

Observed current variability in Gulf of Mannar

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Abstract We present current data from an acoustic Doppler current profiler (ADCP) moored on the continental shelf-break in the Gulf of Mannar (GoM) near Ram Setu during 2010–2011. The observations show that the near-surface, sub-inertial current flows primarily north-westward all round the year. This north-westward flow is punctuated by intraseasonal bursts that last a few weeks. Compared to the current off Kanyakumari, the intrasea-

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sonal fluctuations in the GoM are weaker and in the opposite direction. The flip in direction is linked to eddy-like circulations, which cause the current to bifurcate or merge in the region between Kanyakumari and Ram Setu.

Keywords: Ram Setu; Adam’s Bridge; ADCPs; intraseasonal variability; Monsoon currents.

1 Introduction

In between the southeast coast of India and the west coast of Sri Lanka lies the Gulf of Mannar (GoM; Figure 1). It is a unique zone due to mixing of the Arabian Sea and the Bay of Bengal (BoB) waters, which have distinct physical, chemical, and biological properties. GoM is endowed with rich marine biodiversity and a part of it has been declared a Marine Biosphere Reserve to protect marine wildlife and its environment (Kumaraguru *et al.* 2006). Apart from fisheries, another economic importance of this region is due to the proposed GoM canal. This canal was proposed to cut across the Ram Setu (Adam’s Bridge) and the Palk bay, establishing a shorter passage for ships sailing from the Arabian Sea to the east coast of India, saving about 650 km sailing distance (Rao *et al.* 2011).

The Palk Bay is very shallow (<12 m depth), while the GoM is deep. The Ram Setu separates these two water bodies, and the Pamban Pass is the deepest channel between them. The shallow depths make this region non-navigable and increase the difficulty in collecting in-situ current data. Rao *et al.* (2011) used satellite and climatological sea surface temperature (SST),

chlorophyll, and salinity as tracers to detect transport through this channel between India and Sri Lanka but did not find any significant flow during any season. However, some studies based on large-scale ocean models suggest that this channel is necessary to simulate the salinity gradient in the north Indian Ocean (Han and McCreary 2001; Durand *et al.* 2007). A limited-domain simulation with MIKE 21 (<https://www.mikepoweredbydhi.com>) shows that there is a flow across the Pamban Pass and the Ram Setu and it varies with the season: weak flow into the GoM during the winter monsoon and relatively strong flow into the Palk Bay during the summer monsoon (Jagadeesan *et al.* 2013).

South of India, the local winds force an eastward (westward) current during the summer (winter) monsoon, forming a component of the large-scale monsoon currents (Summer Monsoon Current (SMC) and Winter Monsoon Current (WMC); Shankar *et al.* 2002). The winds are tangential to the coast at the southern tip of India and thus push the surface water away from the coast during the summer monsoon resulting in strong upwelling (Smitha *et al.* 2008). This upwelling and the latent-heat loss due to winds also modulate the SST in this region (Luis and Kawamura 2002). Though these studies have provided hints about the circulation in GoM, long-term in-situ observations are not available for this region.

The objective of this paper is to document the current variability in the GoM using time-series data from an acoustic Doppler Current Profiler (ADCP) deployed on a mooring for several months in 2010 and 2011. This data over

the top ~ 10 – 80 m of the water column allows us to present a description of the current in different seasons. In addition, current data from the mooring off Kanyakumari allows the comparison of the large-scale circulation at the southern tip of India with its imprint on the circulation in the semi-enclosed GoM.

The rest of the paper is organized as follows: the datasets used are described in section 2, the variability of the GoM current is described in section 3, its comparison with the Kanyakumari current is presented in section 4, and section 5 summarises and concludes the paper.

2 Data

We use data from ADCPs deployed on moorings located in the GoM (79.16°E , 8.80°N) and off Kanyakumari (77.40°E , 6.95°N ; Figure 1). Both these moorings are deployed at ~ 1000 m depth. The data from the Kanyakumari ADCP are available from 27 October 2009 to present. The Kanyakumari mooring has been continuously maintained by CSIR-National Institute of Oceanography (CSIR-NIO, India) for the past decade. Though the Kanyakumari data are available for a larger depth range, we present only the current at 50 m in this paper. The current variability off Kanyakumari has been described in detail earlier in Amol *et al.* (2014) and Chaudhuri *et al.* (2020).

The new data presented in this paper are from the GoM and are available with a sampling interval of 15 minutes and a bin size of 4 m in three sets.

– 23 March 2010 to 14 November 2010 (instrument depth ~ 90 m)

- 5 February 2011 to 22 October 2011 (instrument depth ~ 75 m)
- 23 October 2011 to 4 January 2012 (instrument depth ~ 50 m)

In addition to the ADCP data, we use Ocean Surface Currents Analyses Real-time (OSCAR), which represent the average currents over the top 30 m on a 0.33° grid every 5 days (Bonjean and Lagerloef 2002), sea-level-anomaly (SLA) data from altimeter (<https://www.avisio.altimetry.fr>), and ASCAT (Advanced SCATterometer) winds.

3 Current variability in the GoM

As the shelf-break is roughly parallel to 7°N , the GoM alongshore current is the same as the zonal current (Figure 2a). The sign convention is positive for the eastward or upwelling-favourable current. The currents are smoothed using a 5-day box-car filter to remove supra-inertial frequencies.

The GoM near-surface alongshore current flows westward $\sim 83\%$ of the time. The mean alongshore current is -11 cm s^{-1} near the surface and drops to -3 cm s^{-1} at 80 m. This current is punctuated by eastward bursts, which are more frequent during 2011. The bursts extend over a few weeks and are sometimes observed below 50 m as undercurrents (the sub-surface currents directed opposite to the surface current). The eastward current with the longest duration starts from April 2010 and extends over a month. Sub-surface current cores, in which the maximum amplitudes are not observed near the surface, are also evident.

Owing to data gaps, the longest continuous record extends over 11 months. The limited record length permits us to resolve only the intraseasonal periods (Figure 2d). Wavelet analysis shows that the periods shorter than 10 days are patchy and more frequent during the winter monsoon (November–February). The biweekly-band (10–16 days) is strongest during July 2010 and does not show any seasonality. Strong peaks are observed during both the summer (June–September) and the winter monsoons. The strong peaks that occur in the 19–30-day band are found during November–December in both years. Some of the wavelet power in this band lies outside the cone of influence. In the Madden-Julian Oscillation regime (Madden and Julian 1971), the 45-day and 70-day bands are evident. The former (latter) band is weaker during 2010 (2011).

In order to separate the high-frequency current from the low-frequency current, we used a 40-day low-pass filter (Figure 2b, c). The low-frequency current is stronger near the surface and sometimes reverses direction. Such reversals may be associated with baroclinic waves that play an important role in the north Indian Ocean circulation (Shankar *et al.* 2002). The sub-surface current cores are evident in the high-frequency current, and the direction, in general, does not change with depth.

The cross-shore current at the GoM (positive current is poleward) is weaker compared to the alongshore current (Figure 2e). The standard deviation of the cross-shore current (5 cm s^{-1}) is half that of the alongshore current. Like the alongshore current, the cross-shore current also lacks seasonality. The current

flows polewards 75% of the time and has short intermittent bursts in the equatorward direction. The mean current is $\sim 3 \text{ cm s}^{-1}$ and does not vary much with depth. Though wavelets show similar periods as observed in the alongshore current, the lower frequencies in the intraseasonal band are sometimes absent. For example, the strong 70-day period is absent during 2010 and the 45-day period is weaker during June–August 2011.

4 Kanyakumari and GoM

The Kanyakumari mooring, which is separated from the GoM mooring by 283 km, lies on the continental slope off the southern tip of India, and is the westernmost point of the GoM (Figure 1b). Note that the current off Kanyakumari also follows the same convention as that of GoM: the alongshore current is zonal and eastward is positive or upwelling favourable. An opposite sign convention is used in Amol *et al.* (2014) and Chaudhuri *et al.* (2020).

The current off Kanyakumari is much stronger than the GoM current (Figure 3a, c). Unlike the GoM current, the magnitude of the cross-shore current is comparable to the alongshore current off Kanyakumari, and the standard deviation at 50 m for the alongshore (cross-shore) current is 17.5 (15.7) cm s^{-1} . The GoM alongshore current is predominantly westward, but the current off Kanyakumari reverses direction more frequently within a season (Figure 3a). The key difference is that the intraseasonal fluctuations off Kanyakumari are mostly in the opposite direction to that in the GoM. When the current off Kanyakumari flows east (north), the GoM current flows west (south) and vice

versa. There are only a few occasions when current at both locations is in the same direction. For example, the cross-shore currents are in the same direction from July–September 2010.

To quantify the coherence and phase difference between the GoM and off Kanyakumari currents, we used Wavelet Coherence Analysis (WCA). Like the wavelet analysis, the WCA analysis can resolve only the intraseasonal periods owing to data gaps. The WCA shows strong but patchy coherence between GoM and Kanyakumari for both alongshore and cross-shore currents (Figure 3b, d). Though the coherence is strong, the currents at GoM and off Kanyakumari are not in phase. The phase mostly varies between 90° – 180° , which indicates that the GoM current is not in the same direction as the current off Kanyakumari.

This behaviour is also reflected in the average currents. The mean zonal currents at 50 m in the GoM during the summer monsoon (June–August) of 2010 and 2011 are -14 and -8 cm s^{-1} , respectively. The mean zonal currents off Kanyakumari for the same seasons, on the other hand, are weaker and eastward (6 and 2 cm s^{-1} , respectively). The mean current off Kanyakumari is weaker because the current reverses within the season, whereas the current in the GoM is mostly unidirectional.

5 Discussion

We have presented for the first time direct current measurements using an ADCP in the GoM and have compared the current in the GoM with the cur-

rent off Kanyakumari. The current off Kanyakumari is linked to the large-scale dynamics that drives the monsoon currents and the WICC. The monsoon current (WICC) flows westward (poleward) during the winter monsoon and eastward (equatorward) during the summer monsoon, and this seasonality, though weak, is reflected at the Kanyakumari mooring (Amol *et al.* 2014; Chaudhuri *et al.* 2020). Unlike the current off Kanyakumari, the GoM current appears to be affected by the circulation inside the Gulf. The current primarily flows northwestward and does not have a clear seasonal cycle. The directionality obtained from the two-year record is, however, biased because of large data gaps during the winter monsoon, and a longer record would be required to confirm the mean direction of the current. One way to verify the seasonality is to compare the GoM current with the commonly available ocean current data products (see supplementary material for details). The correlation for the near-surface current is weak (< 0.4) as the data products are unable to pick the high-frequency variability of the current most of the time. Except for the OSCAR current, the currents from reanalysis products, which have a temporal coverage of 26 years, flow predominantly northwestwards. The analysis suggest that the GoM current, which is punctuated by high frequency bursts, is mostly unidirectional every year. The reanalysis data also show a seasonal cycle, where the current becomes weak (strong) during the winter (summer) monsoon.

The poor correlation between the GoM and off Kanyakumari currents is expected as the large-scale currents, like the monsoon current, tend to take a

shorter path from the southern tip of Sri Lanka to the west coast of India rather than flow along the coast (Durand *et al.* 2007). Snapshots of SLA and OSCAR currents show that the current between GoM and Kanyakumari splits/merges following the local high or low in the sea level, resulting in the currents at the two locations being in different directions (Figure 1c, d). The high/low could also be formed by small-scale eddies that can cause local changes in the circulation. For example, in Figure 1c, the Kanyakumari mooring is located on the eastern flank of the cyclonic eddy that causes the current to flow southeastwards. In contrast, the current at GoM is relatively weaker and flows in the opposite direction. The weak anti-cyclonic eddy evident in Figure 1d does not cause a change in the direction of GoM current but possibly weakens or modifies it. The eddies form off the southwest coast of Sri Lanka, the interior of the Gulf, and off the southern tip of India (see the animation in supplementary material). They sometimes drift westwards and may be associated with westward propagation of intraseasonal Rossby waves (Shankar *et al.* 2002). Such small-scale eddies are common in Gulfs and Bays around the world (Al Saafani *et al.* 2007; Kang and Curchitser 2013).

Another important feature of the GoM circulation is the presence of short-lived undercurrents. The undercurrents along the west coast of India have an annual cycle and are associated with the upward phase propagation, which causes the depth of the undercurrent to slowly decrease with time (Amol *et al.* 2014). Unlike the seasonal undercurrents, the undercurrent at GoM occurs as bursts and lasts only over a few weeks. Similar undercurrents are evident

at Kanyakumari but are less frequent. The separation of GoM currents into high-frequency and low-frequency currents using a filter shows that the low-frequency current is trapped near the surface, whereas the high-frequency current has strong sub-surface cores (Figure 2b,c,f,g). The undercurrent forms when the low-frequency and high-frequency currents are in the opposite direction. At Kanyakumari, even though the low-frequency current is surface-trapped, the near-surface intraseasonal current is much stronger than the seasonal current. A possible reason for these mid-depth high-frequency bursts is the presence of sub-surface eddies that may be caused by shear in the current as explained by Francis *et al.* (2020) for Cuddalore currents off the east coast of India.

The variations in coastline and topography separate the circulation in semi-enclosed GoM from the large-scale circulation and make this region dynamically distinct. The transport of water through Ram Setu may also impact the GoM circulation and the local biodiversity. Many of the studies that are related to large-scale circulation ignore this small channel owing to its shallow depth. There is a need for more observational and modelling studies in this region, which is important for the economies of Sri Lanka and southern India.

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Author statement

V. Fernando, G. S. Michael, P. A. Tari, M. G. Gaonkar, N. P. Satelkar, and S. T. Khalap were involved in data acquisition. Vineet Jain, and P. Amol drafted the manuscript. Vineet Jain, P. Amol and A. Kankonkar processed, analysed, and interpreted the data. Vineet Jain, P. Amol, S. G. Aparna, and V. Fernando conceived and designed the study.

Research highlights

1. Ocean current data collected in Gulf of Mannar
2. Near-surface current is north-westward over most part of the year
3. Current shows intraseasonal variability
4. Intraseasonal variability in the Gulf of Mannar current is weaker and in opposite direction compared to off Kanyakumari current
5. The opposite direction of Gulf of Mannar and off Kanyakumari currents is linked to local changes in the sea level

References

- Al Saafani M A, Shenoi S S C, Shankar D, Aparna M, Kurian J, Durand F and Vinayachandran P N 2007 Westward movement of eddies into the Gulf of Aden from the Arabian Sea; *J. of Geophys. Res. Oceans* **112(C11)**, <https://doi.org/10.1029/2006JC004020>.
- Amol P, Shankar D, Fernando V, Mukherjee A, Aparna S G, Fernandes R, Michael G S, Khalap S T, Satelkar N P, Agarvadekar Y, Gaonkar M G, Tari A P, Kankonkar A and Vernekar S P 2014 Observed intraseasonal and seasonal variability of the West India Coastal Current on the continental slope; *J. Earth Syst. Sci.* **123(5)** 1045–1074, <https://doi.org/10.1007/s12040-014-0449-5>.
- Bonjean F and Lagerloef G S E 2002 Diagnostic model and analysis of the surface currents in the tropical Pacific Ocean; *J. Phys. Oceanogr.* **32(10)** 2938 – 2954, [https://doi.org/10.1175/1520-0485\(2002\)032<2938:DMAAOT>2.0.CO;2](https://doi.org/10.1175/1520-0485(2002)032<2938:DMAAOT>2.0.CO;2).
- Chaudhuri A, Shankar D, Aparna S G, Amol P, Fernando V, Kankonkar A, Michael G S, Satelkar N P, Khalap S T, Tari A P, Gaonkar M G, Ghatkar S and Khedekar R R 2020 Observed variability of the West India Coastal Current on the continental slope from 2009–2018; *J. Earth Syst. Sci.* **129(1)**, <https://doi.org/10.1007/s12040-019-1322-3>.
- Durand F, Shankar D, Montégut C d B, Shenoi S S C, Blanke B and Madec G 2007 Modeling the barrier-layer formation in the Southeastern Arabian Sea; *J. Clim.* **20(10)** 2109–2120, <https://doi.org/10.1175/JCLI4112.1>.
- Francis P A, Jithin A K, Chatterjee A, Mukherjee A, Shankar D, Vinayachandran P N and Ramakrishna S S V S 2020 Structure and dynamics of undercurrents in the western boundary current of the Bay of Bengal; *Ocean Dyn.* **70(3)** 387–404, <https://doi.org/10.1007/s10236-019-01340-9>.
- Han W and McCreary J P 2001 Modeling salinity distributions in the Indian Ocean; *J. Geophys. Res.* **106(C1)**, <https://doi.org/10.1029/2000JC000316>.
- Jagadeesan L, Jyothibabu R, Anjusha A, Mohan A P, Madhu N V, Muraleedharan K R and Sudheesh K 2013 Ocean currents structuring the mesozooplankton in the Gulf of Mannar and the Palk Bay, southeast coast of India; *Prog. Oceanogr.* **110** 27–48,

- <https://doi.org/10.1016/j.pocean.2012.12.002>.
- Kang D and Curchitser E N 2013 Gulf Stream eddy characteristics in a high-resolution ocean model; *J. Geophys. Res. Oceans* **118(9)** 4474–4487, <https://doi.org/10.1002/jgrc.20318>.
- Kumaraguru A, Joseph E, Marimuthu N and Wilson J 2006 *Scientific information on Gulf of Mannar – A Bibliography*.
- Luis A J and Kawamura H 2002 Dynamics and mechanism for sea surface cooling near the Indian tip during winter monsoon; *J. Geophys. Res. Oceans* **107(2)** 8–1–8–13, <https://doi.org/10.1029/2000JC000455>.
- Madden R A and Julian P R 1971 Detection of a 40–50 Day Oscillation in the Zonal Wind in the Tropical Pacific; *J. Atmos. Sci.* **28(5)** 702 – 708, [https://doi.org/10.1175/1520-0469\(1971\)028<0702:DOADDI>2.0.CO;2](https://doi.org/10.1175/1520-0469(1971)028<0702:DOADDI>2.0.CO;2).
- Rao R R, Girishkumar M S, Ravichandran M, Gopalakrishna V V and Thadathil P 2011 Do cold, low salinity waters pass through the Indo-Sri Lanka Channel during winter?; *Int. J. Remote Sens.* **32(22)** 7383–7398, <https://doi.org/10.1080/01431161.2010.523728>.
- Shankar D, Vinayachandran P N and Unnikrishnan A S 2002 The monsoon currents in the north Indian Ocean; *Prog. Oceanogr.* **52** 63–120, [https://doi.org/10.1016/S0079-6611\(02\)00024-1](https://doi.org/10.1016/S0079-6611(02)00024-1).
- Smitha B R, Sanjeevan V N, Vimalkumar K G and Revichandran C 2008 On the Upwelling off the Southern Tip and along the West Coast of India; *J. Coast. Res.* **24(sp3)** 95 – 102, <https://doi.org/10.2112/06-0779.1>.

Figure captions

Figure 1: Map showing the ADCP mooring locations. (a) North Indian Ocean map. The black boxes mark the region shown in panels b (solid box) and c–d (dashed box). (b) Bathymetry in the GoM and Palk Bay. Data used is from General Bathymetric Chart of the Oceans (GEBCO, <https://www.gebco.net/>). Black circles mark the mooring locations in the GoM (labeled GMM) and off Kanyakumari (labeled KKM). Panels (c) and (d) show snapshots of SLA (cm, colour-scale), ADCP currents (black vectors), OSCAR currents (green vectors), and winds (purple vectors) on 25 March 2011 and 11 September 2011, respectively. The dashed contour marks the 1000 m isobath.

Figure 2: ADCP currents in the GoM. (a) 5-day low-passed alongshore current (cm s^{-1}). (b) 40-day low-passed alongshore current. (c) 40-day high-passed alongshore current. (d) Morlet wavelet power spectra for alongshore current at 16 m. Panels (e)–(h) are same as panels (a)–(d) but for the cross-shore current. The positive current is eastward (northward) for alongshore (cross-shore) current. In panels (d) and (h), the wavelet power and the ordinate axis are plotted on a \log_2 scale. The thick black curve marks the cone of influence for the wavelet power spectra. The horizontal dashed lines mark the 15, 25, 45 and 70-day bands.

Figure 3: Comparison of ADCP currents in the GoM and off Kanyakumari. The data for Kanyakumari is available only from 50 m depth and hence currents at 50 m are compared. Panels (a) and (c) show the alongshore and cross-shore currents off Kanyakumari (red) and GoM (black), respectively.

Panels (b) and (d) show the wavelet coherence of the alongshore and cross-shore currents, respectively. The phase difference (in degrees) is indicated by the arrow directions in the coherence plots. The eastward arrows marks zero phase difference. The GoM current leads (lags) off Kanyakumari current in anti-clockwise (clockwise) direction.

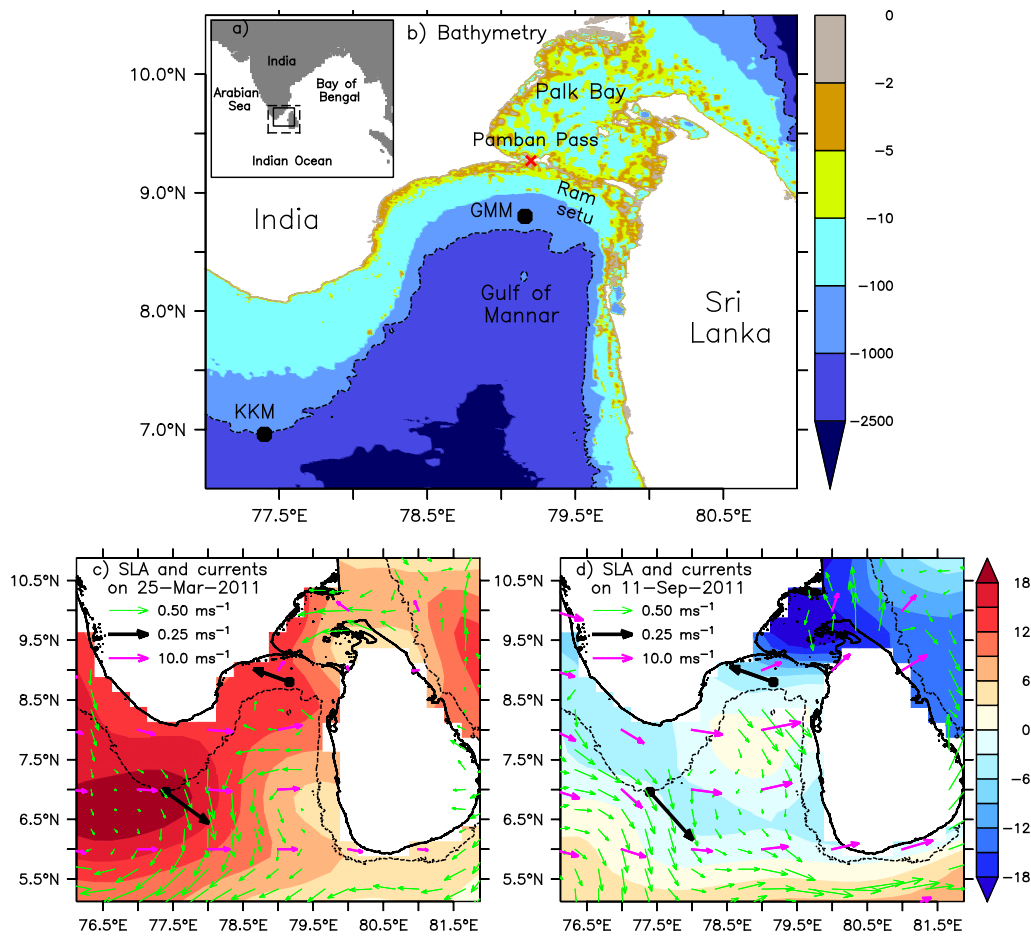


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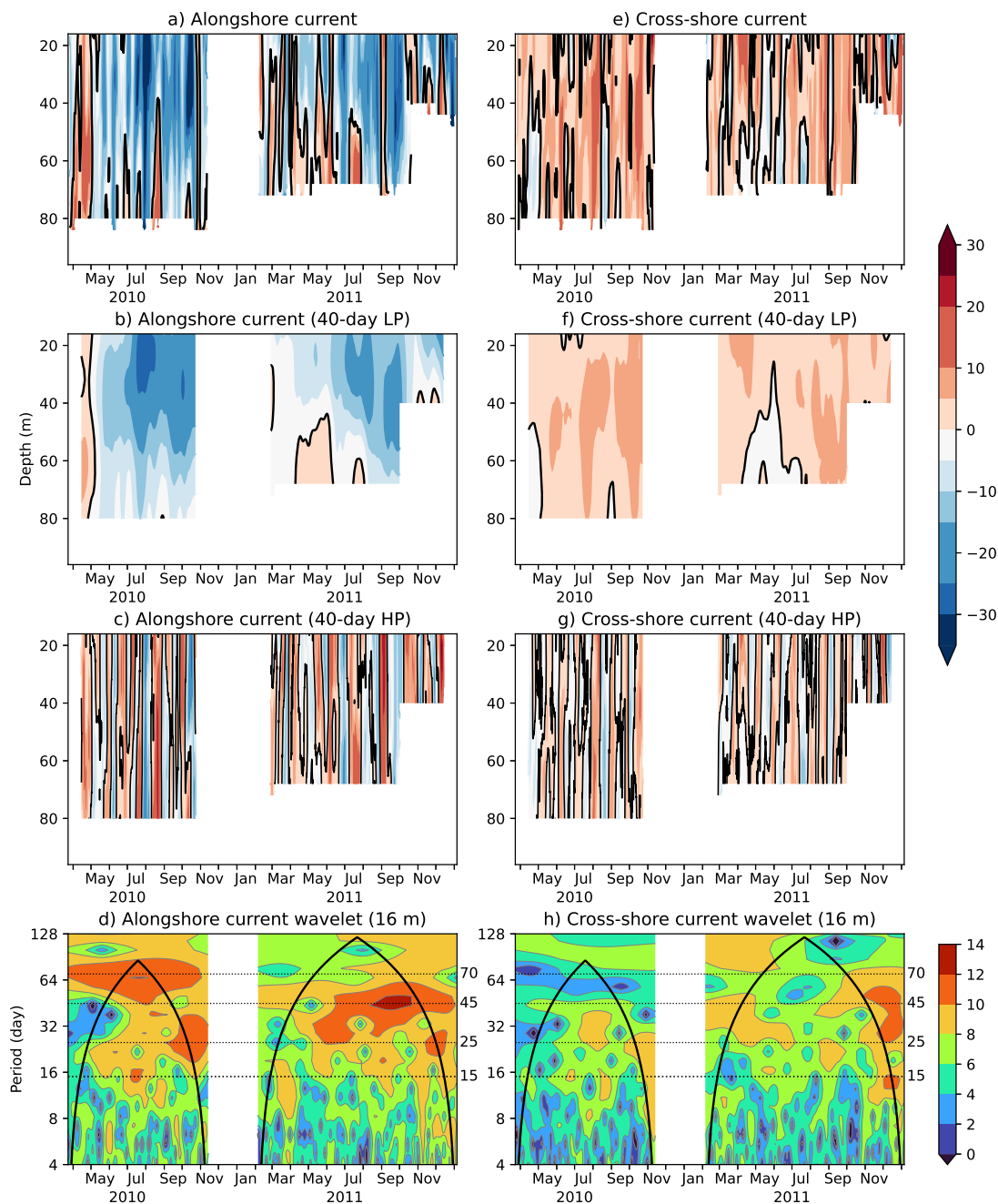


Fig. 2 ADCP currents in the GoM. (a) 5-day low-passed alongshore current (cm s^{-1}). (b) 40-day low-passed alongshore current. (c) 40-day high-passed alongshore current. (d) Morlet wavelet power spectra for alongshore current at 16 m. Panels (e)–(h) are same as panels (a)–(d) but for the cross-shore current. The positive current is eastward (northward) for alongshore (cross-shore) current. In panels (d) and (h), the wavelet power and the ordinate axis are plotted on a \log_2 scale. The thick black curve marks the cone of influence for the wavelet power spectra. The horizontal dashed lines mark the 15, 25, 45 and 70-day bands.

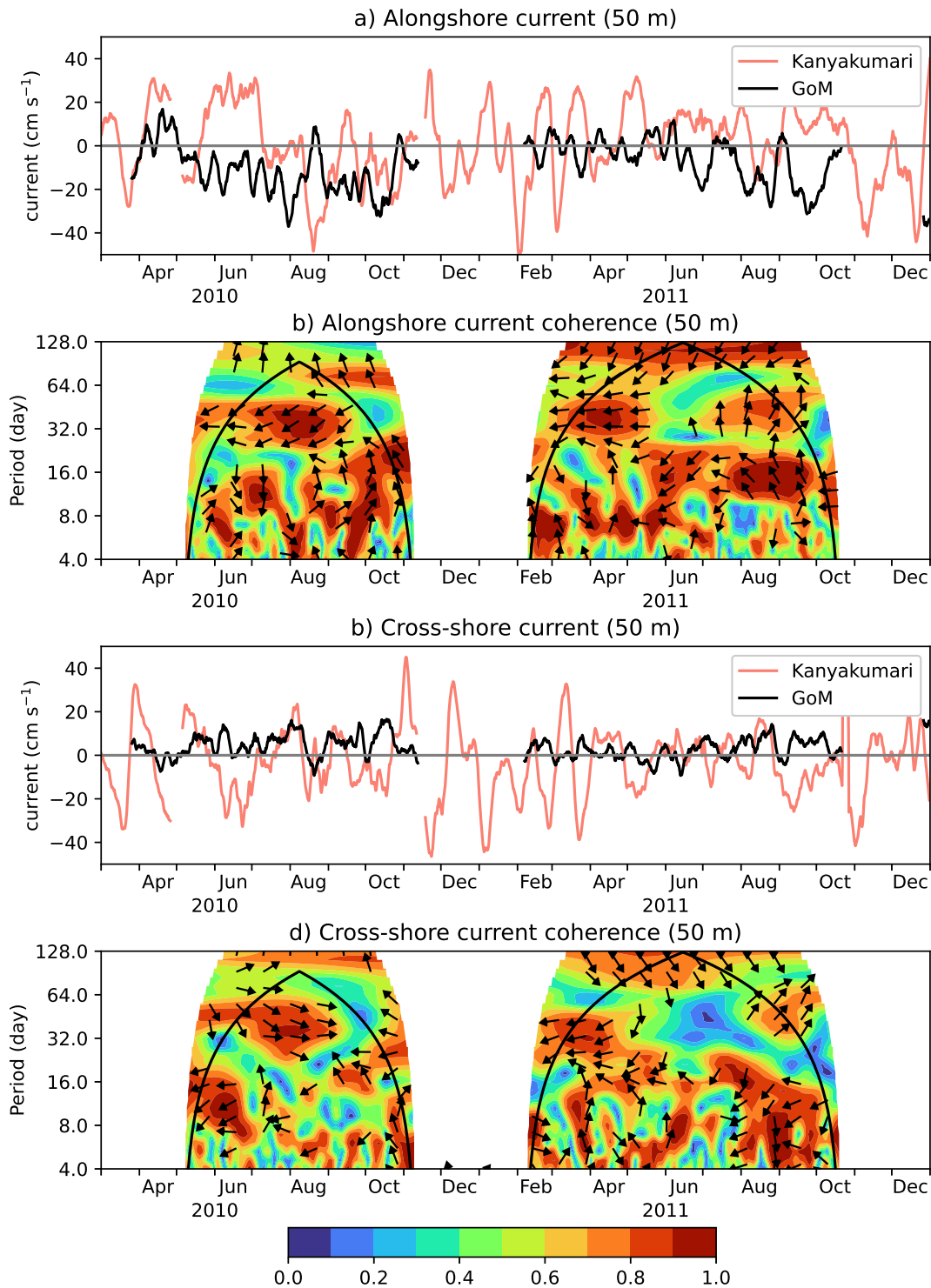


Fig. 3 Comparison of ADCP currents in the GoM and off Kanyakumari. The data for Kanyakumari is available only from 50 m depth and hence currents at 50 m are compared. Panels (a) and (c) show the alongshore and cross-shore currents off Kanyakumari (red) and GoM (black), respectively. Panels (b) and (d) show the wavelet coherence of the alongshore and cross-shore currents, respectively. The phase difference (in degrees) is indicated by the arrow directions in the coherence plots. The eastward arrows mark zero phase difference. The GoM current leads (lags) off Kanyakumari current in anti-clockwise (clockwise) direction.