Multi-model multi-method multi-decadal ocean analyses from the ENACT project

by the ENACT partnership*
*** M. Davey, M. Huddleston, B. Ingleby.(Met Office, UK), K. Haines (ESSC, Reading, UK); P.-Y. Le Traon (CLS, France), A. Weaver (CERFACS, France), J. Vialard (LODYC, France); D. Anderson, A. Troccoli, A. Vidard (ECMWF); G. Burgers. O. Leeuwenburgh (KNMI, Netherlands); A. Bellucci, S. Masina (INGV, Italy); L. Bertino (NERSC, Norway); P. Korn (MPG-IMET, Germany)**
Corresponding author: mike.davey@metoffice.gov.uk

Overview:

The main objective of the European Union ENACT (ENhanced ocean data Assimilation and Climate predicTion) project was to improve the ocean analyses that provide the initial global ocean conditions for seasonal forecasts based on coupled general circulation models (GCMs). Advances were made with regard to the quality of forcing and assimilation data, and with several different data assimilation schemes that were implemented in various ocean GCMs. One major outcome was the production of an ensemble of ocean reanalyses for the period 1962 to 2001, as described in this article. Within the constraints of the experimental design, the ensemble provides estimates of the uncertainty in our knowledge of the ocean state through this period.

Description of the analysis design

The oceans hold much of the information required to predict climate variations at ranges of months to years ahead, so seasonal prediction systems based on coupled GCMs need to be able to make good use of available observations in the calculation of oceanic initial conditions for forecasts. The ENACT aims were to improve the required ocean analyses, and in so doing to generate ocean reanalyses for the past few decades. These reanalyses can be used for retrospective seasonal hindcasts as well as for evaluation to draw climatic inferences about the changing ocean state.

One way of obtaining initial ocean conditions is to force an OGCM with surface fluxes from atmospheric analyses over some period leading up to the time of forecast, usually also including some constraint to observed sea surface temperature (SST). For present purposes, we call this the 'control' method. The next step in complexity is to assimilate ocean observations with a computationally cheap scheme such as a form of optimal interpolation (OI), commonly used by current operational seasonal prediction systems, or a 3D-var variational scheme. With increases in computer power and improvements to algorithm efficiency, it is also becoming feasible to use more advanced assimilation schemes, such as ensemble Kalman filters (EnKF) and 4D-var, with the global coverage and resolution required for forecasting applications. Each of these methods has been applied in the ENACT project, each with substantial improvements made at the development and implementation stages.

Two main periods were defined for study in ENACT: Stream 1 (1987-2001) and Stream 2 (1962-2001). For Stream 1 ocean analyses were produced using all of the assimilation methods listed above: this was also the period selected for the production of sets of CGCM hindcasts with some of the ocean analyses used as initial conditions. Stream 2 corresponds to the ERA-40 atmospheric re-analysis period (1957-2001), with a 5 year adjustment phase before starting data assimilation in 1962. It was not possible to include the EnKF and 4D-var systems in Stream 2 due to their computational expense. A third stream (Stream A, 1993-2001) corresponding to the period for which satellite altimeter data are continuously available was also defined.

The various ocean analyses produced in ENACT are summarised in Table 1 (page 24). The result is a unique multi-model multi-method collection of multi-decadal ocean analysis datasets. Subsets of the data have been archived on a common grid (see appendix), and these are being made available for use by the scientific research community via an OPenDAP/DODS server.

An important feature of ENACT is the use of a common experimental design, with each system using the same observational datasets prepared as part of the project. Daily surface fluxes were obtained from the ERA-40 atmospheric analysis, with a correction to the freshwater flux made to allow for systematic biases. (Comparisons with precipitation observations showed a considerable improvement of the corrected ERA-40 precipitation fields: Troccoli and Källberg, 2004). In situ temperature (T) and salinity (S) datasets were created, using a new quality control system, with data from the World Ocean Database 2001 (WOD01; Conkright et al, 2001). For the period after 1990 additional data were used from; the World Ocean Circulation Experiment (WOCE), Australia (XBT data from 1997), Pacific Marine Environmental Laboratory (Pacific CTD data, Johnson et al. 2002) and GTSPP (used from Jan 2000 onwards as WOD01 coverage tails off). (See Ingleby and Huddleston 2005 for details). The latest version of the in situ dataset is available at http://hadobs.metoffice.com/enact_qc/. An additional by-product of this in situ QC work is a model independent gridded objective analysis, which is denoted ObjA in Table 1.

Another important data source is sea level derived from satellite altimeter measurements. An ENACT partner (CLS) provided improved gridded and along-track sea level anomaly data for the period 1992-2004. Additionally, a mean dynamic topography for 1993-1999 was produced, to provide an absolute reference sea level, and sea level anomaly data were provided for 1986-1989 based on reprocessed GeoSat data.

One problem that was addressed in the design of the ENACT analyses was that of ocean model drift. Without some form of constraint the ocean states in OGCMs tend to drift away from reasonable values. Only where large amounts of ocean data are available can the assimilation be sure to control this problem. The best-observed oceanic field is SST, and we decided to use a strong constraint to observed SST in the form of a relaxation term with a coefficient of 200 $Wm^{-2}C^{-1}$. Even with SST information and assimilation of other data, the sparseness of observed data (particularly S) means that substantial drift still occurs if some form of limitation is not used: moreover, such drift can cause data rejection and degradation of the assimilation process. On the other hand, overly-strong limitations to avoid drift would unrealistically suppress variability on interannual and decadal timescales. After some experimentation, we decided to use a relaxation of subsurface T and S to climatological values (using a running 3-month average climatology derived from the Levitus 1998 gridded dataset), with a 3 year e-folding timescale. This relaxation also effectively sets an upper limit to the memory of the model for the data being assimilated. (For OGCM stability reasons, some minor variations to this strategy were needed in some systems: details are in the full report.) These surface and sub-surface constraints were applied to all the ENACT dynamical analyses, with and without data assimilation. Further work is underway post-ENACT to try to reduce artificial relaxation to a minimum so as to recover more long-timescale variability in the ocean analyses.

Example results for 1962-2001

The ocean analysis datasets are being investigated, both individually and collectively: various results are in the final report and in publications by the partners. To aid assessment we defined a set of 23 oceanic subregions. This article presents a few illustrative collective examples, which provide information regarding the consistency of the analyses, and the accompanying uncertainties.

Fig. 1, page 16, shows 40-year timeseries of upper ocean globally-averaged T anomalies from the longer Stream 2 analyses (hence not all analyses are represented). The anomalies are calculated from monthly-average T fields. The monthly climatology is subtracted in each dataset here to emphasise the interannual behaviour, and averages are taken over the upper 300m. The figure contains three basically different types of analysis. Those labelled ‘CTL’ (control) in the legend are analyses from three different OGCMs with no use of subsurface data assimilation: the interannual variability in these datasets is determined entirely by the surface forcing and the SST relaxation. The one labelled ‘Obj Analysis’ is the objective analysis calculated from the in situ data alone, with no use made of an OGCM or surface forcing or SST information. Note that apart from some light use of the Levitus 1998 subsurface climatology in each case, the ‘CTL’ group is independent of the ‘Obj Analysis’ results. The other timeseries in Fig. 1 are analyses from 6 combinations of OGCMs and assimilation schemes: we shall refer to this as the ASSIM group. (Note: the two contributions from INGV have very similar temperature, but differing salinity.)

Although the analyses in the ASSIM group (that all used in situ ocean T observations) differ in a noisy fashion from month to month, they are quite consistent with each other on interannual timescales, with decadal variability being the dominant feature. (This decadal variability is consistent with that described elsewhere: e.g. Levitus et al. 2005.)

The temporal standard deviations of each of these analyses (indicated in the legend) are quite similar. The ObjA timeseries is very similar to this group. This indicates that the observational data are sufficient to define the broad characteristics of this global-average quantity as reproduced by the assimilation models, and that there are no gross inconsistencies between the model-generated analyses and the data.

The spread each month of the ASSIM and ObjA data is indicated in Fig. 1 by the shading with +/-2 standard deviation limits. This spread is one measure of the uncertainty of monthly-average global-upper-ocean T, with values typically between 0.05 and 0.1C: substantially less than the range of decadal variability. Note: these values are likely to be an underestimate of the true uncertainty, because all analyses used the same forcing. (Note also the relatively large spread in the first few months, as assimilation ‘spins up’ in each model.)

The three CTL timeseries also show a high degree of consistency with each other, but there are some notable differences between the CTL group and the other global-average analyses. The CTL group is slightly warmer in 1969-71 and (more noticeably) in 1984-90, and clearly cooler from 1996 onward, with a distinctly weaker warming trend. At other times the CTL and ASSIM behaviour is quite similar. The differences have important implications, suggesting that the ocean GCMs may have deficiencies in the processes that propagate surface conditions (which are well controlled by SST relaxation) to the upper ocean. (The recent warming differences in Fig. 1 between CTL and ASSIM groups are partly due to the double-correction of the fall rate of some XBT data from 1995 onwards in the in situ dataset: see below.) The regional results for upper ocean temperature similarly show overall high consistency between the various analyses, and episodic differences. (Some episodes of larger-than-usual regional spread are: South Pacific in 1965-66; North West Subtropical Pacific after 1998; North East Atlantic 1972-74; North West Atlantic 1998-2000). Spreads are largest in the southern oceans, where data are sparse and trends are not obvious or well defined. Note: the various regions have a wide variety of behaviour, with interannual variability substantially larger than the global average: in recent years some regions are cooling rather than warming, as described in e.g. Willis et al. 2003, Levitus et al. 2005. An example is provided in Fig. 2, page 16, for the NE Atlantic region (30N-60N, 40W-0E) for Stream 2: note the larger temperature scale relative to Fig. 1.

With regard to upper ocean salinity, there is typically a large spread in the monthly analysis values: often larger than the temporal interannual variability of anomalies. This spread reflects the very sparse nature of salinity observations and also the differing representations of hydrological processes and sources in the analysis systems. Note that unlike T there was no constraint to surface S observations – the uncertainty in S emphasises the need for satellite-derived surface salinity observations. Again, the true uncertainty is likely to be even larger than that of our ensemble: all our models used the same surface fluxes, which undoubtedly also have substantial uncertainties.

The example in Fig. 3, page 16, shows timeseries of upper ocean (0-300m) monthly salinity anomalies averaged over the NE Atlantic region for Stream 2. (Note that 3 of the 6 ASSIM analyses shown assimilated S observations as well as T, as denoted by T+S in the legend.) The analyses have widely varying behaviour: the only common feature is the dip in salinity in the 1970s associated with the ‘Great Salinity Anomaly’ (Dickson et al. 1988), which is evident in the CTL group as well as the ASSIM and ObjA results, but especially in the ECMWF T+S ASSIM. (The ECMWF T+S analysis made use of a new algorithm treating salinity assimilation differently to temperature: Haines et al. 2006.) It would be difficult to deduce any reliable decadal trends from this evidence if all the results are equally trusted. With the advent of improved observational salinity data coverage from the Argo network after 2001 this uncertainty should decrease substantially. The S analyses in some other regions have better defined collective interannual variability than this example, notably in the tropics where substantial interannual vertical displacements can provide consistent S signals in ASSIM, CTL and ObjA.

As well as the anomaly behaviour, the climatological mean values (not shown here) are of interest. In particular, the CTL analyses contain differing systematic model-dependent biases that the assimilation of observations should correct. For globally-averaged upper ocean T, averaged over the Stream 2 period, the mean CTL values are up to two tenths of a degree warmer than their ASSIM counterparts: regional differences can be larger. In some areas assimilation reduces the spread in mean temperature values, but increases the spread in mean salinity values. Model error, data sparseness and the variety of assimilation methods all contribute to the spread in the mean salinity values.

Effect of XBT fall rate correction from 1995 on

As noted above, there is an error involving double correction of some XBT fall rates from 1995 onwards in the in situ dataset developed and used in ENACT. The error means that temperatures are biased higher. Regionally the effect is clearly evident in the subtropical Pacific and Indian regions, but is small (compared to interannual variability) in other areas: e.g. the bias is less than 0.05C averaged monthly over the NE Atlantic region. The dataset has since been corrected. The error is quantified in Fig. 4, which shows the globally averaged upper 300m T timeseries (with monthly mean climatology removed, but annual mean climatology retained) for 1984-2005 for the objective analysis from the ENACT dataset, and for the objective analysis from the revised dataset (i.e. the ENSEMBLES dataset described in Ingleby and Huddleston 2005). (Similar regional timeseries are available at the Met Office website cited above.) From Fig. 4 it is clear that the error resulted in higher analysed global upper ocean T values from 1995 on, with the error decreasing after 2001 as increasing amounts of Argo data become available. The global upper ocean temperature rise in Fig. 1 in the ASSIM and ObjA timeseries after 1995 is increased by this effect.

Summary

Using a mix of models and assimilation schemes, a number of global ocean analyses have been produced in a common framework as a major part of the ENACT project. The result is a unique dataset that is being made available for investigations of ocean climate, variability, uncertainty and processes. The monthly average data (see appendix) are being provided on an OPenDAP/DODS server: see http://www.ecmwf.int/research/EU_projects/ENACT/index.html for details. Some data are also available on a Live Access server with a graphical interface at http://www.nerc-essc.ac.uk/godiva/ . Full details of the ENACT project can be found in the final report, available at the Met Office and ECMWF websites listed.

The advances in ocean analysis made in ENACT are being continued with further development and application to long-range forecasting in the EU ENSEMBLES project (http://www.ensembles-eu.org/), and it is planned to update and extend the current sets of analyses.

No single combination of OGCM and assimilation method is clearly 'the best': each has various advantages and disadvantages. In the context of seasonal forecasting, the advantages of a 'multi-model' approach were clearly demonstrated in the EU DEMETER project (http:// www.ecmwf.int/research/demeter). The developments in ENACT both serve such forecast multi-models and form the first steps in multi-model ocean analysis and monitoring.

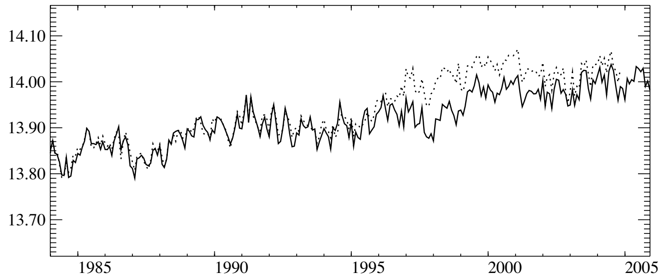

Figure 4: Time series of globally-averaged upper ocean (0-300m) temperature, with the monthly mean annual cycle removed, for 1984-2005, from the ENACT objective analysis (dashed) and from the objective analysis derived from the corrected in situ dataset (solid)

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centre	stream	Data	scheme	OGCM
CERFACS	S1	T, TS	3D-Var, 4D-Var	OPA
	S2	T, TS	3D-Var	
LODYC	Sa	A	4D-Var	OPA
INGV	S1	T	OI	OPA
	S2	T, TS	"	
	Sa	A	"	
NERSC	Sa	A	EnKF	OPA
ECMWF	S1	T, TS	OI	HOPE-E
	S2	T, TS	"	
	Sa	TSA	"	
KNMI	S1	TSA	EnKF	MPI-OM
MPIM	Sa	A	3D-Var	MPI-OM
Met Office	S1	TS	OI	GloSea
	S2	TS	"	(UM)
	Sa	TSA	"	
	1956-2001	TS		ObjA

Table 1: ocean analyses produced in ENACT.

S1 indicates stream1 (1987-2001); S2 is stream 2 (1962-2001); Sa is the satellite stream (1993-2001). T denotes assimilation of in situ temperature data, S salinity, A sea level anomalies from altimeter data. OI denotes use of a type of optimal interpolation assimilation scheme, EnKF denotes an ensemble Kalman filter scheme, ObjA denotes an objective analysis.

For each model there is also a control analysis for which no ocean in situ or sea level data were assimilated. For OPA a control analysis with a higher resolution OGCM version was also produced for comparison.

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Appendix: common data

Common output grid and data:

A common grid similar to the 'Levitus' grid was designated for the post-processed output of select data fields listed below. The grid has one degree horizontal resolution with longitude gridpoints from 0 to 359 and latitude gridpoints from -89 to +89. (There is thus a 0.5 degree latitude shift with respect to the original Levitus grids, to retain points at the equator and at the precise TAO mooring locations). The vertical resolution is as Levitus, with 31 levels at the following depths:

0, 10, 20, 30, 50, 75, 100, 125, 150, 200, 250, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300, 1400, 1500, 1750, 2000, 2500, 3000, 3500, 4000, 4500, 5000, 5500 metres.

Monthly average output data (3D fields)

Potential temperature referenced to the surface (degC); salinity (psu); zonal and meridional velocity components (m/sec), vertical velocity (m/day).

Daily average output data (2D fields):

Sea level (m), SST (degC), surface solar and non-solar heat flux applied as forcing (W/m^2), surface net heat flux (including the SST relaxation term, W/m^2), surface freshwater flux forcing (mm/day), surface net freshwater flux (mm/day), zonal and meridional wind stress (N/m^2), depth of the 20C isotherm (m).

Obituary: Kirill Kondratyev

On 2 May, the ICPO was informed in an email from Tatyana Rotanova, forwarded by Lennart Bengtsson, that Kirill Kondratyev had passed away on 1 May. I have fond memories of meeting and having lunch with Kirill and his wife during the period of the 25 session of the Joint Scientific Committee for WCRP in March 2004. Below, we print the full text of Tatyana's email in tribut to Kirill Kondratyev.

Howard Cattle

Hereby we grievously inform you about the premature decease of Kirill Kondratyev that occurred on the 1st of May, 2006. Our friend and colleague, Kirill Kondratyev was a famous scientist, full Academician of the Russian Academy of Sciences, an acknowledged expert in the area of climate and environment. He is the author of more than one thousand papers in the most prestigious journals as well as of more than hundred monographs and textbooks published in the former USSR, Russia and abroad.

The area of scientific interests of Kirill Kondratyev was extremely broad encompassing the theory of transfer of thermal radiation through the atmosphere, green-house effect, natural and man-induced catastrophes, remote sensing of environment and global climate change.

Kirill Kondratyev was the honorary member of the American Meteorological Society, Royal Meteorological Society of the Great Britain, Academy of Natural Sciences "Leopoldina" (Germany), foreign member of the American Academy of Arts and Sciences, member of the International Astronautic Academy, honorary Doctor of Sciences of the Universities of Lile (France), Budapest (Hungary) and Athens (Greece). During many years he was editor-in-chief of the Russian Journal (Earth Observations and Remote Sensing", he also was member of the editorial board of such journals as "Optics of the atmosphere and ocean", "Proceedings of the Russian Geographical Society", "Meteorology and Atmospheric Physics" (Austria), "Idojaras" (Hungary), "Il Nuovo Cimento C "(Italy), "Atmosfera" (México), "Energy and Environment" (Great Britain).

For his salient scientific attainments Kirill Kondratyev was awarded with the State Award of the USSR, and decorated with a gold medal by the World Meteorological Organization, the Simons gold medal by the Royal Meteorological Society of the Great Britain.

During first 30 years of his scientific career, Kirill Kondratyev was insolubly related to the State University of Leningrad, where he made a way from a professor assistant to the rector of the university. An important part of his activities was also related to the A.I. Boeykov Main Geophysical Observatory.

The next 30 years were tied up with his work at the Institute of Limnology and the Center for Ecological Safety, Russian Academy of Sciences. The latter was the last affiliation of Kirill Kondratyev, where he held the position of the Counsellor of the Russian Academy of Sciences.

Kirill Kondratyev was one of the founders of the Nansen International Environmental and Remote Sensing Centre (NIERSC) in St. Petersburg. For many years he was a co-chairman of NIERSC.

Kirill Kondratyev was participant of Second World War. He was decorated with the honorary sign as a defender of Leningrad, the Order of Lenin, two orders of the Labor Red Banner, order of the Patriotic War and many others.