GLOBAL MEAN SEA LEVEL—WHAT'S OCEAN CIRCULATION GOT TO DO WITH IT?

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I. MOTIVATING REMARKS

❑ Global mean sea level rise reflects ocean mass & steric (i.e., density) change (e.g., ref. 1).

❑ Due to the nonlinearity of the density equation of state, processes effecting global mean steric sea level (η_ρ) change remain opaque.

❑ Using a data-constrained state estimate (ref. 2), we diagnose closed budgets of η_ρ (e.g., ref. 3) to address the following questions—

1. ***Are η_ρ changes mainly controlled by atmospheric forcing (i.e., sea-surface exchanges of heat & freshwater)?***
2. ***Do oceanic transports (e.g., small-scale diffusion & large-scale advection of salinity & temperature) also contribute?***
3. ***How well can the η_ρ budget be constrained by ocean circulation models?***

II. GLOBAL CHANGES

❑ Global ocean heat content **[Fig. 1a]** & freshwater content **[Fig. 1b]** from the state estimate over 1993-2003 show annual, interannual, & decadal changes, with the ocean gradually warming & freshening, in qualitative agreement with IPCC AR4 (ref. 4).

❑ Consistent with warming & freshening **[Figs. 1a-b]**, η_ρ over 1993-2003 exhibits long-term rise **[Fig. 1c]**.

III. STERIC BUDGET

❑ What processes are contributing to the long-term rise in η_ρ over 1993-2003?

❑ We formulate a budget for η_ρ in terms of advection, diffusion, & local forcing (ref. 3).

❑ Long-term rise in η_ρ represents a slight imbalance between a positive trend due to atmospheric forcing & negative trends owing to oceanic advection & diffusion **[Fig. 2]**.

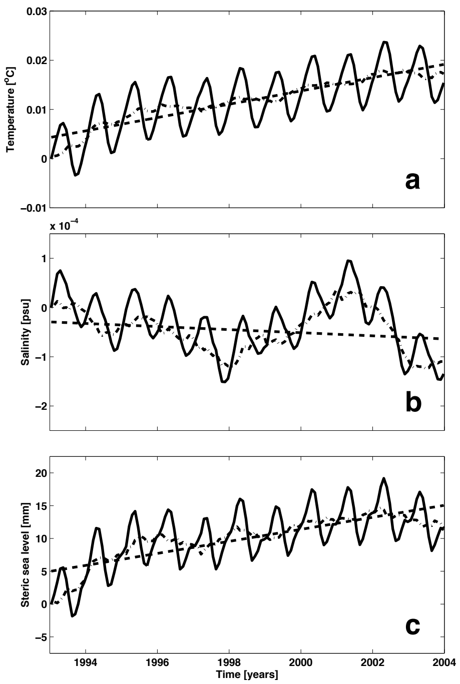

*Fig. 1: Global mean ocean **(a)** temperature, **(b)** salinity, & **(c)** steric sea level anomalies from the estimate over 1993-2003 (solid); non-seasonal series (dash-dot) & linear trends (dashed) are also shown.*

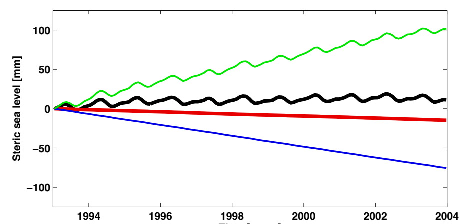

*Fig. 2: Budget for η_ρ (**black**) in terms of advection (**red**), diffusion (**blue**), & forcing (**green**) from the ocean state estimate over 1993-2003.*

IV. ADVECTION CONTRIBUTES?

❑ How is it that advective redistribution contributes to the η_ρ budget **[Fig. 2]**?

❑ Contributions from advection (as well as diffusion) reflect nonlinearities in the equation of state of seawater.

❑ For advection to contribute, flow must occur across pressure surfaces (i.e., isobars) & across temperature or salinity surfaces (i.e., isotherms or isohalines) **[see Fig. 3]**.

V. SENSITIVITY EXPERIMENTS

❑ Are estimates of η_ρ changes **[Figs. 1-2]** sensitive to ocean model formulation?

❑ To gauge the sensitivity of η_ρ changes to representational choices, a set of numerical experiments was performed such that the tracer advection scheme was varied.

❑ Changes in η_ρ are very sensitive, with positive or negative decadal change resulting depending on advection scheme **[Fig. 4]**.

VI. MAIN CONCLUSIONS

✓ **Both advective and diffusive oceanic transports make important contributions to global mean steric sea level change [Fig. 2].**

✓ **Contributions from oceanic transports reflect nonlinearities in density equation of state [Fig. 3].**

✓ **Estimates of global mean steric sea level changes from ocean general circulation models can be sensitive to tracer advection scheme [Fig. 4].**

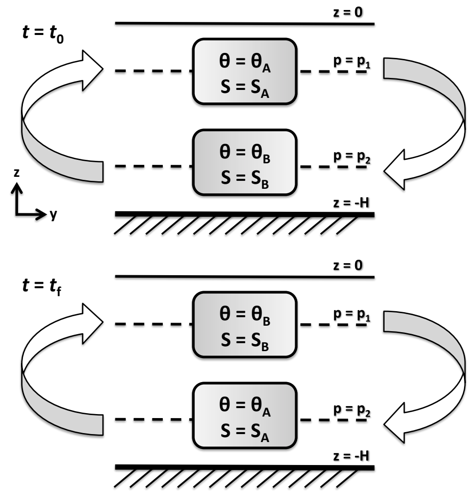

*Fig. 3: A thought experiment. Consider two water parcels (boxes) of equal mass. Parcel **A** (**B**) has temperature θ_A (θ_B) and salinity S_A (S_B). At $t=t_0$ (top), parcel **A** (**B**) feels pressure p_1 (p_2). Now imagine that a circulation (arrows) rearranges the parcels such that, at $t=t_f$ (bottom), parcel **A** (**B**) feels pressure p_2 (p_1). Does this scenario imply a change in steric sea level?*

Given a nonlinear equation of state $\rho(S,\theta,p)$, it can be shown that the combined volume of the two parcels can change (hence steric sea level can change) between t_0 & t_f under this scenario provided two conditions are met:

1. *Flow is across isobars ($p_1 \neq p_2$), &,*
2. *Flow crosses isotherms or isohalines ($\theta_1 \neq \theta_2$ or $S_1 \neq S_2$).*

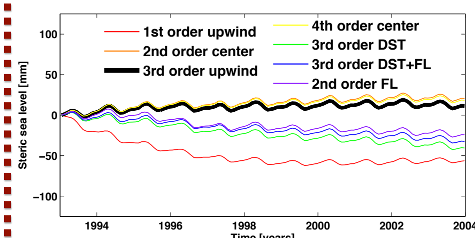

*Fig. 4: Changes in η_ρ produced under advection scheme experiments. Experiments are performed using the following differencing schemes for tracer advection: first order upwind-biased (**red**); second order centered (**orange**); third order upwind-biased (**black**; **from Fig. 2**); fourth order centered (**yellow**); third order direct space time without a flux limiter (**green**) & with a flux limiter (**blue**); & second order with a flux limiter (**purple**).*

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