The importance of refined model resolution for understanding and projecting global, regional, and coastal sea levels

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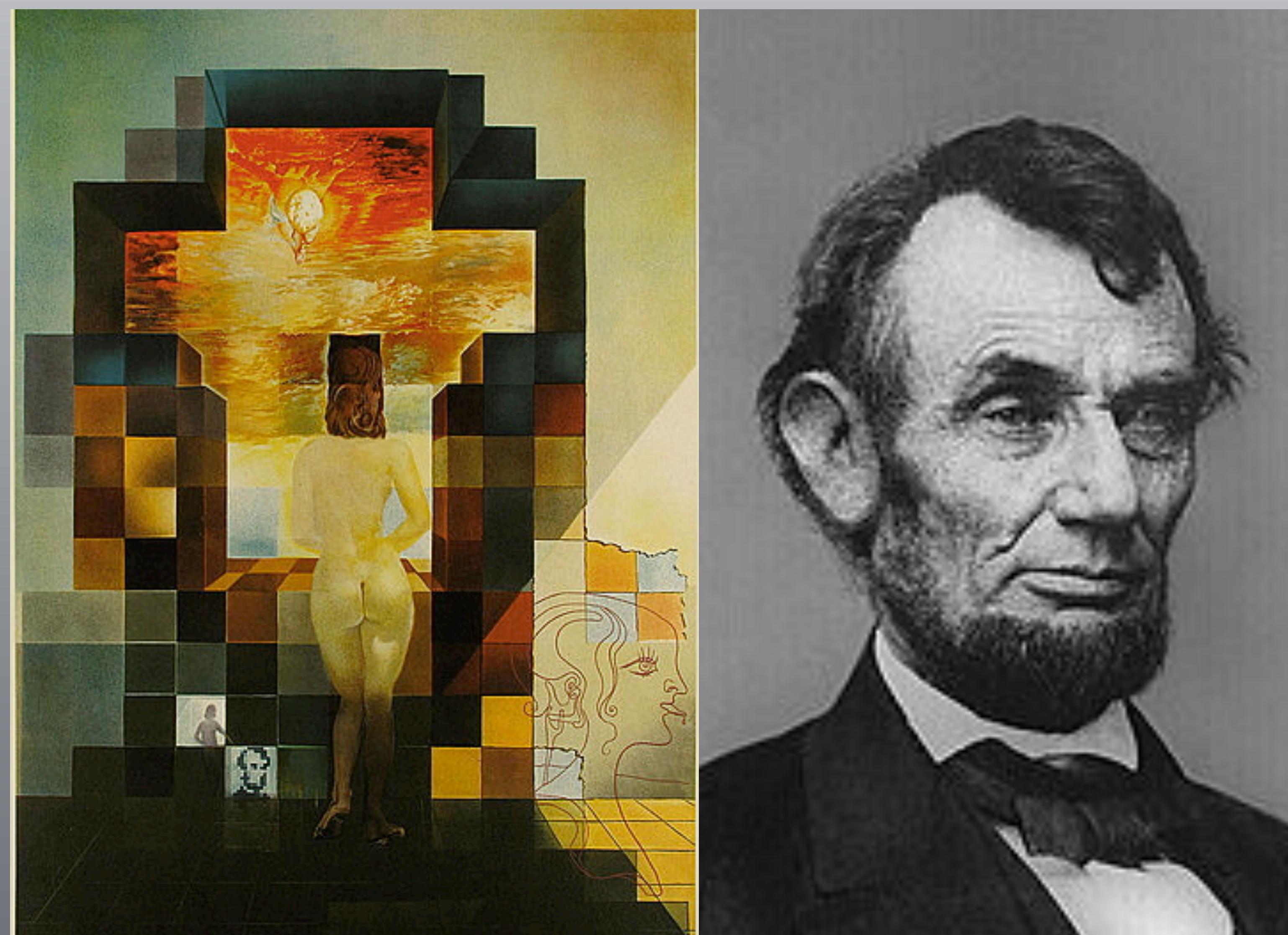
NOAA/GFDL and Princeton University

9 June 2020

GISS Sea Level Seminar

Thanks to numerous collaborators, most of whom are part of the papers cited.

The importance of resolution for simulating ocean fluid dynamics

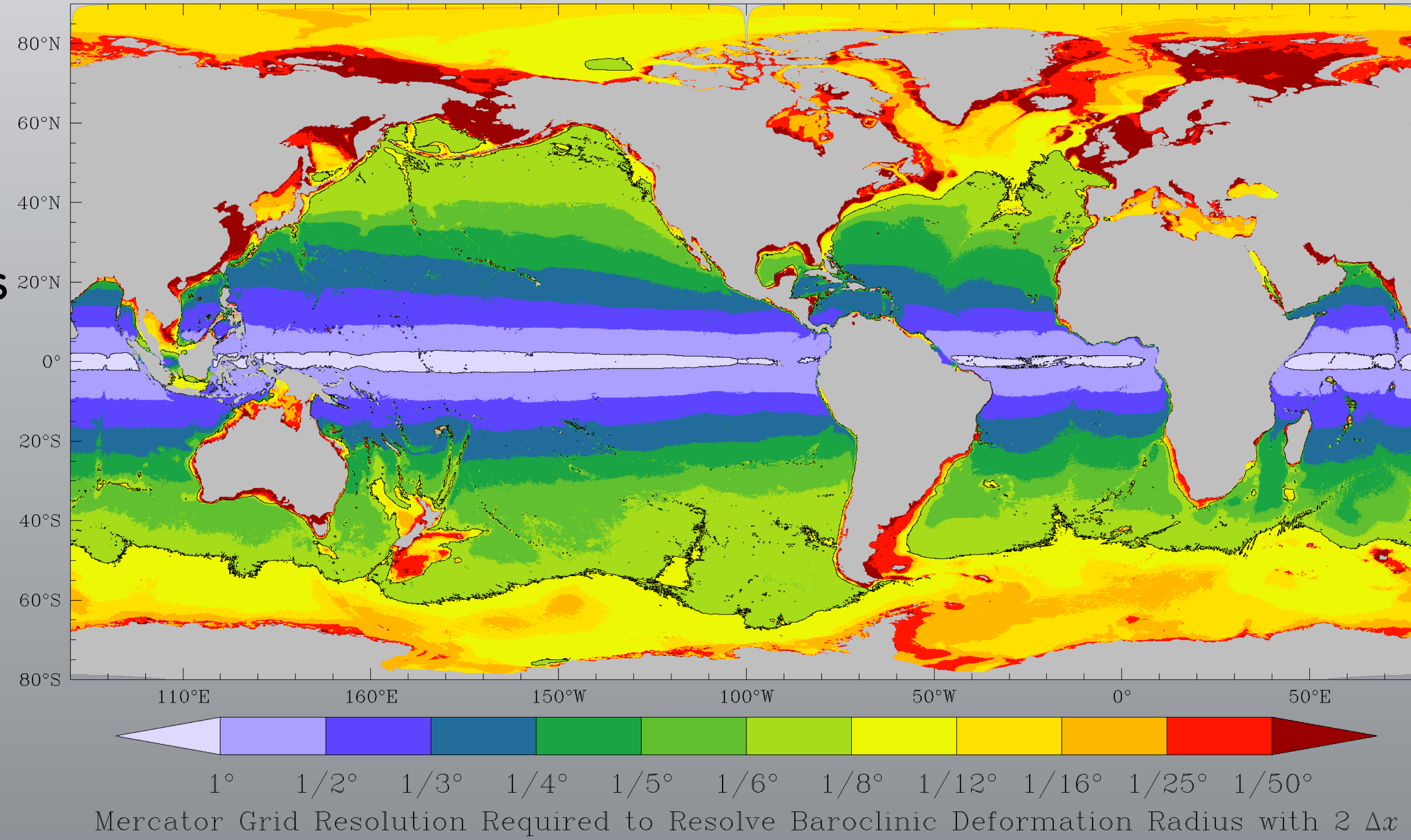


Dalivision versus Clearvision

Metric for resolution

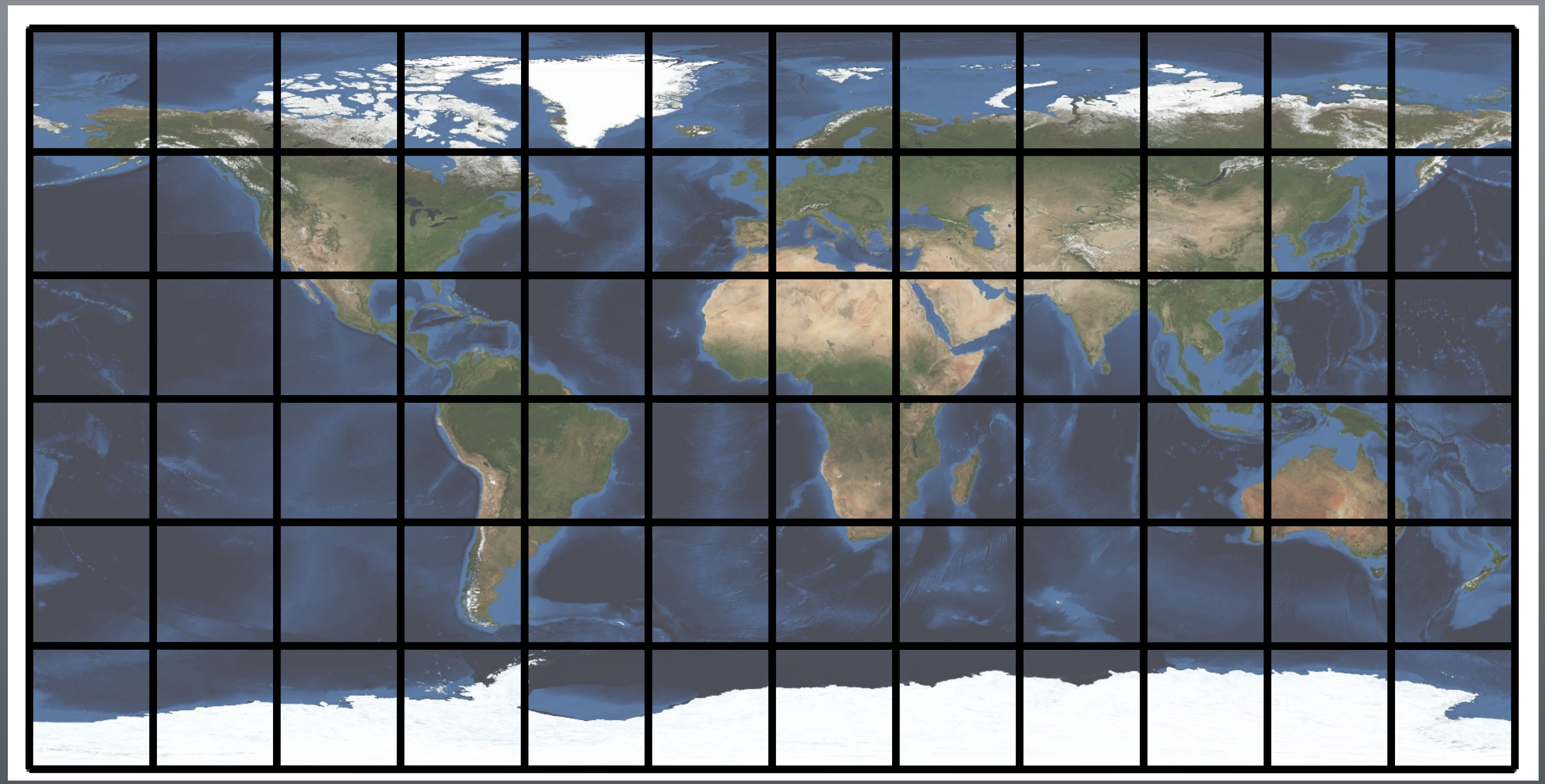
1st baroclinic Rossby radius (mesoscale eddies and coastal waves)

Hallberg, 2013: Using a resolution function to regulate parameterizations of oceanic mesoscale effects, Ocean Modelling, 72, DOI:10.1016/j.ocemod.2013.08.007.

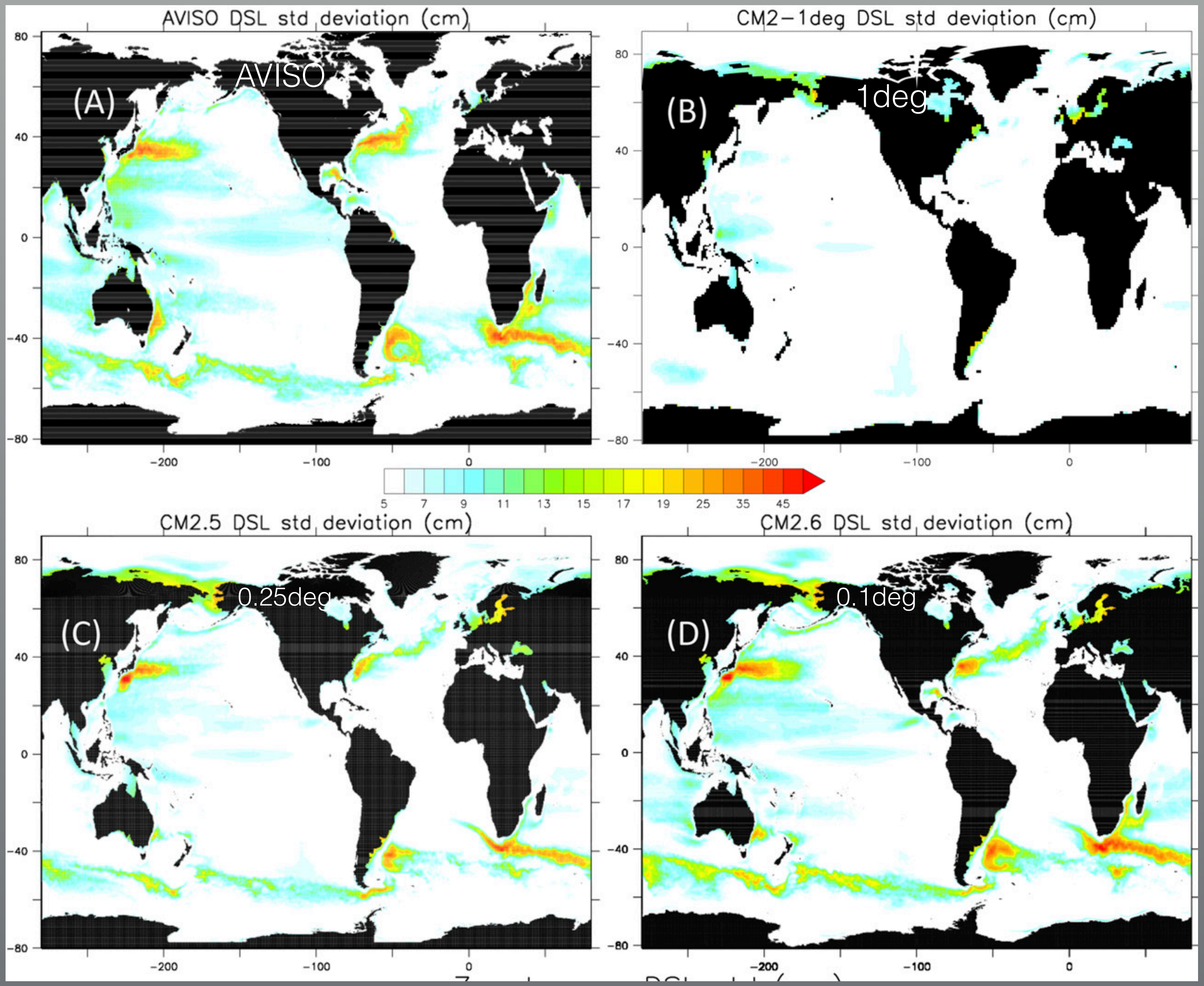


In terms of geostrophic eddy resolution, a 1° ocean model is roughly a 30° atmosphere model.

Courtesy David Marshall, after Peter Killworth



GFDL CM2-O ocean resolution hierarchy of climate models



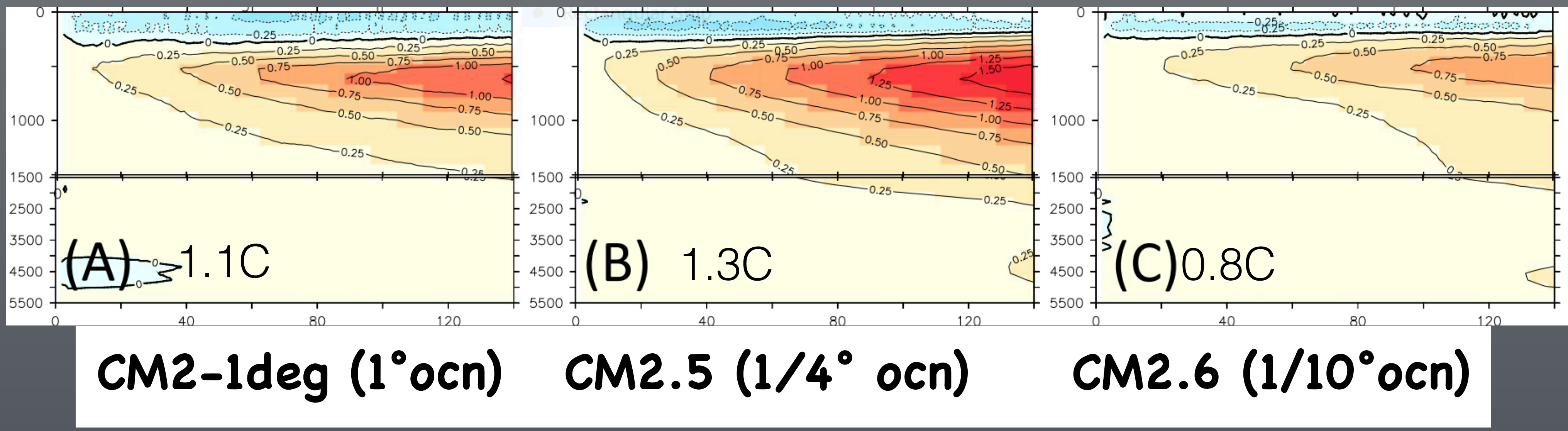
Griffies et al 2015
Roughly 40 studies making use of this hierarchy.

Mesoscale eddies transport heat up to partially compensate for downward pumping from winds. Act to warm SST and cool thermocline.

Major implications for climate model drift and ocean heat uptake.

Evolution of horizontally averaged temperature

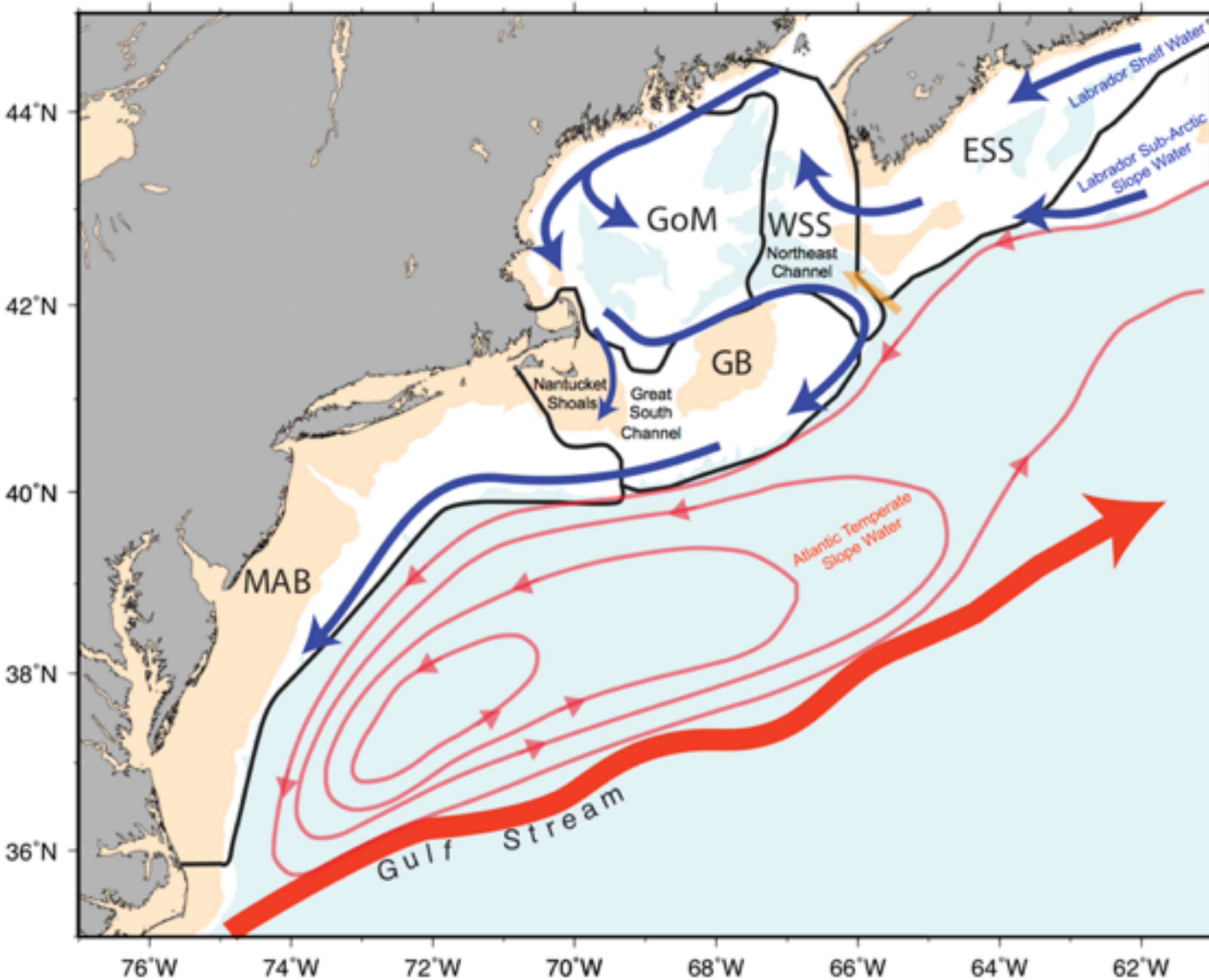
[SST animation link]



Case study I: Northwest Atlantic warming in the Gulf of Maine in response to AMOC reduction

- **Griffies** et al, 2015: Impacts on ocean heat from transient mesoscale eddies in a hierarchy of climate models, Journal of Climate, doi: 10.1175/JCLI-D-14-00353.1
- Saba, **Griffies**, et al, 2016: Enhanced warming of the northwest Atlantic Ocean under climate change, JGR-Oceans, doi:10.1002/2015JC011346

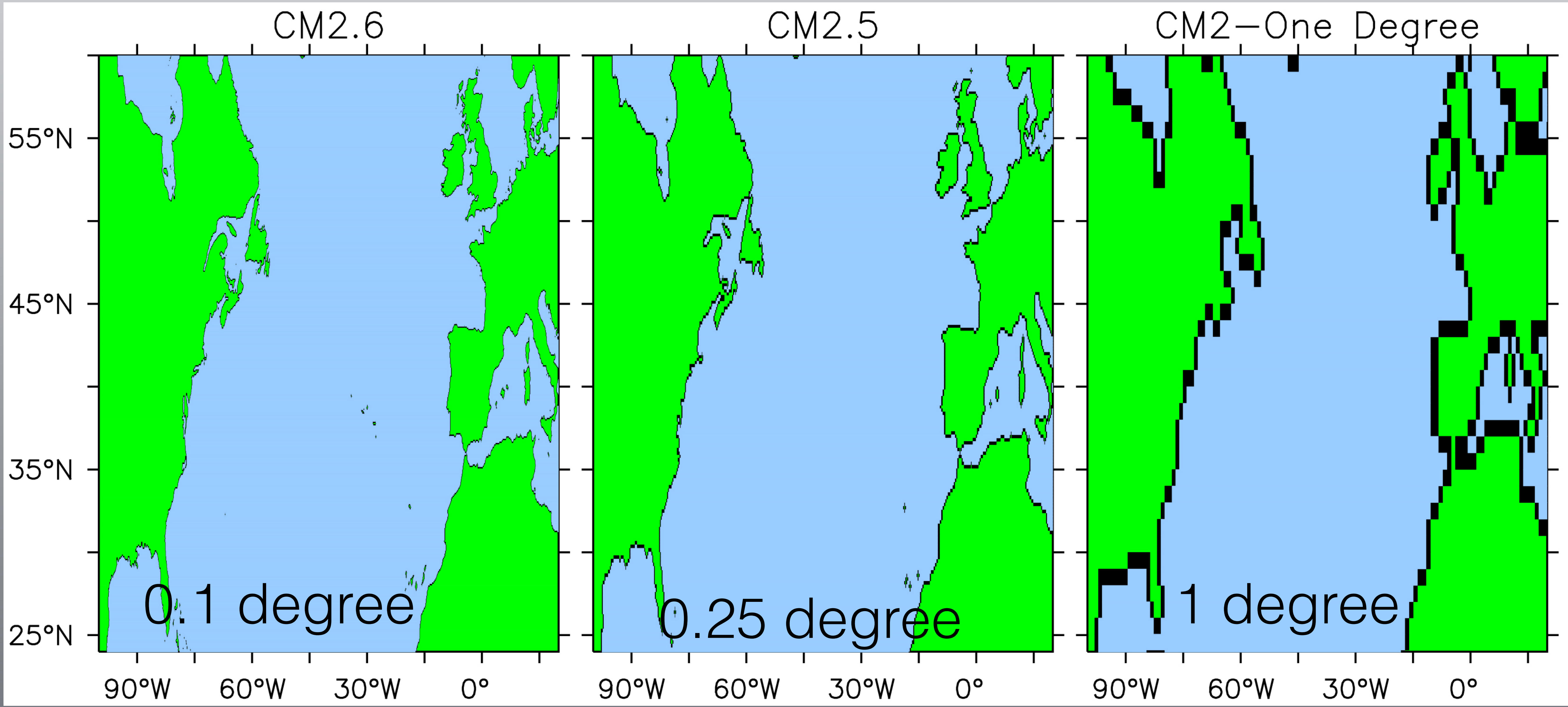
Northwest Atlantic warming



Observed circulation in northwest Atlantic. Gulf of Maine has seen among the largest relative heating anywhere on the planet during recent decades.

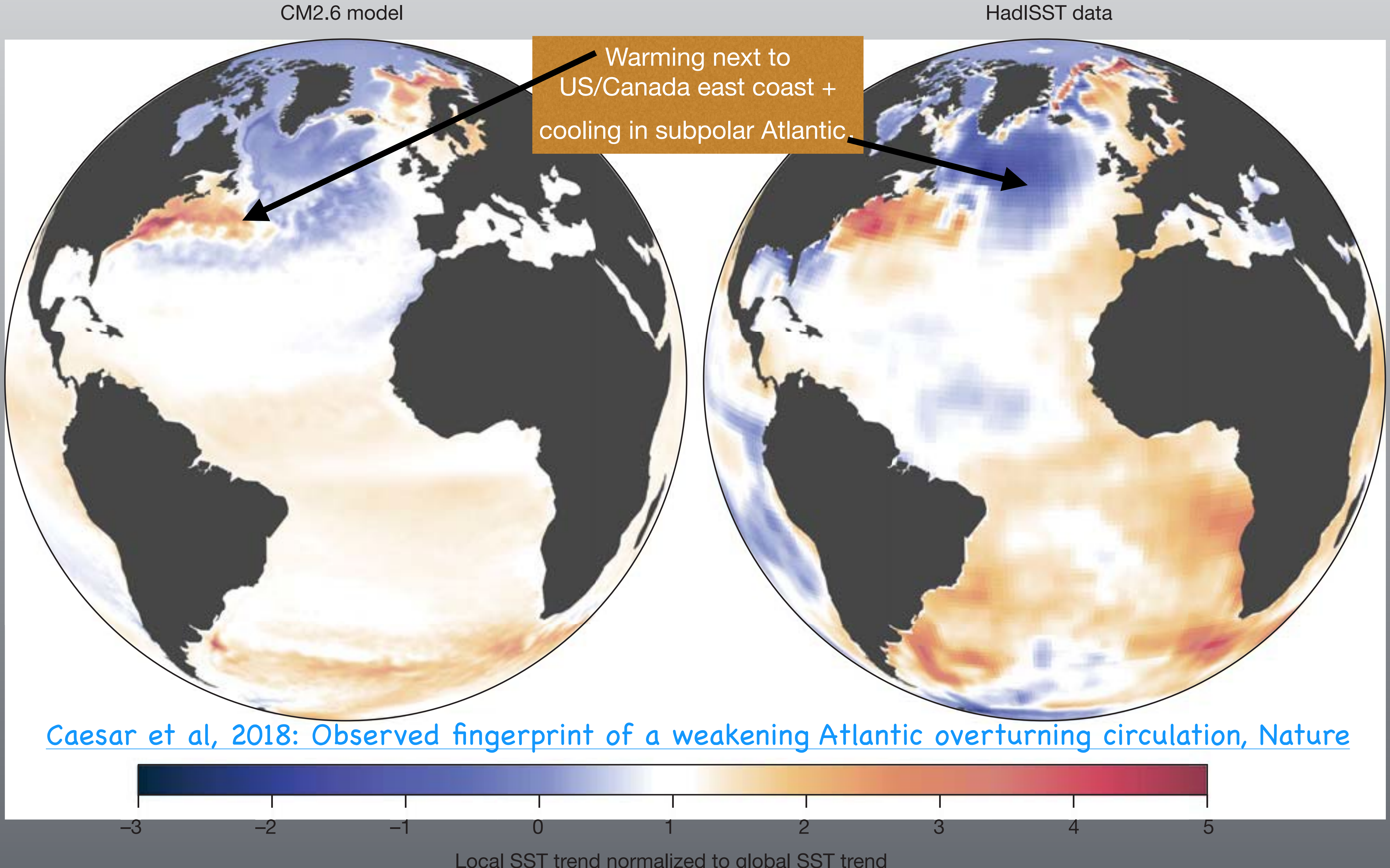
Saba, et al, (2016)

North Atlantic coast using three resolutions



Courtesy Paul Goddard, Univ of Conn

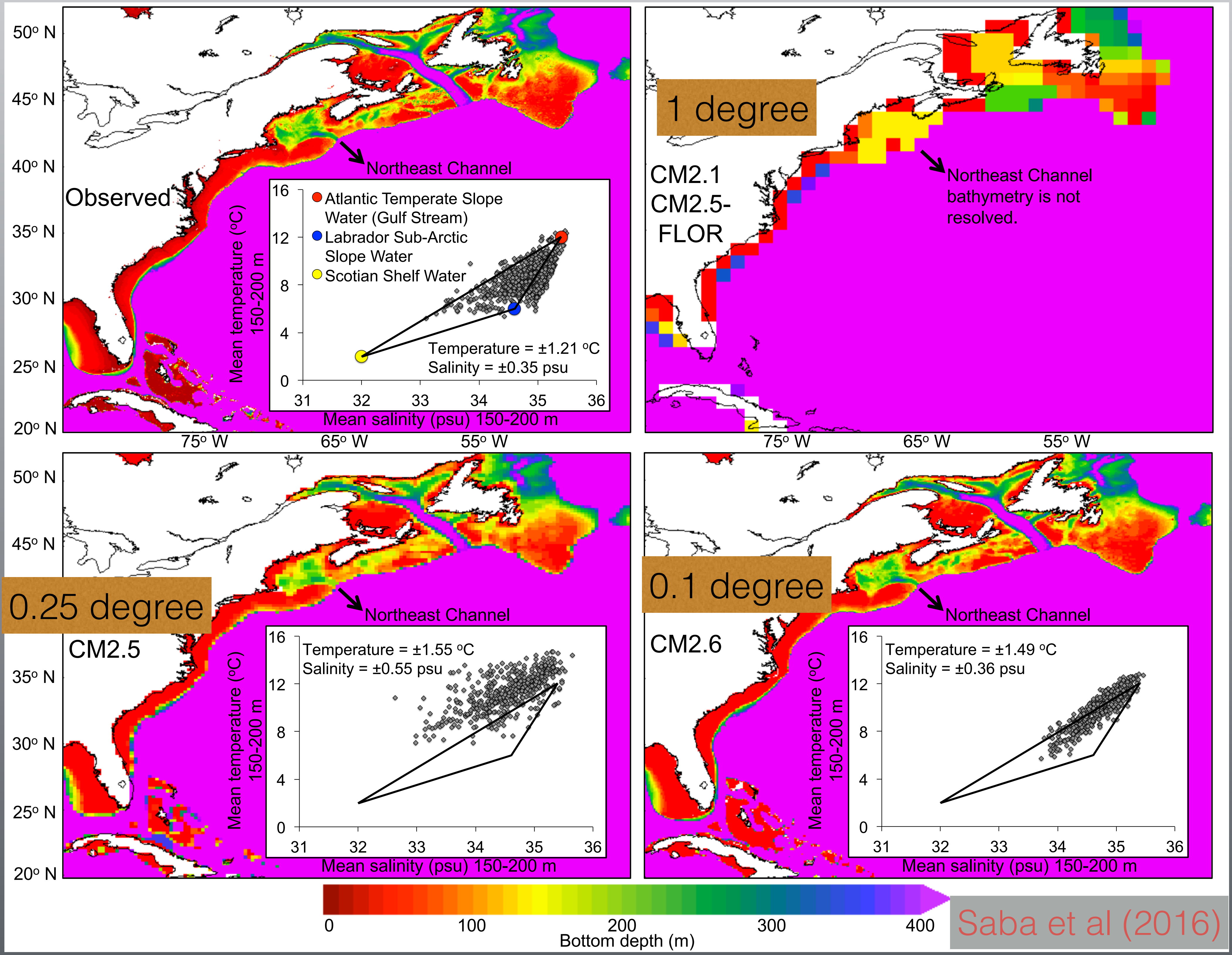
SST fingerprint of AMOC reduction



[Caesar et al, 2018: Observed fingerprint of a weakening Atlantic overturning circulation, Nature]()

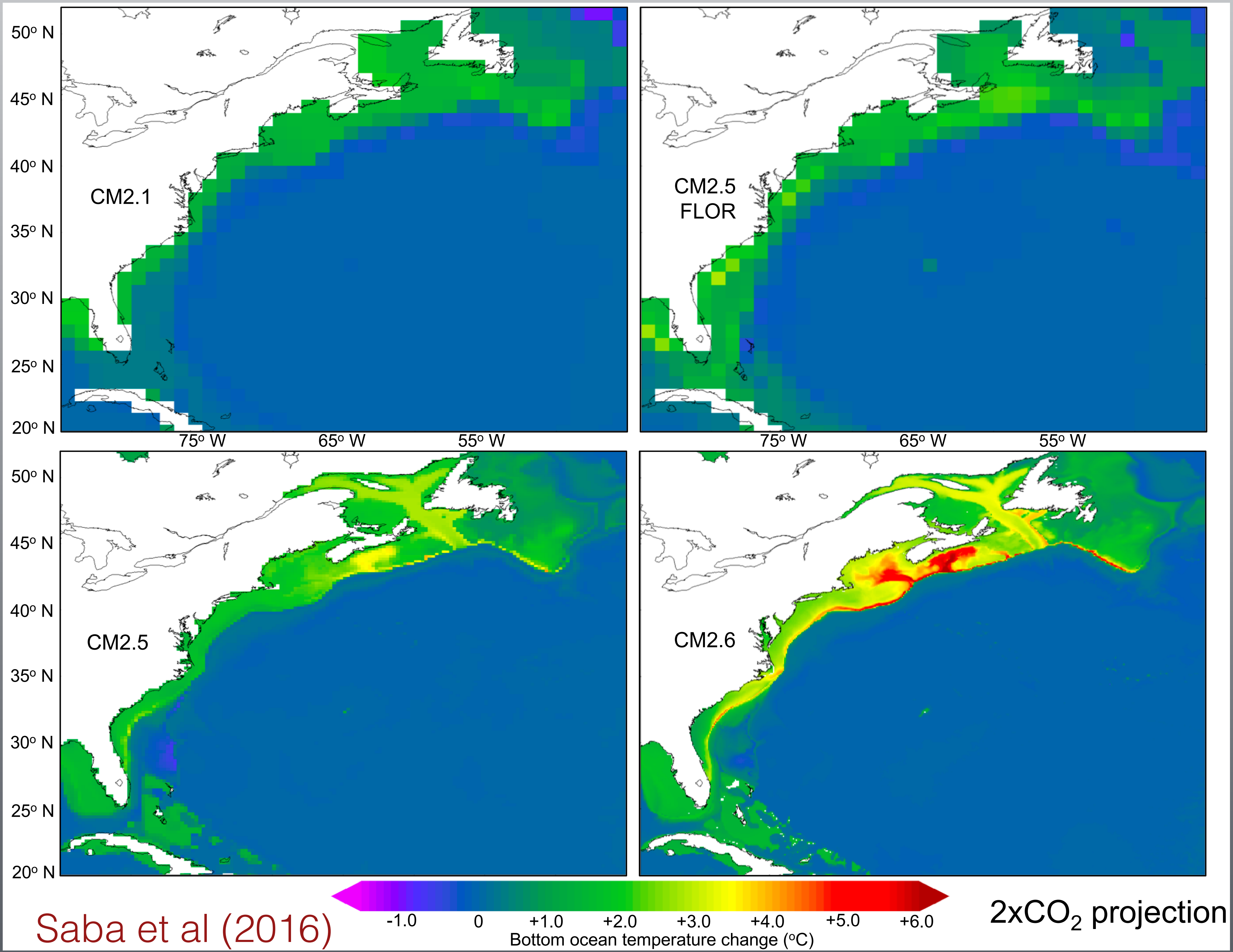
T/S in Gulf of Maine "Northeast Channel"

Finest resolution model has the most realistic water masses.



Projected bottom warming

Finest resolution shows most shelf warming



Saba et al (2016)

$2xCO_2$ projection

Shelf warming is connected to AMOC slowdown in the model.

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

Summary points from North Atlantic studies

- Refined coastal resolution ==> enhanced simulation of coastal water mass properties in regions around the Gulf of Maine (key for North Atlantic fisheries) and other coastal regions along NAmerica.

- Idealized 2xCO2 simulations show warming in the Gulf of Maine associated with changes in AMOC and coastal circulation.

  - Gulf of Maine: observed hot spot for 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? Caesar et al (2018) say "yes", others debate.

- Coarse simulations do not resolve coastal currents/topography and show less coastal warming in climate change simulations.

- Temperature results translate into sea level changes near coast (as seen later).

Case Study II:
A comment on model capabilities to represent eastern Pacific sea level fingerprints from El Nino

Eastern Pacific in the CM2-O hierarchy

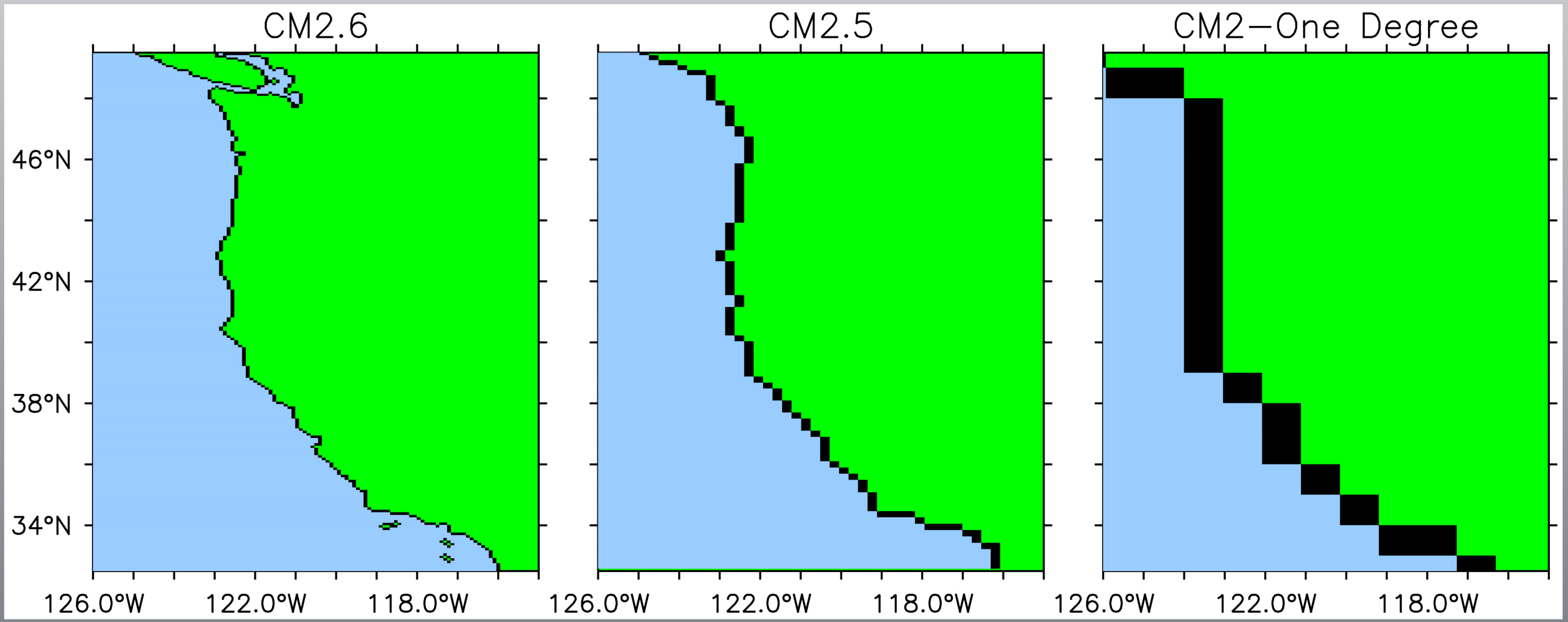
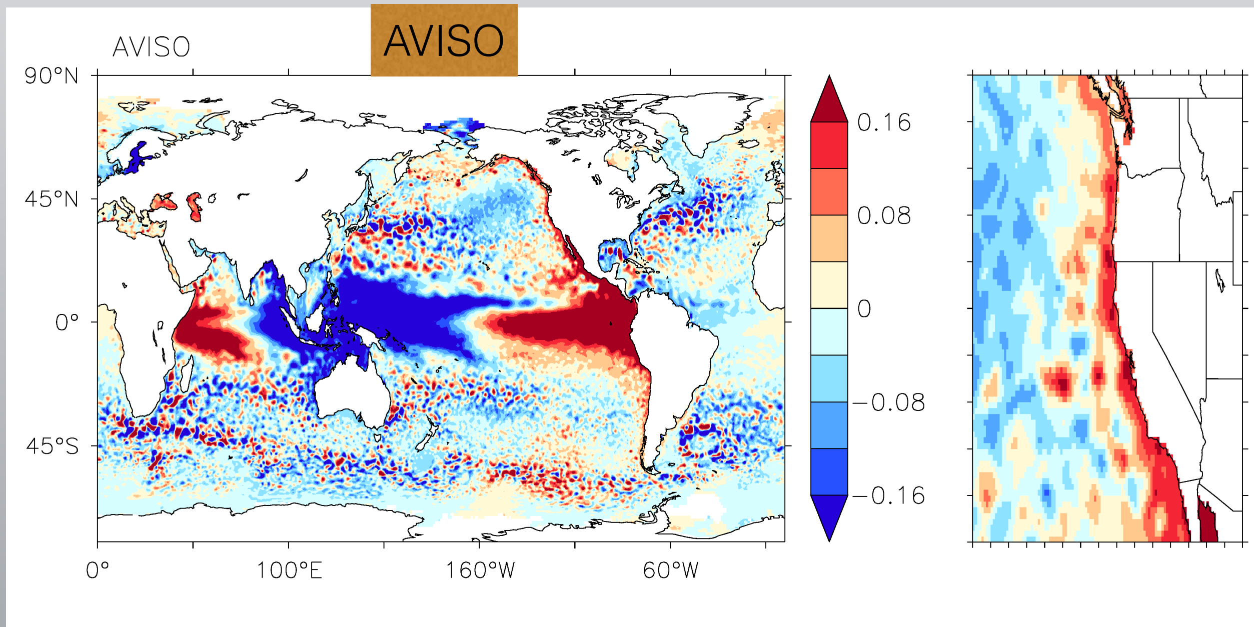


Figure courtesy of Paul Goddard, Un of Conn

El Nino and east Pacific coastal sea level

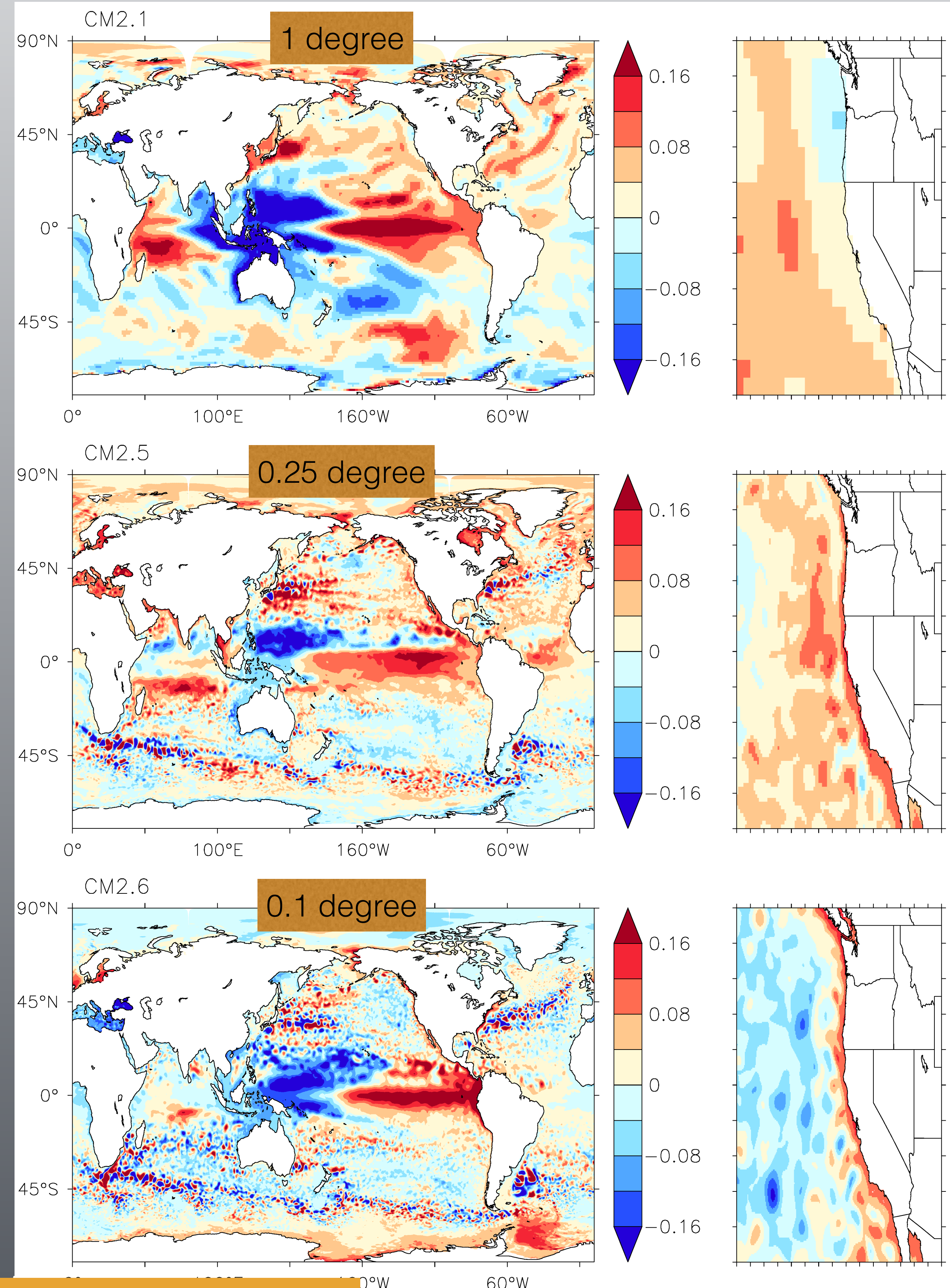


West coast of North America has a relatively narrow continental shelf.

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

Summary points from Pacific

- To represent impacts of large-scale climate fluctuations on coastal sea level requires grid resolution sufficient to resolve the shelf.

- Time scale & amplitude for coastal signals (waves) are sensitive to the shelf resolution.

  - See Hughes, Fukomori, Griffies, Huthnance, Minobe, Spence, Thompson, and Wise (2019) for review.

- It is common to downscale with "hydrodynamic" models to estimate coastal impact. But there are limitations:

  - ☆ Technical issues related to boundary forcing.

  - ☆ Unable to capture feedbacks & interactions of coastal circulation with climate modes and large-scale circulation; e.g., impacts of changes to ENSO, NAO, AMOC, SAM, etc. on changes to extremes. The world is more complex than "trend plus noise".

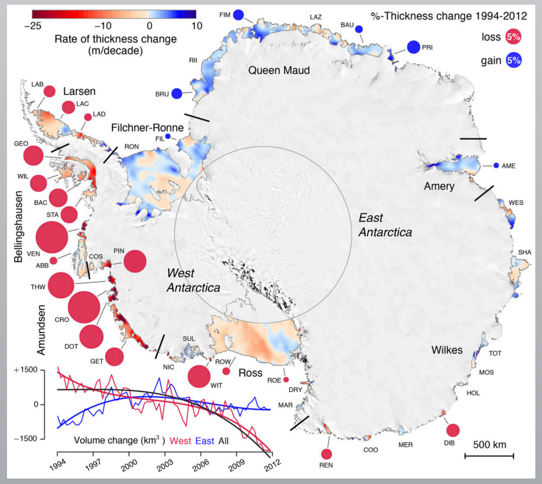
  - ☆ We can loose the conceptual connection and associated mechanical insights when disconnecting "sea level models" from large-scale physical mechanisms that cause sea level changes.

Case Study III:
Antarctic continental shelves:
A role for ocean heating underside of ice-shelves

- Yin, Overpeck, **Griffies**, Hu, Russell, Stouffer 2011: Different magnitudes of projected subsurface ocean warming around Greenland and Antarctica, Nature Geoscience, doi:10.1038/ngeo1189
- Frankcombe, Spence, Hogg, England, **Griffies** 2013: Sea level changes forced by Southern Ocean winds, GRL doi:10.1002/2013GL058104
- Spence, **Griffies**, England, Hogg, Saenko, Jourdain, 2014: Rapid subsurface warming and circulation changes of Antarctic coastal waters by poleward shifting winds, GRL, doi: 10.1002/2014GL060613
- Spence, Holmes, Hogg, **Griffies**, Stewart, England, 2017: Localized rapid warming of West Antarctic Peninsula subsurface waters by remote winds, Nature Climate Change, doi: 10.1038/NCLIMATE3335
- Goddard, Dufour, Yin, **Griffies**, Winton, 2017: CO2-induced ocean warming around the Antarctic ice sheet in an eddying global climate model, JGR-Oceans, doi: 10.1002/2017JC012849

Motivation

- Observed positive rates of ice shelf melt around western Antarctica and peninsula;



- 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.

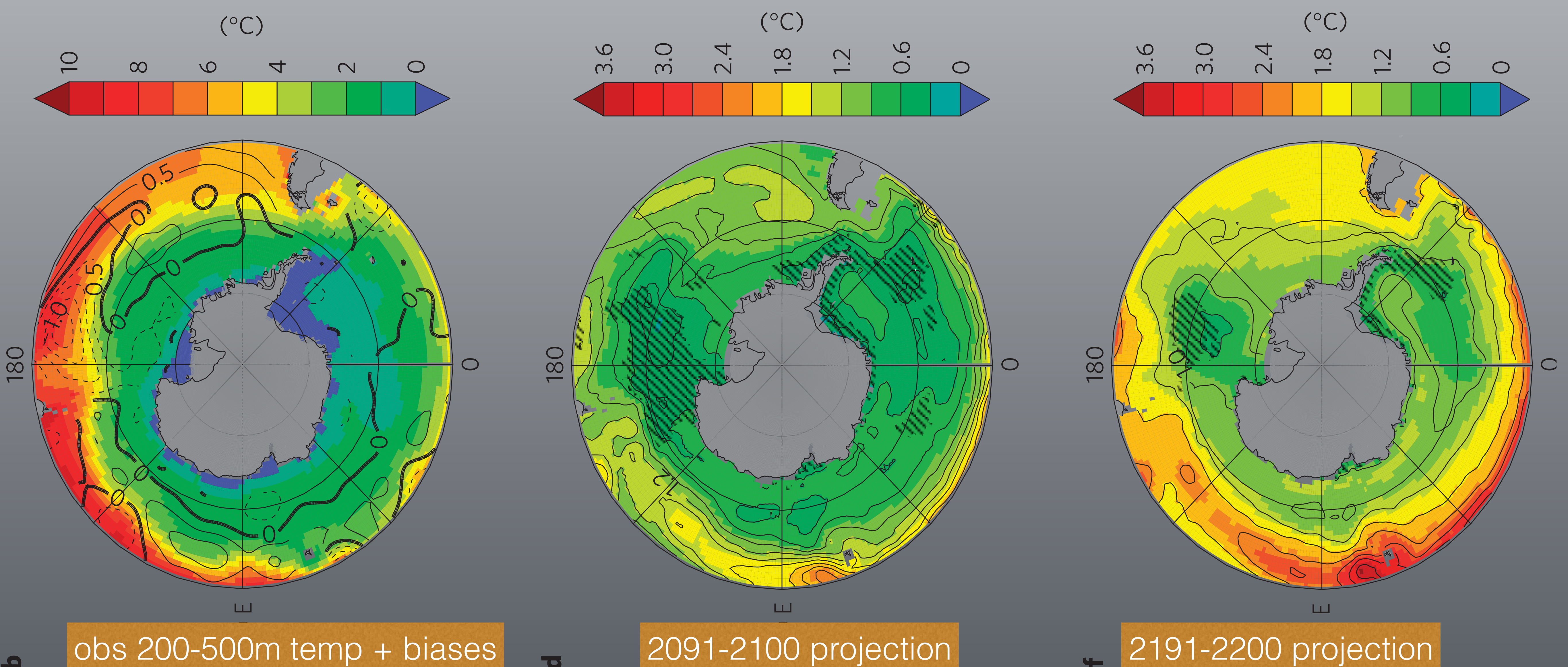
  - ★ **Question A**: What are the physical mechanisms for sub-ice shelf ocean warming? How does warm water get there?

  - ★ **Question B**: Are any of these mechanisms subject to large-scale climate trends, either natural or anthropogenic?

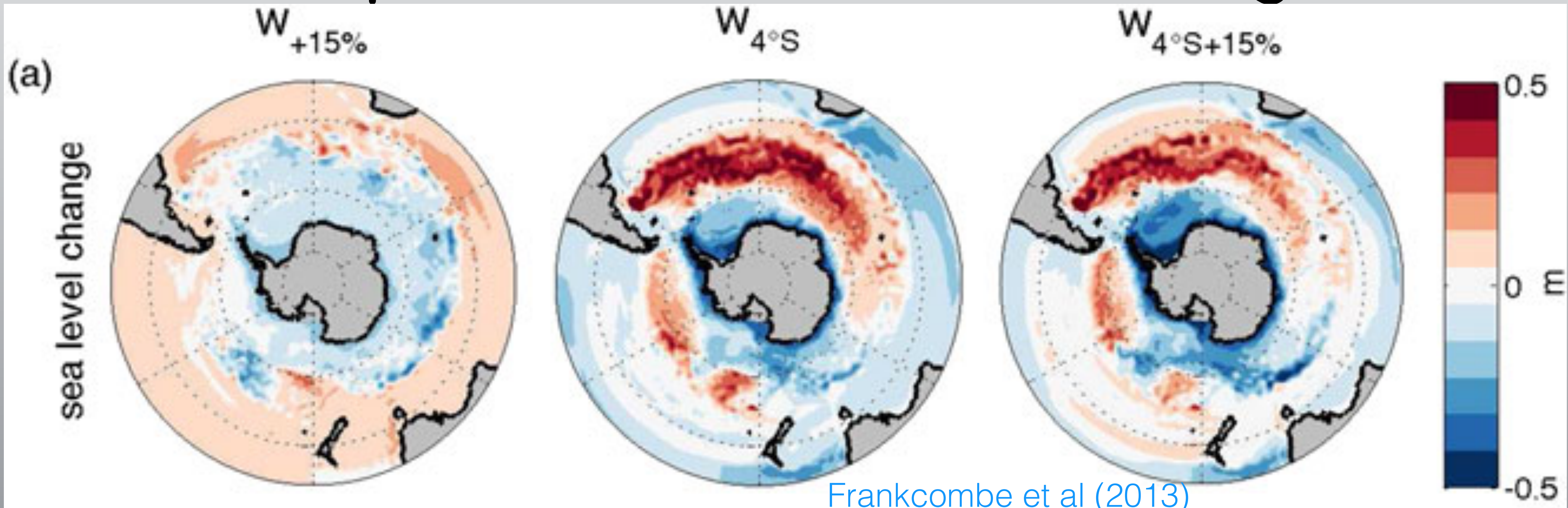
CMIP3-era simulations

Yin et al 2011

- Overall rather coarse representation of sea level features.
- Little representation of coastal processes.
- Coastal processes are key to ocean/ice shelf interactions, but must have finer resolution than in these models to properly capture.



Response to zonal wind changes



Frankcombe et al (2013)

- Atmospheric reanalyses show that Southern Ocean westerlies have shifted poleward. Climate model projections see increases in this trend, particularly when ozone recovers & Southern Annual Mode becomes dominated by CO2 warming.

- Antarctic regional wind patterns are also correlated to large-scale indices such as ENSO.

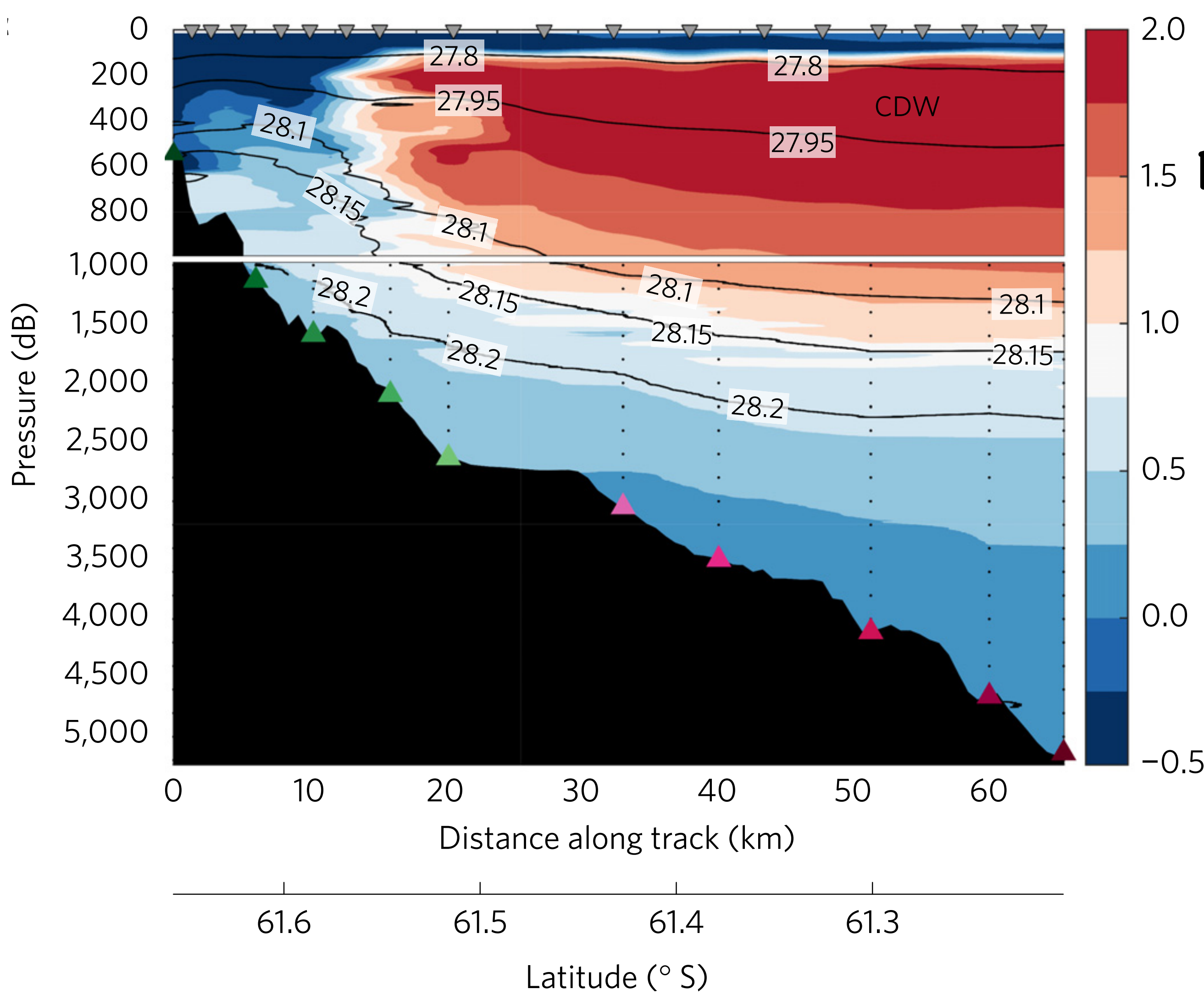
- Key impacts on sea level arise from southward wind shift, more than from increased magnitude.

- Ekman driven changes lead to sea level drop near the coast and rise to north.

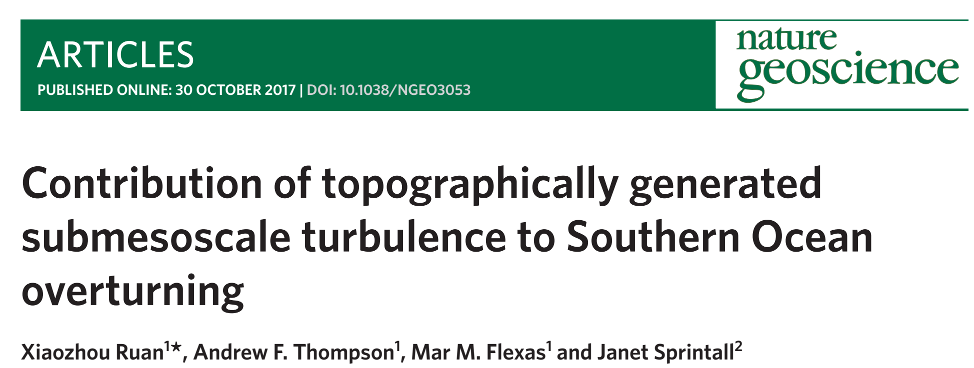
A key question for global sea level:

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

- What are the physical mechanisms?
- Among the mechanisms, are any subject to climate trends?
- See also Ruth Moorman's talk in this seminar series from 26 May 2020.



Example temp section off Antarctic peninsula


ARTICLES
PUBLISHED ONLINE: 30 OCTOBER 2017 | DOI: 10.1038/NGEO3053
nature geoscience

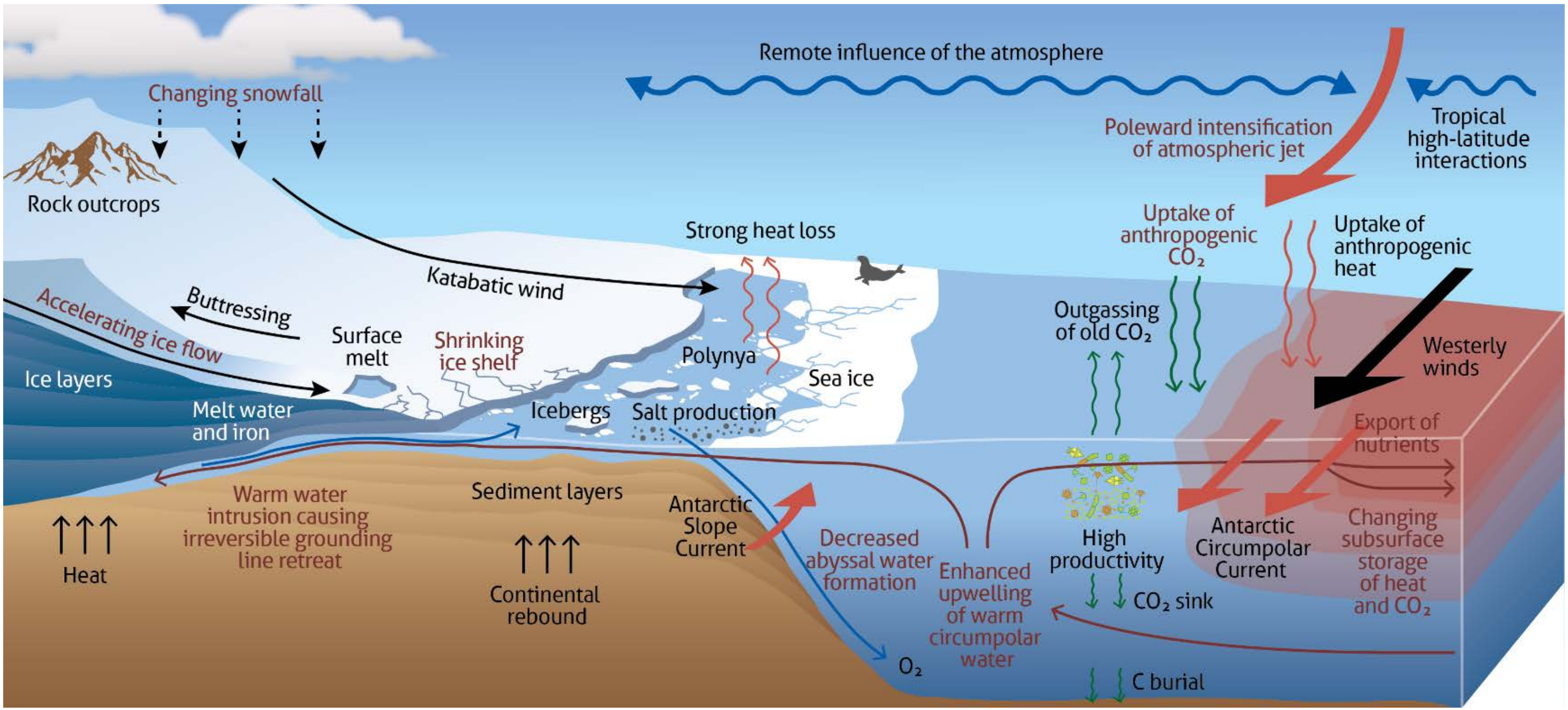
Contribution of topographically generated submesoscale turbulence to Southern Ocean overturning

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

Ruan et al (2017)

Antarctic shelf processes

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



From the newly funded Australian Centre of Excellence for Antarctica Science

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.

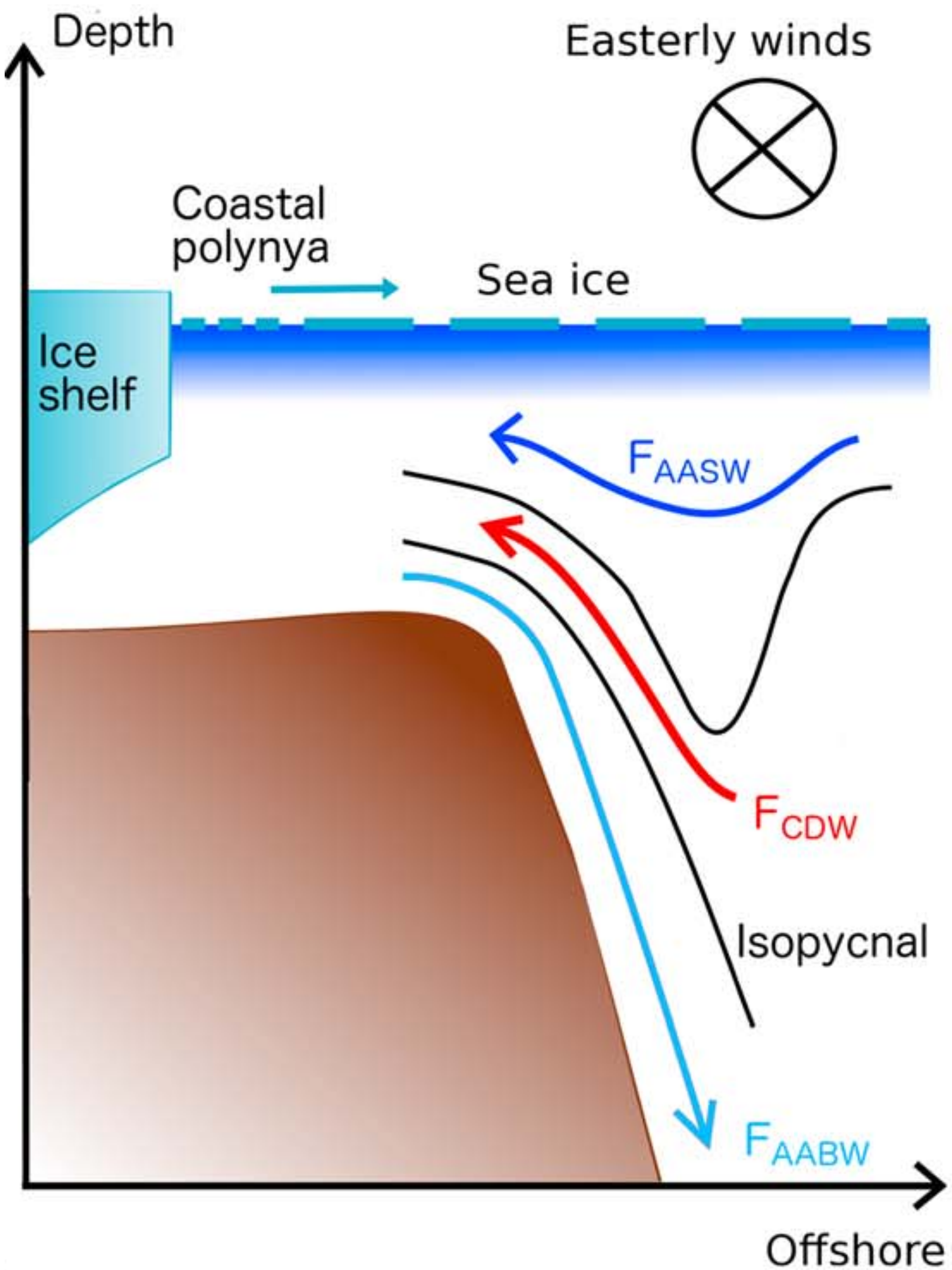
- Arrested (or slippery) Ekman layer (barotropic and baroclinic pressure gradients balance): MacCready and Rhines (1993) (theory), Wahlin et al (2012) observational analysis of ACC filaments onto Amundsen Sea shelf.

- 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), Moorman et al (2020).

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.

Geophysical Research Letters

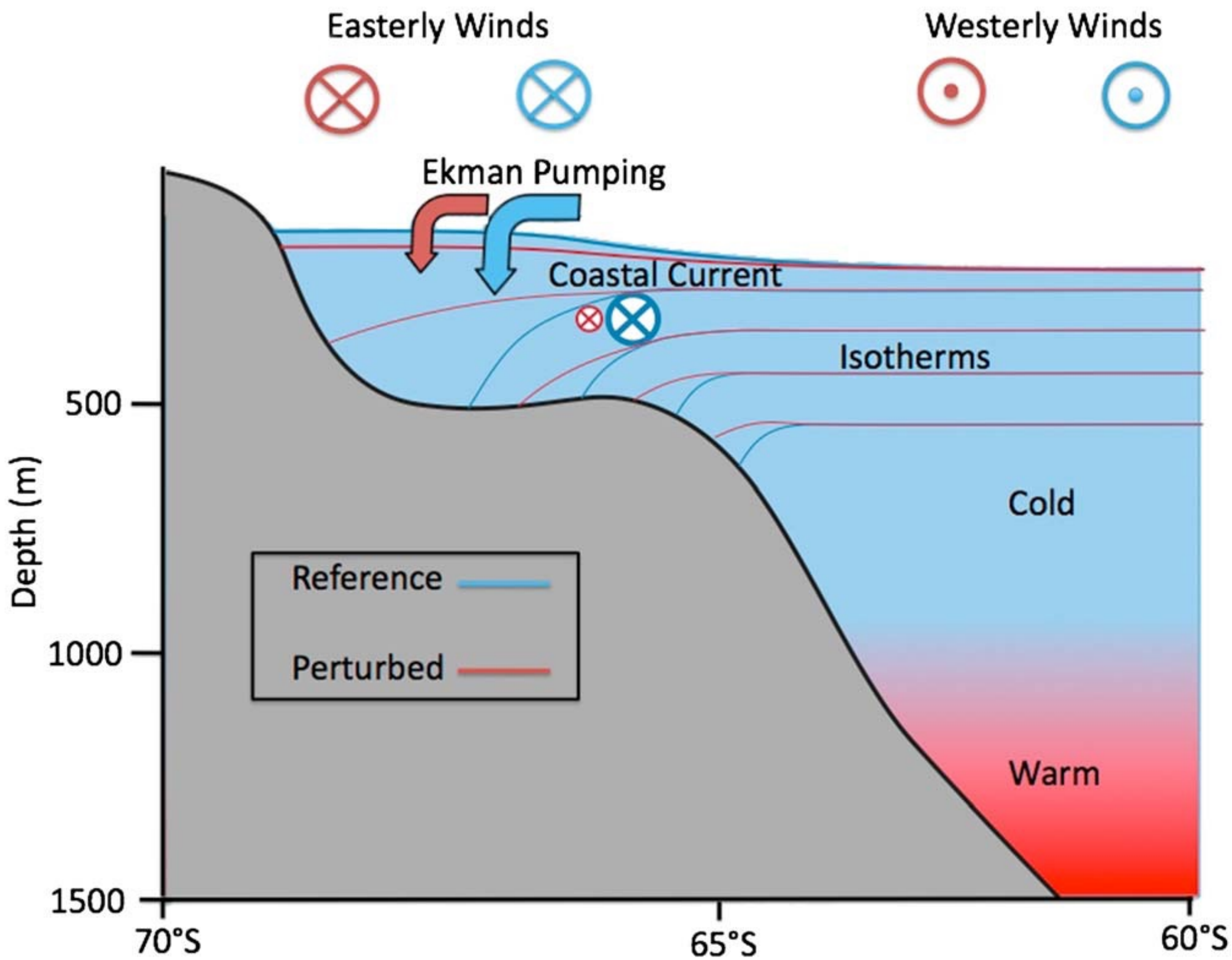
RESEARCH LETTER
10.1002/2014GL062281

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

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

Key Points:

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

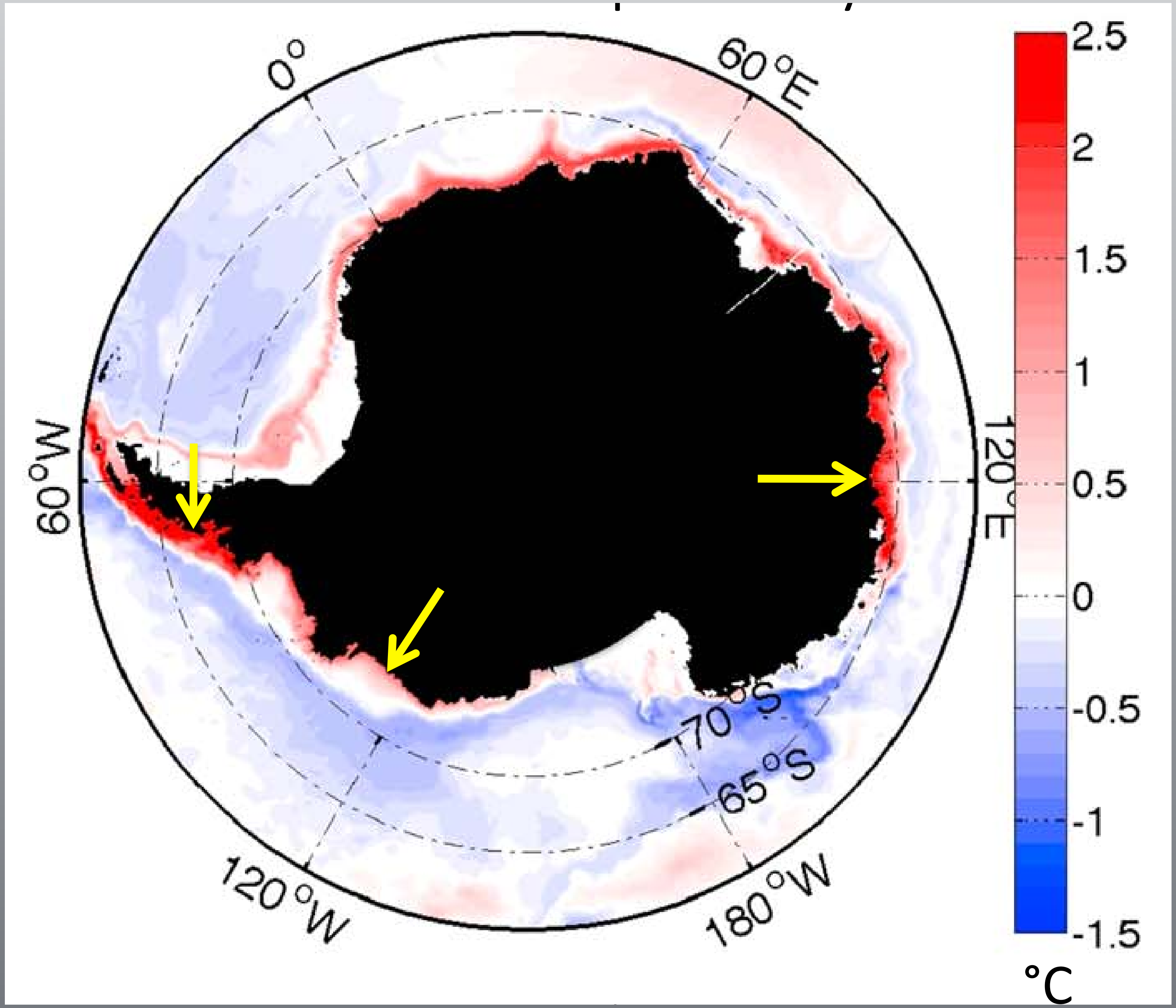
RESEARCH LETTER
10.1002/2014GL060613

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]

Example Ekman-induced temperature changes



4°

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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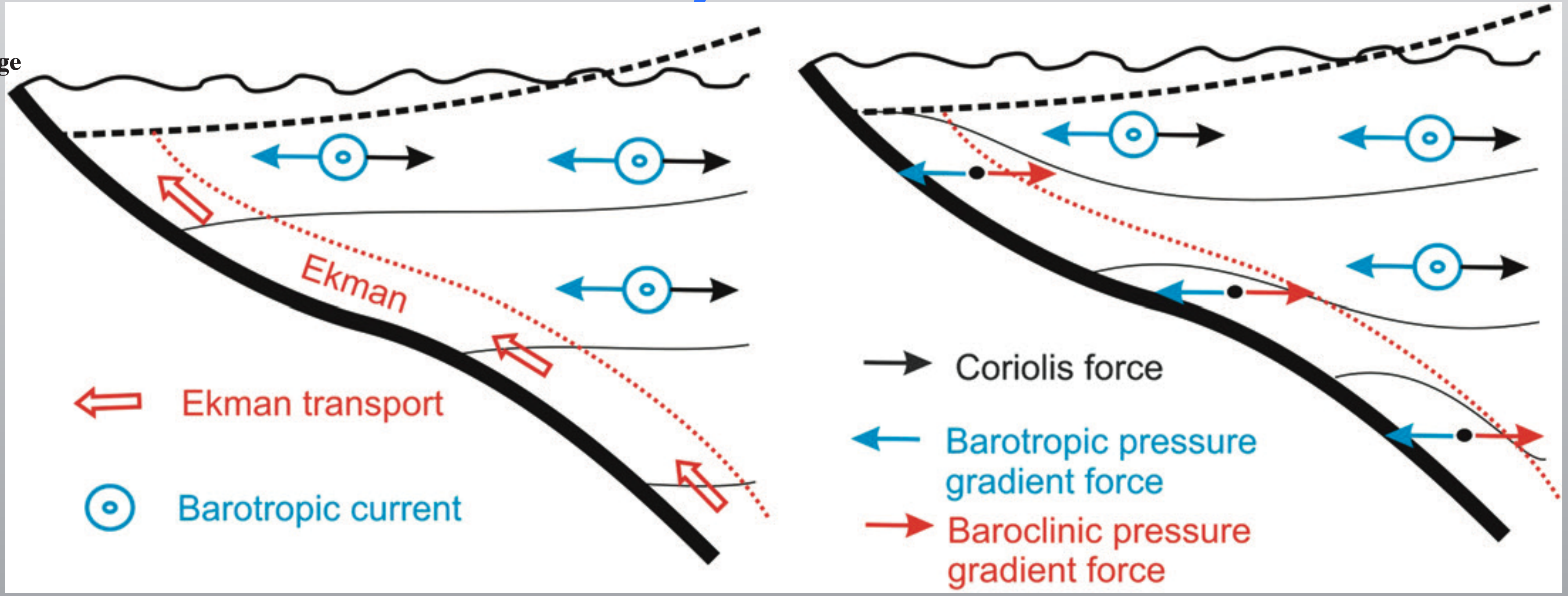


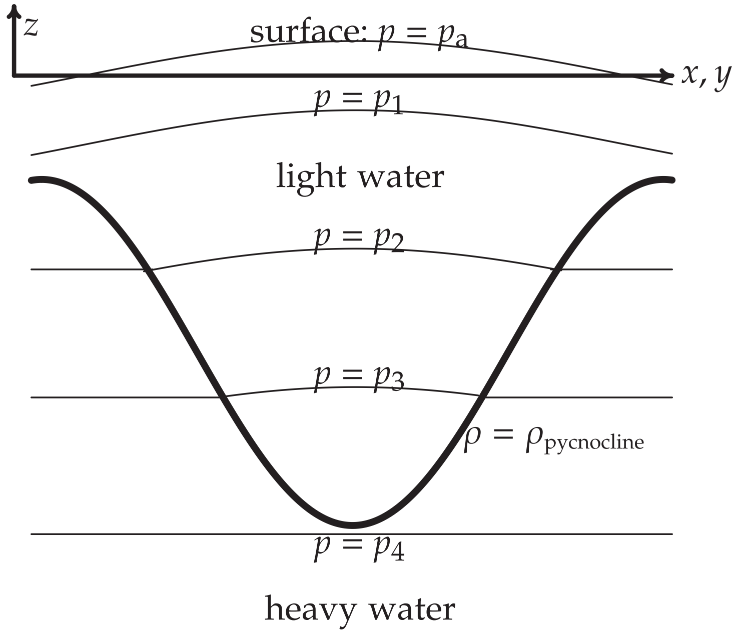
Arrested (or slippery) Ekman layer (barotropic and baroclinic pressure gradients balance): MacCready and Rhines (1993) (theory), Wahlin et al (2012) observational analysis of ACC filaments onto Amundsen Sea shelf.

Arrest time scale: hours to days (fast!)

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

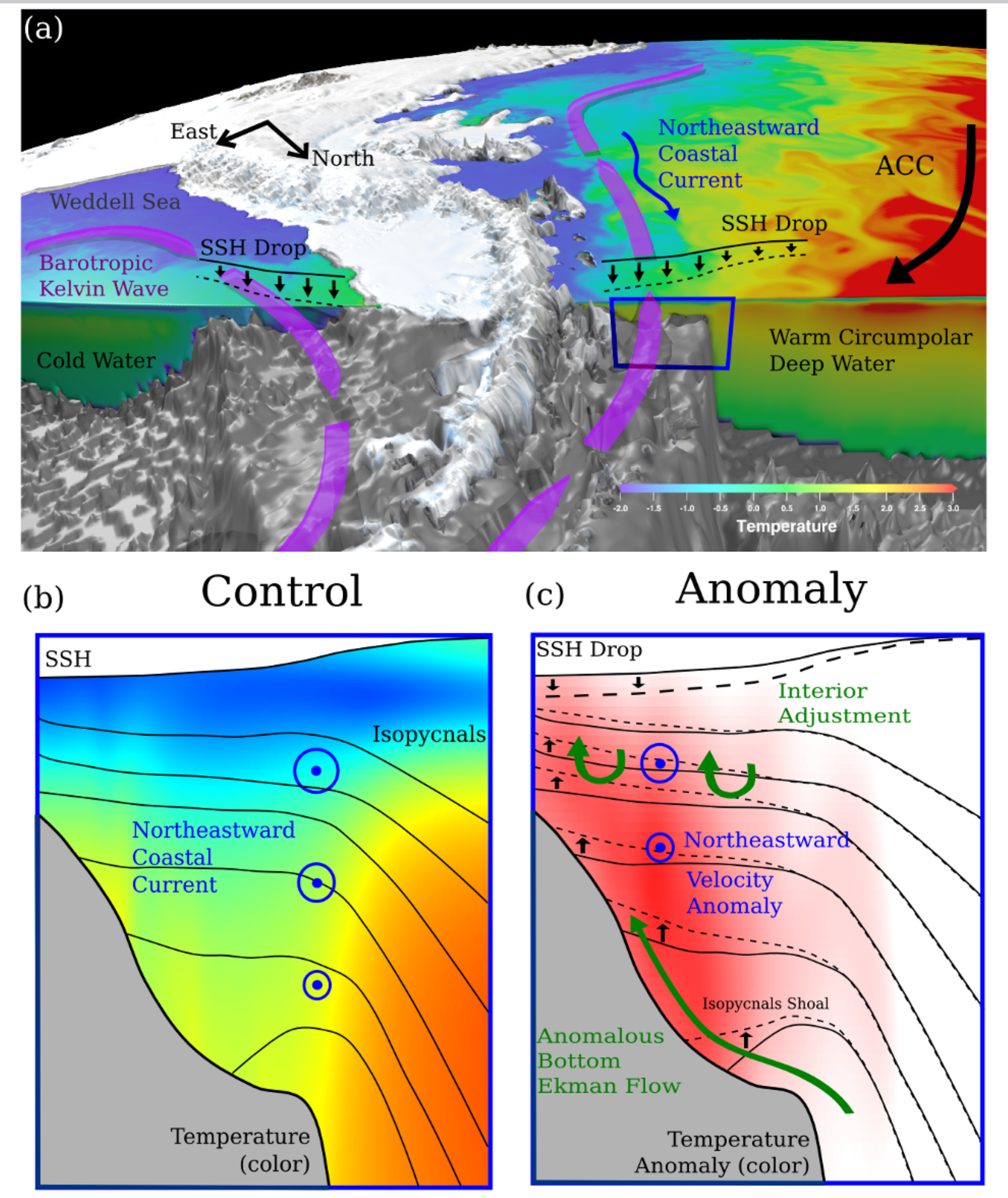
Arrested Ekman thickness $\approx 10*$frictional Ekman

cf: baroclinically adjusted 1.5 layer



Kelvin waves & arrested Ekman layer adjustment

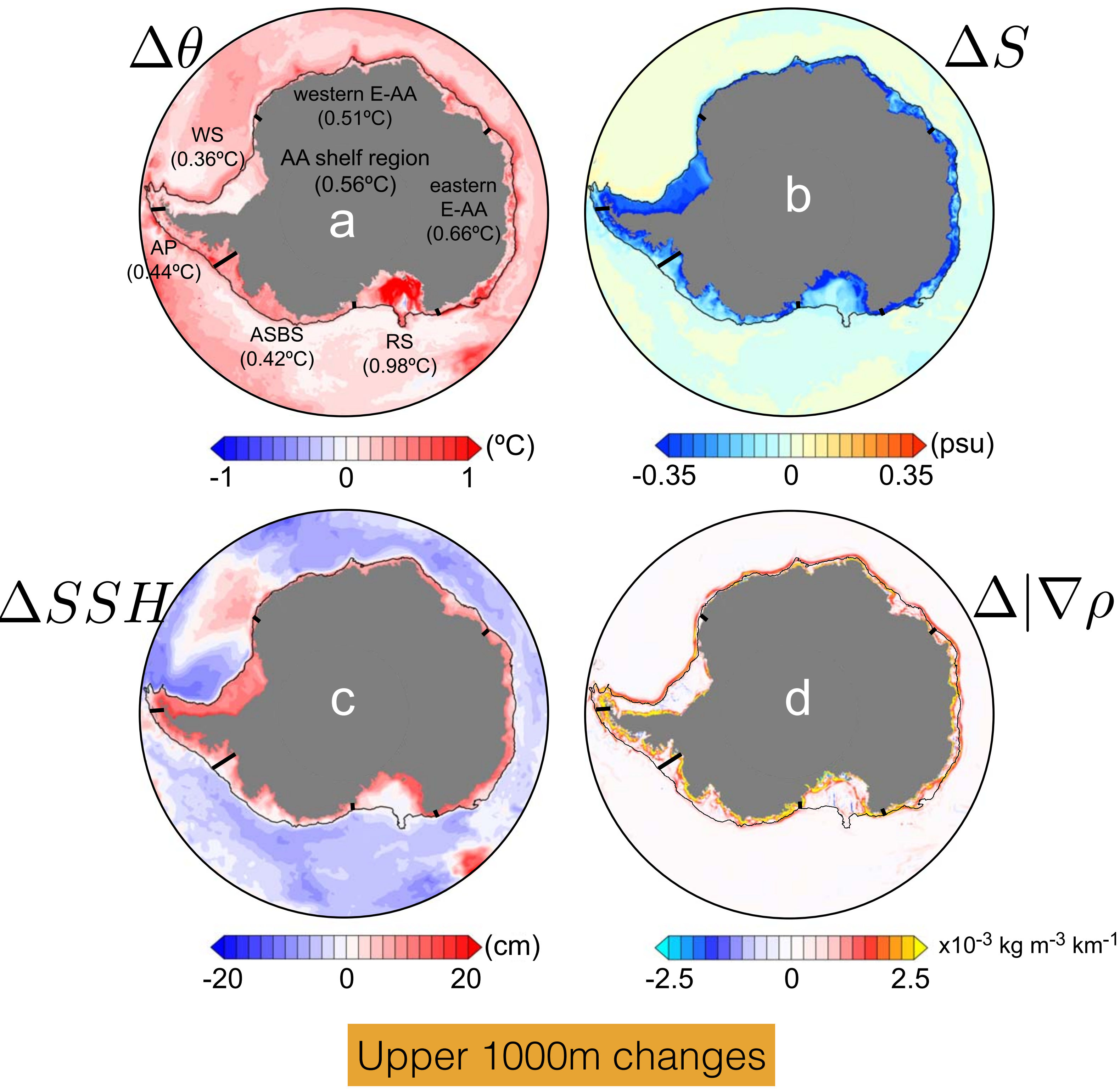
Spence et al 2017



- 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.

2xCO2 changes in GFDL/CM2.6 climate model

Goddard et al 2017



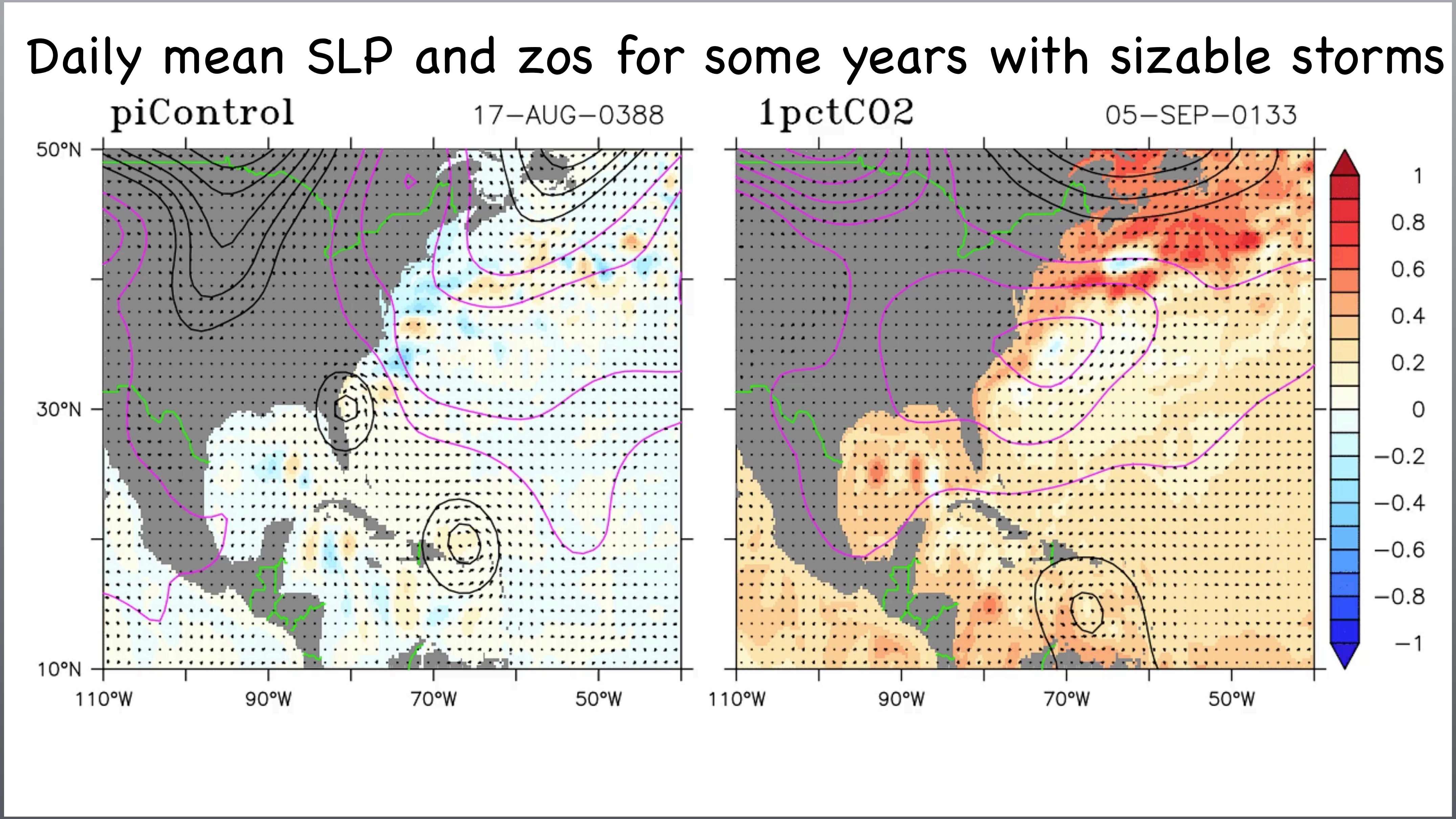
- Broad warming along shelf edge.
- Non-homogenous warming pattern around continent (e.g., Ross sea).
- Shelf freshening and halosteric dominate sea level changes.
- Increased lateral gradient around shelf edge. Regions with less increase show more warming (e.g., Ross Sea).
- See also Moorman et al (2020)

Case study IV: Extreme sea level on US Atlantic/Gulf coast using the GFDL CM4 climate model (1/4th ocean, 100km atmos)

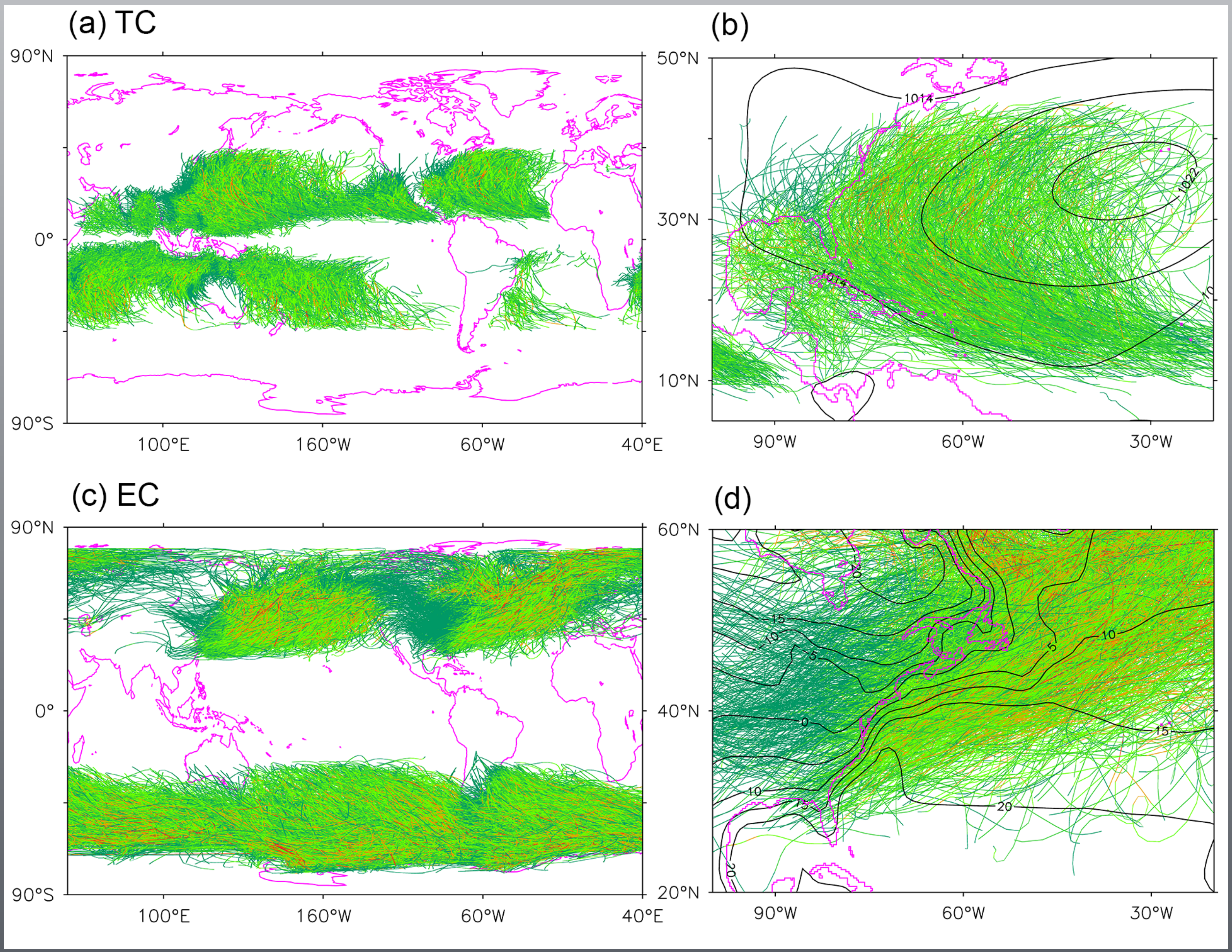
Yin, Griffies, Winton, Zhao, Zanna, 2020: Response of storm-related extreme sea level along the US Atlantic coast to combined weather and climate forcing, Journal of Climate, doi:10.1175/JCLI-D-19-0551.1?mobileUi=0

Model details and example storms

- CM4 = CMIP6 era GFDL climate model (Held et al 2019)
- AM4 = Atmosphere ~100km C92 cubed sphere (Zhao et al 2018a and 2018b)
- OM4 = Ocean Model ~25km OM4 config w/ MOM6 (Adcroft et al 2019)
- CM4 has respectable representation of extreme cyclone events, both tropical and mid-latitude, as well as large-scale climate modes. We can thus meld weather/climate events to study possible changes to sea level extremes.

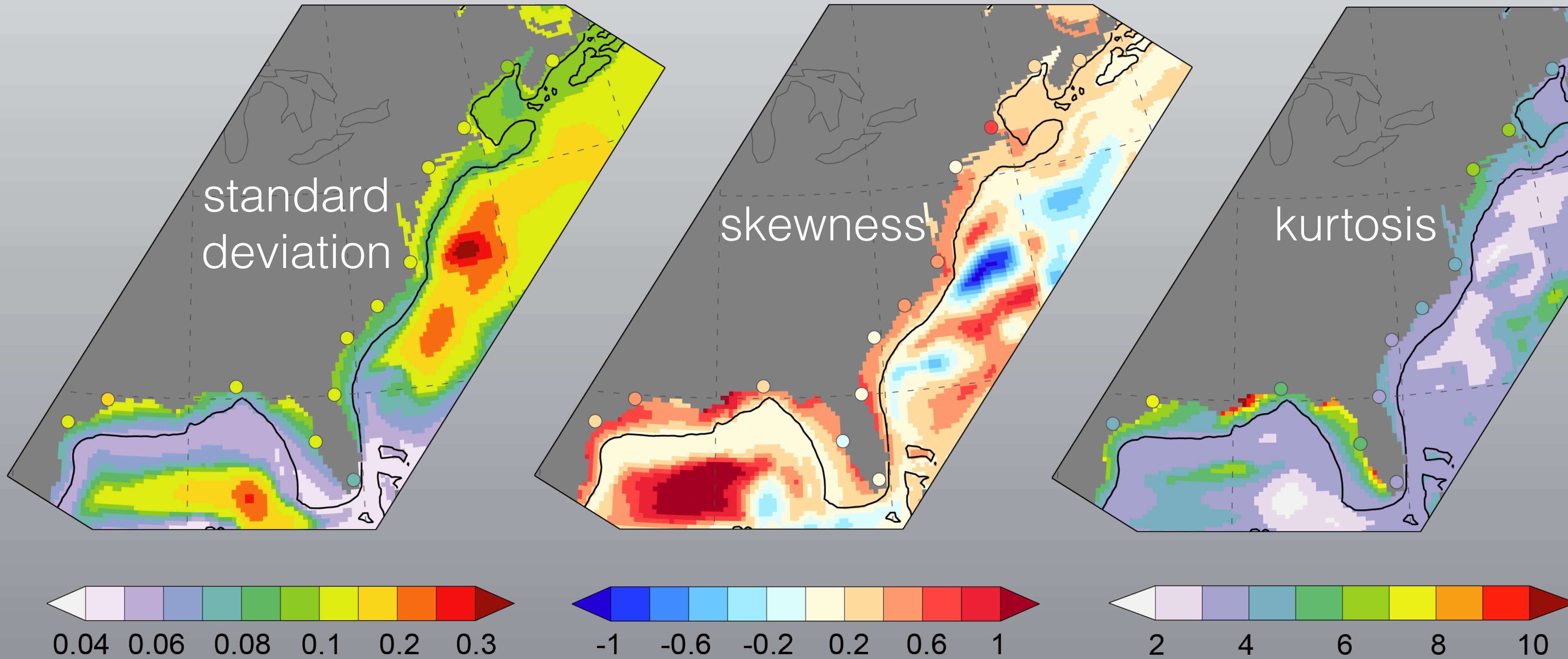


CM4 representation of tropical & extra-tropical cyclones



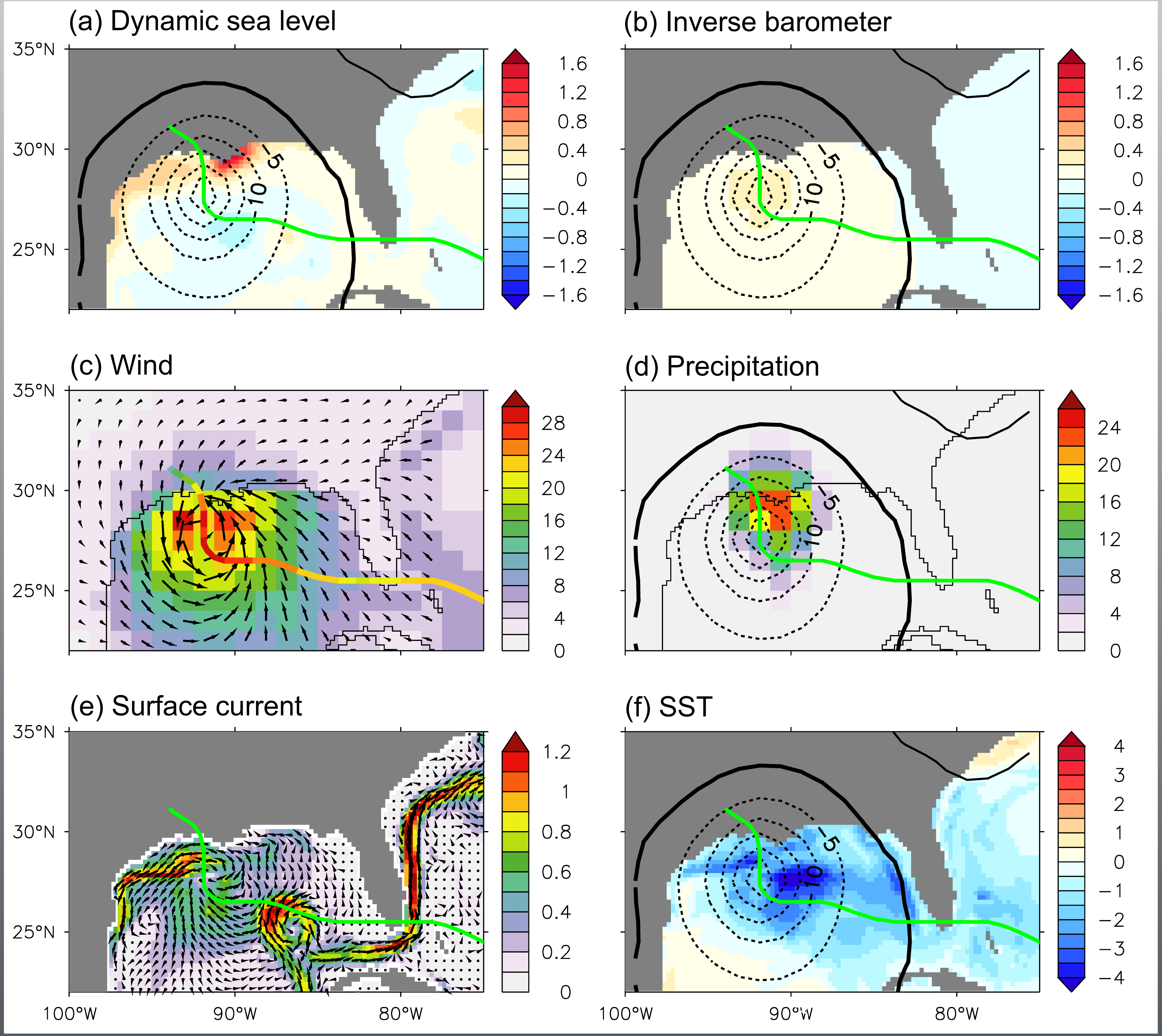
- Model results compare well to observations, though CM4 is missing the strongest TC events.
- We use CM4 to assess possible changes to extreme sea level under 1850 piControl versus idealized 1% CO2.

Statistics of daily sea level in CM4 piControl



- Standard deviation: note blocking of mesoscale eddies from coastal shelf.
- Skewness: ocean rise is greater than ocean fall during a transient event.
  - NE coast: surge associated with N'easters with northeasterly winds create Ekman driven surges along coast that are larger than converse sea level falls.
  - GoM coast: northward movement of TCs adds to the positive landward storm surge on east side of a storm more than seaward winds lead to sea level fall on west side.
- Kurtosis: New Orleans is particularly prone to extreme events due to TCs and geometry.

Example large TC event in CM4

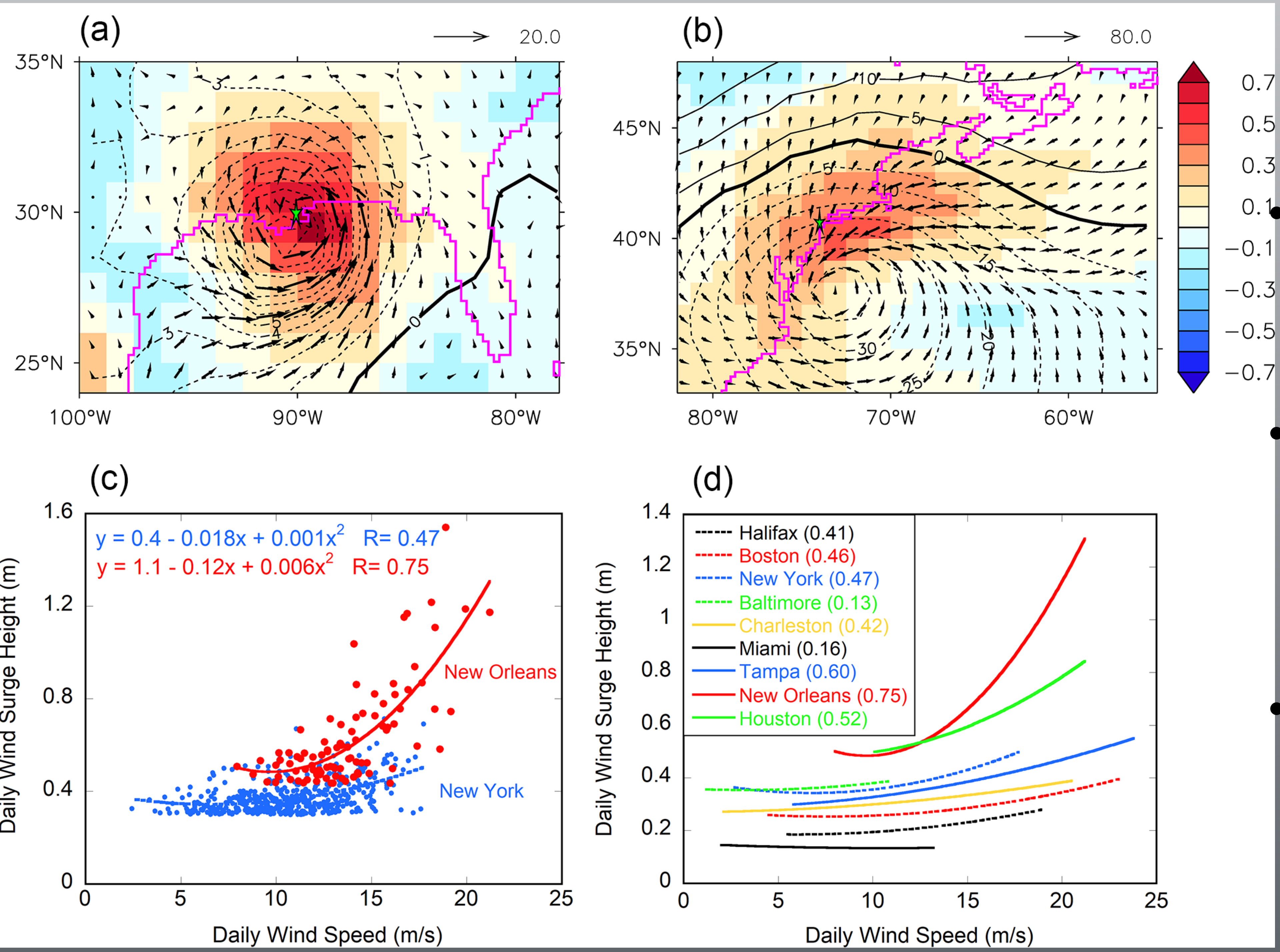


24 Aug year 138

Daily surge height up to 1.8m at New Orleans.

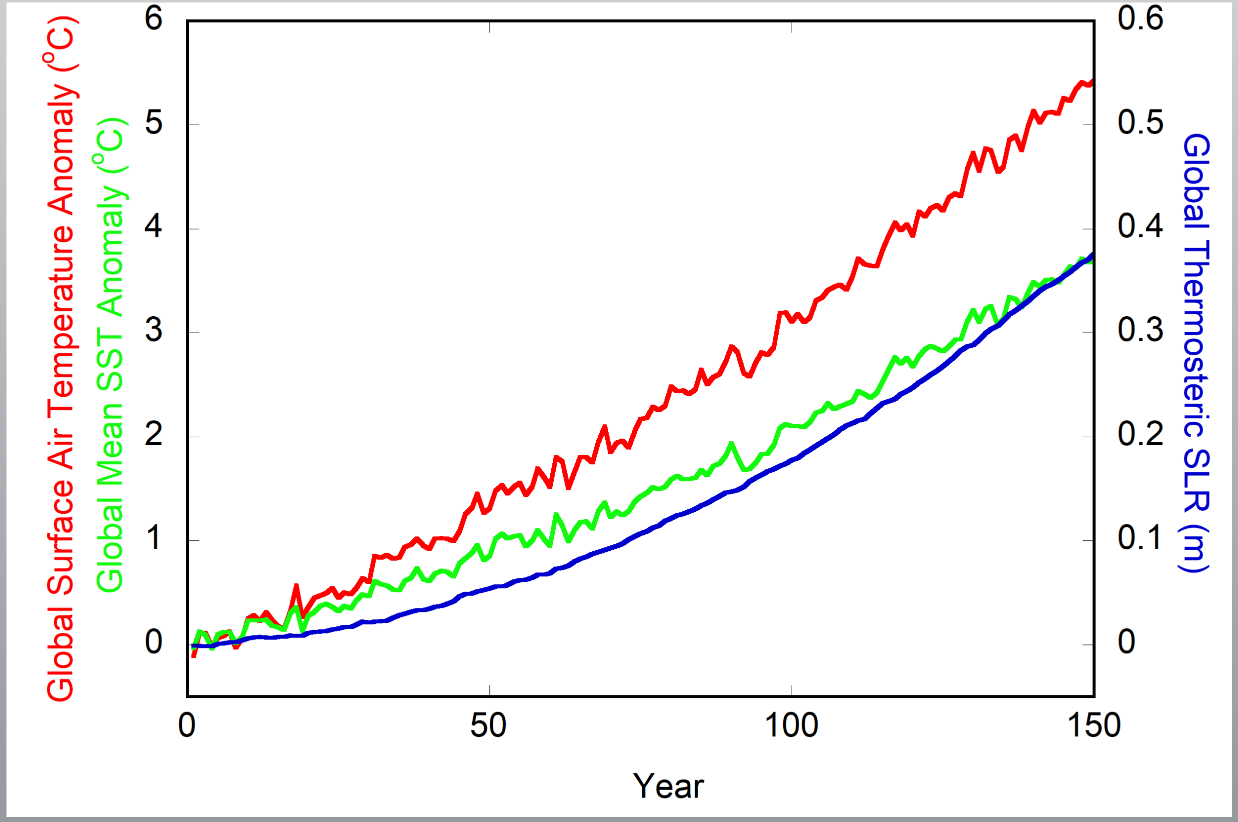
- shading: anomaly
- contours: SLP anomaly
- vectors: surface wind or surface currents
- Green line: TC path

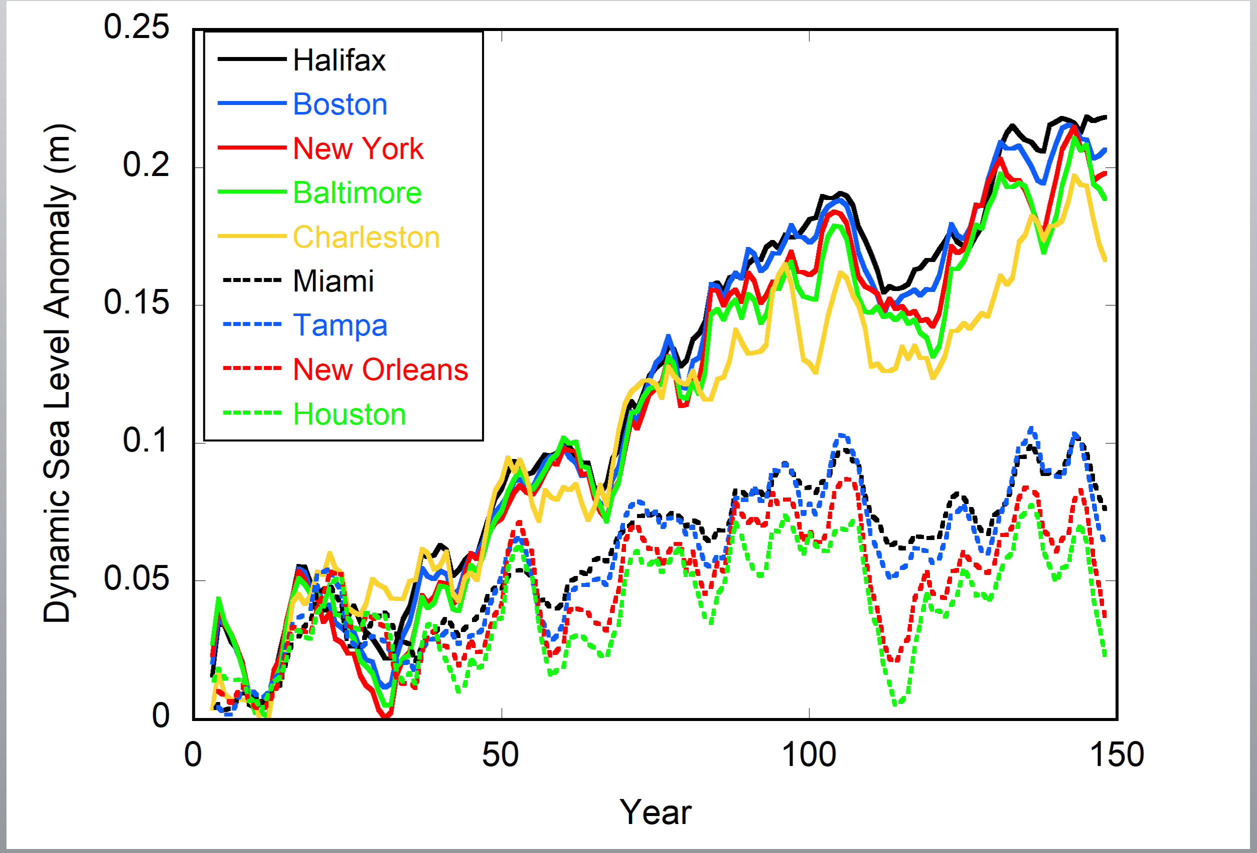
Wind-surge relation

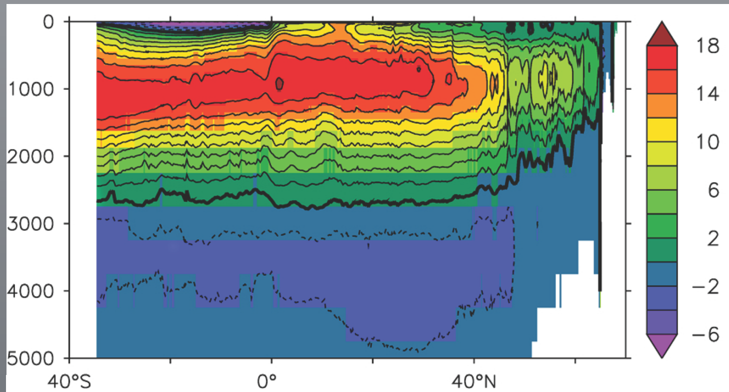


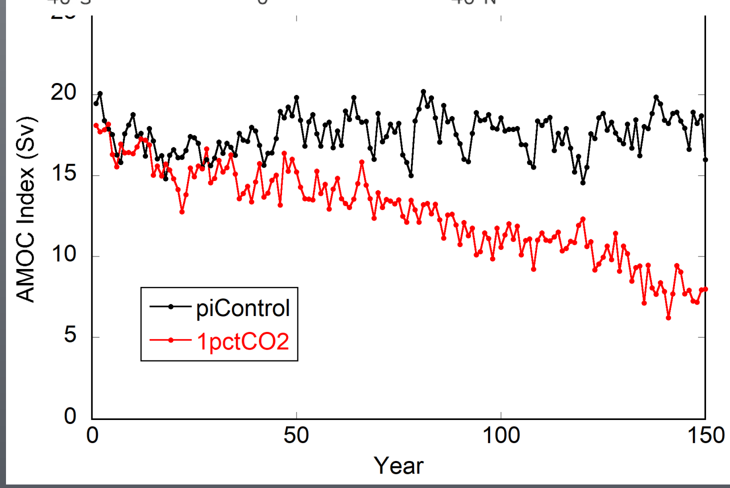
- New Orleans: onshore winds push waters into funneling geometry: a perfect "storm" for storm surge.
- New York: alongshore northeasterly winds induce shoreward Ekman transport.
- Quadratic relation between wind speed and surge height due to quadratic relation between speed & stress.
- Winds account for 80-90% of surge, with remainder due to inverse barometer.

Global and regional sea level in 1pctCO2



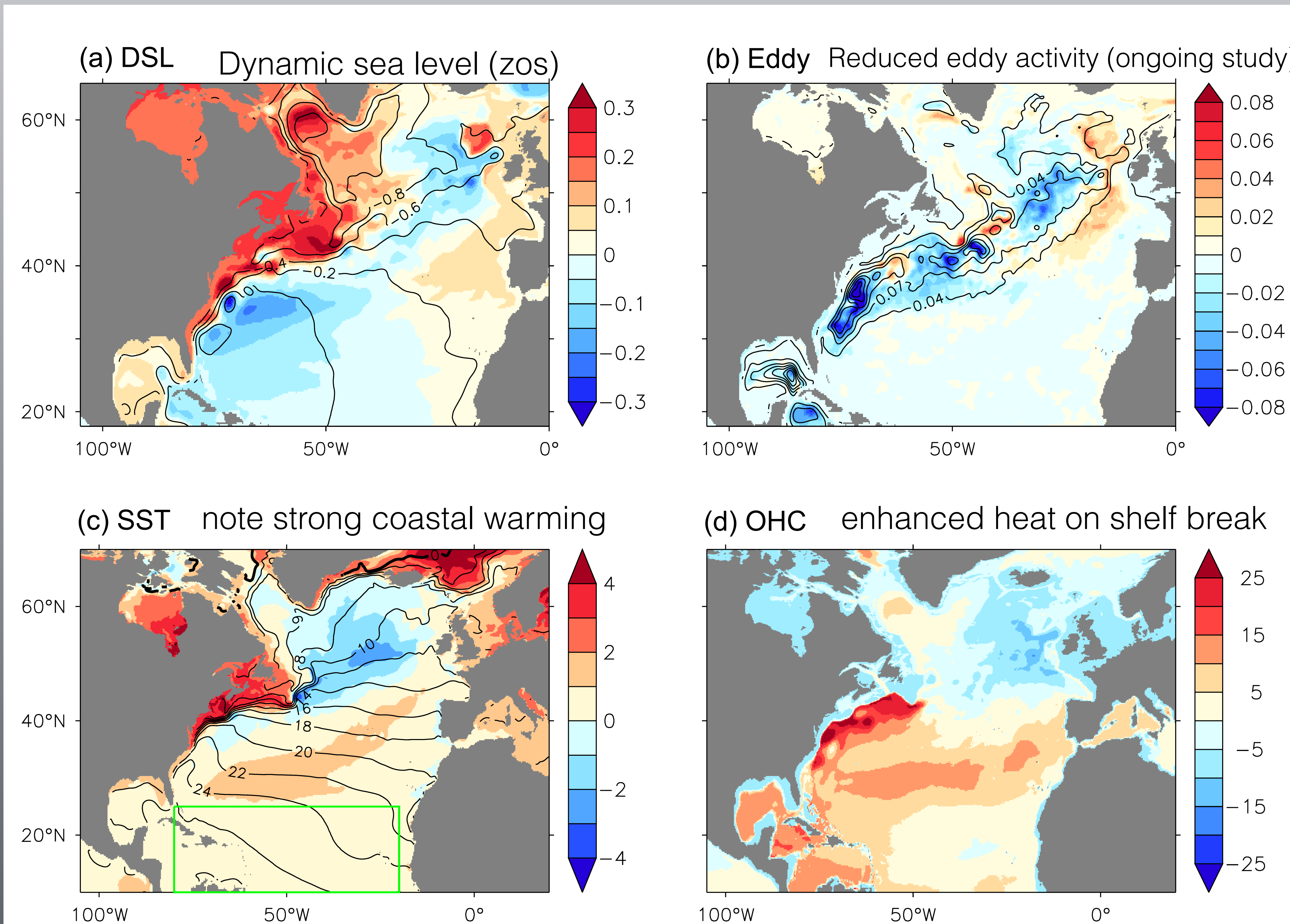






- Increased global mean temp & global thermosteric sea level.
- Dynamic sea level rise (regional patterns) superposed on global rise.
- East coast rise from reduced AMOC.

Patterns of sea level change



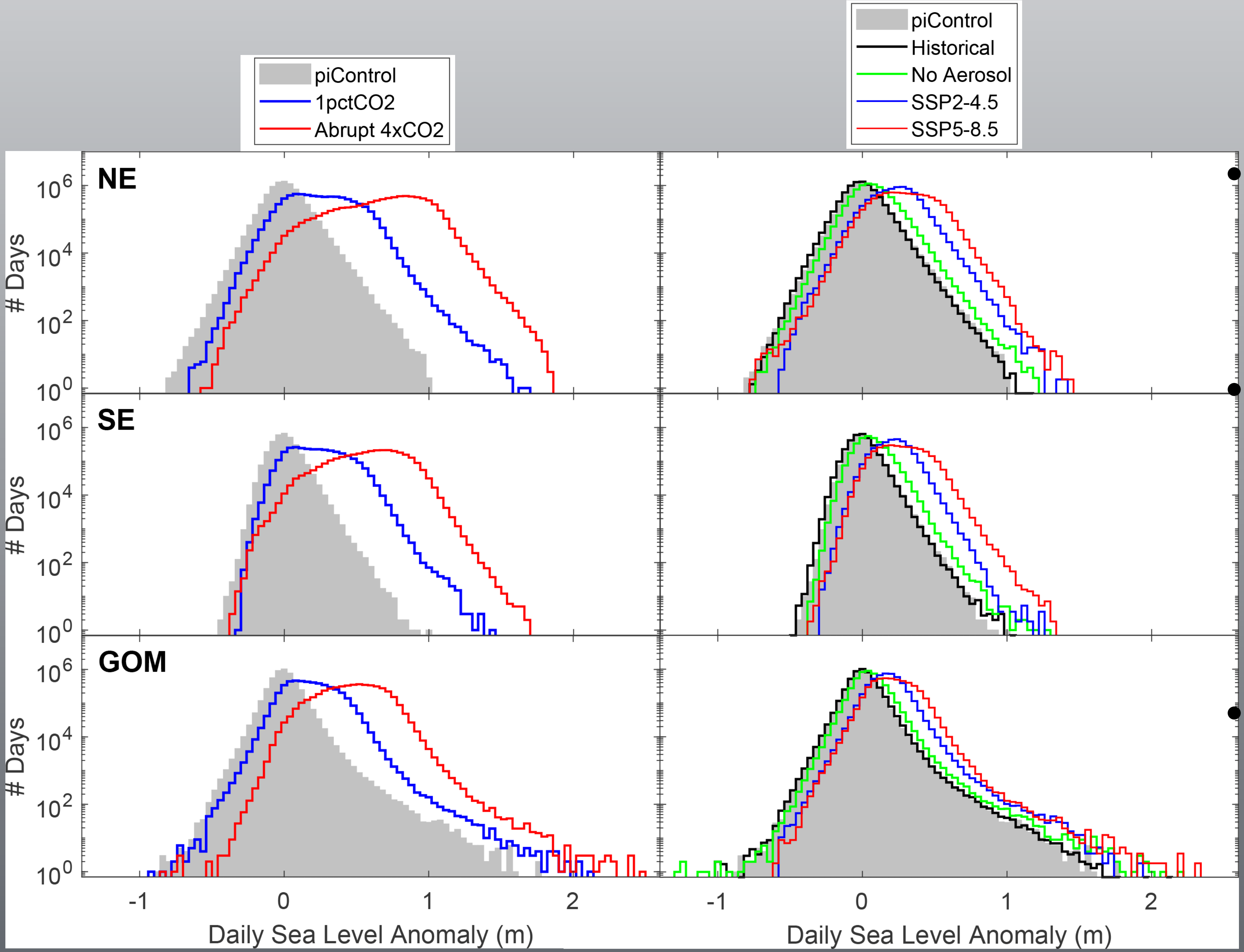
(a,c,d) have global means removed.

Shading: anomalies during years 131-150 of 1pctCO2 (near 4xCO2 period).

Contours: long term means from piControl.

Note heat and sea level rise next to coast; related to AMOC reduction.

Changes to extreme sea level distribution



- Increased external forcing shifts pdf to right, towards higher surge.
- East coast: elevated surge mostly due to increased sea level (from AMOC reduction and global thermosteric).
- Gulf coast: increased surge from global thermosteric plus increased TC intensity.

Comments on extremes study

- Under natural weather processes, the Gulf of Mexico Coast is most vulnerable to storm surge and related daily extreme sea level.

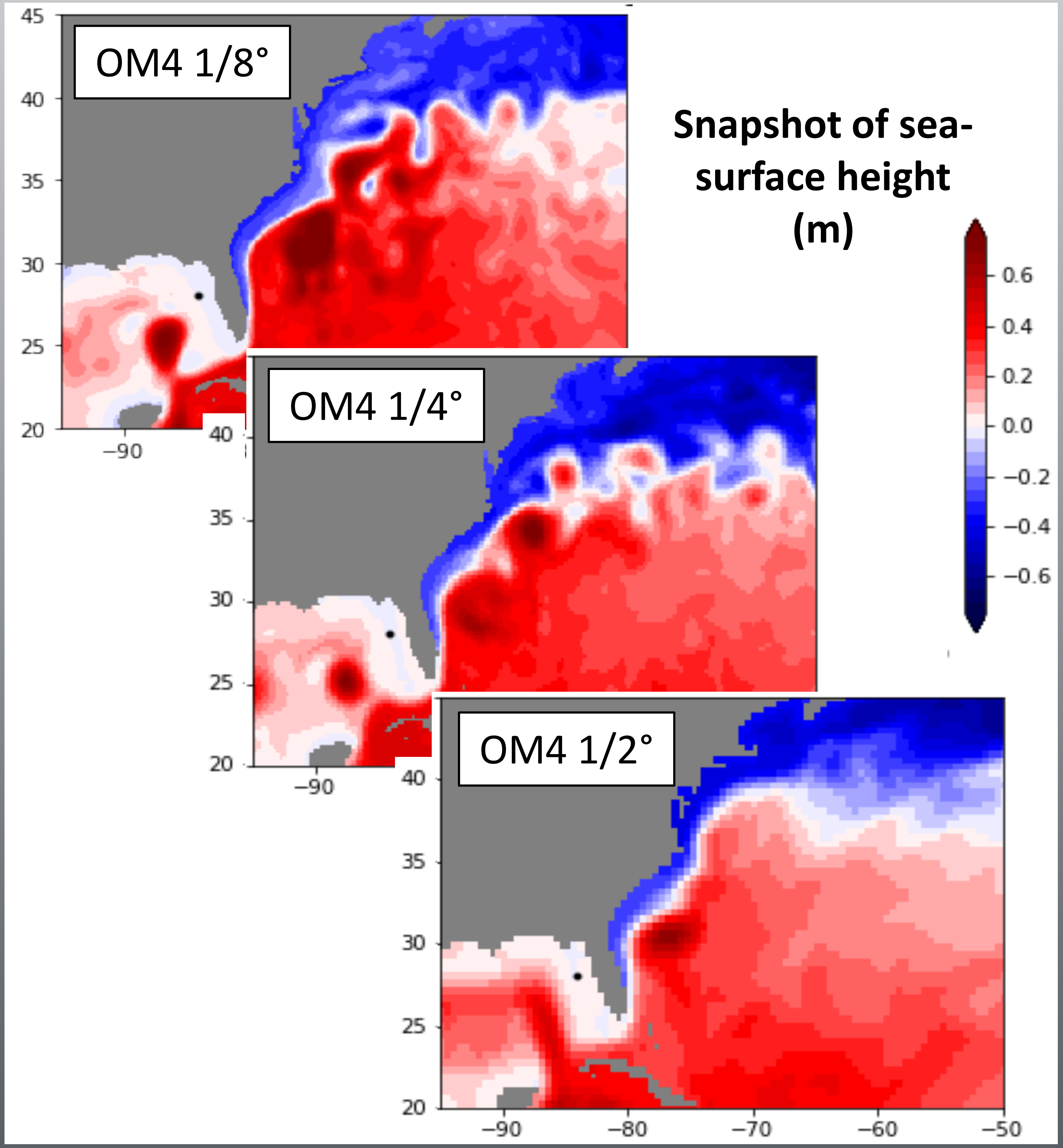
- New Orleans is a notable hot spot (reminder of why; geometry).

- Time of emergence (results not shown): in 1pctCO2 experiments, anthropogenic changes to extremes emerge after ~20 years, even without global mean sea level rise. Note: this time depends on AMOC behavior.

- Along Gulf Coast, the extreme sea level is sensitive to modification of TC characteristics under CO2 forcing.

An ocean grid hierarchy of GFDL climate models

- New class of coupled climate models: OM4 (ocean-ice) and CM4 (coupled climate) and ESM4 (earth system) using MOM6 ocean component.
- Enhanced ocean resolution for coastal processes and eddies + enhanced atmospheric resolution for realistic mid-latitude and tropical storms.
- Also pursuing an even finer resolution 1/12th degree, building on merger with HYCOM. Will possibly see limited coupled simulations as part of a 1/2-1/4-1/8-1/12 hierarchy.
- All run with ~50km cubed-sphere atmosphere.



Closing remarks

- Ocean fluid mechanics becomes ever more important as we ask questions about coastal sea level changes & processes that impact 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 & associated heat transport (waves, instabilities, eddies).
- Fine resolution (e.g., finer than 1st baroclinic Rossby radius) is necessary to faithfully represent key scales of ocean motion and topographic waves.
- Fine atmospheric resolution needed to capture strong forcing events to study extreme sea level.
- And yet, fine resolution is not a magic bullet!
  - ☆ Need better understanding of numerical closures (friction) & boundary conditions.
  - ☆ Need better understanding of flow-topography interactions (waves, eddies, mixing, boundary layers); details matters!

Many thanks for your time

Atmospheric lee waves over Coronation Island
North Weddell Sea, May 2017
Photo by S.M. Griffies