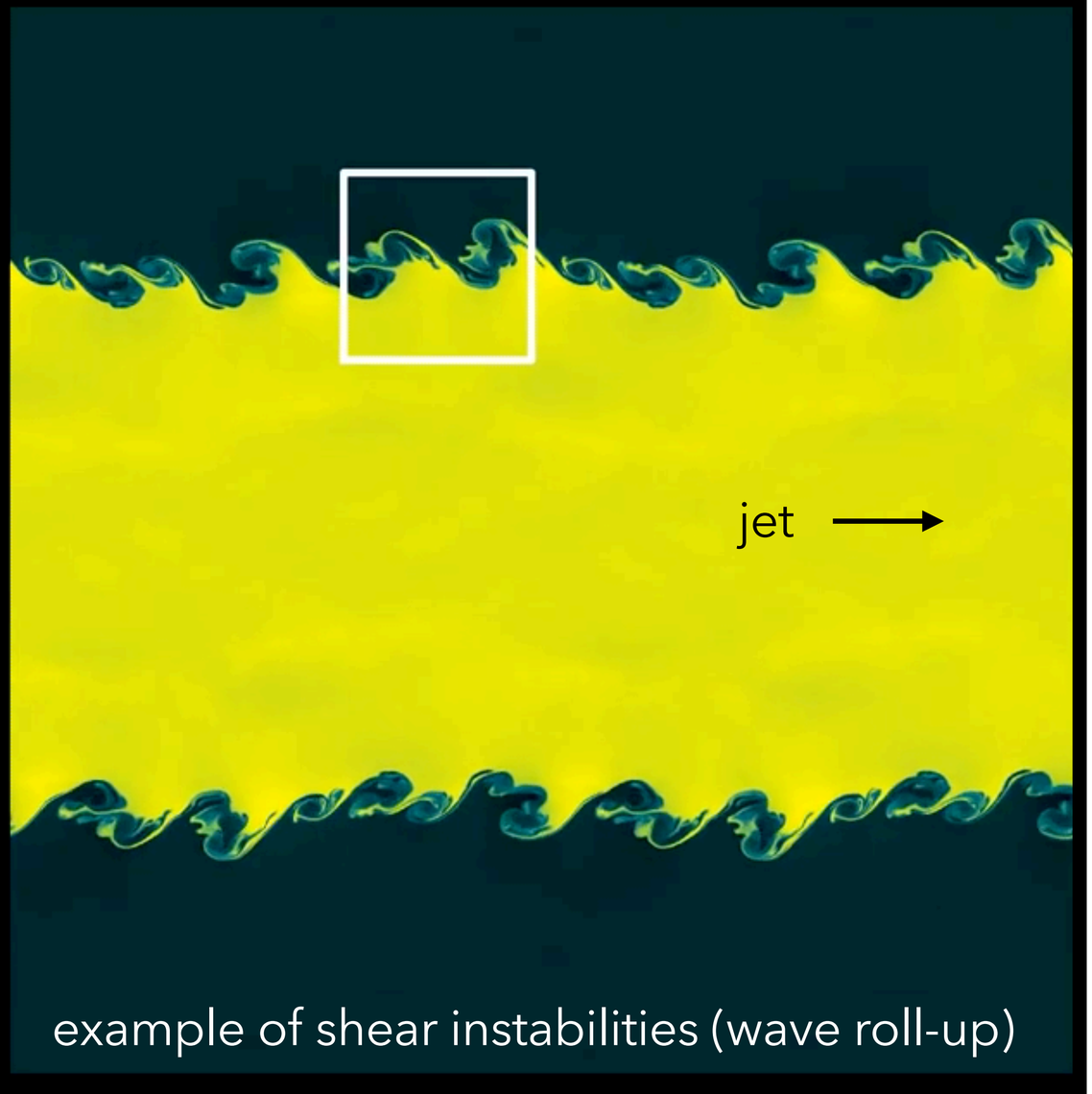
Why is turbulence so challenging? It is MULTISCALE, random but still has structure

Plankton bloom observed from space (NASA)



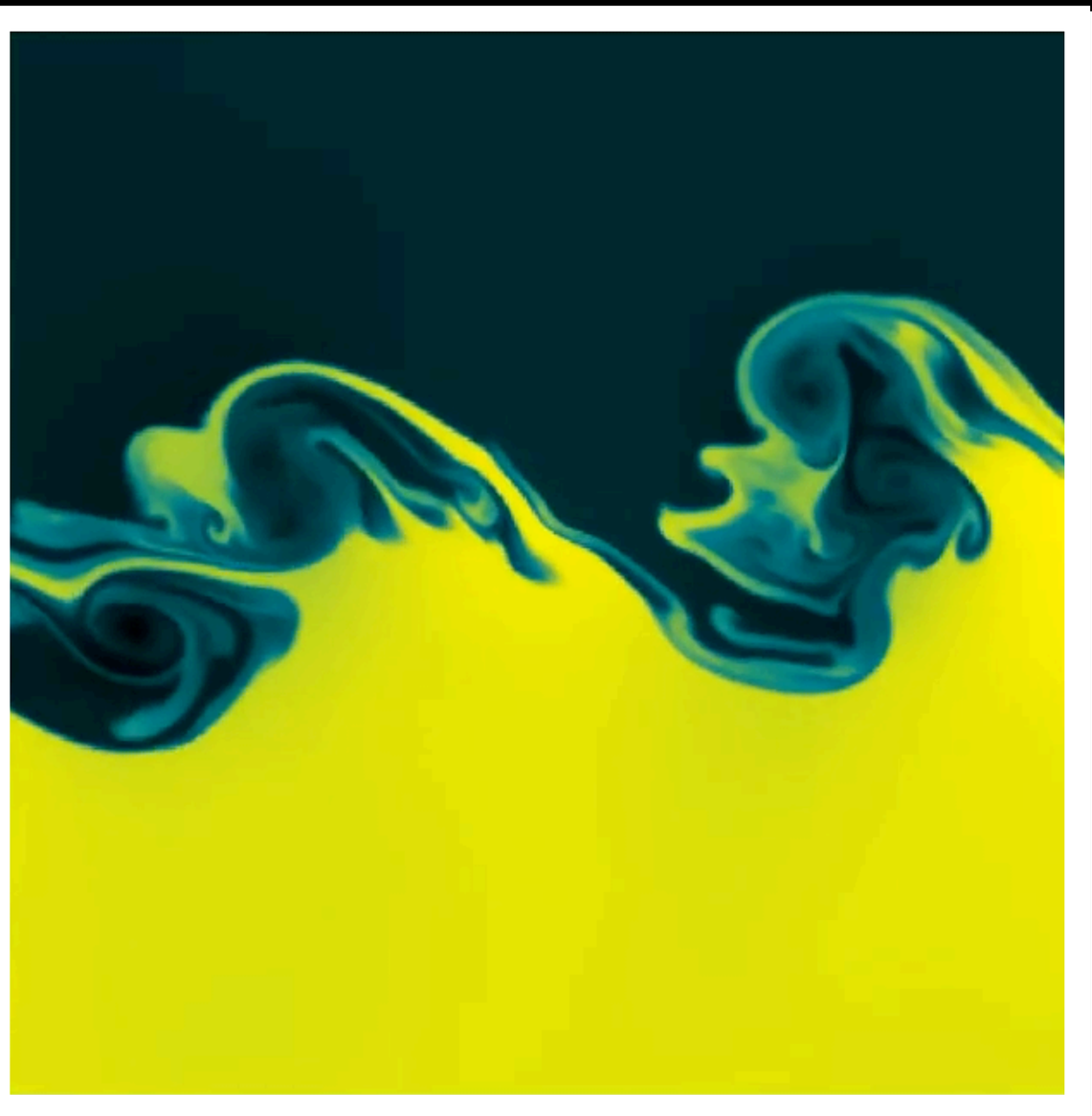
Visualisation of **turbulent mixing** between two fluid (computer model of the equations of fluid mechanics)

Mixing happens at **very small scales** (below mm)

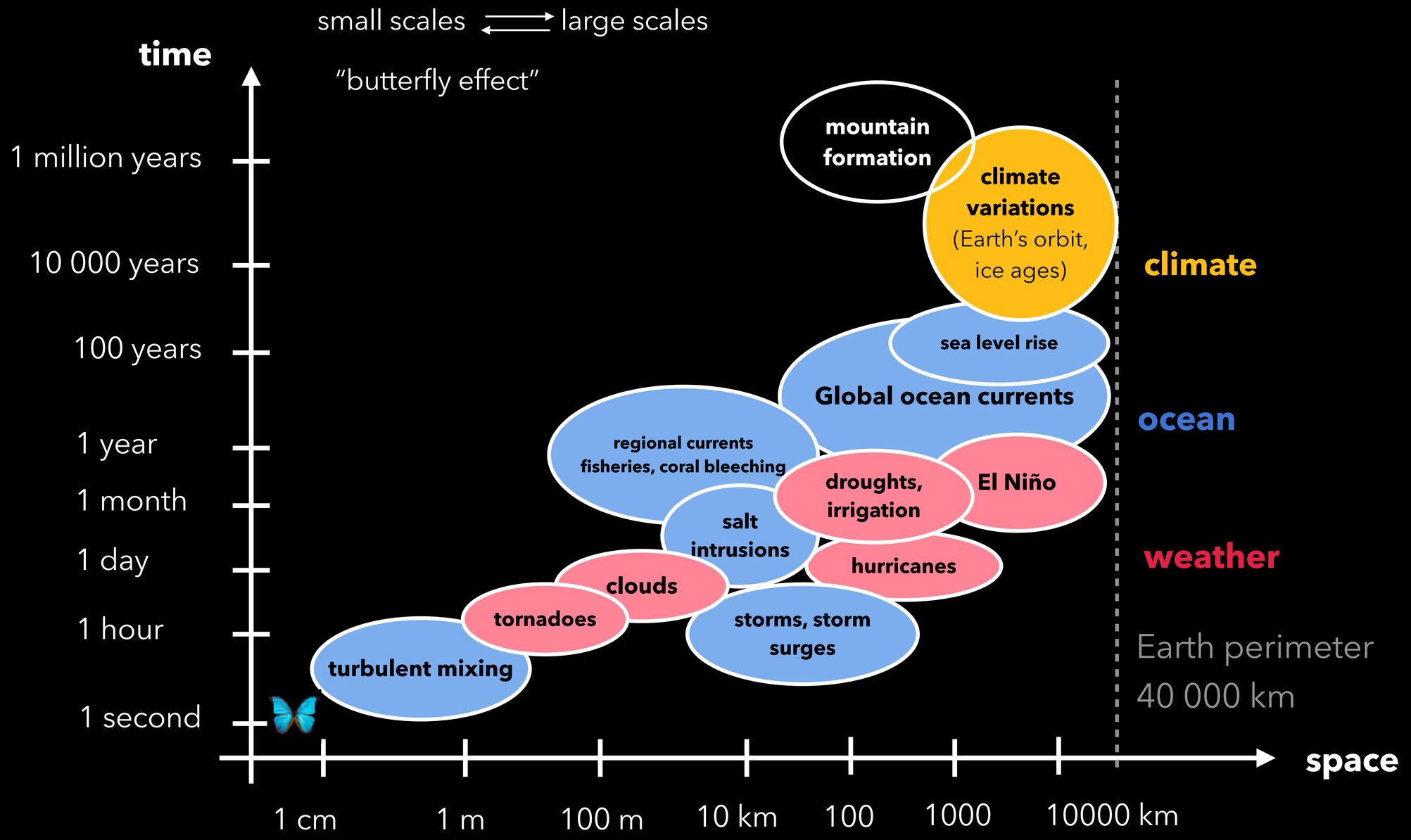


example of shear instabilities (wave roll-up)

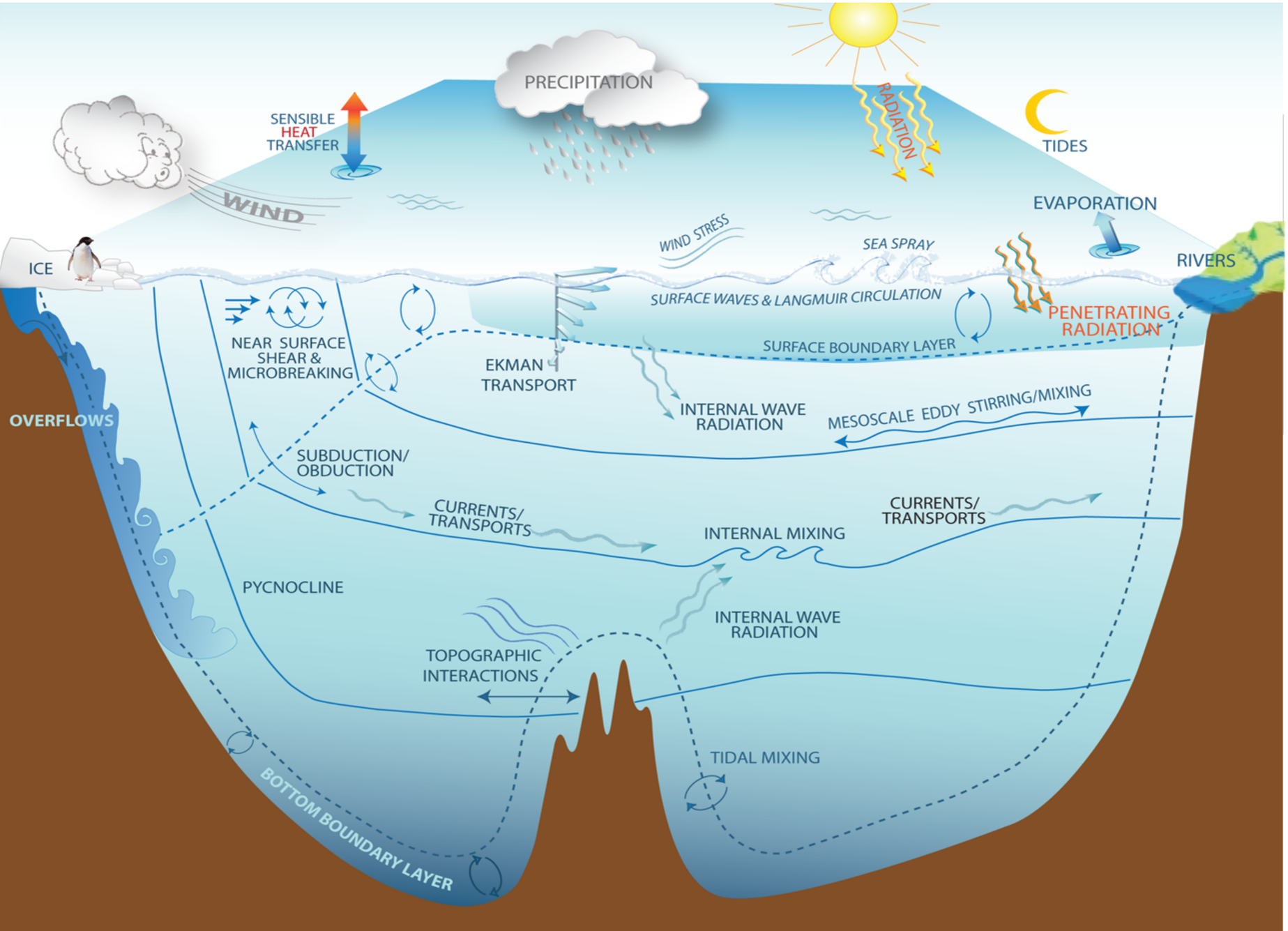
ZOOMED IN



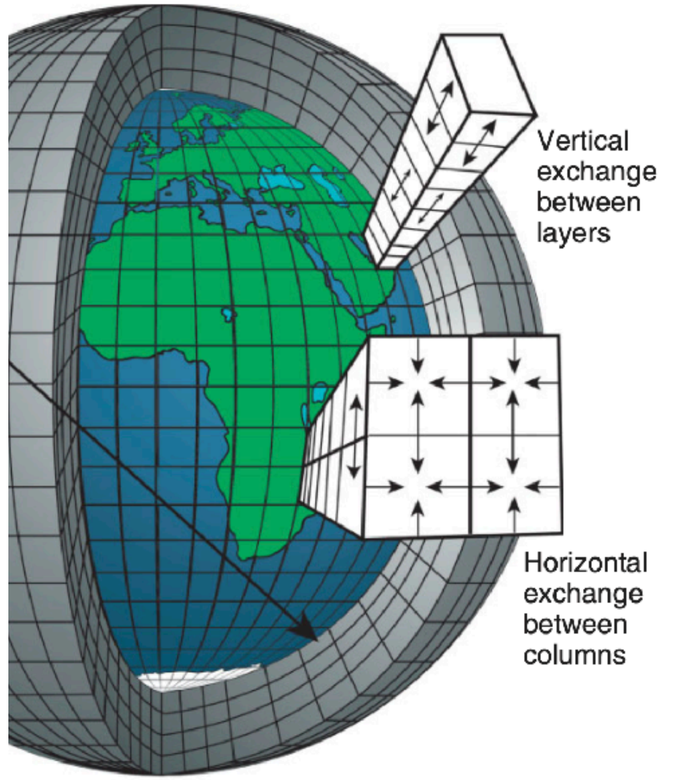
Physical and mathematical modelling = tools to study **nonlinear feedbacks** across time and space



The fascinating variety and complexity of ocean mixing processes



These processes are must be approximated or **"parameterised"** in computational models of the Earth (climate and weather)



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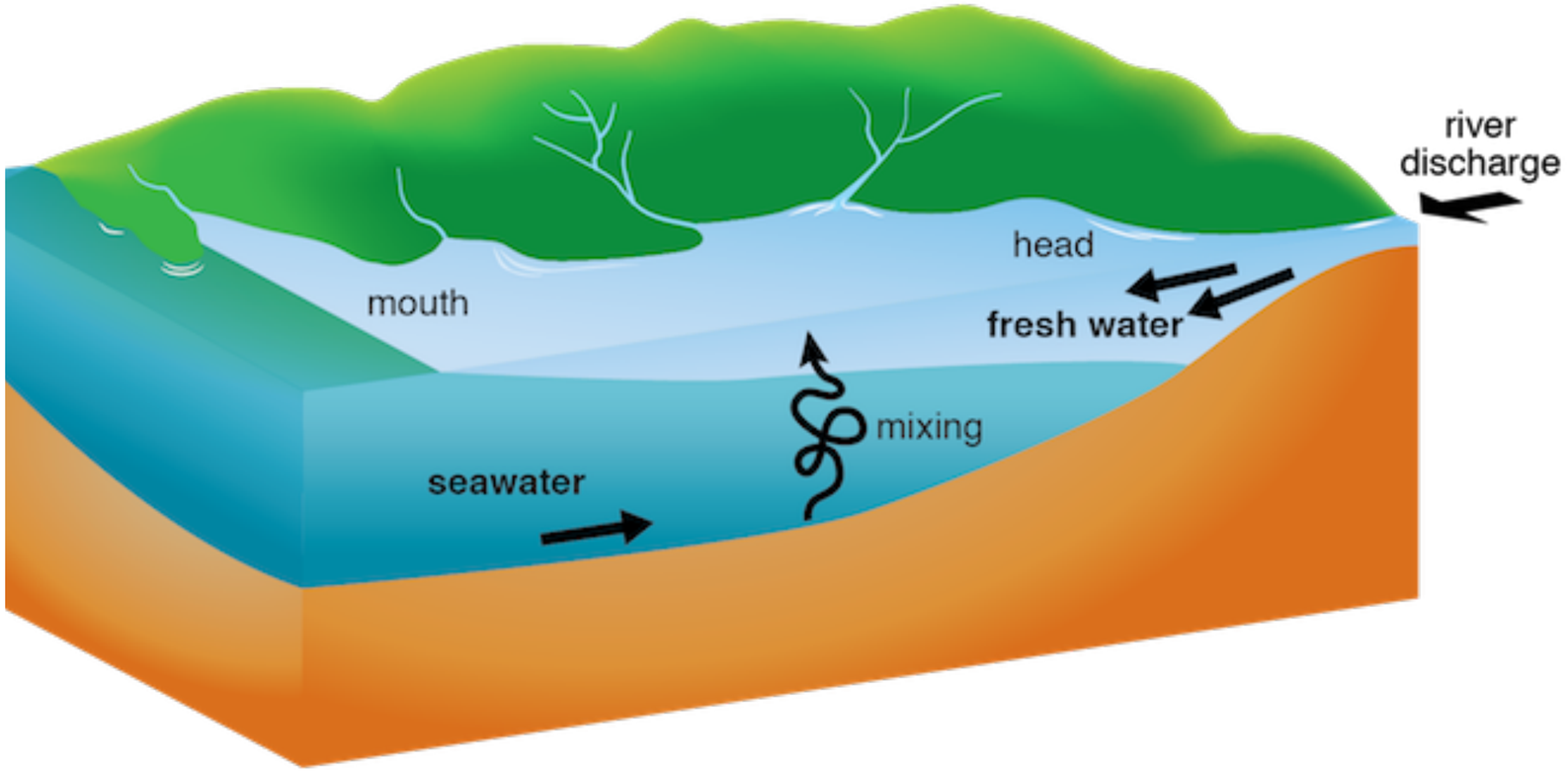
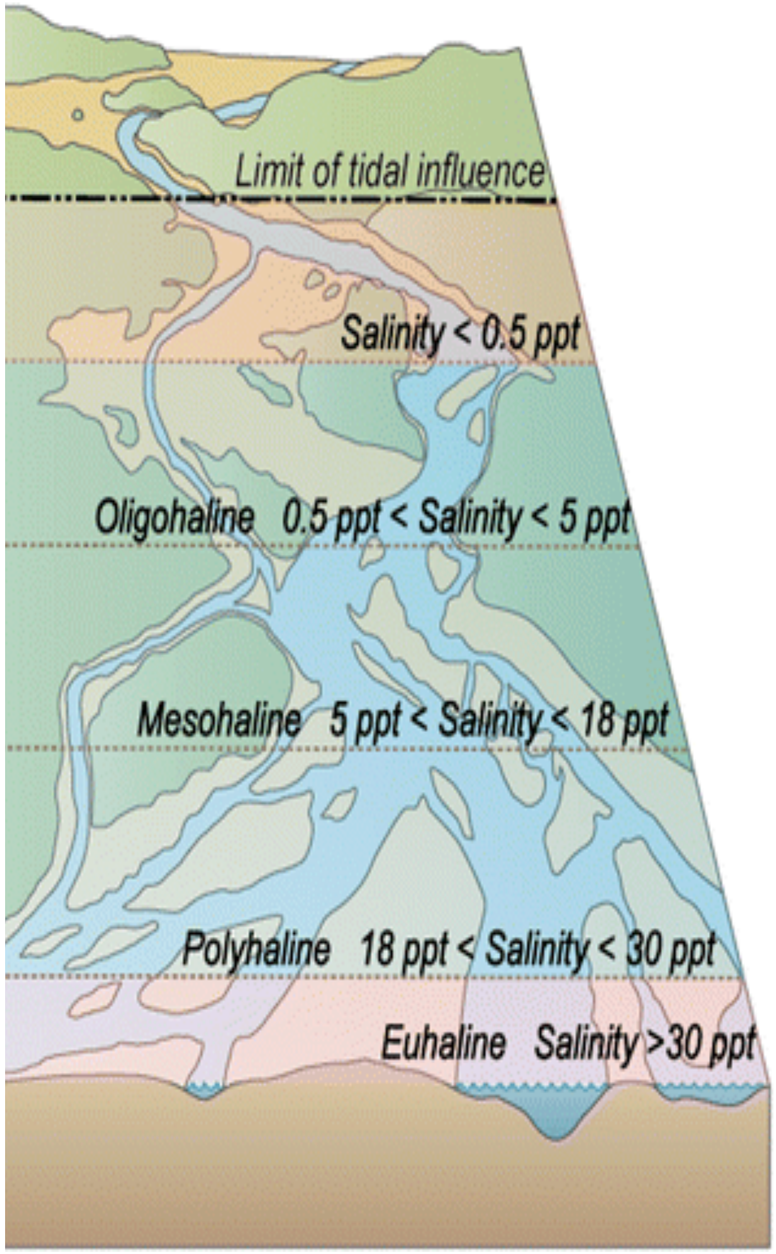
Estuaries are key transition zones between land and ocean

Estuaries are coastal embayments where **seawater mixes with freshwater**

Mixing controls the **circulation** and the **salinity stratification**

These affect **residence times and water quality** (pollution, oxygen etc)





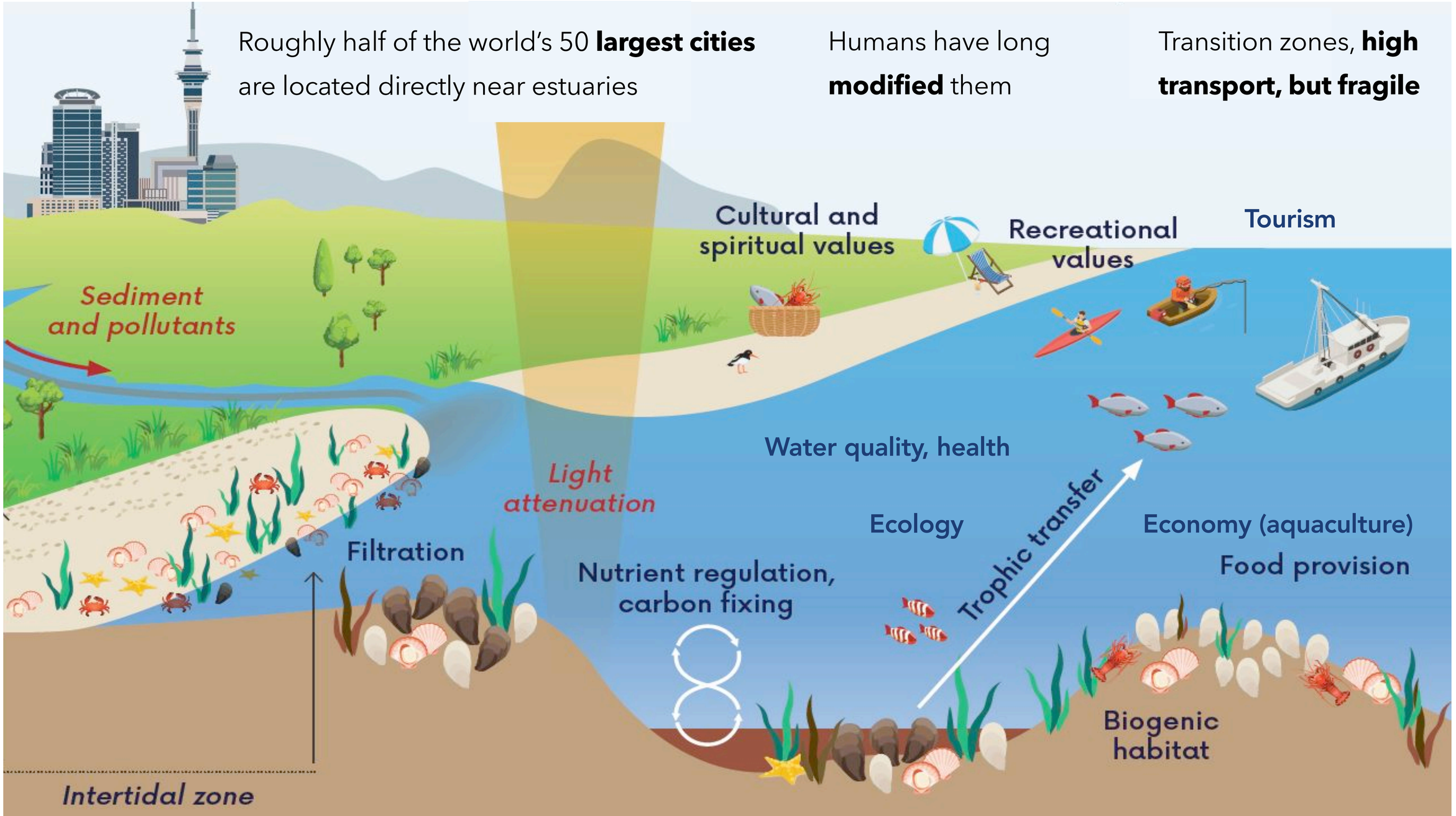
Estuaries provide vital services to society

SustainableSeasChallenge.co.nz

Roughly half of the world's 50 **largest cities** are located directly near estuaries

Humans have long **modified** them

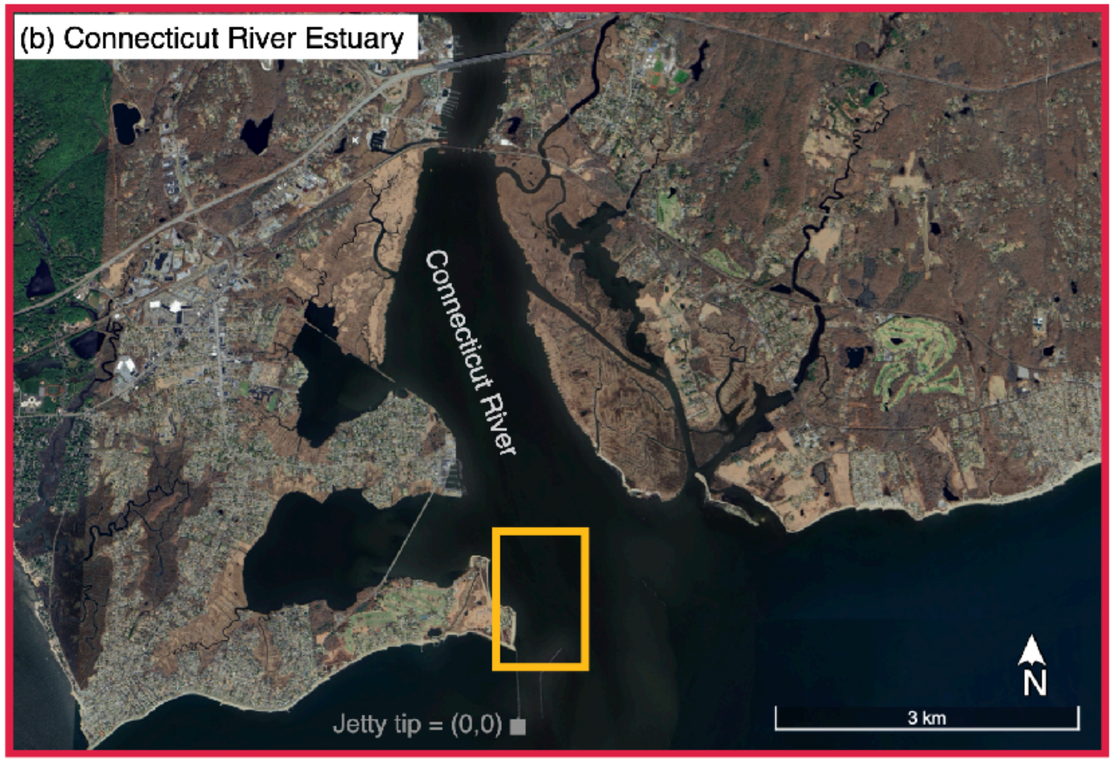
Transition zones, **high transport, but fragile**

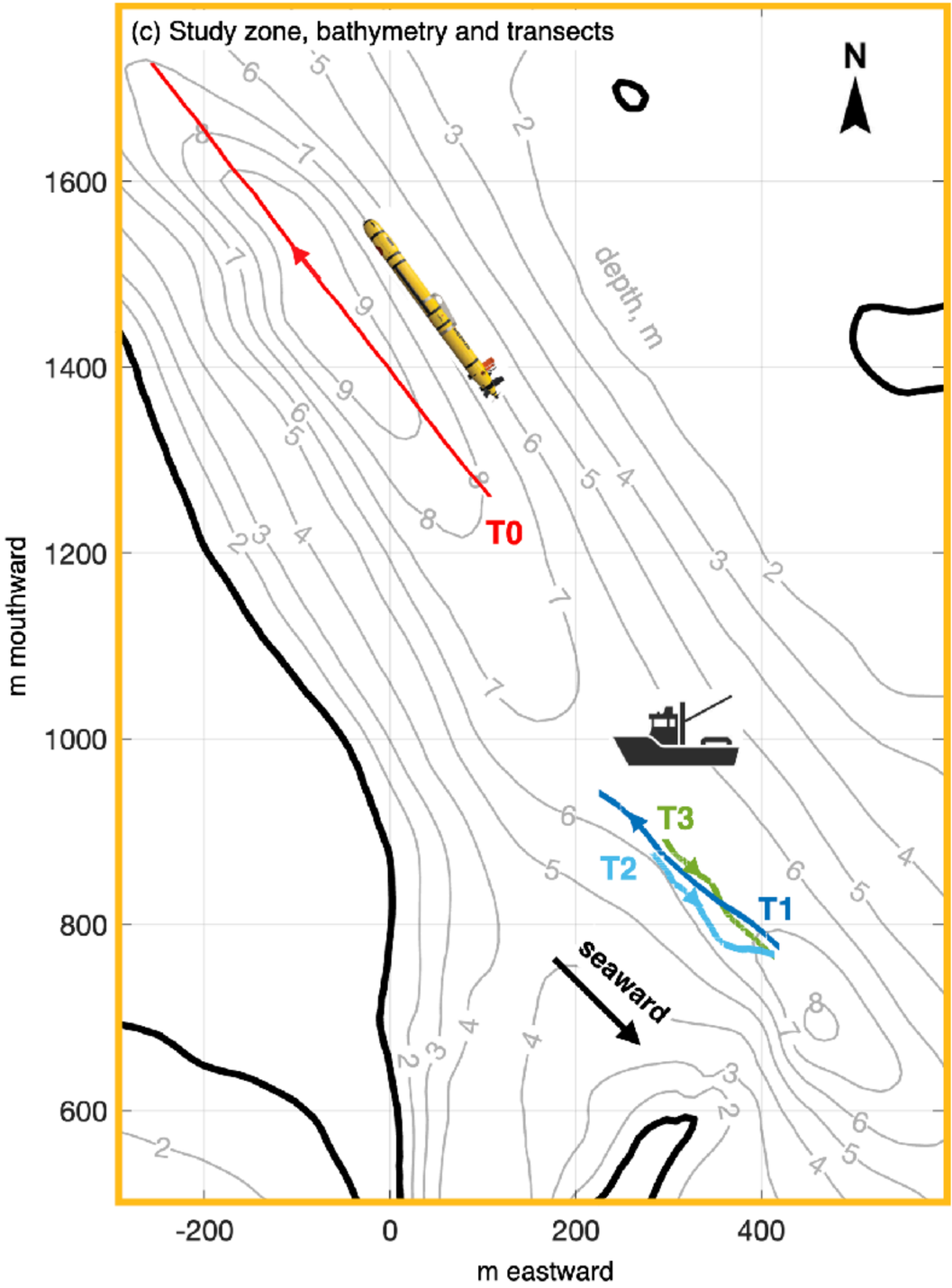


The site

WOODS HOLE OCEANOGRAPHIC INSTITUTION

Campaign
June 2017





The instruments

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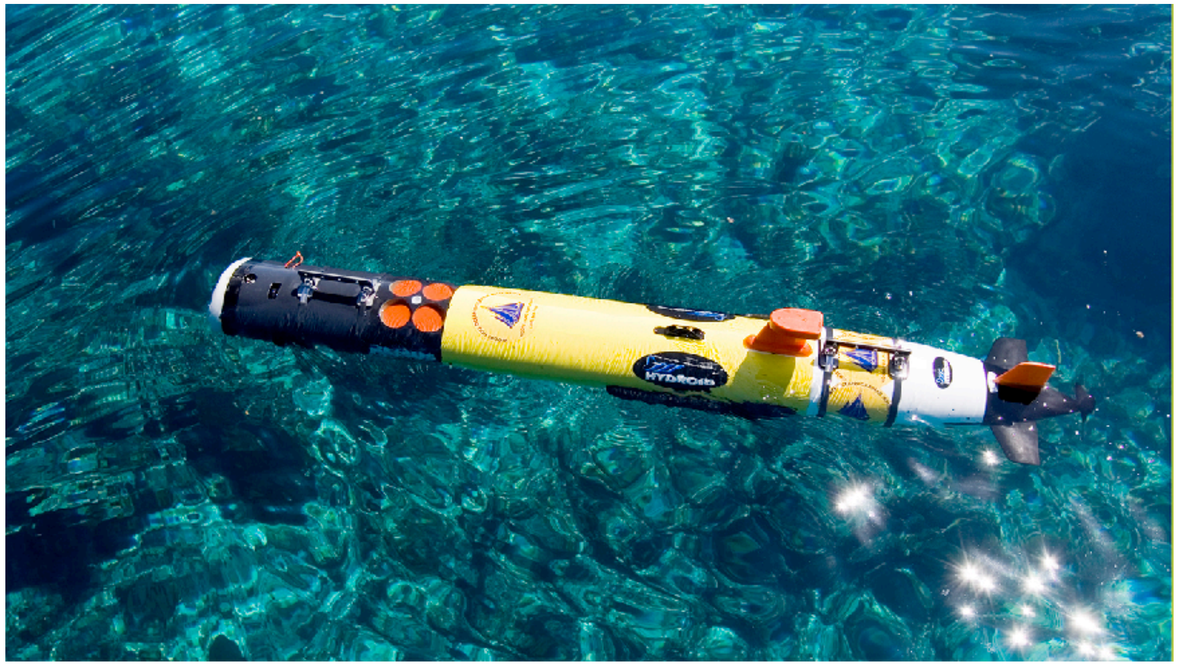
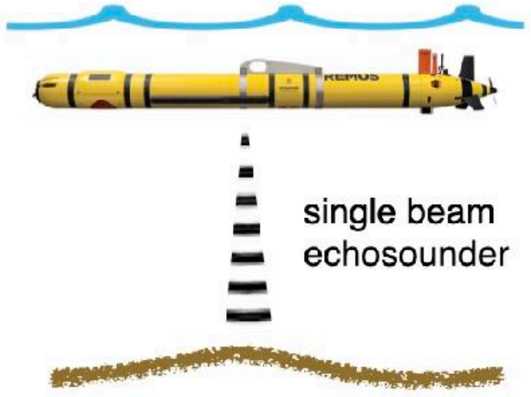
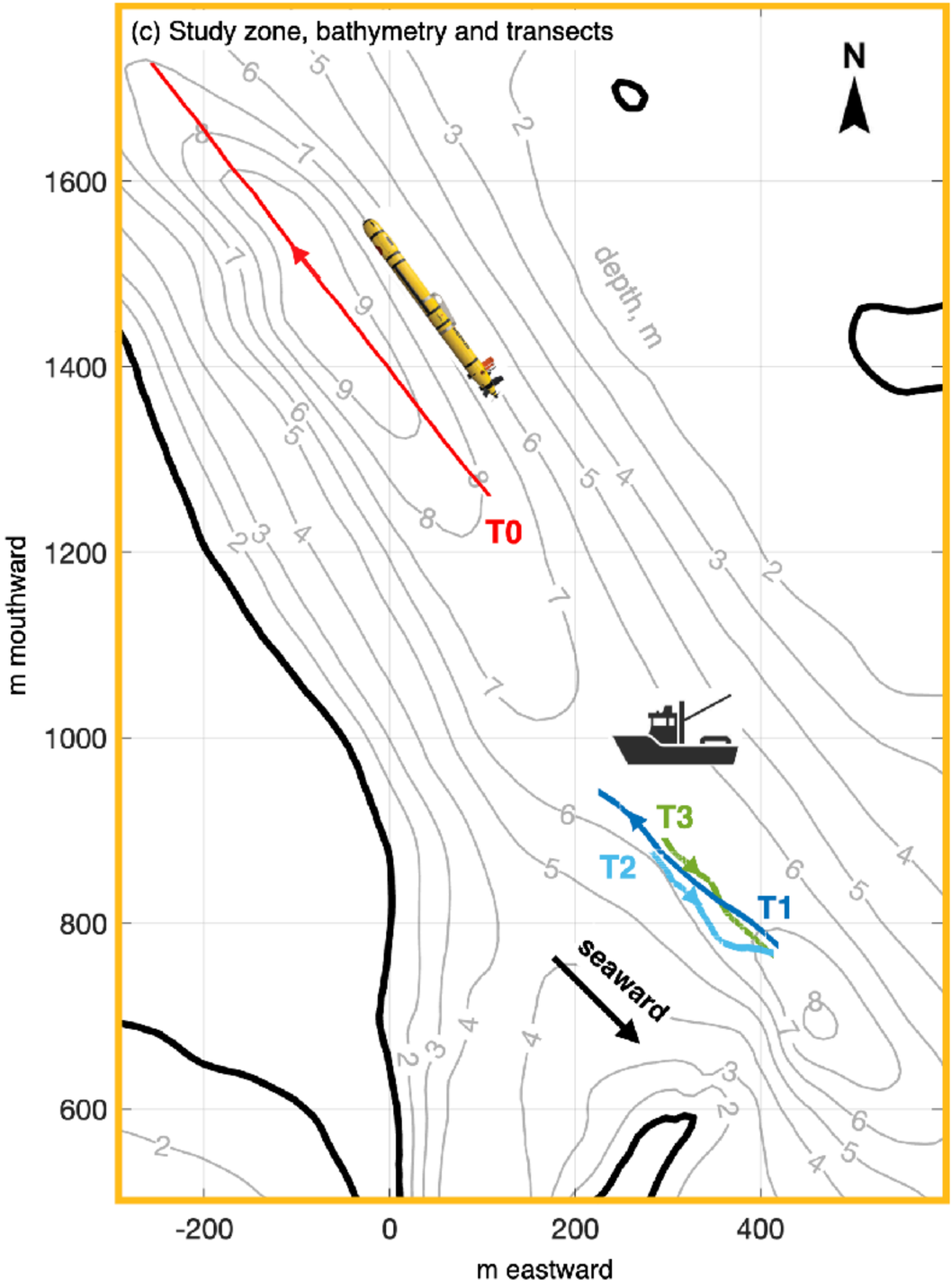


REMUS AUV → **Transect T0**

Autonomous Underwater Vehicle (AUV)





The instruments

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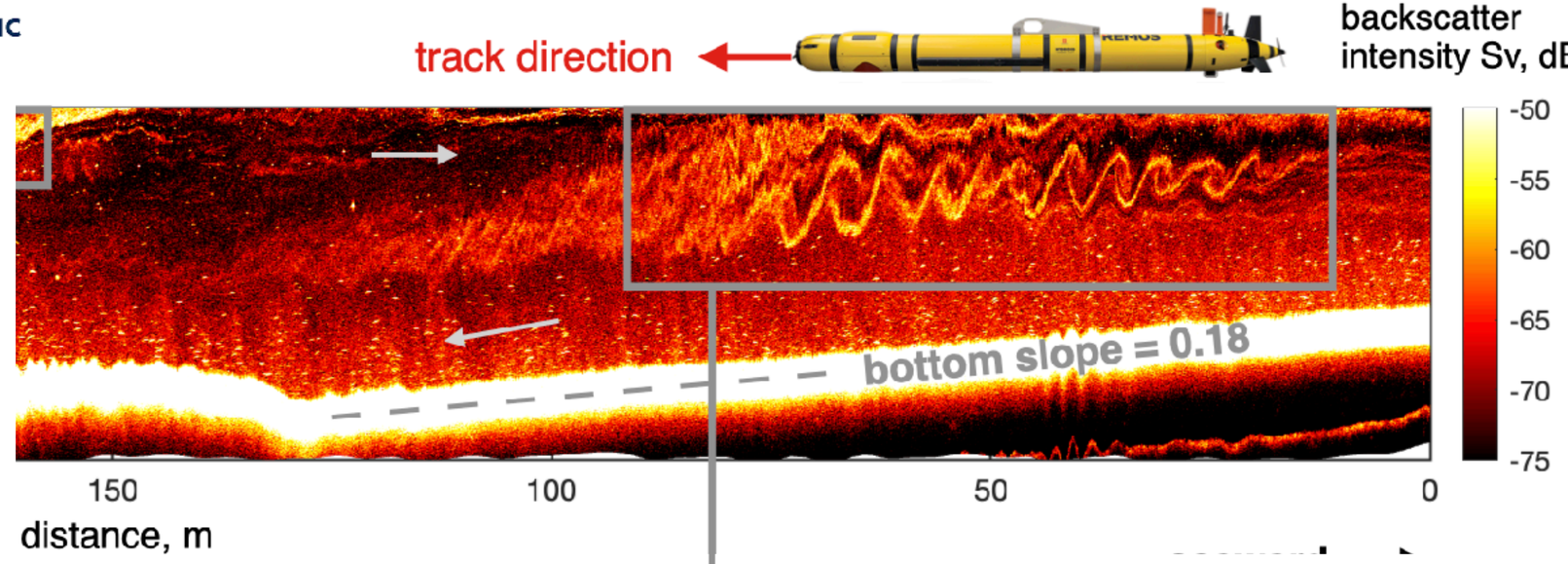
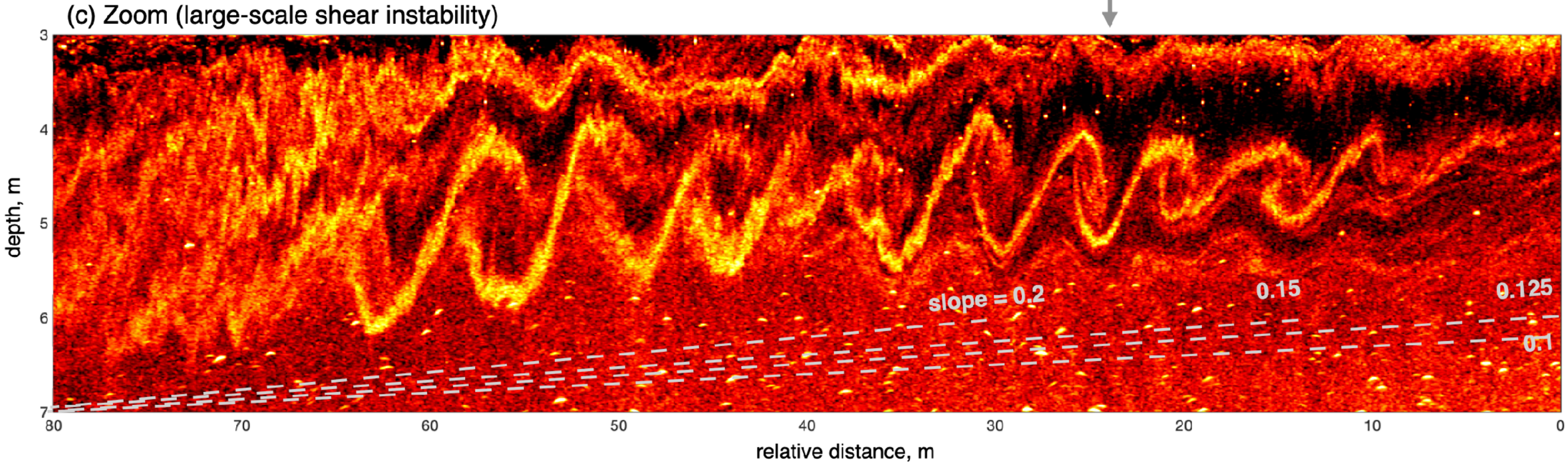
Acoustics data from the Autonomous Underwater Vehicle (AUV)

Scattering of ultrasound by turbulent mixing





Vertical exaggeration = 5 in all figures

The instruments

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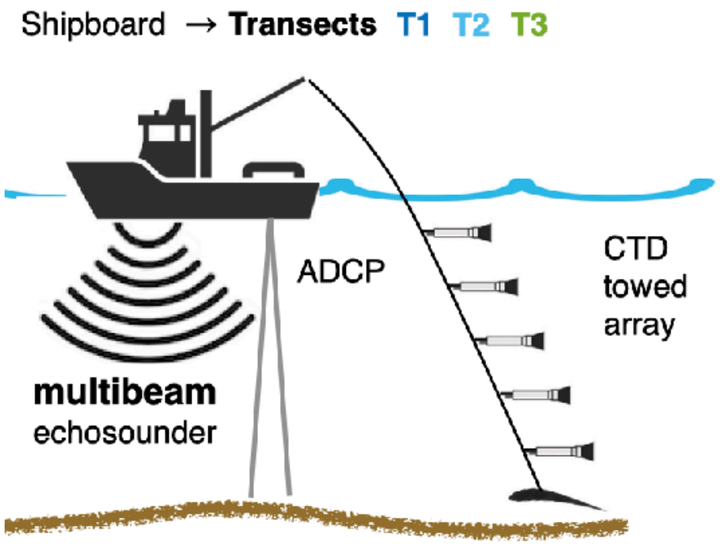
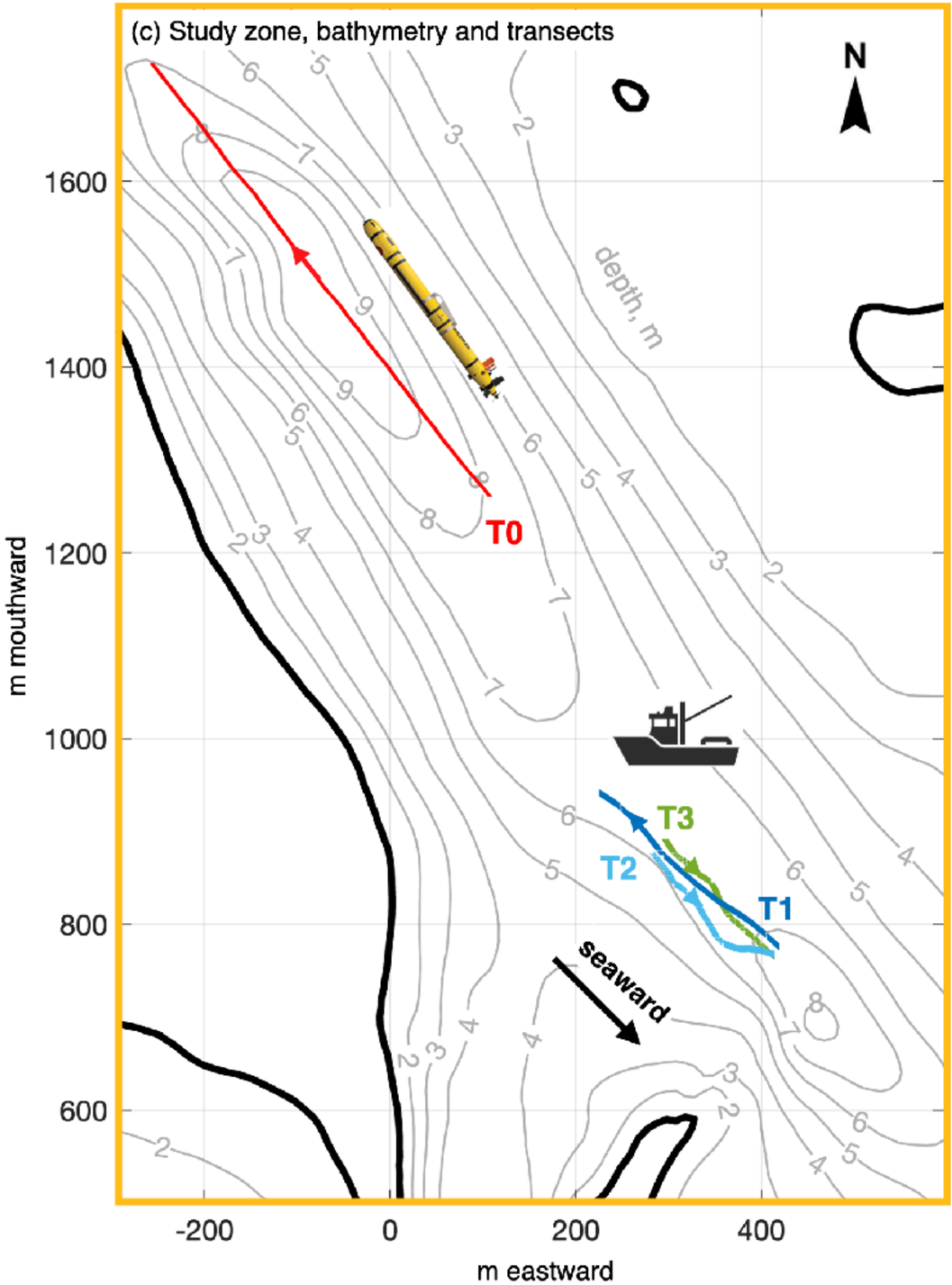


ADCP
Acoustic
Doppler
Current
Profiler

CTD =
Conductivity-
Temperature-
Depth



Shipboard transect T2

From the CTD (Conductivity-Temperature-Depth) towed array

The incoming flood tide tilts the salinity interface

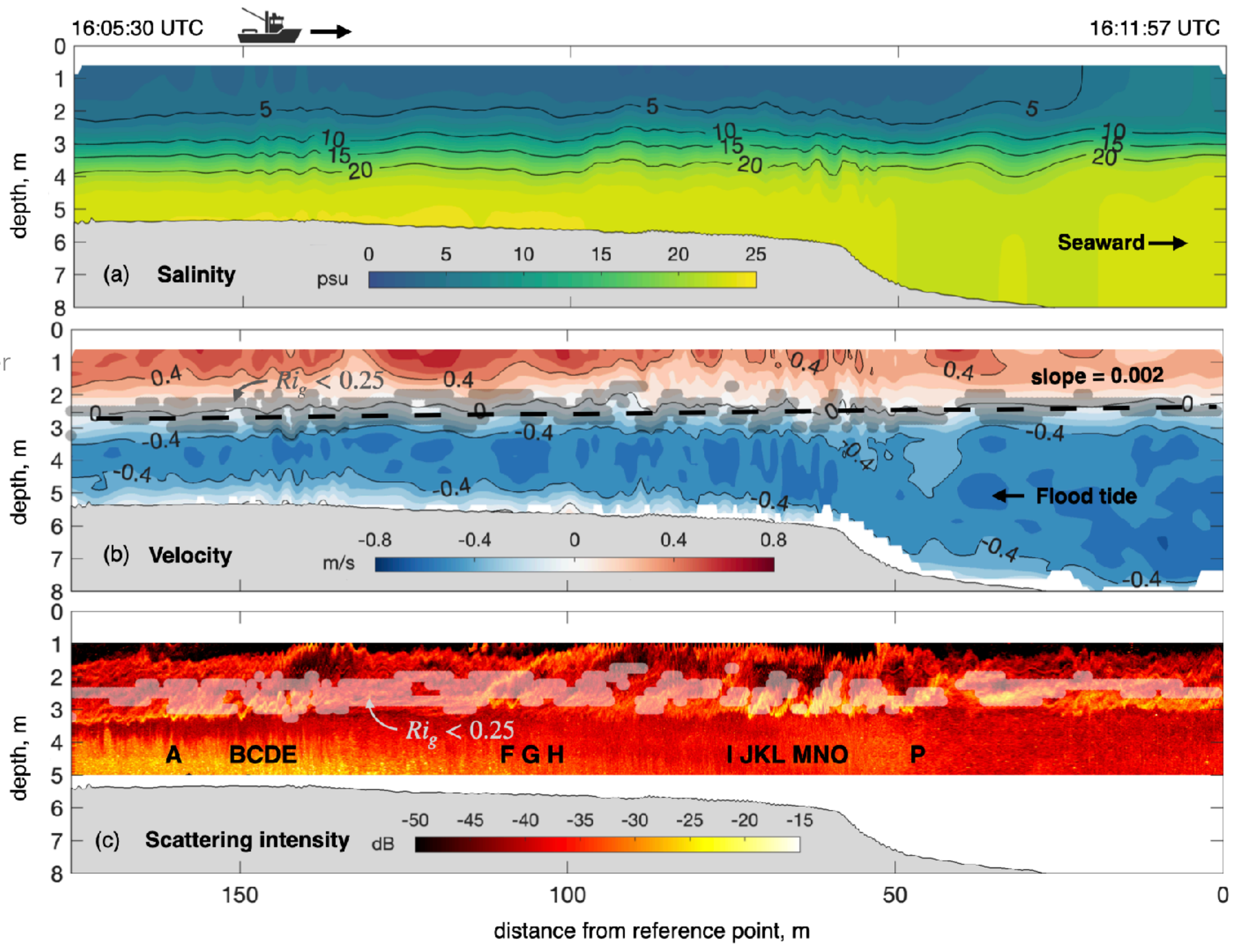
From the ADCP (Acoustic Doppler Current Profiler)

… and forces a strong shear

From the sonar (echosounder)

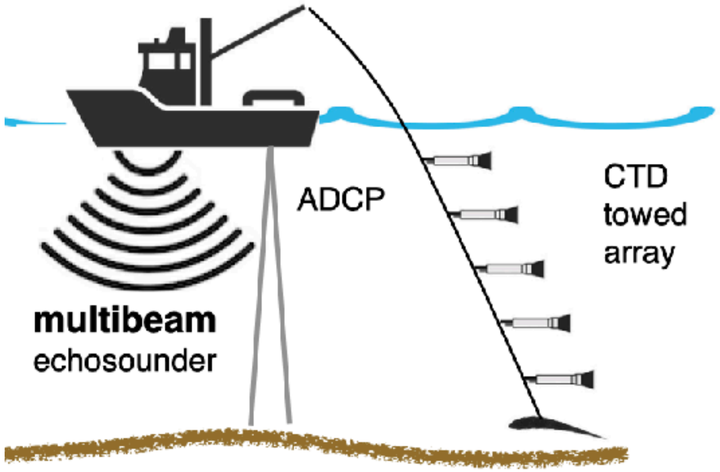
… which leads to shear instabilities and mixing

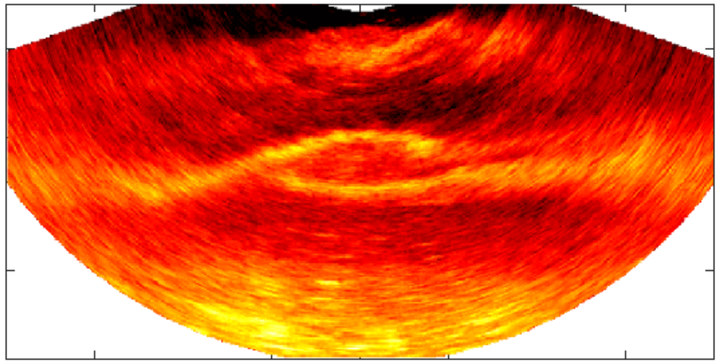
Location predictable by theory (white shading)



Game changer: multibeam sonar

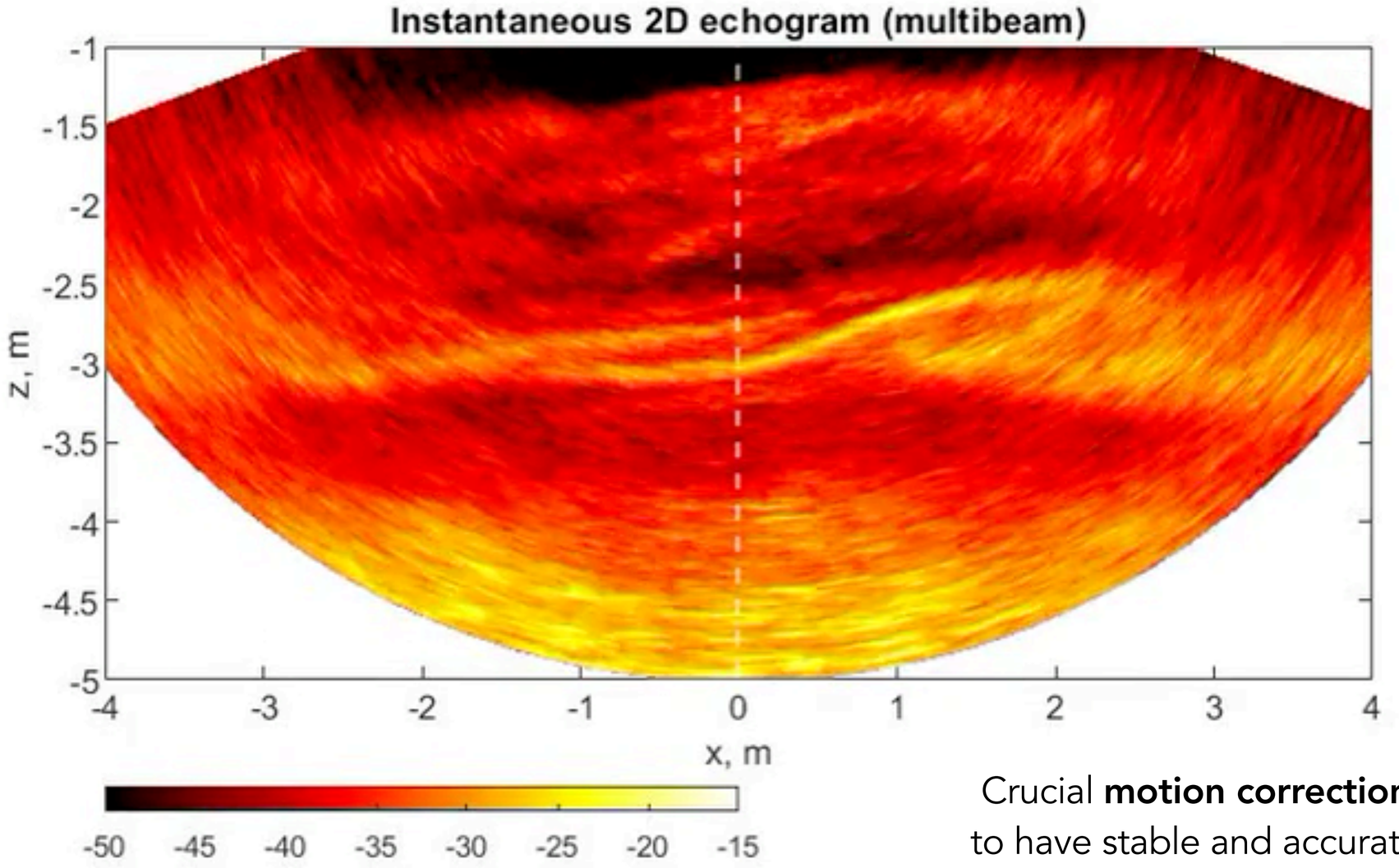
Shipboard → **Transects** T1 T2 T3





Combine 75 beams to create a 120 degree fan

New physics revealed by the multibeam sonar

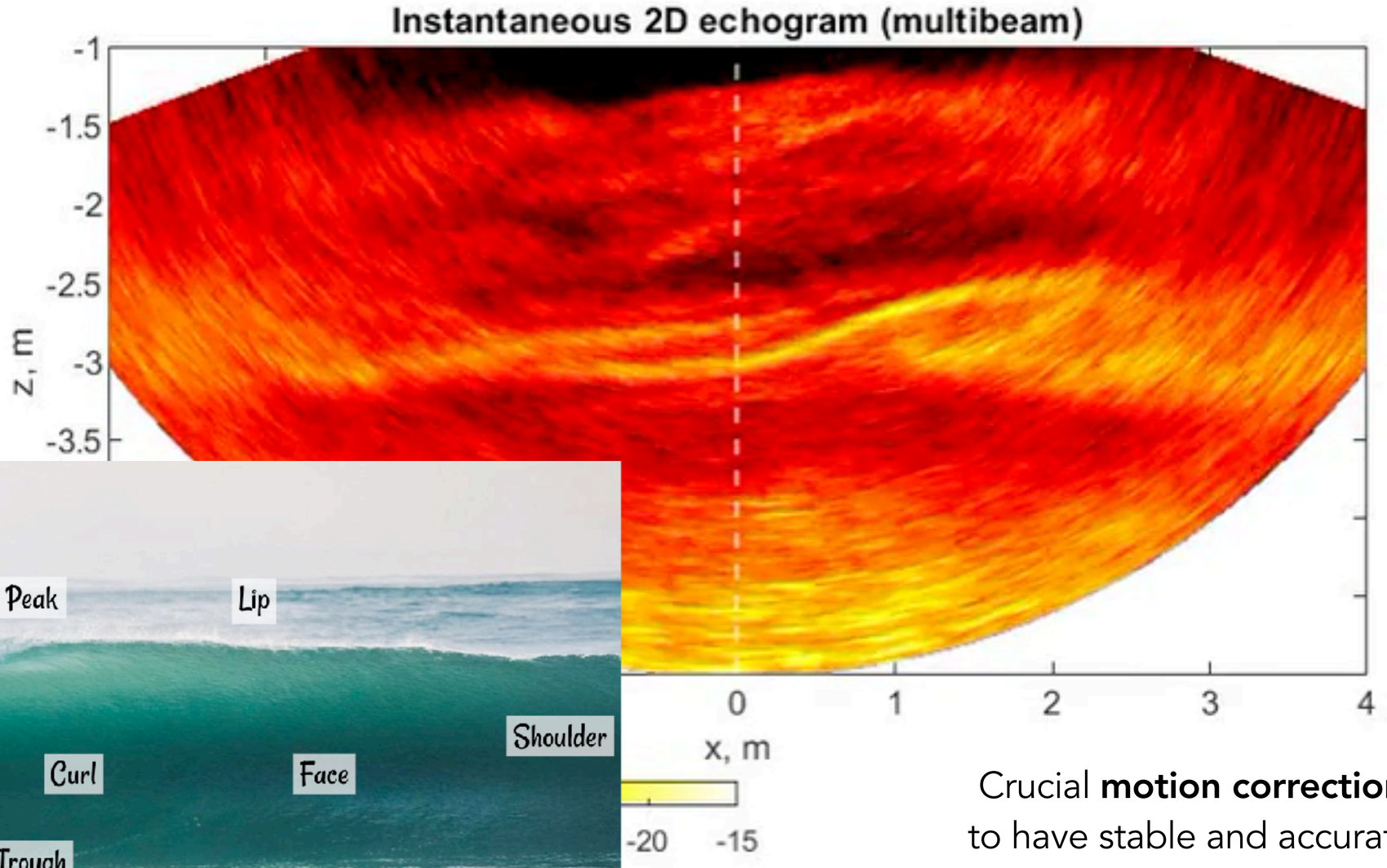


Crucial **motion correction** to have stable and accurate underwater imaging despite motion of the boat

New physics revealed by the multibeam sonar

Turbulence and mixing are **not in the ‘eye’** of the waves, but in the slopes and **‘eyelids’** surrounding them

The **waves faces do not steepen enough to cause a roll up** and ‘eye mixing’



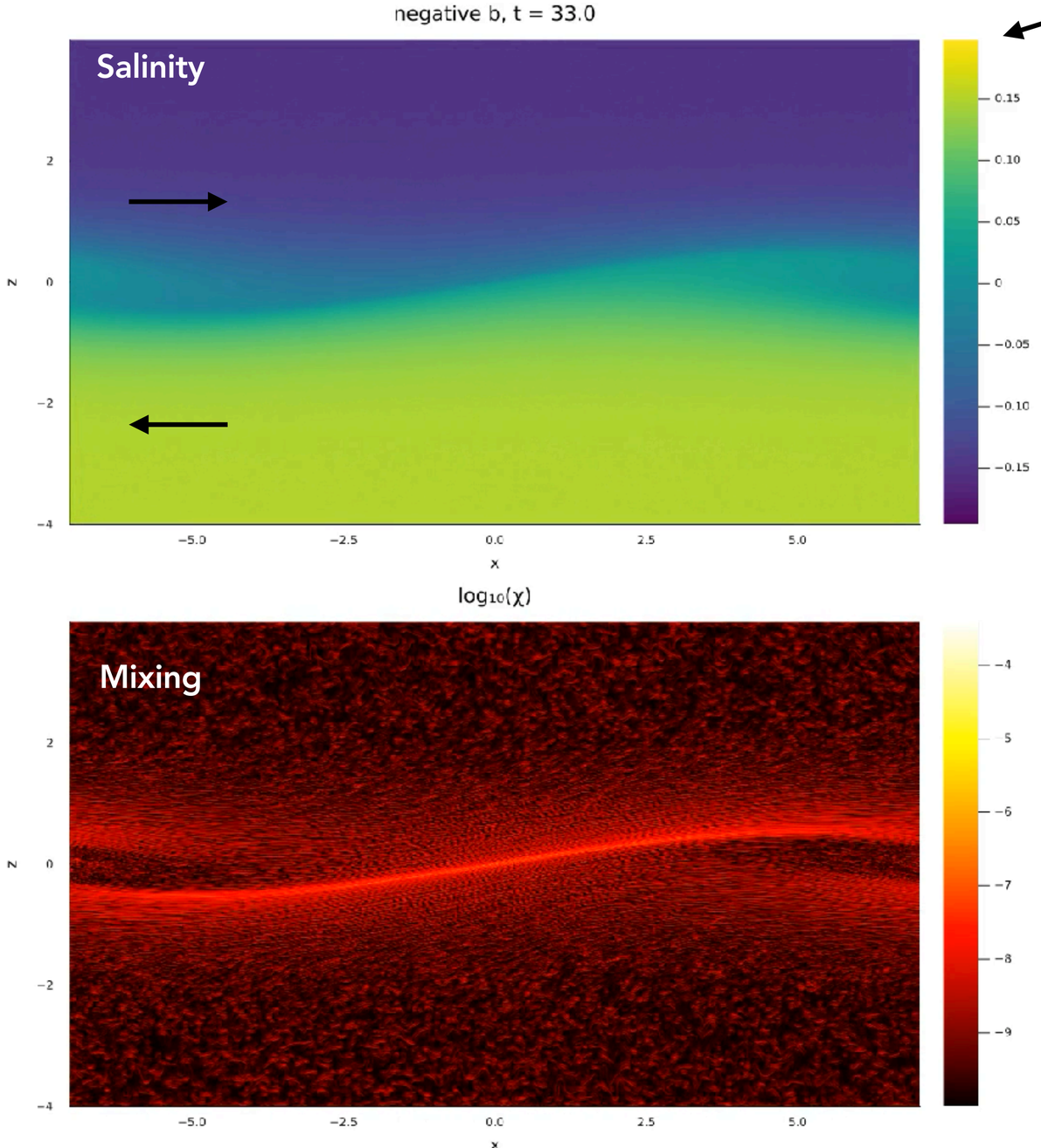
Crucial **motion correction** to have stable and accurate underwater imaging despite motion of the boat

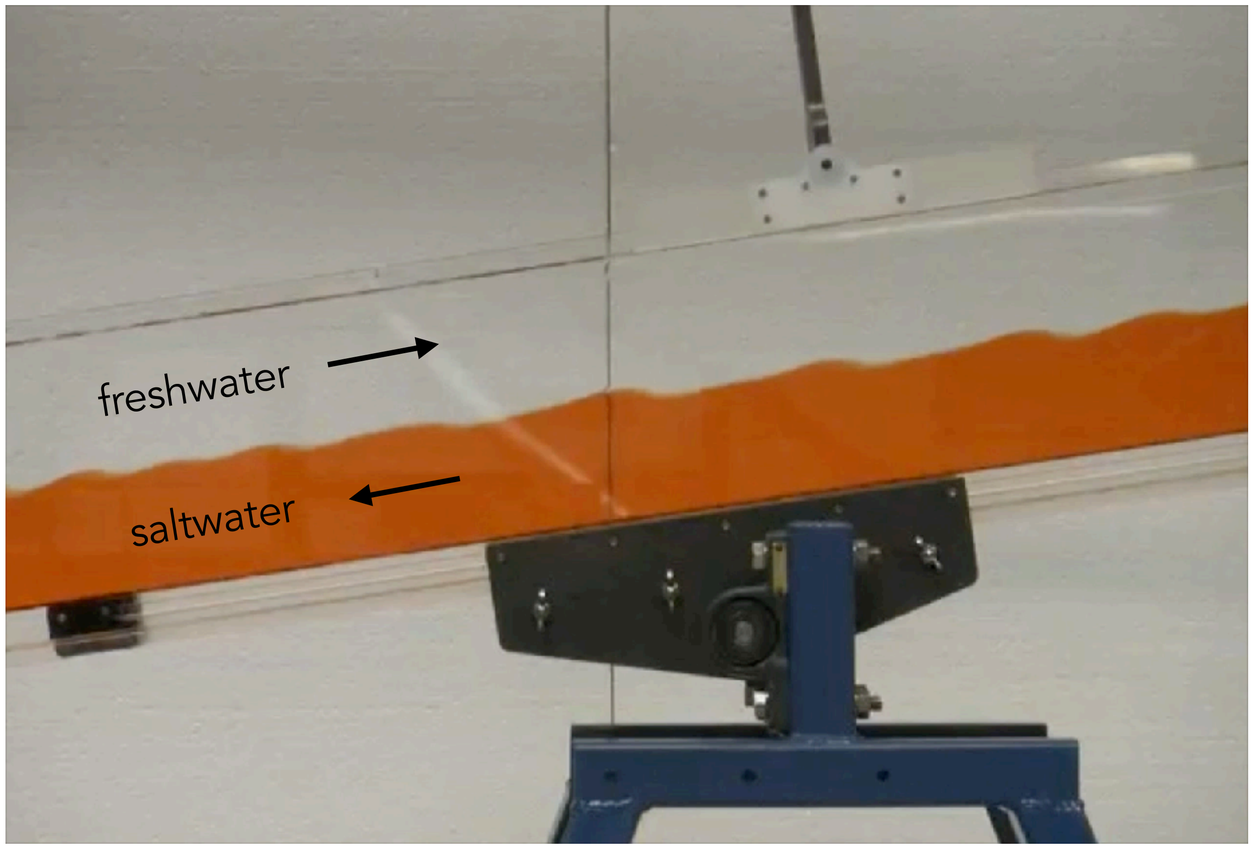
Mixing in the **‘eyes’** at **laboratory** scales

2D grid 12 000 x 12 000, run on a GPU

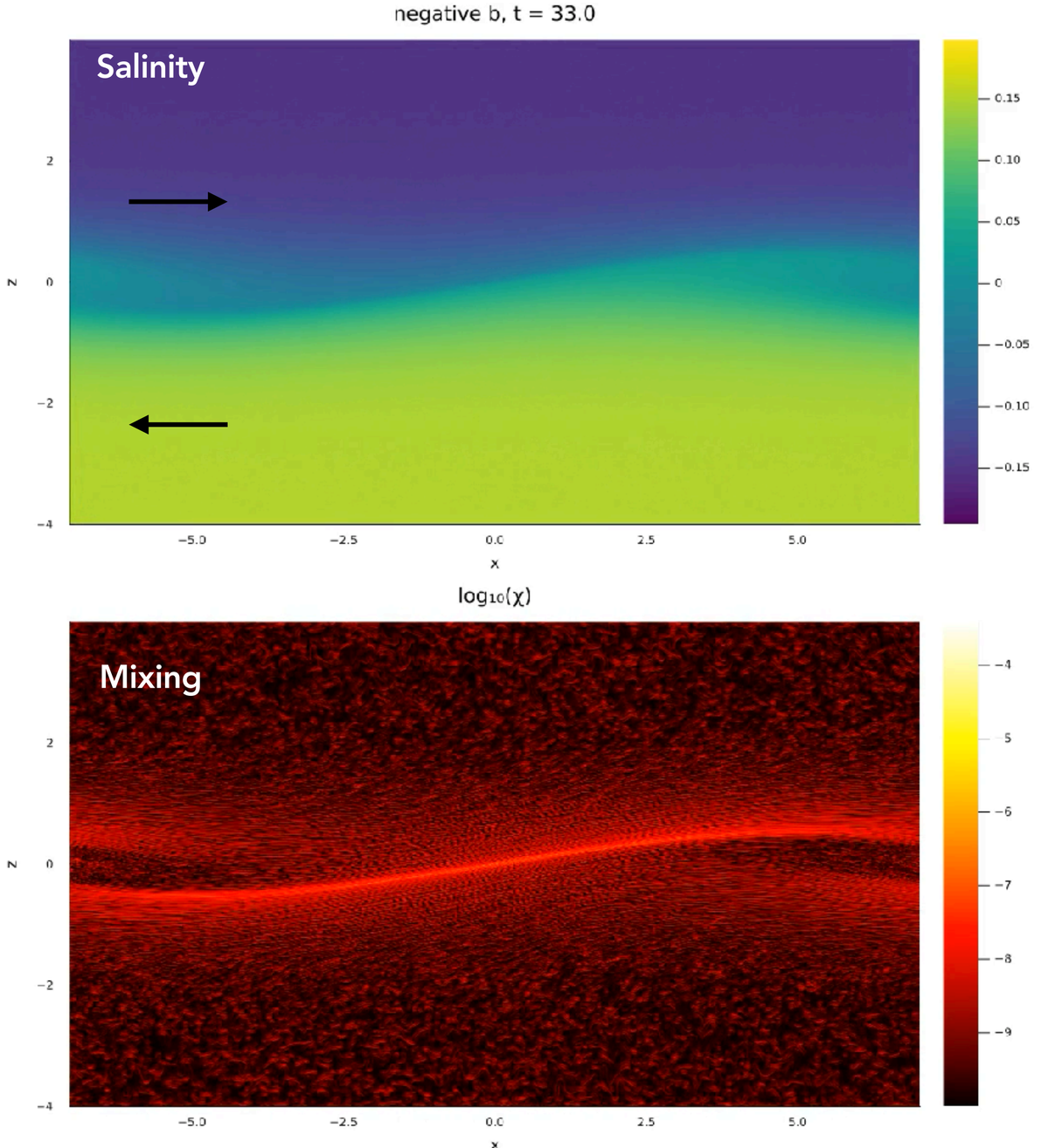
Numerical simulation = mathematical solution of the equations of fluid dynamics on supercomputer

Laboratory experiment = the truth?

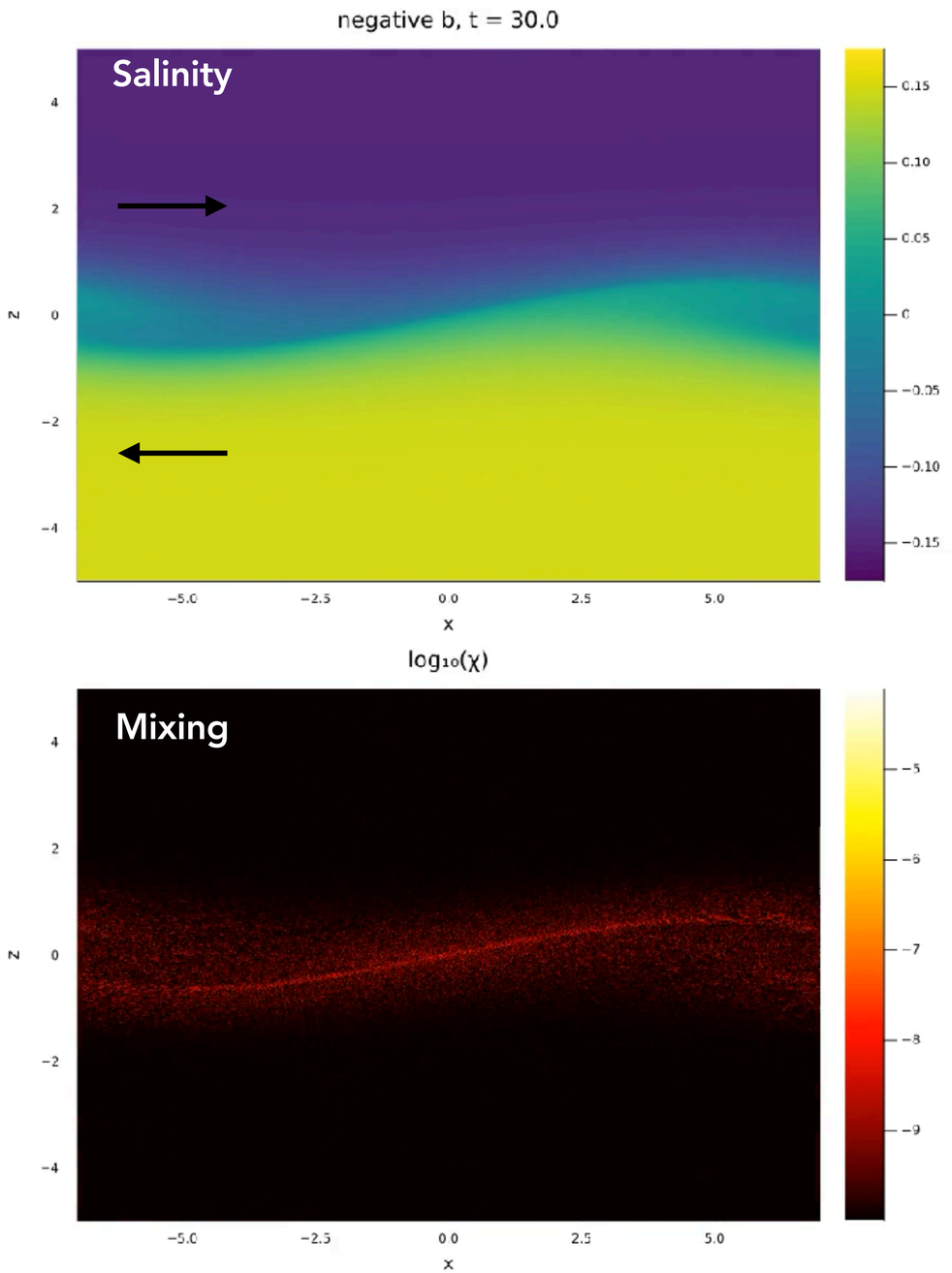




Mixing in the **‘eyes’** at **laboratory** scales



Mixing in the **‘eyelids’** at **field** scales



Mixing in the **'eyes'** at **laboratory** scales

Mixing in the **'eyelids'** at **field** scales

flow speed — thickness of the layer

The difference lies in the **Reynolds number** $Re = \frac{UH}{\nu}$ (a dimensionless parameter)

viscosity of the water

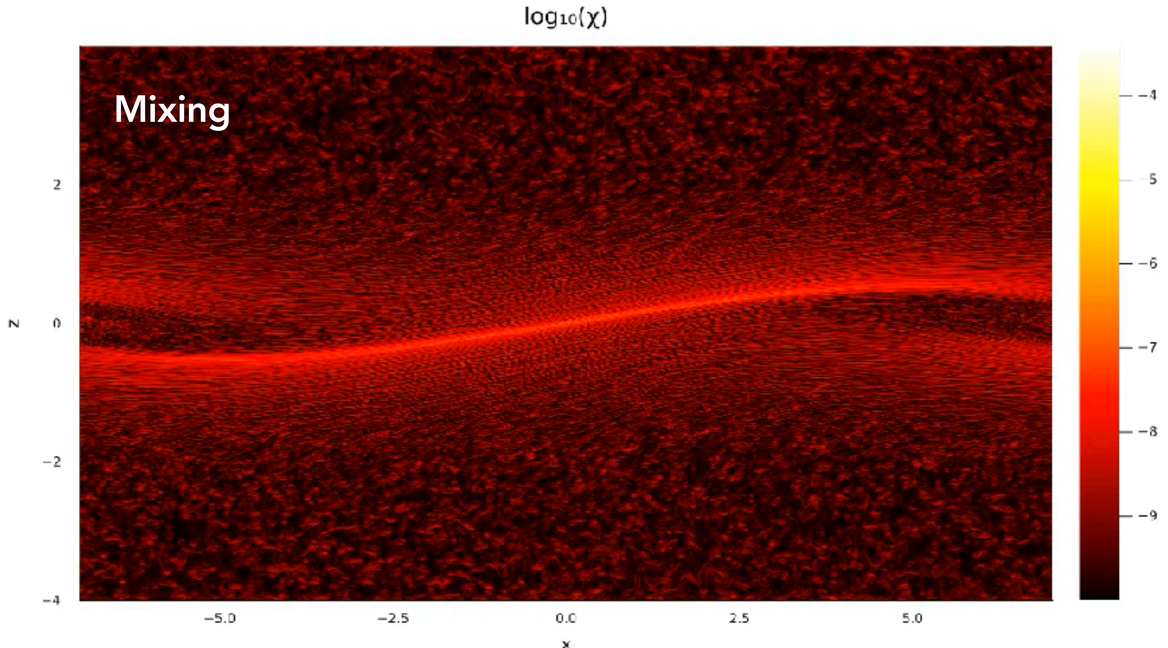
Estimates: 10 cm/s, 10 cm

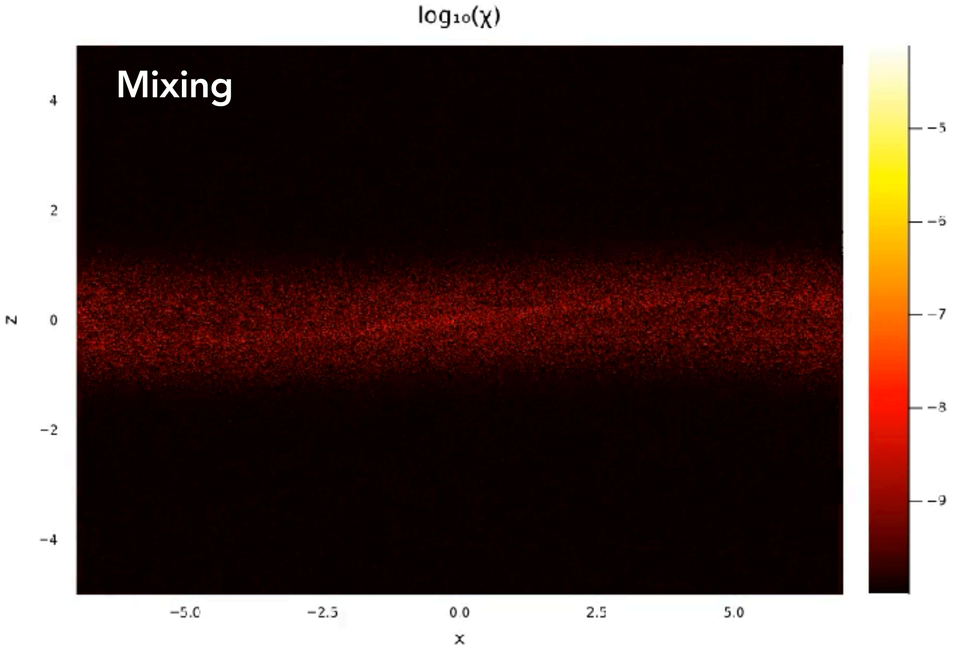
$$Re = \frac{UH}{\nu} \approx \frac{0.1 \times 0.1}{10^{-6}} \approx 10^4$$

50 cm/s, 2 m

$$Re = \frac{UH}{\nu} \approx \frac{0.5 \times 2}{10^{-6}} \approx 10^6 \quad \text{(actually } 8 \times 10^5\text{)}$$

100 times larger in the field! → secondary instabilities (fractal)





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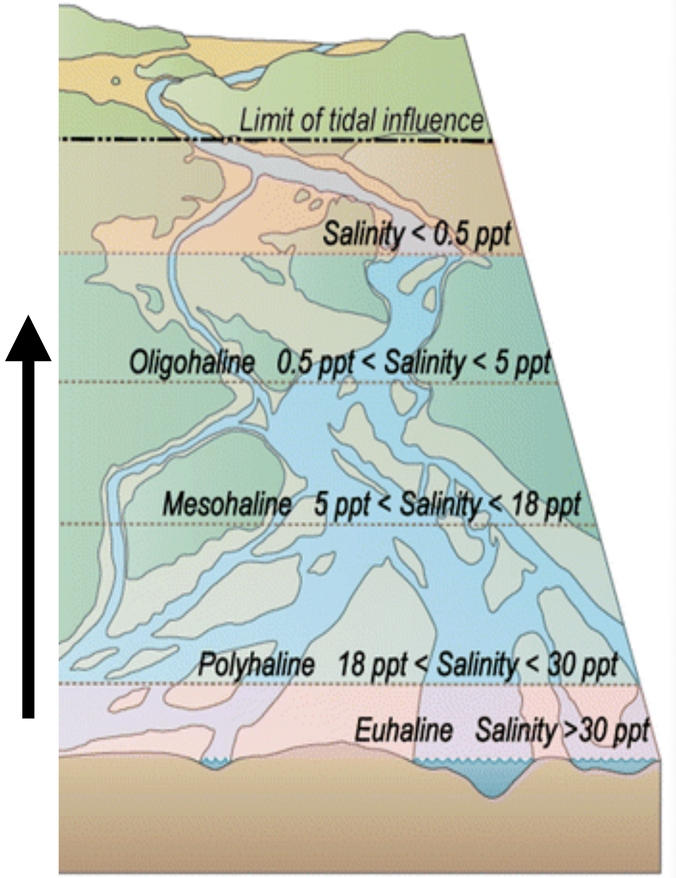
Example 1:

Saltwater intrusions

temporary or permanent **migration** of salt up river

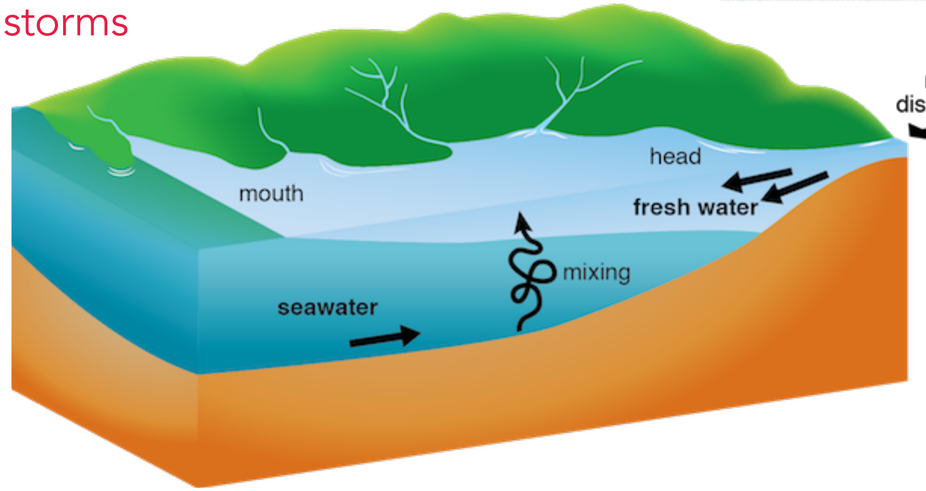


Impacts:

- Drinking water
- Agriculture, irrigation
- Biodiversity

sea-level rise

storms



droughts

Saltwater intrusions: the humanitarian cost

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The great salt drought desiccating Vietnam's Mekong Delta

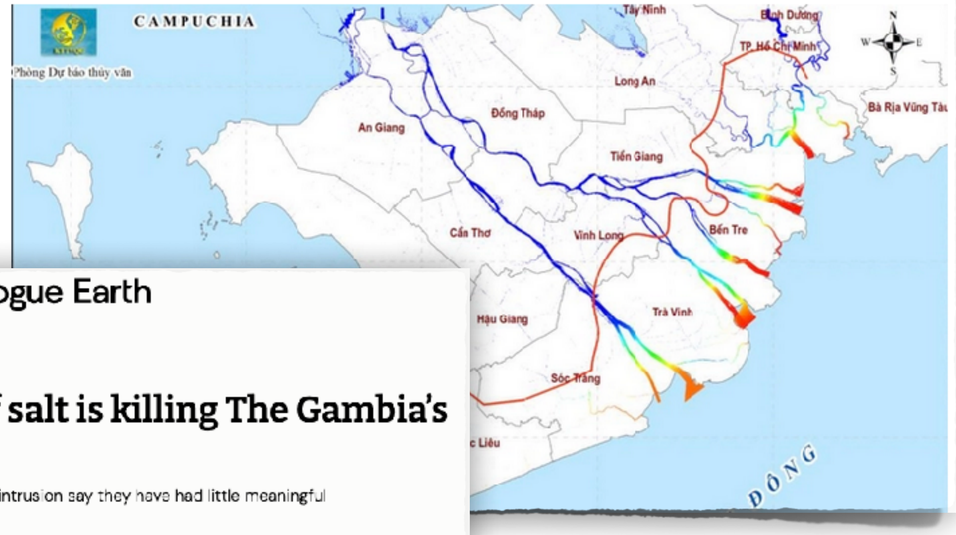
Farmers suffer huge losses and communities struggle amid high levels of seawater intruding into the freshwater delta.

Vietnam News Ho Chi Minh City Travel Economy Education

Vietnam News | Saturday, February 1, 2025, 11:10 GMT+7

Severe saltwater intrusion persists in Vietnam's Mekong Delta during Tet

Experts predicted that salt levels will remain high in the first days of February before gradually decreasing



bangla news বাংলা English

Rising salinity threatens lives and livelihoods in coastal Bangladesh

Published by: Daily Star
ago

TOPICS EXPLORE PROJECTS

Dialogue Earth

FOOD

'We have no one to help us': A tide of salt is killing The Gambia's rice

Farmers scrambling to defend lands and livelihoods from crop-devastating salt intrusion say they have had little meaningful support from the state

Increasingly urgent issue in the **world's big deltas**: Mississippi, Ganges-Brahmaputra, Mekong, Rhine-Meuse, Po…

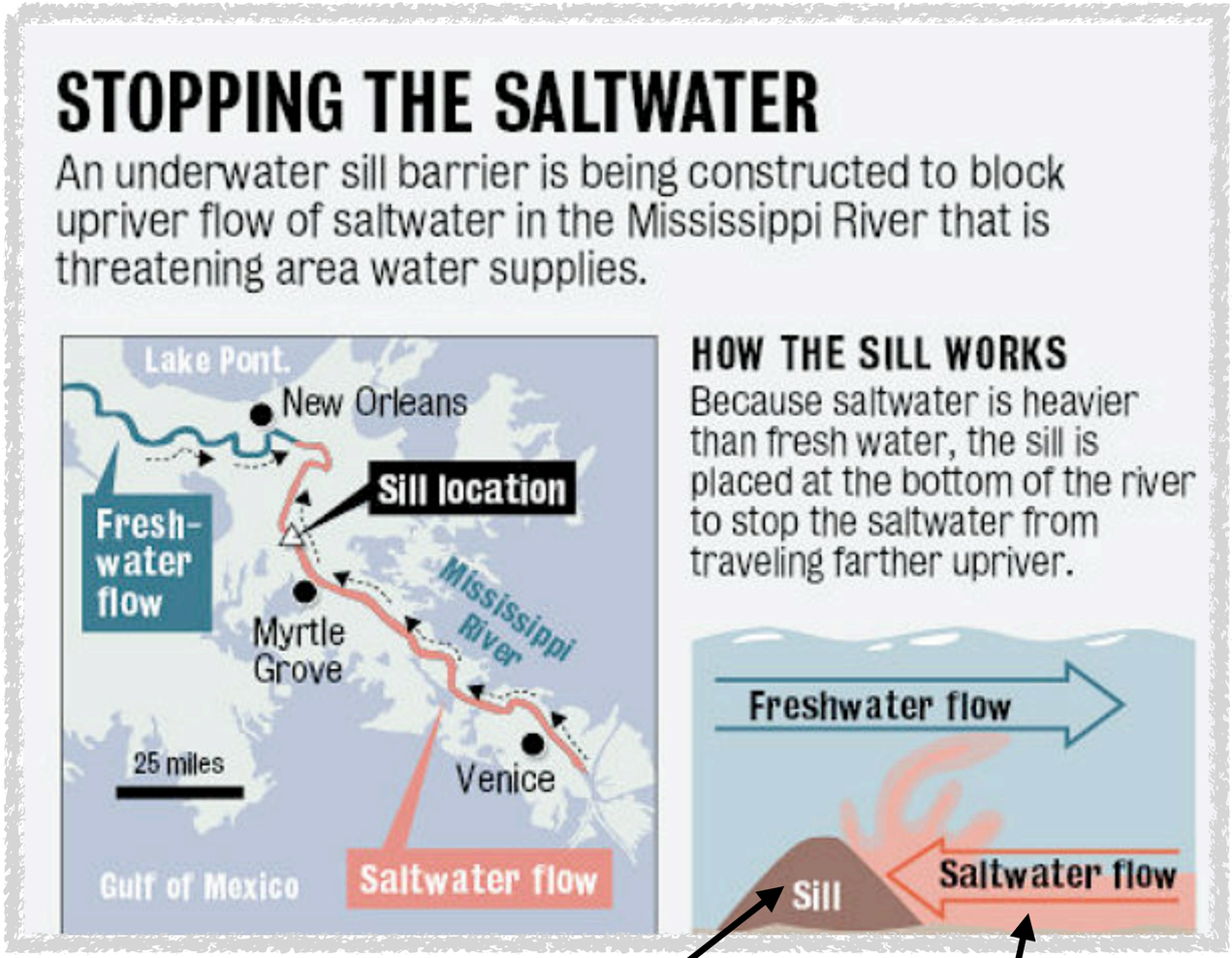
Saltwater intrusions mitigation: the engineering response

CNN Politics

Biden approves emergency declaration in Louisiana for saltwater intrusion that threatens New Orleans

By Ella Nilsen and Betsy Klein, CNN
Published 12:33 PM EDT, Wed September 27, 2023

Pipes carrying sediment crisscross the Mississippi River where the US Army Corps of Engineers is building up an underwater sill intended slow the flow of saltwater up the Mississippi River south of New Orleans on Tuesday. Chris Granger/AP



Will the sill stay here or move? → **sediment transport**

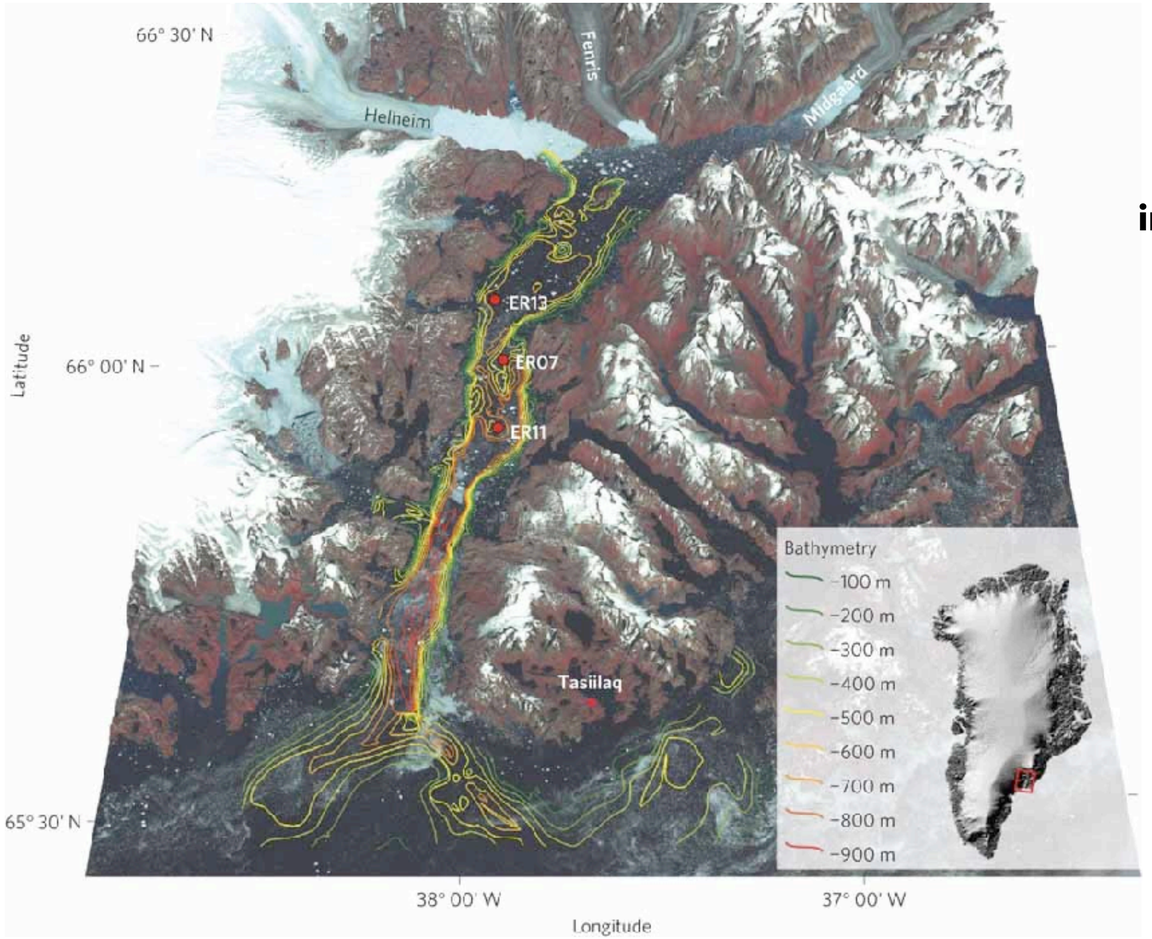
Will the saltwater mix and flow over the sill? → **hydraulics**

Also dredging, locks, bubble curtains… Adaptation in **high-income vs low-income** countries?

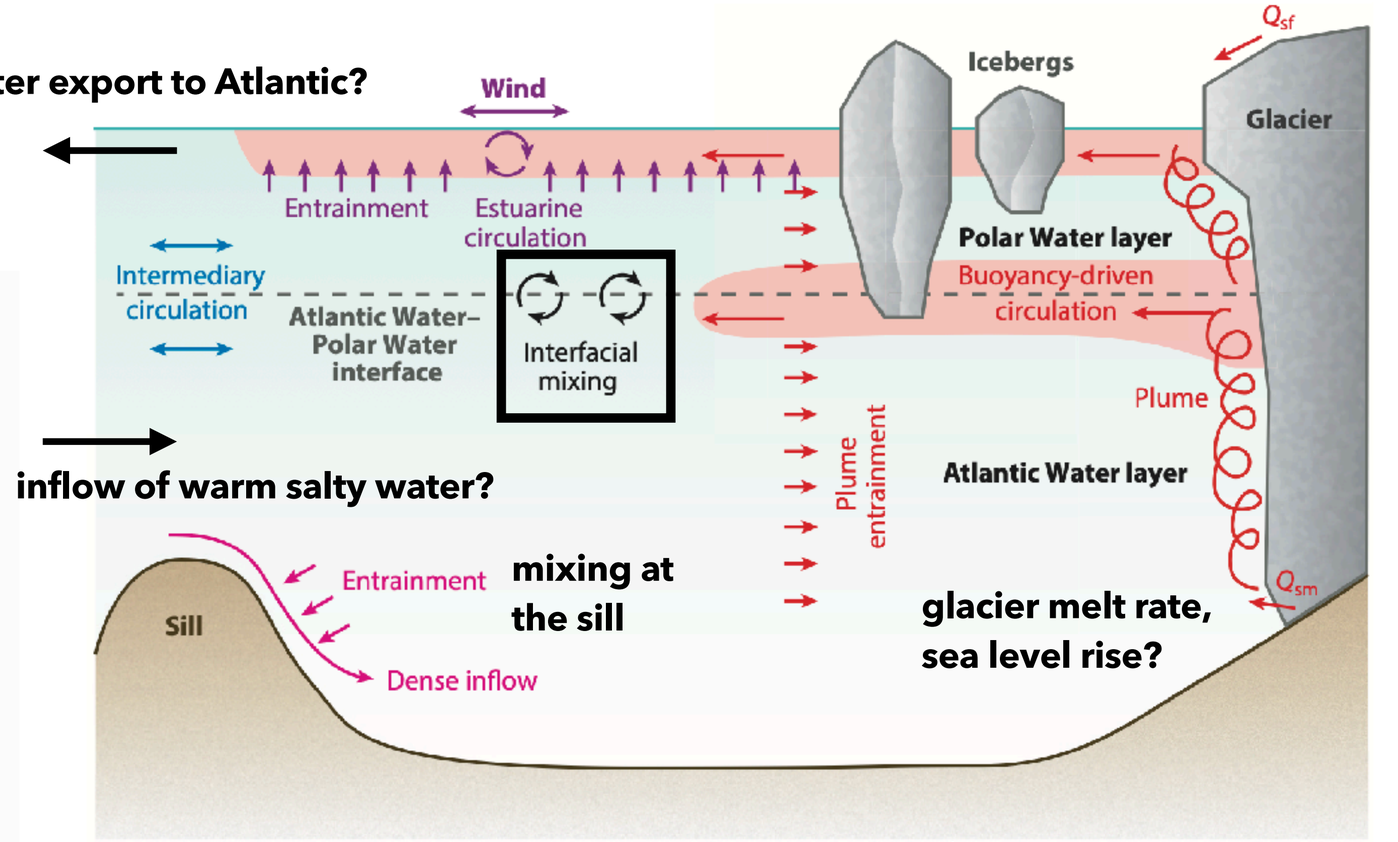
Climate predictions: Greenland's fjords

Melt of the Greenland ice sheet
= 1/4 of the present rate of **sea-level rise**

Fjords are also (special) estuaries



Andresen et al. *Nature Geosciences* (2012)



Straneo & Cenedese, *Ann. Rev. Mar. Sci.* (2015)

Complex physics …

Need to combine insight from field studies, models and laboratory experiments

Climate <u>adaptation</u>: coastal restoration

BBC For you Home News Sport Weather iPlayer

NEWS

Seagrass: UK's biggest restoration project planned off Wales

12 August 2022

Climate

Seagrass has a vital role to play in the climate and nature crisis

DEFRA's "Restoring Meadows, Marsh and Reef" part of the Government £200m "**Flood** and Coastal Innovative Programme"

Seagrass…

- Sequesters carbon
- Protects against erosion
- Absorbs pollution
- Increases biodiversity
- Produces oxygen

Other habitats:

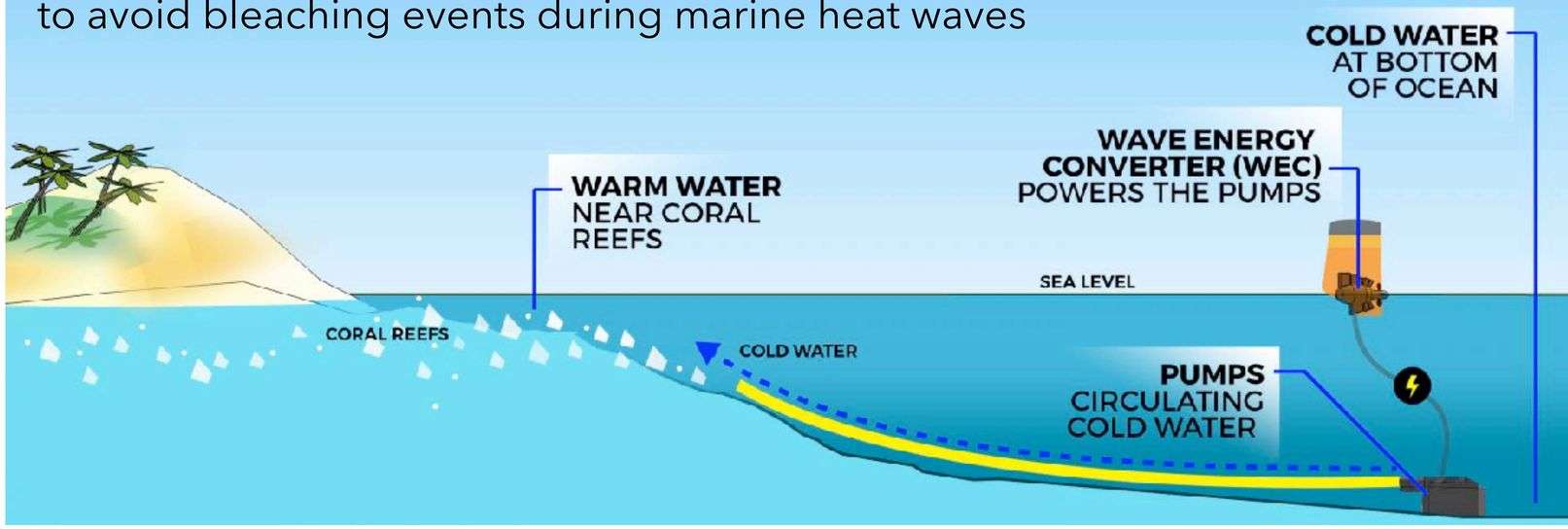
- kelp forests
- salt marshes
- biogenic reefs
- mangrove forests
- coral reefs

↓

Environmental engineering

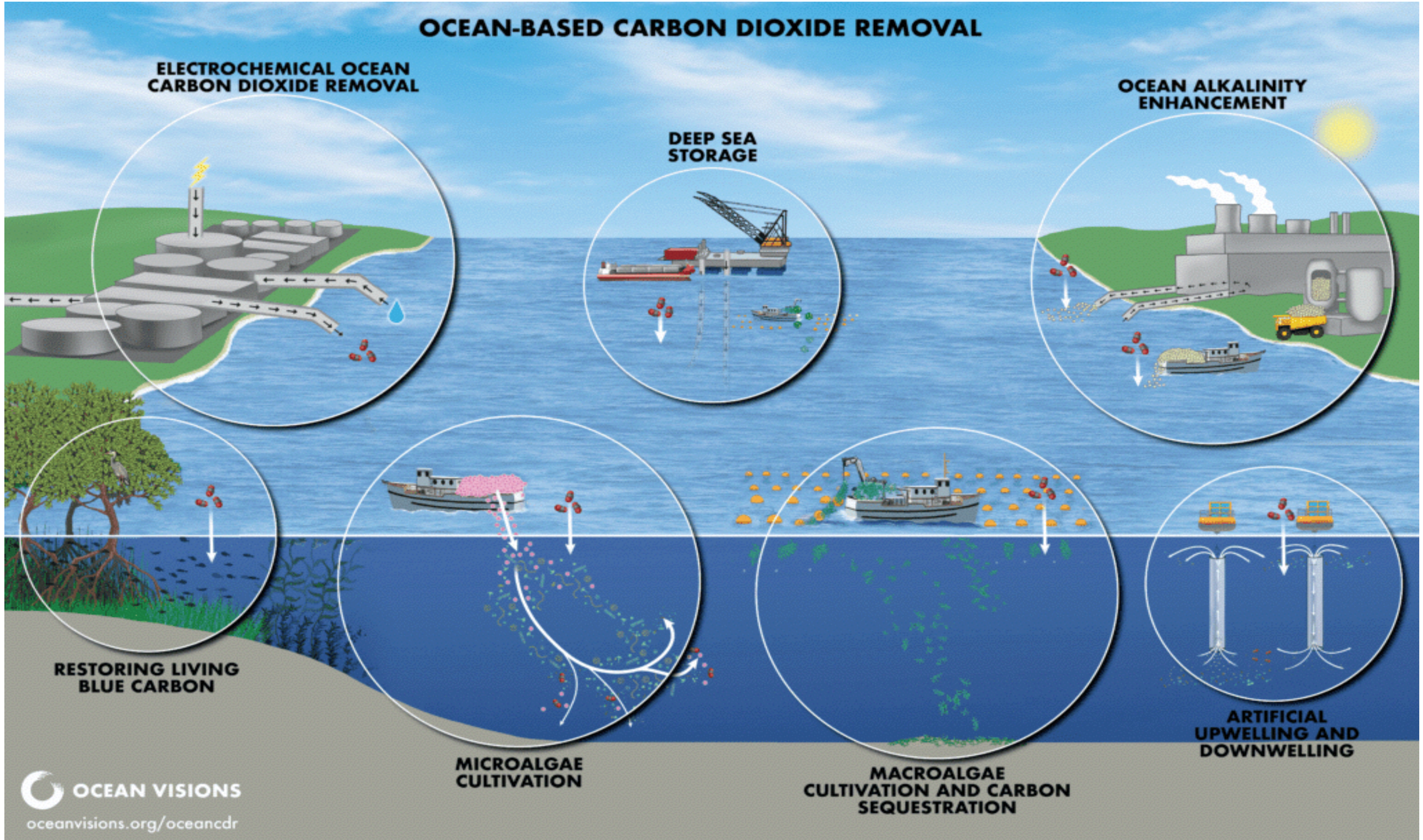
Example: coral reef cooling

to avoid bleaching events during marine heat waves



Climate mitigation: carbon removal

Modelling very difficult but necessary to assess industrial viability and risks



Conclusion: modelling physical processes for environmental and climate impact

Natural variability

Tides, winds, waves

Rainfall, river discharge

Human change (stressors)

Industrialisation, pollution

Agriculture, nutrients

Dredging, mining

Sea-level rise

Sea surface warming

Droughts, storms

FORCING

?

Estuarine and coastal circulation

Temperature and salt stratification

Turbulent mixing

Wind, wave breaking, air/sea fluxes

Turbidity, sediment transport

Spatio-temporal variability

Extreme events

Biogeochemical cycles

PROCESSES

?

Freshwater supply, irrigation, salt intrusions

Pathogens, aquaculture, fishing, food security

Microplastics, heavy metals, toxicity

Erosion, flooding, coastal infrastructure

Insurance and financial sector

Habitat loss and shift

Eutrophication, biodiversity, invasive species

Carbon fixation …

ENVIRONMENTAL IMPACT

Approaches:

Field studies and data —inform→ **Laboratory experiments** —inform→ **Numerical modelling**

Environmental datasets

Remote sensing

Monitoring

Idealise, control parameters, geometry

Discover new phenomena

Parameterise unresolved processes

Study real-world scenarios

Quantify and mitigate risk

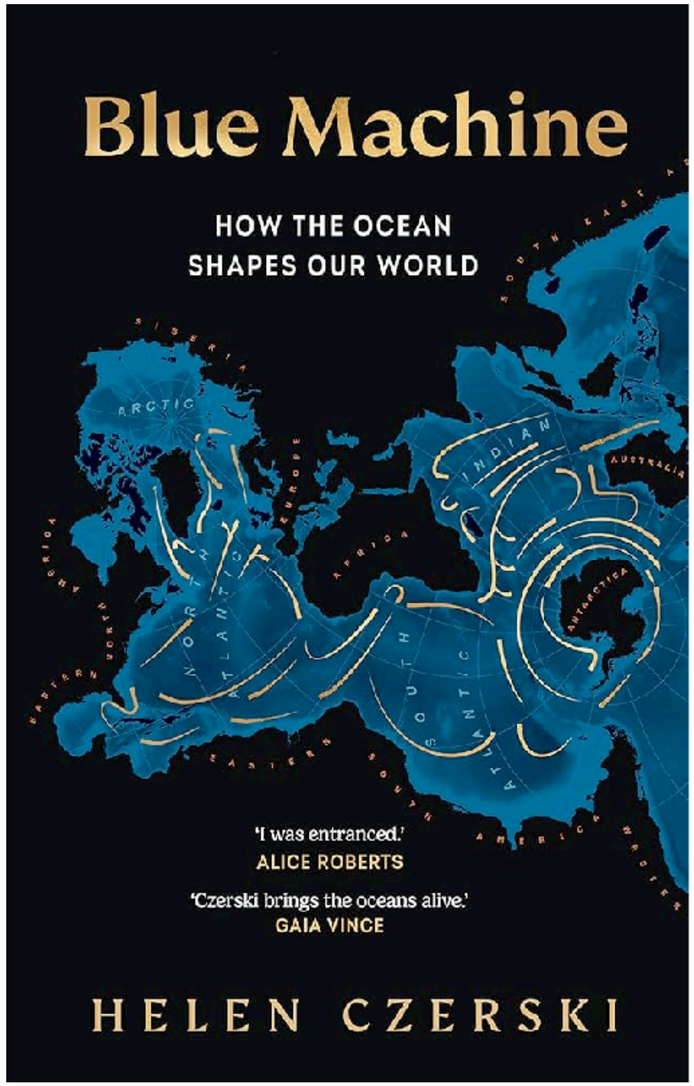
Inform design of solutions

Further reading ...

All of the Earth's ocean, from the equator to the poles, is a single engine powered by sunlight - a blue machine.

In a book that will recalibrate our view of this defining feature of our planet, physicist Helen Czerski […] explains the vast currents, invisible ocean walls and underwater waterfalls that all have their place in the ocean's complex, interlinked system.

Drawing on years of experience at the forefront of marine science, Helen Czerski captures the magnitude and subtlety of Earth's defining feature, showing us the thrilling extent to which we are at the mercy of this great engine.



The oceans exert a vital moderating influence on the Earth's climate system. They provide inertia to the global climate, essentially acting as the pacemaker of climate variability and change, and they provide heat to high latitudes, keeping them habitable.

Climate and the Oceans offers a short, self-contained introduction to the subject. This illustrated primer begins by briefly describing the world's climate system and ocean circulation and goes on to explain the important ways that the oceans influence climate.