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Predicting the East Australian Current

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ABSTRACT

Results are presented from an ensemble prediction study (EPS) of the East Australian Current (EAC) with a specific focus on the examination of the role of dynamical instabilities and flow dependent growing errors. The region where the EAC separates from the coast, is characterized by significant mesoscale eddy variability, meandering and is dominated by nonlinear dynamics thereby representing a severe challenge for operational forecasting. Using analyses from OceanMAPS, the Australian operational ocean forecast system, we explore the structures of flow dependent forecast errors over 7 days and examine the role of dynamical instabilities. Forecast ensemble perturbations are generated using the method of bred vectors allowing the identification of those perturbations to a given initial state that grow most rapidly. We consider a 6 month period spanning the Austral summer that corresponds to the season of maximum eddy variability. We find that the bred vector (BV) structures occur in areas of instability where forecast errors are large and in particular in regions associated with the Tasman Front and EAC extension. We also find that very few BVs are required to identify these regions of large forecast error and on that basis we expect that even a small BV ensemble would prove useful for adaptive sampling and targeted observations. The results presented also suggest that it may be beneficial to supplement the static background error covariances typically used in operational ocean data assimilation systems with flow dependent background errors calculated using a relatively cheap EPS.

1. Introduction

Ocean forecasting has seen major advances in the past decade. Many countries now perform operational forecasts of the mesoscale ocean circulation (see Hurlburt et al., 2009 and references therein). Many of the advances in ocean forecasting are on the back of numerical weather prediction (NWP), particularly those in data assimilation (Cummings et al., 2009). Ocean forecasting is underpinned by satellite observations of sea-level anomalies (SLA) and sea-surface temperature (SST), and in situ observations from Argo floats and a sparse array of tropical moorings (Oke et al., 2009). The most energetic scales of the oceans are in the mesoscale, which is characterized by eddies and meanders, and occurs particularly in western boundary current (WBC) regions. These scales are only marginally resolved by the above-mentioned components of the global ocean observing system. As a result, we expect the errors of operational ocean forecasts to be variable in time. The errors of the day are likely to depend on the coverage of assimilated observations and the stability of the ocean's circulation. For atmospheric flows synoptic-scale forecast errors over the extra-tropics are known to be dominated by the amplification of errors in specifying the initial state whereas forecast errors in the tropics are largely influenced by model error i.e. physics parameterizations. The respective roles of model and initialization errors in ocean forecasting remains a largely open question.

One of the most difficult problems in NWP is to predict regime transitions associated with rapidly growing dynamic instabilities such as those associated with mid-latitude blocking regime transitions (O'Kane and Frederiksen, 2008a). Currently the dominant approaches to ensemble prediction (EP) for synoptic scale weather are based on generating an ensemble of deterministic forecasts whose differences are perturbation vectors, centered about an unperturbed or control forecast. The initial perturbation vectors are typically chosen to capture flow dependent information about the deterministic chaotic system (Pazó et al., 2010). Operational EP systems include those based on singular vectors (Molteni et al., 1996), bred vectors (Tracton and Kalnay, 1993; Toth and Kalnay, 1997) or generalizations of bred vectors such as the ensemble transform (ET) (Wei et al., 2008) and the ensemble transform Kalman filter (ETKF) (Bowler et al., 2009; Wei et al., 2006; O'Kane et al., 2008).

Several data assimilation approaches use ensembles to model the time-evolving background error covariance (Evensen, 2003). These approaches generally require a modest-sized ensemble to reliably represent the background error covariance. If the ensemble is too small, the ensemble is likely to be dominated by sampling error, and the ensemble-based covariance will be corrupted by noise.

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Localization (Houtekamer and Mitchell, 1998) can be employed to reduce the sampling error, but this is not an ideal solution because it can result in the introduction of dynamical imbalance that can degrade the model's performance (Mitchell et al., 2002).

The typical ensemble size needed to model a system's time-evolving background error covariance can be impractical, due to the significant computational requirements. Instead, we seek to explore the possibility of using a very small ensemble of bred vectors (Toth and Kalnay, 1993; Toth and Kalnay, 1997) to qualitatively represent the errors of the day. Bred, Lyapunov and Singular vectors (to the tangent linear operator) (Trevisan and Pancotti, 1998; Pazó et al., 2010) may all be applied to identify the spatial structures of a system's fastest growing modes. Toth and Kalnay (1997) suggest that a systems bred vectors, nonlinear finite amplitude local generalizations of the leading Lyapunov vectors, should have similar structures to the systems background errors. Corazza et al. (2003) presented results to support this conjecture for an atmospheric application using an idealized quasi-geostrophic model. We seek to further examine this idea for an oceanographic case study using an ocean general circulation model. Specifically, we hypothesize that the bred vectors from a small ensemble size (we start with a 4-member ensemble) can provide useful prognostic information about where regions of large forecast or background errors may occur. We seek to determine whether we can use bred vectors to identify when and where instabilities are likely to occur in the ocean; and so-doing identify when and where the forecast skill of an operational ocean forecast system is likely to be low. To this end we develop a breeding system for a regional ocean model of the Tasman Sea (Fig. 1).

The main features of the Tasman Sea are the EAC and its eddies. At any point in time, the EAC is typically characterized by a narrow, strong southward flow adjacent to the continental shelf between about 15°S and 32°S. The EAC typically separates from the coast near Sugarloaf Point (SPt) (denoted in Fig. 1; Godfrey et al., 1980), forming a complicated field of warm- and cold-core eddies. Warm-core eddies are typically large, with diameters of several hundred kilometers, forming every 90 days or so (Mata et al., 2006). Cold-core eddies are smaller, perhaps 50–100 km across (e.g. Oke and Griffin, 2011), and often form at the point where the EAC separates from the coast, or on the peripheries of warm-core eddies. While warm-core eddies are usually well-resolved by altimetry, cold-core eddies are often missed. We therefore expect that forecasting the development of cold-core eddies is problematic, and is unlikely to be skillful. We seek to determine whether a breeding system can reliably and efficiently identify when and where regions of large forecast error occur and if these regions are associated with developing cold-core eddies.

This paper is organized as follows: In Section 2 we discuss the EAC dynamics and the Australian operational ocean forecast system (OceanMAPS). The ensemble prediction methodology and experimental design are described in Section 3, while the results, a discussion and conclusions are presented in Sections 4–6.

2. EAC dynamics

Part of the Western Boundary Current (WBC) system associated with the South Pacific subtropical gyre, the EAC forms near 15°S, and flows along the coast carrying on average 22 Sv ($1\ \mathrm{Sv} = 10^6\ \mathrm{m}^3\ \mathrm{s}^{-1}$) attaining its maximum volume transport at 30°S (Mata et al., 2000) then tending to separate from the coast near SPt (32.5°S) (Godfrey et al., 1980) before flowing southeastward into the Tasman Sea (Wilkin and Zhang, 2007). After the EAC separates from the coast it spawns a rich field of mesoscale eddies evident in the time-mean (13 year) eddy-kinetic-energy field calculated by Schiller et al. (2008) depicted in Fig. 1. The EAC is complex and characterized by large seasonal and mesoscale variability (Ridgway and Godfrey, 1997), wind driven upwelling and eddy formation (Oke and Griffin, 2011; Roughan and Middleton, 2002) and strong eddy–eddy, eddy–mean and eddy–topographic interactions (Ridgway and Dunn, 2003). Although significantly weaker than other WBCs in terms of volume transport, the eddy variability of the EAC is comparable to the aforementioned larger Northern Hemisphere WBCs (Mata et al., 2000).

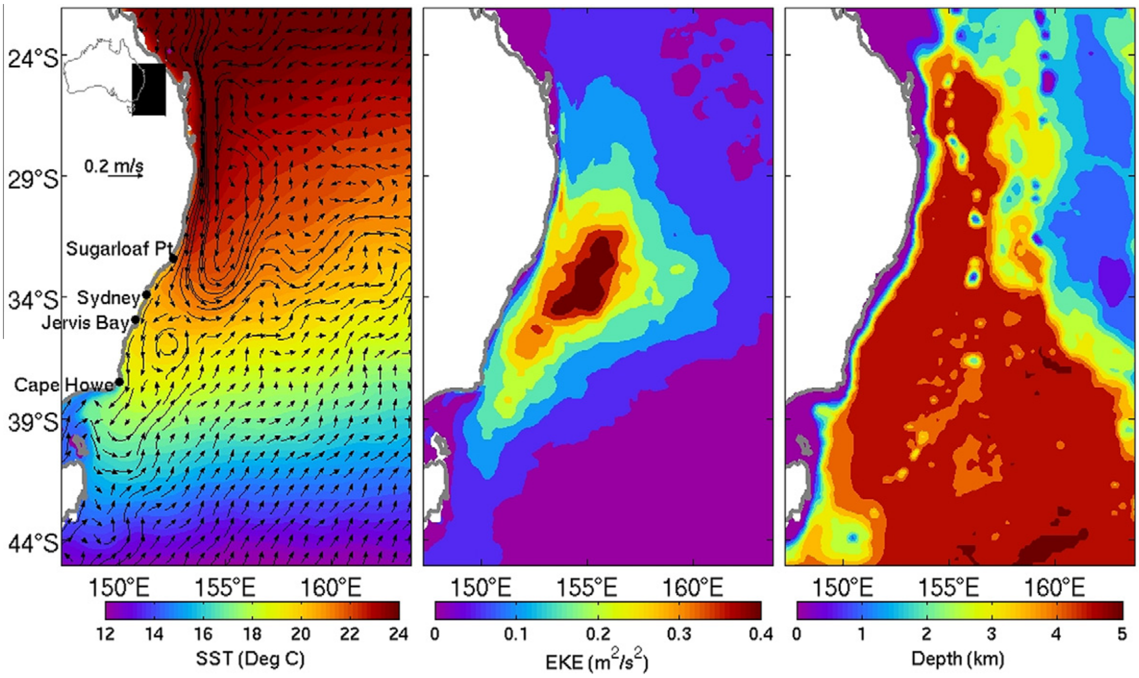

Fig. 1. Thirteen-year average (1993–2006) SST and surface velocities (left), eddy-kinetic energy (EKE; middle) computed from daily mean fields of surface velocity from BRAN2p1 (Schiller et al., 2008), and model topography (right). The inset on the left panel shows the location of the region of interest off south eastern Australia.