A new perspective on warming of the global ocean

Matt Palmer[1], Keith Haines[2], Simon Tett[1] and Tara Ansell[1]

NATURAL ENVIRONMENT RESEARCH COUNCIL
ENVIRONMENTAL SYSTEMS SCIENCE CENTRE

An analysis of historical ocean temperature data relative to fixed isotherms is presented. The method is designed to filter out high frequency "noise" and the influence of circulation changes on estimates of ocean warming. The new approach reveals a more globally-uniform spatial pattern of warming and is more closely related to changes in air-sea heat exchange than previous fixed depth studies. The method also removes some sources of error in the observing system and provides an improved baseline for evaluation of climate models.

1. Data

The data are 7.4 million quality controlled temperature profiles over the period 1956-2004 from the European Union (EU) ENACT (ENhAnced ocean data assimilation and ClimaTe prediction) project [Ingleby and Huddleston, 2007]. The primary data source is the World Ocean Database 2001 [Conkright et al., 2002]. Additional data sources include: the World Ocean Circulation Experiment (WOCE); the Bureau of Meteorology Research Centre (BMRC, Australia); the Commonwealth Scientific and Industrial Research Organisation (CSIRO, Australia); the Pacific Marine Environmental Laboratory (PMEL, USA); the Global Temperature-Salinity Profile Program (GTSPP, Australia, Canada, France, Germany, Japan, Russia); and the Argo profiling array [Davis et al., 2001].

2. Method

Each temperature profile for a given month is assigned to a 2°×2° latitude-longitude grid box and averages are formed from the profiles to produce 588 monthly gridded fields of: (i) the mean temperature of the water warmer than 14°C, (ii) the depth of the 14°C isotherm, and (iii) the mean temperature of each profile down to 220m. We choose the 14°C isotherm because it provides good coverage of the upper water column, at low to mid-latitudes, throughout the historical record, and 220m because it is the time-mean depth of the 14°C isotherm in low and mid-latitudes. We produce a 12 month climatology based on the 49 years of data and construct gridded anomaly fields to remove the seasonal cycle. Volume-weighted mean temperature anomalies and area-weighted mean depth anomalies are computed to produce time series (Figure 1).

To evaluate the spatial coherence of the warming signals we produce trend estimates for anomalies in (i)-(iii) in each 2°×2° grid box over the period 1965-2004 (Figure 2). We divide the monthly temperature anomaly data into four decades (1965-1974, 1975-1984, 1985-1994 and 1995-2004) and only retain grid boxes that have at least 5 observations in each decade. The data coverage prior to 1965 is very poor, so we exclude these data in order to estimate trends over a larger number of grid boxes. The linear trend over the period 1965-2004 is then computed for each grid box using a least-squares fit.

3. Time series

There is a marked reduction in the high frequency variability of the 14°C mean temperature analyses over all ocean basins compared to the 220m analyses. Also at lower frequencies there is a reduction in multi-annual to decadal variability for the 14°C analyses, e.g. the reduced amplitude of the warm anomaly in the 1970s and 1980s in the Pacific and Global time series and the reduced multi-annual variability for the Atlantic and Indian time series throughout. The trends and estimates of high and low frequency variability are summarised in table 1. The trends for the 14°C analyses are much more similar between basins than the 220m analyses. For comparison the Levitus et al. [2005] data shows a trend of 0.032°C for the upper 300m. The smaller Levitus trend could result from the deeper reference depth, to the greater latitudinal extent of their sampling, or because a zero anomaly is assumed when observations are sparse [Locarnini et al., 2006].

Ocean Basin	14°C Analyses			220m Analyses		
	HF Standard Deviation (°C)	LF Standard Deviation (°C)	Linear Trend (°C per dec.)	HF Standard Deviation (°C)	LF Standard Deviation (°C)	Linear Trend (°C per dec.)
Globe	0.046	0.042	0.043	0.077	0.065	0.061
Atlantic	0.078	0.045	0.059	0.12	0.052	0.13
Pacific	0.065	0.057	0.041	0.11	0.089	0.040
Indian	0.14	0.060	0.027	0.21	0.10	0.008

Table 1: Summary statistics computed of mean temperature above the 14°C isotherm and the 220m depth in each ocean basin: the mean temperature trend for the 14°C and 220m analyses; the high frequency (HF) standard deviations (computed from the residuals of the monthly and 5-year low-passed time series); and the low frequency (LF) standard deviations (computed from the residuals of 5-year low passed series and the linear fit).

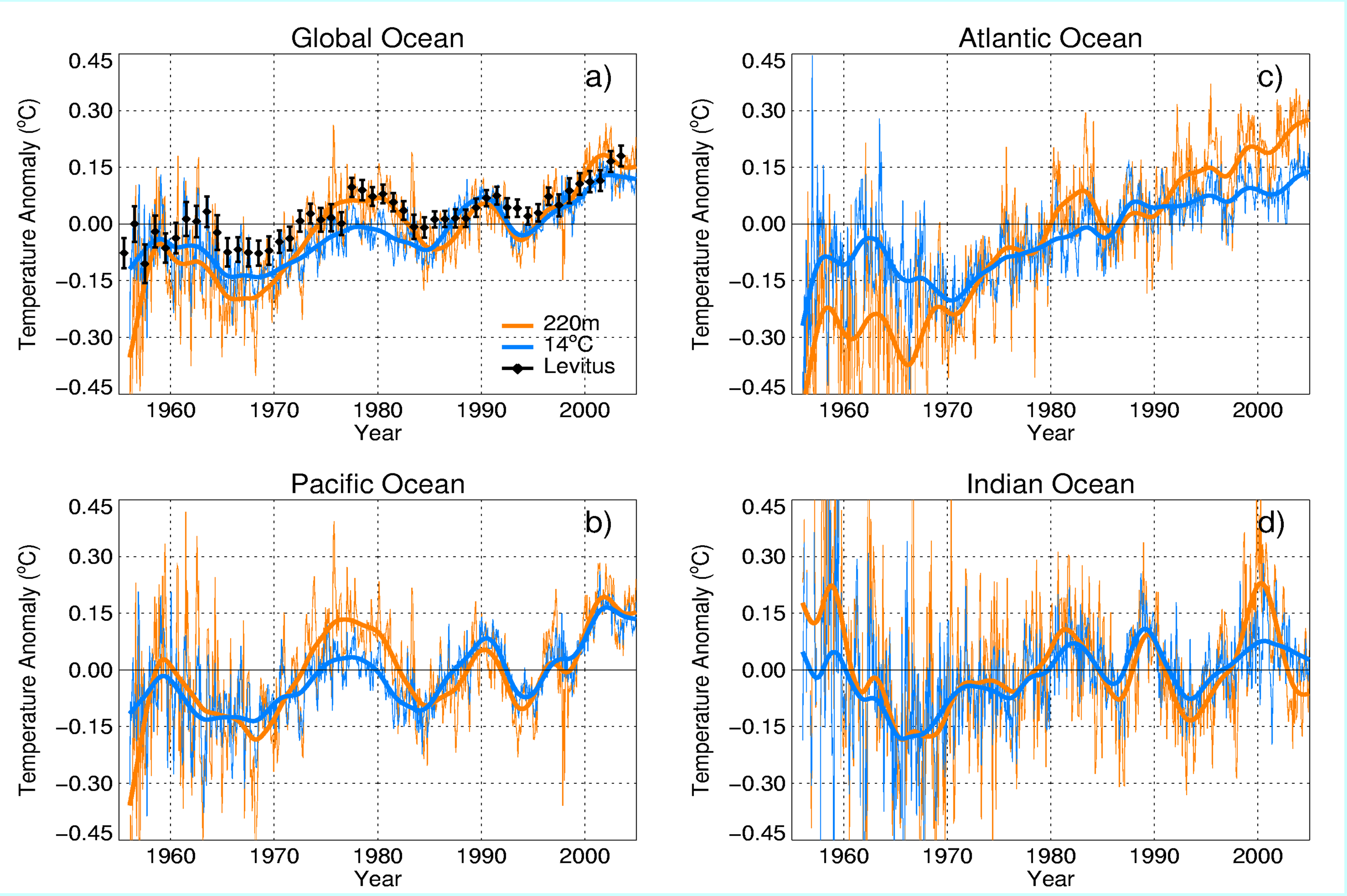

***Figure 1:** Time series of monthly mean temperature anomaly above the 14°C isotherm (blue) and 220m (orange), for: a) Global Ocean; b) Atlantic Ocean; c) Pacific Ocean; and d) Indian Ocean. The thick lines show these data after a 5-year low-pass filter has been applied. These data have been selected to have identical geographical coverage for the 14°C and 220m analyses. Also shown are the annual temperature anomalies with error bars (black) from Levitus et al. [2005] for the upper 300m of the Global Ocean.*

4. Spatial trends

It is clear that the warming trends for the 14°C analysis are more spatially uniform than for the 220m analysis (Figure 2). The area weighted variance about the mean trend is 0.67×10^{-2} and 1.6×10^{-2}°C^2 per decade for the 14°C and 220m analyses, respectively. This difference represents a reduction in the spatial variance of 60% for our new analysis. The 220m mean temperature trends show similar spatial patterns to other recent work [Harrison and Carson, 2007]: notably the warming along the west coast of the Americas; the bands of cooling around 40°N and in the equatorial Pacific; and the dominant warming in the North Atlantic. The regions of cooling are also broadly consistent with heat content trends for the upper 700m, published in the IPCC fourth assessment report [Bindoff et al., 2007]. The spatial pattern of the differences in temperature trends between the 14°C and 220m analyses shows a correlation of 0.77 with trends in the 14°C isotherm depth (Figure 2c) - suggesting a strong link between isotherm depth changes and local heat storage.

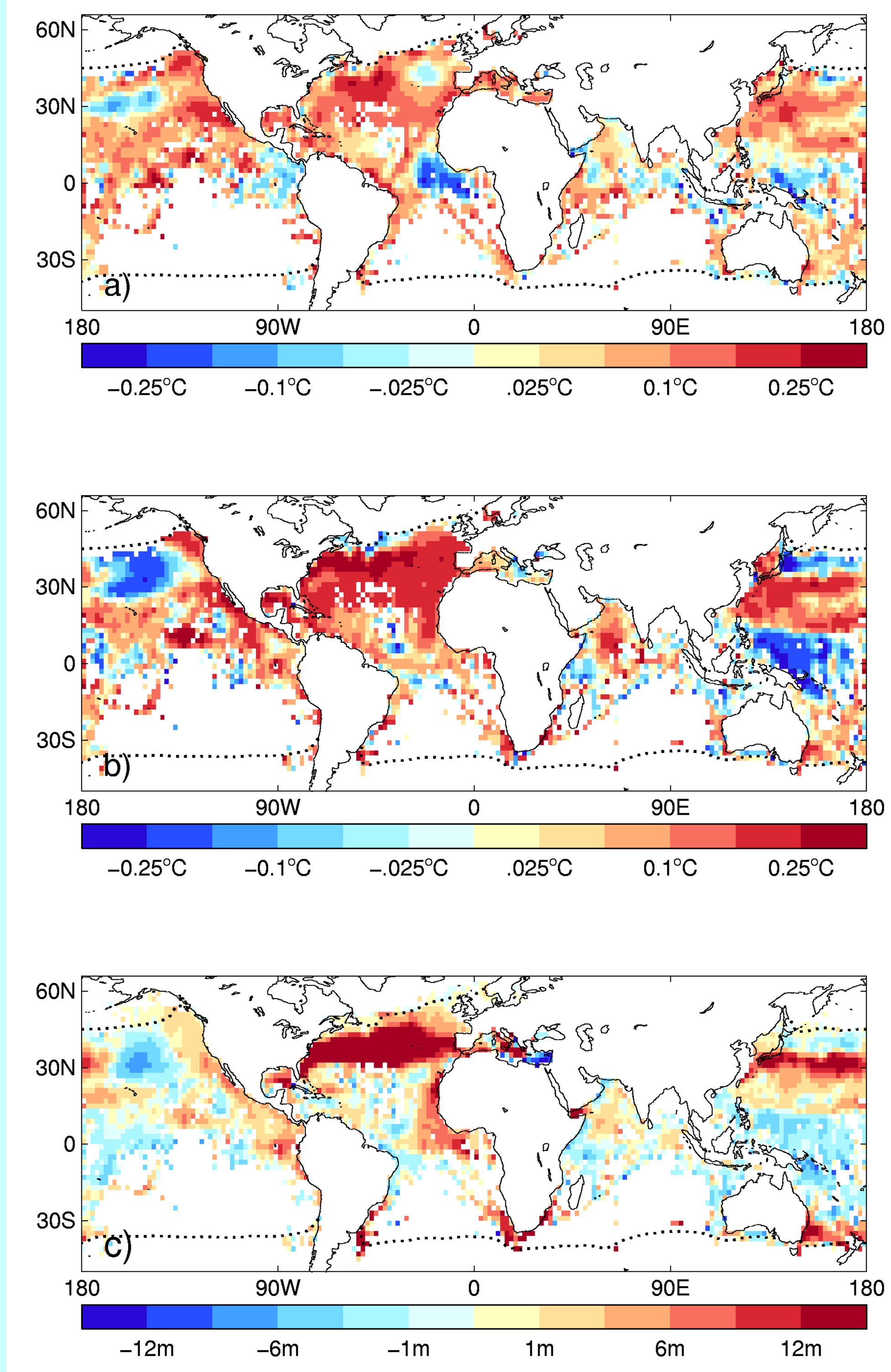

***Figure 2:** a) Trend (°C per decade) in mean temperature above the 14°C isotherm; b) Trend (°C per decade) in mean temperature above 220m; and c) Trend (m per decade) in depth (positive is deepening) of the 14°C isotherm. All trends are computed separately for each 2 ×2 grid box over the period 1965-2004. These data have been smoothed using a 1:2:1 grid box filter to remove some of the grid-scale noise. The dotted lines show the mean position of the 14°C outcrop line for August over the period 1956-2004 from HadISST [Rayner et al., 2003].*

5. Discussion

The analysis of mean temperature above the 14°C isotherm shows a more globally uniform picture of ocean warming over the last 40 years than similar 220m fixed depth analyses, both in terms of trends integrated over the different ocean basins (Table 1) and in spatial uniformity of the local trends (Figure 2). It is the reduction of both high and low frequency variability seen in the time series (Figure 1) that allows these trends to emerge. In a fixed depth analysis contributions to high frequency variability arise from internal waves, mesoscale eddies and rapid variations in wind forced Ekman pumping. Low frequency variations can arise from more prolonged changes in upper ocean circulation. The potential for these phenomena to produce confounding signals in fixed depth estimates of ocean warming is a direct result of dynamical convergence and divergence of upper ocean waters (and vertical heat advection across a fixed depth associated with these processes) combined with the inhomogeneous spatial and temporal observational record. The removal of these sources of variability in the 14°C analyses allows the underlying upper ocean global warming signal due to air-sea fluxes to become dominant in all ocean basins.

An additional advantage of the 14°C analysis is the automatic removal of first-order fall rate errors in XBT data [e.g. Hanawa et al., 1995], which make up a large part of the historical profiles. Fall rate errors are thought to be a major component of the recently documented XBT "warm bias", which may have caused the decadal variability in ocean warming to have been over-estimated [Gouretski and Koltermann, 2007]. We suggest that our new isothermal analyses provide both a more accurate estimate of ocean thermal changes over the twentieth century and a more useful tool for assessing climate model response to greenhouse gas forcing than previous fixed depth analyses.

References:

N. L. Bindoff *et al.*, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. D. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller, Eds. (Cambridge, UK, USA, 2007), chap. 5.

M. E. Conkright *et al.*, "World Ocean Database 2001. Vol 1: Introduction." (*NOAA Atlas NESDIS 42*, U.S. Gov. Printing Office, Washington D.C., 2002).

R. E. Davis, J. T. Sherman, J. Dufour, *J. Atmos. Ocean. Tech.*, **18**, 982 (2001).

V. V. Gouretski, K. P. Koltermann, K.P., *Geophys. Res. Lett.,* **34**, L01610, doi:10.1029/2006GL027834 (2007).

K. Hanawa, P. Rual, R. Bailey, A. Sy, M. Szabados, *Deep-Sea Res.*, **42**, 1423 (1995).

D. E. Harrison, M. Carson, *J. Phys. Oceanogr.*, **37**, 174 (2007).

B. Ingleby, M. Huddleston, *J. Mar. Sys.*, **65**, 158 (2007).

S. Levitus, J. I. Antonov, T. P. Boyer, Geophys. Res. Lett., 32, L02604, doi:10.1029/2004GL021592 (2005).

R. A. Locarnini, A. V. Mishonov, J. I. Antonov, T. P. Boyer, and H. E. Garcia, "World Ocean Atlas 2005, Volume 1: Temperature" (*NOAA Atlas NESDIS 61*, U.S. Gov. Printing Office, Washington D.C., 2006).

N. A. Rayner *et al.*, *J. Geophys. Res.*, **108**, 4407, 10.1029/2002JD002670 (2003).

Acknowledgements: We thank Bruce Ingleby and Ruth Curry for help with processing the EN2 data and John Kennedy for supplying HadISST data. Thanks also to Greg Smith, Helene Banks and Sheila Stark for useful discussions on this work. This work was funded by the UK Department for Environment, Food and Rural Affairs, the Government Meteorological Research and Development Programme, and the Natural Environment Research Council.

Met Office Hadley Centre FitzRoy Road Exeter Devon EX1 3PB United Kingdom
Tel: 01392 885680 Fax: 01392 885681
Email: matthew.palmer@metoffice.gov.uk

[1]Met Office Hadley Centre for Climate Change, Exeter, UK.
[2]NERC Environmental Systems Science Centre, University of Reading, UK.