Warming of the global ocean : consistency of thermal and altimetric fields and dominance of descending density surfaces

Sirpa Häkkinen[1], Peter B. Rhines[2] and Denise L. Worthen[1]
[1]NASA Goddard Space Flight Center, Code 615, Greenbelt, MD 20771, [2]University of Washington, Box 357940, Seattle, WA 98195.

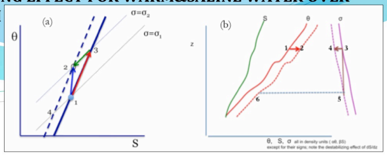
ABSTRACT: The multidecadal warming and interannual and decadal heat content changes in the upper ocean are investigated from observational data sets (NODC & EN4) and from a modeled state estimate (SODA). Multidecadal warming is dominated by a contribution from deepening of the mid-thermocline isopycnals (resulting in an expansion of the subtropical mode water volume) rather than shifts of the temperature/salinity relationship. The multidecadal isopycnal sinking has been the strongest over the southern basins. On interannual to decadal scales, sinking and shoaling of density surfaces dominates ocean heat content changes, while the contribution from temperature changes along density surfaces decreases as time scales shorten. Decomposition of ocean heat content changes into heaving and isopycnal temperature changes is shown to provide insight to the satellite sea surface height measurements of the last two decades.

Here we consider ocean potential temperature (θ) change at fixed depths due to heaving and spice variability: 'heaving' is an Eulerian measure of the temperature change at fixed depths, and implies vertical migration of surfaces of constant θ, either adiabatically (as with changes in wind forcing of a gyre circulation), or through diabatic heat flux divergence. 'Spice' variability is the change in θ and S upon a fixed neutral- density surface (Bindoff and McDougall, 1994). In the Bindoff-McDougall decomposition of θ (similarly for salinity S) changes at depth z ($d\theta/dt|_z$)

$$d\theta/dt|_z = d\theta/dt|_n - dz/dt|_n \, d\theta/dz$$

are divided into a change along the neutral density surface (the 1st term on right) and due to vertical movement of the neutral density surface (dz/dt) (the 2nd term on right). It is linearized with respect to vertical displacements and approximates $d\theta/dz$ from the gridded data. Software available at http://www.teos-10.org/preteos10_software/neutral_density.html is used to compute the neutral density values for each data set (Jackett and McDougall, 1997; Bindoff and MacDougall, 1994). Heat content total, heave and spice are computed by multiplying the temperatures by the gridpoint volume, density, and heat capacity of sea water.

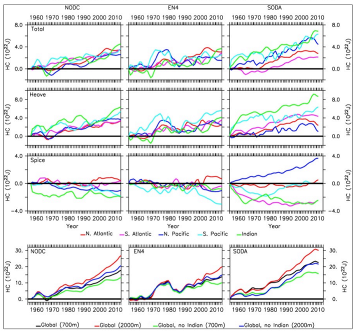
PURE WARMING EFFECT FOR WARM&SALINE WATER OVER COLD&FRESH



(a) In a θ-S diagram warming takes parcel 1 to 2, now parcel 2 appears cooler (and fresher) than the parcel with the same density (point 3) on the original thermocline (solid blue).

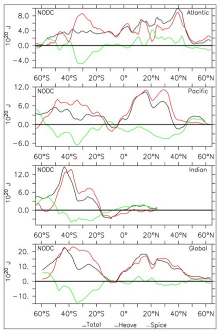
(b) The same warming effect in a z-plane. Warming (1 to 2) moves the density from 3 to 4. Parcel 5 with the same density as before warming (parcel 3) is much cooler than the original parcel (1): Parcel 5 has a corresponding temperature at point 6. Connecting the lines from 1 and 6 to the salinity curve would show that the parcel 6 is also fresher than the parcel 1.

OCEAN HEAT CONTENT VARIABILITY

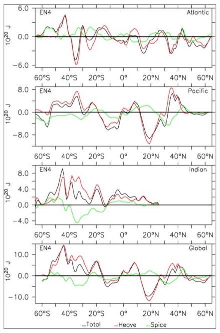


Ocean heat content (in 10^{22} J) integrated over 0-700m in NH and SH basins and their heave and spice components in NODC, EN4 and SODA, top three rows. Heat contents are referenced to 1955. Bottom row: The global heat content (in 10^{22} J) in 0-700m and 0-2000m columns, with and without the Indian Ocean contribution, heat contents are referenced to 1955, except NODC to 1957. Values are smoothed by one binomial filter for SODA and NODC, twice in EN4. (Obs. analysis EN4 from UK Met Office.)

ZONAL OCEAN HEAT CONTENT CHANGES

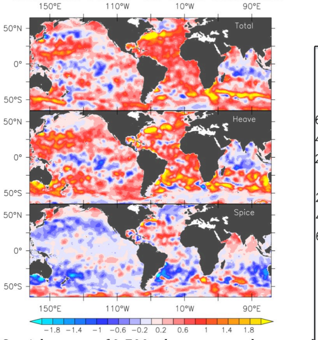


The zonal OHC (0-700m) difference [1997-2011]-[1957-1971] versus latitude (black line) and its decomposition (red for heave; green for spice) are shown for the Atlantic, Pacific and Indian sectors and globally based on the NODC data set. Units are 10^{20} J per one degree of latitude.



The zonal OHC (0-700m) difference [2009-2014]-[2003-2008] versus latitude (black line) and its decomposition (red for heave; green for spice) are shown for the Atlantic, Pacific and Indian sectors and globally based on the EN4 data set. Units are 10^{20} J per one degree of latitude.

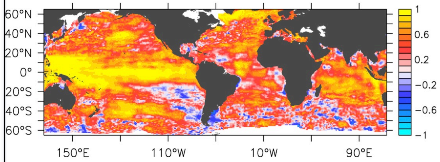
GLOBAL VIEW OF OHC CHANGE



Spatial pattern of 0-700m heat content change and its heave and spice components in NODC from (1957-1971) to (1997-2011). Units are 10^9 J/m^{-2} (OHC divided by the grid area).

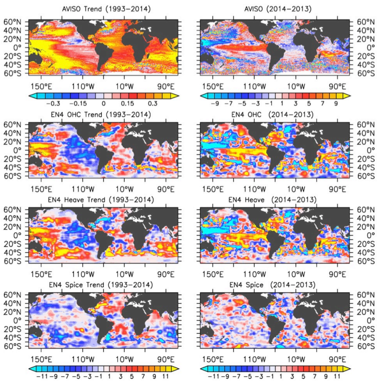
NOTE THE MOSTLY OPPOSING CONTRIBUTIONS FROM SPICE AND HEAVE < ---- SINKING, I.E. WARM HEAVE, LEADS TO COOLING ON NEUTRAL DENSITY SURFACES.

CORRELATION BETWEEN 0-700M OHC AND AVISO SSH



Correlation between annual values (1993-2014) of AVISO Sea surface height and EN4 0-700m heat content (no linear trend removed from data sets). Correlations above 0.5 can be considered significant at 95% level. The tropical and North Atlantic subpolar gyre heat content changes have the strongest signal in altimetric heights.

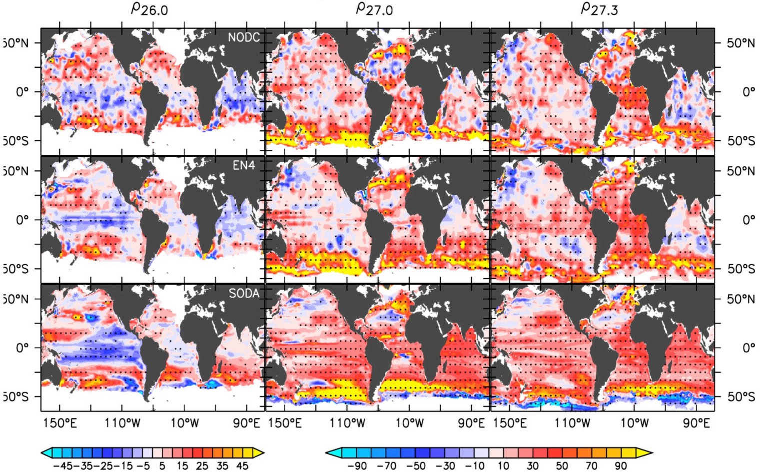
ALTIMETRY ERA AND RECENT OCEAN HEAT CONTENT CHANGES



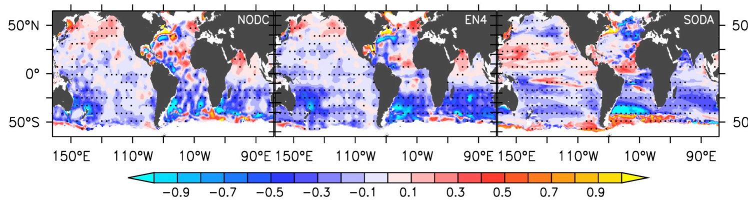
(a) AVISO sea surface height trend (computed from monthly data, in cm/decade) and EN4 OHC 0-700m trend and their heave and spice component trends (computed from annual data, in 10^{18} J/decade).

(b) (**b**) One year difference, 2014-2013, of AVISO SSH (cm) and EN4 (10^{18} J).

LONG TERM TREND IN HEAVING (=SINKING) OF FIXED ISOPYCNALS, ρ = 26.0, 27.0, 27.3

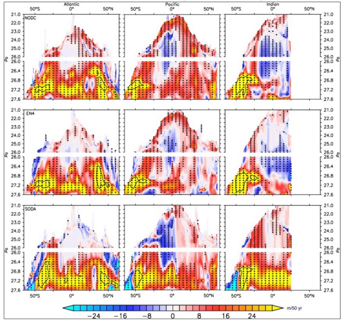


Sinking-shoaling trends (positive downward) of potential density surfaces 26.0, 27.0 and 27.3 for period 1957-2011 shown for NODC, EN4 and SODA, 1st, 2nd and 3rd row respectively. Units are meters per 50years. Trend values significant at 95% level are stippled.



Potential temperature trend °C per 50 years on potential density surface =27.0 for NODC, EN4 and SODA for period 1957-2011. Trend values significant at 95% level are stippled.

LONG TERM TREND IN HEAVING OF ISOPYCNALS (=SINKING)



Zonal average sinking-shoaling trends (positive downward) of potential density surfaces for the Atlantic, Pacific and Indian Oceans for period 1957-2011 shown for NODC, EN4 and SODA, 1st, 2nd and 3rd row respectively. Units are meters per 50years. Trend values significant at 95% level are stippled, the black contour is 50m per 50years. Note the maximum sinking at densities around 27.0, the maximum subtropical mode water density.

SUMMARY

Our analysis of ocean heat content reveals how the global warming effect during the last 50+ years is distributed in the upper ocean above the permanent pycnocline, where the largest heat gain has occurred. We find that the multi-decadal global warming has a robust diagnostic: a wide-spread vigorous sinking of subtropical mid-thermocline isopycnals reaching nearly 100m in 50 years in some locations. The dominant contribution to the fixed depth heat content comes from this sinking (=heaving) of isopycnals where the subtropical mode waters reside. Confidence in the basin-average and zonal-average results arises from the monotonic nature of the OHC increase in most of the world ocean.

This analysis cannot immediately discriminate between dynamically induced adiabatic vertical heaving (for example, subtropical gyre spin-up or subpolar gyre spin-down), changes in lateral advection (for example, in the zonal-mean overturning circulation) and thermodynamic forcing (for example, diabatic change in water-mass renewal due either to warmer or weaker winter winds). However the vertical and lateral structure of θ and S variability as presented here, and their temporal structure provide a framework to analyze both models and the evolving high-resolution ocean observations of the ARGO/altimetry era. This approach applies also to interannual and decadal scales variability, of which we show how the Pacific OHC contains large changes from isopycnal sinking and shoaling episodes due to PDO and ENSO variability. The amplitude associated with these regional OHC variations rival the basin average multidecadal trends. On decadal and longer time scales the spice component shows strength away from equatorial regions in all basins, but at interannual scales its importance is limited. NAO-related variability is a strong part of North Atlantic variability, and its red frequency spectrum makes discrimination of anthropogenic global warming trends difficult.