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**Eddies of the East Australia Current:
Long Term Biological Impacts**

By

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Eddies of the East Australia Current: Long Term Biological Impacts

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Abstract: Anthropogenic climate change is having a significant impact on physical and biological systems throughout the world. Impacts to the southeast Australian coastal ocean will likely result from changes in flow patterns due to an increase in the intensity of the East Australia Current (EAC). The EAC is the main physical feature on the east coast of Australia that is responsible for the redistribution of temperature and nutrients in the region. The main aim of this work is to understand how the EAC eddy field has changed over the last two decades and to concurrently determine long term changes in phytoplankton distribution and abundance in the Tasman Sea. An analysis of the interannual variability of chlorophyll concentration shows moderate spatial and temporal interannual variability with the region, with a significant increasing trend. Results of the eddy analysis indicate the 1-3 eddies are produced annually by the EAC with an average duration of 229 days. Trend in eddy production showed little change over the 18 year period suggesting that other phenomena, besides eddy dynamics, are responsible for the increasing trend of chlorophyll in the Tasman Sea.

Keywords: remote sensing, chlorophyll, eddies, sea surface height

1. Introduction

Anthropogenic climate change is having a significant impact on physical and biological systems throughout the world [1]. Stressors of climate change are anticipated to decrease ocean productivity, alter food web dynamics and shift species distributions [2] [3] [4] resulting in significant social and economic impacts, including impacts to fishing and shipping industries. Climate change will also have wide ranging effects on the coastal and marine environment of south east Australia [5], and species-specific changes in the abundance and seasonal window of growth of phytoplankton and harmful alga blooms [6].

Impacts to the southeast Australian coastal ocean will likely result from changes in flow patterns due to an increase in the intensity of the East Australia Current (EAC). The EAC is the main physical feature on the east coast of Australia that is responsible for the redistribution of temperature and nutrients in the region and its southward penetration into the Tasman Sea has increased over the past 60 years, introducing augmented pulses of warm, high salinity subtropical water during the summer [7] [8].

Eddies are important, not only because they can transport warm, nutrient poor subtropical waters into temperate regions of the Tasman Sea, but also because they are spots of intense biological and physical activity. Eddies embody mechanisms by which the physical energy of the oceans can be converted to trophic energy [9]. Eddies can drive upwelling or vertical and horizontal flow which can concentrate or dilute planktonic organisms or redistribute nutrients from depth to the surface. Food particles and nutrients for fish larvae can be concentrated in eddy frontal structures, and provide increased feeding opportunities for plankton predators [9]. This has implication for understanding the movement and changes in distribution and abundance of important offshore pelagic fisheries and their management [10]. Eddy interactions within 90km of the shelf break off of NSW have also been shown to drive waters onto the continental shelf, enriching the coastal water column and initiating algal blooms [11].

The main aim of this work is to understand how currents in EAC eddy field have changed over the last two decades and to concurrently determine long term changes in phytoplankton distribution and abundance in the Tasman Sea. Using remote sensing and field sampling techniques this proposal aims to:

- 1) Develop an 18-year (1992-2010) census of anticyclonic warm core eddies from satellite altimetry,
- 2) Characterize the long term (1998 -2007) interannual and seasonal variability of phytoplankton distribution and abundance, and
- 3) Develop remote sensing products that apply relevant oceanographic knowledge in support of marine environmental protection.

2. Methods

2.1 Census of Eddies from Sea-level Anomaly Analysis

Satellite radar altimeters can measure sea surface topography and the presence of eddies. Eddies have been shown to have a distinctive signature in sea surface height, ~20 cm, relative to the surrounding waters (Willett, 1996). We followed the methods of Henson and Thomas (2008) to test an objective

eddy identification algorithm on 18 years (1992-2010) of satellite sea level anomaly (SLA) data off the east coast of Australia and in the Tasman Sea. With the data we conducted an eddy census that quantifies the number and location of the eddies and their seasonal and interannual variability. We applied the Okubo-Weiss parameter [12] [13] to identify areas of positive SLA to determine their spatial and temporal distribution (Henson and Thomas, 2008). We obtained multi-mission merged, mapped SLA data from <http://www.aviso.oceanobs.com>. This dataset consists of merged data from ERS, Envisat (European Space Agency missions), Topex/Poseidon and Jason-1 instruments [14]. For each weekly data image we calculated SLA for each pixel location to identify and track eddy areas using a pixel connectivity algorithm [14]. We assessed the annual variability of eddy statistics and then discuss the forcing parameters that may contribute to this variability.

2.2 Interannual Variability of Phytoplankton Biomass

Satellites can also be used to characterize oceanic and eddy habitat using chlorophyll-a concentration and sea surface temperature as a proxy for phytoplankton biomass and productivity. Here, we will use chlorophyll-a concentrations derived from NASA's Sea-viewing Wide Field-of-view Sensor (SeaWiFS) to analyze interannual variability and trends of phytoplankton biomass over the lifetime of SeaWiFS data (1998–2007). We identified areas with improving, declining, and stable chlorophyll concentrations that can provide guidance for understanding the influence of the strengthening penetration of the EAC eddies into the Tasman Sea.

The Sea-Viewing Wide-Field Sensor (SeaWiFS) on the OrbView-2 platform, launched in fall, 1997, provides a time series of phytoplankton chlorophyll-a maps of the global ocean with unprecedented spatial and temporal coverage. Daily 9km, mapped ocean color (chlorophyll a) data was obtained from the Goddard Space Flight Center ocean color data archive, <http://oceandata.sci.gsfc.nasa.gov/>. Methods describing NASA's data processing are discussed elsewhere [15]. NASA SeaWiFS daily data was averaged to create annual means of phytoplankton abundance for the Tasman Sea region. Similarly, maps of annual average temperature were constructed for the region based on data obtained from the NASA Pathfinder dataset from <http://www.nodc.noaa.gov/>.

To investigate the interannual variability of the chlorophyll and SST distributions in the Tasman Sea, annual average maps were constructed for each of these variables. The seasonal maps enabled us to establish the extent of the interannual patterns. However, in order to understand the data structure further, the Empirical Orthogonal Function (EOF) method was used. This statistical approach is a convenient method for analysis of successive images of data distributed in space. Besides its classical oceanographic and meteorological applications, EOF analysis has been largely used to obtain the dominant patterns of residual variance in satellite images time series [16] [17] [18].

The EOF procedure is described in detail elsewhere [19] [20]. The method is based on a decomposition of a multivariate data set into an uncorrelated linear combination of separate functions of the original variables, ranked by variance. The EOF is the same as Principal Component Analysis (Hotelling, 1933). The principal components (PCs) are the amplitudes, which are functions of time of their corresponding spatial eigenfunctions, or EOFs. The analysis separates the data sets into orthogonal modes, and each mode n has an associated variance, a dimensional spatial pattern and a nondimensional time series. The first few EOFs can define the dominant pattern of the variance with the corresponding eigenvalues representing the percentages of total variance explained.

For this study, each grid of annual chlorophyll and SST observation is converted into a vector of the matrix T with dimensions $M \times N$, where M is the number of spatially distributed points (points at the sea surface) and N is the number of points over time (number of images). To study the strong temporal variability associated with chlorophyll and SST variability in the study area, the

climatological mean is subtracted from all data to create the total anomaly. Normalized anomalies were computed using the method described by Emery *et al.* [20]. The linear trend was removed from the data with a fitted polynomial. The annual average images were then assembled into a covariance matrix, the data were temporally de-meanned, and Empirical Orthogonal Function (EOF) analysis was executed on the time-series. The results of the EOF analysis were orthogonal variance modes with their associated eigenfunctions and eigenvectors. The modes were arranged in order of decreasing variance, and only those with eigenvalues above the noise threshold (in this case only the first three) were retained for retained for analysis. This process was carried out over the Tasman Sea study area.

3. Results

3.1 Interrannual Variability of Phytoplankton Biomass

Annual average chlorophyll concentration for the entire Tasman Sea region is shown in Fig. 1. The trend shows a statistically significant increase over the 14 year sample period (1997-2010). The first two modes and their corresponding temporal amplitudes for the EOF analysis of annual chlorophyll concentration, explained 80% of the cumulative variance. Typically the first EOF function would mostly account for the seasonal variability. However, the seasonal signal was removed to allow the inter-annual signal to emerge. Therefore, the first EOF (Fig. 2) mode mainly depicts the inter-annual variability. The first EOF mode explains 75% of the total variance. To understand the results of an EOF analysis, one must simultaneously consider both the eigenfunction (image) and the eigenvector (time-series). Together, they form a spatial pattern (the image) that oscillates according to a temporal pattern (the time-series). Areas of the image that are positive (red and orange in this case) represent areas whose chlorophyll values are above the temporal average when the eigenvector is positive and below the temporal average when the eigenvector is negative. Areas of the image that are negative (blue and purple) behave in an opposite fashion. Areas that have a value of zero (green) do not vary in that particular mode.

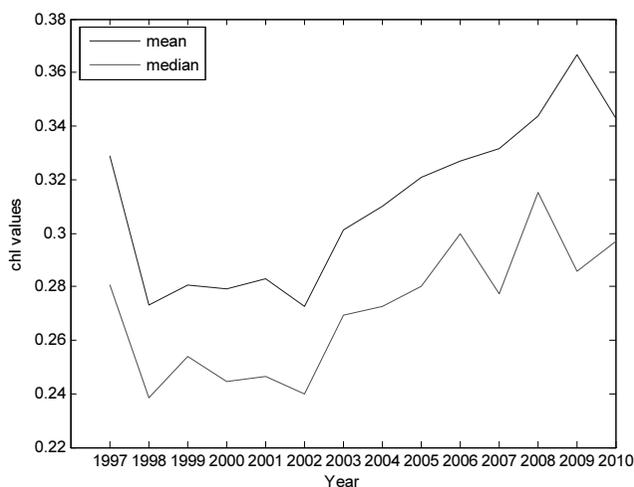


Fig.1 *The annual average temperature for the Tasman Sea region, 1997-2010. The trend shows a statistically significant increase over the 14 year period.*

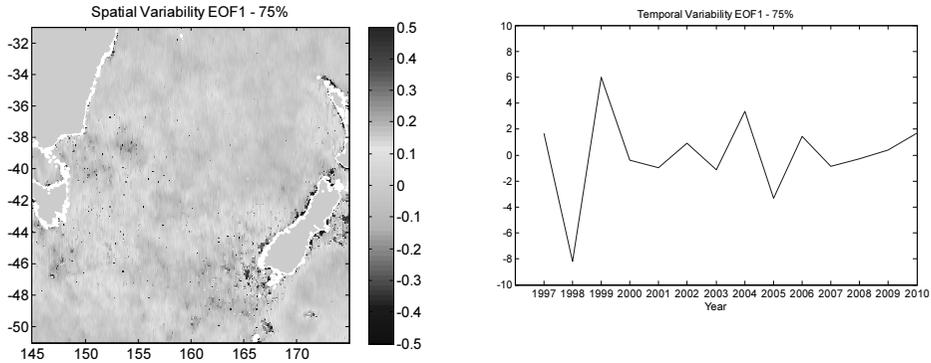


Fig.2 EOF chlorophyll results for the Tasman Sea, EOF Mode 1 eigenfunction (image, left) with the associated eigenvector (time-series, right). The eigenvector (right) illustrates the temporal oscillations of the mode, whereas the eigenfunction on the left illustrates the spatial extent of the oscillation. Referring to the colorbar, red and orange areas oscillate positively with the eigenvector (i.e. they are positive when the eigenvector is positive), and blue and purple areas oscillate negatively with the eigenvector, (i.e. they are negative when the eigenvector is negative).

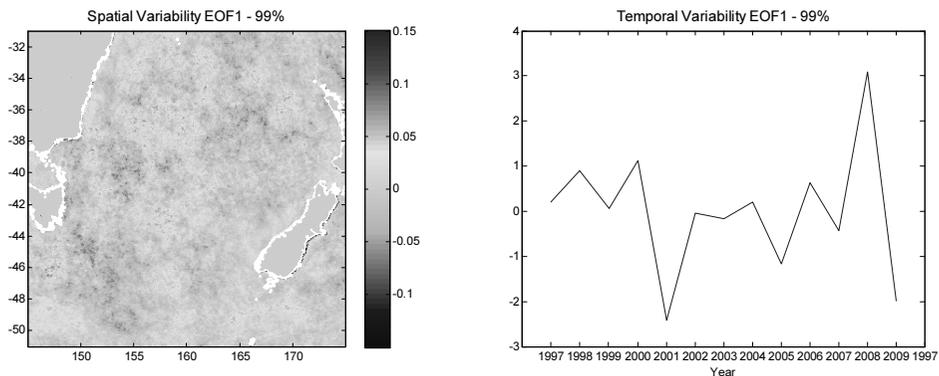


Fig. 3 EOF SST results for the Tasman Sea, EOF Mode 1 eigenfunction (image, left) with the associated eigenvector (time-series, right). The eigenvector (right) illustrates the temporal oscillations of the mode, whereas the eigenfunction on the left illustrates the spatial extent of the oscillation. Referring to the colorbar, red and orange areas oscillate positively with the eigenvector (i.e. they are positive when the eigenvector is positive), and blue and purple areas oscillate negatively with the eigenvector, (i.e. they are negative when the eigenvector is negative).

An EOF analysis of sea surface temperature between 1997 and 2009 is shown in Figure 3. The first EOF mode explains 99% of the total variance, meaning that all the variance in the data is described by that singular mode. Trends in annual average temperature for the Tasman Sea region did not show increasing trend, but exhibit high variability ($\sim 2^\circ$) from year to year (Fig. 4) with the highest average temperature occurring in 1999 and the lowest occurring in 2004.

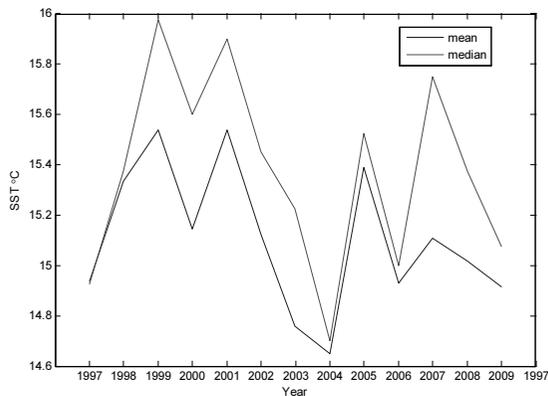


Fig4 .The average annual temperature for the Tasman Sea between 1997 and 2004.

3.2 Census of Eddies from Sea-Level Anomaly

Figure 5 shows an example of the Okubo-Weiss parameter for the week of 29 December 2010. The underlying sea surface temperature highlights the formation of an eddy off of the east coast of Australia. Considering only those eddies that shed from the East Australia current, are within 90km of the shelf break and propagate south of 30°S, the eddy census using SLA data from 1992-2010 showed that over the 18 year sampling period, 49 eddies were produced with a range of 1-3 eddies per year. Eddy duration ranged from 35 to 616 days with an average duration of 229 days (Table 1).



Fig. 5An example of the Okubo-Weiss parameter eddy detection output from the week of 29 December 2010, shown over the monthly sea surface temperature for the Tasman Sea region.

Table 1. The number, time period, and duration of coastal southward penetrating eddies formed over the 1992-2010 period.

Year	Eddy No. (Cyclonic and Anticyclonic)	Time Period	Duration (Days)
1992	1	15 October 1992 - 10 March 1993	146
	2	15 October 1992- October 20 1993	370
1993	1	12 July 1993- 10 November 1993	90
	2	12 July 1993- 10 November 1993	90
1994	1	14 September 1994- 14 July 1995	303
1995	1	29 November 1995- 4 July 1996	218
1996	1	1 August 1996- 21 November 1996	112
1997	1	2 July 1997- 13 August 1997	42
	2	17 September 1997 - 18 March 1998	182
1998	1	10 June 1998 - 27 January 1999	231
1999	1	10 February 1999- 9 June 1999	119
	2	1 December 1999- 28 September 2000	302
2000	1	13 April 2000- 28 September 2000	168
2001	1	15 March 2001- 30 May 2001	66
	2	28 September 2001- 17 November 2002	415
	3	7 November 2001- 16 July 2003	616
2002	1	20 November 2002- 30 July 2003	252
2003	1	4 June 2003- 17 September 2003	105
	2	10 December 2003- 15 July 2004	218
2004	1	21 January 2004- 5 August 2004	197
	2	27 May 2004 – 29 January 2006	612
	3	14 October 2004 – 25 November 2004	42
2005	1	13 April 2005- 29 January 2006	291
	2	23 November 2005 – 27 September 2006	308
2006	1	12 July 2006 – 11 October 2006	91
2007	1	7 March 2007 – 13 June 2007	98
	2	4 July 2007- 20 March 2008	260
2008	1	1 January 2008 – 24 April 2008	114
	2	14 August 2008- 30 December 2008	138
	3	18 December 2008 – 18 November 2009	335
2009	1	28 January 2009 – 14 July 2010	532
	2	19 September 2009 - 7 July 2010	291
2010	1	12 May 2010 – 16 June 2010	35
	2	24 November 2010 – 14 December 2011	385

The third eddy that formed in 2001 was the longest lasting eddy and reached as far south as 44° south. Only two of the 49 eddies reached this far south.

4. Discussion

An analysis of the eddies, as derived from satellite altimetry data, shows that the EAC generates one to three eddies per year, and that these eddies reach as far south as the south east coast of Tasmania. Eddies tend to persist for up to one year. The production of eddies shows a clear seasonal change in intensity throughout the year with a maximum in summer and a minimum in winter. The onset of the summer eddies appears to vary from year to year with the arrival of warm eddy water in the southern Tasman Sea. The cause of this is unknown and is a focus of the further activities planned for the research. It is believed that climatic variability related to the southern annular mode (SAM) and the El Niño Southern Oscillation plays a significant role in this variability.

The Tasman Sea appears to contain the largest non-coastal chlorophyll concentration in the South Pacific Ocean [21]. In this study, phytoplankton abundance and distribution in the Tasman Sea shows an overall, statistically significant increasing trend between 1997 and 2010, though illustrates moderate variability from year to year. The EOF analysis shows areas of highest originating off the southern tip of New Zealand, which propagates westward. The chlorophyll seasonal cycle is characterized by a large austral spring bloom and a much smaller fall bloom separated by periods of lower concentrations. The year in which areas of the Tasman Sea showed a below average concentration of chlorophyll appeared to coincide with the El Niño year of 1998 [22] and conversely, the year which exhibited the most above average concentration coincided with the 1999 La Niña [23]. Sea surface temperature appeared to be mostly above average in the years 2001 and 2009 and mostly below average in 2008. The cause of this pattern and the relationship to chlorophyll concentration is not clear and needs to be investigated further; however, generally, areas of lower temperature appear to coincide with higher concentrations of chlorophyll.

Enhanced vertical mixing, due to the rotation of eddies and the introduction of warm waters into the Tasman Sea are optimal conditions that coincide with increased concentrations of chlorophyll. Though the eddy count does not appear to be increasing, significantly, over the examined time period, and the chlorophyll concentration is significantly (statistically) increasing, suggests that the results of the eddy analysis require further work or that other phenomena are responsible for the increase in chlorophyll concentration over the 13 year period.

These products (sea-surface height and chlorophyll-a concentration maps) developed here will be useful for the purposes of operational oceanography and continued research on climate induced change in regional seas. These products will include real time and climatic statistical data describing the marine environments, including ecological information that could impact knowledge in fisheries management, public health warnings and facilitate management of estuaries and coastal zones. Knowledge of oceanographic climatic variability in ocean currents and productivity can reduce uncertainty in developing climate change adaptation plans and be valuable for insurance risk assessment.

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