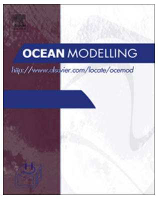
Ocean Modelling 67 (2013) 52–70

Contents lists available at SciVerse ScienceDirect

Ocean Modelling

journal homepage: www.elsevier.com/locate/ocemod



Towards a dynamically balanced eddy-resolving ocean reanalysis: BRAN3

Peter R. Oke [a,*], Pavel Sakov [b], Madeleine L. Cahill [a], Jeff R. Dunn [a], Russell Fiedler [a], David A. Griffin [a], Jim V. Mansbridge [a], Ken R. Ridgway [a], Andreas Schiller [a]

[a] CSIRO Marine and Atmospheric Research and Wealth from Oceans Flagship Program, Hobart, Tasmania, Australia
[b] Bureau of Meteorology Research Centre, Melbourne, Victoria, Australia

ARTICLE INFO

Article history:
Received 17 December 2012
Received in revised form 22 March 2013
Accepted 24 March 2013
Available online 12 April 2013

Keywords:
Ocean reanalysis
Data assimilation
Ensemble Optimal Interpolation
GODAE
Operational Oceanography

ABSTRACT

The generation and evolution of eddies in the ocean are largely due to instabilities that are unpredictable, even on short time-scales. As a result, eddy-resolving ocean reanalyses typically use data assimilation to regularly adjust the model state. In this study, we present results from a second-generation eddy-resolving ocean reanalysis that is shown to match both assimilated and with-held observations more closely than its predecessor; but involves much smaller adjustments to the model state at each assimilation. We compare version 2 and 3 of the Bluelink ReANalysis (BRAN) in the Australian region. Overall, the misfits between the model fields in BRAN3 and observations are 5–28% smaller than the misfits for BRAN2. Specifically, we show that for BRAN3 (BRAN2) the sea-level, upper ocean temperature, upper-ocean salinity, and near-surface velocity match observations to within 7.7 cm (9.7 cm), 0.68 °C (0.95 °C), 0.16 psu (0.18 psu), and 20.2 cm/s (21.3 cm/s) respectively. We also show that the increments applied to BRAN3 – the artificial adjustments applied at each assimilation step – are typically 20–50% smaller than the equivalent adjustments in BRAN2. This leads us to conclude that the performance of BRAN3 is more dynamically consistent than BRAN2, rendering it more suitable for a range of applications, including analysis of ocean variability, extreme events, and process studies.

1. Introduction

The mesoscale ocean circulation is dominated by the generation, evolution, interaction, and decay of eddies. Eddies typically develop as a result of instabilities associated with either the horizontal shear of the circulation – barotropic instabilities; or vertical shears – baroclinic instabilities (e.g., Lee et al., 1991; Marchesiello et al., 2003; Feng et al., 2005). These instabilities are unpredictable, even on short time-scales (e.g., O'Kane et al., 2011). Data assimilation is therefore a necessary tool for initialising and constraining an ocean model to realistically reproduce the mesoscale ocean circulation in either eddy-resolving or eddy-permitting models (e.g., Carton et al., 2000; Oke et al., 2005; Ferry et al., 2007; Carton and Giese, 2008). A free running model, without data assimilation, can produce realistic mesoscale variability - but without data assimilation, a model will not reliably reproduce particular "eddy events", with eddies in the correct place and time, with the correct intensity and characteristics. Most applications of data assimilation involve the sequential adjustment of the model state to keep it aligned with observations (e.g., Dombrowsky et al., 2009; Zhang et al., 2010; Moore et al., 2011). These updates inevitably interfere with the dynamic balance of the model (e.g., Balmaseda and Anderson, 2009; Oke and Griffin, 2011). The adjustments act as a source of momentum, heat and freshwater that is not easily associated with any specific dynamical process. This makes the use of a data assimilating model for understanding processes somewhat problematic. It is therefore a common goal of a data assimilating model to reduce the magnitude of the adjustments, without compromising the fit to observations. Some data assimilating studies have modified the forcing fields and model parameters, rather than the model state (e.g., Stammer et al., 2002; Koehl et al., 2007; Di Lorenzo et al., 2007; Moore et al., 2009). However, the efficacy of these approaches for eddy-resolving applications, where instabilities are prevalent, is unclear. As a result most data assimilating eddy-resolving models, even those based on variational methods, use a sequential approach involving explicit updates to the model state (e.g., Kurapov et al., 2009, 2011; Cummings et al., 2009; Zhang et al., 2010; Moore et al., 2011; Yu et al., 2012). In this study, we present an evaluation of a second generation reanalysis system that is shown to match observations more closely than the first generation system, even though the adjustments during the assimilation step are smaller. This development is a continuation of the Bluelink effort (Schiller et al., 2009a), that was founded under GODAE (Smith, 2000), and continues under GODAE OceanView (www.godae-oceanview.org).

More specifically, we compare the performance of the two most recent versions of the Bluelink ReANalysis (BRAN) – versions 2p1 and 3p5 – hereafter BRAN2 and BRAN3. BRAN is a multi-year integration of the Bluelink ocean model, called the Ocean Forecasting

---

* Corresponding author. Tel.: +61 3 6232 5387; fax: +61 3 6232 5123.
E-mail address: peter.oke@csiro.au (P.R. Oke).

1463-5003/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ocemod.2013.03.008

Australian Model (OFAM); and the Bluelink Ocean Data Assimilation System (BODAS; Oke et al., 2008). OFAM and BODAS are combined by sequentially running the model for several days, then combining a model field with observations of sea-level anomaly (SLA), sea-surface temperature (SST), and in situ temperature and salinity from a range of sources. BRAN can be thought of as an observation-based estimate of the ocean circulation, where the model is being used to interpolate between observations that are sparse in time and space, while also extrapolating the observations to provide estimates of unobserved variables. Analogous analyses of ocean observations exist for single variables (e.g., Le Traon et al., 1998) that have no constraint to dynamics, and multiple variables (e.g., Guinehut et al., 2004, 2006; Ridgway and Dunn, 2010) that attempt to respect the ocean water mass properties and linear dynamics (e.g., geostrophy). By contrast, the type of reanalyses presented here (e.g., Ferry et al., 2007; Oke et al., 2008; Schiller et al., 2008; Balmaseda et al., 2013) use primitive equation dynamics to fit data. The risk of this approach is that the penalty for overfitting the data is potentially much greater (e.g., numerical instability). We therefore monitor this closely by analysing the model mismatch to unassimilated data; and the size of the shocks during each assimilation cycle.

Results from the first BRAN experiment (BRAN1p0; Oke et al., 2005), a 12-year reanalysis, showed that the Bluelink system could produce three-dimensional, time-varying fields that are qualitatively consistent with the real ocean. The configuration of BRAN1p0 was quite immature, and as a result, the model was poorly constrained by observations. The system was refined for BRAN1p5, spanning only 2003–2006, with the addition of the assimilation of SST and other minor changes, resulting in a reanalysis that was closer to observations, but was still poorly constrained (Oke et al., 2008). One of the limitations of BRAN1p5 was the initialisation. BRAN1p5 used a simple Newtonian nudging to initialise the model after each assimilation. This was a conservative approach that succeeded in eliminating much of the "noise" (model-shock) generated after each assimilation, associated with the dynamic imbalance introduced during the update step, but resulting in observations being under-fitted. Version 2p1 of BRAN (Schiller et al., 2008, BRAN2), covered the period 1993–2006, and was largely based on BRAN1p5, but included a few moderate changes to the background error estimates, the initialisation (but still used nudging), and some changes to the model. Like BRAN1p5, BRAN2 under-fitted observations and showed a tendency for the eddies to be somewhat discontinuous in time – a characteristic that is clearly related to the dynamical imbalance introduced after each assimilation. The latest version of BRAN – version 3p5 that is first described here, includes changes to the initialisation (Sandery et al., 2011), localisation method, the assimilation algorithm, and pre-processing of observations and improvements to their error estimates.

In this paper, the model is described in Section 2, and the important aspects of the data assimilation system, including the differences between the BRAN2 and BRAN3 configurations, are described in Section 3. An overview of the assimilated observations is presented in Section 4, followed by a series of comparisons between both assimilated and withheld observations with model fields from BRAN2 and BRAN3 in Section 5. An analysis of the increments, or data assimilation adjustments, in Section 6, then the conclusions in Section 7. The technical details of the assimilation and data-processing are described in Appendix A.

2. Model

The Bluelink ocean model, called the Ocean Forecasting Australia Model (OFAM), has been developed over many years. The first and second versions of OFAM (OFAM1 and OFAM2) are eddy-resolving in the 90°-sector centred on Australia and south of about 20°N. In this study we present results from BRAN2, using OFAM1 – spanning January 1993 to December 2006; and BRAN3, using OFAM2 – spanning January 1993 to September 2012. The key differences between the model used for BRAN2 and BRAN3 are listed in Table 1.

OFAM1 and OFAM2 are configurations of the GFDL Modular Ocean Model (Griffies et al., 2004, OFAM1 uses MOM40d; OFAM2 uses MOM4p1). To date, all versions of OFAM have been developed for analysis and prediction of the upper ocean circulation, so OFAM2 (OFAM1) has 5 m (10 m) vertical grid spacings at the ocean surface and graduated to 10 m vertical grid spacings over the top 200 m. The horizontal grid spacings are 1/10° between 90–180°E and south of about 20°N; 1° across the rest of the Indian Ocean and the Pacific to 60°N; and 2° in the Atlantic and far north Pacific Ocean. The horizontal grid spacing changes gradually over 10° between each transition region. To accommodate the inhomogeneous resolution, the horizontal viscosity is resolution and state-dependent, based on the Smagorinsky scheme (Griffies and Hallberg, 2000). The bottom topography for OFAM2 is based on Smith and Sandwell (1997); and OFAM1 is a blend of DBDB2 and GEBCO topography (www7320.nrlssc.navy.mil/DBDB2WWW; www.ngdc.noaa.gov/mgg/gebco/). The turbulence closure model used by OFAM is a version of the hybrid mixed-layer scheme (Chen et al., 1994). OFAM2 also uses an implicit tidal mixing scheme to represent the mixing associated with tides (Lee et al., 2006). Note that OFAM2 does not include explicit tidal forcing – it merely includes a parameterisation that represents the mixing effects of tides.

For both BRAN2 and BRAN3, OFAM is forced with surface fluxes of momentum, heat, and freshwater. BRAN2 uses 2.5°-resolution, 6-hourly fluxes from ERA-40 (Kallberg et al., 2004) between 1993 and 2002, and fields from the European Centre for Medium-Range Weather Forecasting (ECMWF) operational forecasts (http://data.ecmwf.int/data/d/era40 daily) between 2003 and 2006. BRAN3 uses 1.5°-resolution, 3-hourly fluxes from ERA-Interim (Dee and Uppala, 2009). For BRAN2, the above-mentioned fluxes are applied to OFAM1 unaltered. We found that this resulted in a trend in global averaged MSL due to an imbalance between the precipitation and evaporation (and river) fields (recall that MOM is volume conserving). This resulted in a negative bias in BRAN1.5 and BRAN2 that negatively impacted the assimilation (Oke et al., 2008). For BRAN3, we adjust the surface fluxes in advance to ensure that the freshwater fluxes are globally balanced. This is achieved by adding a small amount of precipitation everywhere – a "drizzle". The magnitude of the drizzle is smaller than all other components of the freshwater budget and changes annually to ensure that the model's global- and annual-averaged MSL remains constant for the duration of the run. We also scale the long wave flux so that

Table 1
Summary of the key differences between models used for BRAN2 and BRAN3. The term "globally balanced" refers to the freshwater fluxes that have been adjusted so that the annual averaged, global average freshwater fluxes are zero; and the global average of applied net heat flux is adjusted to the observed global average.

	BRAN2	BRAN3
Model	OFAM1	OFAM2
MOM version	MOM40d	MOM4p1
Period	1/1993–12/2006	1/1993–9/2012
Vertical resolution	10-m surface	5-m surface
Vertical mixing	Chen	Chen + Lee
Topography	DBDB2 + GEBCO	Smith & Sandwell
Forcing	ERA-40 + ECMWF 6-hourly Unaltered	ERA-Interim 3-hourly Globally balanced