Heat Content of the Global Upper Ocean During the Past Half Century

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INTRODUCTION

This paper examines nine analyses of global 0/700m temperature and heat content during the 43-year period of warming, 1960-2002. Among the analyses are two that are independent of any numerical model, six that rely on sequential data assimilation including a ocean general circulation model and its adjoint (see **Table 1** for more details). Most analyses show gradual warming of the global ocean with an ensemble trend of 0.76×10^8 $Jm^{-2}/10yr$ ($=0.24 Wm^{-2}$) as the result of rapid warming in the early 1970s and again beginning around 1990. One proposed explanation for these variations is the effect of volcanic eruptions in 1963,1982 and 1991. Examination of the impact of these eruptions suggests that eruptions alone cannot explain these heat content variations. A second potential cause is the contribution of heat content variations in individual ocean basins. Examination of the Atlantic, Pacific and Indian basins shows that the character of decadal variability in these basins differs significantly from the global average. A third potential contributor is the effect of time-dependent bias in the set of historical observations. We examine this last possibility by comparing the analyses to the unbiased salinity-temperature depth data set and find a very substantial warm bias in all analyses in the 1970s relative to the latter decades. This warm bias may explain the rapid rise in ocean heat content in the early 1970s, but not the most recent increase that has been occurring since the early 1990s.

Analysis	Time Span	Data	Surface fluxes	Model, res.	Analysis procedure
CERFACS *Davey* (2005)	1962-2001	WOD01, GTSPP, altimeter sea level	ERA 40 Reanal winds, climatological fluxes	ORCA2 vers. OPA 2°x2°-1/2° 16 lev	Sequential
GECCO *Köhl et al. (2006)*	1950-1999	MBTs, XBTs, hydrography, ARGO profiles, nearsurface drifters, Reynolds and TMI SST, altimeter sea level	NCEP Reanal winds, fluxes	MITGCM 1°x1° 12 lev	4DVar
GFDL *Sun et al. (2007)*	1955-1999	MBTs, XBTs, hydrography	NCEP Reanal winds, fluxes	MOM4 1°x1°-1/3° 32 lev	Sequential
GODAS *Behringer* (2005)	1979-2005	WOD98,GTSPP, moored temperature, ARGO, altimeter sea level	NCEP Reanal2 winds, fluxes	MOM3 1°x1°-1/3° 29 lev	Sequential
INGV *Davey* (2005)	1962-2001	WOD01, GTSPP, altimeter sea level	ERA 40 winds, clim. fluxes	OPA 1°x1° 16 lev	Sequential
ISHII *Ishii et al. (2006)*	1945-2005	WOD01, GTSPP	None	None 1°x1° 16 lev	Objective analysis
LEVITUS *Levitus et al.* (2005)	1955-2003	WOD01, GTSPP	None	None 1°x1° 16 lev	Objective analysis
SODA *Carton and Giese* (2007)	1958-2005	WOD05, GTSPP, in situ and AVHRR SST	ERA 40 and QSCAT winds, GPCP rain, bulk heat flux	POP2.1 1/4°x1/4° 21 lev	Sequential
UK-FOAM *Bell et al. (2004)*	1962-1998	WOD01, GTSPP, altimeter sea level	UKMO NWP suite	GloSea 1°x1° 16 lev	Sequential

Table 1. Description of analyses examined, including data utilized and method of analysis implemented in each.

COMPARISON OF ESTIMATES

- In most analyses, global average heat content has two periods of rapid growth, in the late-1960s through early 1970s and again beginning in the early 1990s separated by quiescent or cooling periods in the early to middle 1960s and in the 1980s.
- The major exception is the GECCO 4DVar analysis, which cools until the mid-1970s and then begins a multi-decadal period of warming. Two of the analyses, UK-FOAM and GFDL , show significant additional warming beginning in the mid-1990s.
- The scatter among the individual analyses generally lies within $\pm 1 \times 10^8$ Jm^{-2}.
- The amplitude of the decadal anomalies is $1\text{-}2 \times 10^8$ Jm^{-2} , while the multi-decadal trend of the ensemble is 0.76×10^8 $Jm^{-2}/10yr$, or $0.24 Wm^{-2}$.

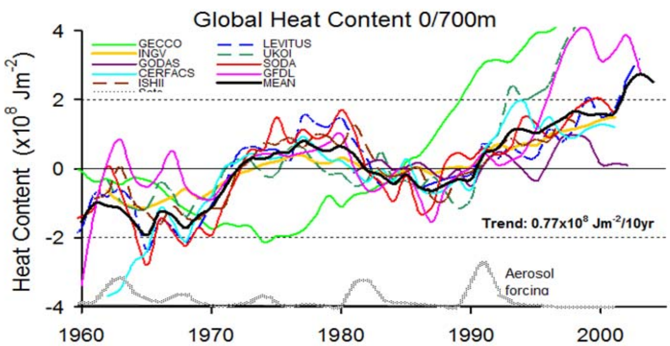

Figure 1. Global average heat content anomalies from the individual 30-yr record means (1966-1995), integrated 0/700m and temporally smoothed with a 1-year running filter. Bold black curve shows the ensemble average of the eight no-model and sequential analyses. Annual volcanic aerosol concentration is plotted along the lower axis (from *Hansen et al.*, 2005*).*

IMPACT OF VOLCANIC ERUPTIONS

We next consider the impact of the three major eruptions in 1963, 1982, and 1991. In order to reduce the influence of ENSO on our interpretation we first regress the Southern Oscillation Index onto the analysis heat content at zero lag and then remove the correlated component of the heat content. Then for each eruption we compute the difference of this filtered four-year heat content average following the eruption minus the four year average up to and including the year of the eruption. The results of this procedure, shown in **Fig. 2**, reveal a complex and varied pattern of change which we interpret as the ocean's response to the three eruptions. The first two eruptions are associated with cooling in the tropical Pacific in many of the analyses as well as in the coupled model results. For Agung the cooling is primarily north of the equator in the coupled model results while for El Chichón it is primarily south of the equator (in both cases the opposite of what one might expect from the distribution of aerosols). In addition to cooling south of the Equator in the Pacific, many of the analyses show a response to El Chichón that includes cooling in the southwestern tropical Indian Ocean and cooling in the Kuroshio-Oyashio extension region of the west. The change in analysis heat content in response to the Mount Pinatubo eruption is general warming except in the western equatorial Pacific. It may be that that for Mount Pinatubo the effects of aerosol shading are overwhelmed by a period of rapid general warming.

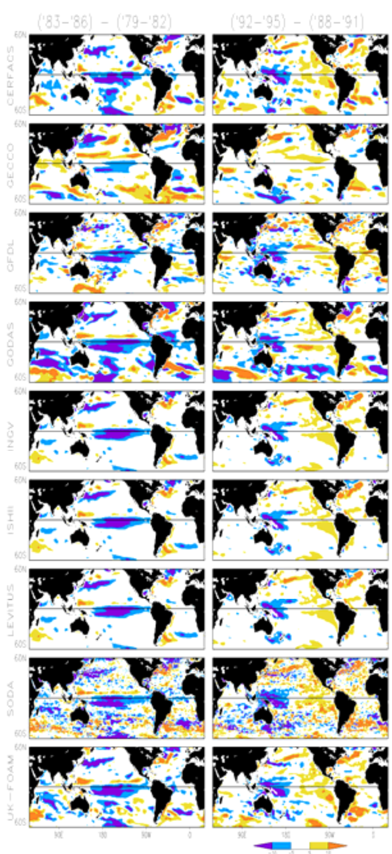

Figure 2. Change in four year average heat content spanning the eruptions of El Chichón (1982), and Mt. Pinatubo (1991). Eight analyses extending back to at least 1962 are shown in the upper panels. Changes exceeding $\pm 5 \times 10^8$ Jm^{-2} are shaded. Lower panels show the change in heat content from a five-member ensemble of the GFDL coupled simulation CM2.1 with complete aerosol forcing. Changes exceeding $\pm 3 \times 10^8$ Jm^{-2} are shaded.

DECADAL VARIATION AND ANALYSIS BIAS

We next consider the decade-by-decade heat content anomalies in each analysis (**Fig. 3**). In order to develop an understanding of the potential biases within the analyses we also examine corresponding decadal estimates of heat content analysis-minus-CTD observation differences. These analysis-minus-CTD observation comparisons are limited to the Northern Hemisphere and to the three decades 1970-1999 in order to ensure sufficient

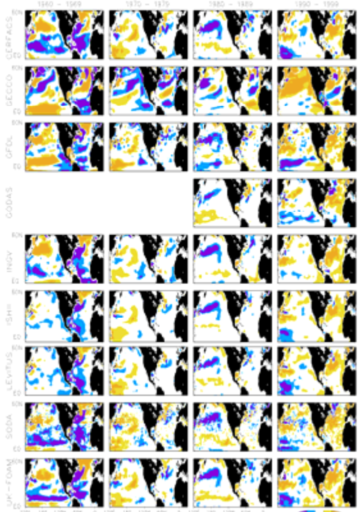

Figure 3. North Pacific and Atlantic heat content anomalies relative to the 30-yr record means averaged by decade: 1960-69, 1970-79, 1980-89, and 1990-99. Anomalies exceeding $\pm 3 \times 10^8$ Jm^{-2} are shaded.

CONCLUSIONS

Examination of the nine analyses shows that the global ocean 0/700m has been warming at a rate of 0.76×10^8 $Jm^{-2}/10yr$ ($=0.24 Wm^{-2}$) during 1960-2002, confirming the results of studies with individual analyses (e.g., *Levitus et al., 2000, 2005*; *Carton et al., 2005*; *Ishii et al., 2006*). Many uncertainties surround these individual estimates due to inadequacies in the historical observation network and the instruments, the techniques used to construct gridded analyses, and even the applicability of estimating a linear trend from the global data. By comparing the analyses to each other and to the historical observation set this paper is intended to shed light on these uncertainties and the presence of natural climate variability and to improve understanding of the utility of the analyses for decadal climate research.

REFERENCES See packet below poster.

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