Tracer Budgets in ECCO—Part I: Overview and Some Applications

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Estimating the Circulation and Climate of the Ocean (ECCO) Summer School
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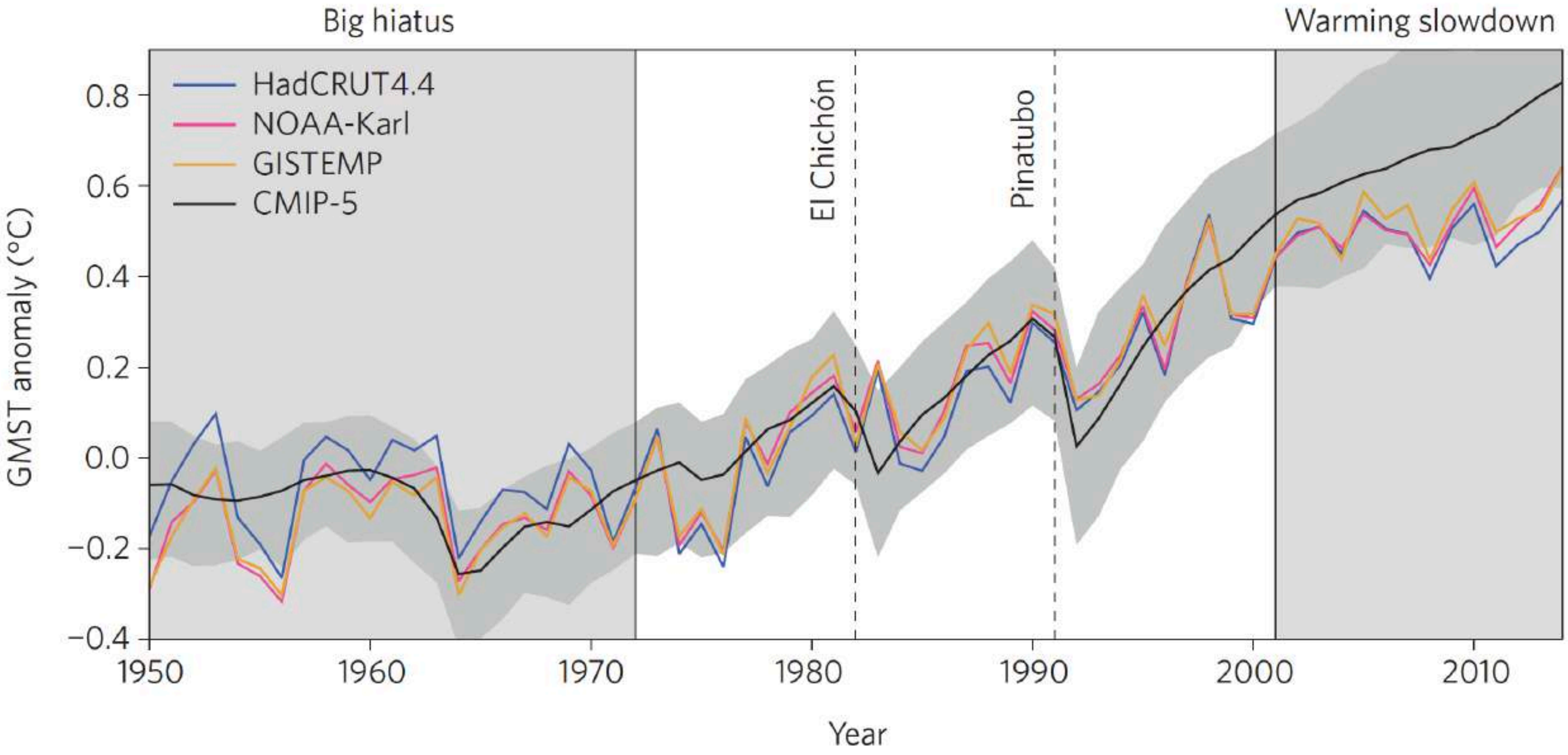
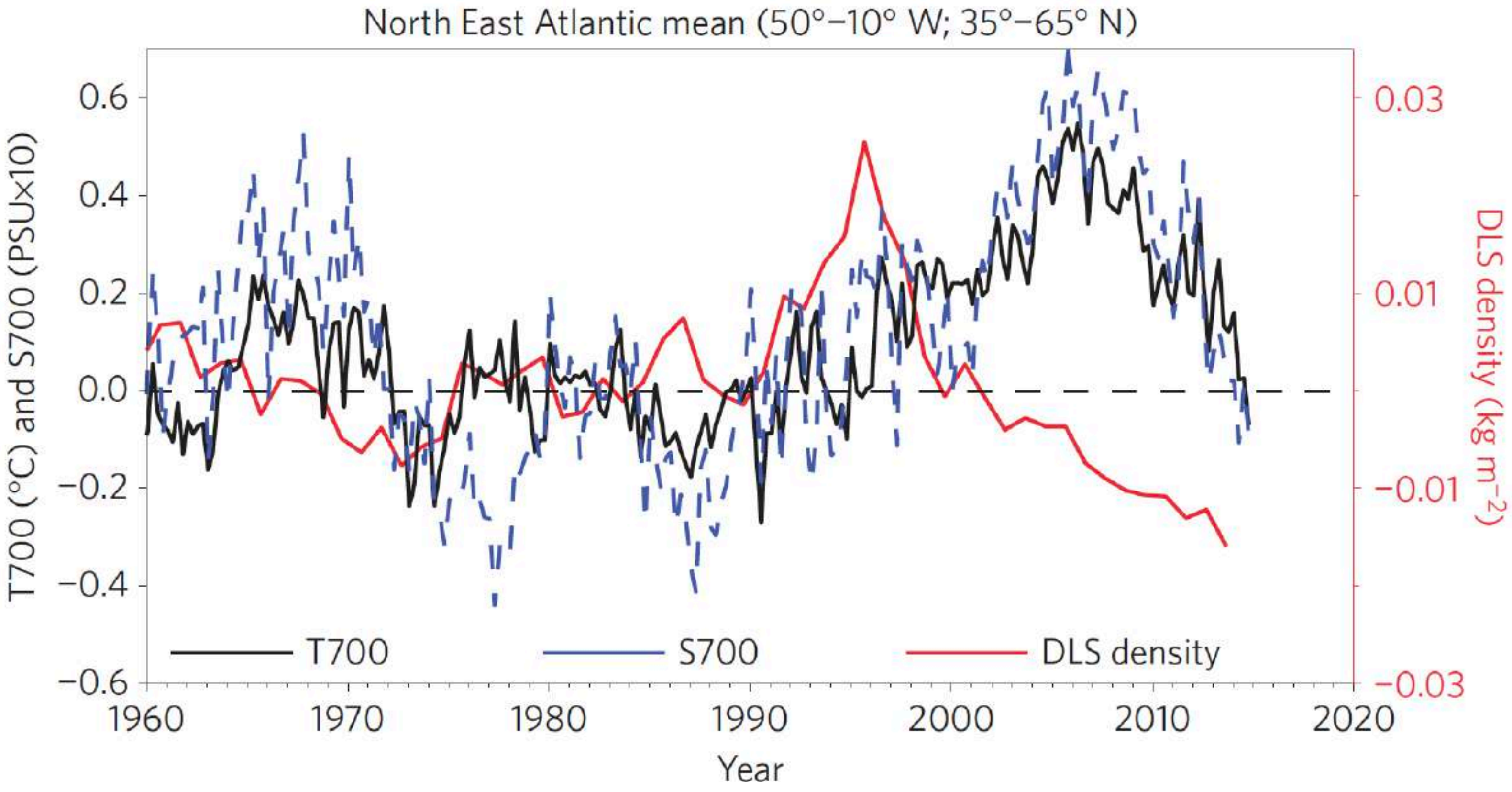
What Drives Changes in Ocean Heat & Freshwater Content?

Sea-Surface Temperature & the ”Slowdown”



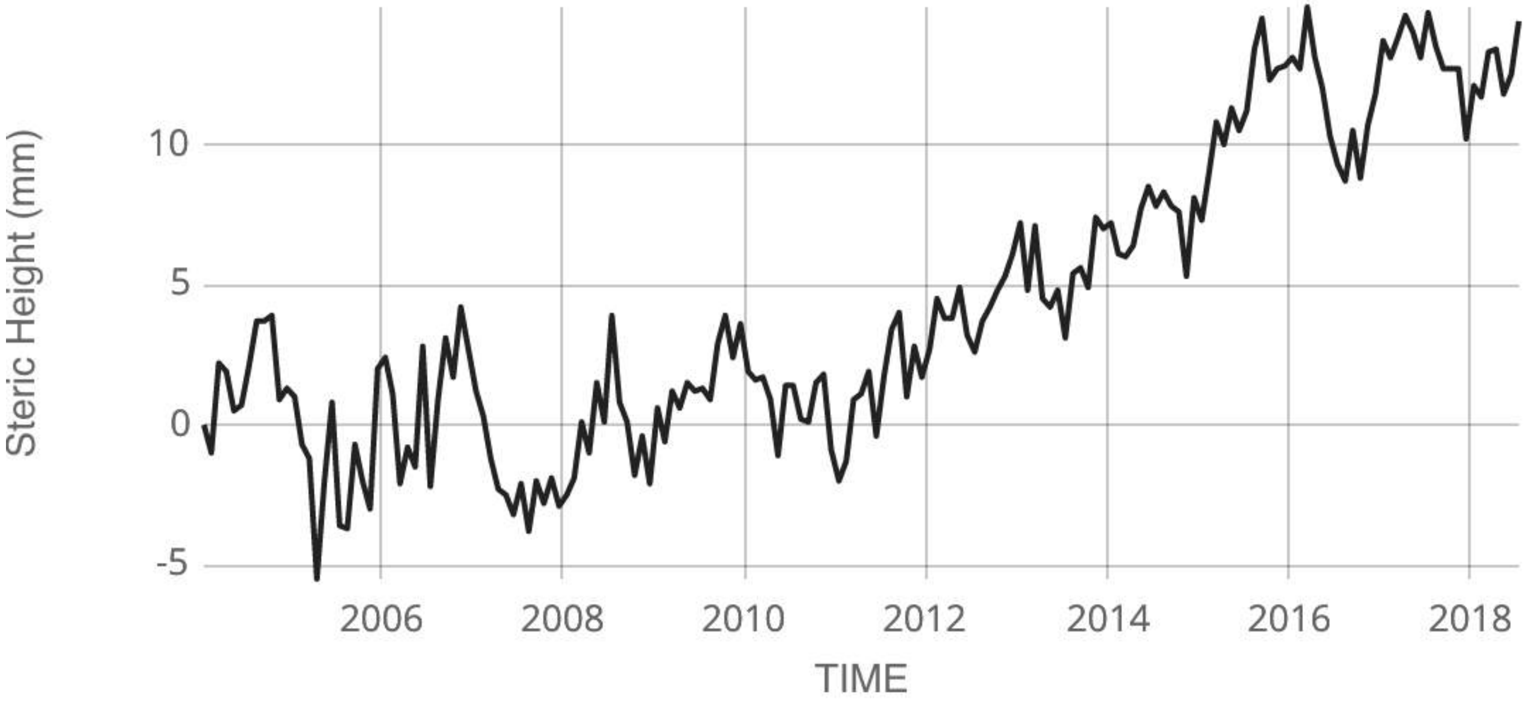
Fyfe et al. (2016), Nat. Clim. Change

Decadal Variability in the Subpolar North Atlantic



Robson et al. (2016), Nat. Geosci.

Ongoing Changes in Global-Mean Steric Sea Level



Roemmich and Gilson (2009), Prog. Oceanogr.
Figure provided by https://sealevel.nasa.gov/

Conservation Laws (in a rescaled coordinate z*)

$$\frac{\partial\left(s^*\theta\right)}{\partial t} = -\nabla_{z^*}\left(s^*\theta\mathbf{v}_{res}\right) - \frac{\partial\left(\theta w_{res}\right)}{\partial z^*} + s^*\mathcal{F}_\theta + s^* D_\theta$$

$$\frac{\partial\left(s^*S\right)}{\partial t} = -\nabla_{z^*}\left(s^*S\mathbf{v}_{res}\right) - \frac{\partial\left(S w_{res}\right)}{\partial z^*} + s^*\mathcal{F}_S + s^* D_S$$

$$z^* \doteq \frac{z-\eta\left(x,y,t\right)}{H\left(x,y\right)+\eta\left(x,y,t\right)} H\left(x,y\right) \;\;,\;\; s^* \doteq 1+\eta/H$$

Pop Quiz

Which of the following processes can, in principle, effect changes in **globally averaged** steric sea level?

a. Sea-surface heat exchanges

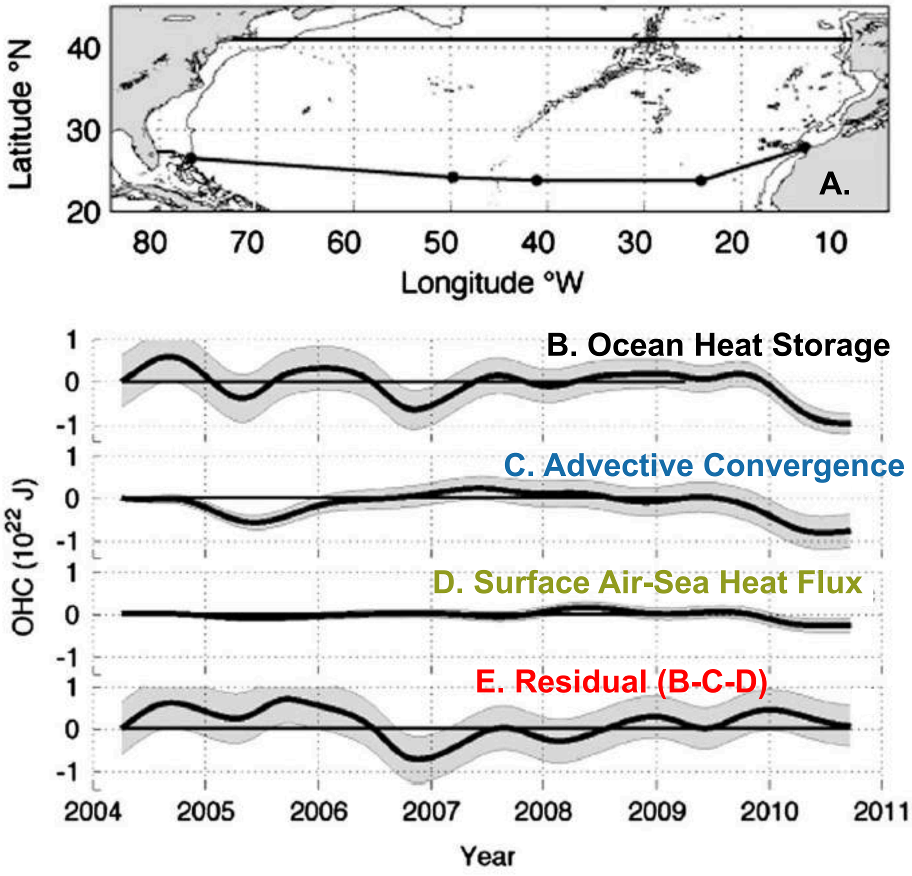
b. Internal ocean heat advection

c. Small-scale mixing of heat

Difficulties of Closing Budgets With Ocean Data & Re-analyses

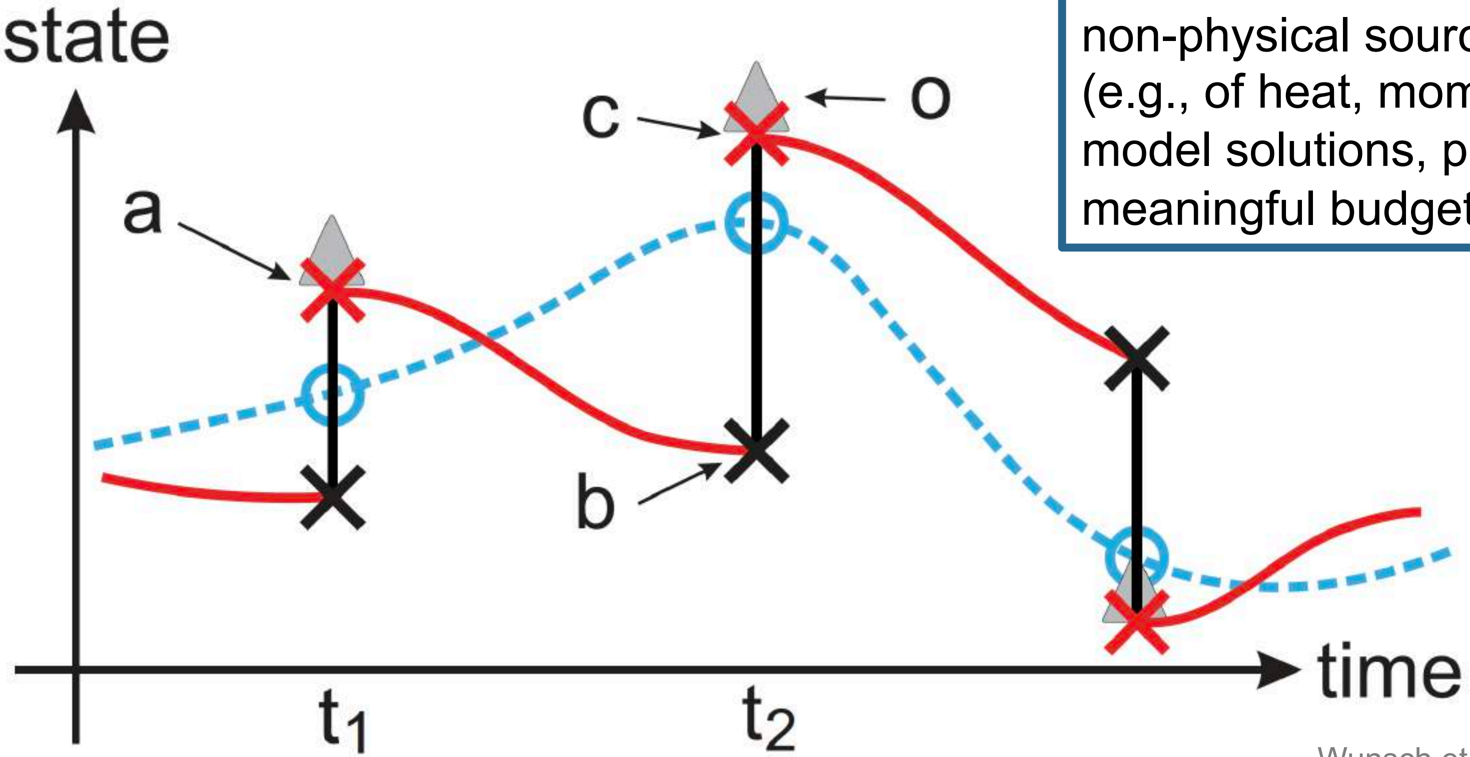
Observational Challenges

- Comprehensive diagnosis of budgets requires data that are uncertain and hard (if not impossible) to make
- Example of the 2009-2010 Subtropical North Atlantic "Cold Anomaly" (Bryden et al. 2014; Cunningham et al. 2013; Roberts et al. 201)



Cunningham et al. (2013), Geophys. Res. Lett.

Challenges Related to Data-Assimilation Products



Some data assimilation methods constrain to data by imparting non-physical sources & sinks (e.g., of heat, momentum, etc.) to model solutions, precluding any meaningful budget analysis.

Wunsch et al. (2009), Oceanography

Diagnosing Budgets Using ECCO Version 4

Discretizing the Primitive Equations

$$\underbrace{\frac{\partial\left(s^*\theta\right)}{\partial t}}_{G^{\theta,tot}} = \underbrace{-\nabla_{z^*}\left(s^*\theta\mathbf{v}_{res}\right) - \frac{\partial\left(\theta w_{res}\right)}{\partial z^*}}_{G^{\theta,adv}} + \underbrace{s^*\mathcal{F}_\theta}_{G^{\theta,forc}} + \underbrace{s^*D_\theta}_{G^{\theta,diff}}$$

$$\frac{s^{*n+1}\theta^{n+3/2} - s^{*n}\theta^{n+1/2}}{\Delta t} = \mathcal{A}\left(\theta, \mathbf{u}^{n+1} + \mathbf{u}_b^{n+1}\right) + s^{*n}\left(\mathcal{F}_\theta^{n+1} + D_{\sigma,\theta}^{n+1/2} + D_{\perp,\theta}^{n+3/2}\right)$$

Required MITgcm Diagnostic Output

Diagnostic	Time	Description (Units)
ETAN	Snapshot	Surface height anomaly (m)
THETA	Snapshot	Potential temperature (°C)
TFLUX	Average	Total heat flux (W m^{-2})
oceQsw	Average	Net shortwave radiation (W m^{-2})
ADVr_TH	Average	Vertical advective flux of pot. temp. (°C m^3 s^{-1})
ADVx_TH	Average	Zonal advective flux of pot. temp. (°C m^3 s^{-1})
ADVy_TH	Average	Meridional advective flux of pot. temp. (°C m^3 s^{-1})
DFrI_TH	Average	Implicit vertical diffusive flux of pot. temp. (°C m^3 s^{-1})
DFrE_TH	Average	Explicit vertical diffusive flux of pot. temp. (°C m^3 s^{-1})
DFxE_TH	Average	Explicit zonal diffusive flux of pot. temp. (°C m^3 s^{-1})
DFyE_TH	Average	Explicit meridional diffusive flux of pot. temp. (°C m^3 s^{-1})

MITgcm diagnostics required to evaluate the grid-cell heat budget

Algorithm

for $t = t_1, t_2, \ldots t_{T-1}, t_T$ **do** ▷ Loop over T time steps (months) t

  $U_{i,j,k} = \texttt{ADVx\_TH}\,\{t\}$ ▷ 3-D **average** zonal advection over month t

  $V_{i,j,k} = \texttt{ADVy\_TH}\,\{t\}$ ▷ 3-D **average** meridional advection over month t

  $W_{i,j,k} = \texttt{ADVr\_TH}\,\{t\}$ ▷ 3-D **average** vertical advection over month t

  $\mathcal{U}_{i,j,k} = \texttt{DFxE\_TH}\,\{t\}$ ▷ 3-D **average** zonal diffusion over month t

  $\mathcal{V}_{i,j,k} = \texttt{DFyE\_TH}\,\{t\}$ ▷ 3-D **average** meridional diffusion over month t

  $\mathcal{W}^{E}_{i,j,k} = \texttt{DFyE\_TH}\,\{t\}$ ▷ 3-D **average** vertical diffusion (explicit) over month t

  $\mathcal{W}^{I}_{i,j,k} = \texttt{DFyI\_TH}\,\{t\}$ ▷ 3-D **average** vertical diffusion (implicit) over month t

  $N^{(0)}_{i,j} = \texttt{ETAN}\,\{t - \Delta t\}$ ▷ 2-D surface height **snapshot** at start of month t

  $N^{(f)}_{i,j} = \texttt{ETAN}\,\{t\}$ ▷ 2-D surface height **snapshot** at end of month t

  $T^{(0)}_{i,j,k} = \texttt{THETA}\,\{t - \Delta t\}$ ▷ 3-D temperature **snapshot** at start of month t

  $T^{(f)}_{i,j,k} = \texttt{THETA}\,\{t\}$ ▷ 3-D temperature **snapshot** at end of month t

  $v_{i,j,k} = h_{i,j,k} A_{i,j} \Delta z_k$ ▷ Grid volume

Algorithm

for $i = i_1, i_2, \ldots i_{I-1}, i_I$ **do** ▷ Loop over I longitude cells i

for $j = j_1, j_2, \ldots j_{J-1}, j_J$ **do** ▷ Loop over J latitude cells j

$s^{*(0)}_{i,j} = \left(1 + N^{(0)}_{i,j} / H_{i,j}\right)$

$s^{*(f)}_{i,j} = \left(1 + N^{(f)}_{i,j} / H_{i,j}\right)$

for $k = k_1, k_2, \ldots k_{K-1}, k_K$ **do** ▷ Loop over K vertical cells k

$G^{\theta,tot}_{i,j,k} = \left(T^{(f)}_{i,j,k} s^{*(f)}_{i,j} - T^{(0)}_{i,j,k} s^{*(0)}_{i,j}\right) / \Delta t$

$G^{\theta,advH}_{i,j,k} = \left(U_{i,j,k} - U_{i+1,j,k} + V_{i,j,k} - V_{i,j+1,k}\right) / v_{i,j,k}$

$G^{\theta,diffH}_{i,j,k} = \left(\mathcal{U}_{i,j,k} - \mathcal{U}_{i+1,j,k} + \mathcal{V}_{i,j,k} - \mathcal{V}_{i,j+1,k}\right) / v_{i,j,k}$

$G^{\theta,advV}_{i,j,k} = \left[\left(1 - \delta_{k,K}\right) W_{i,j,k+1} - W_{i,j,k}\right] / v_{i,j,k}$

$G^{\theta,diffV}_{i,j,k} = \left[\left(1 - \delta_{k,K}\right)\left(\mathcal{W}^{E}_{i,j,k+1} + \mathcal{W}^{I}_{i,j,k+1}\right) - \mathcal{W}^{E}_{i,j,k} - \mathcal{W}^{I}_{i,j,k}\right] / v_{i,j,k}$

$G^{\theta,adv}_{i,j,k} = G^{\theta,advH}_{i,j,k} + G^{\theta,advV}_{i,j,k}$

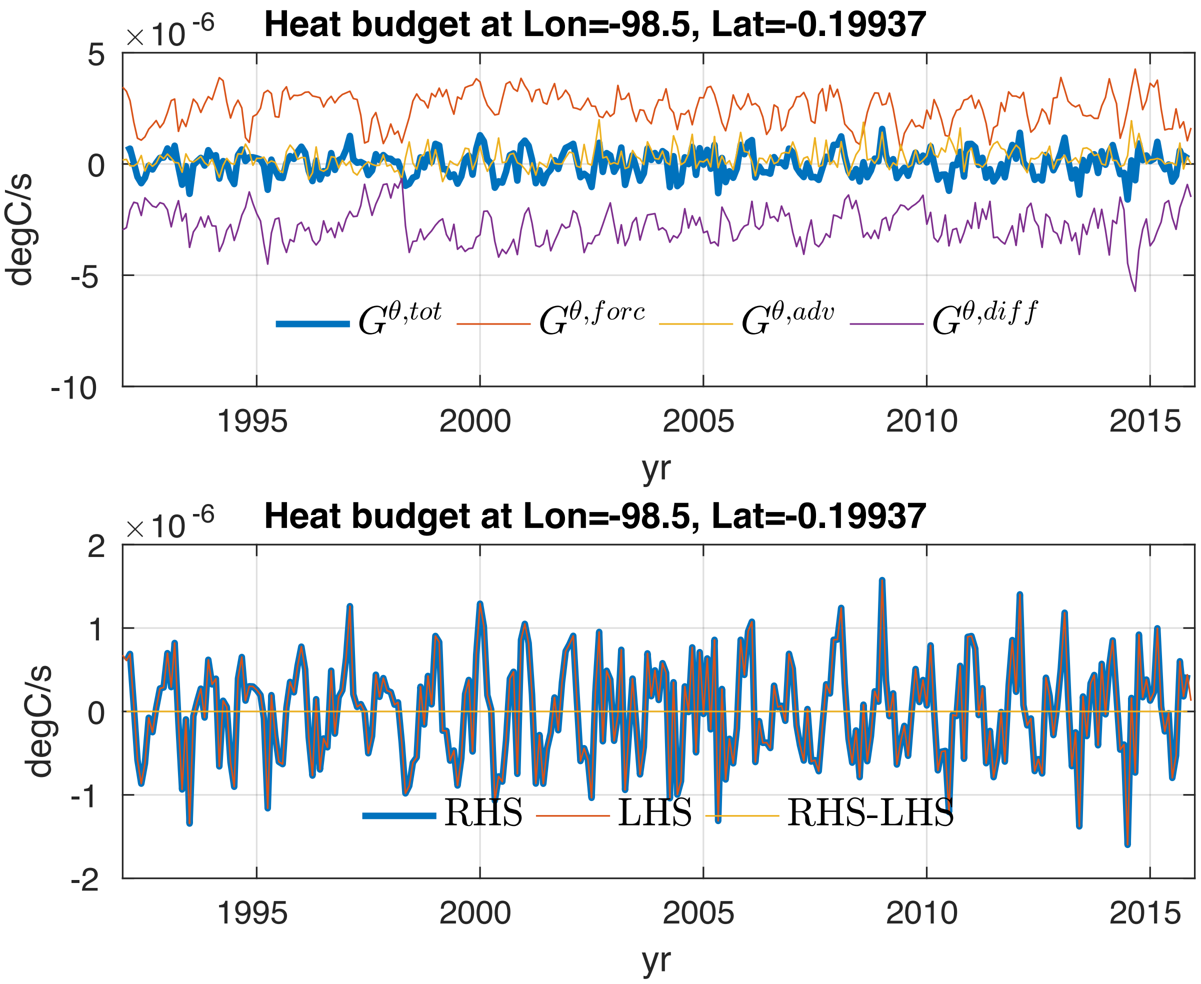
$G^{\theta,diff}_{i,j,k} = G^{\theta,diffH}_{i,j,k} + G^{\theta,diffV}_{i,j,k}$

end for

end for

end for

Example of Closure



A Practical Guide

- For more details, come to tomorrow's tutorial and "hands-on" lab session—
  - Friday, May 24th
  - 3:00-4:00 PM; 4:30-6:30 PM
- A full guide is available and downloadable—
  - https://dspace.mit.edu/handle/1721.1/111094

A Note on Practical Evaluation of Budgets in ECCO Version 4 Release 3

Christopher G. Piecuch (cpiecuch@aer.com)

June 16, 2017

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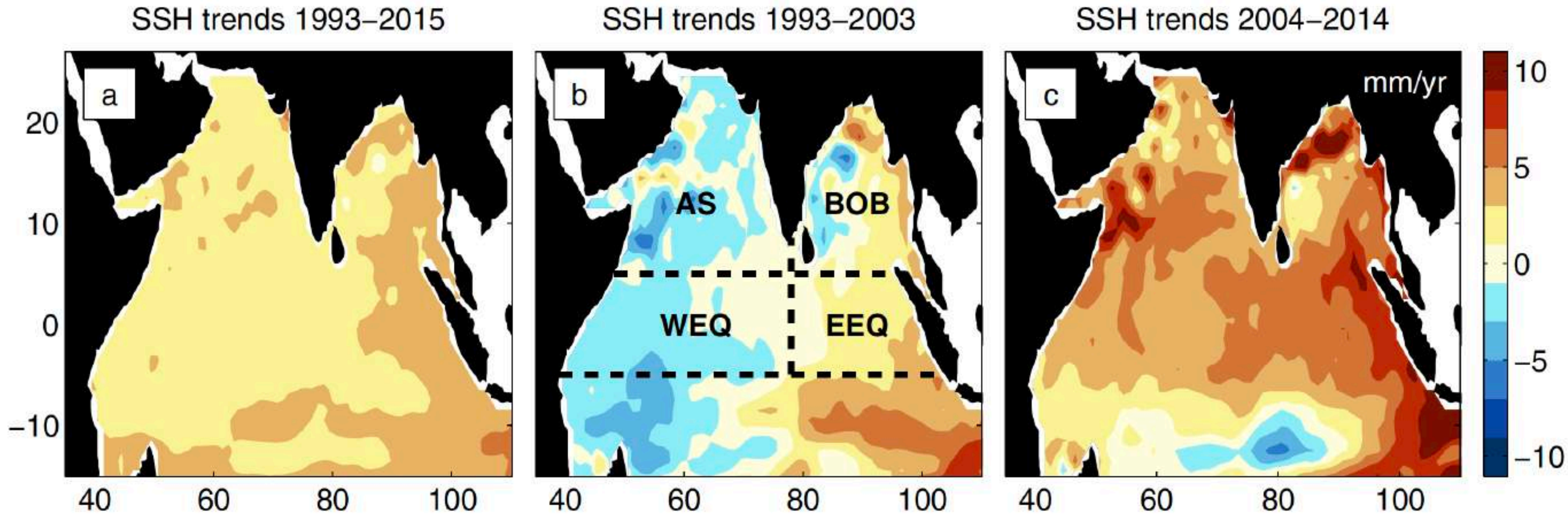
A Few Illustrative Vignettes

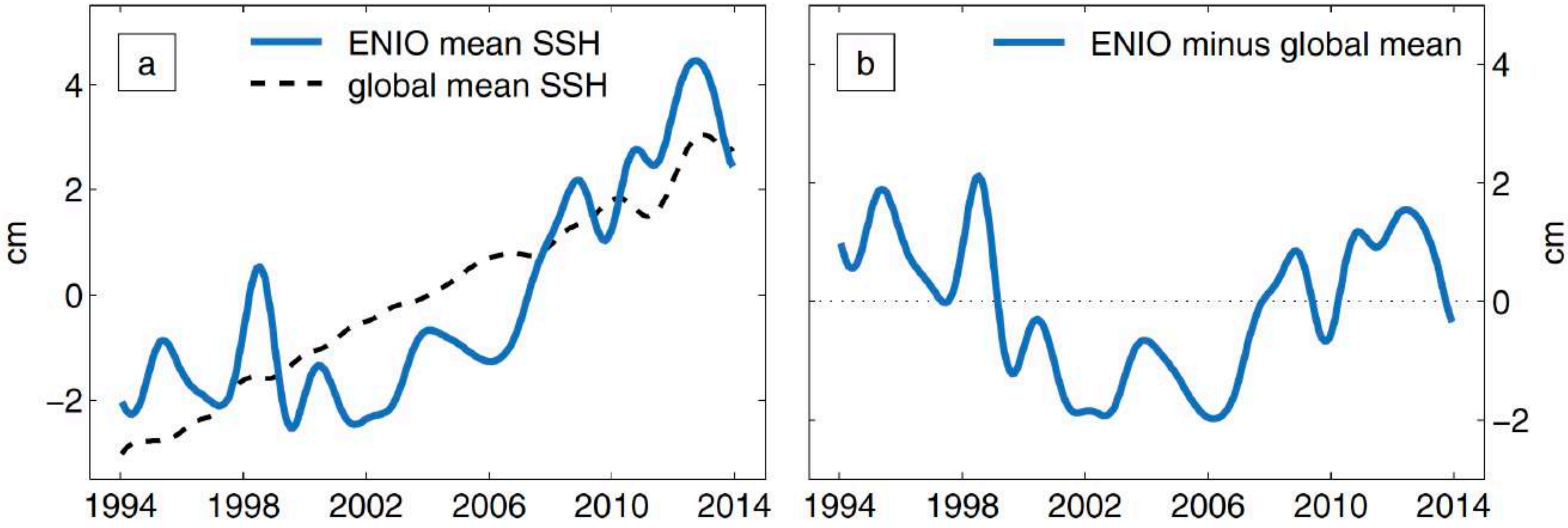
Vignette #1—
Sea Level & Heat Content in the Tropical Indian Ocean

Sea Level & Heat Content in the Tropical Indian



Thompson et al. (2016), J. Geophys. Res. Oceans

Sea Level & Heat Content in the Tropical Indian



Thompson et al. (2016), J. Geophys. Res. Oceans

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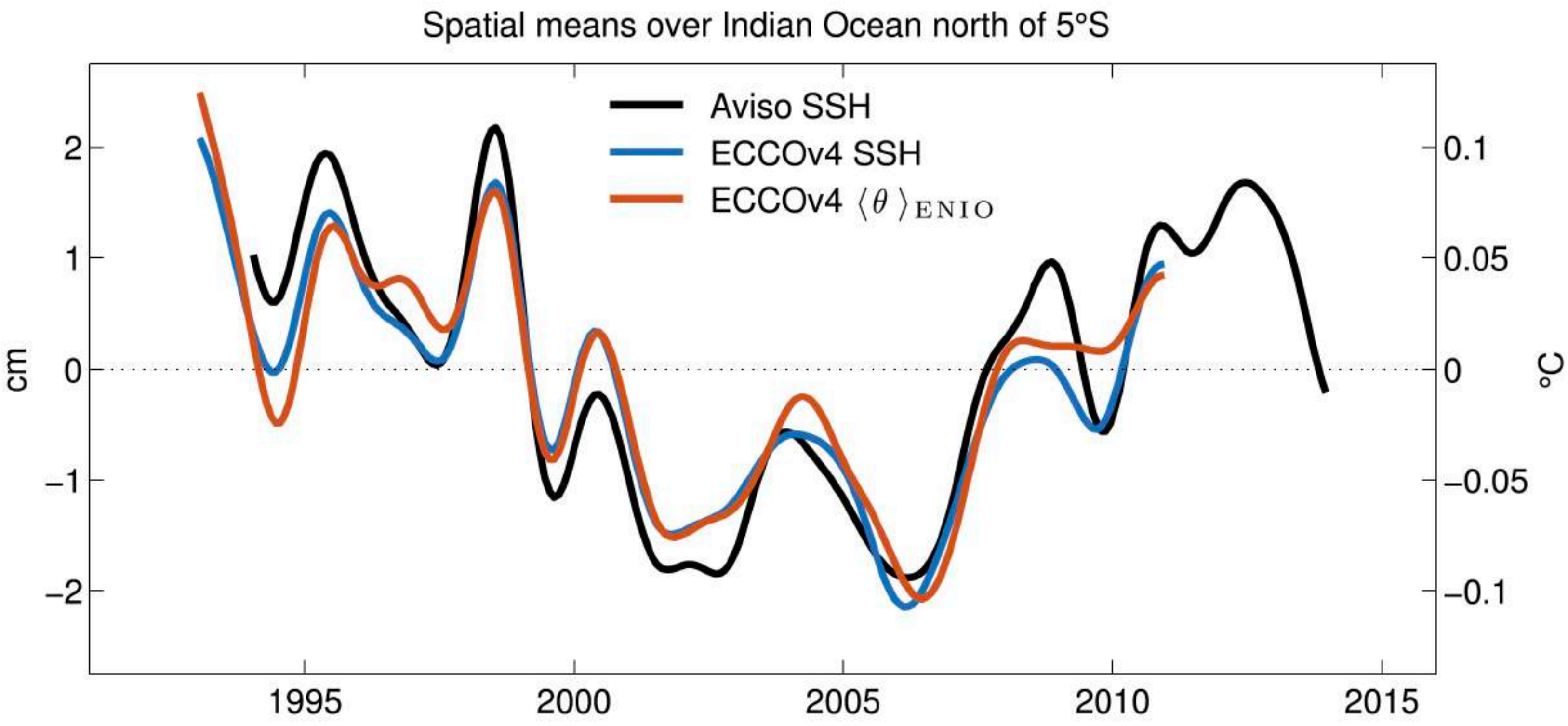

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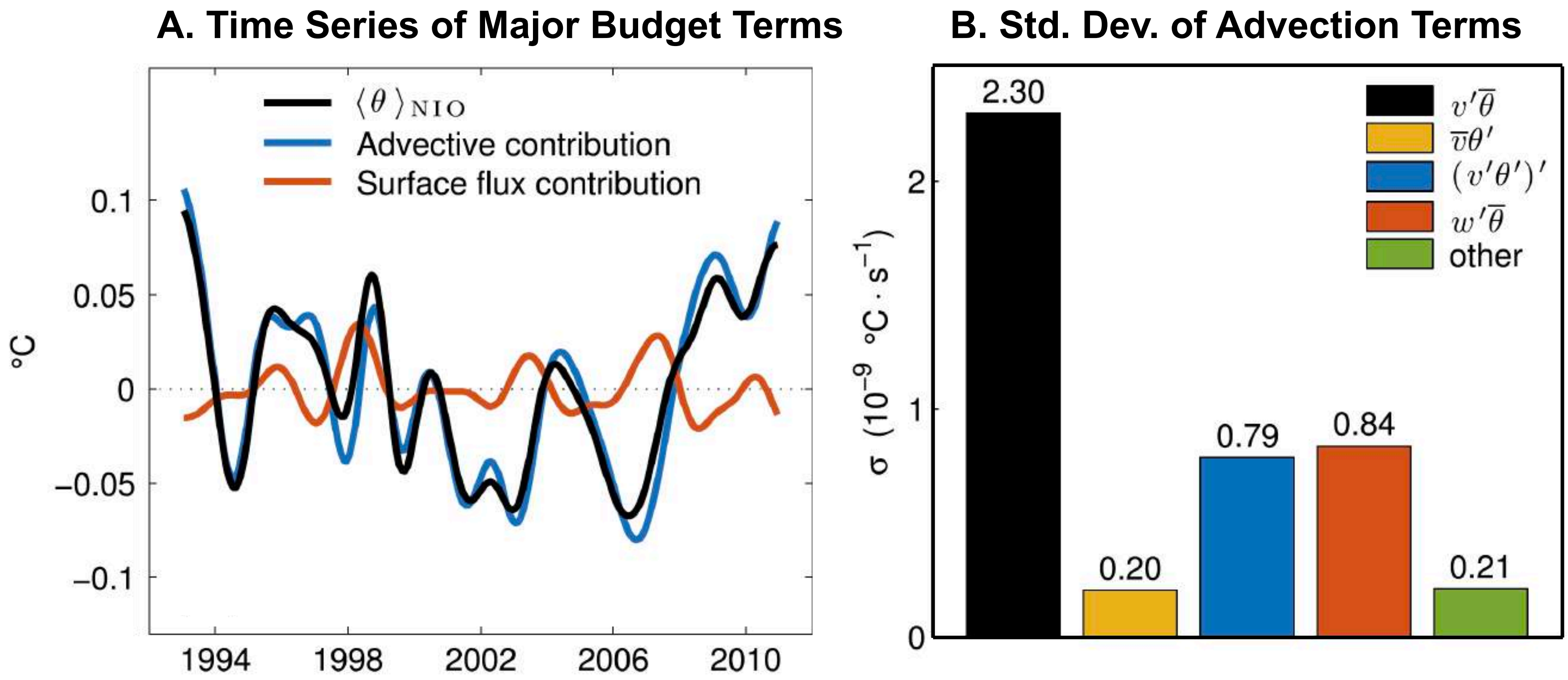

Thompson et al. (2016), J. Geophys. Res. Oceans

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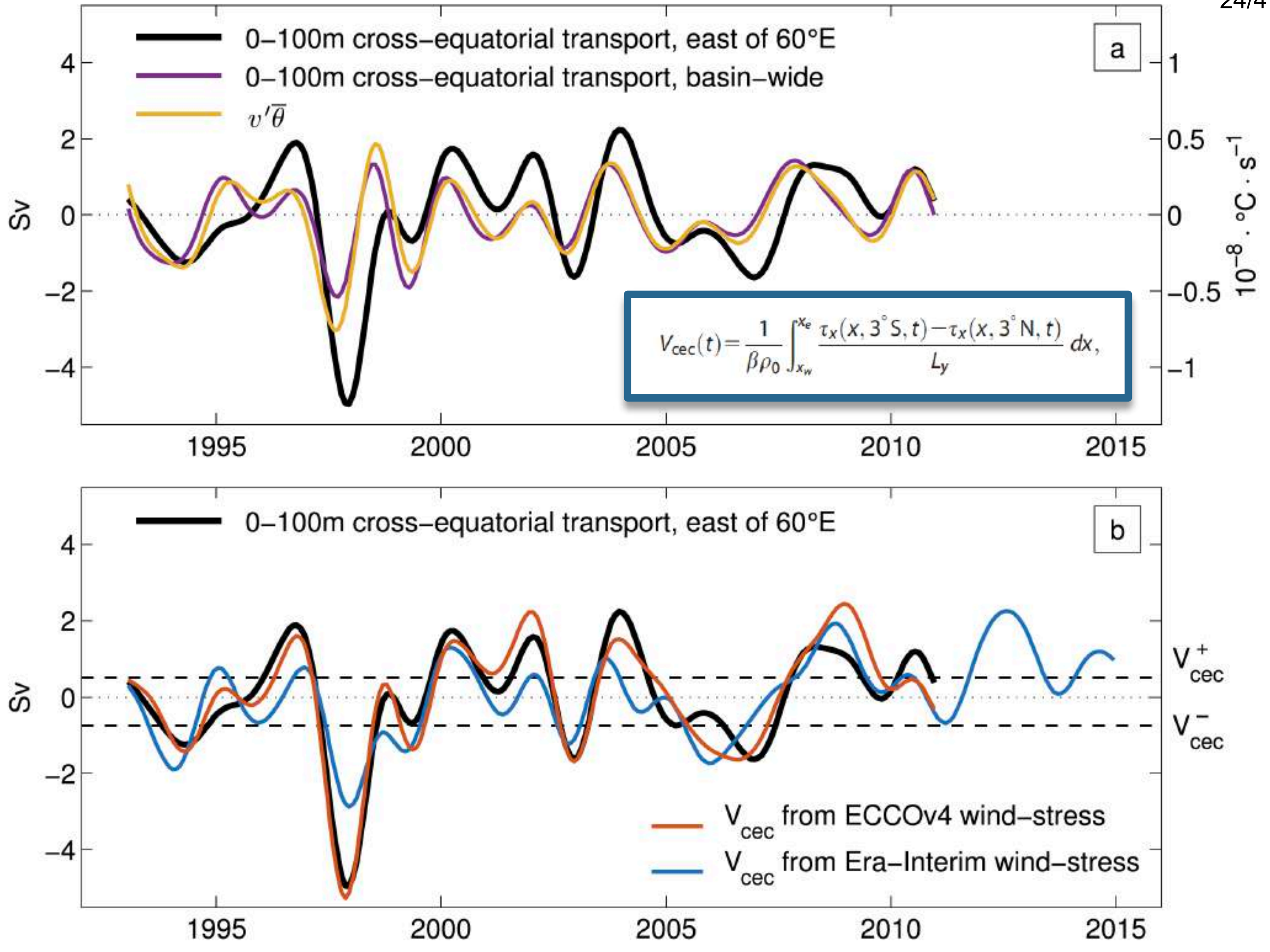
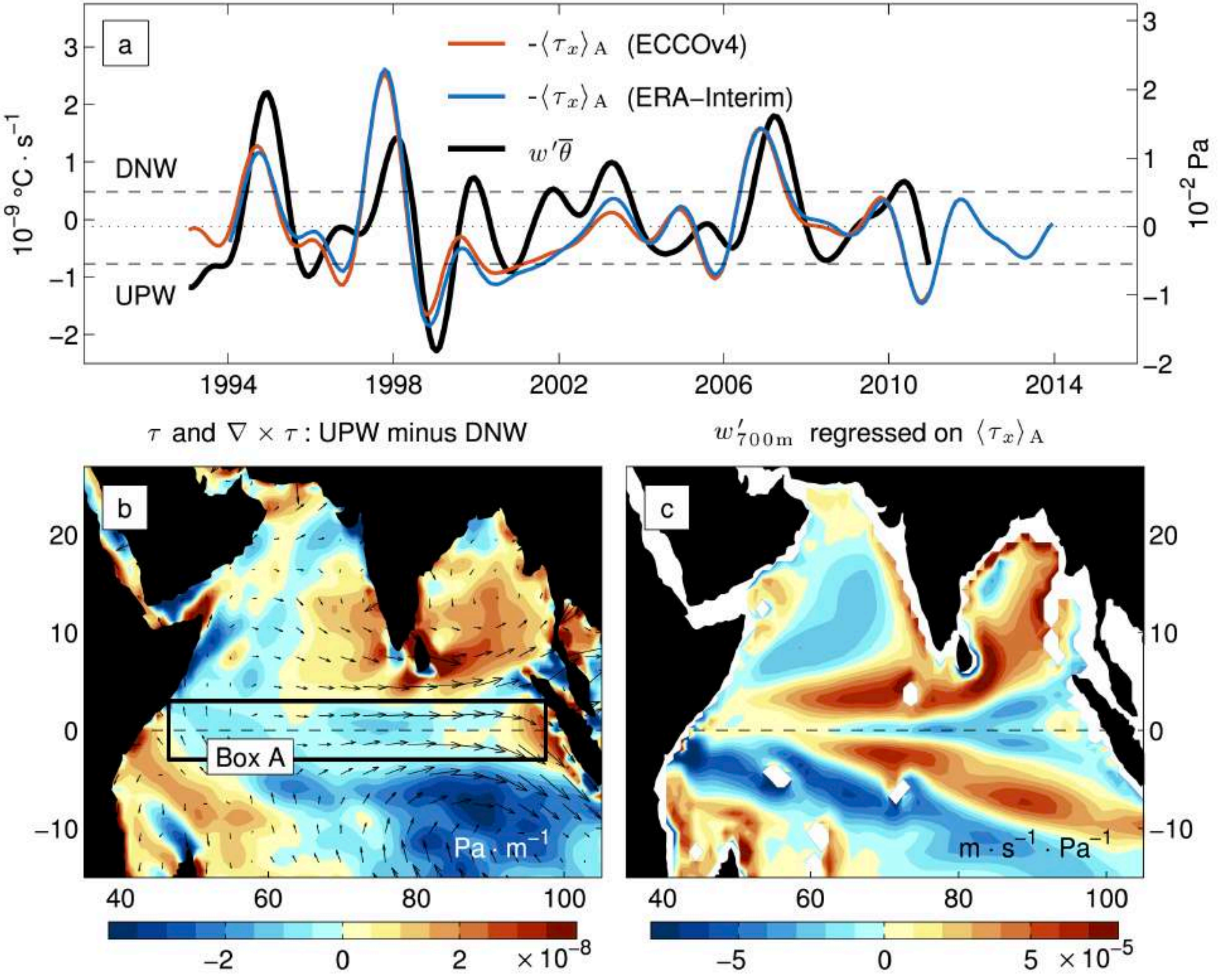


Thompson et al. (2016)
J. Geophys. Res. Oceans

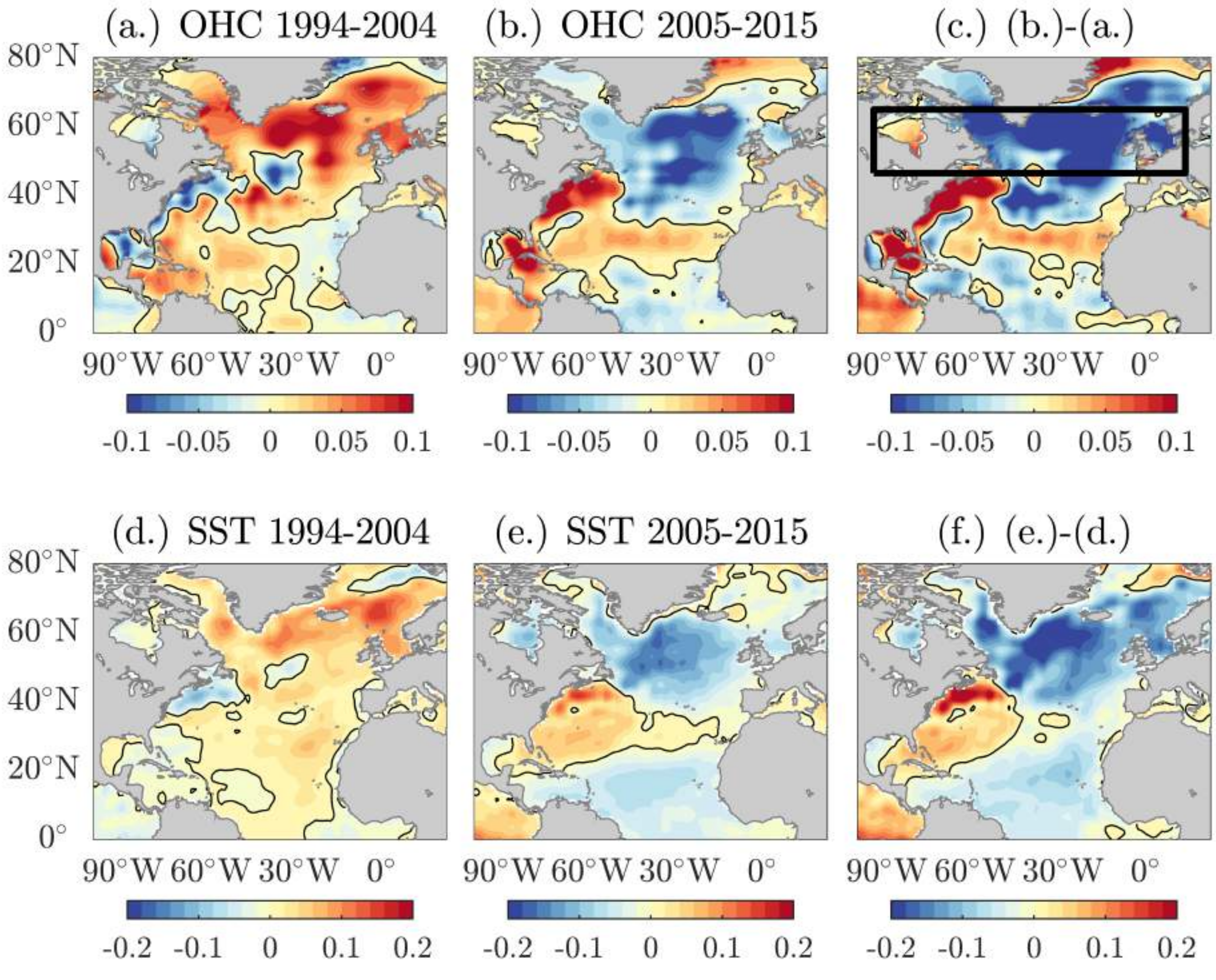
Sea Level & Heat Content in the Tropical Indian



Thompson et al. (2016)
J. Geophys. Res. Oceans

Vignette #2— Decadal Variability in the Subpolar North Atlantic Ocean

Regional Heat Content in the North Atlantic

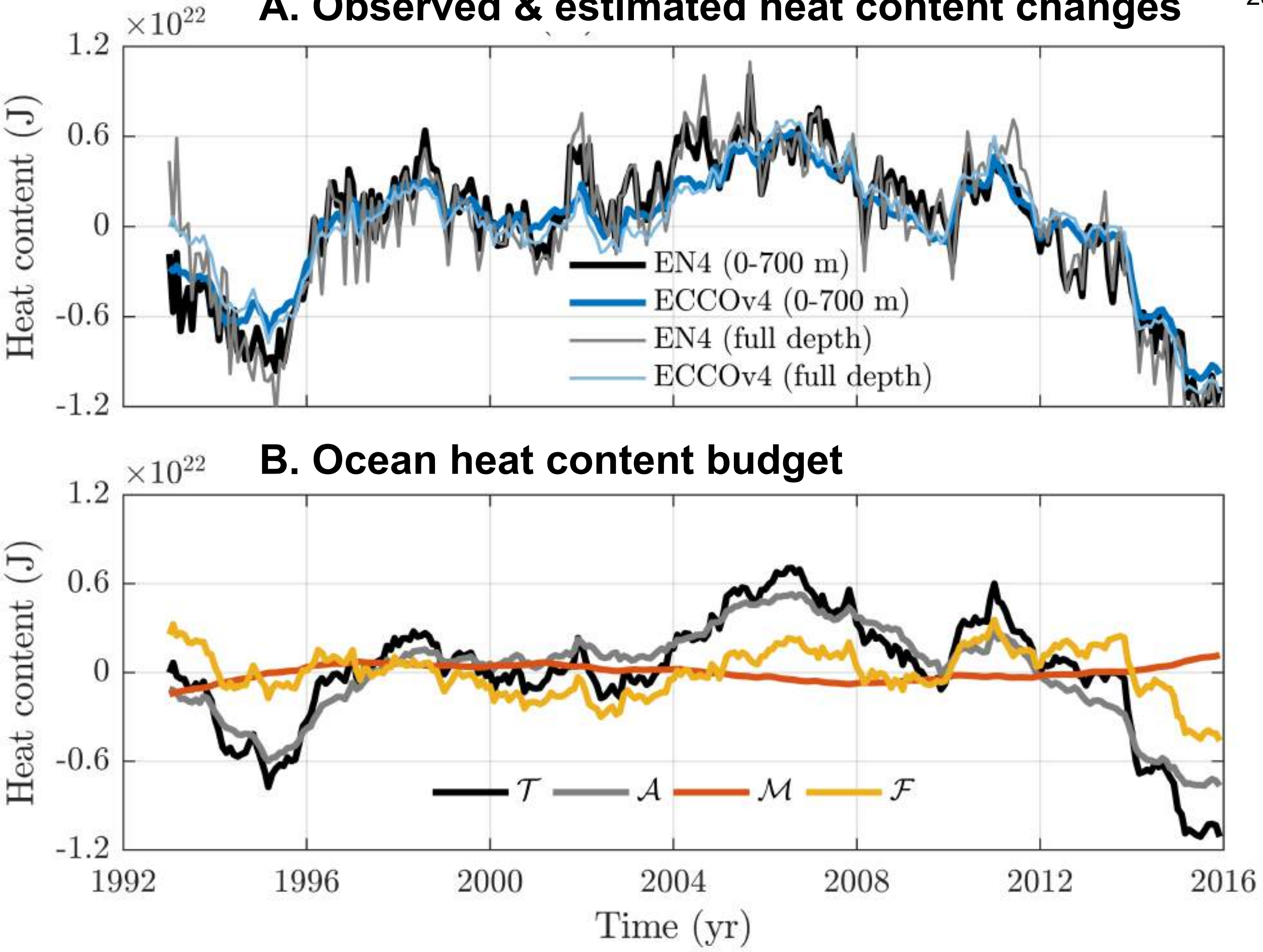


Piecuch et al. (2017), J. Geophys. Res. Oceans

Regional Heat Content in the North Atlantic

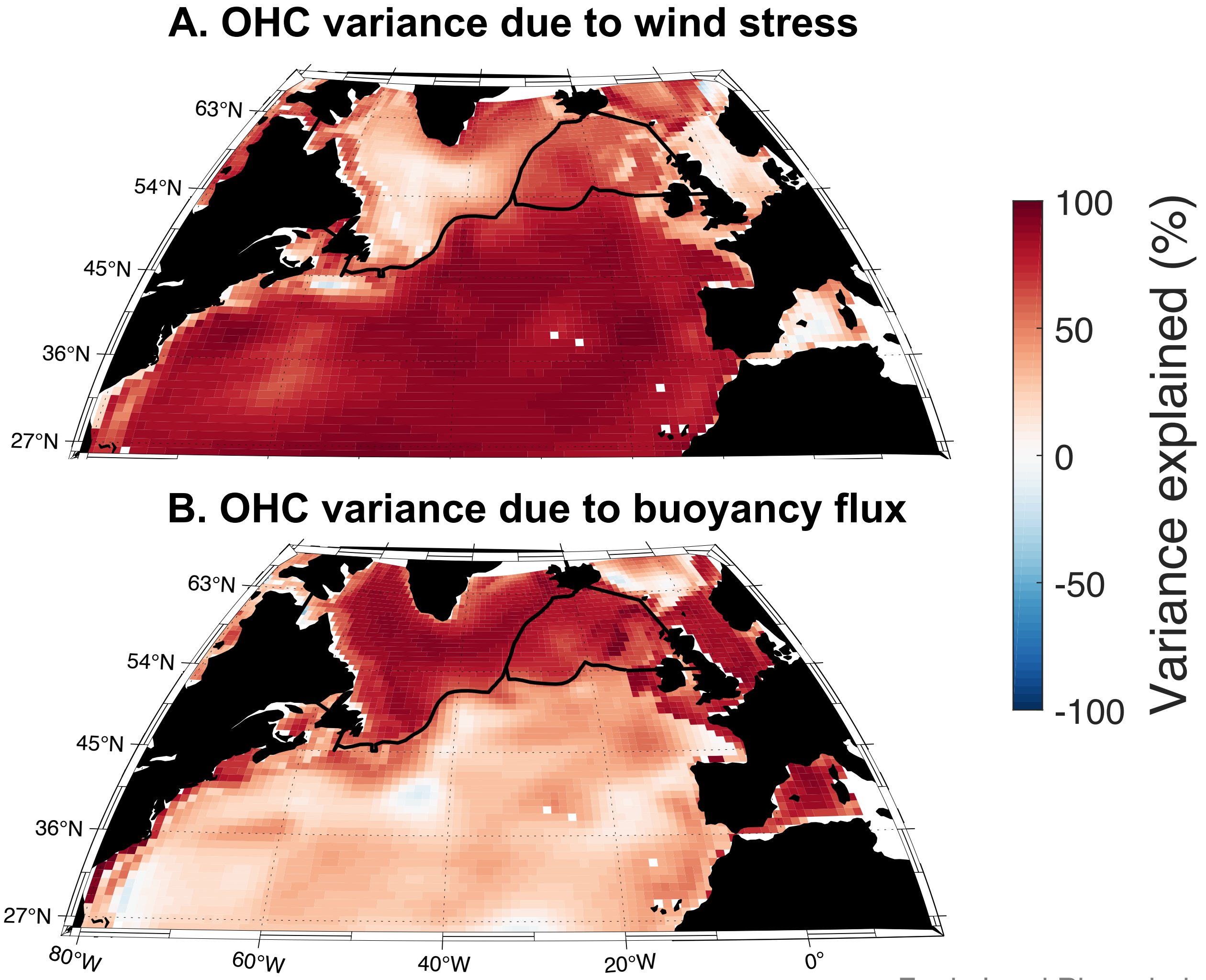
A. Observed & estimated heat content changes

B. Ocean heat content budget



Piecuch et al. (2017), J. Geophys. Res. Oceans

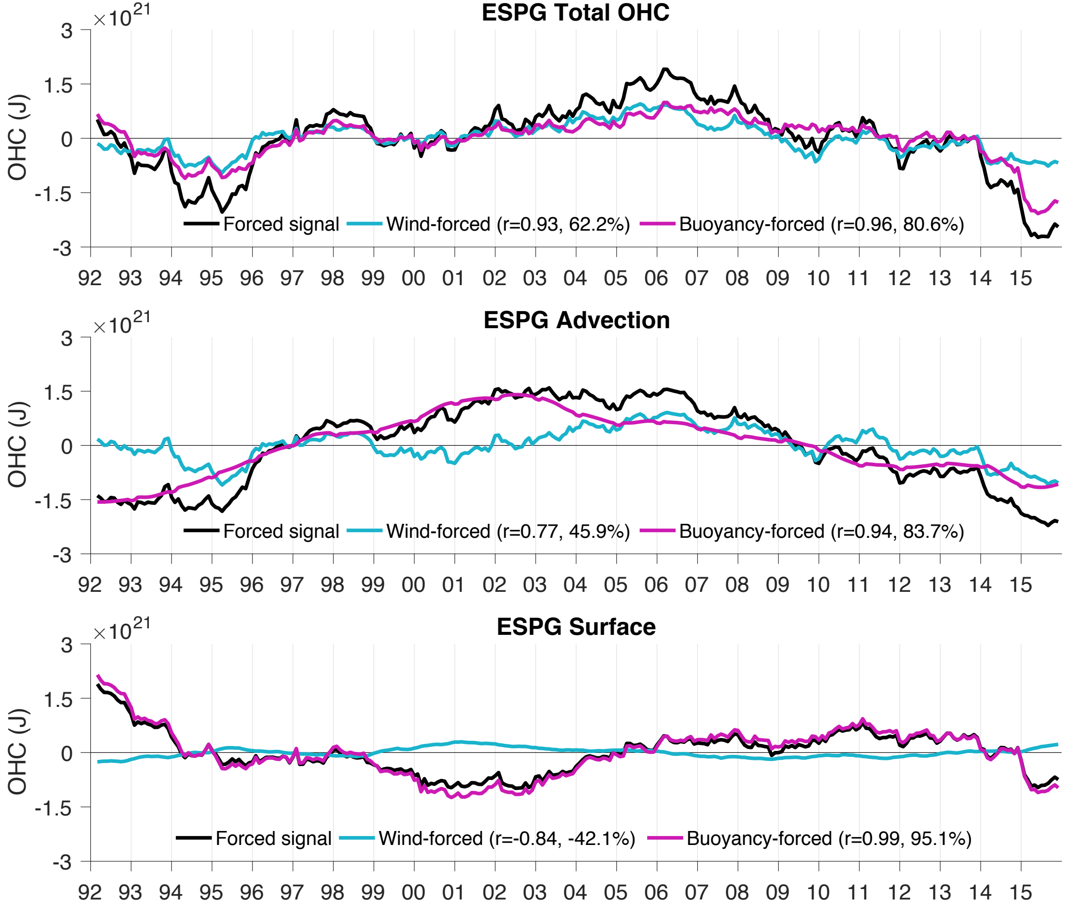
Regional Heat Content in the North Atlantic



Foukal and Piecuch, in prep.

Regional Heat Content in the North Atlantic

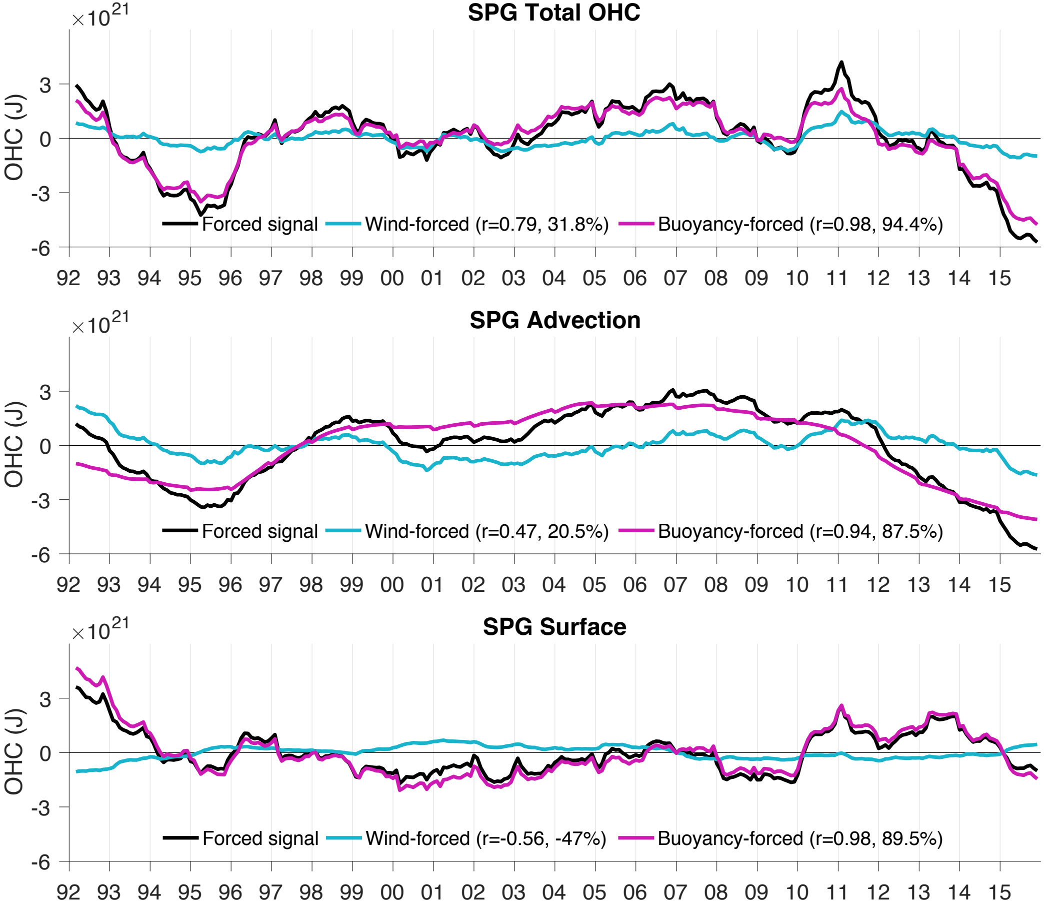
Forcing of Eastern Subpolar Gyre Budget



Foukal and Piecuch, in prep.

Regional Heat Content in the North Atlantic

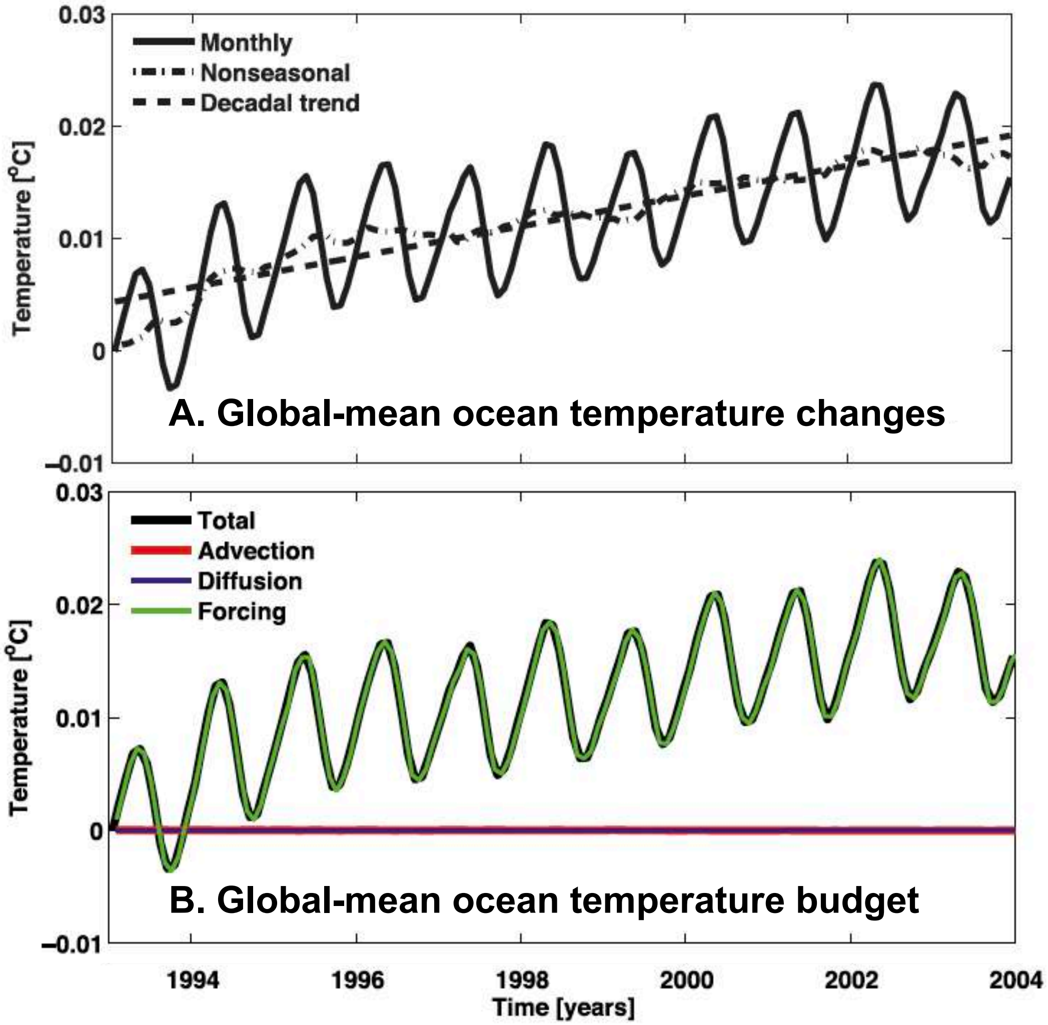
Forcing of Subpolar Gyre/Labrador Sea Budget



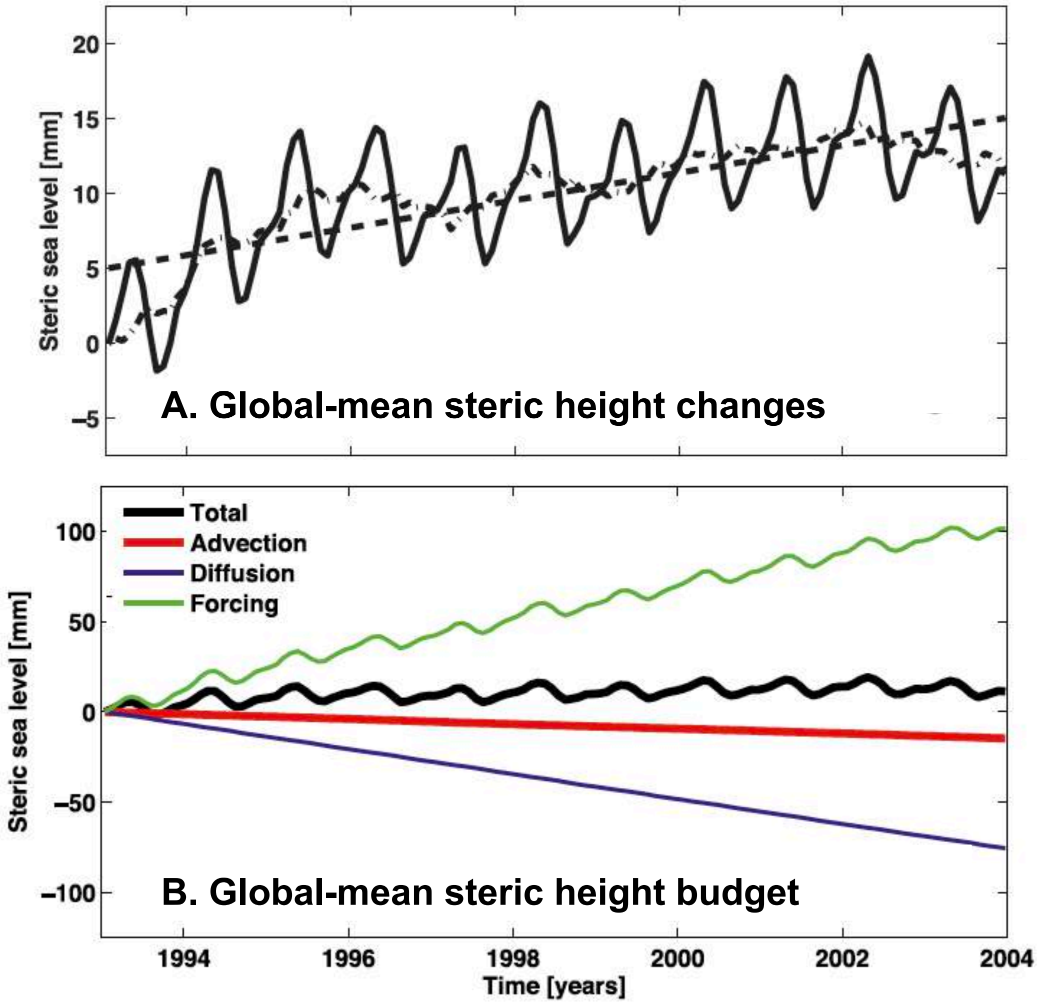
Foukal and Piecuch, in prep.

Vignette #3—
Global-Mean Steric Sea Level Change

Global-Mean Steric Sea Level



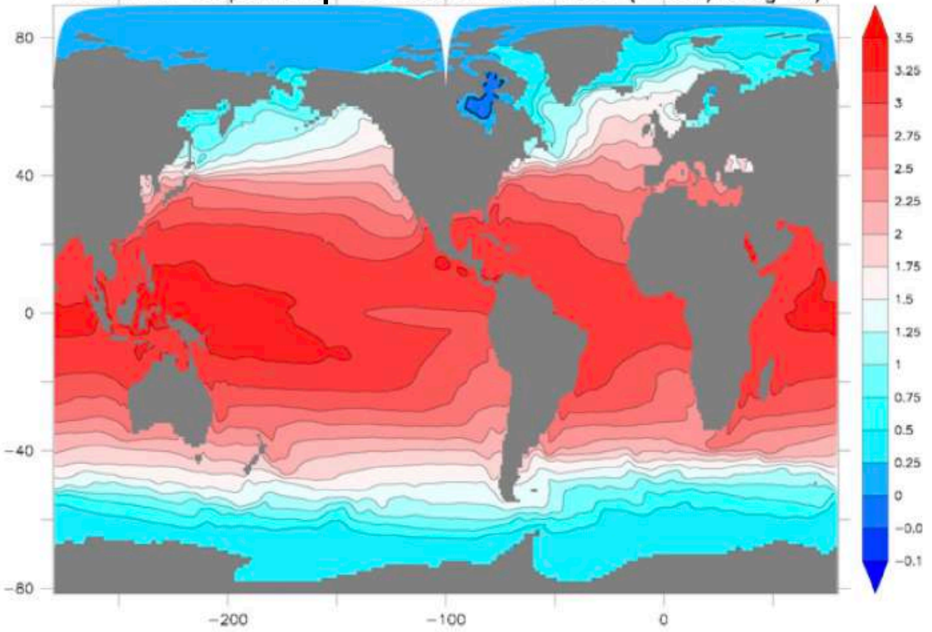
Global-Mean Steric Sea Level



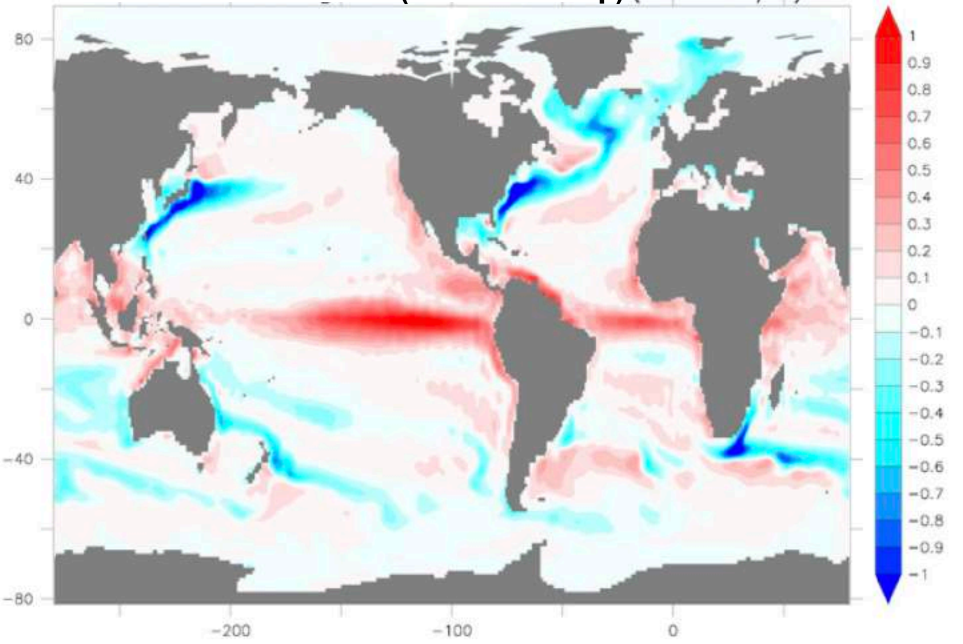
Global-Mean Steric Sea Level

Nonlinear Equation of State Effects

A. Thermal Expansion Coefficient (*1e4/deg C)



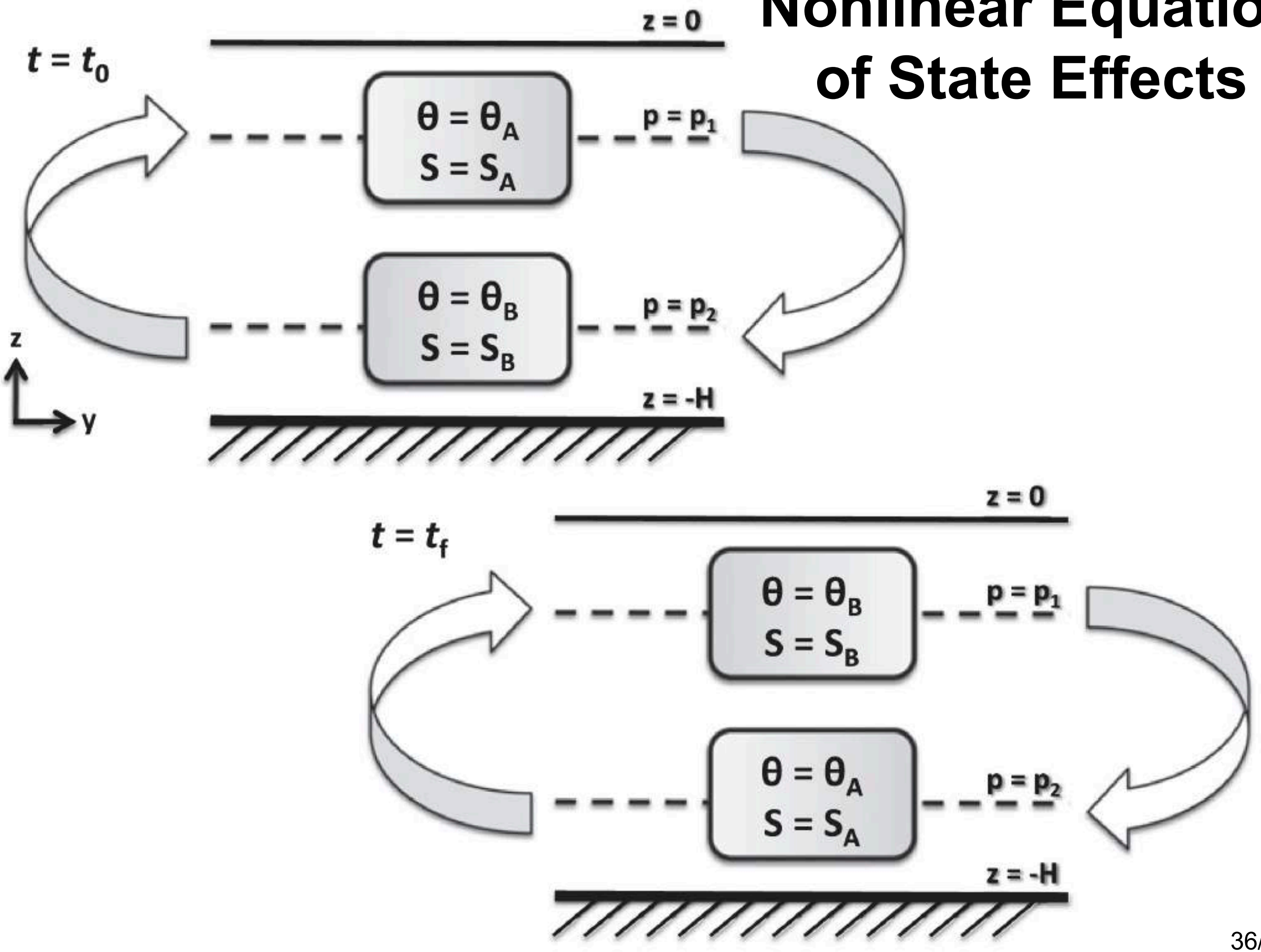
B. Surface Heat Flux (Sea Level Eq.)(*1e8 m/s)



Griffies and Greatbatch (2012), Ocean Modell.

Global-Mean Steric Sea Level

Nonlinear Equation of State Effects



Piecuch & Ponte (2014)
J. Climate

Time is Always Against Us …

- Other examples (that sadly I don’t have time to discuss)
  - Heat budgets—Kim et al. (2004, 2007); Lee et al. (2004); Nie et al. (2013); Buckley et al. (2014); Tamsitt et al. (2016); Ponte & Piecuch (2018); Su et al. (2018); Asbjørnsen et al. (2019) …
  - Salt & salinity budgets—Qu et al. (2011, 2013); Vinogradova & Ponte (2013, 2017); Gao et al. (2014)Ponte & Vinogradova (2017) …
  - Regional steric height budgets—Piecuch & Ponte (2011, 2012, 2013) …
  - Momentum budgets—Sonnewald et al. (2019) …
  - …

Oh, Right … Pop Quiz

Which of the following processes can, in principle, effect changes in **globally averaged** steric sea level?

a. Sea-surface heat exchanges

b. Internal ocean heat advection

c. Small-scale mixing of heat

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Which of the following processes can, in principle, effect changes in **globally averaged** steric sea level?

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Summary

- Budget analysis is a powerful tool for understanding and identifying the mechanisms of oceanic change
- Difficulties with observations often preclude closed budget analyses
- The data-constrained and physically consistent nature of the ECCO state estimates allows for meaningful budget attribution of observed oceanic changes

Thank you.

https://www.metoffice.gov.uk/weather/learn-about/weather/oceans/amoc