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 $G(r, t - t’; r’)$
  - Any parcel in the interior 1) originated from the surface; 2) felt some influence of ocean advection and mixing
  - Estimated for 22 vertical layers, 10°-wide latitudinal bands

![Diagram of Green's function](image)

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 $G(r, t - t'; r')$

Historical Estimate of Passive Atlantic Heat Content

We estimate the first spatio-temporal estimates of the passive component of ocean heat content in the Atlantic basin. By assuming that temperature behaves as a passive tracer, absorbed at the sea surface and carried into the ocean interior via the circulation and mixing, we can rely on methods developed by [LZ:refs] for conservative tracers obeying an advection-diffusion equation with sources and sinks at its surface. The passive temperature anomaly $T$ in the ocean interior at any location $r$ and time $t$ can be expressed as

$$T(r, t) = \int_0^d \int_0^t G(r, t; r_0) T_S(r_0, t_0) \, dt_0$$

where $T_S$ is the sea surface temperature (SST) anomaly relative to 1871, taken from HadISST [refs].

The operator $G(r, t; r_0)$ is defined as the Greens function (GF) which propagates any SST anomaly $T_S$ at a location $r_0$ and time $t_0$ to the interior at location $r$ and time $t$. The GFs reflect the ocean circulation and mixing and can in principle be used to propagate any tracer from the surface boundary condition into the interior, assuming that the tracer is passive and does not affect the circulation. We calculate the GFs, over 10 latitude bands and depth ranging from the ECCO state estimate [refs] using the Transport Matrix Method [refs].

Using Eq. 1, we reconstruct the change in passive ocean heat content from 1871 to 2016 (Fig. a), relative to 1971. The upper 700m of the ocean dominate the passive heat content reservoir (about 88% over the last decade), with a growing storage between 700m-2000m over the past 20 years.
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 \( G(r, t - t'; r') \)

- Time series of observed SST anomalies in different areas
  - HadISST
- Areas= patches defined by their climatological density in each basin (Khatiwala et al, 2009)
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 \( G(\mathbf{r}, t - t'; \mathbf{r}') \)

- Time series of observed SST anomalies in different areas
- HadISST

- Areas= patches defined by their climatological density in each basin (Khatiwala et al, 2009)

\[
T(\mathbf{r}, t) = \int d\mathbf{r}' \int_{1871}^{t} dt' \, G(\mathbf{r}, t - t'; \mathbf{r}') \, T^S(\mathbf{r}', t')
\]
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 $436 \times 10^{21}$ 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

Linear Trends, top 2000 m [ZJ/°lat/decade]

Sea Level Change [cm/°lat]
1971-2016
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

- 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

Global ocean heat content 0-2000 m [10^{21} J] (Zanna et al, PNAS)