Heat content, heat fluxes and feedbacks

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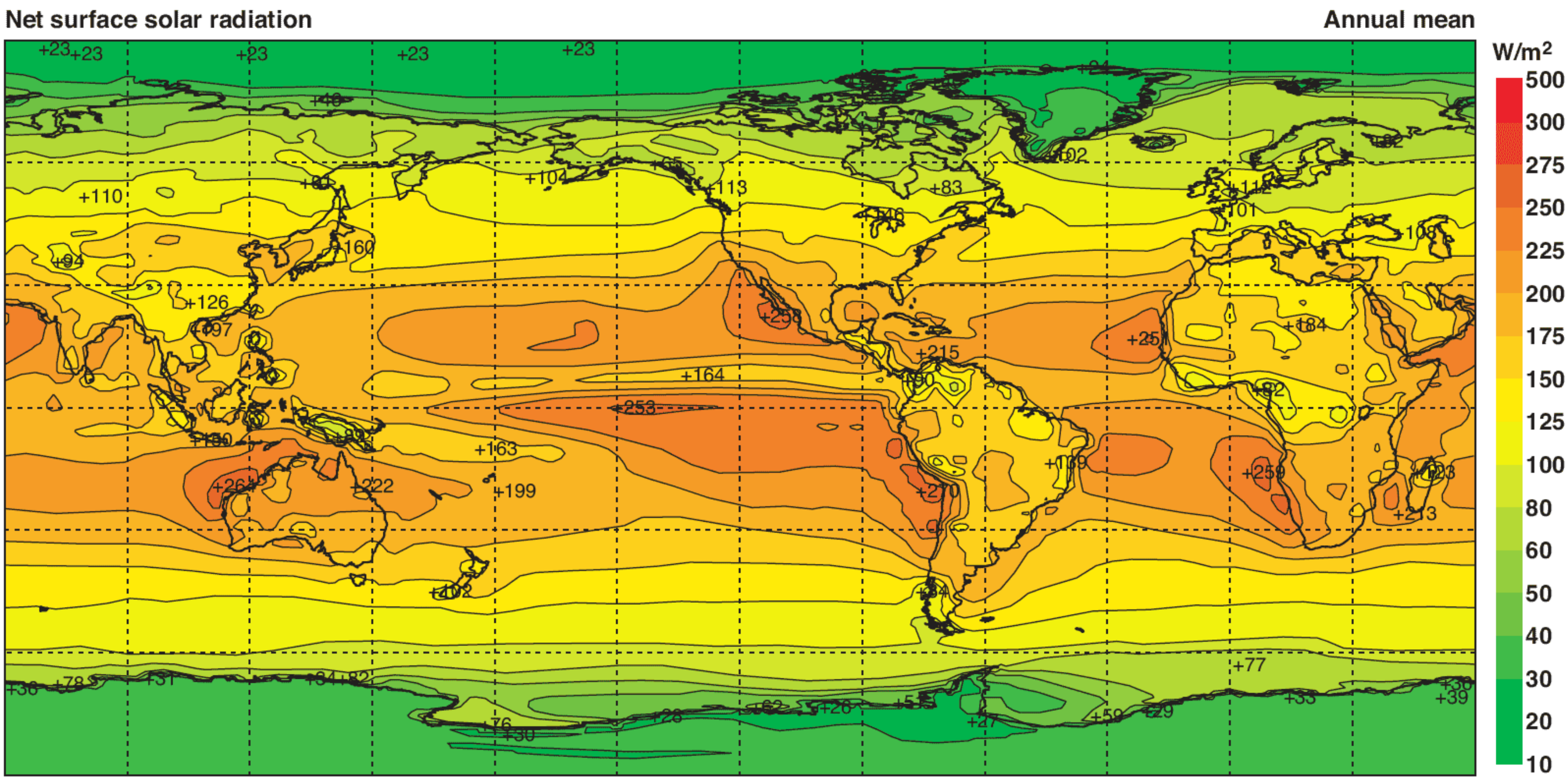
Net shortwave radiation at surface

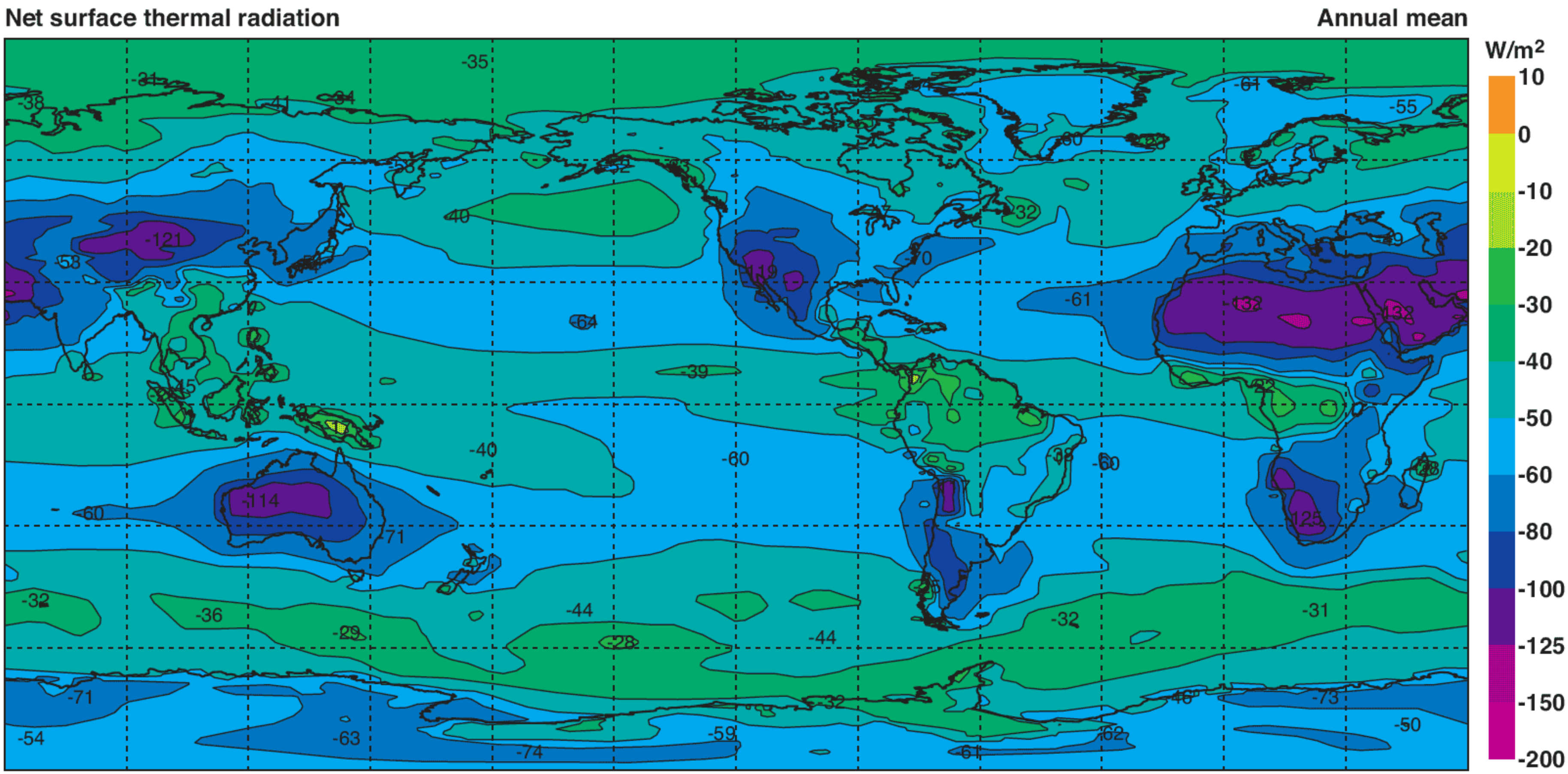
$$Q_{\mathrm{NET}} = \boxed{Q_{\mathrm{SW}}} + Q_{\mathrm{LW}} + Q_{\mathrm{L}} + Q_{\mathrm{S}}$$



Large over the oceans, depends on latitude

Net longwave radiation at surface

$$Q_{\mathrm{NET}} = Q_{\mathrm{SW}} + \boxed{Q_{\mathrm{LW}}} + Q_{\mathrm{L}} + Q_{\mathrm{S}}$$

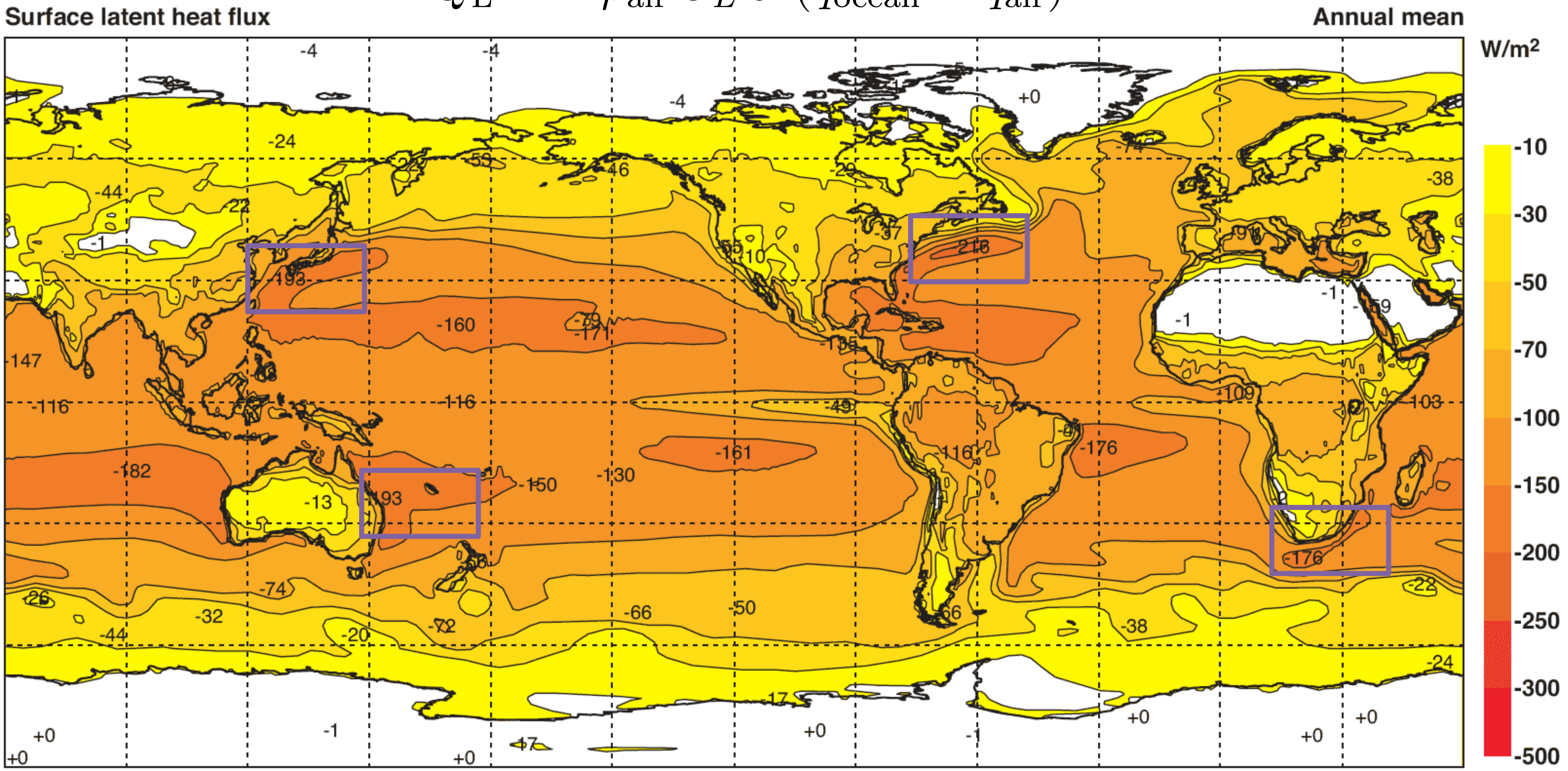


40-60 Watts/m^2 over the oceans

Latent heat flux at surface

$$Q_{\mathrm{NET}} = Q_{\mathrm{SW}} + Q_{\mathrm{LW}} + \boxed{Q_{\mathrm{L}}} + Q_{\mathrm{S}}$$

$$Q_{\mathrm{L}} = L\,\rho_{\mathrm{air}}\,C_L\,U\,(q_{\mathrm{ocean}} - q_{\mathrm{air}})$$

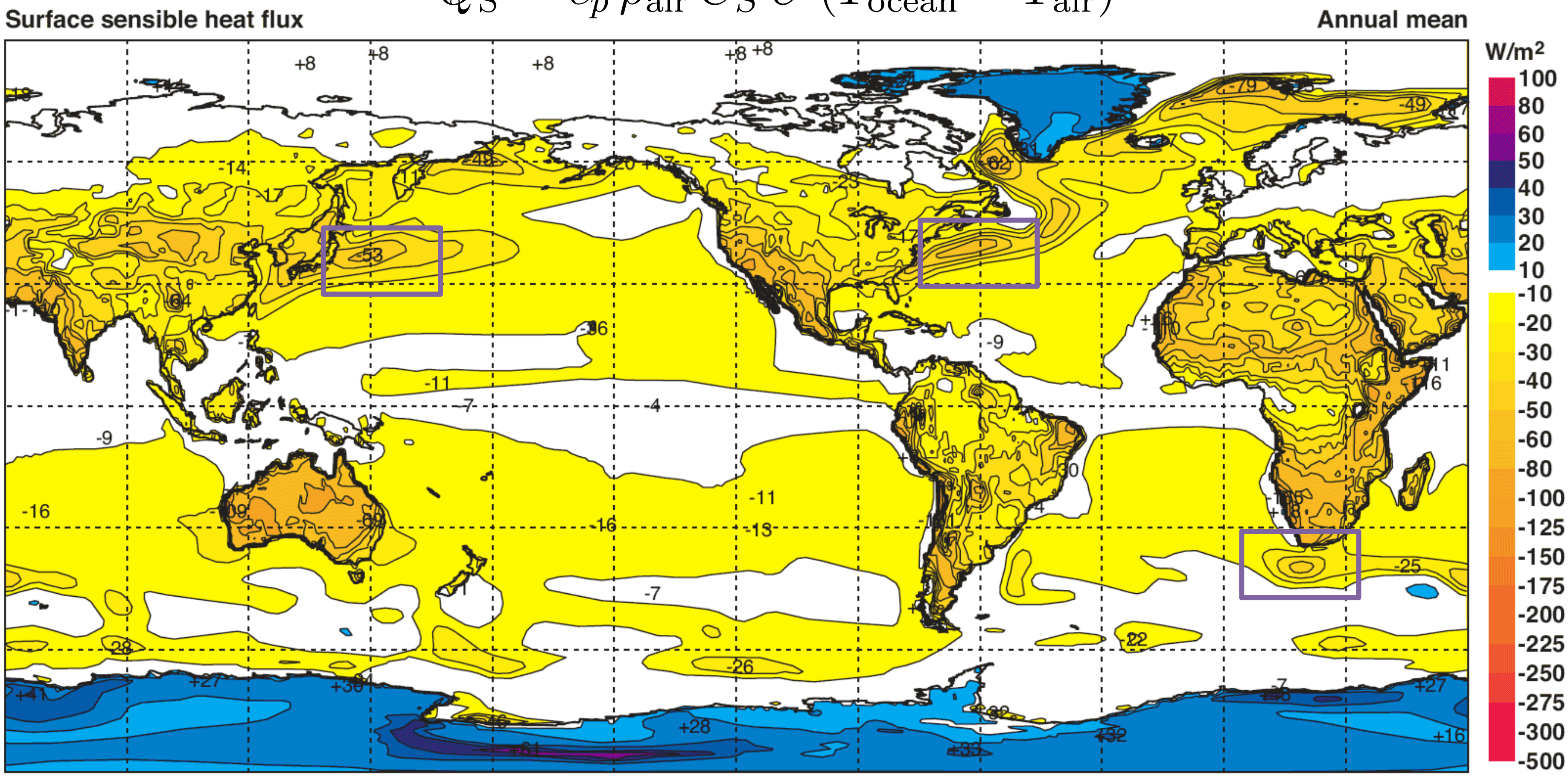


30-200 Watts/m² over the oceans, large in boundary currents

Sensible heat flux at surface

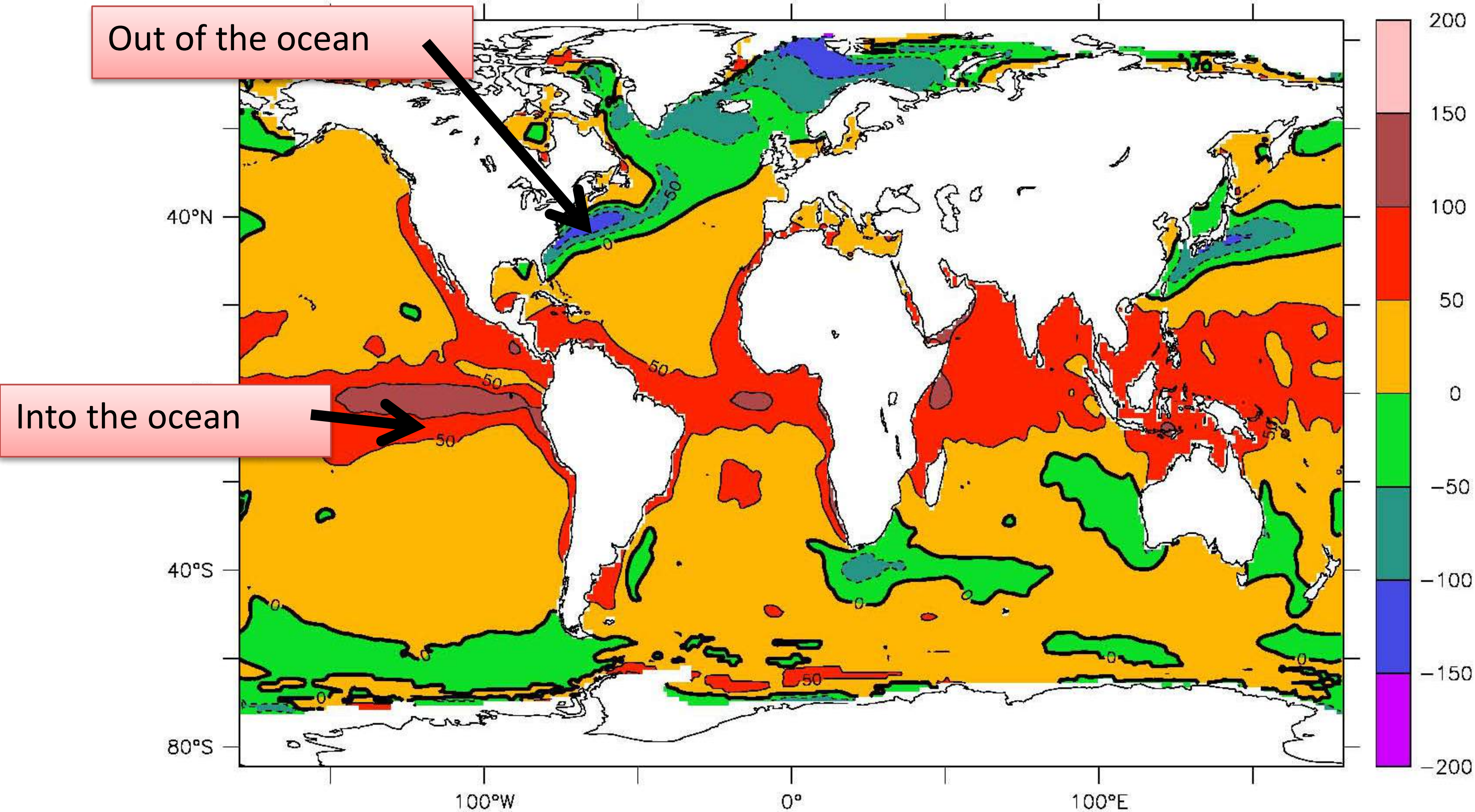
$$Q_{\mathrm{NET}} = Q_{\mathrm{SW}} + Q_{\mathrm{LW}} + Q_{\mathrm{L}} + \boxed{Q_{\mathrm{S}}}$$

$$Q_{\mathrm{S}} = c_p\,\rho_{\mathrm{air}}\,C_S\,U\,(T_{\mathrm{ocean}} - T_{\mathrm{air}})$$



30-60 Watts/m^2 over the oceans, larger in boundary currents

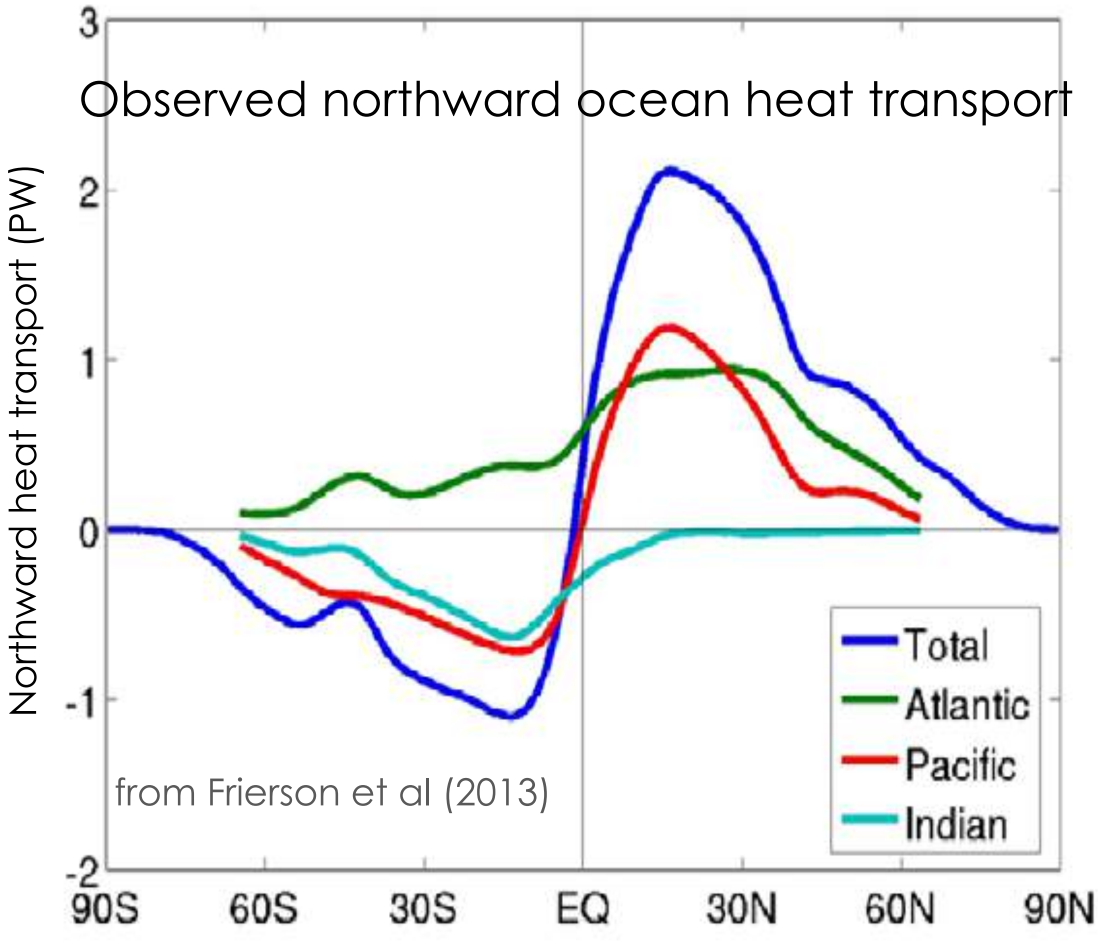
Spatially, the ocean regionally takes up and releases heat ~100 Watts/m^2 (global warming update ~1Watts/m^2)



Net surface flux from the atmosphere to the oceans Watts/m^2: implied ocean heat transport convergence

Paradigm #1:

- Net air-sea flux is driven by the mean ocean heat transport convergence

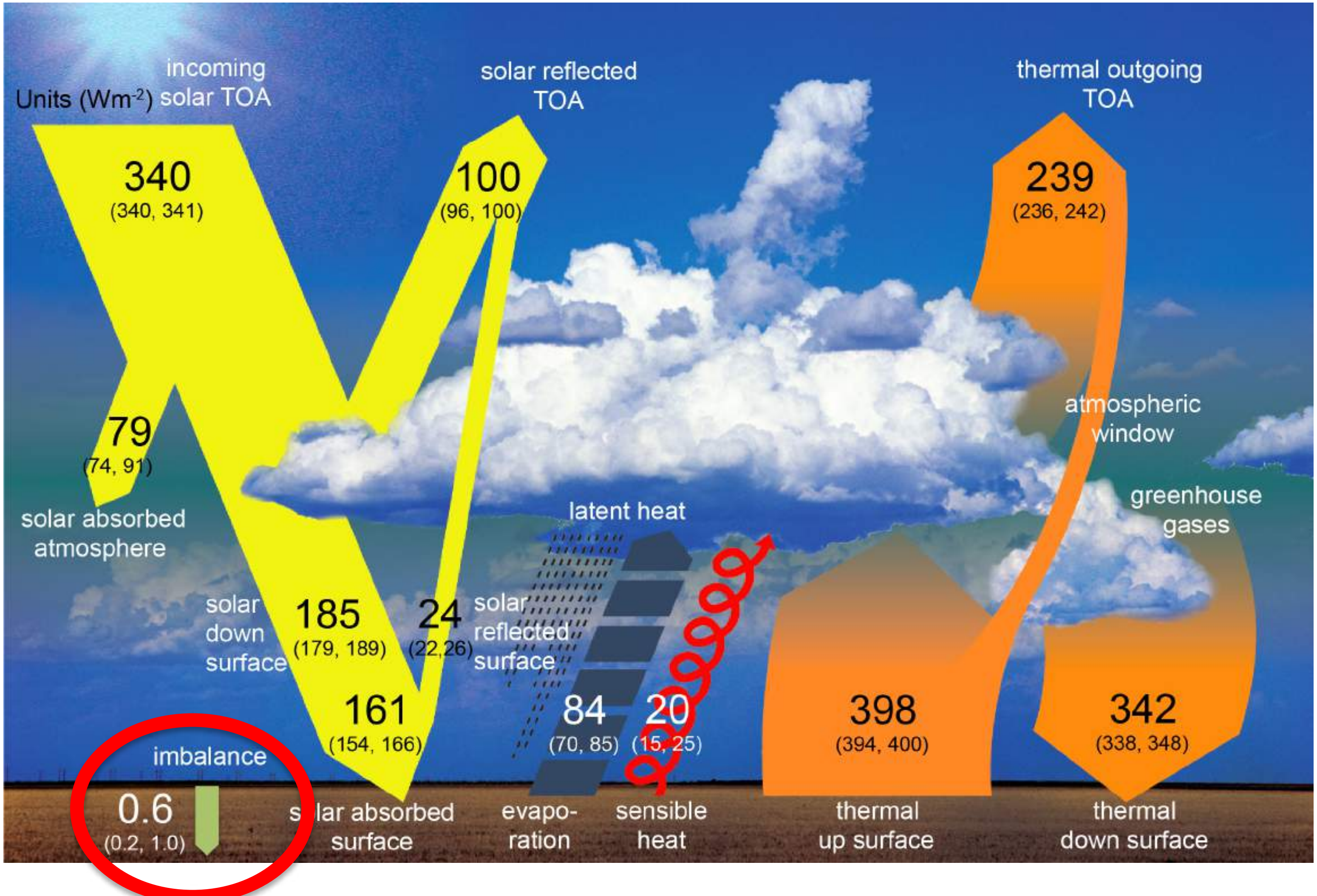


Paradigm #2:

- Anthropogenic climate change warms the ocean

Global Energy Flows

(IPCC, 2013)



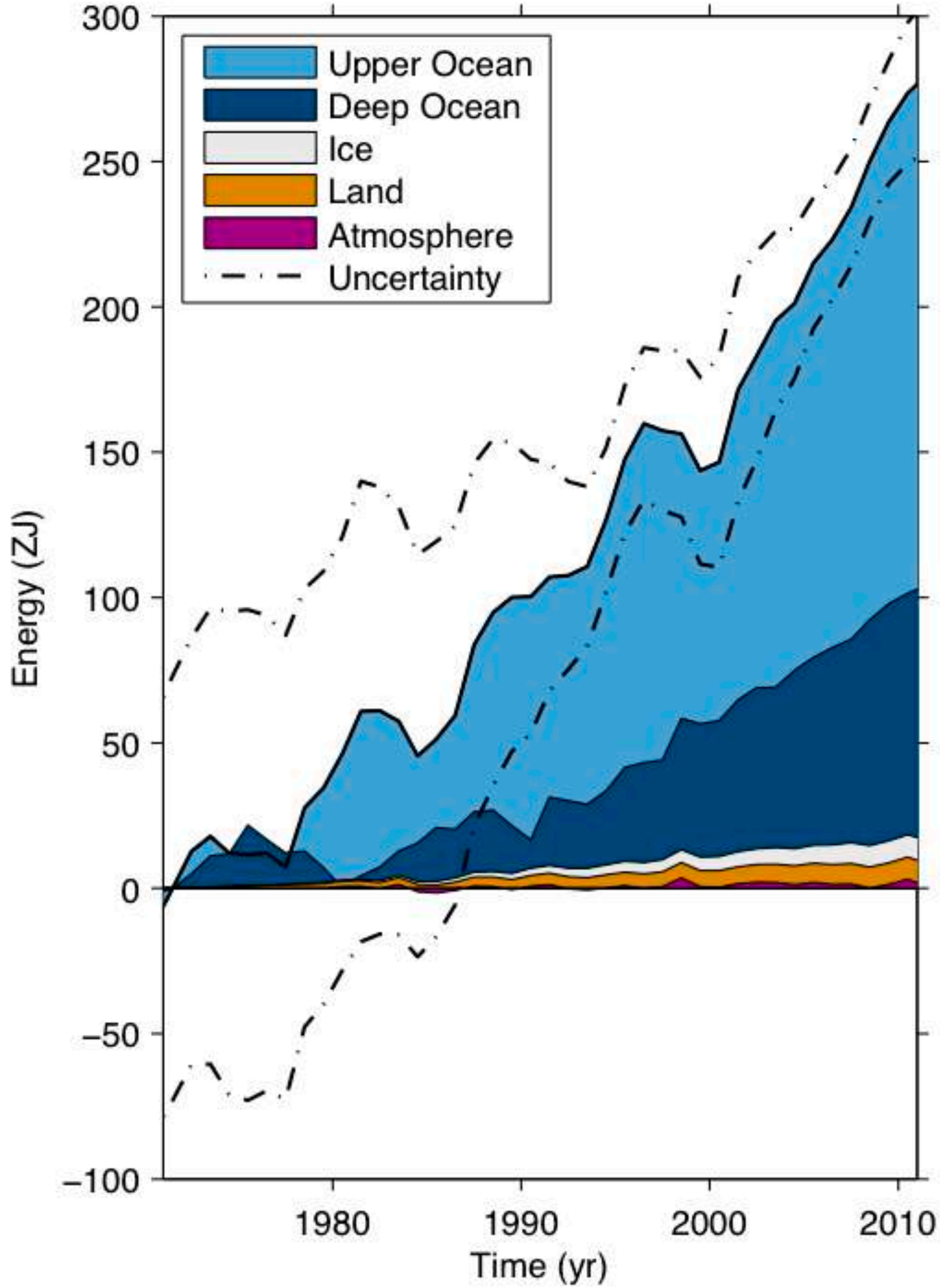
- Imbalance of ~0.6 W m^{-2} (not into corn fields though – ***into the ocean!***)
- "Small" difference of big numbers – measuring storage change robust?

Thermal Energy Storage

(IPCC, 2013)

Observational Assessment:

- 0.4 W m^{-2} 1971–2010
  - Ocean 93%
  - Ice melt 3%
  - Land 3%
  - Atmosphere 1%
- 0.5 W m^{-2} 1993–2010
- Sparser observations make uncertainties larger earlier in time.



Greg Johnson

Paradigm #3:

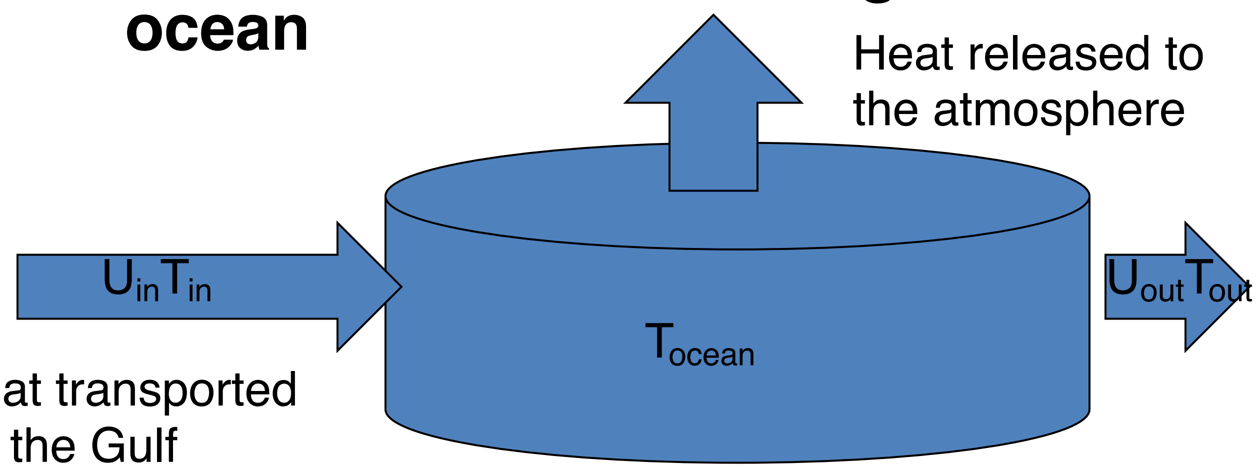
Changes in ocean heat transport convergence control air-sea heat exchanges

Paradigm #4 Changes in ocean heat transport convergence control air-sea heat exchanges

$$\rho_{ocean} H_{ocean} c_p \frac{dT_{ocean}}{dt} = -\rho_{ocean} H_{ocean} c_p \nabla \bullet \vec{u} T - Q_{surface}$$

Heat storage rate in upper ocean **=** **Heat Transport Convergence** **+** **Surface heat flux**

Heat released to the atmosphere



Heat transported By the Gulf Stream

Dong and Kelly (2004) and Kelly and Dong (2006)

On monthly to interannual time scales: what controls SST/Heat content anomalies and air-sea heat fluxes: Focus on the North Atlantic

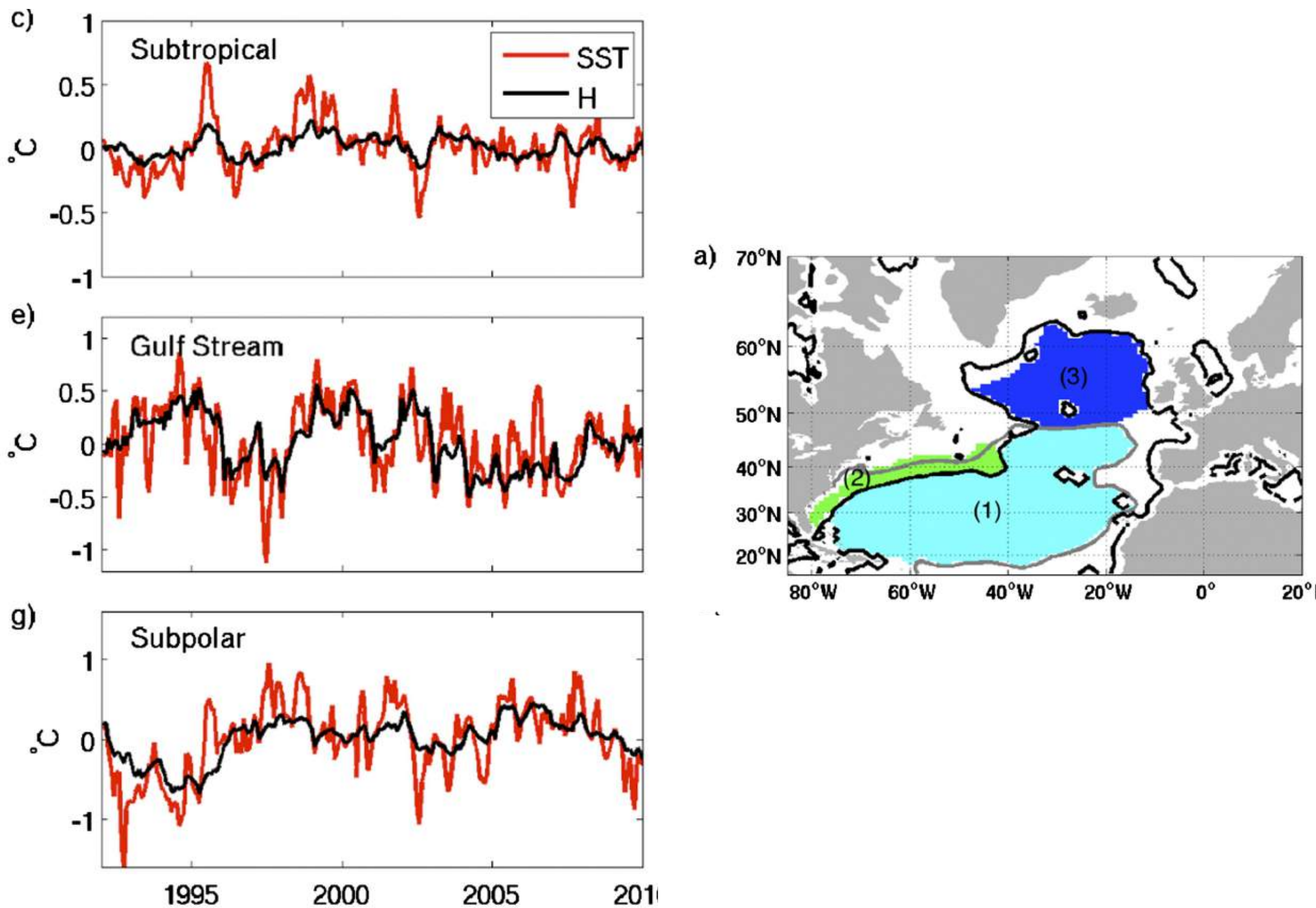
ECCO heat budget Buckley et al (2014)
Observational analysis

Buckley et al, 2014. Use ECCO to construct closed heat budgets for the North Atlantic, down to H_{max}=maximum MLD, $H = \rho C_p H_{max}$

Local forcing explains H

Ocean heat transport convergence explains H

Diffusion and Bolus fluxes control H



Paradigm #4:

Over much of the subtropical oceans, atmosphere controls the interaction with atmospheric noise forcing SST anomalies which are then damped by atmospheric fluxes Frankignoul and Hasselman (1977), Cayan (1992)

Paradigm #3+#4:

- Include the potential of both atmospheric forcing and oceanic forcing

Barsugli and Battisti (1998) ocean-atmosphere interaction
Ocean-noise added Wu et al (2006) (non-seasonal anomaly model)

Add ocean “noise”

$\lambda_a \sim \lambda_o$

Atmosphere noise

$$\rho_{atmos} c_{atmos} H_{atmos} \frac{dT_a}{dt} = \lambda(T_o - T_a) - \lambda_a T_a + N_a$$

$$\rho_{ocean} c_{ocean} H_{ocean} \frac{dT_o}{dt} = -\lambda(T_o - T_a) - \lambda_o T_o + N_o$$

Latent +sensible (turbulent) surface heat flux Q_{turb}

Radiative cooling

Long wave radiation

Ocean noise

= Ocean heat transport convergence anomalies

For a given frequency distribution of Ta and To, depends on two parameters

1. **Depth of the ocean (controls ocean heat capacity)** H_{ocean}
2. **Ratio of atmosphere to ocean forcing** N_o / N_a

$$\rho_{atmos} c_{atmos} H_{atmos} \frac{dT_a}{dt} = \lambda\left(T_o - T_a\right) - \lambda_a T_a + N_a$$

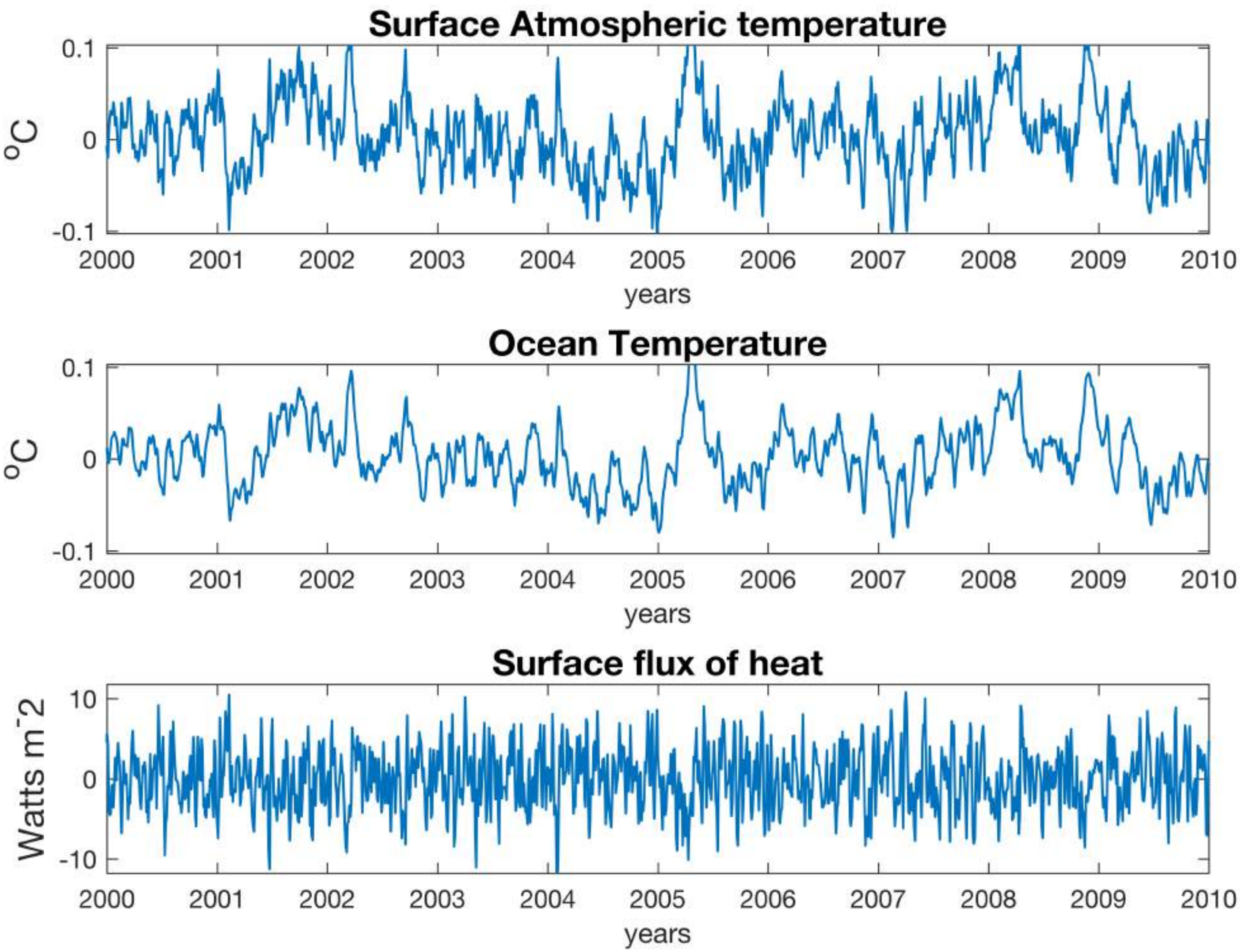
$$\rho_{ocean} c_{ocean} H_{ocean} \frac{dT_o}{dt} = -\lambda\left(T_o - T_a\right) - \lambda_o T_o + N_o$$

$$\lambda_a \sim \lambda_o << \lambda$$

How much impact does the T_o have on air-sea fluxes?

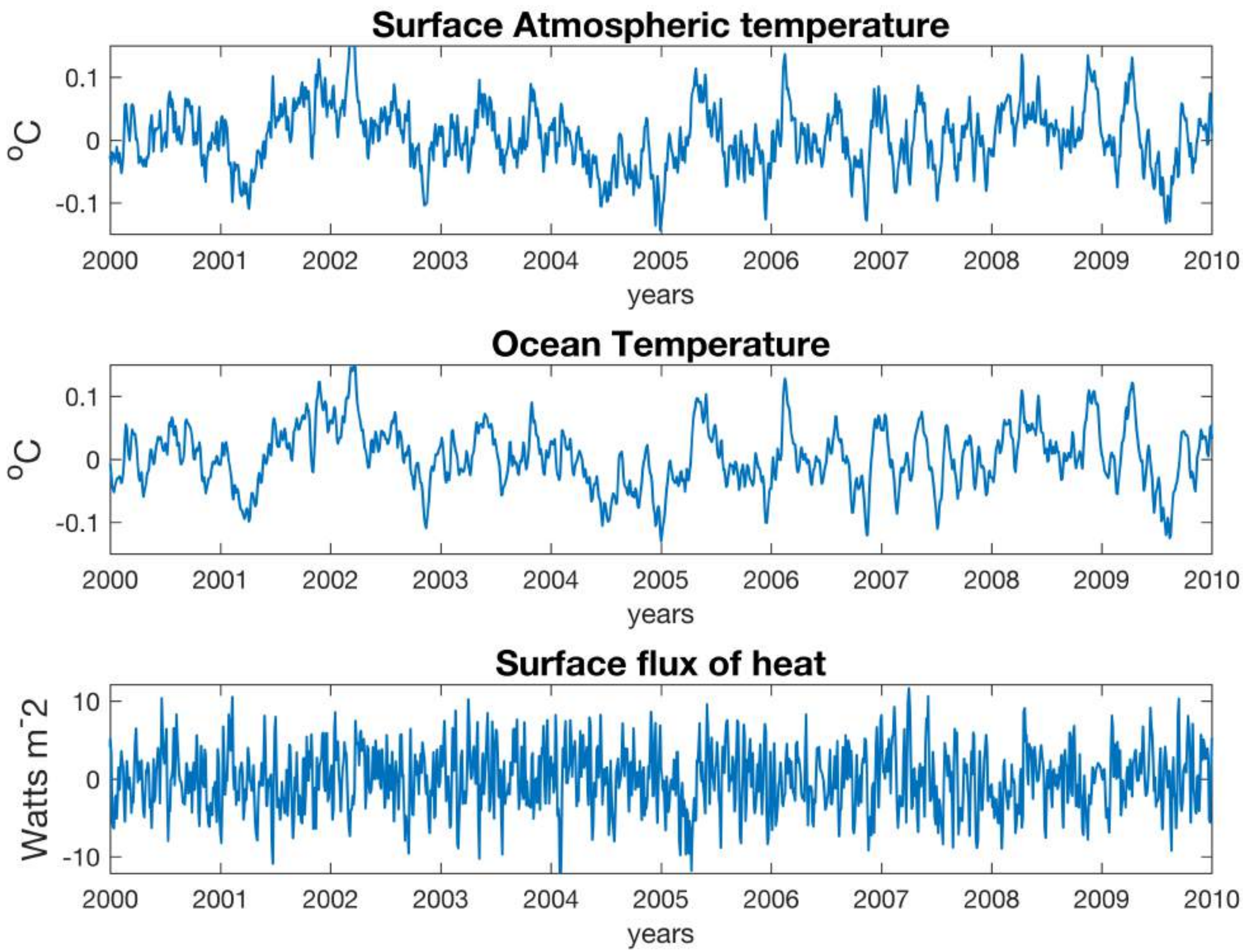
Weak ocean noise 50m depth ocean (Atmosphere controls)

Paradigm #4 (Frankignoul)

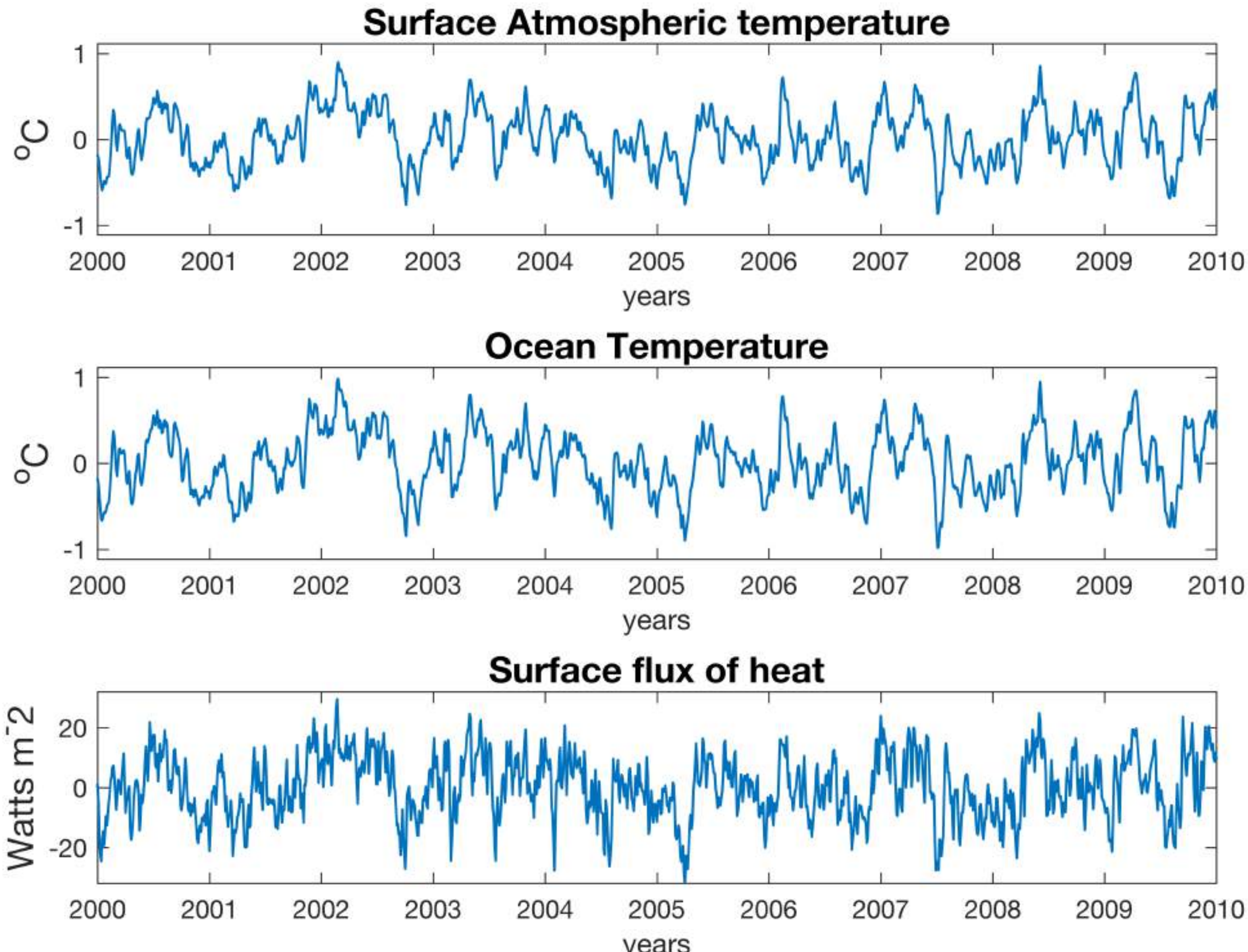


$Q = \lambda(T_o - T_a)$ positive for cooling the ocean

Moderate ocean forcing, Paradigm #4 (Frankignoul)



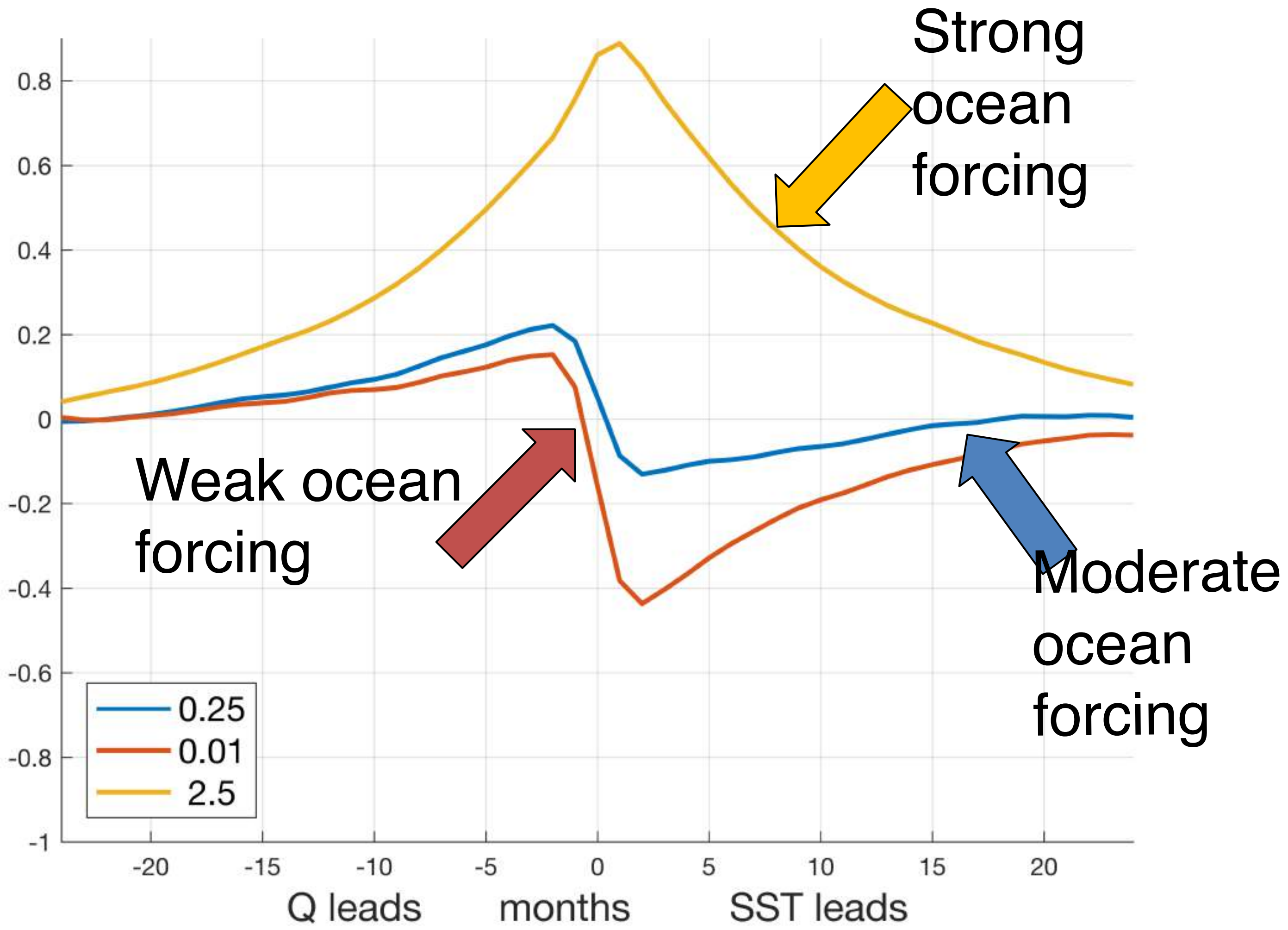
Strong ocean noise: Ocean controls, Paradigm #4



$Q = \lambda(T_o - T_a)$ positive for cooling the ocean

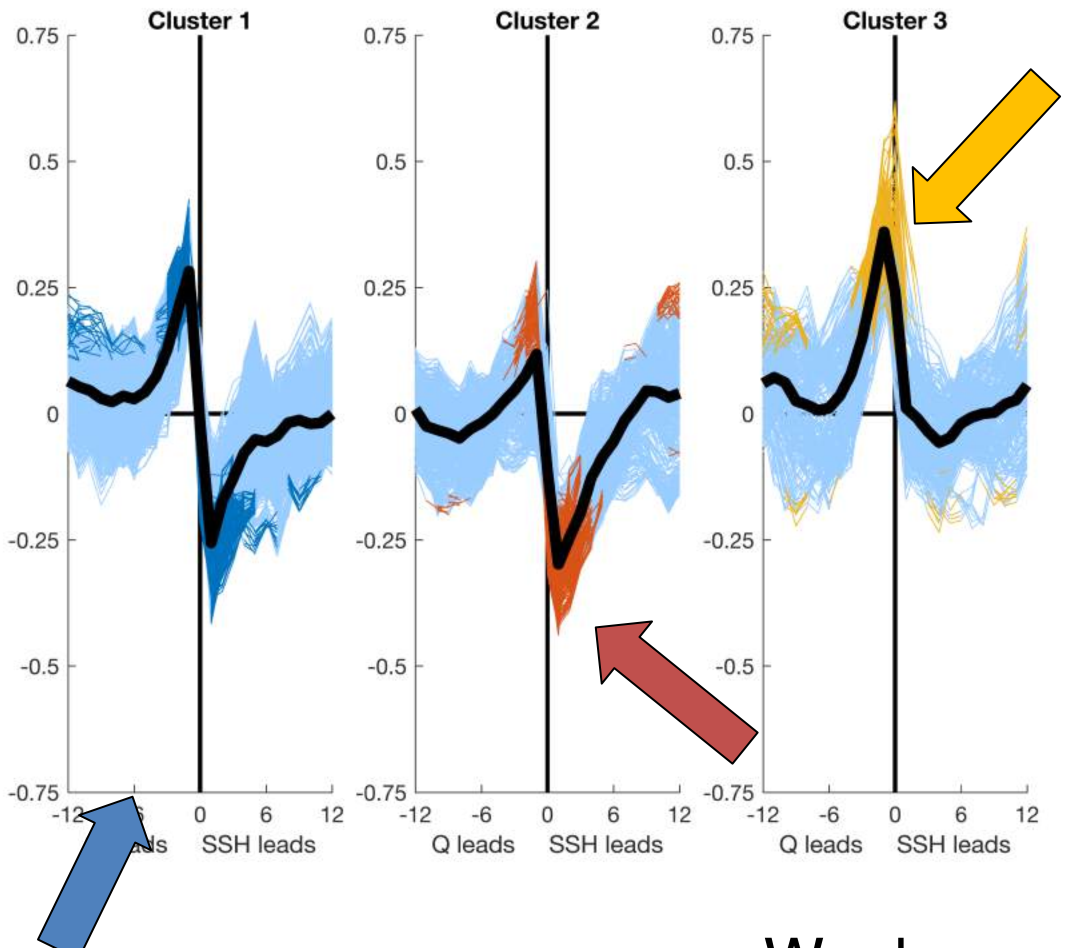
Highly correlated with ocean temperature

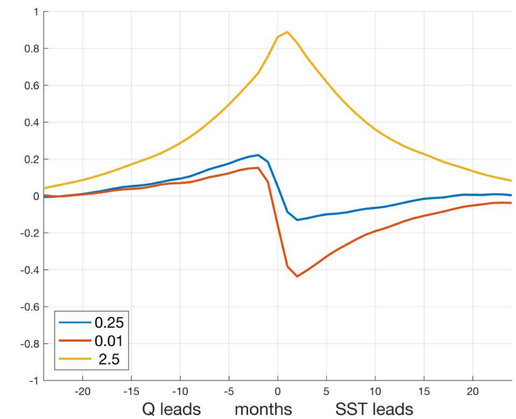
Lagged correlation structure: depends on the relative strength of ocean and atmospheric noise: 25 m ocean.



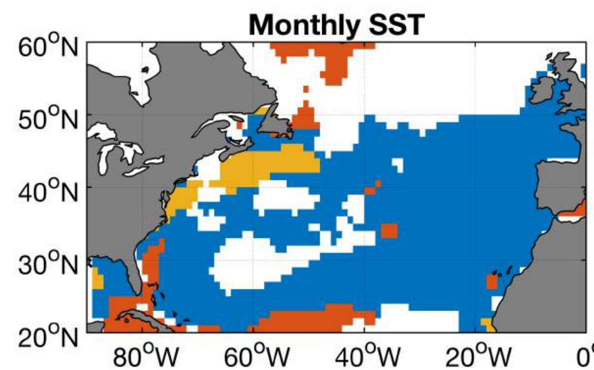
Focus on the North Atlantic
Investigate lagged regressions between SST and Q

Perform a cluster analysis





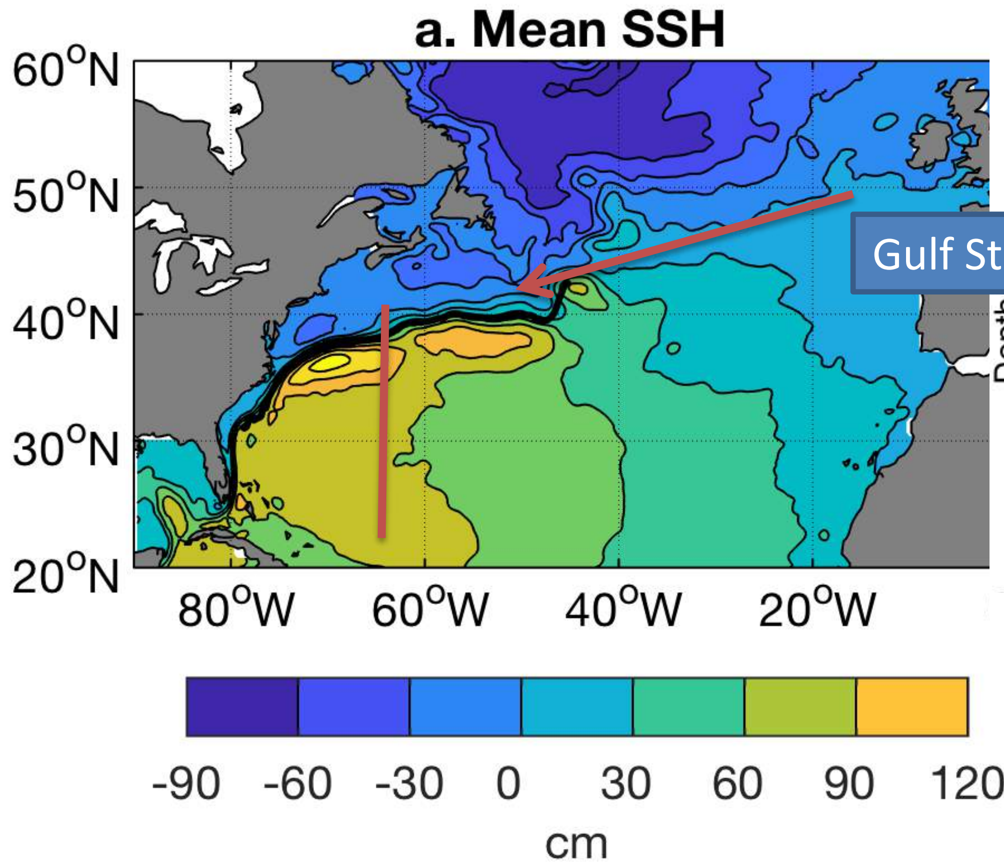
Strong ocean forcing

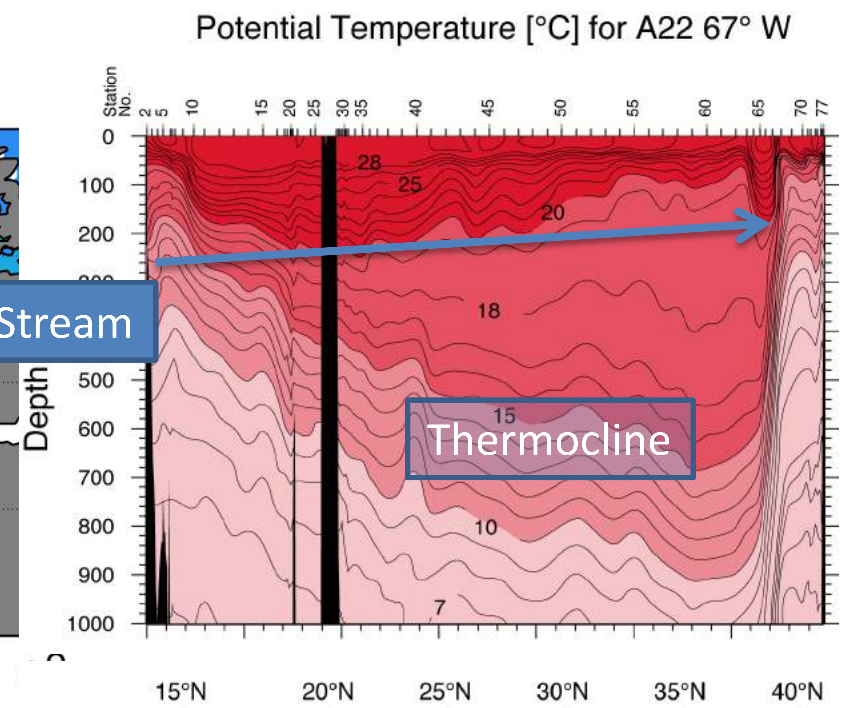


Moderate ocean forcing

Weak ocean forcing

Sea surface height mirrors the temperature structure:
high temperature→high SSH

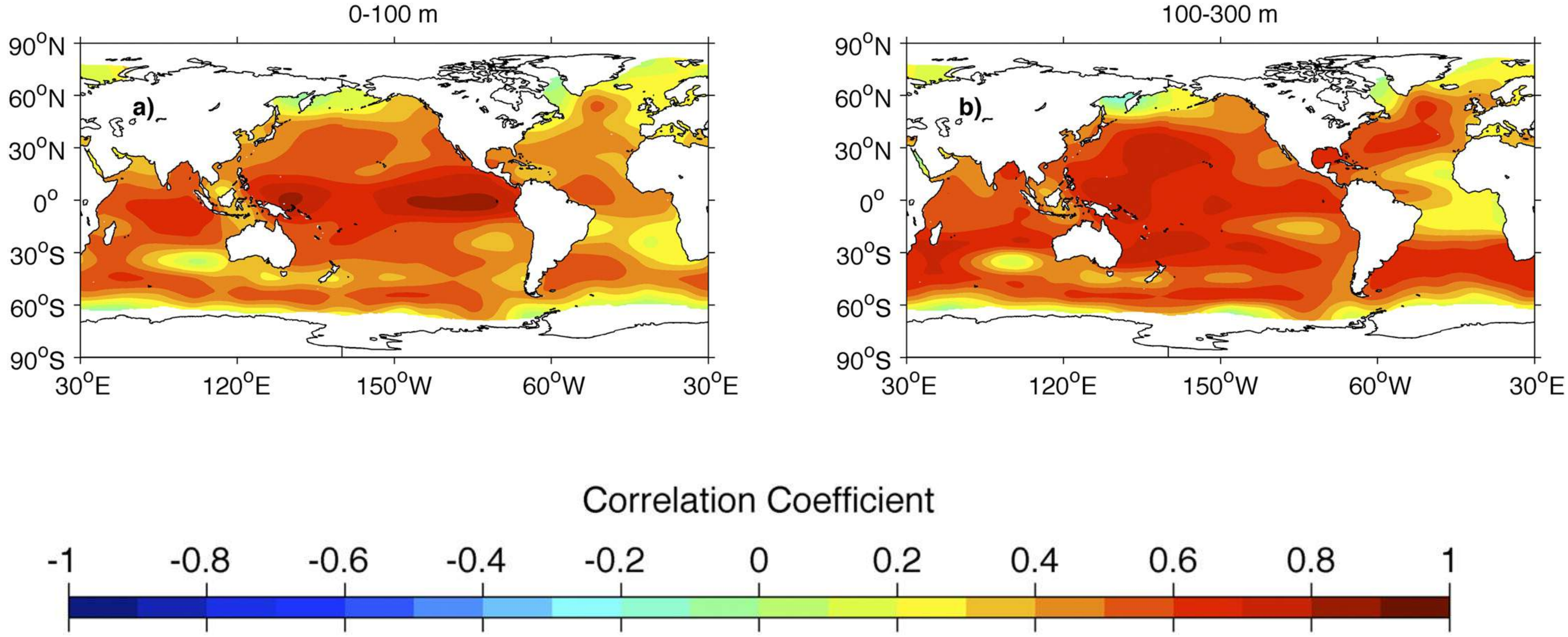




Using sea level can be used as a proxy for heat content. 1993-1999

(Lyman and Johnson, 2014, 1993-2011)

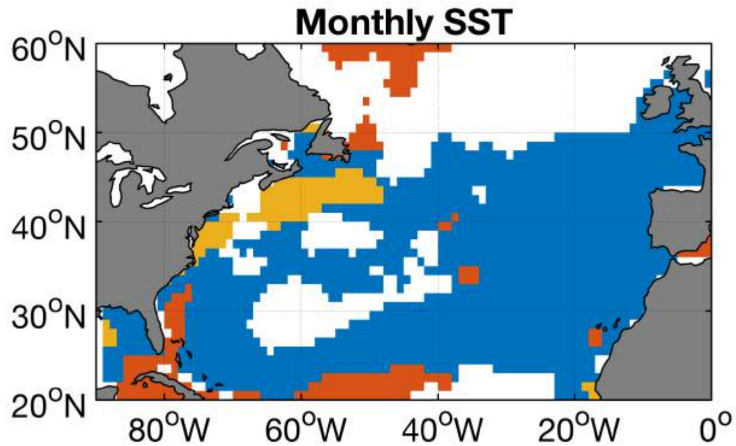
Monthly local sea level determined by thermosteric (thermal expansion), and halosteric (haline contraction). Thermosteric dominates in tropics and subtropics

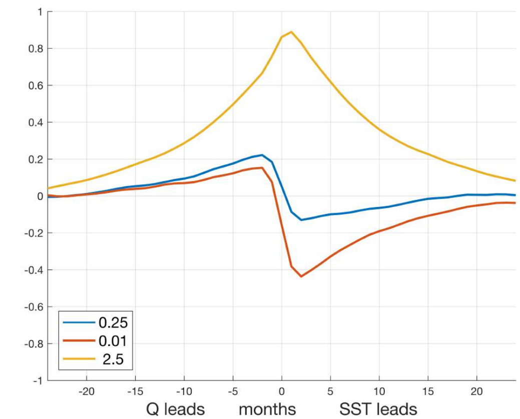


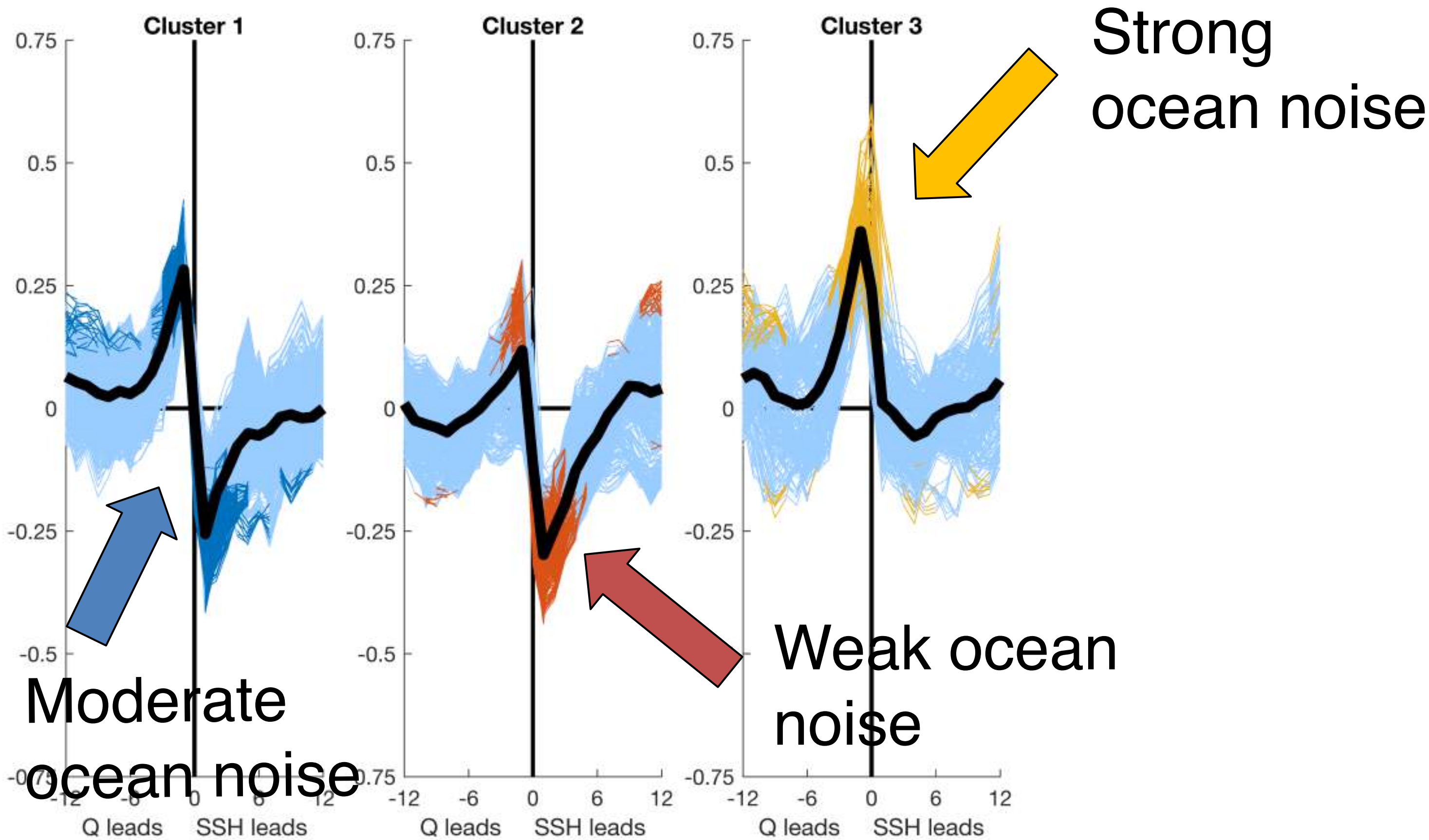
Using observations to look at the relationship between the heat content/SST and surface flux 1993-2016

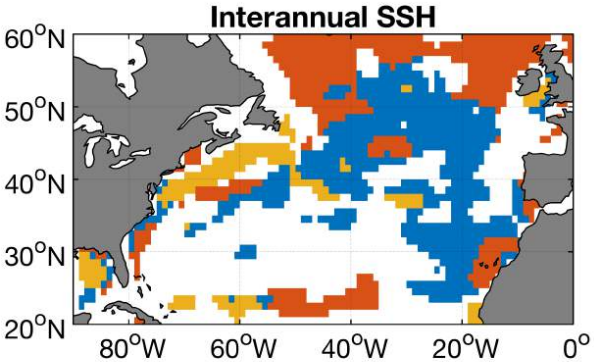
Smooth both with 300 km full width at half max Gaussian smoother

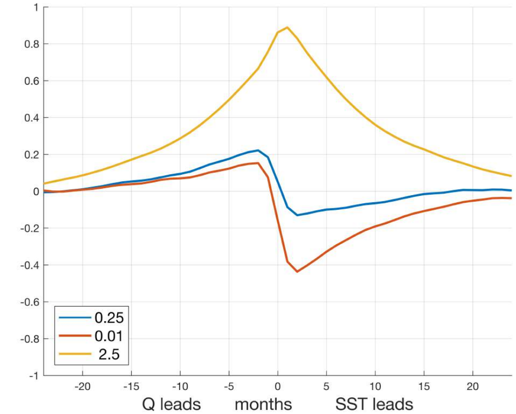
Observational Analysis variables	Source	Comment
Sea surface height (SSH)	Monthly maps of sea level anomaly from Ssalto/Duacs 1/4° x 1/4°, Mercator grid, Aviso	Used as proxy for upper ocean heat content
SST, Turbulent heat flux Q_{turb} Sensible +latent heat flux	OAflux: Objectively Analyzed air-sea fluxes for the Global Oceans (Yu and Weller, 2007)	Fluxes are positive for cooling the ocean.

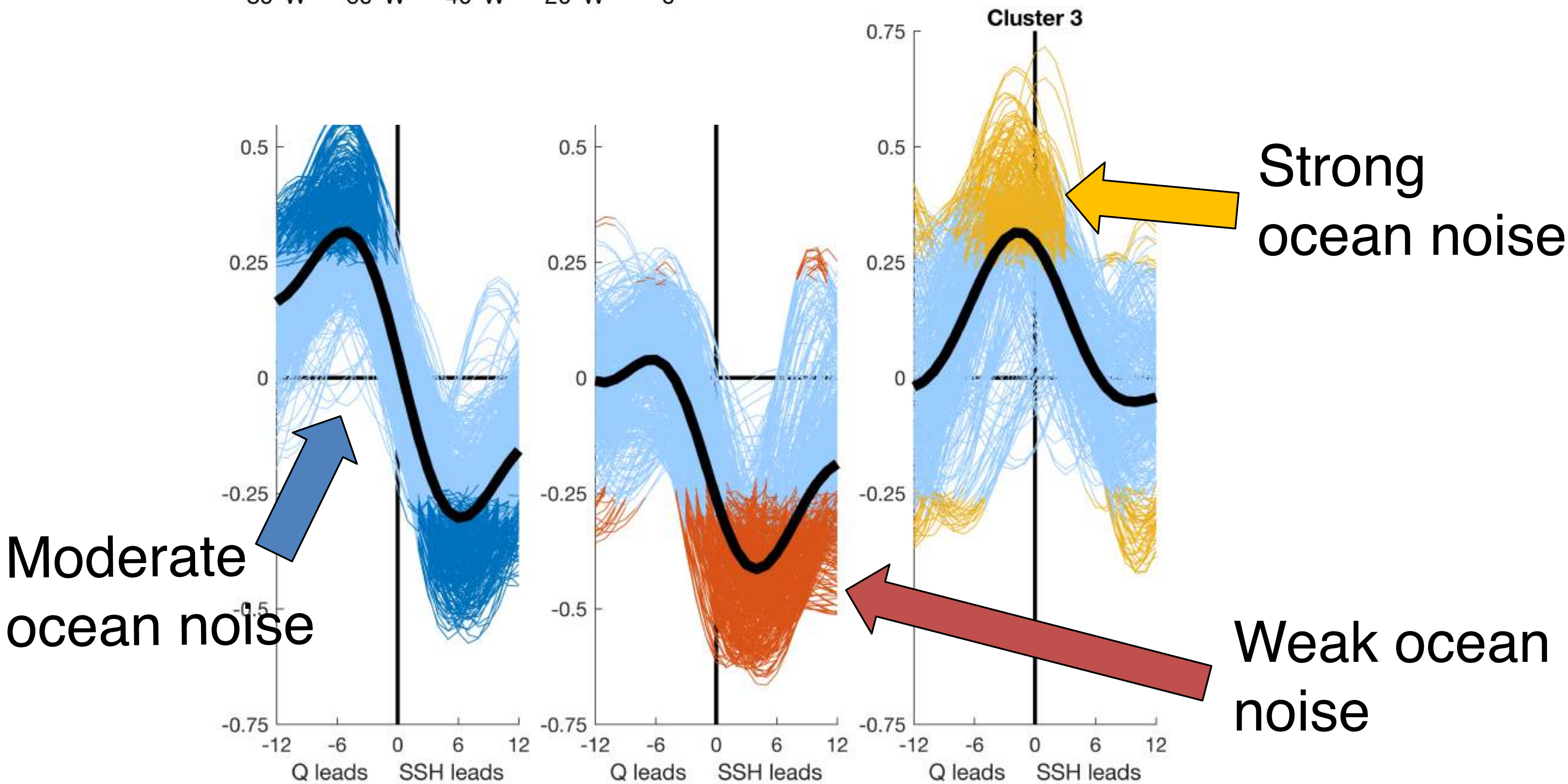

Monthly SST
60°N
50°N
40°N
30°N
20°N
80°W
60°W
40°W
20°W
0°


0.25
0.01
2.5
Q leads
months
SST leads


Cluster 1
Cluster 2
Cluster 3
Q leads
SSH leads
Strong ocean noise
Moderate ocean noise
Weak ocean noise


Interannual SSH
60°N
50°N
40°N
30°N
20°N
80°W
60°W
40°W
20°W
0°


0.25
0.01
2.5
Q leads
months
SST leads


Cluster 3
Strong ocean noise
Moderate ocean noise
Weak ocean noise
Q leads
SSH leads
Q leads
SSH leads
Q leads
SSH leads

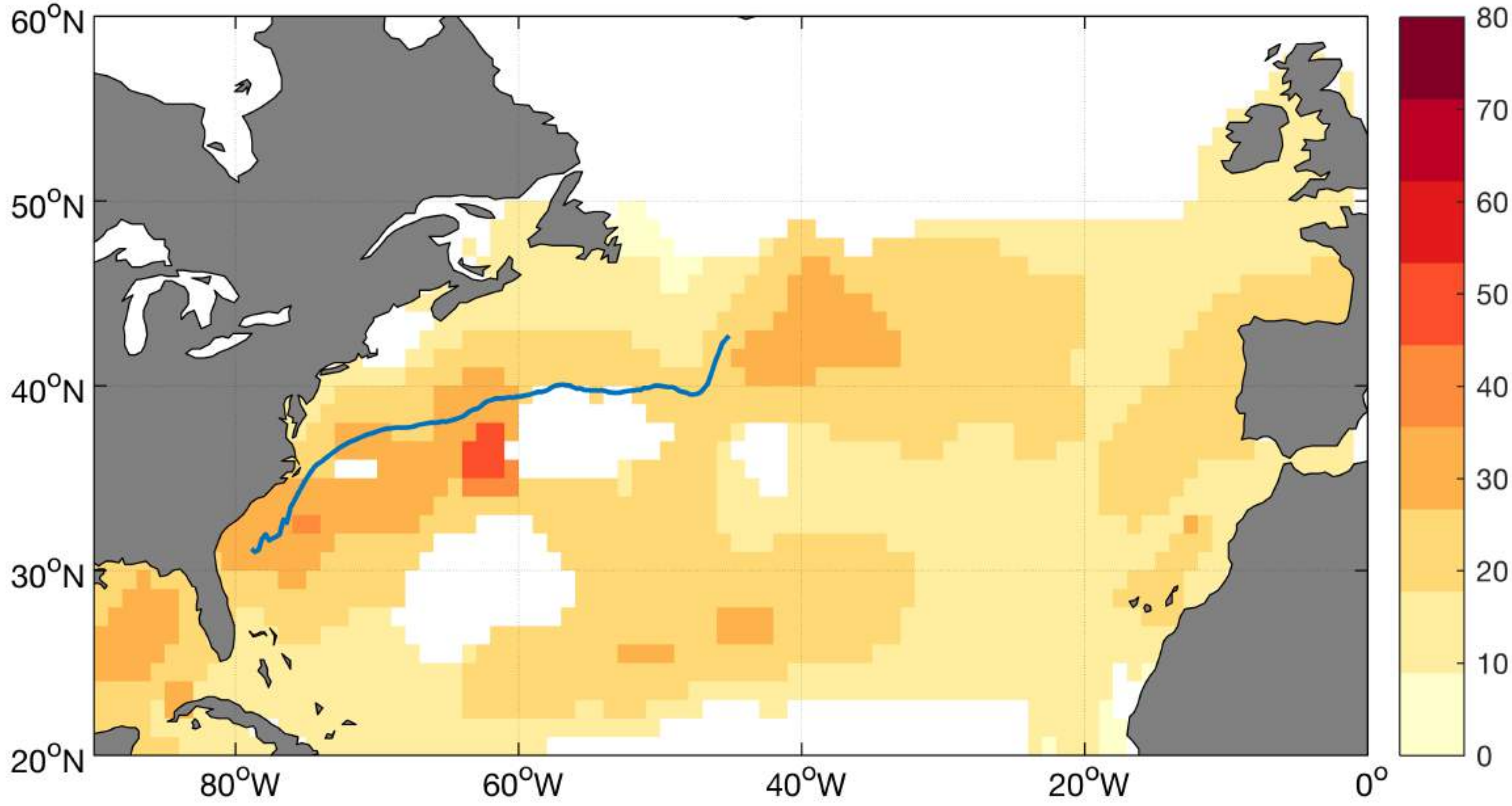
What does this mean for air-sea interaction? Define a feedback: how much Q_{turb} do you get for a 1°C SST anomaly? Frankignoul et al, 1998 (monthly fields).

Regression coefficient evaluated at maximum

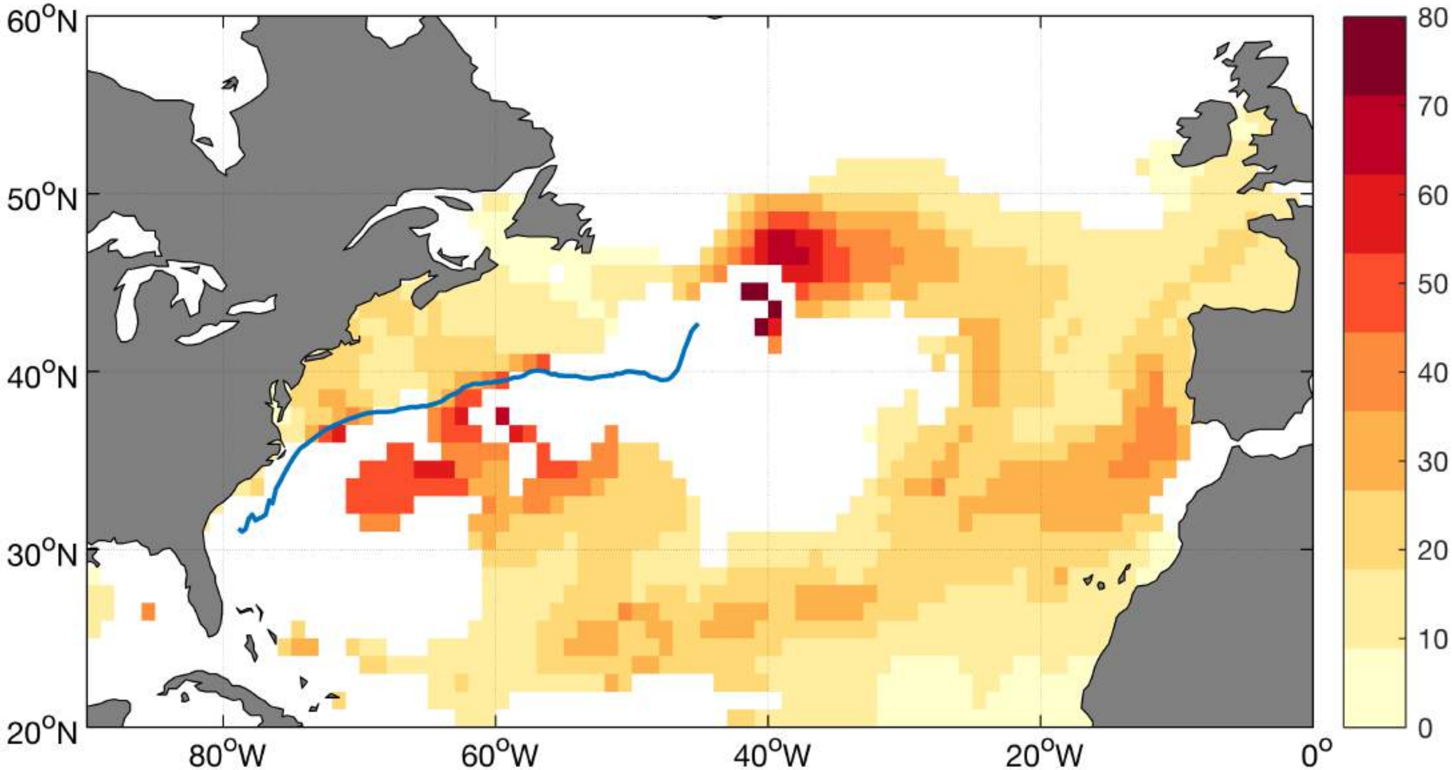
$$\lambda_{SST} = \frac{R_{TQ_{turb}}(\tau_{SST})}{R_{TT}(\tau_{SST})}$$

Autocorrelation coefficient

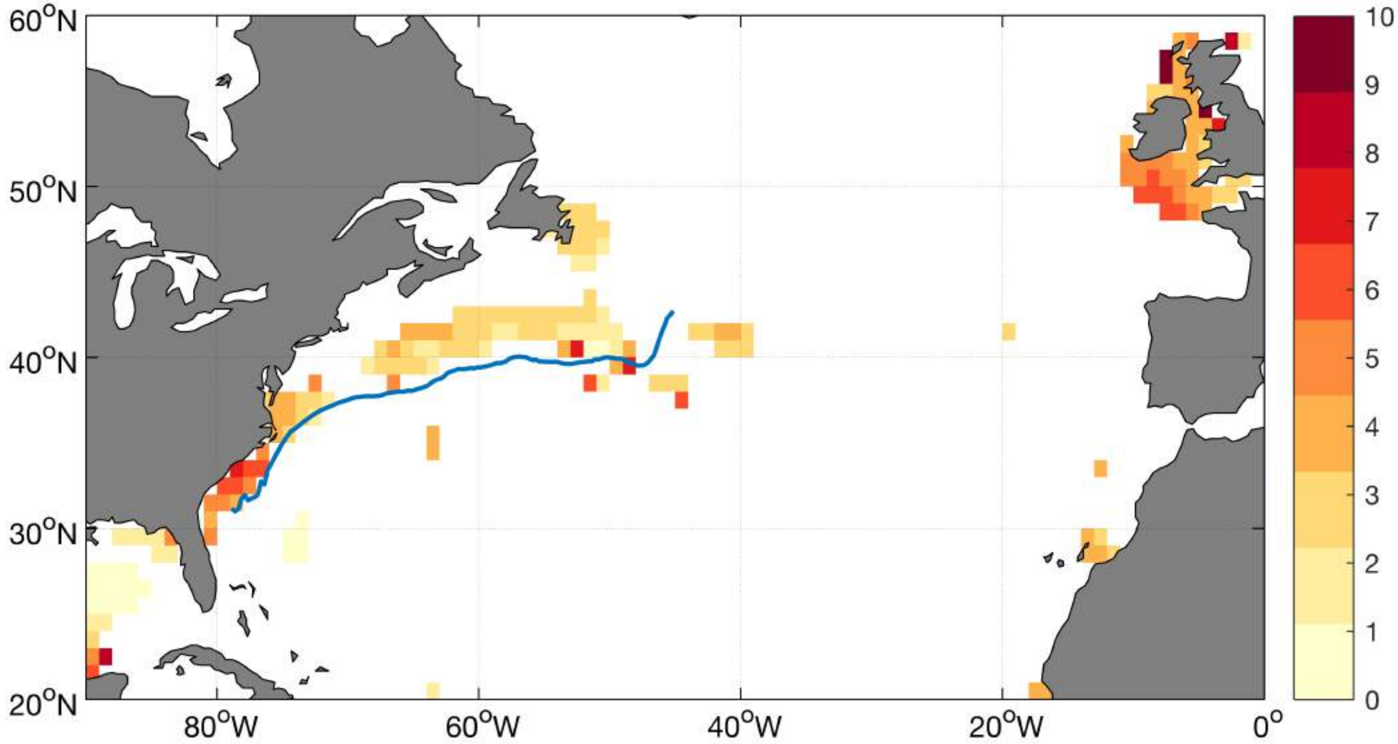
Monthly SST feedback
Watts/m²/°C



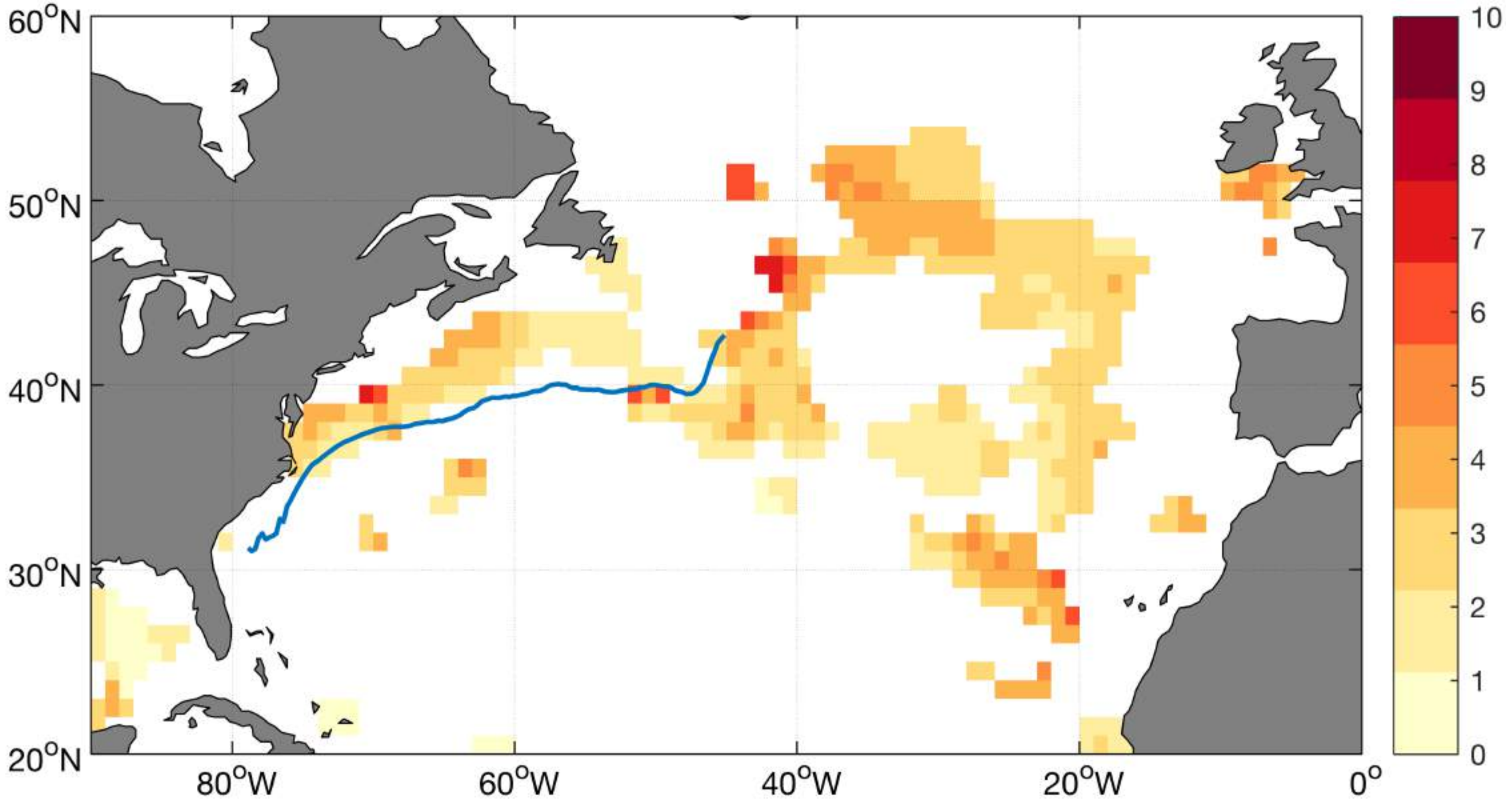
Low Frequency SST feedback
Watts/m²/°C

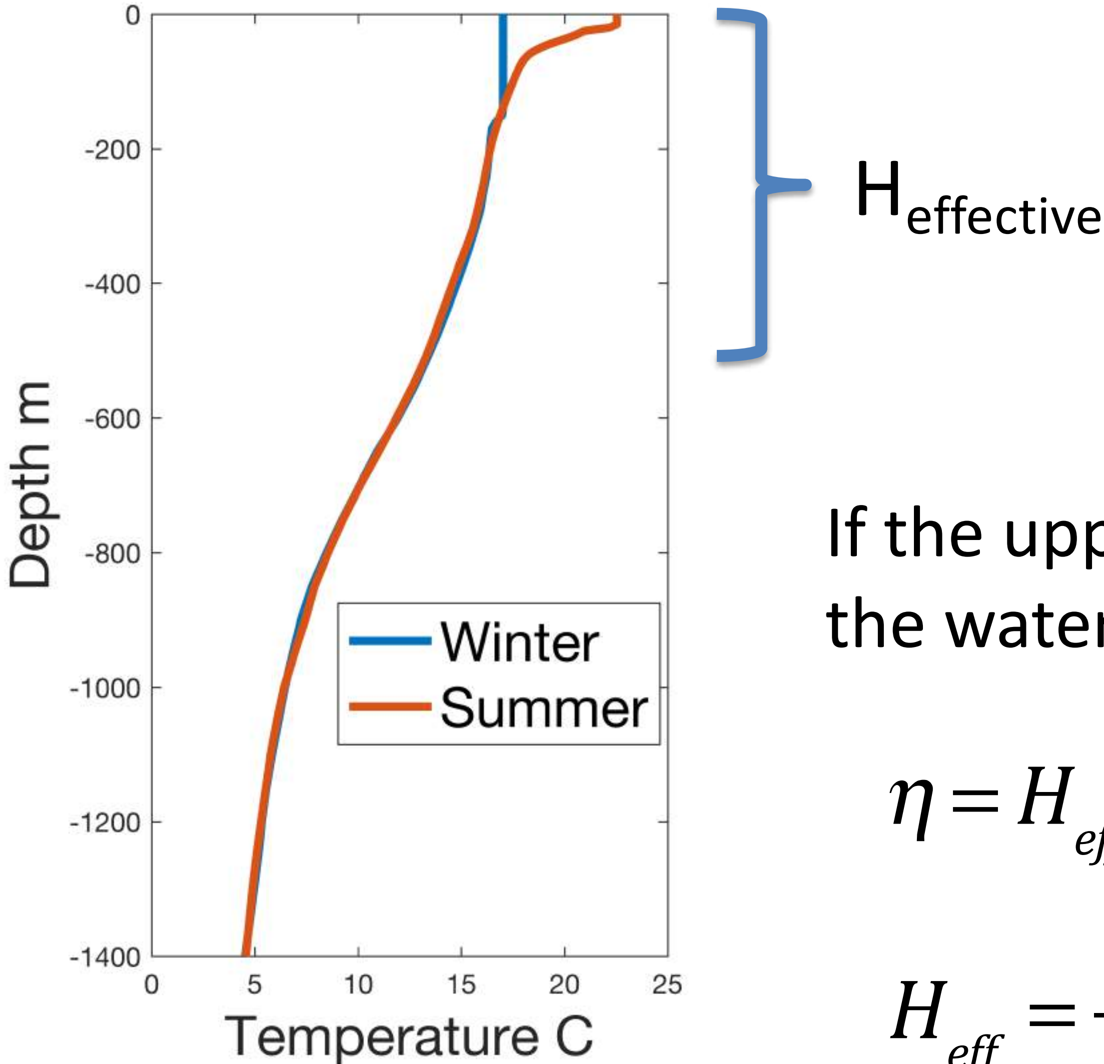


Monthly SSH feedback
Watts/m^2/cm



Interannual SSH feedback
Watts/m^2/cm



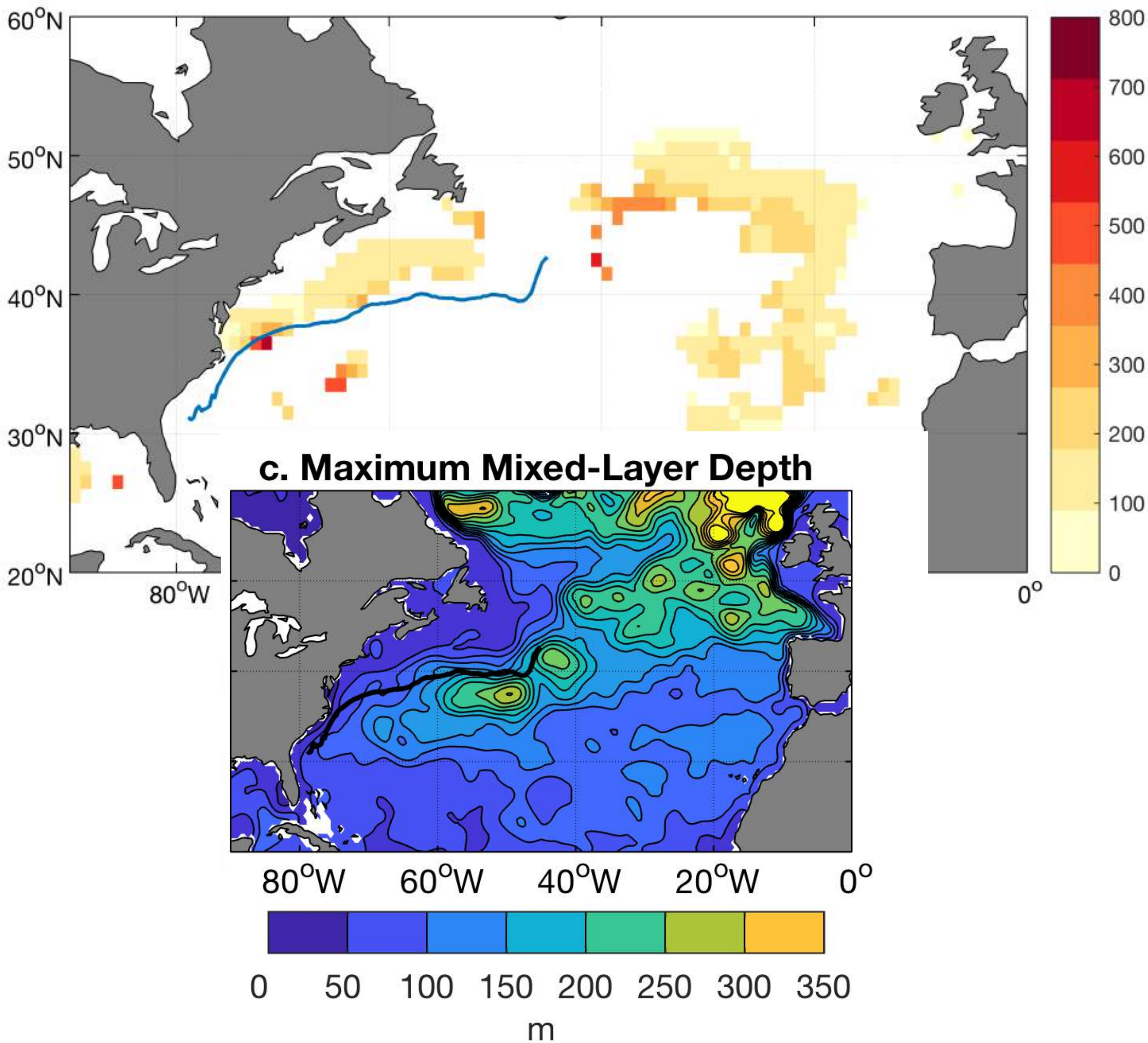


If the upper ocean warms, the water expands→

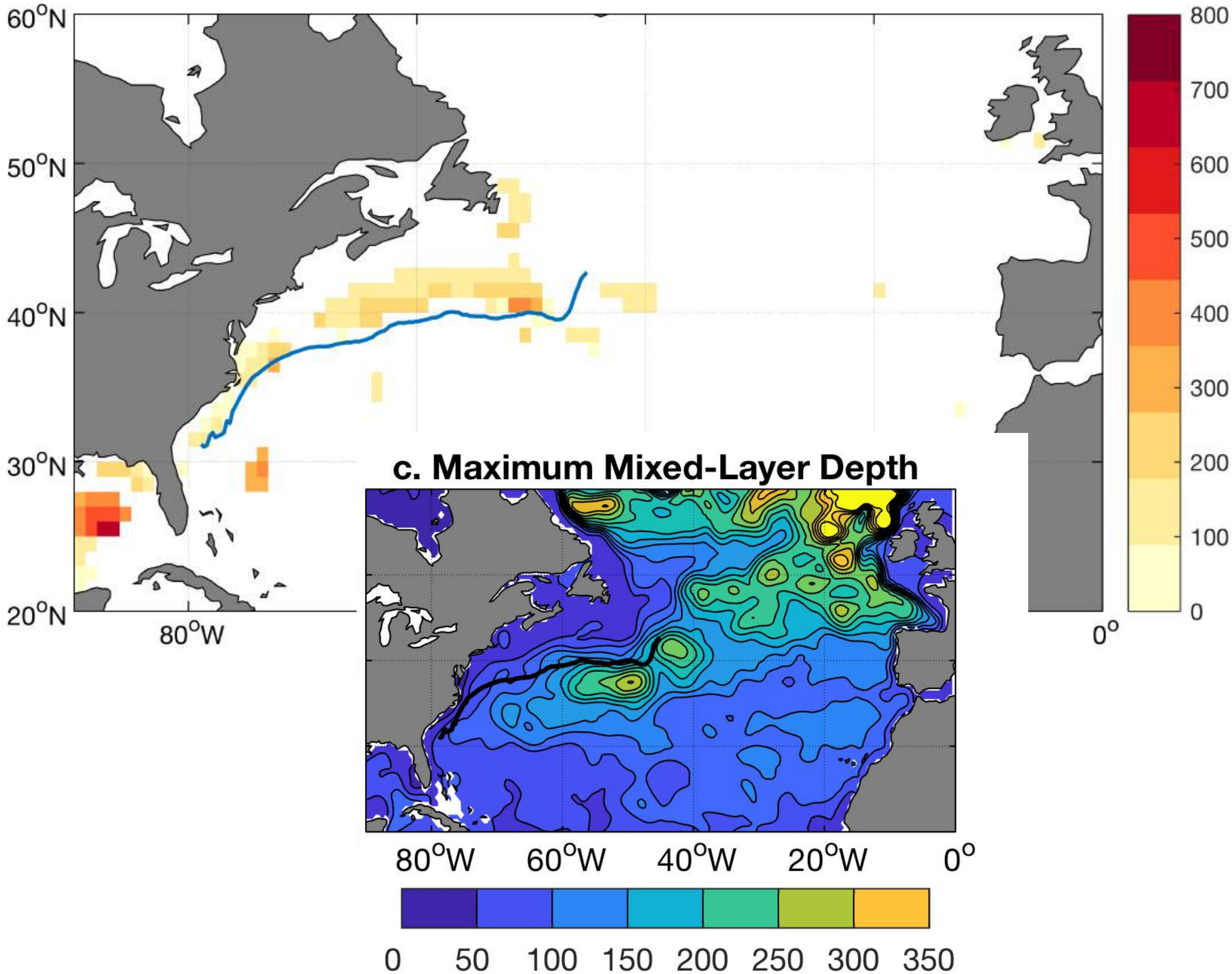
$$\eta = H_{eff} \alpha \Delta T$$

$$H_{eff} = \frac{\lambda_T}{\alpha \lambda_\eta}$$

H_{eff} is bigger than the mixed-layer depth in some places (monthly time scales)

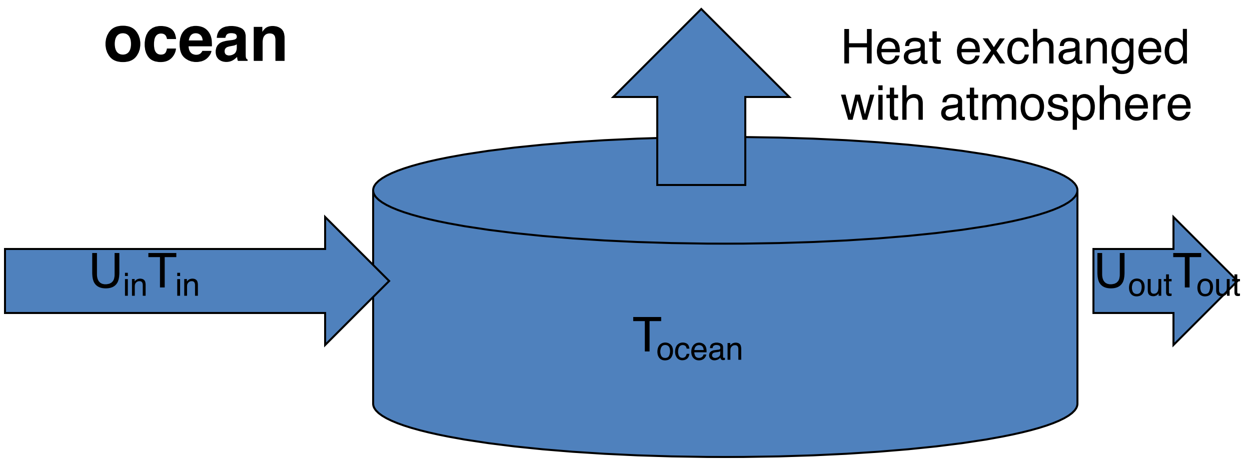


H_{eff} is bigger than the mixed-layer depth in some places (Interannual time scales)



Some of the heat that is release must be fed from the side→ $H_{eff}>H_{MLD}$

Heat storage rate in upper ocean = **Heat Transport Convergence** + **Surface heat flux**



Paradigms

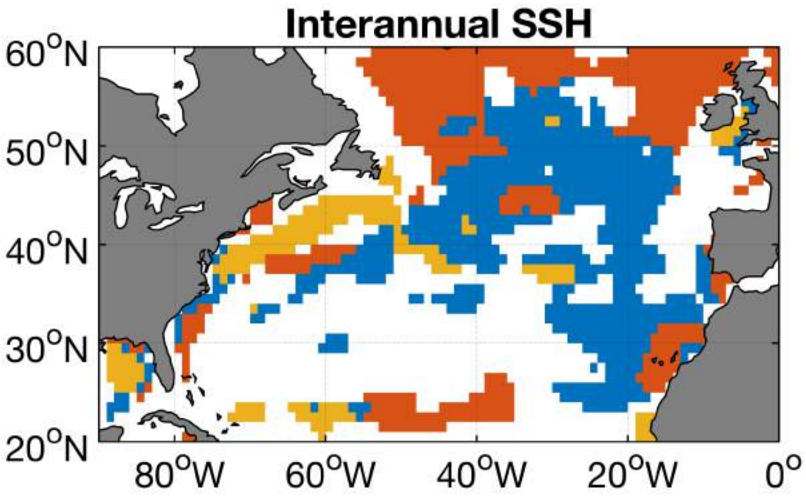
1. Net air-sea flux is driven by the mean ocean heat transport convergence

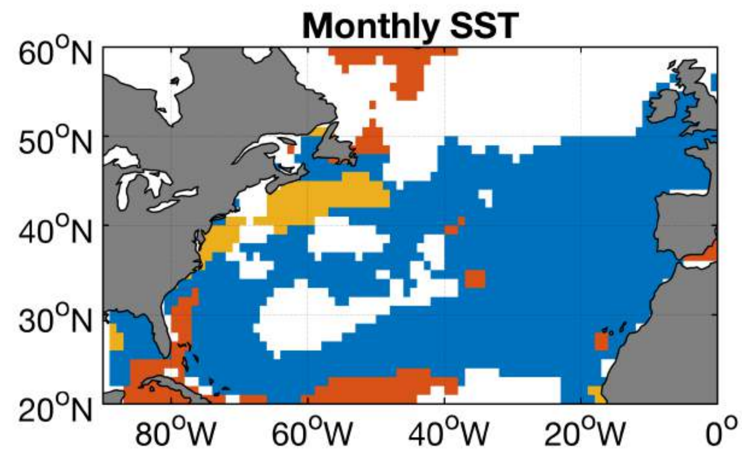
2. Anthropogenic climate change warms the ocean

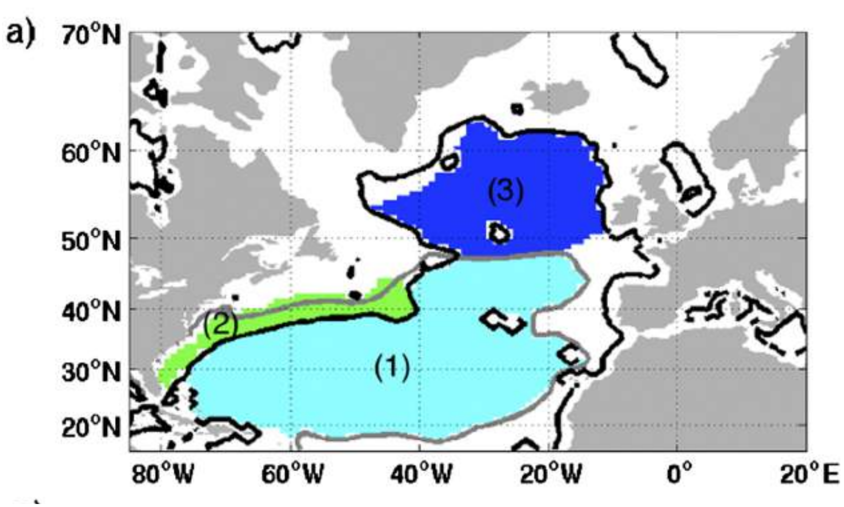
3. SST forced by atmospheric noise are then damped by surface fluxes

4. Changes in ocean heat transport convergence control air-sea heat exchanges

5. Atmospheric fluxes drive ocean changes with little short term feedback







#4 The Gulf Stream: ocean forces heat content anomalies that force Q

#3 Subtropical gyre, atmosphere controls Q, forces heat content/SST anomalies, that are fed back to the atmosphere

#5 Subpolar gyre, atmosphere forces, and no immediate feedback to atmosphere