Near-inertial currents off the east coast of India


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Abstract

We use data from moorings equipped with Acoustic Doppler Current Profilers (ADCPs) and deployed in the Bay of Bengal off the east coast of India from May 2009 to February 2012 to study the near-inertial currents (NICs) on the continental shelf and slope. The data show that the NICs are much weaker at the shelf break than on the slope. Inertial energy is weak all along the east coast during January–April. It is high during the summer monsoon (May–September) in the northern Bay of Bengal and early during the winter monsoon (October–December) in the southern bay; at locations in the central bay, the inertial energy does not show this seasonality. This difference between the northern and southern bay is due to the seasonality in the occurrence of storms, which tend to occur in the north (south) during the summer (winter) monsoon. Variability across years is evident in the three-year record, with the NICs being weaker during 2010–2011 compared to 2009. Upward phase propagation is evident in the data, indicating downward
propagation of energy. During severe cyclones, the data suggest that the strong NICs extend below the thin surface mixed layer in the bay. A comparison of the NICs amplitude with that of the detided (residual) current shows that the NICs make a significant contribution to the observed current on the east-coast slope: the magnitude of the NICs exceeds that of the residual current on the slope in the northern and southern Bay of Bengal on over 10 days in a year, respectively.

1. Introduction

Near-inertial currents (NICs) are commonly observed in the ocean (Webster, 1968; Fu, 1981). They are generated by bursts in the wind, the generation being most efficient if the wind blows for half the local inertial period (Pollard, 1970; Jarosz et al., 2007). The current accelerates downwind, but turns clockwise (anticlockwise) in the northern (southern) hemisphere owing to the earth’s rotation (Vandenbrouck et al., 2000). This difference in the clockwise and anticlockwise parts of the spectra shows a peak only in the vicinity of the inertial frequency $f$ (Fu, 1981). The dominance of the clockwise part of the spectrum over the anticlockwise part starts at sub-inertial periods, reaches a maximum near $f$, and decays at supra-inertial frequencies (Fu, 1981).

NICs have been observed in all parts of the ocean, whether it be the deep ocean (Gregg and Kunze, 1991; Zhai et al., 2005; Mori et al., 2005), the surface layers of the ocean interior away from continental boundaries (Leaman and Sanford, 1975; Haren et al., 1999), or the continental slope (Chen et al., 1996; Jarosz et al., 2007; Aken et al., 2005) or shelf (Huthnance, 1981; Shearman, 2005). In the Indian
Ocean, however, the dearth of current measurements implies that studies of NICs are limited. They have been observed in drifting-buoy data in the South Indian Ocean (Shetye and Michael, 1988) and over most of the Indian Ocean (Saji et al., 2000). NICs have been observed in current-meter data from the Bay of Bengal (Joseph et al., 2007) and the Arabian Sea (Rao et al., 1996), and on the continental shelf off the Indian west coast (Shenoi and Antony, 1991).

Over the last 2–3 decades, direct current measurements have enabled a study of the variability of NICs with time and space in many parts of the world oceans. These measurements have typically been made for a few months to a few years, allowing an analysis of the variability in generation of NICs in time and space. Examples include observations of NICs by Fu (1981), Kundu (1976), and Jarosz et al. (2007).

A problem with the Indian-Ocean NICs studies is that they are based on short records (duration less than a month) (Shenoi and Antony, 1991; Rao et al., 1996) or deal with a specific event, typically the NICs excited by one storm (Joseph et al., 2007). These short records do not permit an analysis of the variability in both time and space. Specifically, is there a seasonality in the generation of NICs? Given the strong seasonality in the monsoon winds over the North Indian Ocean (NIO), it is likely that the NICs show a strong seasonal variability. Likewise, are there spatial variations in the generation of NICs? For example, if we consider, say, the east coast of India (Figure 1a), is the generation of NICs coherent along the coast, or does it vary along the coast? How important is the contribution of the NICs to the total current?
To answer these questions, we use data from moorings, which were equipped with acoustic Doppler current profilers (ADCPs) and deployed on the continental shelf and slope off the Indian east coast. We show that inertial energy is weak on the shelf and strong on the slope, that there is considerable seasonality and inter-annual variability in the occurrence of NICs, and that the NICs make a significant contribution to the total measured current off the east coast. The paper is organised as follows. The data sources and spectral analysis of the data are presented in Section 2. The NICs on the slope are described in Section 3, and Section 4 concludes the paper.

2. Data and spectra

Nine moorings with upward-looking ADCPs (make RD Instruments) were deployed on the Indian shelf and slope in the Bay of Bengal during May 2009 to February 2012 (Figure 1, Table 1). Eight of these moorings formed a shelf-slope pair and were deployed off the east coast of India, with the shelf (slope) mooring deployed in a water-column depth of $\sim 100$ m ($\sim 1100$ m). The pair off Gopalpur in the north and Kakinada at the centre of the coast was deployed for this entire period, but the Kakinada slope mooring was shifted by $\sim 50$ km in May 2010. Off Cuddalore in the south, the mooring pair was deployed during May 2010 to February 2012, and the pair off Ramayapatnam, also at the centre of the coast, during May 2009 to April 2010. The ninth mooring was deployed at ($89^\circ$E, $19^\circ$N) on the slope off the northern boundary of the bay, but in deeper waters (Table 1). It was located roughly off Paradip, which lies at the junction of the western and northern
boundaries of the bay (Figure 1). On the slope, the bottom mounted ADCPs were located at a depth of $\sim 300$–$400$ m from the surface, implying a loss of data in the top $30$–$40$ m; these slope moorings were deployed in a water-column depth of $\sim 1100$ m. On the shelf, the ADCPs were deployed just off the ocean bottom at a water-column depth of $\sim 100$ m. The slope (shelf) ADCPs had a frequency of 75 kHz (300 kHz) and recorded data at an interval of one hour (15 or 30 minutes). Data gaps in depth and time were filled using the method of Kutsuwada and McPhaden (2002). The tidal component of the current was removed using the Tidal Analysis Software Kit (TASK-2000) (Bell et al., 1998). A one-month control file was used to eliminate the tidal components with period less than a month. We used the wavelet transform approach to obtain the spectra. Clockwise and anticlockwise components of the rotary spectra were calculated using the method of Paul and Miller (1996), and the wavelet transform of the velocity was converted as the sum of clockwise and anticlockwise components in time-frequency space. This analysis was applied to vertical averages of the current; the average was computed over a depth range of $40$–$250$ m ($20$–$80$ m) on the slope (shelf).

As expected, the clockwise spectrum dominated the anticlockwise spectrum in the neighbourhood of the inertial frequency on the slope (Figure 2), indicating the existence of NICs. The inertial energy varied along the coast. It was strongest off Paradip and weakest off Cuddalore. The observed inertial frequency, at which the difference between the clockwise and anticlockwise spectra is maximum (Table 2), matched the theoretical inertial frequency at Paradip, but was higher than predicted by theory as one moved south along the coast (Figure 2). The devi-
ation from theory was maximum (8 hours) at Cuddalore. A similar increase in
the inertial frequency compared to theory has been noted elsewhere too (Kundu,
1976).

On the shelf, however, the difference between the clockwise and anticlockwise
spectra was much smaller (Figure 2), indicating weak generation of NICs on the
east-coast shelf. Weak signatures of NICs were evident only off Ramayapatnam
and Gopalpur. Similar results were obtained without vertical averaging: off the
Indian east coast, NICs are weak on the shelf and strengthen offshore. Therefore,
in the rest of this paper, we restrict our attention to NICs on the slope.

3. NICs on the continental slope

We used the clockwise component of the wavelet rotary spectrum to determine
the variability of NICs with season and year and the relationship, if any, between
the NICs and storms. The Bay of Bengal is among the regions of the world oceans
most prone to cyclonic storms (Gray, 1967); the seasonality of these storms is well
known (Rao, 1976), but the effect of the storms or their seasonality on the currents,
particularly the NICs, has been studied only in isolated cases (Joseph et al., 2007).

3.1. Seasonal and interannual variability

The clockwise component of the wavelet rotary spectrum shows seasonality
in the generation of NICs on the slope (Figure 3). At all the locations, the NICs
are weak during January–April. In the northern bay, off Paradip and Gopalpur,
the NICs are strong during the summer monsoon (May–September). Off Cud-
dalore in the south, the NICs are strong only during the winter monsoon (October–December). Seasonality is weaker in the central bay, off Kakinada and Ramayapatnam, with NICs being generated during both summer and winter monsoons.

The data also show interannual variability in the generation of NICs. Off Paradip, Gopalpur, Kakinada, and Ramayapatnam, NICs were much stronger during May–June 2009 compared to May–June in 2010 and 2011. In 2010, the NICs were strongest during October in the northern and central bay. Similar variability over the two years of data is seen off Cuddalore in the south: the NICs were strong throughout November–December in 2010, but were considerably weaker in 2011.

The mixed layer in the Bay of Bengal is generally thin (Montegut et al., 2004; Chatterjee et al., 2012), with its depth decreasing to ∼10 m during July–October in the northern bay owing to the influx of freshwater due to river discharge and precipitation (Shetye et al., 1991). The NICs generally extend much below the thin mixed layer, with the inertial energy being evident as deep as 250 m at all locations at some time (Figure 3). It is the more prolonged bursts, which last over a fortnight, as during May–June 2009 off Paradip and Gopalpur, or during October–December 2010 off Cuddalore, that seem to extend deeper (∼200 m). Shorter bursts, as recorded during September–December 2010 off Kakinada, weaken sharply below 100 m.

Therefore, clockwise rotary wavelet spectra of the vertically-averaged (between 40–250 m) currents tend to be weaker for the shorter bursts (Figure 4). The analysis also shows that the NICs off Paradip and Cuddalore are confined to the inertial band, unlike off Gopalpur, Kakinada, and Ramayapatnam, where the NICs
are often associated with lower-frequency currents.

3.2. Impact of storms on the NICs

Is the seasonality observed in the generation of NICs related to the seasonality of storms over the Bay of Bengal? It is known that storms, particularly depressions, are common in the northern Bay of Bengal during the summer monsoon (Rao, 1976), when strong NICs are observed at the northern locations. During winter, the storms occur in the south (Rao, 1976; Gray, 1967), as do the NICs.

We used wind data from the European Centre for Medium-Range Weather Forecasting (ECMWF) to see if a relation exists between storms and winds. Since the ECMWF winds have a high temporal resolution (three hours), but have a coarse spatial resolution (≈ 150 km) and are based on a model reanalysis (Källberg, 1997), we also used gridded scatterometer wind data (QuikSCAT and ASCAT), which are available as a daily product, but have a spatial resolution of 0.50° and 0.25°, respectively. QuikSCAT (ASCAT) wind data are used from May 2009 to October 2009 (from November 2009 to February 2012). The wind data sources are listed in Table 3. Four cyclonic storms and several deep depressions and depressions occurred in the Bay of Bengal during May 2009 to February 2011 (IMD, 2010, 2011, 2012) (Table 4). This classification of storms, given in Table 6, is as used by the India Meteorological Department (IMD) (WMO, 2010).

The first cyclone, *Aila*, occurred in the northern bay during 23–25 May 2009 (Figure 5). *Aila* was a severe, destructive cyclone (IMD, 2010) and generated the strongest inertial currents during 2009–2012 in the bay (Figure 4). Since the max-
imum pressure drop (968 hPa) and the strongest winds during *Aila* were observed over the northern bay (Figure 5, Table 4), the strongest NICs were generated off Paradip and Gopalpur. The NICs continued even after the cyclone had crossed over land and were strongest immediately following it (Figure 4). Note that the maximum pressure drop occurred as the cyclone crossed land (Figure 5). The winds were much weaker off Kakinada and the NICs here followed the cyclone, rather than occurring during its passage.

The second cyclone, *Laila*, was weaker (Table 4) and occurred during 17–20 May 2010; the maximum pressure (986 hPa) drop during *Laila* occurred in the central bay and the strongest NICs were therefore generated off Kakinada. (The effect of *Laila* must have been felt off Cuddalore as well, but the first mooring was deployed here shortly after the passage of the cyclone.)

The third cyclone, *Jal*, occurred during 4–8 November 2010. It was weaker than the earlier storms (Table 4) and its effect was restricted to the southern and central bay (Figure 5). Strong NICs were observed off Cuddalore and Kakinada (Figure 4).

The fourth cyclone, *Thane*, occurred during 25–31 December 2011 and was comparable to *Laila* (Table 4, Figure 5). Its effect was restricted to the southern bay, with NICs being generated off Cuddalore. Off Kakinada in the central bay, the currents generated at this time had a higher period (≈ 3 days) than the NICs (Figure 4).

Apart from these four cyclones, there were several depressions and deep depressions during 2009–2012 (Table 4). NICs were generated during each of these
events (Figure 4). Since these storms occur over the northern bay during the summer monsoon and the southern bay during the winter monsoon, the central bay is affected during both seasons, but the intensity is weaker there than in the northern or southern bay. Therefore, NICs are observed during both summer and winter monsoons at the central-bay locations like Kakinada and Ramayapatnam (Figure 4).

NICs were seen off the Indian east coast on a few other occasions as well. No storms were reported during the last week of July 2010 by IMD and the winds were weak in the scatterometer data (Figure 4), but strong NICs were observed off Paradip. Another example is the first week of August and the last week of September 2010, when the scatterometer showed a strong wind burst off Kakinada, but the ECMWF winds were much weaker. In both instances, NICs were generated off Kakinada following the burst in winds. There are several such instances of NICs that are not related to storms. In the case of such short and weak events, the scatterometer and ECMWF winds may not capture the wind bursts owing to their poor temporal and spatial resolutions, respectively: an example is the NICs in the last week of October 2009 at off Kakinada (Figure 4).

3.3. Vertical propagation

There was substantial inertial energy below the surface mixed layer (Figure 3). Upward phase propagation, implying downward propagation of energy, was evident during these events at all locations (Figure 6). During Aila (20–23 May 2009), energy propagated down off Paradip to over 250 m. This NICs event must
be locally generated because the strongest current was near the surface (strictly, at the top of the measured depth range); the NICs were stronger below the surface in the aftermath of the cyclone (during 25 May to 5 June). Off Gopalpur, the NICs were much weaker. Here, the first NICs event followed the cyclone; as off Paradip, this event showed considerable downward propagation of energy till 5 June. Off Gopalpur, there was another NICs event during 7–15 June, but the strongest currents during this period occurred at depths below 100 m, suggesting that the NICs were generated elsewhere. Downward energy propagation was evident in the ADCP data from all mooring locations during other storms as well; an example is shown for Kakinada and Cuddalore during cyclone Jal (Figure 6).

At the locations of interest, the climatological mixed-layer depth varies between 18–30 m (Montegut et al., 2004; Chatterjee et al., 2012). Therefore, data on the slope were available only below the thin mixed layers that prevail in the Bay of Bengal. Use of a simple, wind-forced, slab model (Pollard and Millard, 1970) shows that it is possible to simulate the observed NICs at 40 m at the Paradip mooring using ECMWF winds during cyclone Aila. The equations of motion are

\[ \frac{\partial u}{\partial t} - f v = \frac{\tau^x}{\rho a} - cu; \]  

\[ \frac{\partial v}{\partial t} + fu = \frac{\tau^y}{\rho a} - cv; \]  

where \( \tau = (\tau^x, \tau^y) \) is the wind stress, \( \rho \) is the water density, \( a \) is the mixed-layer depth, \( c \) is the damping constant, and \( f \) is the Coriolis frequency at the location. The equations were solved using a fourth-order Runge-Kutta method. Since it
is a slab model, the results will match the observations if the inertial energy is largely confined to the mixed layer and downward propagation of energy is weak. Though this condition was not fulfilled at the mooring locations, $c = 1 \text{ day}^{-1}$ yielded a good match between simulated and observed currents during cyclone *Aila* (Figure 7). The simulated current is valid only in the mixed layer and the observation is most likely to be below the mixed layer, suggesting that the match is likely to be due to the impact of the strong *Aila* winds extending below the mixed layer. The match was not as good at Gopalpur ($c = 2 \text{ day}^{-1}$), where the NICs are weaker, and was poor at Kakinada ($c = 2 \text{ day}^{-1}$) and Cuddalore ($c = 2 \text{ day}^{-1}$) during cyclone *Jal* (Figure 7). Though this exercise is qualitative, it suggests that the NICs may extend even below the thin mixed layers in the Bay of Bengal during severe storms.

4. Summary and discussion

We have used ADCP data from seven moorings deployed during May 2009 to February 2012 off the Indian east coast to document the NICs in coastal waters off India. Though the existence of NICs in this region is expected, the data enable a quantification that was not possible with the short records available from drifters (Shetye and Michael, 1988; Saji et al., 2000) or current-meter measurements (Rao et al., 1996; Joseph et al., 2007). One key result is that the NICs are weak on the east-coast shelf. The likely reason is that the shelf width is less than the local Rossby radius at all locations (Table 5).

The NICs are stronger on the continental slope off the east coast. A similar in-
crease in inertial energy offshore of the shelf break has been reported earlier from several places: examples include (Jarosz et al., 2007; Hisaki and Naruke, 2003). All these places are, however, located in the subtropical or temperate regimes, where the Rossby radius is small. We are not aware of a report from a tropical regime in which the NICs are weaker on the shelf or at the shelf break compared to the slope.

The slope ADCP data show a seasonality in the generation of the NICs. The NICs are not seen largely during January–April at all the mooring locations. They are prominent at the northern locations during May–September, when the strong winds associated with the summer-monsoon depressions and cyclones are observed in the region (Figures 3–4). The storms shift southward following the summer monsoon, and so do the NICs, which are generated off Cuddalore during October–December. In the central part of the coast, the NICs are seen during both summer and winter monsoon owing to effect of storms over the northern and southern bay. Though the data are of limited duration, they reveal considerable interannual variability in the generation of NICs. For example, the NICs were weaker in 2010–2011 than in 2009.

The NICs also exhibit upward phase propagation, implying downward propagation of energy (Figure 6), as has been noted elsewhere too (Kundu, 1976; Leaman and Sanford, 1975; Jarosz et al., 2007). During severe storms such as cyclone *Aila*, strong NICs are seen below the shallow mixed layer (Figures 3 and 6) that is typical of the Bay of Bengal (Montegut et al., 2004; Chatterjee et al., 2012).

We have discussed the importance of low-pressure systems for the generation
of NICs. Another process that has been noted as a generating mechanism for NICs is parametric subharmonic instability (PSI), in which energy is transferred from the tidal current to the NICs in the vicinity of a critical latitude, which is 28.8°N for the $M_2$ tide (Haren, 2005; Alford et al., 2007) and 14.52°N and 13.44°N for the $K_1$ and $O_1$ tides, respectively (Xie et al, 2009; Sun et al., 2011; Xie et al, 2011). The critical latitude for the semi-diurnal tide is north of the basin boundary, but that for the diurnal tides is close to the latitude of Ramayapatnam and Cuddalore. An examination of the tidal constituents shows, however, that the amplitude of the diurnal constituent $K_1$ is less than a quarter of that of the $M_2$ tide in the bay; for $O_1$, the amplitude is an order of magnitude smaller than that of $M_2$ (Murty and Henry, 1983; Sindhu, 2012; Admiralty, 2010). Spectral analysis of the raw ADCPs data also shows (figure not shown) that the diurnal tidal amplitudes are significantly weaker at Ramayapatnam and Cuddalore. Therefore, we rule out the possibility of PSI being a significant contributor to the NICs along the east coast of India.

One question of interest is whether the NICs make a significant contribution to the total current. A histogram of the ratio of the NICs to the total current (Figure 8b, c, d) shows that the NICs is comparable to the residual, i.e., non-tidal and sub-inertial, current on more than nine days in a year off Paradip and Cuddalore; the magnitude of the NICs exceeds half that of the residual current on more than 16 days. Off Gopalpur and Kakinada, the NICs are not comparable to the residual current, the magnitude of the NICs being more than half the residual-current magnitude on just six days in a year.
The histogram of the ratios, however, does not give an idea of the magnitude of the NICs. It does not give a feel for the actual magnitudes of these currents. Therefore, in addition to the histogram, we show a correspondence (also called Kolmogorov-Smirnov) plot (Figure 8a) to show the magnitudes of these two components of the current. In the correspondence plot, the inertial current and residual current are separately sorted (not a unique sort) in ascending order over the entire data record, and the inertial current is plotted against the residual current. Unlike the histogram, which examines the ratio day by day, the correspondence plot merely provides a statistical idea of the current magnitudes. For example, the strong inertial current (over 40 cm/s) seen at Paradip implies a strong inertial current of that magnitude on some day during the period over which the data were collected. It is not necessary that the residual current magnitude was greater than 120 cm/s on that day. All that the correspondence plot gives us is the distribution of the magnitudes of the inertial and residual components. What is evident from the correspondence plot, however, is that the magnitude of the NICs seldom exceeds 10 cm/s; it is higher than 30 cm/s only at off Paradip and Cuddalore.

The NICs are therefore more important in the northern and southern bay, which experience more low-pressure systems than does the central part of the bay (Mooley and Shukla, 1989; Mohapatra and Mohanty, 2004). An implication is that forecasting models are likely to exhibit larger errors in the northern and southern Bay of Bengal during storms owing to the need to simulate the NICs well. The NICs are not only stronger during these extreme weather events, but they are also sensitive to details of the storms, which are often not captured well
by the atmospheric general circulation models, the source of the wind forcing for ocean-forecasting models. Therefore, one can expect larger errors in the predicted current during such weather events.
5. Acknowledgments

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<th>Mooring Type</th>
<th>Longitude (°E)</th>
<th>Latitude (°N)</th>
<th>ADCP Depth (m)</th>
<th>Water Depth (m)</th>
<th>Sampling interval (minutes)</th>
<th>Start Date</th>
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Table 1: Details of ADCP moorings. All ADCPs were upward-looking. 75 kHz RDI ADCPs were deployed on the slope and 300 kHz RDI ADCPs on the shelf.
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<th>Anticlockwise energy</th>
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<td>01-05-09</td>
<td>26-03-10</td>
</tr>
<tr>
<td>-do-</td>
<td>Slope</td>
<td>450</td>
<td>50</td>
<td>400</td>
<td>01-05-09</td>
<td>26-03-10</td>
</tr>
<tr>
<td>Cuddalore</td>
<td>Shelf</td>
<td>550</td>
<td>400</td>
<td>150</td>
<td>01-05-10</td>
<td>22-03-11</td>
</tr>
<tr>
<td>-do-</td>
<td>Slope</td>
<td>300</td>
<td>50</td>
<td>250</td>
<td>01-05-10</td>
<td>22-03-11</td>
</tr>
</tbody>
</table>

Table 2: Magnitude of clockwise and anticlockwise energy at near inertial periods for all shelf and slope locations. The unit of energy is (cm$^2$s$^{-2}$cpd$^{-1}$).
<table>
<thead>
<tr>
<th>Wind data</th>
<th>Website</th>
<th>Spatial resolution (km × km)</th>
<th>Temporal resolution (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECMWF</td>
<td><a href="http://data-portal.ecmwf.int/data/d/interim_daily/">http://data-portal.ecmwf.int/data/d/interim_daily/</a></td>
<td>150 × 150</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 3: Details of wind-data sources.
<table>
<thead>
<tr>
<th>Cyclone/Storm</th>
<th>Cyclone genesis</th>
<th>Estimated lowest central pressure</th>
<th>Estimated highest wind speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Date</td>
<td>Time</td>
<td>Position Lon. (°E)</td>
</tr>
<tr>
<td>Severe cyclonic storm <em>Aila</em> during 23–26 May 2009</td>
<td>23-05-09</td>
<td>0600</td>
<td>88.0</td>
</tr>
<tr>
<td>Deep depression during 20–21 Jul 2009</td>
<td>20-07-09</td>
<td>0300</td>
<td>88.5</td>
</tr>
<tr>
<td>Deep depression during 05–07 Sep 2009</td>
<td>05-09-09</td>
<td>0000</td>
<td>88.0</td>
</tr>
<tr>
<td>Severe cyclonic storm <em>Laila</em> during 17–21 May 2010</td>
<td>17-05-10</td>
<td>0600</td>
<td>88.5</td>
</tr>
<tr>
<td>Depression during 07–09 Oct 2010</td>
<td>07-10-10</td>
<td>0300</td>
<td>84.5</td>
</tr>
<tr>
<td>Deep depression during 13–16 Oct 2010</td>
<td>13-10-10</td>
<td>0600</td>
<td>90.0</td>
</tr>
<tr>
<td>Severe cyclonic storm <em>Jul</em> during 04–08 Nov 2010</td>
<td>04-11-10</td>
<td>0000</td>
<td>92.0</td>
</tr>
<tr>
<td>Depression during 07–08 Dec 2010</td>
<td>07-12-10</td>
<td>0300</td>
<td>82.0</td>
</tr>
<tr>
<td>Depression during 22–23 Sep 2011</td>
<td>22-09-11</td>
<td>0300</td>
<td>87.5</td>
</tr>
<tr>
<td>Deep depression during 19–20 Oct 2011</td>
<td>19-19-11</td>
<td>0000</td>
<td>90.5</td>
</tr>
<tr>
<td>Very severe cyclonic storm <em>Thane</em> during 25–31 Dec 2011</td>
<td>25-12-11</td>
<td>1200</td>
<td>88.5</td>
</tr>
</tbody>
</table>

Table 4: Details of storms, cyclones, and depressions that formed over the Bay of Bengal during May 2009 to February 2012. The information presented here is based on IMD (2010), IMD (2011), and IMD (2012). The IMD classification of storms is based on the maximum wind speed (see Table 6). All times listed are in UTC (Indian Standard Time, or IST, is 5.5 hours ahead of UTC), wind speed is in nautical miles per hour (knots; 1 kt is 0.5 m s\(^{-1}\)), and pressure in hPa (1 hPa is 100 pascals). Note that the time in the ADCP figures is in IST.
<table>
<thead>
<tr>
<th>Shelf location</th>
<th>Shelf width (km)</th>
<th>First mode baroclinic Rossby radius (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gopalpur</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>Kakinada</td>
<td>30</td>
<td>70</td>
</tr>
<tr>
<td>Ramayapatnam</td>
<td>60</td>
<td>75</td>
</tr>
<tr>
<td>Cuddalore</td>
<td>40</td>
<td>80</td>
</tr>
</tbody>
</table>

Table 5: Shelf width and Rossby radius at the ADCP deployment locations.
<table>
<thead>
<tr>
<th>Weather system</th>
<th>Maximum wind speed (kt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-pressure system</td>
<td>≤ 16</td>
</tr>
<tr>
<td>Depression</td>
<td>17–27</td>
</tr>
<tr>
<td>Deep depression</td>
<td>28–33</td>
</tr>
<tr>
<td>Cyclonic storm</td>
<td>34–47</td>
</tr>
<tr>
<td>Severe cyclonic storm</td>
<td>48–63</td>
</tr>
<tr>
<td>Very severe cyclonic storm</td>
<td>64–119</td>
</tr>
<tr>
<td>Super cyclonic storm</td>
<td>≥ 120</td>
</tr>
</tbody>
</table>

Table 6: IMD classification of storms. The maximum wind speed, used as the basis for classification, is given in knots (1 knot equals 0.5 m/s.) This table is based on WMO (2010).
Figure 1: (a) Location of the region of interest in the Indian Ocean. (b) East coast of India, showing the location of all ADCP moorings. Here, “P”, “G”, “K”, “R”, and “C” (the first letters of the name of the location) denote Paradip, Gopalpur, Kakinada, Ramayapatnam, and Cuddalore, respectively. The suffix “S” following the location symbol denotes the shallow (shelf) moorings deployed in a water-column depth of $\sim 100$ m and the suffix “D” denotes deep moorings deployed in a water-column depth of $\sim 1100$ m. The exact water-column depth at each mooring is given in Table 1. The depth contours of 100 m (black dashed line), 200m (gray line) and 1000m (gray dashed line) are plotted.
Figure 2: Clockwise (black) and anticlockwise (dashed line) rotary spectra (vertically averaged) of detided current for all locations. The vertical line indicates the theoretical inertial period ($T = \frac{2\pi}{f}$, where $f = 2\omega \sin \phi$; $\omega$ is the angular frequency of rotation of the earth and $\phi$ is the latitude) at the location. On the shelf (left panels), the data were vertically averaged over 20–80 m to compute these spectra; on the slope (right panels), the data were vertically averaged over 40–250 m.
Figure 3: The clockwise component of the rotary spectrum (cm$^{-2}$s$^{-2}$cpd$^{-1}$) at the inertial period as a function of depth and time at all locations on the slope.
Figure 4: 4-day high-passed wind stress and clockwise wavelet rotary spectra (vertically averaged over 40–250 m) as a function of time for all the slope locations. The value of drag coefficient is based on Han and Webster (2002). Clockwise wavelet rotary spectra is plotted in every third panel from top. The classification of low–pressure systems into cyclones, deep depressions, and depressions is based on the reports of the India Meteorological Department (IMD, 2010, 2011, 2012). The black horizontal line indicates the theoretical inertial period at the location.
Figure 5: Sea-surface pressure and wind velocity vectors for the four cyclones that formed in the region during May 2009 to February 2012: (a) Aila, (b) Laila, (c) Jal, and (d) Thane. ECMWF wind velocity vectors are plotted over the atmospheric pressure at mean sea level. The red circles denote the mooring locations.
Figure 6: Upward phase propagation at the period of the NICs during severe storms. NICs are plotted as a function of depth and time during cyclone *Aila* at Paradip (first row) and Gopalpur (second row), and during cyclone *Jal* at Kakinada (third row) and Cuddalore (fourth row).
Figure 7: Comparison of observed (black) and simulated (dashed line) inertial currents at 40 m depth. Alongshore (left panels) and cross-shore (right panels) components of the NICs are plotted as a function of depth and time during cyclone Aila at Paradip (first row) and Gopalpur (second row), and during cyclone Jal at Kakinada (third row) and Cuddalore (fourth row).
Figure 8: (a) Correspondence plot between magnitude of NiCs and residual current from 1 May 2009 to 10 February 2012. (See the text in Section 4 for a description of the plot.) (b) Histograms showing the percentage contribution of NiCs to the residual. The abscissa shows the ratio (as a percentage) of the daily NiCs and the residual current magnitude; the frequency (left axis) shows the number of days in a year for which the ratio falls in the given ratio band. The black curve shows cumulative frequency (right axis). Histogram is computed considering data from 1 May 2009 to 30 April 2010 (365 days). The number in each panel (bold front) represent the number of days in which inertial and residual current magnitude are less than 5 cm s$^{-1}$. (c) Same as figure b but from 1st May 2010 to 30th April 2011 (365 days). (d) Same as figure b and c but from 1st May 2011 to 10th February 2012 (286 days).