

Development of Ice-Ocean Reanalyses Using the $S(T)$ Assimilation Method

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Main Aim: to produce a multi-decadal high-resolution global ocean reanalysis using physically-motivated assimilation techniques and to use this reanalysis to reconstruct water mass variability and study ocean climate signals.

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1. Introduction

Ocean assimilation is of great importance for both initialising operational oceanography and coupled models for seasonal forecasting. In addition, ocean reanalysis can aid in the detection of climatically important signals from the diverse historical ocean data that are available.

Our focus is on improving the realism of ocean data assimilation schemes and using assimilation to investigate ocean climate signals. In particular, we examine the benefits of combining temperature (T) and salinity (S) assimilation methods and of assimilating $S(T)$ as the observable property. This allows us to exploit the larger spatial and temporal decorrelations of this quantity, compared with $S(z)$, allowing flow dependent assimilation and recovery of water mass information.

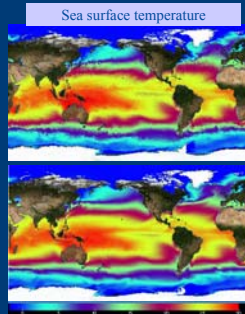


Fig. 1: 5-day mean sea surface temperature from (a) the 1/4° resolution reanalysis (top panel), and (b) the 1° resolution reanalysis (bottom panel)

2. $S(T)$ Assimilation Method

Standard method:

$$1. T_a(z) = T_b(z) + K_T [T_o(z) - H T_b(z)]$$

$$2. S_a(z) = S_b(z) + K_S [S_o(z) - H S_b(z)]$$

$S(T)$ algorithm:

$$1. T_a(z) = T_b(z) + K_T [T_o(z) - H T_b(z)]$$

$$3. S'_a(z) = S_b(z) + \Delta S_{S(T)}$$

} from T obs

$$4. S_a(z) = S'_a(z) + K_S [S_o(z) - H S_a(z)]$$

} from S obs

• Here, 'a', 'b' and 'o' refer to analysis, background (before assimilation) and observed values of temperature (T) and salinity (S). K_T and K_S are gain matrices evaluated on depth and temperature levels respectively

• The salinity balance increment (Eq. 3) maintains water mass properties (i.e. $S(T)$) in the absence of salinity data.

• The $S(T)$ increment (Eq. 4) is independent from the balance increment and acts to correct water mass properties directly. Additionally, this allows the spreading of increments over greater distances due to longer covariance scales of $S(T)$.

Implementation Details

- Assimilate *in situ* temperature and salinity data only
- Observations from quality-controlled ENSEMBLES data set
 - Produced by UK MetOffice
 - EN3_v1c (Inglis and Huddleston, 2007)
- Uses NEMOVAR online observation operator (FGAT)
- Simplified Analysis Correction Method (Lorenc, 1991)
 - Implemented within NEMO code for z and T levels
- Spatially-varying length scales (Carton et al., 2000):
 - ZONAL: 450km tropical to 375km mid-latitudes
 - MERID: 250km tropical to 375km mid-latitudes
- T -level increments only used between 40N-40S
 - Outside this region z -level increments are used.
 - z -level increments also applied over upper 100m.
- 5-day assimilation cycle with 1-day incremental analysis updating.

NEMO Model and Forcing Details

- OPA9 ocean model
 - 46 z -levels (thicknesses from 6m-250m)
 - free surface, partial steps, energy-ctrophy conserving momentum advection, TKF vertical mixing
- LIM2 ice model
 - 3-layer model (2 ice, 1 snow)
 - Dynamic-thermodynamic
- Global tripolar grid
 - ORCAO25: Global 1/4° resolution
 - ORCA1: Global 1° resolution
 - Tropical enhancement to 1/3°
- DRAKKAR Forcing Set 3 (DFS3): (Bjodeu et al., 2008)
 - T,Q,U,V: ERA40/ECMWF Operational Analyses
 - Qlw, Qsw, Precip, Snow : CORE (ISCCP), with reduction applied to precipitation at high latitudes
 - 60 day / 10m SSS relaxation

4. $S(T)$ Reanalyses

Using the $S(T)$ assimilation method (Box 2), two reanalyses have been produced:

- 1° reanalysis from 1958-2007
- 1/4° reanalysis from 1987-2007

Both the 1° and 1/4° control simulations show a downward drift in heat content anomaly (Fig. 4), which is corrected with assimilation. In fact, both reanalyses show a significant warming trend and are in good agreement with the estimates from observations (Levitus et al., 2005) and other reanalyses (Carton and Stanorelli, 2008).

Note: The 47-year 1/4° control run shown here is the simulation produced by the DRAKKAR Consortium (Barnier et al., 2008) known as ORCAO25-G70.

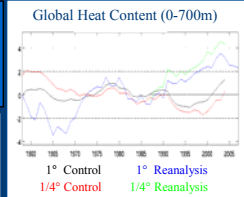


Fig. 4: Global ocean heat content anomaly ($\times 10^{18} \text{ Jm}^{-2}$) integrated from 0-700m. The anomalies for the 1/4° reanalysis are shown relative to the mean for the 1/4° control to highlight the impact of assimilation.

5. Global Synthesis Intercomparison

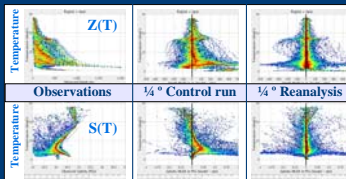


Fig. 5: Probability density functions (PDF) of (top row) observed isotherm depth and the PDFs of misfits for the 1/4° control and reanalysis runs for the North Pacific Ocean. The bottom row shows the PDFs of observed $S(T)$ and misfits for the control and reanalysis runs. For a given isotherm, the colours indicate the log of the probability. Comparisons are made using data from the ENSEMBLES dataset for September 2004.

By evaluating model differences from observations as a function of isotherm, a more accurate assessment of the thickness and position of water masses (i.e. $z(T)$) and their properties (i.e. $S(T)$) can be obtained. In the North Pacific, the $S(T)$ analysis reveals mode water errors in the 1/4° control run which are mostly corrected in the reanalysis (Fig. 5, horizontal bar at 17°C in $z(T)$). In addition, a large saline bias is found in the water mass properties of the control (between 3-10°C), which is eliminated in the reanalysis. These errors are present to varying degrees in the various reanalysis products due to differences in the models and assimilation methods used (Fig. 6). In particular, syntheses which use long-window adjacent methods (ADVAR), such as in the ECCO project, tend to show characteristics more akin to the control simulations, whereas sequential methods show a tighter fit to observations.

As part of the CLIVAR Global Synthesis and Observations Panel (GSOP) Intercomparison a new web-based tool, OceanDIVA (Gemmell et al., 2008) was designed to assess water mass properties across a number of ocean synthesis products. This tool provides a framework for evaluating the agreement of different syntheses with a given set of observations via OPENDAP (www.rdg.ac.uk/oceandiva).

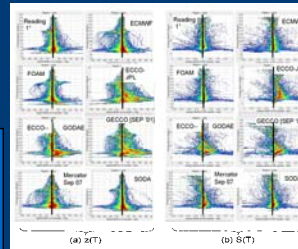


Fig. 6: Probability density functions (PDF) of misfits in (a) isotherm depth, $z(T)$, and (b) water properties, $S(T)$, for various ocean reanalyses. For a given isotherm, the colours indicate the log of the probability. Comparisons are made using data from the ENSEMBLES dataset for September 2004.

6. Arctic IPY Studies

Work is underway as part of the IPY ASBO and EU-DAMOCLES projects to use the $S(T)$ reanalyses to investigate the Arctic freshwater budget and exchanges with the Atlantic.

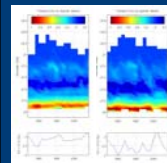


Fig. 7: Denmark Strait transport as a function of density class for the 1/4° control (left) and reanalysis simulations (right). The bottom row shows transports for waters with a density greater than 27.8 kg/m^3 .

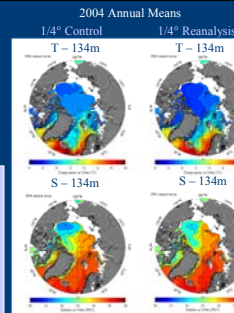


Fig. 8: 2004 Annual mean temperature (top row) and salinity (bottom row) for the 1/4° control (left) and reanalysis (right) simulations.

3. Evaluation against climatology and *in situ* data

A series of 3-year experiments (Table 1) were performed over the period 2002-4 to test the impact of the different assimilation increments (Eq. 1-4), as well as to evaluate the influence of Argo observations (Smith and Haines, 2008). Note the large differences with climatology present in the control simulation (Ct), which are corrected by the assimilation (Fig. 2). When Argo data is withheld, a significant benefit from $S(T)$ assimilation is found in the subtropical North Atlantic and tropical Pacific Oceans (Fig. 3). These results highlight the importance of $S(T)$ assimilation for historical reanalysis in the pre-Argo period.

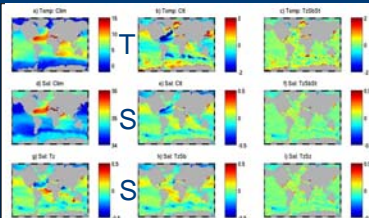


Fig. 2: Temperature (upper) and salinity (lower) fields averaged over 300-1000m for the World Ocean Atlas 2001 climatology (left column), and annual-mean 2004 model anomalies from this climatology for the 1° resolution model control run (no assimilation; centre column) and (right column).

Experiment	T_a (Eq. 1)	S_a (Eq. 3)	S'_a (Eq. 4)	S_a (Eq. 2)	Argo
Ct	✓	✗	✗	✗	✗
Tz	✓	✗	✗	✗	✗
TzSb	✓	✓	✗	✗	✓
TzSbSt	✓	✓	✓	✗	✓
TzSz	✓	✗	✗	✓	✓
TzSbSt-A	✓	✓	✓	✗	✓
TzSz-A	✓	✗	✗	✓	✗

Table 1: List of 3-year experiments over the period 1 January 2002 to 31 December 2004. All runs were performed using the DFS3 forcing (see Box 2), and initialized from the end of a 44-year free model run. The columns indicate which assimilation increments are applied for each experiment, where T_a refers to temperature assimilation (Eq. 1), S_b to the balance salinity increment (Eq. 3), S'_a to salinity assimilation along isotherms (Eq. 4), S_z to depth level assimilation (Eq. 2), and the last column indicates whether Argo data was assimilated.

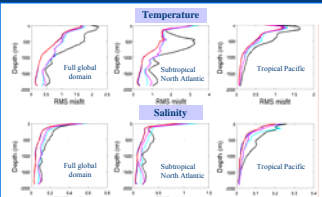


Fig. 3: Root-mean-squared (RMS) misfits of temperature (upper) and salinity (lower) for the 1° resolution model experiments (see Table 1 for descriptions). Comparisons are made over the period 2002-4 using the model background (i.e. before observations are assimilated).

7. Summary

The $S(T)$ algorithm has been implemented into the NEMO global ice-ocean model and two reanalyses have been made: a 50-year reanalysis at 1° resolution, and a 21-year reanalysis at 1/4° resolution. Overall, the assimilation is able to prevent drifts in many ocean metrics, and brings the model in better agreement with accepted values. An evaluation of water mass properties in various ocean syntheses performed as part of the CLIVAR-GSOP intercomparison, shows that the $S(T)$ reanalyses provide excellent agreement with *in situ* observations.

References

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