Reconstructing Ocean Heat Storage & Transport

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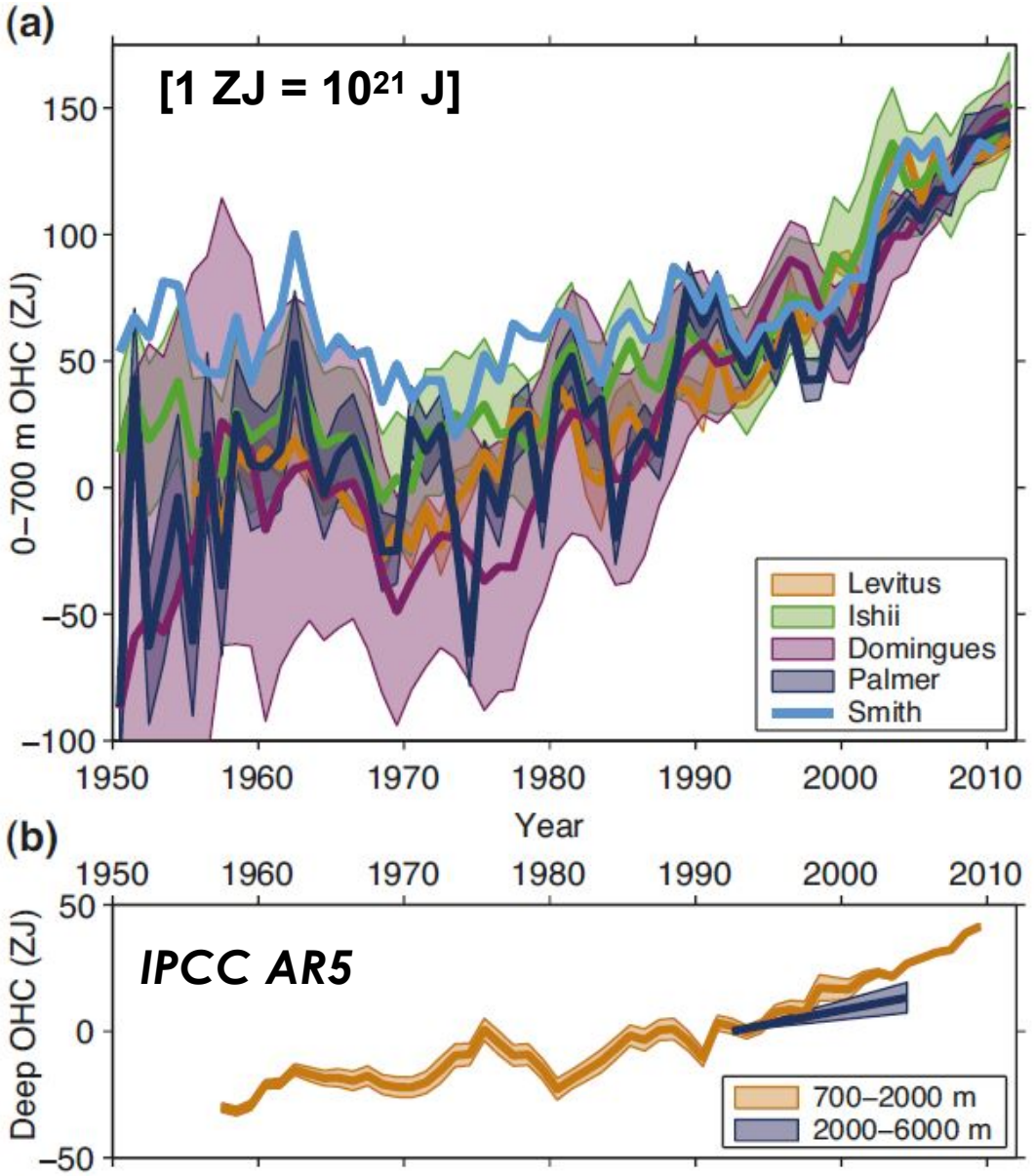
Zanna, Khatiwala, Gregory, Ison, Heimbach, Accepted in PNAS

Motivation: Ocean Heat Content (OHC) Estimate

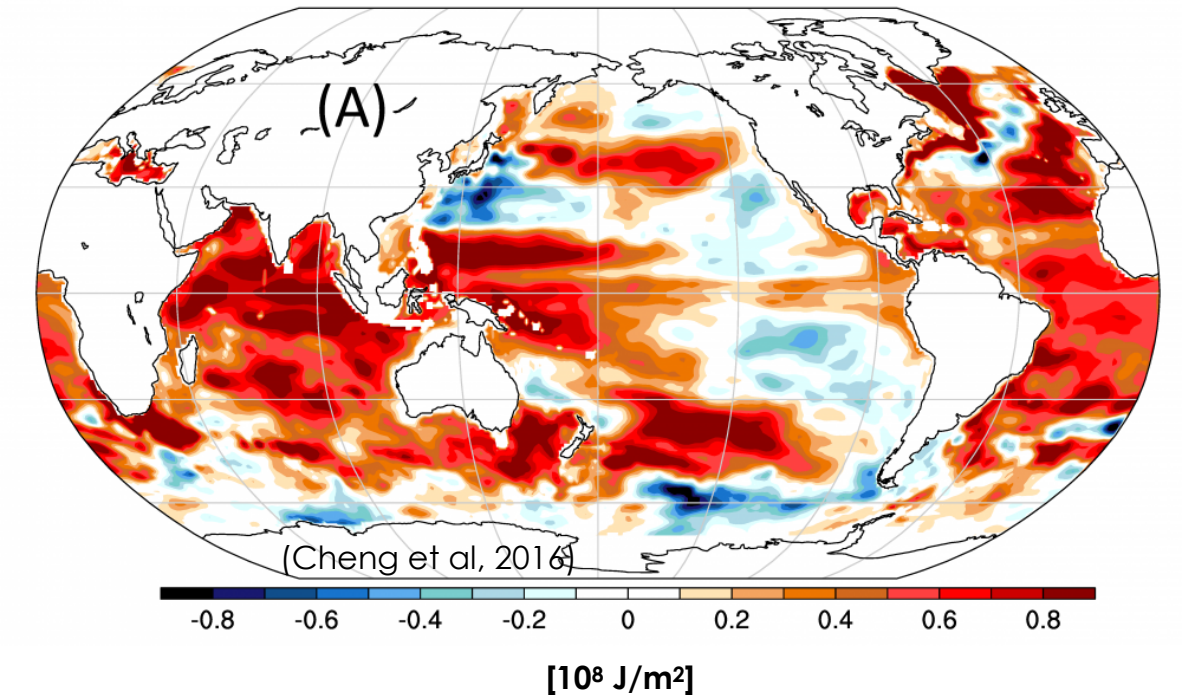
- More than 90% of energy imbalance is absorbed by the oceans
- Sparse data + Infilling of 3D temperature data
- Reduction of error from mapping *(e.g., Cheng et al., 2017)*
- No estimates prior to 1950s



Motivation

- Can we extend estimates of OHC back in time?
- Can we infer how ocean circulation may have influenced regional heat content patterns over the last few decades ?

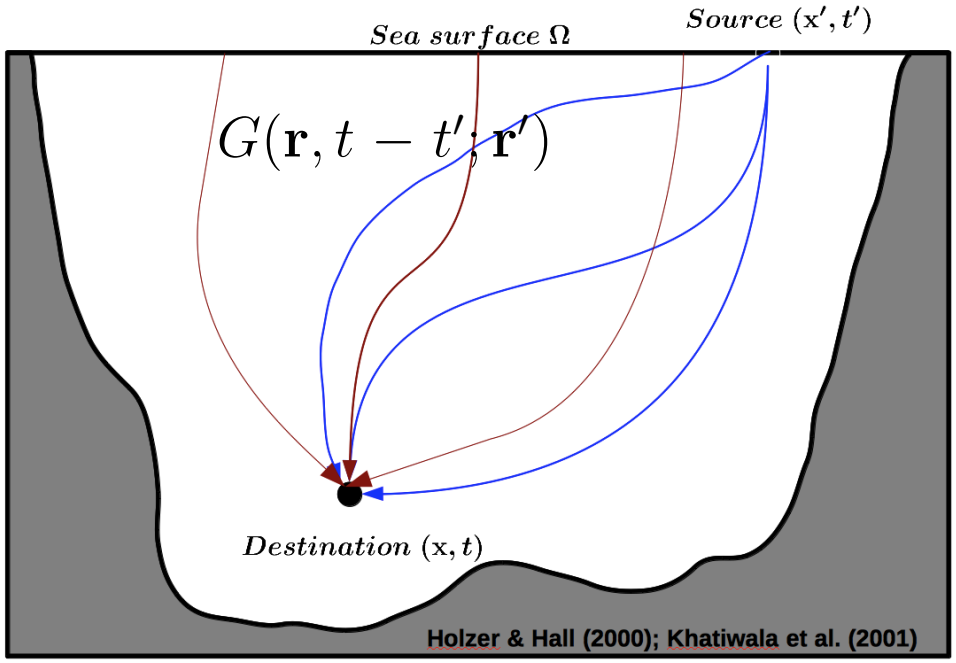
700m- Heat Content Trend 1993–2015



➡ **Heat content reconstruction based on sea surface temperatures from 1871 & time-mean ocean circulation (advection + mixing)**

A time-mean Model Ocean Pathways

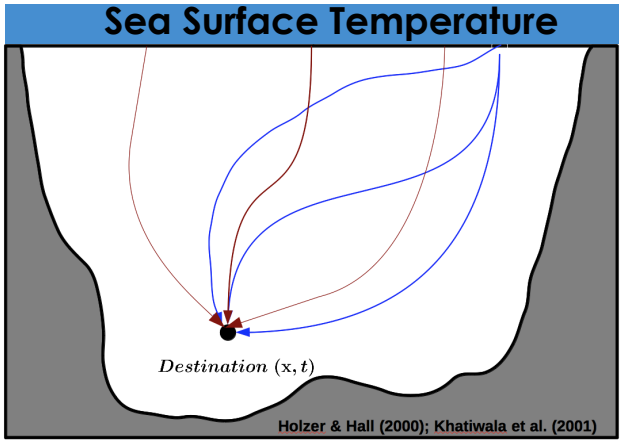
- Green's function/Boundary Propagator $G(\mathbf{r}, t - t'; \mathbf{r}')$
  - Any parcel in the interior 1) originated from the surface; 2) felt some influence of ocean advection and mixing
  - Derived from ECCO state estimates (1992-2008) using Transport Matrix Method *(Khatiwala, 2007)*
  - Estimated for 22 vertical layers, 10°-wide latitudinal bands



(for ocean/ atmosphere: Wunsch 1996, Hall & Plumb 1998, Waugh & Hall 2002)

Sea Surface Temperatures as Boundary Conditions

- SST
  - set at the sea surface by atmospheric forcing
  - then propagated into the ocean interior as a passive tracer by $G(\mathbf{r}, t - t'; \mathbf{r}')$



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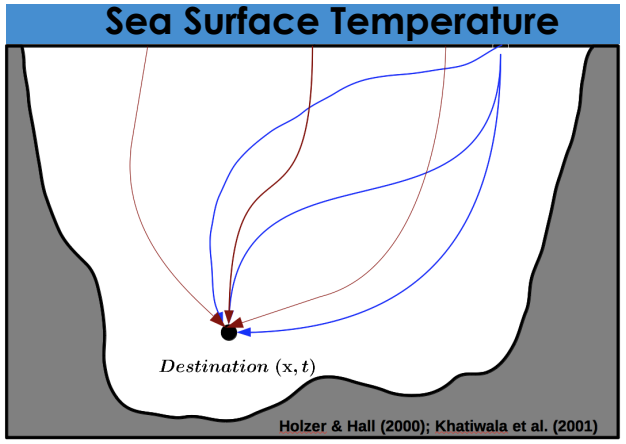

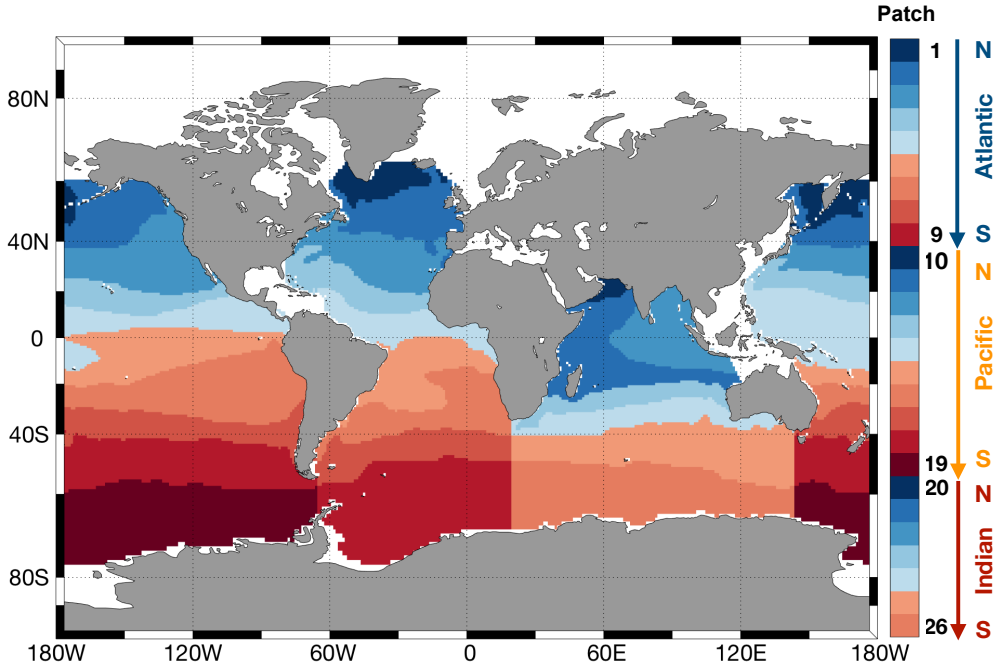

- Time series of observed SST anomalies in different areas HadISST
- Areas= patches defined by their climatological density in each basin *(Khatiwala et al, 2009)*

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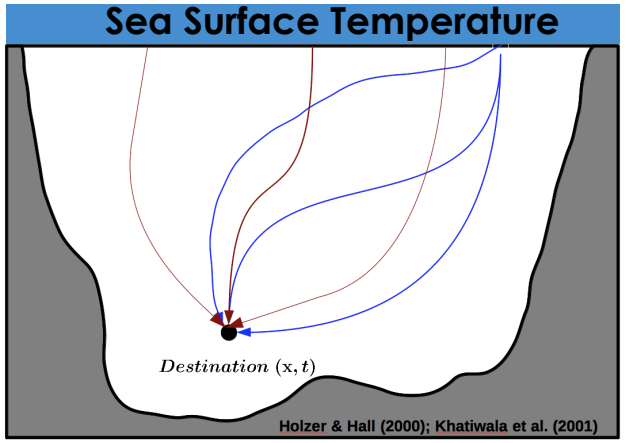

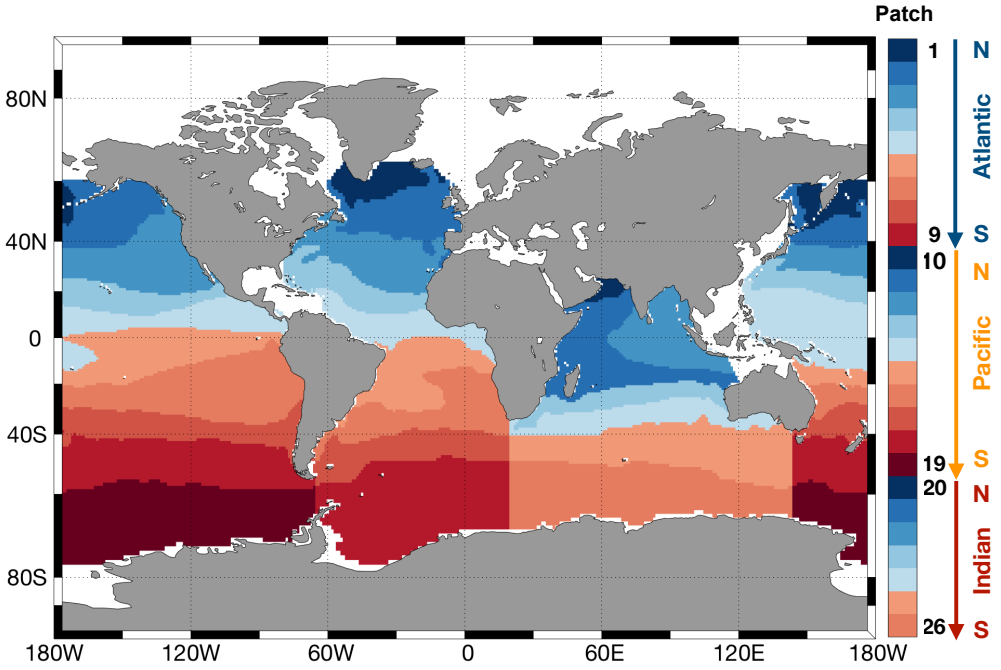

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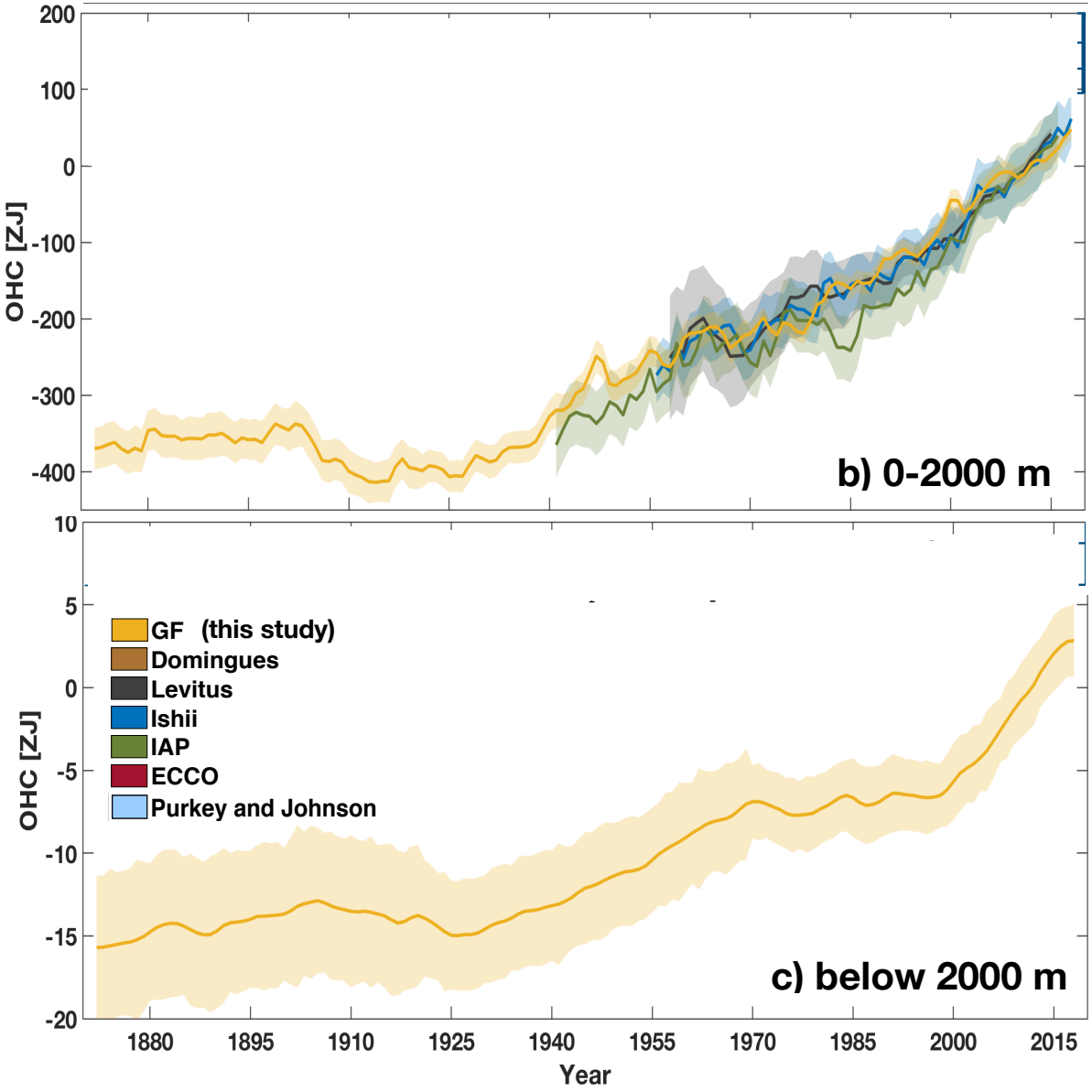
$$T(\mathbf{r}, t) = \int d\mathbf{r}' \int_{1871}^{t} dt'\, G(\mathbf{r}, t - t'; \mathbf{r}')\, T^S(\mathbf{r}', t')$$

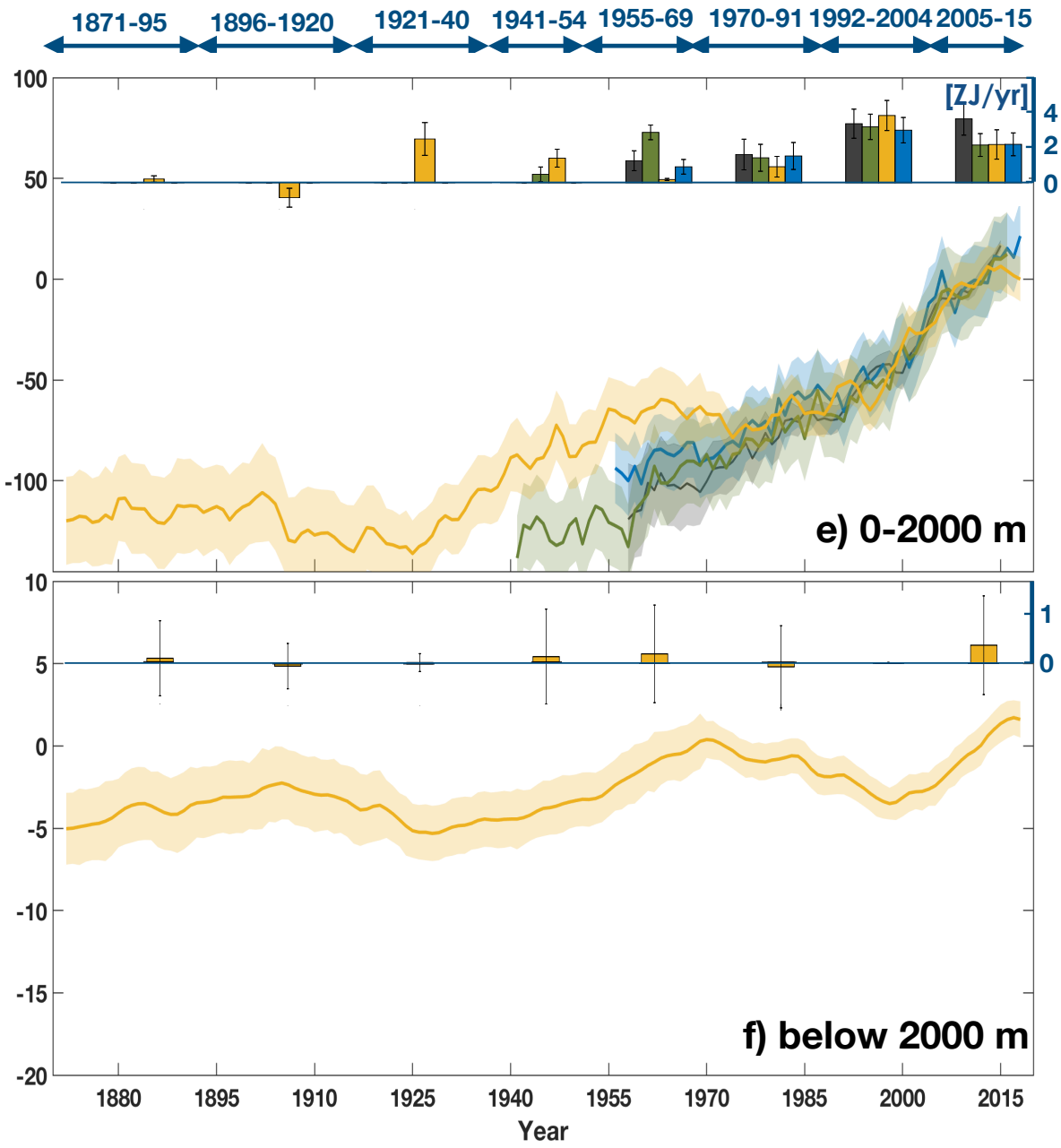
Passive OHC Global reconstruction

- Consistent estimates over 1955-2017 *(large spread amongst estimates)*
- Redistribution by ocean circulation changes integrates to ~ zero
- Global warming of the ocean from 1871 to 2017 of **436 x 10^{21} Joules**
- Heat storage during 1920-1945 is roughly the same as over 1990-2015



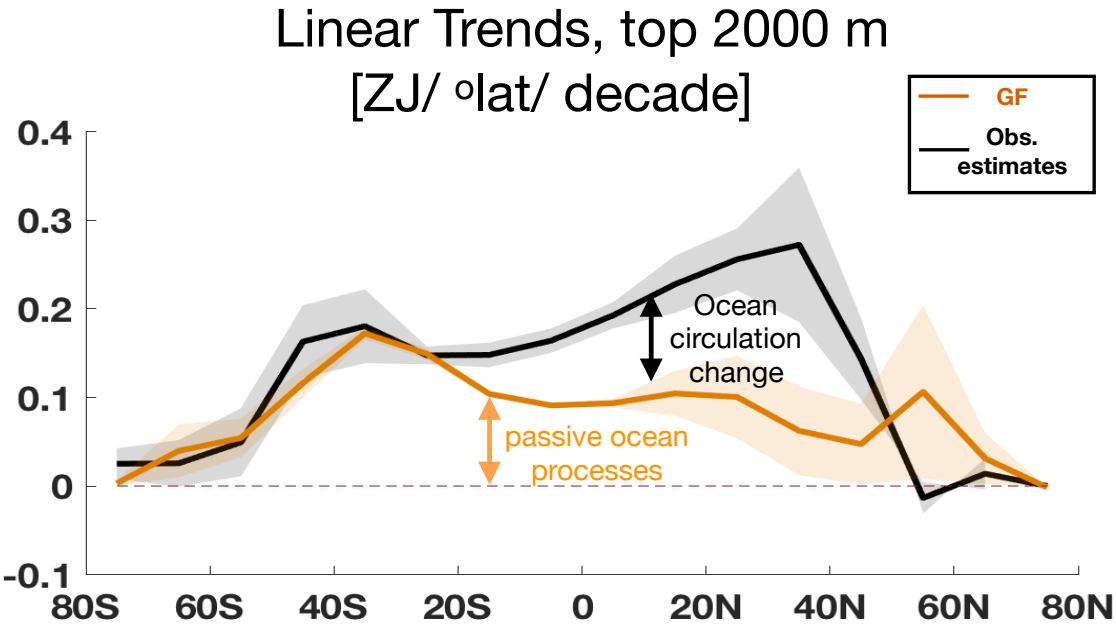
Passive OHC Atlantic Reconstruction

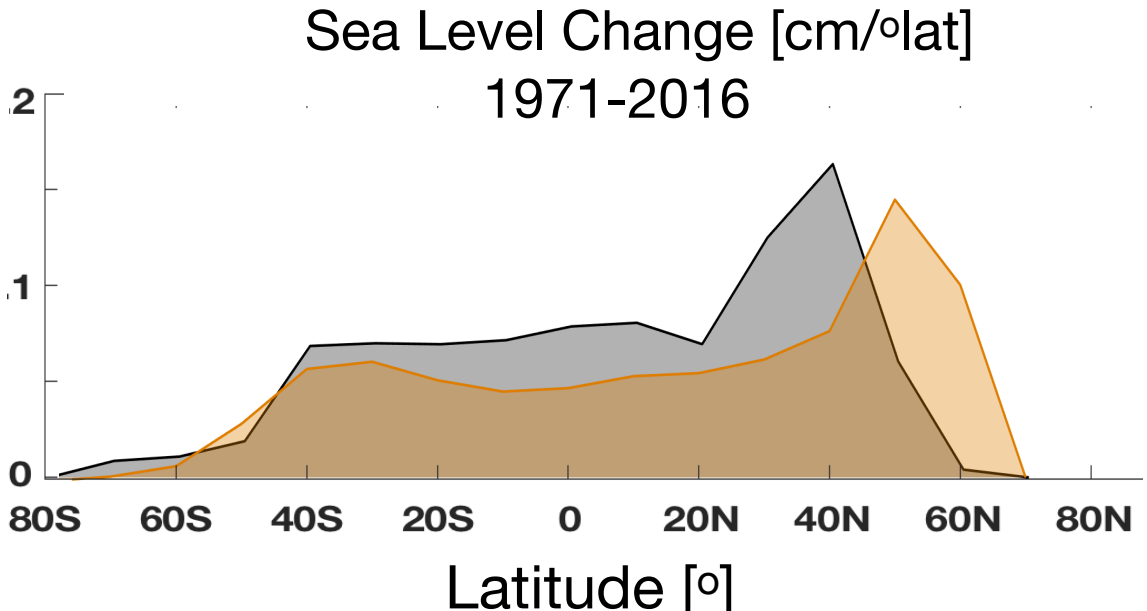
- Larger discrepancies between reconstruction and direct measurements
- Substantial decadal fluctuations in the upper & deep ocean



Atlantic Latitudinal Distribution

- Up to 1/2 (**~ 0.1 ZJ/lat/ decade**) of low- to mid-latitude warming + sea level rise associated with **changes in ocean circulation**





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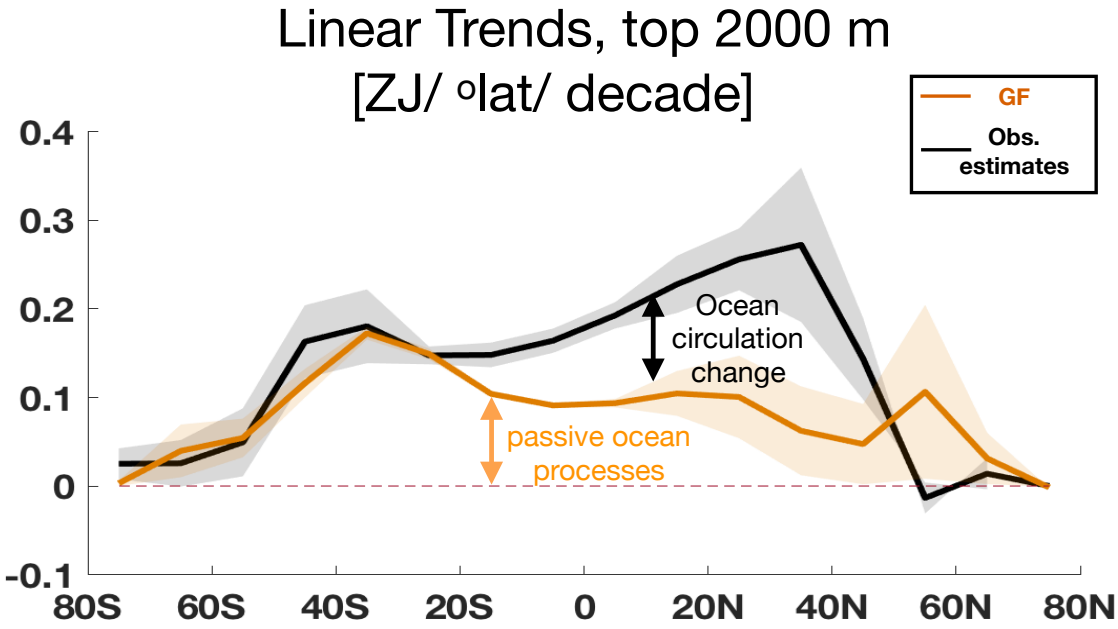

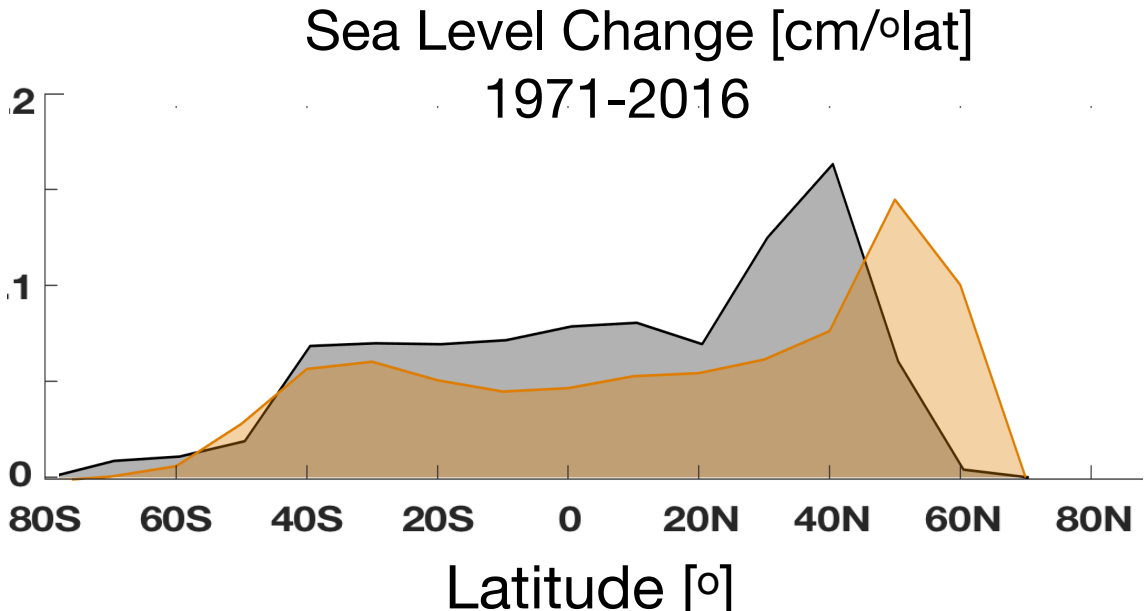

- OHC change btw 1971-2016 is consistent with weakening of meridional heat transport
- Wind, buoyancy mixing-driven ?
- Natural and/or forced ?

Summary

- Reconstruction back to 1871 of (passive) ocean heat storage, consistent with direct measurements over 1955-2017, but with large uncertainties
- Why does it work? good time-mean model of ocean processes, heat transport associated with ocean circulation changes integrates to zero globally, SST is a good indicator of changes in air-sea exchanges
- Regionally, detection of decadal changes in redistribution leading to ~ 0.1 ZJ/yr/decade of heat convergence in the mid-latitude Atlantic