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Key Points:

- The EAC separation latitudinal range has not changed considerably from 1980 to 2010
- EAC water transport across the EAC separation point has increased from 1980 to 2010
- EAC water transport inside eddies has increased particularly from 2005 onward

Supporting Information:

- Figures S1–S3

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Long-term trends in the East Australian Current separation latitude and eddy driven transport

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Abstract An observed warming of the Tasman Sea in recent decades has been linked to a poleward shift of the maximum wind stress curl, and a strengthening of the poleward flow along the coast of southeastern Australia. However, changes in the East Australian Current (EAC) separation latitude, as well as in the contribution of the EAC, the EAC extension and its eddy field to the total southward transport due to such a strengthening remain unknown. This study uses 30 years (1980–2010) of the Ocean Forecast for the Earth Simulator (OFES) sea surface height and velocity outputs to obtain a three decade long-time series of (i) the EAC separation latitude, (ii) the southward transport along the coast of southeastern Australia (28°S–39°S), and (iii) the southward transport across the EAC separation latitude. A Lagrangian approach is implemented and the spin parameter Ω is used to provide a quantitative distinction between the transports occurring outside and inside (cyclonic and anticyclonic) eddies. Significant positive trends of the low pass southward transports indicate that the intensification of the poleward flow has occurred both within the EAC and in the EAC extension. In addition, a significant increase in southward transport inside and outside eddies is found. Importantly, the contribution of eddy driven transport has a large temporal variability and shows a sharp increase from 2005 onward. Finally our results show that the EAC has not penetrated further south but it has separated more frequently at the southernmost latitudes within the region where it typically turns eastward.

1. Introduction

Western boundary currents (WBCs) have induced the largest warming of temperate regions observed in the ocean in the last century [e.g., Wu *et al.*, 2012], and future climate scenarios predict similar changes [Matear *et al.*, 2013]. Characterizing the transport and temporal variability of these dynamical systems (WBCs) over recent decades is therefore, crucial to better understand future implications. The East Australian Current (EAC) is the western branch of the South Pacific subtropical gyre; it flows poleward along the coast carrying warm water from tropical to mid latitudes and separates from the continent between 30°S and 34°S giving rise to the Tasman Front [e.g., Godfrey *et al.*, 1980]. In the region where the EAC veers eastward, mesoscale eddies are often formed and advected southward within the EAC extension which continues flowing southward along the coastline [e.g., Mata and Tomczak, 2000]. The EAC, the mesoscale eddies, and the EAC extension are the dominant circulation features along the east coast of Australia and as such, they influence the local climate and the distribution of marine organisms with planktonic larvae. Recent studies have shown that the geographical range of certain species has extended south along the east coast of Australia [Johnson *et al.*, 2011]. Concurrently, Hill *et al.* [2008] observed an increase in temperature and salinity of the Tasman Sea from 1994 to 2005. Such evidence suggests that warm water is being advected further south along the coast of southeastern Australia increasing the water temperature in the Tasman Sea and delivering larvae viable to recruit into higher latitudes allowing the colonization of new habitats.

Ongoing climate change, in particular a southward shift in latitude of the maximum wind stress curl, has been linked to a strengthening of the South Pacific subtropical gyre [e.g., Oke and England, 2004; Cai *et al.*, 2005; Roemmich *et al.*, 2007]. The shift of the location of strong westerly winds over the midlatitudes has both quasi-decadal fluctuations, and a longer time (100 years) positive trend [Thresher, 2002]. Decadal oscillations of the transport induced by the EAC (the western boundary current of the South Pacific subtropical

gyre) have been observed across 34°S between Sydney (Australia) and Wellington (New Zealand) [Ridgway *et al.*, 2008]. Temporal variability over longer time scales (interdecadal) has been inferred from wind field changes. For instance, Hill *et al.* [2008] used Godfrey's island rule to compute transport through the Tasman Sea from mean wind stress curl in the South Pacific and found that transport doubled in 50 years. The intensification of wind-driven circulation offers an explanation for the observed increase in temperature and salinity in the Tasman Sea and the observed poleward shift of the southern limit of temperate species distribution along the coast of southeast Australia. However, there is lack of evidence of whether the spin up of the South Pacific subtropical gyre implies a strengthening of the EAC extension, a southern penetration of the EAC, or a combination of such factors. Oliver and Holbrook [2014] compared Ocean Forecasting Australia Model outputs from present and future climate scenarios and found that the EAC transport is projected to vary little, increasing only 0.2 Sv or the equivalent to 0.7%, while the transport of the EAC extension is expected to increase by approximately 40% (4.3 Sv). Here we examine whether similar mechanisms have prevailed in past decades (1980–2010) during which a warming of the Tasman Sea has been observed. Specifically, we investigate where along the coast of southeastern Australia transport has intensified, whether such intensification occurred in transport inside or outside eddies, and if the EAC has extended further south. Previous studies have found that the latitude at which the EAC deflects east varies seasonally occurring further north in the austral winter than in summer [e.g., Ridgway and Godfrey, 1997]. However, continuous long-time records of the separation latitude and the southward transport across such “dynamic barriers” are lacking, and variability in the separation latitude over long-time scales (i.e., larger than annual) remains elusive.

In this study, we use outcomes from an eddy-solving hydrodynamic model to compute a 30-year long-time series of the latitude at which the EAC separates, and the southward transport along the coast of southeastern Australia (28–39°S). This provides a comprehensive assessment of the trends and variability of transport induced by the EAC and its extension over decadal time scales. Furthermore, changes in temporal fluctuations of southward transport with latitude are investigated and linked to forcing mechanisms such as mesoscale eddies and ENSO events.

Although the EAC separation at roughly 32°S might act as a physical barrier to alongshore southward transport, mesoscale eddies that are often formed in this region [e.g., Cresswell and Legeckis, 1986; Bowen *et al.*, 2005] could provide a mechanism by which particles/propagules that are advected offshore along the Tasman front can be brought back close to shore. In that sense, these mesoscale eddies may allow for the dispersal of larvae along the coast downstream of the EAC's separation point by recirculating larvae episodically. Indeed, studies have identified eddies as one of the main drivers of recruitment pulses elsewhere along analogous western boundary currents [Limouzy-Paris *et al.*, 1997; Kasai *et al.*, 2002]. Moreover, mesoscale eddies influence water properties through vertical mixing processes, which in turn have the potential to affect larval survival [e.g., Irison *et al.*, 2004; Bakun, 2010]. Hence, whether the transport of larvae occurs inside or outside eddies is relevant for the fate of larvae and future successful recruitment.

There are extensive studies on the characteristics of mesoscale eddies along the coast of southeastern Australia [e.g., Cresswell and Legeckis, 1986; Macdonald *et al.*, 2013], their influence on biophysical properties [Everett *et al.*, 2012], how they modulate the separation of the EAC from the continent [e.g., Bowen *et al.*, 2005; Mata *et al.*, 2006], and their potential role in connectivity [e.g., Roughan *et al.*, 2011; Coleman *et al.*, 2011]. However, the contribution of eddies to southward transport, and their long-term temporal variability has received little attention. In this study, we quantify for the first time the proportion of transport that is carried outside and inside cyclonic and anticyclonic eddies as the EAC travels south over long temporal scales. This helps elucidate whether mesoscale eddies aid the dispersal of larvae beyond the EAC separation from the continent, and how temporally variable transport might be, both inside and outside of eddies.

2. Methods

2.1. Circulation Model

The Ocean Forecast for the Earth Simulator, OFES, is an ocean general circulation model based on the Modular Ocean Model (MOM3) run in the Earth Simulator with a horizontal resolution of 1/10° and 54 vertical layers. This model has the capability to reproduce mesoscale activity embedded in background global-scale circulation, the adequate positioning of energetic western boundary currents, and their separation [Sasaki

Figure 1. (a–c: top) Snapshots of Sea Surface Height (SSH, color-scale) and SSH isolines (black contours). The white dots indicate the location where the maximum southward geostrophic velocity occurs at 28°S; the black dots indicate the separation latitude (ϕ) given by the location where the angle of the geostrophic velocity at the SSH isoline is smaller than 70° clockwise from the geographical north. (d) Unfiltered (every 3 days, gray line) and low pass (>30days, red line) EAC separation latitude time series. (e) Unfiltered (every 3 days) EAC separation latitude time series over the time period shaded gray in Figure 1d, the black dots indicate the times shown in Figures 1a–1c.

et al., 2006]. *Masumoto et al.* [2004] configured the model over a near-global domain (75°S and 75°N), performed a simulation forcing it with NCEP/NCAR reanalysis outputs and data from the World Ocean Atlas, and showed it captures the large Sea Surface Height (SSH) variability that occurs along the EAC and realistic variations in velocity fields. A more local study on the Tasman leakage by *van Sebille et al.* [2012] showed that OFES is in good agreement with observations around Australia. More recently, a study on heat budget along the EAC found that annual mean transports at 28°S obtained from OFES agree with those computed from observations [Wang *et al.*, 2013]. OFES outputs are therefore ideal to investigate circulation along the coast of southeastern Australia. In this study, SSH and the three components of the 3-D velocity fields produced within OFES are used.

2.2. Separation Latitude and Model Observation Comparisons

The latitude at which the EAC veers eastward and separates from the coast is estimated adapting the method described in *van Sebille et al.* [2009]. This method identifies the path of a current using geostrophic velocities and SSH isolines and has been used successfully to capture the separation of the Agulhas current [e.g., *de Ruijter et al.*, 1999; *Beal et al.*, 2011]. The first step is to identify the SSH associated with the core of the stream; in order to do this for the EAC, we select the maximum southern geostrophic velocity at 28°S (between the coast and 160°E) where the EAC is well-consolidated [Ridgway and Dunn, 2003]. The corresponding SSH isoline (hereafter EAC SSH isoline) is identified, followed, and the latitude at which it veers eastward is recorded as the separation latitude (Figure 1). This procedure is conducted each time step (i.e., every 3 days) computing the geostrophic velocities from SSH fields obtained with OFES.

The mesoscale eddies that often form along the coast of southeastern Australia modulate the separation of the EAC from the continent [e.g., *Bowen et al.*, 2005; *Mata et al.*, 2006]. Eddy shedding might cause a northward separation of the EAC in a similar way that it induces a retraction in other WBCs such as the Agulhas Current east of Africa [van Sebille *et al.*, 2009]. Conversely, a reattachment could make the EAC water separate further south. The method used in the present study to identify the EAC separation latitude is able to account for the effect of both eddy detachment and reattachment by using fields of SSH, a variable that

Figure 2. Cumulative probability of the EAC separation latitude time series (1992–2010) computed from OFES, BRAN, and AVISO data sets. A Kolmogorov-Smirnov test shows that the cumulative probability functions are statistically indistinguishable ($p = 0.289$, $ks = 1 < C_{(\alpha=0.05)} = 1.36$).

consistently captures mesoscale eddies, and is often used in algorithms that have been shown to track eddies adequately [e.g., *Lindo-Atichati et al.*, 2013]. Specifically, when an eddy detaches, the EAC SSH isoline either separates from the SSH isoline that defines the eddy's edge, or veers east abruptly; in both cases, the conditions to determine the location of the EAC separation (i.e., following the EAC SSH isoline and the location where it veers east) resolve and recognize eddy detachments. Similarly, when an eddy reattaches, the EAC SSH isoline merges with that of the

eddy, thereby influencing the location where it turns east and hence, the recorded latitude where the EAC separates (Figure S1 in supporting information).

OFES outputs are chosen for the present study because they have been shown to represent mesoscale ocean dynamics adequately [e.g., *van Sebille et al.*, 2012; *Wang et al.*, 2013], and offer one of the longest time series of velocities (30 years) at high temporal resolution (3 daily) along the coast of southeastern Australia. However, the model is free-running with surface winds and flux fields from NCEP data. On the other hand, the BlueLink ReAnalysis (BRAN), a multiyear model integration with data assimilation, provides a reanalysis of the state of the ocean around Australia with a daily temporal resolution [Oke et al., 2008] and is often used to investigate the circulation in this region [e.g., *Oke and Griffin*, 2007; *Brassington et al.*, 2011]. Thus, a comparison between OFES, BRAN, and observed SSH from the Archiving Validation and Interpretation of Satellite Oceanographic data (AVISO) was conducted over the period of time when the three data sources coincide (from 1992 to 2010). Previous studies have compared either OFES [e.g., *Masumoto et al.*, 2004; *van Sebille et al.*, 2012], BRAN [e.g., *Oke et al.*, 2008], or both [e.g., *Wang et al.*, 2013] against observed SSH fields and showed that their mean and variability agrees. The temporal mean and standard deviation have the same order of magnitude, and their spatial structures show similar patterns (Figure S2 in supporting information). For example, supporting information Figure S2 shows a higher SSH mean in the north than in the south, low SSH variability along the north-eastern area of the study region ($\sim 0.1\text{m}$), and high SSH variability along the south east between 30°S and 38°S (up to $\sim 0.3\text{m}$). This is likely due to the formation of mesoscale eddies and their advection.

Beyond comparing mean fields, we compare the outcomes when using observed SSH from AVISO and modeled SSH from BRAN and OFES to compute time series of the EAC separation latitude. These time series are obtained from 1992 to 2010 (the time encompassed by all three data sets) at a 7 day temporal resolution (the lowest temporal resolution of all data sources which corresponds to AVISO). Results from a Kolmogorov-Smirnov test support the null hypothesis ($p = 0.289$, $ks = 1 < C_{(\alpha=0.05)} = 1.36$) of the separation latitude time series from all data sources having the same cumulative distribution function (Figure 2). This suggests that a 30 year time series of the EAC separation latitude computed from OFES SSH has the correct statistical properties (e.g., frequencies at which the EAC separates at specific latitudes) and is therefore suitable to explore the presence of long temporal trends.

2.3. Transport

A Lagrangian approach is used to compute the southward transport along the coast of southeastern Australia and across the EAC separation latitude. This method captures transport patterns induced by the EAC by releasing particles at 28°S , where the current is most coherent [e.g., *Ridgway and Dunn*, 2003]. In order to account for most of the EAC variability, the location (depth and longitude) and number of particles released at each time step (3 days) is determined by the instantaneous southward transport. Specifically, at every time step, the southward transport occurring through each cell at 28°S is computed, sorted in ascending order, and used to compute the percentage of cumulative southward transport (Figure 3). Particles are released at those cells where up to 95% of the cumulative southward transport at 28°S occurs and tagged with the corresponding flux for further analysis. The criterion used to choose the locations for particle

Figure 3. (a) Instantaneous (5 March 2008) southward transport (color-scale) through a latitudinal section at 28°S. The zonal dimension of the cells is 10 km and the vertical dimension increases with depth from 5 m at the surface to 330 m at the bottom. Cells are numbered in ascending order depending on the transport occurring through them. The numbers are used to identify those cells over which 15–95% of the cumulative transport occurs (indicated by the white dots). (b) Instantaneous (5 March 2008) cumulative southward transport, the 15 and 95% of the cumulative transport are indicated with grey dots. On the 5 March 2008, 193 particles were released at cells numbered 1987–2180.

release allows capturing a high proportion of the transport (up to 95%) using a reasonable number of particles (typically between 200 and 350 yielding a total of 1.03×10^6 particle trajectories).

Particles were released every 3 days for 30 years and tracked using the Connectivity Modelling System [CMS v1.1, Paris *et al.*, 2013]. Each particle contributes to the southward transport at any given latitude with the volume of water with which it was tagged (i.e., the water volume that flows through the cell where the particle was seeded at the time of release). When computing the southward transport across the EAC separation latitude such contribution is considered at the time the particle crosses the Tasman Front. Similarly, the southward transport at any latitude along the coast of southeastern Australia is computed adding the contribution of every particle at the time it crosses the latitude of interest for the last time. Therefore, to quantify the southward transport occurring as far as 39°S, it is necessary to track the particles over a period of time that allows them to be advected south from their release location (at 28°S) past 39°S. The particles released at 28°S traveled past 39°S within 14–300 days. Figure 4a shows that the percentage of particles located poleward of 39°S increases fourfold from 1% to 4% in the first 200 days of advection, and approaches a 5% asymptote after approximately 300 days. This indicates that only a small fraction is advected poleward of 39°S, and that the large majority of these particles reach this latitude in 300 days or less. Similarly, the frequency distribution of the latitudinal position of particles converges after approximately 300 days of advection (Figure 4b). Hence, 1 year long trajectories suffice to quantify southward transport between 28 and 39°S. All particle trajectories (released every 3 days from 1980 to 2010) are taken into account to compute the 30 year long southward transport time series; due to a ramp-up effect (it can take up to 300 days for a particle to reach 39°S), the time series before 1981 and after 2009 are not regarded in any further analysis. To quantify transport occurring inside or outside eddies, a distinction between particles that are outside or inside an eddy (cyclonic or anticyclonic) at the moment they contribute to the southward transport is made using the spin parameter (see section 2.5). Because a particle only contributes to the southward transport once it crosses a particular latitude for the last time, there is no overestimation of transport inside eddies due to eddy reattachment.

2.4. Temporal Variability

2.4.1. Wavelet and Cross-Correlation Analyses

A wavelet analysis is used to show temporal changes in power and significance of variability occurring at different frequencies in time series of the separation latitude, southward transport across the separation latitude, and southward transport along the coast of southeastern Australia. The temporal mean of the spectral power at each frequency, hereafter the global wavelet spectrum, is computed for the southward

Figure 4. (a) Percentage of particles located south of 39°S relative to the total number of particles as a function of time from release. (b) Gaussian curves fitted to the latitude frequency distribution of particle's positions at different days from release. The latitude frequency distributions are computed as the % of particles relative to the total amount of particles located at any given latitude.

transport occurring at 28°S–39°S, every 0.1 degree, and used to discern the magnitude and significance of variability in southward transport with different frequencies as a function of latitude. The wavelet analysis is conducted on normalized signals (i.e., the anomaly divided by the standard deviation), using code from *Torrence and Compo* [1998], and considering the bias correction described and implemented by *Liu et al.* [2007]. In addition, the maximum regression coefficient and phase lag obtained from cross correlation analysis between El Nino 3.4 index and the low pass (>30 days) time series of the separation latitude (absolute values), and southward transport are recorded. El Nino 3.4 index is obtained from NOAA (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/).

2.4.2. Interdecadal Trends in Transport and EAC Separation Latitude

To investigate the presence of a trend over three decades, linear regressions are computed by fitting a line and testing the hypothesis of the slope being significantly different from zero. Such analyses are conducted on the low pass (>10 years) separation latitude time series, the low pass (>10 years) transport anomaly across the separation latitude, and the low pass (>10 years) southward transport anomalies from 28°S to 39.5°S every 0.1°. Regressions are computed separately for total southward transport and for transport carried inside and outside eddies (cyclonic and anticyclonic).

2.5. Spin Parameter

In order to discern if southward transport occurs inside or outside eddies, we use the spin parameter Ω to identify rotation. This parameter was first applied to a Lagrangian framework by *Veneziani et al.* [2004]; and implemented to account for transport inside eddies [e.g., *Doglioli et al.*, 2006; *van Sebille et al.*, 2012] or the distribution of eddies [*Griffa et al.*, 2008]. This approach allows distinguishing looping from nonlooping trajectories and also determines the direction of rotation (cyclonic or anticyclonic). The spin parameter Ω is related to the angular velocity of the Lagrangian velocity anomaly and corresponds to the vorticity field of the trajectories embedded in eddies. It is given by:

$$\Omega = \frac{u' dv' - v' du'}{EKE \Delta t} \quad (1)$$

where u' and v' are the east-west and north-south Lagrangian velocity anomalies, respectively (with $u = \bar{u} + u'$ being a decomposition of the velocity field into the time mean $\bar{u}$ and time varying component u' within each $1/10^\circ$ by $1/10^\circ$ grid cell), du' and dv' are the time differentials of the east-west and north-south Lagrangian velocities, respectively, $\langle \rangle$ represent an average for values over 30 days of a particle trajectory, Δt the time step used to record particle position (6 h), and EKE the eddy kinetic energy which is in turn given by:

$$EKE = 0.5 \langle u'^2 + v'^2 \rangle \quad (2)$$

The first step toward estimating Ω is gridding the domain in cell sizes of $1/10^\circ$ by $1/10^\circ$ and computing the mean Lagrangian velocity for each cell considering all the particles that crossed it. The velocity anomalies

Figure 5. (top) Single particle trajectory and corresponding spin parameter (Ω) value, different colors are used to identify trajectories inside a cyclonic eddy (blue), anticyclonic eddy (red) and outside eddies (gray), distinction between 30 day segments is done using different color tones. (a) SSH field (color-scale), and geostrophic velocities (arrows) simultaneous to the first segment of the trajectory inside a cyclonic eddy, (b) SSH field (color-scale) and geostrophic velocities (arrows) simultaneous to the first segment of the trajectory inside an anticyclonic eddy. (bottom) Three trajectories are shown to exemplify the skill of the spin parameter to discern between anticyclonic (red, $\Omega > 0.2$), cyclonic (blue, $\Omega < -0.2$), and straight (gray, $|\Omega| < 0.2$) trajectories, different color tones are used to distinguish 30 day trajectory segments.

are obtained by subtracting the instantaneous Lagrangian velocity from the mean Lagrangian velocity of the grid cell where the particle is located. These values are substituted in equation (1) to obtain a value of Ω for each 30 day segment of each particle trajectory. The particle's position is recorded every 6 h, hence, a spin value for each trajectory segment is calculated as an average over 120 values. The spin value at the time a particle crosses a latitude is used to discern if the southward transport occurred inside or outside an eddy. A threshold value of $\Omega = 0.2 \text{ days}^{-1}$ is used to discriminate between looping and not looping trajectories; for $|\Omega| \geq 0.2 \text{ days}^{-1}$ the trajectory is looping, and for $|\Omega| < 0.2 \text{ days}^{-1}$ the trajectory is not looping; in addition, when $\Omega \leq -0.2 \text{ days}^{-1}$ the trajectory is cyclonic and when $\Omega \geq 0.2 \text{ days}^{-1}$ the trajectory is anticyclonic. The choice of the threshold value is somewhat arbitrary because it depends on local flow average characteristics but threshold values between 0.15 and 0.3 days^{-1} proved useful to recognize eddies in the Tasman Sea by *van Sebille et al.* [2012] and a threshold of 0.2 days^{-1} appears accurate for discriminating between looping and nonlooping trajectories (Figure 5). The spatial distribution of the mean and standard

Figure 6. Frequency distribution of the EAC separation latitude obtained over 30 years and fitted Gaussian curve given by: $f(x) = 0.7 \exp - [(x - 28.7) / 0.47]^2 + 1.7 \exp - [(x - 30.8) / 3.67]^2$, ($R^2 = 0.89$). The frequency distribution is computed as the % of time relative to 30 years that the EAC separates at any given latitude.

deviation of Ω is also used to infer the locations along the coast of southeastern Australia where the formation of eddies prevails.

A particle's position is recorded every 6 h; such temporal frequency allows depicting the entrainment of particles inside eddies in the region. *Everett et al.* [2012] synthesized the characteristics of eddies present in the Tasman Sea using the mesoscale eddies database of *Chelton et al.* [2011]. These authors identified 92–95 km wide eddies with rotational speeds of 45–50 cm/s along the coast of southeastern Australia. A particle entrained in an eddy with such characteristics would take approximately 2 days to complete a rotation along the edge of the eddy. Thus, a 6 h temporal resolution provides enough data (eight positions within a rotation) to capture a looping trajectory. In fact, the entrainment of particles within smaller eddies (~60 km wide), often cyclonic, that also form along the EAC and prevail for a few weeks [*Mullaney and Suthers* 2013] is also detected as shown by particle trajectories, the corresponding spin parameter, and simultaneous sea surface height and geostrophic velocity fields (Figure 5). In order to elucidate the spatial distribution of anticyclones and cyclones, the spin temporal mean and standard deviation of the absolute spin are computed at every location and used to produce spatial structure maps.

3. Results

3.1. Separation Latitude

The EAC separates from the coast between 30.7°S and 32.4°S 50% of the time over the 30 year period; however, it can separate anywhere between 28°S and 38°S. Mesoscale eddies modulate temporal variability in the EAC separation latitude. Particularly, the detachment of eddies provokes an abrupt northward retraction of the latitude where the EAC separates (e.g., from 32.4°S to 29.2°S within only ~10 days, Figure 1) while the development of eddies induces a slow southward progression of the separation. A similar influence of mesoscale eddies on temporal fluctuations of the location where the current separates from the continent was also seen for the Agulhas Current [*van Sebille et al.*, 2009]. The EAC separation latitude frequency distribution shows peaks at 28.7°S and 30.8°S (Figure 6).

The wavelet analysis shows significant temporal variability of the EAC separation latitude occurring over a wide range of periods from 90 days to 7 years. Nevertheless, only variability with periodicities up to 9 months is significant in the global wavelet spectrum (not shown). The correlation analysis shows that the separation latitude (absolute value) has a significant ($r = 0.31$, $p < 0.001$) positive correlation with El Niño 3.4 index at a phase lag of approximately 15 months. Finally, the range of latitudes at which the EAC separates 50% of the time, hereafter also referred to as the EAC separation zone, has not changed in 30 years. However, the slope ($0.02 \text{ degrees year}^{-1}$) of the line fitted to the low pass (>10 years) separation latitude time series is significantly different from zero ($p < 0.001$) implying a poleward displacement of the mean EAC separation latitude of approximately 67 km over 30 years (1980–2010).

3.2. Spin Parameter

The spin parameter values indicate the presence of both, cyclonic and anticyclonic eddies but only 13.5/3.5% of the spin values are above/below $0.2/-0.2 \text{ days}^{-1}$. The spatial distribution of mean spin values larger

Figure 7. (top) spatial distribution of the mean and standard deviation of the absolute spin parameter computed across all particle trajectories. The 50 and 4200 m isobaths are shown for reference (black contours).

than 0.2 days^{-1} indicate that eddies are most often formed from 29°S southward, following the coastline, east of the 4200 m isobath which at these latitudes (29°S – 38°S) lies between 55 and 170 km from the shore (Figure 7). Within this region, the standard deviations of the spin are also high ($>0.2 \text{ days}^{-1}$, Figure 7) suggesting that the presence of eddies in the region is intermittent.

3.3. Transport

The mean low pass (>30 days) southward transport and its variability decrease monotonically as the EAC flows southward from $13.5 \pm 7.0 \text{ Sv}$ at 28°S to $1.4 \pm 1.08 \text{ Sv}$ at 39°S (Figure 8a). Similarly, the mean southward transport inside eddies decreases by an order of magnitude with latitude, from $2.5 \pm 3.36 \text{ Sv}$ at 28°S to 0.24 ± 0.43 at 39°S (Figures 8b.1 and 8c.1) and it is an order of magnitude larger inside anticyclones than inside cyclones at most latitudes. As a result, the temporal mean of the contribution to southward transport inside eddies varies little across latitudes, from $15.8 \pm 12.8 \%$ at 28°S to $12.7 \pm 18.3 \%$ at 39°S (Figure 8d) being approximately twice as large inside anticyclones than inside cyclones (Figures 8b.2 and 8c.2). The slightly smaller contribution at higher latitudes is due to a decrease in the contribution of transport inside cyclones (Figure 8c.2).

The southward transport across the separation latitude is of similar magnitude as that occurring at 33°S latitude. The low pass (>30 days) signal has a mean of $8.4 \pm 2.8 \text{ Sv}$, with a range from 1.2 to 18 Sv while the unfiltered series (every 3 days) varies within 0.3–31.0 Sv (Figure 9a). The mean contribution to southward transport across the separation latitude of the transport inside eddies is $12.1 \pm 7.2 \%$ and is equipartitioned between anticyclones and cyclones (9b). This contribution has a large temporal variability reaching up to 55% and shows an abrupt increase in the last 5 years of our data (2005–2010, Figure 9c).

3.3.1. Wavelet and Cross-Correlation Analyses of Transport

The wavelet analysis of southward transport across the EAC separation latitude (Figure 10a), and southward transport along the coast of southeastern Australia (28°S – 39°S) shows that the spectral power within the 90–180 day periodicity is more often larger and significant from 1995 onward. The global wavelet spectrum of the southward transport across the separation latitude reveals significant variability with periods of 1 year or less peaking at periodicities of approximately 1 year, 30, and 80 days (Figure 10b). The global wavelet spectrum of the total southward transport along the coast of southeastern Australia shows significant variability within the same periodicities (up to 1 year), and most energetic signals with periods of 90–180 days and 1 year. The annual variability is significant at every latitude along the coast (from 28°S to 39°S), with larger spectral power (17 or higher) between 28°S and 34°S while shorter period variability (90–180 days) is most powerful (20–30) from 28°S to 32°S (Figure 10c). Finally, variability of the southward transport across the EAC separation latitude with periodicities of 2–8 years is significant from 1992 onward (Figure 10a).

The correlation analysis between Nino 3.4 and southward transport across latitude gives similar results to correlations with the separation latitude. The correlations are small but significant ($R^2 < 0.1$, $p < 0.05$) for

Figure 8. Low pass (>30 days) time series at 28–39°S of (a) total southward transport, (b) southward transport within anticyclonic eddies, and (c) southward transport within cyclonic eddies. (d) Contribution of the transport inside eddies to the total transport. Temporal mean (solid line) and 95% confidence limits (dashed line) at 28–39°S of (a.1) total southward transport, (b.1) southward transport within anticyclonic eddies, and (c.1) southward transport within cyclonic eddies; the x axis is plotted in logarithm scale for clarity. Temporal mean (solid lines) and 95% intervals (dashed lines) of the eddy contribution to the total southward transport at 28–39°S (b.2) within anticyclonic eddies, (c.2) within cyclonic eddies, and (d.2) within anticyclonic and cyclonic eddies; the x axis is plotted in logarithm scale for clarity.

southward transport all along the coast, and increase with latitude reaching a maximum at approximately 37°S. The phase lag at which the maximum correlation is significant is 12 months.

3.3.2. Interdecadal Trends in Transport

Low pass (>10 years) time series of southward transport show a slight increase in magnitude at all latitudes and across the separation latitude (Figure 11). More conclusively, the trend analysis revealed a statistically significant positive trend in the low pass (>10 years) southward transport across the separation latitude inside eddies ($p \ll 0.01$, slope = $1.4 \times 10^{-1} \text{ Svyr}^{-1}$), as well as that occurring only inside anticyclonic eddies ($p \ll 0.01$, slope = $0.57 \times 10^{-2} \text{ Svyr}^{-1}$) or cyclonic eddies ($p \ll 0.01$, slope = $0.791 \times 10^{-2} \text{ Svyr}^{-1}$). No significant trend was found in the low pass (>10 years) southward transport across the separation latitude outside eddies, and a marginally significant positive trend was found in the low pass (>10 years) total southward transport across the separation latitude ($p = 0.034$, slope = $0.18 \times 10^{-2} \text{ Svyr}^{-1}$). Similarly, a statistically significant positive trend was found in the low pass (>10 years) total southward transport ($p \ll 0.01$, $1.7 \times 10^{-2} \text{ Svyr}^{-1} < \text{slope} < 4.7 \times 10^{-2} \text{ Svyr}^{-1}$), the low pass (>10 years) southward transport occurring inside eddies ($p \ll 0.01$, $0.5 \times 10^{-2} \text{ Svyr}^{-1} < \text{slope} < 2.7 \times 10^{-2} \text{ Svyr}^{-1}$), and separately inside anticyclonic ($p \ll 0.01$, $0.5 \times 10^{-2} \text{ Svyr}^{-1} < \text{slope} < 4.9 \times 10^{-2} \text{ Svyr}^{-1}$) or cyclonic eddies ($p \ll 0.01$, $0.02 \times 10^{-2} \text{ Svyr}^{-1} < \text{slope} < 1.2 \times 10^{-2} \text{ Svyr}^{-1}$) all along the coast of southeastern Australia (28°S–39°S). The southward

Figure 9. (a) Unfiltered (every 3 days) and low pass (> 30 days) time series of southward transport across the EAC separation latitude; the first and last years of the time series (indicated by the thick light gray line) are neglected in all analyses. (b) Low pass (> 30 days) time series of southward transport across the EAC separation latitude carried within anticyclones (dark gray) and cyclones (light gray). (c) Time series of the contribution of the transport inside eddies to the total southward transport across the EAC separation latitude.

transport outside eddies has a significant positive trend from 29°S southward ($p < 0.01$, $0.06 \times 10^{-2} \text{ Sv y}^{-1} < \text{slope} < 2.0 \times 10^{-2} \text{ Sv y}^{-1}$).

4. Discussion

This study uses 30 year long-time series to document the variation of the latitude at which the EAC separates from the continent and the transport variation of the East Australian Current water along the coast of southeastern Australia (28°S to 39°S). Results reveal the variability along the coast and temporal fluctuations in the transport induced by the EAC and its extension. This approach provides the means to discern whether an observed warming of the Tasman Sea, previously associated with changes in the wind stress curl and a spin up of the South Pacific subtropical gyre [e.g., Hill *et al.*, 2008], is related to a southward movement in the EAC separation latitude, a strengthening of the EAC extension, or both. Even though large mesoscale variability in the EAC transport has been attributed to the presence of eddies [e.g. Mata *et al.*, 2006; Wilkin and Zhang, 2007], there exist no estimates of the transport occurring inside these flow structures.

Figure 10. (a) Wavelet power spectrum of the southward transport across the EAC separation latitude. (b) Global wavelet spectrum of the southward transport across the EAC separation latitude. (c) Global wavelet spectrum of the southward transport at $28\text{--}39^{\circ}\text{S}$; only the power of significant periodicities is plotted. The log base 2 logarithm of the power is plotted for clarity.

Figure 11. Low pass (>10 years) time series at 28°S–39°S of (a) total southward transport, (b) southward transport within anticyclones, (c) southward transport within cyclones. (d) Low pass (>10 years) southward transport across the EAC separation latitude. (e) Low pass (>10 years) of the EAC separation latitudes.

This study makes the first quantitative distinction between transport of East Australian Current water outside and inside (cyclonic and anticyclonic) mesoscale eddies along the coast of southeastern Australia and examines its temporal variability.

4.1. Separation Latitude

It is well known that the EAC flows poleward along the coastline before separating from the continent and veering eastward. Generally the separation has been identified somewhere between 31°S and 33°S [e.g. Boland and Church, 1981]. Using 30 years of data from 1980 to 2010, we found that 50% of the time the EAC turns east within a similar latitudinal range (30.7°S–32.4°S) but that it separates most often at either 28.7°S or 30.8°S (Figure 6). Interestingly, these two latitudes are in close proximity to narrow points of the continental shelf, Cape Byron and Smoky Cape at 28.6°S and 30.9°S where the continental shelf (distance between the coastline and the 200 m isobath) is 22 km and 16 km wide, respectively. The narrowing of the

shelf has previously been linked to acceleration and separation of the jet [e.g., *Oke and Middleton, 2000; Roughan and Middleton, 2002*]. However, this is the first study to show the EAC often separates immediately downstream of these narrow choke points.

Results suggest that ENSO influences temporal fluctuations of the latitude where the EAC separates from the continent. The wavelet spectrum of the EAC separation latitude shows significant variability with periodicities of 2–6 years between 1991 and 2010 (not shown); such periods agree with the frequency at which ENSO events occur (2–7 years) [e.g., *McGregor et al., 2012*]. In addition, a 15 month lagged significant correlation coefficient between the EAC separation latitude and El Niño 3.4 index was found. Because ENSO events prevail between 12 and 18 months [e.g., *McGregor et al., 2012*], the 15 month lag implies a maximum southern/northern displacement of the EAC separation occurring 6–9 months after the end of an El Niño/La Niña. This suggests that the relaxation of an ENSO event induces a shift in the EAC separation; specifically, a southward progression when an El Niño event finishes, and a northward retraction when a La Niña event decays.

Our results show that the low pass (10 years) EAC separation latitude has a significant negative trend that implies a 67 km poleward displacement over 30 years. This result is in agreement with findings by *Matear et al. [2013]* and *Oliver and Holbrook [1994]* who show that the EAC separation point is expected to move ~90 km poleward under a climate change scenario projected ~60 years after the present climate scenario. Nevertheless, we found that 50% of the time the EAC separates within a latitudinal range that encompasses a distance (~200 km) an order of magnitude larger than the poleward shift suggested by the slope of the trend. Therefore, the EAC has not extended further south considerably but it does separate at the southernmost latitudes within the separation zone more often.

It has been suggested that the presence of New Zealand induces a separation of the EAC at 34°S by blocking the westward propagation of Rossby waves south of this latitude [*Warren, 1970*]. However, *Tilburg et al. [2001]* showed that the location where the EAC separates is due to the wind stress field by matching observed EAC separation latitudes with outputs from a linear model forced with monthly climatological winds and bathymetry that either included or excluded New Zealand. Thus, an increase of the wind stress in the Southern Hemisphere most pronounced from 1970 [e.g., *Marshall, 2003*] is expected to induce a long-term trend in the EAC separation latitude over the investigated time period (1980–2010). Although our results do not show a considerable poleward EAC penetration, the interdecadal trend is significant. Moreover, separation further south than 34°S occurs 12.5% percent of the time suggesting that the presence of New Zealand does not constrain the separation of the EAC north of 34°S. In addition, the temporal variability and interdecadal trend of the latitude where the depth averaged (up to 800m) maximum eastward velocity between 28°S and 39°S across a longitudinal section at 155°E occurs (not shown), is remarkably similar to that of the EAC separation latitude (Figure S3 in supporting information). Such similarity would be expected if the EAC and Tasman Front are part of a wind-driven gyre and their temporal variability is due to changes in the wind field. Even though the possibility of New Zealand's presence influencing the location where the EAC separates from the continent cannot be ruled out, our results show that it does not suppress an interdecadal response of the EAC separation latitude variability.

4.2. Transport Temporal Variability

The global wavelet spectrum of southward transport along the coast of southeastern Australia corroborates results from previous studies which found significant temporal variability in the EAC within the mesoscale 100–180 day band [e.g., *Bowen et al., 2005; Mata et al., 2006*], and with annual periodicities associated with a stronger/weaker EAC during summer/winter [e.g., *Ridgway and Godfrey, 1997*]. Not surprisingly, the power of the annual variability weakens sharply south of the latitude where the EAC separates most frequently (from ~34°S poleward) confirming the conspicuous annual signal in the EAC. Interestingly, the largest correlations with ENSO are found from 37°S southward where fluctuations of southward transport over time scales within the range of ENSO temporal fluctuations (2–4 years) are significant in the local spectrum approximately 20% of the time. The 12–18 month duration of ENSO events and the phase lag (12 months) of significant positive correlations between the southward transport and el Niño 3.4. index imply that an increase/decrease in southward transport along the coast of southeastern Australia occurs approximately 6–9 months after an El Niño/La Niña event decays, particularly at 37°S or higher latitudes. However, the

regression coefficients indicate that only 10% of the variability of the low pass transport could be explained by an ENSO relaxation.

The quasiperiodic formation and downstream advection of eddies where the EAC separates from the continent is well established and linked to large mesoscale variability in the flow. For example, *Bowen et al.* [2005] found that the region along the coast of southeastern Australia with highest eddy activity lies between 30°S and 35°S. In addition, *Wilkin and Zhang* [2007] found that the mesoscale variability in the EAC surface velocity relates to eddies and has maximum amplitudes in the same latitudinal range. In agreement, maps of the $|\Omega|$ mean and standard deviation obtained from particle trajectories over 30 years indicate that eddies form all along the coast of southeastern Australia within a region that has been called the “eddy avenue” [Everett et al., 2012, Figure 11]. Furthermore, the global wavelet spectrum of southward transport at 28°S–34°S and across the separation latitude shows significant temporal fluctuations with the same periodicities as those associated with mesoscale eddies (90–180 days, Figures 10b and 10c). The temporal mean of the contribution of transport inside eddies to the total southward transport is 2% larger within a similar region, equatorward of 36°S. However, such contribution has considerable temporal variability particularly at higher latitudes (from 36°S poleward) where it becomes three times as large toward the end of the time series reaching 50% (Figure 6d d.2). Furthermore, the wavelet analysis of the southward transport shows that the local spectral power with mesoscale periodicity (90–180 days) is larger from 1995 onward at all latitudes (not shown). Thus, the impact of eddies on the flow variability appears to have increased with time becoming significant by the end of the 30 year period investigated here (1980–2010), i.e. from 1995 onward. A future enhancement of the eddy field along the coast of southeastern Australia is also suggested by an increase in the sea level variance for a climate change scenario [Oliver and Holbrook, 2014]. Thus, mechanisms associated with past strengthening of the poleward flow are similar to those observed in climate projections.

This study confirms the presence of a significant positive temporal trend of southward transport induced by the EAC and its extension over a 30 year period (1980–2010). In addition, it shows that this trend is a consequence of an increase in both the southward transport occurring inside eddies (anticyclones and/or cyclones), and outside eddies. The strengthening of the EAC is significant from 28°S poleward, and the maximum intensification occurs at 30.6°S. This finding is in agreement with results from *Cai* [2006] who found a considerable increase in transport south of 30°S using the Sverdrup balance to compute the wind-driven circulation caused by a positive trend in the wind stress curl from 1978 to 2002. The rate of intensification found in the present study is, however, an order of magnitude smaller than that proposed by *Cai* [2006]. Specifically, we found a maximum increase rate of $4.6 \times 10^{-2} \text{ Sv y}^{-1}$ while *Cai* [2006] estimated an increase of $37.5 \times 10^{-2} \text{ Sv y}^{-1}$ (an increase of 9 Sv from 1978 to 2002). Such discrepancy can be explained by two factors; first, *Cai* [2006] transport estimates are not constrained to be solely within EAC water as in the present study. Second, estimates of *Cai* [2006] are based on increments due to the strongest and statistically significant positive trends of wind stress curl occurring from December to May (1978–2002). This eliminates temporal variability of the wind stress curl, particularly those that are not associated with positive trends resulting in a maximum estimate of the rate of increase in the wind driven circulation.

Our results show that the wind-driven strengthening of the poleward flow along the coast of southeastern Australia is associated with an increase in both the EAC and its extension as well as with transport occurring outside and inside eddies (cyclonic and anticyclonic) but not with a southward penetration of the EAC.

This study shows that the contribution of transport inside eddies to the total southward transport as well as its mesoscale temporal variability is increasing. In the long-term, such an increase in the amount of transport inside eddies might change contemporary dispersal patterns observed in this region by promoting retention and inducing patchy connectivity along the coast.

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Acknowledgments

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