What determines the evolution of global mean sea surface temperature?

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Motivation

- Global mean sea surface temperature (GMSST) is a variable of primary interest in studies of climate variability and change. GMSST is essential in characterizing surface climate.

- Temporal evolution of GMSST can be influenced by heat flux forcing at the air-sea interface ($F$) and by diffusion ($D$) and advection ($A$) processes internal to the ocean.
  
  To what extent can $A$ affect balance between $F$ and $D$?

- Determining these different factors can provide insight on the nature of air-sea interactions and climate processes. Surface climate controlled by internal heat redistribution?

- Calculations of $F$, $D$, $A$ from data alone are prone to large uncertainties and plagued by difficulties in getting a closed heat budget.

Can we gain insight into the nature of GMSST variability using a state estimate that fits most features of the observed GMSST behavior, while providing a closed heat budget in terms of $F$, $D$, $A$ consistent with evolution of GMSST?
**Approach**

- Examine the latest global state estimate produced by the consortium for Estimating the Circulation and Climate of the Ocean (ECCO version 4; *Forget et al., 2015, Geo. Model Dev.*)
  - Release 3 fields available for period 1993-2015
  - Constrained to most available data (in situ T+S, satellite SST, altimetry, GRACE, Aquarius)
  - Fit to data by adjusting initial conditions, boundary forcing, and internal mixing coefficients within prescribed uncertainties
  - Solution of free running MITgcm with no hidden sources or sinks of heat and a closed heat budget on the model grid
- Explore GMSST budget (in time integrated form)
  \[
  \text{GMSST} = A + D + F
  \]
  where SST taken to be temperature in 10-m thick top layer in solution
For time mean, forcing mostly cools surface (except near equator and some higher latitudes), balanced by warming effects from diffusion and advection.

Small imbalances in the time mean terms give rise to weak positive trend in GMSST with advection weaker but important for the budget.
GMSST (detrended fields)

- ECCO estimate of GMSST consistent with observations
- Large annual cycle in $F, D$ but visible semi-annual cycle in GMSST
- Interannual and longer time scale variability relatively weaker

SST data from Reynolds et al. (2002, J. Climate)
Mean seasonal cycle

- Good qualitative agreement between amplitude/phase of mean seasonal cycle in ECCO estimate and data
- Main balance between forcing and diffusion
- Small residual responsible for seasonal cycle, advection negligible
- Semi-annual cycle in GMSST
- Small differences in phase and amplitude of $F$, $D$
- GMSST can follow behavior of $D$ (e.g., over July-October) rather than $F$
Nonseasonal variability

- ECCO fit to the data excellent at interannual and longer time scales
- El Niño, La Niña signals well captured
- Balance between $F$ and $D$ still clear for interannual variability but...
- ...advection also important (e.g., 1997-98 El Niño, decadal variations)
Frequency analysis $T$ vs. $F+D$

Relation between forcing+diffusion and GMSST

- Close correspondence between $F + D$ and GMSST at annual and semi-annual periods
- Results for most other periods, particularly $> 1$ year, imply non-negligible effects of advection
Frequency analysis $F$ vs. $D$

Relation between forcing and diffusion

- Mostly out of phase over all periods
- $D$ coherent with and larger than $F$ at semi-annual band
- Decaying coherence and admittance amplitudes at periods $> 1$ year
Frequency analysis

Power spectra of all budget terms and residual temperature (ECCO minus data)

- Advection most important at longest periods
- Interannual GMSST well resolved (small residual ECCO minus data)
- $D$ slightly larger than $F$ at semi-annual band, vice versa for annual band
- GMSST typically smaller than other terms in budget
Some conclusions

- Physically consistent state estimates (free solutions of a model constrained by data) make it possible to explore mechanisms responsible for GMSST variability.

- Expected balance between surface heat flux and mixing is clear at the seasonal time scale, but advection is not negligible particularly at periods longer than one year.

- GMSST not simply tracking surface heat flux effects with diffusion mitigating the forcing (e.g., semi-annual periods).

- Advection plays a visible role in the GMSST budget but there are no instances where it seems to dominate the variability in GMSST.
- Observed evolution of GMSST reproduced without any nonseasonal wind stress forcing
- Heat flux forcing differences relate to impact of wind forcing on SST
- Differences in $F$ mostly compensated by changes in $D$
- Decadal variability in $A$ not primarily controlled by wind forcing
Top 100m budget (mean, trends)

- Top 100m global mean temperature warmed by diffusion, cooled by advection and forcing!

- Forcing trend becomes positive if integrated over top 150m (influence of small shortwave radiation flux)

<table>
<thead>
<tr>
<th>GMSST trends (°C/yr)</th>
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<tbody>
<tr>
<td>ECCO: 0.0026</td>
</tr>
<tr>
<td>Forcing: −0.0267</td>
</tr>
<tr>
<td>Diffusion: 0.2637</td>
</tr>
<tr>
<td>Advection: −0.2344</td>
</tr>
</tbody>
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Top 100 m (detrended fields)

- SST data from Reynolds et al. (2002, J. Climate)

- Annual cycle in near-surface global mean temperature driven by $F, D$ much less important

- No semi-annual cycle in near-surface global mean temperature

SST data from Reynolds et al. (2002, J. Climate)
Mean seasonal cycle (top 100 m)

- Global mean temperature over top 100m follows mainly surface forcing
- Advection and diffusion both negligible
- Much weaker semi-annual cycle
Nonseasonal variability (top 100 m)

- Interannual variability in temperature over top 100 m tracks observed GMSST
- Top 100 m temperature follows advection to a large extent, particularly over some El Niño/La Niña events

Trends and annual+semiannual cycle removed

**a. ECCOv4r3 top 100–m versus SST data (nonseasonal)**

**b. ECCOv4r3 top 100–m budget (nonseasonal)**

- Estimate
- Observations
- Total
- Forcing
- Diffusion
- Advection

Yearly data from 1994 to 2015.