Low-frequency SST and Upper-Ocean Heat Content Variability in the North Atlantic

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Observed Atlantic SST anomalies

- **Observations indicate Atlantic SSTs exhibit significant low-frequency variability** (Bjerknes 1964; Kushnir 1994; Ting et al. 2009).

- **The origin of Atlantic SST anomalies depends on timescale**
  - Intraannual to interannual: response to local atmospheric forcing (Frankignoul and Hasselmann, 1977),
    - e.g. the North Atlantic Oscillation (NAO) tripole (Cayan, 1992).
  - Longer timescales (how long?) ocean circulation may play a role.
    - e.g. basin-scale SST anomalies in the North Atlantic, termed Atlantic Multidecadal Variability (Kerr, 2000; Knight et al., 2005).
    - thought to be related to variations in the Atlantic Meridional Overturning Circulation (AMOC; e.g. Kushnir, 1994; Delworth and Mann, 2000) and/or gyre circulations (Hakkinen and Rhines, 2004; Hakkinen et al, 2011).

- **Relative importance of atmospheric forcing and ocean dynamics in SST variability has implications for predictability.**
  - Dominance of local atmospheric forcing -> little predictability.
  - Dominance of slow ocean processes -> high potential for predictability.
Approach

What are relative roles of local atmospheric forcing and ocean dynamics in upper-ocean heat content (UOHC) variability in the North Atlantic?


- MITgcm least squares fit to observations using adjoint (Forget et al., 2015 a,b)
- fit achieved by adjusting initial conditions, forcing, and model parameters
- satisfies equations of motion & preserves property budgets (Wunsch & Heimbach, 2013)
- Atmospheric forcing: ERA-Interim
- Ocean data:
  - In-situ: Argo, CTDs, XBTs, mooring arrays
  - AVHRR & AMSR-E SST and satellite altimetry
- Model details (Forget et al., 2015b)
  - New global grid (LLC90), includes Arctic, 50 vertical levels, partial cells
  - Nominal 1° resolution with telescopic resolution to 1/3° near Equator
  - State of the art dynamic/thermodynamics sea ice model
Low-frequency Atlantic SST variability

Analysis of monthly data, seasonal cycle removed by simply subtracting out the mean monthly climatology.

- Atlantic SST variability in ECCO similar to Reynolds (2002) gridded SST.
- Pattern resembles classic “NAO tripole”
- Spectra are red at high frequencies: slope=-1.6
- Spectra flatten out at timescales of 2—5 years

Buckley et al, 2014, J. Climate
Upper ocean heat content variability

Heat Content integrated over maximum climatological mixed layer depth, D:

\[ H = \rho_o C_p \int_{-D}^{\eta} T \, dz \]

- Measure of heat contained in “active” ocean layers.
- Relevant for explaining SST anomalies.
- Avoids strong contributions from vertical diffusion and eliminates entrainment (Deser et al., 2003; Coetlogon and Frankignoul, 2003).

Mixed layer depths in ECCO v4 compare favorable to those in Argo.

Forget et al., 2015, *Ocean Sci. Discuss.*

Buckley et al., 2014, *J. Climate*
Upper ocean heat content variability

Heat Content integrated over maximum climatological mixed layer depth, D:

\[ H = \rho_o C_p \int_{-D}^{\eta} T \, dz \]

- EOFs of H resemble those of SST, but more variability where deep MLD
- PC time series
  - have more low frequency variability
  - Have less high frequency variability
  - Spectra of PC time series are steeper
- Associated with significant SST variability that resembles first EOFs of SST.

Buckley et al., 2014, *J. Climate*
Upper ocean heat content budget

\[
\rho_o C_p \int_{-D}^{\eta} \frac{\partial T}{\partial t} \, dz = -\rho_o C_p \int_{-D}^{\eta} \nabla \cdot (u T + u^* T) \, dz - \rho_o C_p \int_{-D}^{\eta} \nabla \cdot K \, dz + Q_{net}
\]

- Advection is important in creating \( H_t \) variability along the Gulf Stream Path and in regions in the subpolar gyre
- Diffusive transports only important in boundary regions of subpolar gyre
Origin of advective heat transport convergence

\[
C_{adv} = -\rho_o C_p \left( \int_{-D}^{\eta} \nabla \cdot \left( \bar{u}T + \bar{u}^*T \right) \, dz \right) = -\rho_o C_p \left( \int_{-D}^{\eta} \nabla \cdot \left( \bar{u}T \right) \, dz \right) - \rho_o C_p \left( \int_{-D}^{\eta} \nabla \cdot \left( \bar{u}^*T + \bar{u}^*T \right) \, dz \right),
\]

\[\text{linear: } C_{lin} \quad \text{bolus: } C_{bol}\]

Overbars denote monthly means, primes are deviations from monthly means

\[
F = 1 - \frac{\text{var}(C_{adv} - C_{lin})}{\text{var}(C_{adv})}
\]

What portion \(C_{adv}\) is explained by \(C_{lin}\)?
Ekman + geostrophic convergences

Separate (linear) advective heat transport into Ekman and geostrophic parts. Henceforth drop overbars to indicate monthly means

\[ C_{ek}(\mathbf{u}_{ek}, w_{ek}, T) = -\rho_0 C_p \int_{-D_{ek}}^{\eta} \nabla \cdot (\mathbf{u}_{ek} T) \, dz + \rho_0 C_p \, w_{ek}(-D) \, T(-D), \]

\[ C_g(\mathbf{u}_g, w_g, T) = -\rho_0 C_p \int_{-D}^{\eta} \nabla \cdot (\mathbf{u}_g T) \, dz + \rho_0 C_p \, w_g(-D) \, T(-D), \]

- \( \mathbf{u}_{ek}, \mathbf{u}_g \) are horizontal Ekman and geostrophic velocities
- \( w_{ek}, w_g \) calculated from \( \mathbf{u}_{ek}, \mathbf{u}_g \) using the continuity equation

\[ F = 1 - \frac{\text{var}(C_{lin} - C_{ek} - C_g)}{\text{var}(C_{lin})} \]

\[ \Rightarrow C_{ek} + C_g \approx C_{lin} \]
Contributions of Ekman and geostrophic parts

- Both $C_{ek}$ and $C_{g}$ largest in regions of strong currents/fronts. In these regions $C_{g} > C_{ek}$.
- $C_{ek} > C_{g}$ over portions of the ocean’s interior, including the region south of the Gulf Stream and the eastern basin.
Separate Ekman heat transport convergences into parts due to variability in the velocity field, temperature field, and their covariability.

- Overbars are averages over ENTIRE 19-year ECCO estimate
- Primes are deviations from these averages

\[
C_{ek}(u_{ek}, w_{ek}, T) = C_{ek}(\bar{u}_{ek}, \bar{w}_{ek}, \bar{T}) + C_{ek}(u'_{ek}, w'_{ek}, \bar{T}) + C_{ek}(\bar{u}_{ek}, w'_{ek}, T') + C_{ek}(u'_{ek}, \bar{w}_{ek}, T')
\]

Changes in Ekman mass transports due to local wind variability—reflects local atmospheric forcing

Changes in temperature field

Co-variability of Ekman transports and temperature

Buckley et al, 2015, J. Climate
Variance of $H_t$ explained by various terms

- Over much of the subtropical and subpolar gyres, $Q_{net} + C_{ek} + C_g$ explains most of the variance of $H_t$.
- $C_{ek} + Q_{net}$ explains more of the variance than $Q_{net}$ alone, particularly in gyre interiors.
- $C_g$ plays a role along the Gulf Stream path.
Role of local atmospheric forcing

- Response of the atmosphere to mid-latitude SST anomalies is modest compared to internal atmospheric variability (Kushnir et al., 2002; Schneider and Fan, 2012)
- Hypothesis: $C_{ek} + Q_{net} = C_{loc}^{*}$ is a measure of impact of local atmospheric forcing on H

![Fraction variance of $H_t$: $C_{loc}^{*}$](image)

$C_{loc}^{*}$ explains >70% of the variance of $H_t$ in the interior of the subtropical and subpolar gyres.

Analysis of budgets in various regions and timescales will aid in confirming/rejecting this hypothesis (see Buckley et al., 2014, 2015).
Conclusions

• We utilize a dynamically consistent ocean state estimate (ECCO) to quantify the upper-ocean heat budget in the North Atlantic on monthly to interannual timescales.

• We introduce 3 novel techniques:
  • Heat content is integrated over the maximum climatological mixed layer depth (integral denoted as $H$).
  • Advective heat transports are separated into Ekman and geostrophic parts, a technique which is successful away from boundary regions.
  • Air-sea heat fluxes and Ekman heat transport convergences due to velocity variability are combined into one “local forcing” term.

• We find:
  • Over broad swaths of the North Atlantic, including the interiors of the subtropical and subpolar gyres, >70% of the variance of $H_t$ can be explained by local air-sea heat flux + Ekman transport variability.
  • Geostrophic convergences play a role along Gulf Stream Path.
Conclusions (cont.)

North Atlantic separated into regions based on underlying dynamics and budgets of H analyzed in detail (see Buckley et al., 2014, 2015)

• Subtropical gyre
  • local forcing dominates on all timescales resolved by the 19-year ECCO state estimate.

• Gulf Stream
  • local forcing dominates for periods less than 6 months; geostrophic convergences increasingly important on longer timescales.
  • Geostrophic transports are anticorrelated with air-sea heat fluxes, suggesting H variability is forced by geostrophic convergences and damped by air-sea fluxes.

• Subpolar gyre:
  • local forcing dominates for periods less than 1 year
  • geostrophic transports, bolus transports, and diffusion play a role on longer timescales.

The timescale at which ocean dynamics becomes important in setting H depends strongly on region.
Future work

• Can origin of upper-ocean heat content (UOHC) anomalies aid in understanding regional variations (and model spread) in predictability of UOHC?
  • Dominance of atmospheric forcing -> low predictability?
  • Role of geostrophic ocean dynamics -> high predictability?
  • Applying these ideas to understand predictability in CMIP5 models.

• Determine origin of geostrophic convergence anomalies over the Gulf Stream path
  • Shift of Gulf Stream path due to remote wind forcing?
  • Change in strength of deep western boundary current?

• H variability is associated with AMOC variability. Is AMOC variability passive thermal wind response to H variability or does AMOC play role in H budget in some regions (e.g. Gulf Stream)?

• Analysis has determined regions where more complex dynamics are important in H budget.
  • e.g. diffusion and bolus transports are important in Mann Eddy region.
  • Region may be important in decadal AMOC variability (Buckley and Marshall, subm.)
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Mean temperature: comparison to in-situ data

Misfits to in-situ observations: $T_e - T_o$

Non-optimized simulation

Optimized solution: ECCO v4 (r3/iter3)

Forget et al., 2015b GMD
Divide into regions based on dynamics:

• Gyre interiors: fraction of variance of $H_t$ explained by $C_{loc}* > 0.7$
• Subtropical and subpolar gyres divided by zero in mean barotropic streamfunction.
• Gulf Stream path: mean speed $> 7$ cm s$^{-1}$ and fraction variance of $H_t$ explained by $C_{loc}* < 0.7$

**SST and upper-ocean temperature**

\[ T = \frac{H}{(\rho_{o}C_p V)} \]
Present budgets in two ways:

- Fluxes contributing to $H_t$
- Temporally integrated budgets (contributing to $T$), $V=$volume of region

\[
\int_0^t \frac{H_t}{\rho_o C_p V} dt = \int_0^t \frac{C_{adv}}{\rho_o C_p V} dt + \int_0^t \frac{C_{diff}}{\rho_o C_p V} dt + \int_0^t \frac{Q_{net}}{\rho_o C_p V} dt.
\]

- Similarly dividing $C_{lin}, C_{bol}, C_{ek}, C_{g}, C_{loc}$ by $\rho_o C_p V$ and integrating in time yields $T_{lin}, T_{bol}, T_{ek}, T_{g},$ and $T_{loc}$. 
Subtropical gyre interior

FLUXES
• Dominant terms: $Q_{\text{net}}$, $C_{\text{ek}}$, $C_{\text{loc}}$
• $C_{\text{loc}}$ dominates on intrannual timescales
• $C_{\text{ek}}T+C_{\text{ek}}vT$ role for $\tau>2$ yrs.
• $C_{g}$, $C_{\text{diff}}$, $C_{\text{bol}}$ negligible => $C_{\text{loc}}=C_{\text{ek}}+Q_{\text{net}}$
• $C_{\text{loc}}$ dominates on all timescales

TIME INTEGRATED
• $T_{\text{loc}}$ explains 92% of the variance of $T$
• $T$ anomalies are locally forced on all timescales resolved by ECCO
Gulf Stream Region

**FLUXES**
- $C_{loc}$ dominates for $\tau < 6$ mo.
- $C_g$ plays an increasing role on longer timescales
- $C_{ek}^T + C_{ek}^\nu T$ negligible
- $C_{loc}^*$ and $C_{loc}$ are indistinguishable

**TIME INTEGRATED**
- $T_g$ important in $T-T_o$ budget
- $T_g$ and $T_Q$ highly anticorrelated (-0.90)
- $T_Q$ likely reflects damping of $T$ anomalies created by ocean dynamics
Subpolar gyre interior

FLUXES
- \( C_{\text{loc}} \) dominates for \( \tau < 1 \) yr.
- \( C_g, C_{\text{diff}}, C_{\text{bol}} \) play a role for \( \tau > 1 \) year.

TIME INTEGRATED
- \( T_{\text{diff}} + T_{\text{bol}} \) has significant low frequency variability.
- \( T_{\text{diff}} + T_{\text{bol}} \) and \( T_Q \) are anticorrelated (-0.77).
- \( T_Q \) likely reflects damping of \( T \) anomalies created by ocean dynamics.