

## Surface current and wave measurement during cyclone *Phailin* by high frequency radars along the Indian coast

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Cyclone *Phailin* originated in the east central Bay of Bengal (BoB) and crossed into the Indian mainland after traversing through the BoB. High frequency radar (HFR) operated by the National Institute of Ocean Technology could track the surface currents and high wave activity within its measuring limits. The radar data provide valuable information on the surface dynamics during the cyclone period. The HFR observations compare well with those of wave rider buoy. This opens up opportunities for observing the wave conditions during the cyclonic period over longer distances from the shore. This method is relatively more robust as HFR is less likely to be disrupted due to the passage of cyclones, unlike moored systems.

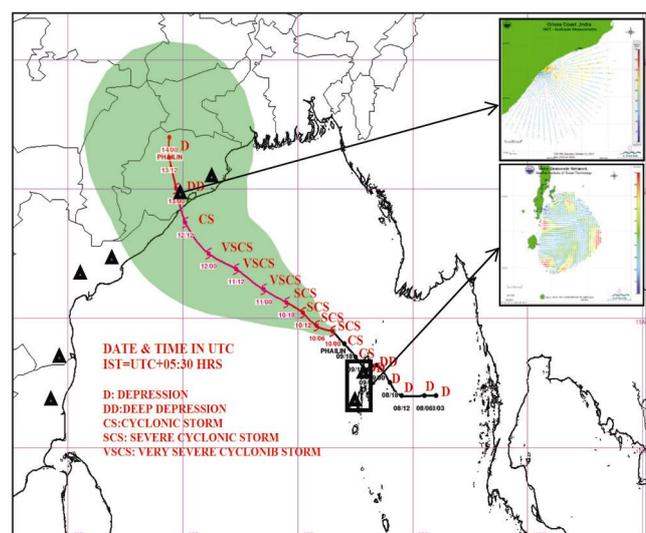
**Keywords:** Coastal currents, cyclone, waves, high frequency radar, remote sensing.

THE cyclonic storm *Phailin* originated near the Andaman and Nicobar Islands on 8 October 2013, with a low pressure formation and later moved across Andaman Island to the central Bay of Bengal (BoB). The cyclone made landfall along Odisha coast near Gopalpur after forming into a very severe cyclonic storm (<http://www.imd.gov.in/section/nhac/dynamic/phailin.pdf>). The passage of the cyclone created havoc with its torrential rain and high velocity winds to the coastal villages of southern Odisha and northern Andhra Pradesh. Various agencies like National Institute of Ocean Technology (NIOT), Indian National Centre for Ocean Information Services (INCOIS), National Institute of Oceanography (NIO) and India Meteorological Department (IMD) had observation systems in place to obtain information on the cyclonic formation, movements and its impact on the coastal regions<sup>1,2</sup>. In this communication, we analyse the data obtained from the high frequency radar (HFR) system, which is a relatively new technique for remotely measuring the surface waves and currents from installations on the shore<sup>3</sup>.

The HFR network along the Indian coast consists of 10 CODAR-make systems. Among these, six are on the east coast, two in the Gulf of Khambhat and two on the

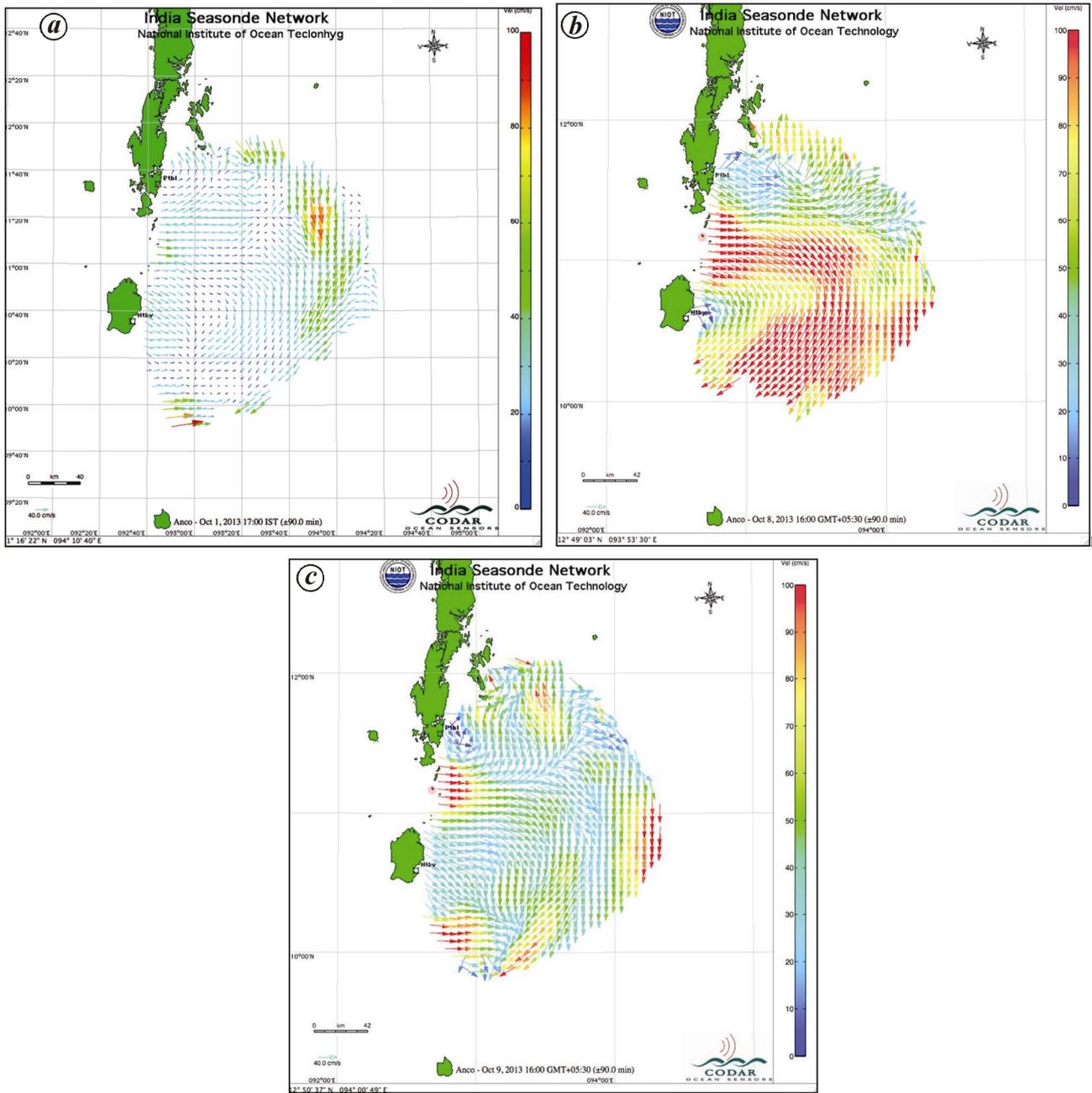
Andaman Islands which continuously observe the ocean surface parameters. A HFR system consists of one transmitting and one receiving antenna, signal generating and receiving circuitry, and data processing software. Typically, a HFR system is installed at a site near the coast. It measures surface oceanographic parameters, up to about 200 km depending upon the transmitting frequency used (4.4 MHz in this case). Every single HFR installation is capable of measuring the wave parameters, while it requires a pair of radars to measure the surface current vector.

The current measurements are carried out using the transmission of electromagnetic waves<sup>4</sup>. These signals scatter off from the ocean surface when they come in contact with an ocean wave, that is exactly half of the broadcast signal wavelength (68 m in this case). This phenomenon is similar to the Bragg scattering<sup>5</sup>. Since, there are abundant waves of all wavelengths present in the ocean; there are always plenty of waves that fit this criterion. In ideal conditions with ideal ocean waves, we can predict the shift in frequency of the returning signal based on the size of the ocean wave (it is half the wavelength of the transmitted signal) and its calculated phase speed<sup>6-8</sup>. In the real world, ocean surface waves are never ideal. Surface currents due to their shear on the waves cause a resultant shift in the frequency of the returning signal by Doppler effect. The frequency increases if the current pulls the waves towards the transmitter and decreases if it pushes them away. By measuring this Doppler shift, we can determine the speed of the currents towards or away from the transmitter<sup>9</sup>. To calculate the directions of the currents, we need a second HFR installation measuring the same currents from a different angle<sup>10</sup>.

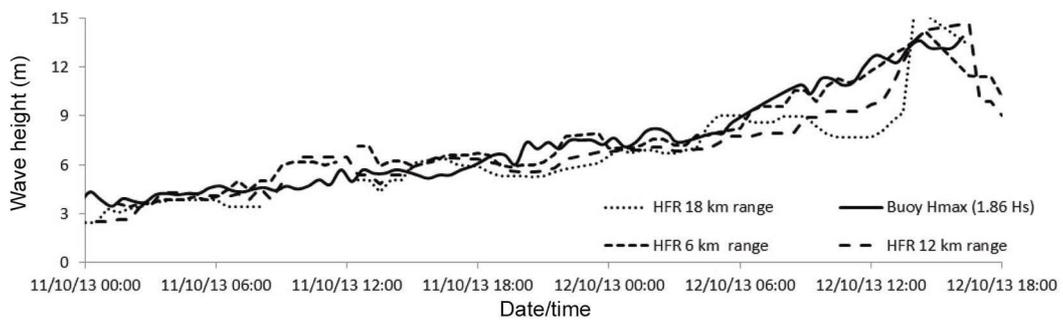


**Figure 1.** High frequency radar (HFR) network (delta symbol) of the east coast of India. (Inset) (Top right) Radial vector of Gopalpur. (Right bottom) Total vector of Hutbay and Port Blair with cyclone *Phailin* track. (Source: IMD, New Delhi.)

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**Figure 2.** HFR-measured surface current: *a*, Prior to the cyclone (1 October 2013); *b*, During cyclone crossing (8 October 2013); *c*, After the cyclone (9 October 2013).



**Figure 3.** Time series plot between HFR wave heights at different range cells and buoy wave height.

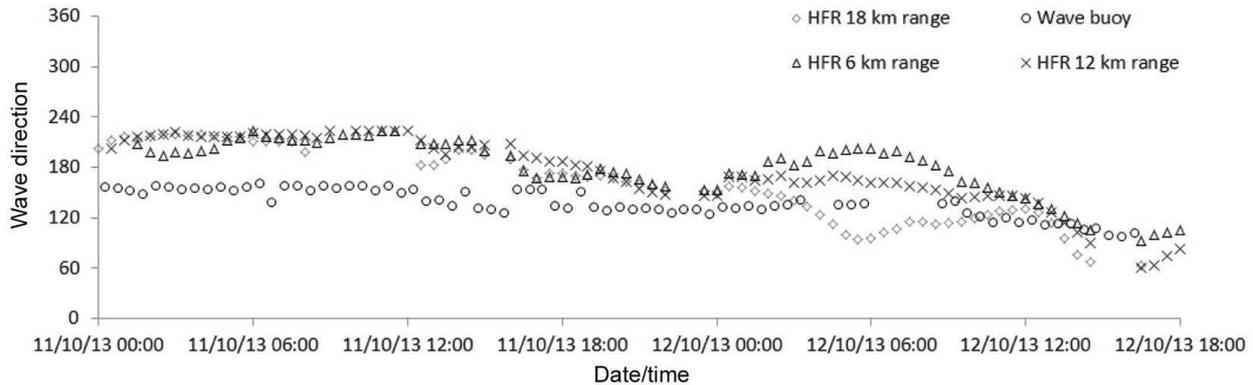


Figure 4. Time series plot between wave directions at different HFR range cells and buoy wave direction.

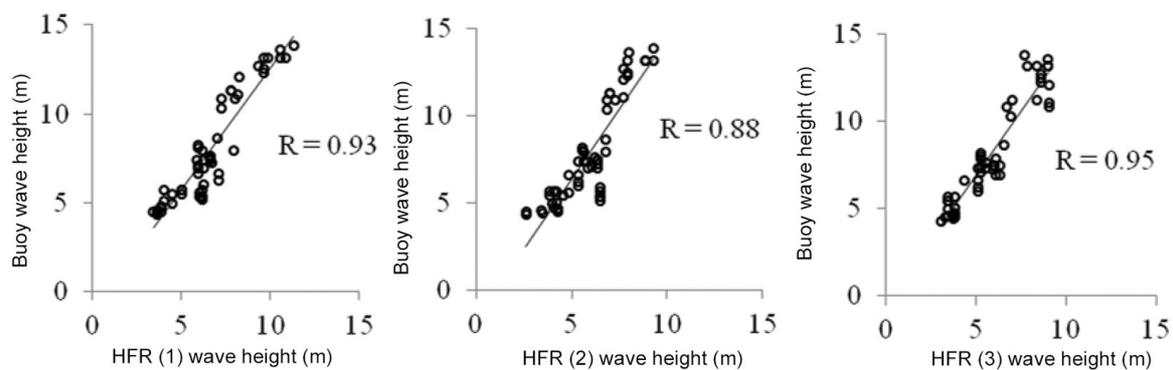


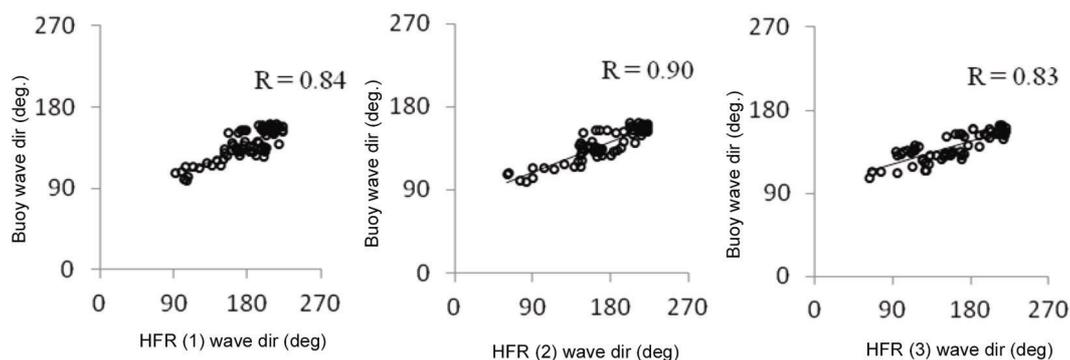
Figure 5. Scatter plot between buoy and HFR wave height.

We can then calculate the current vector by merging the radial currents obtained from the two individual sites to get the resultant velocity.

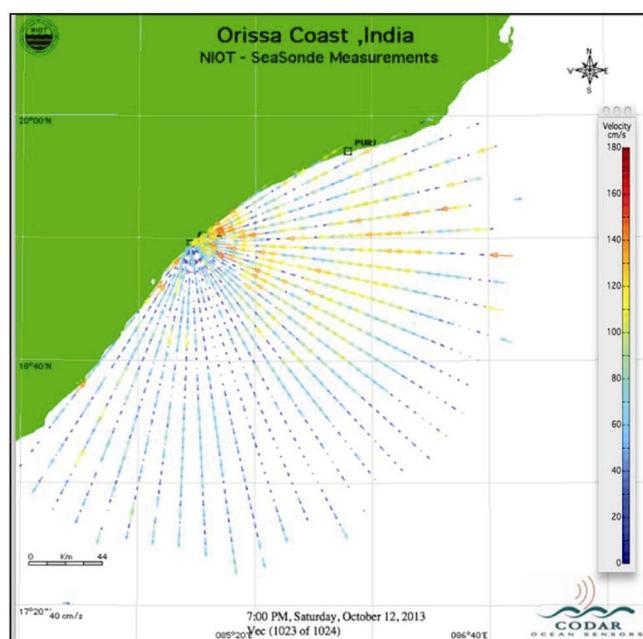
As the cyclone passed through the Andaman Islands, the two HFRs at Port Blair and Hut Bay captured the signature of the cyclone in the surface current patterns (Figure 1). The HFRs are located on the southeastern side of the Islands. The wave condition in this region during the cyclone was low (<1.2 m) and could not be captured by HFR, because of the limitation in the frequency of signal used<sup>11,12</sup>. However, the surface current pattern prior to, during and after the cyclone shows interesting features (Figure 2 a–c). A cross-meridional flow between the Islands was observed, which makes an outflow of water from the western part of the Islands to the eastern part (Figure 2 a). The currents in the eastern part of the Andaman Islands vary in magnitude between 60 and 80 cm/sec during normal weather conditions. However, during cyclone *Phailin* on 8 October 2013, there was a major increase in the flow pattern of the region. The velocity of the currents increased to a maximum of 150 cm/sec, as it was pushed southward by the cyclonic winds (Figure 2 b). Increase in surface current speeds due to high winds was also reported by buoy BD12 (ref. 2). The maximum wind speed of 14 m/sec was recorded by BD12 and CB01 moored buoy locations near Andaman Islands during the

cyclone period (<http://odis.incois.gov.in/index.php/in-situ-data/moored-buoy/moored-data>). Subsequently, there was a drop of 6.4 hpa atmospheric pressure on 8 and 9 October 2013 and a drop of 3.7°C in water temperature prior to the cyclone arrival (between 7 and 8 October 2013) recorded at CB01 buoy location. The sudden drop in air temperature, pressure and increase in wind speed could induce strong air–sea fluxes near the ocean surface, resulting in increase in the surface current. The intensity of the resultant flow showed a steep increase in the velocity by about 50–60 cm/sec. After the cyclone passed the Andaman Islands (9 October 2013), the normal pattern of surface flow was restored in the region, with weaker inter-meridional flow from the central BoB (Figure 2 c). This provides us with an opportunity to study the flow pattern of the surface currents during a cyclonic event in this particular region with special geographic features. A detailed study would give more insights into the dynamics of water flow in the event of a cyclone and also provide a general understanding of the ocean current pattern in the region.

The cyclone *Phailin* made landfall along the Gopalpur coast in Odisha. HFR installed at the Gopalpur port jetty measured the wave height at different range cells, viz. 6, 12 and 18 km at 27, 48 and 49 m water depths respectively. Significant wave height ( $H_s$ ) was determined by



**Figure 6.** Scatter plot between buoy and HFR wave direction.



**Figure 7.** Radial currents observed at Gopalpur during landfall on 12 October 2013 at 1900 h.

averaging of the highest one-third of waves in the measurement period. The maximum value of a wave in a wave record is called maximum wave height ( $H_{\max}$ ). The observed  $H_s$  and  $H_{\max}$  ( $1.86 \cdot H_s$ ) of the buoy deployed at 17 m water depth off Gopalpur has been compared with those of the first three cells of the radar (Figure 3). The wave height reported by the HFR was found to closely match with maximum wave height ( $H_{\max}$ ) reported by the buoy. Significant wave height measured by the buoy was about 7 m. The maximum wave height measured by the buoy (13 m) closely matched with that of HFR (14 m)<sup>1</sup>. The wave direction from the HFR during the cyclone period matched well with the measured buoy data (Figure 4). The regression analysis shows that the correlation coefficient between the buoy and HFR is 0.92 and 0.86 for  $H_{\max}$  and wave direction respectively (Figures 5 and 6).

The HFR gives current vectors by merging the radials from two sites which have coverage of the same area. Due to unavailability of the radials from Puri, only those from Gopalpur were analysed during the cyclonic event. The radial components indicate a stark increase of surface current from 12 pm onwards on 12 October 2013, when the cyclone reached near the Gopalpur offshore water (Figure 7). A circular movement of water was observed as the cyclone approached the Gopalpur coast for its landfall. Later, as it moved into the land, the circular pattern turned into southward-flow currents.

The coverage area of the HFRs has limitations on observing the weather systems like a cyclone as HFRs observe only a small area compared to the large size of a cyclone. However, the data provide insights into the surface ocean hydrodynamics during a cyclonic event, especially along the coastal areas which come directly or indirectly under the influence of the cyclone. The radars have the capacity to provide current and wave data in a temporal as well as spatial domain on a real-time basis, which in the event of a cyclone can be monitored for scientific as well as rescue operations. The other advantages of HFR include its land-based installation that reduces maintenance cost and risk of disruption during severe environmental conditions like cyclone.

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## Active channel systems in the middle Indus fan: results from high-resolution bathymetry surveys

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**Multibeam swath bathymetry survey was carried out in the middle Indus fan region in the eastern Arabian Sea. Using high-resolution bathymetry data, major morphological features such as the Raman seamount and the Laxmi ridge have been mapped. This study also reveals the presence of sinuous channel systems, continuing towards the distal fan. Though there are several reports on the presence of channels in different regions of the Indus fan, we report here the presence of active channels to the east of the Laxmi ridge. The total length of all channels along the channel axis**

**is about 915 km. The individual spreads of the channels vary from 189.8 to 1980.5 m. Most of the channels are shallow with the average depth measuring about 60 m. The longest channel is about 256.3 km long, 702 m wide and about 57 m deep. The channels observed are similar to the land-based fluvial channels. The channels identified are highly sinuous in nature, their meanders and cut-off meanders are similar to the characteristics of fluvial channels. In general, average channel course in the study area is more than twice the straight course.**

**Keywords:** Active channel systems, bathymetry survey, morphological features, submarine fan.

THE Indus fan in the Arabian Sea is the second largest submarine fan in the world, next only to the Bengal fan. The Indus fan extends in the Arabian Sea for about 1500 km and is up to 960 km wide, covering an area of ~1.12 million sq. km (refs 1–3). It is relatively young and therefore the surrounding sedimentary basins have moderate sediment thickness, usually not exceeding 3 km, with the exception of those off the Pakistan shelf and Surat, where sediments are >6 km thick<sup>4</sup>. The upper Indus fan extends from the foot of the continental slope at about 1000 m water depth to about 3300 m water depth, the middle fan extends up to about 3900 m and the lower fan up to a depth of 4600 m (refs 5–7).

Swath bathymetry surveys in the eastern Arabian Sea were carried out during the 26 days scientific cruise on-board *ORV Sagar Kanya* (SK-306) in October–November 2013 to obtain high-resolution bathymetric data towards preparatory site surveys for the proposed scientific drilling of International Ocean Discovery Program (IODP) in the Arabian Sea. In this communication we present the salient findings of the survey.

Vessel hull-mounted deep-water SB-3012 Multibeam Echosounder was used to carry out the present survey, which operated at 12 kHz frequency with an effective 150° of swath and provided coverage of five times the water depth. The data were acquired using Hydrostar software, whereas EIVA Navipac and ArcGIS 10.2 were used for processing and interpretation. A total of 27 coast-parallel traverses were made during the survey. The survey was carried out from 16°00'00"N to 18°12'10"N lat. and 67°53'27"E to 69°49'01"E long. A total of around 7740 line km data were collected along the charted track lines, covering an area of 54,253 sq. km. The location map and survey area are shown in Figure 1. The overall bathymetry map from the survey area is shown in Figure 2.

The general topography is quite smooth and non-undulating with depths varying from 3000 to 3600 m. The data provide clear dimensions and images of the Laxmi ridge and the Raman seamount – the most significant features in the area. The Raman seamount extends from 17°20'25"N to 16°53'43"N and 68°56'20"E to 69°07'10"E; it is about 49 km long and 23 km wide, N–S elongated with a height

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