Motivation
- Observations indicate Atlantic SSTs exhibit significant low-frequency variability (Kerr, 1994; Kirtman et al., 2009).
- e.g. Atlantic Multidecadal Oscillation (Kerr, 2000; Knight et al., 2005)
- The origin of Atlantic SST anomalies remains to be quantified.
- Likely depends on timescale
- Intrannual to interannual:
  - response to local atmospheric forcing
  - e.g. wind variability from baroclinic Rossby waves
- Long-term (low frequency) ocean circulation may play a role.
- Ocean dynamics that are important have not been isolated

Upper-ocean heat content variability
- Heat content integrated over maximum climatological mixed layer depth (D)
- Measure of heat contained in "active" ocean layers
- Relevant for understanding SST
- Avoids strong contributions from diffusion and eliminates entrainment effects (Bretherton et al., 2003; Csanady and Frankignoul, 2003; Buckley et al., 2014)
- Define:
  \[ H = \rho C_p \int_0^D \nabla^2 \theta dz \]

Maximum Climatological mixed layer depth (D)

To right:
(a) The first two PC time series of monthly H anomalies (seasonal cycle removed) over the North Atlantic and (b) their respective power spectra. EOF1 and EOF2 explain 50% and 11% of the variance, respectively.
(c-d) The first two EOFs of North Atlantic H:
- The spatial patterns of SST variability associated with the first two PC time series of North Atlantic H, obtained by projecting the PC time series onto monthly SST anomalies (seasonal cycle removed).

Dynamics of Advevtive heat transport convergences
- Temperature misfits (left) first guess; solution (right) optimized EUCO v4 solution at 100 m depth for all in situ data (Argo, CTDs, XBTs, SeaD) averaged over 1992-2010. Misfits are calculated for each cell and at T-E_T, where T_E are observational profiles and T= are the corresponding profiles from the model.

Comparison to observations
- Temperature Misfits
- Optimal. Temperature Misfits at 100 m

ECCO version 4 state estimate (1992-2010)
- MTgEm least squares fit to observations using adjoint (Wunsch et al., 2009)
- ft achieved by adjusting initial conditions, forcing, and model parameters
- well-suited to understand UOHC variability because it satisfies equations of motion and preserves property budgets exactly (Wunsch and Heimbach, 2005)
- Atmospheric forcing: ERA-Interim
- Ocean data:
  - In-situ: Argo, CTDs, XBTs, mooring arrays
  - Satellite: AVHRR & AMSR-E SST, altimeter
- Model Details (R Forget)
  - New global grid (LCCO): includes Arctic, 50 vertical levels with partial cells
  - Nominal 1° resolution with telescopic resolution to 1/3 near Equator
  - State of the art dynamic/thermodynamics sea ice model
  - Nonlinear free surface + real freshwater fluxes

Regional Budgets
- Temporally integrate:
- 1) Subtropical gyre interior
- 2) Gulf Stream region
- 3) Pole
- Variance of H, and fluxes
- Variance explains 90% of the variance of H
- Qg dominates for \( > 70 \) % of the variance of H
- H anomalies formed by C_c
- Subpolar gyre
- C_c dominates for \( < 1 \) yr
- C_c plays a role for \( \tau > 3 \) yr

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 domain)
  - Advevtive 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.
  - Over most regions, variability of Ekman heat transport convergences is dominated by variability in the velocity field.
  - Over broad areas of the North Atlantic, the interior of the subtropical and subpolar gyres, >70% of the variance of H can be explained by local air-sea heat flux + Ekman transport variability.
  - Geostrophic convergences play a role along Gulf Stream Path.
  - North Atlantic separated into regions based on underlying dynamics and budgets of H analyzed in detail.
- Subtropical gyre
  - local forcing dominates on all timescales.
- Gulf Stream
  - local forcing dominates for periods less than 6 months; geostrophic convergences increasingly important on longer timescales.
  - Geostrophic convergences are anticorrelated with air-sea heat fluxes, suggesting H variability is forced by geostrophic convergences and dampened 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.

References
- In press.
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