Remotely Sensed Seasonal Shoreward Intrusion of the East Australian Current: Implications for Coastal Ocean Dynamics

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Abstract: For decades, the presence of a seasonal intrusion of the East Australian Current (EAC) has been disputed. In this study, with a Topographic Position Index (TPI)-based image processing technique, we use a 26-year satellite Sea Surface Temperature (SST) dataset to quantitatively map the EAC off northern New South Wales (NSW, Australia, 28–32°S and ~154°E). Our mapping products have enabled direct measurement (“distance” and “area”) of the EAC’s shoreward intrusion, and the results show that the EAC intrusion exhibits seasonal cycles, moving closer to the coast in austral summer than in winter. The maximum EAC-to-coast distance usually occurs during winter, ranging from 30 to 40 km. In contrast, the minimum distance usually occurs during summer, ranging from 15 to 25 km. Further spatial analyses indicate that the EAC undergoes a seasonal shift upstream of 29°40′S and seasonal widening downstream. This is the first time that the seasonality of the EAC intrusion has been confirmed by long-term remote-sensing observation. The findings provide new insights into seasonal upwelling and shelf circulation previously observed off the NSW coast.

Keywords: satellite remote sensing; quantitative mapping; spatial analysis; the East Australian Current; New South Wales; coastal upwelling; shelf circulation

1. Introduction

Originating from the equator, the East Australian Current (EAC) is a highly dynamic western boundary layer of the South Pacific Gyre, and it is characterized by warmer Sea Surface Temperature (SST) off the eastern coast of Australia [1]. Among Western Boundary Currents (WBCs), the EAC is unique, featuring very high spatiotemporal variability [1–6]. Along its main path off the south-east margin of Australia, the EAC frequently encroaches onto the continental shelf [1]. Such shoreward intrusion significantly changes continental shelf-slope biophysical dynamics in the region [7–10]. Usually, the EAC intrusion drives coastal bottom layer uplift or upwelling through Ekman pumping, which in turn changes the shelf-slope temperature and nutrient dynamics [7,8,11,12]. Additionally, the EAC intrusion intensifies surface alongshore flow, generates vertical (surface-bottom) current sheer and eventually induces circulations on the adjacent continental shelf [4]. The ecological ramifications of the EAC’s shoreward intrusion are thus wide ranging and far reaching [10,13–17].

The EAC is a dynamic eddy-current system that features periodic intrinsic mean-der (every 20–45 days) and larger-amplitude fluctuation (every 60–100 days), which is associated with the EAC’s eddy shedding [4,5,12,18–24]. Recently, submesoscale frontal eddies were observed being generated every ~7 days on the inshore edge of the EAC, which add additional complexity to this dynamic system [25,26]. A more recent study also demonstrated that the EAC is an eddy-dominant system with very high variability [6]. The
latest quantitative mapping study by Xie et al. [1] confirmed the dynamic nature of the EAC system.

The EAC is such an energetic oceanographic feature that its low-frequency (e.g., seasonal) variability is usually overshadowed and hence rarely detected [1,4,18]. For example, Schaeffer et al. [27] inferred from mooring array current data that the EAC’s shoreward intrusion occurs all year round without any clear seasonal cycles. Further, Schaeffer et al. [12] suggested that the EAC intrusion features a high-frequency cycle (every 90–100 days), as is inferred from current-driven bottom layer transport. However, both current velocity and bottom layer transport are indeed not a precise representation of the EAC’s shoreward intrusion. In a new mapping study, Xie et al. [1] quantified the EAC’s shoreward intrusion (“area” and “distance”) using Himawari-8 SST data of high temporal resolution. Using the quantitative mapping results, their study confirmed the high-frequency EAC intrusion, as suggested by Schaeffer et al. [12,27]. Their study also indicated the seasonality of the EAC intrusion based on the two seasonal cycles between 2015 and 2017. In addition, indirect evidence such as the seasonality of coastal upwelling and shelf circulation off northern New South Wales (NSW) has hinted at the EAC’s seasonal shoreward intrusion, as the regional wind patterns are unlikely the driver [8,28–31].

To date, no long-term and direct observation of the EAC’s seasonal shoreward intrusion has been provided. The two-year dataset provided by Xie et al. is rather limited and lacks robustness and statistical power for the investigation of seasonal-scale variability [1]. This limits our ability to fully understand the EAC and the adjacent shelf-slope hydrodynamics. This study attempts to fill the research gap by conducting quantitative mapping of the EAC using a 26-year Advanced Very-High-Resolution Radiometer (AVHRR) SST dataset spanning between 1992 and 2018 (Section 2).

Remotely sensed SST images have enabled the quantitative and semiautomatic mapping of ocean currents such as the Leeuwin Current [32] and the EAC [1] as they have warmer SST signatures [33,34], which can be distinguished from background ocean using a TPI technique [35]. By analyzing the spatiotemporal patterns of the EAC mapping results from the long-term SST dataset, we aim to provide direct evidence and the underlying mechanism of the EAC’s seasonal shoreward intrusion (Sections 3 and 4) and demonstrate its impacts on coastal ocean dynamics (Section 4).

2. Materials and Methods

Our study area covers the coastal ocean off northern NSW between 28 and 32.5°S, upstream of the typical EAC separation point at 32–33°S [36,37] (Figure 1a). In this area, the EAC is most significant and continuous [6,36], and its SST signature is therefore most recognizable [1] (Figure 1a). Along the south-east Australian margin, the continental shelf is narrow (20–50 km), and the slope is very steep, with water depth increases dramatically from ~200 m (at the shelf-break) to 2000–4000 m (Figure 1a).

We used monthly Advanced Very-High-Resolution Radiometer (AVHRR) SST images for the period between April 1992 and March 2018 to map the EAC. Available from the Integrated Marine Observing System (IMOS, Australia), this dataset contains Level 3 foundation SST (SSTfnd) products derived from AVHRR observations on all available National Oceanic and Atmospheric Administration (NOAA, USA) polar-orbiting satellites [38]. The SSTfnd is obtained by adding a constant 0.17 °C to the SSTskin measurements following the removal of measurements with low surface wind speeds (<6m/s by day and <2m/s at night). Validation against buoy SSTfnd observations for the central date indicate typical 2014 biases of <0.03 °C and standard deviations of 0.6 °C. The spatial resolution is 2 km, and each grid represents the monthly average of all the highest-quality SST observations [39,40].
Figure 1. Study area and East Australian Current (EAC) mapping. (a) A monthly Advanced Very-High-Resolution Radiometer (AVHRR) Sea Surface Temperature (SST) image of September 2009. (b) Topographic Position Index (TPI) calculation of the SST image shown in (a). The arrow (in purple) indicates the boundary between the EAC and shelf waters at 29°30′S. (c) SST profile (red curve) and corresponding TPI value (green curve) along the cross-EAC section (green line) depicted in (a,b). The dashed line represents the TPI threshold (0.17). (d) Vectorization of the mapped EAC’s SST signature (red polygon) and calculation of the “area” and “distance” of the on-shelf EAC waters. The current field for September 2009 is shown in the background (Integrated Marine Observing System (IMOS) Ocean Current data, with a spatial resolution of ~10 km). In (a,c), significantly lower water temperature (in green) in the coastal area indicates an upwelling event.

The Topographic Position Index (TPI) [35] is a local-based image processing algorithm that has been successfully applied to map large-scale ocean currents [1,32] and other oceanographic features such as coastal upwelling [28,41]. In this study, as in [1], we calcu-
lated the TPI (Equations (1)–(3)) of each SST image to capture the strong zonal temperature gradient between the EAC and its surrounding waters (Figure 1b,c). Then, a TPI threshold (mean + 0.5 std) was applied to extract the EAC from the background ocean (Figure 1c,d). The derived EAC was then vectorized for subsequent spatial analysis (Figure 1d). For detailed TPI calculation and mapping procedures for the EAC, one can refer to [1].

\[
TPI(x, y) = \text{SST}(x, y) - M(x, y)
\]

\[
M(x, y) = \frac{\sum_{i=-n}^{n} \sum_{j=-n}^{n} \text{SST}(x-i, y-j)}{N^2}
\]

\[
n = \frac{N-1}{2}
\]

where \((x, y)\) is the position of an image pixel, \(M\) is the average SST of a neighborhood centered at \((x, y)\) and \(N\) is the pixel number of the neighborhood. We used a square window of \(75 \times 75\) pixels to calculate TPI \((N = 75)\), which is slightly larger than the typical width of the EAC’s core flow.

Two indices, area and distance, were utilized to quantify the EAC’s shoreward intrusion [1] (Figure 1d). First, the spatial extent of EAC components between the coastline and the shelf-break line was defined as the “area” index (hereafter referred to as “area”). Second, to measure the EAC’s proximity to the coast, we drew meridional sections at 1/6 degree intervals. The lengths of the section components between the coastline and the inshore edge of the on-shelf EAC waters (green lines in Figure 1d) were then averaged to obtain the EAC’s “distance” index (hereafter referred to as “distance”). After that, we conducted wavelet analyses [42,43] to decompose the time series of these two indices into time-frequency space so that we can determine the dominant frequencies in the time-series signal.

Further, we investigated the possible mechanisms associated with the EAC’s shoreward intrusion (i.e., variability of the EAC’s width and path). Firstly, as in [1], the EAC’s width was calculated by averaging all the lengths of meridional sections bounded by the inner and outer boundaries of the EAC (Figure 1d). Secondly, we produced quantitative maps of the EAC by combining all the monthly EAC maps from 1992 to 2018, statistically showing the EAC’s location, frequency, main path and centerline.

3. Results
3.1. The EAC’s Shoreward Intrusion: Time Series, Wavelet Analysis and Statistics

Time series (1992–2018) of the “area” and “distance” of the EAC’s shoreward intrusion are shown in Figure 2(a1,b1). In general, high-frequency fluctuations were observed throughout the “area” and “distance” time series, indicating that the EAC intrusion can occur all year round. On average, the area index is \(3169 \pm 1772\) km\(^2\), occupying \(17.98 \pm 10.05\%\) of the continental shelf (Figure 1a). In extreme EAC intrusion events, the EAC was observed occupying more than 40% of the shelf (e.g., 41.46% in January 1997, 43.55% in April 2005 and 46.55% in February 2016, as highlighted (red dots) in Figure 2(a1)). Overall, the distance index is \(26.87 \pm 4.29\) km. During extreme events, the distance is typically reduced to less than 20 km. For example, in the above-mentioned extreme cases, the distances were 18.02, 17.48 and 18.80 km, respectively (Figure 2(b1)).
Figure 2. (a1) Time series of the EAC’s intrusion area (left Y-axis) and the corresponding area percentage of the continental shelf (right Y-axis). Red dots represent three extreme EAC intrusion events mentioned in the text. (a2) Local wavelet power spectrum and (a3) global wavelet power spectrum (red line). In (a2), the color bar indicates wavelet power levels; the bold black curve indicates the “cone of influence” below which edge effects become important. The black contours in (a2) and the dashed black line in (a3) denote the 95% confidence level using a chi-square ($\chi^2$) test. (b1–b3) Corresponding plots for the “distance” index. (c) Monthly average of the distance (red) and area (percentage) (blue) of on-shelf EAC waters. The error bars indicate 95% Confidence Intervals (CIs) (n = 26).

The results of the wavelet analyses are shown in Figure 2(a2,a3,b2,b3). Generally, high-frequency variability at the period of around 0.25 years (i.e., ~90 days) was observed throughout the entire time series of both “area” and “distance,” as shown by the black contours in the local power spectra (Figure 2(a2,b2)) and the small peaks in the global power spectra (Figure 2(a3,b3)). This is not surprising because the EAC encroachment has been associated with its high-frequency intrinsic oscillation and eddy shedding in a mapping study using six-day composited Himawari-8 SST images [1]. However, in our study, the power of the high-frequency signal is considerably weaker, which is most likely due to the use of the monthly averaging SST data.

This study focuses on the lower-frequency variability of the EAC’s shoreward intrusion. Significantly, a clear annual signal was detected from the wavelet spectra (Figure 2b,c). The local spectra (Figure 2(a2,b2)) identify a consistent higher-power band with a period of one year throughout the time series. This one-year periodicity is also clearly identified as the highest peak in the global power spectra (Figure 2(a3,b3)). From 1992 to 2018, this
annual signal is continuous and statistically significant (based on chi-square test) except for just some short periods (e.g., 2000–2002 and 2012–2013; Figure 2(a2,b2)). This indeed demonstrates that, while the EAC intrudes shoreward at higher-frequencies (e.g., every 60–100 days) all year round (Figure 2) [1,4,12], the intrusion also exhibits seasonal cycles (detailed below).

The monthly variability of the EAC’s shoreward intrusion is shown in Figure 2c. Generally, both “area” and “distance” of the EAC intrusion undergo a clear seasonal cycle, confirming that the EAC is closer to the coast in austral summer than in winter. Specifically, the area (percentage) reaches its maximum during January (3955 ± 692 km²; 22.44 ± 3.93%), February (4186 ± 688 km²; 23.75 ± 3.91%), and March (4224 ± 750 km²; 23.96 ± 4.26%). Correspondingly, this is a period when the distance drops to its minimum, being 24.63 ± 1.85 km, 24.35 ± 1.28 km and 23.69 ± 1.15 km, respectively. In contrast, the area (percentage) is lowest in June (2149 ± 586 km²; 12.19 ± 3.32%) and July (2161 ± 556 km²; 12.26 ± 3.16%) when the maximum distance was observed (29.38 ± 1.65 km in July). The overall (26 years) monthly mean indicates that the EAC waters could be ~10 km closer to the coast in summer than in winter.

In Figure 3, we compare the maximum and minimum EAC-to-coast distances in winter and summer, respectively, from 1992 to 2017. In general, the maximum EAC-to-coast distance occurs during winter (blue line), ranging from 30 to 40 km. In contrast (red line), the minimum distance usually occurs during summer, ranging from 15 to 25 km. The difference (black line) between the maximum distance in winter and the minimum distance in summer is 10.86 km (mean), with a standard deviation of 3.41 km. As the continental shelf off southeast Australia is narrow (~25 km) [44], such seasonal intrusion of the EAC could exert significant influence on coastal hydrodynamics in this region (discussions in Sections 4.2 and 4.3).

**Figure 3.** Comparisons of the maximum and minimum EAC-to-coast distances in winter and summer, respectively, from 1992 to 2017. The maximum (minimum) distance in winter (summer) was obtained from the monthly data (Figure 2(b1)) of June, July and August (December, January and February) in each year.

### 3.2. Quantitative Maps of the EAC: Location, Frequency, Main Path and Centerline

Spatially, the EAC’s shoreward intrusion is directly associated with changes in the EAC’s path and/or width. This is demonstrated in the long-term composite maps of the EAC (Figure 4). Along the north NSW coast (28–32°S) and onshore of the shelf-break, both areal extent and frequency of EAC intrusion are considerably larger in summer than in winter (Figure 4b,c). This coincides with the seasonal shift of the EAC’s main path, represented by an area with an EAC frequency > 50%, and its centerline, with the seasonal widening of the EAC (Figure 4d).
Figure 4. Quantitative maps of the EAC: location, frequency, main path and centerline. (a) Location and corresponding frequency of the EAC generated by combining all the monthly maps of EAC from 1992 to 2018. The dual black lines delineate the main path of the EAC with a frequency > 50%. The bold black line is a centerline of the EAC’s main path. (b) The EAC’s main path generated by combining all the monthly EAC maps in summers and (c) in winters from 1992 to 2018. (d) The centerlines of (a) (26 years), (b) (summer) and (c) (winter). The bottom right panel provides the intra-annual variation of the EAC’s width downstream of 29°40’S (mean width (bold pink line) ± standard deviation (dotted pink line)), x-labels “a” to “d” represent January to December. (e) Meridional displacement (km) of the centerline from 28°20’S to 32°S (comparison between summer and winter, with the positive value denoting the centerline (summer) being closer to the coast and negative value further offshore). The vertical dotted line denotes zero displacement. The horizontal dotted gray line denotes the latitude of 29°40’S upstream of which the centerline exhibits notable seasonal shifts.

Specifically, downstream of 29°40’S, the three centerlines (summer, winter and 26-year) generally overlap, with insignificant meridional (cross-shelf) displacement of 2.03 ± 0.98 km between summer and winter (Figure 4d,e). However, in this area, the EAC’s width exhibits significant seasonality, being broadest (52.85 ± 13.44 km) in December (austral summer) and narrowest (42.44 ± 11.50 km) in July (austral winter) (Figure 4d). This seasonal broadening of the EAC is also clearly shown in Figure 4b,c, where the EAC’s main path, downstream of 29°40’S, is notably narrower (~10 km) in winter than in summer.

In contrast, upstream of 29°40’S, the EAC’s path (centerline) undergoes considerable seasonal shift (Figure 4d,e). The centerline is centered at ~154°0’E and is on average ~8 km closer to the coast in summer than in winter. At 28°30’S, we observed the maximum shoreward displacement of 11.67 km (Figure 4e). In terms of the EAC’s width, we noted that it is similar in summer (44.87 ± 12.80 km) and winter (46.05 ± 12.41 km) in this area.

4. Discussion

4.1. On the Mechanism of EAC’s Seasonal Intrusion: Shift or Widening?

For decades, it has been disputed as to whether the EAC exhibits a seasonal shoreward intrusion. Although it is challenging to detect the low-frequency variability of this dynamic eddy-current system, previous research does provide some useful insights. For instance, from a broader synoptic structure of the EAC based on steric height data, Ridgway and Godfrey [3] hinted at the seasonal shift of the EAC’s axis (being closer to the coast in summer). However, in a recent study using four years’ HF radar observation, Archer et al. [4] demonstrated that the EAC axis does not exhibit any significant seasonal displacement. Instead, Archer et al. [4] suggested that the EAC’s seasonal shoreward movement is due to the EAC’s widening (5~15 km) during summer. Nevertheless, the finding only reflects the EAC component within a rather limited area between 30 and 31°S. In a recent mapping study, Xie et al. [1] also identified seasonality in the EAC’s shoreward intrusion, which
coincides with the EAC’s seasonal broadening (10–15 km). However, their study period (2015–2017) is too short to statistically demonstrate the EAC’s seasonality.

In this study, in the area downstream of ~29°40′S (Figure 4d,e), our results agree with Archer et al. [4], showing that seasonal shift of the EAC’s path is insignificant with mean displacement between seasons of ~2 km. In addition, our results indicated that, in summer, the EAC exhibits a considerable widening of ~10 km (Figure 4b–d), a magnitude that is consistent with the above recent studies [1,4]. As our results were derived from the quantitative mapping using a 26-year-long dataset with a large spatial coverage, we are confident that, downstream of ~29°40′S, the seasonal shoreward intrusion of the EAC is due to its seasonal widening. Theoretically, the width of the western boundary layer will increase if the lateral viscosity increases [45]. This could occur as a consequence of an increase in eddy activity in a WBC system [46]. Downstream, the seasonal widening of the EAC is likely due to such seasonal eddy activity, in light of the mounting evidence of increased eddy kinetic energy in this area during summer [4,6,47–49].

Upstream of ~29°40′S (Figure 4d,e), however, our results reveal a different mechanism, indicating that seasonal shift of the EAC’s path is the main driver of the EAC’s seasonal shoreward intrusion, as previously alluded by Ridgway and Godfrey [3]. We observed an insignificant difference (~1 km) of the EAC width between summer and winter (Section 4.2). In contrast, we observed a considerable shift of the EAC’s path (centerline) which is on average ~8 km closer to the coast in summer than in winter (~154°0′E, Figure 4d,e). These results demonstrated that, upstream of ~29°40′S, the EAC’s seasonal shoreward intrusion is mainly due to the seasonal shift of the EAC’s path. Such seasonal shift (i.e., onshore/offshore current transport across the \(f/H\) contours in summer/winter) reflects the seasonal advection of potential vorticity (APV [50]) near the continental shelf at ~154°0′E as demonstrated by Bhatt [51] using BRAN2.1 reanalysis data [52,53]. According to Bhatt [51], the Joint Effect of Baroclinity and Relief (JEBAR [54,55]) contributes significantly to the seasonal APV in this area (~154°0′E), where the role of wind stress curl is significantly weaker.

4.2. Implications for Coastal Upwelling

The EAC is a major driving force of coastal upwelling along the eastern margin of Australia, with the intensity of upwelling being proportional to the EAC’s proximity and strength [11,12,29]. Figure 1a–c indicates an upwelling event occurred in the coastal area where both water temperature (color scale: green; 19–20 °C) and TPI value (color scale: green; negative) were significantly lower than that of the sea water further offshore. The EAC can be significantly accelerated (enhanced southward advection) through either cross-shelf encroachment into shallow waters or topographic acceleration where the flow path narrows. This in turn causes an increase in bottom stress and an extension of the bottom boundary layer (BBL) shut-down time. As a result, the prolonged Ekman pumping via the BBL forms coastal upwelling [8,11,29,56]. This mechanism of current-driven upwelling has been confirmed by recent observations from mooring arrays, ocean gliders and HF radars [12,27,55,57].

Due to the EAC’s high-frequency shoreward intrusion [1,4,12], the EAC-driven coastal water uplift actually occurs all year round off south-east Australia [12,14,27,28,30]. However, this “all-year-round” upwelling could also exhibit a seasonal cycle, as hinted by previous studies (e.g., [28–30]). For example, Oke and Middleton found a greater occurrence of thermal fronts off the north NSW coast during spring and summer periods [29]. Rossi et al. also found that, between 25 and 32°S, current-driven upwelling typically maximizes in summer or spring [30]. However, they attributed such seasonal upwelling simply to the seasonal cycle of the EAC’s southward transport, which is strongest in summer and weakest in winter [3]. More recently, Huang and Wang observed a similar seasonal pattern of upwelling along the north coast of NSW using 14 years of MODIS SST data [28]. They suggest that such seasonality is more likely current-forced than wind forced because of the lack of strong and persistent northerly winds. In fact, the above findings have hinted
at the role of the EAC in the seasonal coastal upwelling. In this study, through direct measurement, we were able to provide robust evidence of the EAC’s seasonal intrusion into the coastal water. Accordingly, we are confident to suggest that the intensified coastal upwelling during summer is mainly due to the combined influence of increased shoreward proximity and southward transport of the EAC.

4.3. Implications for Shelf Circulation

The EAC’s shoreward intrusion also drives circulations on the continental shelf [4,8,27]. On the shelf, the surface current varies linearly with the EAC’s shoreward proximity [4]. As there is mounting evidence showing that the EAC’s shoreward intrusion features high frequency and a large amplitude [1,12], it is not surprising that the flow pattern on the shelf exhibits very high variability [4].

However, the seasonal shoreward intrusion of the EAC, as identified in this study, could also considerably change the shelf dynamics off northern NSW. In fact, Wood et al. observed significant seasonality in the vertical shear of alongshore flow velocity, with large vertical current shear occurring in summer but very small current shear in winter [31]. They attributed such seasonal current shear simply to seasonal changes in temperature gradient across the shelf (i.e., the thermal wind effect). They also excluded the role of winds as the local wind pattern indeed prevents the formation of a steady seasonal shelf circulation. Although the thermal wind theory has provided a convincing argument for the relatively weak current shear in winter, the strong current shear in summer was only partially explained by the theory [31]. The EAC’s seasonal shoreward intrusion, as demonstrated in our study, therefore provides a deeper understanding of the seasonal shear on the shelf. In summer, as the EAC moves further shoreward, surface along-stream flow is significantly intensified through the EAC’s downstream advection [4]. The enhanced surface flow in turn contributes to a stronger vertical current shear (circulation) on the shelf. Accordingly, we suggest the seasonal shelf circulation indeed reflects a joint effect of increased EAC shoreward intrusion and increased cross-shelf temperature gradient (thermal wind effect) in summer [31].

4.4. Impacts of Climate Processes on the EAC Encroachment?

Climate processes such as El Niño/Southern Oscillation (ENSO) could play a role in the interannual to decadal variability of the EAC’s current transport and east coast sea level [58]. However, whether climate processes have an impact on the EAC’s spatiotemporal variability and the extent of the impact remains unresolved. From the time-series EAC encroachment between 1992 and 2018 (Figure 2), we noted that the EAC’s shoreward intrusion exhibits some interannual variability. However, we are not able to relate the variability to external climate signals such as El Niño and La Niña. In fact, the main pathway of the ENSO’s influence occurs through the Indonesian seas and around a waveguide around the western and southern margins of Australia [59]. As such, a previous study has shown that the EAC transport undergoes variations on interannual timescales, but the ENSO’s signal is very weak in the observations [33]. However, excluding the influences of the climate on the EAC intrusion requires more careful examinations. Indeed, detecting climate signals from the EAC’s spatial variations is challenging, because the climate signals could be overshadowed by the EAC’s high-frequency intrinsic fluctuations [1,4,18]. We propose that long-term, sustained and systematic in situ and remotely sensed observations with a high temporal resolution are crucial for future investigations over the influence of climate processes on the dynamics and spatiotemporal variability of the EAC system.

5. Conclusions

For decades, identifying the low-frequency variability of the EAC was hindered by its high-frequency intrinsic fluctuations. This study provides direct measurement (“area” and “distance”) of the EAC’s shoreward intrusion using EAC maps generated from monthly AVHRR SST images and with a robust TPI-based mapping technique. Subsequent spatial
and temporal analyses on 26 years of intrusion measurements and EAC maps show that the EAC's shoreward intrusion undergoes a consistent and significant seasonal cycle, which is associated with the EAC's seasonal shift upstream and seasonal widening downstream. To our knowledge, this is the first time that the seasonality of the EAC's shoreward intrusion has been quantified and analyzed. Importantly, our results have provided new insights into the seasonal upwelling and shelf circulation previously observed in the study area. We suggest that the EAC is the main driver of the seasonal ocean dynamics off northern NSW.

In summary, the key findings of this study are as follows:

- The EAC undertakes a seasonal shoreward intrusion of ~8 km upstream of 29°40′S;
- The EAC undertakes a seasonal widening of ~10 km downstream of 29°40′S;
- The minimum EAC-to-coast distance usually occurs during summer, ranging from 15 to 25 km; and
- The maximum EAC-to-coast distance occurs during winter, ranging from 30 to 40 km.

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