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Estimation of the Effect of Eddies on Coastal El Niño Flows Using along-Track Satellite Altimeter Data

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THE FLORIDA STATE UNIVERSITY
COLLEGE OF ARTS AND SCIENCES

ESTIMATION OF THE EFFECT OF EDDIES ON COASTAL EL NIÑO FLOWS USING
ALONG-TRACK SATELLITE ALTIMETER DATA

By

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ABSTRACT

During an El Niño anomalous westerly winds in the central equatorial Pacific push the equatorial water eastward, raising the sea level in the eastern equatorial Pacific and lowering it in the western equatorial Pacific. In the western equatorial Pacific, this sea level signal leaks through gaps in the western equatorial Pacific boundary, lowering sea level all around the western and southern coasts of Australia. Opposite anomalies occur during La Niña when the equatorial winds are easterly. Assuming geostrophic balance and no normal flow into the boundary at interannual frequencies, we expect the sea level anomaly to be spatially constant all along the western and southern Australian coasts, but instead it is only spatially constant along the boundary north of about 22°S . South of this latitude, in the region of the Leeuwin Current, the amplitude of the interannual signal decreases. This unexpected drop is not explained by local wind stress, bottom friction, or Bernoulli conservation of energy of the large-scale flow. Theory is developed to show how this drop in interannual sea level may be explained by energetic, high frequency, small scale Leeuwin Current eddies that interannually dissipate the El Niño sea level signal along the coast. This theory is tested with coastal sea level station measurements and along-track altimetry data from TOPEX/Poseidon, Jason-1, and OSTM/Jason-2 satellites. The interannual variation in divergence of the eddy field momentum flux is calculated over a box along the southwest coast of Australia and found to be correlated with the interannual coastal flow through the box and the southward along-shelf sea level decay. The surprisingly short dissipation time scale is only about 2 days, much shorter than the interannual time scale.

The theory is also tested off the western coast of South America where the original coastal El Niño flow was named. Interannual sea level decay along the shelf edge is observed, and the interannual southward flow along the shelf edge is found to be highly positively correlated with the along-shelf sea level decay with a dissipation time scale of a few days. Dynamics similar to the Australian case likely apply.

CHAPTER ONE

INTRODUCTION

Along the western coast of Australia, the interannual sea level is highly correlated with the El Niño–Southern Oscillation (ENSO). During an El Niño, anomalous westerly winds in the equatorial Pacific push water eastward and lower the sea level in the western equatorial Pacific (Fig. 1). This drop in sea level appears along the coast of Indonesia and the western and southern coasts of Australia as the interannual signal leaks through gaps in the western equatorial Pacific. During La Niña, the sea level increases in the western equatorial Pacific as a result of anomalous easterly winds, which cause the sea level along the western Australian coast to also rise. Pariwono et al. (1986) found that the interannual sea levels along the coast of Australia were correlated with El Niño, and Clarke (1991) proposed the leaky western Pacific mechanism that drives this, as illustrated in Fig. 1.

At interannual time scales we expect the flow to be quasi-geostrophic. Therefore, the interannual sea level should also be spatially constant along the coast so that there is no flow into the boundary. But surprisingly, as shown by Li and Clarke (2004) and Clarke and Li (2004), coastal interannual sea level and altimeter-estimated interannual sea level near the shelf edge are not spatially constant. Rather, south of about 22°S, especially just seaward of the shelf edge, the interannual sea level amplitude decreases.

These results were confirmed using TOPEX/Poseidon, Jason-1, and OSTM/Jason-2 altimeter sea surface heights (SSHs) and eight monthly western Australian coastal sea level records (see Fig. 2). The SSHs were available from NASA's physical oceanography data website <http://podaac.jpl.nasa.gov> from January 1993 through July 2011 and the monthly sea levels from the Permanent Service for Mean Sea Level (PSMSL) website <http://www.psmsl.org> from January 1993 through December 2010. These records were longer than the January 1993 through April 2002 records available to Clarke and Li (2004) and Li and Clarke (2004). Monthly time series with the mean annual cycle removed were low-pass filtered with the 11-point symmetric Trenberth (1984) filter to obtain the interannual sea level estimates. The filter

removes more than 90% of the amplitude of frequencies higher than $2\pi/8$ months and passes through over 80% of the amplitude of frequencies lower than $2\pi/2$ years.

Figure 1. The leaky equatorial Pacific mechanism during an El Niño, as proposed by Clarke (1991). Anomalous westerly winds blow water east across the Pacific ocean, uniformly lowering (L) sea level in the western equatorial Pacific and along the western and southern Australian coasts. The dashed line denotes the 200 m isobath. During La Niña, the equatorial winds are easterly, and the sea level in the western equatorial Pacific and around the Australian coast is anomalously high [from Li and Clarke 2004, Fig. 1].

Interannual sea level variability was examined at the coast, shelf edge, and 100 km from the shelf edge with three separate Empirical Orthogonal Function (EOF) analyses at these locations (Figs. 2 and 3). The first mode EOF in each case describes almost all the variance, and the time variation is essentially the same for the first Principal Component in each case. As found by Clarke and Li (2004) and Li and Clarke (2004), the interannual sea level signal

amplitude about 100 km seaward from the shelf edge drops steeply south of about 22°S (blue curve in Fig. 3(a)). To a lesser extent, the interannual sea level also drops southward from about the same latitude at the coast and shelf edge (red and green curves in Fig. 3(a)). Figure 3(a) also shows that the sea level amplitude decreases seaward from the coast, suggesting, by geostrophy, that there is an interannual flow parallel to the coast and shelf edge. Since the sea level difference between the blue and green curves increases southward, the interannual flow along the shelf edge must be increasing southward. This interannual flow has been previously examined by Feng et al. (2003), Clarke and Li (2004), and Li and Clarke (2004).

Figure 2. Map of the western Australian coast. The black lines show the TOPEX/Poseidon, Jason-1, and Jason-2 satellite tracks, and the gray line shows the approximate position of the shelf edge (200 m isobath). The colored dots give the locations of the sea level measurements used in the interannual EOF analysis. Red shows the location of the coastal sea level stations, green shows the locations where the satellite tracks cross the shelf edge, and blue shows measurements approximately 100 km from the shelf edge. Tracks 90, 101, 166, 177, and 253 are labeled.

Figure 3. (a) Structure function of the 1st mode EOF of the interannual sea level along the coast of southwestern Australia from 14°S – 35°S at the coast (red, 94% of variance), shelf edge (green, 96% of variance), and approximately 100 km seaward from the shelf edge (blue, 84% of variance). Figure 2 shows a map of these locations. (b) Principal Component time series for the 1st mode EOFs corresponding to (a).

The Principal Components (Fig. 3(b)) of the first mode EOF of the interannual sea levels along the coast [$r = -0.79$; $r_{\text{crit}}(95\%) = -0.49$], shelf edge [$r = -0.79$; $r_{\text{crit}}(95\%) = -0.42$], and 100 km seaward from the shelf edge [$r = -0.71$; $r_{\text{crit}}(95\%) = -0.41$] are strongly negatively correlated with the El Niño index, Niño 3.4, the monthly SST anomaly averaged over the equatorial Pacific region from 5°N to 5°S and 120°W to 170°W. Here and elsewhere, the significance level of the correlation has been calculated using the method of Ebisuzaki (1997). These strong negative correlations are consistent with the mechanism shown in Fig. 1 and the previous work on the interannual shelf edge flow (Fig. 3). Specifically, when the sea level is

high off the coast of northwestern Australia during a La Niña, there is a southward interannual flow along the shelf edge where the interannual sea level decays. The opposite occurs during an El Niño.

Why is there a drop in interannual sea level amplitude along the coast and shelf edge? There are several possibilities, including alongshore interannual wind stress forcing, bottom friction, and energy conservation along the shelf edge as the interannual flow is generated. We consider each of these below.

Observations suggest that the decrease in interannual sea level is not a result of wind stress. Masumoto (2002) found that the correlation between the zonal wind stress and the first and second modes of the EOF of the interannual ocean dynamic heights along the western coast of Australia was insignificant. Masumoto's result is suggestive, but since the alongshore sea level slope is associated with the alongshore wind stress rather than the zonal wind stress (see e.g., Enfield and Allen 1980), the alongshore component of the interannual wind stress should be examined. This component was calculated using wind stress data from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS). The analysis for the period from January 1991 through December 2010 showed that the interannual alongshore wind stress was negligibly correlated with the interannual sea level or its slope. Therefore, the observed interannual alongshore sea level slope is not caused by the local wind stress.

The observed sea level decay is not a result of bottom friction either. Pizzaro et al. (2001) found that bottom friction along the continental shelf and continental slope has negligible effects on ENSO timescales except at the coast where the surface and bottom boundary layers meet.

Another possibility is that the anomalous sea level amplitude fall is associated with conservation of energy as Bernoulli's principle is applied to flow at the shelf edge in the presence of the Leeuwin Current. This current has a mean speed of about 50 cm s^{-1} , is around 100 km wide, and runs parallel to the shelf edge off Western Australia (see, e.g., Tomczak and Godfrey 1994). To see how this conservation of energy mechanism works on an interannual time scale, suppose a La Niña is occurring. Then, the sea level along the shelf edge north of about 23°N , where the Leeuwin Current begins, is anomalously high. As the associated higher potential energy is gradually converted to increased kinetic energy and increased flow along the

shelf edge, the anomalous sea level along the coast falls. Anomalies of opposite sign occur during El Niño. But calculations based on a nonlinear model similar to that of Clarke and Li (2004) show that the interannual sea level amplitude fall due to this mechanism is only about 6% of the fall observed (see Appendix A).

Although the above Leeuwin Current mechanism fails, it is curious that the decay in interannual sea level amplitude along the shelf edge coincides with the approximate 23°S – 34°S location of the Leeuwin Current (see Fig. 3). Another possible mechanism is that the alongshore decay in interannual sea level signal is dissipated by mesoscale eddies associated with the Leeuwin Current.

The presence of mesoscale eddies in the Leeuwin Current region is well known (Andrews 1997; Pearce and Griffiths 1991). Griffin et al. (2001) used plots of sea surface temperatures, sea level anomalies, and chlorophyll-*a* concentrations to show that eddies exist off the southwestern coast of Australia. Deng et al. (2008) used bimonthly along-track ocean dynamic heights from 1993-2002 to show the locations of the eddies in the region, and Feng et al. (2005) observed that the eddy field from 28°S to 31°S reduces the energy in the mean flow. Feng et al. also found that the surface eddy kinetic energy in the Leeuwin Current region is stronger during La Niña years and weaker during El Niño years. But it was not clear whether this changing eddy energy converged or diverged and affected the interannual sea level slope and interannual flow.

The purpose of this research is to use coastal and satellite-estimated sea level data to determine whether the eddies off the southwest coast of Australia in the region of the Leeuwin Current dynamically affect the large-scale interannual flow and cause the interannual sea level amplitude to fall southward. In the next chapter, the theory supporting this hypothesis will be discussed. We will then use coastal sea level station data and satellite altimetry data to document the interannual flow variability in Chapter 3. In Chapter 4, we will test the theory of Chapter 2 and show that eddies are responsible for the interannual fall in sea level amplitude and are related to the interannual flow along the shelf edge off southwestern Australia. Chapter 5 examines whether the theory can describe the interannual variations in the coastal flow off Peru, the flow that originally gave rise to the term “El Niño.” Conclusions will then be presented in Chapter 6.

CHAPTER TWO

THEORY

2.1 Eddies, Interannual Flow, and Alongshore Fall in Interannual Sea Level Amplitude

To understand the dynamics of the interannual sea level near the eastern ocean boundary, we consider the momentum equations in Cartesian coordinates. We will use a coordinate system where x is perpendicular to the shelf and y is along the shelf, with positive y southward as in Fig. 4.

Figure 4. The right-handed coordinate systems (x,y) and (n,s) where x is perpendicular to the shelf edge and seaward, y is parallel to the shelf edge, n is perpendicular to the satellite tracks and s is along the satellite track. As shown in the diagram, θ is the angle between the x and s axes. Unit vectors in the x , y , n , and s directions are $\mathbf{i}$, $\mathbf{j}$, $\mathbf{e}_n$, and $\mathbf{e}_s$, respectively.

Since the drop in sea level is southward along the shelf edge, we are interested in the y -momentum equation,

$$v_t + \mathbf{u}_H \cdot \nabla v = -g\eta_y - fu + \frac{Y_z}{\rho_*} \quad (1)$$

where v is the flow in the y -direction, u the flow in the x -direction, $\mathbf{u}_H$ the horizontal velocity, z the vertical (upward) coordinate, Y the turbulent stress in the y direction, t the time, ∇ the horizontal gradient operator, g the acceleration due to gravity, η the sea level displacement, and ρ_* the mean water density. Note that the y pressure gradient divided by ρ_* has been approximated by $g\eta_y$ since all analysis will take place at or near the surface where the fluctuating pressure is $\rho_*g\eta$.

The flow is quasi-geostrophic so

$$\mathbf{u}_H \cdot \nabla v = \nabla \cdot \mathbf{u}_H v. \quad (2)$$

Write

$$\mathbf{u}_H = \mathbf{u}_{seas} + \mathbf{u}' + \mathbf{u}'' \quad (3)$$

where $\mathbf{u}_{seas}$ is the mean and seasonal cycle, $\mathbf{u}'$ the interannual signal found by low-pass filtering $\mathbf{u}_H - \mathbf{u}_{seas}$ and $\mathbf{u}''$ is the remainder. Substituting the expression (3) into (2) gives a 9-term sum. However, since the largest velocities are in $\mathbf{u}_{seas}$ and the eddy velocity $\mathbf{u}''$ and since $\mathbf{u}_{seas}$ by definition has no interannual variability, the interannual contribution to the 9-term sum comes from the eddy flux term

$$(\nabla \cdot \mathbf{u}_H v)' \approx (\nabla \cdot \mathbf{u}_H'' v'')' \quad (4)$$

where $()'$ denotes the interannual contribution of a variable.

As noted earlier in the Introduction, the interannual wind forcing cannot explain the alongshore sea level gradient so it can be dropped from (1). Since $v'_t \sim \omega v'$ and Clarke and Li (2004) estimate $v' \sim 2 \text{ cm s}^{-1}$, we have, for $\omega \sim 2\pi/3$ years, $v'_t \sim 1.3 \times 10^{-9} \text{ m s}^{-2}$ at interannual frequencies. But η' at the coast and shelf edge fall by about 1 – 2 cm from 22°S to 33°S (Fig.

3(a)), so $g\eta'_y \sim 10^{-7} \text{ m s}^{-2}$ at the shelf edge (see Fig. 3) and $v'_t = g\eta'_y$. Therefore (1) can be reduced to

$$(\nabla \cdot \mathbf{u}''_H \mathbf{v}'')' + f u' = -g\eta'_y. \quad (5)$$

In addition, the interannual flow at the shelf edge is blocked, so $f u'$ is negligible there and (5) can be written as

$$D' = (\nabla \cdot \mathbf{u}''_H \mathbf{v}'')' = -g\eta'_y \quad (6)$$

where D' is used for the interannual eddy momentum flux divergence for notational simplicity.

Equation (6) connects the interannual amplitude changes in the small-scale eddy variability with the large-scale interannual sea level slope. Why should the eddy variability vary interannually? Previous work (Feng et al. 2003; Clarke and Li 2004) has shown that the Leeuwin Current varies interannually. Perhaps when it strengthens during La Niña, there is more eddy variability and positive flux divergence D' , and when it weakens during El Niño there is less eddy variability and negative D' . If this hypothesis were true, then we would expect

$$Rv' = D' \quad (7)$$

where R^{-1} has the dimension of time and is the eddy dissipation time. Note that if both (6) and (7) are true then

$$Rv' = -g\eta'_y. \quad (8)$$

In order to test the relationships (6) and (7), we must be able to estimate D' . In the next section we discuss how this might be done using along-track altimeter data.

2.2 Calculation of the Divergence of the Eddy Momentum Flux

The eddies are assumed to be quasi-geostrophic, and so surface currents can be estimated from gradients of altimeter-estimated SSHs. Along-track SSH measurements from the Integrated Multi-Mission Ocean Altimeter Sea Surface Height (SSH) Climate Data Record were used in the analysis. This data set combines along-track altimeter data from TOPEX/Poseidon, Jason-1, and OSTM/Jason-2 altimeter satellites by interpolating the individual Geophysical Data Records to a

common reference orbit. The data were available from January 1993 through July 2011, with SSH measurements taken every 10 days. The along-track resolution of the altimeter data is excellent for mesoscale dynamics analysis and provides a measurement every 6 km or so, but the distance between tracks is around 315 km.

The satellite altimeter height is noisy, so the geostrophic velocity $\mathbf{u}''$, which involves a gradient of SSH, is even noisier, and the divergence $\nabla \cdot \mathbf{u}''\mathbf{v}''$ is even noisier still. In addition, except where satellite tracks cross, we are only able to calculate the component of $\mathbf{u}''$ perpendicular to the satellite track rather than the vector $\mathbf{u}''$. In this section, we estimate $D' = (\nabla \cdot \mathbf{u}''\mathbf{v}'')'$ by averaging over a box.

Since we want to test (6) at the shelf edge, ideally our box should have a straight shelf edge as one side. The other three box edges should be satellite tracks so we can estimate velocities. The box should be as narrow as possible so that we stay close to the shelf edge. Box 1 (see Fig. 5) meets these criteria, and so our theoretical analysis will focus on this box.

Box 1 is bounded by the satellite Tracks 101, 166 and 177 and the shelf edge (see Figs. 2 and 5). It follows from the divergence theorem that the average of $\nabla \cdot \mathbf{u}''\mathbf{v}''$ over the box can be written

$$A^{-1} \iint_A \nabla \cdot \mathbf{u}''\mathbf{v}'' dA = A^{-1} \int_{\Gamma} \mathbf{u}''\mathbf{v}'' \cdot \mathbf{e}_n ds = A^{-1} \int_{\Gamma} v'' U'' ds \quad (9)$$

where A is the area of the box, Γ is the curve around the box, $\mathbf{e}_n$ is the normal to that curve, and $U'' = \mathbf{e}_n \cdot \mathbf{u}''$. Write

$$\mathbf{u}'' = u''\mathbf{i} + v''\mathbf{j} = U''\mathbf{e}_n + V''\mathbf{e}_s \quad (10)$$

where $\mathbf{e}_s$ is the unit vector tangent to the edge of the box in a right-handed system of axes as in Fig. 4. Taking the dot-product of the second of the two equalities of (10) with $\mathbf{j}$, we have

$$v'' = U''\mathbf{e}_n \cdot \mathbf{j} + V''\mathbf{e}_s \cdot \mathbf{j}. \quad (11)$$

Substituting the expression for v'' in (11) into (9) gives

$$A^{-1} \iint_A \nabla \cdot \mathbf{u}''\mathbf{v}'' dA = A^{-1} \int_{\Gamma} (U'')^2 \mathbf{e}_n \cdot \mathbf{j} ds + A^{-1} \int_{\Gamma} (U''V'')\mathbf{e}_s \cdot \mathbf{j} ds, \quad (12)$$

and thus the estimate for D' averaged over the area A is

$$D' = A^{-1} \int_{\Gamma} \left[(U'')^2 \right] \mathbf{e}_n \cdot \mathbf{j} \, ds + A^{-1} \int_{\Gamma} (U''V'')' \mathbf{e}_s \cdot \mathbf{j} \, ds. \quad (13)$$

Figure 5. Box 1 where D' was estimated off the southwestern coast of Australia. The solid lines correspond to the satellite tracks and the dashed line to the shelf edge (200 m isobath). Tracks 101, 166, 177, and 90 are labeled. Point C indicates the crossover point of Track 166 and Track 101. Point E is the location of the intersection of Track 166 and Track 177.

The “eddy” surface velocity component U'' , which is perpendicular to the satellite track, can be calculated at a given along-track measurement point every 10 days by geostrophy from the along-track “eddy” SSH estimates η'' . At each along-track point, η'' is found as a 10-day time series by removing the mean, seasonal cycle, and interannual and lower frequency variability from the original 10-day SSH time series. The 10-day sea level slope time series for the geostrophic estimate was found from η'' at a given along-track point by a least squares fit of 5 along-track points, the point itself and its two nearest neighbors on each side. We decided to use

five along-track points to calculate U'' because this corresponds to a distance of about 30 km which is small enough to resolve the sea level slope for the eddies in the region with typical diameters of about 100 km (see, e.g., the western Australian eddy observations in Pearce and Griffiths 1991; Waite et al. 2007). Fewer than a 5-point fit will also resolve the eddy scale, but using more points enables a better estimate of the sea level slope.

By construction, the 10-day U'' time series only contains relatively high frequencies, but $(U''U'')'$ contains a mean and may vary interannually if the amplitude of U'' varies interannually. Thus, after removal of the mean, the interannual contribution $(U''U'')'$ can be non-zero and contribute to D' as in (13).

The along-track eddy component V'' (see (10)) cannot be obtained from a single track but can be estimated for a given track at a location where two tracks intersect. Thus, the term $(U''V'')$ in (13) can only be calculated at a few points along the bounding curve Γ . For Box 1 (Fig. 5), the two relevant points are C and E . Table 1 suggests that $(U''V'')$ is probably comprised mostly of ‘noise’ since at both points C and E it is not significantly correlated with $(U''U'')$, with $(U''U'')$ averaged along any satellite track bounding the box, or with Niño 3.4. In addition (see Table 1), at both C and E it has a root-mean-squared (RMS) value smaller than $(U''U'')$. Based on this we dropped the $(U''V'')$ integral when calculating D' in (13).

Note that the curve Γ around the edges of the box in (13) includes the 200 m isobath where no satellite data are available. However, since eddies do not ride up onto the shelf, we assume that $U'' = 0$ along the shelf edge. This implies that the shelf edge part of Γ does not contribute to the integrals in (13).

Table 1. RMS values of $(U''U'')$ and $(U''V'')$ at points C and E in Fig. 5 and the correlations of $(U''V'')$ with Niño 3.4 and $(U''U'')$.

		RMS (CM ² /S ²)	CORRELATION WITH NIÑO 3.4	CORRELATION WITH $(U''U'')$
C	$(U''U'')$	372	$r = 0.53$ Lag = 4 m	$r = 1.0$
	$(U''V'')$	219	$r = 0.30$ Lag = 4 m	$r = .39$
E	$(U''U'')$	704	$r = -0.51$ Lag = 1 m	$r = 1.0$
	$(U''V'')$	318	$r = -0.26$ Lag = 1 m	$r = 0.34$

CHAPTER THREE

INTERANNUAL ALONG-SHELF FLOW

3.1 Along-track Sea Level Structure

In order to check the key relationships (7) and (8), we must estimate the large-scale interannual flow v' . To do this, we will first analyze the along-track SSH data previously described. In the past, reliable altimeter SSH measurements were not available close to the coast, but recently the merged TOPEX/Poseidon, Jason-1, and OSTM/Jason-2 along-track data have been uniformly processed so that reliable data are available as close as 15 km from the coast.

North of 22°S, Clarke and Li (2004) found that the interannual seaward SSH slope was very gentle and that the SSH is highly correlated with the coastal sea level, but south of 22°S, much larger seaward and alongshore sea level gradients and therefore stronger interannual flows were obtained. This is consistent with our results in Fig. 3, and here we concentrate on the region offshore of the western Australian coast south of 22°S.

In this region there are 3 ascending satellite tracks that intersect the coast (Tracks 101, 177, and 253). Tracks 101 and 177 clearly cut across the shelf edge, while Track 253 runs almost parallel to the shelf edge (Fig. 2). Also Track 166 is a descending track that is parallel to the southwestern Australian coast about 100 km from the shelf edge.

The correlations and least squares regression coefficients of the interannual SSHs along Tracks 101, 177, 253, and 166 on the nearest coastal sea level stations where the tracks cross the coast are shown in Fig. 6. In particular, just seaward of the shelf edge, especially on Tracks 101 and 177 which are not parallel to the shelf edge (Fig. 2), there's a sudden drop in correlation and regression coefficients. This signifies a sharp decrease in amplitude of the coastal and shelf signal and, by geostrophy, an interannual flow component at right angles to the tracks.

Figure 6. Correlation and least square regression coefficients of interannual along-track SSH on interannual coastal sea level for Tracks 101 ((a) and (b)), 177 ((c) and (d)), 253 ((e) and (f)) and 166 ((g) and (h)). For each track the coastal sea level used in the calculations corresponds to the coastal sea level station nearest to where the track crosses the coast (Track 101, Carnarvon; Track 177, Geraldton; Tracks 166 and 253, Fremantle). The bold black vertical line shows the location of the shelf edge, and the other vertical black lines show where the satellite tracks cross. The red shaded lines in (a) – (d), (g) and (h) correspond to these sections of the tracks from Box 1 (see Fig. 5).

Surprisingly, further seaward the regression and correlation coefficients of SSH on Tracks 101 and particularly 177 on coastal sea level then begin to rise again (Fig. 6(a) – (d)), reaching correlation values of ≈ 0.7 and regression coefficients near unity (Track 177) and about 0.65 (Track 101)! This suggests that there is an interannual flow hundreds of kilometers further from the coast in the direction *opposite* to the shelf edge flow. Figure 2 of Clarke and Li (2004) shows a similar result, but this behavior was not discussed in their paper.

The correlation and regression results for Track 166 (Fig. 6(g) and (h)) reveal another surprising result. Due to the changing shelf edge direction, Track 166 initially crosses the shelf and its edge near Bunbury and Fremantle but then runs approximately parallel to the shelf edge for several hundred kilometers (Fig. 2). The surprising result is that, just seaward of the shelf edge and the intersection with Track 253, the regression coefficient increases (Fig. 6(h)). This increase means that the alongshore flow near the shelf edge is in the *opposite* direction to that on the adjacent shelf and at other sections along the coast where the interannual sea level amplitude falls. Farther northward along the track where it is approximately parallel to the shelf edge but about 80 km from it, changes in the slope of the SSH suggest that the large scale interannual flow at this distance from the coast is not parallel to the shelf edge, i.e., it appears to undergo large-scale meanders. Note that along Track 166 in the region just seaward of the shelf edge where the flow reverses and for a large section of the track where the “meanders” occur, the correlation of the SSH with the coastal sea level is greater than 0.6, suggesting that these features are real.

3.2 Quantitative Estimates of the Interannual Flow Along the Shelf Edge

In the previous subsection we described qualitative changes in the interannual flow based on slopes in interannual SSH deduced from a correlation and regression analysis. Here we attempt to estimate those interannual flows quantitatively. In particular, to verify the theoretical relationships (7) and (8) for Box 1, we will need to estimate v' for this box. Since the satellite Tracks 101 and 177 do not cross the shelf edge at right angles (Fig. 5), we cannot calculate v' directly from the gradient of the sea level along the track, and we proceed as follows.

First note that the gradient of η' along the shelf edge η'_y is about 1 cm in 1000 km (see, e.g., the green curve in Fig. 3 from 22°S to 32°S) or 10^{-8} whereas calculations of interannual sea level gradients η'_s along the edges of Box 1 are of order 10^{-7} (order 1 cm in 100 km), an order of magnitude larger. Since $\nabla\eta'$ can be written as

$$\nabla\eta' = \eta'_s \mathbf{e}_s + \eta'_n \mathbf{e}_n = \eta'_x \mathbf{i} + \eta'_y \mathbf{j}, \quad (14)$$

by taking the dot product of both sides of the second equality with $\mathbf{e}_s$ we obtain

$$\eta'_s = \eta'_x \mathbf{i} \cdot \mathbf{e}_s + \eta'_y \mathbf{j} \cdot \mathbf{e}_s = \eta'_x \cos\theta + \eta'_y \sin\theta, \quad (15)$$

where θ is the angle between the x and s axes (see Fig. 4). Because $\eta'_y = \eta'_s$ and therefore $\eta'_y \sin\theta = \eta'_s$, from (15) we have

$$\eta'_x \approx \eta'_s / \cos\theta. \quad (16)$$

Hence

$$v' = g\eta'_x / f = g\eta'_s / f \cos\theta. \quad (17)$$

The along-track gradient η'_s for the northern and southern edges of Box 1 were obtained by calculating an EOF of the interannual SSH estimates along each of these edges and then estimating η'_s from the first EOF structure function in each case. This procedure is justifiable because the first EOF describes most of the SSH variance, specifically 94% for Track 101 and 80% for Track 177. Also, an EOF analysis is appropriate if all the interannual SSHs are in phase in time, and calculations showed that this is indeed the case — maximum lag correlations between the interannual SSH measurements used in the v' calculations along each track occurred when the lag was zero months.

Table 2 shows the results for v' at the Box 1 northern (Track 101) and southern (Track 177) edges. The Principal Component has been scaled so that its variance is 0.5. This implies that the EOF structure functions are representative of the dimensional amplitude of the flow. At both the northern and southern edges of Box 1, v' is positively well correlated with shelf edge and coastal sea levels and negatively well correlated with Niño 3.4 in accordance with what would be expected by the Fig. 1 mechanism. The along-shelf edge interannual flow at the southern end of Box 1 is much stronger than the flow at the northern end.

Table 2. Based on (17), estimates of the interannual along-shelf edge flow v' at the northern (Track 101) and southern (Track 177) edges of Box 1. The SSHs used in the first mode EOF calculation for Tracks 101 and 177 near the shelf are marked in red in Fig. 6. Also shown are the correlations r and critical correlations r_{crit} at the 95% significance level of the Principal Component time series of the first mode EOF with the interannual sea level at the shelf edge, the nearest coastal station, and Niño 3.4. The maximum correlations were all found at a lag of zero months.

	Track 101	Track 177
Along-shelf flow amplitude (v')	0.9 cm s ⁻¹	3.4 cm s ⁻¹
Correlation of v' with shelf edge η'	$r = 0.93$ $r_{\text{crit}} (95\%) = 0.48$	$r = 0.89$ $r_{\text{crit}} (95\%) = 0.45$
Correlation of v' with coastal η'	$r = 0.83$ $r_{\text{crit}} (95\%) = 0.56$	$r = 0.82$ $r_{\text{crit}} (95\%) = 0.54$
Correlation of v' with Niño 3.4	$r = -0.67$ $r_{\text{crit}} (95\%) = 0.40$	$r = -0.73$ $r_{\text{crit}} (95\%) = 0.42$

3.3 Interannual Flow on the Shelf

Our main focus is on the verification of the theory of Chapter 2. However, interannual flow on the continental shelf is of interest in its own right since even weak interannual flows can transport particles hundreds of kilometers and profoundly affect marine populations (see, e.g., Li and Clarke 2004; Clarke and Dottori 2008). Below, interannual flow on the southwestern Australian continental shelf is considered, beginning with an examination of the spatial structure of the SSH and coastal sea level across the shelf.

Figure 6 shows that the correlation of interannual SSHs on the shelf with the nearest interannual coastal sea level measurement is very high for all tracks considered, and that, particularly for Track 101 and Track 253, there is a small but discernible fall in the regression coefficients across the shelf. Also noticeable in all tracks in Fig. 6 is that even though the correlation of the closest SSH measurement to the coastal sea level is very high, the corresponding regression coefficient is only between 0.8 and 0.9. Therefore, the gradient calculated from the coastal sea level measured in situ and the satellite SSH estimate that is closest to the coast is unrealistically very much greater than that found from the shelf SSH gradient. The interannual SSH estimates appear to be systematically slightly underestimating the real interannual sea level.

Estimates of v' on the shelf can be obtained from (17) using an EOF analysis in the same way the v' results at the shelf edge were obtained in Table 2. The results are shown in Table 3. The interannual flows are weaker than those at the shelf edge but are still strong enough to transport particles hundreds of kilometers along the shelf.

Table 3. Estimates of v' on the shelf obtained using a least squares fit slope of the first mode structure function of the EOF of the interannual along-track SSH and the correlations and regression coefficients of v' with the nearest interannual coastal sea levels for Tracks 101 (Carnarvon), 177 (Geraldton), 166 (Fremantle), and 253 (Fremantle).

	Flow amplitude on shelf (v')	Correlation of v' with nearest coastal η'	Regression coefficient of v' with nearest coastal η'
Track 101	1.3 cm s ⁻¹	$r = 0.94$ $r_{\text{crit}} (95\%) = 0.64$	$b = 0.75$
Track 177	0.9 cm s ⁻¹	$r = 0.98$ $r_{\text{crit}} (95\%) = 0.69$	$b = 0.91$
Track 166	0.6 cm s ⁻¹	$r = 0.94$ $r_{\text{crit}} (95\%) = 0.69$	$b = 0.83$
Track 253	2.5 cm s ⁻¹	$r = 0.95$ $r_{\text{crit}} (95\%) = 0.69$	$b = 0.85$

CHAPTER FOUR

TESTING THE THEORY

4.1 Introduction

Using coastal sea level data and along-track SSH measurements, we have shown that there is a drop in interannual sea level along the shelf edge and the coast of western Australia south of 22°S. We have also observed an interannual flow along the shelf edge that spatially coincides with the Leeuwin Current. Since bottom friction and wind stress effects on the interannual sea level in the region are negligible, we will now check to see whether Leeuwin Current eddies are causing the observed drop in interannual sea level along the shelf edge by dissipating energy interannually.

In Chapter 2 we established that if eddies are responsible for the fall in sea level amplitude along the shelf edge, then in accordance with (6), the interannual divergence of the eddy flux D' should be correlated with $-g\eta'_y$ and have the same amplitude. In addition, the interannual divergence of the eddies is likely caused by interannual variations of the Leeuwin Current, and so we expect that D' should be proportional to v' as in (7). Equations (6) and (7) can be combined to form (8), and in this chapter we will test all three of these relationships.

4.2 Results

As discussed in Chapter 2, D' can be estimated near the shelf edge for Box 1 (Fig. 5) using (13) with the $(U''V'')$ integral in that equation dropped and the integral along the shelf edge put to zero since $U'' \approx 0$ there. Under such approximations, calculations show that in accordance with (7), D' averaged over Box 1 is correlated [$r = 0.59$, $r_{crit}(95\%) = 0.37$] with v' estimated from an average of v' at the northern and southern edges of the box using Tracks 101 and 177 (see Fig. 5).

The D' and v' time series are calculated from noisy data, and in such circumstances the standard least squares regression of D' and v' is not the reciprocal of v' on D' . A better

regression coefficient when the noise in both variables is unknown is the ratio of the standard deviations (Clarke and Van Gorder 2012). This gives a dissipation time R^{-1} of only 3.1 days! This is much shorter than the interannual time scale and indicates that the interannual flow is strongly dissipated by the eddies. Figure 7 shows a plot of the Rv' time series calculated over Box 1 and the D' time series calculated with Tracks 101, 166, and 177 (green) and with only Tracks 101 and 177 (blue). The blue and green plots are nearly the same because Track 166 is nearly parallel to the coast and so for this track $\mathbf{e}_n \cdot \mathbf{j} \approx 0$ in (13).

Figure 7. Divergence of interannual eddy momentum flux D' calculated with Tracks 101, 177, and 166 (green) and with Tracks 101 and 177 (blue) over Box 1. The red curve shows Rv' calculated over Box 1.

The correlation of the divergence of the eddy flux over Box 1 with the along-shelf interannual sea levels as in (6) was also calculated and found to be positively correlated [$r = 0.41$, $r_{crit} (95\%) = 0.34$]. In addition, the Root Mean Square (RMS) values of $-g\eta_y$ and D' were

almost equivalent ($5.4 \times 10^{-6} \text{ cm s}^{-2}$ and $5.5 \times 10^{-6} \text{ cm s}^{-2}$, respectively), i.e., the appropriate regression coefficient is nearly unity.

Finally, the relationship (8) was analyzed. The correlation of v' with $-g\eta_y$ was very strong [$r = 0.91$, $r_{crit}(95\%) = 0.48$]. The dissipation time scale R^{-1} from this analysis was 3.2 days, practically the same as R^{-1} calculated from (7).

CHAPTER FIVE

WESTERN COAST OF SOUTH AMERICA ANALYSIS

On average, for most of the calendar year, the coastal current off Peru is northward, and the water is cold. But around Christmas time the current reverses, the flow is southward, and the water is warmer. From at least the late nineteenth century, fishermen at the port of Paita in northern Peru (Fig. 8) have called this warm current ‘El Niño’ (The Child Jesus) because it typically starts around Christmastime. But the strength and duration of this current varies greatly from year to year, and we now know that it is connected to coupled ocean-atmosphere interaction in the central equatorial Pacific and to climatic variability around the globe. The name ‘El Niño’ is now associated with higher than normal sea surface temperatures in the central-eastern equatorial Pacific and a stronger than normal southward flow.

During an El Niño when the anomalous westerly winds lower the sea level in the western equatorial Pacific and around Australia (Fig. 1), they also raise it in the eastern equatorial Pacific and along the western coastlines of the Americas. Anomalies of opposite sign occur during La Niña. As in the western Australian case, we expect the sea level to be spatially constant along the coast and shelf edge, but Li and Clarke (2007) demonstrated that the interannual amplitude falls southward and is associated with a strong interannual flow along the shelf edge.

Similar to the results of Li and Clarke (2007) but using a longer altimeter sea level record from January 1993 through July 2011, the first mode EOF structure function of the interannual altimeter SSH along the shelf edge of South America shows a sharp drop in interannual amplitude from 6°S to around 16°S (Fig. 9). The Principal Component time series of the first mode EOF has a strong positive correlation with Niño 3.4 [$r = 0.75$; $r_{\text{crit}} (95\%) = 0.44$]. Since the 1997 – 1998 El Niño dominates the Principal Component, the strong correlation of the interannual sea level and Niño 3.4 without this event is also confirmed [$r = 0.73$; $r_{\text{crit}} (95\%) = 0.39$].

Coastal sea level data from the University of Hawaii Sea Level Center (<http://uhslc.soest.hawaii.edu/>) from February 1994 through December 2006 were used to also calculate the interannual sea level drop along the western coast of South America. The sea level

data available along this coast is limited, but an EOF of the interannual sea levels at the locations (see Fig. 8) with the most complete time series was taken. The structure function (Fig. 9(a)) shows a drop in sea level similar to that along the shelf edge, and the Principal Component time series (Fig. 9(b)) is highly positively correlated with Niño 3.4 [$r = 0.85$; $r_{\text{crit}}(95\%) = 0.55$]. The interannual coastal sea level data is also strongly positively correlated with the interannual altimeter SSHs along the shelf edge [$r = 0.95$; $r_{\text{crit}}(95\%) = 0.64$].

Figure 8. Map of the western coast of South America from 2°S to 35°S. The black lines show the TOPEX/Poseidon, Jason-1, and Jason-2 satellite tracks, and the dashed line shows the approximate position of the shelf edge. Note that the shelf edge is quite narrow along most of the coast. The green dots and red dots correspond to the locations of sea level measurements along the shelf edge and coast, respectively.

Figure 9. (a) Structure function of the 1st mode EOF of the interannual sea level along the western coast of South America from 4°S – 35°S at the shelf edge (green, 88% of variance) and coast (red, 60% of variance). Figure 8 shows a map of these locations. (b) Principal Component time series for the 1st mode EOFs corresponding to (a).

What causes the fall in interannual sea level amplitude along the coast? Pizarro et al. (2001) showed that coastal alongshore wind stress and bottom friction have negligible influence on the interannual sea levels along the western coast of South America, and an analysis similar to that in Appendix A shows that the interannual sea level fall along the coast is much too steep to be explained by conservation of energy and the observed interannual shelf edge flows of Li and Clarke (2007) and mean flows of Chaigneau and Pizarro (2005b). Can the sharp fall in interannual shelf edge SSH and coastal sea level be explained by eddies as in the Australian case?

Eddies and small-scale flows do exist in this region. Using surface drifters, Chaigneau and Pizarro (2005a) found that eddies generated from the Chile-Peru Current propagate seaward with a speed of 6 cm s^{-1} north of 15°S and 3 cm s^{-1} south of 30°S . These eddies have a typical diameter of order 30 km which is considerably smaller than the eddies off Australia. The smaller diameter, lower latitude, and faster propagation made it much more difficult to calculate this variability from altimeter data, and in the South American case it was not possible to calculate the interannual eddy divergence D' well enough, even with along-track data. However, it is still possible to estimate R^{-1} from the shelf edge sea level gradient and v' using (8). To do this, we need to estimate v' .

Previous along-track altimeter estimates of v' have been given by Li and Clarke (2007) for the 11-year period from January 1993 to December 2003. They showed that the coastal interannual flow is southward (northward) during an El Niño (La Niña) when the sea level is higher (lower) than normal at the coast and shelf edge. Li and Clarke based their analysis on separate EOF first mode structure functions of SSHs along Tracks 39, 115, 191, and 13. Figure 10 shows similar along-track analyses but for the much longer January 1993 through December 2010 record available to us. As found by Li and Clarke, the first EOF explains almost all of the variance, and the seaward drop in along-track interannual sea level along Tracks 39, 115, and 191 implies that there is an interannual alongshore flow at the shelf edge (Fig. 10).

The method of calculating v' here was similar to that of the v' calculations along the southwestern coast of Australia in Chapter 3. Figure 10 shows the structure function and Principal Component time series of the interannual SSHs along Tracks 39, 115, 191, and 13. Along tracks 39, 115, and 191, the interannual sea level amplitude decreases from the coast and shelf edge for about 100 km and then flattens out. Note that the shelf is quite narrow where Tracks 39 and 13 cross but much wider where Track 191 crosses. The slopes of the interannual SSH along Tracks 39, 115, and 191 were calculated with a least squares fit of the structure function of the first mode EOF of the interannual SSHs along each track in their respective regions of decreasing SSH seaward of the coast and shelf. For each track, the sea level amplitude flattens at around 75 km – 100 km from the shelf edge. Equation (17) was used with each of the along-track interannual sea level gradients η'_s to find v' . The resulting interannual along-shelf flow amplitudes at Tracks 39, 115, and 191 were highly correlated with Niño 3.4 as

shown in Table 4. The alongshore flow appears to be approximately 100 km wide from around 6°S to 14°S. There also seems to be an opposing northward flow seaward of the coast at Track 13.

Figure 10. The structure function of the first mode EOF of the interannual SSH along (a) Track 39 (97% of variance), (c) Track 115 (97% of variance), (e) Track 191 (93% of variance), and (g) Track 13 (92% of variance), and their corresponding Principal Component time series (b) Track 39, (d) Track 115, (f) Track 191, and (h) Track 13.

The correlation of v' averaged over Tracks 39, 115, and 191 (see Table 4) in the main region of interannual sea level drop along the shelf edge with $-g\eta_y$ in this same region is highly

positively correlated [$r = 0.99$; $r_{\text{crit}}(95\%) = 0.49$] off the western coast of South America. Note that Track 13 was not used to calculate v' because η_y' begins to flatten there. The dissipation time scale from this relation (8) was found to be 1.8 days, even shorter than R^{-1} calculated for southwestern Australia in Chapter 4. The correlation and dissipation scale were also checked with the 1997-1998 El Niño event removed from the data. The correlation was found to be $r = 0.98$ ($r_{\text{crit}}(95\%) = 0.46$), and the dissipation time scale was 2.4 days.

Table 4. The interannual alongshore flow magnitude and correlations of the EOF of the first mode Principal Component time series of the along-track interannual sea levels at Tracks 39, 115, 191, and 13 with Niño 3.4. Results are also given for v' and its correlation with Niño 3.4 when the 97-98 El Niño has been removed from the data.

	Along-shelf flow amplitude (v')	Correlation of v' with Niño 3.4	Along-shelf flow amplitude with 97-98 El Niño removed	Correlation of v' with Niño 3.4 with 97-98 El Niño removed
Track 39	6.2 cm s ⁻¹	$r = 0.72$ $r_{\text{crit}}(95\%) = 0.42$ Lag = 0 m	4.0 cm s ⁻¹	$r = 0.74$ $r_{\text{crit}}(95\%) = 0.40$ Lag = 1 m
Track 115	5.8 cm s ⁻¹	$r = 0.70$ $r_{\text{crit}}(95\%) = 0.43$ Lag = 0 m	3.6 cm s ⁻¹	$r = 0.64$ $r_{\text{crit}}(95\%) = 0.42$ Lag = 1 m
Track 191	5.4 cm s ⁻¹	$r = 0.73$ $r_{\text{crit}}(95\%) = 0.43$ Lag = 1 m	4.0 cm s ⁻¹	$r = 0.69$ $r_{\text{crit}}(95\%) = 0.38$ Lag = 2 m
Track 13	-1.1 cm s ⁻¹	$r = 0.68$ $r_{\text{crit}}(95\%) = 0.46$ Lag = 2 m	0.4 cm s ⁻¹	$r = 0.56$ $r_{\text{crit}}(95\%) = 0.39$ Lag = 2 m

CHAPTER SIX

CONCLUSIONS

Along the coast and shelf edge off western Australia the interannual El Niño sea level amplitude decreases poleward. Our analysis showed that this fall in amplitude corresponds to a surprisingly short dissipation time scale of only a few days, much shorter than the El Niño interannual time scale. Using along-track altimeter data and theory, it was shown explicitly that this interannual dissipation was due to interannual variations in small scale, high frequency eddy variability. These interannual changes in eddy variability are correlated with the large-scale shelf edge flow in the way one might expect. Specifically, during a La Niña when the western Australian coastal and shelf edge sea levels are higher than normal, the Leeuwin Current is anomalously strong, the loss of energy due to eddies is greater than normal and the shelf edge and coastal anomalous sea level fall southward. Opposite conditions apply during El Niño; the coastal and shelf edge sea levels are lower than normal, the Leeuwin Current is anomalously weak, there is less loss of energy due to eddies and the sea level does not fall as rapidly southward, i.e., the negative along-coast and along-shelf edge sea level anomaly dissipates.

Off South America analysis showed that a similar fall in interannual sea level amplitude near the coast and shelf edge is associated with anomalous alongshore flow and a similar dissipation time scale of a few days. It is likely that the signal dissipation along this coast is also due to the interannual divergence of the eddy momentum flux, as energetic eddies have been documented off this coast. However, in this case an explicit eddy flux divergence calculation could not be done successfully even with the high-resolution along-track altimeter data. The eddies in this region are of smaller horizontal scale and nearer to the equator so, by geostrophy, the SSH signal is smaller and the eddy velocities not accurate enough to calculate interannual variations of the eddy flux divergence. Nevertheless, it is likely that the along-track satellite data analysis used to analyze the effect of eddies on the large scale flow is not limited to the Leeuwin Current example.

APPENDIX A

ENERGY CONSERVATION AND SEA LEVEL FALL ALONG THE SHELF EDGE

Observations show that the interannual sea level amplitude falls along the shelf edge and the interannual shelf edge flow increases (see Fig. 2 and accompanying discussion in the text). To see if the fall in interannual sea level amplitude (and potential energy) along the shelf edge can be explained by conservation of energy and increasing kinetic energy (through increasing v' amplitude), consider the y -momentum equation,

$$\frac{Dv}{Dt} = -g\eta_y - fu. \quad (\text{A.1})$$

At the shelf-edge, there is no flow into the boundary so $u = 0$, and at interannual and lower frequencies v_t is negligible. Therefore (A.1) simplifies to

$$v v_y + g\eta_y = 0 \quad (\text{A.2})$$

which is equivalent to

$$\left(\frac{1}{2} v^2 + g\eta \right)_y = 0. \quad (\text{A.3})$$

The along-shore low-frequency flow v can be written as $v = \bar{v} + v'$, where $(\bar{})$ denotes the mean plus the annual cycle and $()'$ denotes the interannual signal. Substituting this into (A.3) gives

$$\frac{1}{2} (\bar{v}^2 + 2\bar{v}v' + (v')^2) + g\bar{\eta} + g\eta' = \text{constant}. \quad (\text{A.4})$$

Since $(v')^2$ is small compared to $(\bar{v})^2$, it may be dropped from (A.4). Looking at the interannual anomalies only, (A.4) becomes

$$\bar{v}v' + g\eta' = \text{constant}. \quad (\text{A.5})$$

Since (A.5) is constant, $\bar{v}v' + g\eta'$ at a northern location N is equal to $\bar{v}v' + g\eta'$ at a southern location S and so

$$\overline{v_S v'_S} + g\eta'_S = \overline{v_N v'_N} + g\eta'_N. \quad (\text{A.6})$$

The drop in interannual sea level along the western coast of Australia begins at around 22°S where $\overline{v_N v'_N} = 0$. Hence the fall in interannual sea level is

$$\Delta\eta' = \frac{\overline{v_S v'_S}}{g}. \quad (\text{A.7})$$

Assuming an average along-shore mean flow of 50 cm/s and an interannual flow of 2 cm/s, $\Delta\eta' = 0.1$ cm. This drop in sea level is much smaller than the observed interannual sea level decay of 1.5 cm and therefore cannot account for the drop along the western Australian coast.

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BIOGRAPHICAL SKETCH

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