Interannual Variations of Wind Regimes off the Subtropical Western Australia Coast during Austral Winter and Spring

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ABSTRACT

Off the Western Australia coast, interannual variations of wind regime during the austral winter and spring are significantly correlated with the Indian Ocean dipole (IOD) and the southern annular mode (SAM) variability. Atmospheric general circulation model experiments forced by an idealized IOD sea surface temperature anomaly field suggest that the IOD-generated deep atmospheric convection anomalies trigger a Rossby wave train in the upper troposphere that propagates into the southern extratropics and induces positive geopotential height anomalies over southern Australia, independent of the SAM. The positive geopotential height anomalies extended from the upper troposphere to the surface, south of the Australian continent, resulting in easterly wind anomalies off the Western Australia coast and a reduction of the high-frequency synoptic storm events that deliver the majority of southwest Australia rainfall during austral winter and spring. In the marine environment, the wind anomalies and reduction of storm events may hamper the western rock lobster recruitment process.

1. Introduction

The coast of Western Australia (WA) is unique in that the ocean circulation is dominated by the poleward-flowing Leeuwin Current (LC), driven by an anomalously large meridional pressure gradient set up by the warm, low-density tropical Pacific Ocean water entering the Indian Ocean (IO) through the Indonesian Archipelago (Meyers et al. 1995; Feng and Wijffels 2002). During the austral summer (December–February), seasonally strong southeasterly winds (Fig. 1a) hinder the LC flow, while during the austral winter (June–August) maximum poleward geostrophic transport by the LC is reached when the northward wind stress decreases (Fig. 1b; Feng et al. 2003). Interannual variation of the LC strength is influenced remotely by zonal wind anomalies in the tropical Pacific related to El Niño–Southern Oscillation (ENSO) events due to the existence of equatorial and coastal waveguides via the Indonesian Archipelago (Clarke and Liu 1993; Meyers 1996; Feng et al. 2003, Wijffels and Meyers 2004; Feng et al. 2005). The poleward transport of the LC is a key factor influencing sea surface temperature and fisheries recruitments off the WA coast as well as regional climate (Caputi et al. 2001; Feng et al. 2008). This study aimed to...
identify additional mechanisms that influence regional marine environment and fisheries recruitments due to climate variability operating in the IO.

In a comprehensive review of the Indian Ocean dipole (IOD), Schott et al. (2009, p. 26) concluded that, “Overall, results from both observations and models suggest to us that the IOD is a natural mode of the IO coupled system, which either can be externally triggered, by ENSO, for example, or can self-generate, provided the thermocline off Sumatra is shallow enough to support Bjerknes feedback.” Further, observation and modeling studies have demonstrated that Indian Ocean SST gradients (including the IOD pattern) can have a significant influence on climate in (southwest) Australia (Frederiksen and Balgovind 1994; Frederiksen et al. 1999; Saji and Yamagata 2003a; Ashok et al. 2003; Ummenhofer et al. 2008, 2009b). For example, Saji and Yamagata 2003a and Ashok et al. 2003 show that the IOD leads to the formation of low precipitation, warmer temperature, and positive geopotential height and anticyclonic circulation anomalies in the extratropics. Such results are consistent with earlier teleconnection studies (i.e., Ambrizzi et al. 1995; Ambrizzi and Hoskins 1997), suggesting that tropical divergence anomalies can propagate to such latitudes via Rossby wave propagation. In some El Niño events, ENSO might affect southwestern Australia climate through the intermediary of the IOD during the austral spring (Cai et al. 2011b).

Saji et al. (2005) noted that wavelike anomalies exist in the southern extratropics all year-round (Rogers and van Loon 1982; Kidson 1988) and possibly a large part of these simply result from internal atmospheric dynamics (Hartmann and Lo 1998). Thus, the observed correlation between the IOD and Southern Hemisphere atmospheric variability may not reflect a real teleconnection process, but may be a result of statistical aliasing with the internal variability, such as the southern annular mode (SAM).

Lau and Nath (2004) arrive at such conclusions, suggesting that due to the seasonal dependence of the amplitude of the observed annular mode, the SAM precedes the IOD and may lead to initiation of IOD events in austral spring. Fawcett (2009) concluded that this may have been the case for 2008, with the IOD and the SAM both in their positive phases. Cai et al. (2011a) provide some detailed summary on the relations between the IOD, ENSO, and the SAM; however, it is imperative to further address this topic through additional diagnoses to understand the robustness of this relationship.

The surface wind of southwestern Australia is emphasized because it might have an impact on the marine environment. For example, recruitment processes for a key fishery species—the western rock lobster (*Panulirus cygnus*)—off the lower WA coast is strongly influenced by the physical environment, with westerly winds (and related Stokes drift) being highly correlated with interannual variation in recruitment and settlement of the species in coastal waters (Caputi et al. 2001; Feng et al. 2011). Our hypothesis is that the general direction and intensity of the winter westerlies, wave activity, and high frequency storm events over the southeast IO are aligned in such a way that aids in the transport of the late-stage larvae toward the WA coast when the majority return; the easterly wind anomalies due to positive IOD (pIOD) when it occurs interrupts this recruitment.

Overall, the present study aims to investigate the response over the southeast IO due to IOD forcing and ascertain whether such conditions hypothesized above can arise independent of other climate modes such as the SAM, with implications for the WA marine environment and recruitment processes of a key fishery species. The paper is structured as follows. In section 2, we describe the observational and modeling tools used in the study. Section 3 applies empirical orthogonal function (EOF) and

![Fig. 1. Maps of NCEP–NCAR long-term surface winds (U0) for (a) austral summer and (b) austral winter during 1970–2010.](image-url)
partial regression (or equivalently partial correlation) analysis to seasonal SST and wind stress anomalies to highlight interannual climate variability modes and regional teleconnection patterns. Section 4 expands on the dynamical mechanisms of the anomalous atmospheric conditions in the southeast IO extratropics due to the IOD mode during winter and spring. We then discuss in section 5 the evolution of such wind stress and related "synoptic scale" storm event anomalies and the impact on the marine environment, providing an example of the implications to the valuable western rock lobster fishery off the WA coast. Conclusions are presented in section 6.

2. Data and model experiment

Global monthly reanalyses from the National Centers for Environment Prediction–National Center for Atmospheric Research (NCEP–NCAR) project (Kalnay et al. 1996) were used to examine atmospheric fields, such as vertical and horizontal circulation and geopotential heights. An updated version of the Met Office Hadley Centre Sea Ice and SST reanalysis (HadISST1) (Rayner et al. 2003) with a horizontal resolution of 1° latitude/longitude was used to examine the SST field. ENSO was monitored using the Niño-3.4 index, which is the average SST anomalies over 5°S–5°N, 170°–120°W. The IOD was monitored with the dipole mode index (DMI) (Saji et al. 1999), which is the difference of the area mean SST anomalies between a western IO region (10°S–10°N, 50°–70°E) and an eastern IO region (10°S–equator, 90°–110°E). The SAM index was obtained from the British Antarctic Survey (Marshall 2003), calculated from station-based mean sea level pressure (MSLP) observations. The analysis was conducted over the period 1970–2010. Significance of relationships was based on the significance of the associated correlation coefficients, which was when $p < 0.1$ and assuming normal distribution.

The atmospheric general circulation model (AGCM) used for the experiments in this study was the Community Atmosphere Model, version 3 (CAM3), which uses an Eulerian spectral dynamical core and includes physical packages for convection, turbulence, and cloud. Further, the model uses triangular truncation at T42 (equivalent grid spacing of 2.8° latitude/longitude) and has 26 vertical levels. Further details on CAM3 may be found in Collins et al. (2004). In the first experiment [the control experiment (CTL)], we implemented seasonally varying climatological SST as the lower boundary condition. In the second experiment [the tropical IO perturbed SST experiment (IOD)], an idealized pIOD SST anomaly pattern (Fig. 2) including the region to the north of Australia (Nicholls 1989; Watterson 2001, 2010) was imposed. The SST pattern was constructed by regression of the IO SST upon the DMI for August–October, preceding the peak IOD wind anomalies during September–November. Anomalies were scaled so that the negative anomaly in the eastern pole was approximately $-2^\circ C$, almost twice the natural amplitude of pIOD events, so as
to amplify the response to pIOD, and imposed throughout the year, as the seasonal-mean responses were not sensitive to whether we imposed steady seasonal-mean SST or the evolution of SST anomalies. Regions outside of the tropical IO (20°S–20°N) were masked (made zeros) with only climatological SSTs implemented, and smoothing the edges of the anomalies was not considered important as, apart from the eastern edge, the anomalies were small at the boundary of the SST perturbations and therefore not considered to have a significant influence on the results.

In addition, two sensitivity experiments were conducted: one involved only imposing the negative eastern pole anomaly (IOD_east) and the other, the magnitude of the imposed SST anomaly pattern in the first perturbation experiment was reduced by half (IOD_half). All experiments were conducted for 20 years and the results from the CTL experiment were subtracted from those from the three perturbation experiments to obtain the anomalies due to the different imposed SST anomalies in the latter experiments. Anomalies were tested for significance using a two-tailed Student’s $t$ test.

FIG. 4. (a) Composite of anomalous NCEP–NCAR surface wind (m s$^{-1}$) for July–November during negative EOF years as compared to the long-term climatological mean (see text for details). (b) As in (a) but for zonal wind stress ($\tau_x$, N m$^{-2}$). (c),(d) As in (a),(b), but for positive EOF years as compared to the long-term climatological mean. Areas where the differences are significant (90% confidence level from a two-tailed Student’s $t$ test) are contoured.

FIG. 5. Annual cycle of the rms of the monthly anomalies of the dipole mode index (DMI, gray line), Niño-3.4 index (black line), and southern annular mode index (SAM, dashed line).
3. Observed interannual variability of winter/spring wind regimes

This section extends the known structure of the IOD in the tropics (Saji et al. 1999; Krishnamurthy and Kirtman 2003; Shinoda et al. 2004; England et al. 2006; Cai et al. 2009) to higher latitudes. The second EOF of zonal wind stress ($t_x$) during July–November related to the IOD over the Indian Ocean basin captures 16.7% of the variance (Fig. 3a; the first EOF depicts a SAM-like pattern, not shown). It has largest loadings near the equator in the eastern portion of the basin, indicating that easterly wind anomalies are associated with a pIOD. A relative maximum of the same sign covers the far eastern subtropical IO centered on ~30°S and extending over the coast of Western Australia. A third but oppositely signed loading region is centered near ~52°S.

The time series of the EOF (Fig. 3b) shows the well-known events of pIOD in 1982, 1994, 1997, and 2008, and the time series is highly correlated with the DMI (0.82, $p < 0.001$) and $t_x$ averaged over a region adjacent to the lower WA coast (0.78, $p < 0.001$). This result highlights the association between the tropical IOD variability represented by both winds and SSTs and WA winds. The same spatial pattern as in Fig. 3a results from composite maps of zonal wind speed and wind stress for the years when the EOF time series is negative.

![Figure 6](image-url) (a) Lag–lead partial correlation of SST (shading) on the DMI (SON) and partial regression of surface wind stress on DMI (SON), independent of Niño-3.4 and SAM. Areas where the explained variance is significant (90%) are shaded, and magnitudes of wind correlations smaller than $5 \times 10^{-3}$ N m$^{-2}$ per index unit are not plotted. (b) As in (a) but for Niño-3.4 (November–January) independent of DMI and SAM. (c) As in (a) but for SAM (concurrent) independent of Niño-3.4 and IOD.
TABLE 1. Correlations of monthly selected variables and climate modes over the period 1970–2009. SST is averaged over 24°–31.5°S, 109°–115°E during September–February; \( \tau \), and 2–7-day variance height are averaged over 26°–38°S, 100°–120°E during July–November. Climate indices were averaged over September–November values for DMI, October–December values for Niño-3.4, and June–August values for the SAM index. Significant correlations at the 95% level are marked in bold.

<table>
<thead>
<tr>
<th>Puerulus settlement index</th>
<th>SST</th>
<th>( \tau )</th>
<th>( Z^2 ) (2–7 days)</th>
<th>Niño-3.4</th>
<th>DMI</th>
</tr>
</thead>
<tbody>
<tr>
<td>SST</td>
<td>0.51</td>
<td>0.36</td>
<td>0.37</td>
<td>-0.46</td>
<td>-0.33</td>
</tr>
<tr>
<td>( Z^2 ) (2–7 days)</td>
<td>0.37</td>
<td>0.16</td>
<td>0.51</td>
<td>-0.25</td>
<td>-0.06</td>
</tr>
<tr>
<td>Niño-3.4</td>
<td>-0.46</td>
<td>-0.51</td>
<td>-0.18</td>
<td>-0.39</td>
<td>-0.36</td>
</tr>
<tr>
<td>DMI</td>
<td>-0.35</td>
<td>-0.25</td>
<td>-0.39</td>
<td>-0.4</td>
<td>-0.35</td>
</tr>
<tr>
<td>SAM</td>
<td>-0.33</td>
<td>-0.06</td>
<td>-0.36</td>
<td>-0.45</td>
<td>0.23</td>
</tr>
</tbody>
</table>

\(-1 \sigma\) (Figs. 4a,b), and for years when the zonal pattern is positive (westerly anomalies off the WA coast) and greater than \(+1 \sigma\) (Figs. 4c,d). The wind analysis at higher latitude shows that, when easterly anomalies occur off WA, westerly anomalies also occur in the central to eastern equatorial IO, as is well known during pIOD events (Saji et al. 1999; Saji and Yamagata 2003b). On the other hand, when the easterly anomalies occur off WA, westerly anomalies also occur in the Southern Ocean, mirroring the wind pattern response due to the positive (high) phase of the SAM (Thompson and Wallace 2000; Hendon et al. 2007). The response in the composites when westerly anomalies occur off WA is not as pronounced (Figs. 4c,d), apparently due to asymmetry in the positive and negative IOD events. For example, the zonal westerly anomaly band off WA does not extend as far west in the IO, and oppositely signed anomalies are seen south of Madagascar. In addition, there is only a small equatorial signature in surface winds (Fig. 4c) and no signature in \( \tau \) (Fig. 4d). There still exists an oppositely signed band of anomalies over the southern extent of the domain centered \( \sim 55^\circ \)S, again consistent with the negative phase of the SAM.

This leads to the question: to what extent are the zonal wind anomalies observed off WA (Fig. 3b) due to climate modes IOD and/or SAM? To further explore the nature of the atmospheric circulation fluctuations over this region relating to modes of variability, we use partial correlation and regression analysis to delineate the impact of each mode on the region of interest off WA. The season when each climate mode is strongest was selected according to the interannual root-mean-square variation for each month of the year (Fig. 5). We used September–November values of the DMI, November–January values of Niño-3.4, and concurrent seasonal values of the SAM (i.e., March–May value of the SAM with March–May SST and winds).

Figure 6 displays the partial correlations of the DMI, Niño-3.4, and SAM with gridded SST during individual seasons, austral autumn [March–May (MAM)], winter [June–August (JJA)], spring [September–November (SON)], and summer [December–February (DJF)] for the period 1970–2010. In addition, to quantitatively visualize atmospheric circulation anomalies related to each climate mode, we have superimposed the partial regression coefficients of wind stress as vectors. First, Fig. 6a (left panels) highlights that the response in SST associated with the DMI is generally localized along the equatorial IO and south of Sumatra/Java, with correlations increasing during austral winter and peaking in spring. In contrast, the partial correlation of the response in SST associated with Niño-3.4 is of larger magnitude and more widespread (Fig. 6b, middle panels). Strong negative correlation is seen in the western Pacific Ocean from austral winter to summer, with an influence reaching into the east IO. This signal propagates along the north and west coasts of Australia, consistent with coastal dynamics mechanisms for remote forcing and the propagation along respective equatorial and coastal waveguides in the region (Wijffels and Meyers 2004). A basinwide warming occurs during summer. While typical SST anomalies in the IO during ENSO are only one-third to one-half as large as those in the equatorial central and eastern Pacific, the high mean temperatures in the former imply that small changes can drive significant circulation anomalies (Shinoda et al. 2004; Lan et al. 2009). The response in SST associated with the SAM is small, confined to Southern Ocean latitudes where wind responses may force localized anomalies year-round (Fig. 6c, right panels).

Turning our attention to influences on atmospheric circulation, the partial regressions of wind stress on climate indices reveal similar seasonality structure. Overall, it is confirmed that responses to both the IOD and the SAM (Figs. 6a,c, left and right panels) can potentially account for the perturbations observed in Fig. 4 during the austral winter and spring, hence the concern whether the two are independent (Lau and Nath 2004). From correlation analysis we suggest that the relationship is not significant (Table 1) when the SAM precedes the IOD: suggesting that they are independent, however,
requires a more extensive lead–lag analysis for ascertaining true independence not performed here. For example, in the case of the IOD related to an anticyclonic circulation pattern over the Australian continent, easterly (and southeasterly) wind anomalies overlie most of the continent with westerly (and northwesterly) wind anomalies south of the continent during winter (JJA) (Fig. 6a). This could impact on the usual equatorward migration of the subtropical ridge during this time of year. The anticyclonic feature appears to dissipate during spring (SON) with easterly anomalies extending farther west over the IO. In the case of the SAM during winter, however, when the subtropical ridge extends equatorward into lower subtropical latitudes (north of ~30°S, Fig. 1b), anomalous easterlies associated with a positive SAM also overlie most of the IO and WA coast between ~20° and 40°S (Fig. 6c). These easterly anomalies then retreat south, following the subtropical ridge, during austral spring and summer to be generally confined southward of ~30°S. Last, for the case of ENSO, relatively small wind anomalies are present independent of the other climate modes (Fig. 6b, middle panels), with the largest influence
observed over the austral summer, with which this study is not concerned.

4. AGCM IOD experiment and dynamical mechanisms

In this section AGCM experiments demonstrate that the subtropical easterly wind anomalies over southwestern Australia during a pIOD can be generated by the SST anomalies in the tropical IO. The AGCM experiment produces divergence and a downward motion over the tropical eastern IO, similar to observations (Figs. 7a,d), as well as atmospheric Rossby waves that then propagate into the extratropics and over the Australian continent (Fig. 7). Overall, the response in the southern IO displays clear atmospheric wave train structures (Hoskins and Karoly 1981; Gill 1982; Saji and Yamagata 2003a; Cai et al. 2011b) with a strong response over the Australian continent (Fig. 7). The IOD experiment confirms that the positive sea level pressure anomalies persist through the spring, as shown by the composite of July–November (Figs. 7b,e).

Fig. 8. (a) Surface zonal wind (m s$^{-1}$) for July–November regressed onto the DMI. (b) As in (a) but for 200 mb. Areas where the explained variance is significant (90%) are shaded. (c),(d) As in (a),(b) but the difference between the IOD perturbed and CTL experiments.

In the IOD experiment, maximum amplitude of the response occurs in the easterly anomalies along the equatorial IO, and easterly anomalies also overlie much of the southeast IO and Australian continent (Fig. 8c). The regression of surface winds on the DMI (Fig. 8a) also shows easterly anomalies over similar regions in observations, as in the IOD experiment, in addition to closely resembling Figs. 3, 4a. Thus, the easterly anomalies off the WA coast can be explained as part of the Rossby wave response to tropical divergence due to the IOD. Further, the AGCM simulation shows how the lower-tropospheric zonal wind anomalies strengthen upward through the troposphere (Fig. 9) and reveals the baroclinic nature over the equator and an equivalent barotropic nature over the midlatitudes. At 200 mb easterly anomalies are still present over southern Australia and off the WA coast, while return flow occurs from the west over the equatorial IO (Figs. 8b,d).

The largest discrepancy between the maps of regression of sea level pressure (Figs. 7b,c) and geopotential height (Figs. 7c,f) anomalies and the IOD experiment results is that the center of the anomaly south of Australia is simulated farther south than observations. The omission of the western IO positive SST anomaly from the perturbed forcing field (refer to Fig. 2) in a second AGCM experiment, referred to here as the IOD_east experiment, was
tested. This replicates the suppression of atmospheric convection associated with the concurrent El Niño events that generally occur over the western equatorial pole (Figs. 10a–c). Overall, the negative pressure anomaly, seen in Fig. 7e, centered over 40°S, 70°E does not arise due to such convection and wave train propagation being suppressed over the western equatorial IO, and the positive anomaly south of the Australian continent is now positioned farther north and is more consistent with the observed regression map (Fig. 10b). Similarly, in the troposphere at 200 mb (Fig. 10c) the position of the positive height anomaly south of the Australian continent is consistent with the regression map (Fig. 7c) but of a smaller magnitude.

The third AGCM experiment, referred to here as the IOD_half experiment (Figs. 10d–f), also improves agreement with the observed regression maps. The improvement in this simulation compared to the initial IOD experiment includes a suppression of the upward and downward vertical velocities over the western and eastern equatorial IO, respectively, which are now of similar magnitude to the observed IOD regression map (Fig. 10d). Consequently, the wave train propagating from the western equatorial IO is not as pronounced, as seen by the reduction of the negative sea level pressure anomaly at 40°S, 60°E; therefore, it does not interfere as much with the wave train propagating from the eastern equatorial IO (Fig. 10e). At 200 mb the anomalies are still situated farther south than the observed regression map, suggesting that the interference at this level is presumably greater than at the surface (Fig. 10f). The Rossby wave trains are dislocated slightly westward in the model compared to the observations, presumably due to the larger spatial extent of the positive SST anomalies compared to the negative anomalies in the experimental setup. The sensitivity experiments also suggest the high nonlinearity of the IOD teleconnection in southern Australia.

5. Potential impacts of the IOD on western rock lobster recruitment

Caputi et al. (2001) showed that late austral summer and early autumn (February–April) SSTs off the WA coast, which are important to western rock lobster larvae survival, can be forced by Leeuwin Current advection, as well as ocean memory from as early as the previous September when the mixed layer is deepest (Feng et al. 2008). The species has an oceanic larvae phase dispersed widely over the southeast IO, relying on physical mechanisms to be carried back to settle on shallow reefs along the coast of WA (Feng et al. 2011). In addition, previous studies have documented the positive relationship between warm SST (mostly during La Niña events with stronger LC) and above-average recruitment to the western rock lobster (WRL) fishery (Table 1) (Pearce and Phillips 1988; Caputi et al. 2001; Caputi 2008). This relationship, which has been maintained for nearly 40 years, produced an anomalous result for the 2008/09 season, in particular, as it was the lowest recruitment in about 40 years and was associated with a La Niña event, a strong LC, and above-average SST. This has called for the need to observe what other environmental factor(s) may have contributed to this result—in particular, the influence of the IOD. Using observed settlement since the late 1960s, currently collected by the Department of Fisheries Western Australia, we assess the relationships with atmospheric anomalies presented in the preceding sections due to climate modes (Table 1). An annual “puerulus settlement index” is derived from a monthly sampling program that looks at the abundance of late larval-stage lobsters (puerulus) settling on inshore reefs along the WA coast, peaking between August and January each year (Caputi et al. 2001). This index has always shown a strong correlation with commercial catches of lobsters three to four years later (Caputi 2008; de Lestang et al. 2009).
Evident from the correlation of SST with the settlement along the WA coast (Fig. 11a) is the established link between interannual variability along the coastal waveguide due to ENSO and LC transport forcing SST anomalies along the WA coast (Fig. 6b, MAM highlights the sustained anomalies after ENSO peaks). Here, positive correlations represent enhanced settlement associated with positive SST anomalies of the previous September–February period (Table 1). In contrast, the map of wind stress regressed onto the settlement index (Fig. 11a) resembles that of the atmospheric circulation associated with the IOD (Fig. 6a) and the SAM (Fig. 6c), however, in opposite phases (negative and positive regression coefficients in Figs. 6, 11, respectively), more than ENSO (Fig. 6b). For example, here enhanced settlement is associated with westerly anomalies over the midlatitude and equatorial regions of the IO, and easterly anomalies south of the Australian continent. Westerly winds (and related Stokes’s drift) off WA have previously been shown to affect the puerulus settlement of the species in coastal waters (Feng et al. 2011).
This study further implies the impact of the IOD on southern Australia (i.e., ocean surface conditions relevant for rock lobster recruitment, atmospheric pressure, and circulation) is through atmospheric teleconnection rather than oceanic (Table 1), and in a similar manner to the SAM. Zonal wind anomalies generated in the extratropics as a result of the Rossby wave train propagation due to the divergence from the tropical SST anomalies related to the IOD presumably generate zonal advection anomalies in the underlying ocean. This would certainly have an impact on the transport of WRL larvae situated in the upper surface waters off the coast of WA (Caputi et al. 2001), with easterly (westerly) wind anomalies, when they occur, hindering (aiding) their transport back to the coast to settle. Correlation of zonal wind stress with puerulus settlement is significant (Table 1), although it is only moderate, as other mechanisms have also been postulated to hinder (aid) the return of larvae back to the coast, such as low-frequency geostrophic flows associated with ENSO (Clarke and Li 2004).

A correlation between storminess (inferred by rain) during late austral winter and spring over southwest WA and the species settlement has also previously been reported (Caputi et al. 2001). Saji and Yamagata (2003a) showed that there is significant correlation between the IOD and southwest WA rainfall during austral winter and spring, which is to a large extent associated with synoptic-scale storm events off the coast (Fig. 12). The result is a prominent reduction in the synoptic-scale storm activity over the southern portion of Australia (Fig. 12b). This response is presumably due to changes in development, orientation, and circulation of the subtropical jet and synoptic systems over the continent (Risbey et al. 2009a,b; Ummenhofer et al. 2009a).

Figure 11b highlights areas of synoptic-scale storms that correlate with settlement when the majority of lobster larvae return to the coast during July–November. It is interesting to note that there could be a relation between this spatial result and the spatial correlation of the IOD with the same field (Fig. 12b). The correlation of interannual variability between the high frequency variance height and puerulus settlement (Table 1) is of similar magnitude to that of the relationship with zonal wind stress, further implying that the IOD could be a dominant driver of such conditions over the WA coast, providing a potentially important link between atmospheric impacts and fisheries recruitment. Another mode of interannual variability that also has an impact on the Australian continent, the SAM, displays similar features such as associated changes in pressure and circulation in the southern IO. Hendon et al. (2007) found that variations in the SAM can account for up to ~15% of the weekly rainfall variance in the same region during this time of year. Therefore, it stands that monitoring the three climate modes—ENSO, the IOD, and the SAM—alongside future settlement may improve our understanding of the environmental relationships with the species.

6. Conclusions

Easterly wind anomalies and associated reduced synoptic-scale storminess off the west coast of Australia from late austral winter through spring can be explained as part of the Rossby wave response due to divergence over the tropical IO during a positive IOD. Variations in SST in the tropical IO act to trigger convection anomalies, thereby generating vertical motion, and the resulting divergence acts as an atmospheric Rossby wave source. This
phenomenon is shown to be related to climate variability locally in the equatorial IO rather than the Pacific and Southern Oceans. Previous studies suggest that a link exists between the SAM (winter/spring) and the IOD (spring), with the SAM leading and possibly initiating the IOD in the near absence of ENSO influences. However, we suggest that a similar atmospheric response south of the Australian continent can be driven purely by the IOD, although it can co-occur with the high phase of the SAM during both seasons. Several AGCM experiments support the observed correlation and regression analysis of atmospheric circulation anomalies due to the IOD that highlight the IO role in their variations. For example, the strong wave train emanating from the IO helps explain why the IOD circulation response is strong in the southern extratropics and along the WA coast. More frequent occurrence of pIOD events in recent decades (Cai et al. 2009) may partly explain the reduction in southwest WA rainfall related to high frequency storm activity in the midlatitude westerlies. In addition, we demonstrate a possible link between the IOD with recent poor fisheries recruitment as surface winds are not favorable during austral winter/spring that may have generated offshore advection anomalies in recent years, counteracting the positive effect that a La Niña event usually has on such settlement.

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