Understanding & projecting global, regional, and coastal sea level

Reasons to include coastal ocean processes in global models

Stephen Griffies

NOAA/GFDL and Princeton University

7 May 2018 Australia

Thanks to numerous collaborators (direct and indirect), many of whom are in this audience!

Outline

- Concerning ocean model resolution
- Case Study I: Northwest Atlantic
- Case Study II: Eastern Pacific
- Case Study III: Antarctic shelves
- Closing comments

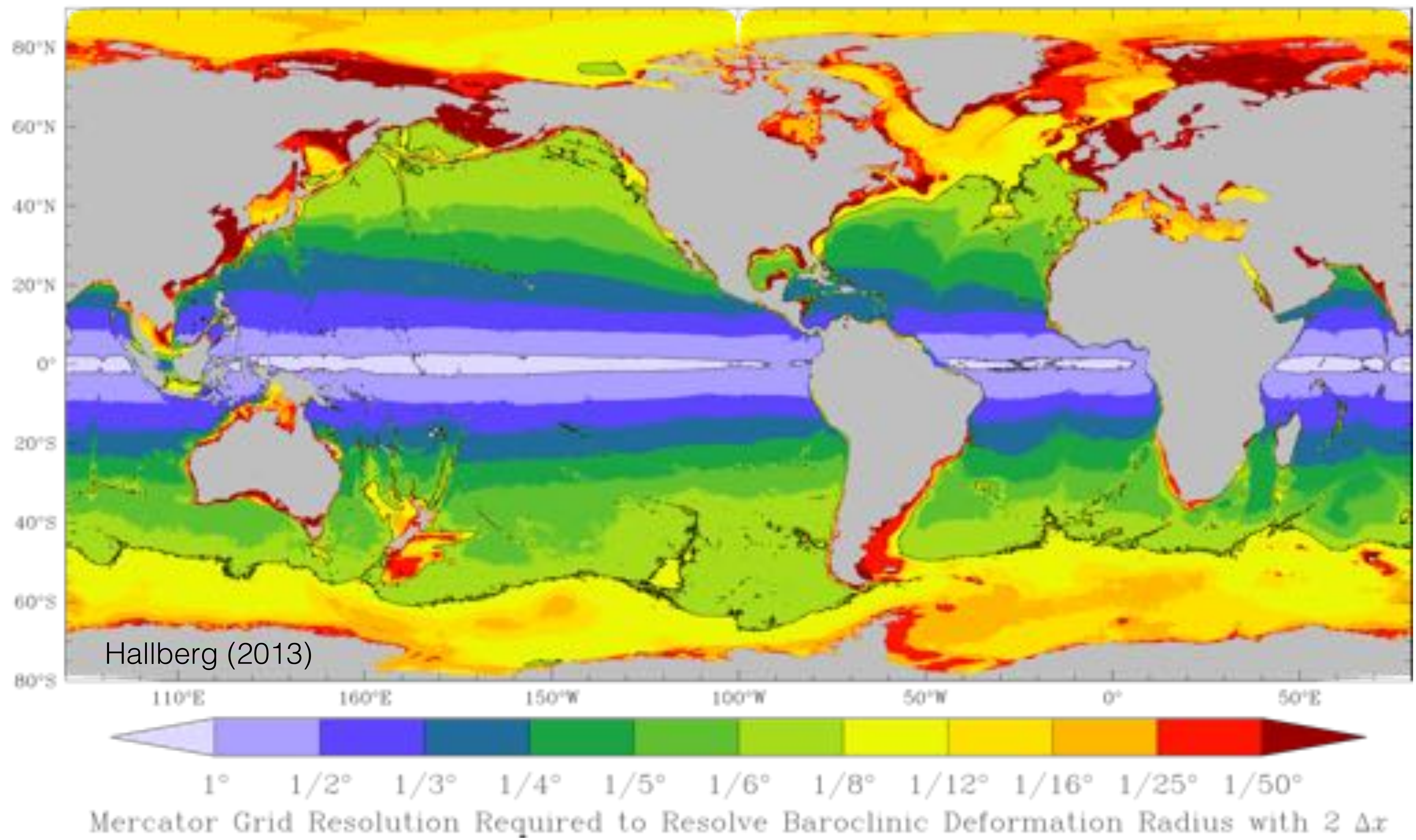
Concerning ocean model resolution

The importance of resolution for simulating ocean fluid dynamics

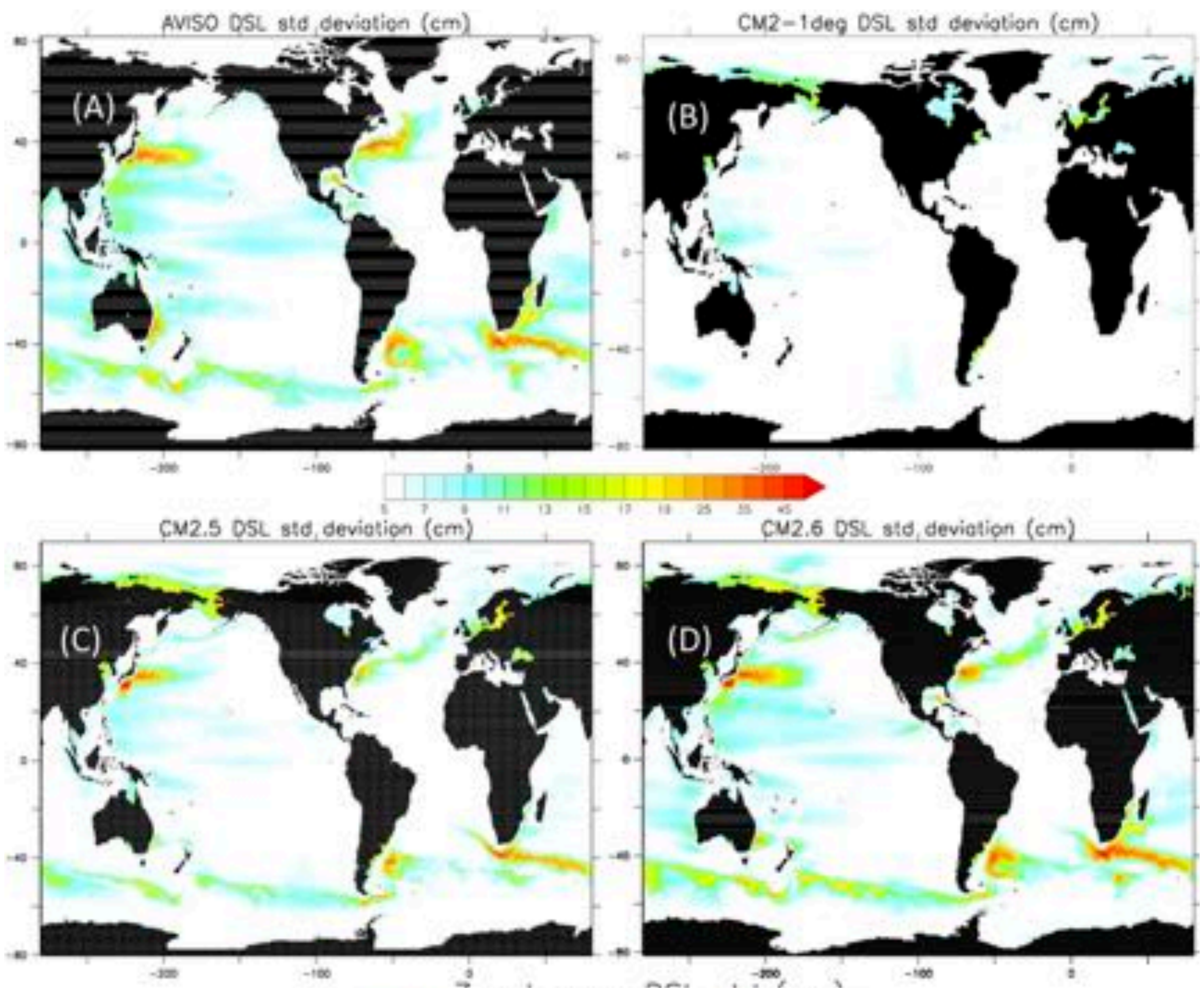

Dalivision versus Clearvision

Metric for resolution

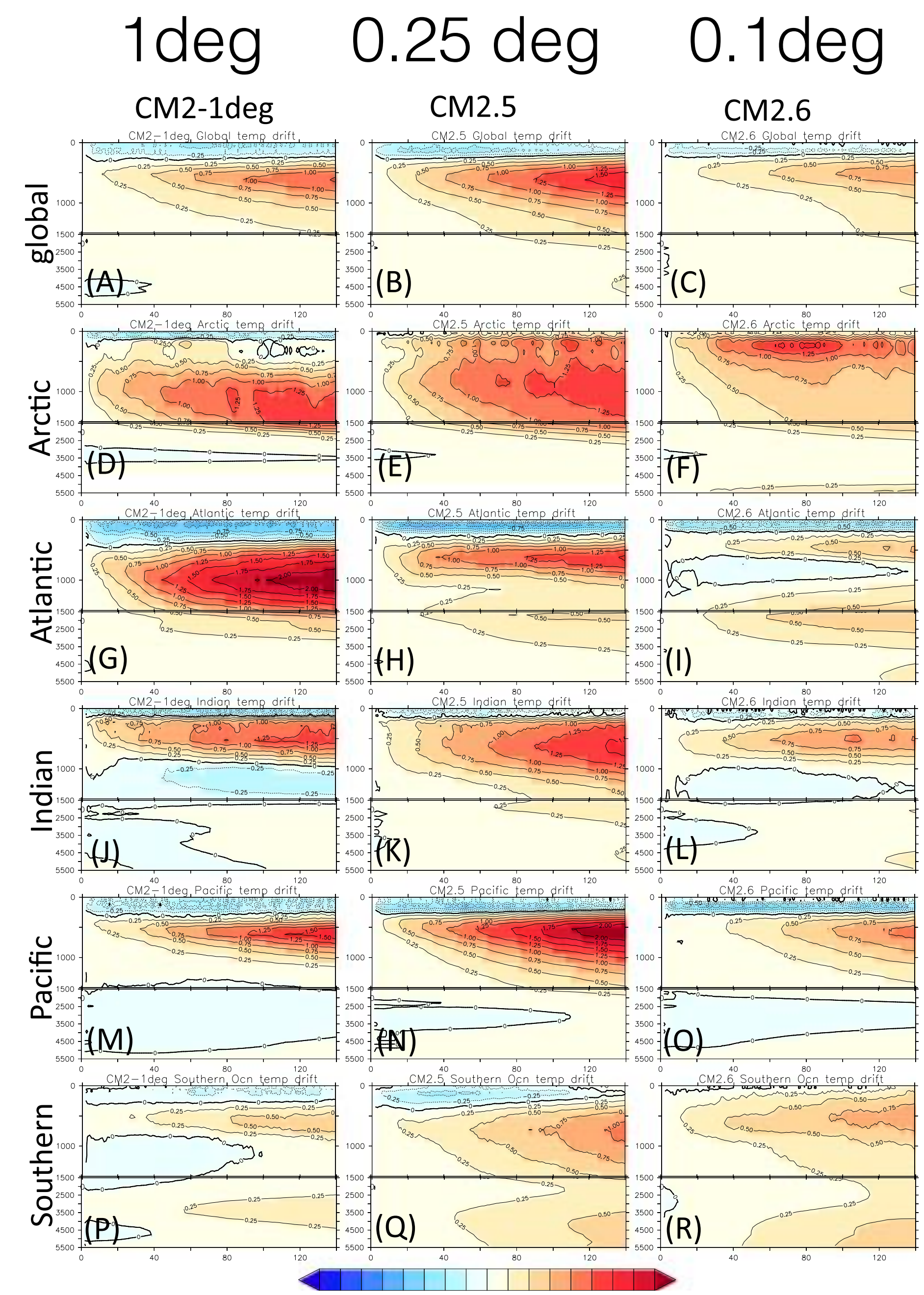
1st baroclinic Rossby radius (mesoscale eddies and coastal waves)



GFDL climate model resolution hierarchy



JOURNAL OF CLIMATE VOLU



Impacts on Ocean Heat from Transient Mesoscale Eddies in a Hierarchy of Climate Models

STEPHEN M. GRIFFIES,* MICHAEL WINTON,* WHIT G. ANDERSON,* RUSTY BENSON,* THOMAS L. DELWORTH,* CAROLINA O. DUFOUR,+ JOHN P. DUNNE,* PAUL GODDARD,# ADELE K. MORRISON,+ ANTHONY ROSATI,* ANDREW T. WITTENBERG,* JIANJUN YIN,# AND RONG ZHANG*

Mesoscale eddies transport heat up to partially compensate for downward pumping from winds.

Major implications for climate model drift and ocean heat uptake.

Case Study I: Northwest Atlantic

An example where coastal resolution can greatly affect sea level (and temperature) signals where they most matter to society.

Saba et al (2015): Northwest Atlantic warming

AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Oceans

RESEARCH ARTICLE

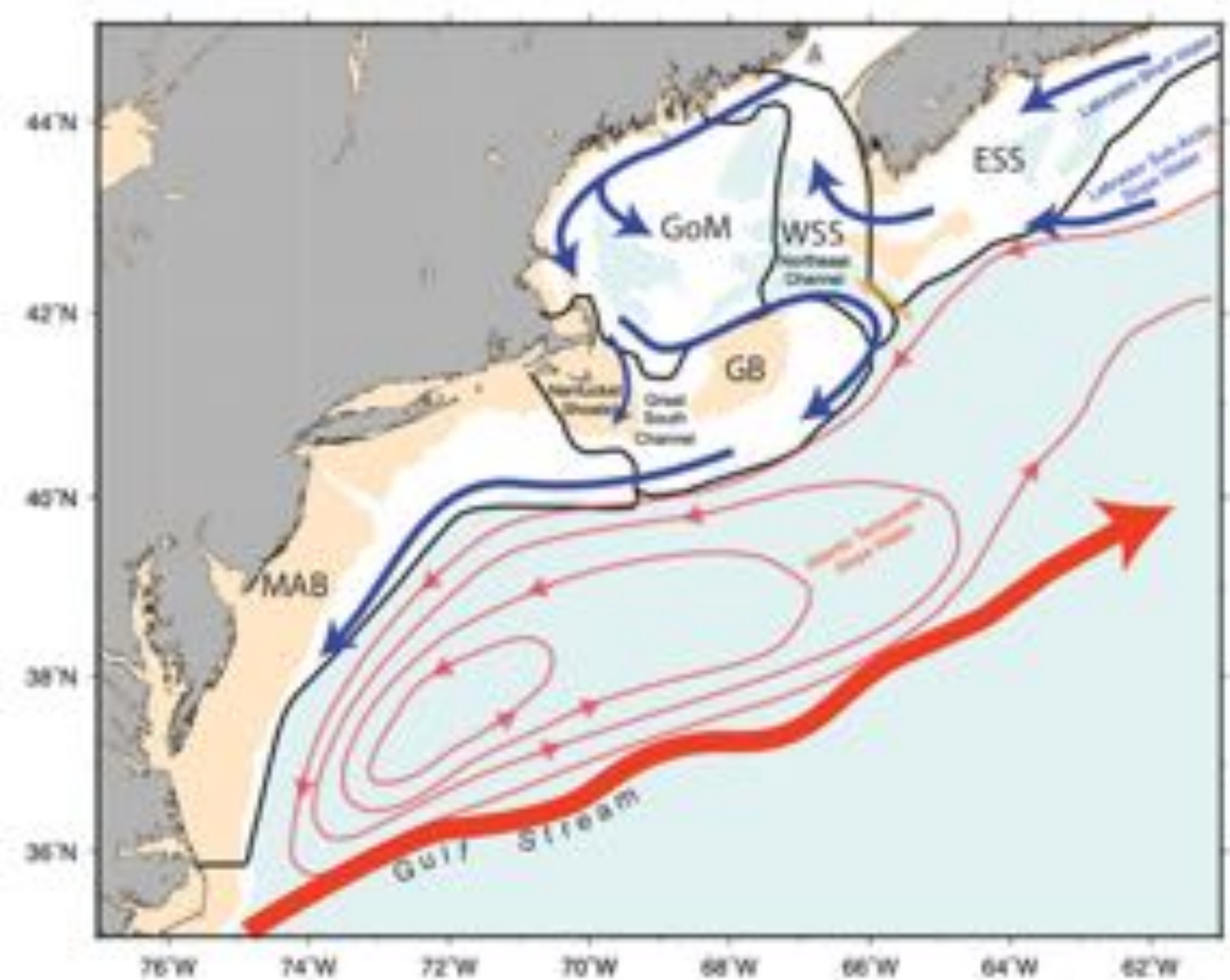
10.1002/2015JC011346

Key Points:

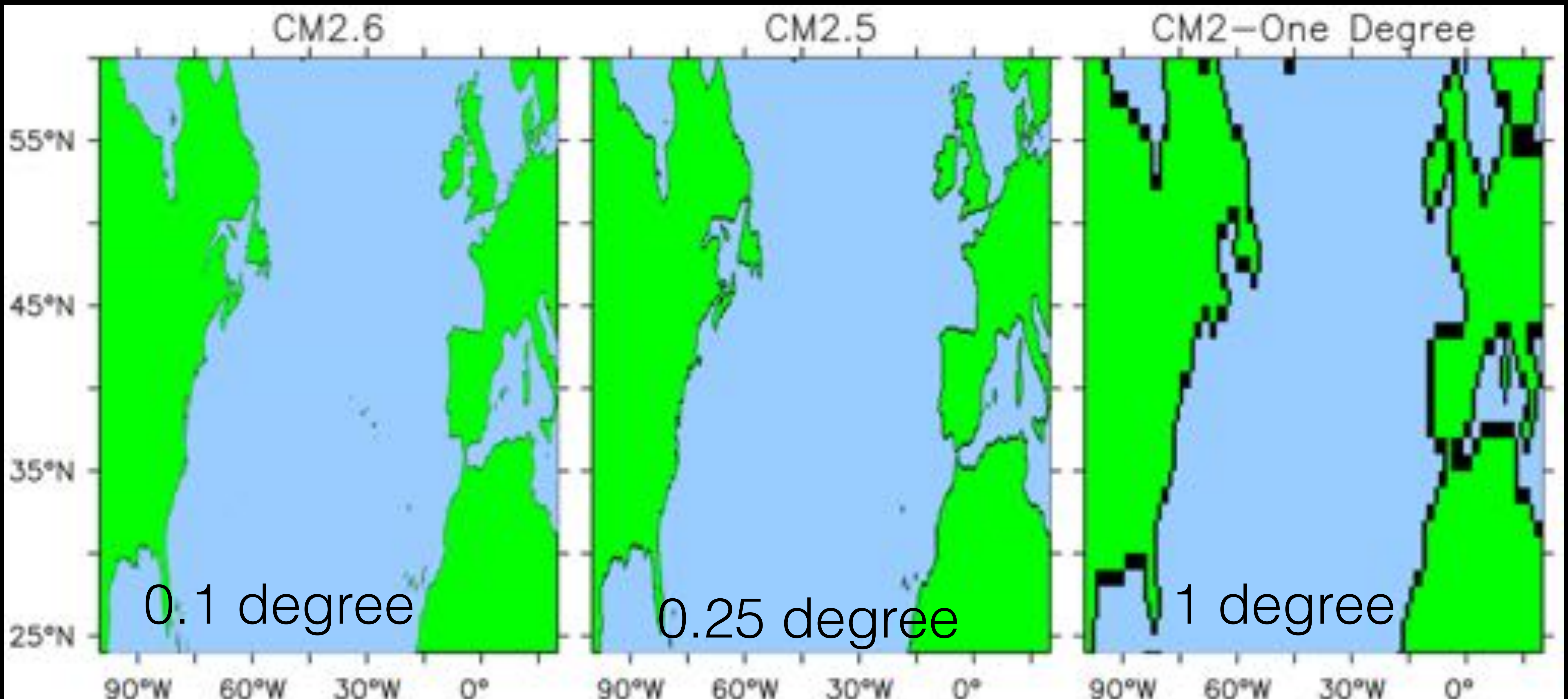
- Northwest Atlantic circulation bias is reduced in a high-resolution global climate model
- Atmospheric CO_2 doubling over 70–80 years results in an enhanced

Enhanced warming of the Northwest Atlantic Ocean under climate change

Vincent S. Saba[1], Stephen M. Griffies[2], Whit G. Anderson[2], Michael Winton[2], Michael A. Alexander[3], Thomas L. Delworth[2], Jonathan A. Hare[4], Matthew J. Harrison[2], Anthony Rosati[2], Gabriel A. Vecchi[2], and Rong Zhang[2]



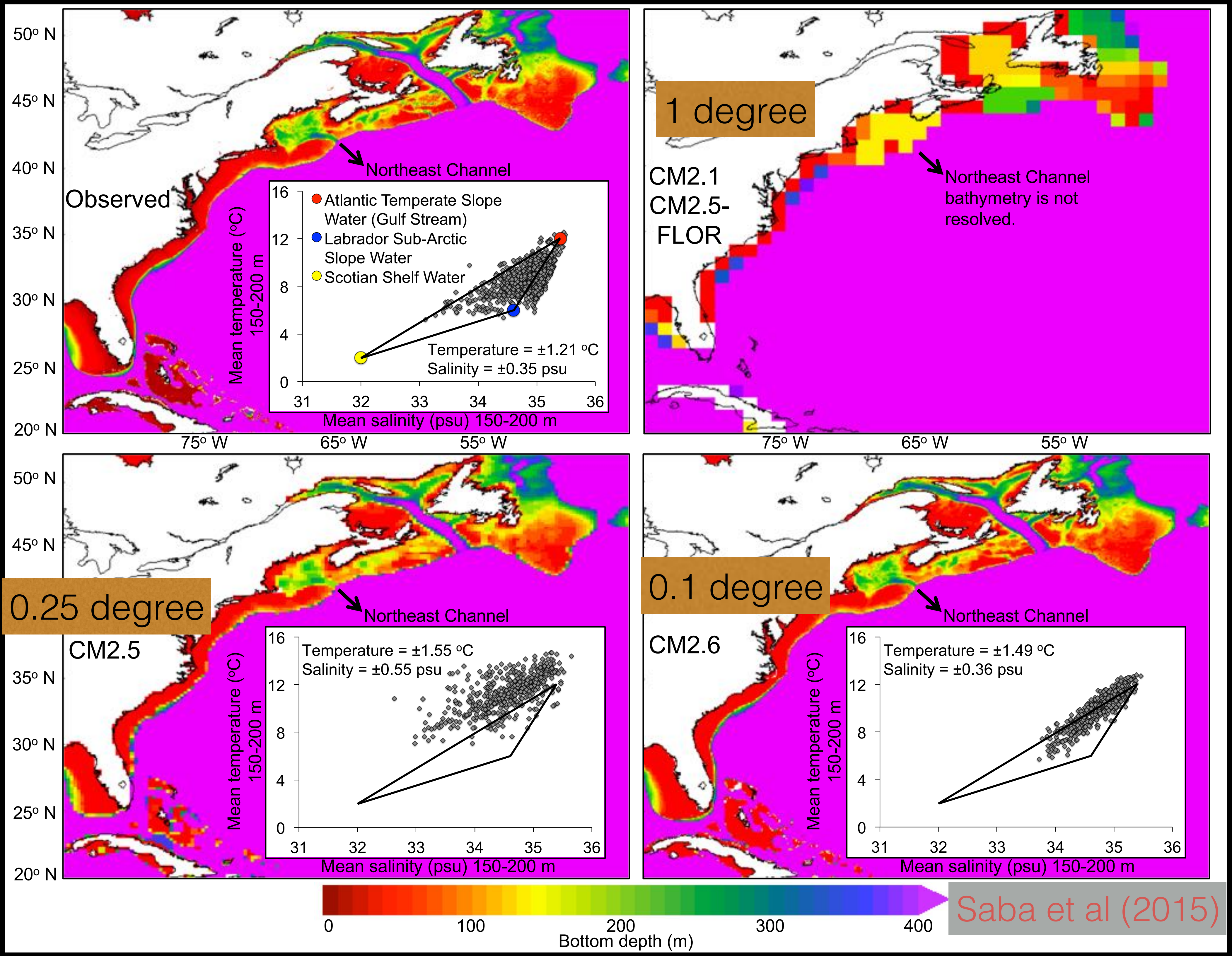
North Atlantic coast using three resolutions



Courtesy Paul Goddard, Univ of Conn

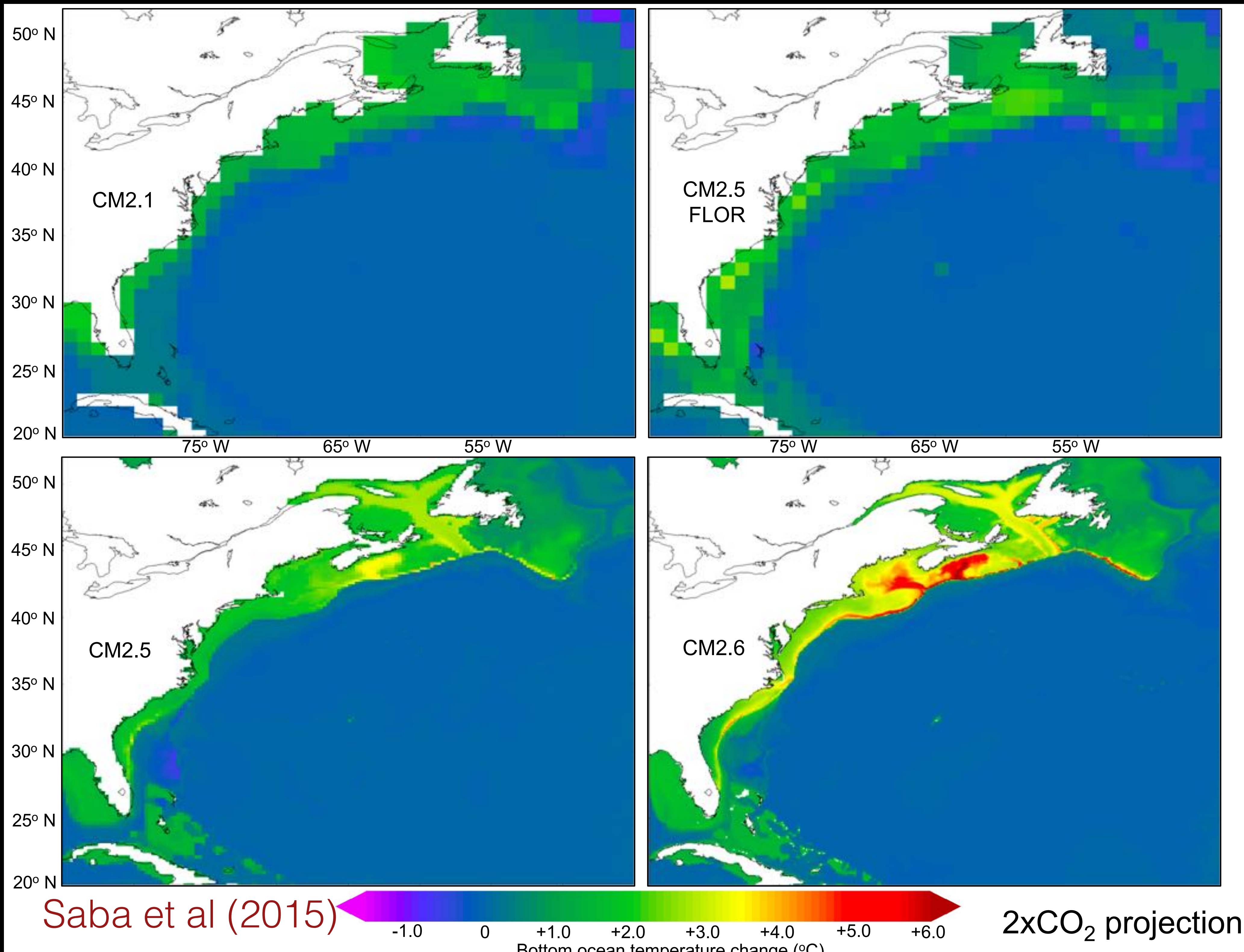
T/S in Gulf of Maine "Northeast Channel"

Finest resolution has the most realistic water masses.



Projected bottom warming

Finest resolution shows far more warming.

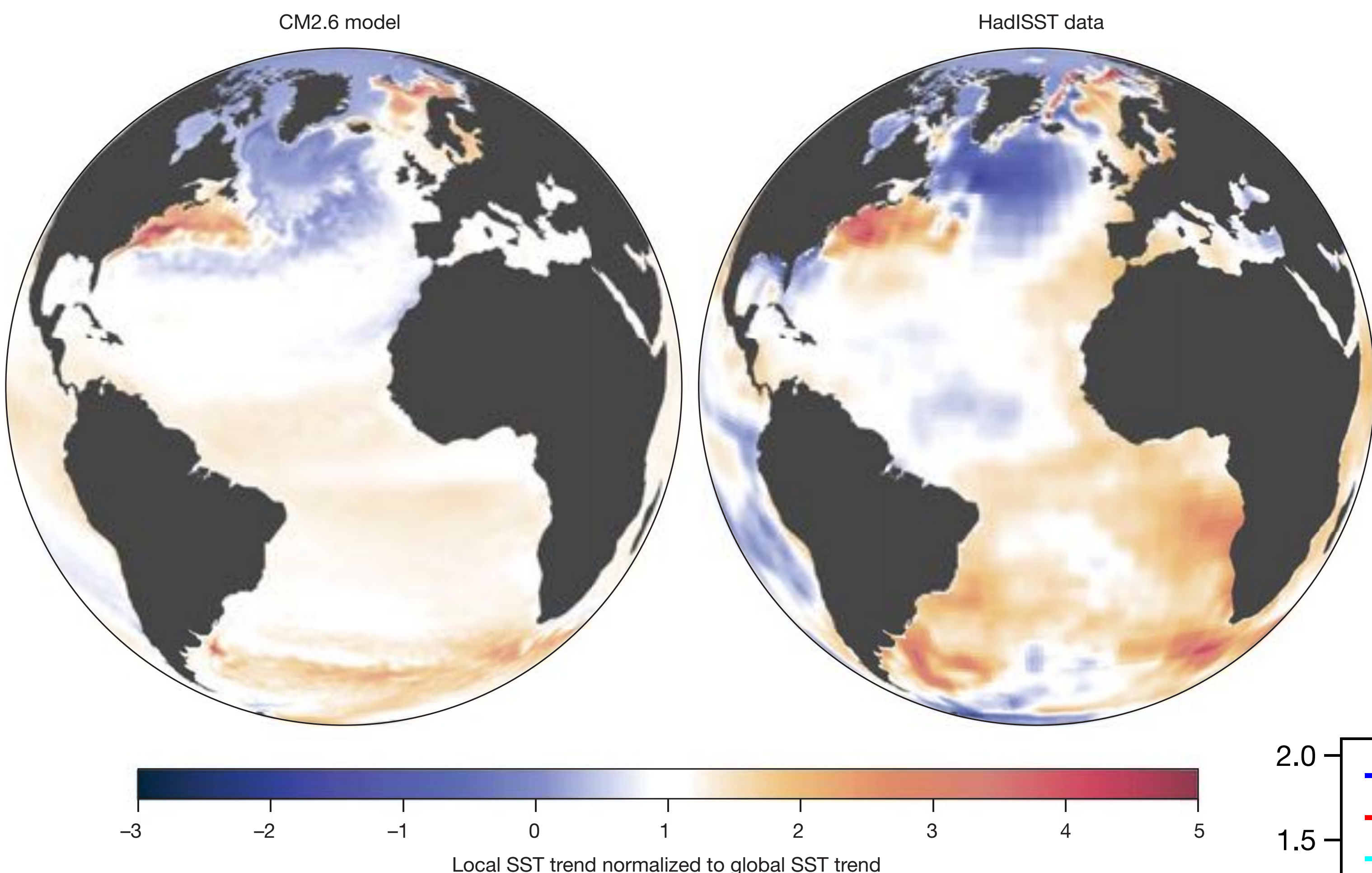


Warming connected to AMOC slowdown.

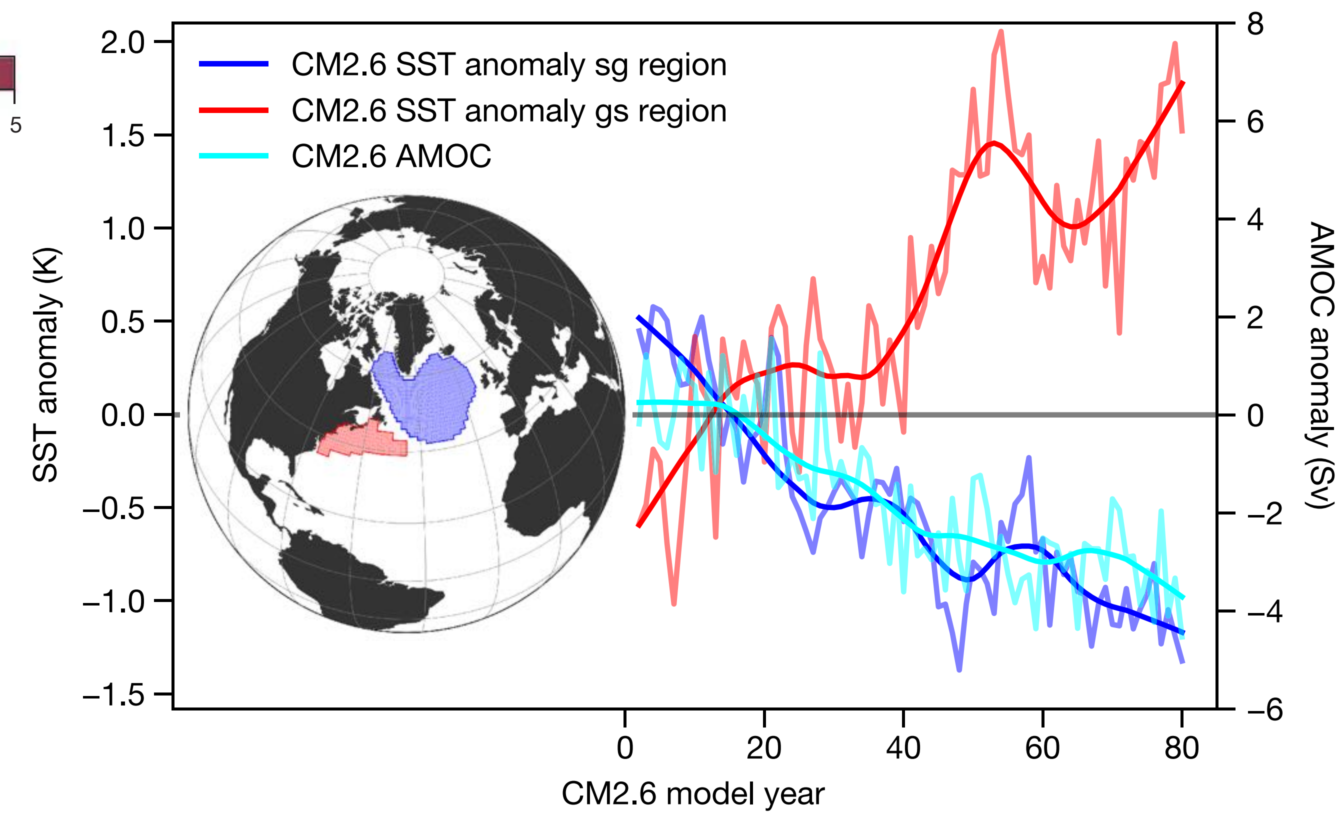
Gulf of Maine is a notable ocean “heat wave” region in early 21st century.

SST fingerprint of AMOC reduction

Caesar et al (2018) Nature



CM2.6 idealized 2xCO2
compared to HadSST



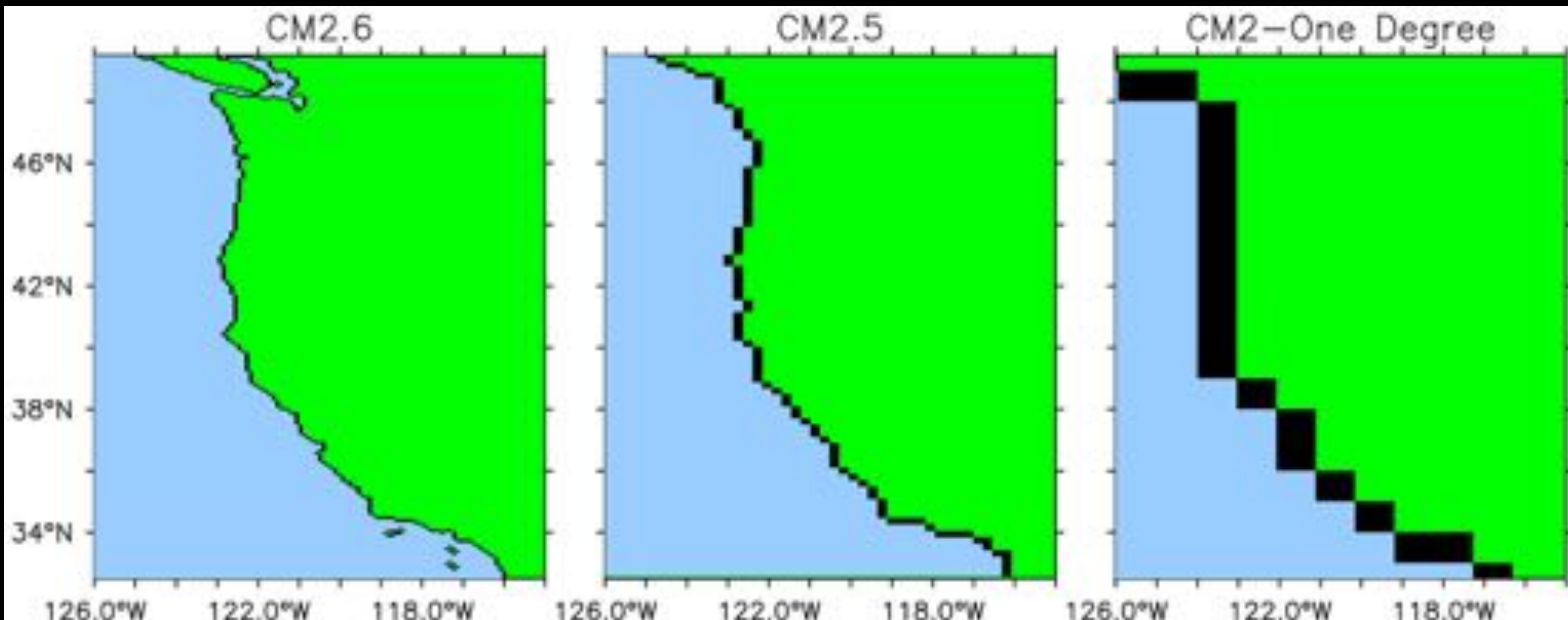
Summary points from Atlantic studies

- Refined coastal resolution allows for enhanced simulation of coastal water mass properties in regions around the Gulf of Maine (key region for North Atlantic fisheries) and other coastal regions along North America.
- Idealized 2xCO2 simulations show remarkable warming in the Gulf of Maine associated with changes in AMOC and coastal circulation.
  - Gulf of Maine is an observed "hot spot" for ocean warming or "ocean heat waves".
- SST fingerprint in CM2.6 simulations show intriguing similarities to observed SST trends.
  - Model SST fingerprint is related to simulated AMOC reduction. Is AMOC trend also the case for observed SST trends?
- Simulations with coarser models do not allow for resolution of coastal currents and show far less coastal warming features in climate change

Case Study II: Eastern Pacific

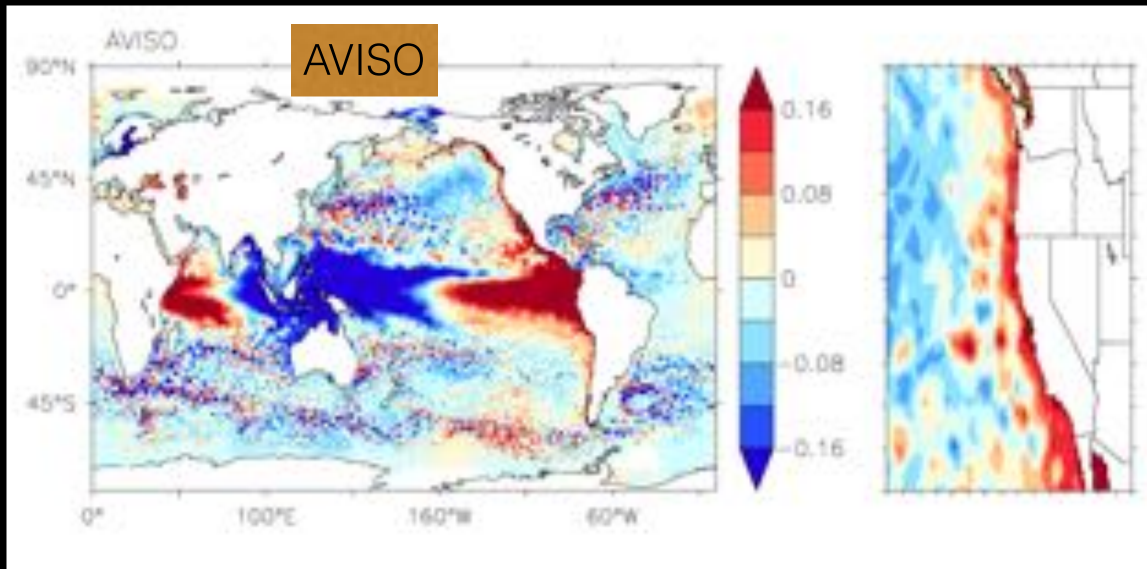
An example where coastal resolution can greatly affect sea level signals where they most matter to society.

Eastern Pacific



Courtesy Paul Goddard, Un of Conn

Sea level and El Nino in east Pacific

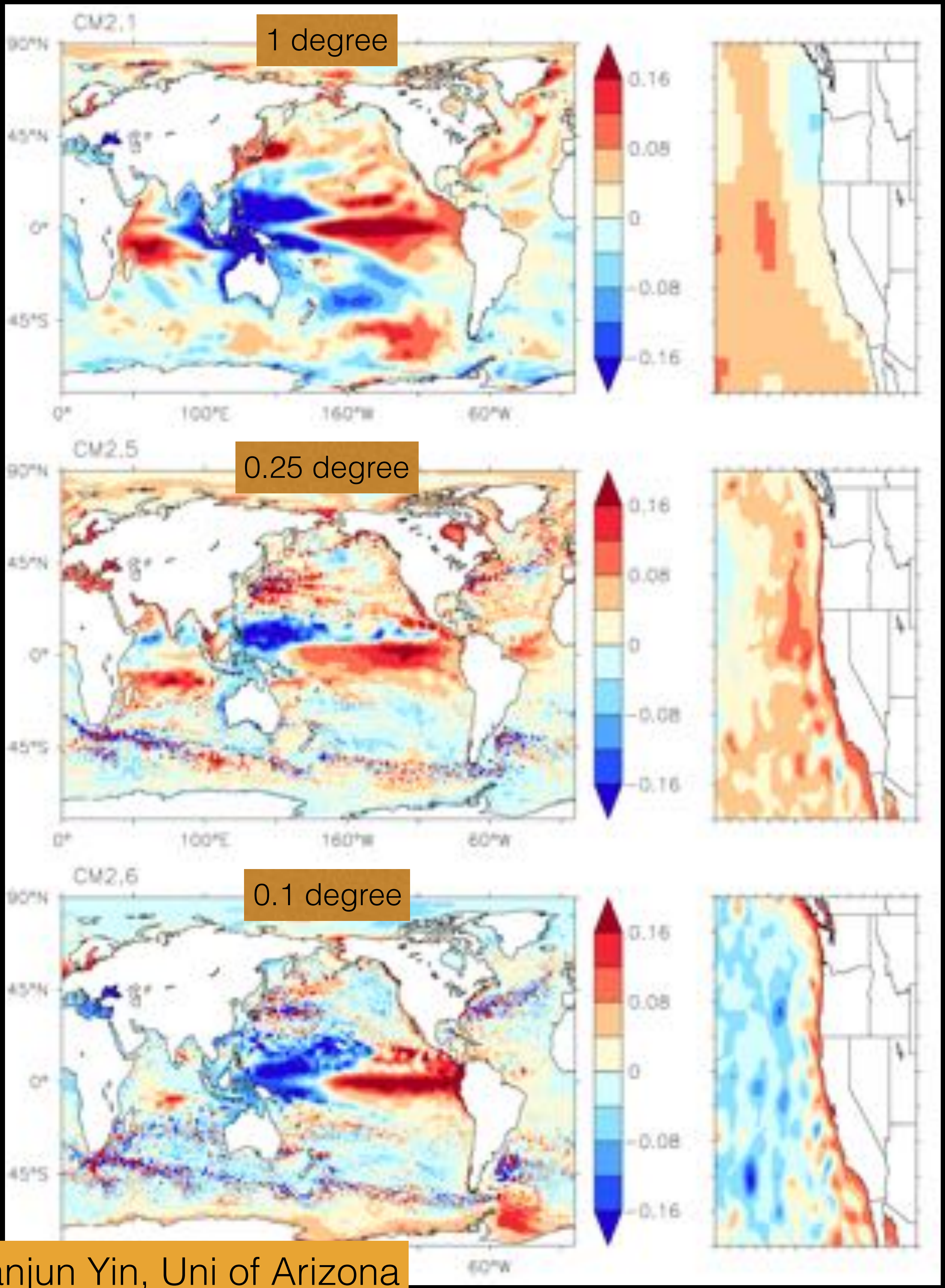


West coast of North America has relatively narrow continental shelves.

Coastal wave guide and currents thus require fine grid resolution.

Here we show sea level patterns for El Nino peak monthly maximum in models. Note that 1-degree shows very strong El Nino but still a weak sea level signal on coast.

Even 0.1 degree has reduced amplitude relative to AVISO.

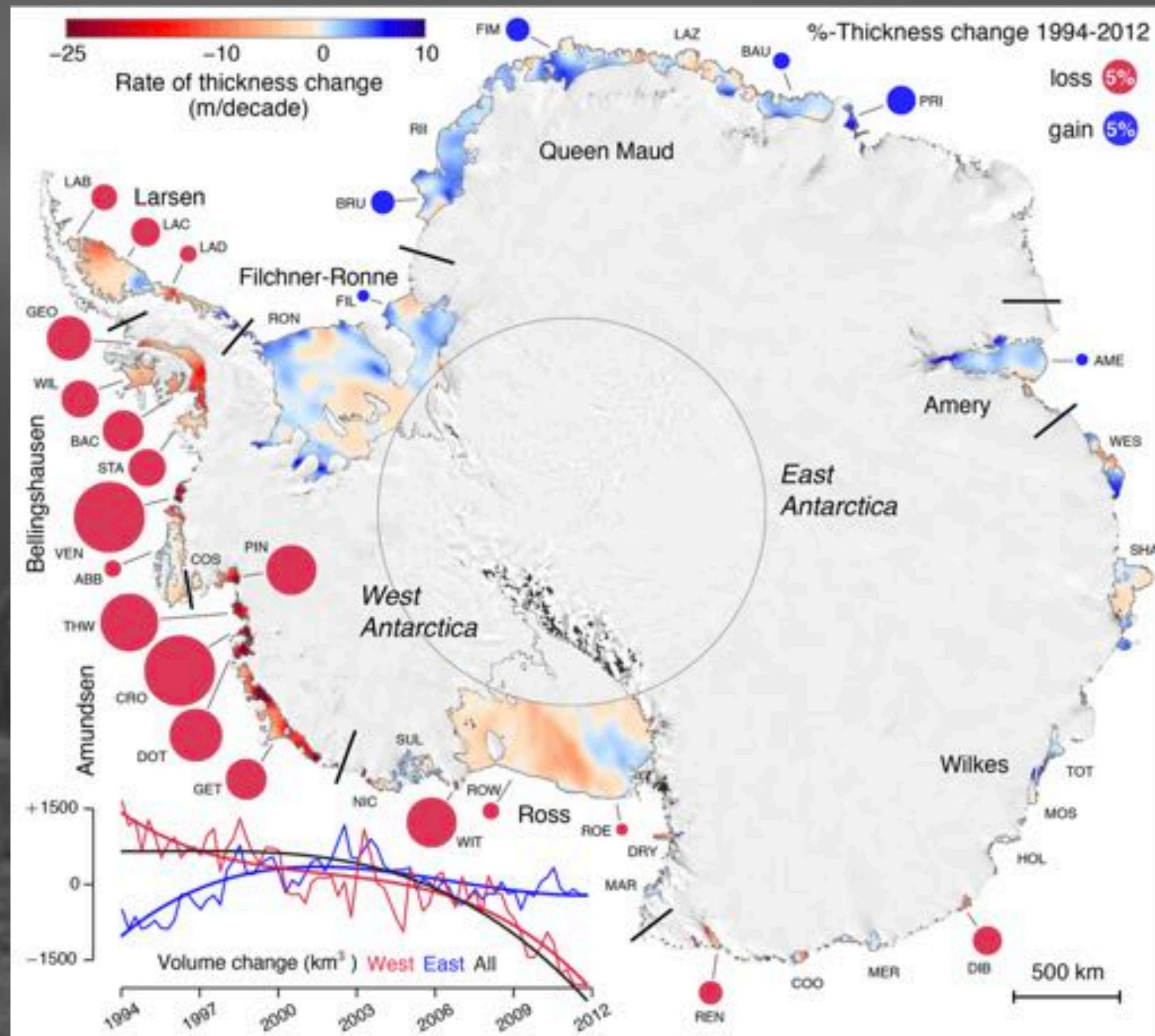


Courtesy Jianjun Yin, Uni of Arizona

Case Study III:
Southern Ocean & Antarctic shelves

An example where regional/coastal processes can potentially impact global sea level.

Ice shelf melting around Antarctica



Volume loss from Antarctic ice shelves is accelerating

Fernando S. Paolo,[1*] Helen A. Fricker,[1] Laurie Padman[2]

Paolo et al 2015

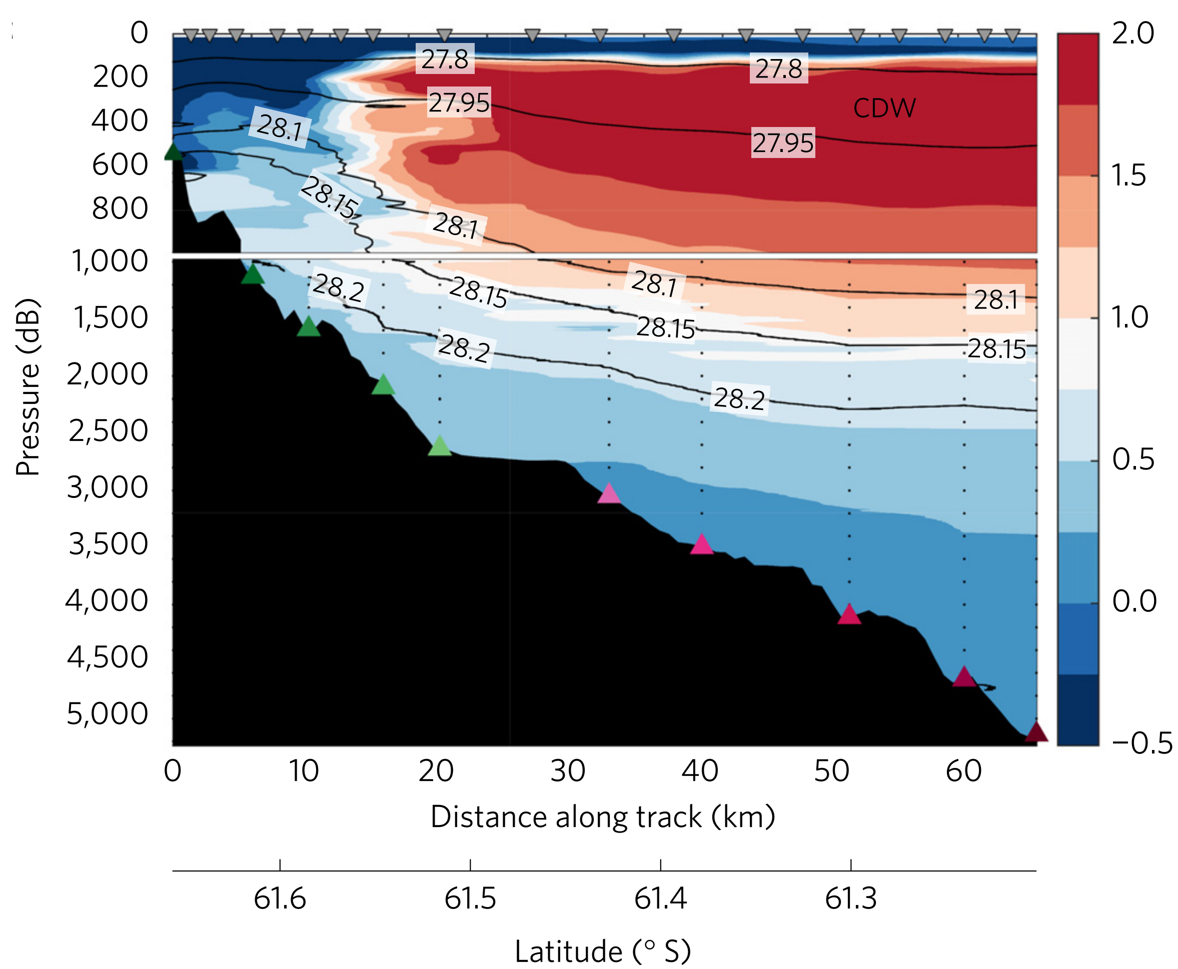
Motivation

- Observed positive rates of ice shelf melt around western Antarctica and peninsula (e.g., Paolo, Rignot, others);
- Adjacent land ice melt represents a significant, and growing, contributor to sea level rise.
- Relatively warm sub-ice shelf seawater is the dominant contributor to ice shelf melt.
  - ★ **Question A**: What are the physical mechanisms for sub-ice shelf ocean warming? How does warm water get there?
  - ★ **Question B**: Are any of these mechanisms subject to large-scale climate trends, either natural or anthropogenic?

The key question for sea level is:

How/when/where warm offshore Circumpolar Deep Water (CDW) will move towards the Antarctic continental shelf and under the ice shelves?

- What are the mechanisms?
- Among the mechanisms, are any subject to climate trends?



Temp section off Ant peninsula

ARTICLES | nature geoscience

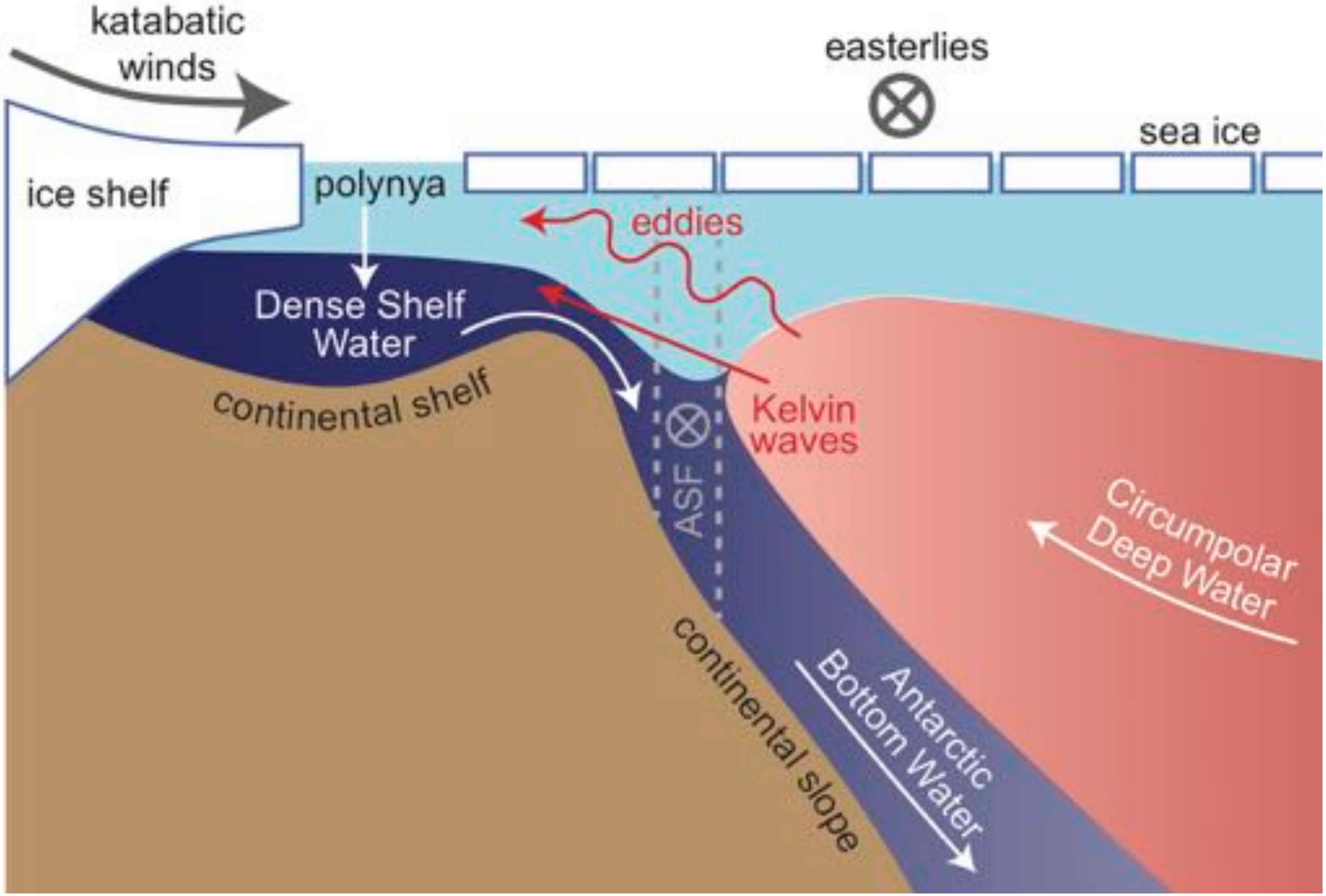
PUBLISHED ONLINE: 30 OCTOBER 2017 | DOI: 10.1038/NGEO3053

Contribution of topographically generated submesoscale turbulence to Southern Ocean overturning

Xiaozhou Ruan[1*], Andrew F. Thompson[1], Mar M. Flexas[1] and Janet Sprintall[2]

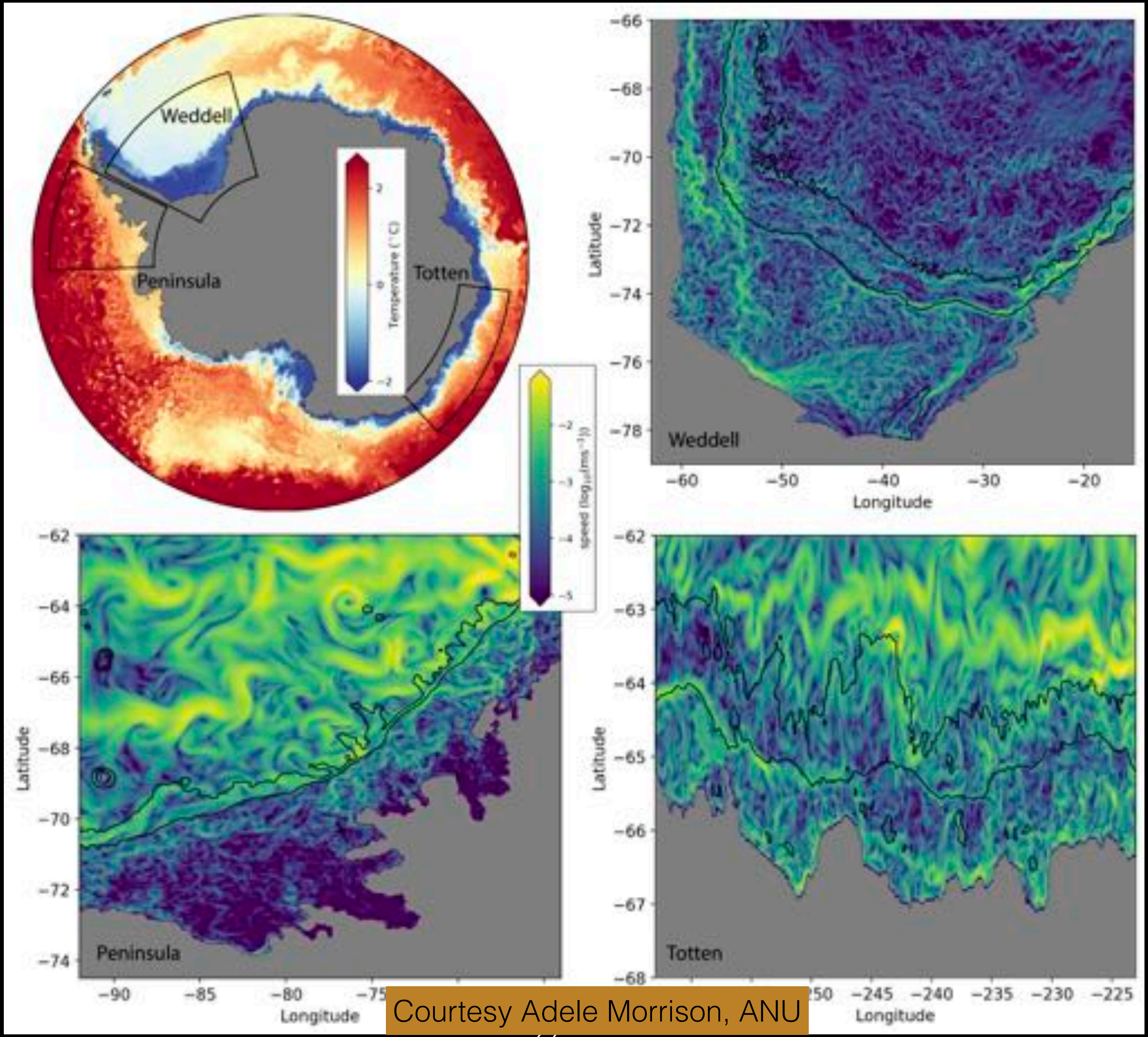
Antarctic shelf processes

Generally see cold fresh coastal waters adjacent to warm salty offshore Circumpolar Deep Water (CDW).



Courtesy Adele Morrison (ANU) and Matthew England (UNSW)

Sample temp/speed from Australian global 0.1 deg model



Courtesy Adele Morrison, ANU

Proposed mechanisms for getting CDW across shelf

- Tidal induced mixing (M2 critical latitude): Robertson (2013) studies of Amundsen Sea. Stewart, Klocker, Menemenlis (2017) simulations (1/48 degree global)

- Eddy-induced transport: mesoscale eddies pump CDW into ice shelves: Stewart and Thompson (2013) focus on Antarctic Peninsula, Arthun et al (2013) study eddies under Weddell Sea ice shelf.

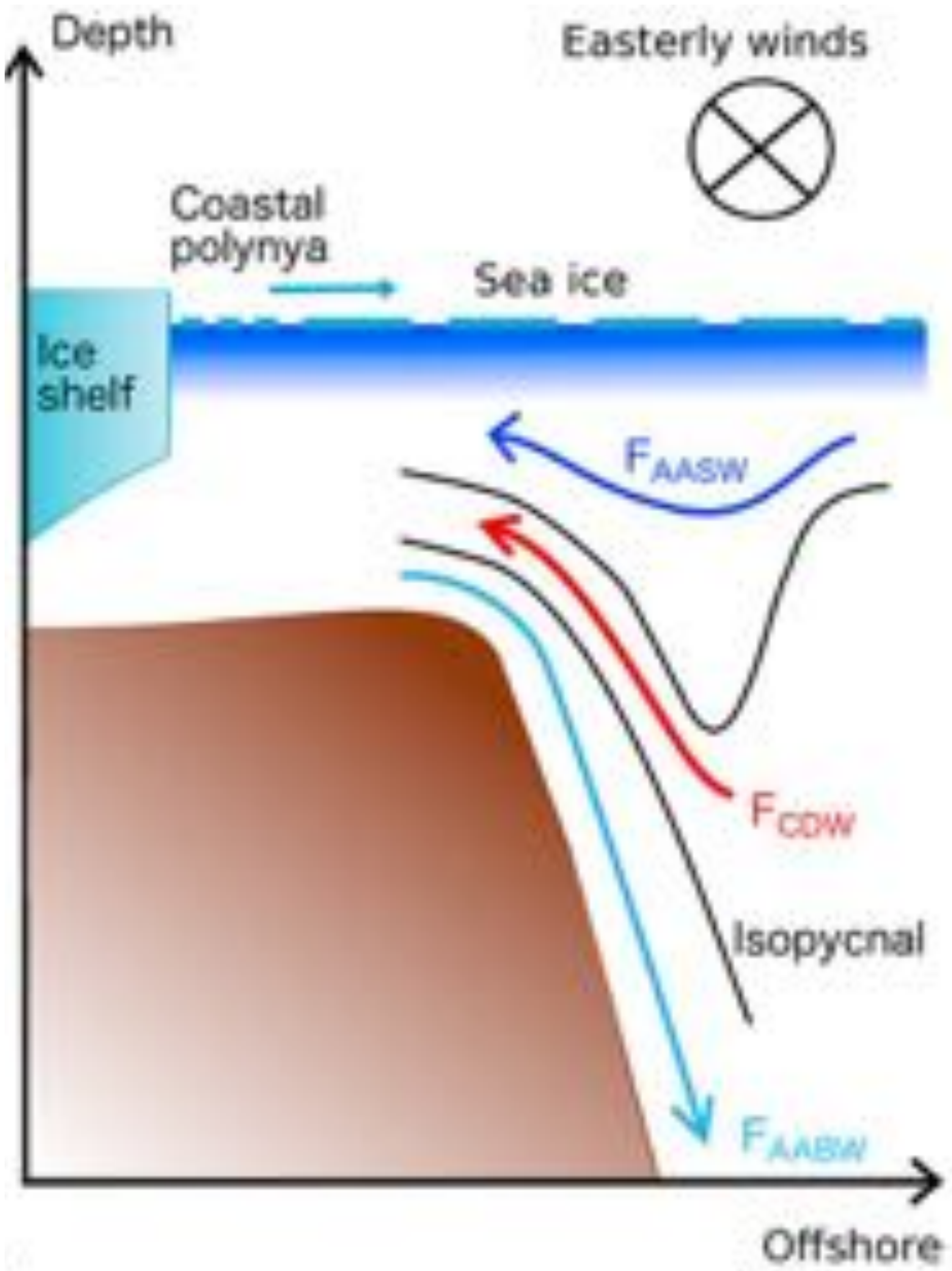
- Arrested (or slippery) Ekman layer (barotropic and baroclinic pressure gradients balance): MacCready and Rhines (1993) (theory), Wahlin et al (2012) observational analysis of ACC filaments onto Amundsen Sea shelf.

- Changes to Ekman pumping from weakened coastal easterlies under climate change: Spence et al (2014).

- Baroclinic/arrested Ekman adjustment to boundary Kelvin wave signal induced by wind trends: Spence et al (2017): remote winds can induce rapid changes along Antarctic peninsula.

- Increases to baroclinicity of the Antarctic Slope Front from freshening can place a negative feedback to the heat transport: Goddard et al (2017).

Eddy-induced mechanism



Mesoscale eddies pump CDW into continental shelves: Stewart and Thompson (2013) focus on Antarctic Peninsula, Arthun et al (2013) study Weddell Sea shelf. Both use idealized model domains.

Note the importance of isopycnal linkage between shelves and CDW.

Also note shelves can act as an eddy "killer" by dissipating eddy energy.

Geophysical Research Letters

RESEARCH LETTER
10.1002/2014GL062281

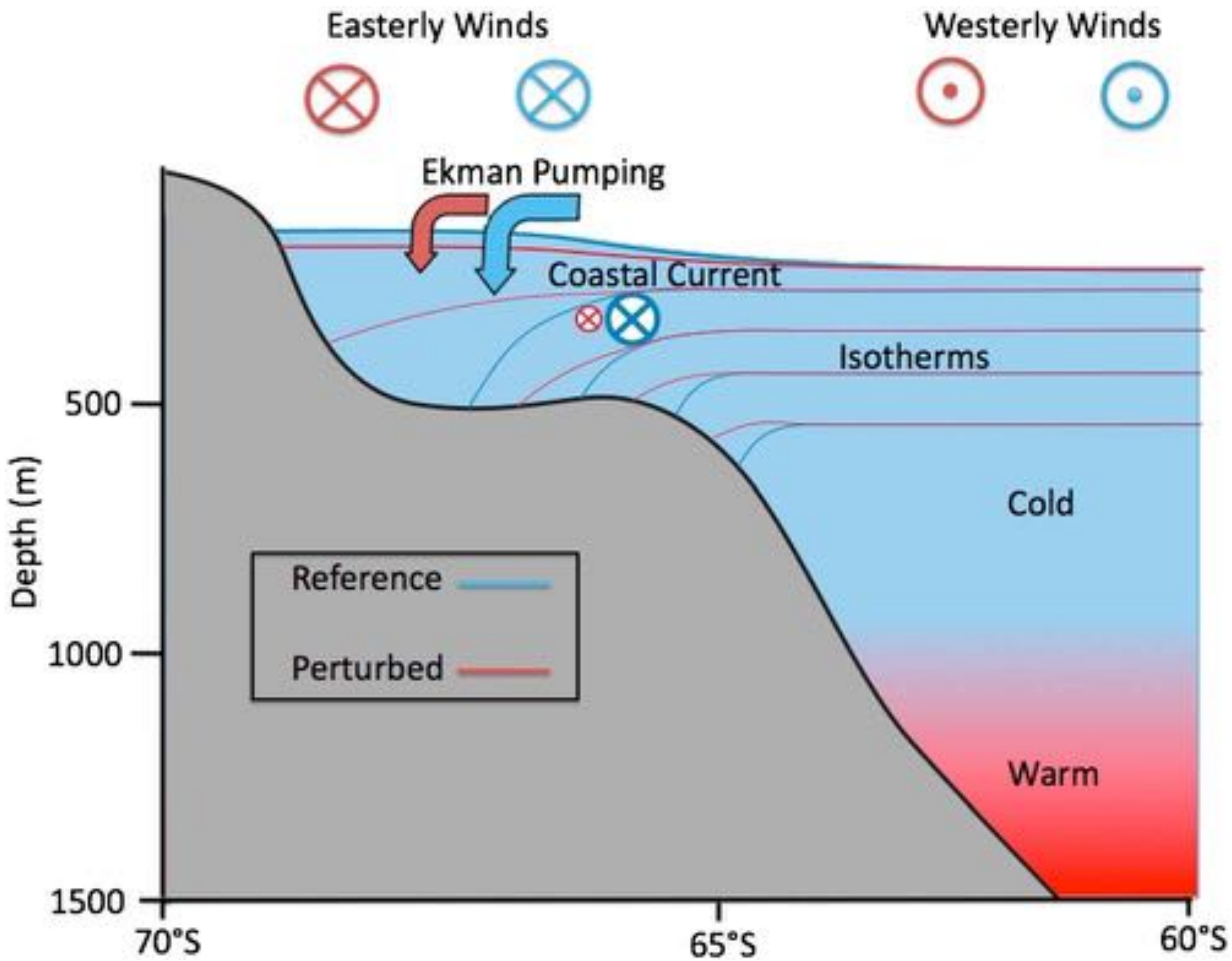
Eddy-mediated transport of warm Circumpolar Deep Water across the Antarctic Shelf Break

Andrew L. Stewart[1] and Andrew F. Thompson[2]

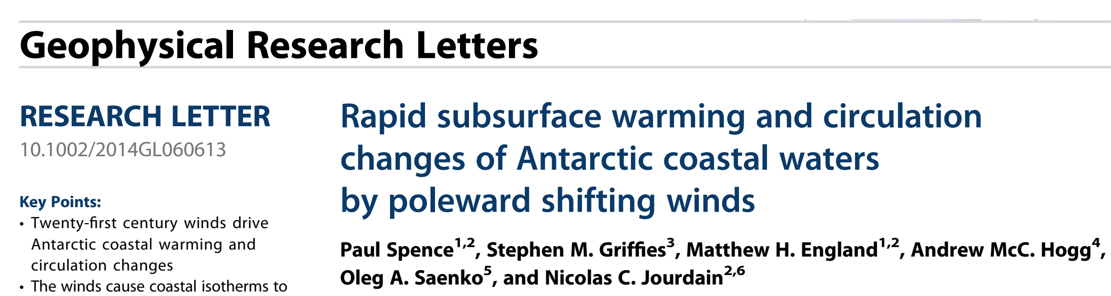
Key Points:

Return to mechanism summary slide

Ekman/wind mechanism



Changes to Ekman pumping from weakened easterlies under climate change: Circum-Antarctic response in realistic model domain. Spence et al (2014).


Geophysical Research Letters

RESEARCH LETTER
10.1002/2014GL060613

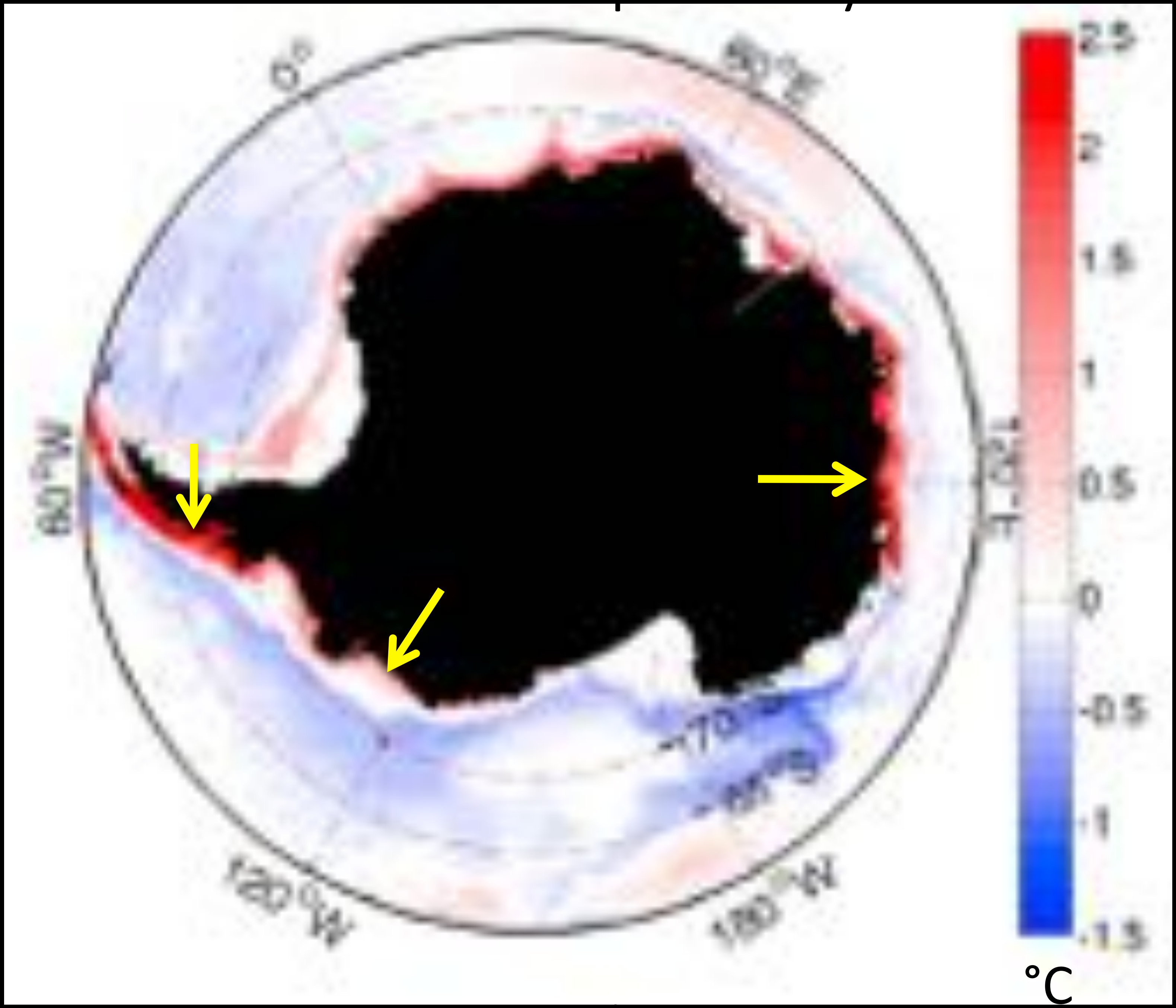
Key Points:
- Twenty-first century winds drive Antarctic coastal warming and circulation changes
- The winds cause coastal isotherms to

Rapid subsurface warming and circulation changes of Antarctic coastal waters by poleward shifting winds

Paul Spence[1,2], Stephen M. Griffies[3], Matthew H. England[1,2], Andrew McC. Hogg[4], Oleg A. Saenko[5], and Nicolas C. Jourdain[2,6]

Return to mechanism summary slide

Example Ekman-induced temperature changes



Model response to a four degree latitude southward wind shift around continent. CDW shoals, with warming upwards of 2C. (Spence et al 2014)

Arrested Ekman layer mechanism

Some Implications of Ekman Layer Dynamics for Cross-Shelf Exchange in the Amundsen Sea

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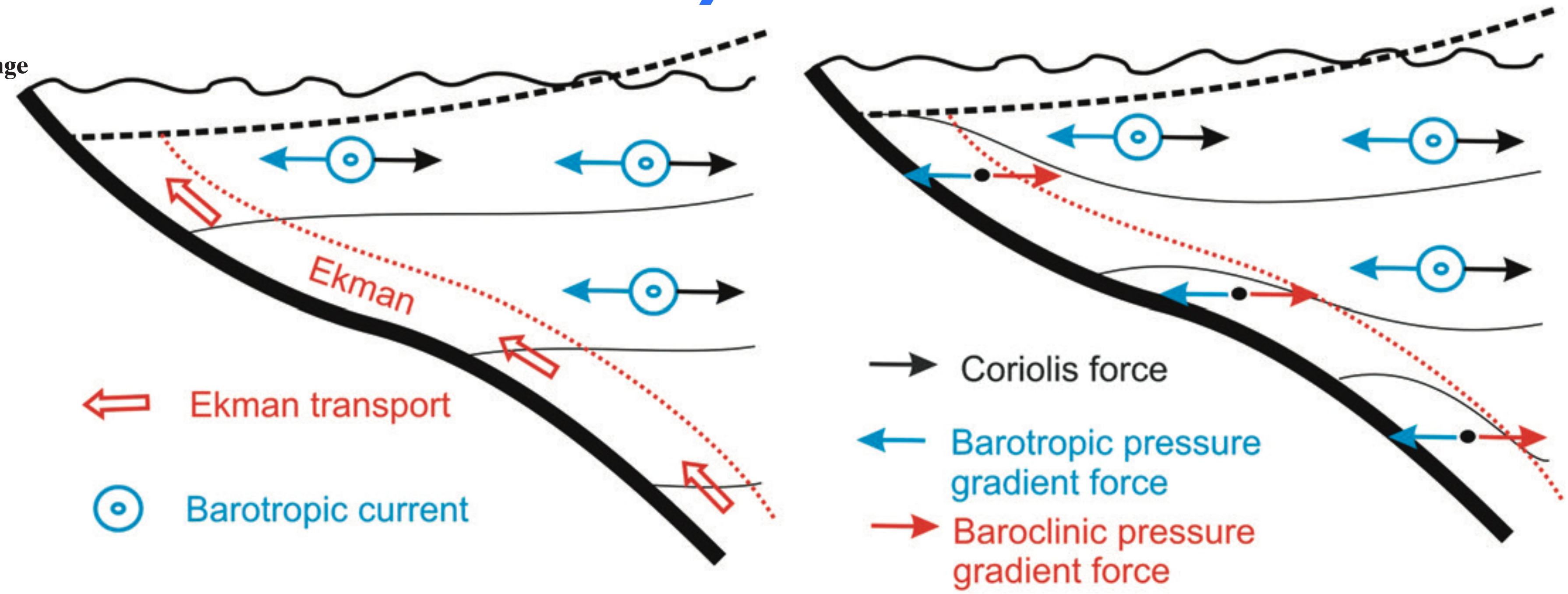


Arrested (or slippery) Ekman layer (barotropic and baroclinic pressure gradients balance): MacCready and Rhines (1993) (theory), Wahlin et al (2012) observational analysis of ACC filaments onto Amundsen Sea shelf.

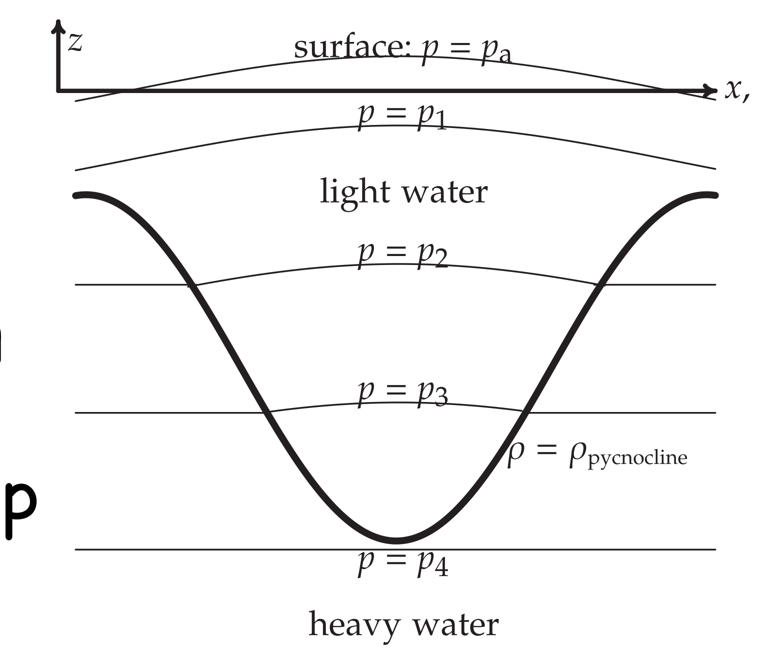
Arrest time scale: hours to days (fast!)

$$\tau = f/(N\,\alpha)^2$$

Arrested Ekman thickness $\approx 10*$ frictional Ekman

See also Webb, Holmes, Spence, England (2018) in prep

cf: baroclinically adjusted 1.5 layer



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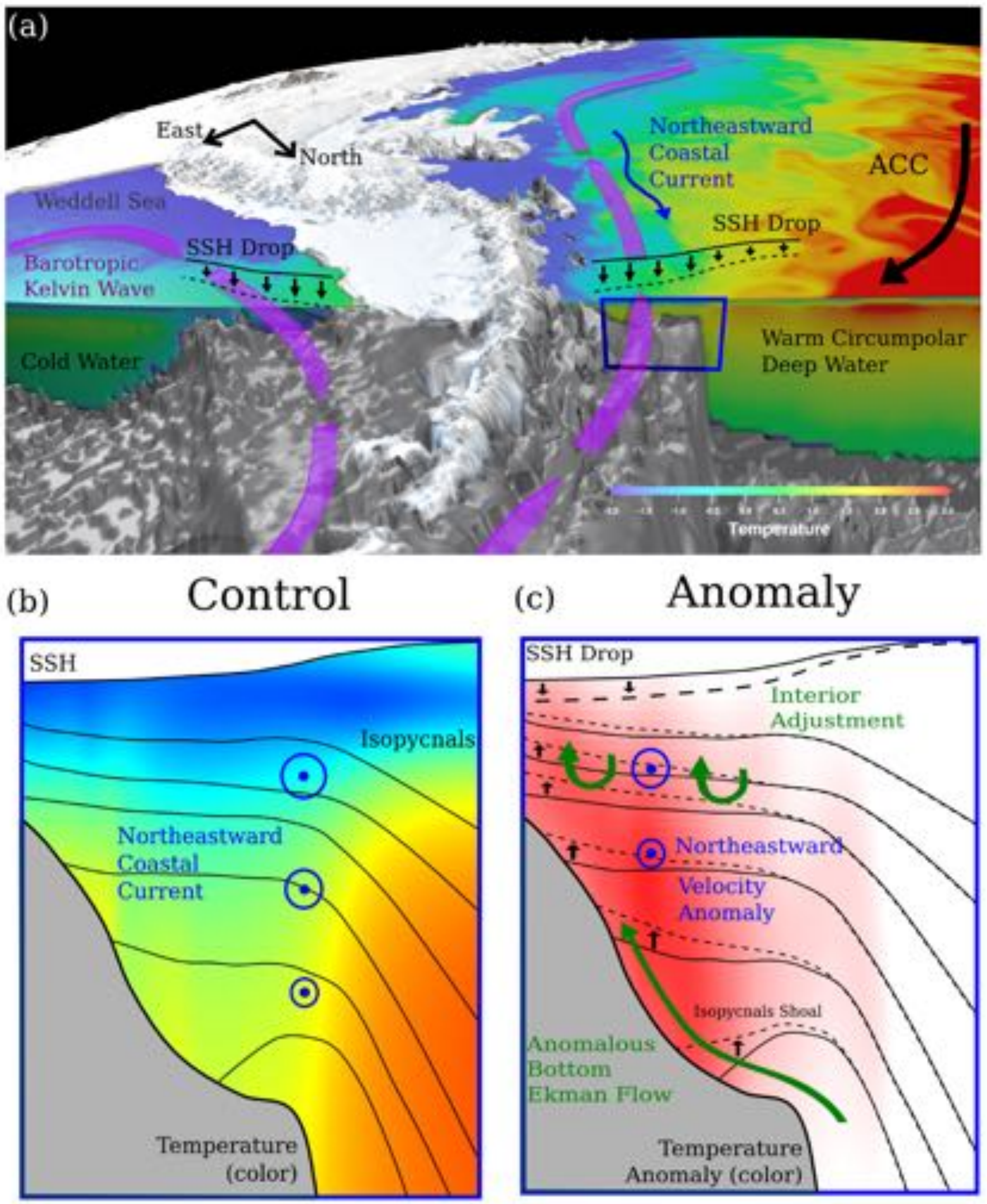
Kelvin waves and arrested Ekman layer adjustment



nature climate change ARTICLES
PUBLISHED ONLINE: 17 JULY 2017 | DOI: 10.1038/NCLIMATE3335

Localized rapid warming of West Antarctic subsurface waters by remote winds

Paul Spence[1]*, Ryan M. Holmes[1,2], Andrew McC. Hogg[3], Stephen M. Griffies[4], Kial D. Stewart[3] and Matthew H. England[1]

- Winds depress sea level off East Antarctica.
- Kelvin wave sends sea level depression around coast (non-dispersive waves).
- Shoreward anomalous barotropic pressure gradient.
- Arrested Ekman and interior baroclinic adjustment causes upslope flow, shoaling warm CDW along shelf.
- Western Peninsula is particularly prone to warming due to steep bottom (strong f/h flow and strong baroclinicity and Ekman adjustment) and proximity to warmer CDW in ACC.
- Return to mechanism summary slide

2xCO2 changes in GFDL/CM2.6 climate model

Journal of Geophysical Research: Oceans

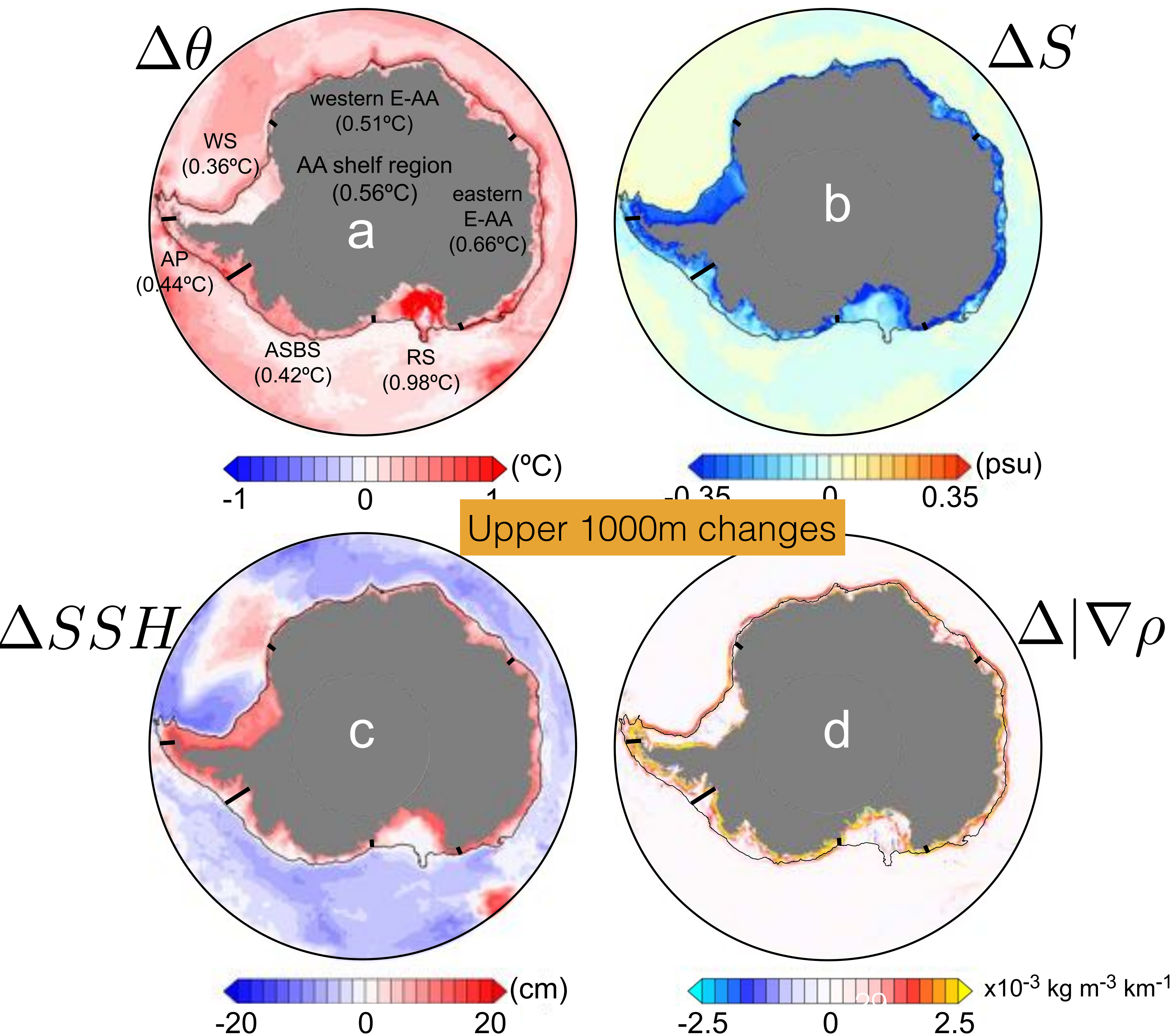
$(\delta x, \delta y) = 5$ km

RESEARCH ARTICLE
10.1002/2017JC012849

Special Section:
The Southern Ocean Carbon
and Climate Observations and

CO_2-Induced Ocean Warming of the Antarctic Continental Shelf in an Eddying Global Climate Model

Paul B. Goddard[1], Carolina O. Dufour[2,3], Jianjun Yin[1], Stephen M. Griffies[4], and Michael Winton[4]



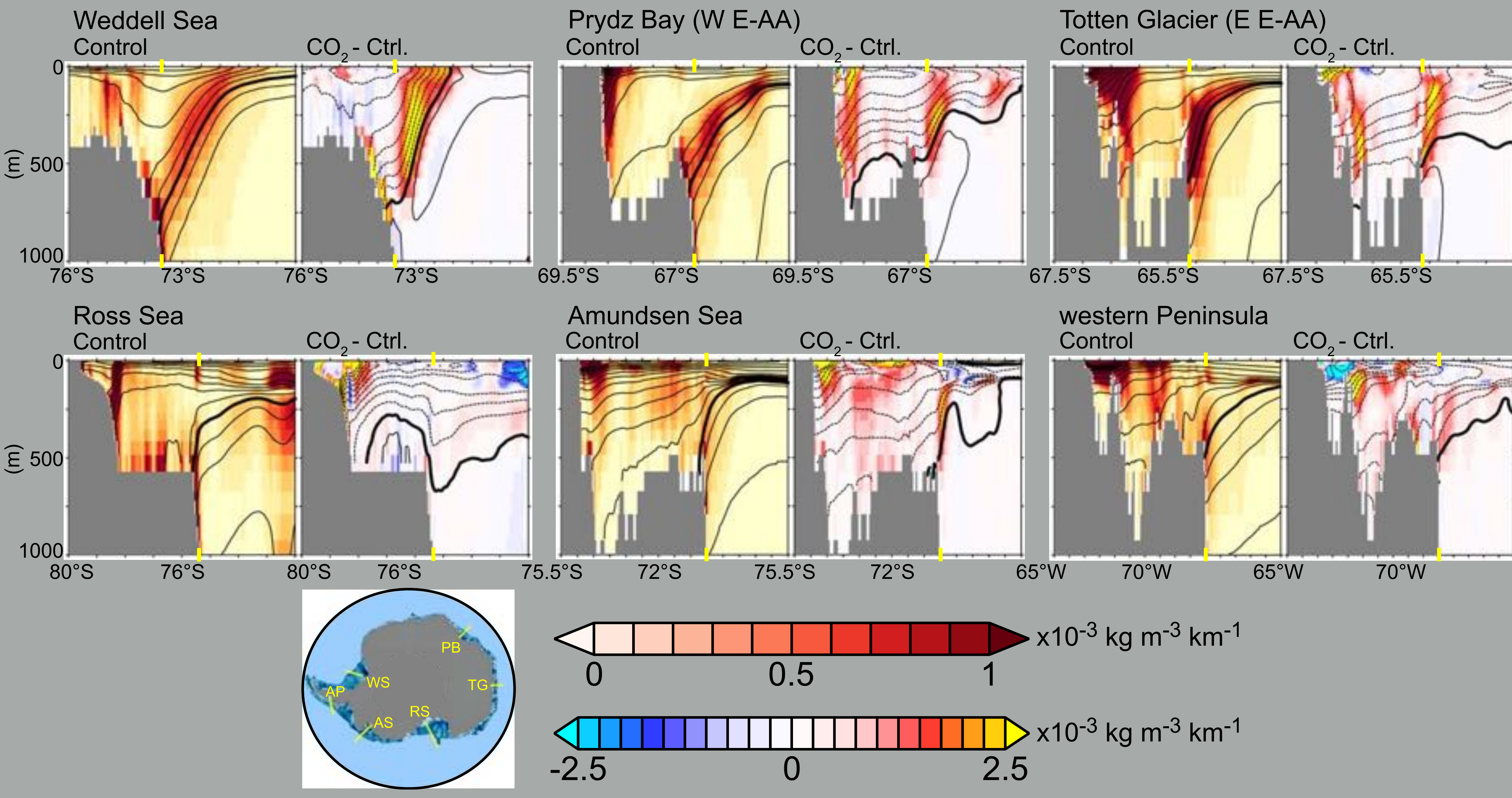
Broad warming along shelf edge.

Non-homogenous warming pattern around continent.

Shelf freshening and halosteric dominate sea level changes.

Increased lateral ρ gradient around shelf edge. Regions with less increase show more warming (e.g., Ross Sea).

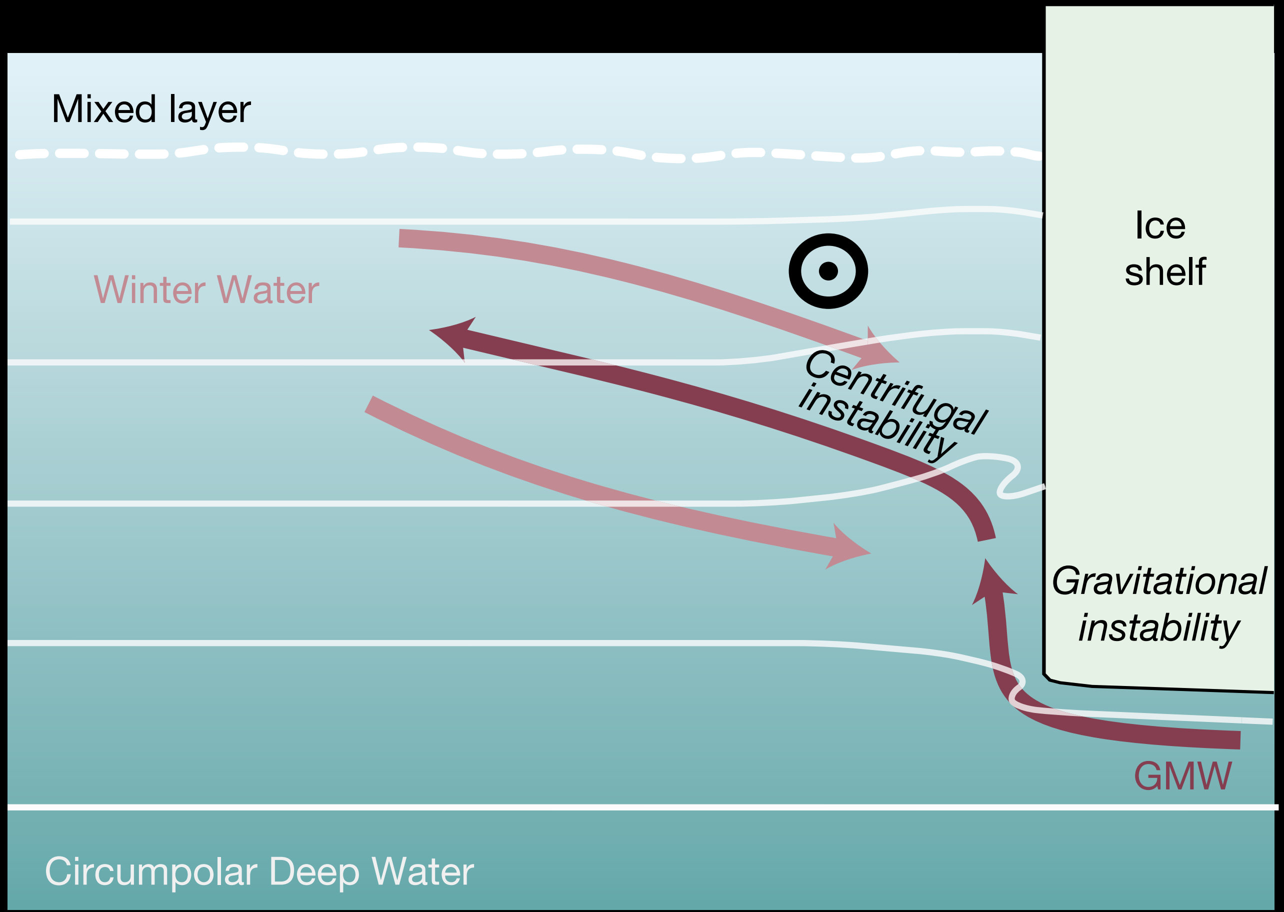
Salinity induced changes to shelf barolinicity



Mesoscale eddying models are not sufficient for full story

- Full story may require a fine resolution models, with ~500m grids to get high latitude mesoscale eddies; ice-shelf cavities to get geometry; tides to get exchanges; coupled model to get realistic forcing, etc.

- Even finer grids (~50m) are needed to get submesoscale processes (centrifugal instability) found in field measurements to be important for the export of melt water (Naveira Garabato et al 2017).



Closing remarks

- Ocean fluid mechanics becomes ever more important as we ask questions about coastal sea level changes and processes that impact on those changes.
  - ⋆ coastal waves for teleconnections and time scales of transient responses;
  - ⋆ mesoscale & submesoscale instabilities and eddies near coasts transferring properties offshore or onshore;
  - ⋆ ocean / ice-shelf interactions and associated heat transport (waves, instabilities, eddies).

- Fine resolution (e.g., finer than 1st baroclinic Rossby radius) is necessary to faithfully represent key scales of motion and topograpihic waves.

- But fine resolution is not sufficient.
  - ⋆ Need better understanding of numerical closures (friction) and boundary conditions.
  - ⋆ Need better understanding of flow-topography interactions (waves, eddies, mixing, boundary layers); details matters!

- Physical oceanographers have discovered/re-discovered examples of how flow-topography interactions are key to how the ocean works & how it plays a role in climate change and sea level.

Global, regional, process studies

- Some questions require global models
  - ★ AMOC fluctuations and downward trend
  - ★ ENOS impacts on coast
  - ★ ENSO teleconnections to Antarctic region

- Some can be addressed by regional models
  - ★ Circus-Antarctic regional models; capture Spence et al wave mechanism in presence of vigorous eddy activity.

- Some can be addressed by process models
  - ★ Submesoscale instabilities and interactions with sea ice and ice shelves

We should aim for close interaction between the various efforts to help build understanding while enhancing capabilities. COSIMA has a role to play in this endeavor.

Many thanks for your time

Atmospheric lee waves over Coronation Island
North Weddell Sea, May 2017

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