COMPUTATIONAL
CLIMATE & OCEAN GROUP
at UC Davis



AI for Oceans & Marine Systems

How we can gain insight and help build resilience

Maike Sonnewald

Climate Change AI Summer School 2026

UCDAVIS

Overview

The physical, chemical and biological ocean

What is changing?

Warming, sea level, acidification, marine heatwaves, and the knock-on effects on plankton and fisheries

What data is there understand and predict the ocean?

In-situ observation, remote sensing, and numerical models, and the gaps each leaves

Why ML?

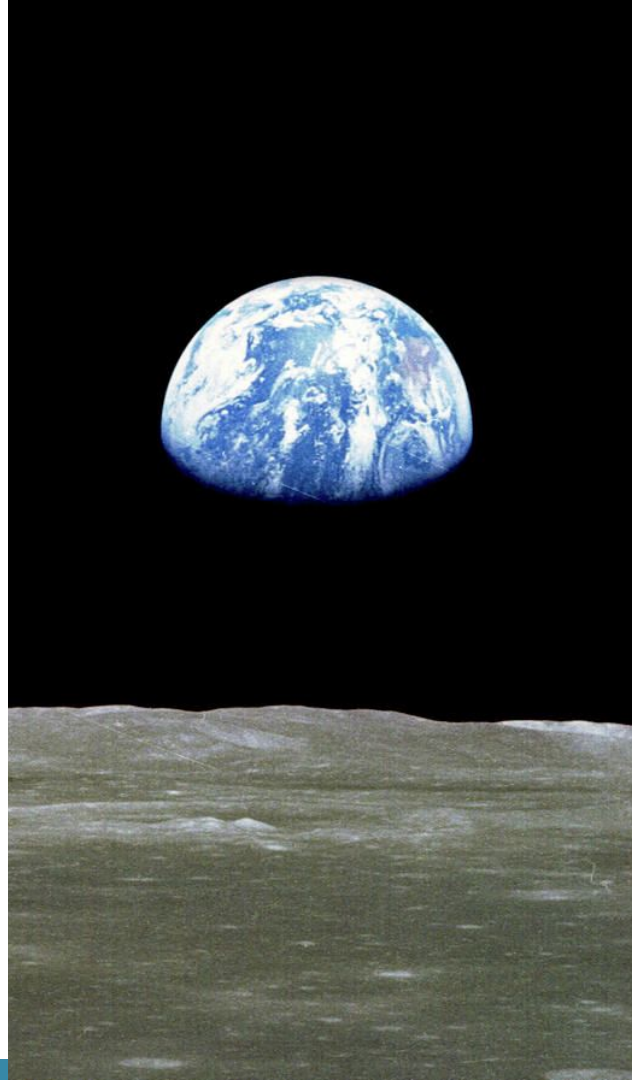
A short introduction and overview

Case studies

Satellite pCO_2, Antarctic plankton, heatwave attribution, and Atlantic ocean circulation

Should it be called planet Ocean?

The ocean covers about 70% of Earth’s surface and contains 97% of its water.

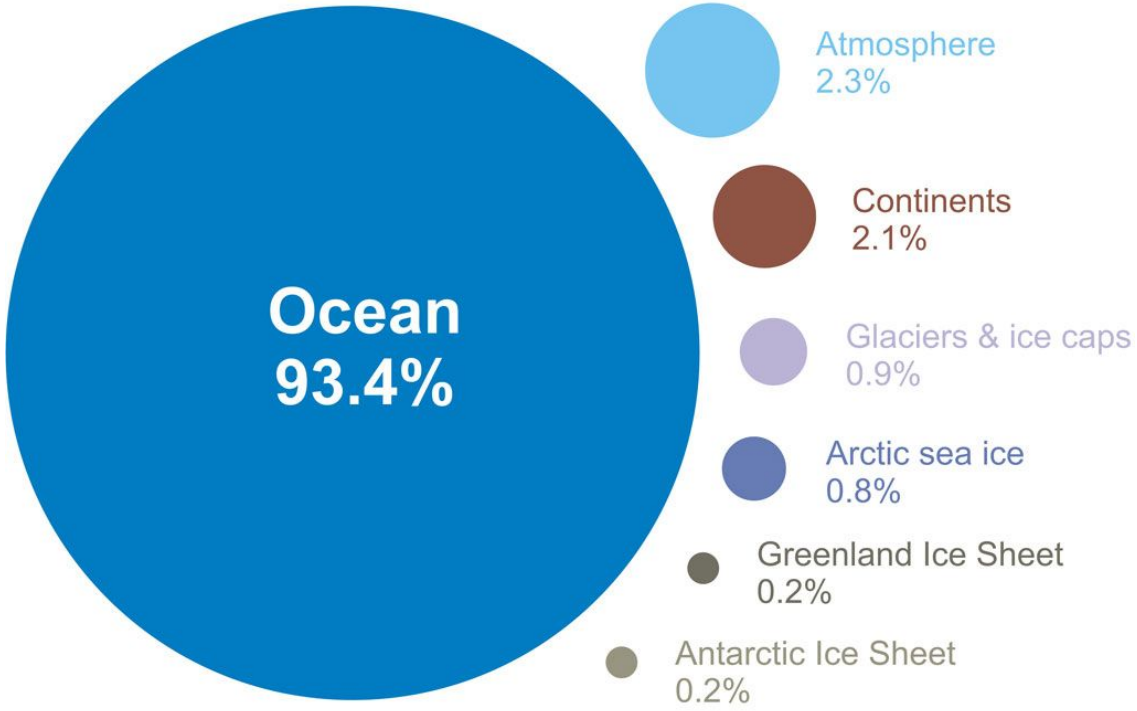


How much of the anthropogenically added heat goes into the ocean?



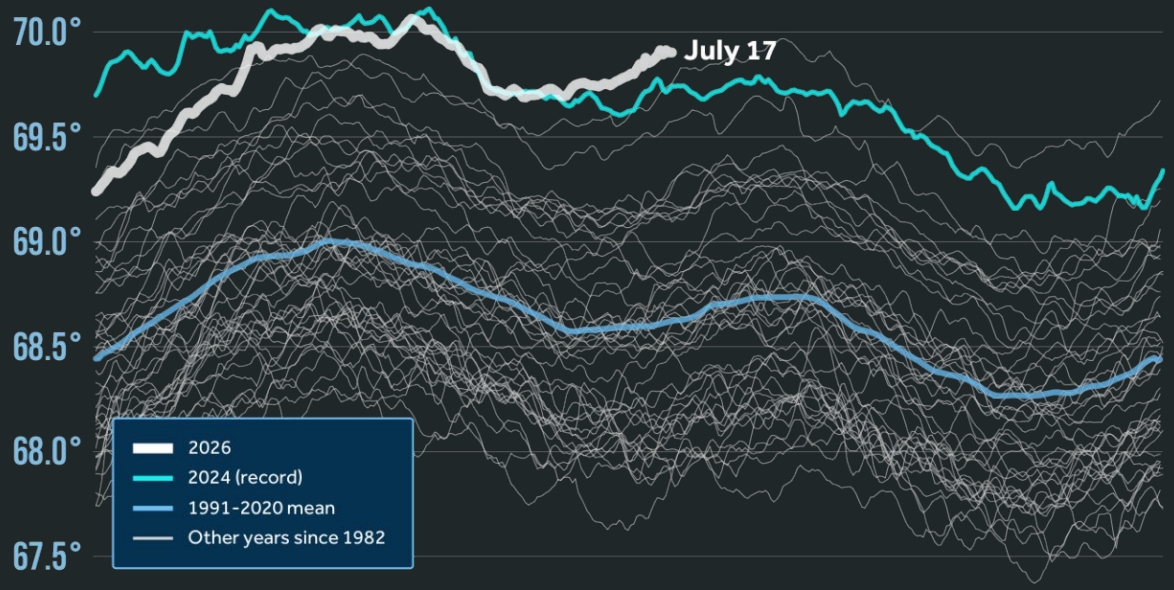
https://partici.fi/86456312

Where is global warming going?



http://skepticalscience.com/

Daily global ocean surface temperature (°F)



Data for 2026 includes January 1 through July 17. Source: NOAA OISSTv2.1.

The services the ocean provides



71%

of Earth's surface is ocean



~90%

of global-warming heat is stored in the ocean



~25%

of our CO_2 emissions absorbed by the sea



50%+

of the oxygen you breathe made by ocean plankton

The ocean has different ocean basins of different sizes

Smallest: Arctic 5.4 million sq miles

Largest: Pacific > 60 million sq miles

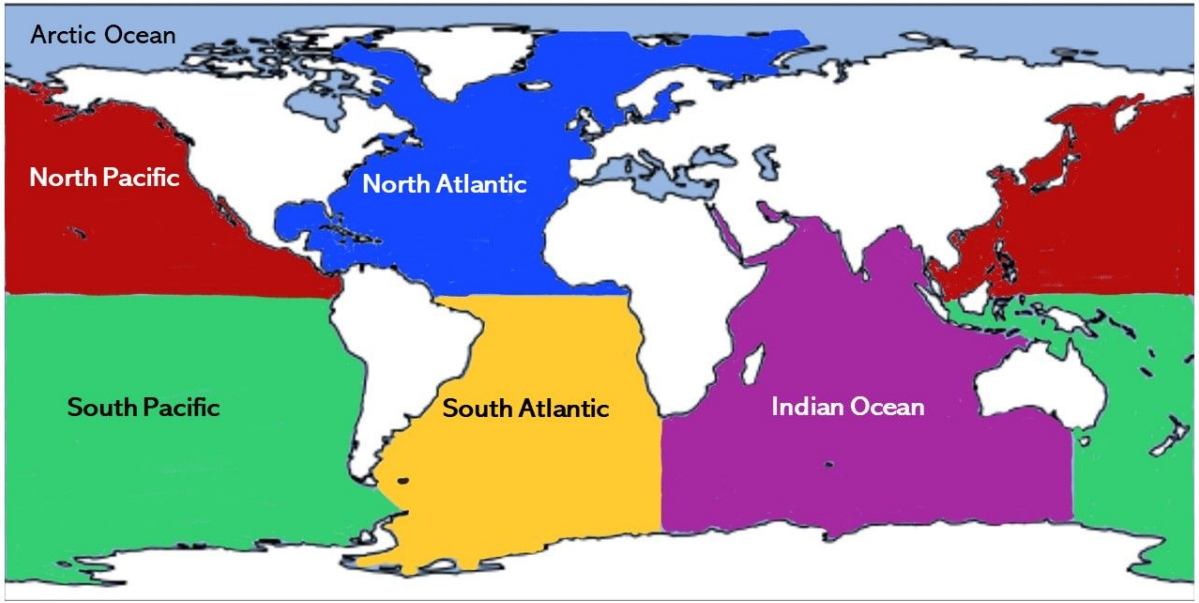
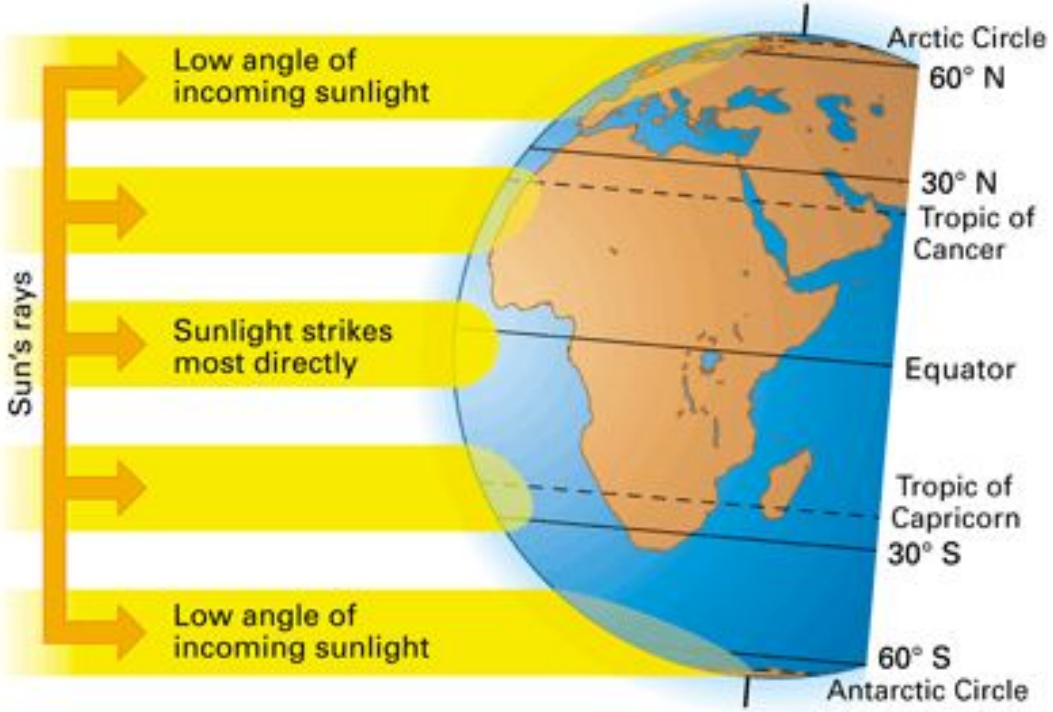


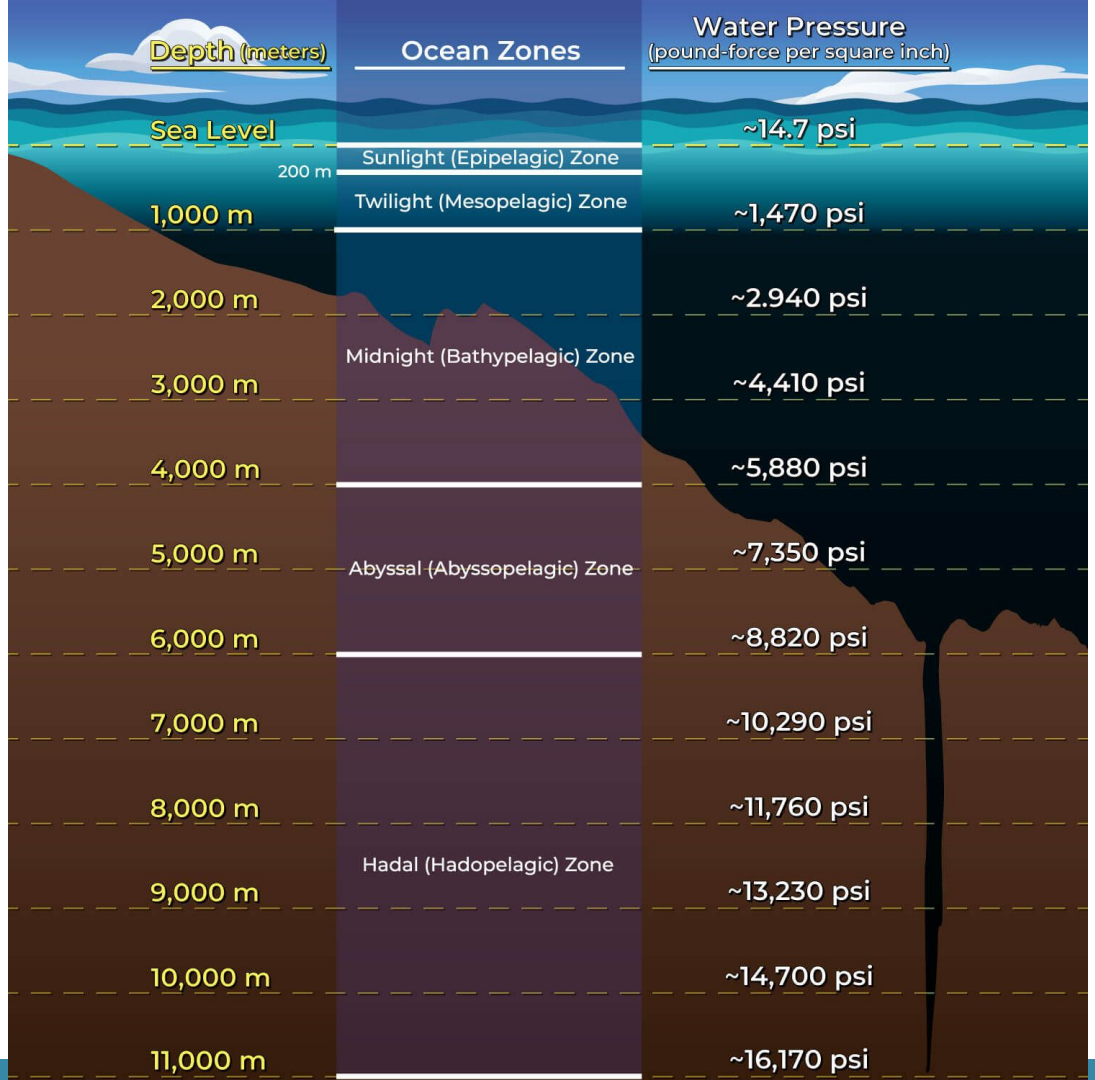
Image: wikipedia.com

Unequal heating has a big impact



himaya.com

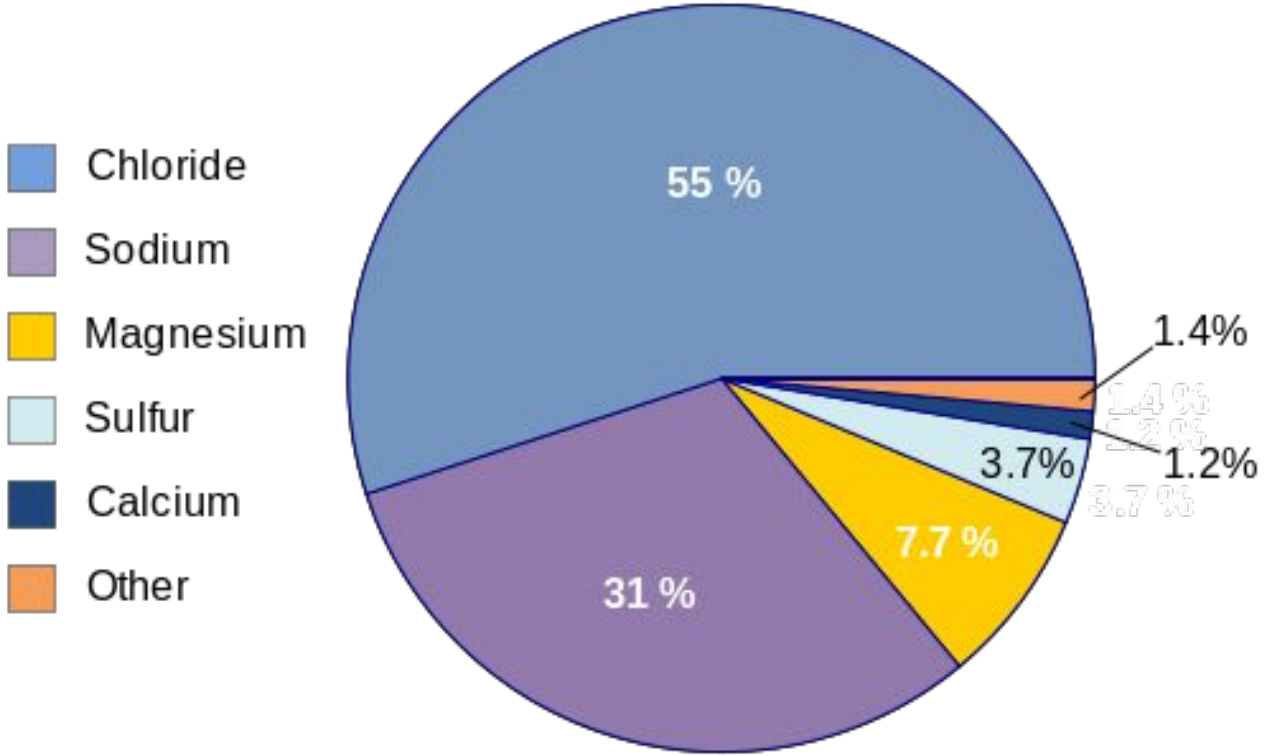
Light



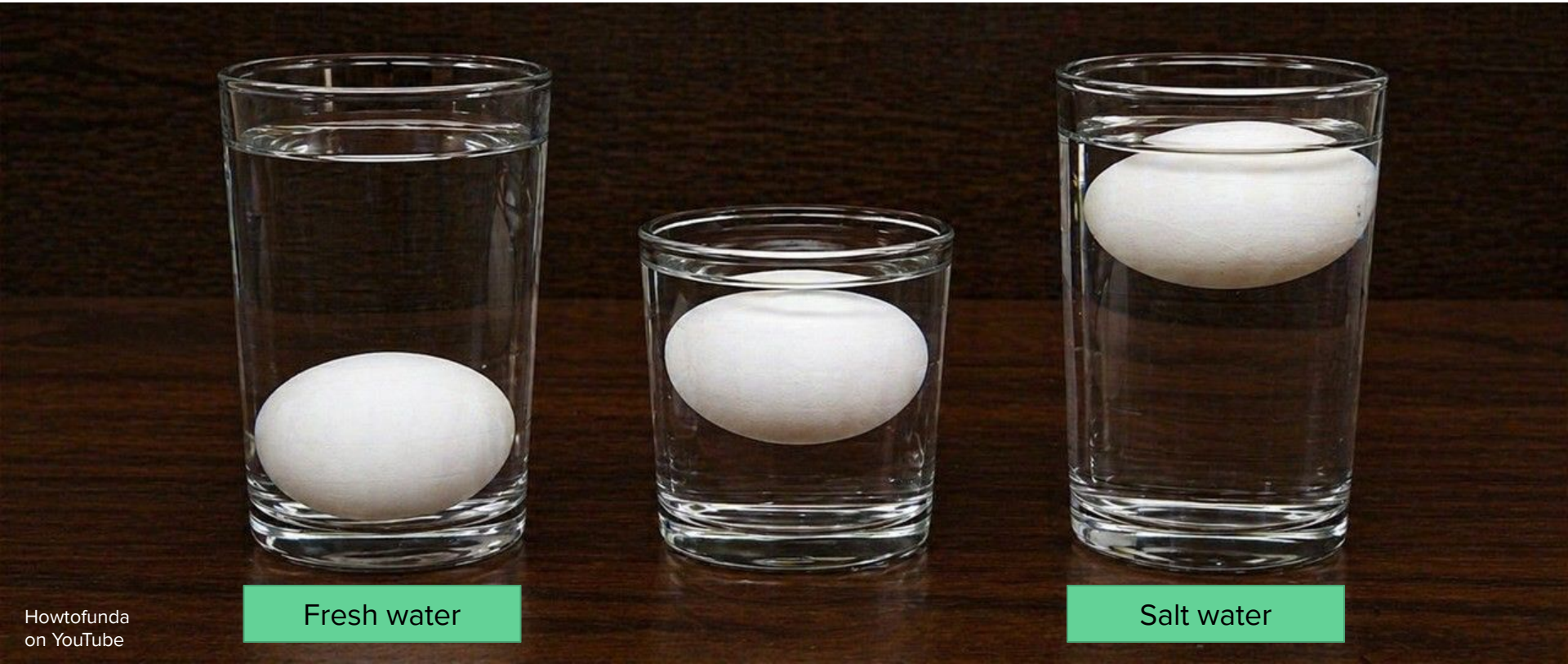
Pressure

surfertoday.com

Seawater consists of water and other compounds

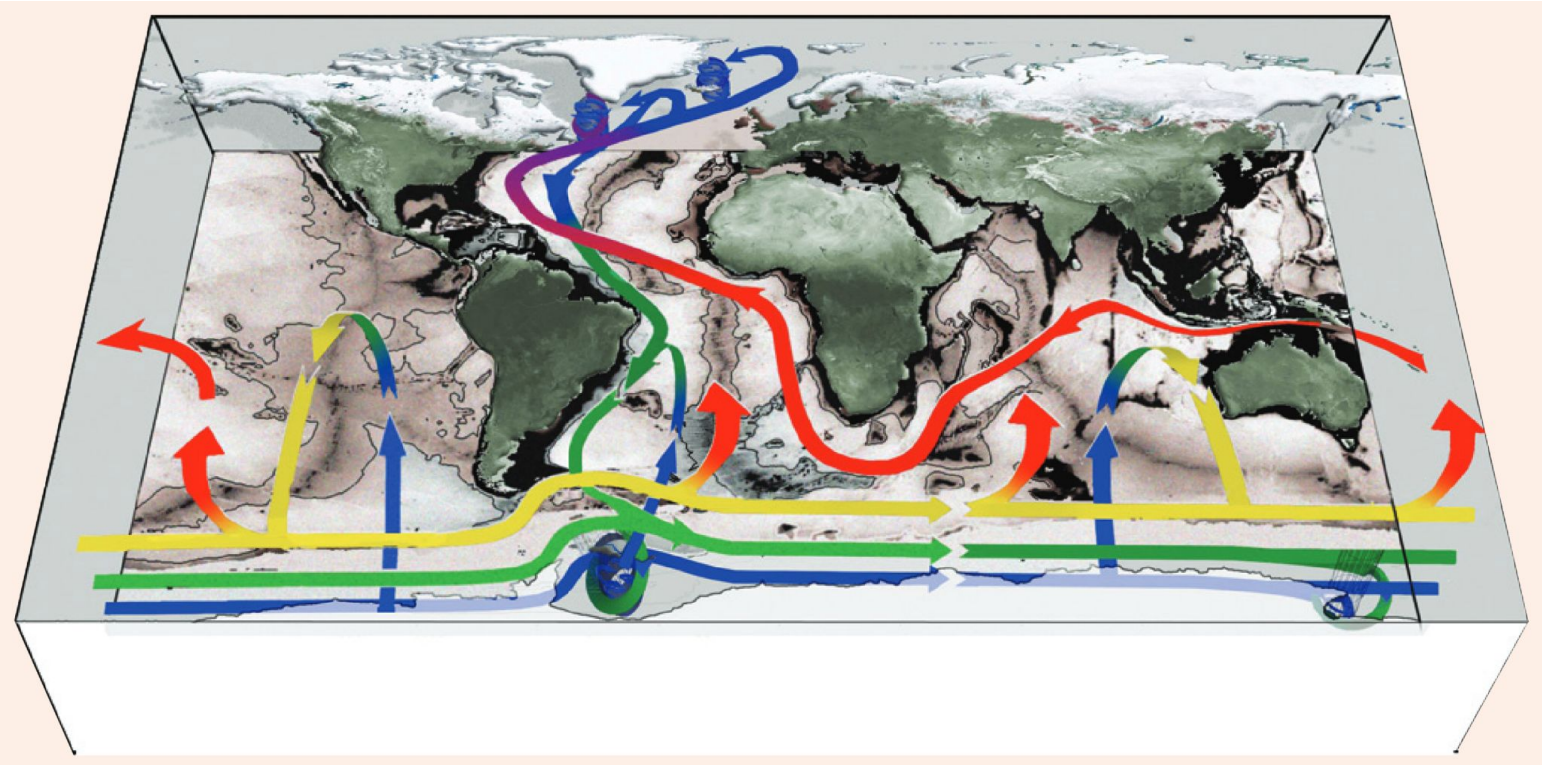


Salty water is denser than freshwater



Howtofunda
on YouTube

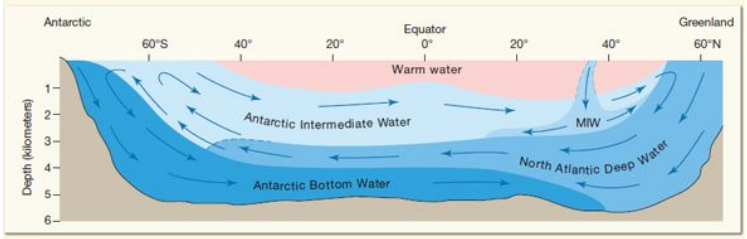
The ocean circulation is an emergent global phenomenon



[Marshall & Speer, 2012]

Cold Hot

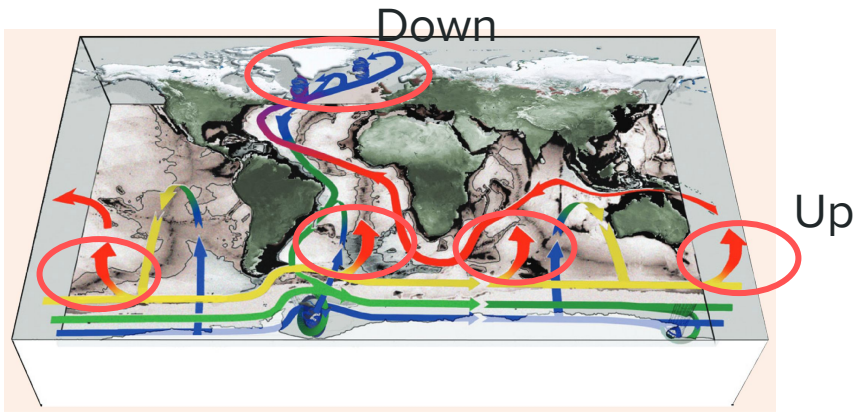
A global “conveyor”



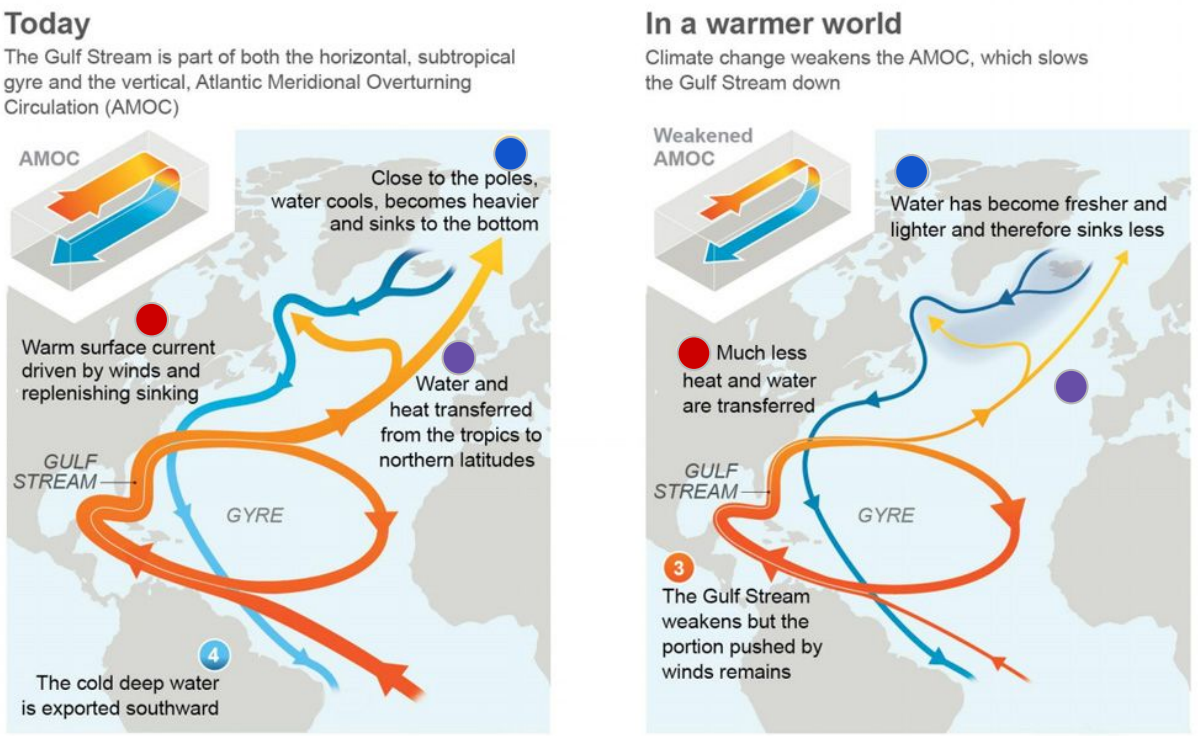
- Asymmetrical heating/cooling, along with brine rejection from ice formation create the Thermohaline circulation
- Referred to as the ‘meridional overturning circulation’

Changes in overturning circulation have **big** climate impact

- The ocean is layered with the heaviest/densest water at the bottom
- Intense cooling and ice formation at the poles create very dense waters



Major currents may change in a warmer climate: Gulf Stream example

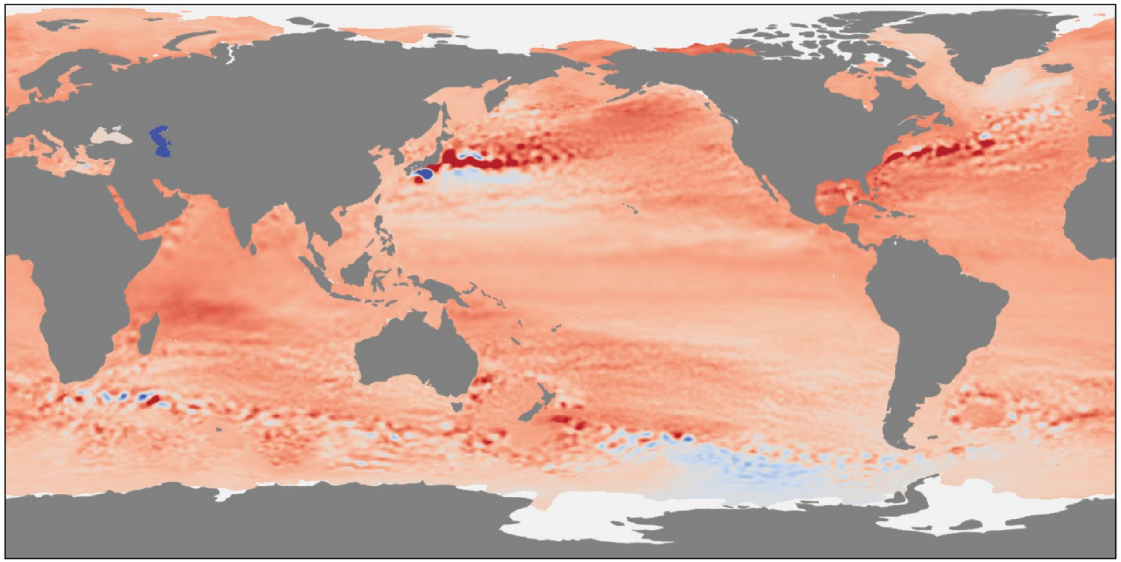


- Gulf stream shifts north
- Path of heat delivery moves
- Less dense/heavy waters

IPCC 6th Assessment Report

Sea level trends from February 1999 to May 2025

Data: CMEMS Ocean Monitoring Indicator based on C3S sea level product • Credit: C3S/ECMWF/CMEMS



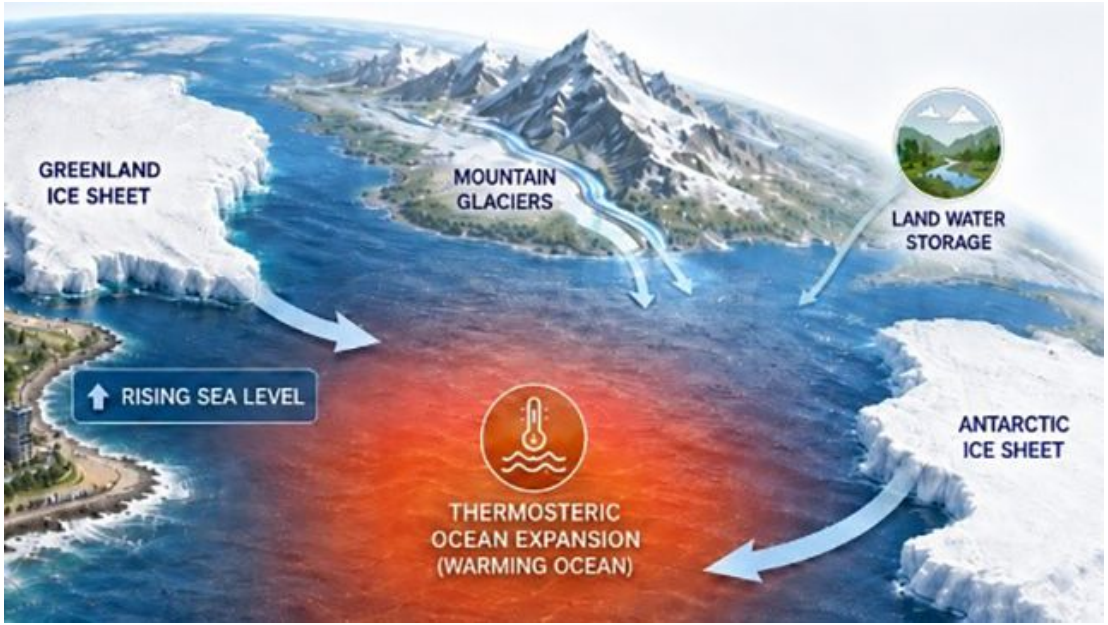
PROGRAMME OF THE EUROPEAN UNION

opernicus Europe's eyes on Earth

Climate Change Service

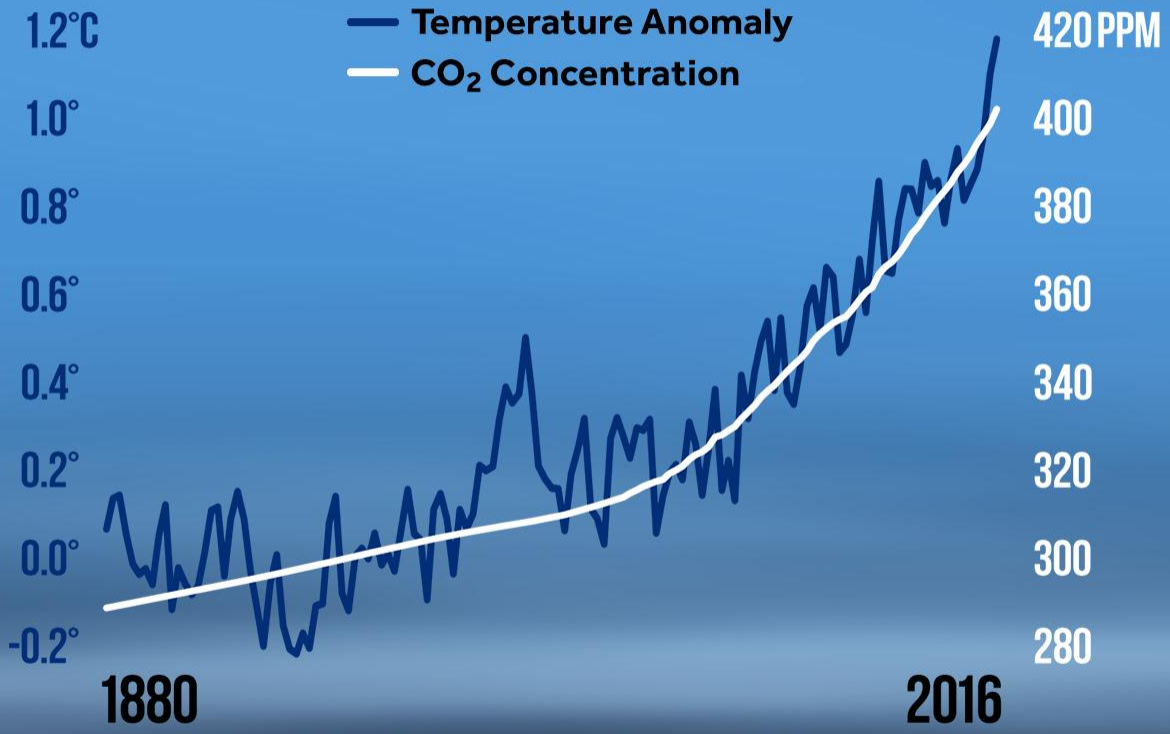
IMPLEMENTED BY ECMWF

Sea level rise has several sources



sciencealert.com

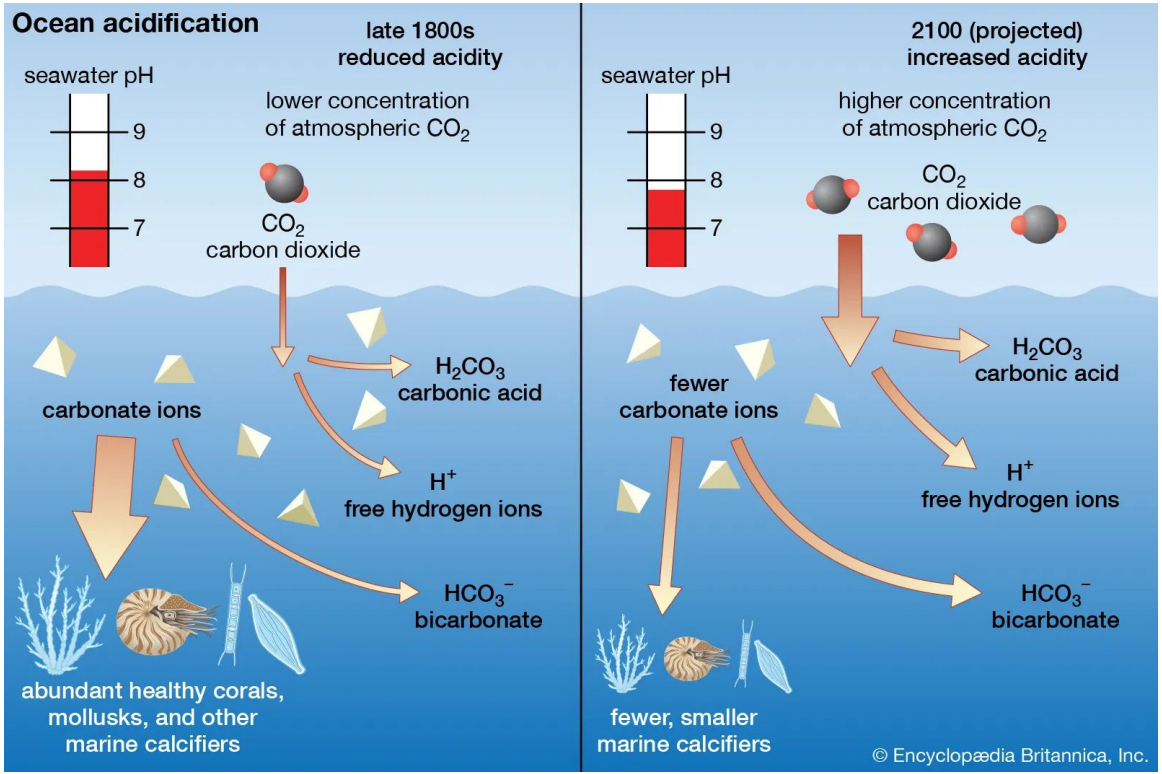
Global Temperature and Carbon Dioxide



Global temperature data averaged and adjusted to early industrial baseline (1881-1910).
Source: NASA GISS, NOAA NCEI, ESRL

CLIMATE CENTRAL

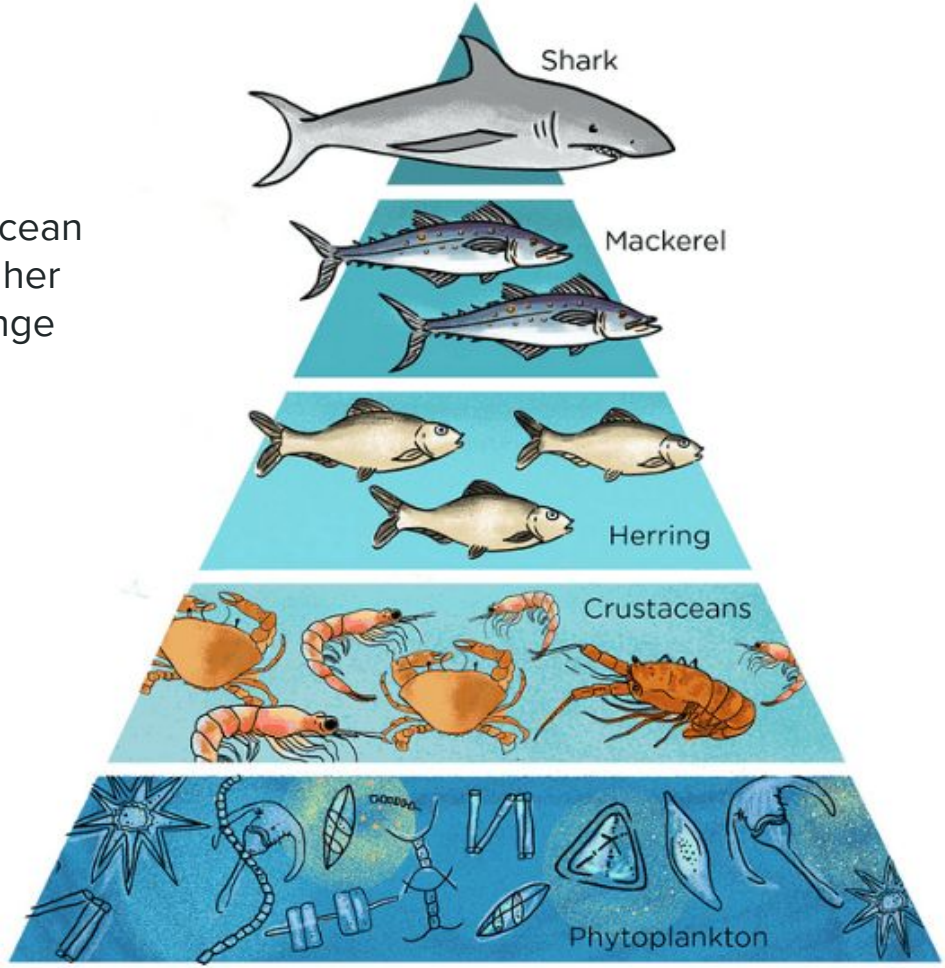
Climate change will make the ocean more acidic



britanica.com

Marine life

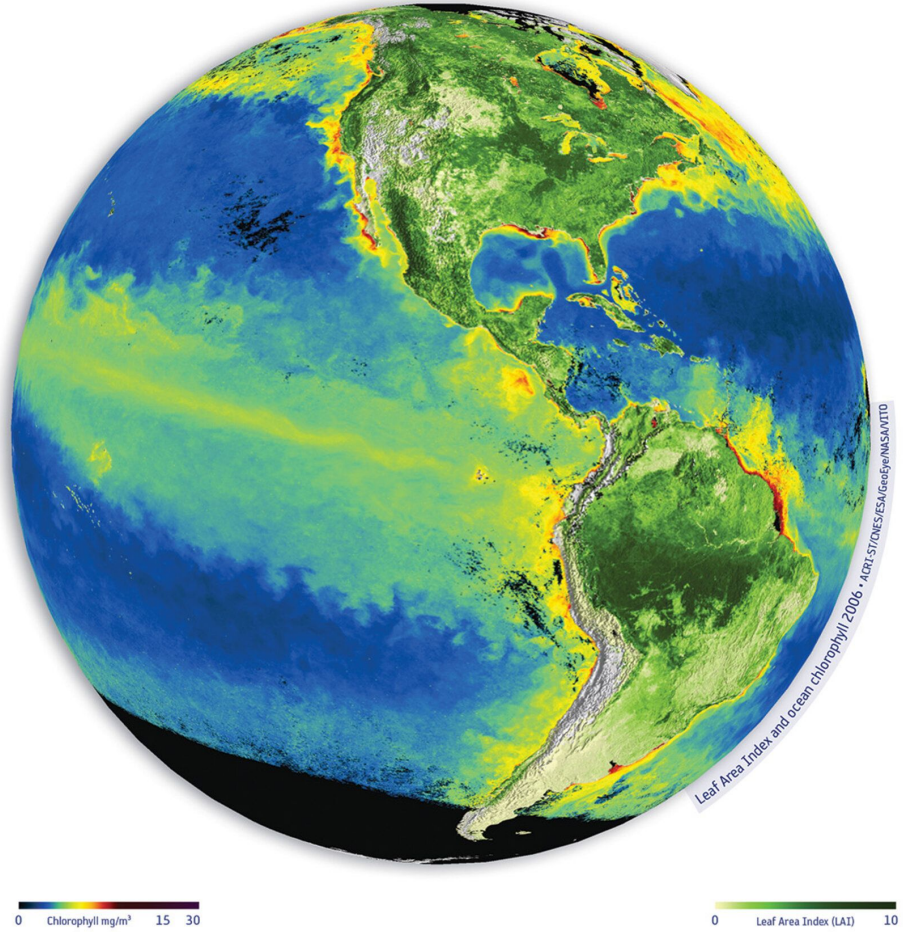
The food-web rests on ocean “plants”, with species higher up comprising a wide range



ocean.org

The base: Plankton

Just like terrestrial plants, plankton produce chlorophyll and rely on sunlight and nutrients to grow and there are many types



The base: Plankton

The plethora of types range orders of magnitude in size and have different “niches” expressed, for example, in what they need to flourish:

Some build shells, and some make their own nutrients!

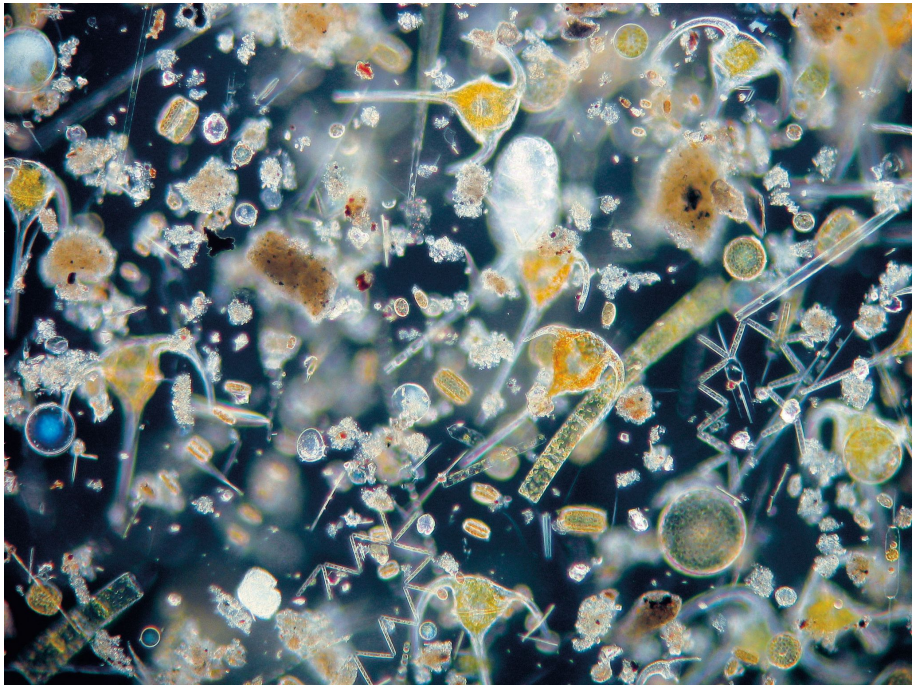
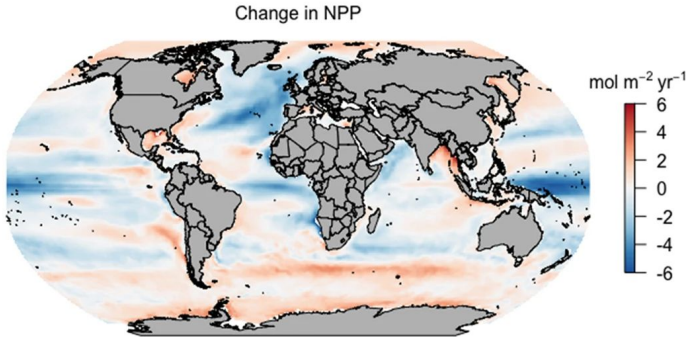


Photo: Annegret Stuhr, GEOMAR

The base: Plankton

Net primary production (NPP) is predicted to change drastically



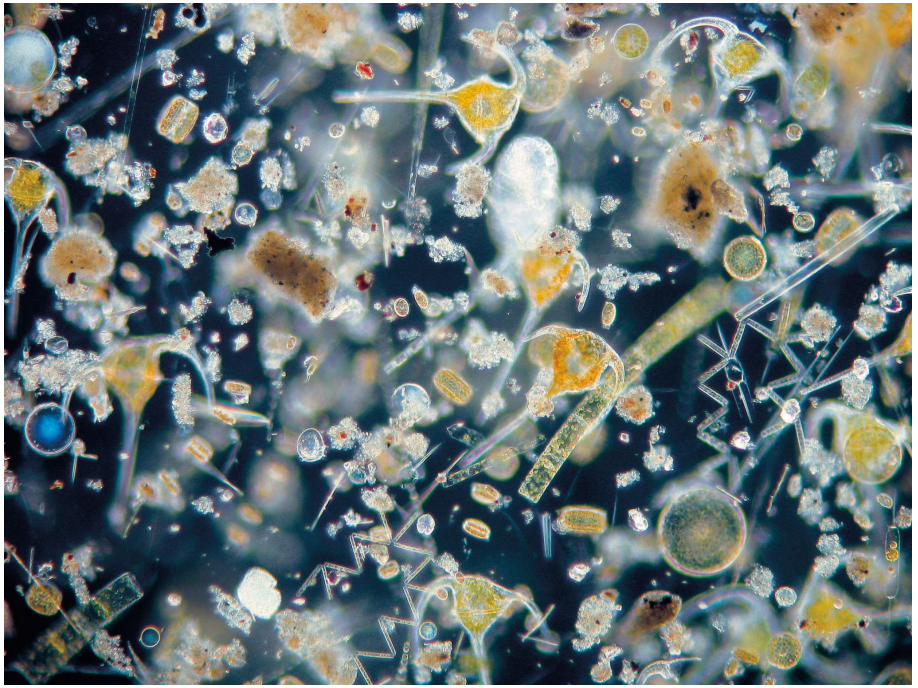


Photo: Annegret Stuhr, GEOMAR
Ratnarajah etal., 2023

The base: Zooplankton

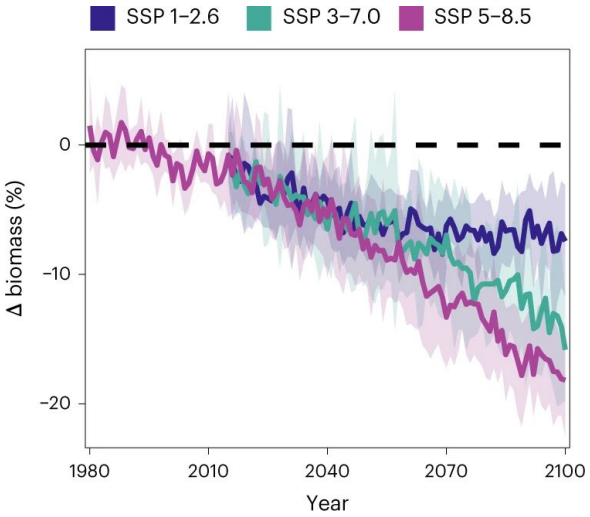
Microscopic organisms that “graze” on other plankton also range widely in size and form



Tyler Rohr http://communities.springernature.com/

Fisheries and conservation

Fish rely on zooplankton for food



Heneghan et al., 2023

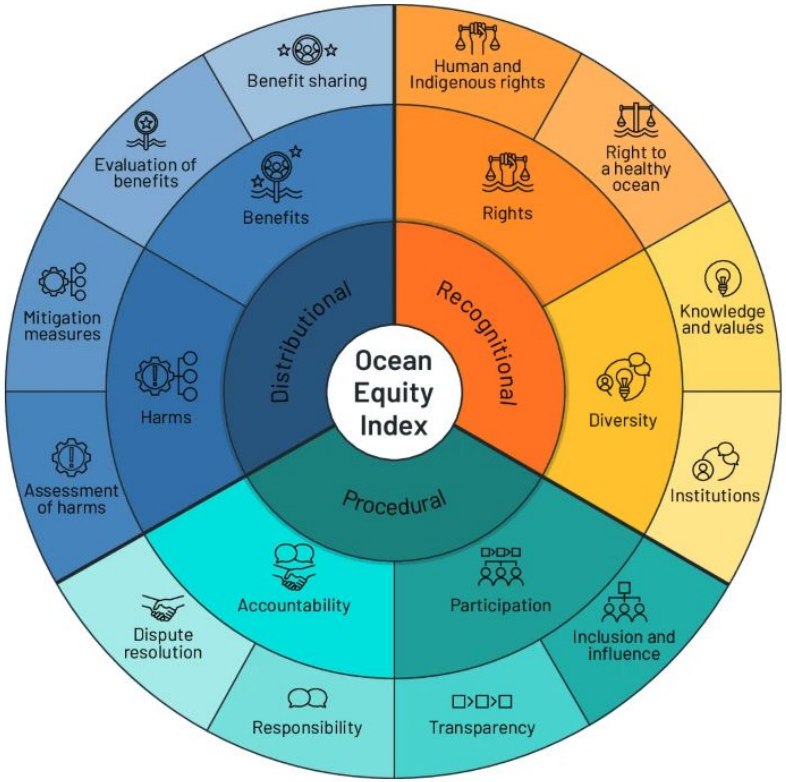


400 tons of jack mackerel caught by a Chilean purse seiner.
Photo via Wikimedia Commons.

Equity and stakeholders

Who carries risk? Who benefits?

Some communities are more vulnerable than others, for example, living in low-lying coastal states, or in fisheries-dependent livelihoods, and may not have finances for adaption



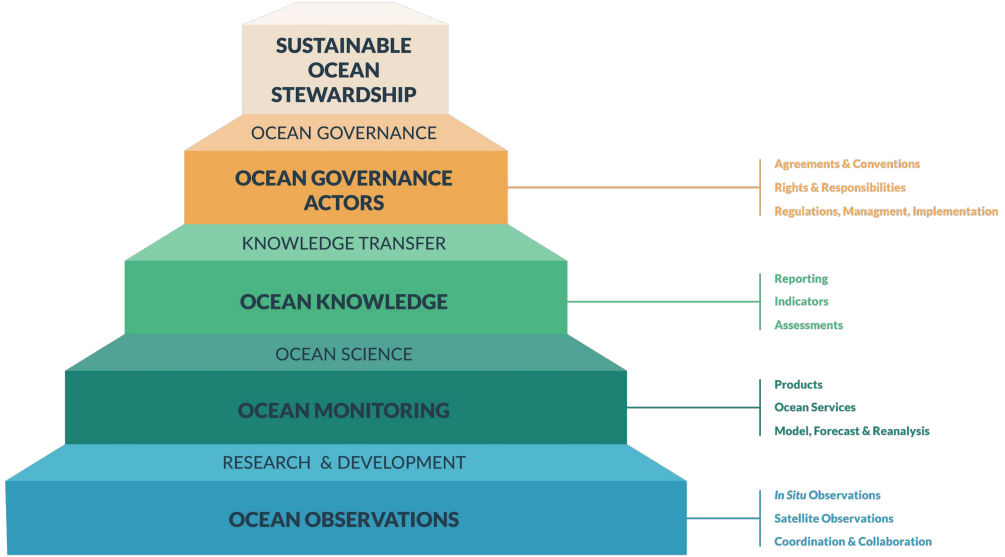
Blythe et al., 2026

Ocean resources and governance

Ocean resources span a wide range of activities including fishing, tourism, shipping, and environmental protection

Most governments have individual policies, together with some regional and global governing bodies, and laws governing international waters

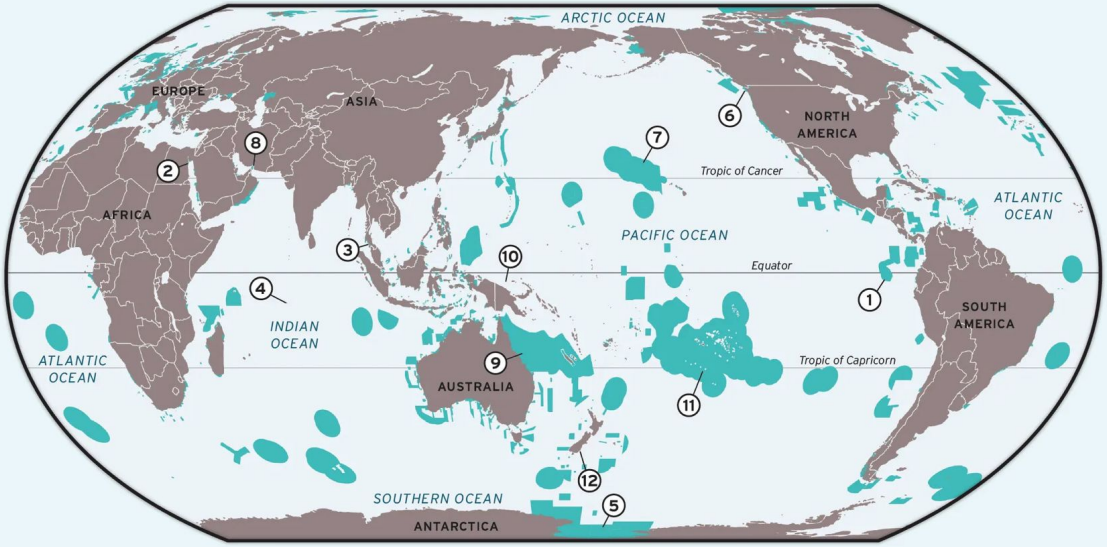
Global initiatives exist for ocean conservation, such as the 30 by 30 to designate 30% of Earth's land and ocean area as protected areas by 2030



2. How much of the ocean do you think is currently a Marine Protected Area able to protect biodiversity?

https://partici.fi/86456312

Marine Protected Areas

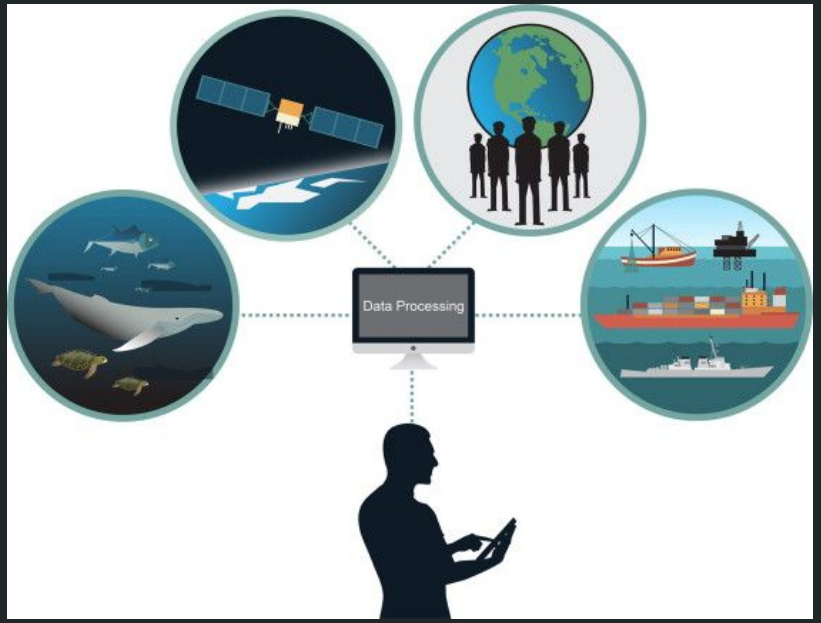


Source: UNEP-WCMC and IUCN (2026), Protected Planet: The World Database on Protected and Conserved Areas (WDPCA) [On-line], [07/2026], Cambridge, UK: UNEP-WCMC and IUCN. Available at: www.protectedplanet.net.

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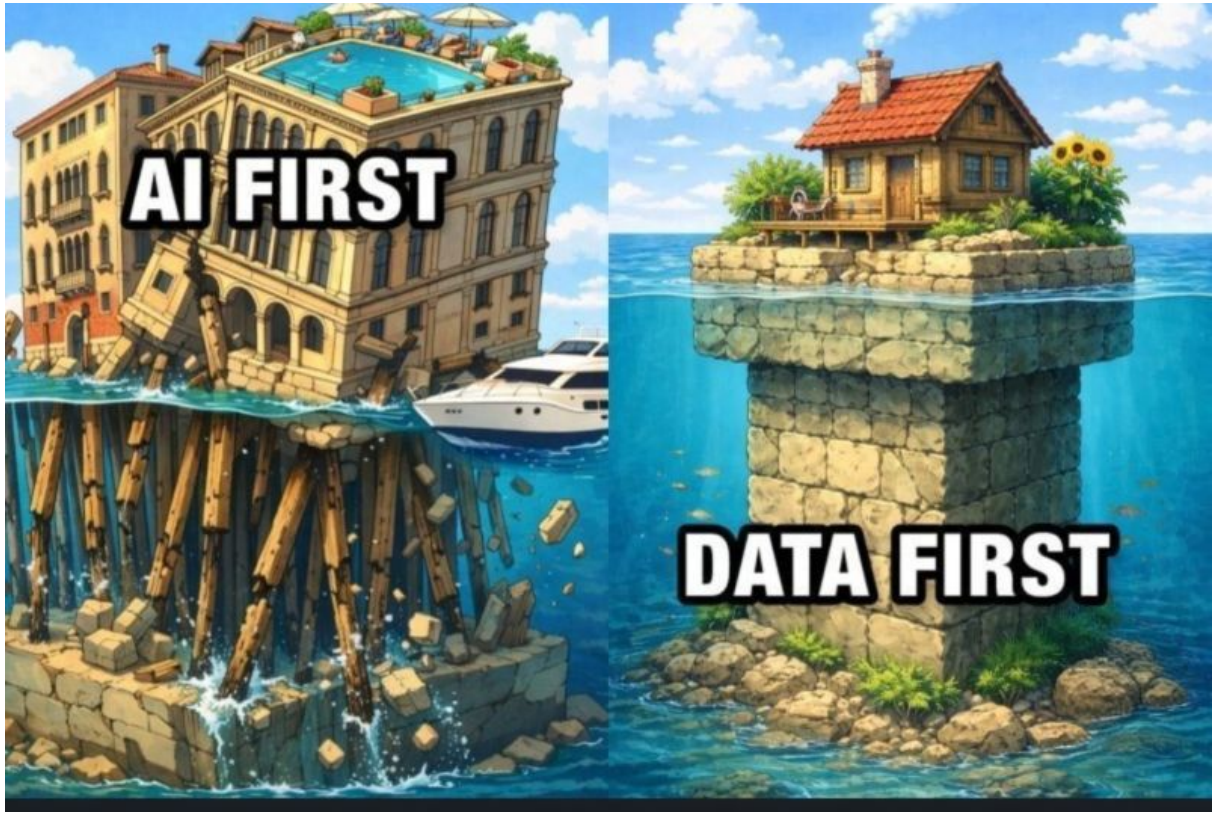
A data revolution, or a data problem?

Are we data rich and insight poor, or data poor and rich in insight?



Maxwell et al., 2015

Our AI is only as powerful as our data

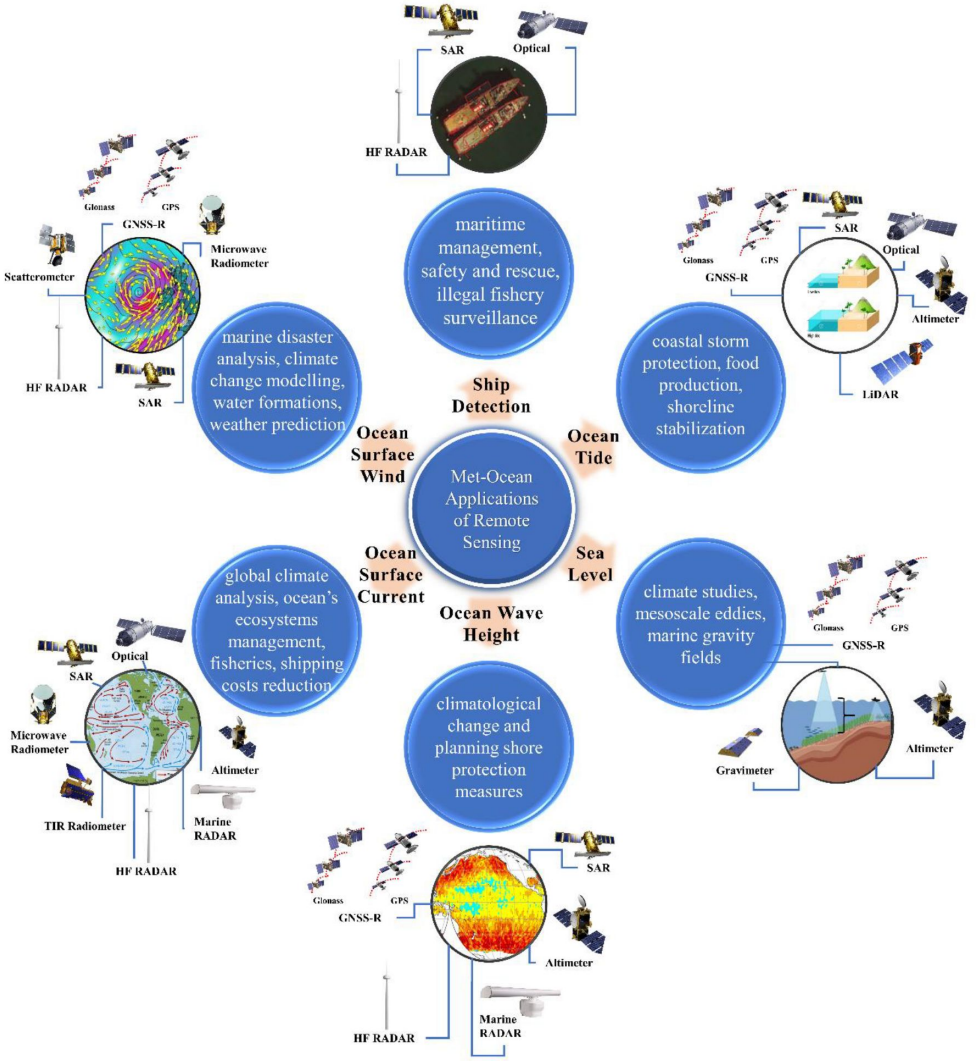


linkedin.com

Observations: Collected “in-situ”

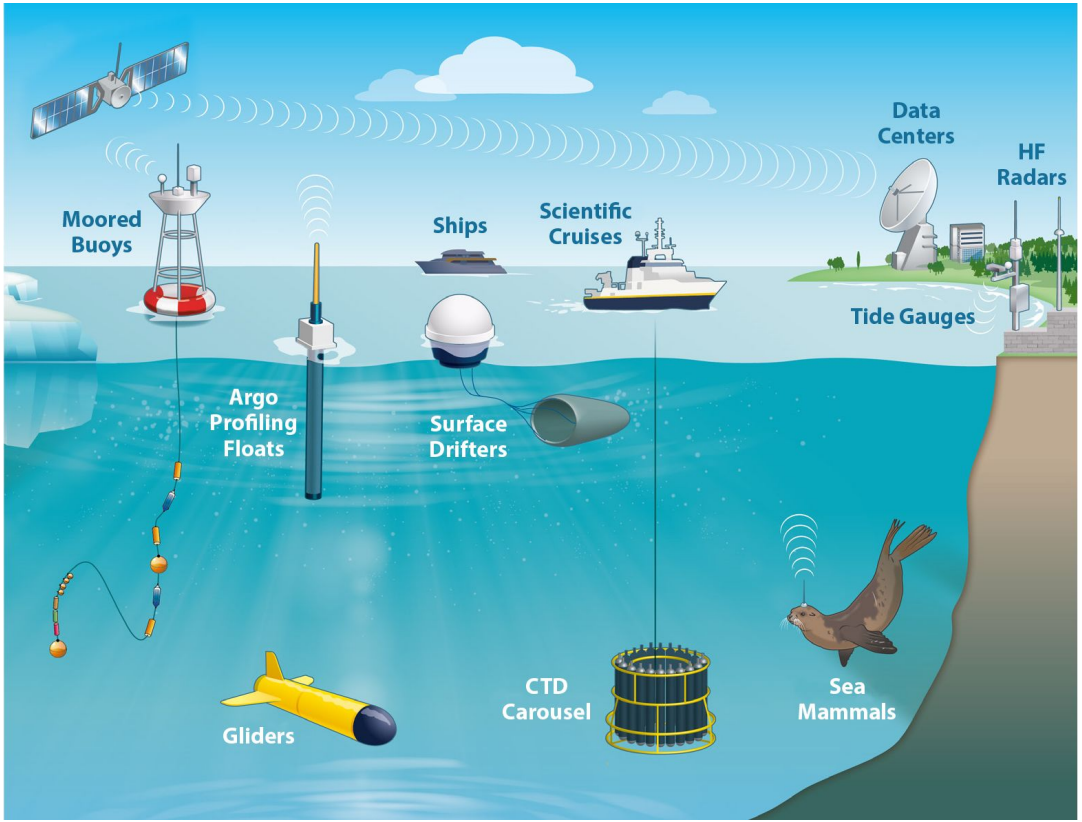


Observations: Remote sensing



Amani et al., 2022

Observations: A global network



Observations can come with a little help…

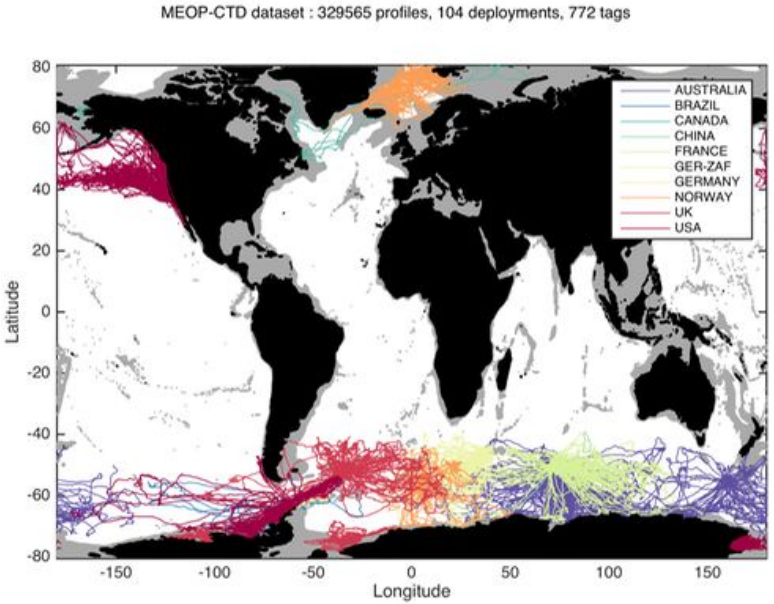
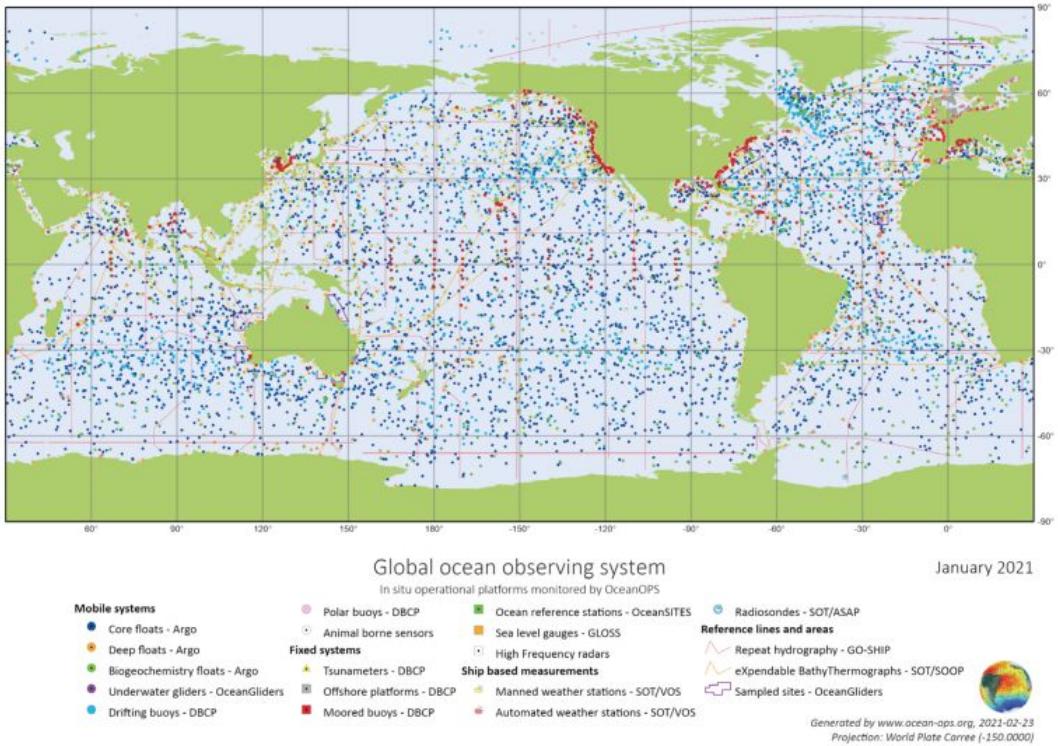


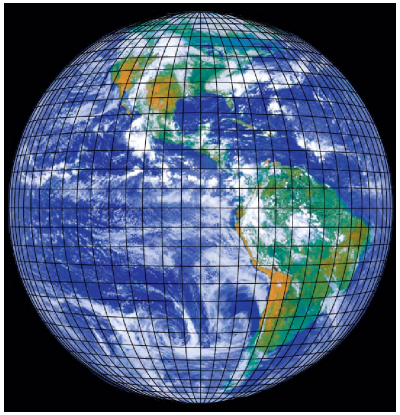


Photo: D. Costa

Equity in observations?

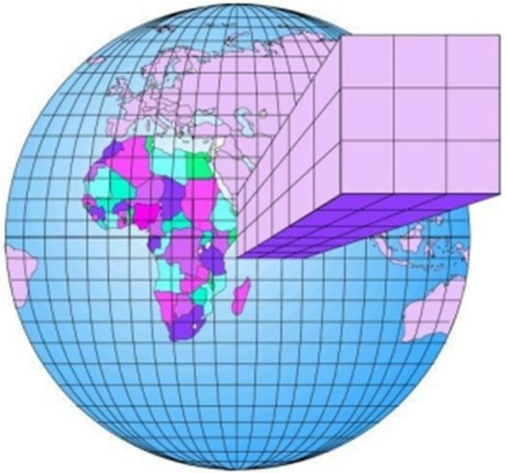


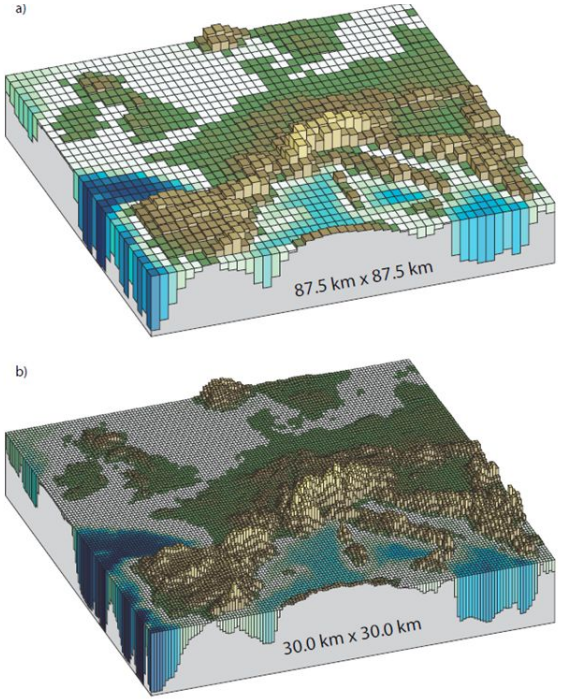
Numerical models



Grids extend downward into the land surface and oceans.

Just like on television, higher resolution means more realism





Numerical models: Primitive equations

Navier-Stokes + equation of state: Thin rotating fluid on a sphere

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} - fv = -\frac{1}{\rho_o}\frac{\partial P}{\partial x} + \frac{\partial}{\partial z}\left(K_m\frac{\partial u}{\partial z}\right) + F_u, \quad \text{Momentum (u component)}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} + fu = -\frac{1}{\rho_o}\frac{\partial P}{\partial y} + \frac{\partial}{\partial z}\left(K_m\frac{\partial v}{\partial z}\right) + F_v \quad \text{Momentum (v component)}$$

$$\frac{\partial P}{\partial z} = -\rho g, \quad \text{density}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0, \quad \text{continuity}$$

$$\frac{\partial \theta}{\partial t} + u\frac{\partial \theta}{\partial x} + v\frac{\partial \theta}{\partial y} + w\frac{\partial \theta}{\partial z} = \frac{\partial}{\partial z}\left(K_h\frac{\partial \theta}{\partial z}\right) + F_\theta, \quad \text{Advection of temperature}$$

$$\frac{\partial s}{\partial t} + u\frac{\partial s}{\partial x} + v\frac{\partial s}{\partial y} + w\frac{\partial s}{\partial z} = \frac{\partial}{\partial z}\left(K_h\frac{\partial s}{\partial z}\right) + F_s, \quad \text{Advection of salinity}$$

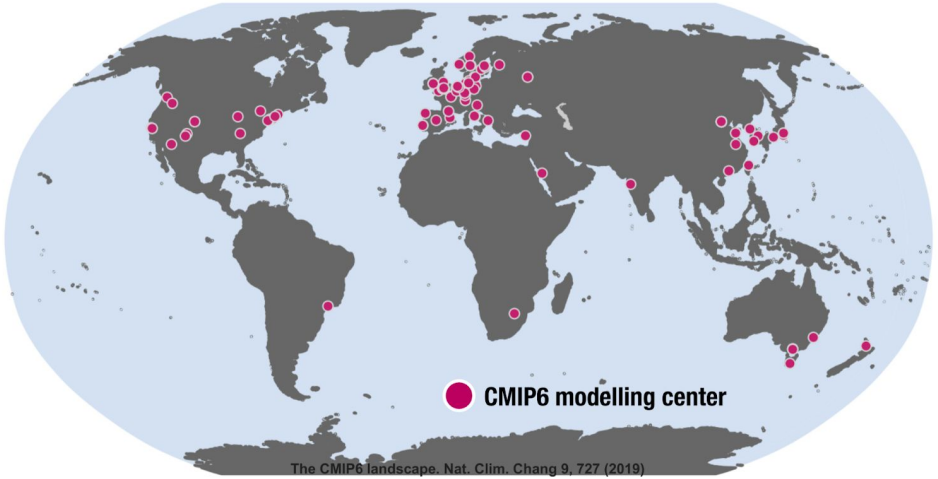
$$\rho = \rho(\theta, s), \quad \text{Density as a function of S and T}$$

The Climate Model Intercomparison Project

WCRP CMIP6

World Climate Research Programme

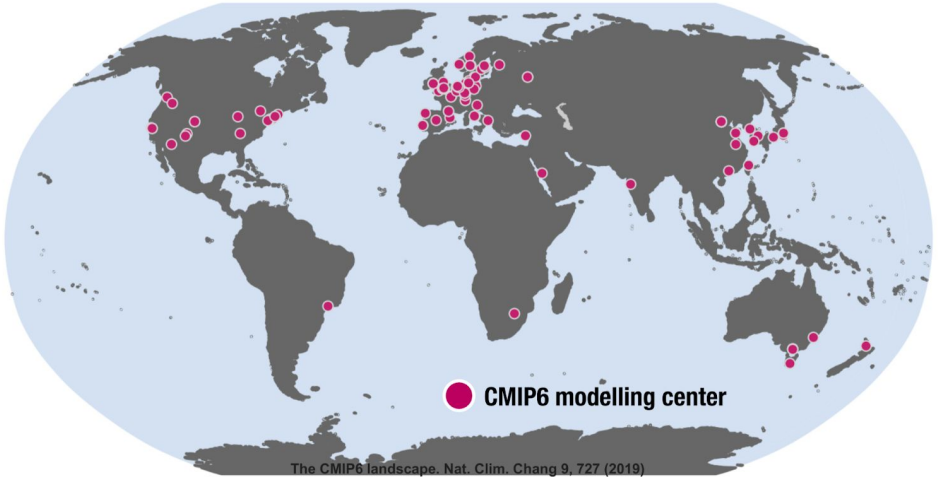
Modeling centers collaborate globally to run and share experiments of how societies' actions will impact climate



Equity in model development and data sharing?

Few models are developed in the Southern Hemisphere, so insight from these areas may be less well captured

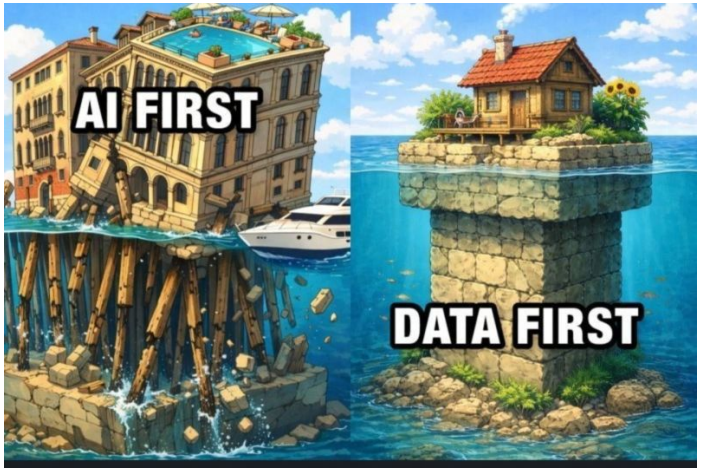
Only a fraction of the data can actually be shared, so data to get insight on e.g. why the ocean is changing is difficult to get



Continued support for gathering data is vital

It is tempting to only focus on AI, but continuing support for improving the data AI relies on in crucial

Creating datasets with a balanced representation of locations and developers can improve equity



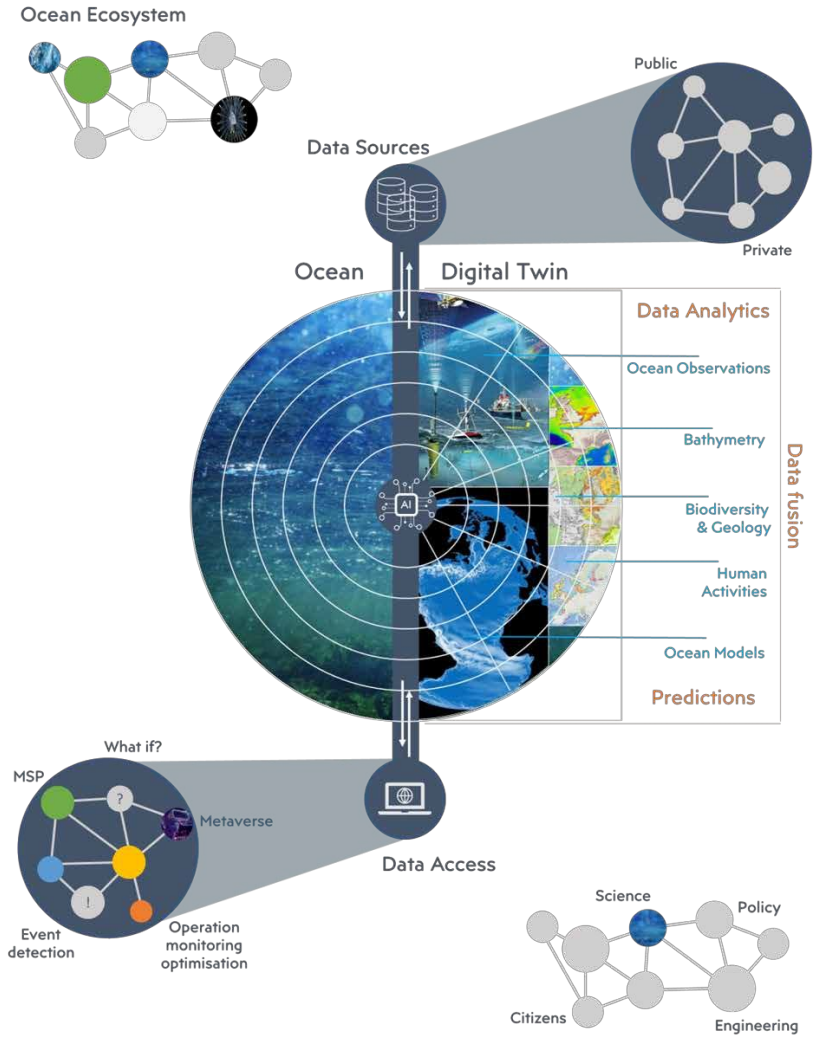
Break: What do you think most important to you to protect in the ocean?



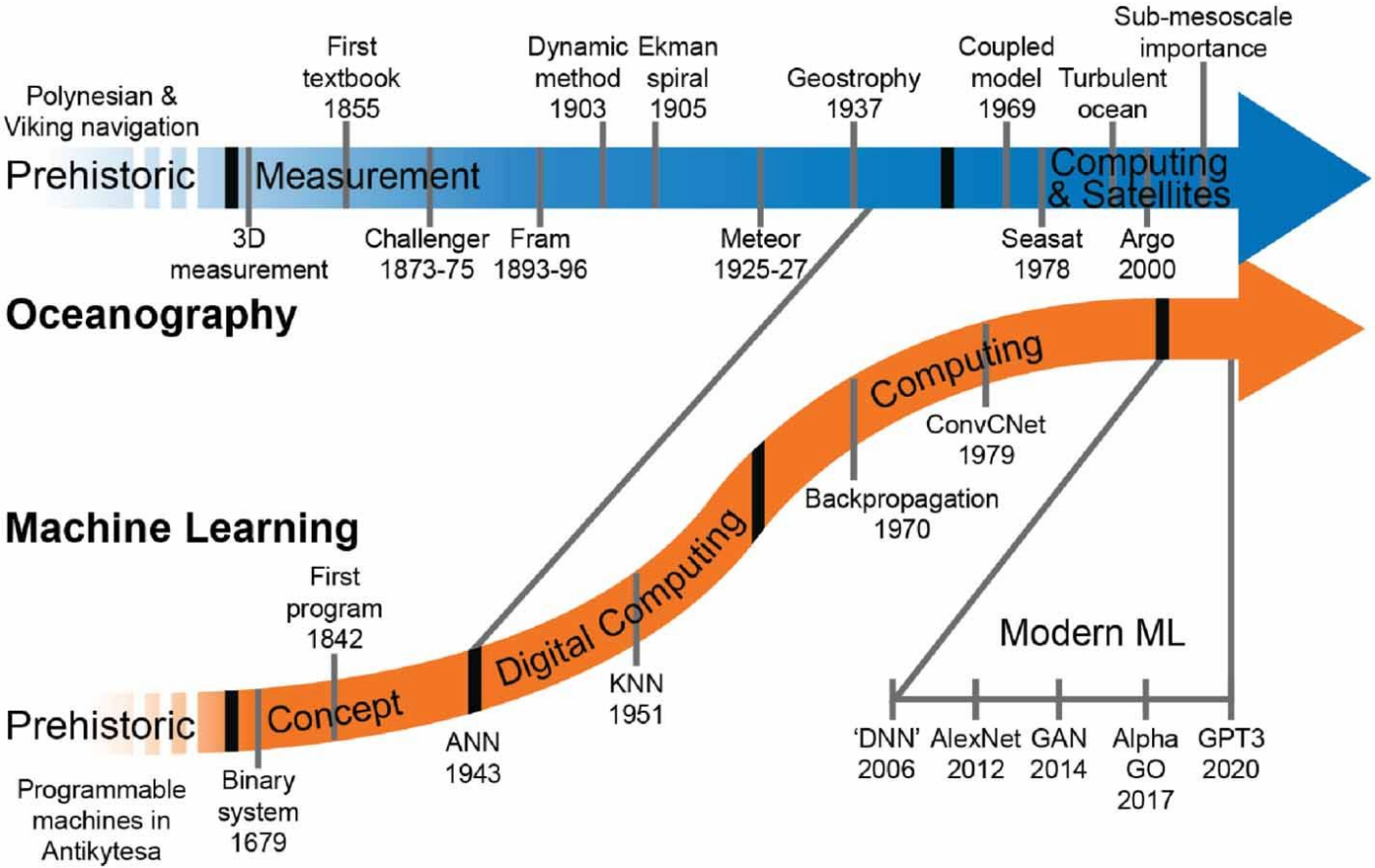
https://partici.fi/86456312

AI for Oceans and Marine Science

How we can learn and help build resilience



Bronner, Sonnewald and Visbeck, 2023



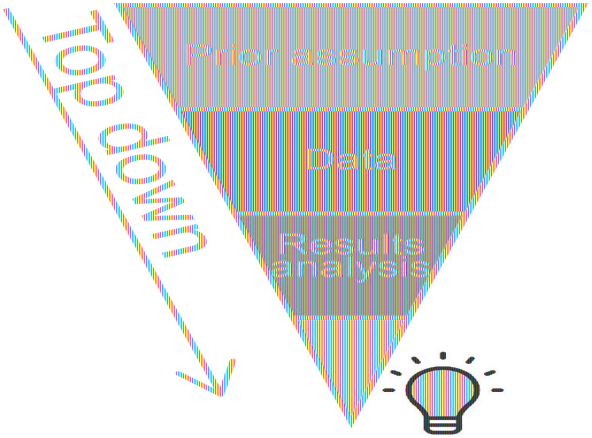
Sonnewald et al., 2021

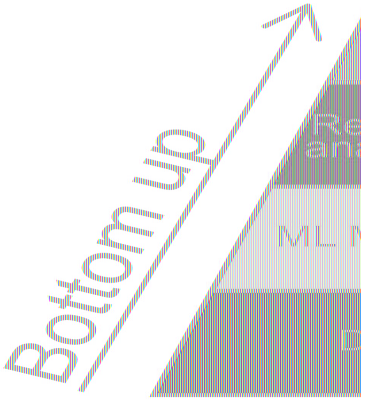
ML: The missing piece?

Too simple:
Theoretical descriptions tend to be oversimplified

Too hard:
Inferring basic principles from data alone is extremely difficult

The bridge: ML





Sonnewald et al., 2021

ML within oceanography



- Observation operators
- Gap filling
- Error detection and bias correction
- Synthesis of observations
- In situ feature detection

- Learn equations and boundary conditions
- Unsupervised learning to understand dynamics and causality
- Learn process interactions
- Learn sub-grid-scale representation of models

- Learn low-order models
- In situ updates of boundary conditions
- Speed-up simulations via emulation and preconditioning
- Compare models against observations
- Uncertainty quantification

- Data assimilation
- Error correction
- Down-scaling
- Understand climate response
- Improve signal-to-noise
- In situ alarm systems

- Alarm systems
- Climate mitigation
- Route planning
- Oil spilling
- Flooding

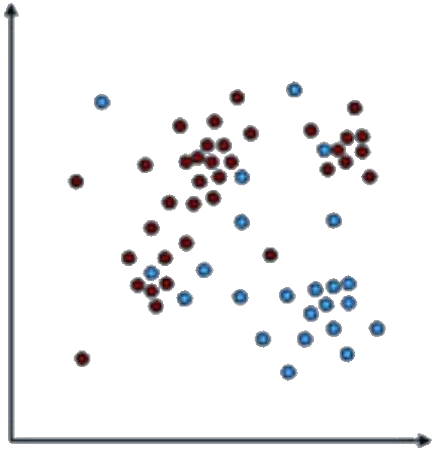
Sonnewald et al., 2021

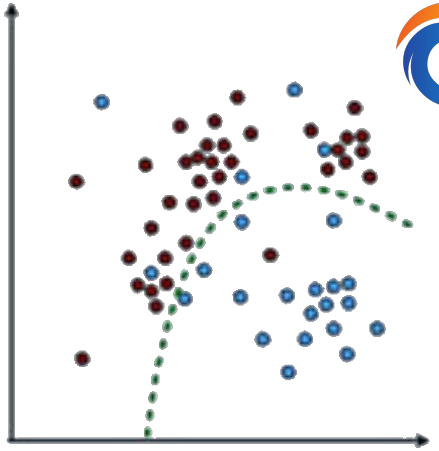
Supervised

-Labeled data

Supervised unsupervised

-Decision boundary

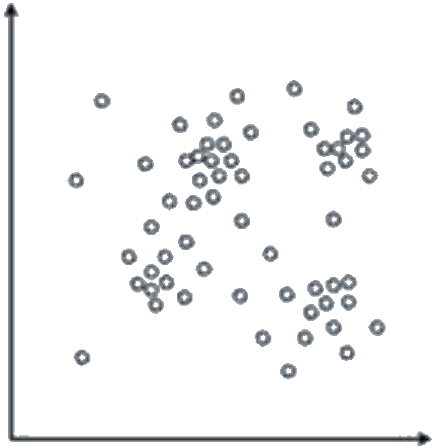




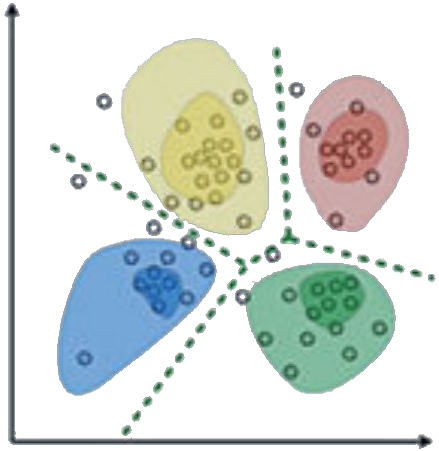
Unsupervised

-No labels

-Identify structures



Training data

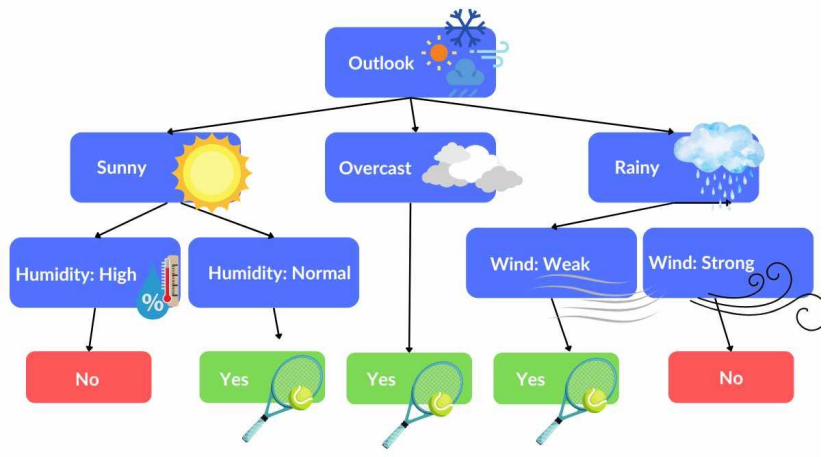


Resulting model

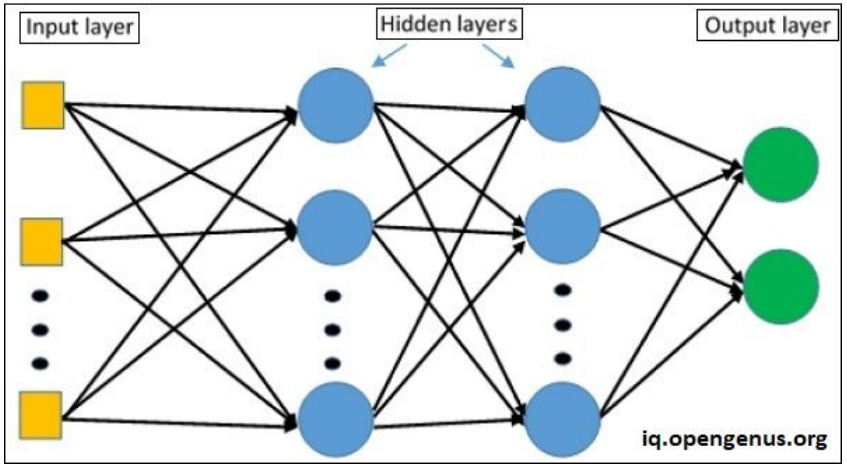
Langs et al., 2018

Two supervised ML methods

Random forests



Neural networks

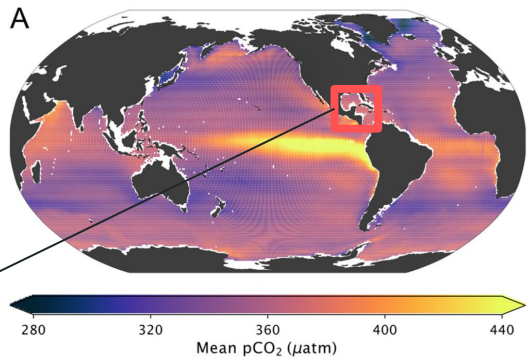


spotIntelligence.com

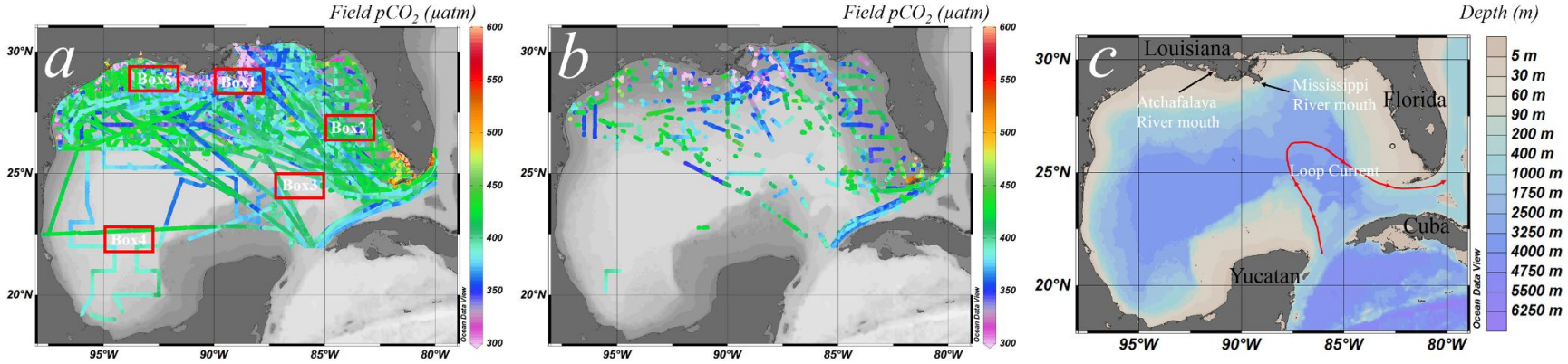
ML for **monitoring ocean surface pCO_2**

Measuring CO_2 requires great effort

There is no known function between another predictive variable and surface pCO_2



Gulf of Mexico



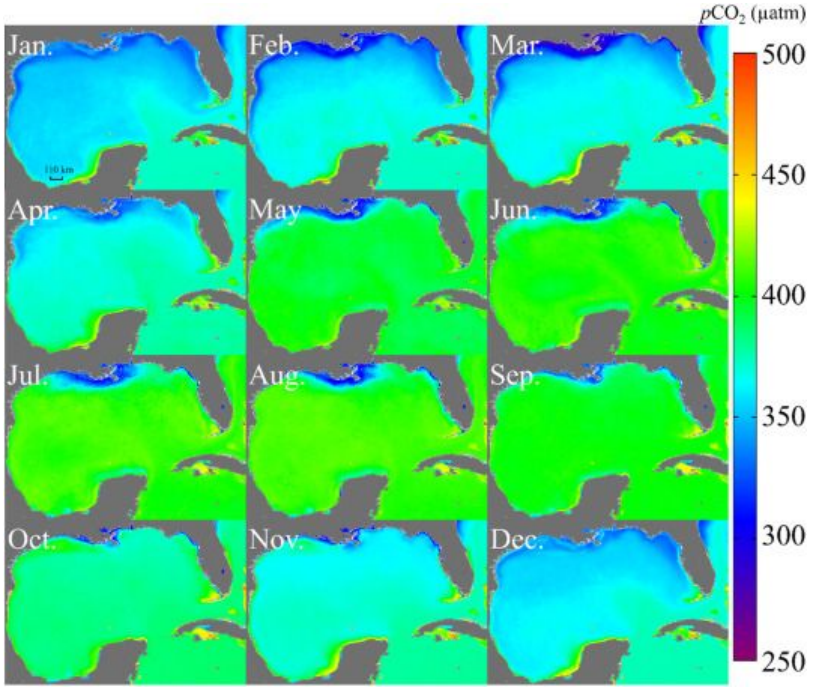
Chen et al,. 2019

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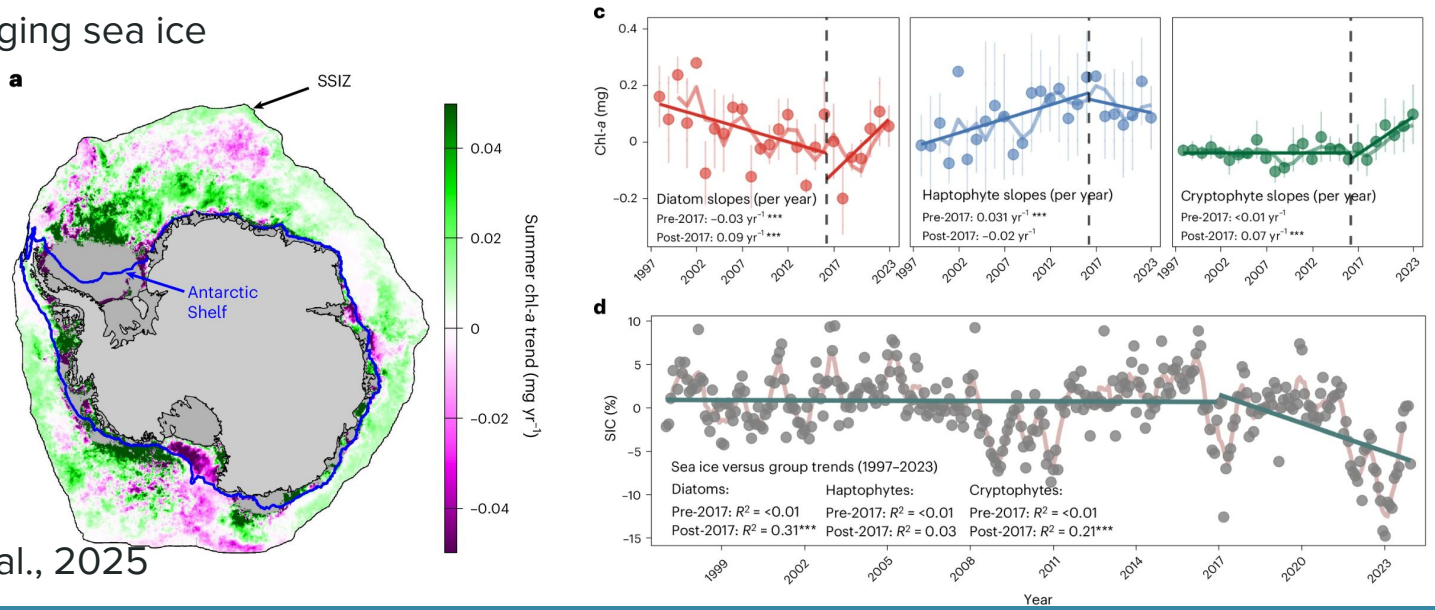
Chen et al,. 2019 used an ML **random forest** method to have satellites predict pCO_2



ML for **monitoring Antarctic plankton**

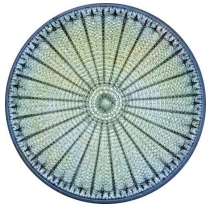
Phytoplankton are critical to the Antarctic marine food web and carbon sequestration, yet long-term shifts in their community composition are poorly understood

Hayward et al., 2025 used ML random forests to show how community composition has changed with changing sea ice



Hayward et al., 2025

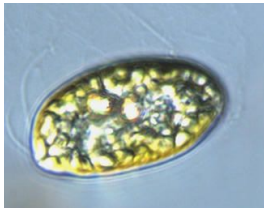
ML for **monitoring Antarctic plankton**



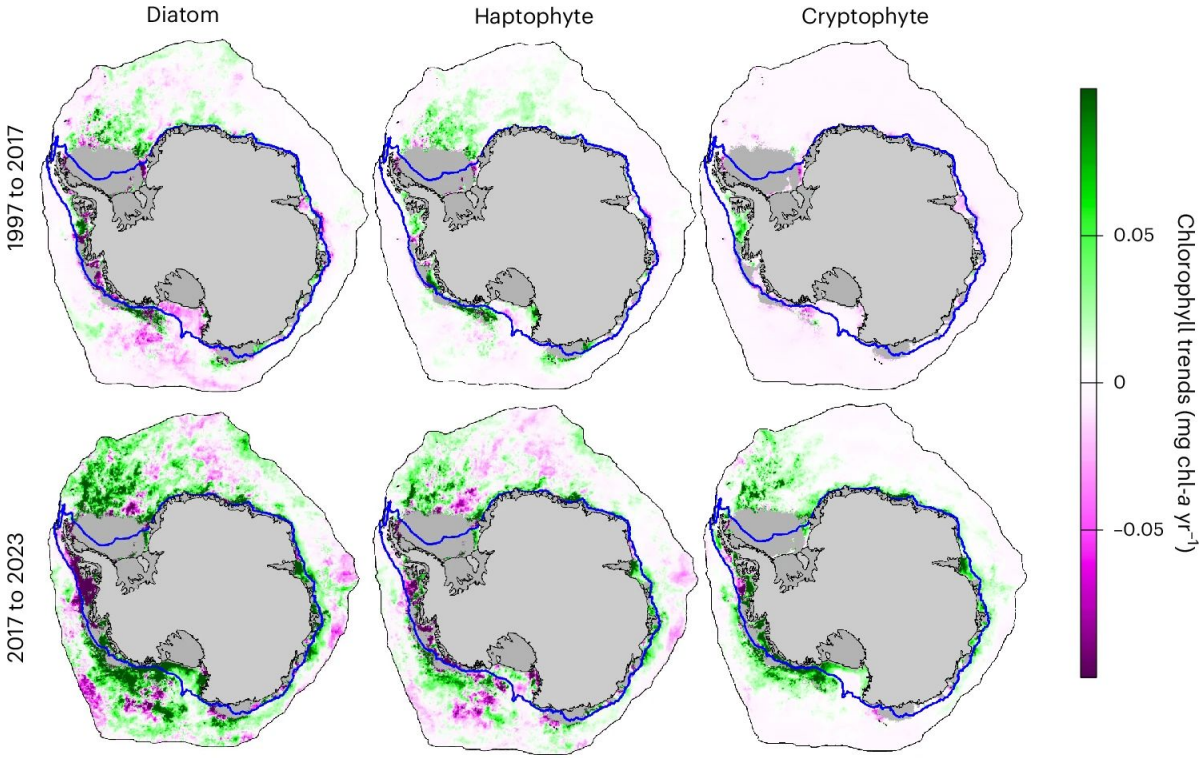
Diatoms



Haptophyte



Cryptophyte



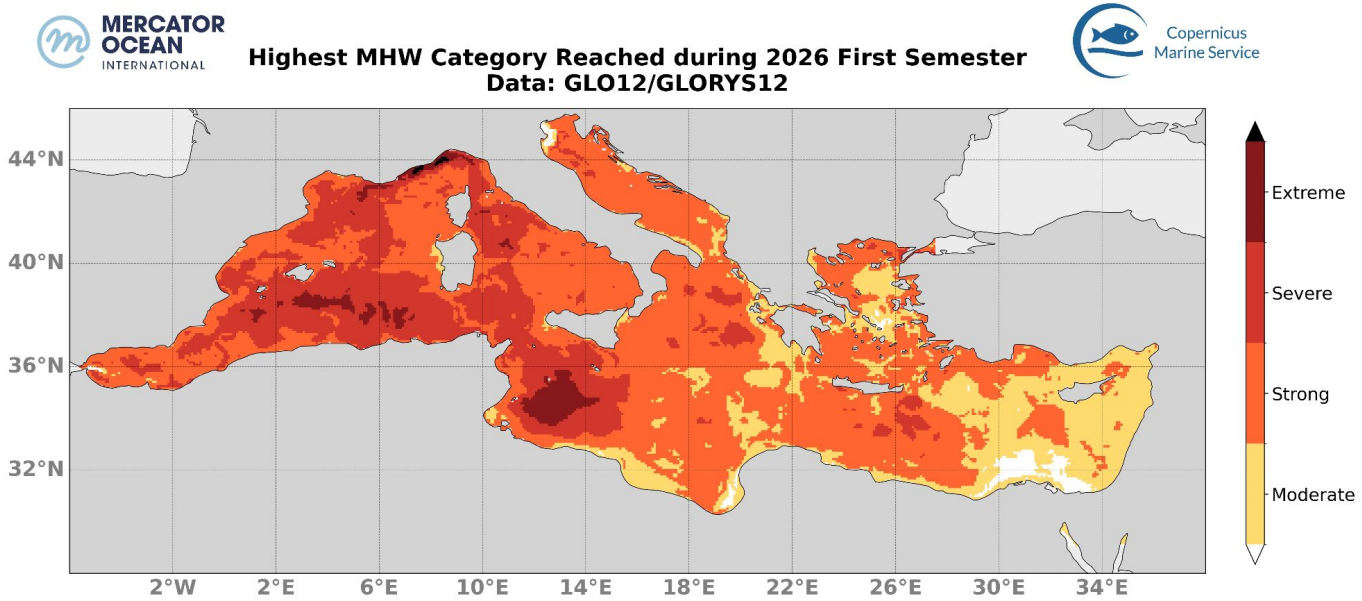
R. Graves, Wikipedia.com, J Oyandomari

3: How much of the Mediterranean surface ocean experienced a heatwave during the first semester of 2026?

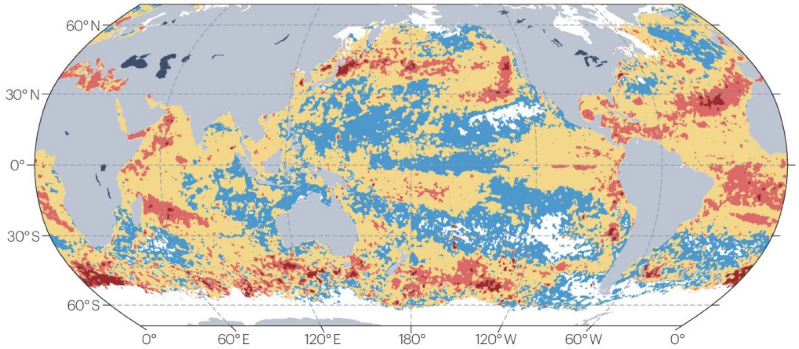


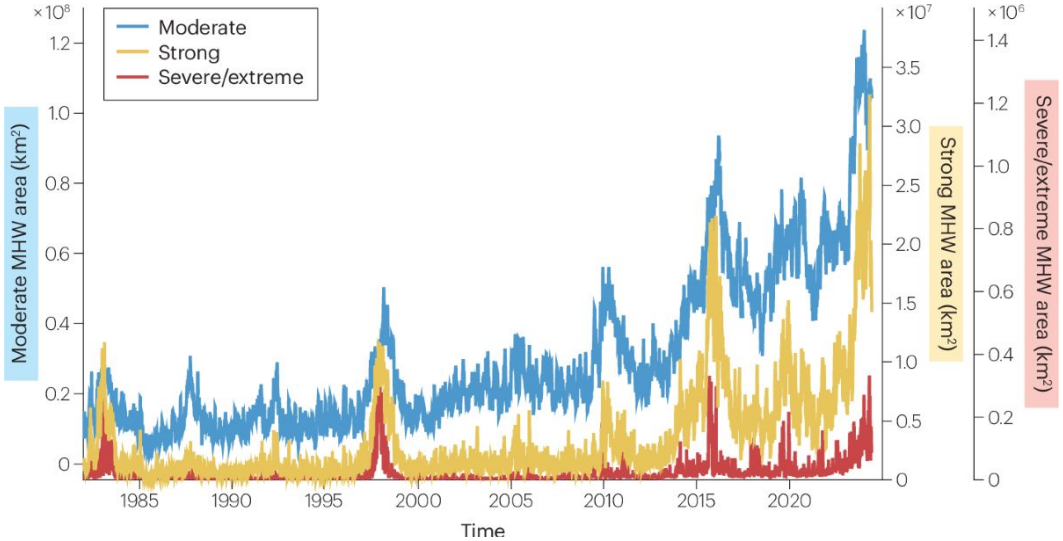
https://partici.fi/86456312

How much of the Mediterranean surface ocean experienced a heatwave during the first semester of 2026?



Marine heatwaves are becoming more common and severe





Wernberg et al., 2025

MARINE HEATWAVE IMPACTS



CHANGES RANGES OF SPECIES' HABITATS



IMPACTS ECONOMICS OF FISHERIES



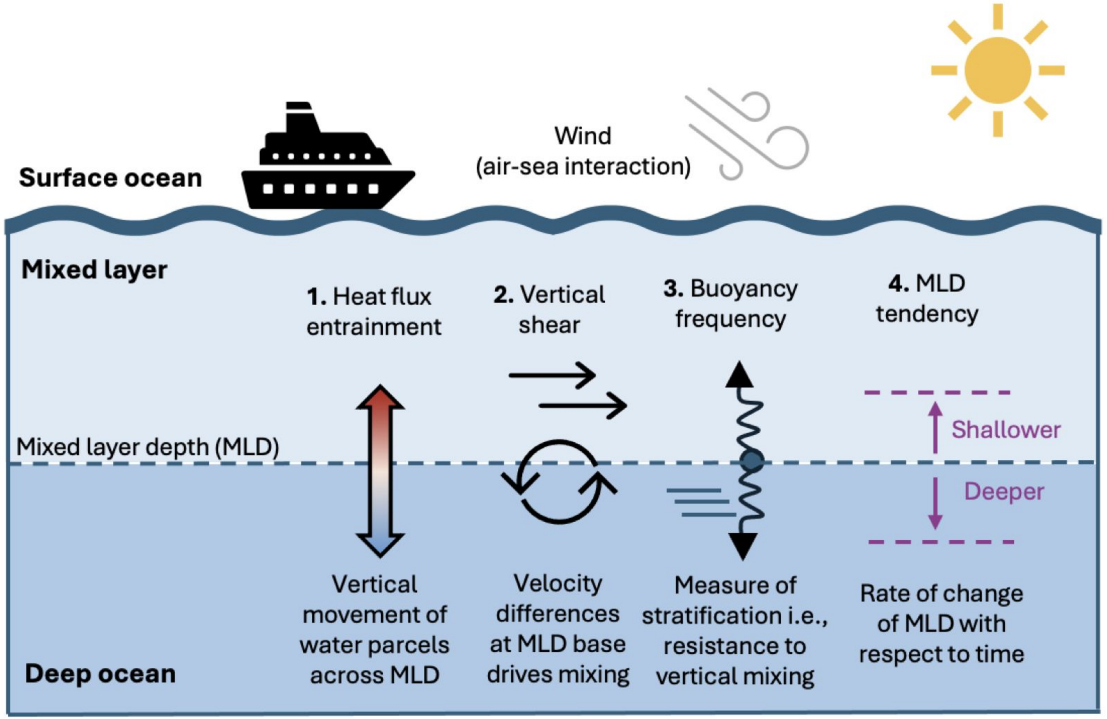
BOOSTS TROPICAL STORMS & HURRICANES



BLEACHES CORAL

CLIMATE CENTRAL

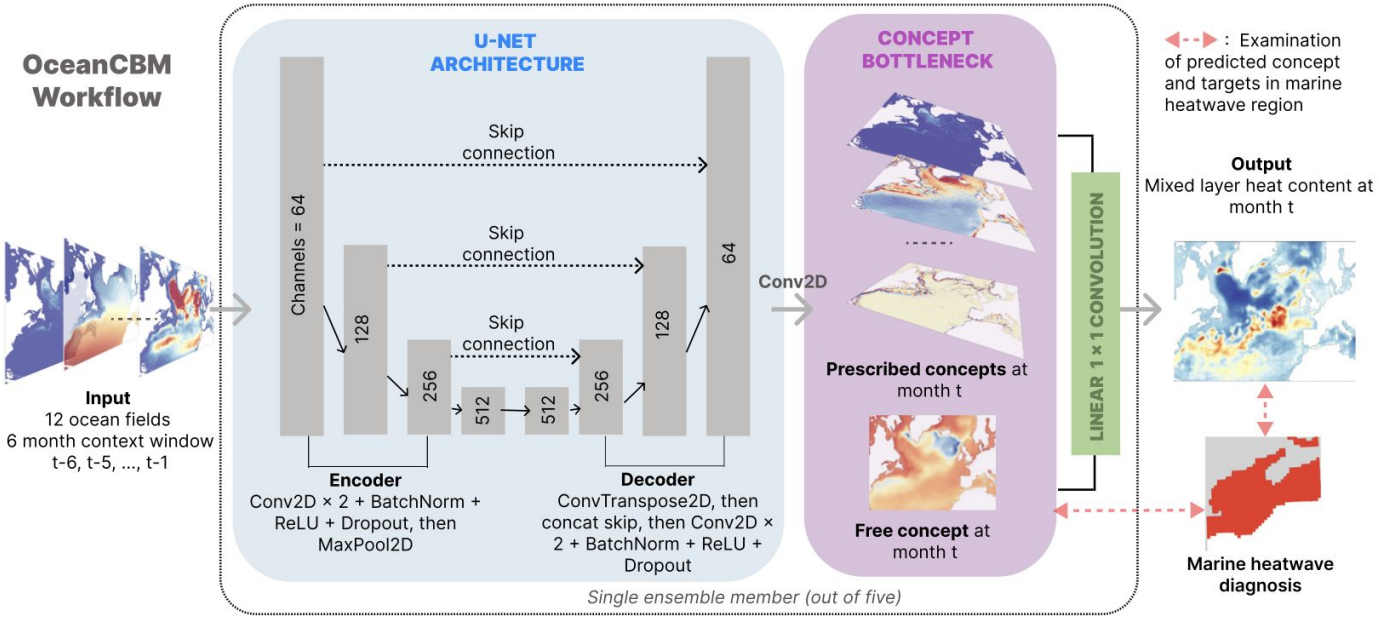
ML for **marine heatwaves prediction and attribution**



Suri et al., 2026

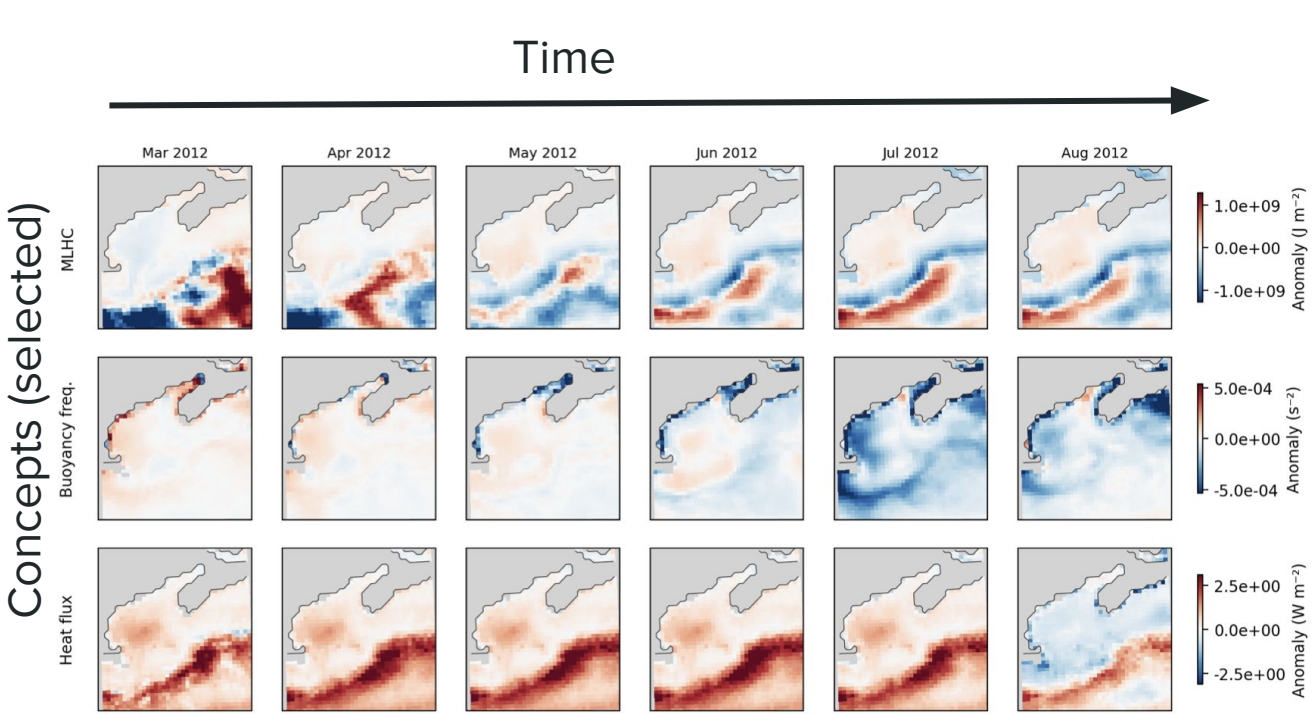
ML for **marine heatwaves prediction and attribution**

Predict ocean mixed layer heat content **telling network to choose** what was important

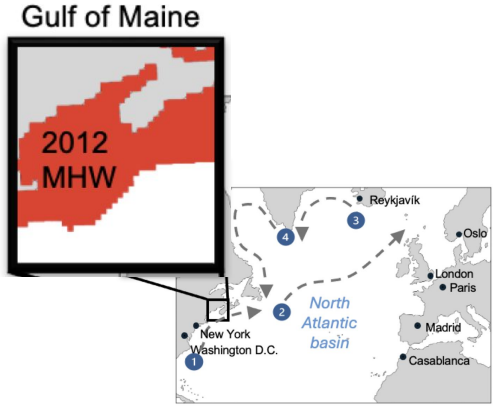


Suri et al., 2026

ML for **marine heatwaves prediction and attribution**

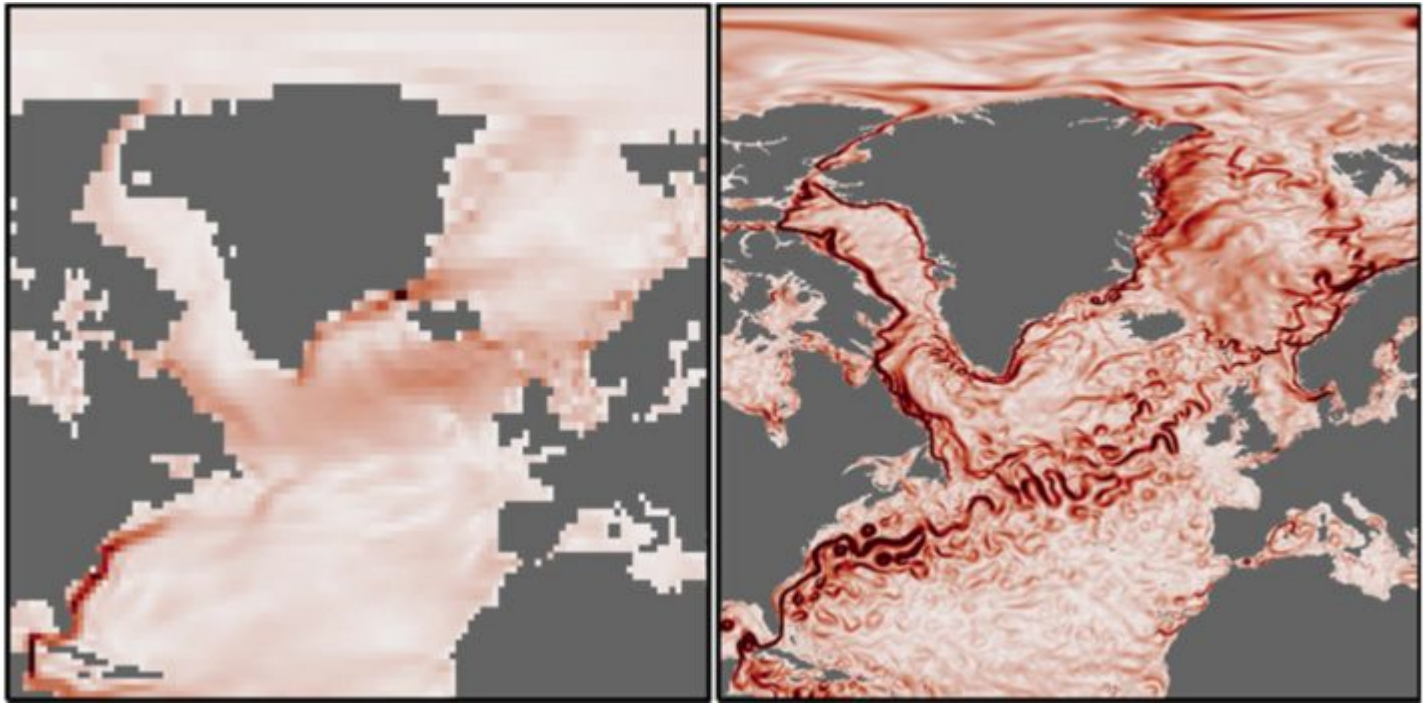


Suri et al., 2026

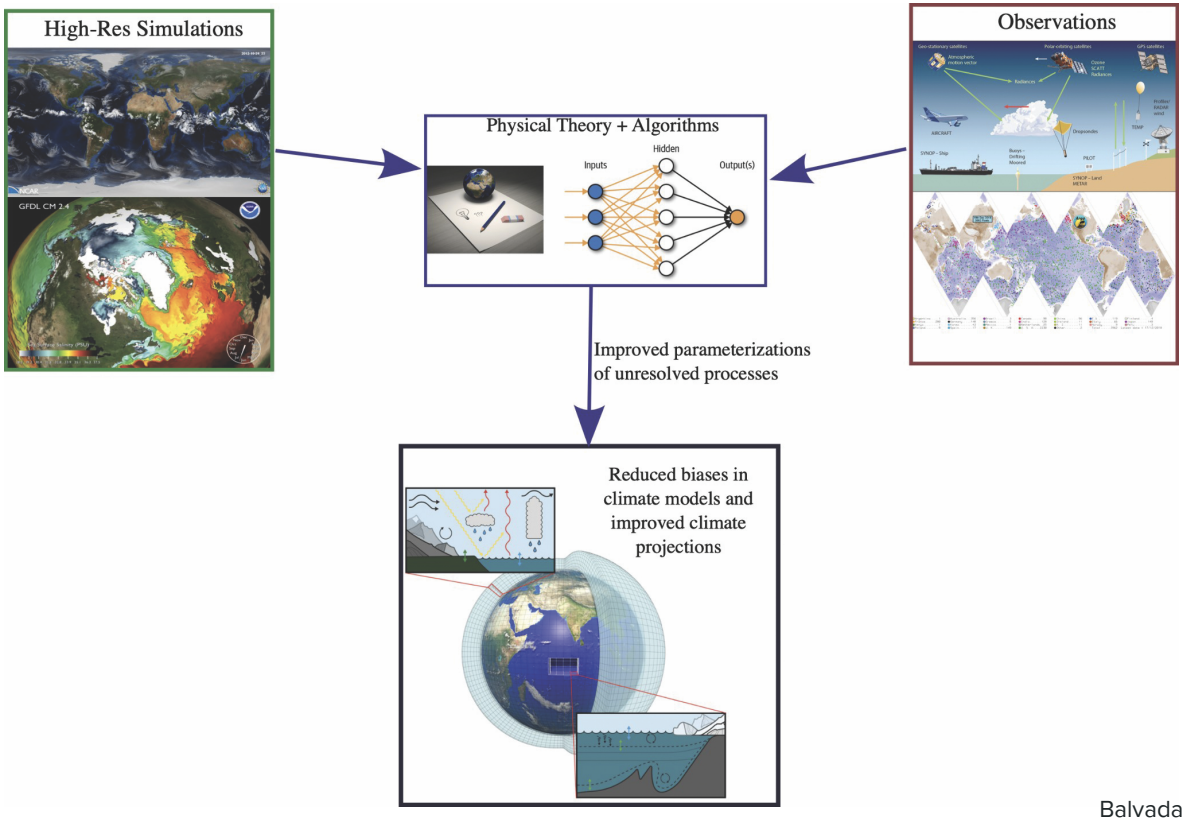


Conclusion:
Atmospheric heat input that warmed the mixed layer
+
increased stratification trapped heat near the surface

ML for **ocean model parameterization**



ML for **ocean model parameterization**



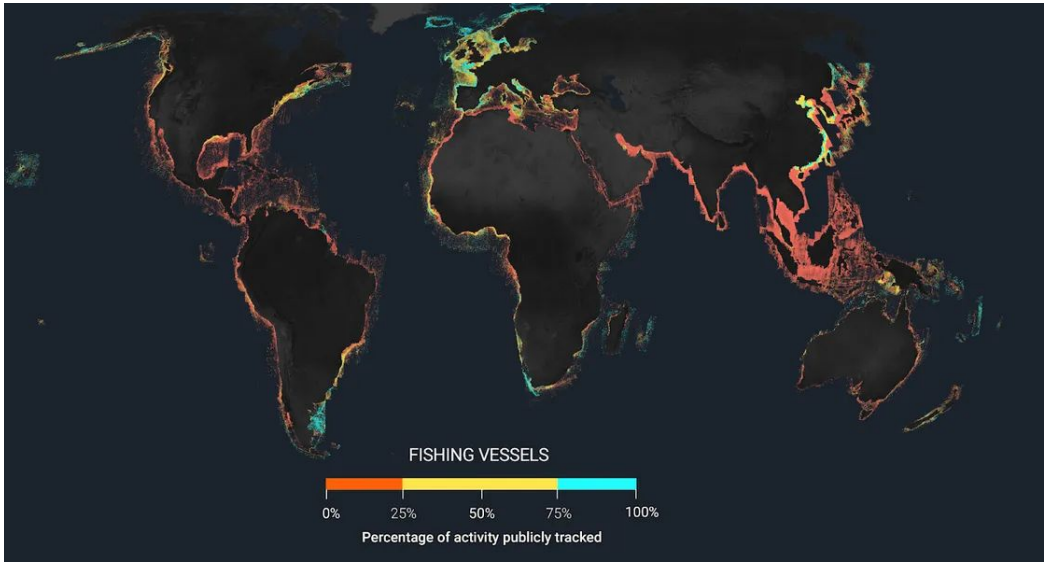
Balvada and Zanna, 2022

ML for **ocean fisheries management**

Global Fishing Watch provide a near-real-time map of industrial fishing activity to combat illegal activities

They use vessel tracking data and AI

Available data gives e.g. position, speed and heading, but not intent. AI classifies a vessel's *type* (trawler, longliner, purse seiner) and then infer if it is transiting or actively fishing



ML for **ocean fisheries management:** A note on who benefits

Global Fishing Watch surfaces illegal activity, but enforcement capacity is unevenly distributed

Detection without capacity can shift burden where there is less capacity



Ocean circulation under climate change deep dive

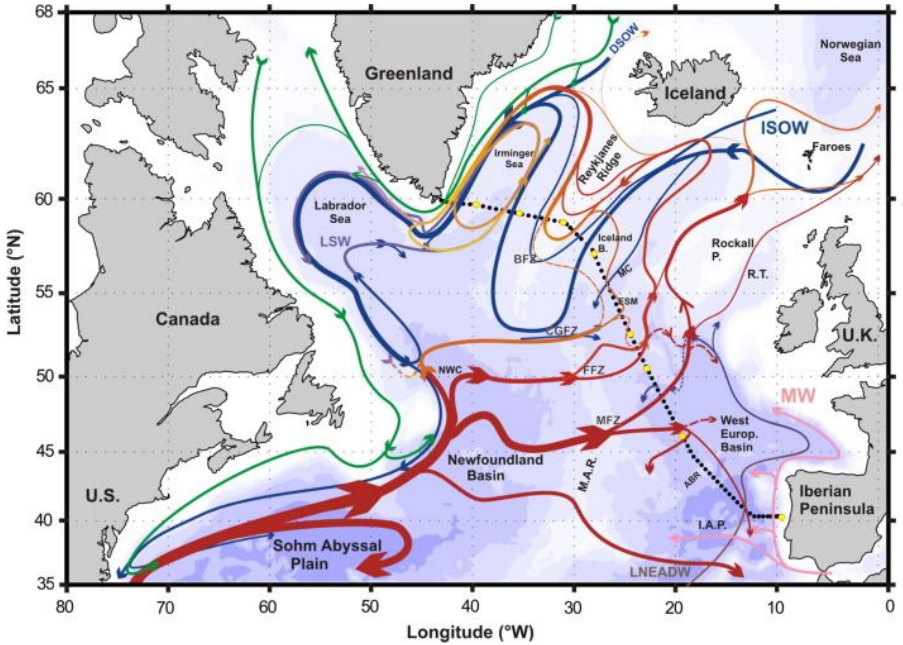
Atlantic Meridional Overturning Circulation (AMOC):

- Heat transport to Europe
- Atmospheric patterns
- Droughts
- Sea level USA East coast
- Hurricanes



Iceland made the move of designating the risk of an AMOC shutdown a **national security threat**

We will use ML to understand the AMOC change in CMIP



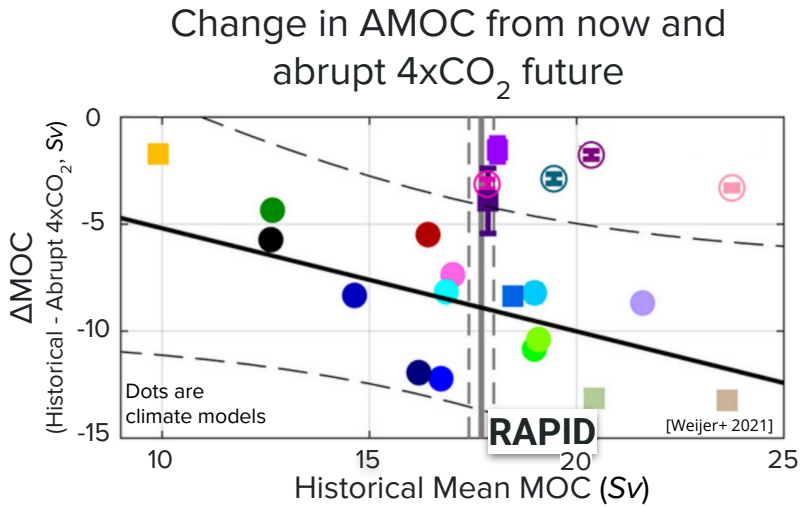
Assessed as simplistic metric: Flow rate at 26ºN

One number to describe complex currents?

Daniault et al., 2016

CMIP often has little data to **understand** change

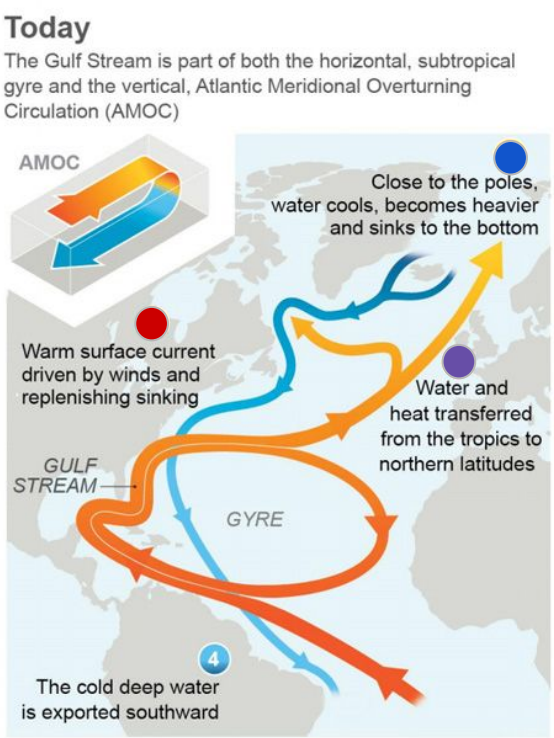
- Bulk metrics common
  - E.g.: Atlantic Meridional Overturning Circulation (A MOC) metric
- Measures the strength and volume transport of the AMOC
- Tracks how fast warm water moves north and cold water returns south
- Current volume transport: Measured using ocean depth, velocity, temperature, and salinity
  - Array Locations: Monitored across latitude lines 26.5°N (RAPID), 34.5°S (SAMBA), and subpolar regions.

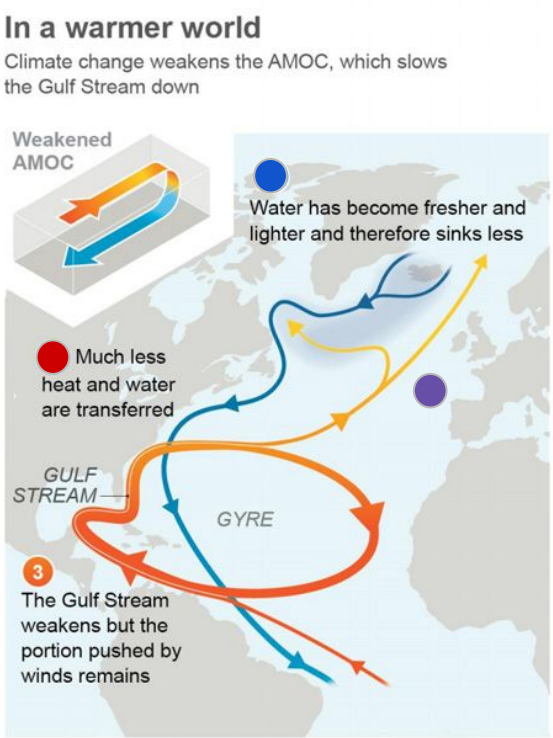


1 Sv = 10^6 m^3/s

Will the Gulf Stream shut down under climate change?

We can see fingerprints of change in dynamics

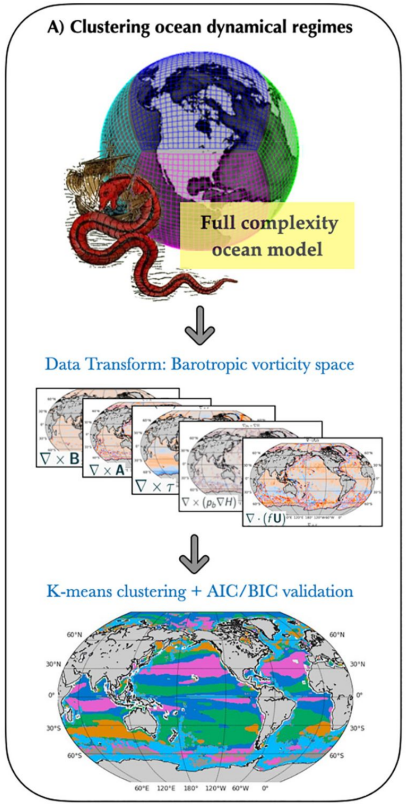


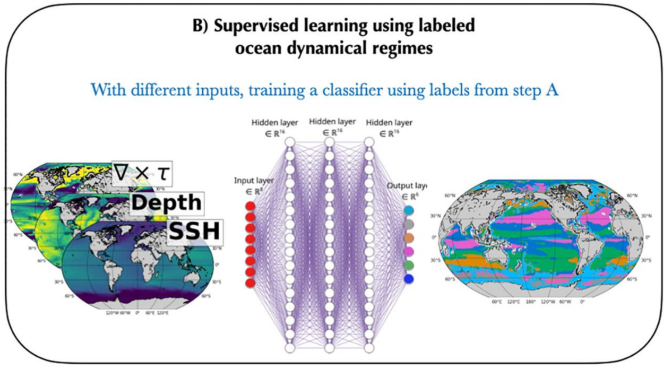


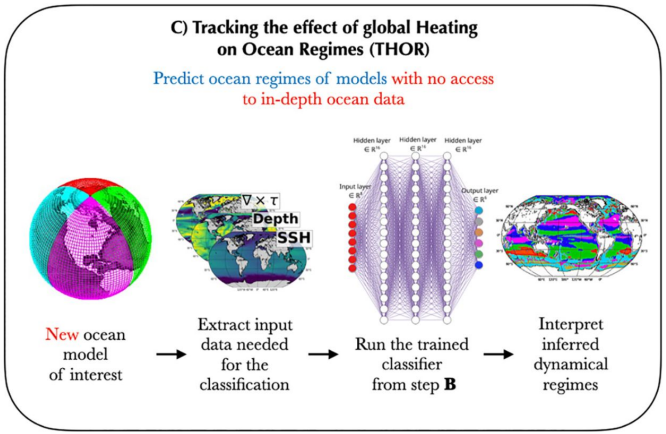
- Gulf stream shifts north
- Path of heat delivery moves
- Less dense/heavy waters

Adapted from IPCC AR5

Method: Tracking global Heating with Ocean Regimes (THOR)







Infer current detail with sparse available data

Equitable computing: open-source and cloud HPC

GitHub maikejulie/DNN4Cli

FAIR

AWS

Sonnewald and Lguensat, 2021, ***JAMES***

Sonnewald, et al., 2021, ***International Conference on Machine Learning (ICML)* workshop paper spotlight**

Gille [...], **Sonnewald** et al., 2018, **Open Code Policy for NASA Space Science, white paper**

Tackle overwhelming complexity of fluid dynamics in climate models

Full complexity ocean model component



Symbolic Transform

Fundamental equation space framework

(Barotropic vorticity equation)

Advection

Wind and Bottom Stress

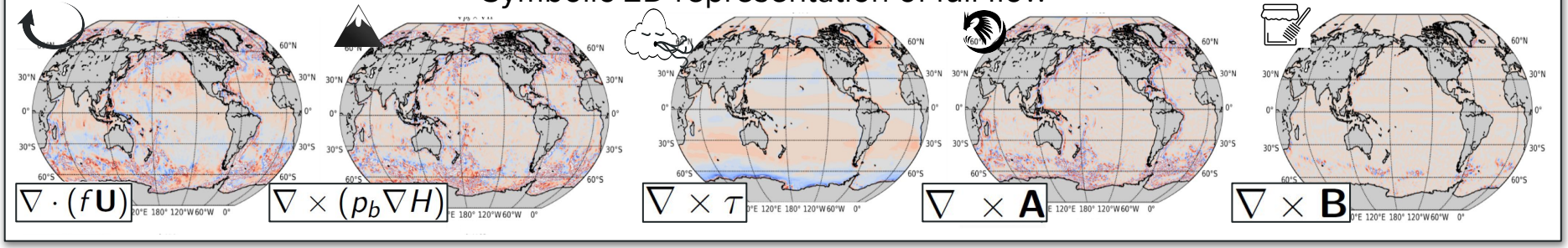
Lateral Viscosity

$$0 = \nabla \cdot (f\mathbf{U}) - \nabla \times (p_b \nabla H) + \nabla \times \tau - \nabla \times \mathbf{A} + \nabla \times \mathbf{B}$$

Bottom Pressure Torque

Non-linear Torque

Symbolic 2D representation of full flow



[SWH **2019 ESS**]

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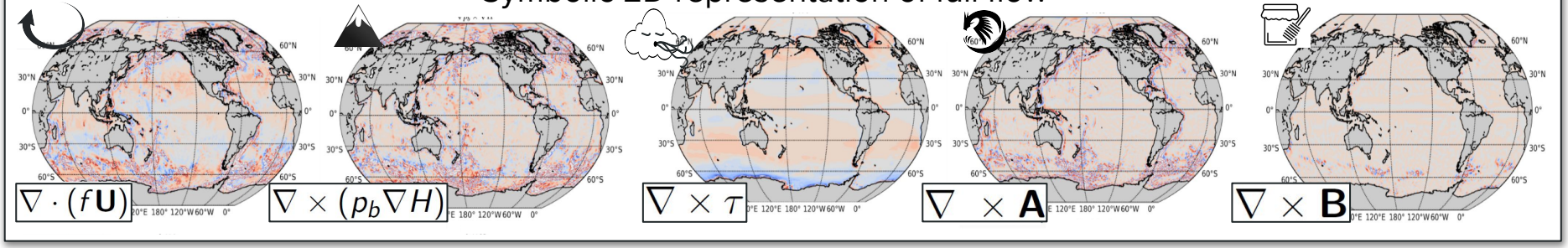
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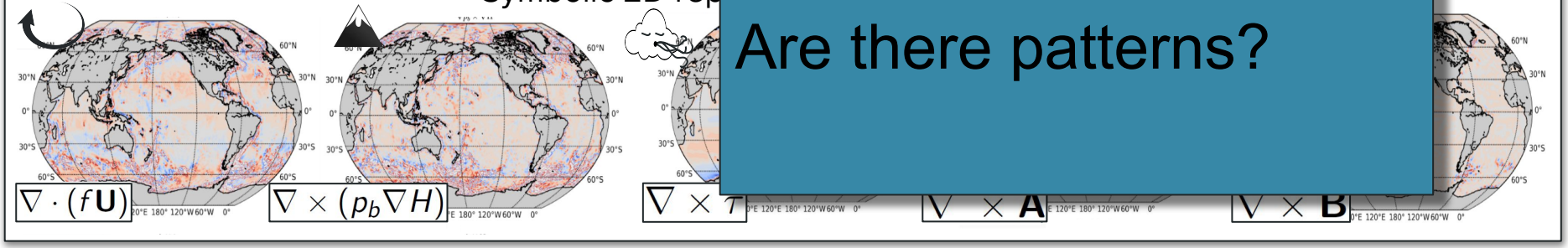
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Bottom Pressure Torque

Non-linear Torque

Symbolic 2D rep



Are there patterns?

[SWH **2019 ESS**]

Tackle overwhelming complexity of fluid dynamics in climate models

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Advection

Wind and Bottom Stress

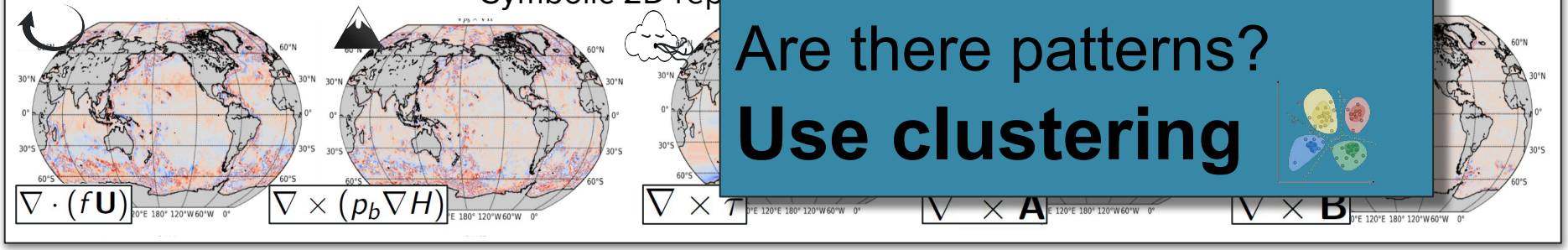
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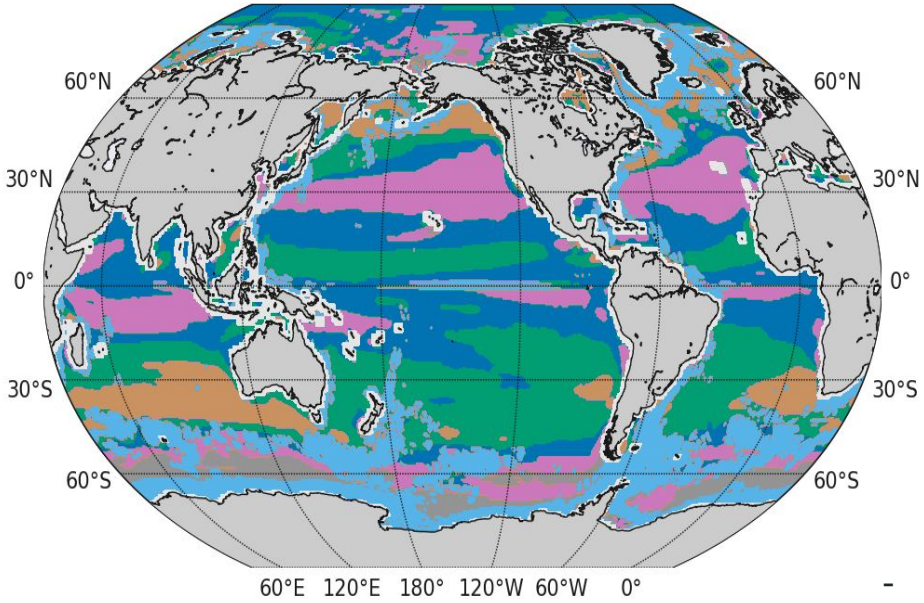
Symbolic 2D rep

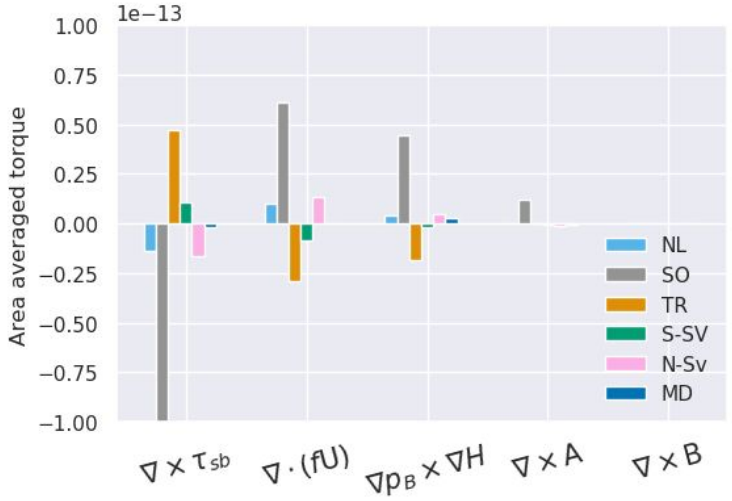


Are there patterns?

Use clustering

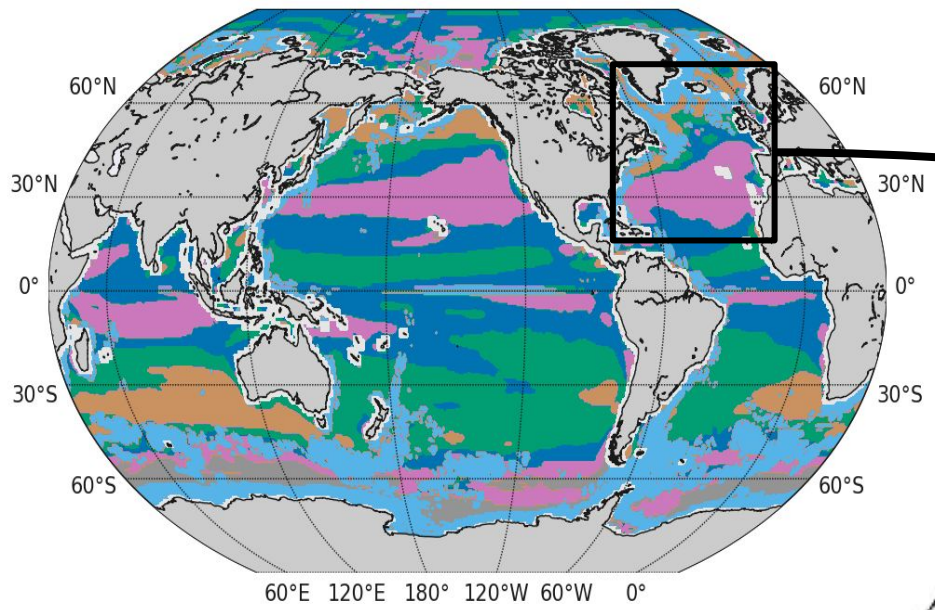
[SWH **2019 ESS**]





- Coherent regions emerge
- Regimes signify balance of terms in the equation

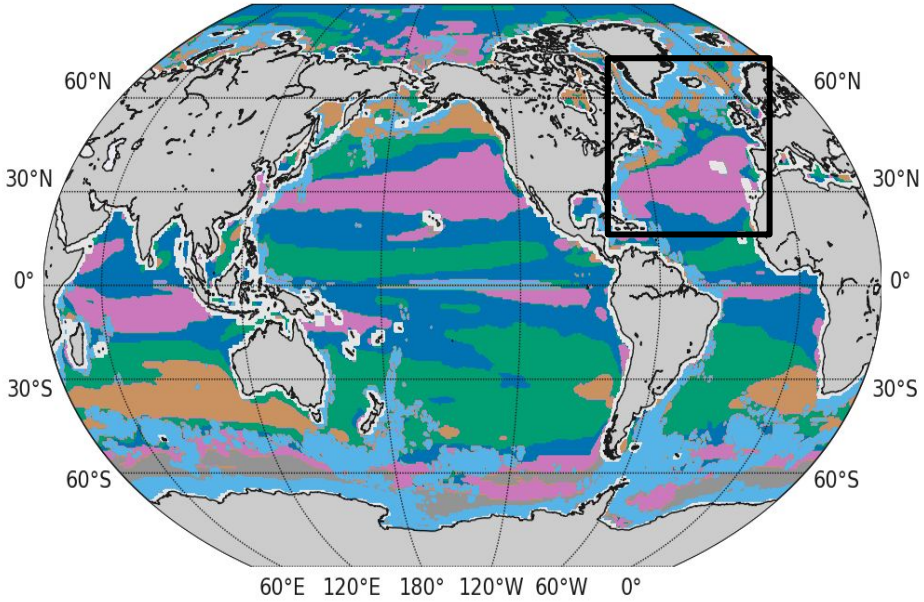
NL-Non-linear	**SO**- Southern Ocean	**TR**- Transitional
S-SV- SH Sverdrupian	**N-SV**- NH Sverdrupian	**MD**- Momentum dominated

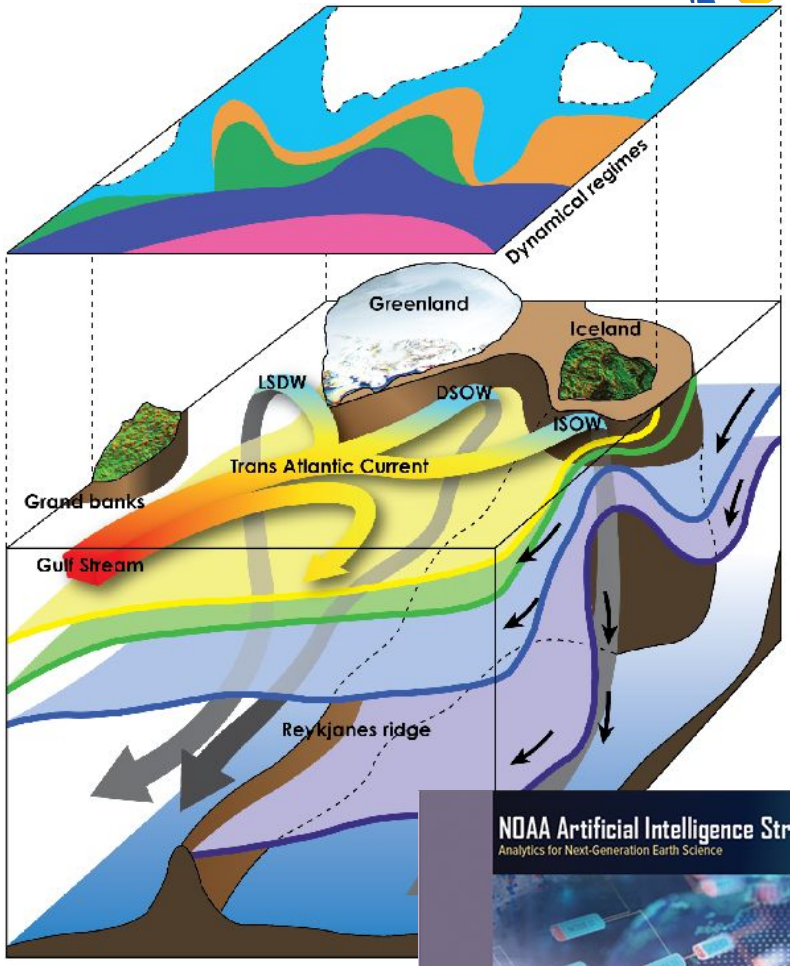




New knowledge: Sonnewald, Reeve & Lguensat, 2023
Main: Sonnewald, Wunsch & Heimbach, 2019,
Formalism: Kaiser, Sanches, Sonnewald & Livrenco, 2022



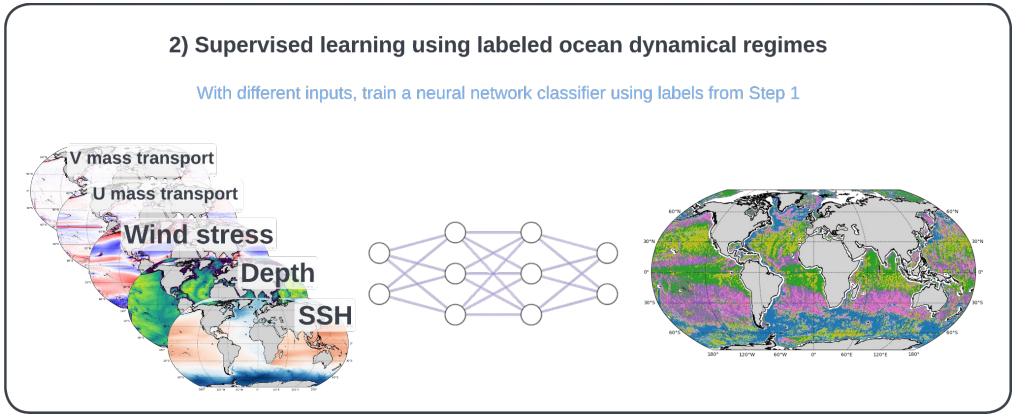




Regimes reveal 3D ocean features tied to e.g. heat transport

- Warm currents brought north (red)
- Cool as basin is crossed (yellow)
- Sink to depth (gray)

Learning regimes from readily available fields

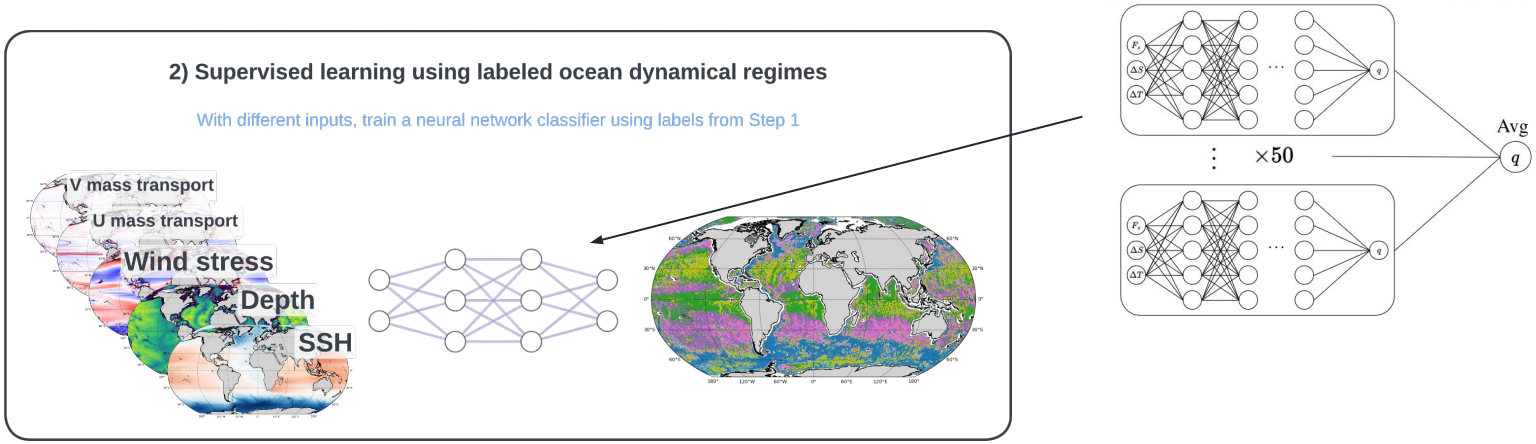


- Inputs: Approximate “words”
  - Sea surface height (ZOS) + x/y gradients
  - Depth (column height) + x/y gradients
  - Wind stress curl ($\nabla \times \tau$)
  - Depth summed monthly mass transport (umo_2d + vmo_2d)
  - Coriolis parameter (f)

- Labels provide “context”: 6 dynamical regimes
- Deep Ensemble (50 MLP) for uncertainty quantification
- Application of eXplainable AI techniques

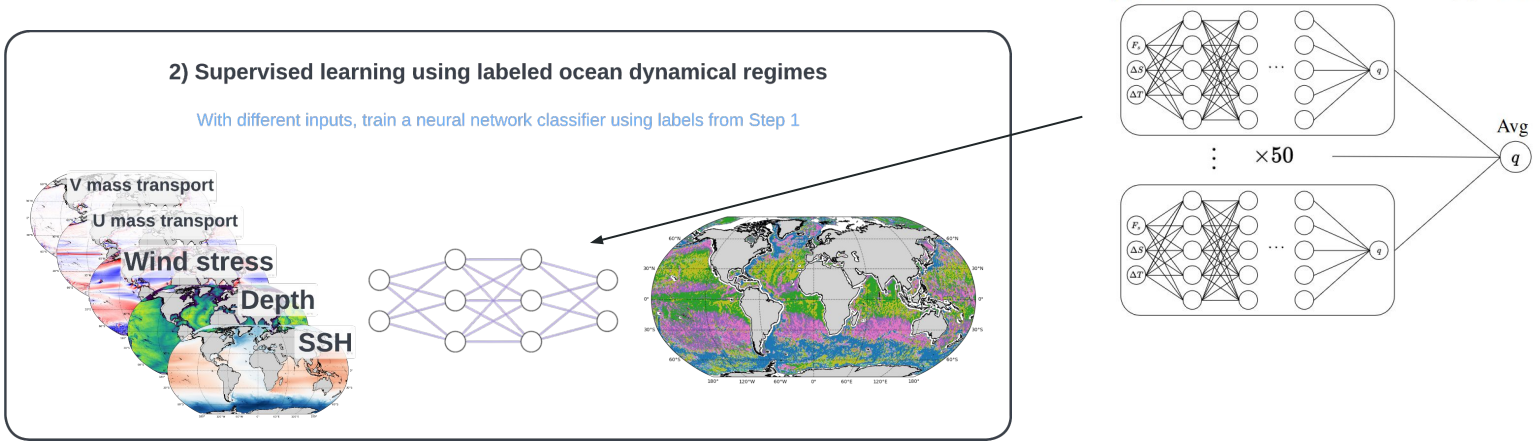
Sonnewald, Reeve & Lguensat, in press, **Nature Comm. Earth and Env.**
Main: Sonnewald, Wunsch & Heimbach, 2019, **ESS.**
Formalism: Kaiser, Sanches, **Sonnewald** & Livrenco, 2022 **Eng Appl AI**

Learning regimes from readily available fields



- Inputs: Approximate “words”
  - Sea surface height (ZOS) + x/y gradients
  - Depth (column height) + x/y gradients
  - Wind stress curl ($\nabla \times \tau$)
  - Depth summed monthly mass transport (umo_2d + vmo_2d)
  - Coriolis parameter (f)
- Labels provide “context”: 6 dynamical regimes
- Deep Ensemble (50 MLP) for uncertainty quantification
- Application of eXplainable AI techniques

Learning regimes from readily available fields



- **Inputs available from CMIP:**
  - Sea surface height (ZOS)
  - Depth (column height)
  - Wind stress curl ($\nabla \times \tau$)
  - Depth summed monthly mass transport
  - Coriolis parameter (f)

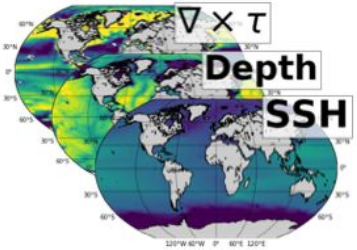
- **ML model:**
  - Deep Ensemble (50 MLP) for uncertainty quantification
  - Application of eXplainable AI techniques

Apply to different climate scenarios to understand changes

THOR: Recognizing regimes in an unseen model

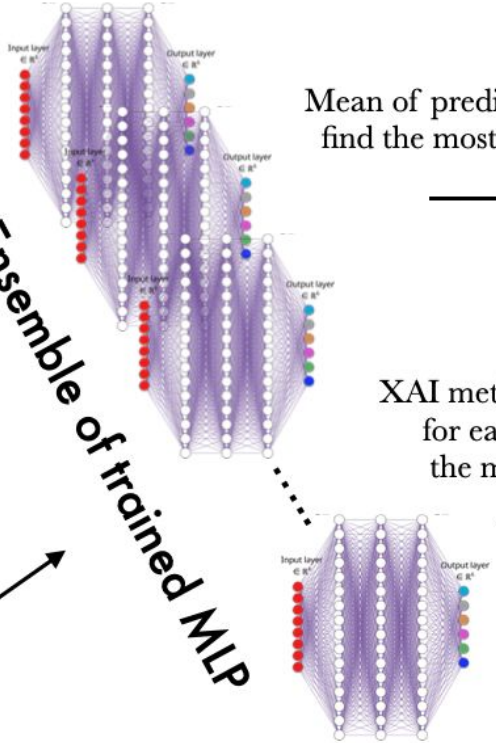


Ocean model of interest



Extract input data needed by the classifier

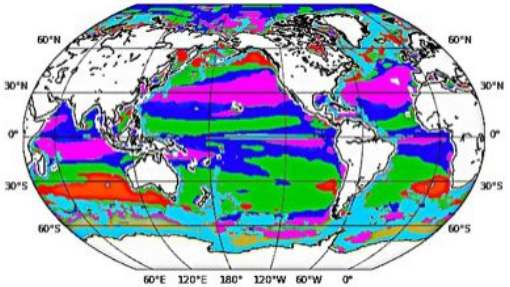
Ensemble of trained MLP



Mean of predictions is used to find the most probable class

Classification

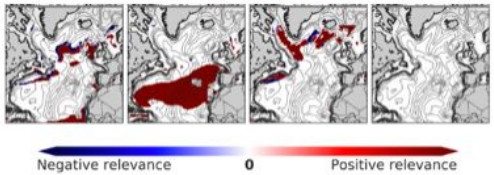
Predict dynamical regimes in unseen data



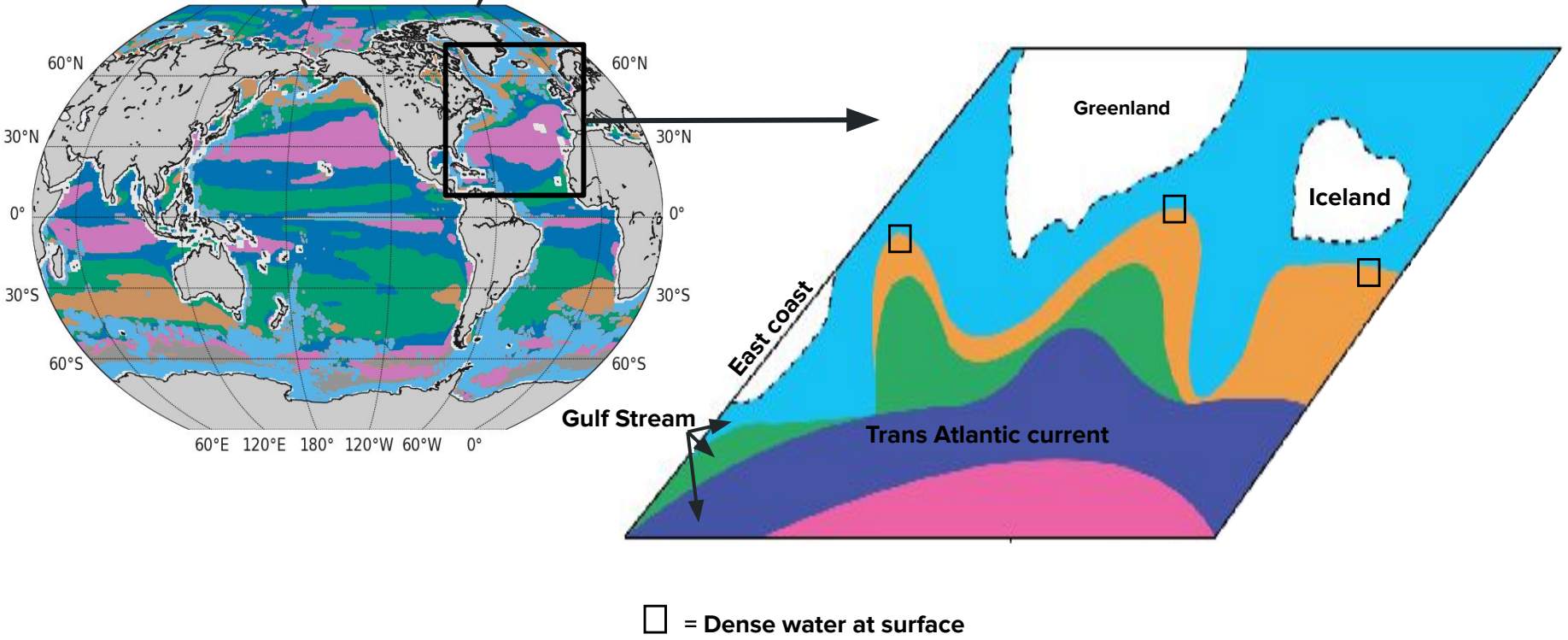
XAI method (ex: LRP) is used for each MLP to obtain the mean of relevances

Explainability

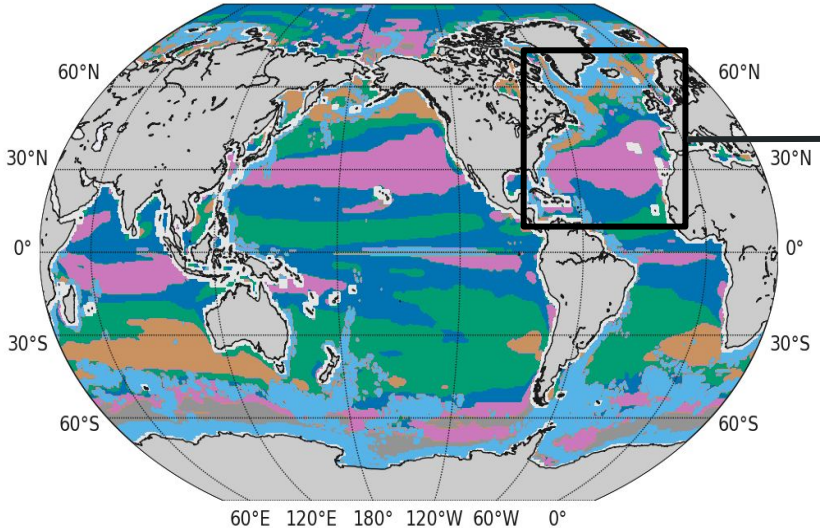
Attribute predictive skill to input features

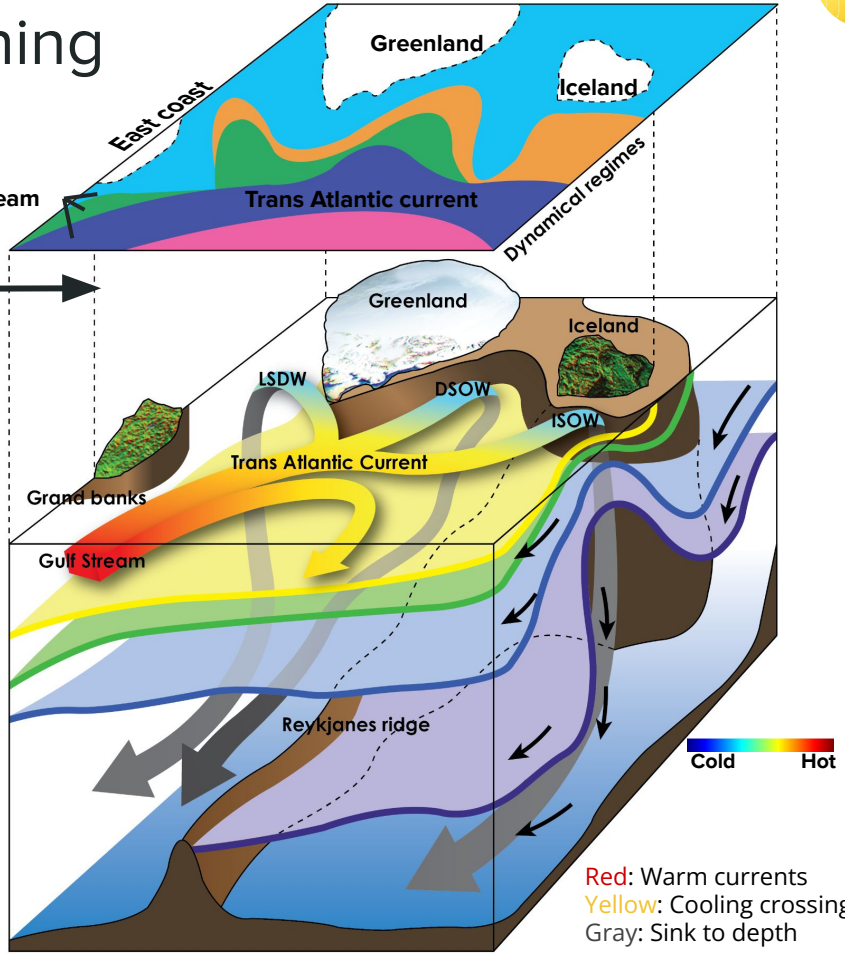


THOR for diagnosing processes of the Atlantic meridional overturning circulation (AMOC)



THOR for diagnosing processes of the Atlantic meridional overturning circulation (AMOC)





THOR used for CMIP models

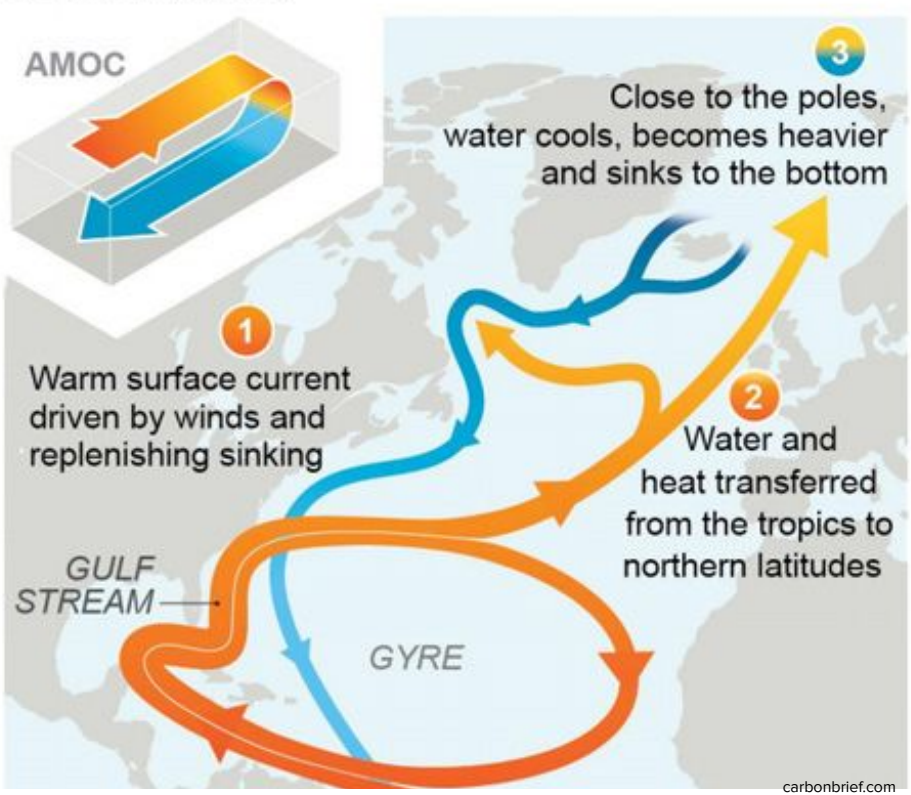
Diagnose processes to speed up tuning and parameterisation of models

GFDL and IPDL

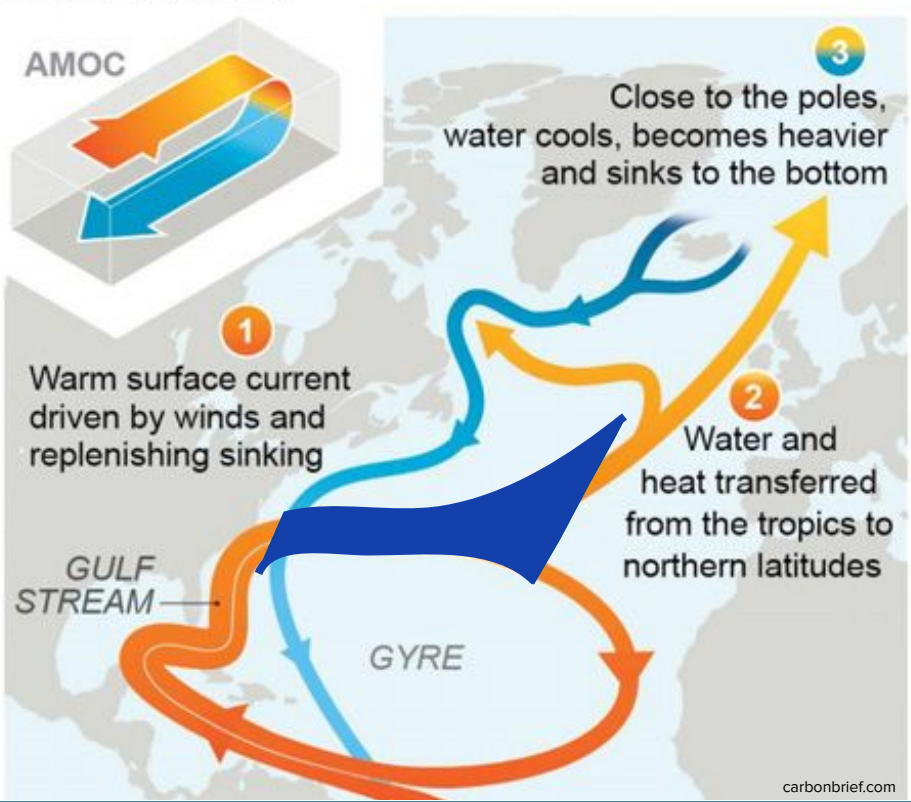


Red: Warm currents
Yellow: Cooling crossing basin
Gray: Sink to depth

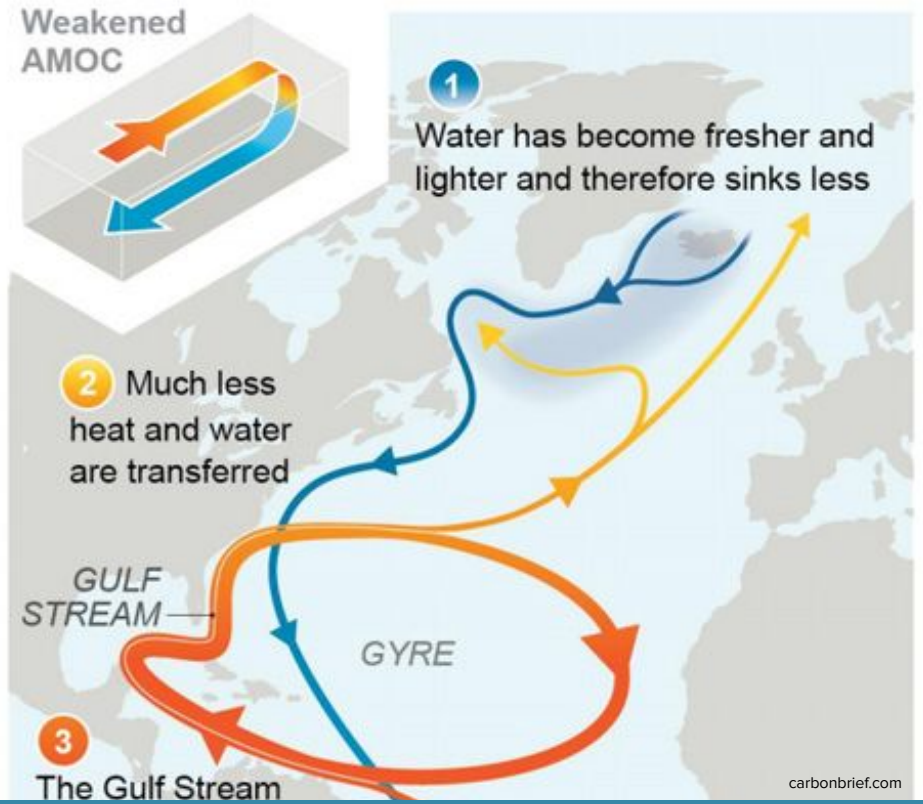
How will the overturning weaken under climate change?



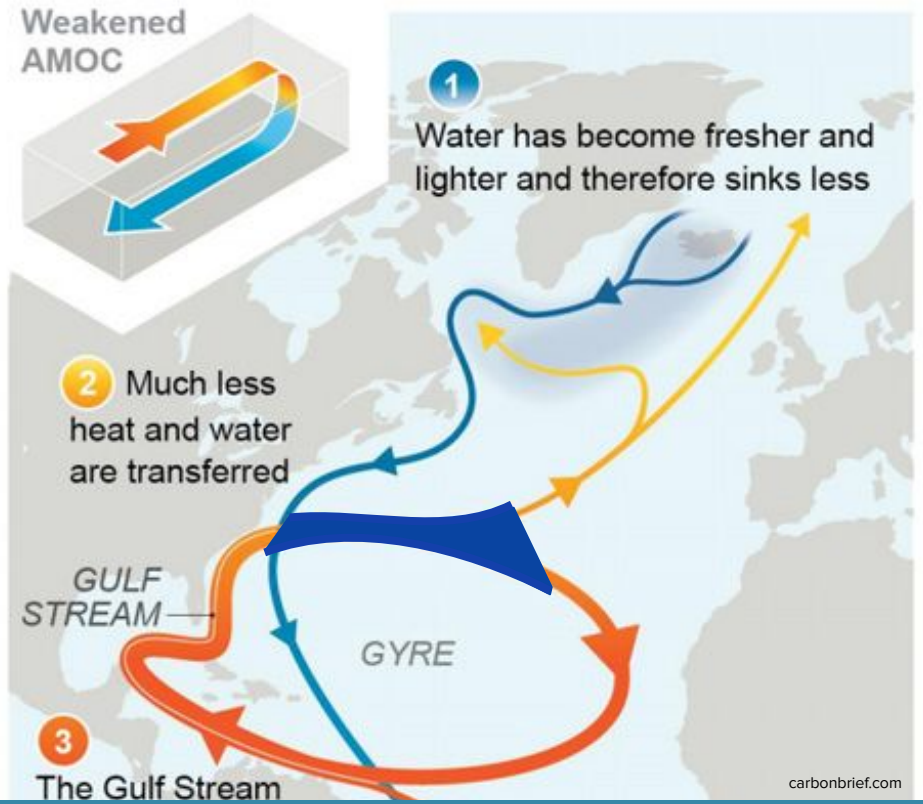
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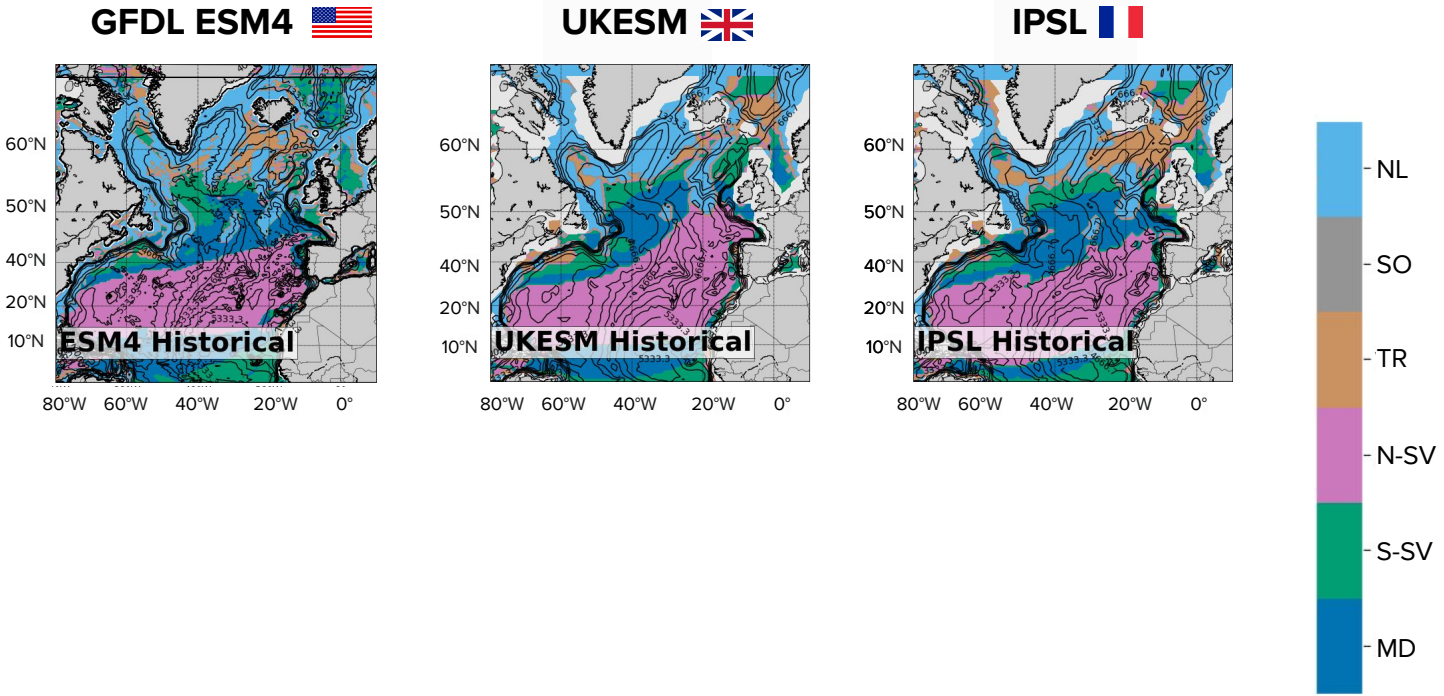


How will the overturning weaken under climate change?



THOR reveals processes changes in abrupt CO_2 quadrupling scenario

'Historical' scenarios look similar but future scenarios reveal disparities

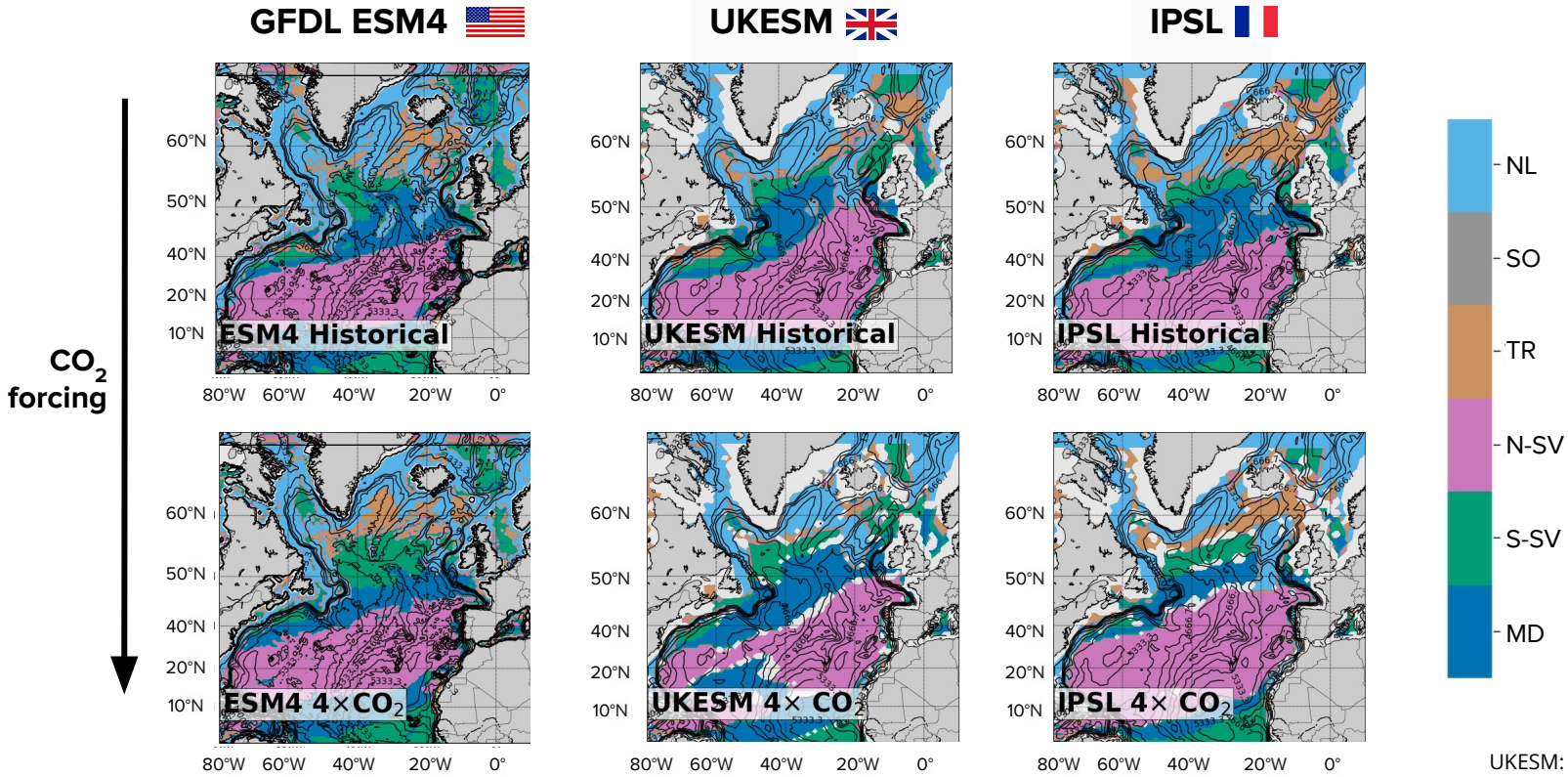


UKESM: [Senior+ 2020]
IPSL: [Boucher+ 2020]

[SL 2021 **JAMES**]

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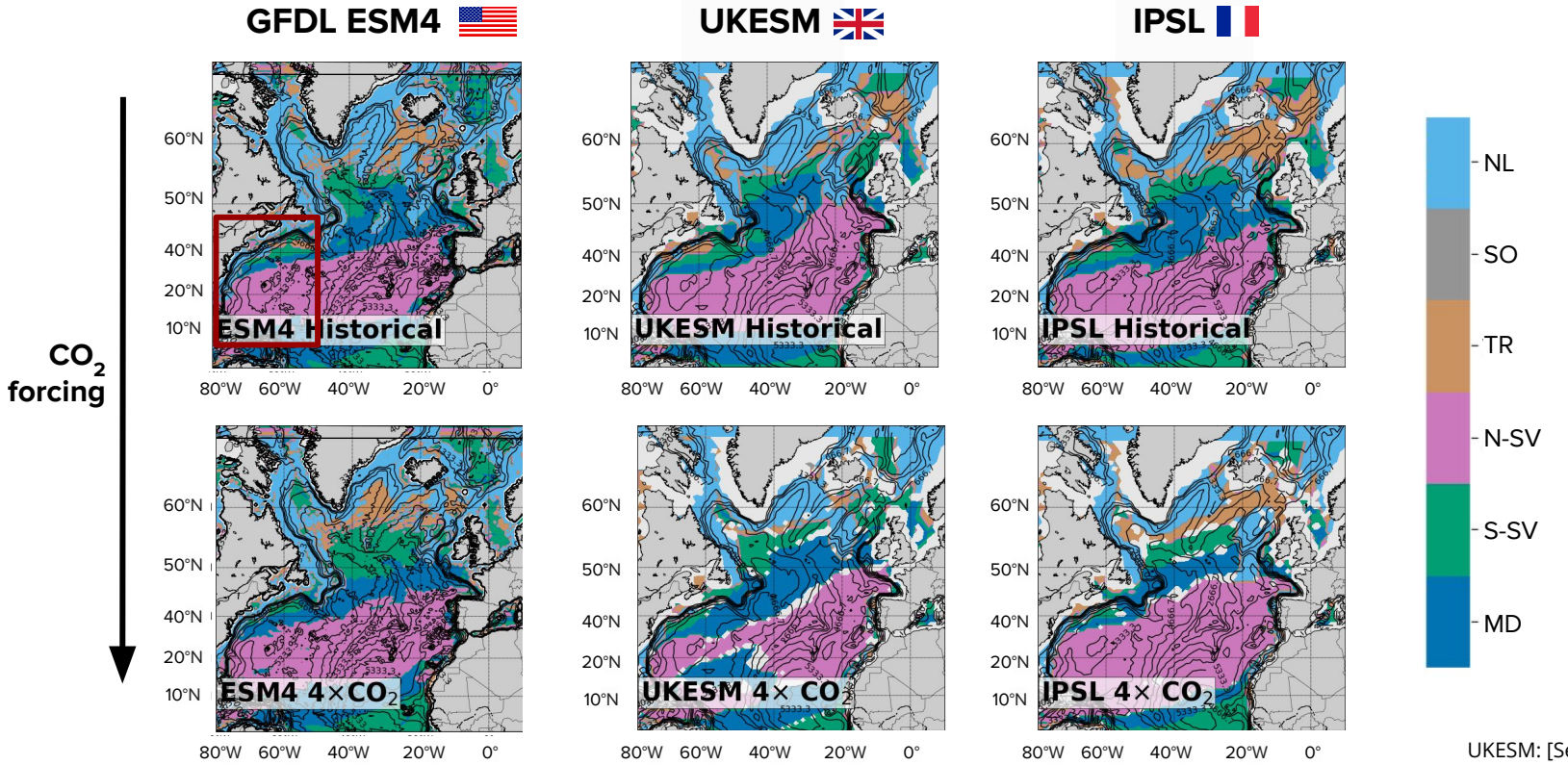


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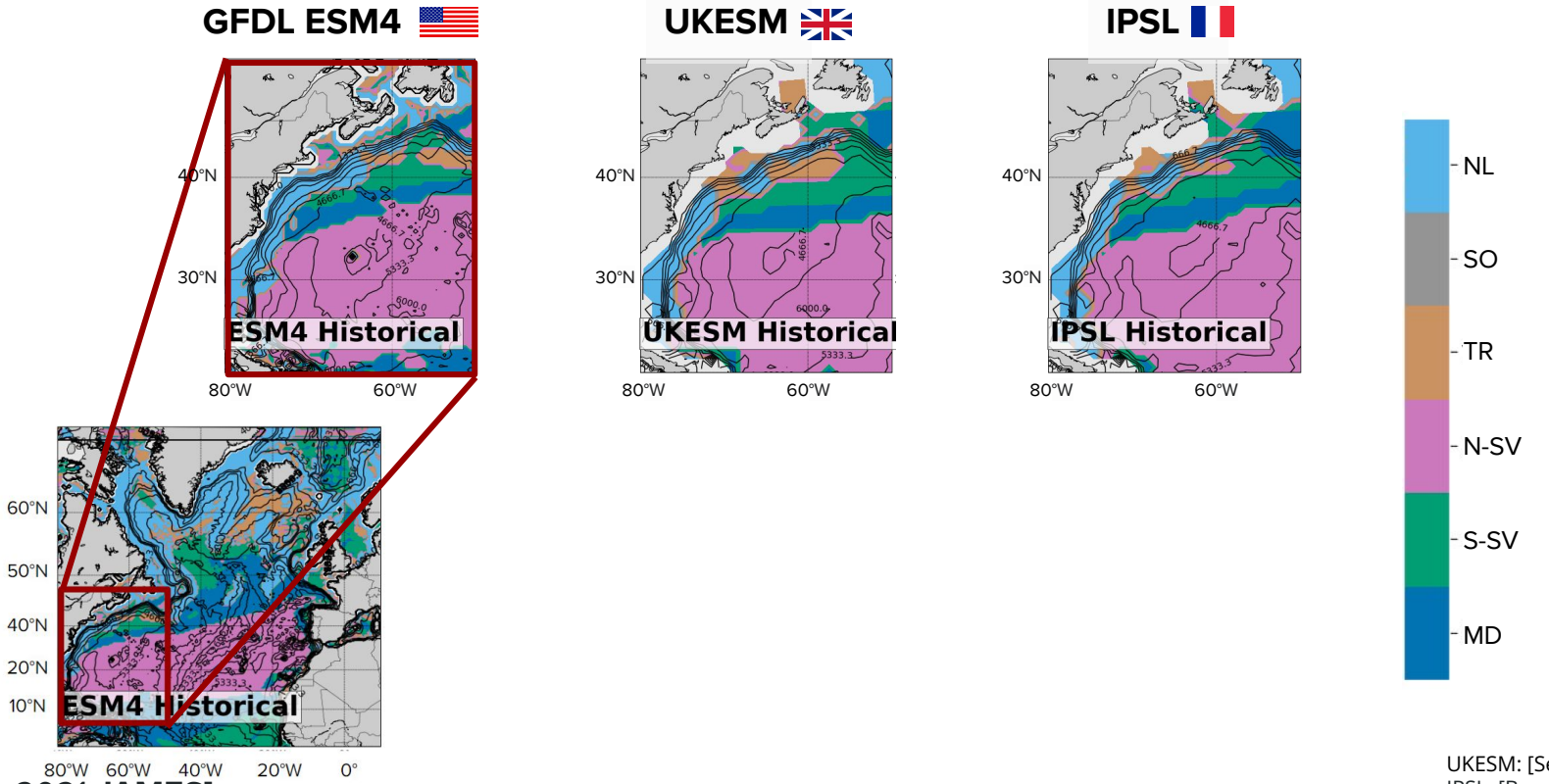


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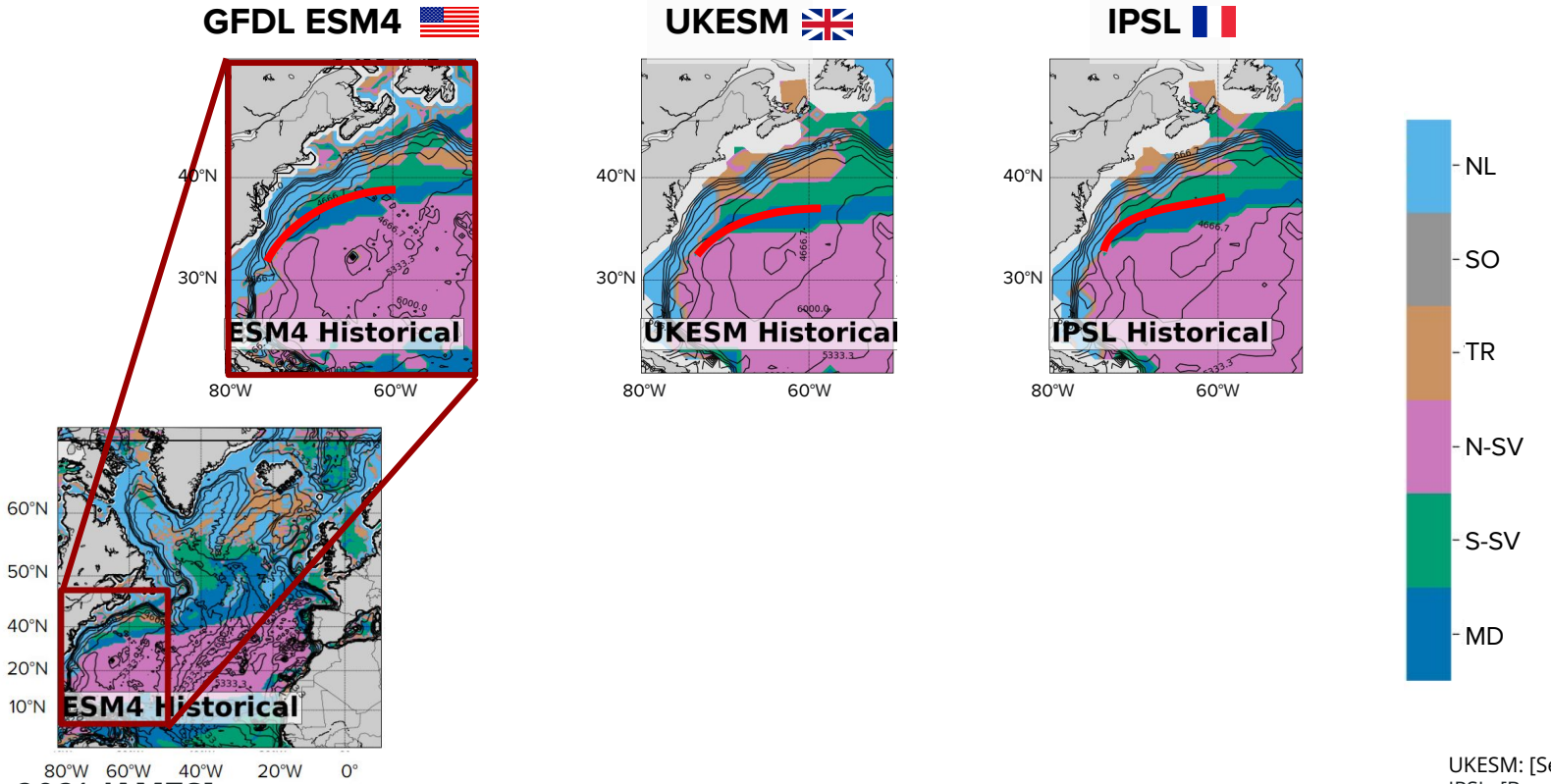


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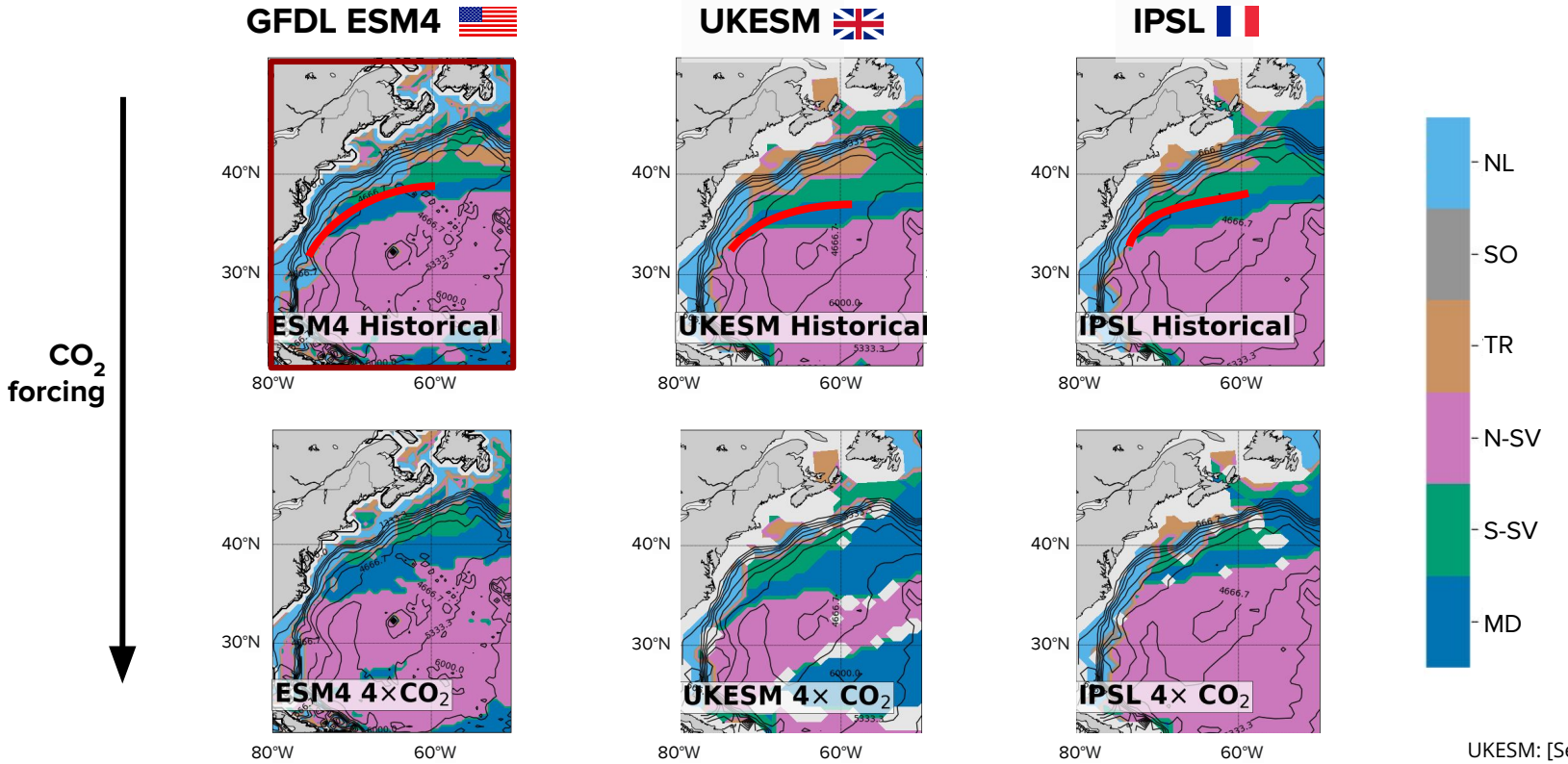


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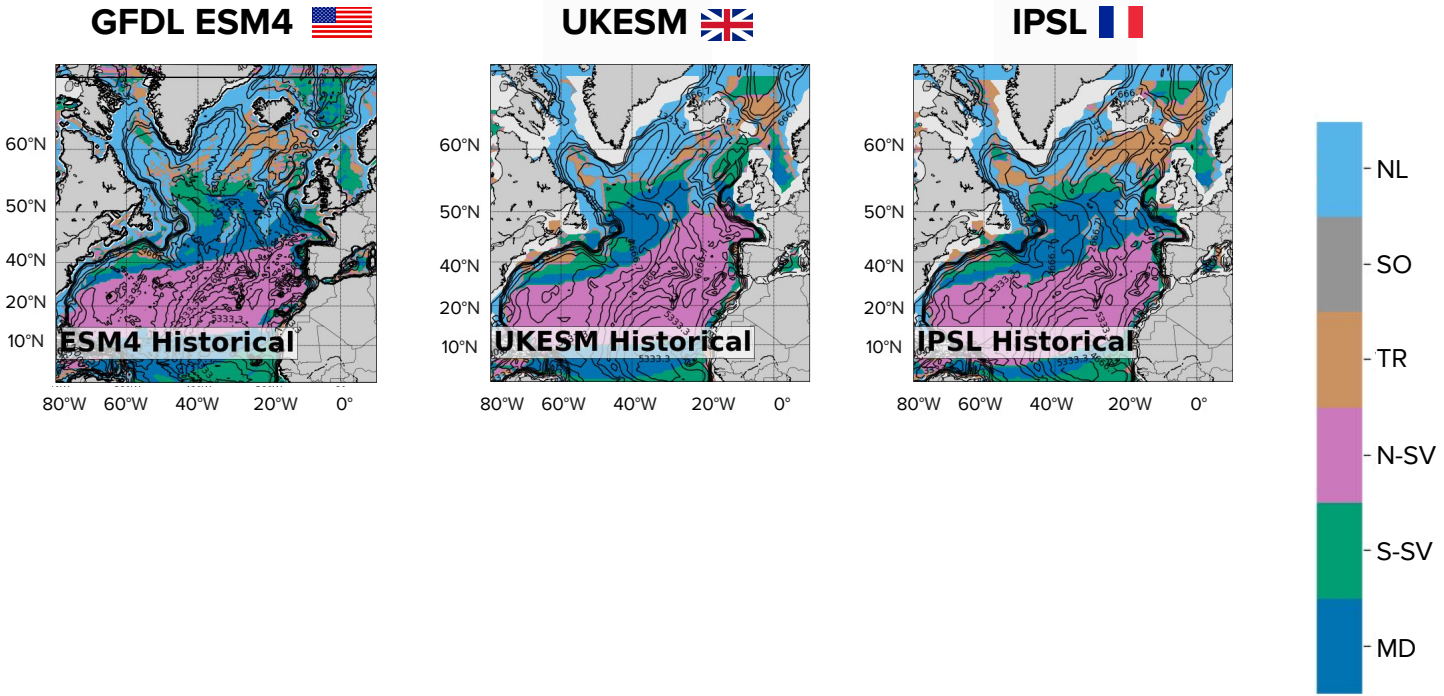


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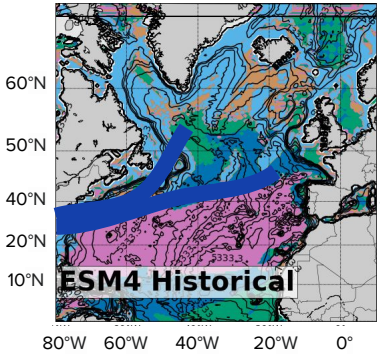
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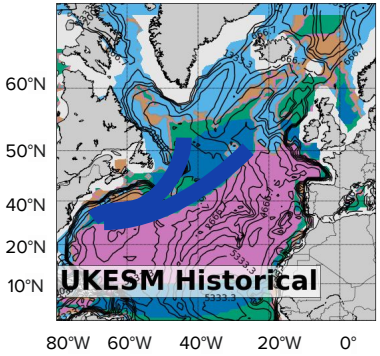
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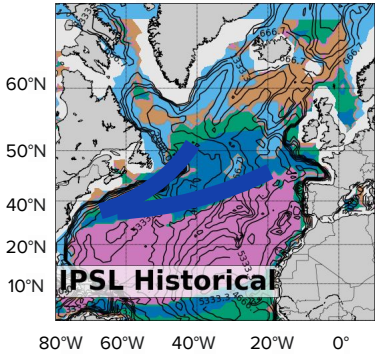
GFDL ESM4

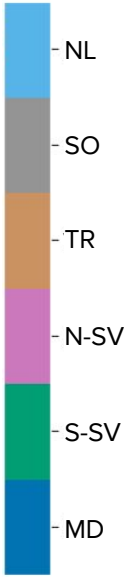


UKESM



IPSL



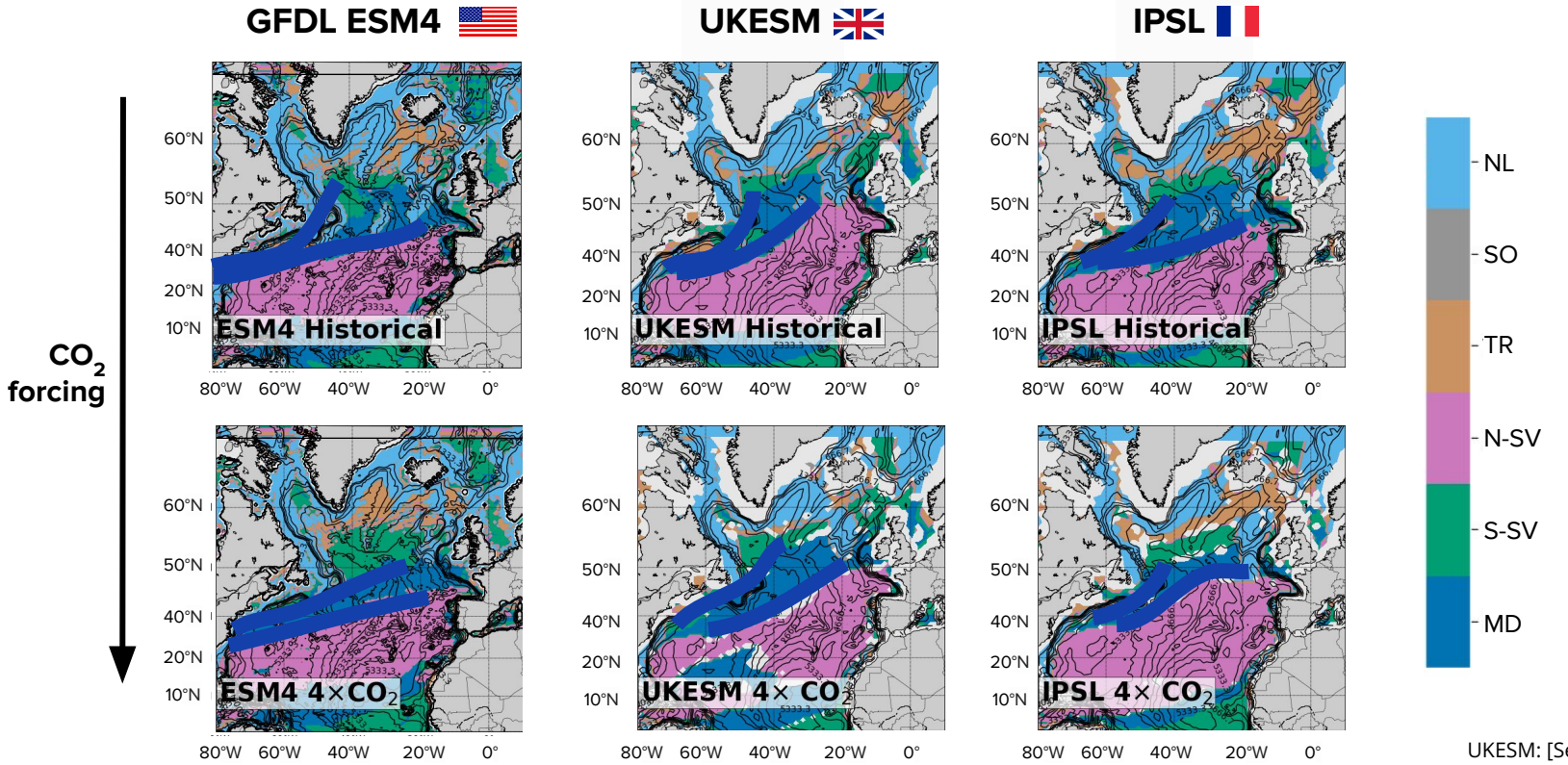


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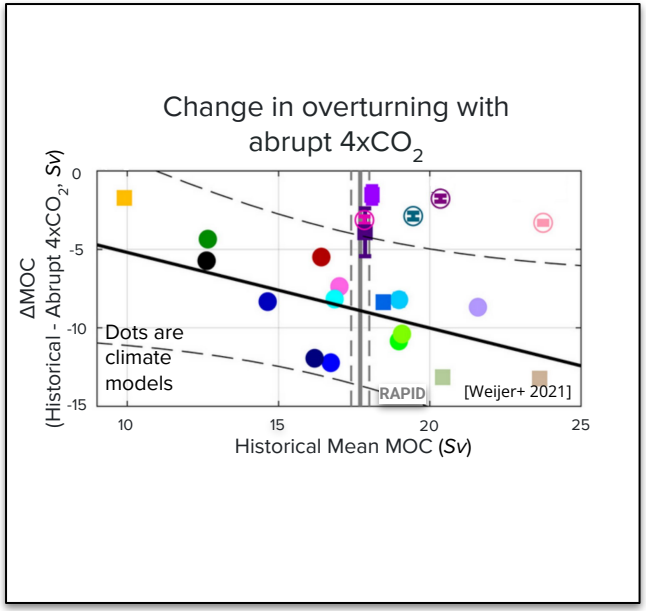


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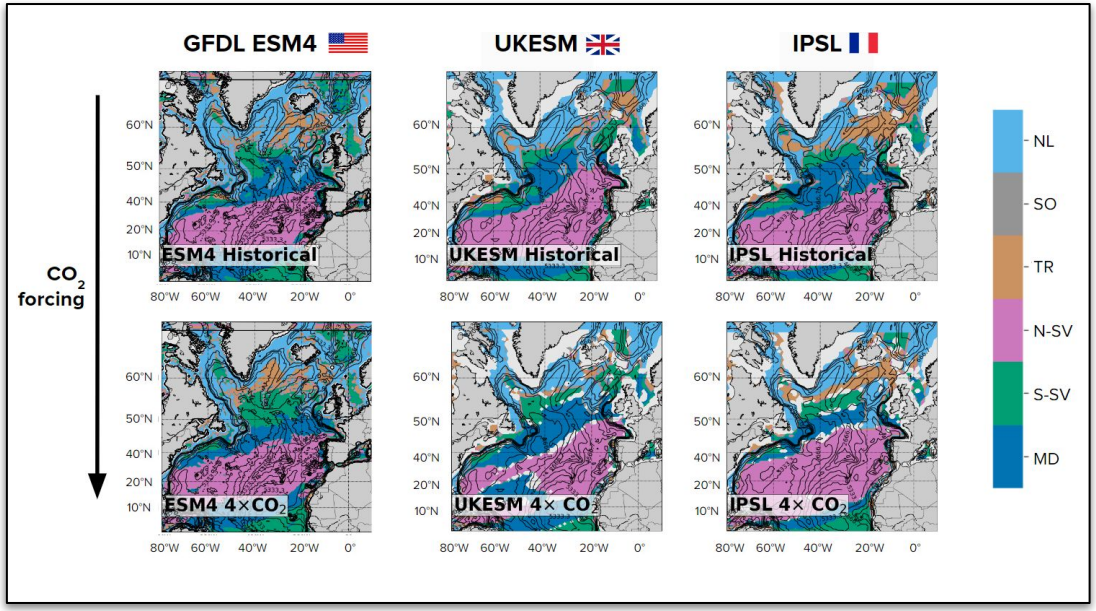
[SL 2021 **JAMES**]

New method offers great improvement

Previous



New method from **SL** 2021 **JAMES**



Datasets

Physical ocean:
Global Ocean Observing Systems (GOOS): https://www.ocean-ops.org/goosreport/
Copernicus Marine (CMEMS) for reanalysis, satellite and forecasts data: https://marine.copernicus.eu/
CMIP6 Climate model data: https://esgf.github.io/

Ocean Biogeochemistry and ecosystems:
Surface Ocean CO_2 Atlas (SOCAT): https://socat.info/
NASA OceanColor, and PAC: https://pace.gsfc.nasa.gov/
Marine biodiversity data Ocean Biodiversity Information Systems (OBIS): https://obis.org/
Species occurrence Global Biodiversity Information Facility (GBIF): https://www.gbif.org/

Human pressures:
Global Fishing Watch (open API): https://globalfishingwatch.org/
Allen Coral Atlas: https://www.allencoralatlas.org/

Polar: MEOP: http://www.meop.net/ (the seals!)

Tools

Ocean AI model Samundra: https://m2lines.github.io/Samudra/docs/

Using the data Python toolbox Pangeo stack: https://pangeo.io/

Resource for compute:
Google Colab: https://colab.research.google.com/
Copernicus WEkEO: https://wekeo.copernicus.eu/

Exciting (big!) open problems

Coastal and shelf seas where models and satellites are worst:
Complex bathymetry, river inputs, and tides made this difficult. Downscaling and emulation for coastal risk.

Extrapolation to future climate states:
A model trained on the historical ocean asked about $4\times CO_2$ is extrapolating by construction. THOR and OceanCBM are work on this.

Sub-grid parameterisations in models:
ML schemes that look good offline and then drift or blow up online. Very active field.

Interpretability that is mechanistically valid:
OceanCBM is one attempt, the general problem is very open.

Small-scale fisheries:
Detection that doesn't depend on cooperative broadcast.

Multi-modal fusion:
Ocean colour + in situ + acoustics + eDNA for community composition.

How to get involved!

Researchers and students:
Come to meetings: Ocean Sciences Meeting, EGU/AGU, Climate Informatics, and the CCAI workshops at NeurIPS/ICML/ICLR
Contribute to codes e.g. THOR (regime approach transfers to other basins and variables) or Samundra. There are many!

NGOs and governments:
The UN Ocean Decade endorsement route, GOOS and its regional alliances (IOGOOS, GOOS Africa), IOC-UNESCO's ODIS, and Global Fishing Watch's partnership programme

Funders:
Funding for ocean climate work is cut in areas traditionally supporting. While all research is important, especially sustained time series, observation infrastructure in the Global South, and *capacity* should be supported

AI for Oceans & Marine Systems

The ocean in the climate system

97% of the water, 90% of the excess heat, ~25% of our CO_2, >50% of the oxygen

Simple physics, with emergent complex patterns

Density contrasts drive an overturning circulation with global reach

Consequences of a changing climate

Warming, acidification and heatwaves reach primary production, zooplankton and fisheries

Data rich, insight poor or the opposite?

Observations, satellites and models each cover only part of the problem

ML is the bridge, not the destination!

GORDON AND BETTY MOORE FOUNDATION

NSF

NOAA