Submesoscale turbulence:
A frontier of ocean research

Scott Bachman
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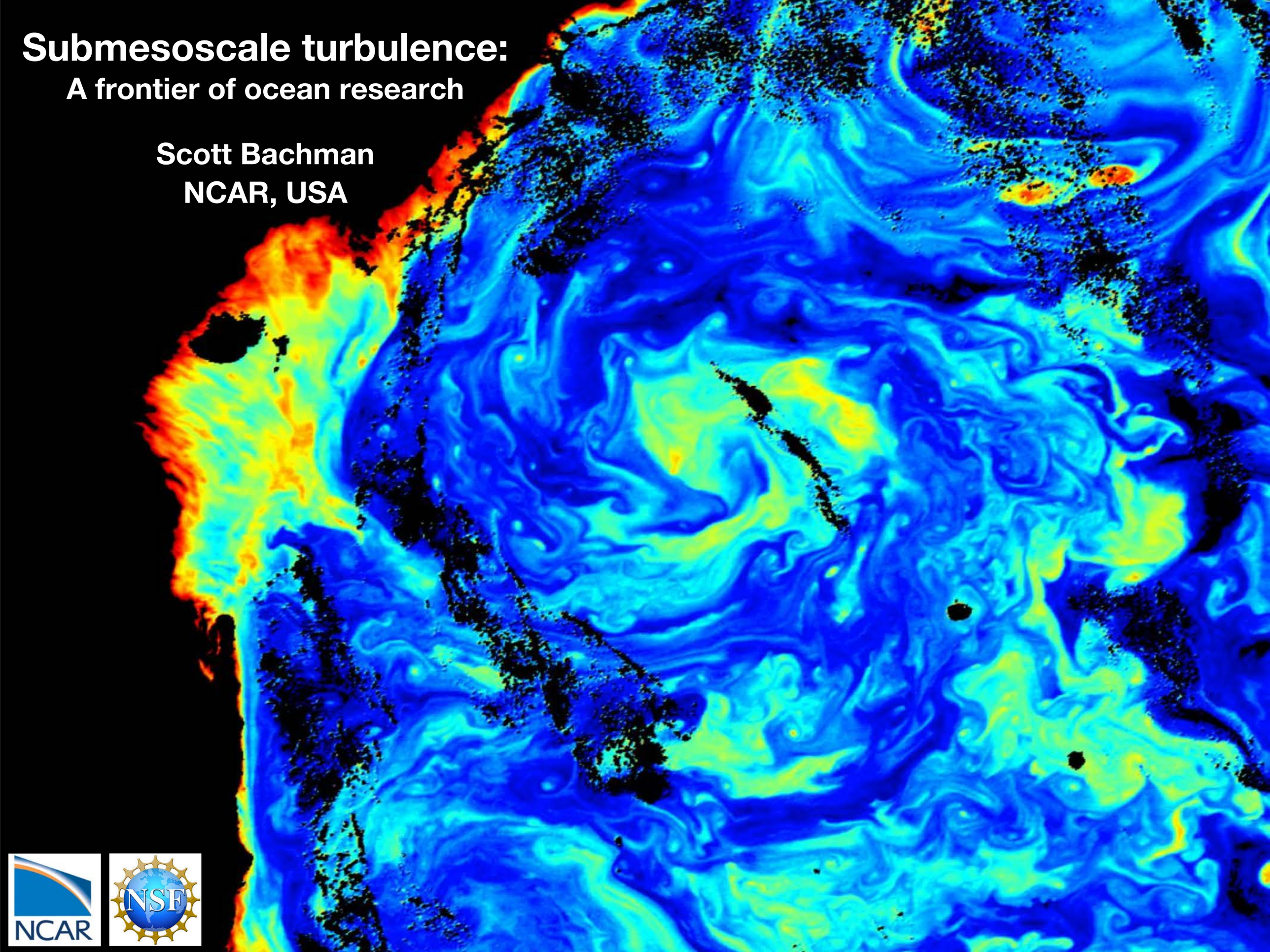

Nobody really knows how ocean submesoscales affect climate extremes.

Oceanic mesoscale eddies
$1/10^\circ$ **POP simulation**

Oceanic mesoscale eddies
$1/10^\circ$ POP simulation

What are submesoscales?

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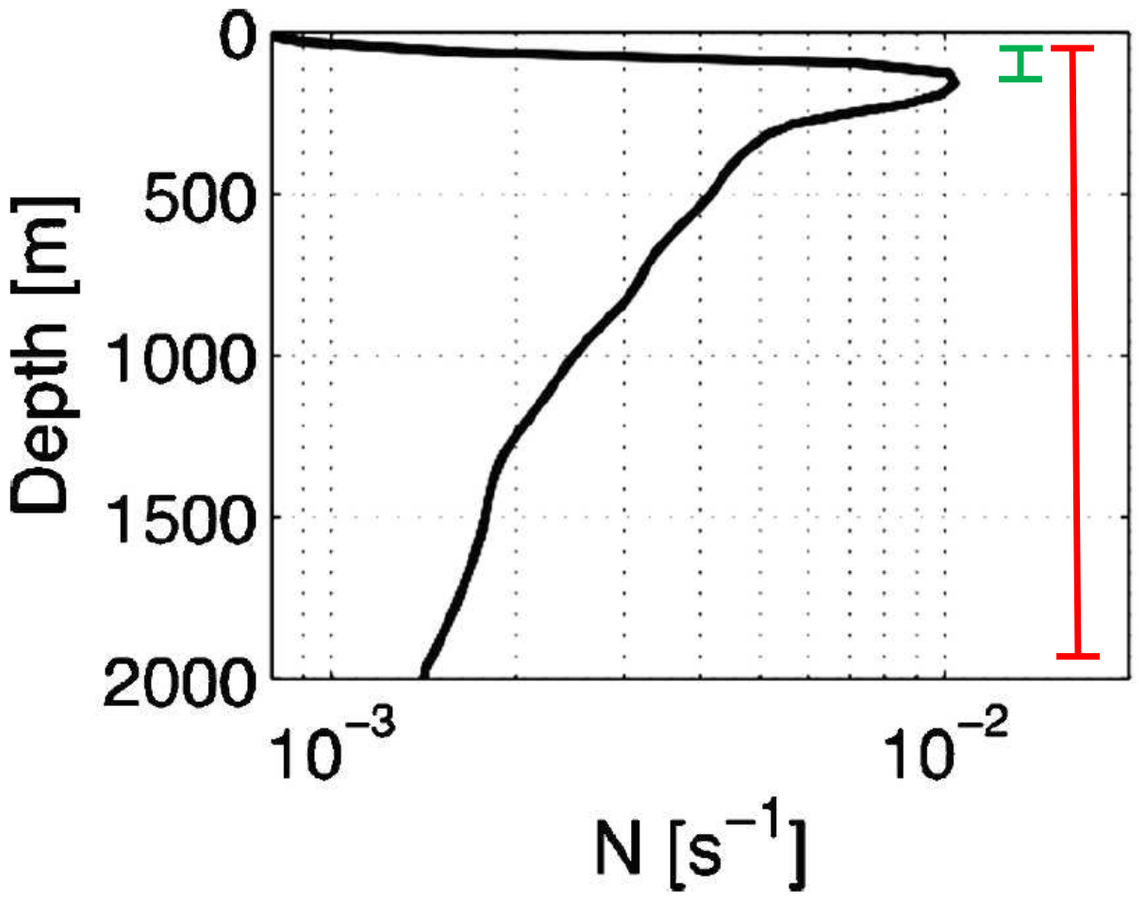


SeaSoar buoyancy frequency profile, $(35^\circ N,\ 132^\circ W)$

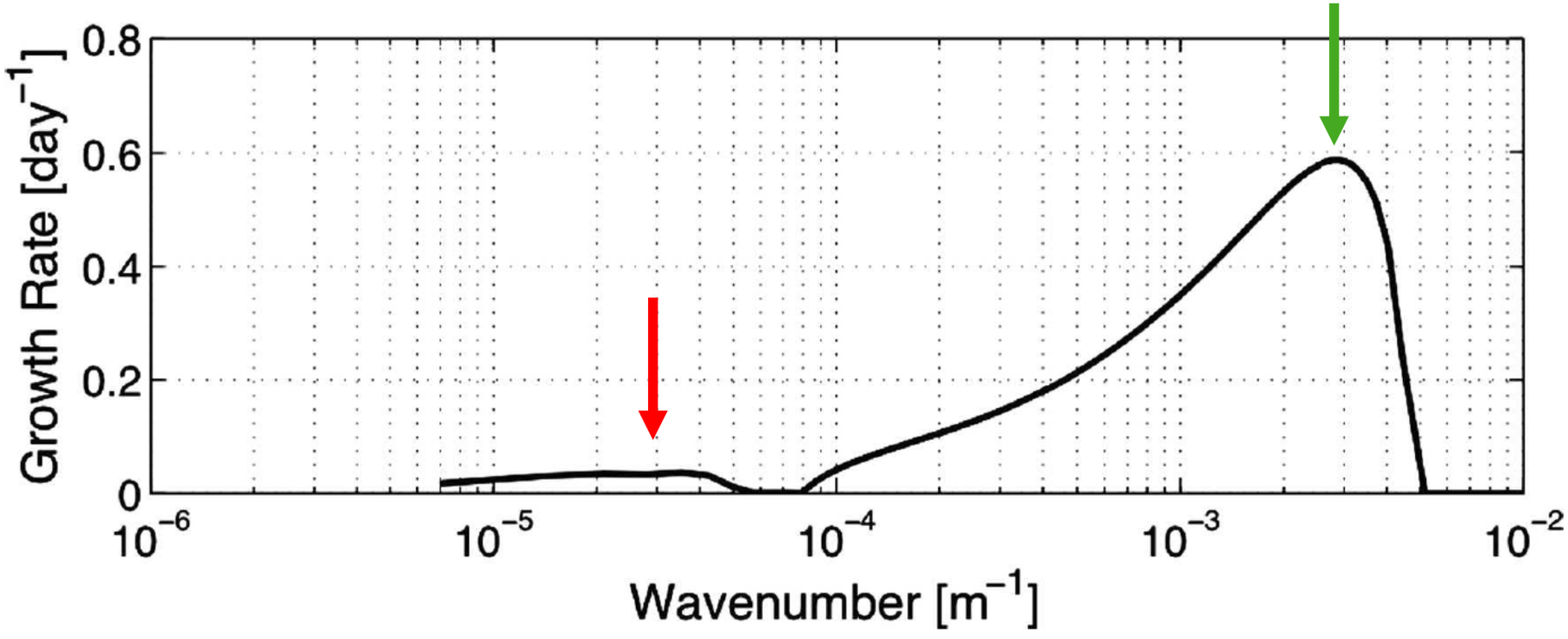
$$L \sim \frac{NH}{f} \qquad f = 10^{-4}\ \mathrm{s}^{-1}$$

$$N \sim 1 \times 10^{-3}\ \mathrm{s}^{-1}$$

$$H = 100\ \mathrm{m}$$

$$L = O(1\ \mathrm{km})$$

(SUBMESOSCALE)

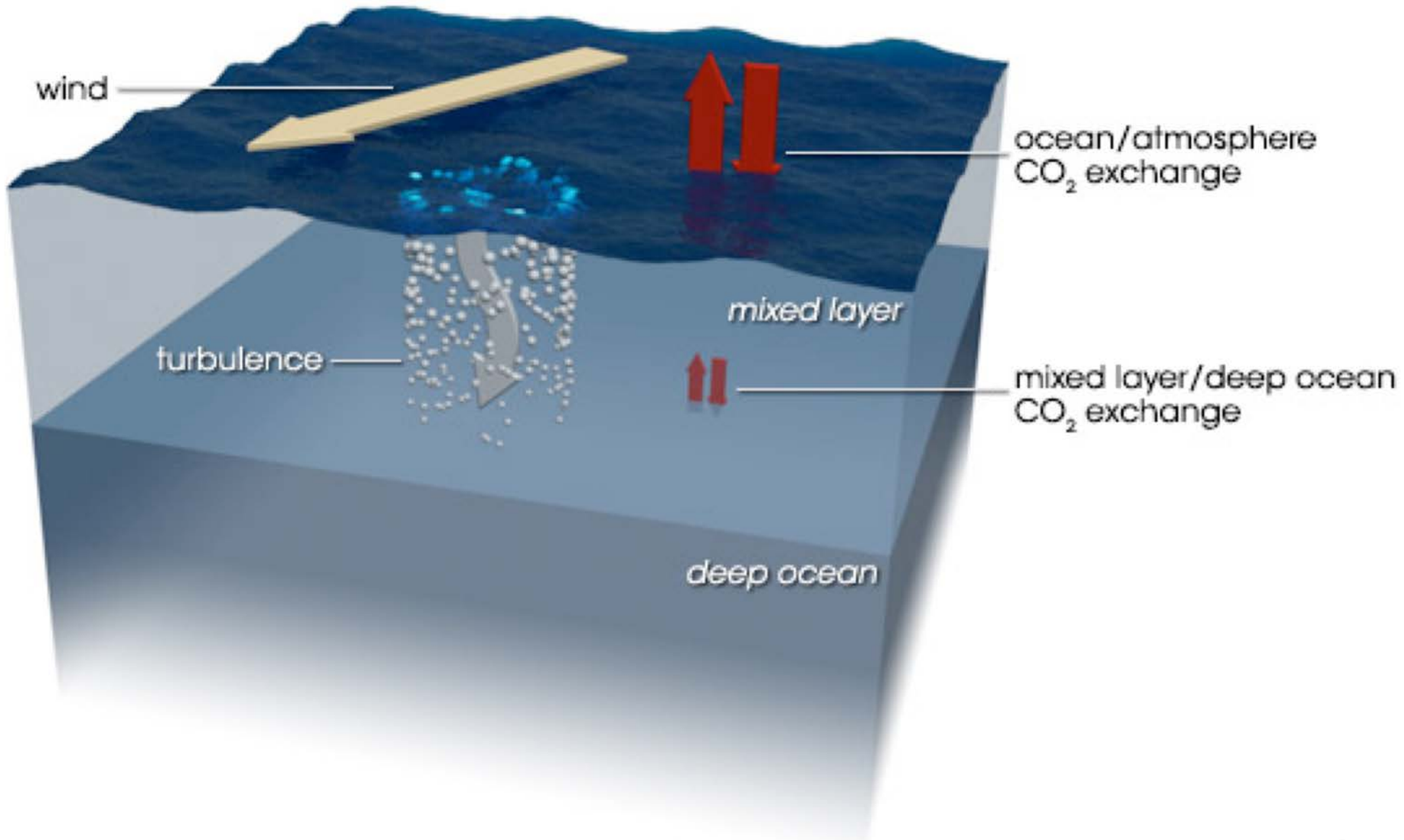


Boccaletti et al., (2007)

What are submesoscales?

$$Ro = O(1)$$

$$Ri_b = O(1)?$$



Submesoscale dynamics are generally associated with the surface mixed layer, the contact point between the ocean and the atmosphere.

Courtesy: http://earthobservatory.nasa.gov/Features/OceanCarbon/

Why are submesoscales a “frontier”?

OBSERVATIONAL

Too small/fast for ship surveys

Too big for shipboard instrument detection

Too small for most satellites

Hard to distinguish from IGWs in vertical profiles or single-point time series

THEORETICAL

Not well-described by simplified equation sets.
Ro = 1, Ri = 1. Marginal control by rotation/stratification.

N(z) highly variable in SBL and BBL. Can’t just scale it

DYNAMICAL

Affected heavily by the atmosphere

COMPUTATIONAL

Too small for climate models
(and many regional models)

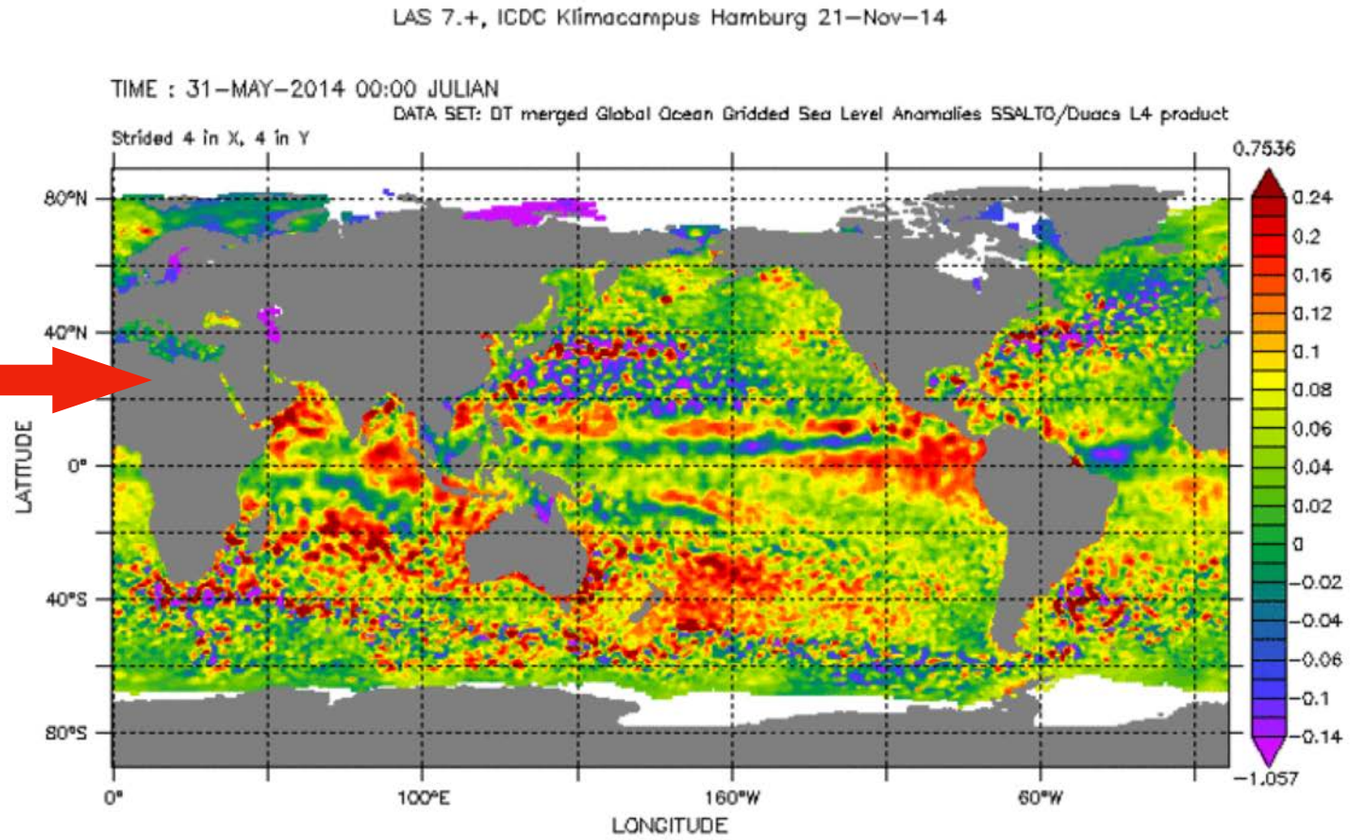
Submesoscales: an observational "frontier"

Too small for most satellites

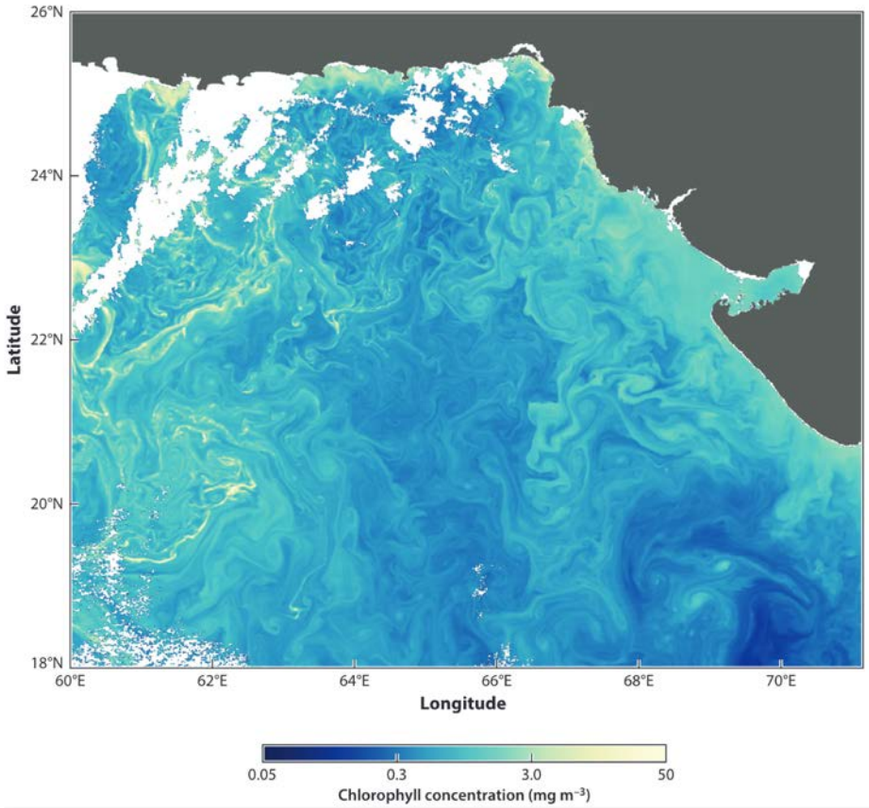
$1/4^\circ$ **resolution** ≈ 25 **km**

Submesoscales: $1 - 10$ **km**

$Ro = \mathcal{O}(1)$ **: "Geostrophic velocity" likely not a good approximation**

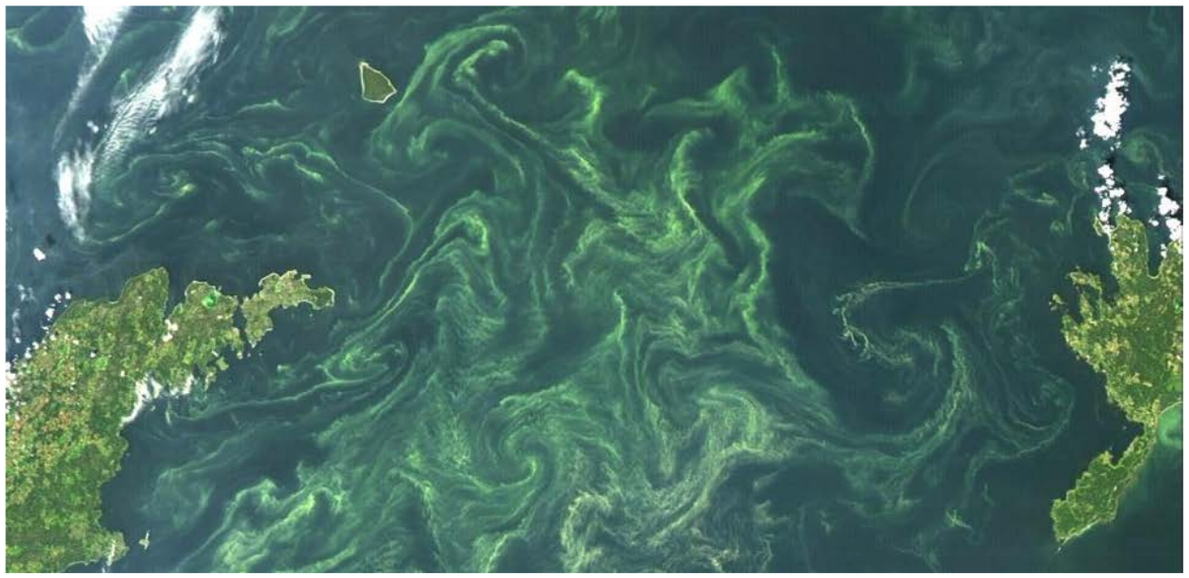


Sea Level Anomalies 2014 (m) **Courtesy: ICDC, U. Hamburg**



MODIS Arabian Sea chlorophyll, 2005

Mahadevan (2016)



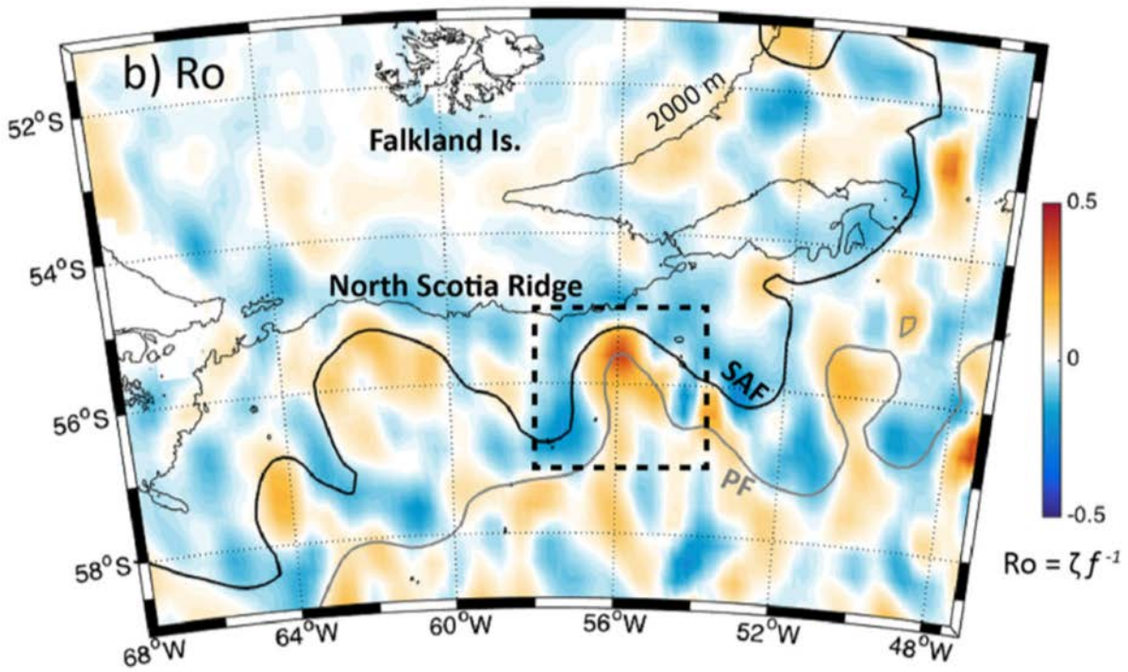
MODIS enhanced-color cyanobacteria (Baltic Sea, 2003)

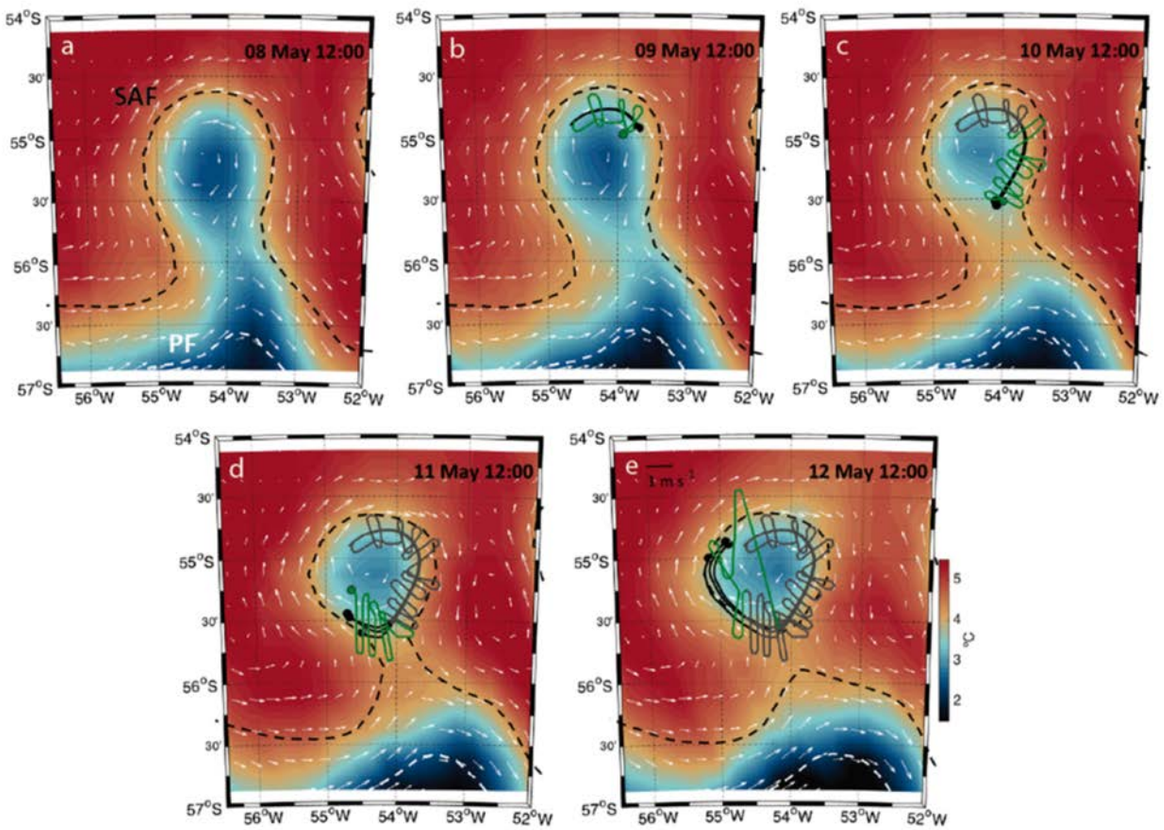
http://www.wimsoft.com/Various_HABs/Satellite_detection_of_HABs.htm

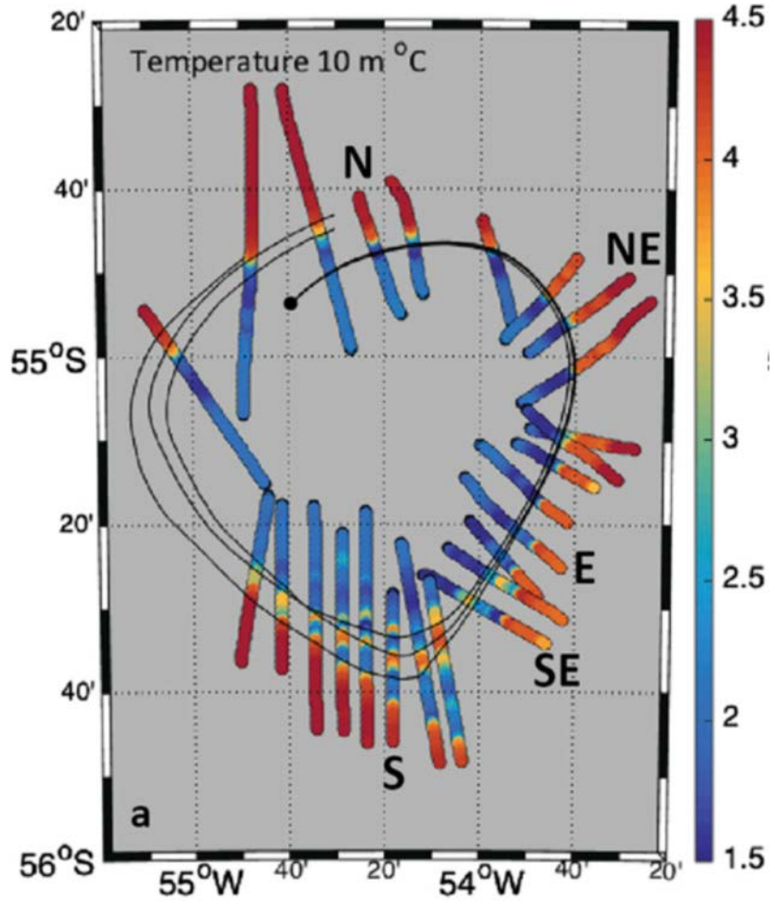
Submesoscales: an observational "frontier"

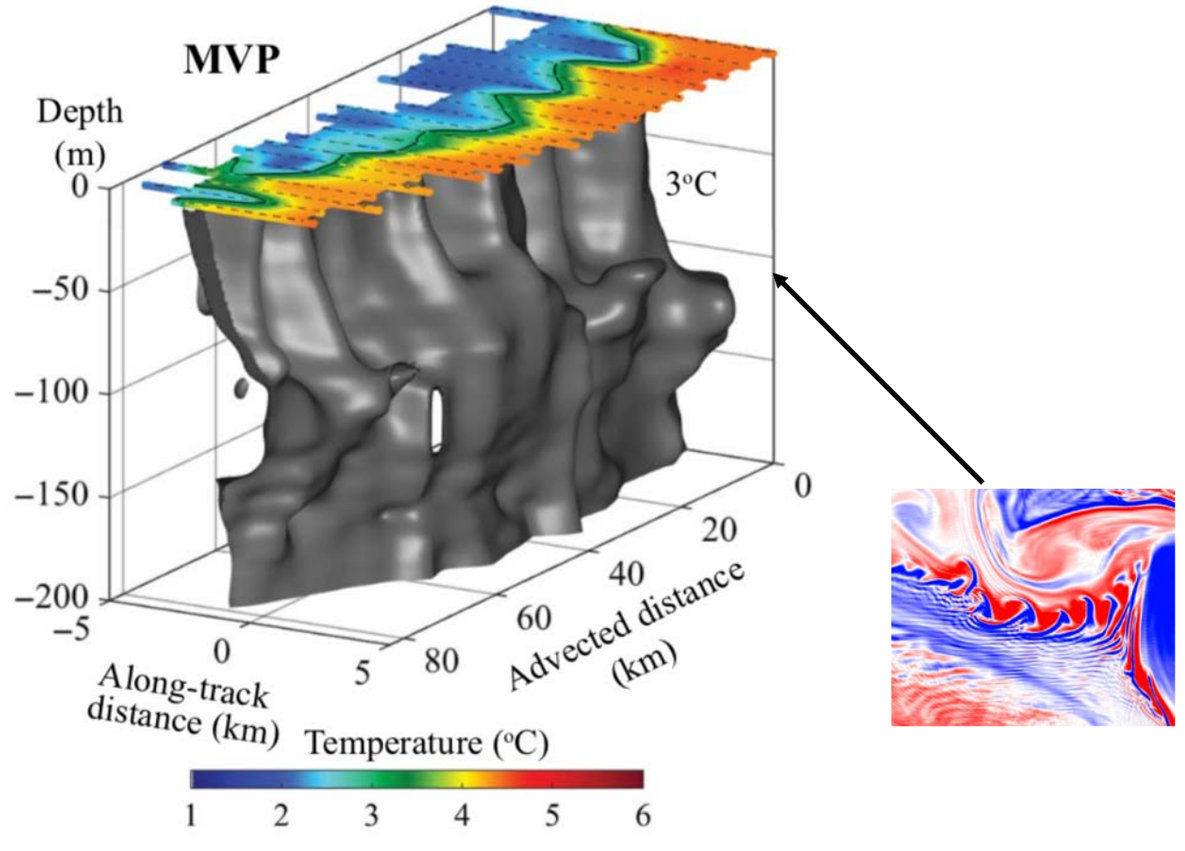
Too small/fast for ship surveys

(www.smiles-project.org)









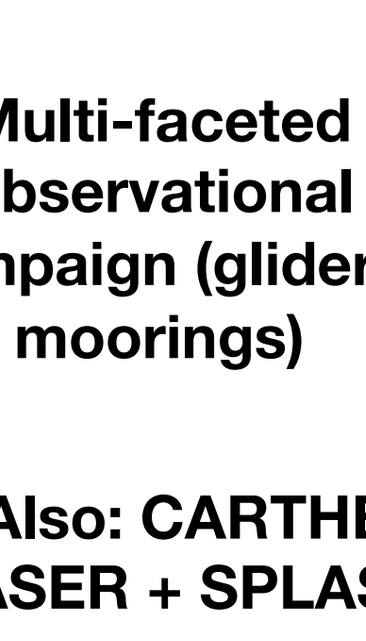
Submesoscales: an observational "frontier"

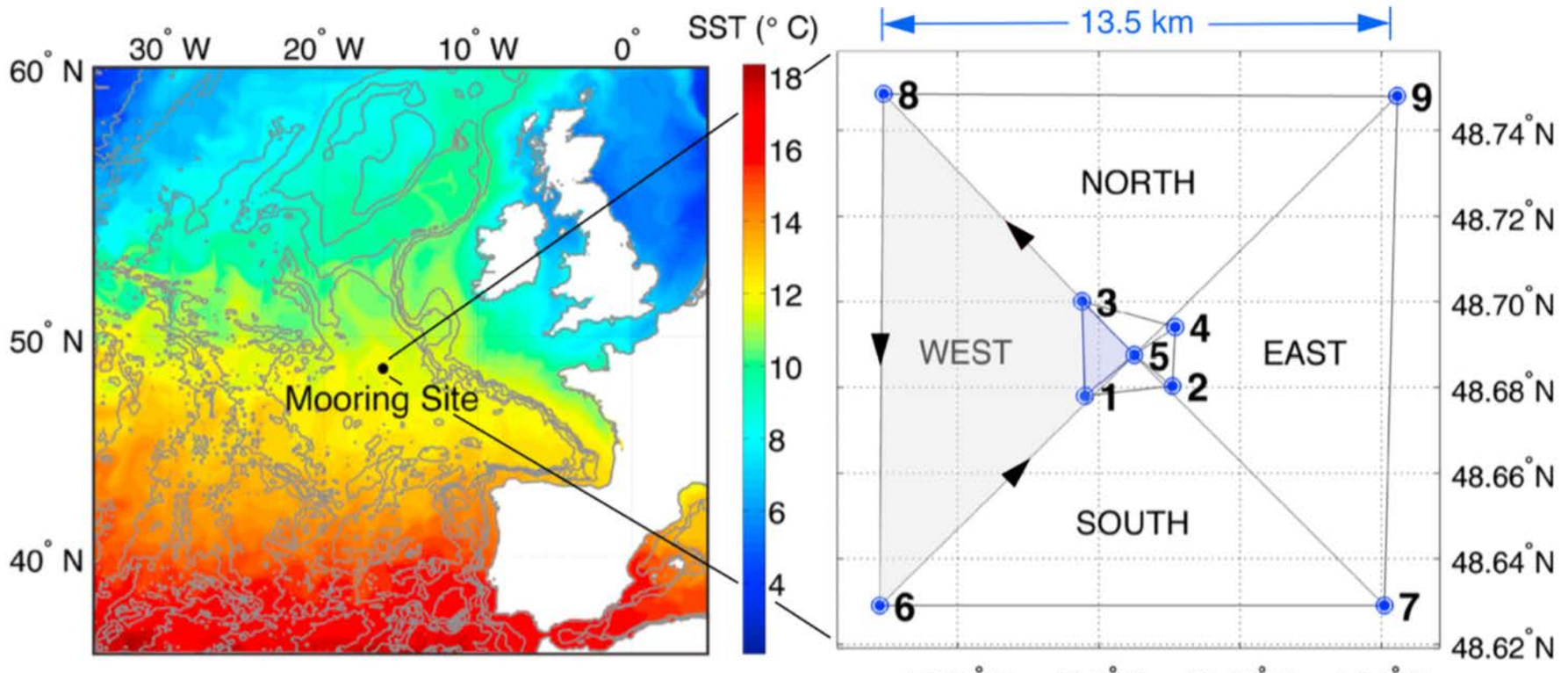
OSMOSIS (2012-2013)

Multi-faceted observational campaign (gliders, moorings)

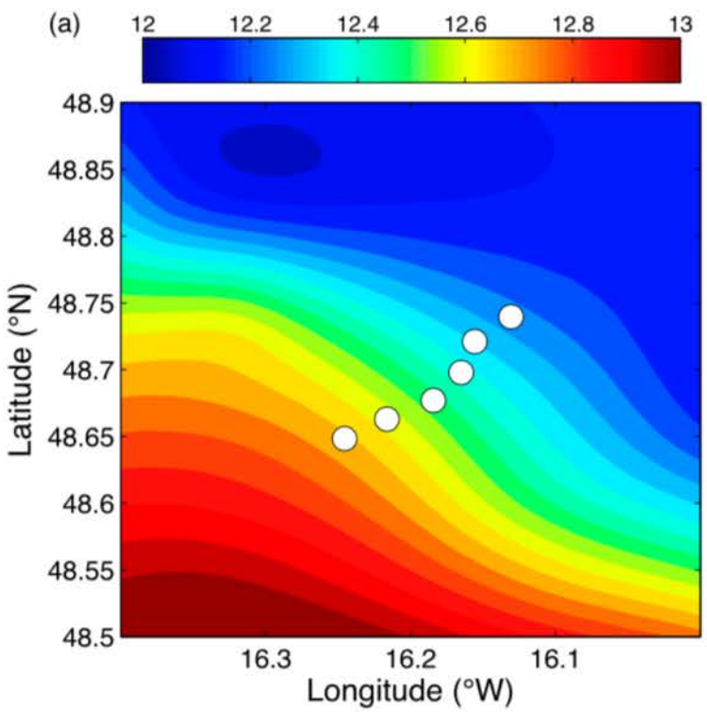
Also: CARTHE (LASER + SPLASH)

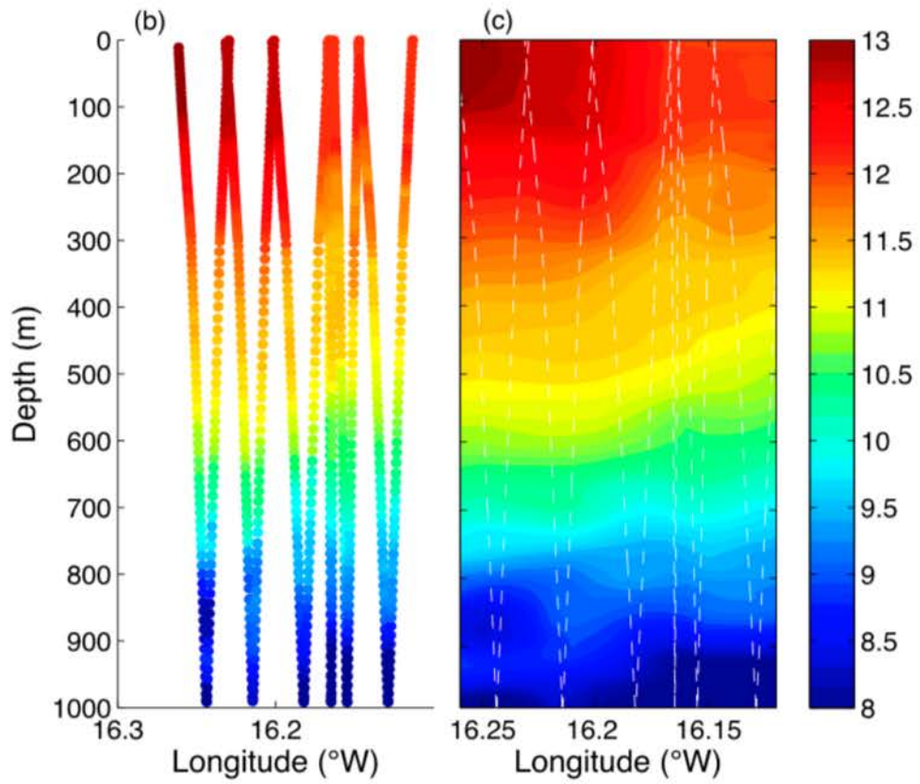
1500 drifters, 15000 drift cards, 5 drones, 6 boats, 2 planes, aerostats, etc.





Buckingham et al. (2016)



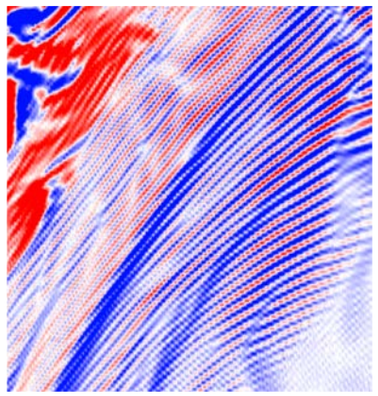


Thompson et al. (2016)

Submesoscales: a theoretical "frontier"

Dynamics:

rotational and balanced



non-rotational and unbalanced

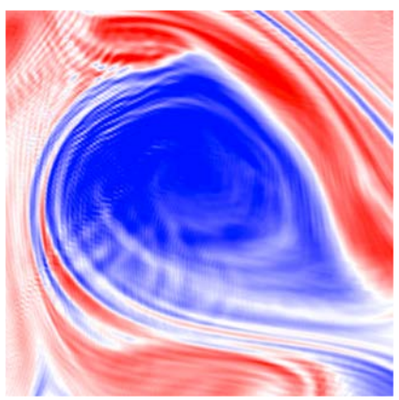
Physics:

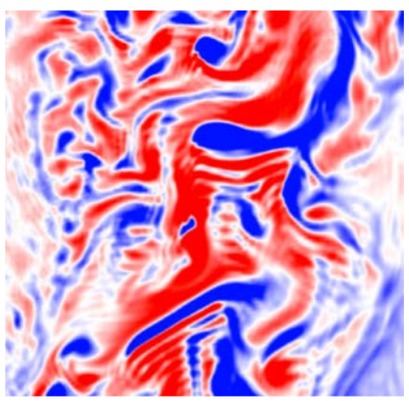
climate forcing → balanced instabilties → forward energy cascade / IG wave emission / turbulent bottom drag → isotropization → dissipation

Descriptors:

planetary scale — mesoscale — submesoscale — microscale

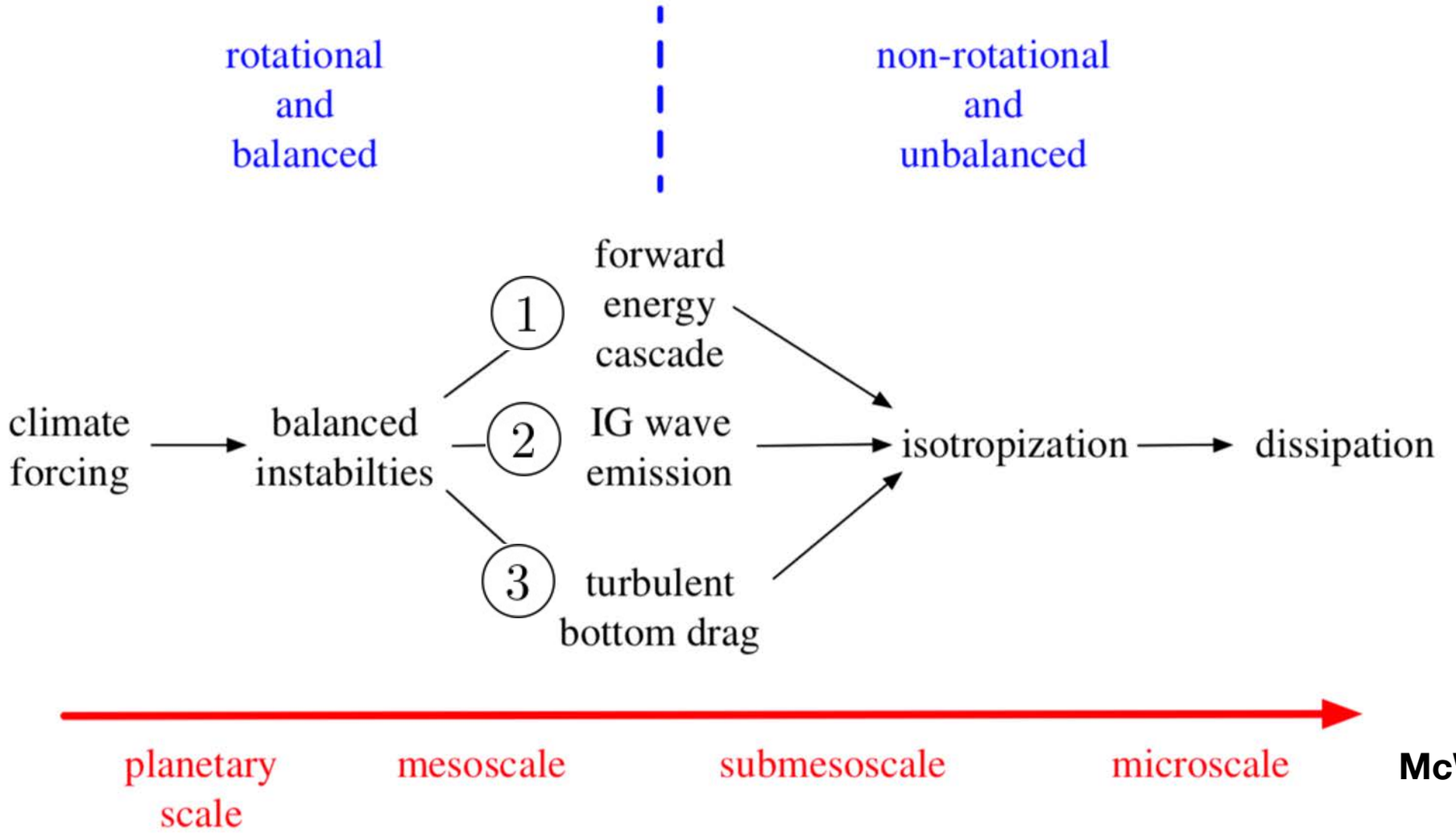
McWilliams (2016)





Equations: **PG** **QG** **"Balanced"** **3D**

Submesoscales: a theoretical "frontier"



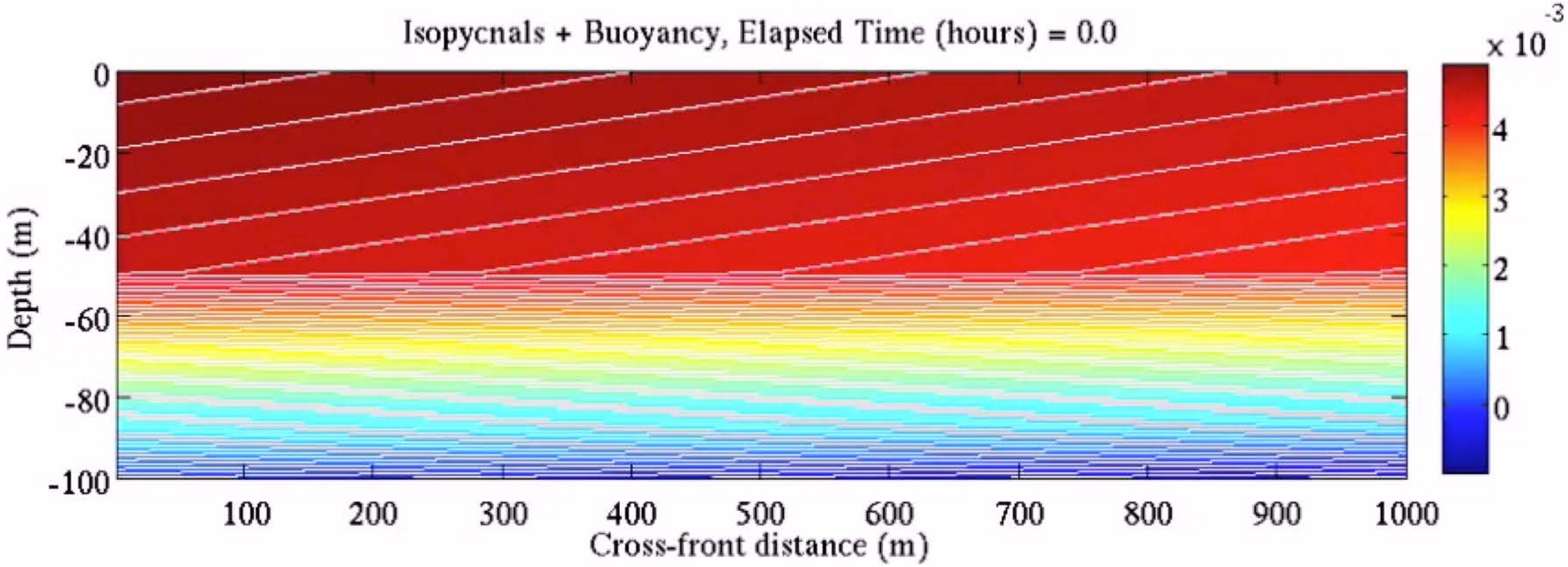
McWilliams (2016)

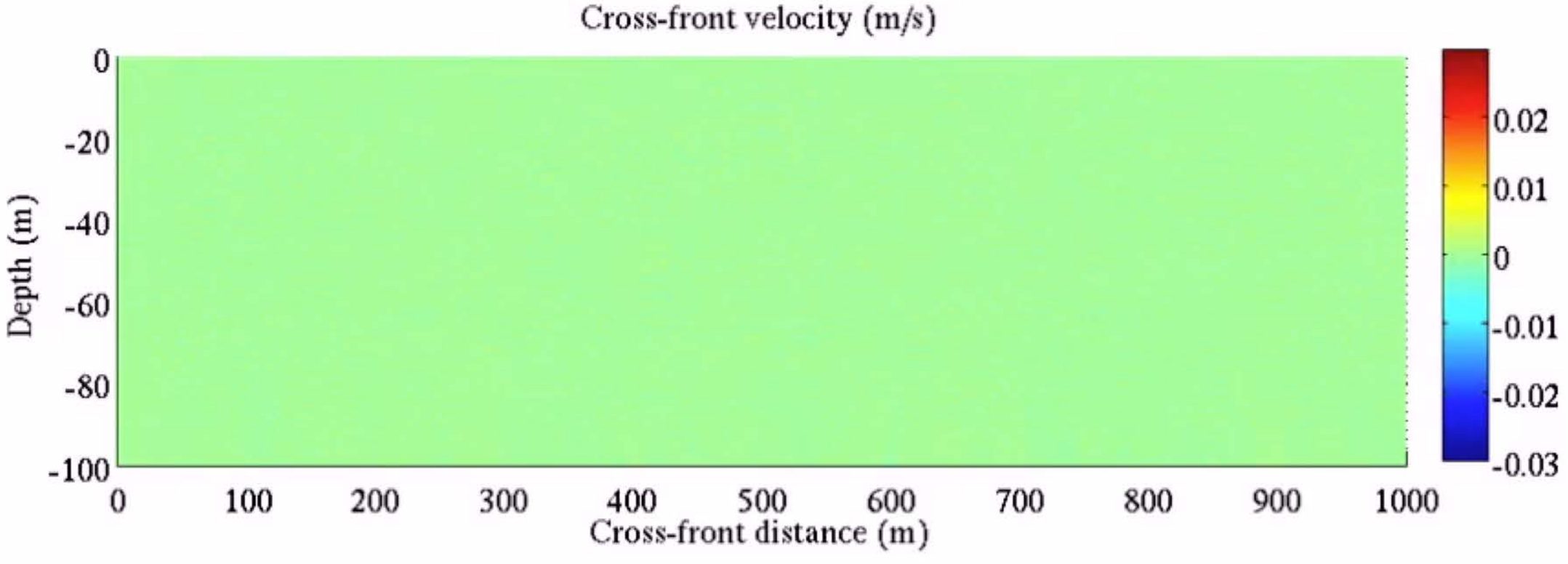
① **Significant downscale energy pathway**

② **"Usually weak"; frontogenesis? (Shakespeare and Taylor, 2014)**

③ **Most ocean flows well-separated from bottom**

Submesoscales: a theoretical "frontier"

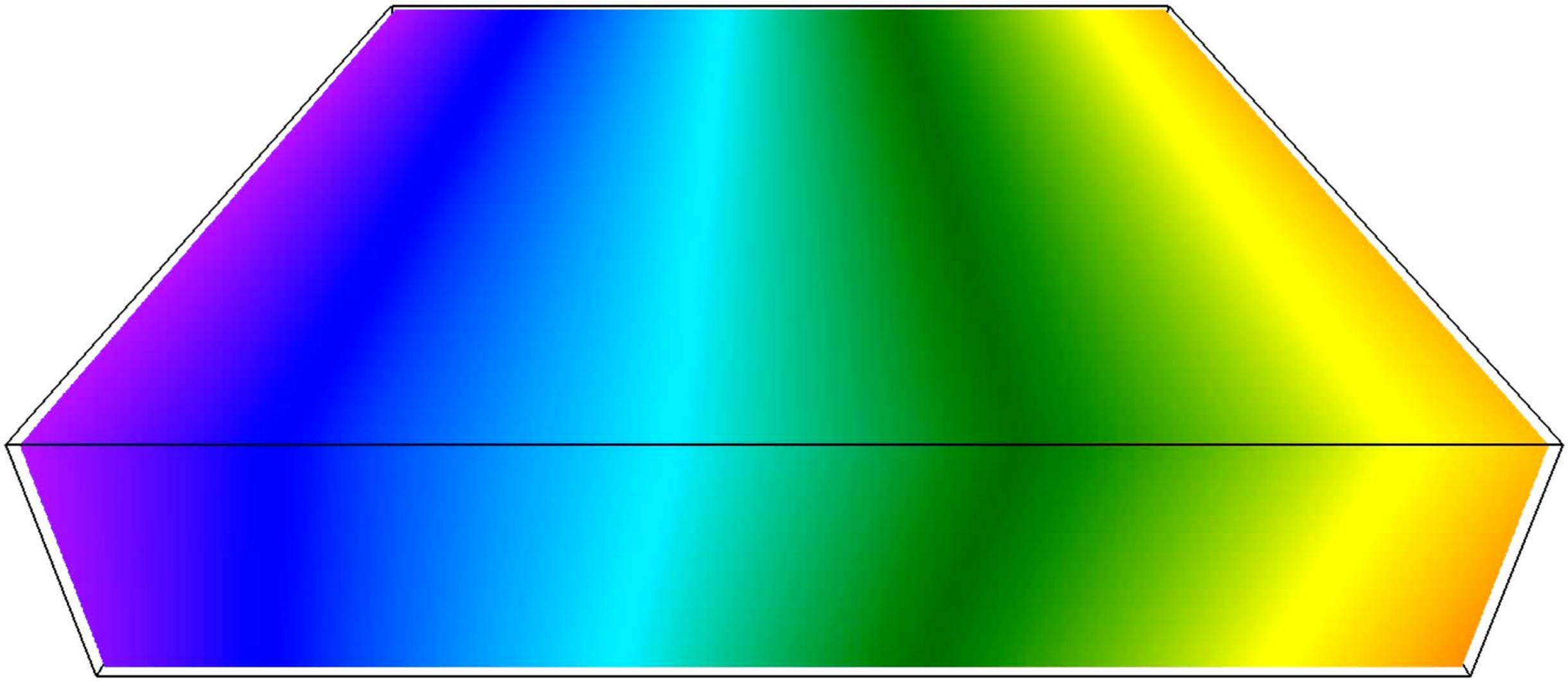




Downscale energy transfer

Movie courtesy of John Taylor

Submesoscales: a theoretical “frontier”



Upscale energy transfer

Movie courtesy of Megan Stamper

Submesoscales: a modelling "frontier"

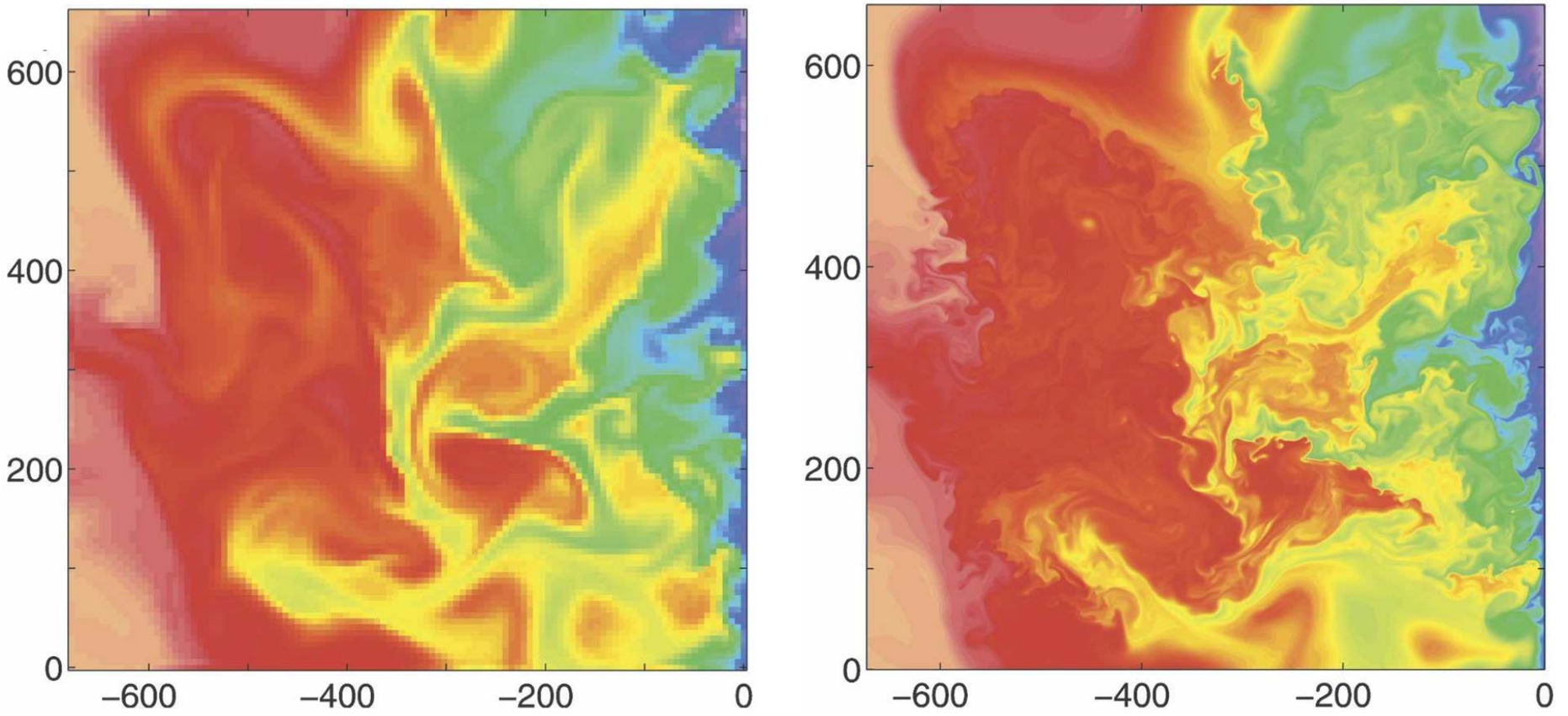


Figure 4 from Capet et al. (2008)

Submesoscale dynamics act on short timescales (O(1) day) and small spatial scales.

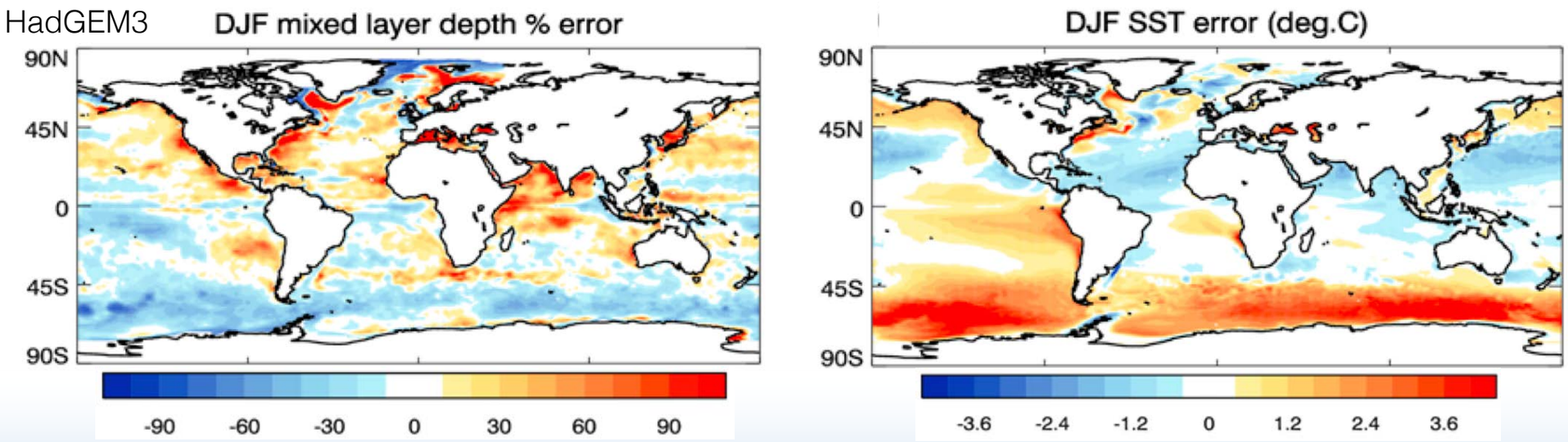


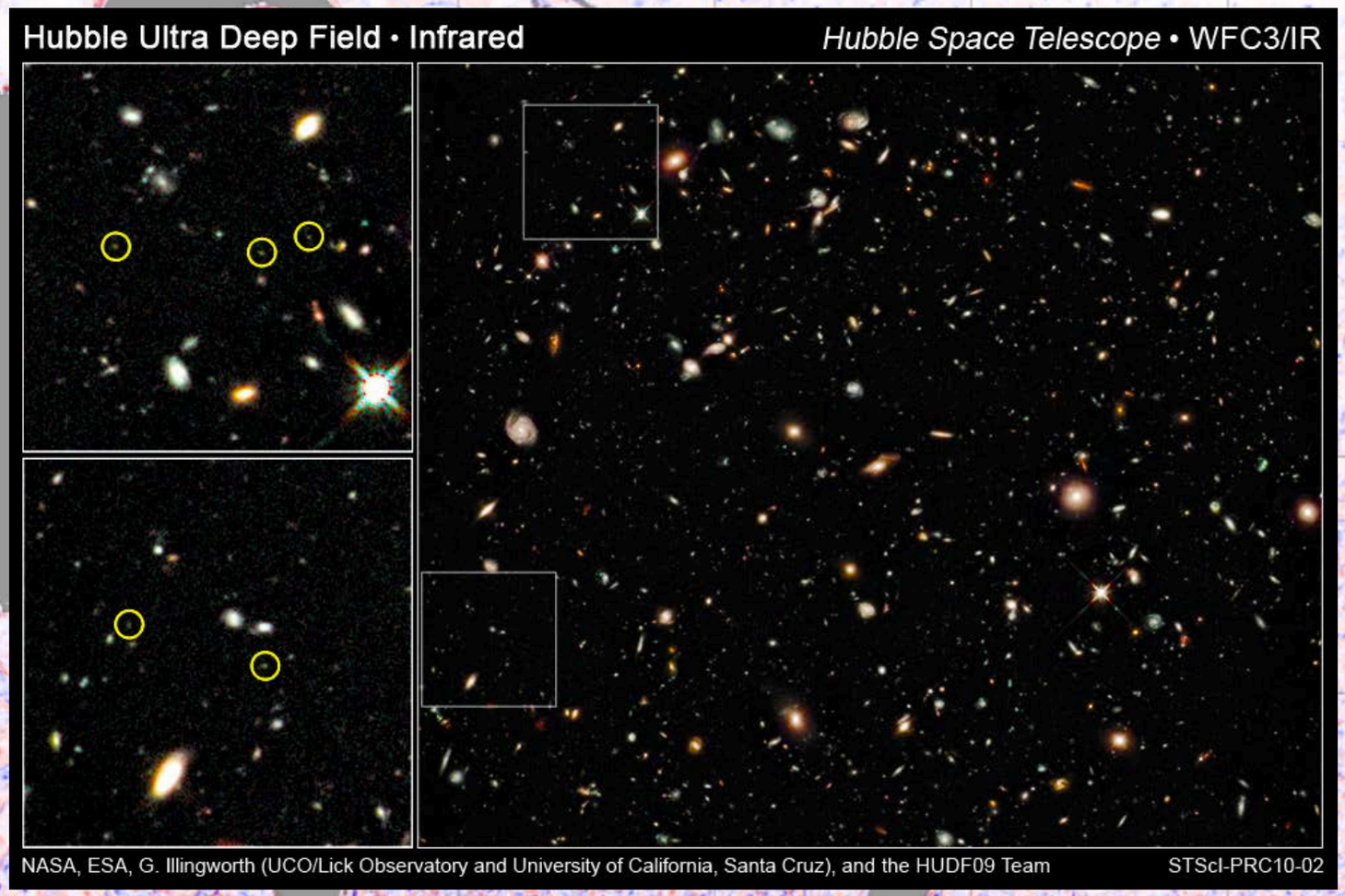
Figure 1 from Belcher et al. (2012)

GCMs have SBL biases in Southern Ocean: too shallow, too warm.

UNIVERSITY OF CAMBRIDGE

Submesoscales: a modelling "frontier"

Largest MITgcm sim ever!
70k cores, NASA Pleiades



Courtesy of Ryan Abernathey

http://maps.actualscience.net/MITgcm_llc_maps/llc_4320/

Submesoscales: Why they matter

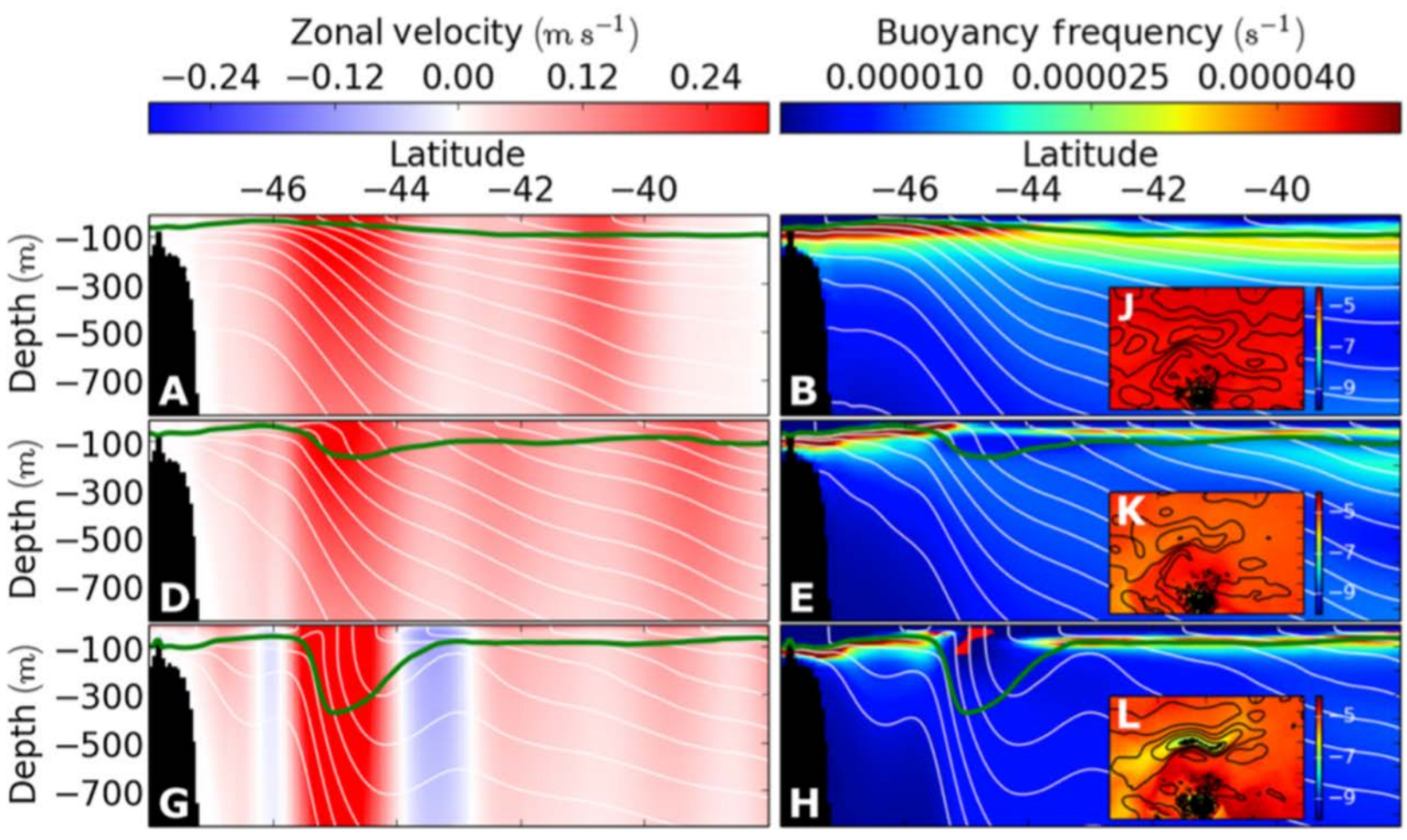
Reduction of usable wind work by mean circulation (Thomas and Taylor, 2010)

Restratification of the SBL (Boccaletti et al., 2007)

Nutrient flux into euphotic zone (Mahadevan et al., 2012; Omand et al., 2015; Mahadevan, 2016)

Long-range transport of chemical and water mass properties (Wang and Dewar, 2003)

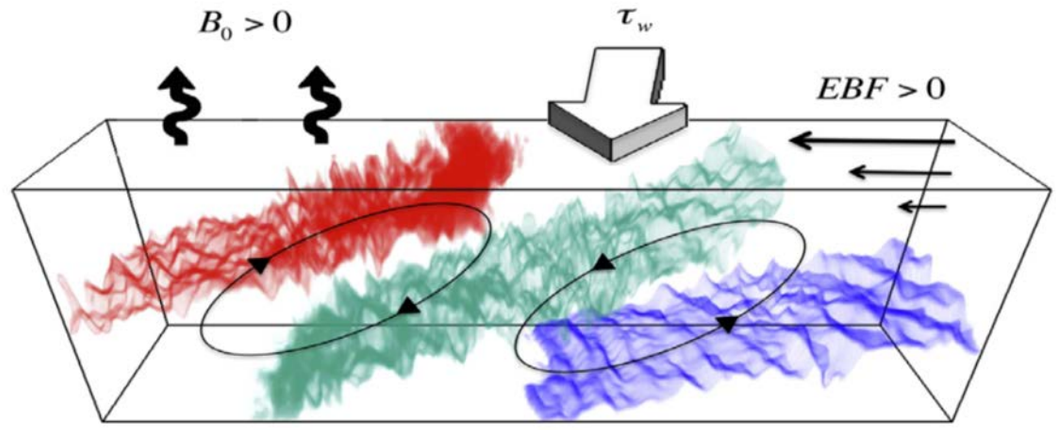
Modulate ventilation of mode waters (e.g. Klocker, 2018)



Klocker (2018)

Submesoscales: Trendy dynamical topics

Boundary PV injection/extraction
(Thomas and Ferrari, 2008; Callies and Ferrari, 2018; Wenegrat et al., 2018)



Bachman et al. (2017)

Barotropic suppression of submesoscales
(Taylor et al., 2018; Stamper et al., 2018; Bachman et al., 3450?)

Surface wave interactions
(McWilliams and Fox-Kemper, 2013; Hamlington et al., 2014; Haney et al., 2015)

Bathymetric effects and the BBL
(Lazar et al., 2017; Callies, 2018; Wenegrat et al., 2018b)

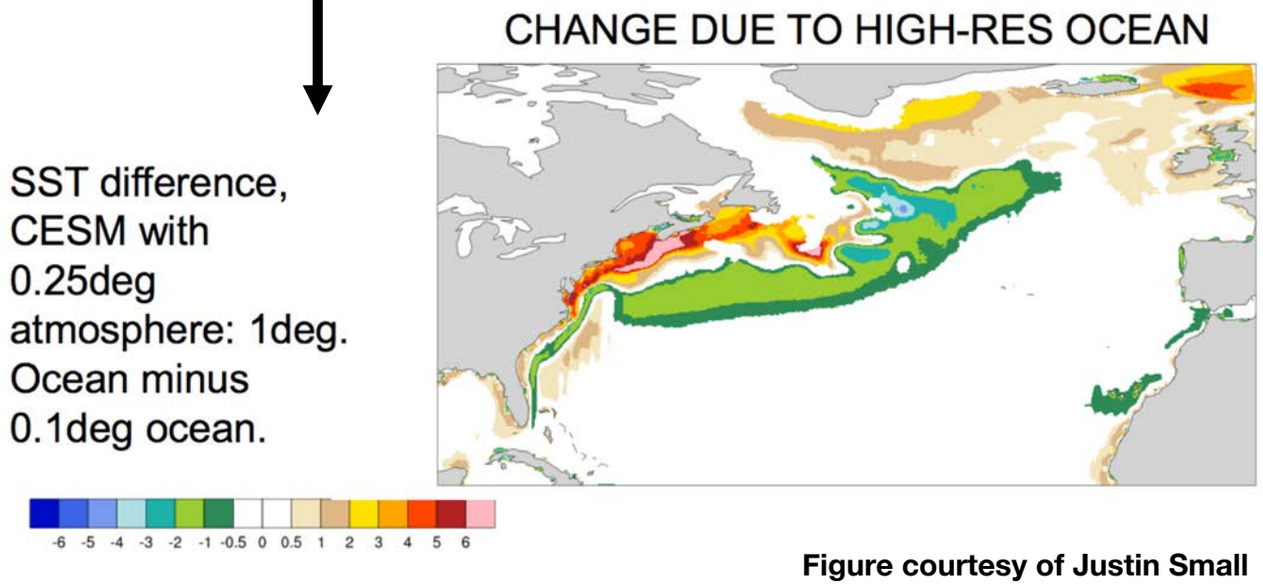
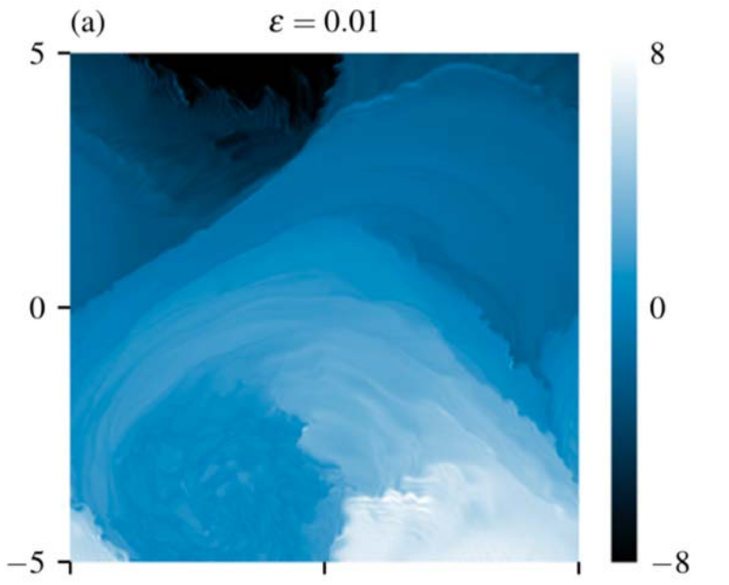
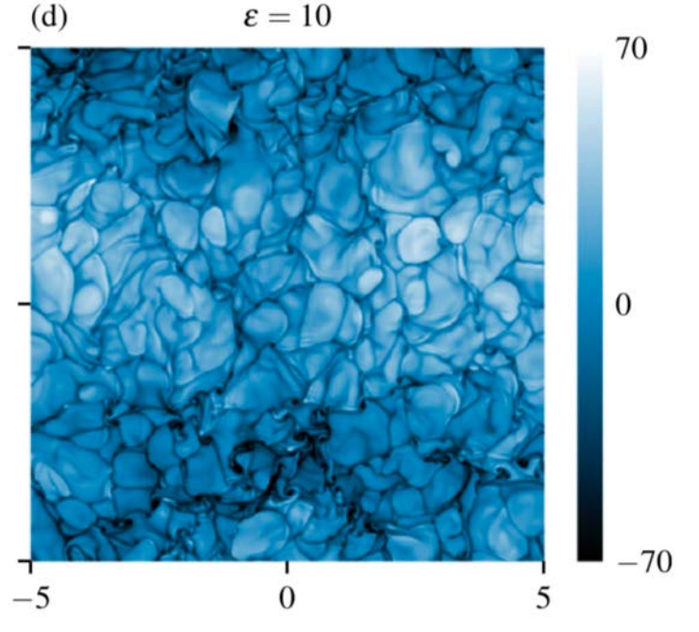


Figure courtesy of Justin Small





Callies and Ferrari (2018)

Submesoscales and climate

We do *not* understand how submesoscales will impact future climate (or vice versa)
(ongoing collaboration between NCAR and U. Hawaii)

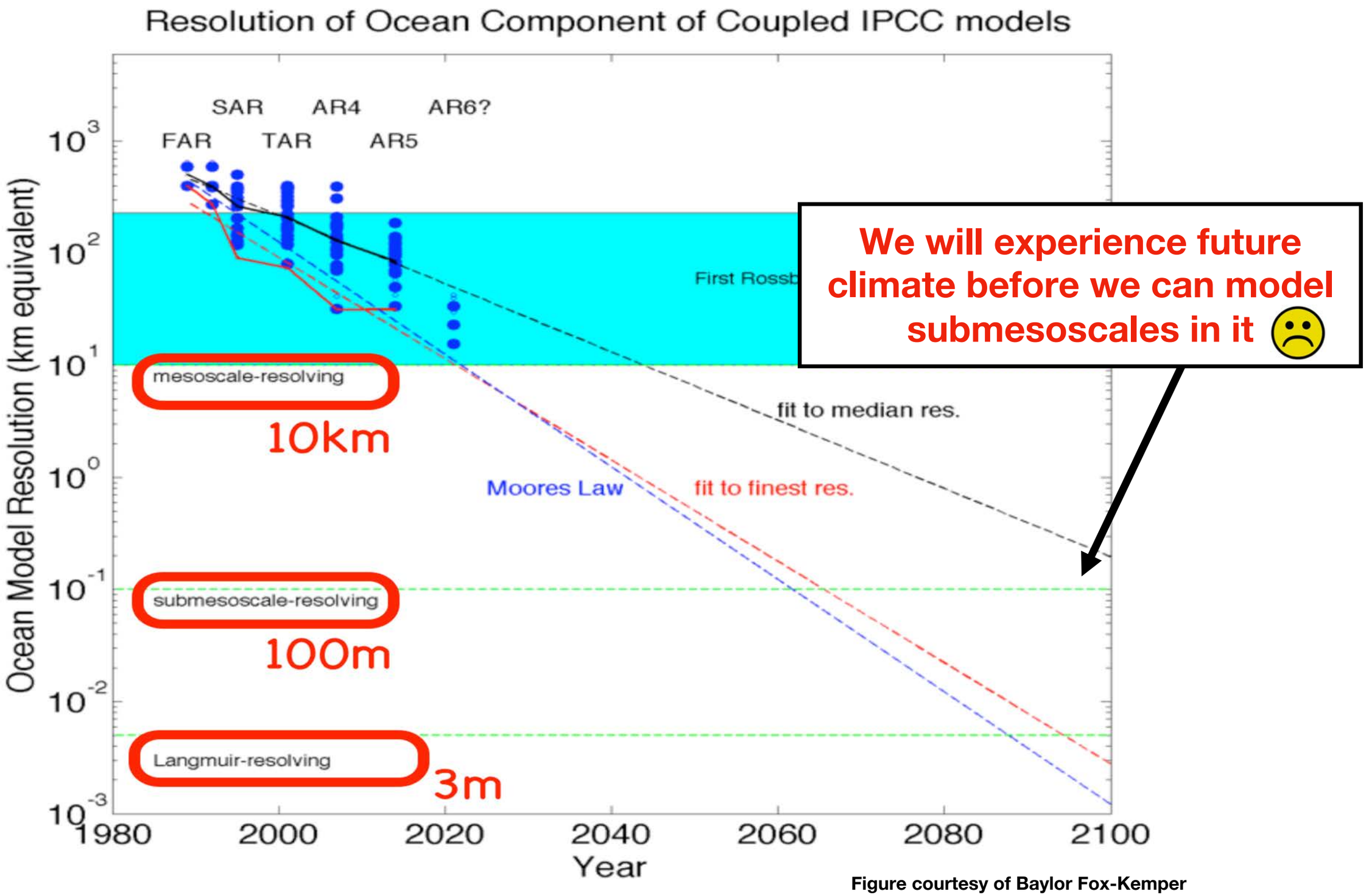
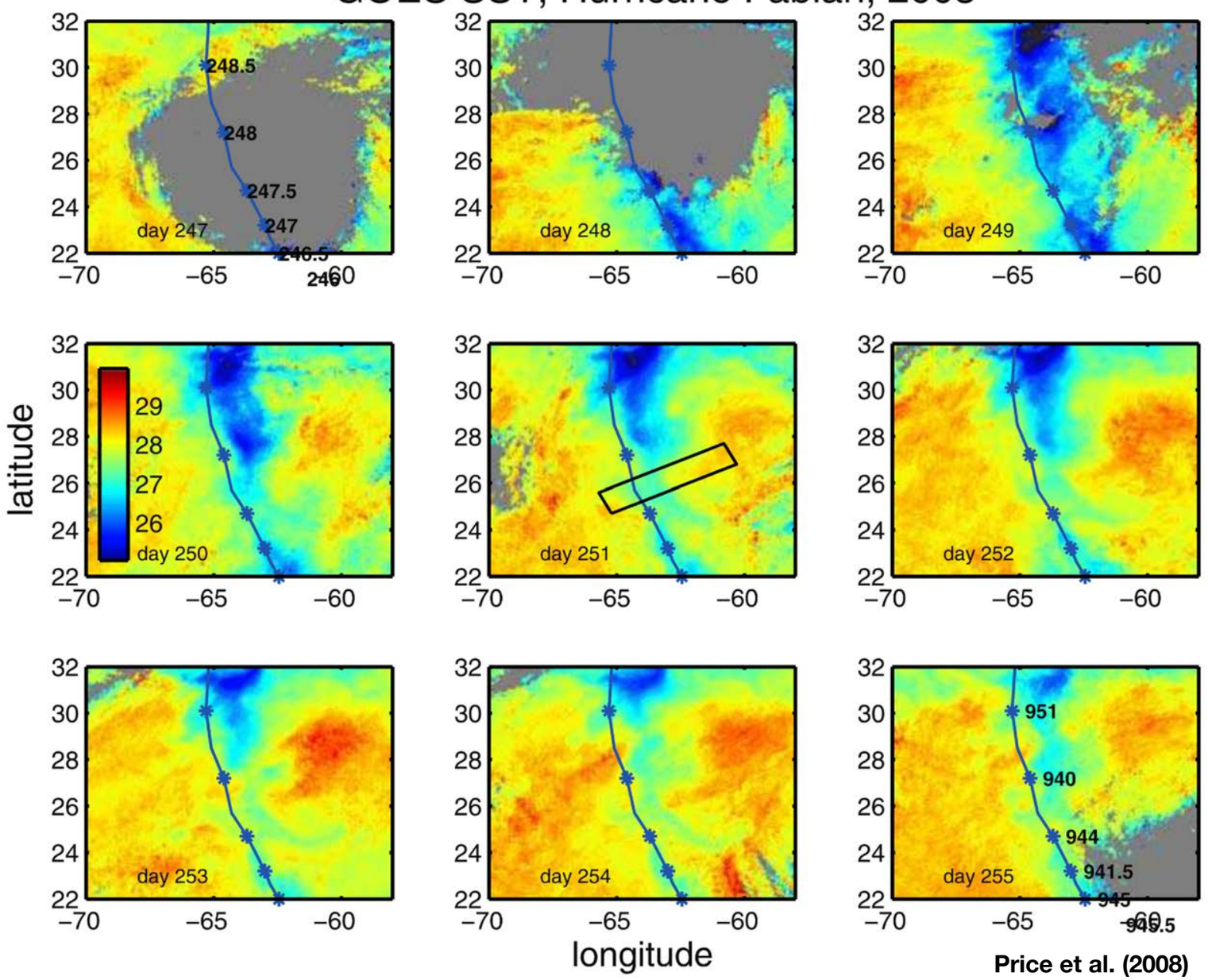


Figure courtesy of Baylor Fox-Kemper

Submesoscales and climate extremes

ex. Submesoscale influence on hurricane cold wakes

GOES SST, Hurricane Fabian, 2003



Price et al. (2008)

Reduction of SST by

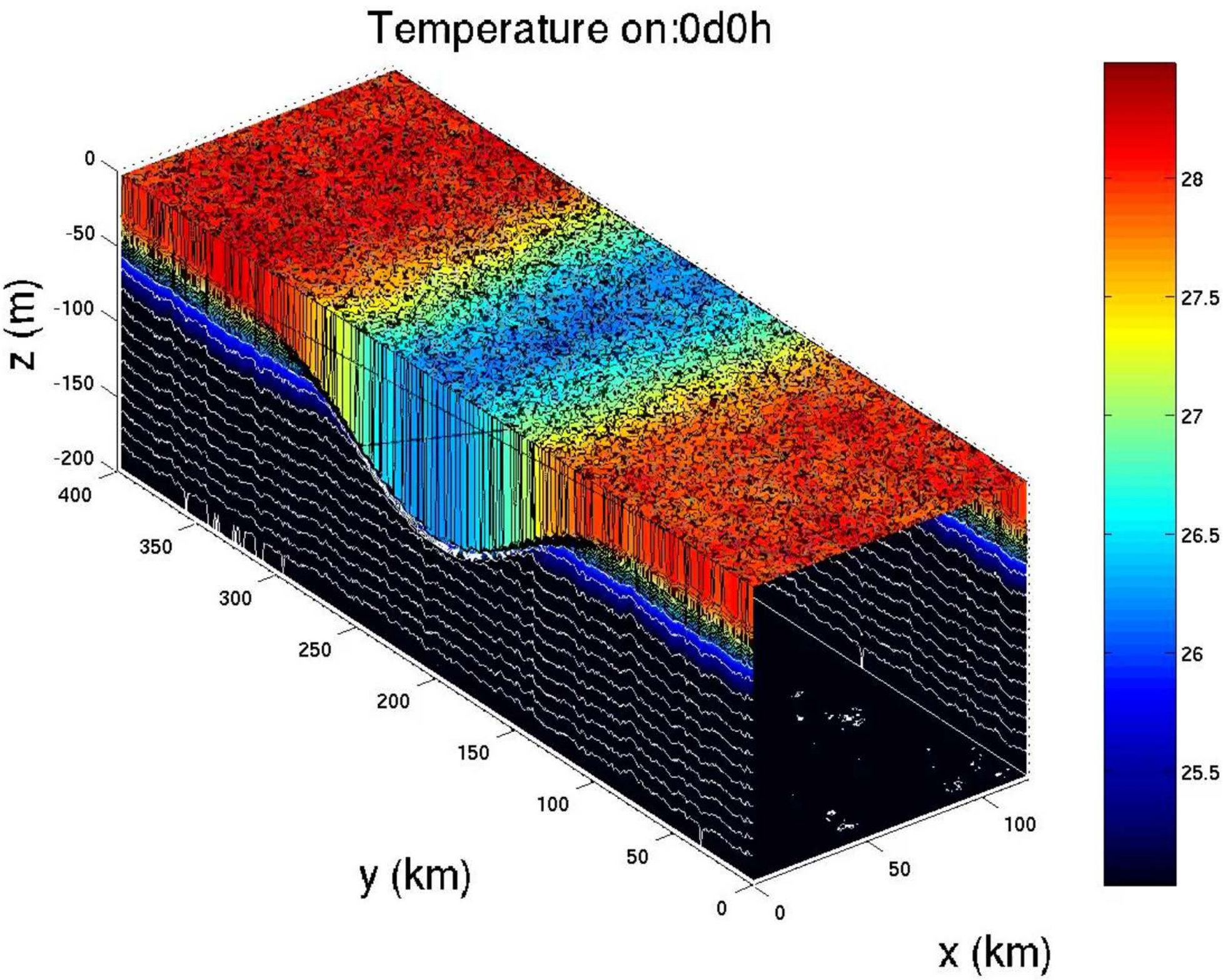
2° **to** 4°

Reduced ocean-to-atmosphere heat flux

Reduced hurricane intensity

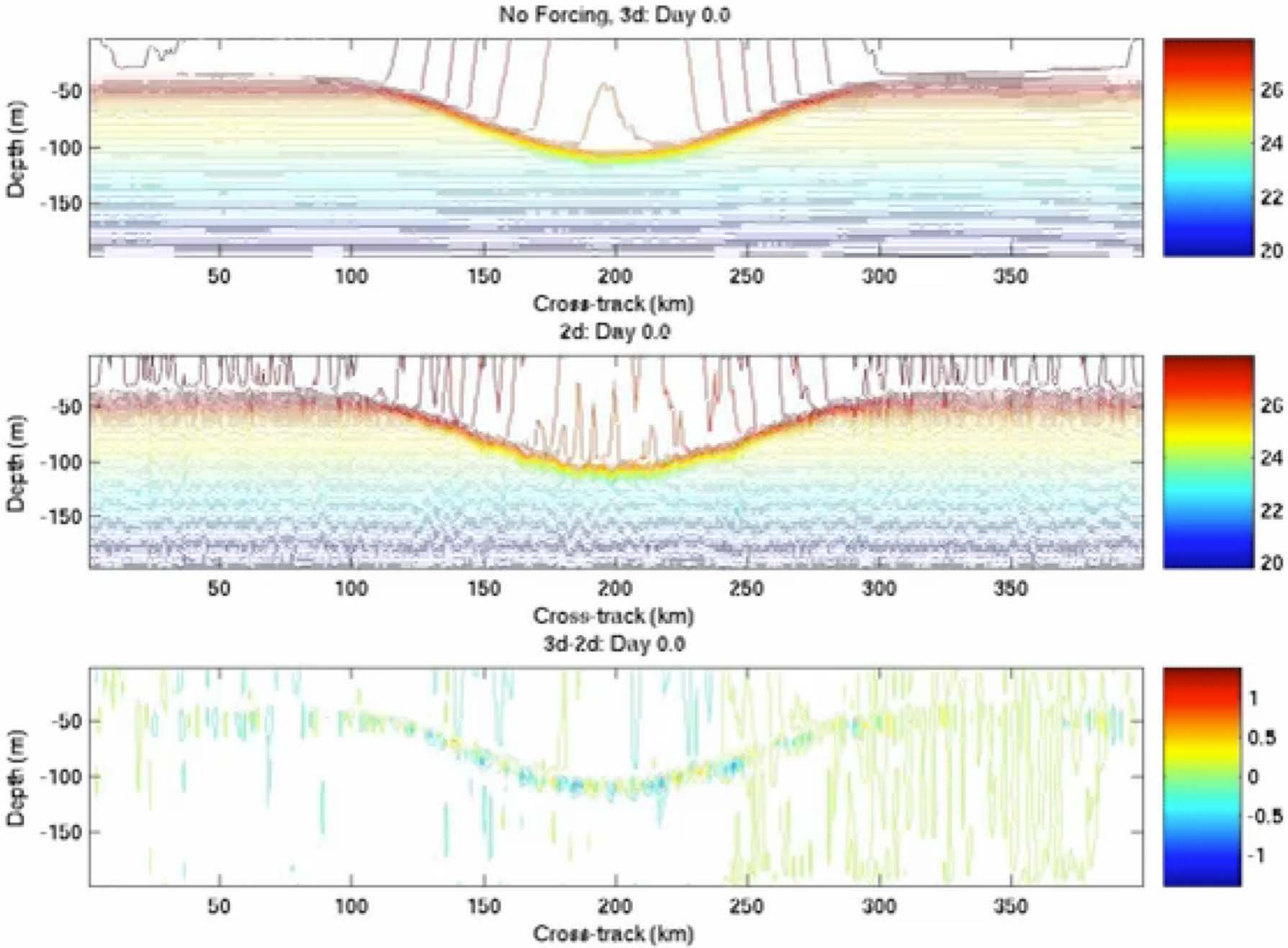
SST recovery via SHF; internal recovery driven by restratification

Submesoscales and climate extremes



Movie courtesy of Sean Haney

Submesoscales and climate extremes



Movie courtesy of Sean Haney

Submesoscales and climate extremes

Cyclone	$\tau_{ebf}\,(days)$	$2\tau_{sf}\,(days)$	$\tau_{eddy}\,(days)$	$SST\,(days)$
Fanapi	400 ± 600	320 ± 60	110^{+50}_{-30}	14 ± 2
Frances	200 ± 200	230 ± 50	300 ± 100	29 ± 2
Igor	400 ± 200	320 ± 60	210^{+20}_{-50}	N/A
Katrina	200 ± 300	180 ± 40	210^{+40}_{-80}	6 ± 2
Model	178	220 ± 40	46	N/A

Haney et al. (2012)

Do cold wakes affect subsequent hurricane strength via lingering heat or stratification anomaly?

Affect their trajectory?

Climate impacts? Does cold wake bolus extend beneath wintertime MLD?

Probably not (Jansen et al., 2010)

Modulate equatorial upwelling (hence ENSO phenomena)

Major NOAA (USA) study underway

Summary

Oceanic submesoscales are:

- Not well-observed!
- Challenging from a dynam ctive
- Way beyond the realm l GCMs
- Coupled to mesoscale and surface waves
- Affected signif navior
- A possible influ through BBL

McWilliams (2016)