Modelling the ocean circulation – Status and frontiers

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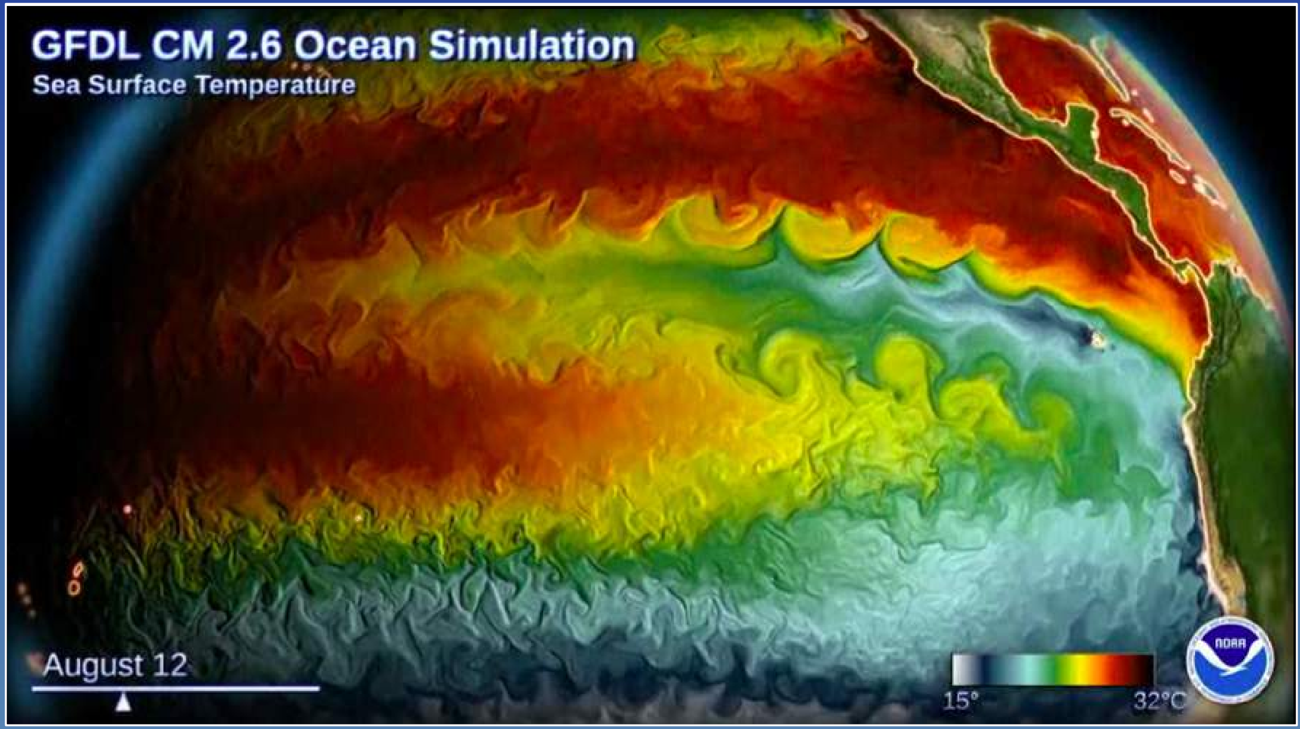
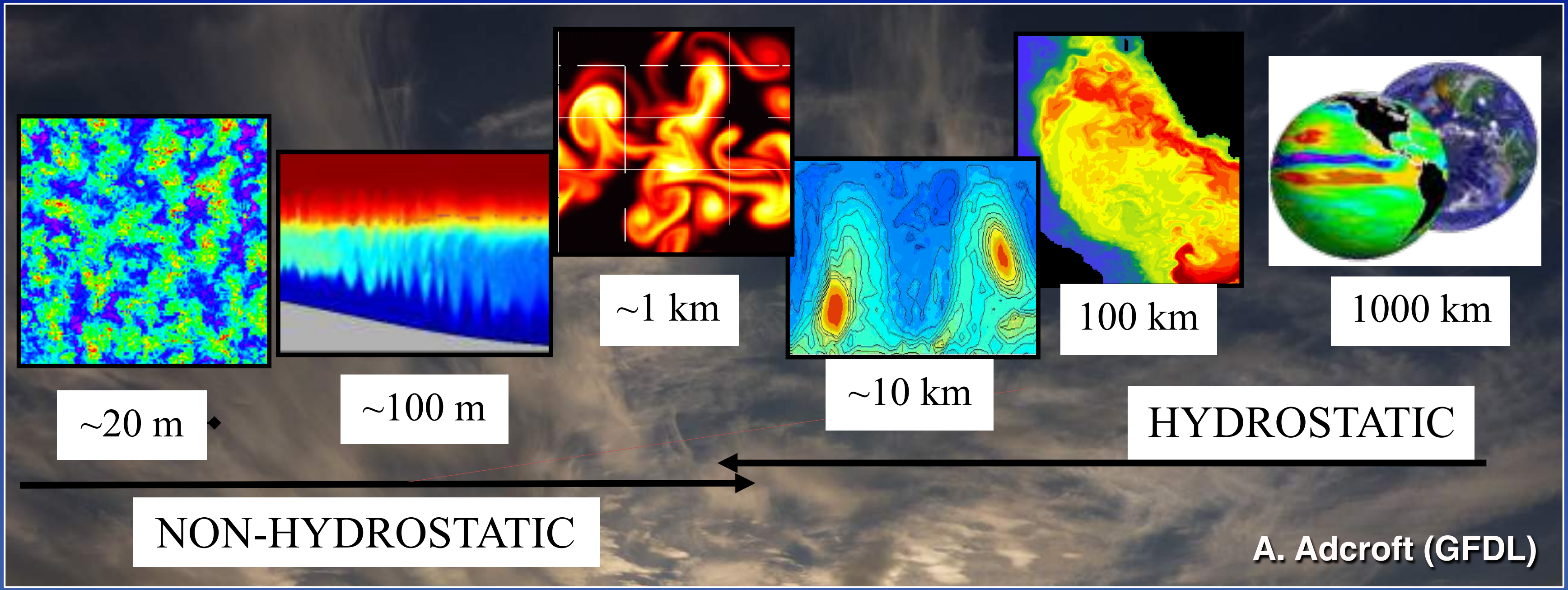
Modelling the ocean circulation – Motivation

Ocean modelling – the use of numerical simulations of the equations of motion as an experimental tool to assess (or predict) the mechanisms controlling how the ocean circulates, and how it interacts with the climate system.



Modelling the ocean circulation – Overarching challenge



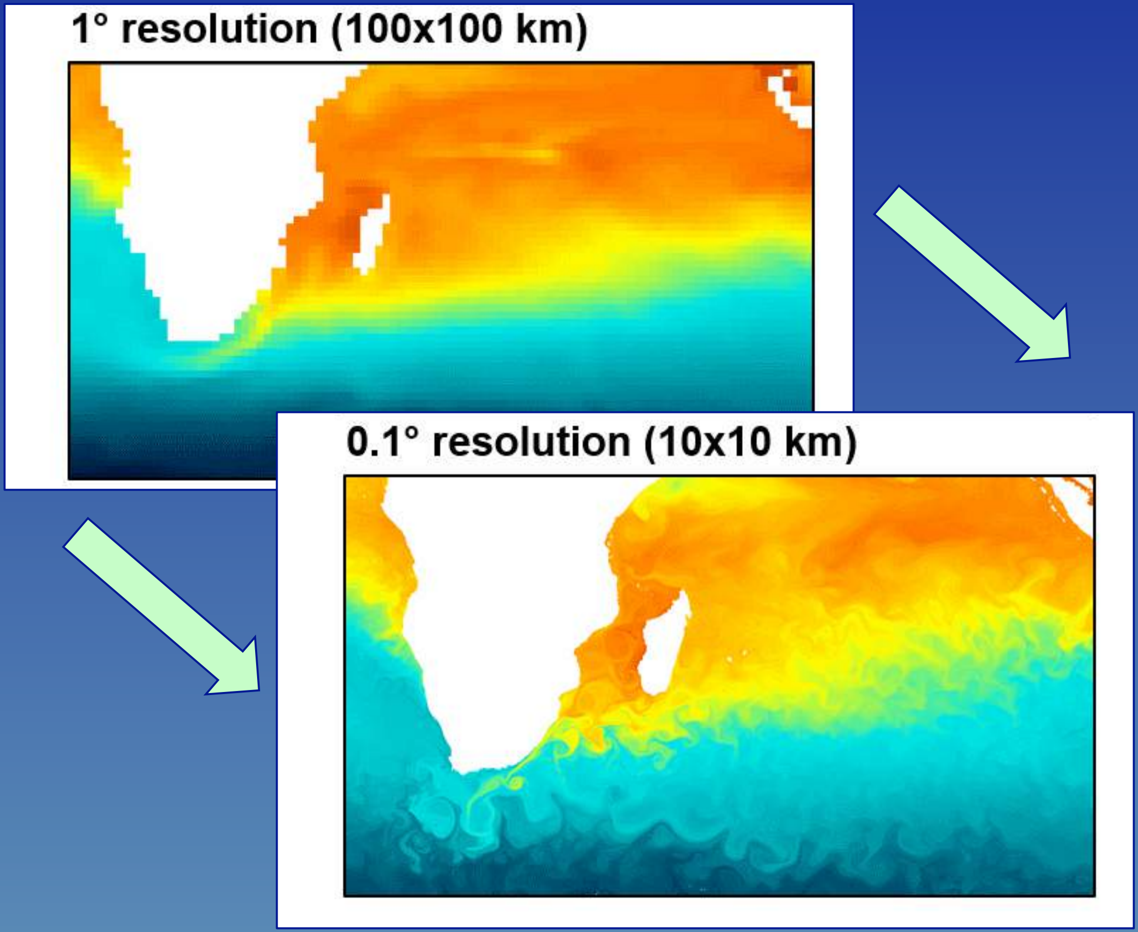
Direct Numerical Simulation (DNS) of global ocean circulation:

1 mm spacing requires ~10^4 times Avogadro's number of grid cells time-stepped with ~1 s for ~1000 years → Very far from practical!

Vast problem requiring rational *parameterisations* – encapsulating understanding of the effects of unresolved flows onto resolved flows.

A (very brief) history of ocean modelling

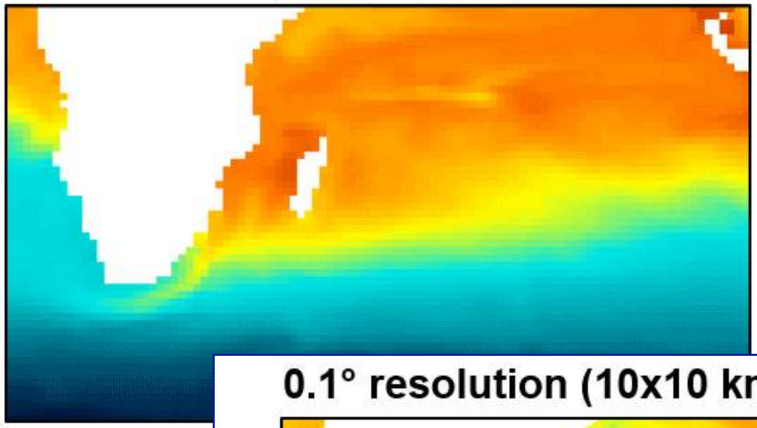
Recent decades of progress in modelling the ocean circulation have focused on: (a) achieving gradual increases in resolution



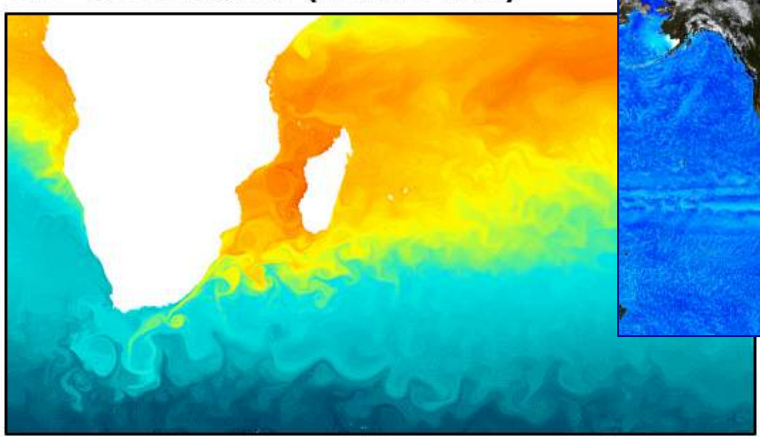
A (very brief) history of ocean modelling

Recent decades of progress in modelling the ocean circulation have focused on: (a) achieving gradual increases in resolution
(b) developing parameterisations of sub-grid-scale processes
– usually evaluated against climatologies.

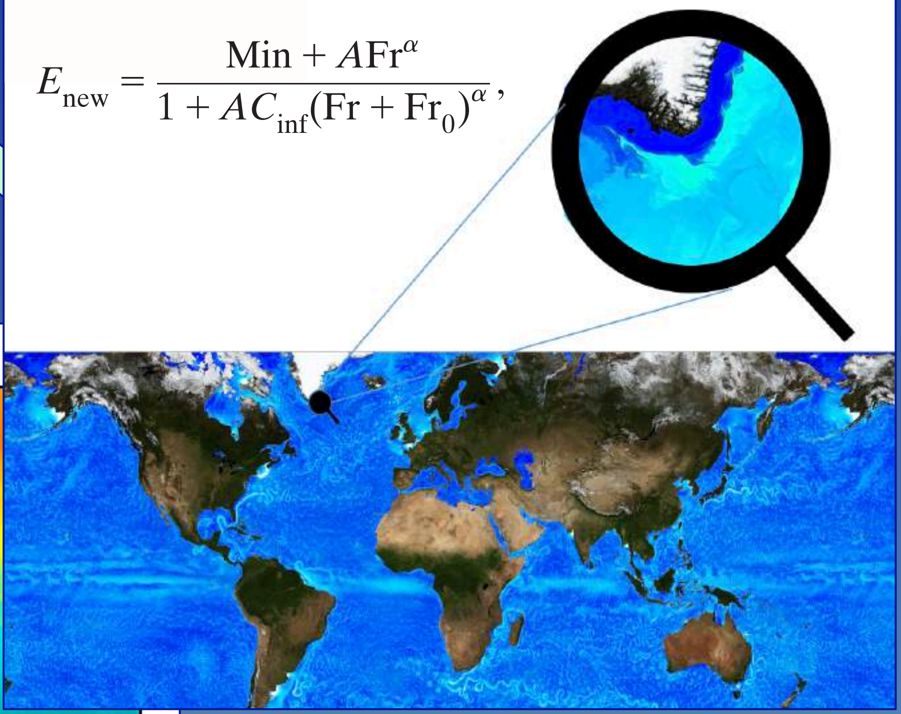
1° resolution (100x100 km)



0.1° resolution (10x10 km)



$$E_{\text{new}} = \frac{\text{Min} + A\text{Fr}^{\alpha}}{1 + AC_{\text{inf}}(\text{Fr} + \text{Fr}_0)^{\alpha}},$$



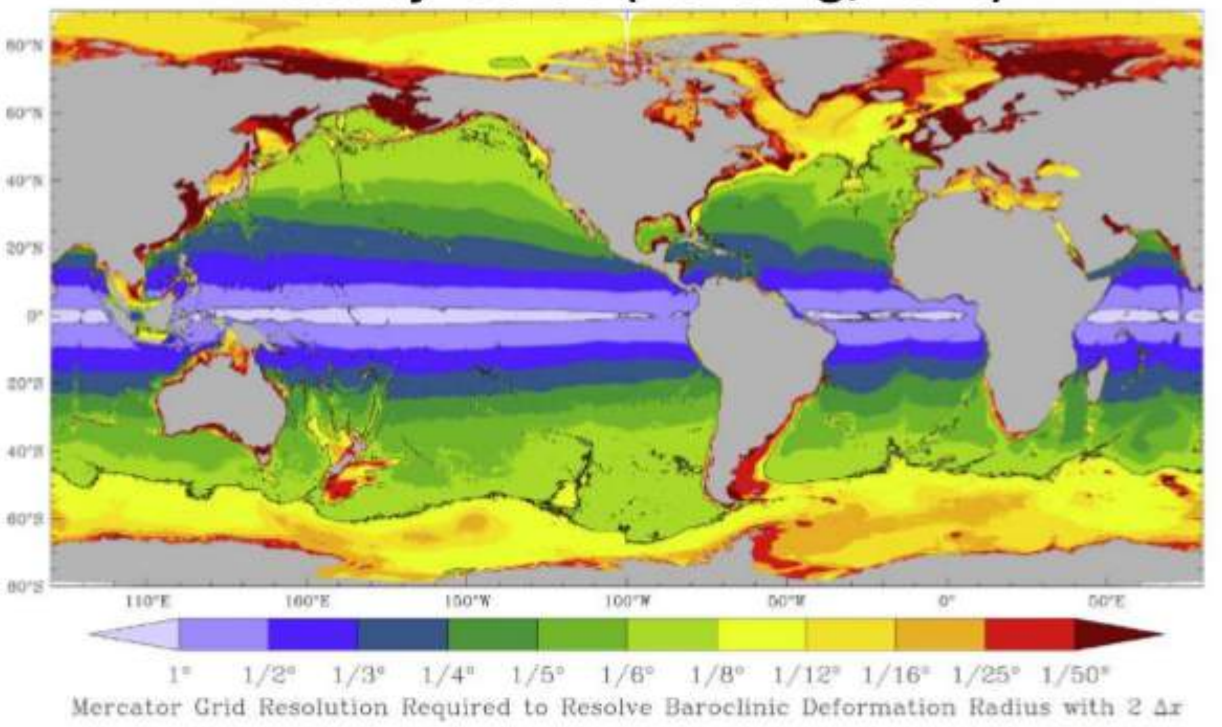
A (very brief) history of ocean modelling

Not all increases in resolution are the same → Step change in model skill when the critical threshold for resolution of largest, energy-containing mesoscale eddies reached...

First-baroclinic Rossby radius $\boxed{L = N h / f}$

N = buoyancy frequency
h = vertical scale of pycnocline
f = inertial frequency

Rossby radius (Hallberg, 2013)



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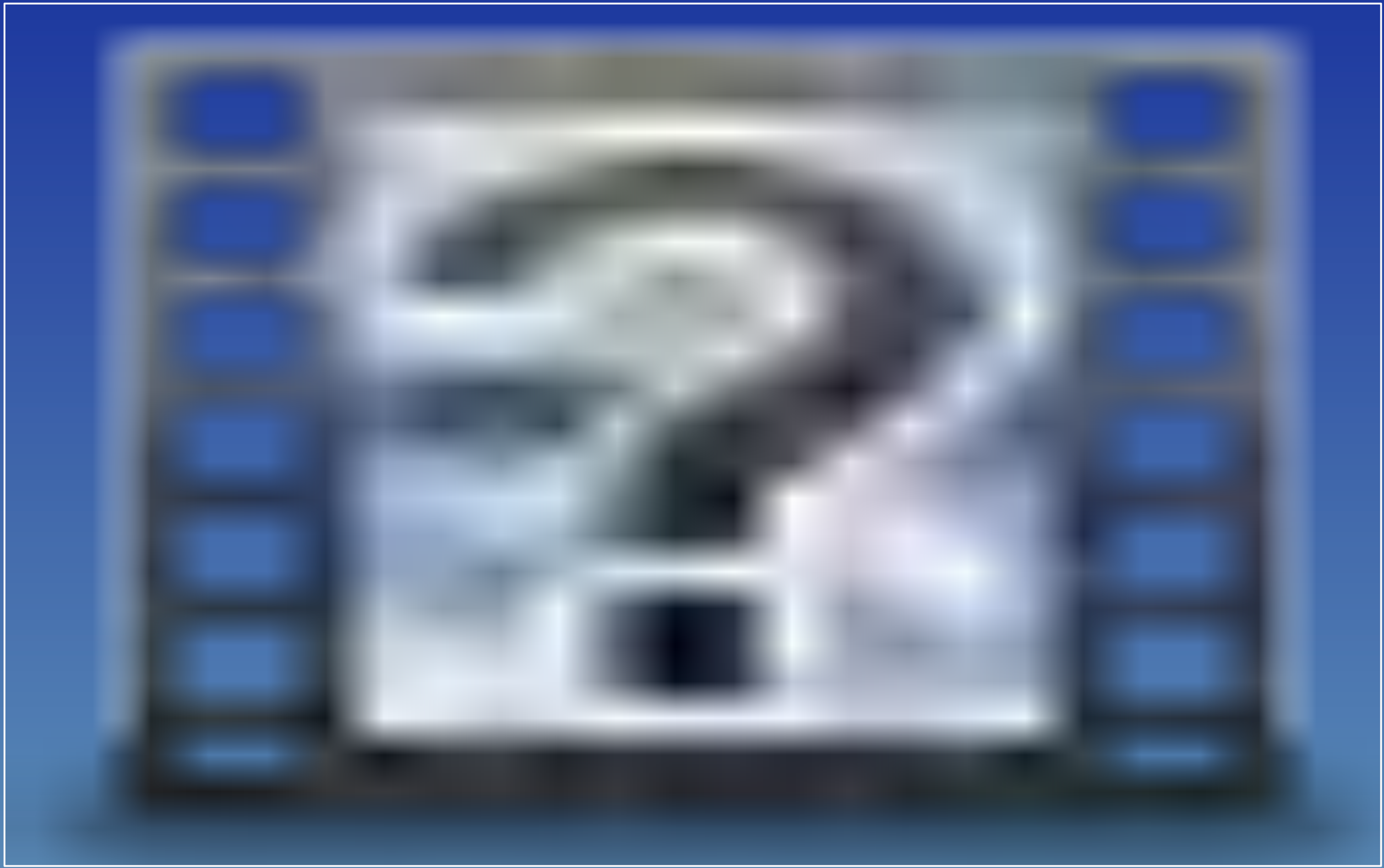
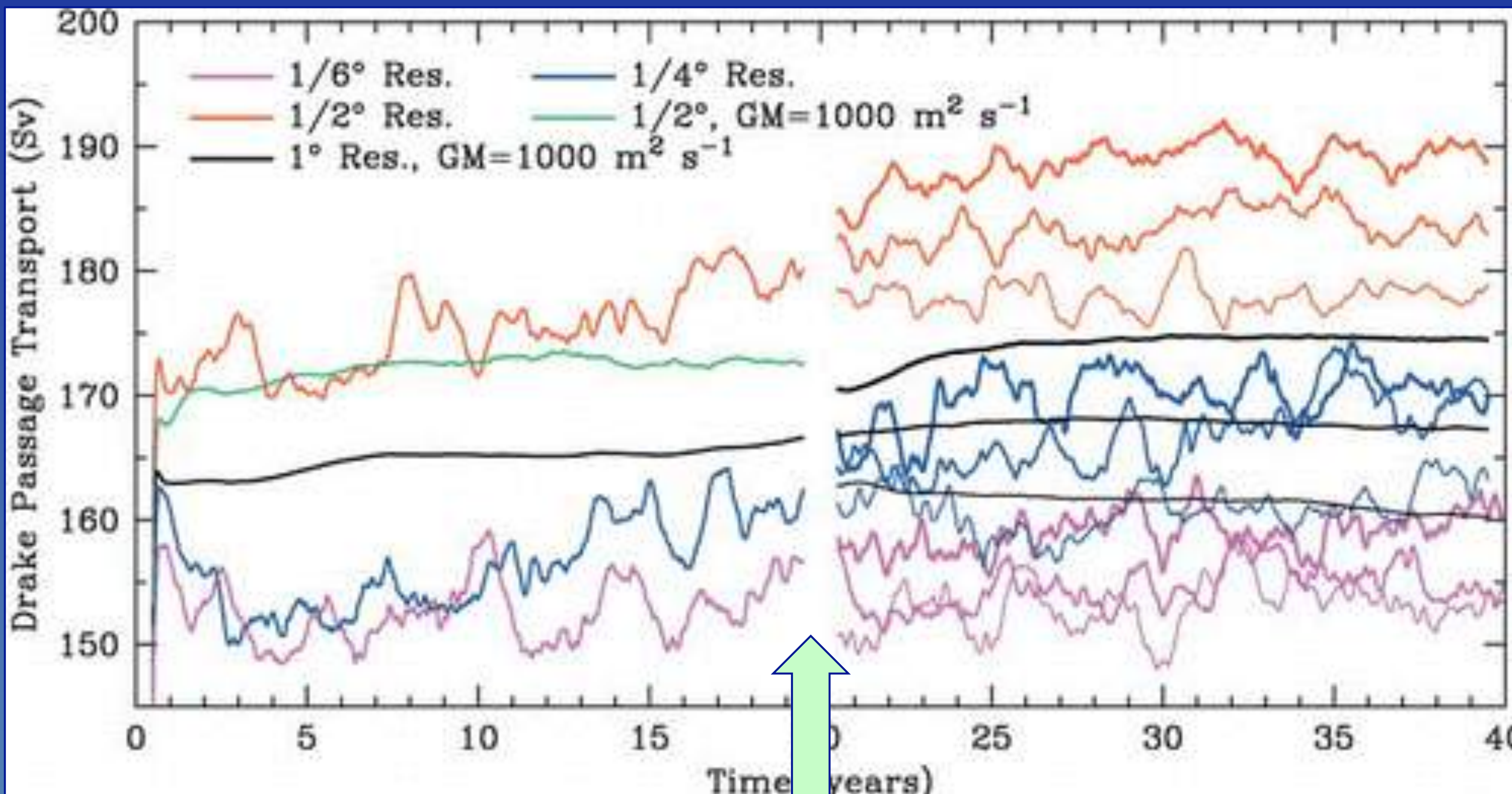


R. Hallberg
(GFDL)

A (very brief) history of ocean modelling

Partial resolution of mesoscale eddies results in fundamental changes in model behaviour…

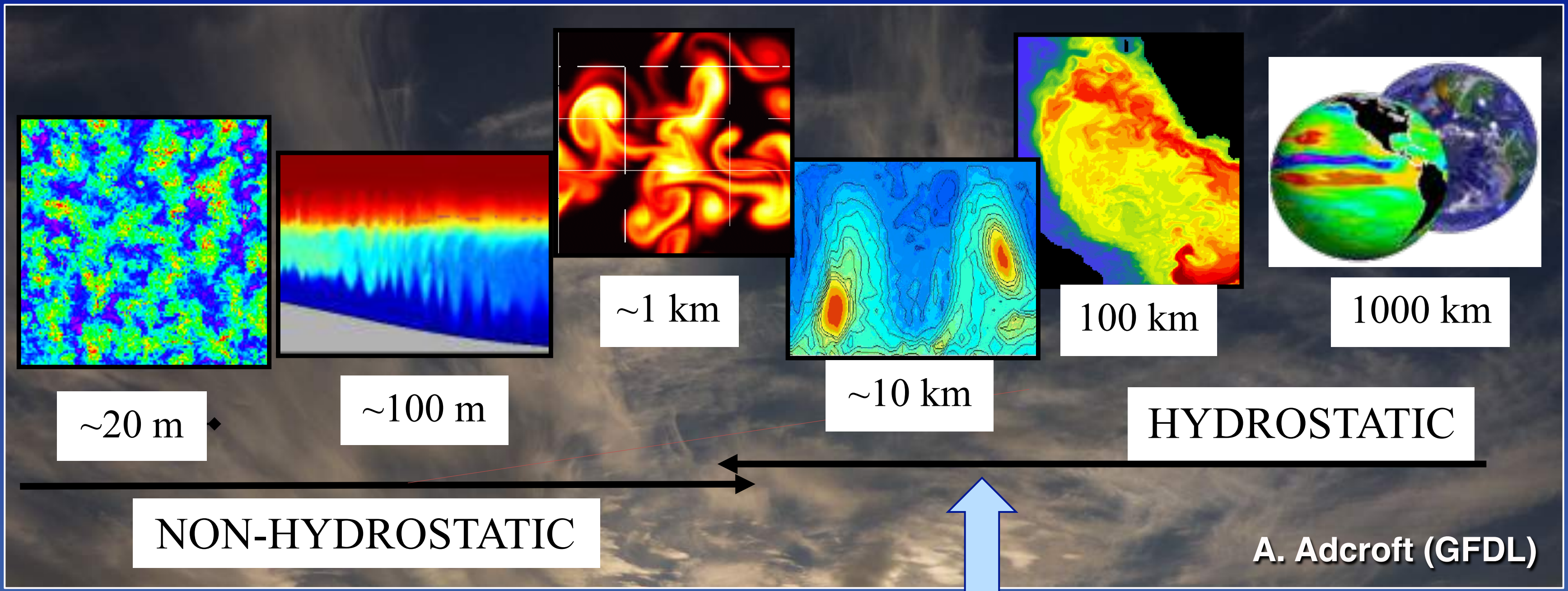
Drake Passage transport response to wind forcing perturbations for a range of model resolutions



Hallberg & Gnanadesikan (2006)

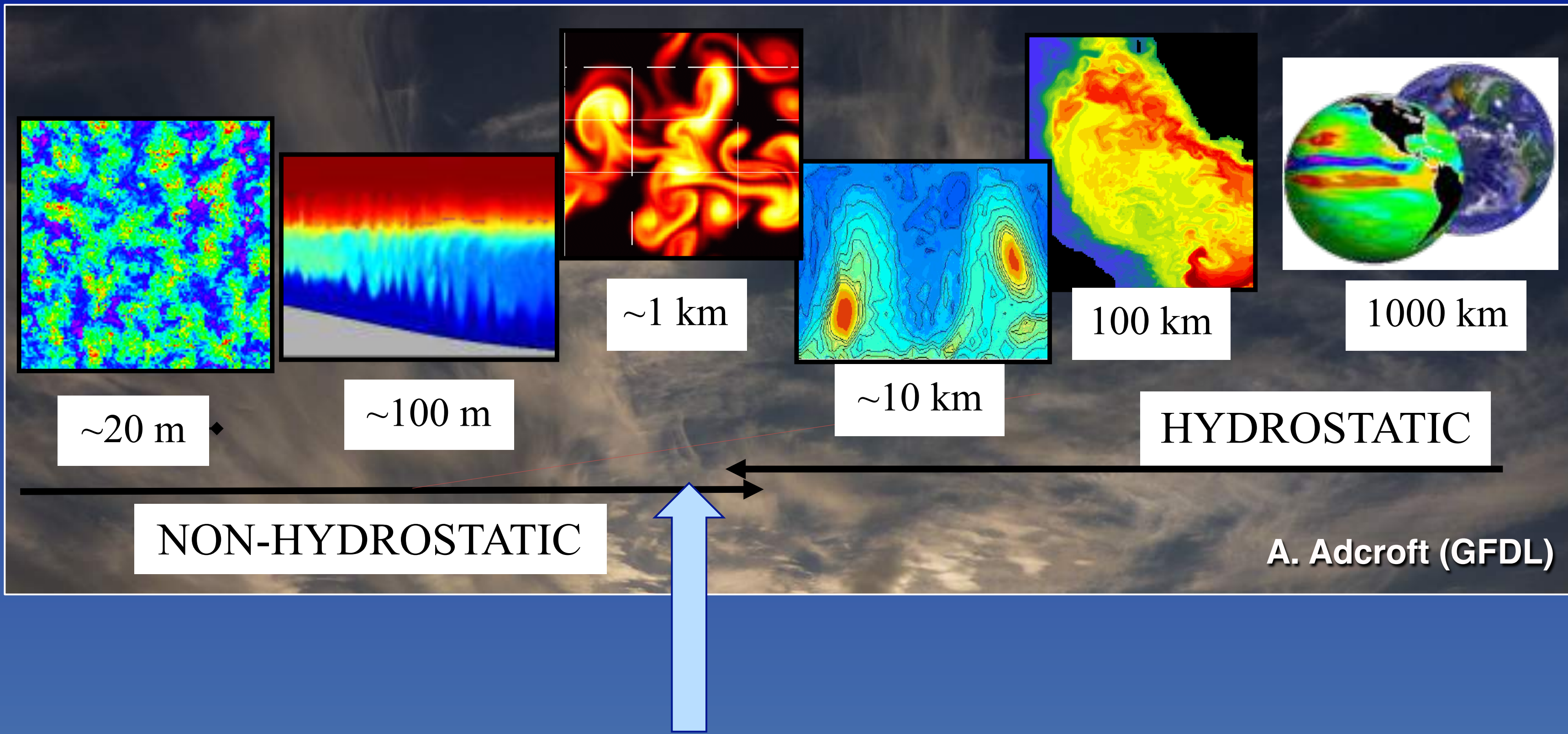
Step change in wind forcing

Modelling the ocean circulation – Status



Ocean modelling is presently at a stage in which eddy-permitting / eddy-resolving models are routine → The role of mesoscale dynamics in shaping ocean circulation and climate is becoming reasonably well understood.

Modelling the ocean circulation – Emerging challenge

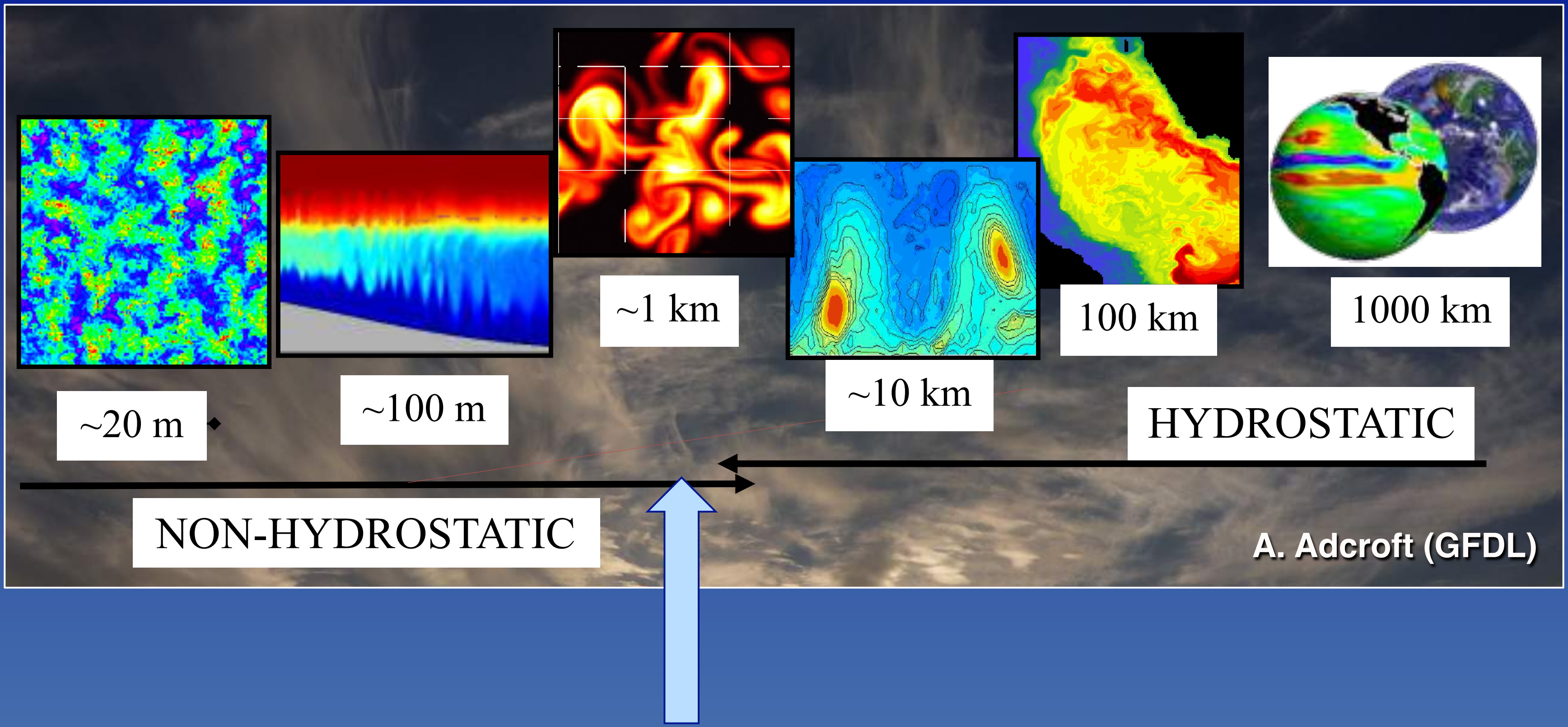


Mixed-layer Rossby radius $L_{ml} = N\, h_{ml} / f$

Horizontal wavelength of internal waves generated at boundaries $L_{iw} \sim 2\pi\, U / f$

N = buoyancy frequency
h_{ml} = mixed layer depth
f = inertial frequency
U = horizontal velocity scale

Modelling the ocean circulation – Emerging challenge

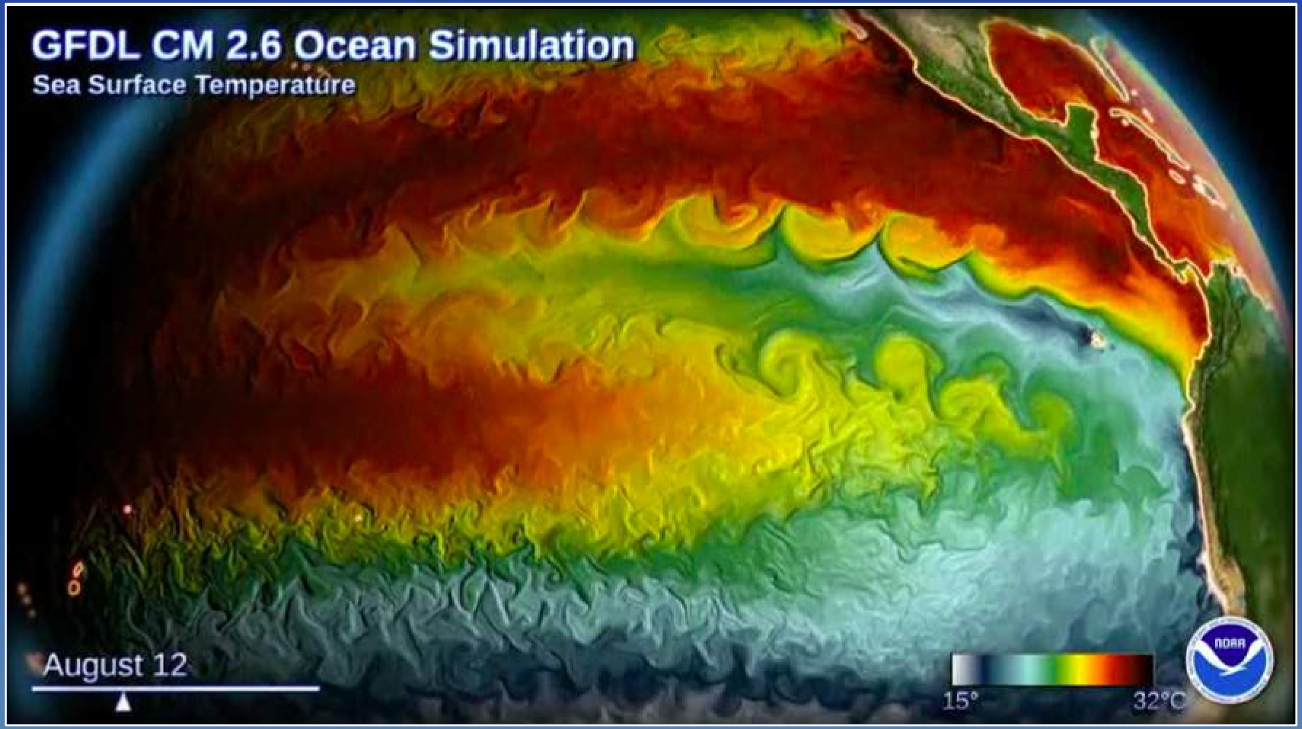


In recent years, the resolution of (regional) ocean models has started approaching O(1 km), and has uncovered a new zoo of – *submesoscale* – processes with large-scale impacts that are only beginning to be investigated…

NATIONAL
COMPUTATIONAL
INFRASTRUCTURE

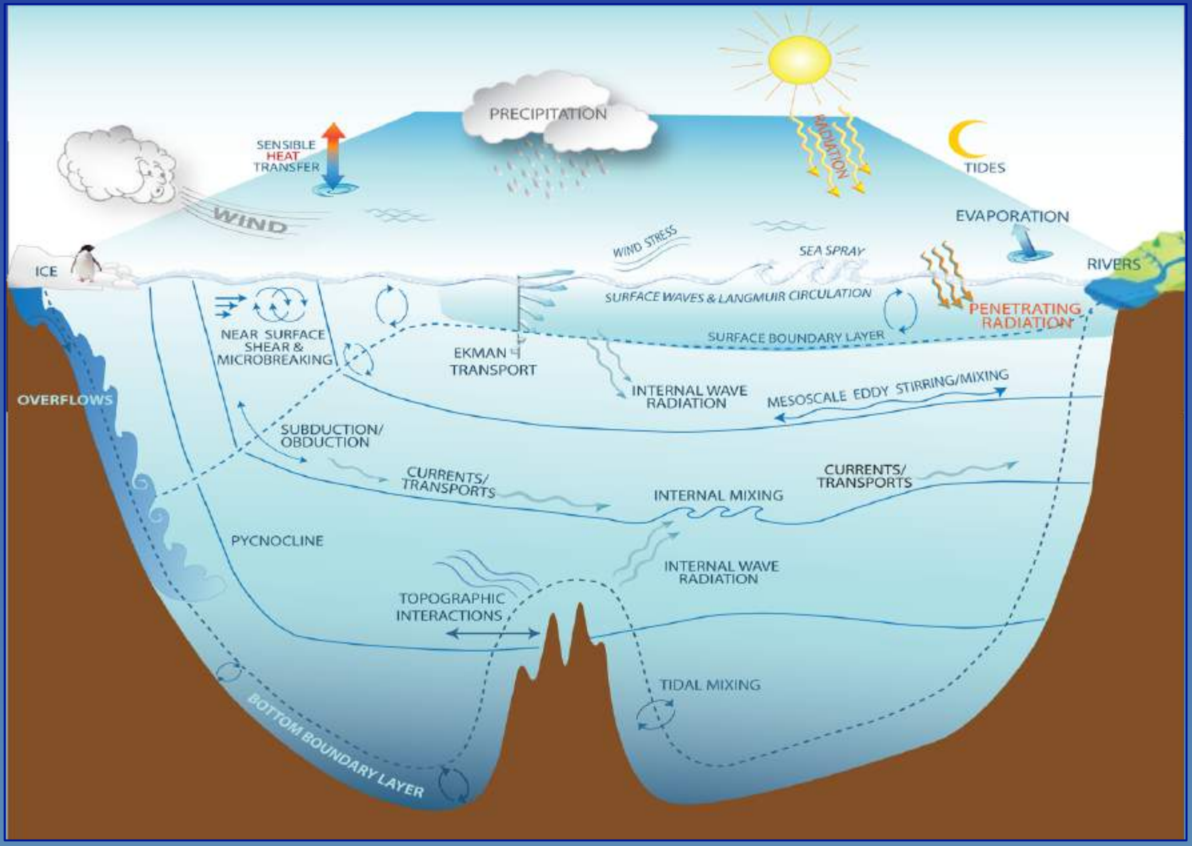
What to expect from increasing ocean resolution (and where to expect it)

The dynamics of the ocean interior away from boundaries are generally characterised by small Rossby number (Ro ~ U / fL << 1), well approximated by quasi-geostrophic dynamics, and adequately represented in eddy-resolving ocean models.



What to expect from increasing ocean resolution (and where to expect it)

Near the ocean's *boundaries* (land, ice, atmosphere), abrupt variations in stratification (triggered by e.g., intensified diabatic and frictional forcing) or water column thickness (associated with e.g., rough or steep land and ice topography) lead to the emergence of flows with higher-order dynamics (Ro ~ O(1)).



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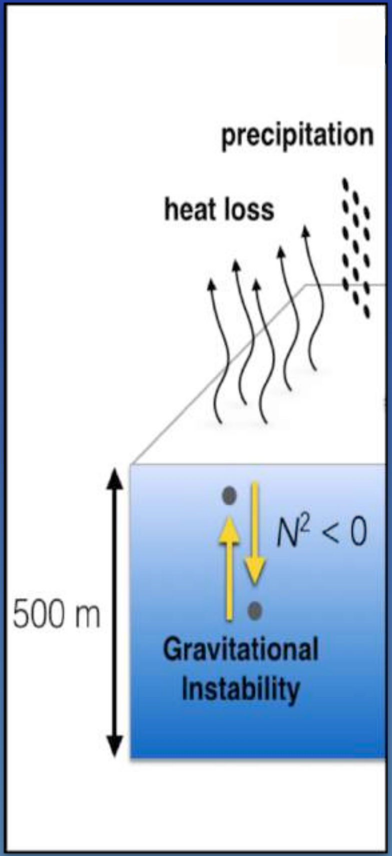
By necessity, these flows happen in important places, where the ocean exchanges heat, freshwater, momentum and gases with the land, ice or atmosphere.

➔ Resolving this new dynamics is thus very likely to change the big picture of how the modelled ocean circulation behaves.

Submesoscale physics at the ocean – atmosphere boundary

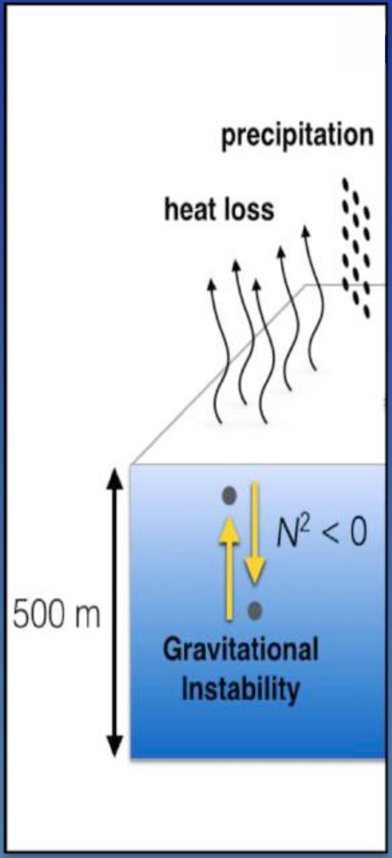
Evolution of the upper-ocean mixed layer: theory

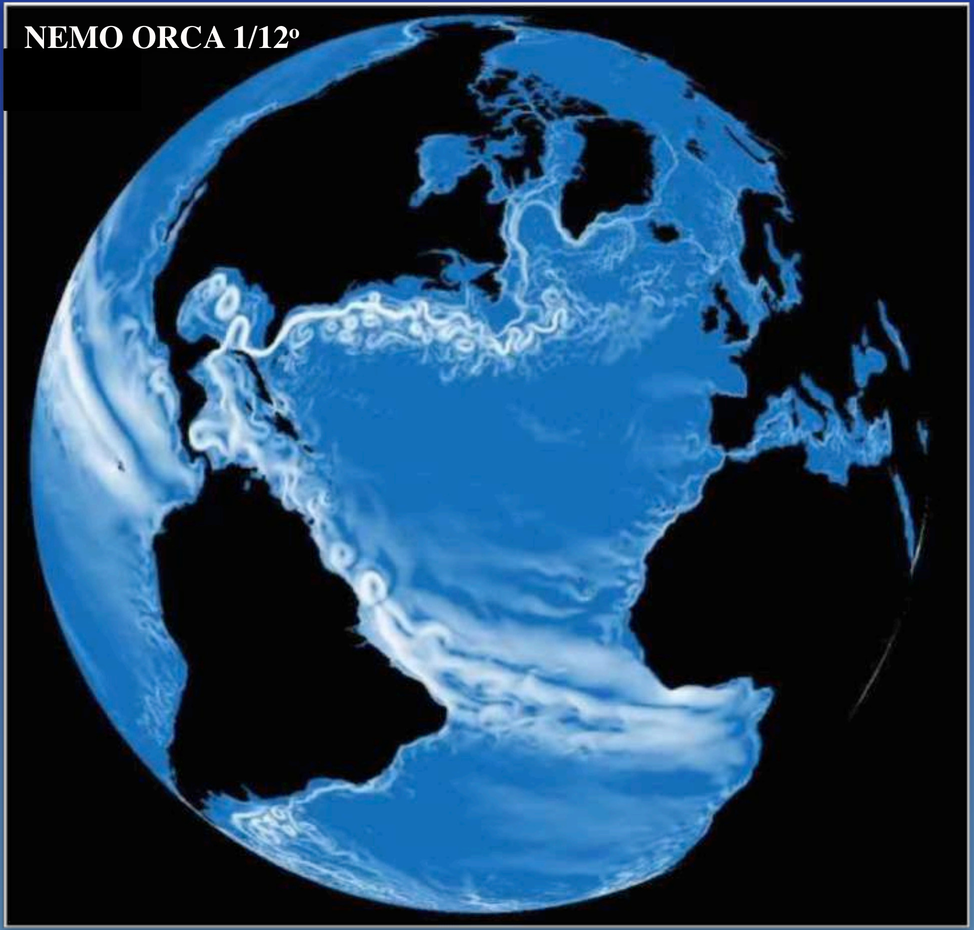
- **Classical view of the mixed layer is 1-d**



Evolution of the upper-ocean mixed layer: theory

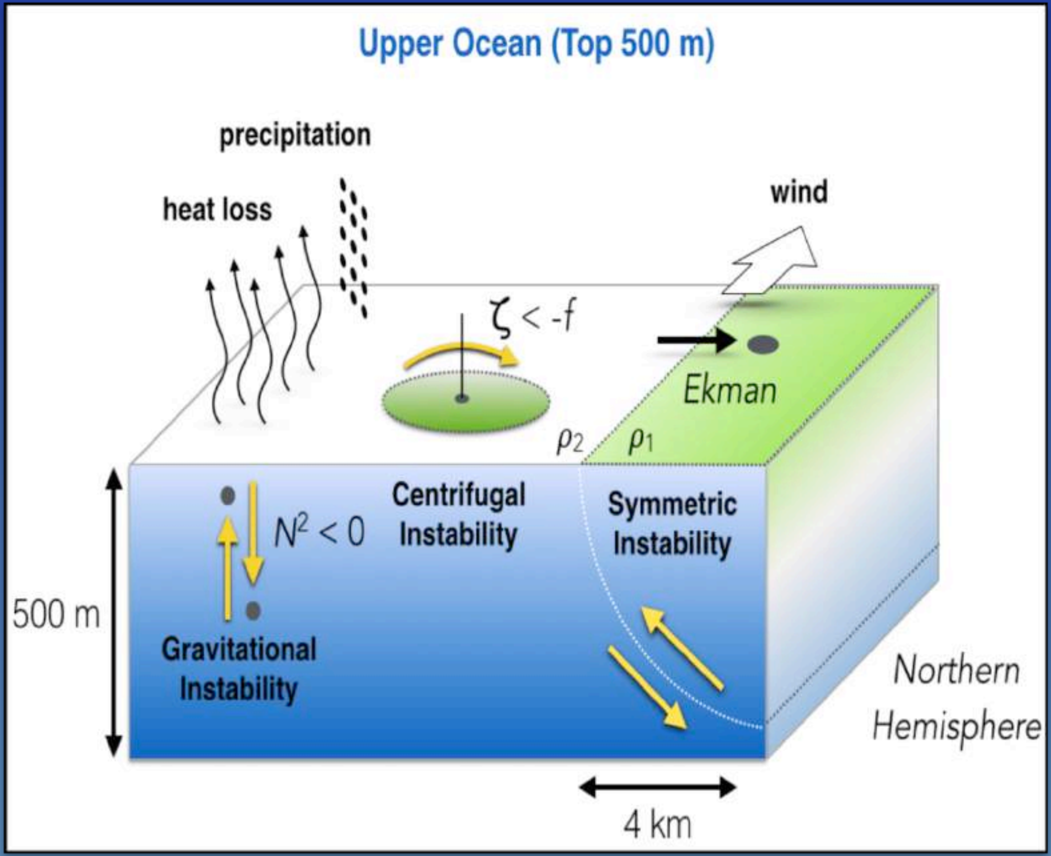
- **Classical view of the mixed layer is 1-d**
- **This physics enters climate-scale models of the ocean circulation via parameterizations such as KPP (Large et al., 1994)**





Evolution of the upper-ocean mixed layer: theory

In the presence of lateral density fronts, a very different view of the mixed layer emerges in which a range of other (3-d) dynamical instabilities are permitted by the equations of motion.



A balanced flow undergoes dynamical instability when

$$fq = f(f\hat{k} + \nabla \times \mathbf{u}) \cdot \nabla b < 0,$$

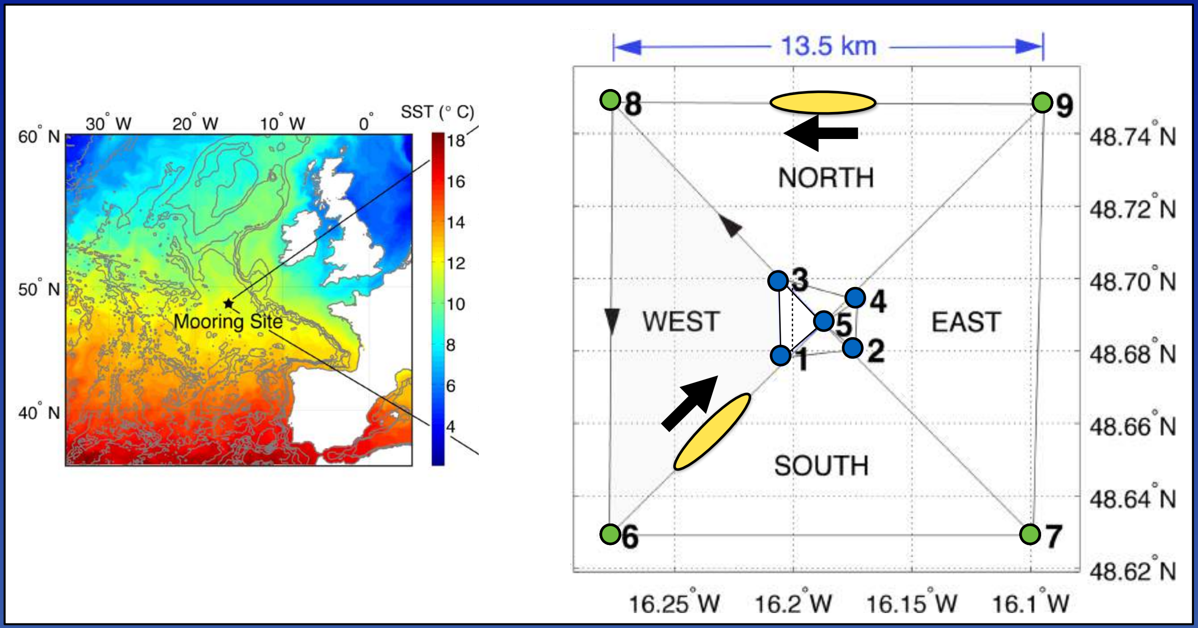
with f = Coriolis parameter, q = potential vorticity, u = velocity and b = buoyancy.

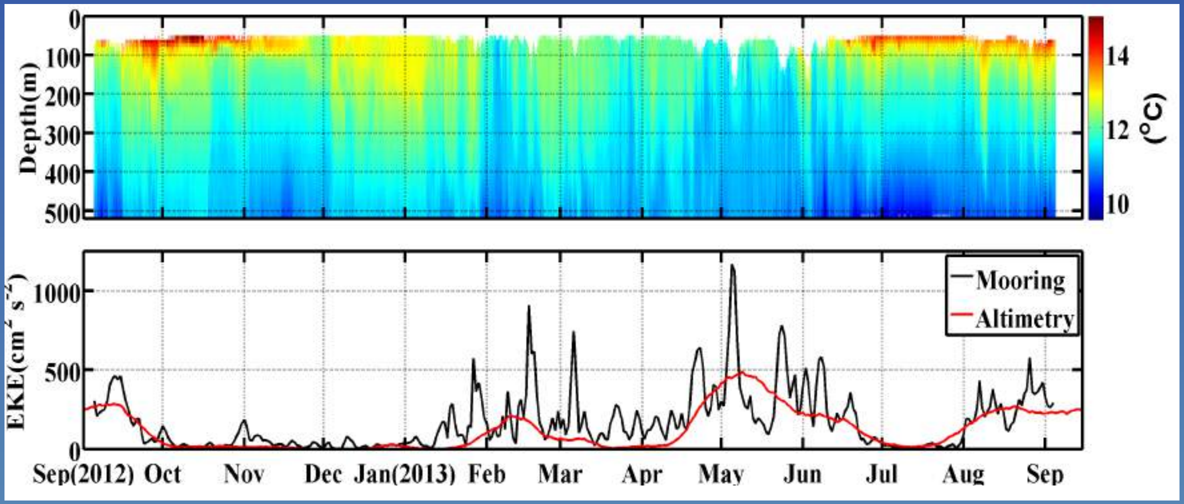
This condition is met when:

$N < 0$ ➔ gravitational instability
$f\zeta < -f^2$ ➔ centrifugal instability
$|\nabla_h b| > f^2 N^2$ ➔ symmetric inst.

Hoskins (1974)

An annual cycle of the ocean surface boundary layer (OSBL)

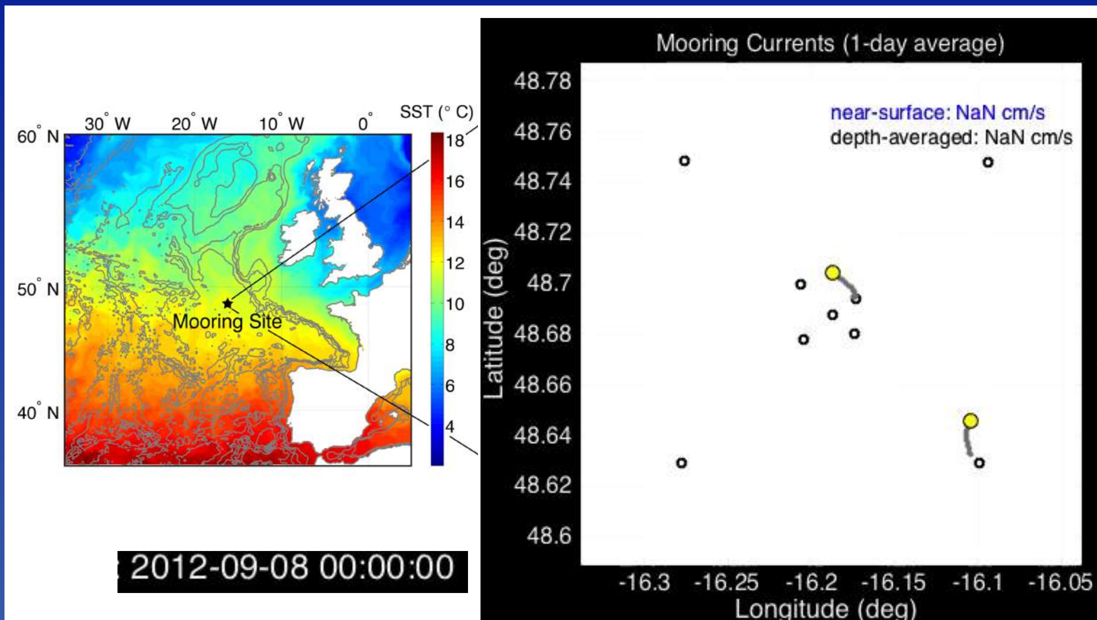


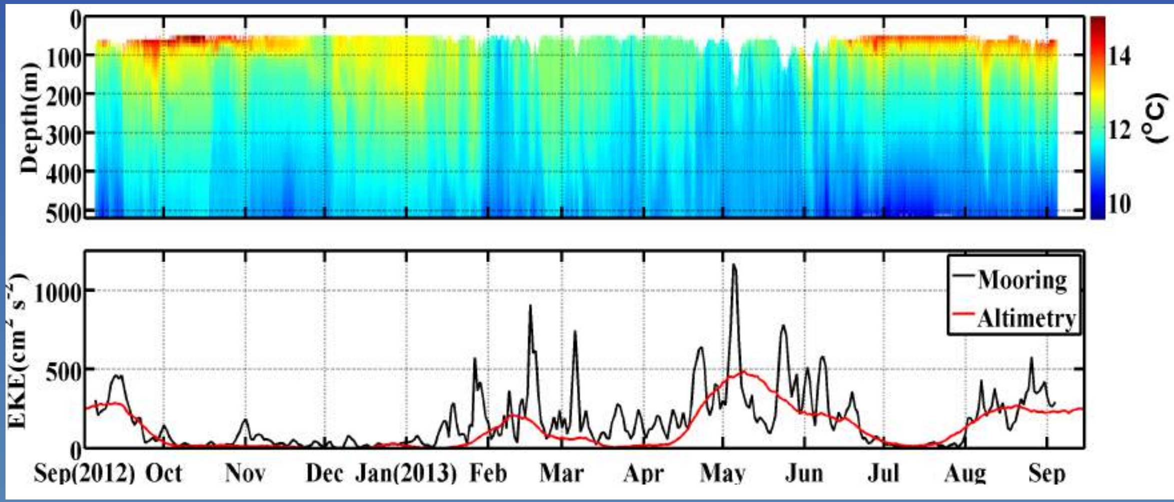


OSMOSIS experiment

- An annual cycle of the OSBL's evolution and its underpinning dynamics in a typical mid-ocean region, with weak mean flow and low-to-moderate mesoscale eddy activity
- 2 nested mooring arrays (9 moorings, including instruments for point measurements of ε) and 2 gliders focussing on upper 500 m, deployed for 1 year next to a meteorological buoy

An annual cycle of the ocean surface boundary layer





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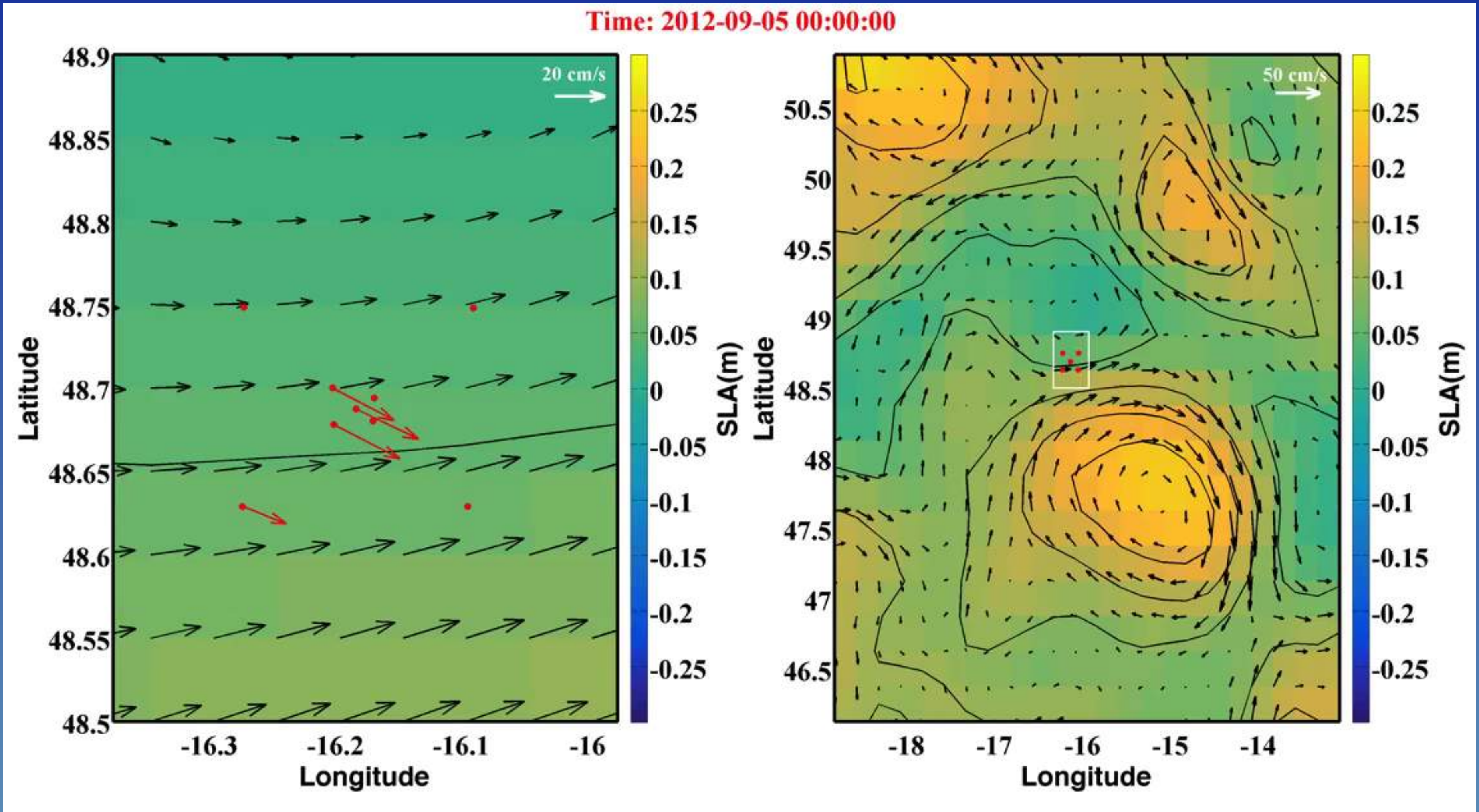
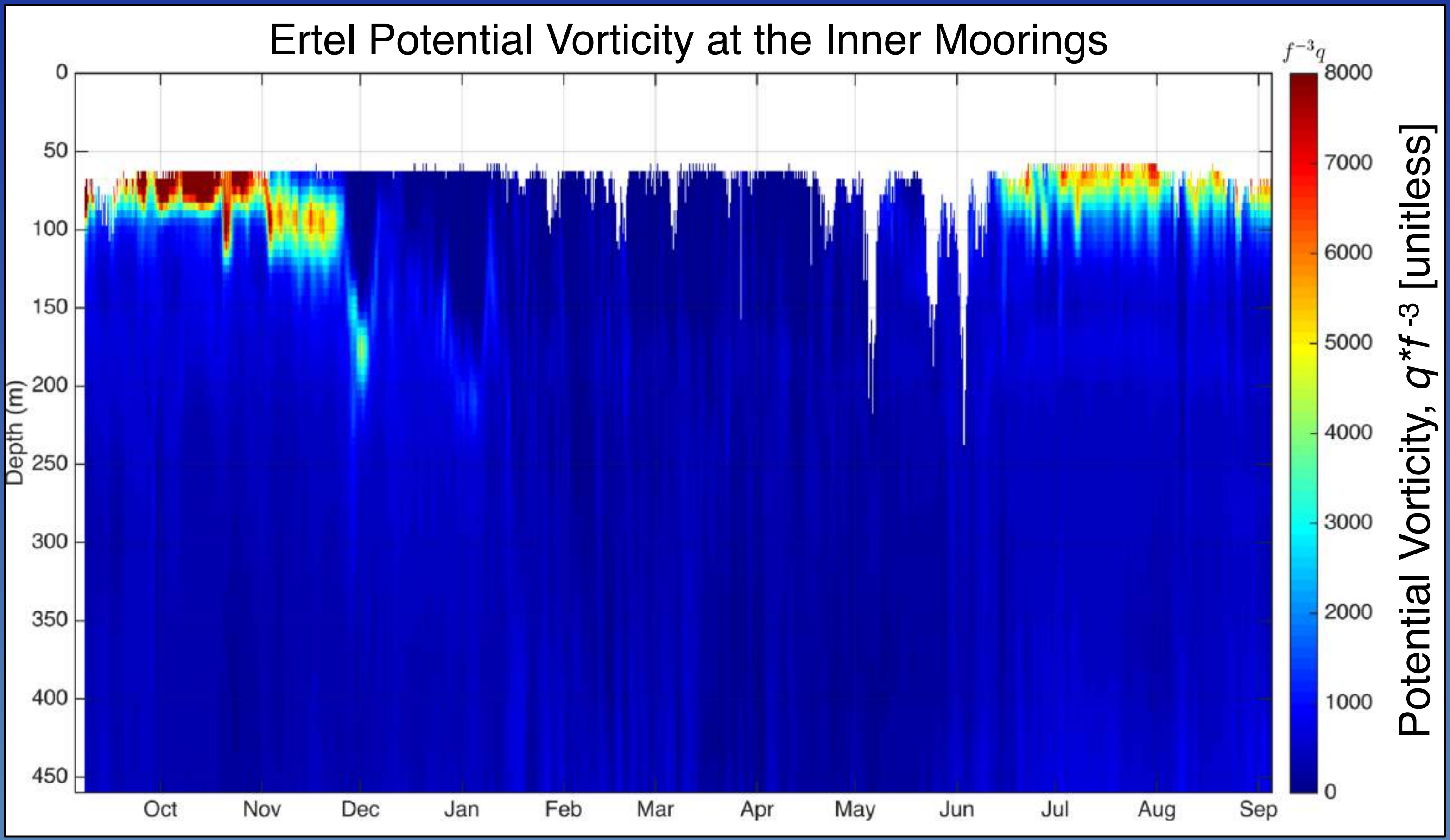
An annual cycle of the ocean surface boundary layer

The in situ observations reveal rich flow variability on horizontal and time scales shorter than those resolved by altimetry and characteristic of the submesoscale, particularly in winter and early spring.



An annual cycle of the ocean surface boundary layer: de-stratification

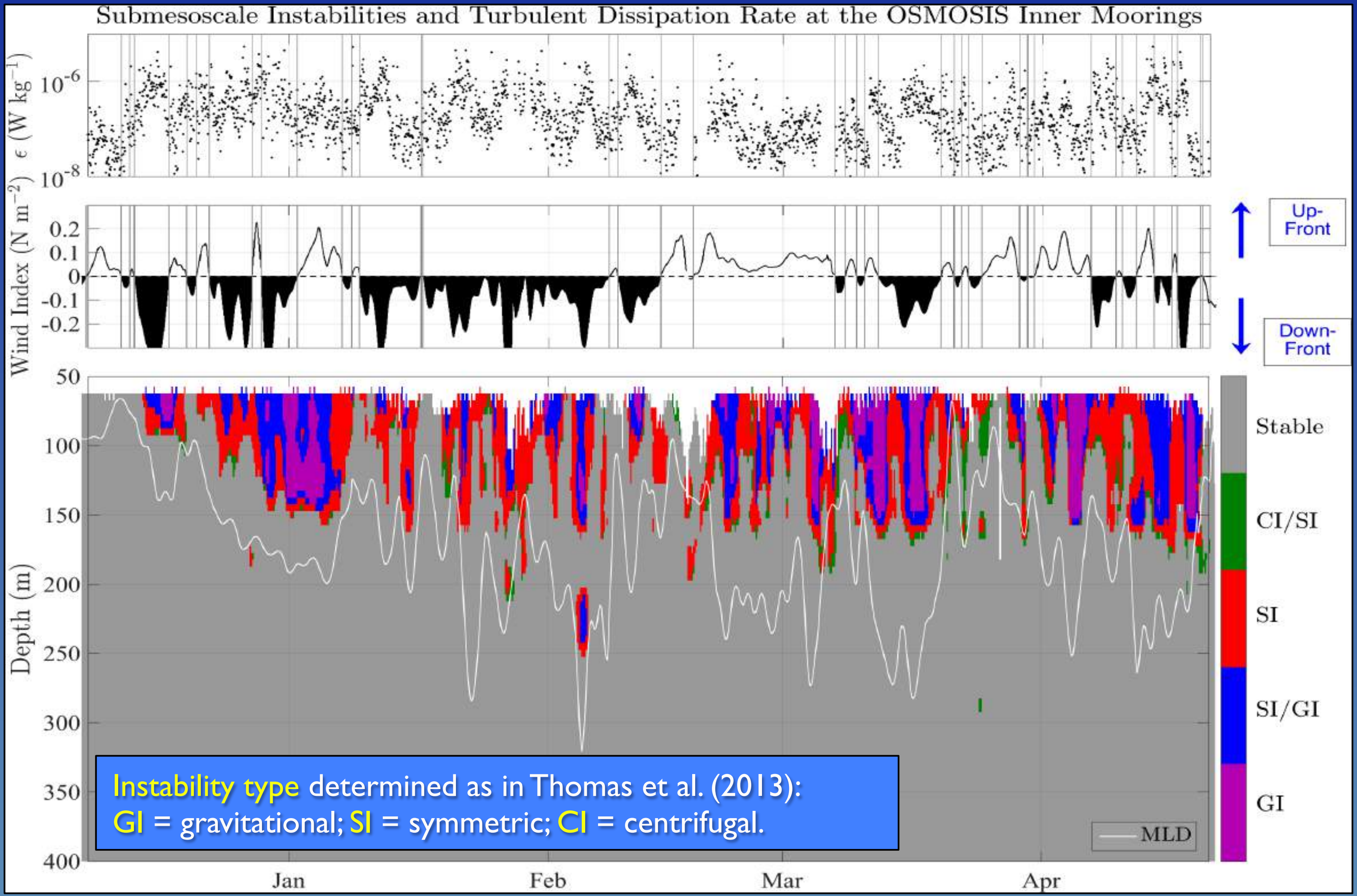
As the ocean de-stratifies in the autumn and during the entire period of enhanced (sub-)mesoscale eddy variability, areas of near-zero or negative PV appear, associated with abrupt changes in mixed layer depth.



Buckingham *et al.* (in prep.)

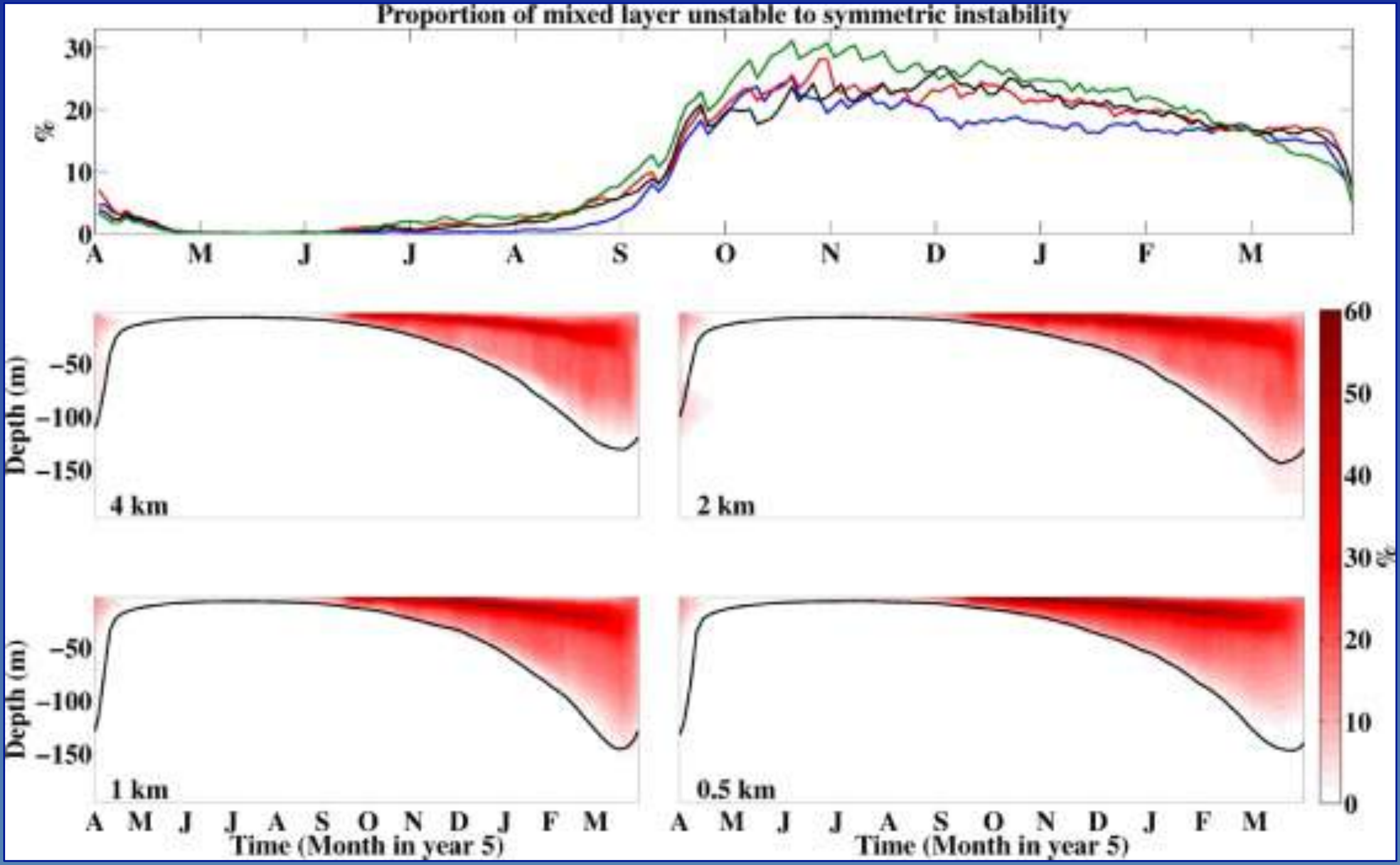
An annual cycle of the ocean surface boundary layer: de-stratification

Negative *fq* events are generally triggered by *downfront winds* and elicit *intensified upper-ocean turbulent dissipation* and *mixed layer deepening*. 63% of these events are associated with *symmetric instability*.



An annual cycle of the ocean surface boundary layer: de-stratification

The observed significance of symmetric instability in de-stratifying the upper ocean is reproduced in a regional model with resolution of < 2 km.



Brannigan *et al.* (2015)

An annual cycle of the ocean surface boundary layer: de-stratification

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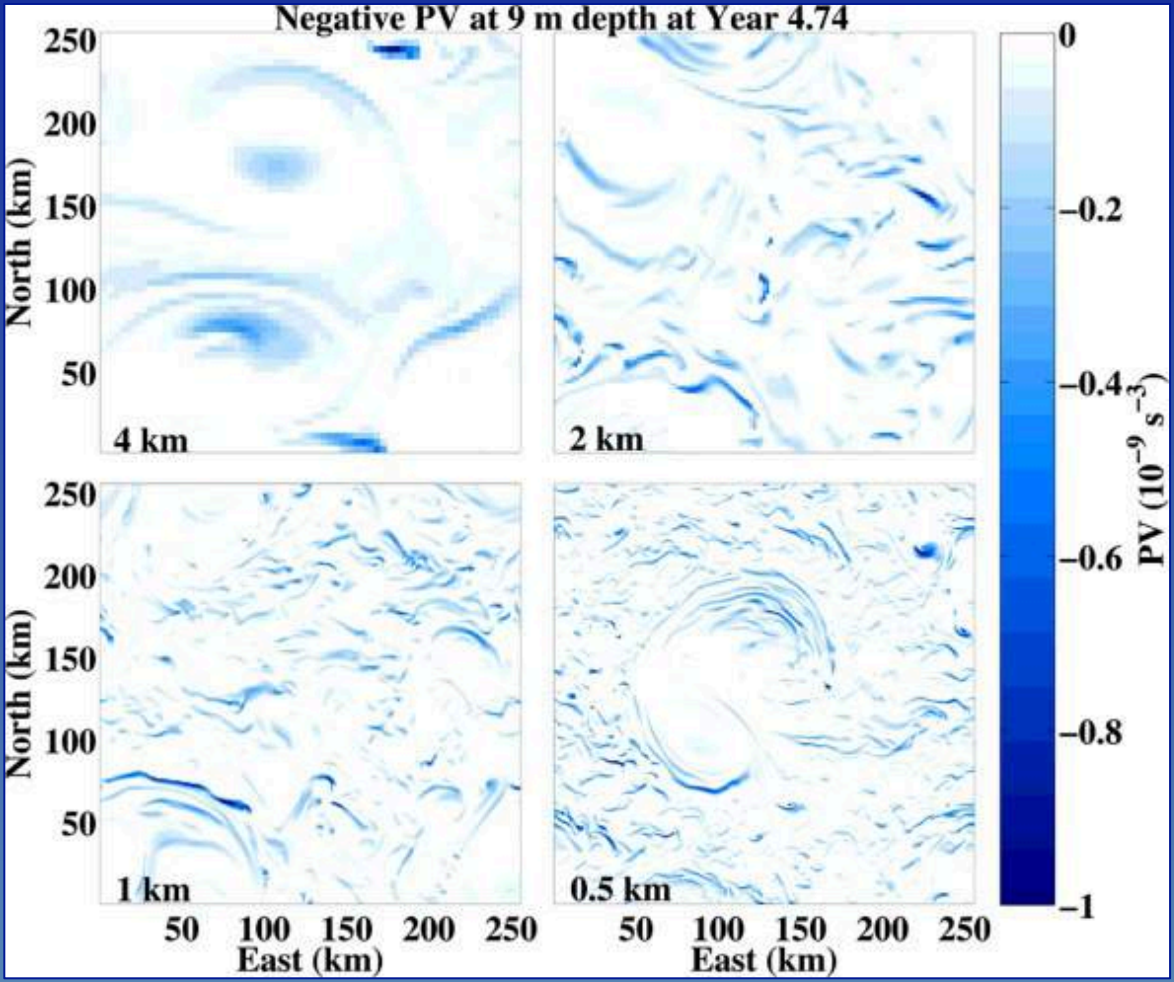
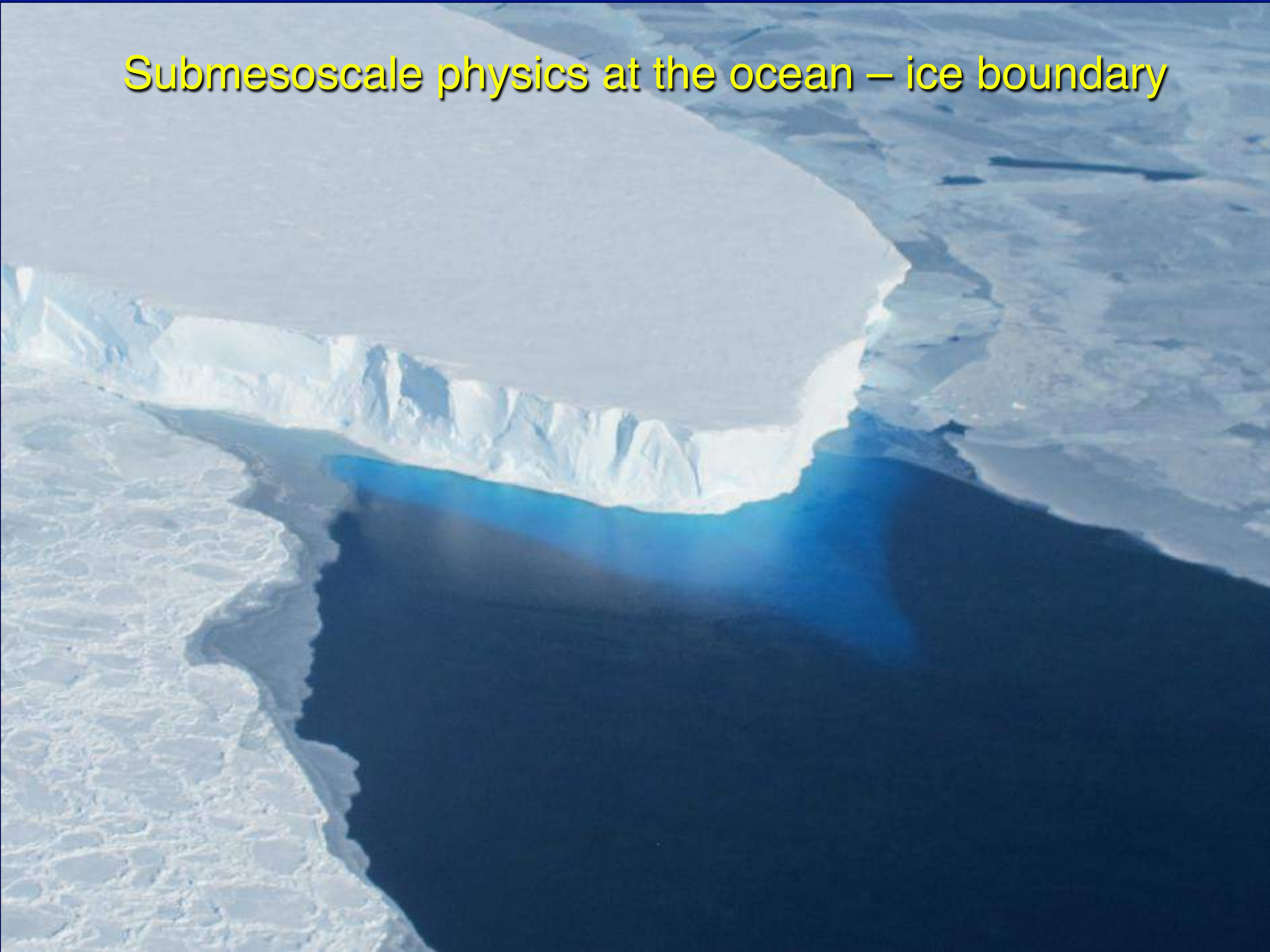


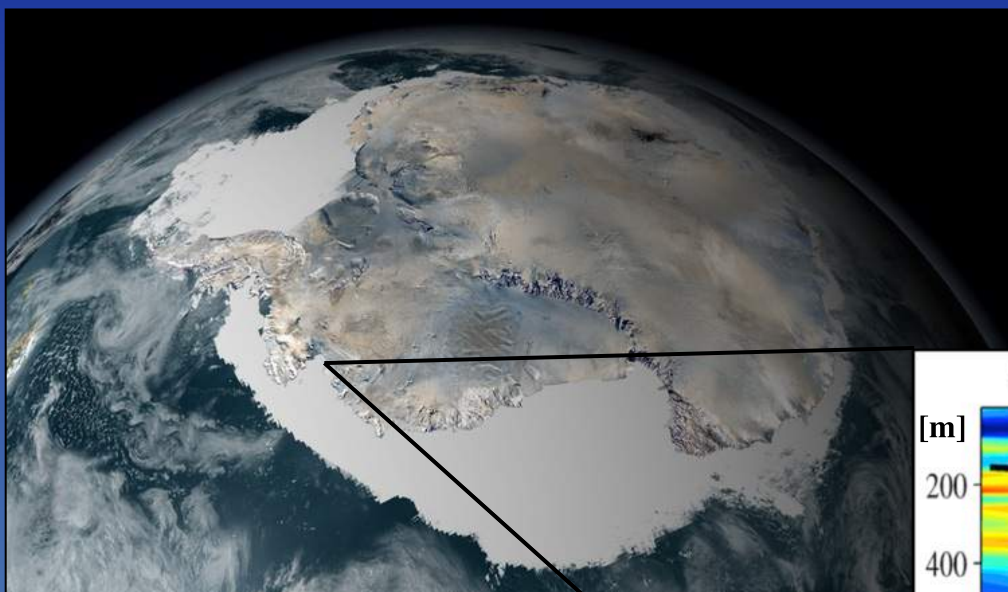
Year 4.74 = Late December

Submesoscale physics at the ocean – ice boundary

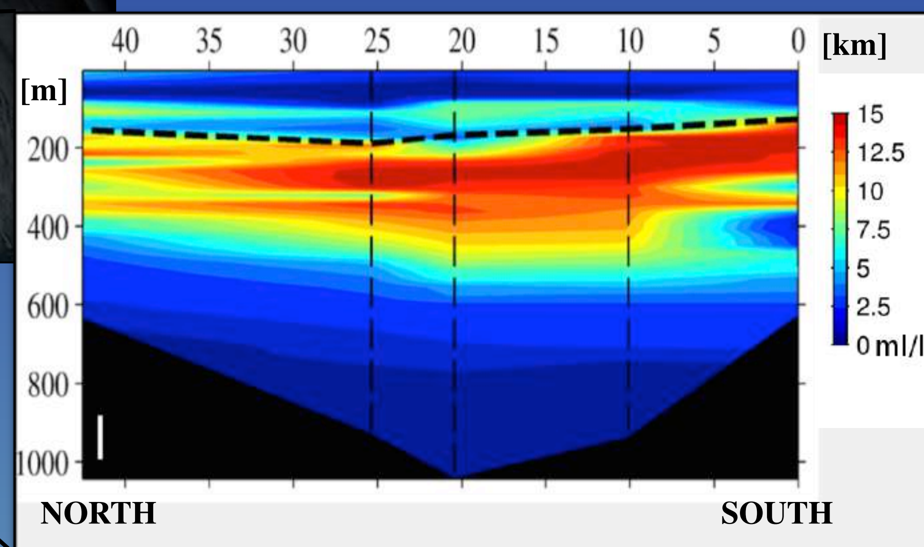


Why is meltwater from ice shelves concentrated in the thermocline?

The meltwater exported from beneath Antarctic ice shelves is regularly *concentrated in the thermocline*, not at the surface. This is important in determining how accelerated ice shelf melting will impact the circulation and climate of the Southern Ocean.



Meltwater fraction (colour) at the Pine Island Ice Shelf (PIIS) calving front in 2010

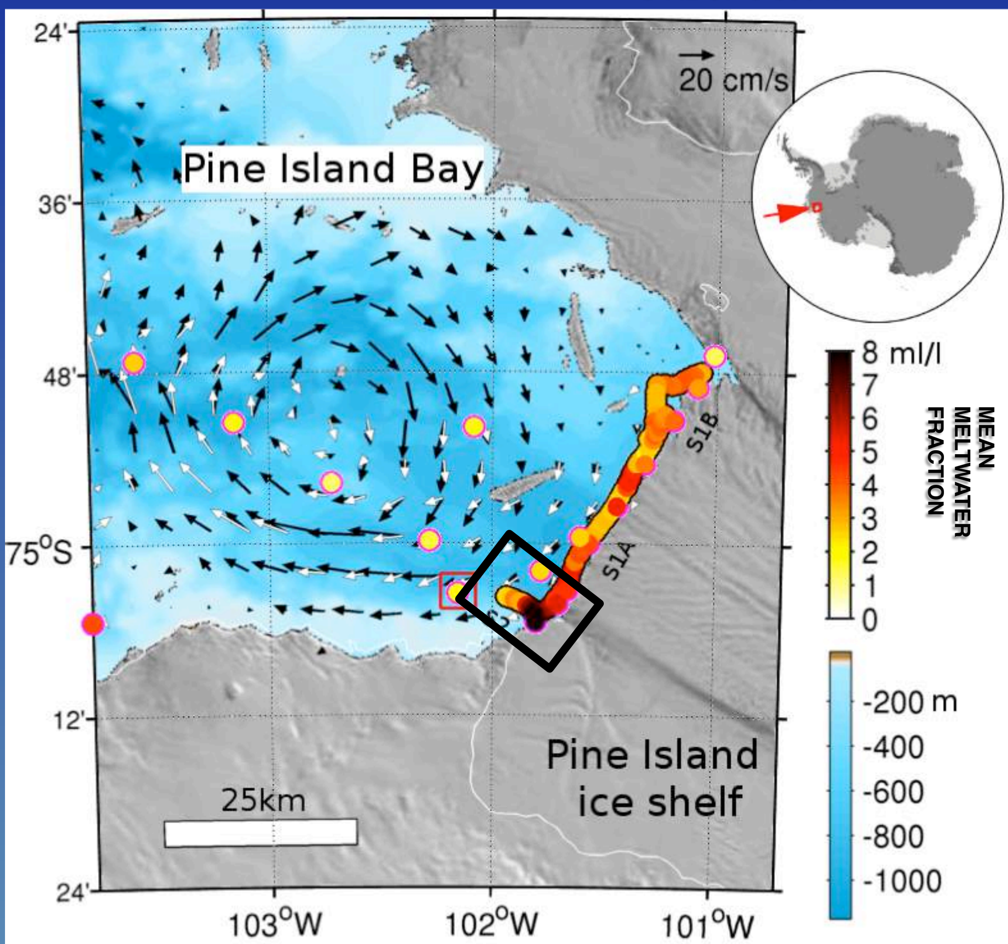


Dutrieux *et al.* (2014)

Why is meltwater from ice shelves concentrated in the thermocline?

iSTAR expedition (Jan – Mar 2014): 60 fine- and microstructure profiles collected along the Pine Island Ice Shelf calving front, at a horizontal resolution of < 600 m and a distance of < 1 km from the calving front

S-ADCP 0-300 m



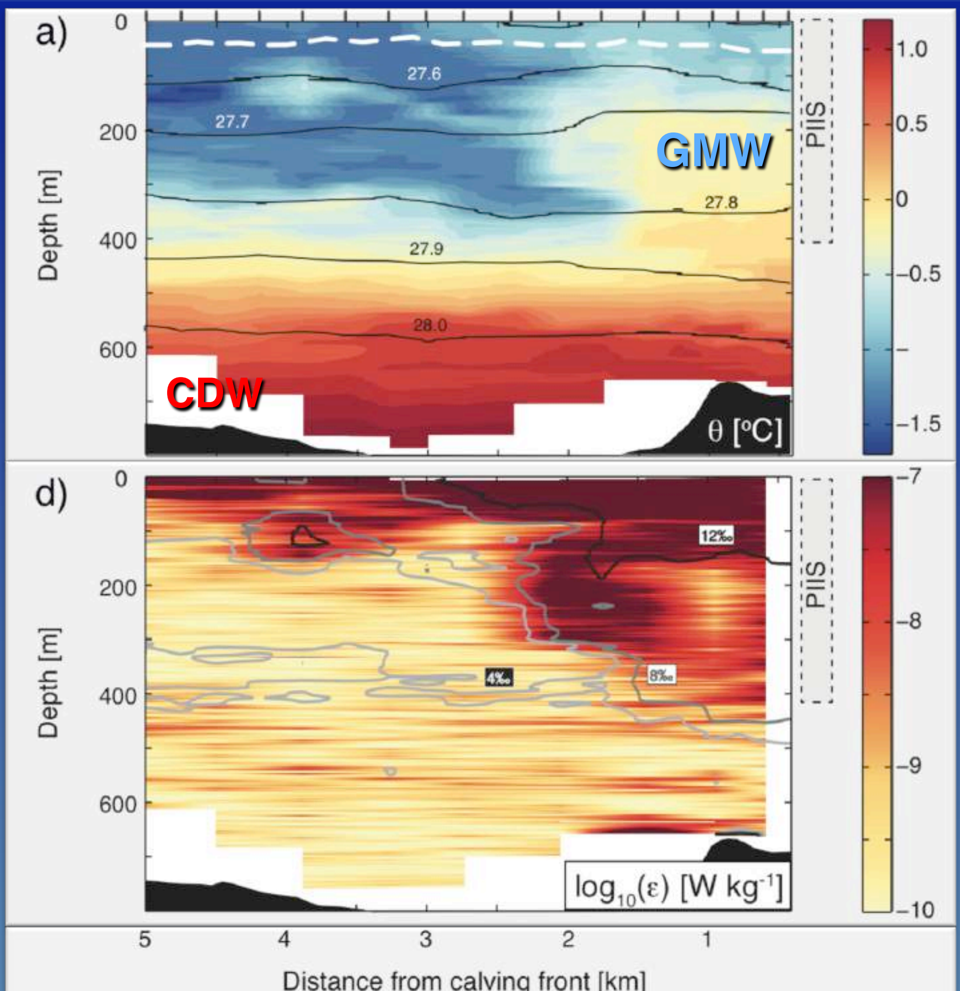
Rockland VMP-2000 microstructure profiler deployed from the *RRS James Clark Ross*

Naveira Garabato *et al.* (2017)

The Pine Island calving front

Why is meltwater from ice shelves concentrated in the thermocline?

Observations along the main meltwater outflow from beneath Pine Island Ice Shelf (PIIS). The outflow's ascent is arrested by submesoscale *centrifugal instability*, which triggers intense small-scale turbulence that rapidly dilutes meltwater.



CDW = Circumpolar Deep Water

GMW = Glacially Modified Water

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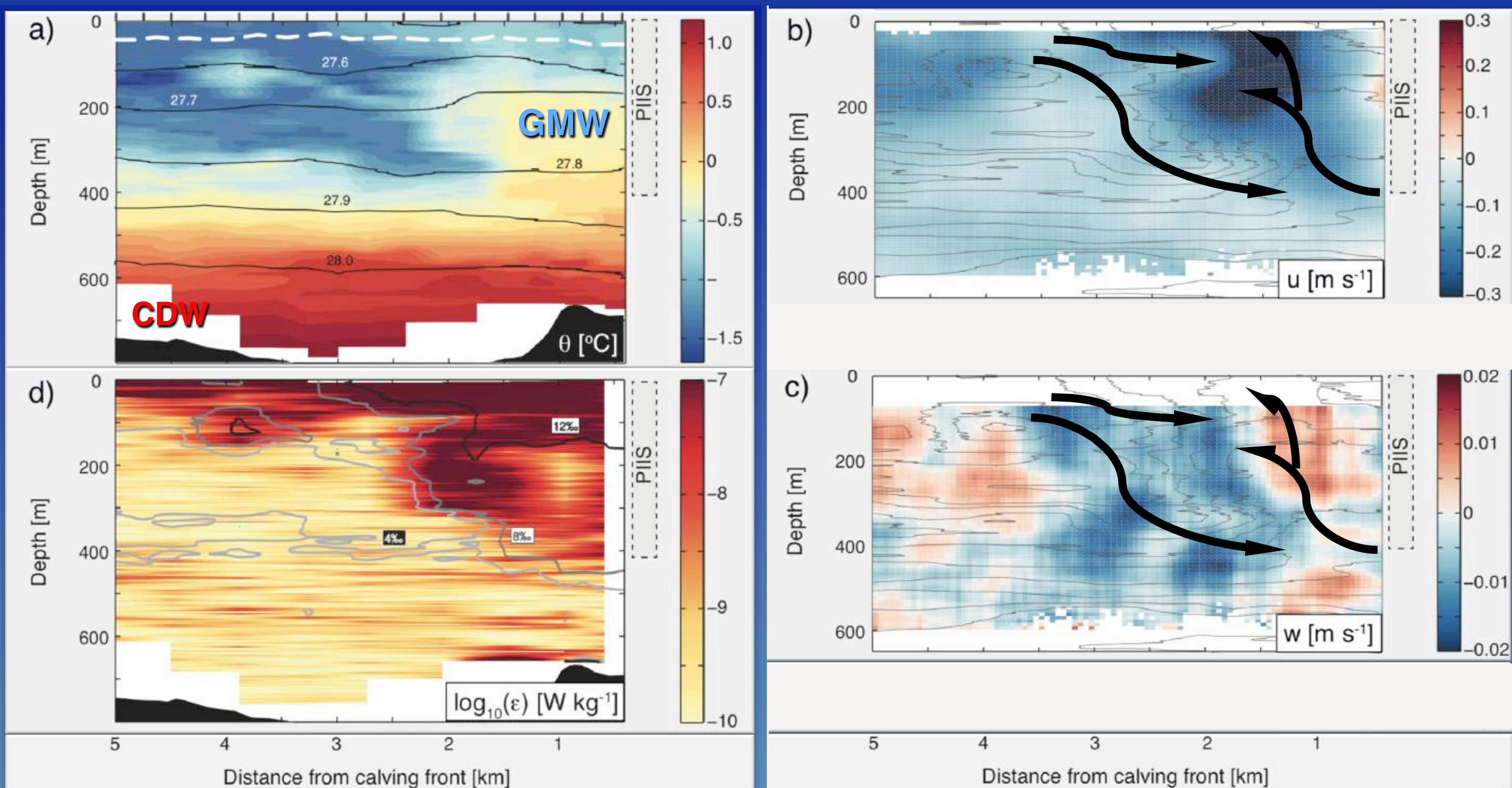

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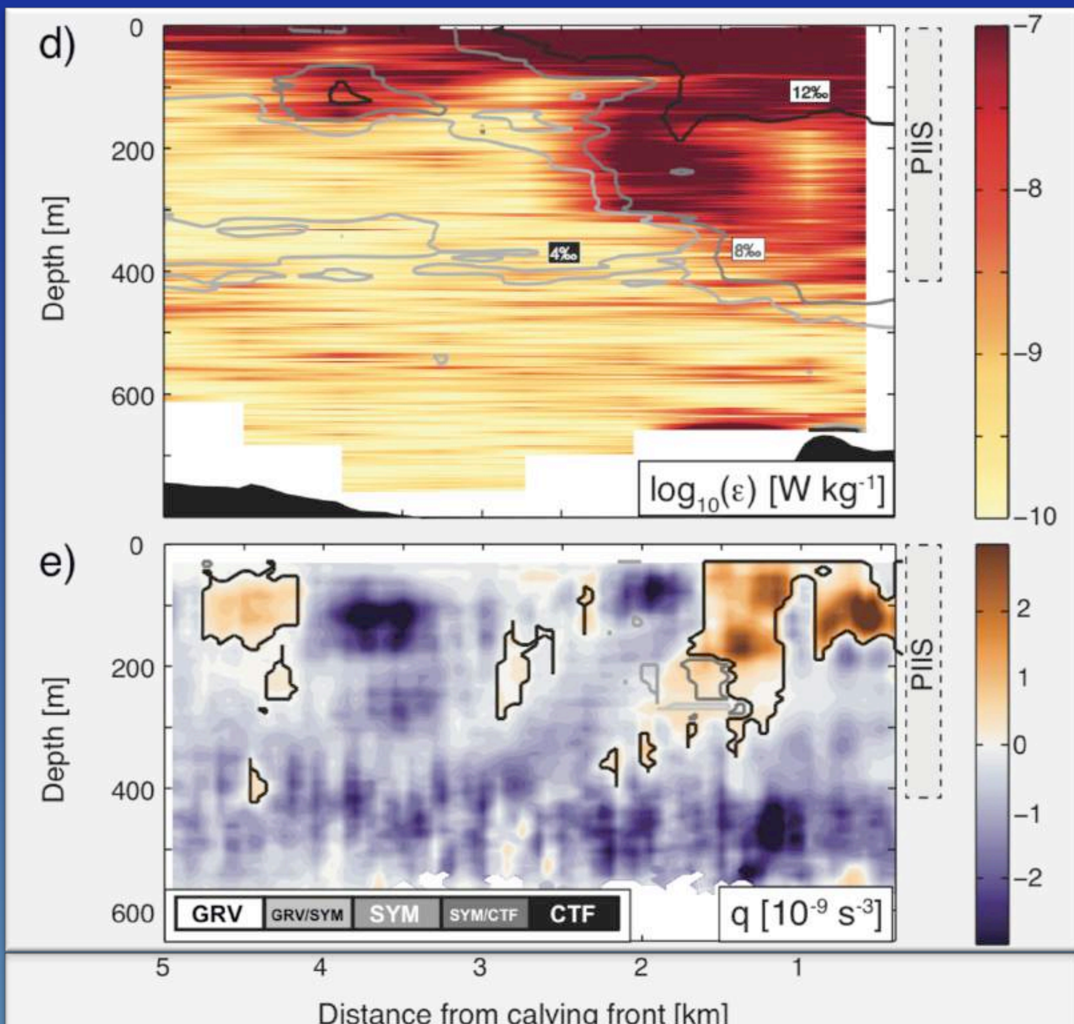

Instability type determined as in Thomas et al. (2013):

GRV = gravitational
SYM = symmetric
CTF = centrifugal

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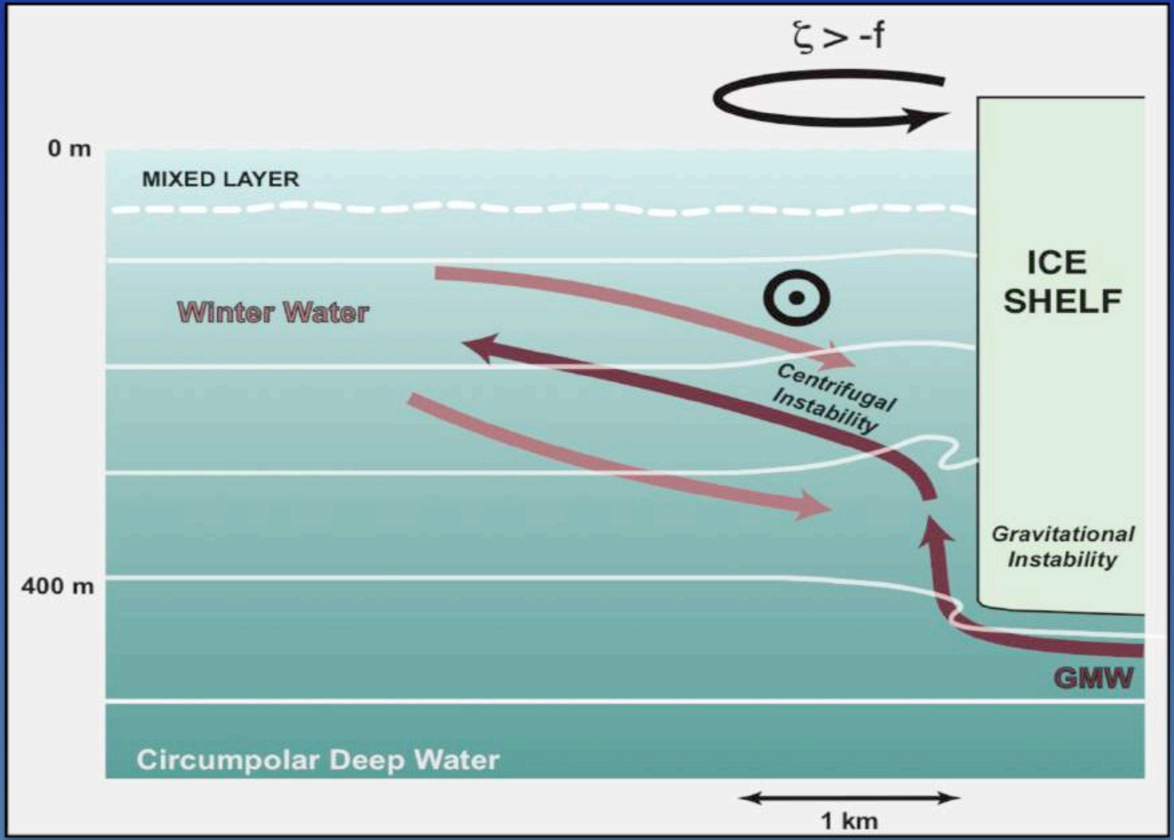
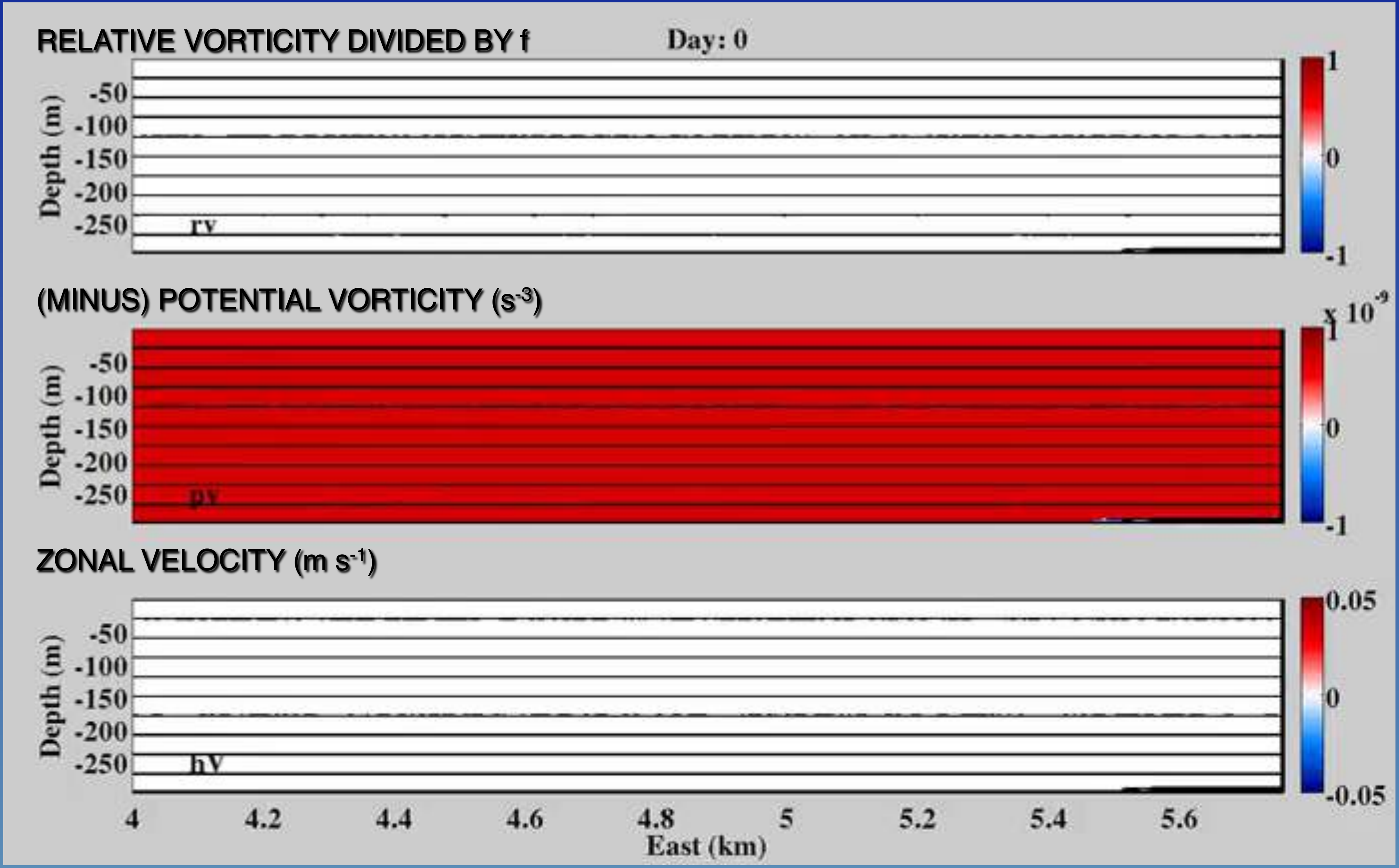
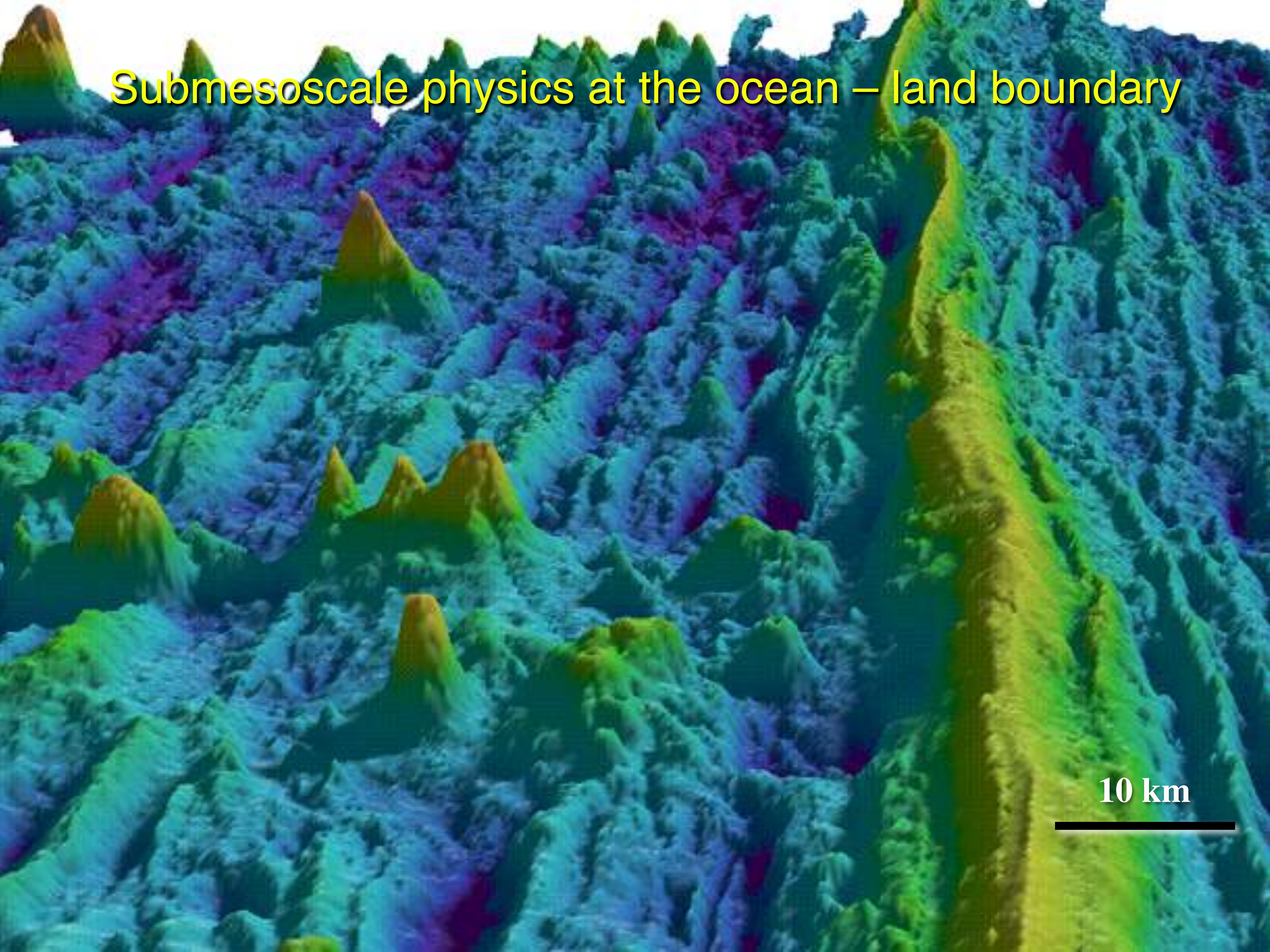


An idealised model of an Antarctic ice shelf's outflow

The simulation displays an 'outflow plume' that undergoes centrifugal instability with characteristics broadly similar to observations…



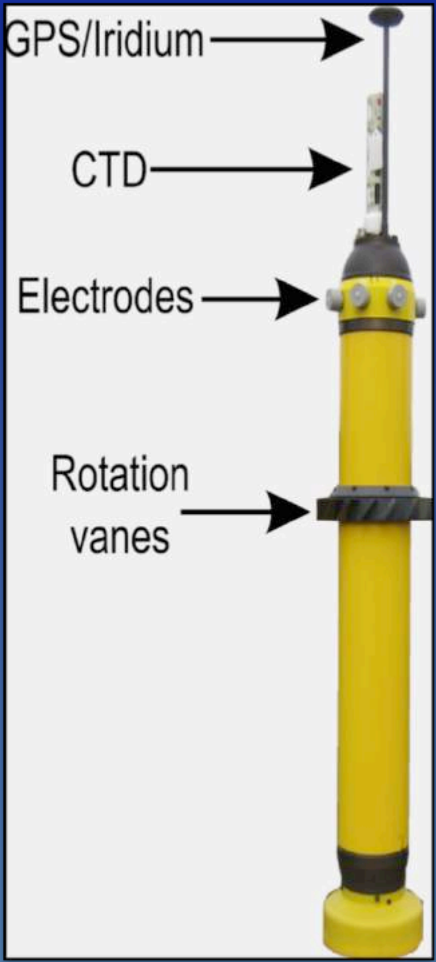
Submesoscale physics at the ocean – land boundary

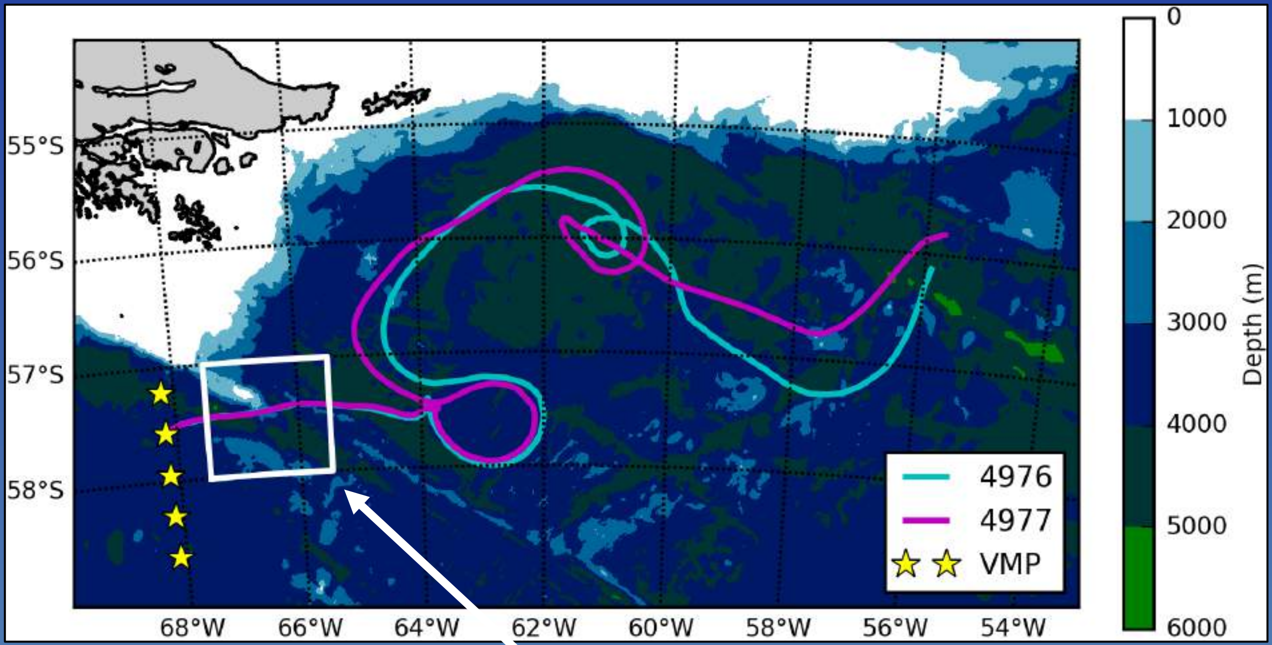


The role of small-scale topography on the dynamical balance of the ACC

Two EM-APEX floats were deployed together as part of the DIMES experiment on 30th Dec 2010 in an ACC jet, and profiled continuously (every ~3 h) for ~4 months measuring hydrography and horizontal and vertical velocity.

EM-APEX float





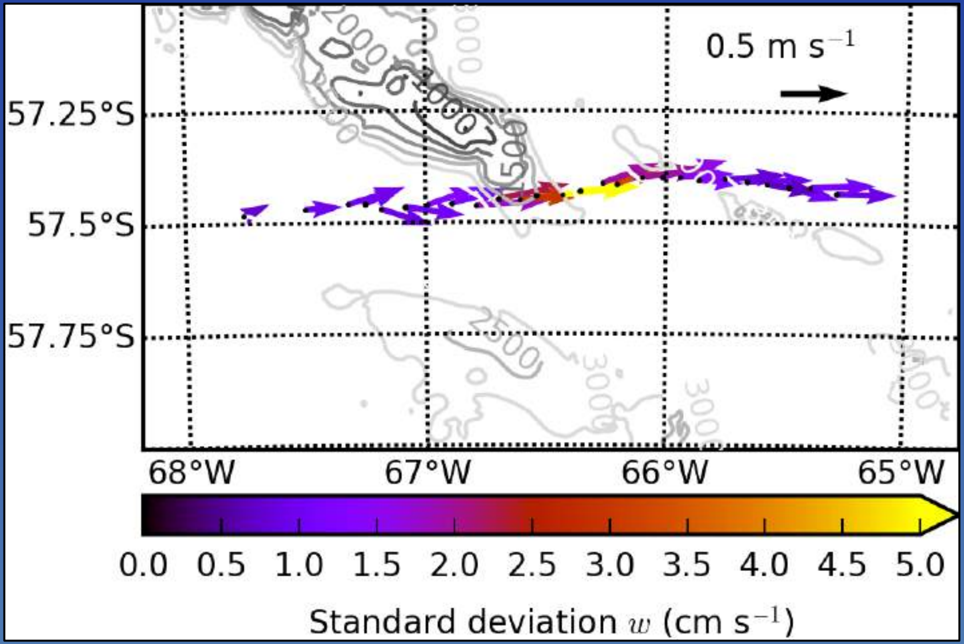
A large lee wave was observed here, as the ACC jet flowed over a steep, ~1500 m tall ridge extending ~20 km across.

Cusack *et al.* (2017)

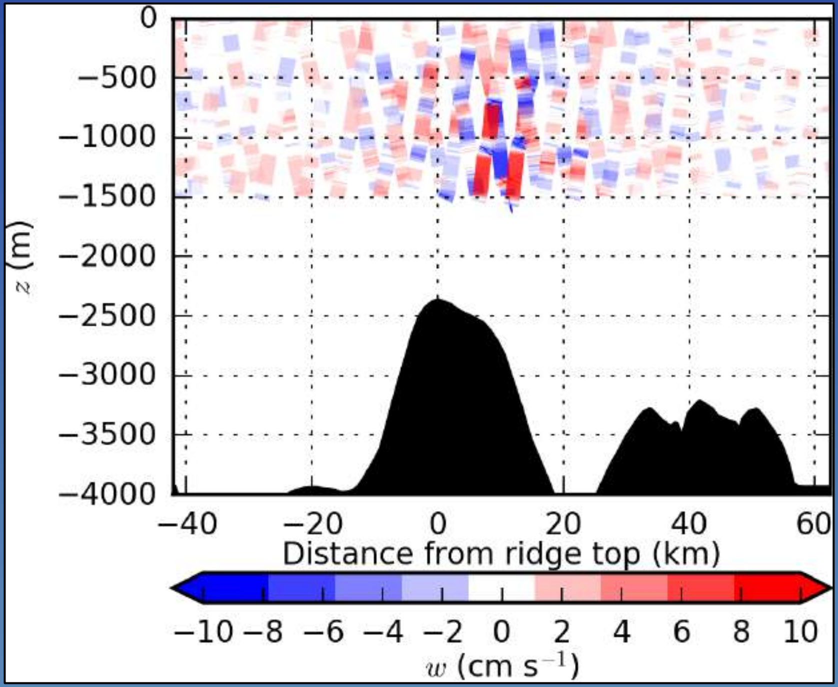
The role of small-scale topography on the dynamical balance of the ACC

Large vertical velocities over the ridge indicate the presence of a large lee wave, generated as the ACC jet impinges on the ridge.

Horizontal velocity (vector) and rms vertical velocity (colour) measured by one of the EM-APEX floats



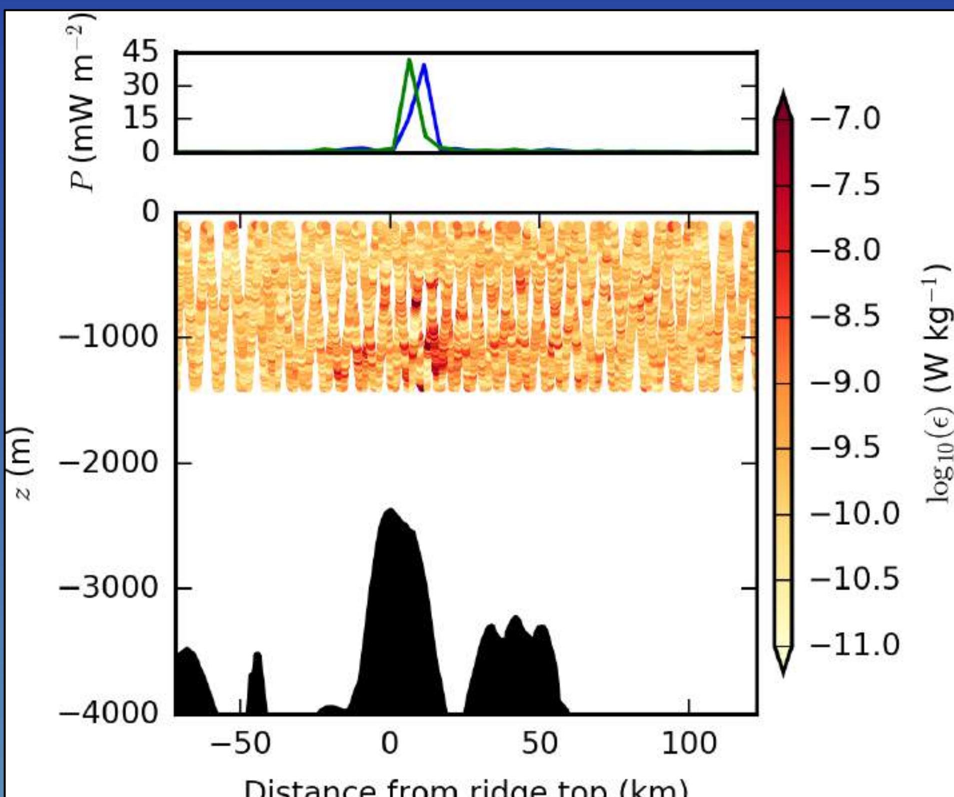
Vertical velocity (colour) measured by the EM-APEX floats



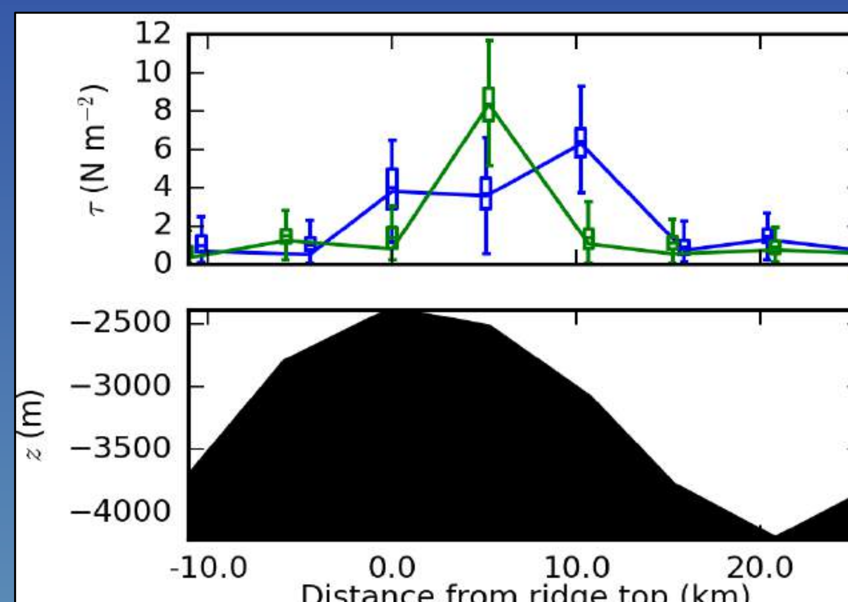
The role of small-scale topography on the dynamical balance of the ACC

The lee wave is associated with intense turbulent kinetic energy dissipation and large drag, which suggest that the ridge plays an important role in the regional energy and momentum budgets of the ACC jet.

Turbulent kinetic energy dissipation rate (shading), and its vertical integral (lines) quantified from EM-APEX observations. Cf. wind work on the ACC ~ 10 mW m^{-2}.

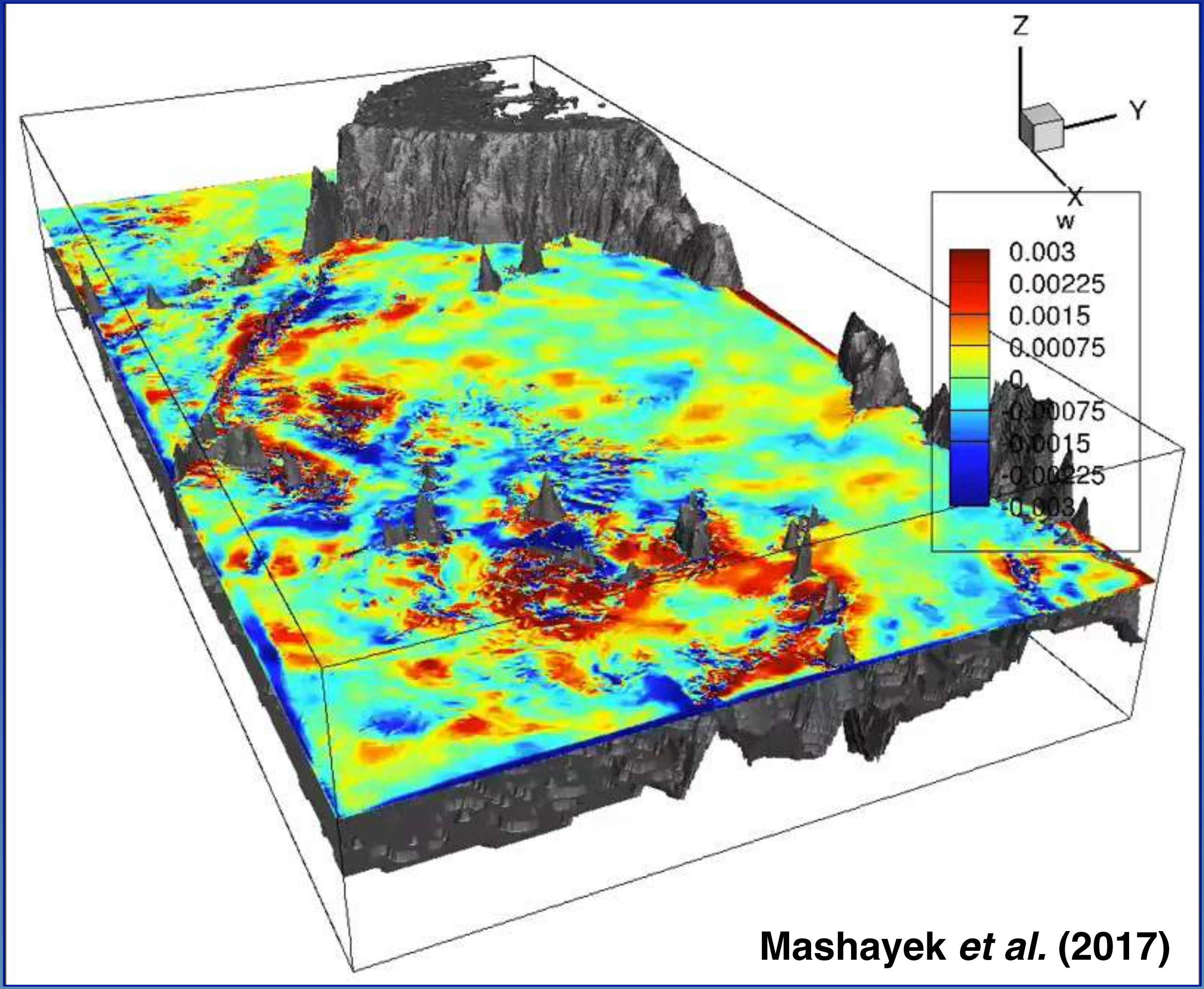


Lee wave drag quantified from EM-APEX observations. Cf. wind stress on the ACC ~ 0.1 N m^{-2}.



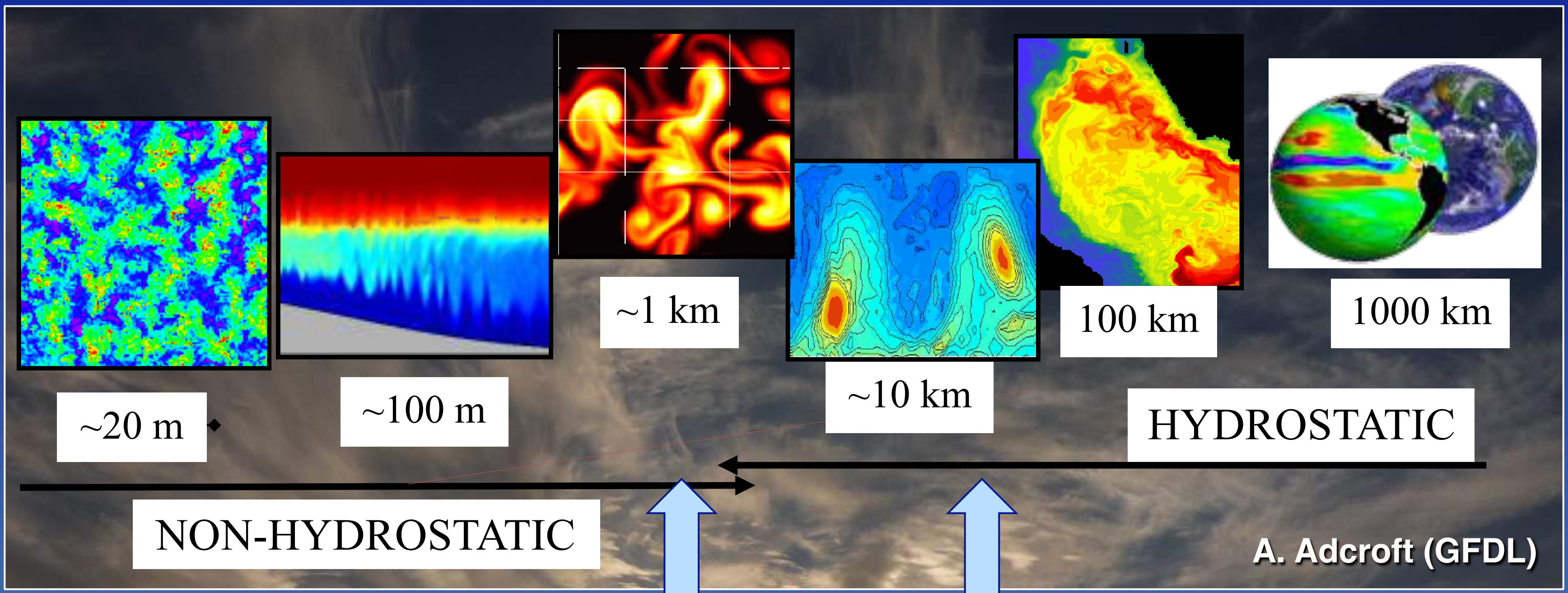
The role of small-scale topography on the dynamical balance of the ACC

A regional model (with horizontal resolution of 500 m) reveals vertical flows and associated rates of turbulent dissipation and wave drag akin to those measured.



Mashayek *et al.* (2017)

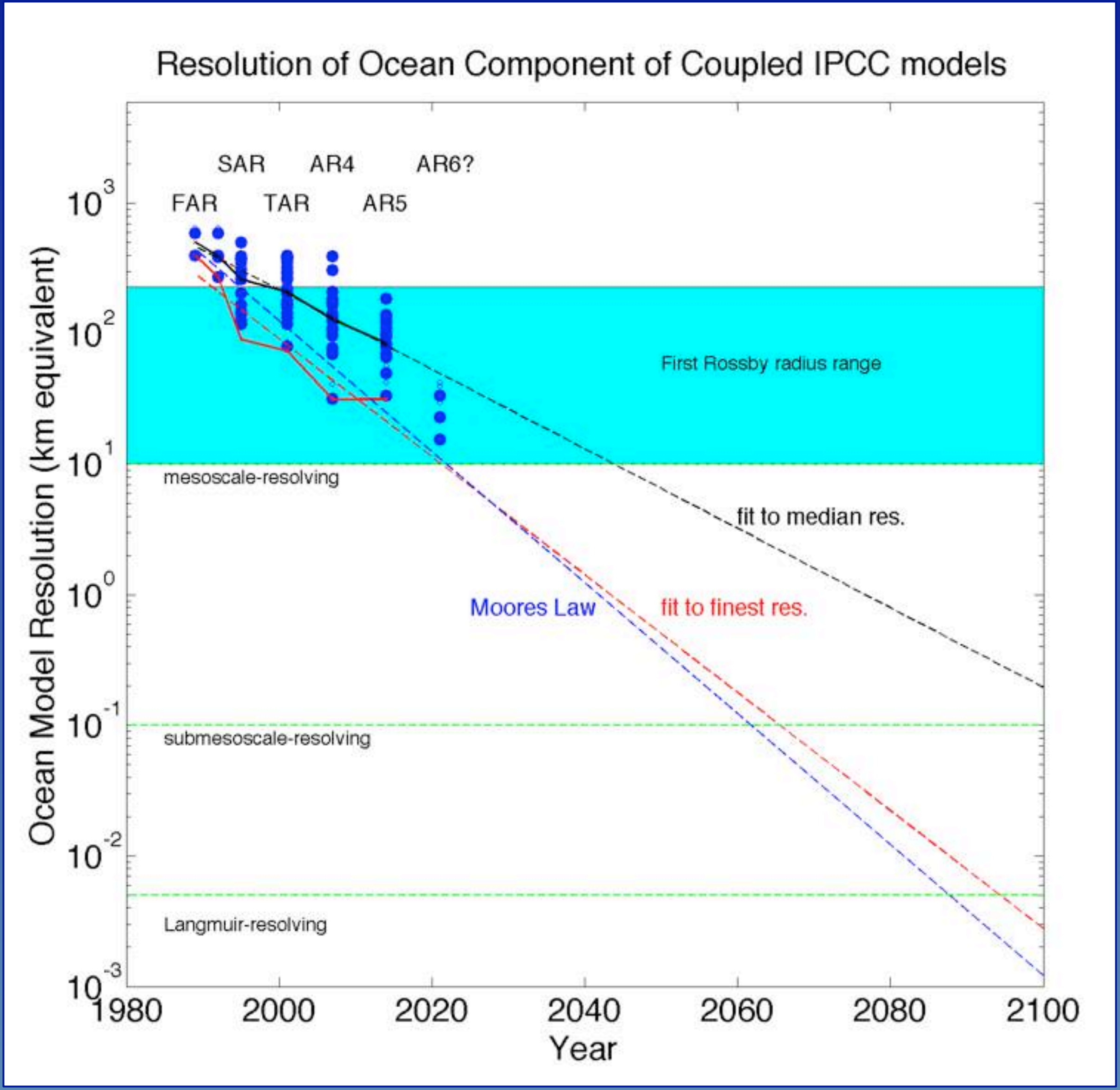
Conclusions and outlook



Submesoscale Revolution
2010s - ?

Mesoscale Revolution
1990s – 2000s

Conclusions and outlook



B. Fox-Kemper (Brown)