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ORIGINAL PAPER

Space borne SAR observations of oceanic internal waves in North Bay of Bengal

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Abstract Sea surface manifestations of internal waves (IW) in the shallow continental shelf waters of North Bay of Bengal have been observed in almost all seasons imaged by Synthetic Aperture Radar (SAR) images of ERS1/2 and Envisat ASAR missions during the period 1993–2004. Shoreward propagating short-period IW packets are observed particularly in summer stratified coastal waters Off Chilka region. In summer waters, prominent short-period shoreward propagating internal waves of consecutive imageries of ERS-1/2 SAR (12th and 13th April 1996) are studied. On 4th October 2003, Envisat ASAR imaged strong surface manifestations of huge internal wave group wavelengths and those propagations were discussed in detail. In the research, we also made an attempt for temporal distribution of IW signatures on SAR in North Bay of Bengal.

Keywords Internal waves · Synthetic aperture radar · Bay of Bengal · Temporal distribution

1 Introduction

Oceanic internal waves are interesting and important phenomena to Oceanographers, and they exist in all levels of the water column in deep oceans as well as in marginal areas. Generated mechanisms are believed to be tidal flow (Apel 2002) over underwater obstacles (Seamounts, shelf breaks, and troughs). Other proposed generation mechanisms are frontal boundaries and seasonal wind conditions; among the variety of internal waves, very energetic waves are created by reversing tidal flow over topography in a stratified environment (Bians 1982). Finally, IW features allow the assessment of the subsurface

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hydrographic, velocity structure, and mixed layer depth, in particular in combination with numerical models.

The manifestation of IW can be captured by a variety of remote sensing instruments, e.g., by ship radar, ground-based radar, photographic camera, and airborne imaging radar. Mainly internal wave has been detected by SAR from space borne (Apel 2002), for example SIR-C, ERS-1/2, Envisat ASAR, Radarsat-1/2 and so on. Satellite SAR images record a snapshot view of a vast two-dimensional IW field (Zhongxiang et al. 2004), particularly on the continental shelf, and in the coastal ocean, a great diversity of IW behavior has been intimately projected by SAR profiles.

Internal waves manifest the sea surface with alternating bands of rough and smooth water, which appear as light and dark strips (Alpers 1985) on Satellite images. The strips can be tens to hundreds of kilometers in length and persist on the surface for several days as the IW move through the ocean. In world oceans, Apel and Gonzalez (1983), Alpers (1985), da Silva et al. (1998), Liu et al. (1998), Valansenko and Alpers (2005) etc. have carried out various studies on SAR internal wave imaging mechanism, backscattering features, and models.

In Bay of Bengal & Andaman sea, using in situ measurements, IW of varying period of heights are studied by Hareesh Kumar et al. (2002), Murthy (2000), Sarma et al. (1991), Antony et al. (1985), and the depth of thermocline undergoes an annual cycle (La Fond and Poornachandra Rao 1954), as well as oscillations with periods equal to tidal cycles (Hareesh Kumar et al. 2008), and shorter period are also prominent because they occur between the shallow, low-density surface layer, and the denser water below. Vertical oscillations or internal waves by convergence and divergence appear as long bands of alternately smooth and rough water on the surface (La Fond 1961). In this cogitation, on SAR images acquired by the Envisat of image mode over Northern Bay of Bengal (18–20°N, 84–86°E), strong surface manifestations of distinct groups of shelf edge crossing and shoreward propagating numerous IW packets are imparted.

2 Observational data

Number of SAR images in different missions are acquired for IW signatures in Northern Bay of Bengal from 1995 to 2006 and shown in Table 1. Particularly in this paper we made

Table 1 List of SAR images in various missions acquired for IW signatures in North Bay of Bengal from 1995 to 2006

Mission	Date	Spatial coverage in Km
ERS 1	15th September 1995	~100 × 100
ERS 1	12th April 1996	~100 × 100
ERS 2	13th April 1996	~100 × 100
Envisat image mode (strip of three images)	04th October 2003	~300 × 100
Envisat wide swath	18th February 2004	~405 × 405
Envisat image mode	01st May 2004	~100 × 100
Envisat wide swath	15th January 2005	~405 × 405
Radarsat-1 scan SAR narrow	19th September 2005	~300 × 300
Radarsat-1 scan SAR wide	20th September 2005	~500 × 500
Envisat image mode	26th September 2006	~100 × 100

an attempt to understand Oceanic Internal wave propagation, behavior, and their characteristics in Northern Bay of Bengal for summer and spring seasons. SAR image profiles of consecutive days ERS1/2 SAR on 12th & 13th April 1996 and Envisat Advanced Synthetic Aperture Radar (ASAR) of two images in Image Mode (Single Strip i.e. ~200 × 100 km) on 4th October 2003 at 0420 UTC, are discussed in this study. NCEP re-analysis (1.1° × 1.1° resolution) six hourly wind data (U and V components) is used for analysis of generated mechanism.

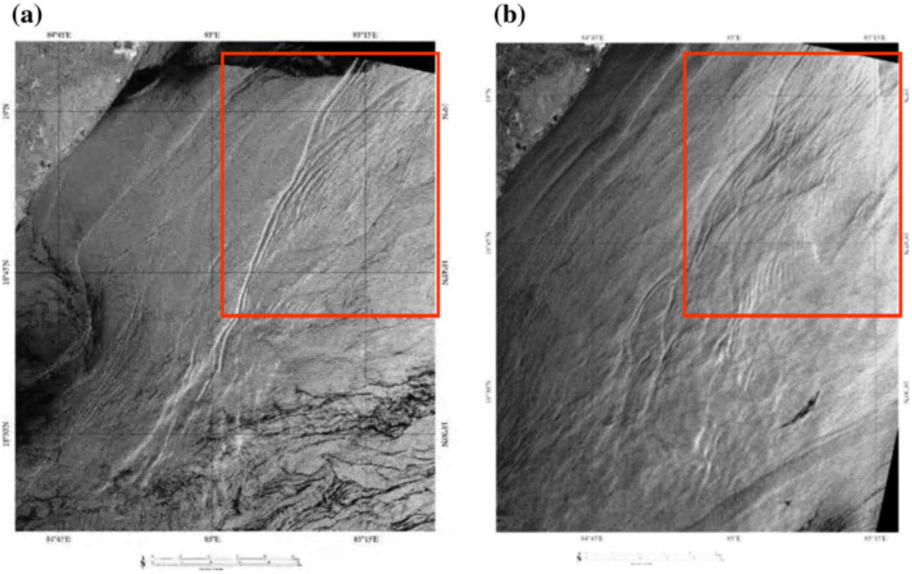
3 Discussion

Sea surface manifestations of IW which are imaged by twenty SAR profiles are observed in North Bay of Bengal from quick looks. The images span most calendar months and are spread out between 1993 and 2005.

3.1 Prominent SAR signatures of IW on summer stratified coastal waters

Energetic and prominent short period IWs are identified in the coastal waters of North Bay of Bengal by the ERS1/2 SAR during the month of April 1996. Substantial surface signals of a non-linear IW activity were observed during 9th April to 28th April 1996 off Chilka Lake region by the quick looks of ERS1/2 SAR. These IWs are believed to be generated by the strong tidal currents, which are crossing at the shelf edge.

Successive days, SAR Image profiles of onboard ERS-1 and ERS-2 on 12th April 1996, the first day ERS-1 SAR processed ocean image depicted in Fig. 1a which shows roughness pattern associated with three groups of short period IW trains are propagating shoreward. Each group has few packets of bright long leading waves with six to four



ERS-1 12th April, 4:51 UTC
Res. 30 m

ERS-2 13th April, 4:51 UTC
Res.12.5 m

Fig. 1 **a** Prominent surface signatures of IWs. **b** IWs of different time periods moving toward the coast

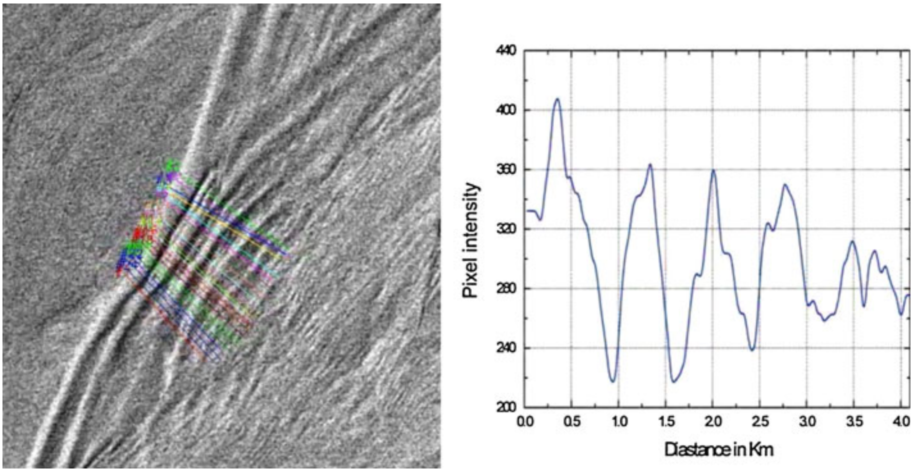


Fig. 2 Accumulation of different periods of IW packets and their wavelengths (**a**) Continuation of Fig. 1a, Clearly showing two groups of rank-ordered internal wave packets on shelf edge

trailing crests, and the crest separation lengths or wavelengths of first two are large compared to rarer one. In Fig. 2, we can observe the interesting feature at the center of the rectangle marked region, converging of two groups IWs packets having different periods.

The region of overlapping or converging of two different period groups of IWs formed as a very bright elevated crests of IW packet may be due to increase in amplitudes by the fast moving, North West propagating IW packet. We can also observe that in front of bright IW packet, dissipating slowly shoreward moving groups of IWs packets are observed.

Toward the top of image (Fig. 1a) before the intersection, the left side of IW packet having a very bright leading crest and following five to six crests of few kilometers spatial coverage is shown. East of bright IW's packet, a large spatial length of less intensity, depression IW packet having three crests running toward the coast having direction of 320° (Clock wise from north) is clearly seen in Fig. 3. The intersection of different period of IW packets may be due to different phase speeds caused by interaction of the tidal currents with bottom topography at the shelf edge. The water depth (not shown in Figs) at the intersected region is about 80 m based on GTOPO 30 elevation dataset compiled by the US Geological Survey's EROS Data.

The wavelength of IWs after intersection is 800 m, and the wavelength of right-sided long-crested IW packet is about 850 m. In association with main packets of IW, secondary generated small period internal waves are also observed. Those may be generated by the local interaction of IW with bottom topography. Beside IW features, dark area can be found in upper and center of the image (Fig. 1a) due to the wind speed is below threshold of SAR image and below of the image the streaked ribbon like patterns of low backscatter are may be due to accumulation of surfaces (Da Silva et al. 1998).

After 24 h, SAR image by ERS 2 of the same arena (Fig. 1b) also showed significant shore ward propagating two groups of IW phenomena with less intensity compared to previous day, but secondary waves with main packets are observed in the whole imaged area. So these prominent imaged IW may be generated by the interaction of strong tidal currents with the bottom topography at the continental shelf edge.

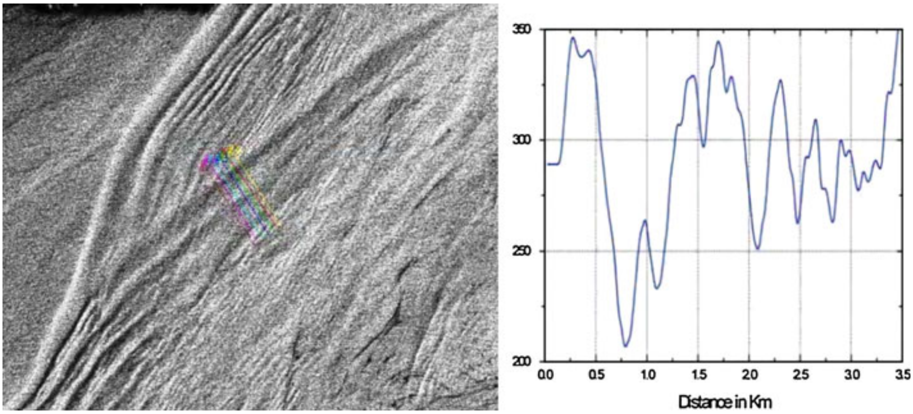


Fig. 3 Closer view of fast moving depression type IW packet showed in Fig. 1a and plot of cross section about ten transects averaged against the packet

3.2 Short-period IW groups on image mode Envisat ASAR on 4th October 2003

Substantial numbers of shoreward propagating IW are observed on the images of Envisat ASAR 4th October 2003 at 04:21 UTC of shelf waters of North Bay of Bengal, showed in Fig. 4 (Frame 1) and Fig. 5 (Frame 2). About hundred Kilometers spatial coverage and thirty meters spatial resolution processed these images showing several long groups of IW packets are propagating toward the coast. A general look of these SAR profiles (Figs. 4 and 5) ascertained that groups of IW packets are usually characterized by several dominant features. Initially, single wave of depressions that propagate toward the coast as soon as they cross the continental shelf edge are evaluated as rank-ordered IW packets.

The individual oscillations are non-sinusoidal, with predominantly downward displacements, the amplitudes are rank ordered with the largest at the front of the packet and the smallest at its rear; wavelengths and crest lengths are also rank ordered, with the longest waves again at the front of the group (Apel 2002) and the number of individual oscillations within the packet increases as its moves toward the coast.

Two groups of successive passage of IW packets in lower left marked area of Fig. 4, of transects profiles are depicted in Fig. 5. The front packet having five and back one having four and their wavelengths and crest lengths appeared to decrease toward the trailing edge of the group. Based on methodology of Porter, 1999, the typical wave separation or wavelength between IW has been derived from an image intensity slice taken across the wave packet showed in Fig. 5. From the slice, typical separations of front and back IW packets can be deduced as an average about 500 and 600 m. It is also observed that the wavelength and crest length of the IW packets from decreasing significantly from the front to rear in the packet also from the front to back groups of the packets exhibit the non-linear dispersive wave nature. Here, we can also observe that well-developed nonlinear packets of IW are clearly visible even in 30 m water depths, and the distance between the front and back of IW packets is about 5.8 km (Fig. 6), which showed that their period is very low.

Generation of rank-ordered large number of IW as packets from the single wave depressions or nascent solitons (Apel 2002), when those are crossing at the shelf edge slope, is seen in Fig. 7 (Continuation frame of the Fig. 4). Dark regions observed in Figs. 4 and 7 are the areas where surface roughness is reduced and may be due to the presence of

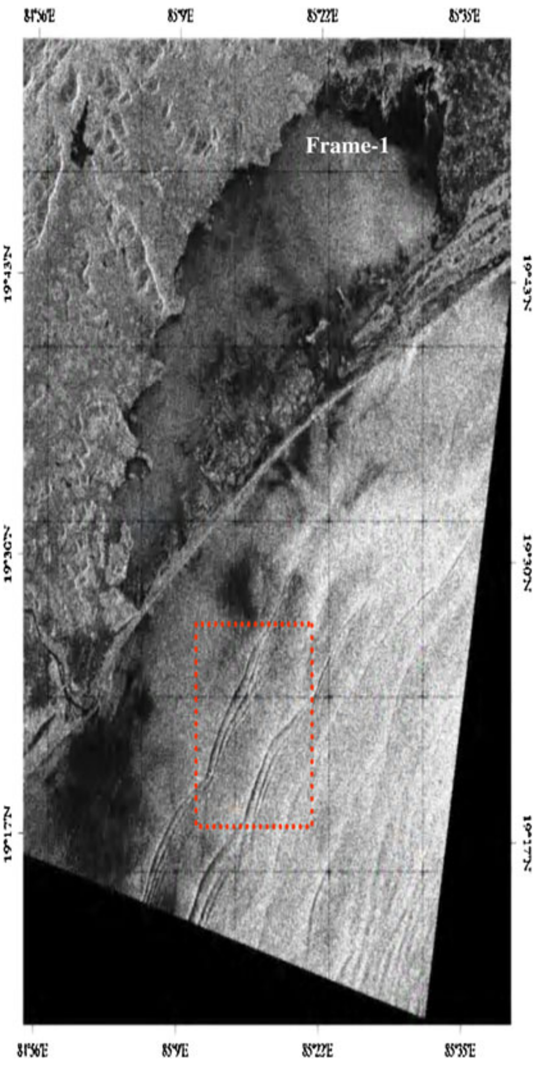
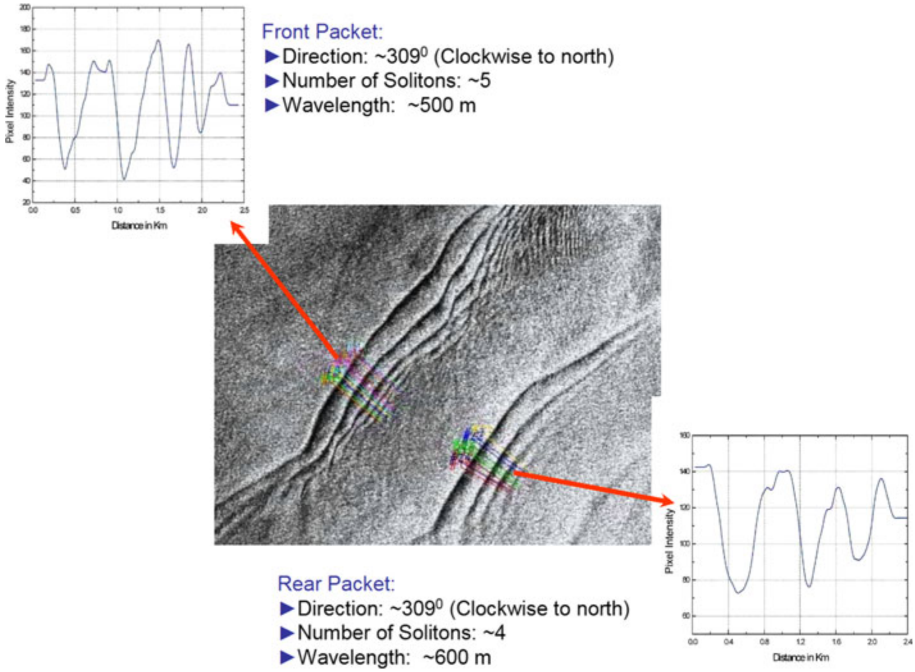


Fig. 4 Short period IW groups at off Chilka Lake (Resolution 100 m)

organic matter on the water surface, or imputable to reduced wind speed (Da Silva et al. 1998), or wave–current interactions (Alpers 1985).

Close look of the IW packet in Fig. 8, which is marked in Fig. 7, having nearly ten crests following with two Nascent solitons and their transect profiles, are employed in Fig. 9. The average wavelength of shoreward propagating packet is about 550 m, and the successive single depressions of IWs are about 400 m and 380 m. It is interesting to note that the number of solitons in each packet is increasing from top to bottom of the first and second SAR images (Figs. 4 and 7), whereas the wavelength decreases. Complement to SAR data, NCEP re-analysis (1.1° × 1.1° resolution) six hourly wind data (U and V components) averaged over 2nd to 6th October 2003 are shown (Fig. 10) with high surface winds near SAR imaged area, and these high surface winds may be with strong variable wind stress and shall be the generating force for these SAR imaged IW phenomena.



Front Packet:
- ▶Direction: ~309^0 (Clockwise to north)
- ▶Number of Solitons: ~5
- ▶Wavelength: ~500 m

Rear Packet:
- ▶Direction: ~309^0 (Clockwise to north)
- ▶Number of Solitons: ~4
- ▶Wavelength: ~600 m

Fig. 5 Close look of the two groups of IW packets on 4th Oct 2003 (*Frame 1*) and their cross sections

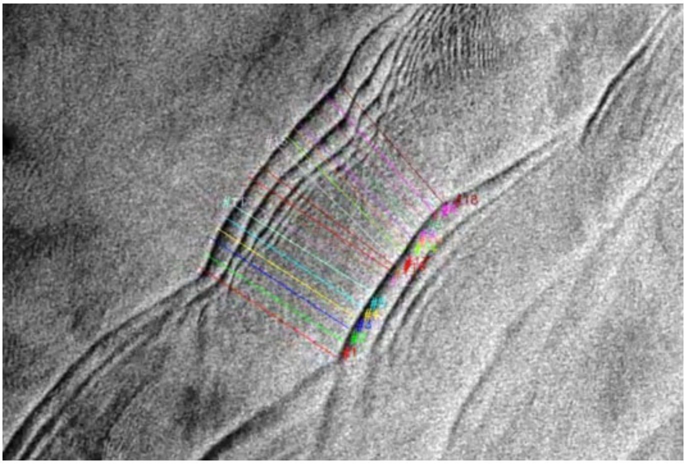


Fig. 6 Distance between front and back IW packets ~5.8 km

3.3 Temporal distribution of IW over North Bay of Bengal by ERS, Envisat and Radarsat SAR during 1993–2005

SAR imaging IW packets appeared from spring (September) to summer (May). Generally in summer i.e., during pre-monsoon northern Bay of Bengal will be stratified. From Table 2, April month prominent short period IW packets are ascertained in the coastal

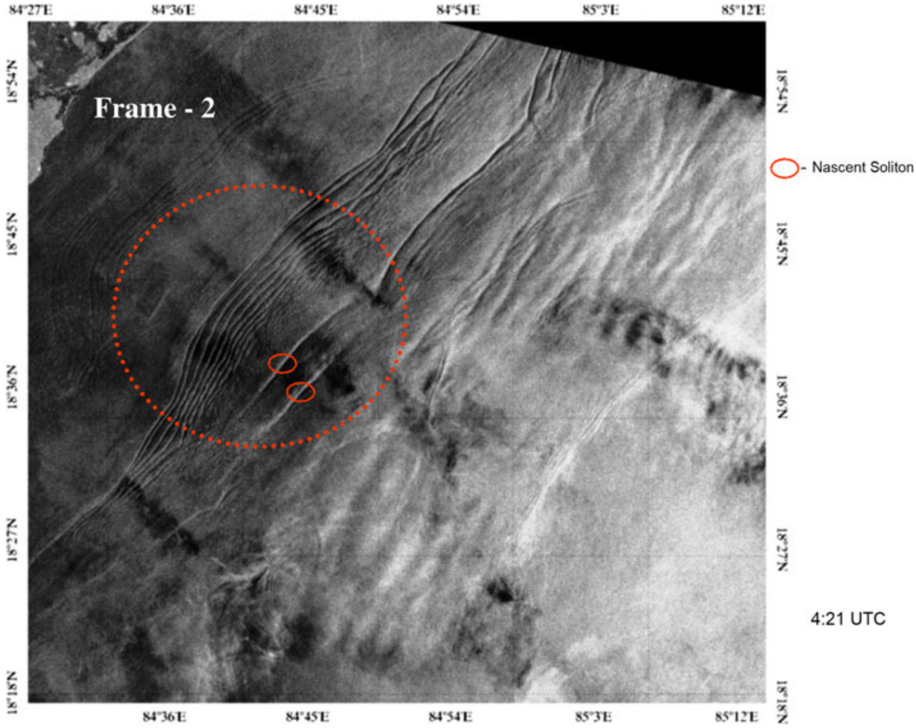


Fig. 7 Coastal oceanic internal waves (continuation of *Frame 1*)

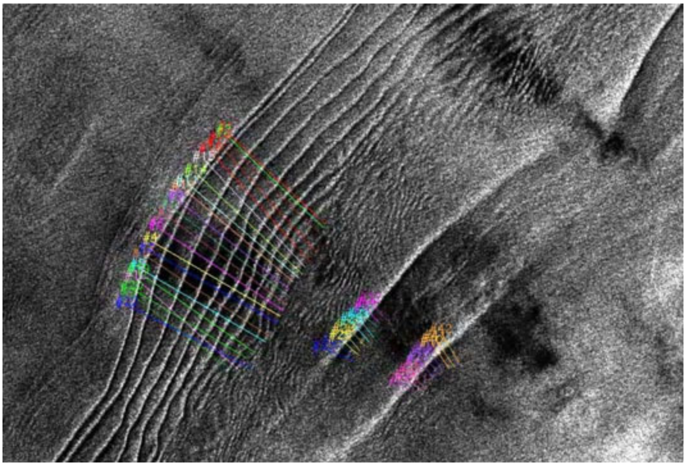


Fig. 8 Large number of IW solitons packet and two Nascent solitons

waters of North Bay of Bengal. In the same region, we also observed during the months of September and October. One image of Envisat ASAR of wide swath imaged open ocean large IW packet in the month of February in 2004. During the field data collection (January

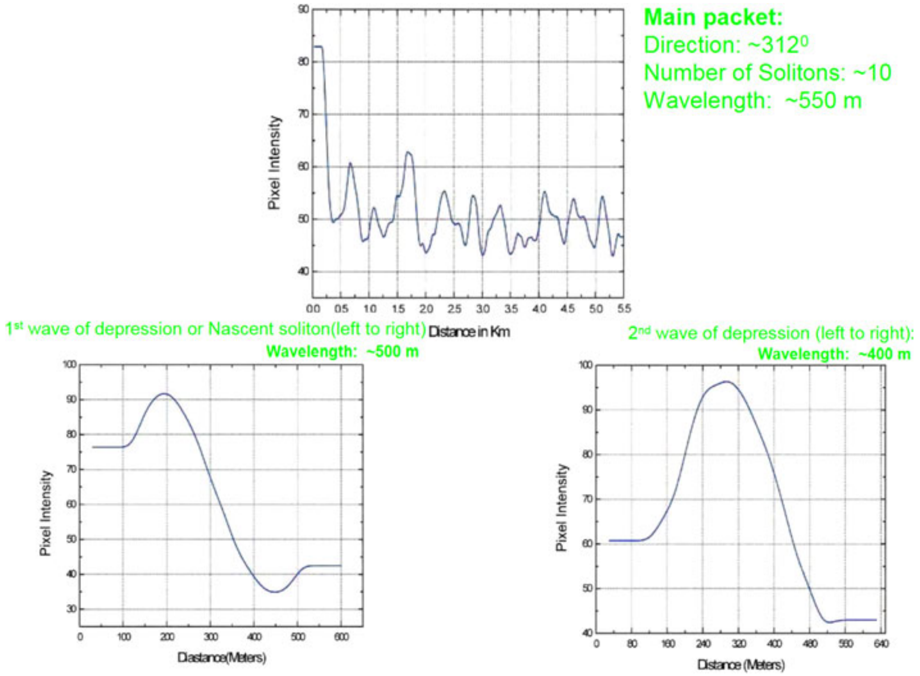


Fig. 9 Transect profiles of IW packets of Fig. 8

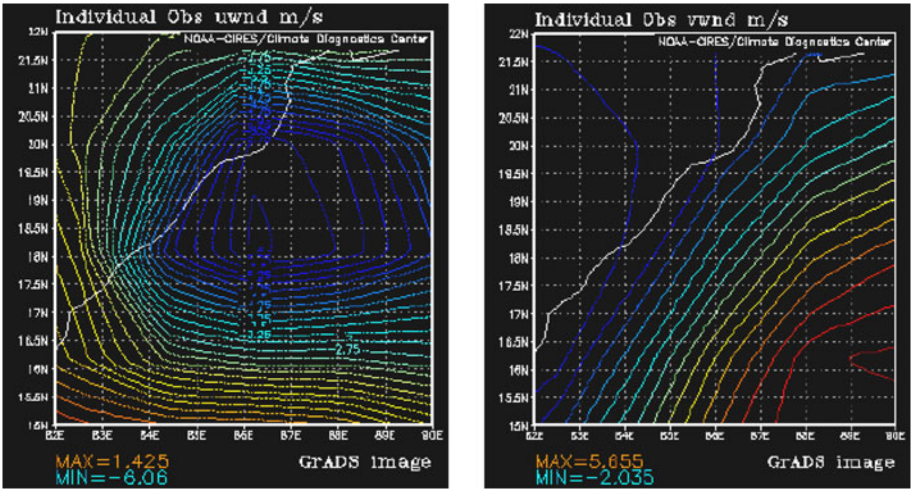


Fig. 10 NCEP re-analysis U and V wind components averaged over 2nd to 6th October 2003, displaying high-magnitude surface winds near SAR imaged area of IWs on 4th October 2003

2005 and September 2005), we collected Envisat ASAR wide swath, but we failed to detect the surface signatures which may be due to unfavorable conditions for imaging on SAR profiles.

Table 2 Temporal distribution of IW over North Bay of Bengal

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
No. of SAR data	1	1		12	1			6	3			
Year	2005	2004		1993 1996	2005			1993 1995 2000 2005	2003 2004			
Months when IW observed		●		●	●			●	●			

4 Summary and conclusions

Surface signatures of IW in the shallow continental shelf waters as well as in deep waters are observed in North Bay of Bengal imaged by SAR profiles. Short period, long groups of IW packets are revealed at shelf break on Envisat ASAR images having with large crest lengths. Initially single wave of depressions (Nascent Solitons) propagate toward the coast, and those evaluated as rank-ordered internal wave packets by interaction with the shelf edge slope exhibit the non-linear dispersive wave nature.

Short period and near inertial period, long groups of IW packets are revealed on Envisat ASAR of 4th October 2003 and 18th February 2004 images with large crest lengths. Prominent IWs packets are observed on time series ERS1/2 SAR images of 12th and 13th April 1996 on the continental shelf of the North Bay of Bengal. The observed substantial signatures on the SAR profiles are the modulation by IW-induced surface currents to surface capillary waves, which are major backscattered energy of the transmitted pulse of the SAR antenna. The stronger modulation current is the greater the gray level contrast or backscattering coefficient in the imagery. On the other hand, the modulation current depends on the amplitude of the internal wave. Hence, the gray level contrast on a SAR image profile can be used to some extent as an indicator of IW amplitude, but vicenary relationship between them still needs to be accomplished.

The observed diversity of IW behavior is an indicator of the complexity of the dynamic environment on the continental shelf. For instance, the sharp changes in bottom topography at the continental shelf and the fresh water runoff originating from the Mahanadi River may be caused by the vertical stratification of sea water as a complicated horizontal structure in our study area.

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