Ocean mixing and its role for climate

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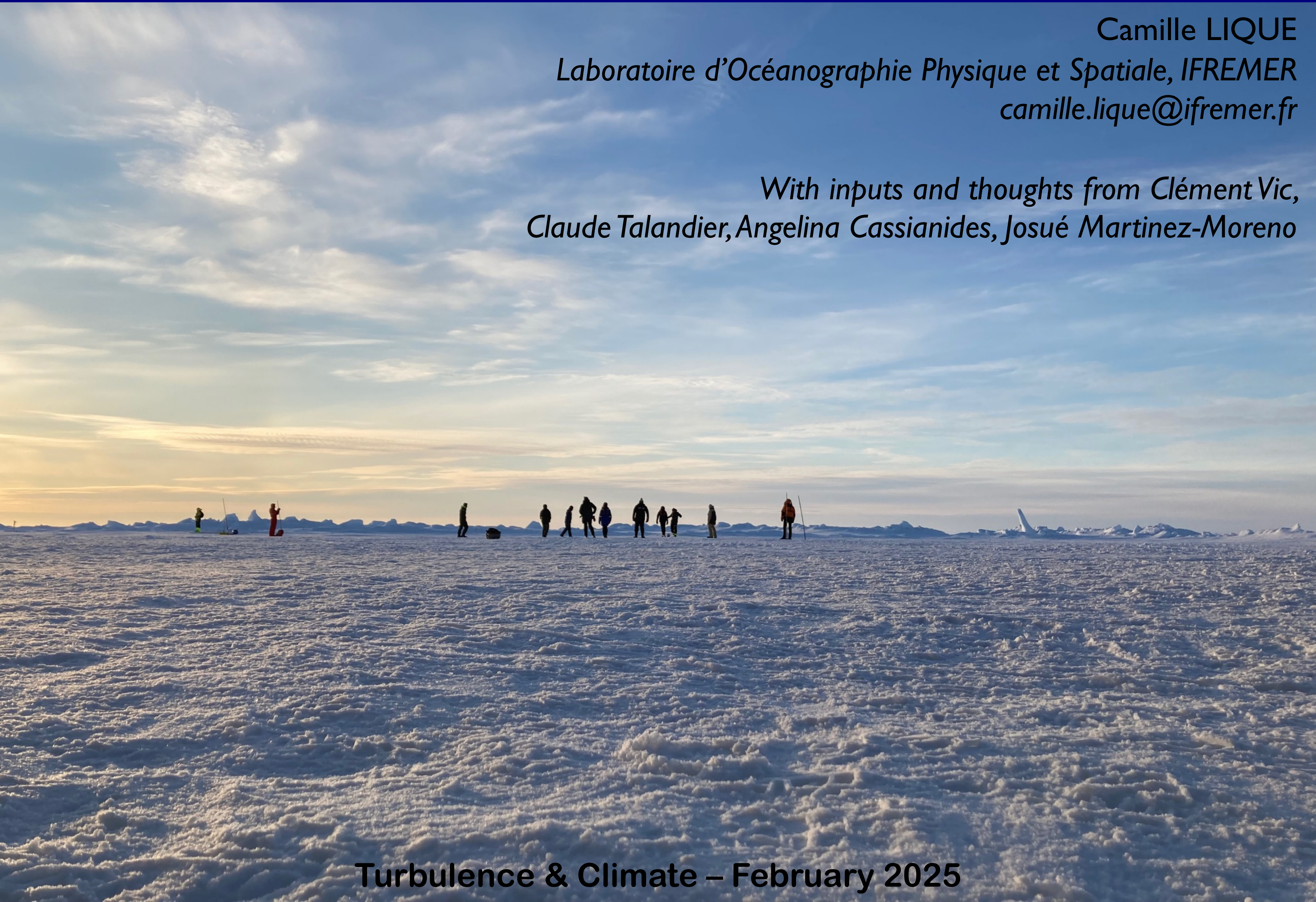
With inputs and thoughts from Clément Vic, Claude Talandier, Angelina Cassianides, Josué Martinez-Moreno



Turbulence & Climate – February 2025

Ocean mixing and turbulence : definitions (or lack thereof)

Introduction of the book 'Ocean Mixing' by Meredith & Naveira Garabato 2022

Ocean mixing – the three-dimensional turbulent interleaving and blending of oceanic waters with different properties (Eckart, 1948; Welander, 1955) – plays a critical part in defining almost every aspect of the ocean's structure and role within the Earth system.

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Atmospheric and Oceanic Fluid Dynamics (Vallis, textbook 2006) : Turbulence is **high Reynolds number** fluid flow, dominated by **nonlinearity,** containing both **spatial and temporal disorder**. No definition is perfect, and it is hard to disentangle a definition from a property, but this statement captures the essential aspects. A turbulent flow has **eddies** with a spectrum of sizes between **some upper and lower bounds**, the former often determined by the forcing scale or the domain scale, and the latter usually by viscosity. The individual eddies come and go, and are inherently unpredictable.

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Reynolds number in the ocean

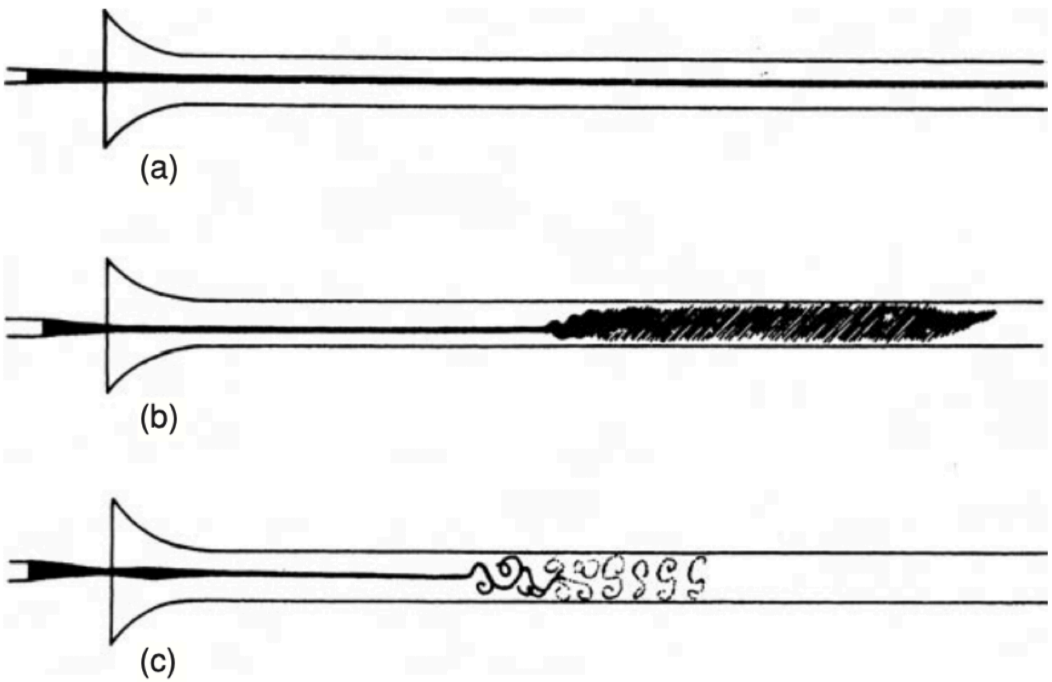

Figure 1.2. Reynolds' experiment, described in his paper published in 1883. Flow through the tube is from left to right. The shape of the entry to the tube within a large tank of still water on the left is to ensure a smooth flow. (a) A band of dye passes down the tube when the flow is relatively slow, or at a low Reynolds number, *Re*. (b) When $Re > 1.3 \times 10^4$, the flow becomes turbulent. As observed by eye, the band of dye is dispersed across the width of the tube. (c) An image obtained with a very brief electric spark, showing that the onset of turbulence, and its later form, is associated with eddies of size comparable to the tube diameter.

Reynolds number $Re = \dfrac{Ud}{\nu}$

U : flow speed

d : diameter of the tube (generally, distance between flow boundaries)

ν : viscosity of water (10^{-6} m^2 s^{-1})

Above a critical* Re (order of 10^4), the flow becomes turbulent and sheds eddies.

*the exact value depends on the geometry of the flow and the nature of the disturbance

Thorpe 2007

Reynolds number in the ocean

What is the Reynolds number in the ocean ?

$U = 10^{-3} - 10^{0}$ m s^{-1}, $d = 10^{3} - 10^{6}$ m (depth or lateral boundaries), $\nu = 10^{-6}$ m^2 s^{-1},

$Re = 10^6$ to $10^{12} \gg 10^4$, so the ocean is turbulent at all scales !

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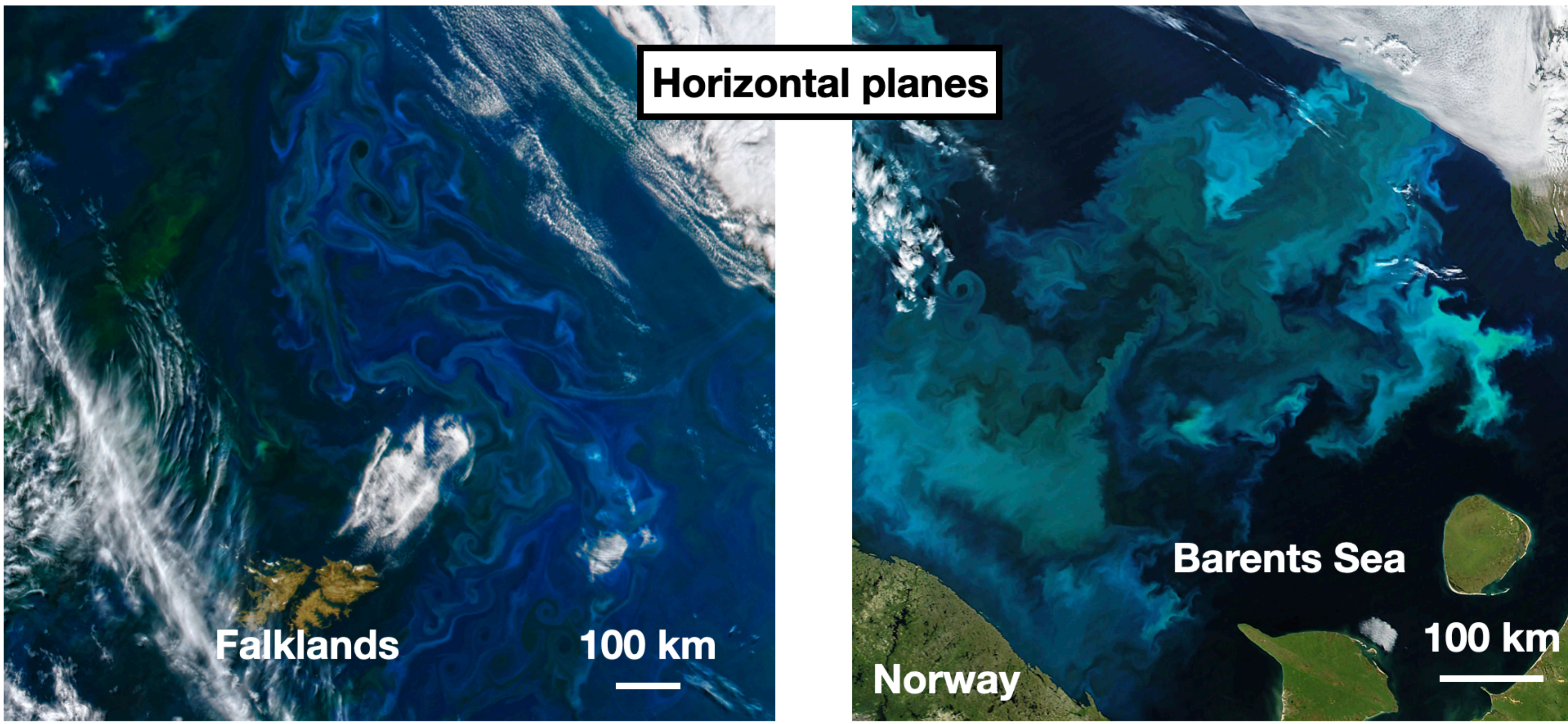

Images from Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite

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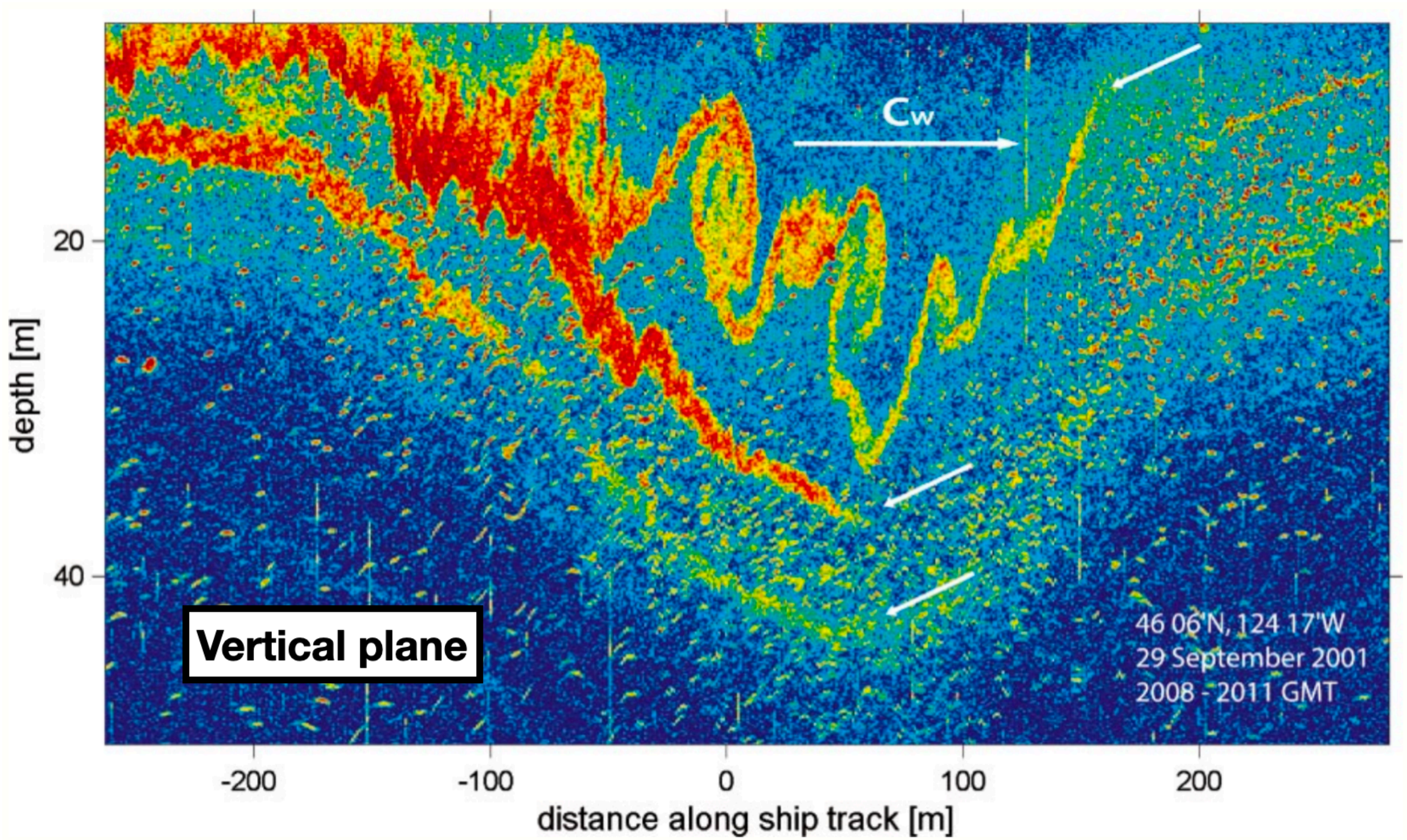


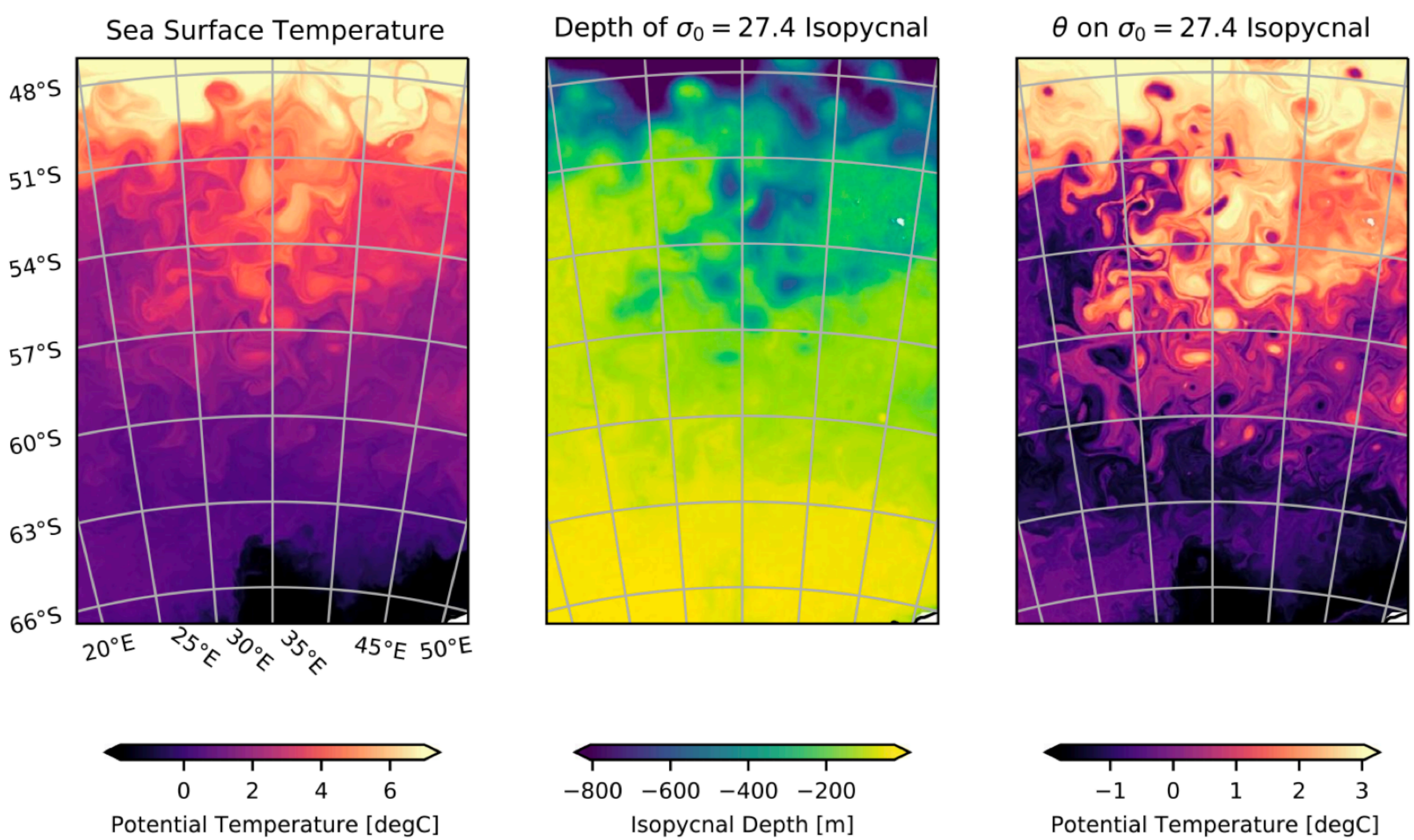
Acoustical snapshot of a propagating internal solitary wave (Moum et al. JPO 2003)

Two regimes of ocean turbulence

	Geostrophic turbulence	3-D small-scale turbulence
Turbulence source		
Typical scales		
Effects		
Turbulent diffusivity coefficient		

Two regimes of ocean turbulence

- Geostrophic turbulence: Stirring along density surfaces
  > By modulating the large scale circulation and thus the interaction with the atmosphere, it has an upscaling effect



Large-scale temperature gradient and mesoscale patterns of stirring from a numerical simulation (LLC4320)

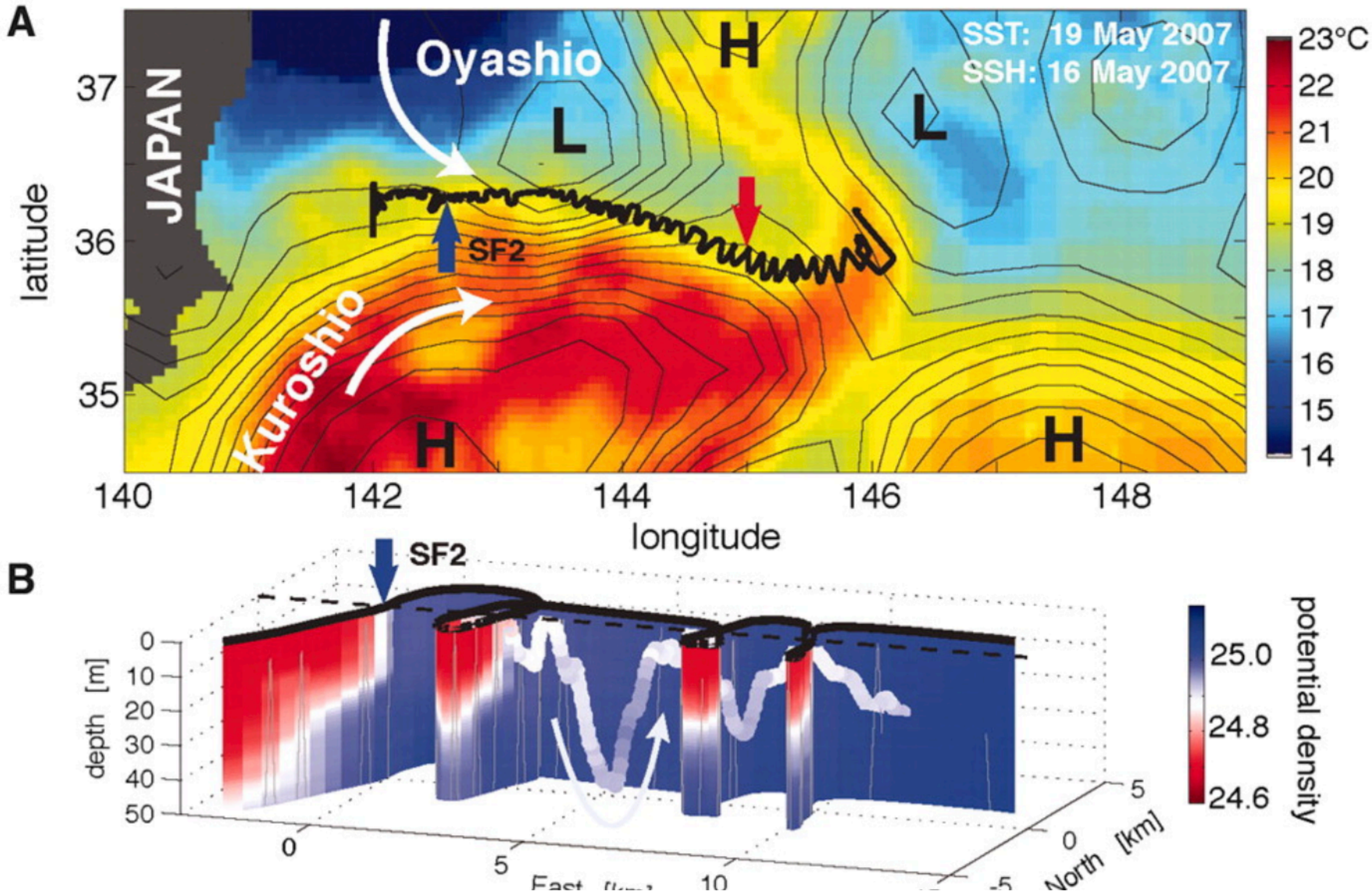
Rocha et al. GRL 2016, Abernathey et al. Ocean Mixing book 2022

Two regimes of ocean turbulence

	Geostrophic turbulence	3-D small-scale turbulence
Turbulence source	Mostly, baroclinic instability of the basin-scale currents, generates mesoscale eddies.	
Typical scales	Several radius of deformation L = 10-100 km H = thermocline to water column	
Effects	Stirring and diffusion along density surfaces, called **isopycnal mixing**	
Turbulent diffusivity coefficient	$K_{C\parallel} = 10 - 10^4\ \mathrm{m^2 s^{-2}}$ along isopycnals $K_{C\perp} = 0\ \mathrm{m^2 s^{-2}}$ across isopycnals $K_{C\parallel} \gg \kappa_C$ (molecular diffusivity)	

Two regimes of ocean turbulence

- 3D small scale turbulence:



Surface front in the Kuroshio, sampled by floats and a ROV
Enhanced level of turbulence in the submesoscale front

D'Asaro et al., 2011 Science

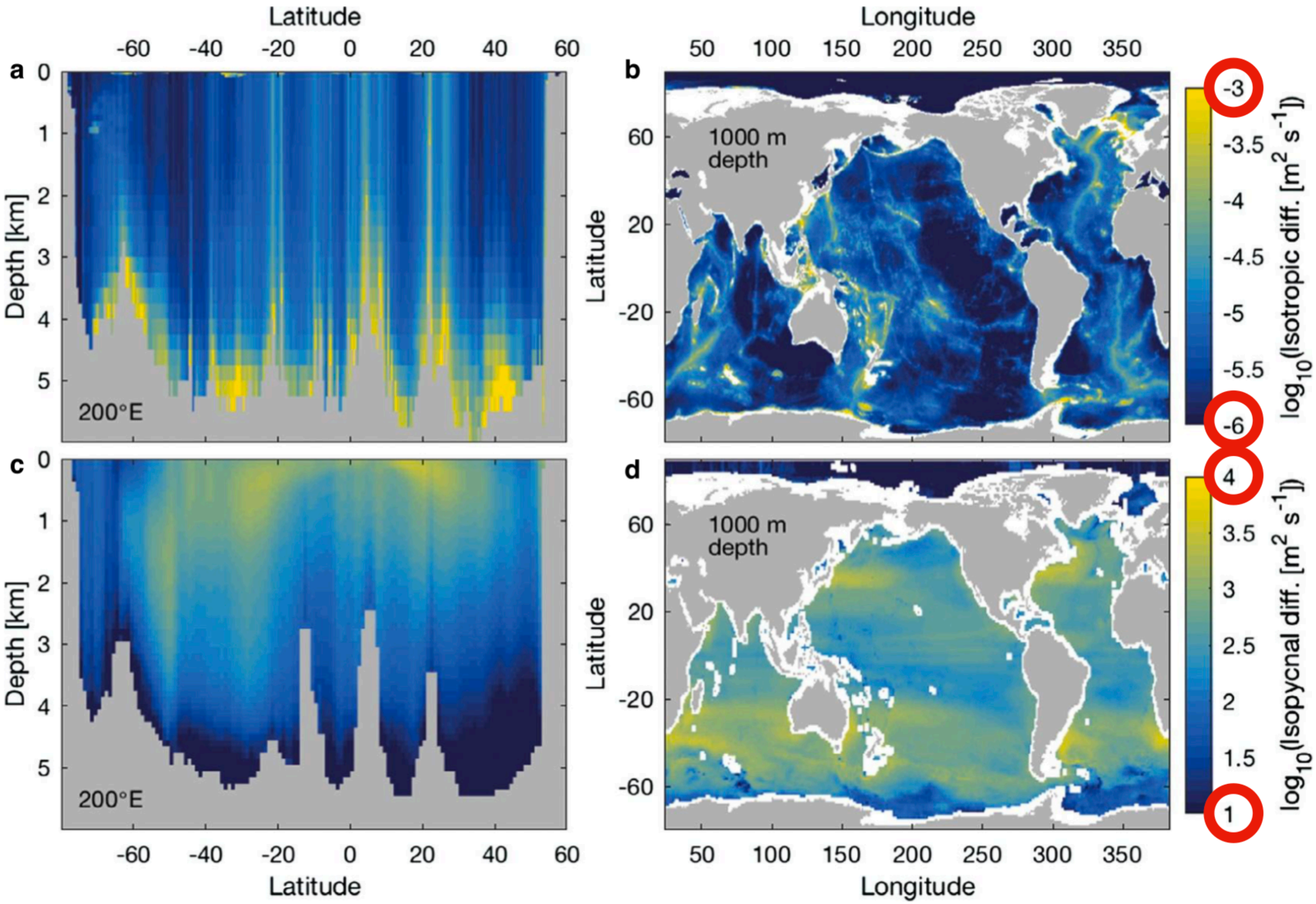
Two regimes of ocean turbulence

	Geostrophic turbulence	3-D small-scale turbulence
Turbulence source	Mostly, baroclinic instability of the basin-scale currents, generates mesoscale eddies.	Internal wave breaking, gravitational and shear instabilities
Typical scales	Several radius of deformation L = 10-100 km H = thermocline to water column	L ~ H ~ 1-100 m
Effects	Stirring and diffusion along density surfaces, called **isopycnal mixing**	**Isotropic mixing**, including mixing across density surfaces, called **diapycnal mixing**
Turbulent diffusivity coefficient	$K_{C\parallel} = 10 - 10^4\ \mathrm{m^2s^{-2}}$ along isopycnals $K_{C\perp} = 0\ \mathrm{m^2s^{-2}}$ across isopycnals $K_{C\parallel} \gg \kappa_C$ (molecular diffusivity)	$K_C = 10^{-6} - 10^{-2}\ \mathrm{m^2s^{-2}}$ in the interior $K_C > 10^{-2}\ \mathrm{m^2s^{-2}}$ in boundary layers $K_C \gg \kappa_C$ (molecular diffusivity)

Two regimes of ocean turbulence

K_C from 3-D small-scale turbulence (tidally-induced)

$K_{C\|}$ from geostrophic turbulence



De Lavergne et al. 202 – Ocean Mixing book

How to observe and measure turbulence and mixing in the ocean ?

Diapycnal mixing:

The diapycnal mixing coefficient κ is linked to energy dissipation ϵ through :

$$\kappa = \Gamma \frac{\epsilon}{N^2}$$

With the mixing efficiency $\Gamma = \frac{\text{Change in background potential energy due to mixing}}{\text{Energy expended}}$

And N^2 the buoyancy frequency squared.

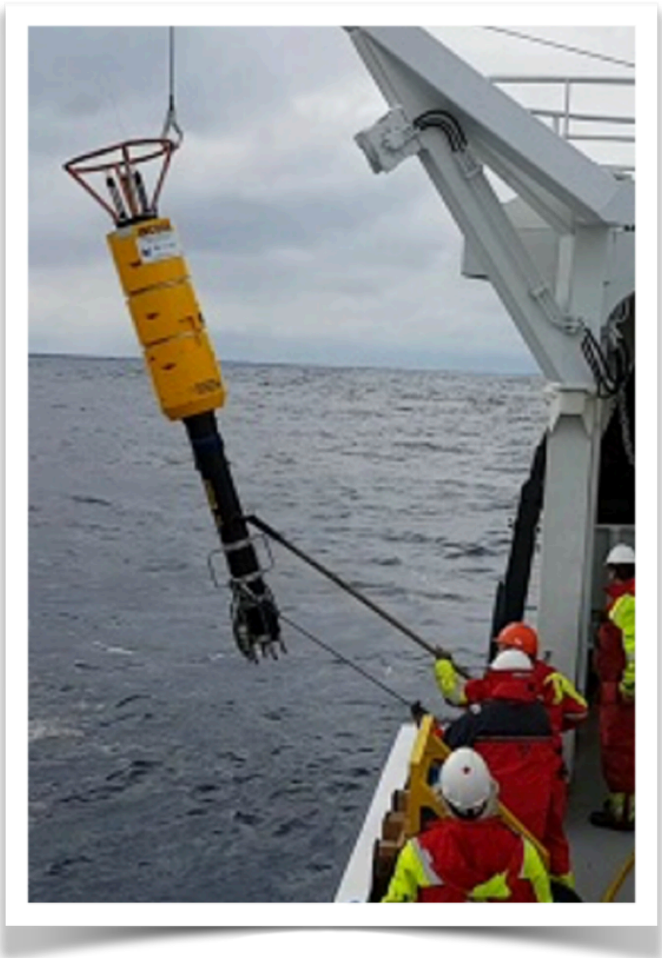
In general $\Gamma = 0.2$ is a fairly good approximation.

see Gregg et al. ARMS 2018 for an extended review

How to observe and measure turbulence and mixing in the ocean ?

Diapycnal mixing:

(1) *Microstructure estimates*



Instrument: Vertical Microstructure Profiler (VMP) measures $\partial u / \partial z$ at 512 Hz with a sinking velocity of ~0.5 m/s, which makes a resolution of ~1 mm.

Technique: compute velocity shear spectrum $\psi(k)$ (k is the vertical wavenumber) and compare to 'standard' spectra to infer the shear variance that is linked to dissipation

$$\varepsilon = \frac{15}{2}\nu\left(\frac{\partial u}{\partial z}\right)^2 = \frac{15}{2}\nu\int_0^\infty \psi(k)\mathrm{d}k$$

Pros: most reliable estimate of kinetic energy dissipation

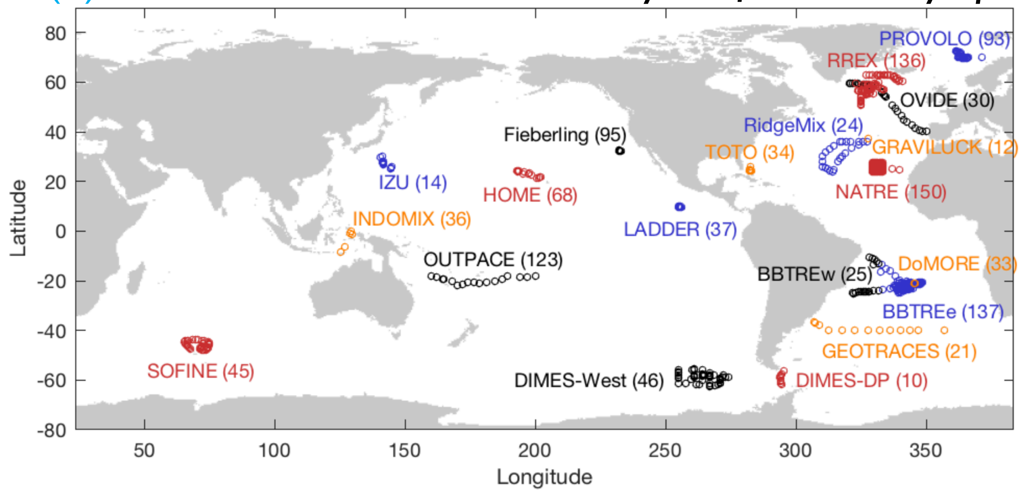
Cons: expensive, time-consuming, difficult to deploy limited spatial coverage

see Frajka-Williams et al, Chap 14 in Ocean Mixing Book 2022

How to observe and measure turbulence and mixing in the ocean ?

Diapycnal mixing:

(1) *Microstructure estimates: very useful, but very sparse!*



Synthesis of the available (in 2020) direct observations of dissipation from microstructure - 19 projects, 1169 profiles

De Lavergne et al. 2020

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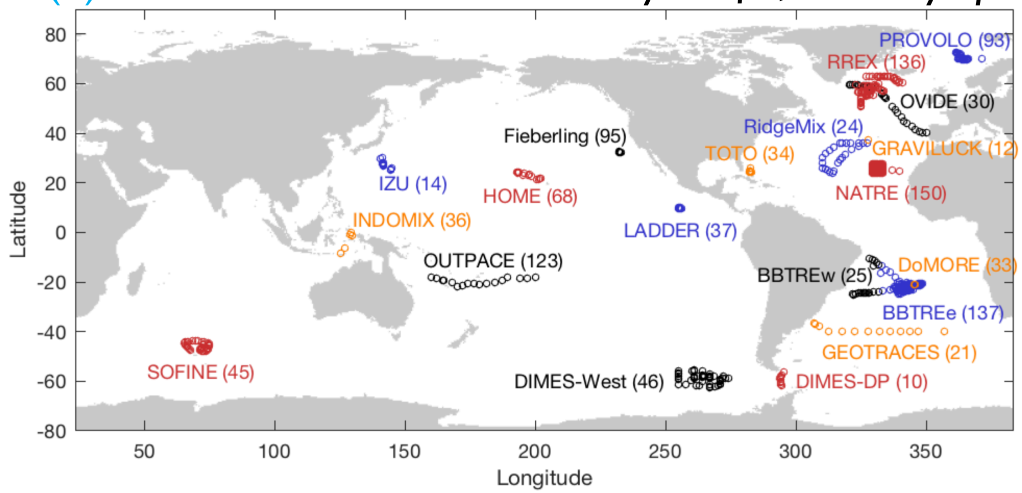

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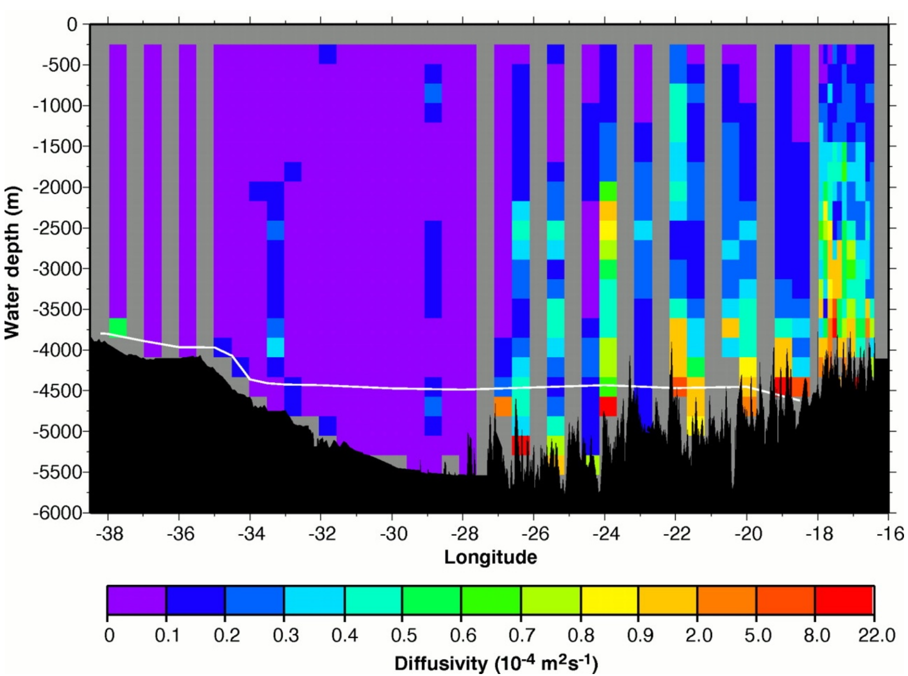

Section across the Brazil Basin

De Lavergne et al. 2020, Polzin et al. 1997 Science

How to observe and measure turbulence and mixing in the ocean ?

Diapycnal mixing:

(II) *Fine structure estimates*

Instrument: Conductivity-Temperature-Depth (CTD) measures temperature, salinity and pressure at 1 Hz (standard) with a sinking velocity of ~0.5 m/s, which makes a resolution of ~50 cm

Technique: compute the density strain $\xi_z = \frac{N^2 - N^2_{fit}}{\overline{N^2}}$ and strain variance $\langle \xi_z^2 \rangle$ in segments (~200 m thick) to estimate the kinetic energy dissipation ε.

Pros: cheap, a lot of data available, CTDs are mounted on Argo floats, …

Cons: only get wave-related dissipation, not reliable close to rough topography, large uncertainty (larger for low level of dissipation)

see Frajka-Williams et al, Chap 14 in Mixing Book 2022

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Pros: cheap, a lot of data available, CTDs are mounted on Argo floats, …

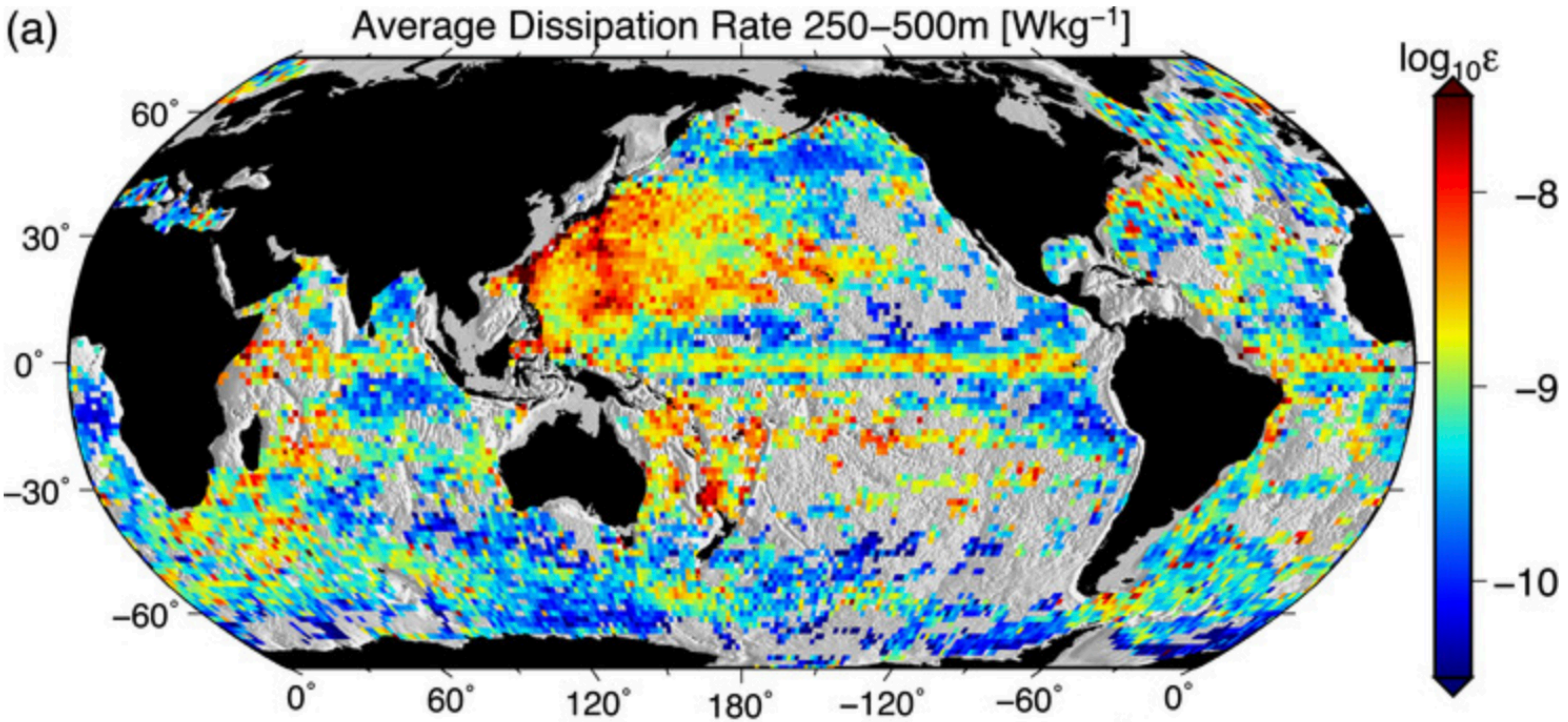
Cons: only get wave-related dissipation, not reliable close to rough topography, large uncertainty (larger for low level of dissipation)

NB : often close to the noise level of the instruments
But…can be combined to ADCP-derived velocity field to incorporate vertical shear

see Frajka-Williams et al, Chap 14 in Mixing Book 2022

Diapycnal mixing:

(II) *Fine structure estimates*

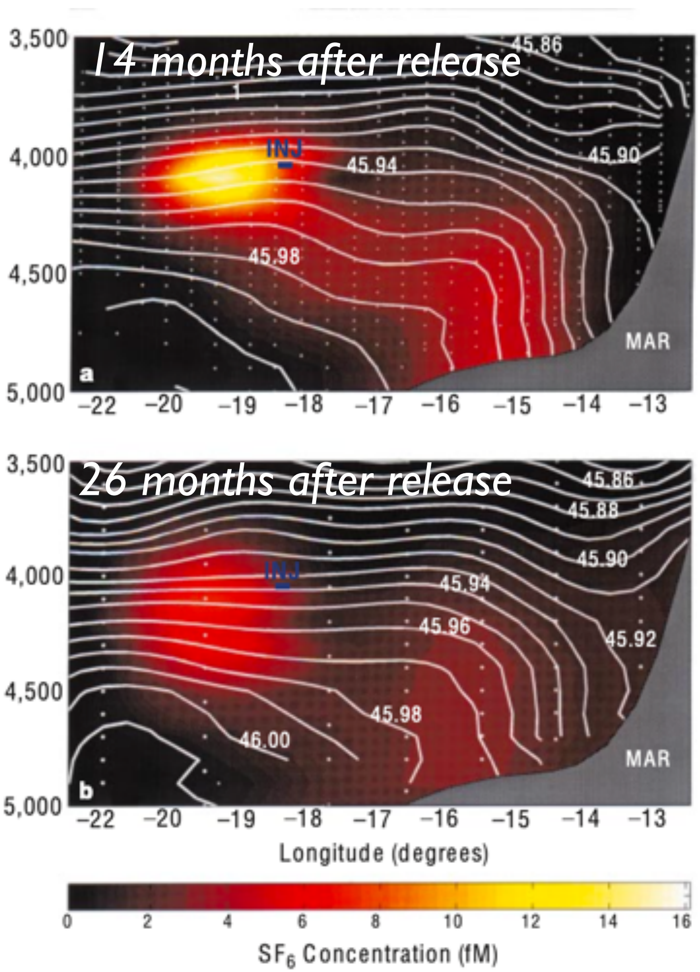


Whalen et al. 2015, from Argo float data (2005-2014)

How to observe and measure turbulence and mixing in the ocean ?

Diapycnal mixing:

(III) *Tracer Release Experiments (TREs)*



Instrument: passive tracer release (SF6, …) + Sampling with a rosette

Technique: seed a passive tracer on a target density layer and come back later to sample its spread. Measure the tracer spread in density space.

Pros: measures the mixing actually seen by any passive tracer (Carbon, Iron, …)

Cons: expensive, difficult to anticipate the spread

Ledwell et al. 2000 Nature

How to observe and measure turbulence and mixing in the ocean ?

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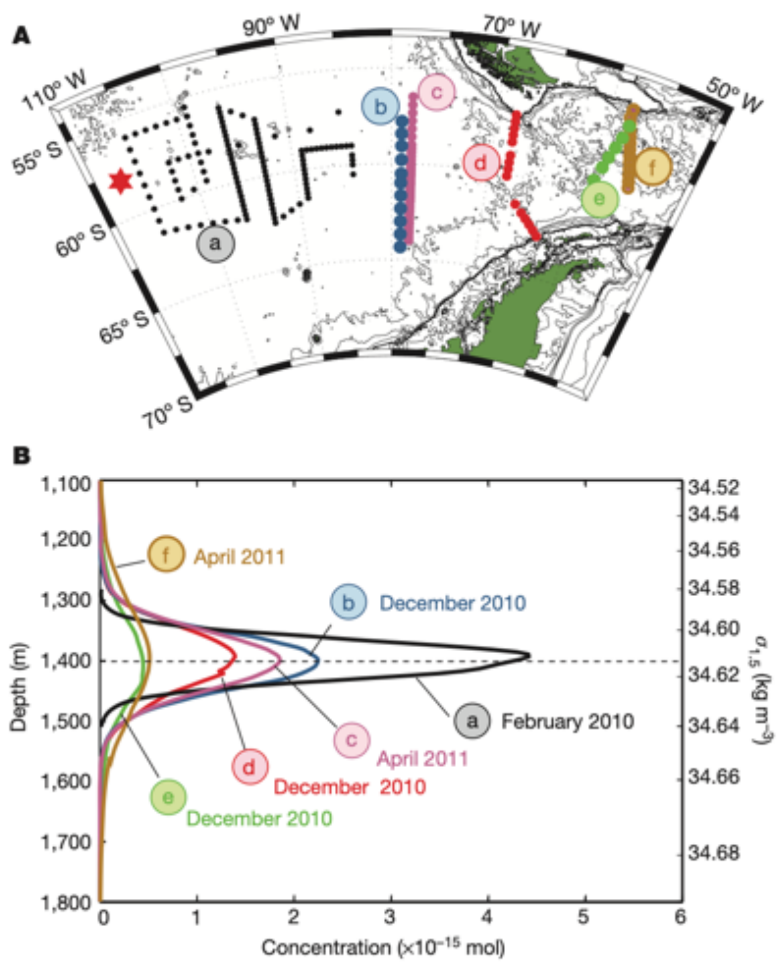
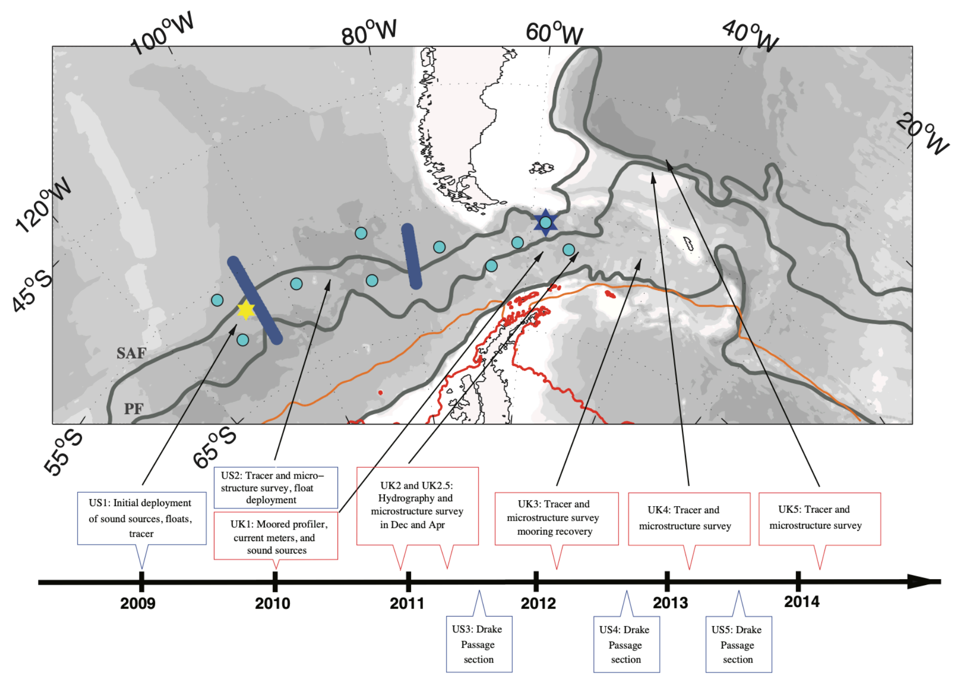


DIMES experiment in the ACC



Watson et al. 2013 Nature

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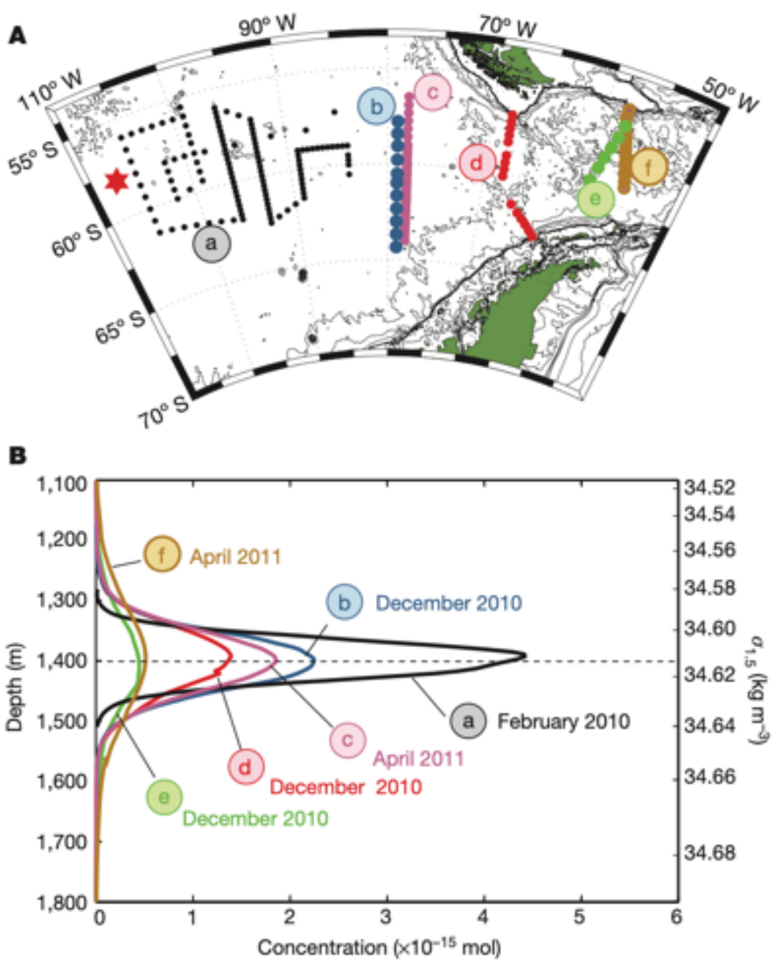
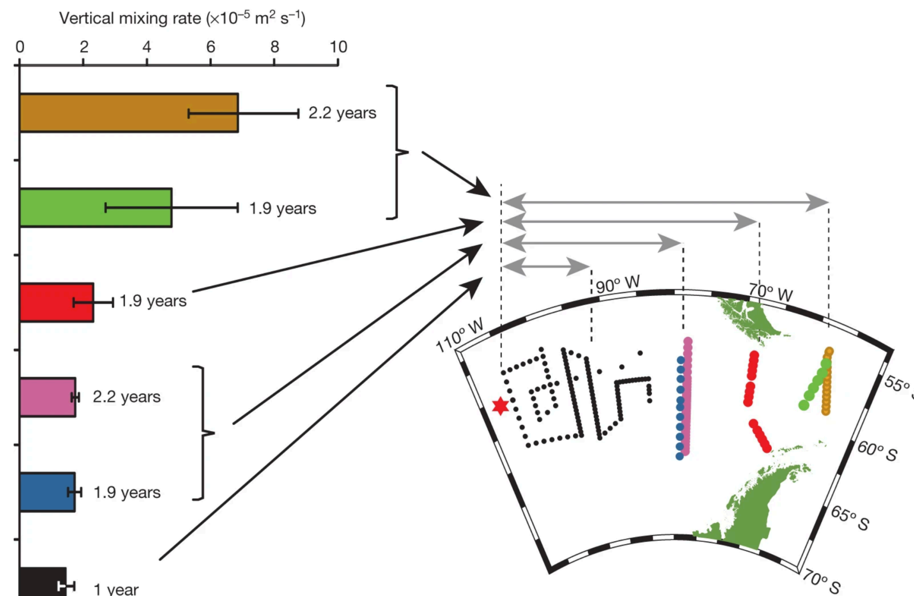




These are calculated from the second moments of the mean profiles in Fig. 1. They are averages over the times since release, and their spatial extents are indicated by the grey arrows above the inset. The approximately threefold increase in the mean when averaged over a path including the Drake Passage indicates that diffusivities increase by at least an order of magnitude east of 70° W compared to west of 70° W. We note that the water column in the Drake Passage is less stratified than in the eastern Pacific, and so the tracer distribution on survey (a) in Fig. 1 occupies a wider depth span when mapped in a Drake Passage depth–density profile than when used in the calculations of ref. 19. Correspondingly, the diffusivity shown here for the Pacific sector after one year is about 25% larger than that quoted in ref. 19. Error bars show 95% confidence limits, calculated from the statistics of individual profiles (see Supplementary Information for details).

Watson et al. 2013 Nature

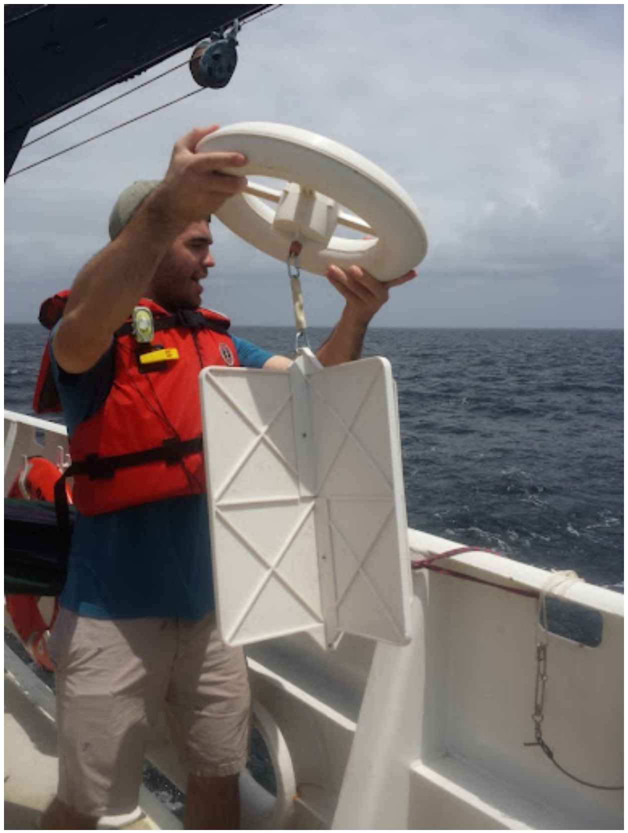
How to observe and measure turbulence and mixing in the ocean ?

Isopycnal mixing:

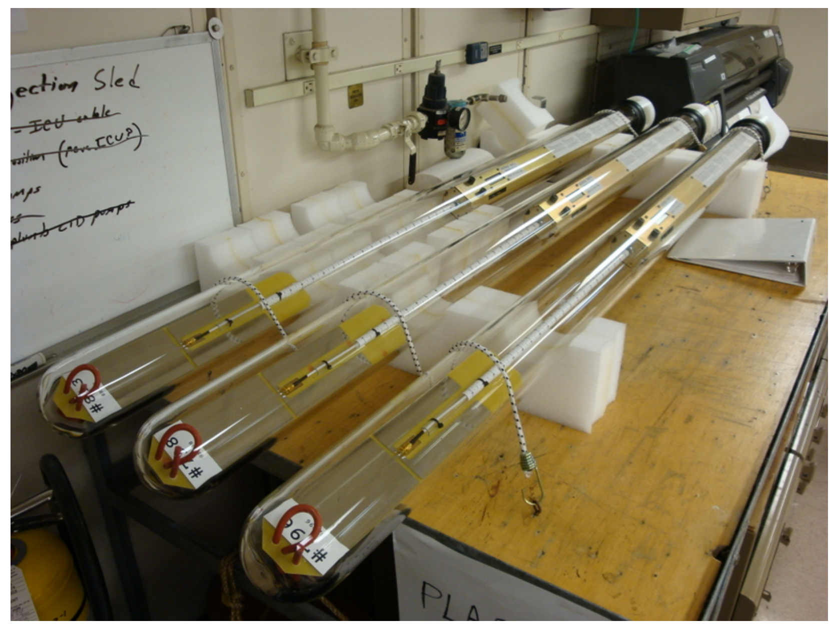
(I) *Lagrangian floats and drifters*

Instrument: Surface or isopycnal floats (positioned through acoustic positioning)

Technique: rely on statistical techniques studying the motion of single particles or the relative dispersion of groups of particles



Carthe surface drifters:
low cost, biodegradable



RAFOS float

How to observe and measure turbulence and mixing in the ocean ?

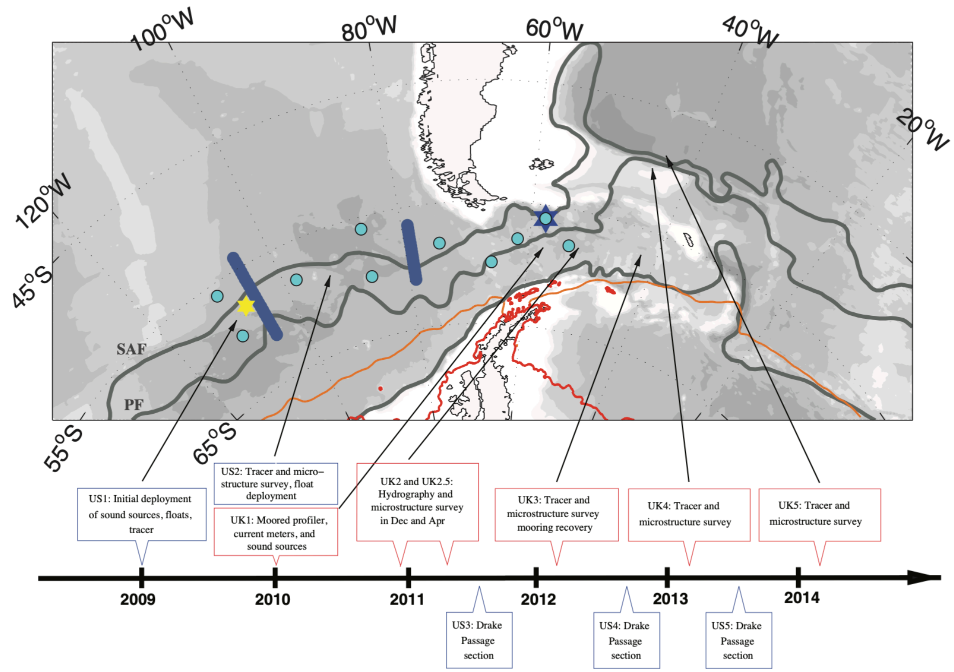
Isopycnal mixing:

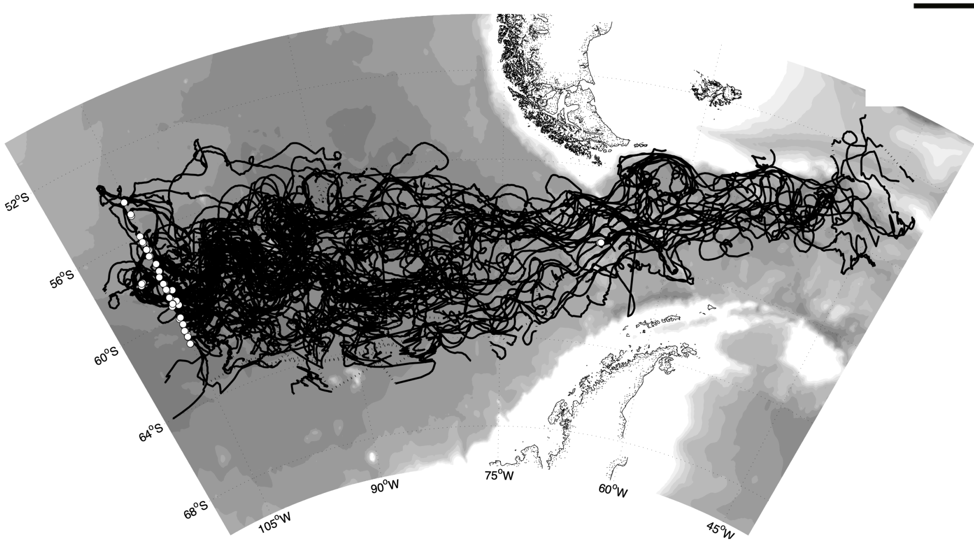
(Ia) *Lagrangian floats and drifters*

64 RAFOS float deployed at 1000m
(neutral density surface $\gamma = 27.7$)

Diffusivity of $800 \pm 200\ m^2\ s^{-1}$

DIMES experiment in the ACC



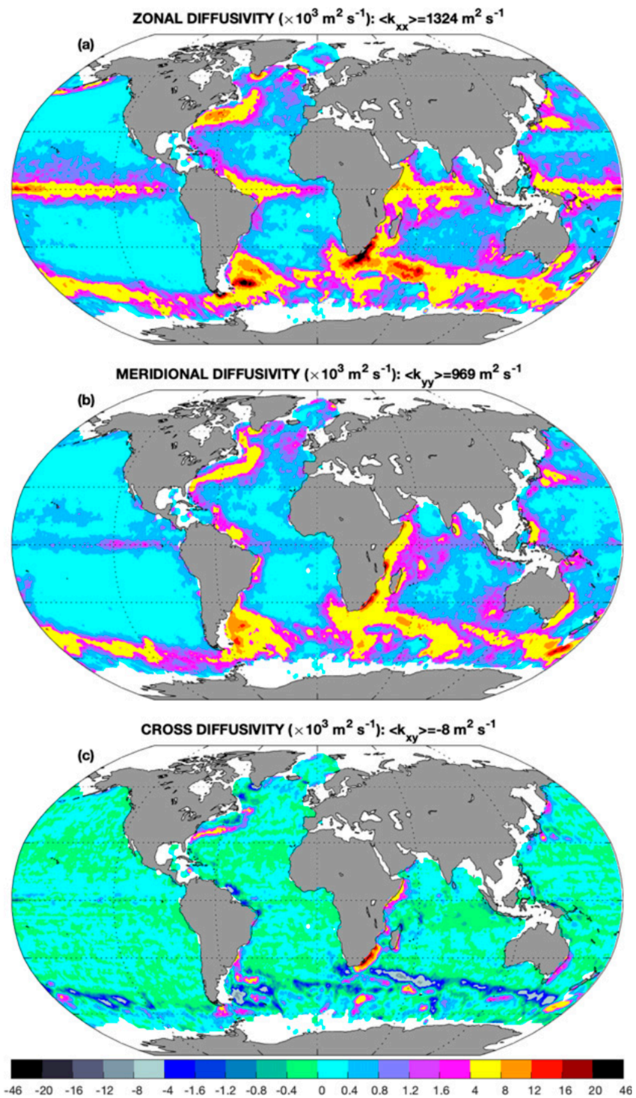


LaCasce et al. 2014

How to observe and measure turbulence and mixing in the ocean ?

Isopycnal mixing:

(Ib) Eulerian methods from velocity fields



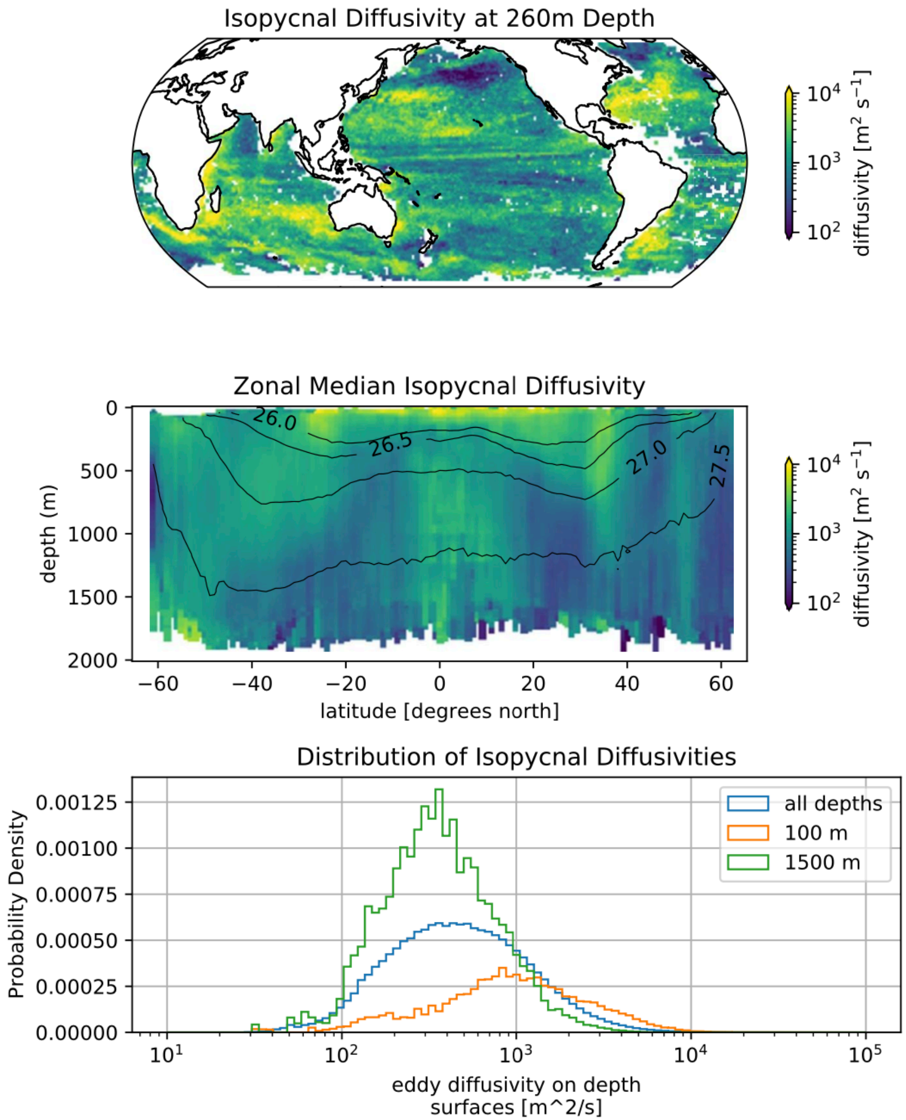
Instrument: velocity fields obtained from satellite altimetry, of Argo float displacement at 1000m

Technique:
- Derivation of trajectories in the velocity field
- Repeat the Lagrangian method! (dispersion across trajectories)

Sevellec et al. 2022

How to observe and measure turbulence and mixing in the ocean ?

Isopycnal mixing:
(II) Eulerian methods applied to tracers



Instrument: repeated CTD cast from hydrographic campaign, Argo float… to measure tracer (e.g. salinity) variance

Technique:

- estimates of length scales from the variance of properties and directly applying mixing length theory

$$\lambda = \langle S'S' \rangle^{\frac{1}{2}} / \langle \, | \nabla \{S\} | \, \rangle$$

$$\kappa_h = c_0 \lambda u_{rms}$$

Cole et al. 2015

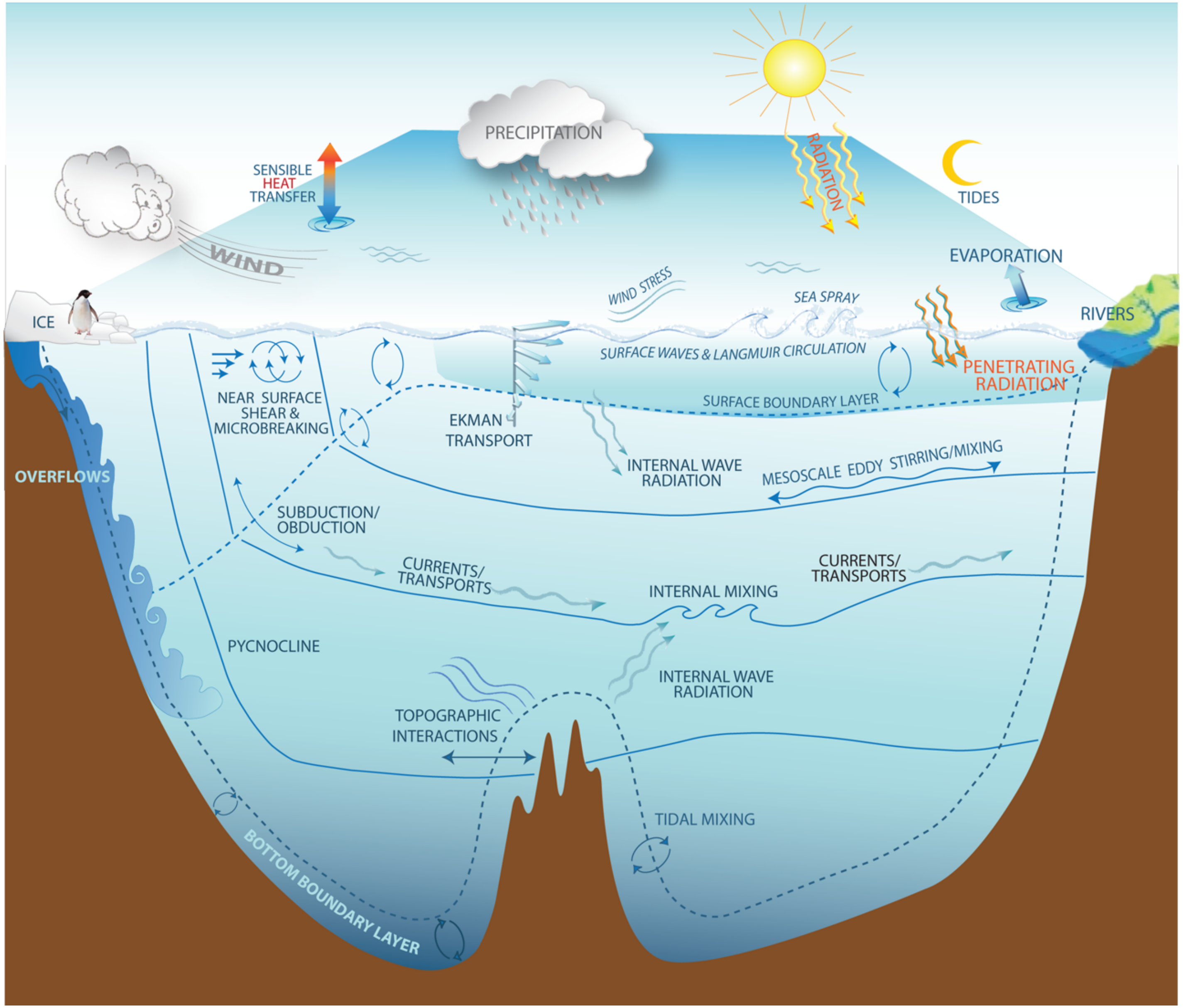
How to observe and measure turbulence and mixing in the ocean ?

Isopycnal mixing:
all in all, we have:
- only a few direct estimate
- large spatio-temporal variations
- large uncertainty

Study	Region	Depth	Method	K [1000 $m^2 s^{-1}$]
D1	Arctic	Surface	rpd, basin	1.1
D2	Cal. current	15 m	spd, basin	3.5/3.1
D3	Adriatic	15 m	spd, basin, bss	1.0/.0
D4	Pacific NEC	15 m	spd, 6 groups, zc	2.3
D4	N. Pac subtrop.	15 m	spd, 6 groups, zc	12.4
D5	N Atl.	15 m	spd, zc	1–23
D5	N. Atl.	$z < 1500$ m	spd, zc	0.07–1.8
D6	trop. Pacific	15 m	spd, bins, bss	5-74/2–9
D7	Norw. sea	15 m	rpd, basin	2.9
D8	Gulf stream	15 m	rpd	14
D8	E. subtrop. Atl.	15 m	rpd	1.7
D9	ACC	15 m	spd, basin, bss	9.0/2.0
D10	E. Nordic seas	15 m	spd, cluster & bin	0.7–2.4
F1	Newf. basin	$\sigma = 27.2$	spd, basin	5.8/5.6
F1	Newf. basin	$\sigma = 27.5$	spd, basin	3.6/4.1
F2	Canary basin	700 m	spd, basin	1.5
F2	Newf. basin	700 m	spd, basin	3.5
F2	Corner rise	700 m	spd, basin	4.1
F3	ACC basin	$\sigma \sim 27.7$	spd, asymp	0.8
F4	ACC & Scotia sea	500–1500 m	spd, asymp	0.7–2.8
F5	ACC (S. Pac.)	500–1500 m	rpd	N/A
DF1	global map	15+400–1000 m	spd, zc	0–40
DF2	global map	15 m	spd, zc vs. asymp	0–10(asymp)
T1	Cal. current	4000 m	Spread	0.02
T2	Subtr. N, Atl.	300 m	Spread	1.5/0.6
T3	Guinea dome	300 m	Spread	1–1.2/0.5
T4	Brazil basin	4000 m	Spread	0.1
T5	Drake passage	1500 m	Corrected spread.	0.7

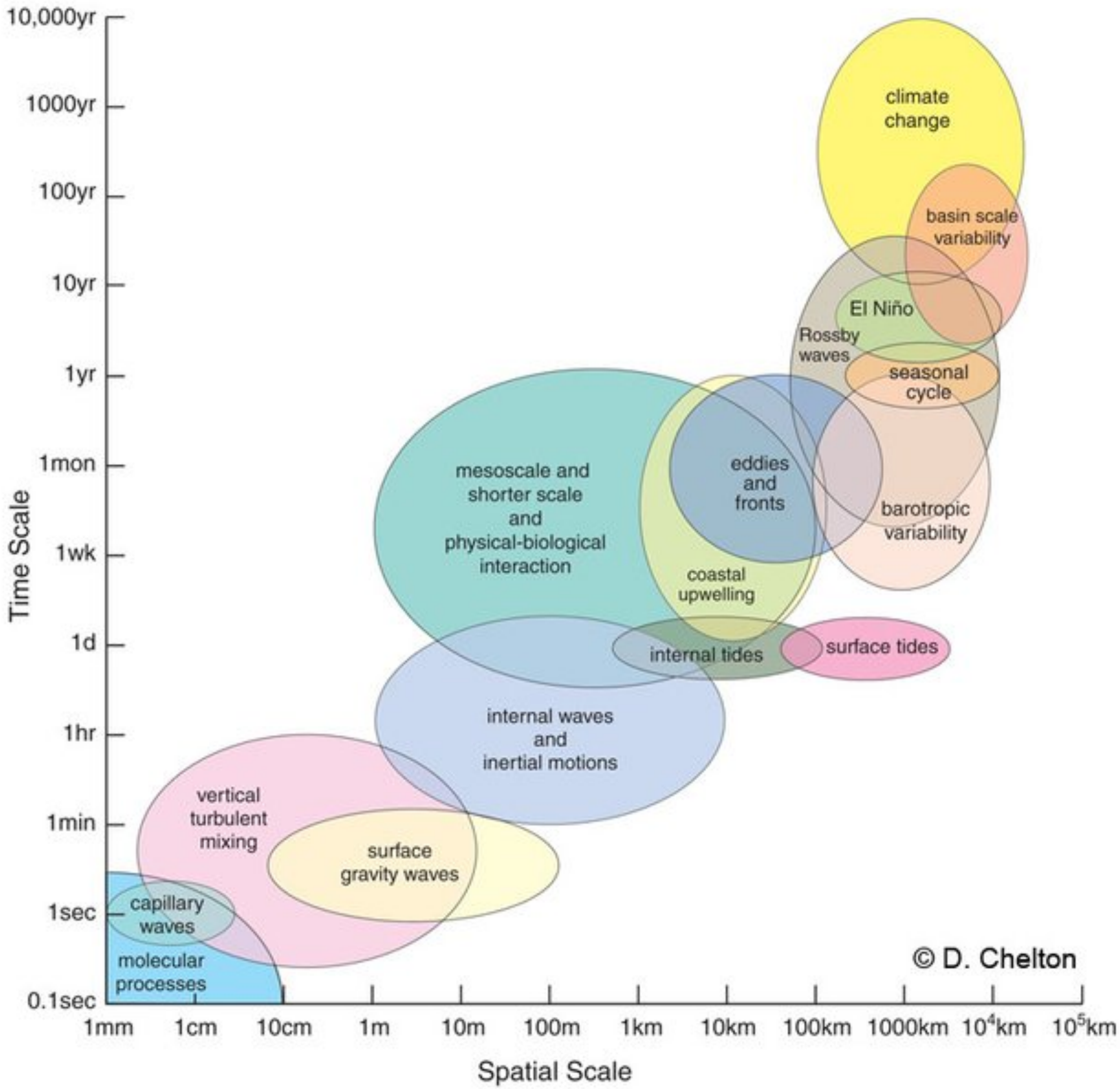
Abernathey et al. 2022 – review of all the existing direct estimates

Mixing and turbulence: processes to consider



Source: https://www.gfdl.noaa.gov/ocean-mixing/

Mixing and turbulence: processes to consider



But we also need to consider the scale interactions!

Mixing and turbulence: processes to consider

In the rest of this talk, I will focus on a few processes, looking also *at their impacts on the larger scales*

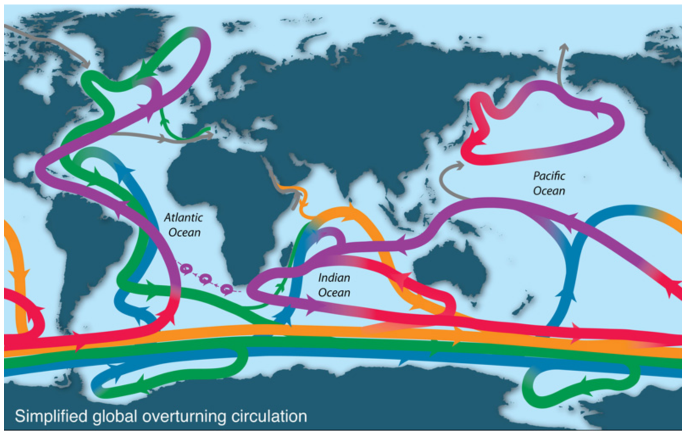
(i) Vertical/diapycnal mixing in the global ocean and its impacts on the large scale ocean circulation and climate

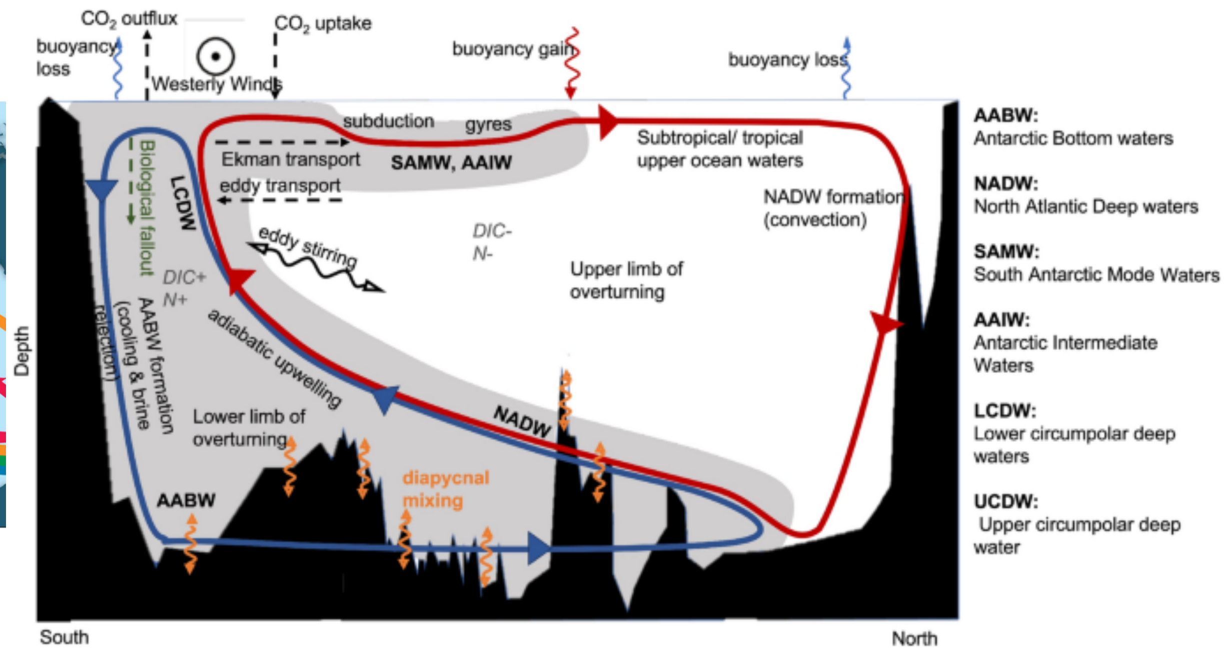
(ii) Eddies in the Arctic and their impact/interactions with sea ice

(iii) Vertical mixing in the Arctic and impact on sea ice (or lack thereof)

Vertical mixing and MOC

- Many aspects of the MOC (Meridional Overturning Circulation) are dependent on diapycnal mixing





- *'A two-loop system, consisting of an adiabatic upper cell fed by North Atlantic Deep Water (NADW) formation in the subpolar North Atlantic, overlying a largely diabatic lower cell fed by Antarctic Bottom Water (AABW) formation in the polar Southern Ocean'*

- *In the Atlantic, NADW is formed through surface densification + mixing at overflow*

- *In the Southern Ocean, diapycnal mixing contributes to lightening AABW and SAMW*

Talley 2013; Ellison et al. 2022, Melet et al. 2022

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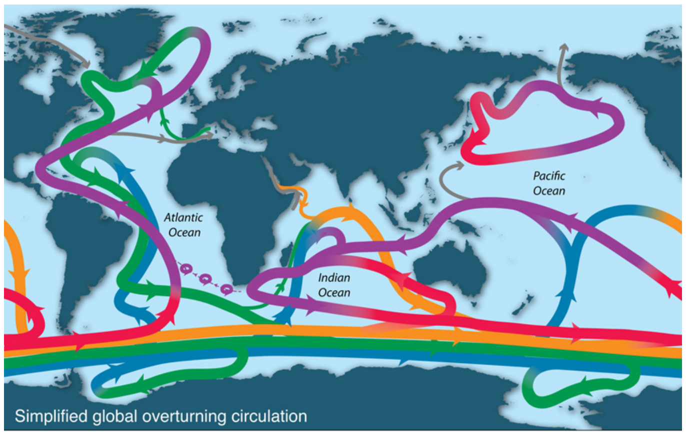
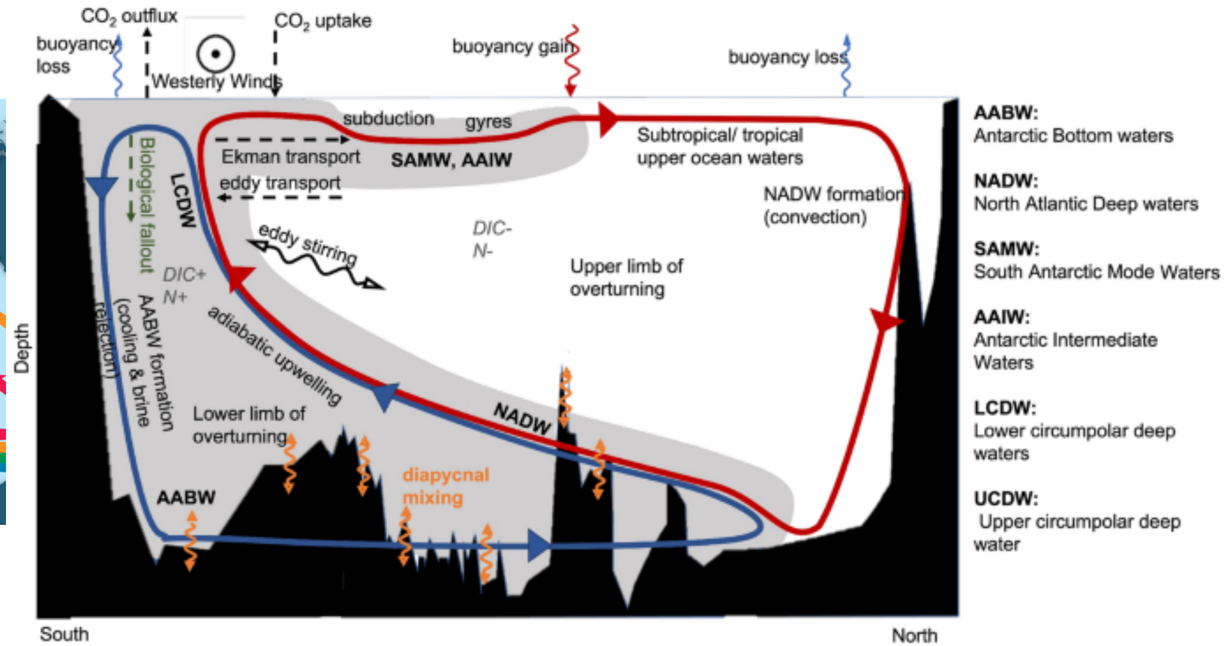
- Many aspects of the MOC (Meridional Overturning Circulation) are dependent on diapycnal mixing



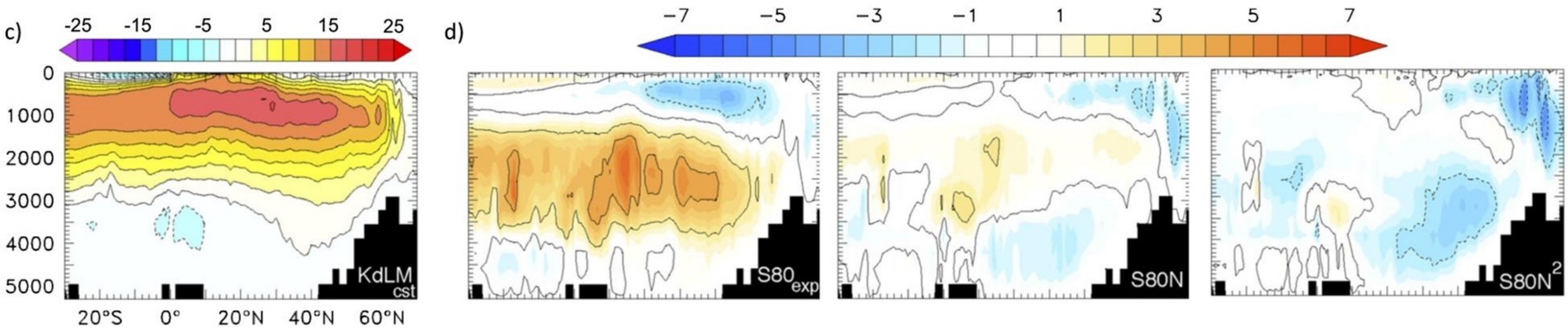


- *In the limit of overturning being diffusively-driven, the overturning strength would scale with the diapycnal diffusivity Kd^2/3 for the NADW overturning, and Kd^1/2 for the AABW overturning. These scalings indicate an increase in overturning strengths with a uniform increase in diffusivities. As meridional heat transport (MHT) is connected to the MOC, it also increases with increases of uniform diffusivities (e.g., Vallis and Farneti, 2009).*

Talley 2013; Ellison et al. 2022, Melet et al. 2022

Vertical mixing and MOC

- Many aspects of the MOC (Meridional Overturning Circulation) are dependent diapycnal mixing
- In climate models, the simulated MOC also largely depends on the spatial distribution of the vertical diffusivity, and in particular of the tide-induced dissipation
  Future changes of the MOC may be impacted by changes in dissipation?



AMOC (1000yr average) in simulations with different spatial (restricted to the continental slopes) and vertical distributions of the vertical diffusivity

Melet et al. 2016

Vertical mixing and MOC

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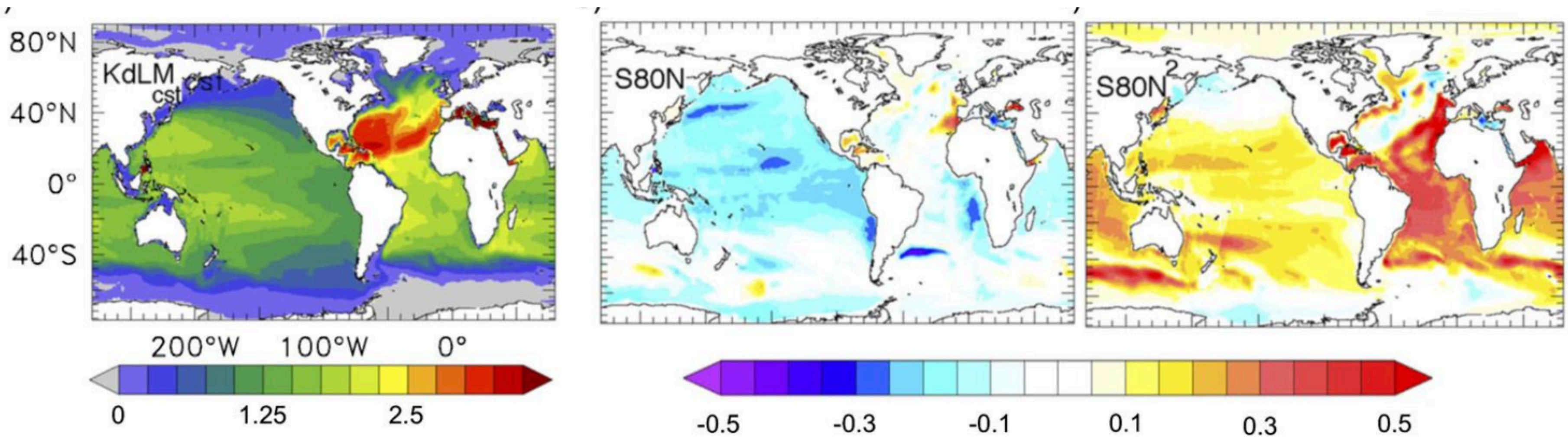
- In climate models, the simulated MOC also largely depends on the distribution of the vertical diffusivity, and in particular of the tide-induced dissipation
  Future changes of the MOC may be impacted by changes in dissipation?
- Also impacts heat and carbone uptakes, and spatial distribution of sea level rise

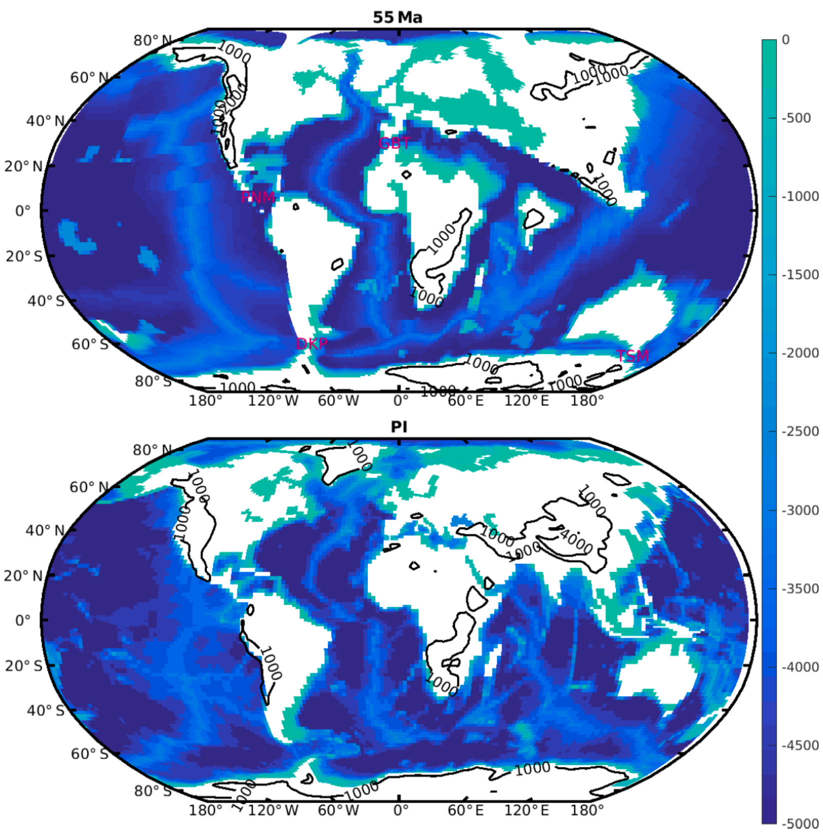


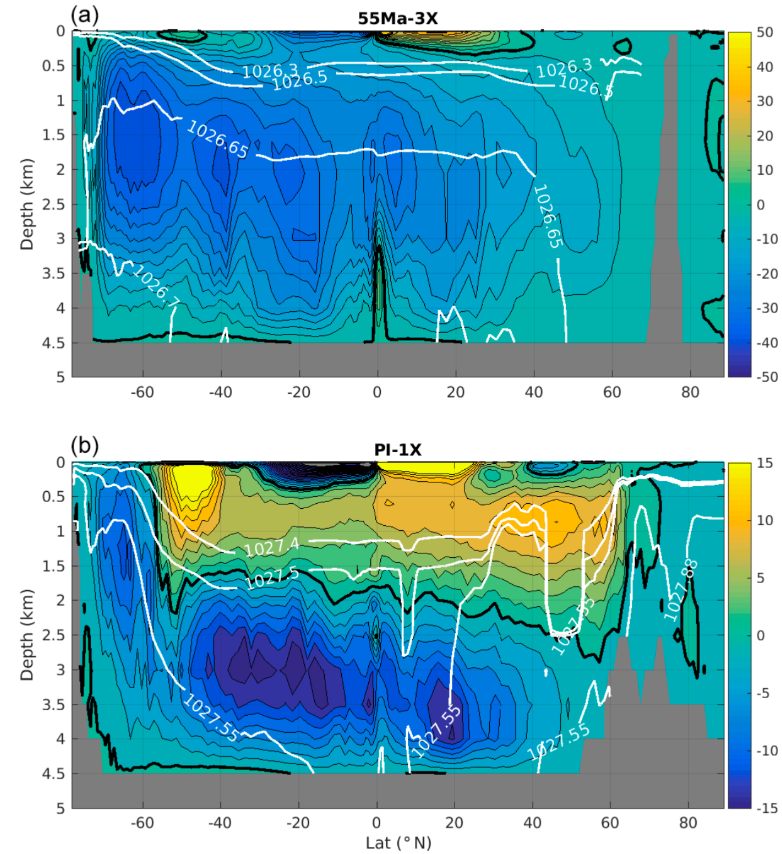
Thermosteric sea level (TSSL) referenced at the ocean bottom (m) (1000yr average) in simulations with different spatial (restricted to the continental slopes) and vertical distributions of the vertical diffusivity

Melet et al. 2016

Vertical mixing and MOC

- The importance of vertical mixing for the intensity and structure of the MOC nicely exemplified when looking at climate of the past





- *During the Ypresien (55Ma), the bathymetry/topography was very different*
- *And thus the ocean circulation was different too!*
  - *> No AMOC, only a SOMOC*
  - *> 20°C in the Southern Ocean, no Antarctic Ice Sheet*

Zhang et al. 2020, Ladant et al. 2024

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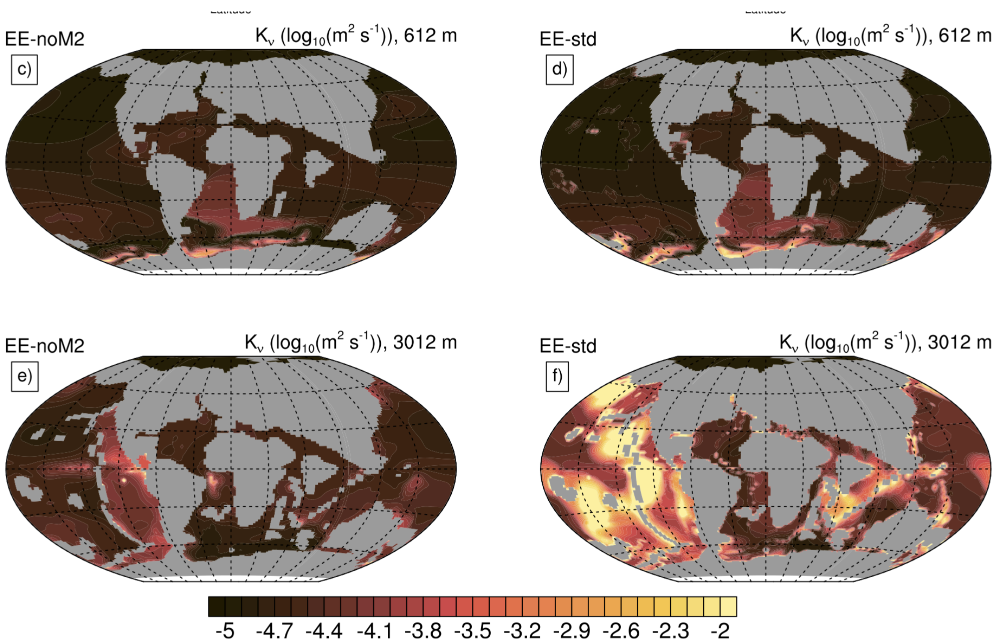

log(Kz) in m^2/s

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- *But different continent also means different M2 tides and abyssal tidal induced mixing!*

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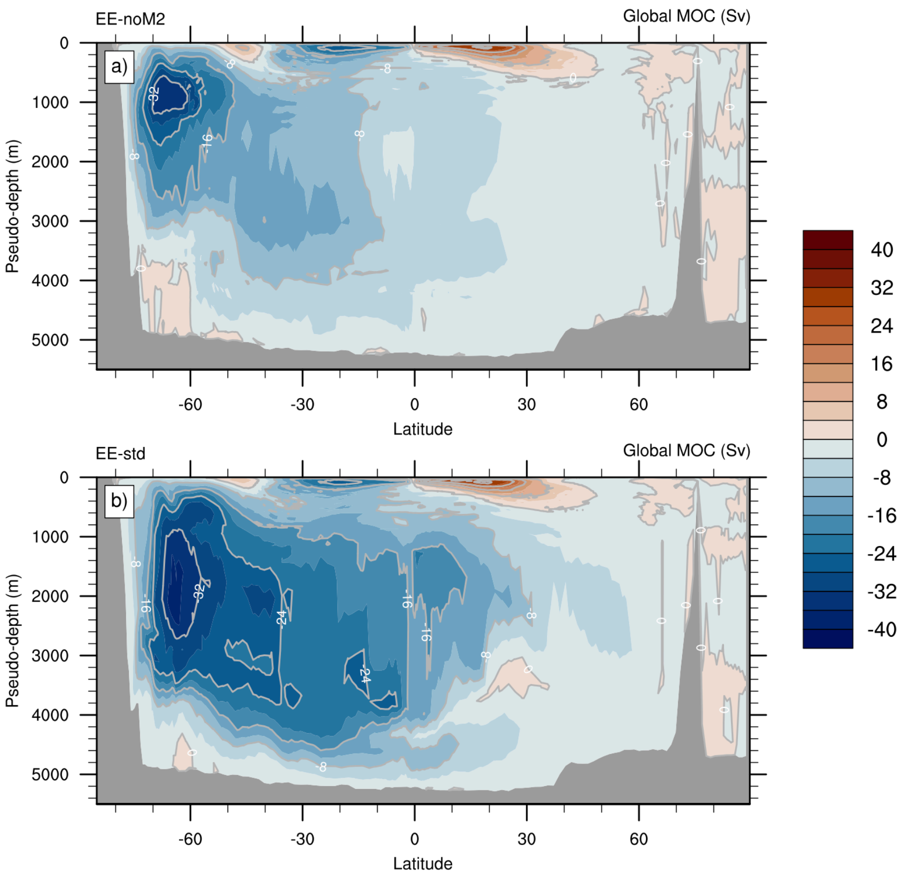

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- *And thus the ocean circulation was different too!*
  > No AMOC, only a SOMOC
  > 20° in the Southern Ocean, no Antarctic Ice Sheet

- *But different continent also means different M2 tides and abyssal tidal induced mixing!*

- *Modifies the SST by up to 5°, and alters the distribution of BGC tracers (eg O2)*

Zhang et al. 2020, Ladant et al. 2024

Mixing and turbulence: processes to consider

In the rest of this talk, I will focus on a few processes, looking also *at their impacts on the larger scales*

(i) Vertical/diapycnal mixing in the global ocean and its impacts on the large scale ocean circulation and climate

    In a climate model, the level and spatial distribution of diapycnal mixing strongly affect the ocean circulation, and in particular the intensity of the AMOC

(ii) Eddies in the Arctic and their impact/interactions with sea ice

(iii) Vertical mixing in the Arctic and impact on sea ice (or lack thereof)

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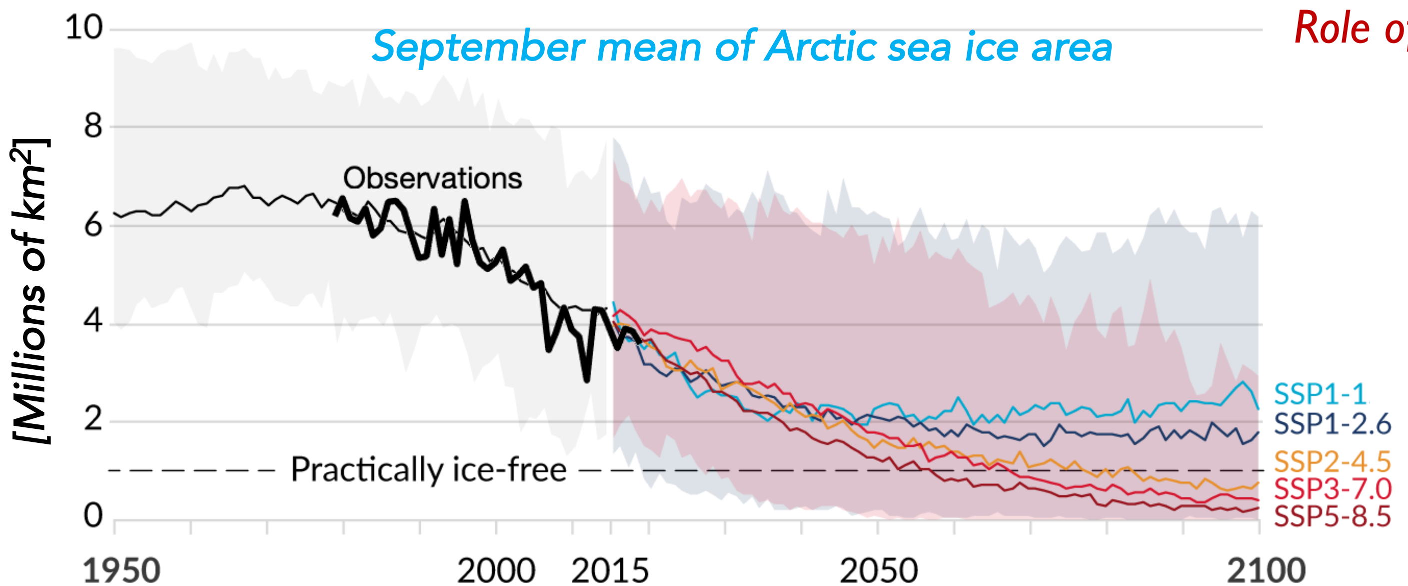
(ii) Eddies in the Arctic and their impact/interactions with sea ice

(iii) Vertical mixing in the Arctic and impact on sea ice (or lack thereof)

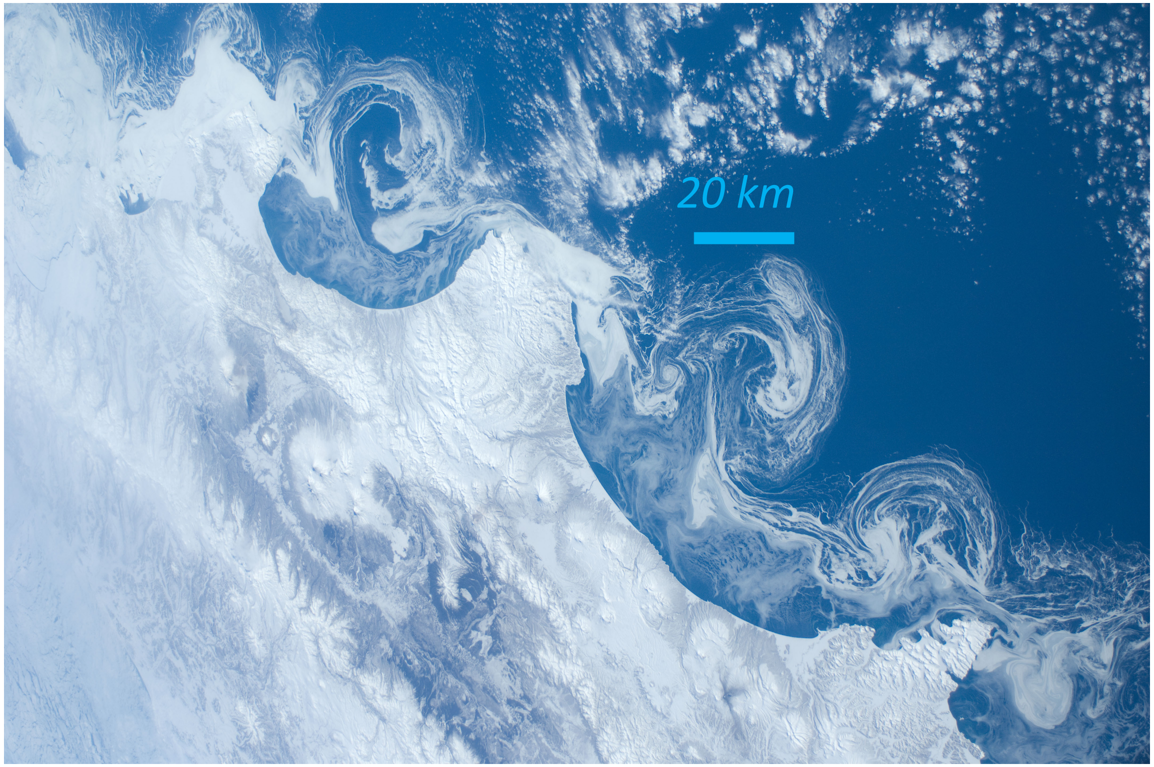
The Arctic is changing a lot in response to climate change

Role of the ocean?



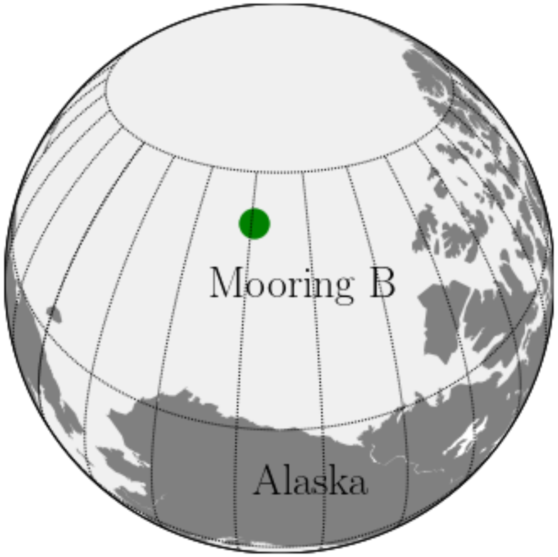
Eddy signature in sea ice motion

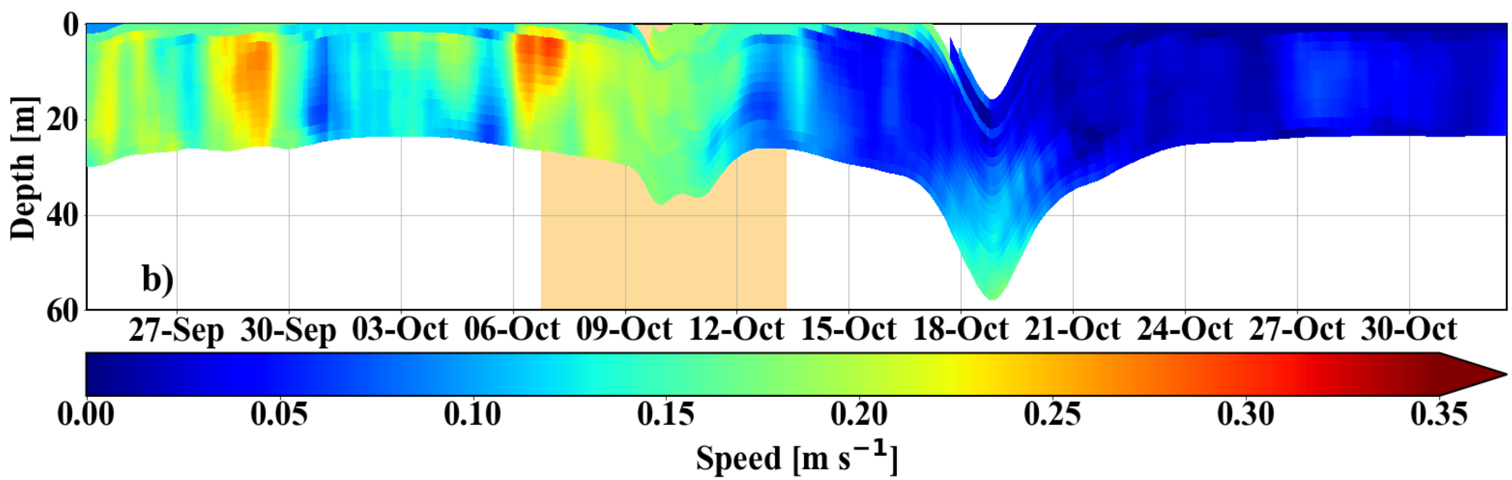
Picture taken form the ISS, March 2012 (credit: NASA)
Along the coast of Russia



Eddy signature in sea ice motion

- We observe an eddy passing by a mooring in the Canadian Basin in Oct. 2017





Data from BGEP (WHOI); Cassianides, Lique & Korosov 2021

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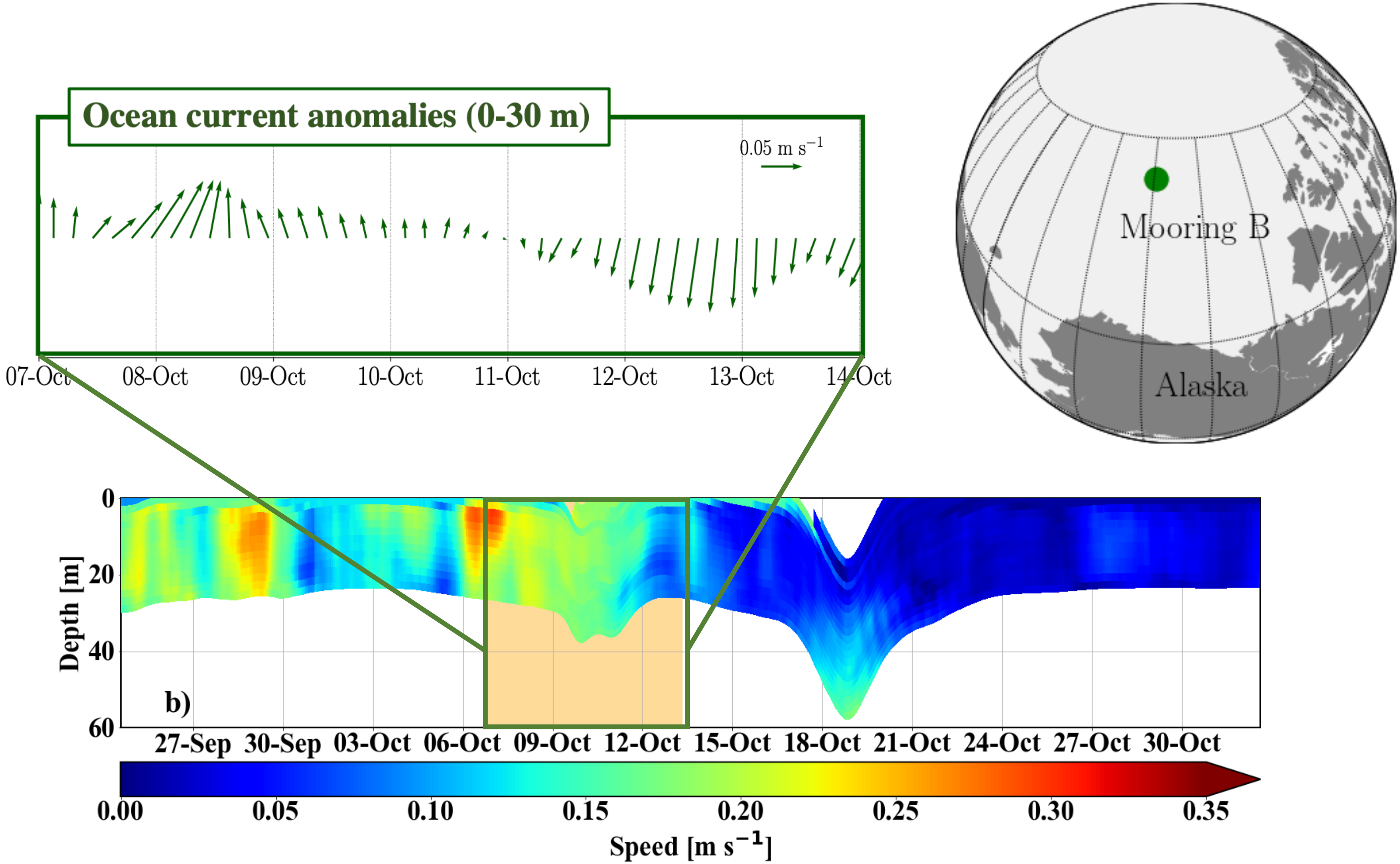

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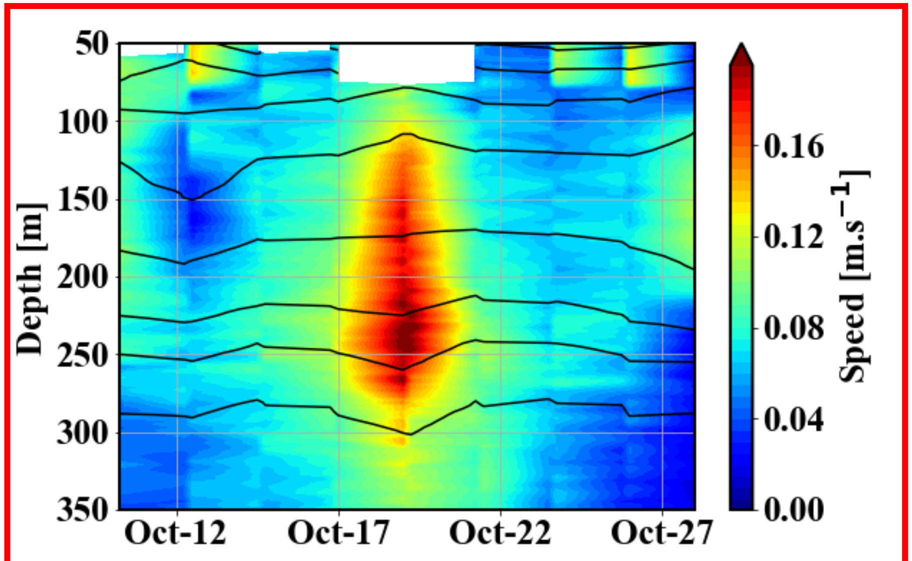
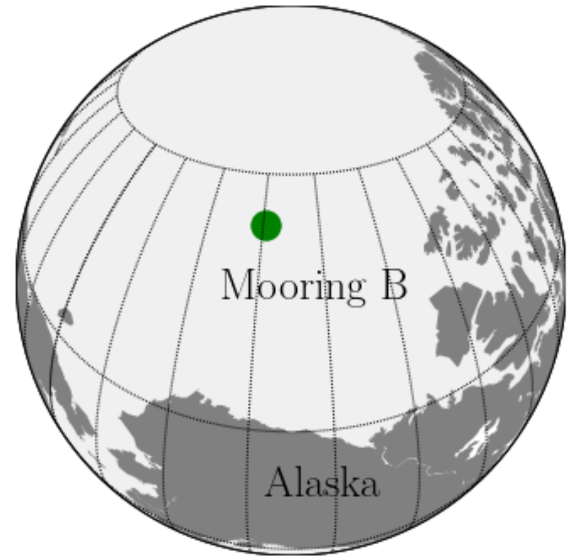
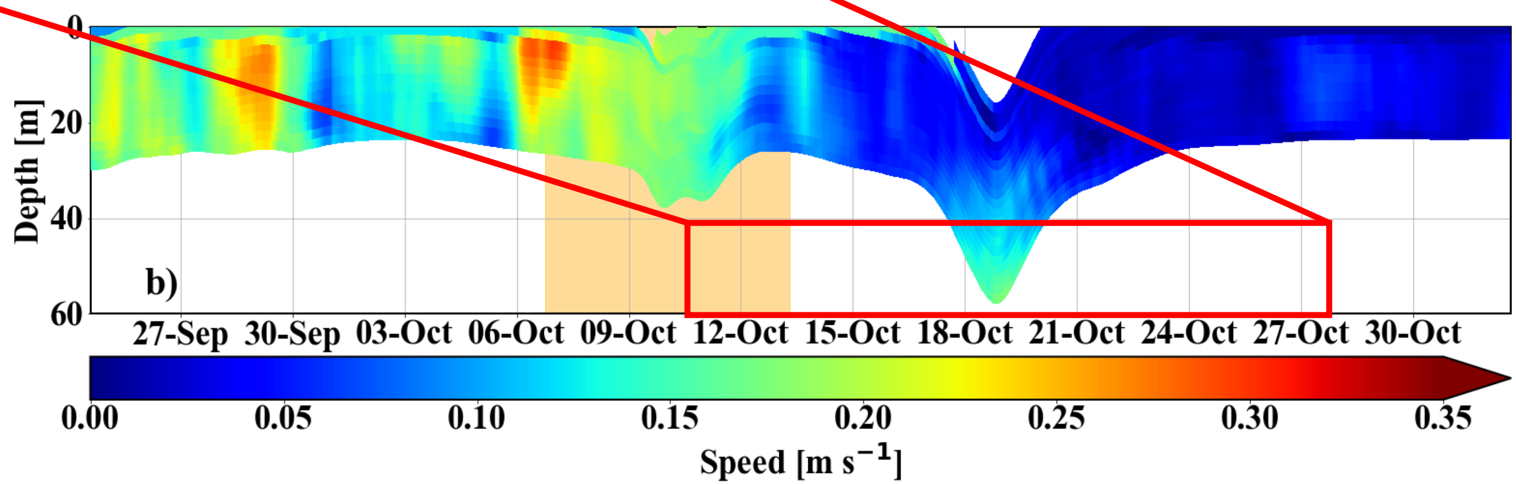






Data from BGEP (WHOI); Cassianides, Lique & Korosov 2021

Eddy signature in sea ice motion

- We observe an eddy passing by a mooring in the Canadian Basin in Oct. 2017

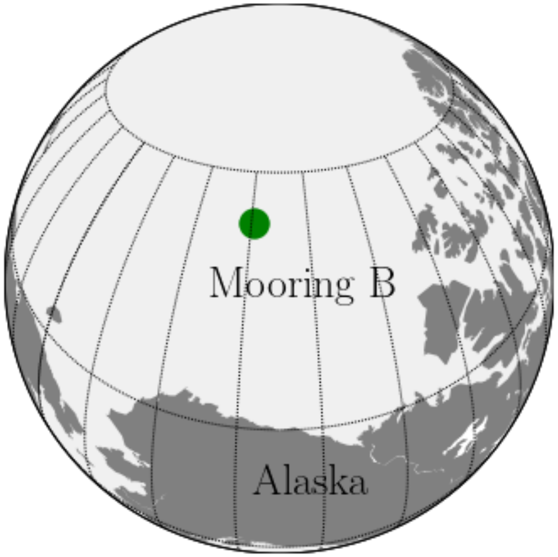
Eddy properties:

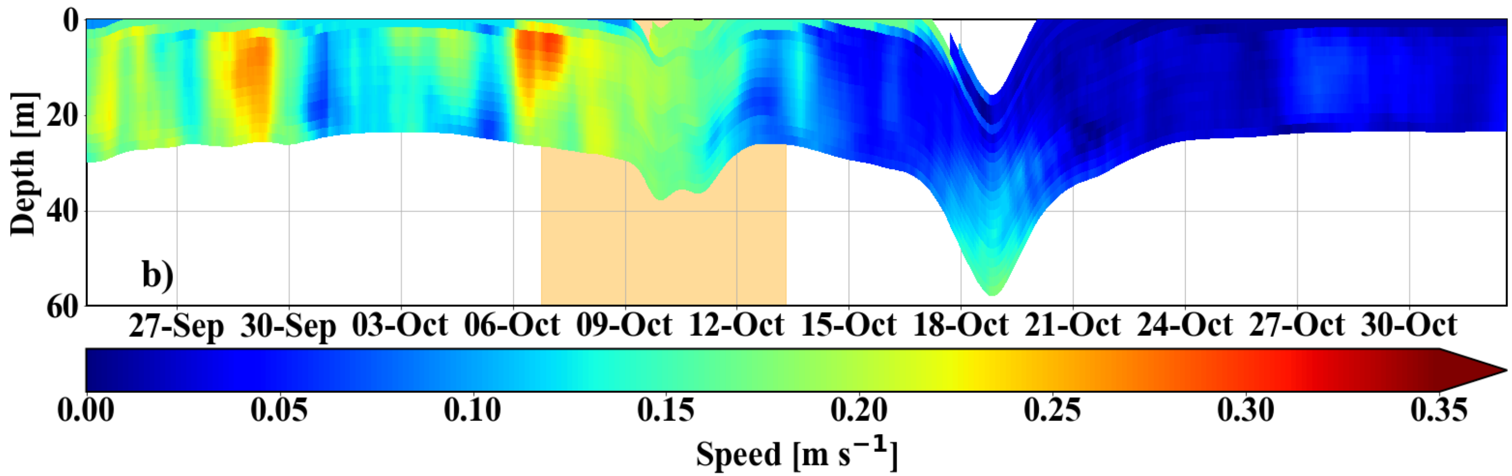
- dipole (anticyclone on top, cyclone below),

- horizontal scale of 80–100 km (for Rd ~ 10km)

- persisted over a week,

- vorticity of ~10^{-5} s^{-1}

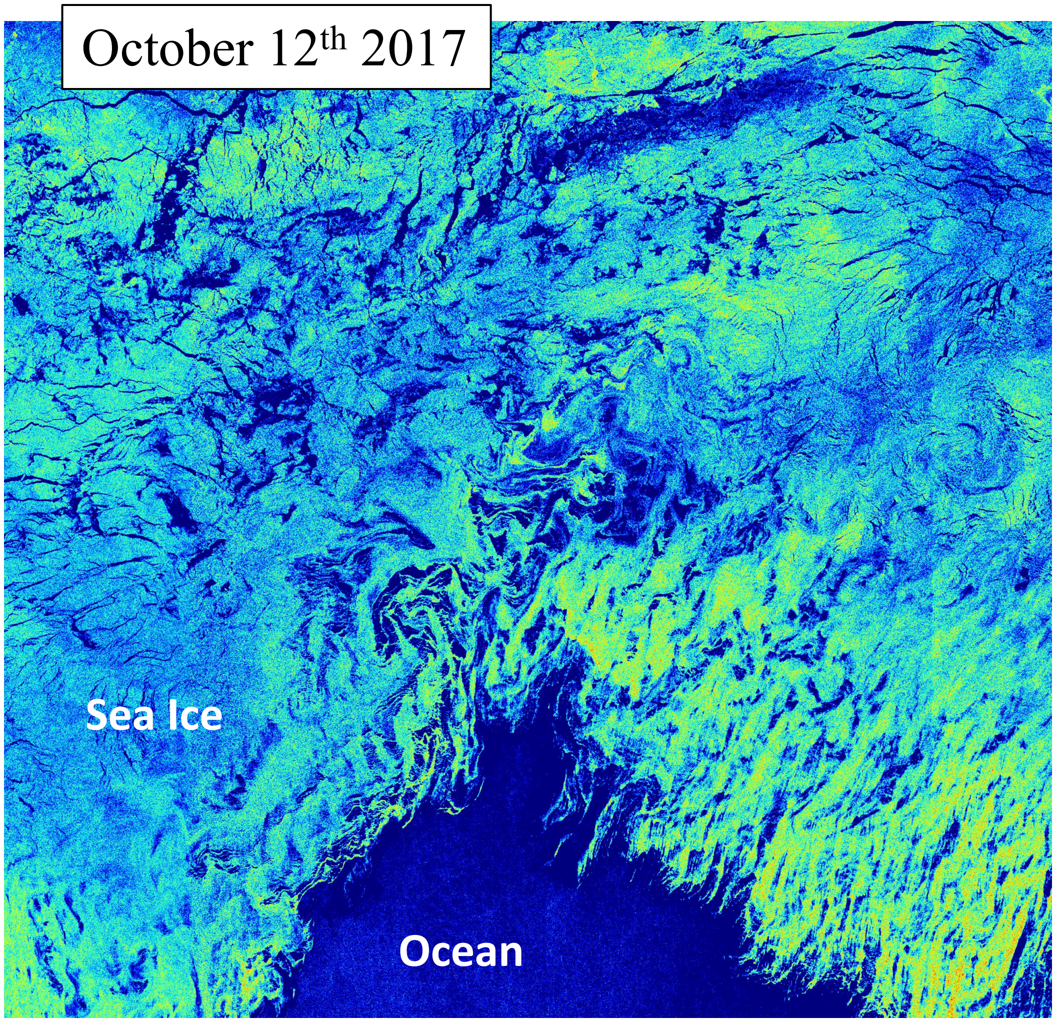


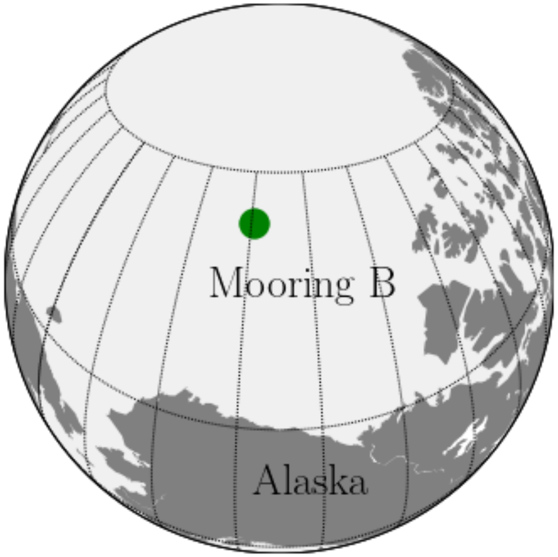


Data from BGEP (WHOI); Cassianides, Lique & Korosov 2021

Eddy signature in sea ice motion

- We observe an eddy passing by a mooring in the Canadian Basin in Oct. 2017
- Its signature in sea ice is not visible at first sight in SAR images



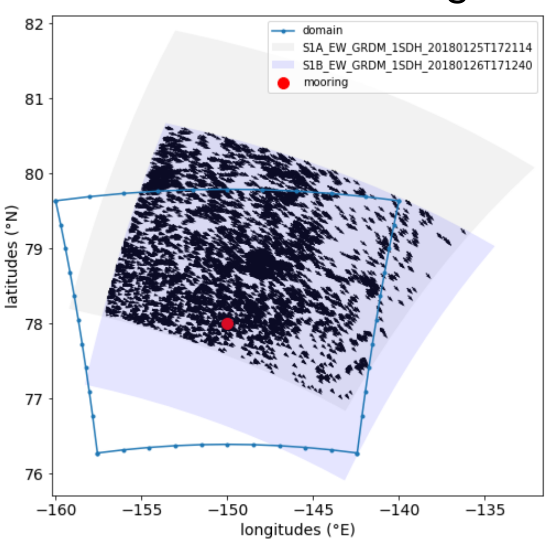


Data from SAR Sentinel 1A/1B; Cassianides, Lique & Korosov 2021

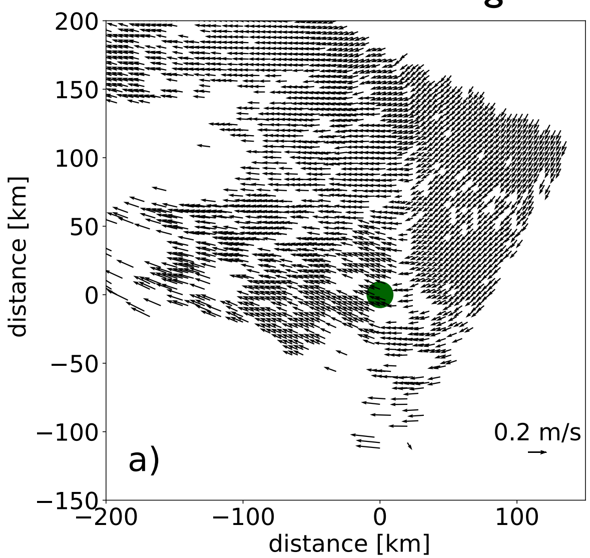
Eddy signature in sea ice motion

- We reconstruct the sea ice drift by using the correlation between successive SAR images
- We estimate sea ice vorticity: $$\zeta_{ice} = \frac{\partial v_{ice}}{\partial x} - \frac{\partial u_{ice}}{\partial y}$$

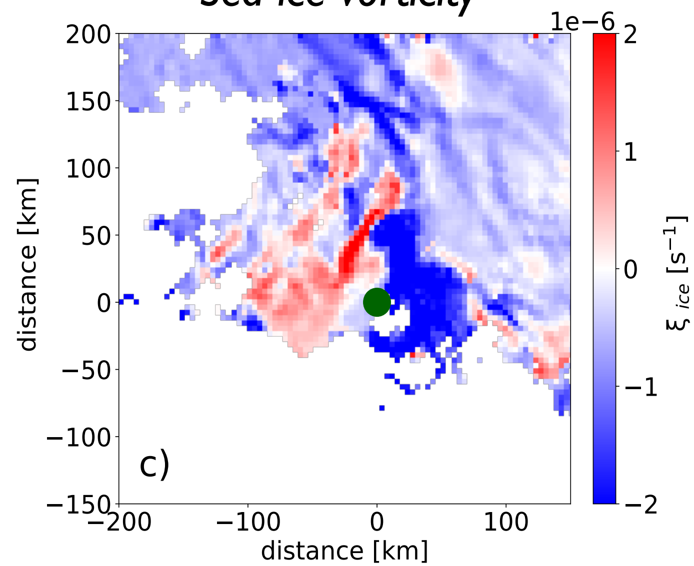
Feature Tracking



Pattern Matching



Sea ice vorticity



Time average: Oct. 7-13 2017

Data from SAR Sentinel 1A/1B; Method: Korosov & Rampal 2017; Cassianides, Lique & Korosov 2021

Eddy signature in sea ice motion

- We reconstruct the sea ice drift by using the correlation between successive SAR images

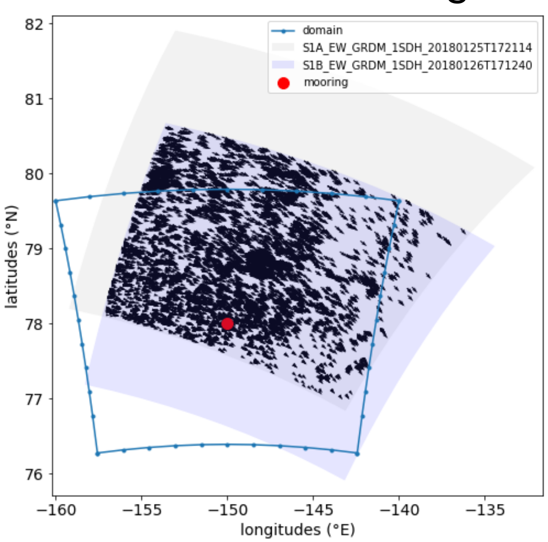
Eddy properties: dipole, horizontal scale of 80–100 km, persisted over a week, vorticity of ~10^{-5} s^{-1}

Anomaly in sea ice vorticity: ~10^{-6} s^{-1}, horizontal scale of 100 – 200 km, persisted over a week

As a comparison, the characteristics of Arctic cyclone:

size ~ 200-1000km, persistance ~1-2 day,

Feature Tracking



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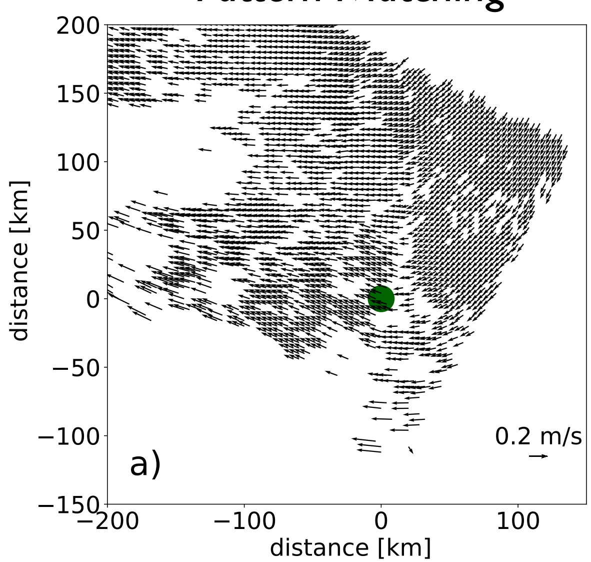
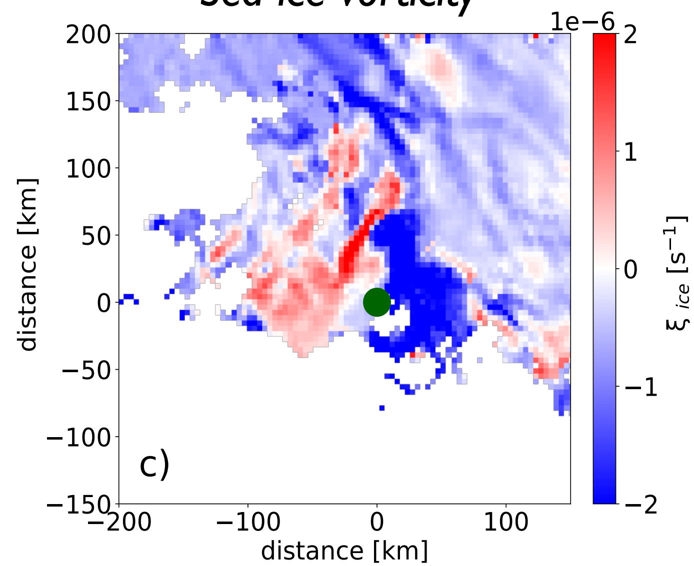


Sea ice vorticity



Time average: Oct. 7-13 2017

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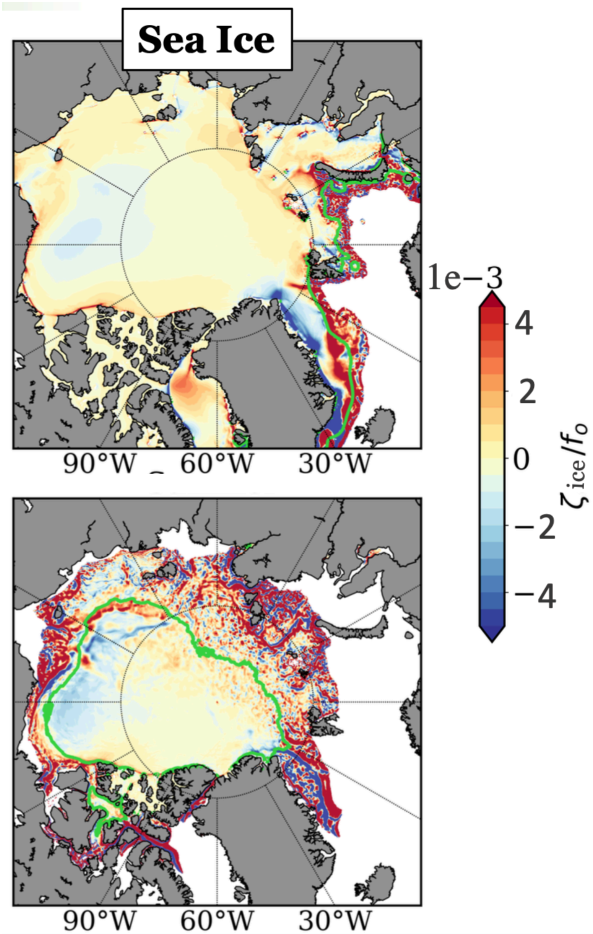
Eddy signature in sea ice motion at the basin scale

- Does it matter at the pan-Arctic scale?
- We look at the mean (1995-2015) sea ice vorticity in summer and winter, simulated by a high resolution ocean-sea ice model

WINTER

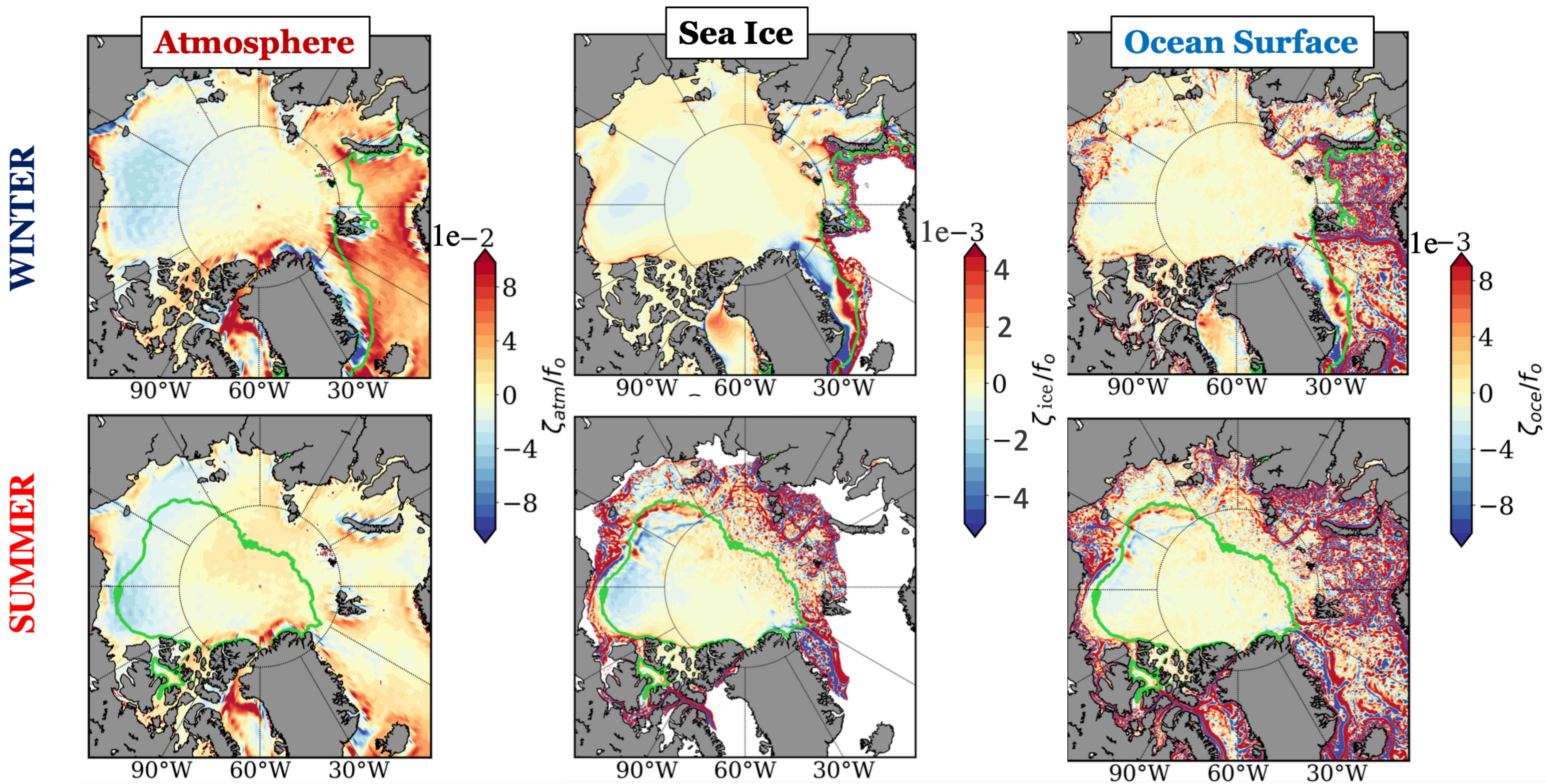
SUMMER



Data from CREG12 simulation @3-4km resolution; PhD thesis of A. Cassianides 2023

Eddy signature in sea ice motion at the basin scale

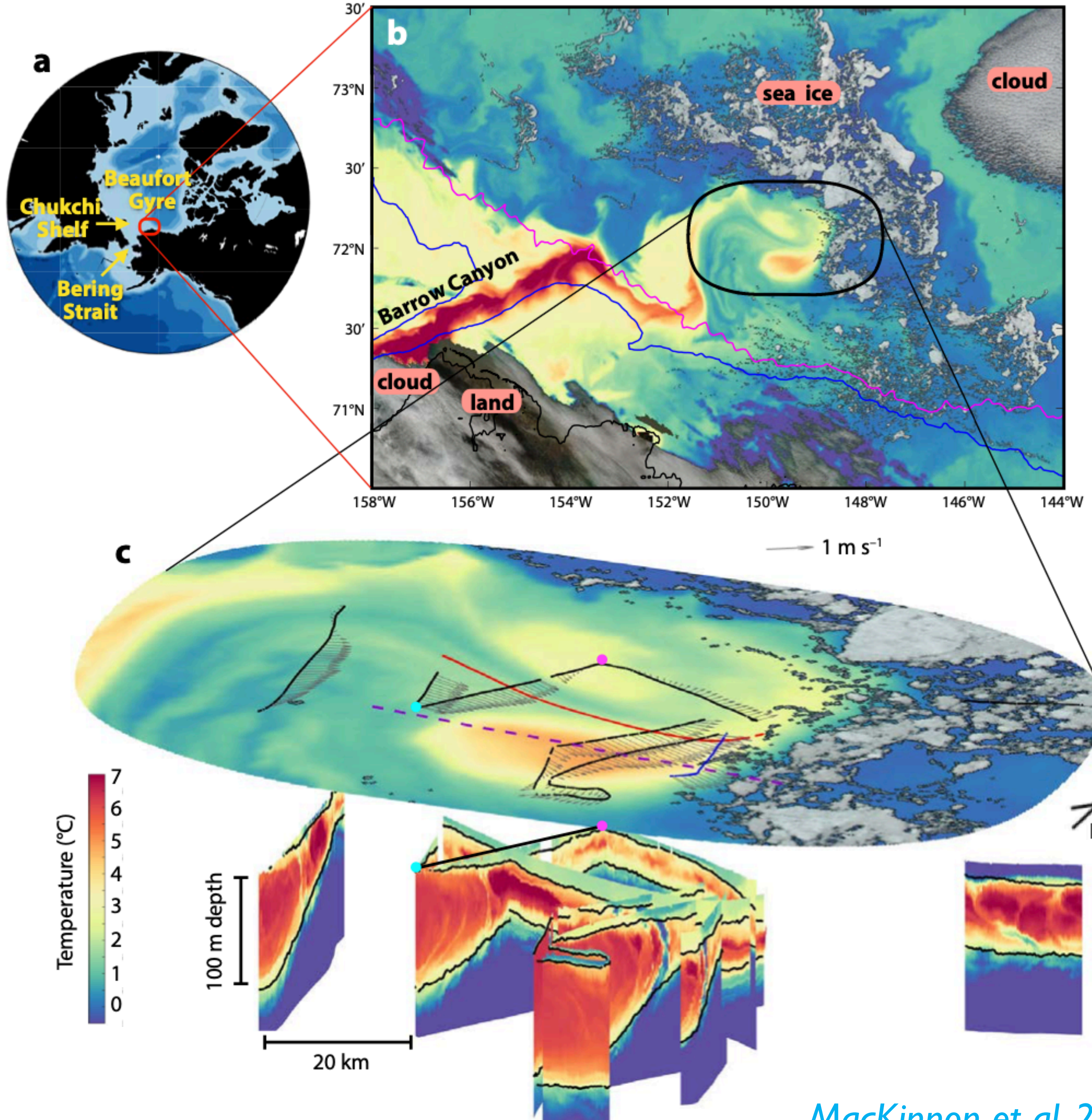
- At the pan-Arctic scale, sea ice vorticity carries the signature of both the atmoshere and the ocean (*specially in summer, when concentration are below 80% and the rheology gets negligible*)
- In return, under concentrated sea ice, eddies get dissipted by sea ice induced friction!



Data from CREG12 simulation @3-4km resolution; PhD thesis of A. Cassianides 2023

Eddy and sea ice melting and freezing

- Observations and idealized models have suggested that heat flux within eddies can enhance sea ice melt

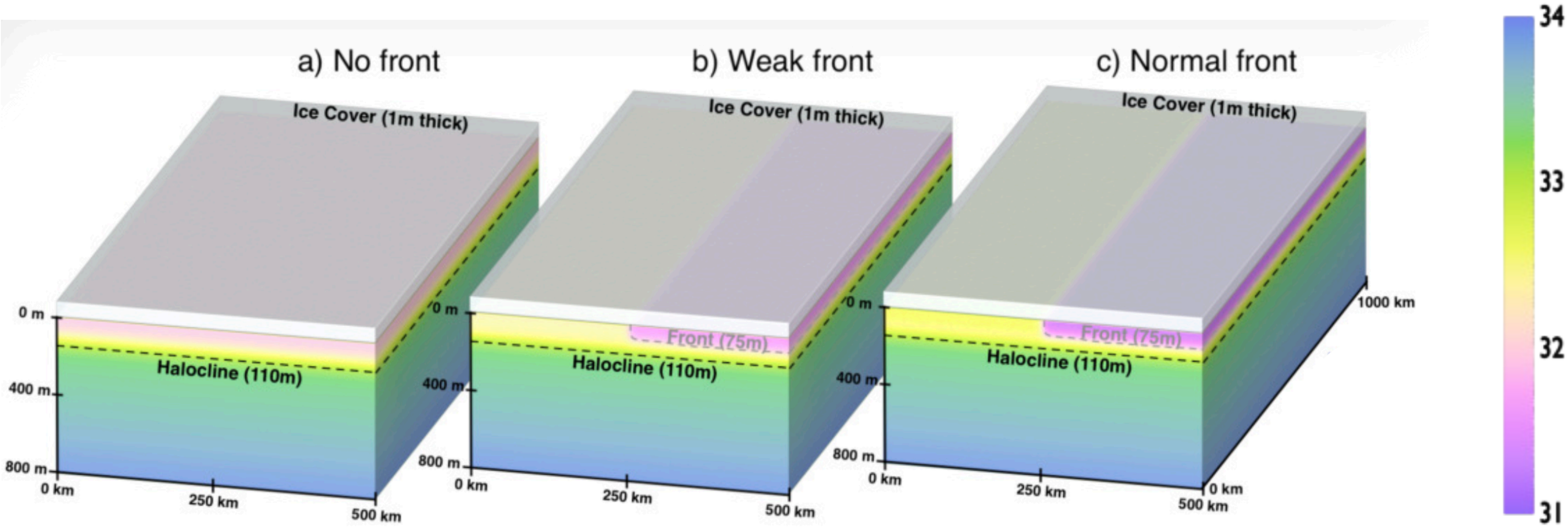


MacKinnon et al. 2021, Fine et al. 2021

Eddy and sea ice melting and freezing

- What about sea ice formation?
  - *We consider a 'shoe box' at high resolution representative of the marginal ice zone (with or without a front), forced with a mean seasonal cycle of the air temperature (no wind and a very small sea ice drift)*
  - *We focus on the sea ice formation stage*

Salinity - Initial conditions

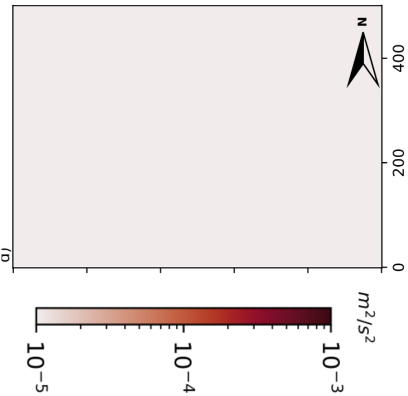


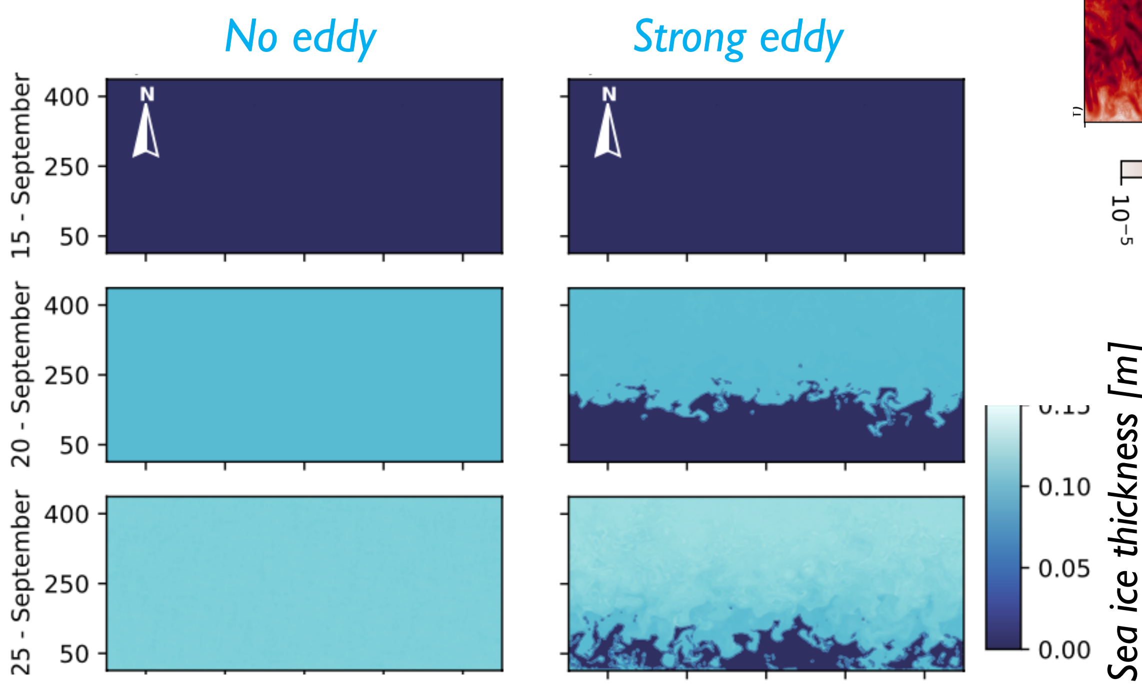
Martinez-Moreno et al. 2025

Eddy and sea ice melting and freezing

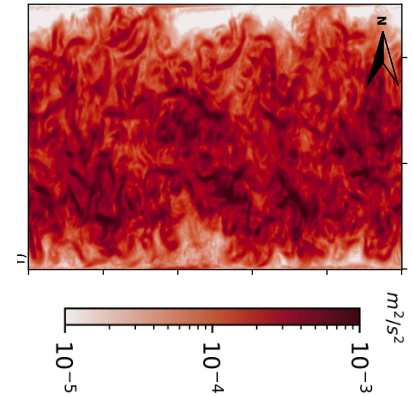
- What about sea ice formation?

Surface KE





Surface KE



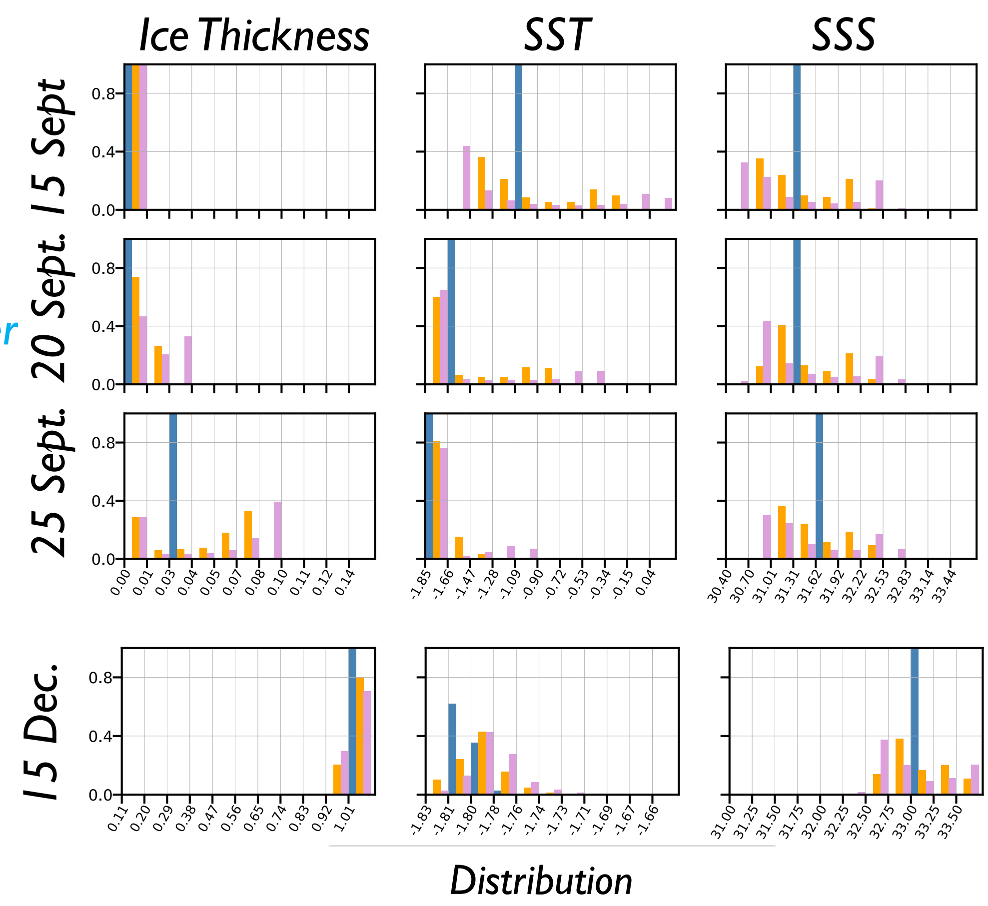
Martinez-Moreno et al. 2025

Eddy and sea ice melting and freezing

- In the presence of eddies, we see herogeneity in sea ice thickness, that lasts for at least a few months

No Sea Ice

Sea ice forms (earlier in the presence of eddies)



No Eddy *Weak Eddy* *Strong Eddy*

Martinez-Moreno et al. 2025

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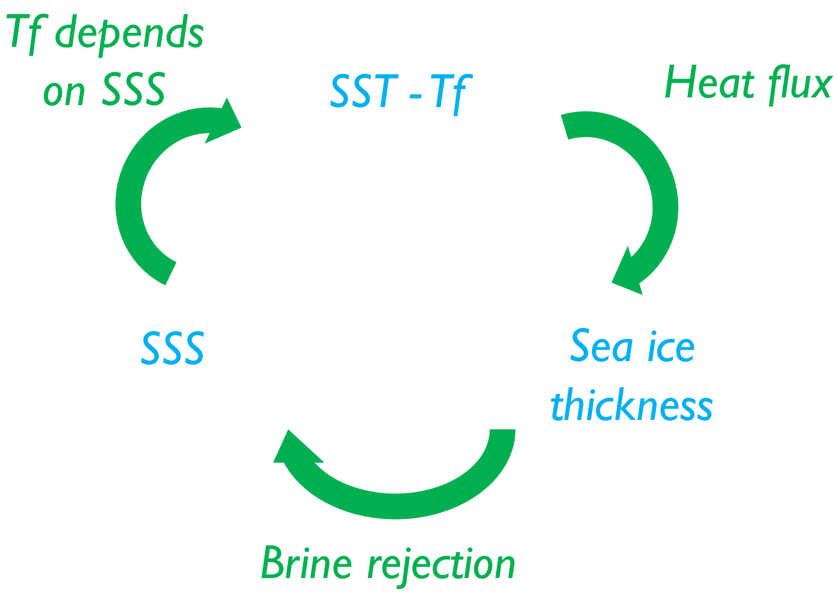
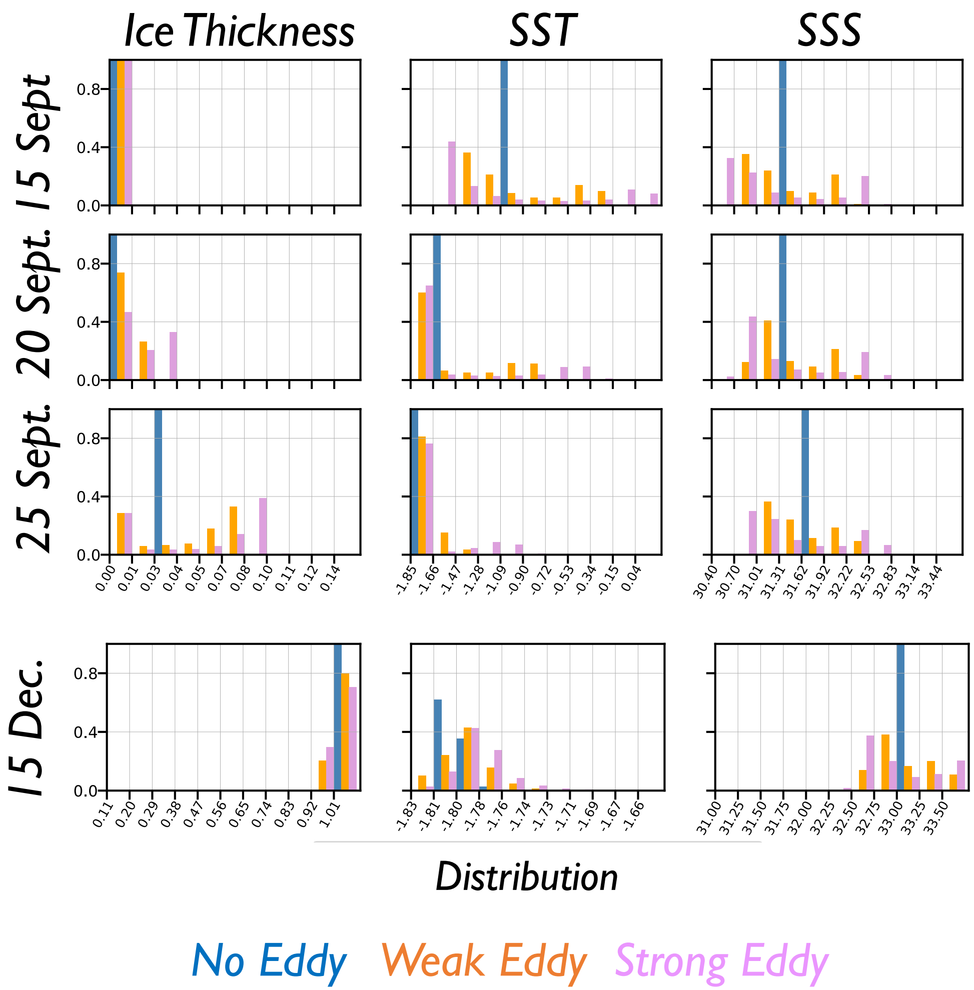
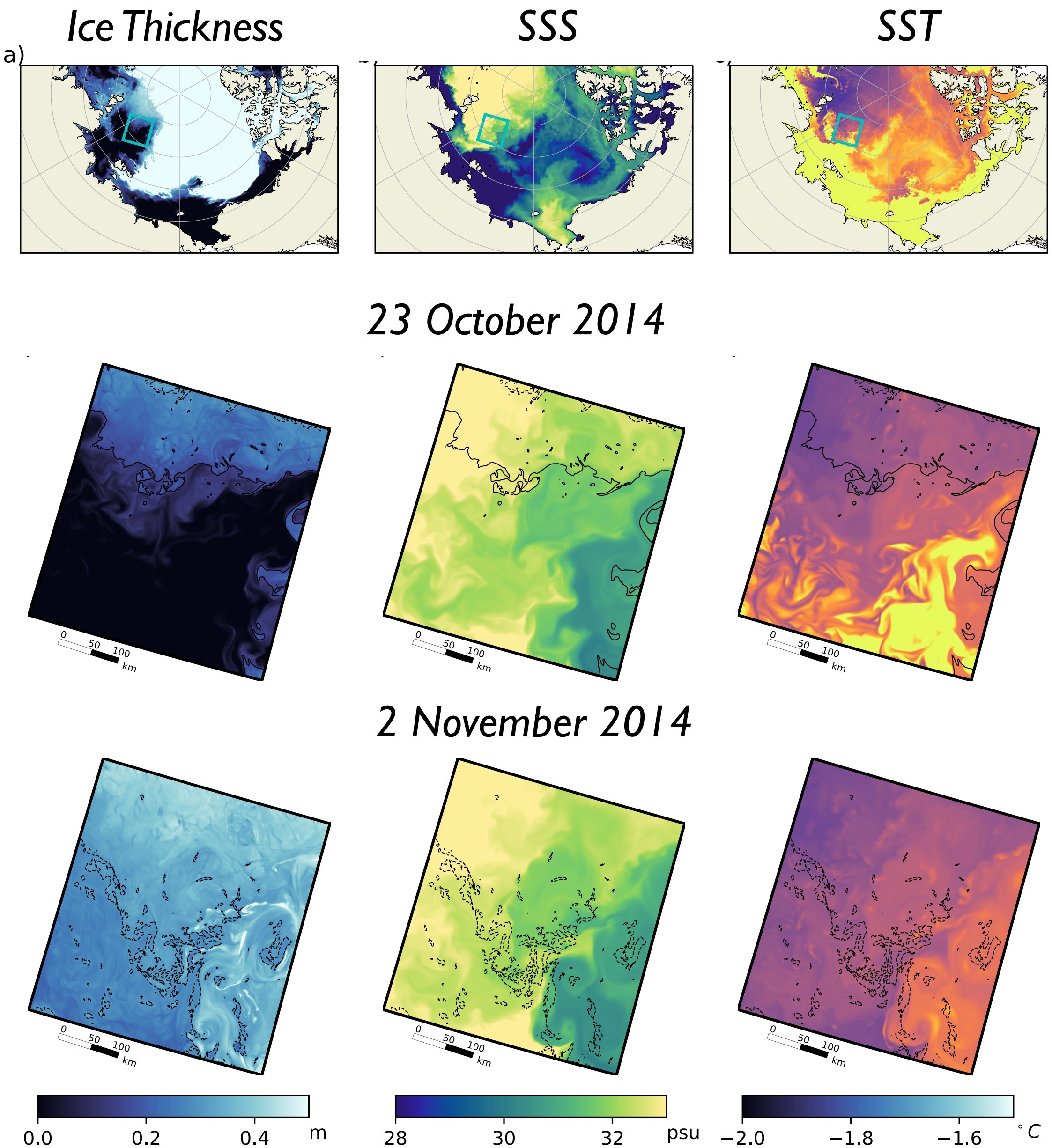




Martinez-Moreno et al. 2025

Eddy and sea ice melting and freezing



- The same mechanism appears to be at play in our realistic simulation at very high resolution
- It could drive some heterogeneity in the sea ice conditions and further affect its evolution (ability to break and deform for instance)

Data from SEDNA @800m, Martinez-Moreno et al. 2025

Mixing and turbulence: processes to consider

In the rest of this talk, I will focus on a few processes, looking also *at their impacts on the larger scales*

(i) Vertical/diapycnal mixing in the global ocean and its impacts on the large scale ocean circulation and climate

In a climate model, the level and spatial distribution of diapycnal mixing strongly affect the ocean circulation, and in particular the intensity of the AMOC

(ii) Eddies in the Arctic and their impact/interactions with sea ice

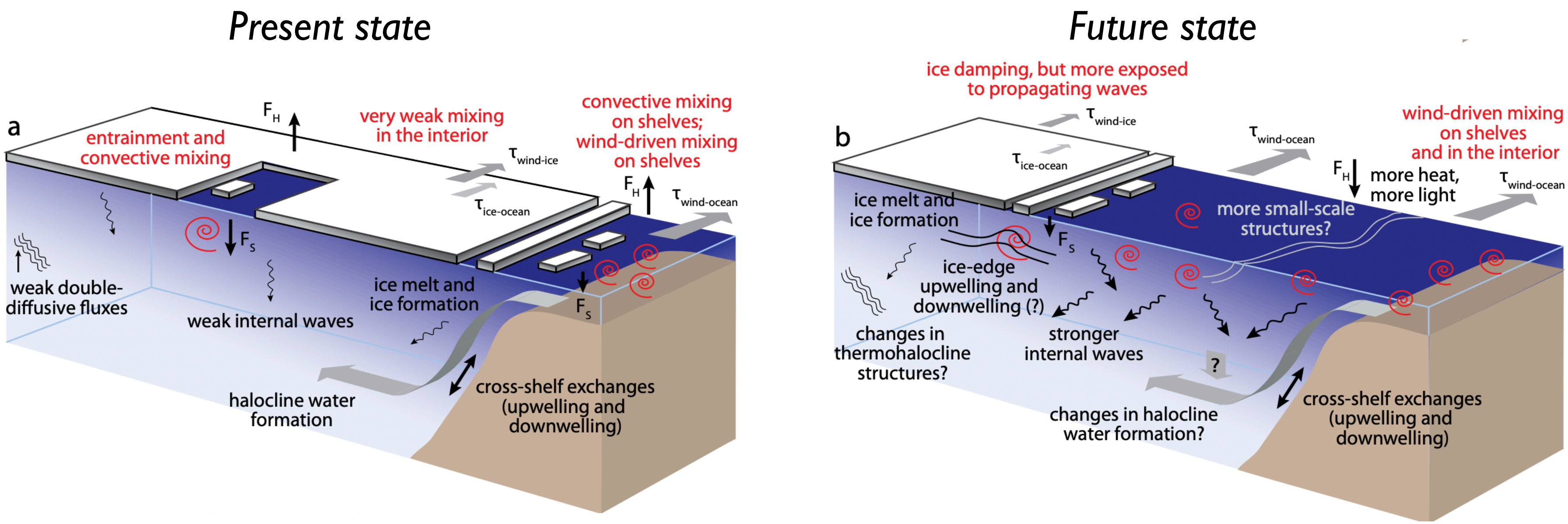
Eddies affect the vorticity of sea ice but gets dissipated by sea ice in return

Eddies can modulate the sea ice melting and formation rate, and seed heterogeneity in sea ice conditions

(iii) Vertical mixing in the Arctic and impact on sea ice (or lack thereof)

Vertical diffusion and heat flux in the Arctic

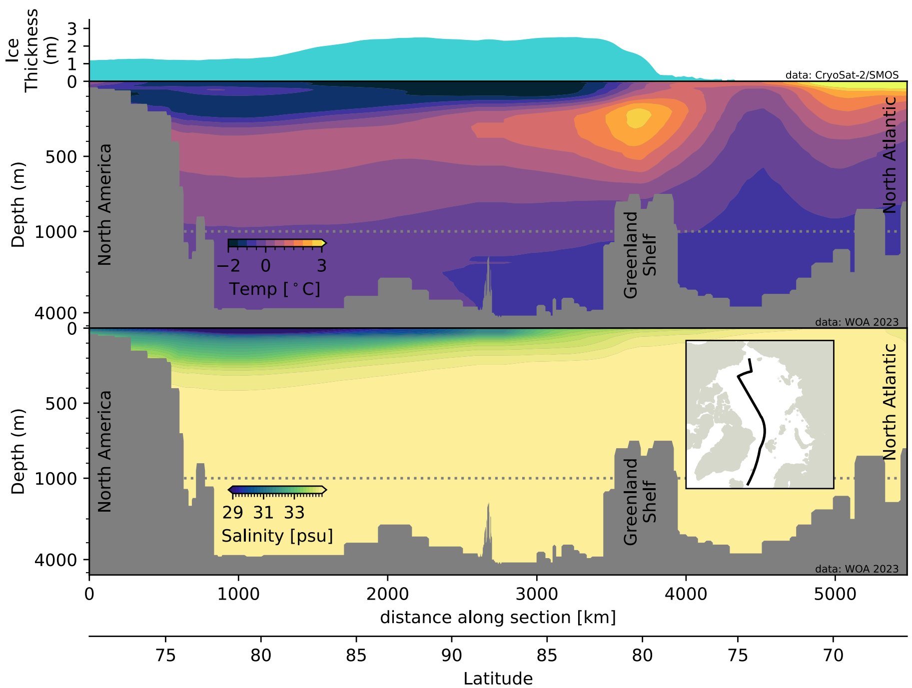
- Hypothesis from the review of Rainville et al 2011:
  We speculate that one of the most profound impacts of climate changes in the Arctic will be the transition from an ocean that is driven locally by thermohaline processes (mainly ice melt and formation) to an ocean that, during the summer, is also strongly wind-driven. Turbulent mixing severely impacts mixing in the upper ocean, on the shelves, at the slope, and in the interior …also **causing oceanic heat to rise**, with implications for ice melt



Rainville et al. 2011

Vertical diffusion and heat flux in the Arctic

- Hypothesis from the review of Rainville et al 2011: More turbulent mixing in the future
- The Arctic current state has two important characteristics
  - > very low diffusivity in the interior
  - > a warm layer storing heat at depth under a strongly stratified halocline



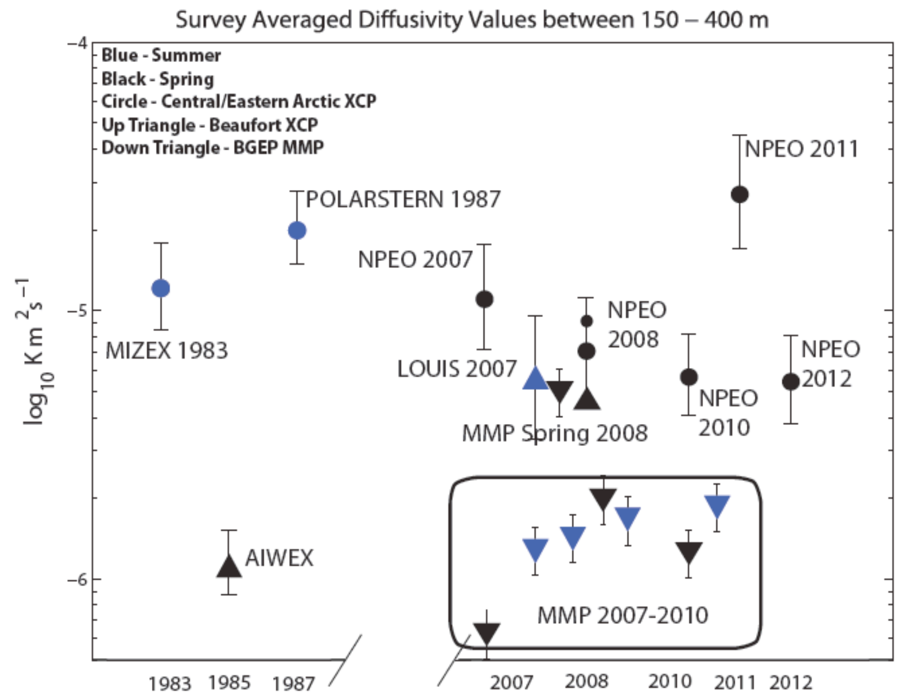
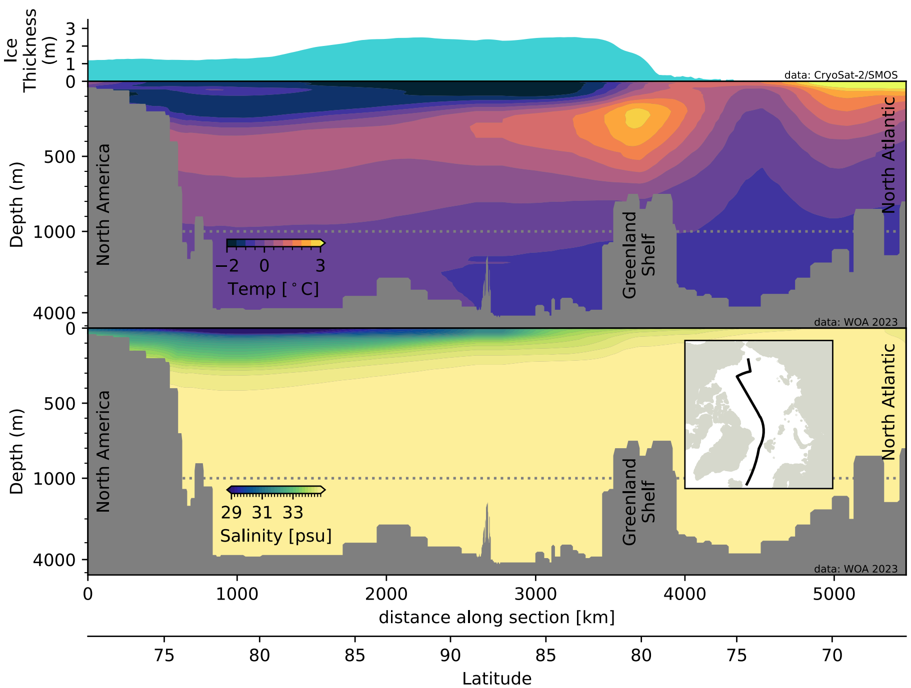
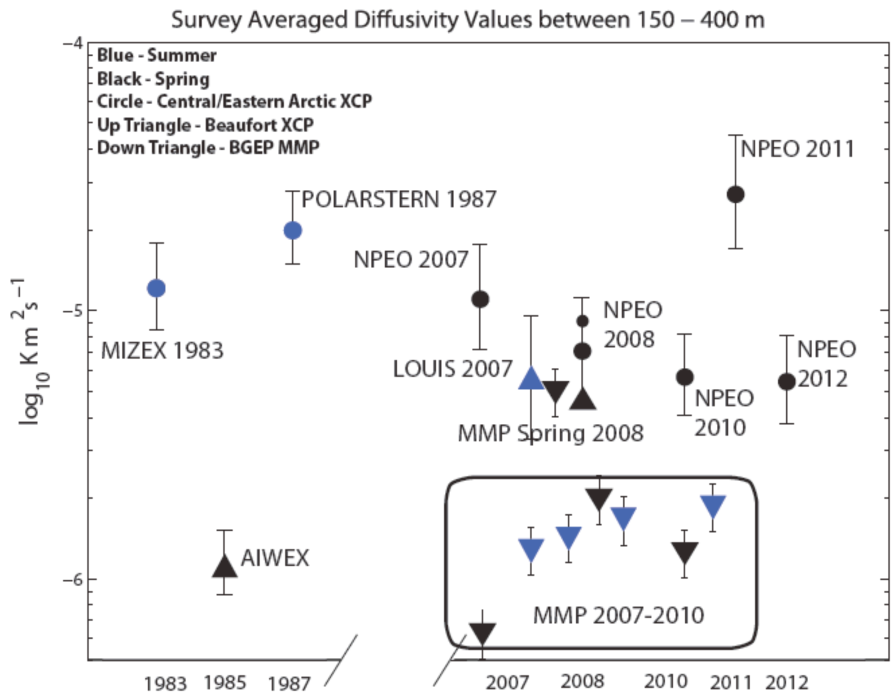


Fig. courtesy of G. Meneghello (WOA climatology); Guthrie et al. 2013

Vertical diffusion and heat flux in the Arctic

- Hypothesis from the review of Rainville et al 2011: More turbulent mixing in the future
- The Arctic current state has two important characteristics
  > very low diffusivity in the interior
  > a warm layer storing heat at depth under a strongly stratified halocline
- Could it matter for sea ice?





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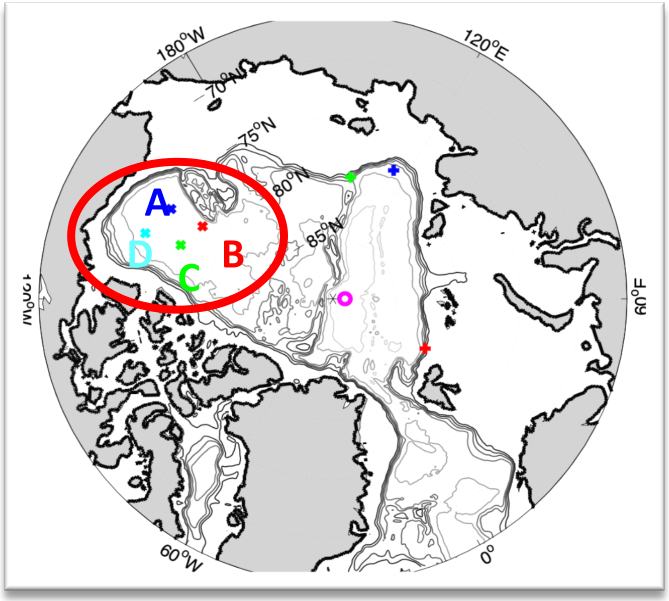
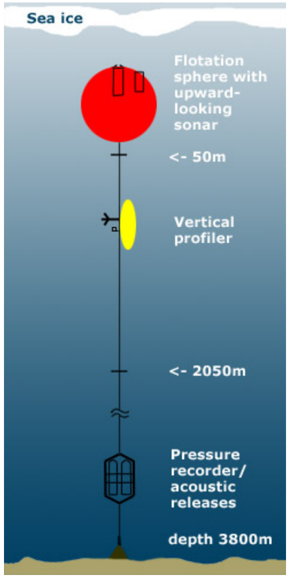
Vertical diffusion and heat flux in the Arctic

- Vertical heat flux estimated from mooring observations





- 4 moorings observing T, S, U,V twice daily since 2003
- Estimate vertical heat flux

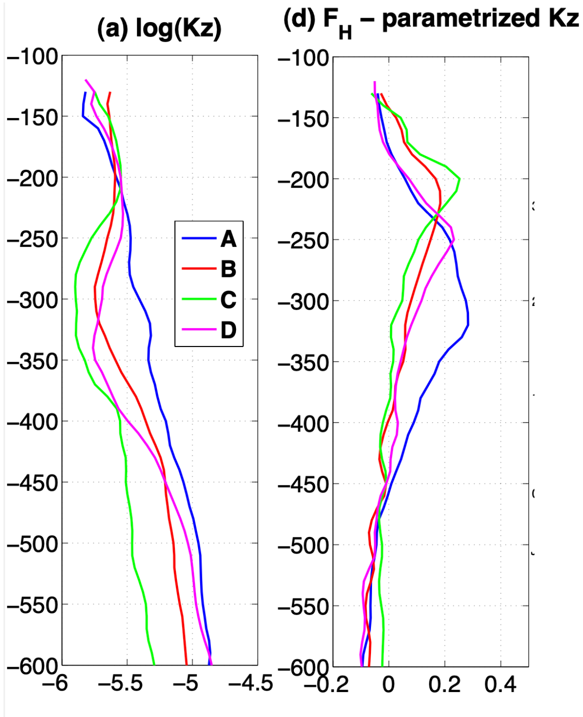
$$F_H = \rho_0 C_p Kz \frac{\partial T}{\partial z}$$

- Kz estimated from fine scale parameterization, considering shear and strain!

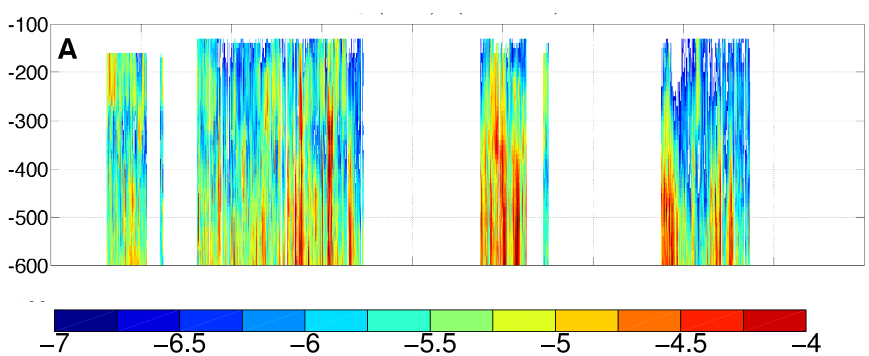
Lique et al. 2014

Vertical diffusion and heat flux in the Arctic

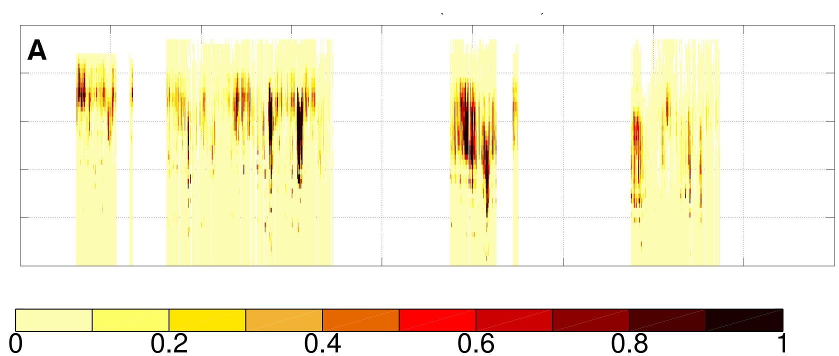
- Vertical heat flux estimated from mooring observations



- despite a warming over the period…
- Kz and F_H are super small !
  - Kz ~ 10-6 – 10-5 m2/s;
  - F_H ~ 0.1 – 0.3 W/m2
- except when eddies are passing by…



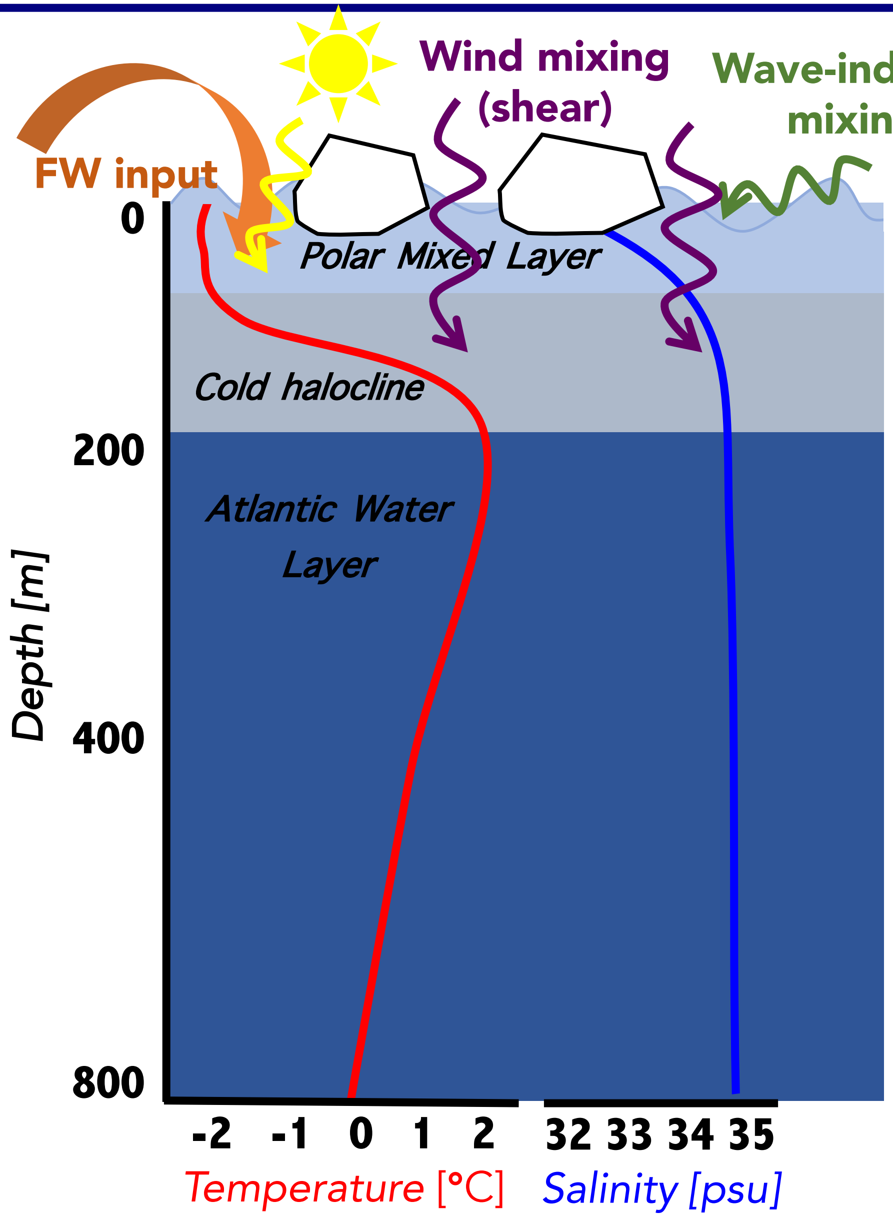
log(Kz) in m^2/s



Heat Flux in W/m^2.

Lique et al. 2014

Vertical diffusion and heat flux in the Arctic



In the future, as the ice cover reduces:

Competing effects to consider to understand the influence of the ocean on sea ice:

> wind-induced mixing increase
> surface wave processes emerge
> warming at the surface

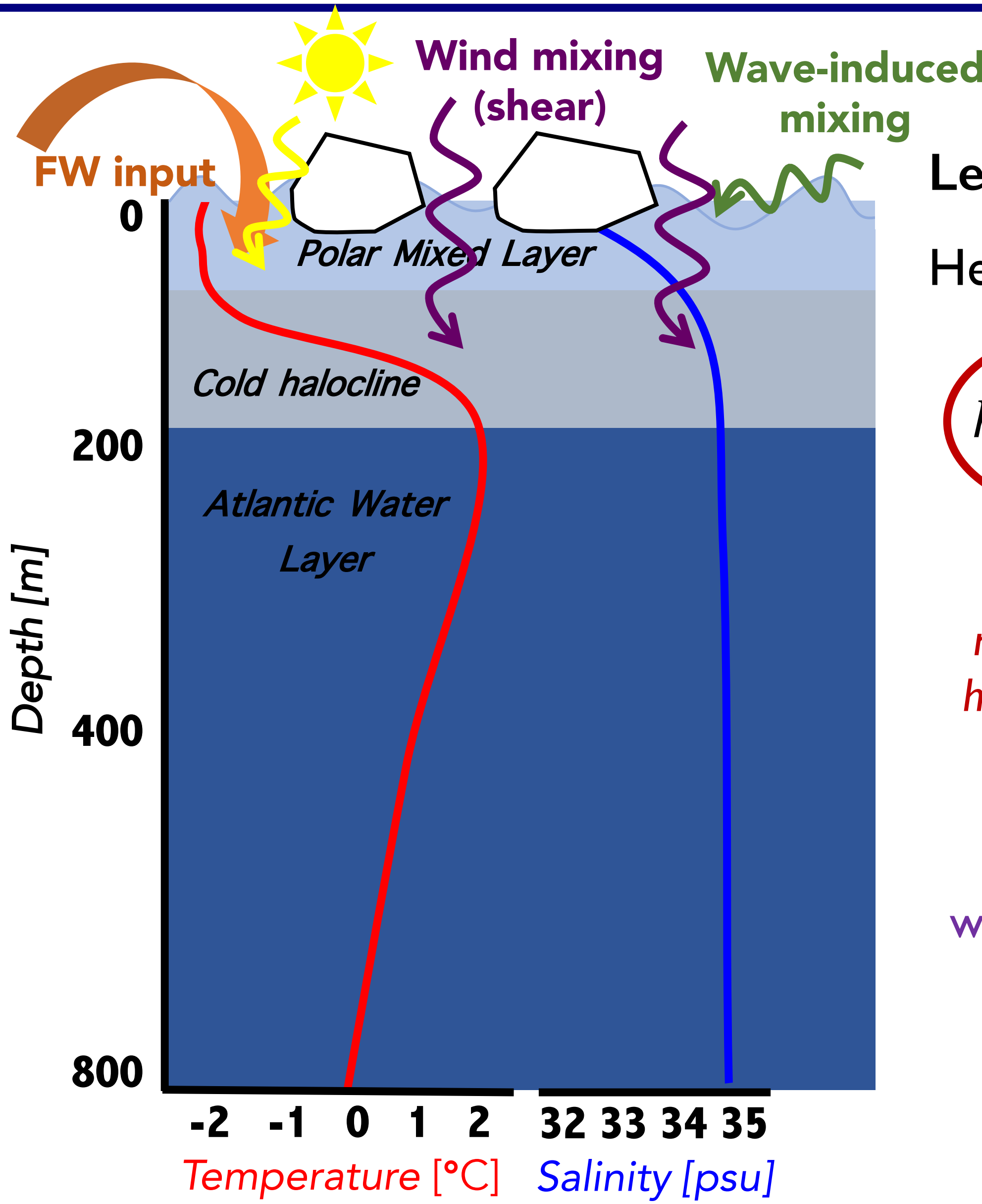
Stratification decreases

> More FW input from Precip, runoff, advection, sea ice melt (?)
> warming of the subsurface

Stratification increases

Davis et al. 2014

Vertical diffusion and heat flux in the Arctic



Let's put it into equations:

Heat budget for the mixed layer (ML):

$$h_{ML}\left\langle \frac{\partial T_{ML}}{\partial t} \right\rangle = K_z \frac{\partial T}{\partial z}_{(z=-h_{ML})} + adv$$

Change of mixed layer heat content

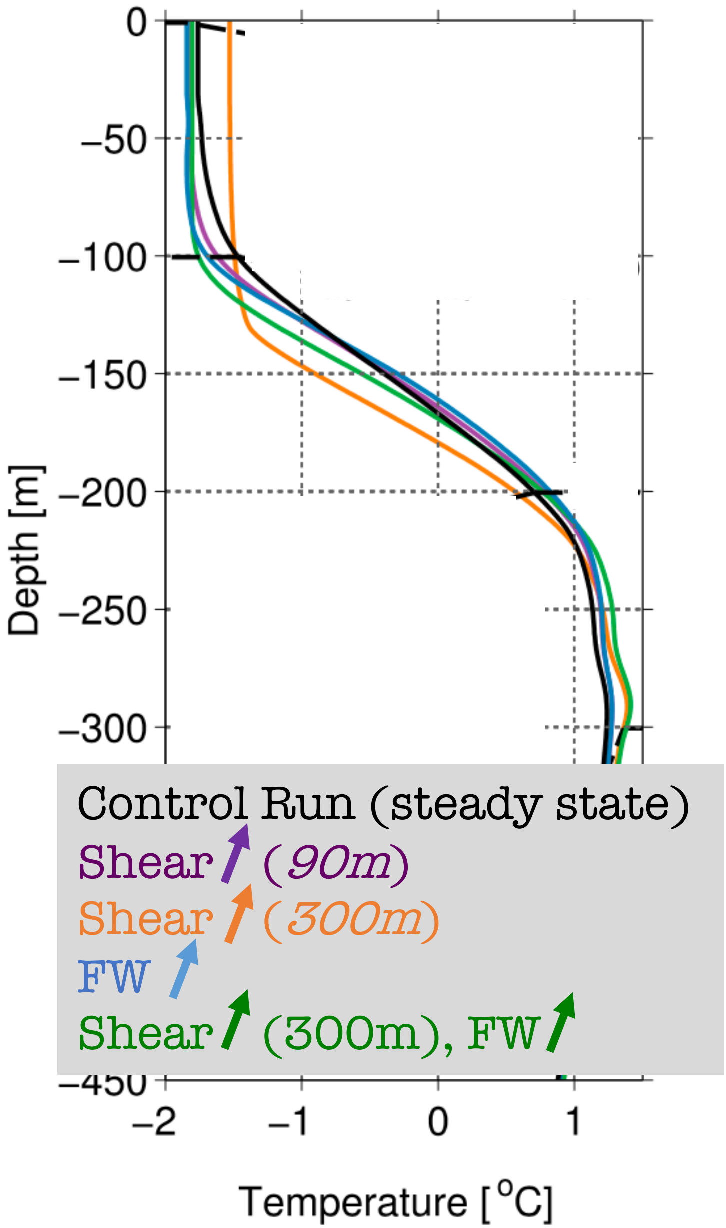
Vertical heat flux at the based of the mixed layer

Advection of heat

with $Kz \propto 1/Ri$ and $Ri = \frac{\text{stratification}}{\text{shear}}$

Davis et al. 2014

Vertical diffusion and heat flux in the Arctic



Let's put it into equations:

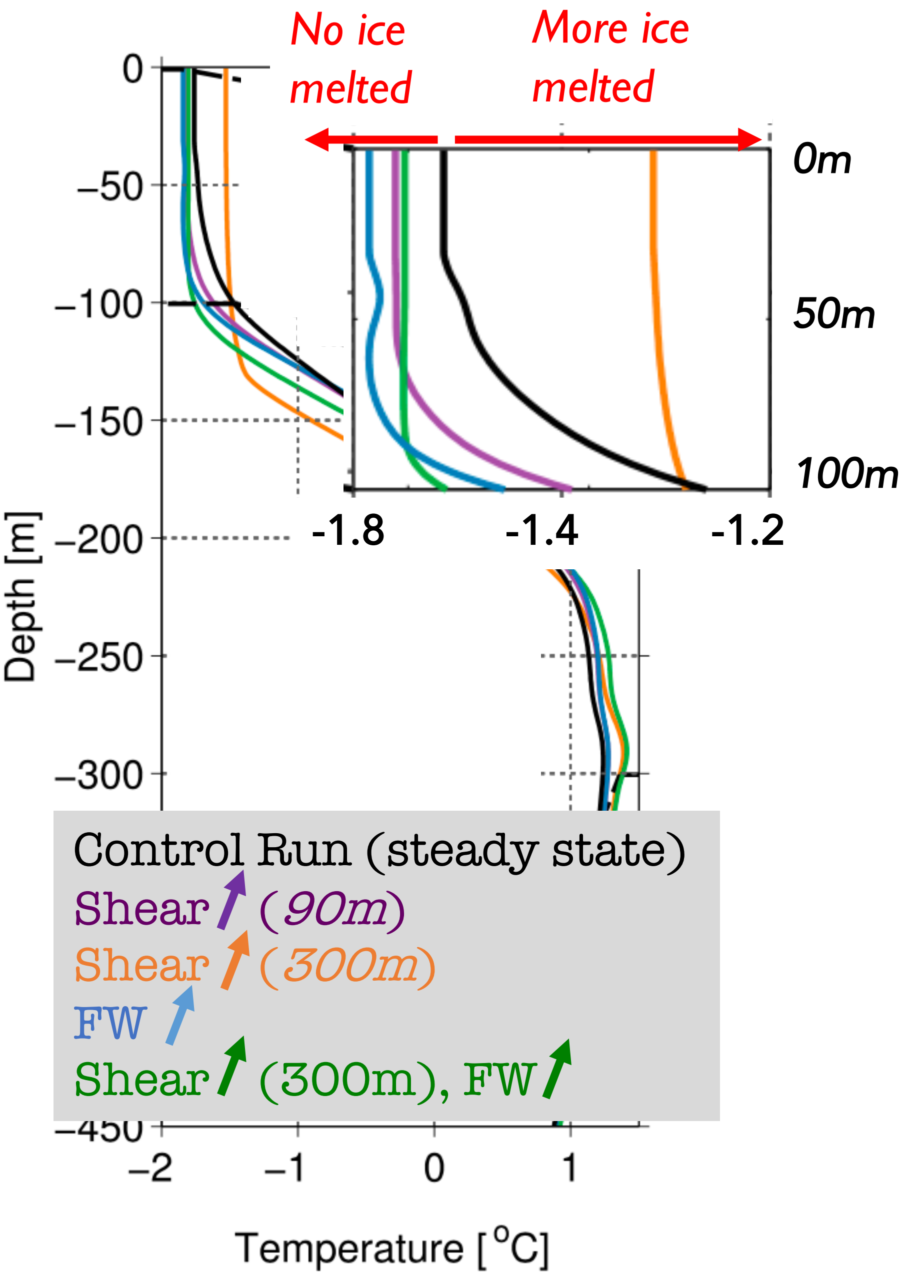
Heat budget for the mixed layer (ML):

$$h_{ML}\left\langle\frac{\partial T_{ML}}{\partial t}\right\rangle = K_z \frac{\partial T}{\partial z}_{(z=-h_{ML})} - adv$$

- *We explore the sensitivity to changes in shear during summer and FW input*
- *After 40 years, changes in FW input dominate and stratif. tends to increase (decreasing Kz!!)*

Results from GOTM 1D model; Davis et al. 2014

Vertical diffusion and heat flux in the Arctic



Let's put it into equations:

Heat budget for the mixed layer (ML):

$$h_{ML}\left\langle\frac{\partial T_{ML}}{\partial t}\right\rangle = K_z \frac{\partial T}{\partial z}_{(z\,=\,-h_{ML})} - adv$$

- *We explore the sensitivity to changes in shear during summer and FW input*
- *After 40 years, changes in FW input dominate and stratif. tends to increase (decreasing Kz!!)*
- *…So that sea ice is unaffected.*

Results from GOTM 1D model; Davis et al. 2014

Mixing and turbulence: processes to consider

In the rest of this talk, I will focus on a few processes, looking also *at their impacts on the larger scales*

(i) Vertical/diapycnal mixing in the global ocean and its impacts on the large scale ocean circulation and climate

In a climate model, the level and spatial distribution of diapycnal mixing strongly affect the ocean circulation, and in particular the intensity of the AMOC

(ii) Eddies in the Arctic and their impact/interactions with sea ice

Eddies affect the vorticity of sea ice but gets dissipated by sea ice in return

Eddies can modulate the sea ice melting and formation rate, and seed heterogeneity in sea ice conditions

(iii) Vertical mixing in the Arctic and impact on sea ice (or lack thereof)

There is a competition between changes in stratification and mixing

For now (and likely in the future) heat stored at depth is unlikely to impact sea ice

But there are other processes that need to be considered (eg surface waves)