Using ML to let modeling, theory and observations inform each other

Maike Sonnewald[1,2]

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[1]MIT & [2]Harvard

Introduction

Why ML?

Goal of science/geoscience:
Have precise and accurate understanding of the natural world.

Motivation: My ocean bias

Ocean covers 70% of the Earth's surface

Heat capacity 1100 $>$ times atmosphere

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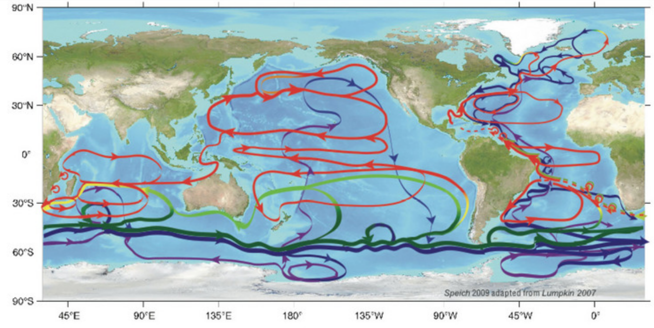
Ocean covers 70% of the Earth's surface

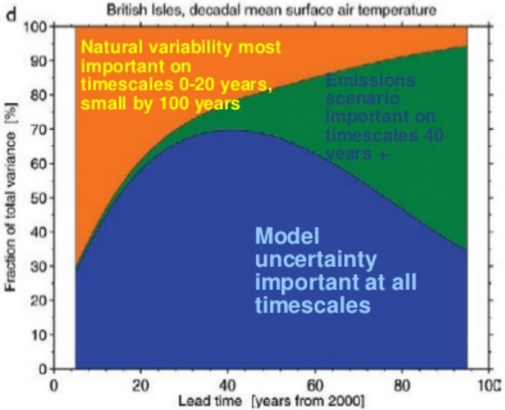
Heat capacity 1100 > times atmosphere

Since 1955, over 90% of excess heat from greenhouse gasses has gone into oceans



The ocean takes up about 71% of Earth's space, but 95% of the ocean remains unexplored. NOAA

Source of uncertainty in climate scenarios

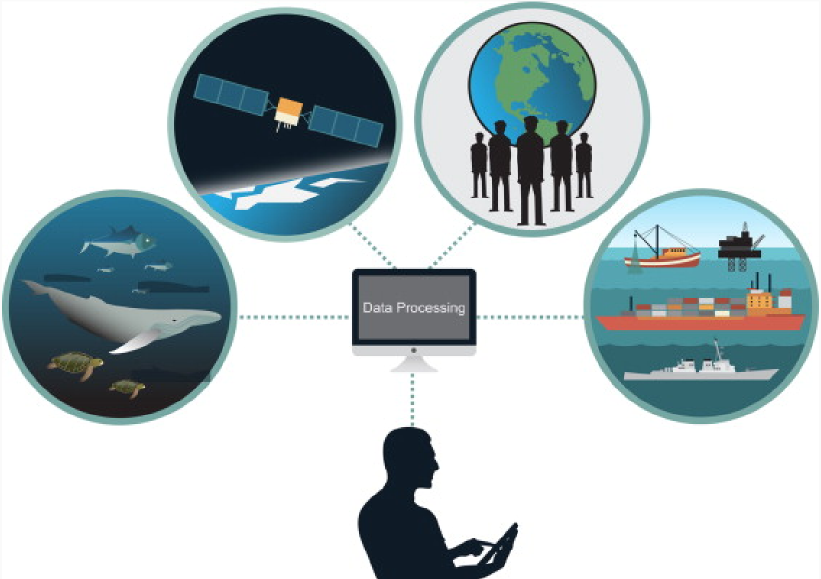


That depends on the timescale that we are looking at...

ipcc INTERGOVERNMENTAL PANEL ON climate change

We are becoming data rich in oceanography

Maxwell 2015, Kim Martini and Sonnewald et al 2013



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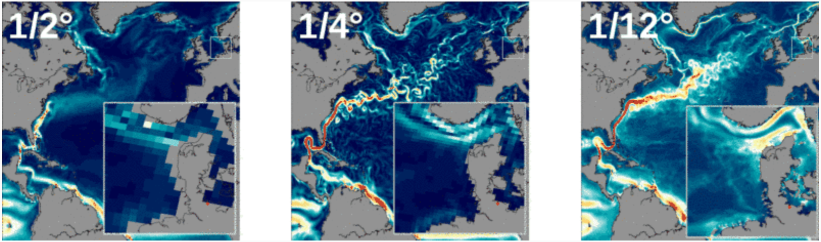
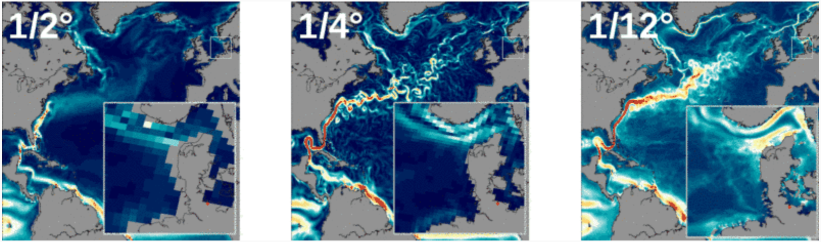
Big data can be overwhelming

Observations are hard



NEMO (Geomar)

Observations are hard

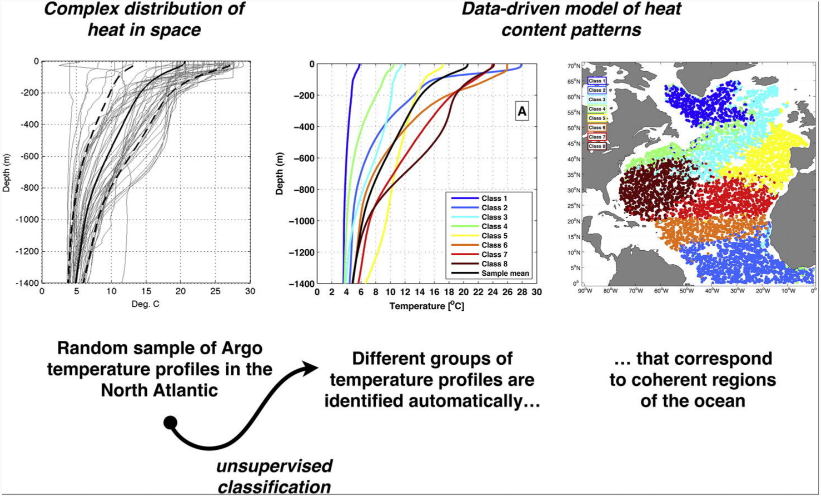


NEMO (Geomar)

The ocean is big with unquantified variance:

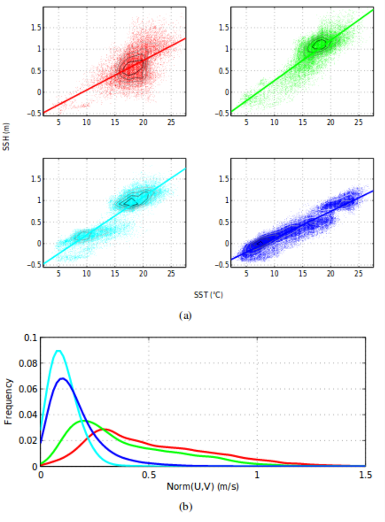
Huge+costly effort to gather data often relying on serendipity

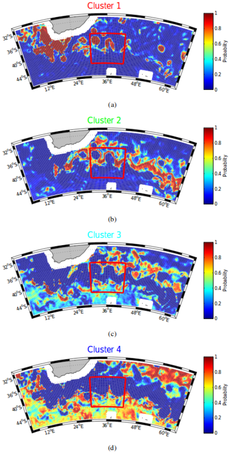
Observations+ML



Maze 2014

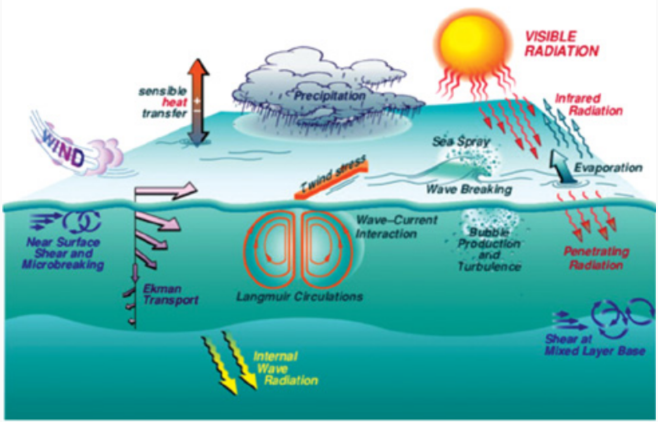
Observations+ML





Tanedo, 2014 (IEEE)

Structural model uncertainty



Weller, WHOI

Sources of uncertainty are many and varied:

Huge+constly efforts to improve "accuracy" even in the absence of complete observational understanding.

Machine Learning to the rescue?

Can ML help?

- Find “emergent” patterns in models
- Group sparse observations
- Infer theoretical underpinning
- What can we do with these patterns?

Case studies:

1: Physical Oceanography looking to improve understanding of western boundary currents

2: Ocean ecological compositions to understand long term monitoring

...Global dynamical regimes

Theory: Barotropic Vorticity equation

Momentum equations:

$$\partial_t \mathbf{u} + f\mathbf{k} \times \mathbf{u} = -\frac{1}{\rho_0}\nabla p + \frac{1}{\rho_0}\partial_z \tau + \mathbf{a} + \mathbf{b}, \partial_z p = -g\rho, \nabla \cdot \mathbf{v} = 0.$$

-Depth integrate, take curl

Barotropic Vorticity:

$$0 = \overbrace{\nabla \cdot (f\mathbf{U})}^{\text{Advection}} - \underbrace{\nabla \times (p_b \nabla H)}_{\text{Bottom Pressure Troque}} + \overbrace{\nabla \times \tau}^{\text{Wind and Bottom stress}} - \underbrace{\nabla \times \mathbf{A}}_{\text{Non-linear Torque}} + \overbrace{\nabla \times \mathbf{B}}^{\text{Lat. Visc.}}$$

e.g. Sverdrup balance:

Wind stress curl and advection balance locally

$$\nabla \cdot (f\mathbf{U}) = \nabla \times \tau$$

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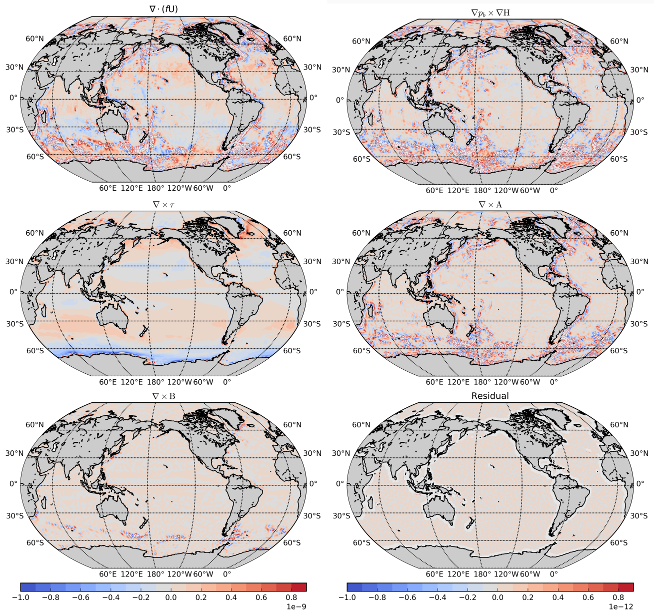
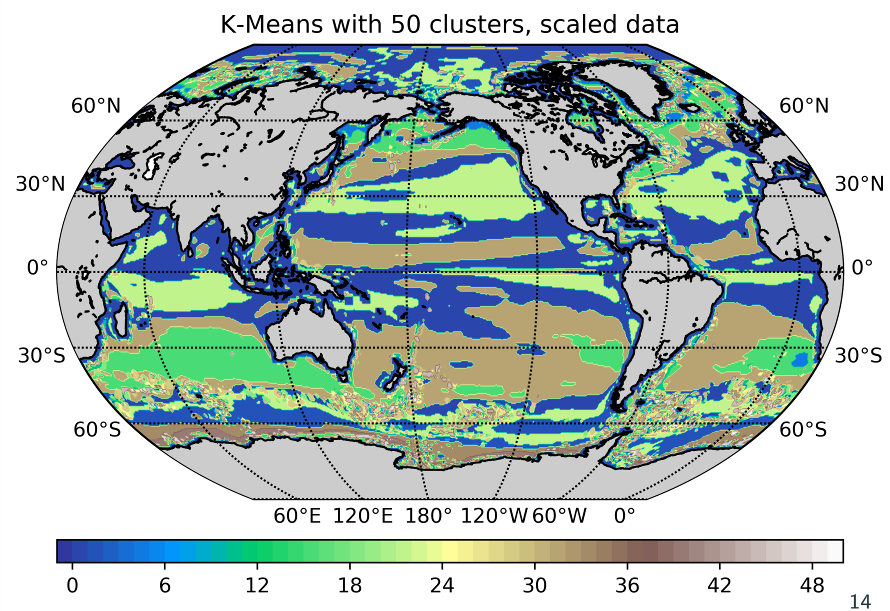
..Is this real? Is every location unique?

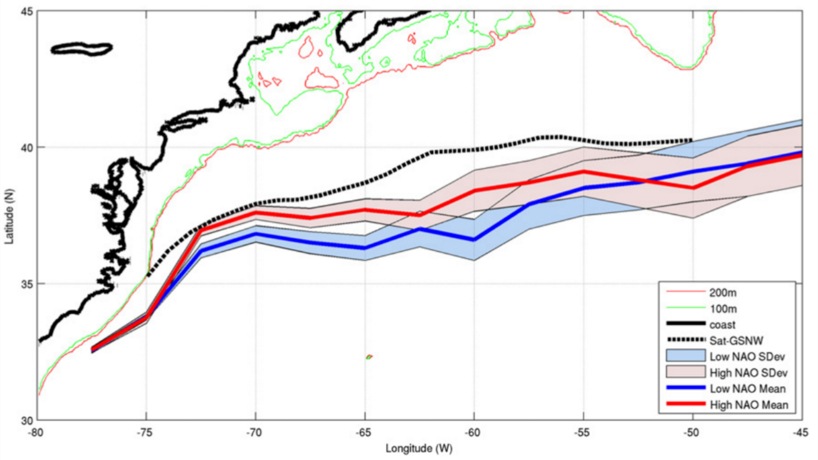
$$0 = \nabla \cdot (f\mathbf{U}) - \nabla \times (p_b \nabla H) + \nabla \times \tau - \nabla \times \mathbf{A} + \nabla \times \mathbf{B} \ (\mathbf{ms}^{-1})$$



Dynamical regions

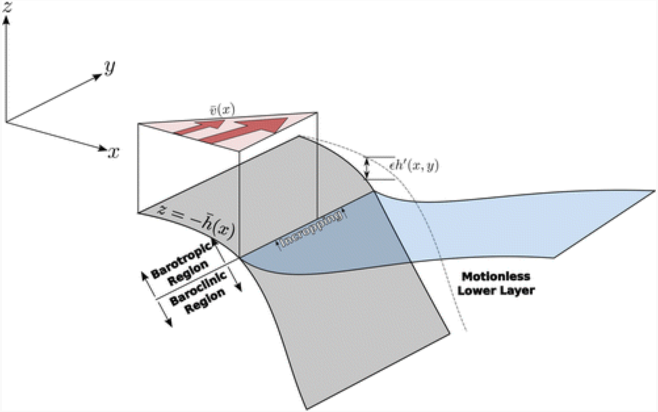


The thing about Gulf Stream seperation



Schoonover 2017

The thing about Gulf Stream seperation



Schoonover 2017

Somewhat ad-hoc parameterization

Bathymetric interaction tuning

Knowing what the real ocean is doing+how variable this is

The thing about Gulf Stream seperation

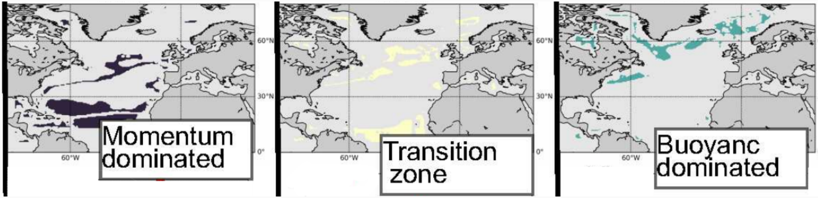
The depth integrated (Barotropic) vorticity:

$$0 = \underbrace{\nabla \cdot (f\mathbf{U})}_{\text{Planetary vorticity advection}} + \underbrace{\frac{1}{\rho_0}\nabla \times (p_b \nabla H)}_{\text{Bottom Pressure Torque}} + \overbrace{\frac{1}{\rho_0}\nabla \times \tau}^{\text{Wind and bottom stress}} + \underbrace{\nabla \times \mathbf{A}}_{\text{Non-linear torque}} + \overbrace{\nabla \times \mathbf{B}}^{\text{Viscous torque}} \qquad \text{(Eq 1)}$$

Following Mertz and Wright (1992) we distinguish a momentum driven torque of the depth averaged pressure, and the baroclinic Joint Effect of Baroclinicity and Relief (JEBAR) term:

$$\frac{1}{\rho_0}\nabla \times (p_b \nabla H) = \underbrace{\frac{1}{\rho_0}\nabla \times (\overline{p}\nabla H)}_{\text{Torque of depth averaged pressure}} - \underbrace{\nabla \times \left[\frac{\chi \nabla H}{H}\right]}_{\text{JEBAR}} \qquad \text{(Eq 2)} \qquad \chi = \frac{g}{\rho_0}\int_H^z z\rho \, \mathrm{d}z \qquad \text{(Eq 3)}$$

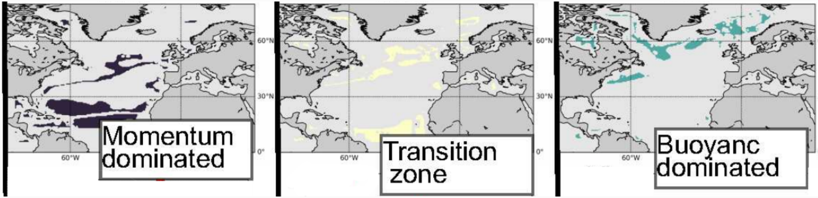
The theory that could help



Area, name	Leading terms	Boyancy vs Momentum
12.2%, Quasi-Sverdrupian	$0 \approx \nabla \times \tau_{sb} + \nabla \cdot (f\mathbf{U})$	NA
15.7%, Momentum Dominated	$0 \approx \nabla \cdot (f\mathbf{U}) + \nabla \times \tau_{sb} + \frac{1}{\rho_0} \nabla \times (p_b \nabla \mathrm{H})$	$\mathrm{JEBAR} < \frac{1}{\rho_0} \nabla \times (\overline{p} \nabla \mathrm{H})$
61.1%, Transition Zone	$0 \approx \nabla \times \tau_{sb} + \nabla \cdot (f\mathbf{U}) - \frac{1}{\rho_0} \nabla \times (p_b \nabla \mathrm{H})$	$\mathrm{JEBAR} \approx \frac{1}{\rho_0} \nabla \times (\overline{p} \nabla \mathrm{H})$
3.6%, Buoyancy Dominated	$0 \approx \nabla \times \tau_{sb} + \nabla \times \mathbf{A} - \frac{1}{\rho_0} \nabla \times (p_b \nabla \mathrm{H})$	$\mathrm{JEBAR} >> \frac{1}{\rho_0} \nabla \times (\overline{p} \nabla \mathrm{H})$
≈5.7%, Dominantly non-linear	$0 \approx \nabla \cdot (f\mathbf{U}) + \nabla \times \tau_{sb} + \frac{1}{\rho_0} \nabla \times (p_b \nabla \mathrm{H}) - \nabla \times \mathbf{A}$	$\mathrm{JEBAR} >> \frac{1}{\rho_0} \nabla \times (\overline{p} \nabla \mathrm{H})$

The theory that could help

Free-slip: BPT is uphill-flow, no-slip: BPT is viscous stress divergence (Hughes & de Cuevas 2001)



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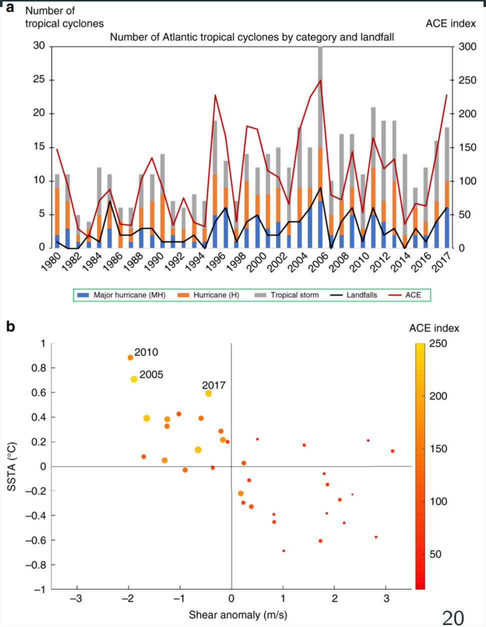
Improve hurricane forecast?

Motivation:

“Extreme weather events cost the lives of 246 lives in the US alone since 2018 alone and 5000 world wide.”

(NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2019)



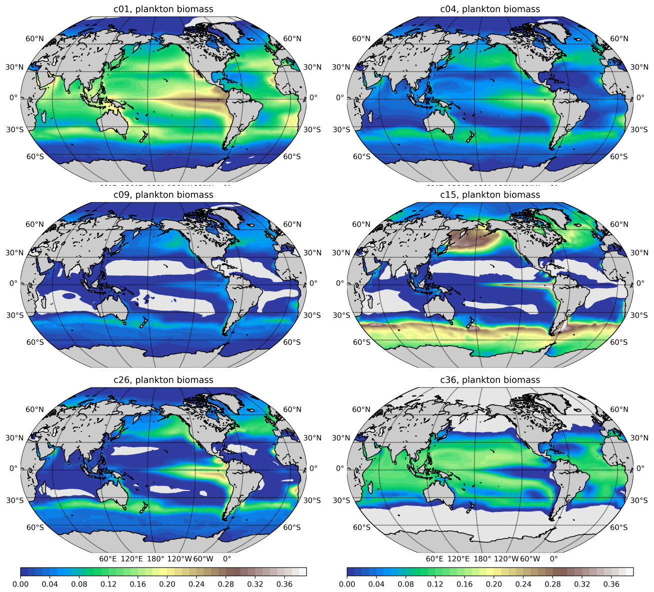
Cliff hanger:

Edge computing

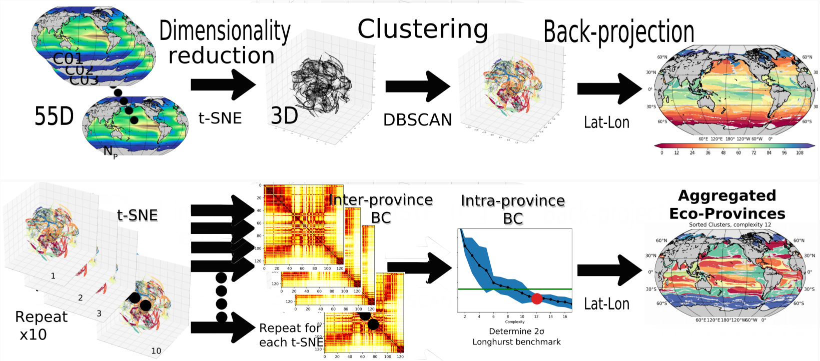
- Recognize key lacking data
- Target using clusters/regions
- Infer where to sample
- Inform modeller

…Global ecological regimes

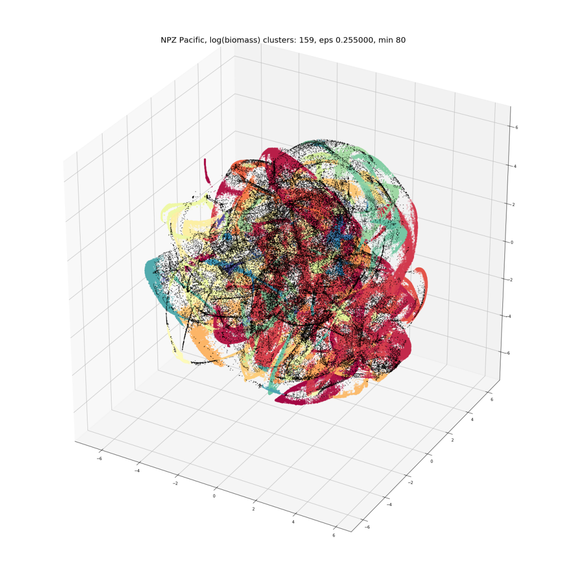
Complicated: 51 species (biomass) and 4 nutrients



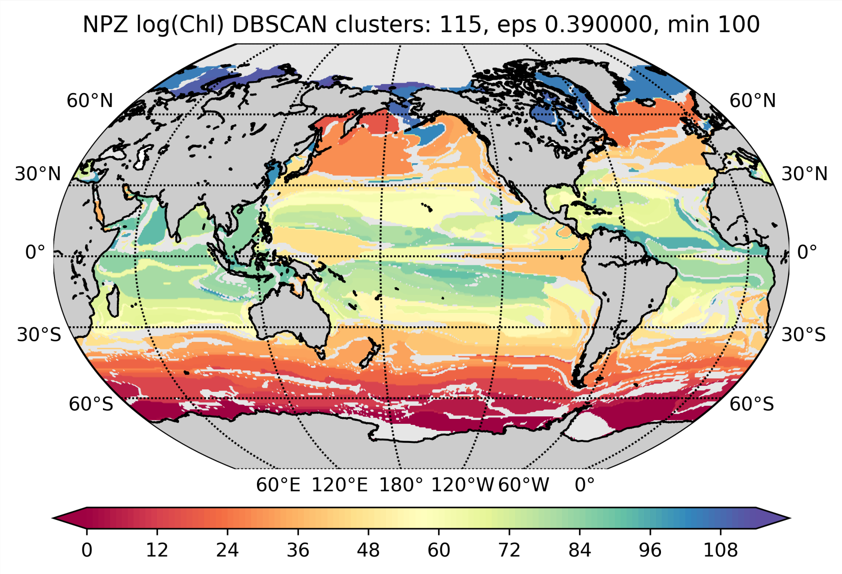
Finding clusters → Aggregated Eco-Provinces



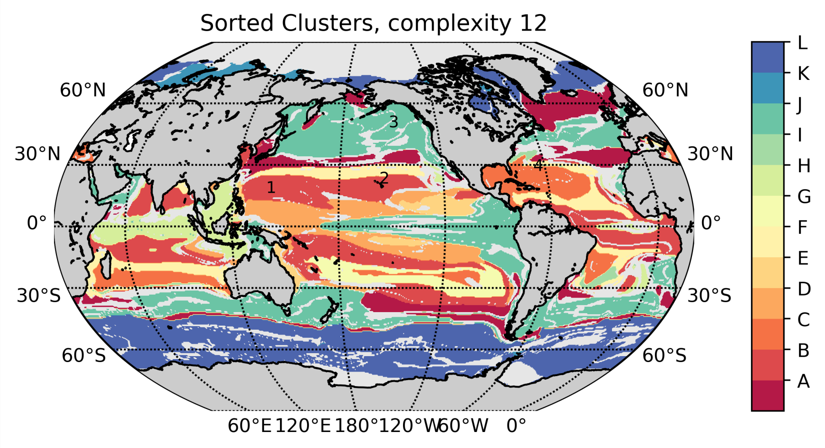
Unsupervised learning: DBSCAN

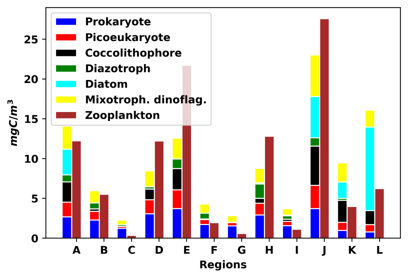


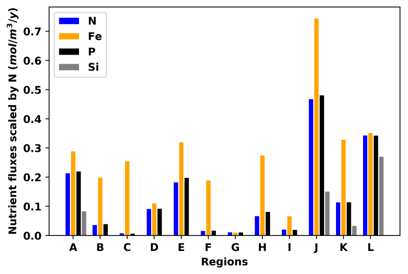
Eco-Provinces



Aggregated Ecological Provinces

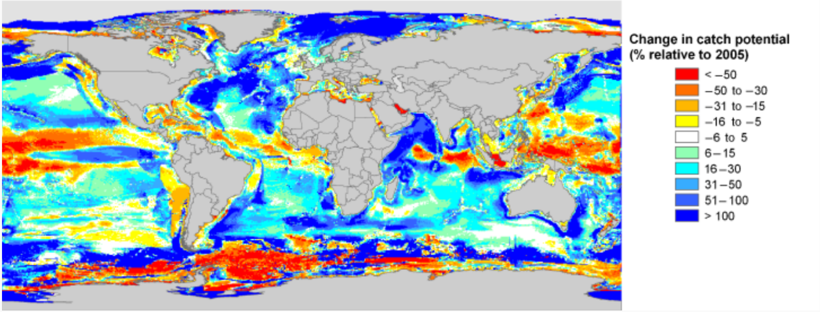






- Similar biomass/chl but different community structure
- Biomass is poor predictor of zooplankton: Trophic cascades?

Fisheries: Where is the zooplankton?



Around 85% of global fish stocks are over-exploited, depleted, fully exploited or in recovery from exploitation

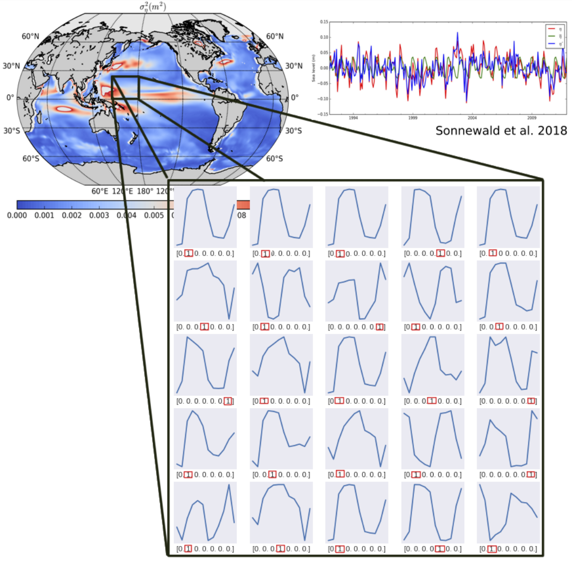
All West African coastal fisheries have declined 50% in just 30 years.

UN Food and Agriculture Organisation

Synergy

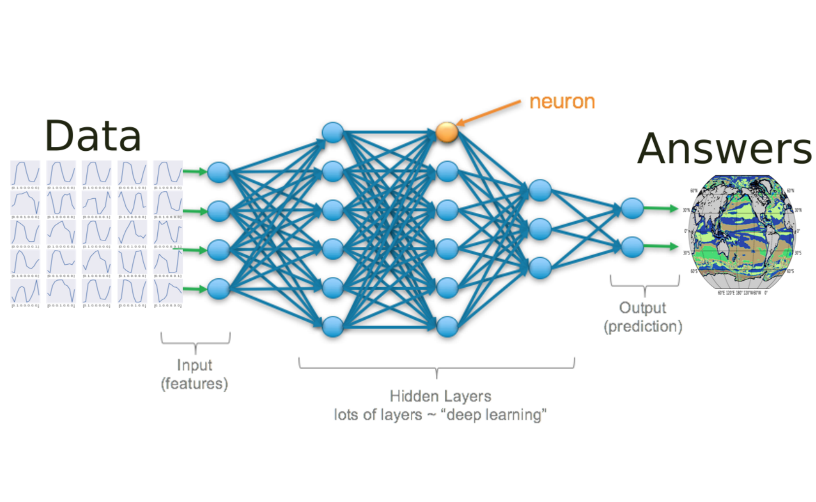
ML in its many flavours

Input?

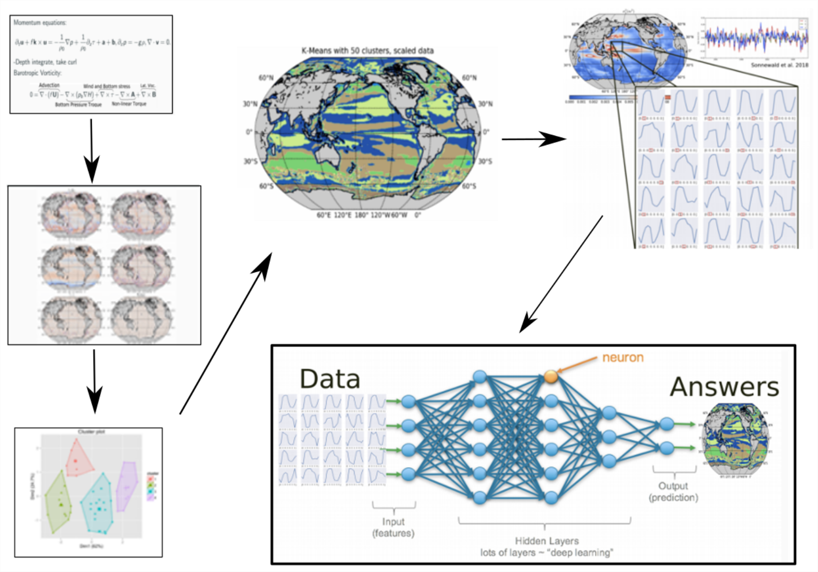


Can we develop a predictive model?

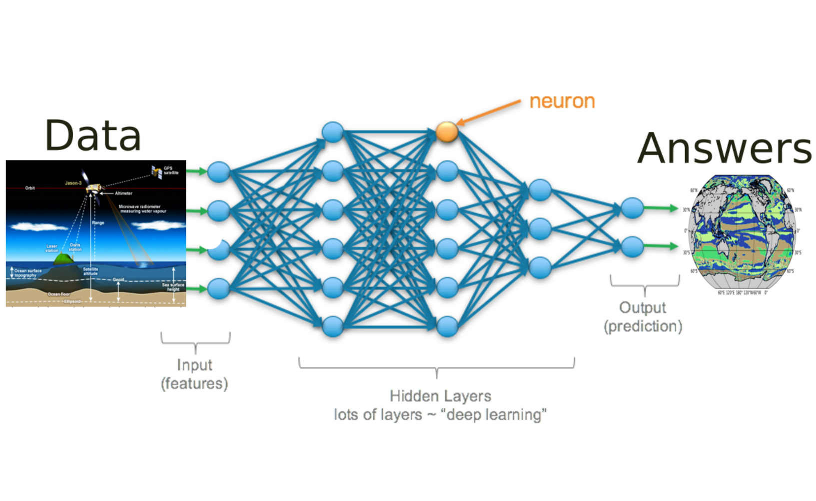
Model.png



Predictive model



Can use observations to improve models?



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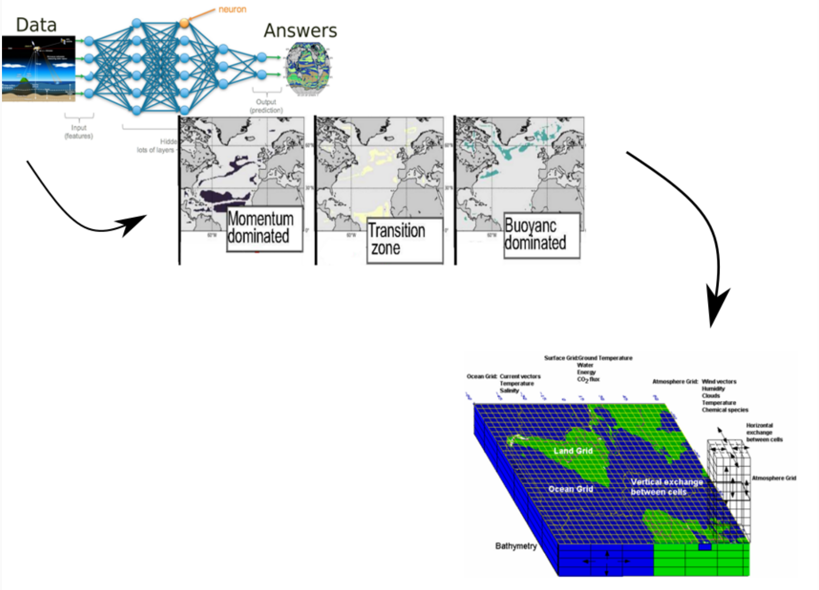
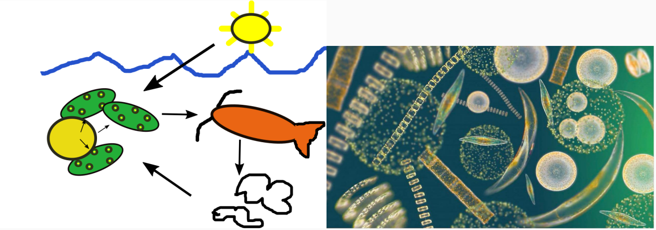
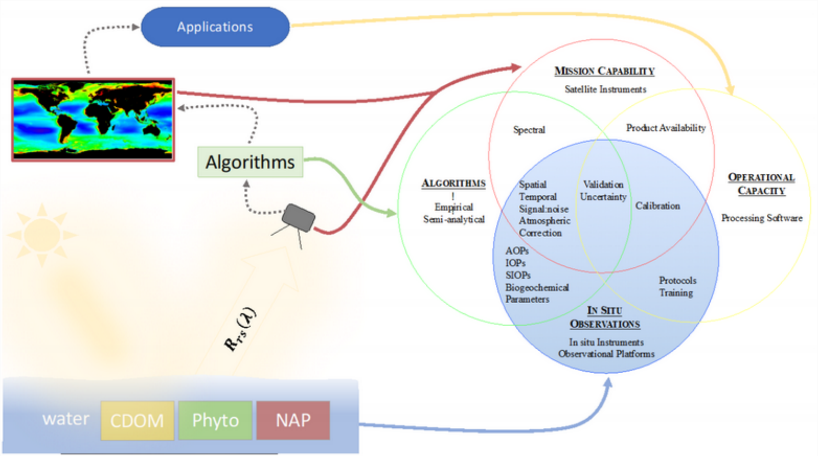


Can ML improve ecosystem models?



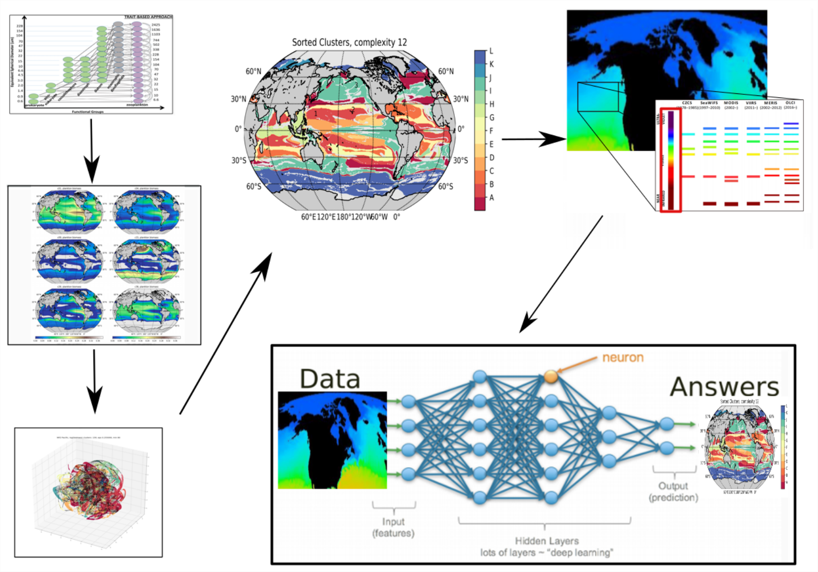
It's complicated

Can ML improve ecosystem models?

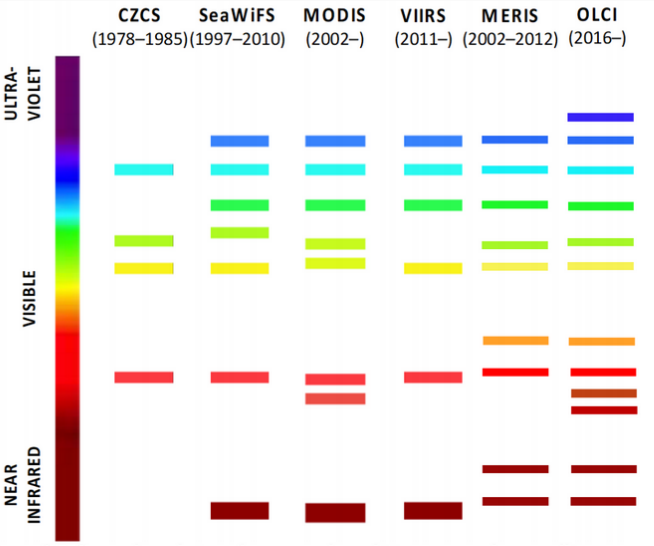


Real world may be instructive

Ecoprovinces are again... complicated...

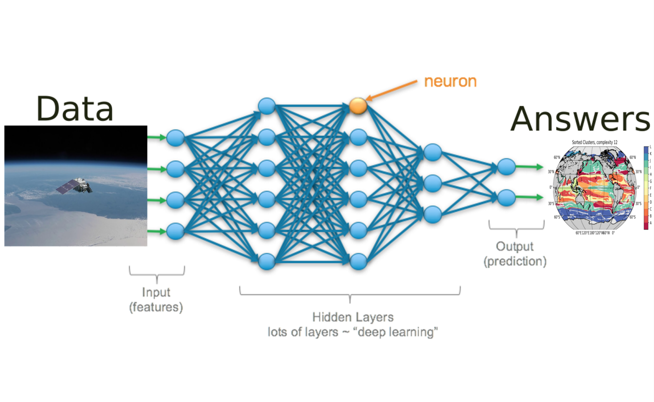


Future looks colourful!



Future looks colourful: PACE

Future looks colourful: Predictive model



Summary

...Can unsupervised learning give system insight?

Can ML help?

- Make complicated data complex
- Allows insight to parameterize and simplify
- Create synergy between models, theory and observations

ML towards the goal of science/geoscience:
Have precise and accurate understanding of the natural world.