Seasonal Sea Level Variability Estimated From a Data-Constrained General Circulation Model

Sergey V. Vinogradov, Rui M. Ponte*
Atmospheric and Environmental Research, Inc., Lexington, Massachusetts, USA

Patrick Heimbach and Carl Wunsch
Massachusetts Institute of Technology, Cambridge, USA

sergey@aer.com

*Presenting author

Summary

The ECCO-GODAE v2.177 product combines numerous types of oceanographic observations, including data from all the altimetric missions, 1992-2004, with the MIT general circulation model in an optimization procedure that minimizes model-data misfits in a least-squares sense. The result is an estimate of the global ocean state (temperature, salinity, currents and sea level) and the surface atmospheric forcing fields (wind stress, heat flux and freshwater flux) since 1992 that is consistent within error bars with the observations. This estimate of sea surface variability on seasonal scales is studied in this work. The annual cycle tends to be more important than the semi-annual cycle, except in tropical regions. The seasonal cycle in the wind field is the primary driver for the sea level variations in the tropics, and seasonal surface heat flux variations is the dominant forcing in mid-latitudes. A substantial part of the sea level variability can be assigned to changes in thermosteric height; integrals of thermosteric height to 100 m depth in mid-latitudes and to 200 m in the tropics explain 80% of the annual cycle in sea level. Bottom pressure changes are also important in shallow and near-coastal areas, and in some deep-ocean regions (Southern Ocean, North Pacific) where bottom relief leads to enhanced barotropic motions. The difference between sea level variability in coastal areas and the open ocean is also highlighted in comparisons among the ECCO-GODAE estimate, altimetry observations and tide gauges. Estimates of the seasonal cycle in global mean sea level are ~3.5 mm (maximum in April) for the thermosteric component and ~5.5 mm (maximum in October) for the net freshwater component, which are comparable to previous data estimates.

Model/Data Comparison

TOPEX/POSEIDON/Jason-1 (TPJ) is one type of data constraint used in ECCO.

Figure 1 presents a comparison of ECCO with TPJ and independent data set – tide gauges – using 156 monthly records

- Mean correlation with TPJ is 0.6 (on 28,070 time series); higher in tropics and northern high-latitudes, lower in mid-latitudes and along ACC
- Mean correlation with tide gauges is 0.7 (on 450 time series); better for island stations (deep ocean) than in coastal regions

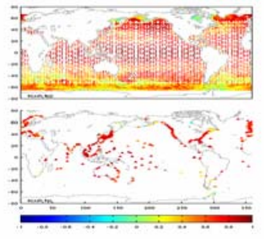

Figure 1: Correlation between model and TPJ (top) and tide gauges (bottom)

Global Mean Sea Level (GMSL)

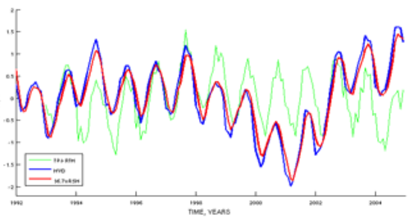

Figure 2: Three estimates of the global hydrological cycle.

GMSL provides insight on the planetary hydrological cycle.

Green curve is the difference between TPJ GMSL and steric GMSL as estimated by ECCO.

Blue curve is GMSL from integrated surface freshwater flux as estimated by ECCO.

Red curve is GMSL calculated as halosteric term times ρ/Δρ – the "Munk Multiplier" (Munk, *Science 300*, 2003).

- All 3 curves show annual cycle of similar amplitude and phase
- Green curve has more high-frequency signal due to TPJ data and less inter-annual variability
- Both red and green curves show similar low-frequency modulations

Regional Sea Level

Seasonal cycle in SSH (Figure 3):

- predominant (>80% of the total variance) in the tropical Indian and Atlantic, and in northwest Pacific Ocean
- significant (>50%) in many other tropical and mid-latitude areas
- weak (<20%) at high latitudes, particularly in the Southern Ocean, and in the tropical Pacific, where there is strong inter-annual variability

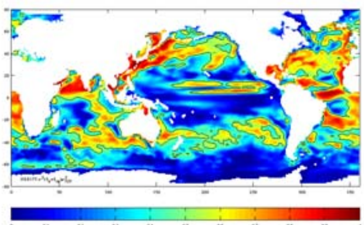

Figure 3: Ratio of the variance of the mean seasonal cycle (annual+semiannual) to the total variance of SSH. Contour line = 0.5

Annual cycle

Annual **amplitudes** (Figure 4a):

- strongest (10-15 cm) within western boundary currents (Kuroshio, Gulfstream), zonal bands in the tropical Pacific, and in tropical Indian Ocean
- elevated in shallow semi-enclosed seas and coastal regions (e.g., Indonesian seas)
- moderate (3-6 cm) in mid-latitudes, North Atlantic and Mediterranean
- weak (<3 cm) in most of the Southern Ocean south of 45˚S

Annual **phases** (Figure 4b):

- reversal of seasons between N and S hemispheres
- no visible footprints of western boundary currents
- phase contours have mostly zonal distribution

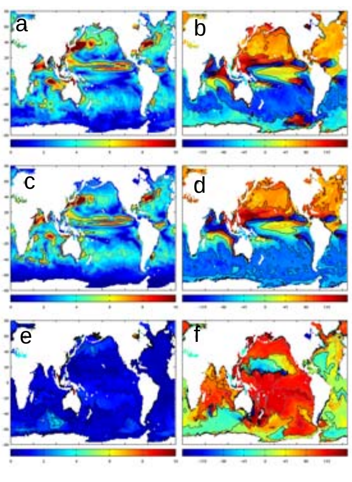

Figure 4: Annual cycle (amplitude in cm, and phase in deg) for the full sea level (a,b), thermosteric height (c,d), and bottom pressure (e,f). Phases are as in *cos(ωt+φ)*.

- Vertically-integrated thermosteric height contributes most of annual variability in SSH (cf Figures 4c,d and 4a,b)
- Exceptions occur at high latitudes, particularly in the Southern Ocean, and also over many shallow coastal regions, where bottom pressure plays important role (Figure 4e,f) as earlier studies suggested (e.g., Ponte, *JGR 104*, 1999)
- Most of the annual steric variability contributing to SSH comes from the upper 200 meters but deeper contributions can be found in several areas (Figure 5)

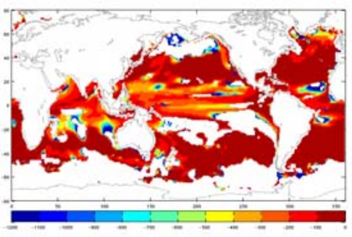

Figure 5: Depth to which it suffices to integrate the steric height in order to explain > 80% of the annual SSH signal. Blank areas are regions where bottom pressure is important.

Forcing mechanisms

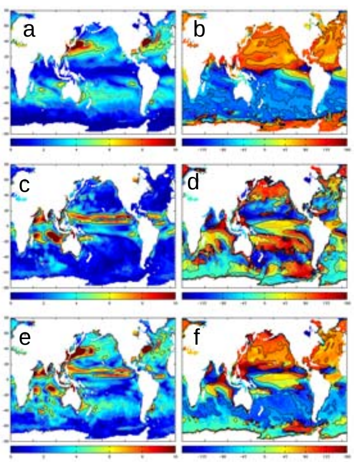

Figure 6: Amplitudes and phases of annual cycles in sea level: (a,b) Exp1, (c,d) Exp2, (e,f) sum of Exp1 and Exp2.

In addition to the constrained model run, two additional forcing experiments were carried out (Figure 6) with all but one forcing field set to its time-mean value over the integration period.

Exp1,"time-dependent **surface heat flux**":

- Annual pattern in SSH (Figure 6a,b) resembles pattern in heat flux (not shown), implying a strong local effect of the heating on the annual sea level variability
- High amplitudes in mid-latitudes, along western boundary currents, are mainly driven by heat flux

Exp2, "time-dependent **wind stress**":

- Wind-driven signals are most important in the tropics, shallow and semi-enclosed seas and coastal areas (cf Figures 6c,d and 4a,b)
- Addition of the wind- and surface heat flux-driven sea level signals (Figure 6e,f) provides an annual pattern very similar to one of the full forcing experiment (cf Figure 4a,b). However, there are some differences in detail, in part due to non-linear oceanic response to different kinds of forcing.

Variability of the annual cycle

Year-to-year variability of the annual amplitude/phase (Figure 7):

- does not exceed 4 cm/80˚
- mostly below 1cm/40˚
- elevated in the tropics – associated with the changes in the annual winds from year to year (cf Figure 6c).
- largest year-to-year changes in the central tropical Indian Ocean and in the northern tropics of the western Pacific.
- in the Southern Ocean, annual amplitudes are weak (Figure 4a) and phases may vary considerably (40-60˚).

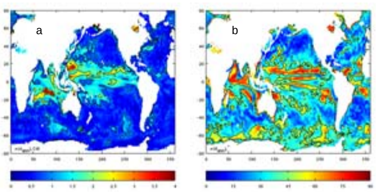

Figure 7: Standard deviation of the annual amplitude (a) and phase (b) of sea level over 13 years.

Semi-annual cycle

The semi-annual signal (Figure 8) is mostly below 5 cm amplitude

- Semi-annual cycle is comparable or dominates over annual cycle in few areas of the tropical oceans
- Tropical Indian Ocean: maximum semi-annual amplitudes, associated with a basin-scale resonance involving interaction of Kelvin and Rossby waves (e.g., Fu, *JPO*, 2007) and driven by monsoonal variability
- Semi-annual cycle may represent just the irregularity in annual harmonics instead of a realistic 6-month signal (Tsimplis and Woodworth, *JGR 99*, 1994)

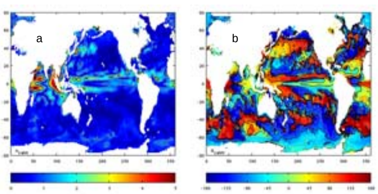

Figure 8: Semi-annual cycle in sea level: (a) amplitude and (b) phase.