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Variability, coherence and forcing mechanisms in the New Zealand ocean boundary currents

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ABSTRACT

Several fast, narrow boundary currents flow along the eastern margin of New Zealand forming part of the western boundary current system of the South Pacific. In this study, using over 20 years of satellite altimeter observations and *in situ* data, we investigate the mean and variability of the current transports at seasonal, interannual and decadal time scales. We relate the means and fluctuations of the currents to the Southern Oscillation Index and to potential drivers of the circulation, including local and basin-scale winds. We also investigate the barotropic and baroclinic responses of the currents to basin-scale wind forcing using Rossby wave models. We find the currents are highly variable and there are no discernible trends in the transports since 1993. There is little coherence between transports along the boundary, suggesting a range of mechanisms drive the variability of the currents individually rather than the system as a whole. There is little correspondence between transports in any of the boundary currents and the El Niño/Southern Oscillation. We also find that the transports are not well described by the arrival of linear Rossby waves. At decadal time scales, only transports in the Subantarctic Front show a close correspondence with the variability of the wind stress curl averaged over the South Pacific. Seasonality is significant in two of the currents, likely driven by seasonality in local winds. In contrast with the larger East Australian Current, which forms part of the same South Pacific western boundary current system, we see collectively little evidence of a link between trends and variability in the New Zealand boundary currents and large-scale or local wind forcing.

1. Introduction

Western boundary currents (WBCs) flow along the eastern margin of New Zealand bringing both the warmest and the coldest waters into the region (Fig. 1). The narrow and swift currents are responsible for distributing heat, salt and nutrients influencing the regional climate and the local environment including fisheries off the east coast of New Zealand (e.g. Dunn et al., 2009). It has been shown that changes in the western boundary currents impact coastal ecosystems, for example harmful algal blooms are associated with anomalous inflows of subtropical waters (Rhodes et al., 1993). Variability of the flows is particularly relevant for the Subtropical Convergence off eastern New Zealand, where the mixing of macro-nutrient rich subantarctic water with micro-nutrient rich subtropical water fuels productivity along Chatham Rise, supporting fisheries of economical importance to New Zealand (Murphy et al., 2001). In order to have some predictive capability in the regional ocean climate, we need to understand the ocean dynamics along the entire eastern margin of New Zealand and the connection to the winds over the South Pacific.

South of 34°S, New Zealand forms the western margin of the South Pacific Subtropical Gyre (SPSG) (Fig. 1a). The currents along northeastern New Zealand are part of the same WBC system as the East Australian Current (EAC), one of the most energetic WBCs globally (Stammer, 1997) (Fig. 1b). Part of the flow in the EAC continues along the Australian coast east of Tasmania, where it is the EAC extension (EAC ext.) (Ridgway and Godfrey, 1994), but a significant part of the EAC separates from the coast at around 32°S (Godfrey et al., 1980), turning east across the Tasman Sea in a flow associated with the Tasman Front (TF) (Sutton and Bowen, 2014) to partially source the East Auckland Current (EAUC) (Stanton et al., 1997). The EAUC flows southwards along eastern New Zealand until East Cape at 34°S (Stanton et al., 1997). A portion of the flow continues along the coast as the East Cape Current (ECC) which then separates from the coast north of Chatham Rise. A system of semi-permanent eddies: the North Cape Eddy (NCE), East Cape Eddy (ECE) and Wairarapa Eddy (WE) are prominent features of the mean and variable circulation off northeastern New Zealand (Roemmich and Sutton, 1998; Chiswell and Roemmich, 1998; Chiswell, 2003; Ridgway and Dunn, 2003; Stanton

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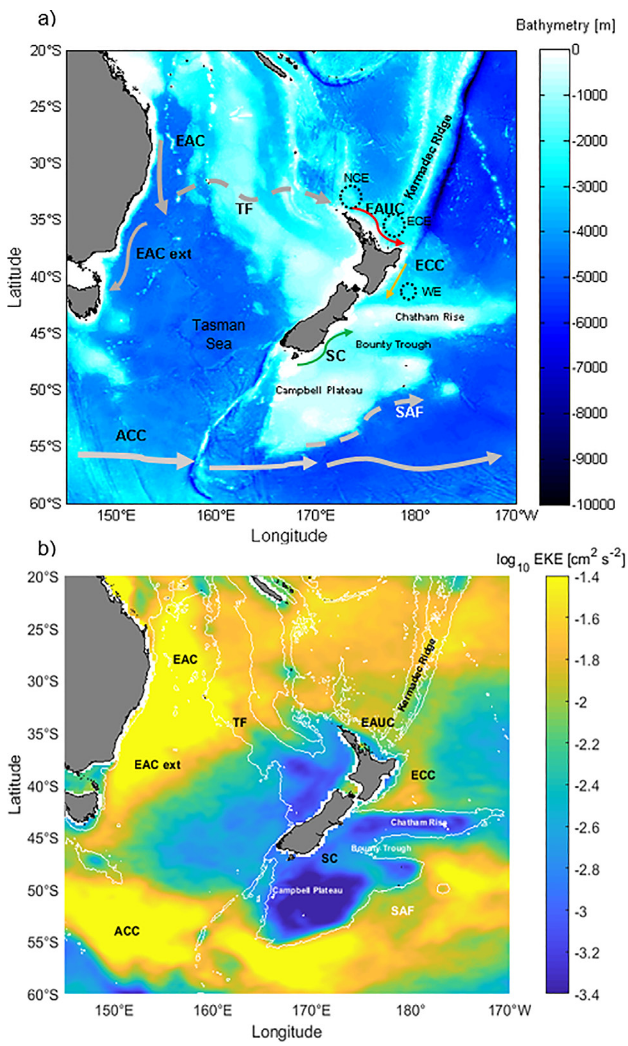

Fig. 1. (a) Schematic of the main surface currents and fronts in the South Pacific western boundary current system. Bathymetry is shown by the color scale with land masses in dark grey. The main bathymetric features are the Kermadec Ridge, Chatham Rise, Bounty Trough and Campbell Plateau. The main currents and fronts are: ACC = Antarctic Circumpolar Current; EAC = East Australian Current and extension (EAC ext.); Tasman Front = TF; EAUC = East Auckland Current; ECC = East Cape Current; SC = Southland Current; SAF = Subantarctic Front. The dashed circles are the semi-permanent eddies: the North Cape Eddy (NCE), East Cape Eddy (ECE) and Wairarapa Eddy (WE). (b) The mean eddy kinetic energy (EKE) field for the period 1993 to 2014 calculated using velocities derived from Archiving, Validation, and Interpretation of Satellite Oceanographic data (AVISO).

and Sutton, 2003; Chiswell, 2005).

To the south, the Southland Current (SC) flows northwards along the east coast of the South Island of New Zealand. Waters in the SC are predominantly of subantarctic origin but a small strip of subtropical water is always present along the coast (Sutton, 2003). The SC is responsible for much of the relatively cold water advected to the region south of Chatham Rise (Sutton, 2001).

Southeast of the SC, the Subantarctic Front (SAF) constitutes the northernmost branch of the Antarctic Circumpolar Current (ACC). The ACC is the world's largest current system connecting the Atlantic, Indian and Pacific oceans via intense flow meanders and fronts (Orsi et al., 1995). The flow of subantarctic water associated with the SAF is the largest flow in the New Zealand region, with estimated transports of 50 Sv (Stanton and Morris, 2004) and 56 Sv (Bowen et al., 2014) along the southeastern flank of Campbell Plateau.

The subantarctic and subtropical currents converge southeast of Chatham Rise in a confluence region characterised by strong fronts and eddy activity (Fernandez et al., 2014). The flows leave the New Zealand margin continuing eastward as the South Pacific Current (Stramma et al., 1995).

Previous studies have analysed the mean flow and the fluctuations of the WBCs off New Zealand individually (see Chiswell et al., 2015 for a review). Most studies are based on relatively short time series thereby providing information of the mean and variability of the currents over limited periods of time. Studies using a linear model of the wind-driven circulation around islands called the "Island Rule" (Godfrey, 1989), have shown that observed mean transports in the EAUC and EAC are close to the values required to balance the wind-driven flow in the gyre (Stanton, 2001; Oliver and Holbrook, 2014). The seasonality of the currents has been investigated in a wide range of studies from short records (Chiswell, 2001) or from individual years of data (Stanton and Sutton, 2003) with more detailed studies of seasonal circulation only reported for the EAC (Ridgway and Godfrey, 1997; Holbrook and Bindoff, 1999).

Interannual to decadal variability of the South Pacific WBCs has been of interest in recent years, with most of the research focused on the response of the EAC to large-scale wind forcing over decadal time scales (Ridgway and Hill, 2012). An increased circulation of the SPSG during the 1990s was observed and linked to an increase in the basin-scale wind stress curl (Roemmich et al., 2007). Hill et al. (2008) showed long-term trends in the coastal temperature and salinity east of Tasmania are associated with a southward extension of the EAC due to the intensification in the SPSG circulation. They used the Island Rule to show that large-scale changes in winds lead to changes in the transport of the EAC extension. Holbrook et al. (2011) connects the multi-decadal variability of the transports of the EAC to low-frequency El Niño/Southern Oscillation (ENSO) signals. While increasing trends in subtropical SST and eddy activity have been observed in the confluence region east of New Zealand and were associated with trends in basin-scale wind forcing (Fernandez et al., 2014), there is little research focused on ENSO-related transport variability in all of the New Zealand boundary currents. Multi-decadal records can now be used to investigate the mechanisms driving the flow (including the mean), the interannual to lower-frequency fluctuations and the amplitude of the annual cycle in the New Zealand WBCs.

Some of the variability in the boundary currents may be due to the arrival of Rossby waves. Rossby waves have been observed in all the ocean basins of the world (Chelton and Schlax, 1996; Qiu et al., 1997; Cipollini et al., 2001) and potentially account for some of the variability in the EAC (Wang et al., 1998; Holbrook et al., 2011). North of New Zealand, Bowen et al. (2006) used a combined heating/cooling and baroclinic Rossby wave model to explain 40–60% of the observed sea surface height variance between 20°S and 32°S. Qiu and Chen (2006) used a similar model to explain much of the variance at annual or lower frequencies observed in sea-level at mid-latitudes of the South Pacific for the 1994–2006 period. Laing et al. (1998) and Chiswell (2001) detected signals in the EAUC with the characteristics of baroclinic Rossby waves. In the East Cape Current (ECC), Chiswell (2005) hypothesized that instabilities shedding eddies result from the arrival of these perturbations from the east. However, Stanton and Sutton (2003) relate the variability in the EAUC to the strength of anticyclonic flow around the quasi-stationary NCE and find no evidence of westward propagating signals. While the variability of the Southland Current (SC) has been linked to local winds (Chiswell, 1996) and low frequency signals have been observed in the subantarctic region (Morris et al., 2001), it is unclear to what extent westward propagating signals may influence transports of the subantarctic boundary currents.

The aim of this paper is to investigate for the first time the coherence in the boundary flows along the entire eastern margin of New Zealand. We investigate how the mean, interannual, decadal and seasonal variability are related to potential drivers of the circulation, in particular the relationships with local and gyre-scale winds and the