

## BAROCLINIC MODELING OF THE SOUTH PACIFIC GYRE

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### 1. INTRODUCTION

Australia's climate is now well-known to be changing on decadal and longer time scales (Power et al. 1999a,b; Timbal et al. 2006; CSIRO-BoM 2007). To improve climate prediction in Australia, it is essential that we better understand the cause and effects of climate changes. Since the early 1990s, satellite altimeter derived sea surface heights combined with in situ subsurface temperature and salinity measurements from World Ocean Circulation Experiment (WOCE) hydrographic data, a repeat XBT survey, and data from the global Argo array, confirm that the South Pacific subtropical gyre circulation has been intensifying over the past decade or so (Willis et al. 2004; Qiu and Chen 2006; Roemmich et al. 2007). In addition, historical observations show evidence for a multi-decadal upper ocean warming of the southwest Tasman Sea east of Tasmania (Holbrook and Bindoff 1997; Ridgway 2007). This suggests that the reported intensification ("spin-up") of the South Pacific Gyre circulation since the early 1990s may actually be part of a multi-decadal, or longer-term, increase in the gyre intensity and southward extension of the East Australian Current (EAC). Indirect evidence from corals suggests that this may be part of a 300-year trend in this EAC behavior (Thresher et al. 2004).

Since the late 1970s, climate change in the Southern Hemisphere has been marked by a strengthening of the circumpolar westerly winds extending from the stratosphere to the troposphere and Earth's surface (e.g., Hurrell and van Loon 1994; Thompson and Solomon 2002; Gillett and Thompson 2003). Modeling studies suggest that these positive changes in the Southern Annular Mode (SAM) may result from greenhouse warming (e.g., Kushner et al. 2001) and ozone depletion (e.g., Shindell and Schmidt 2004). More recent modeling studies, using a linear Sverdrup ocean model forced with wind stress trends since 1978, suggest that Antarctic ozone depletion and changes in SAM may be responsible for the southward shift and decadal spin-up of the "super-gyre" since the 1990s, including a strengthening of the EAC through the Tasman Sea (Cai 2006), which would warm the region. Projected warming experiments using the CSIRO Mark-3 climate model have also been performed (Cai et al. 2005).

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Analogous multi-decadal changes in the circulation were identified in an earlier ocean general circulation model (OGCM) simulation forced by changes in the latitude of the Southern Hemisphere (SH) sub-polar westerly winds (Oke and England 2003). These studies provide valuable benchmarks to our understanding of 20th Century southwest Pacific Ocean climate changes.

Baroclinic Rossby waves play a critical role in South Pacific Ocean climate changes, including changes in western boundary circulation, from seasonal to interannual to multi-decadal time scales (e.g., Holbrook and Bindoff 1999; Qiu and Chen 2006; McGregor et al. 2007, 2008; Kessler and Gourdeau 2007). Taking account of at least first order baroclinic effects is essential in order to successfully model the timing of both El Niño - Southern Oscillation (ENSO) and decadal scale climate changes in this region. The relatively slow westward propagation speeds of baroclinic Rossby waves, which decrease polewards (it takes about two years for Rossby waves to cross the Pacific basin at 10°S and close to a decade at 30°S), make them an ideal deterministic tool to be translated into enhanced forecasts of the timing and amplitude of interannual-to-decadal climate changes over Australia.

This paper examines observed and filtered sea level changes at the Fort Denison tide gauge site in Sydney, Australia, in the context of decadal climate variability as represented by the Interdecadal Pacific Oscillation index. The strong climatic relationship prompts the intermediate-complexity modeling and analysis of the baroclinic transport anomalies in the East Australian Current - the western boundary current of the South Pacific Gyre - against the observed sea level changes at Fort Denison. We find that the strength of this relationship is both surprising and remarkable.

### 2. DECADAL VARIABILITY AND SEA LEVEL

Previous research has shown that Australia's rainfall, temperature and wheat crop yield are highly and significantly correlated (at the 95% confidence level) with the Southern Oscillation index (SOI) when the Interdecadal Pacific Oscillation index (IPOI) is less than -0.5, i.e., when the background state of the tropical Pacific Ocean is in its cool phase (Power et al. 1999a). Conversely, there appears to be no relationship between Australia's rainfall, temperature or wheat crop yield and the SOI during the IPOI warm phase (Power et al. 1999a). Over the eastern part of Australia, and specifically New South Wales and the Murray Darling Basin, there is a very strong and highly significant relationship between summer rainfall changes and on-

shore/off-shore winds on interannual-to-decadal time scales (Rakich et al. 2008). Further, flood risk along the New South Wales/southern Queensland coast appears to be modulated by the IPO (e.g., Micevski et al. 2006), as does the mean wave direction off southeastern Australia (Goodwin 2005).

This begs the question, “Is there a relationship between New South Wales coastal sea level and the IPO?” As a case study example, this question has been explored based on sea level variations from the long-record and well established Australian east coast tide-gauge site at Fort Denison, Sydney (see Fig. 1). The monthly sea level time series is provided by the Permanent Service for Mean Sea Level (PSMSL) [http://www.pol.ac.uk/psmsl/] (Woodworth and Player 2003) and is de-trended and 11-pt filtered here for comparison with the IPOI. [Note: the raw Fort Denison sea level time series has a significant centennial time-scale increasing trend.] It is found that there is a relatively strong relationship between the filtered/de-trended monthly Fort Denison sea level and the IPOI, the correlation coefficient between the two time series being  $r = 0.65$ , significant at the 95% level.

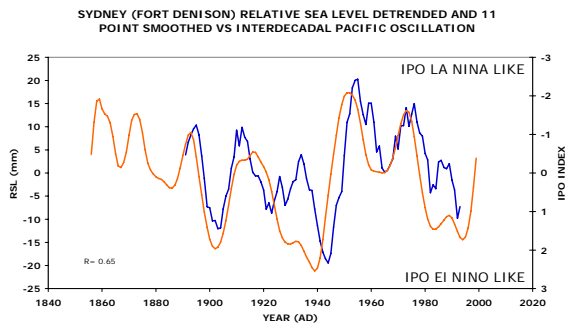


Figure 1: Relationship between 11-pt filtered and de-trended monthly Fort Denison relative sea level (blue line) and the IPO index (orange line). [Goodwin 2009, in preparation]

We now ask, “Are the mechanisms that drive Fort Denison sea level variations understandable from a South Pacific Ocean climate dynamics perspective?” More specifically, “Is there any clear connection between the South Pacific Gyre circulation, East Australian Current changes, and Fort Denison sea level?” To explore these mechanisms, we adopt an intermediate-complexity ocean dynamical modeling approach, here using a linear, first baroclinic-mode ocean model driven by the large-scale South Pacific winds to simulate the upper ocean transport changes around the South Pacific Gyre.

### 3. MODEL

The baroclinic ocean model is a 1 1/2-layer model of the stratified ocean (e.g., Philander 1990, pp. 106-108) resolved on a  $1^\circ \times 1^\circ$  spatial grid (the Arakawa C-grid of Mesinger and Arakawa 1976). The upper and lower ocean density layers are separated by an

interface, which represents the pycnocline. Since ocean water density is a function of temperature, salinity and pressure, the pycnocline represents the depths over which the largest vertical density gradient occurs, taking account of all three factors. The reduced gravity,  $g'$ , reflects the density difference between the upper and lower layers. The typical value of  $g' = 0.03 \text{ m s}^{-2}$  (Tomczak and Godfrey 1994, p 37) is used here. The lower layer is assumed to be motionless and infinitely deep.

Church et al. (2005) have shown that there is a clear relationship [their Fig.1b,c] between global mean sea level (full ocean depth) and global ocean heat content integrated over the upper 300m, demonstrating the strong relationship that exists globally between sea level variations and upper ocean heat content to the mean depth of the thermocline. This clearly demonstrates the importance of the ocean’s vertical structure (or “baroclinicity”) to sea level variations, with the upper 300m being paramount. For our relatively simple 1 1/2-layer baroclinic model ocean used in a large-scale context, we can usefully consider the thermocline as a surrogate for the pycnocline. With this in mind, the baroclinic model is configured with a mean depth thermocline of 300m.

Motion in the upper layer is driven by the applied wind stresses (per unit density),  $\tau$  ( $\text{m}^2 \text{ s}^{-2}$ ), which are anomalies from the long term monthly means (i.e., seasonal cycle removed). The associated response of the ocean is displayed by the vertical displacement of the pycnocline,  $\eta$  (m), and the horizontal components of the flow velocity. Since the thermocline may be used as a surrogate for the pycnocline in this model representation, and given that the thermocline depth is a useful and appropriate climatic base metric to define the upper ocean heat content (or warm water volume), the terms thermocline and pycnocline may be used interchangeably for our purposes. The ocean dynamics are described by the linear reduced-gravity form of the shallow-water equations detailed below (Equations 1-3):

$$u_t - fv + g'\eta_x = \tau^x / H \quad (1)$$

$$v_t + fu + g'\eta_y = \tau^y / H \quad (2)$$

$$g'\eta_t + c_1^2 (u_x + v_y) = 0 \quad (3)$$

where  $u$  and  $v$  are the eastward and northward components of velocity respectively ( $\text{m s}^{-1}$ ) and  $t$  is time (s).

The relatively simple model dynamical equations facilitate the generation and propagation of baroclinic planetary waves in response to large scale wind stress forcing at the surface and oceanic adjustment from horizontal pressure gradients. These planetary waves include not only first baroclinic mode westward propagating Rossby waves, but also boundary Kelvin waves including Kelvin waves along the equatorial boundary. With a mean depth thermocline (here the pycnocline) of 300m, the first baroclinic mode Kelvin wave speed  $c_1 = 3 \text{ m s}^{-1}$ . The first baroclinic mode Rossby wave speed ( $\text{m s}^{-1}$ ) is  $C_R = \beta (c_1^2 / f^2)$ ,

where  $f$  ( $s^{-1}$ ) is the Coriolis parameter and  $\beta$  ( $m^{-1} s^{-1}$ ) is the derivative of  $f$  northwards. The Fischer's (1965) numerical scheme is utilized for model time stepping, with a time-step of two hours sufficient for a  $1^\circ$  resolution domain. Rossby wave speeds decrease polewards, resulting in Pacific basin transit times of  $<2$  yr at  $10^\circ S$ ,  $\sim 8$  yr at  $25^\circ S$ , and more than a couple of decades at  $40^\circ S$ .

#### 4. MODELING SEA LEVEL VARIATIONS

Climate change is arguably the most significant problem facing our planet. The recent Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2007) indicates that global sea level rose at an average rate of 1.8 [1.3-2.3] mm per year during the period 1961-2003. Based on oceanic instrumental records since 1955, the global ocean heat content also increased during the past 50-yr. Continuous sea level histories (time series) extending back in time prior to 1950 are sparse and based on palaeo-climatic records and a small number of tide-gauge records. One recent global sea-level reconstruction using instrumental records and empirical orthogonal functions facilitates studies back to 1870 (Church and White 2006).

Basin-wide spatial maps of time-varying satellite altimeter derived sea surface height anomalies provide an excellent quantitative description of Rossby wave crests/troughs or gyre-scale geostrophic circulation changes across the globe (e.g., Chelton and Schlax 1996; their Fig. 4). Furthermore, the clear relationship between global mean sea level (full ocean depth) and global ocean heat content integrated over the upper 300m, demonstrates the strong relationship that exists between sea level variations and upper ocean heat content to the mean depth of the thermocline (Church et al. 2005; their Fig.1b,c). This begs the question, "Is there potential for the baroclinic ocean model to predict the timing of sea level changes in response to large-scale changes in wind stress?"

To test this, in the South Pacific Gyre context, the baroclinic model was forced with wind stresses across the Southern Hemisphere from 1960-2004. The wind stress data used to force the model are from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) (Kalnay et al. 1996). Since recent studies suggest that the increased intensity of the South Pacific Gyre and EAC is caused by strengthened westerlies in the Southern Hemisphere (e.g., Cai et al. 2005; Cai 2006; Qiu and Chen 2006; Roemmich et al. 2007), it was hypothesized that the baroclinic model might at least broadly represent the Southern Hemisphere wind stress forced EAC transport anomalies above the thermocline and that contributed to gyre transport changes between 1960 and 2004.

Modeled southward transport anomaly variations above the thermocline (pycnocline) were calculated from the baroclinic model output near to the east Australian coast and across the EAC at  $34^\circ S$ . This model simulation of the upper ocean transport

anomalies was compared against observed sea level variations from the long-record and well established Australian east coast tide-gauge site at Fort Denison, Sydney (see Fig. 2). The comparison is remarkable. Perhaps somewhat surprisingly, the relatively simple linear baroclinic model simulation of the upper ocean EAC transport anomalies across  $34^\circ S$  represents an impressive hindcast surrogate of the interannual-to-decadal time scale sea level changes that have been observed at Fort Denison, Sydney since 1960.

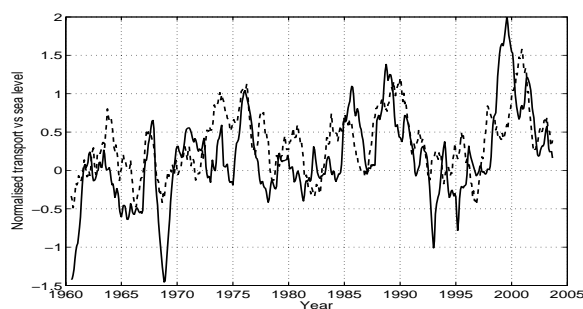


Figure 2: Time series of the modeled monthly EAC baroclinic transport anomaly across  $34^\circ S$  [bold line] plotted against the observed sea level anomaly at Fort Denison, Sydney [dashed line]. An annual running mean has been applied. Sea level lags gyre intensity by 9-mth [ $r = 0.54$ , significant at 99% confidence level after accounting for serial correlation]. The series are normalized and shifted by the 9-mth lag for visual comparison.

This is remarkable and impressive for a number of reasons. While the Fort Denison tide gauge site is contained well within the semi-enclosed Sydney Harbour, and would seem to be well away from direct influences of the EAC, the observed sea level variations are well represented by the modeled EAC transport variations. Further, it confirms the relationship between EAC intensity and changes in the Southern Hemisphere winds, and demonstrates that Fort Denison sea level varies in a manner that is strongly and significantly related to variations in the South Pacific Gyre intensity. Not only is this remarkable, it is also very useful since the model-determined EAC baroclinic transport and projected sea level variations represent the Pacific Ocean's western boundary response to large-scale climate changes expressed in the Southern Hemisphere winds. Hence this provides scope for model experimental design to investigate and diagnose the role of large-scale climate modes, including ENSO and SAM, on EAC transport and sea level changes. It also provides scope to investigate the role of multi-decadal and long time scale wind stress changes on sea level rise, including human-induced climate change forcing.

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