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RESEARCH ARTICLE

Ocean circulation around Sri Lanka

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Abstract: Sri Lanka, located in the northern Indian Ocean with the Arabian Sea on its western side and the Bay of Bengal on its eastern side and experiences bi-annually reversing monsoon winds. This brief overview explored the dynamics of the surface circulation and coastal upwelling in the waters around Sri Lanka, particularly along the southern coast, using satellite imagery and numerical simulations using the Regional Ocean Modelling System (ROMS). The results confirmed the presence of the reversing current system, between the equator and Sri Lanka, in response to the changing wind field: the eastward flowing Southwest Monsoon Current (SMC) during the Southwest (SW) monsoon and the westward flowing Northeast Monsoon Current (NMC) during the Northeast (NE) monsoon, respectively. Along the eastern and western coasts, during both monsoon periods, flow is southward converging along the south coast. During the SW monsoon the Island deflects the eastward flowing SMC southward whilst along the east coast the southward flow results from the Sri Lanka Dome recirculation. The major upwelling region was located along the south coast resulting from southward flow converging along the south coast and subsequent divergence associated with the offshore transport of water. The location of the flow convergence and hence the upwelling centre was dependent on the relative strengths of wind driven flow along the east and west coasts: during the SW (NE) monsoon the flow along the western (eastern) coast was stronger migrating the upwelling centre to the east (west).

Keywords: Island-mass effect, monsoon, Sri Lanka, surface circulation, upwelling.

INTRODUCTION

The Island of Sri Lanka occupies a unique geographic/topographic and oceanographic location in the equatorial northern Indian Ocean, with the Arabian Sea on its western side and the Bay of Bengal on its eastern side (Figure 1). The Island is an extension of the Indian sub-continental landmass into the ocean with deeper water (water depths > 2000 m) on either side of the Island. The interaction between the ocean currents and the Island topography controls the ocean circulation (de Vos *et al*., 2014). From an oceanographic perspective, location of Sri Lanka is unique with its offshore waters transporting water with different properties, originating from Bay of Bengal and the Arabian Sea, through reversing ocean currents, driven by monsoon winds (Schott & McCreary, 2001; Su *et al*., 2021). The northern Indian Ocean is characterised by bi-annually reversing monsoon winds resulting from the seasonal differential heating and cooling of the continental land mass and the ocean. The Southwest (SW) monsoon generally operates between June and October and the Northeast (NE) monsoon operates between December through April (Tomczak & Godfrey, 2003). The transition periods are termed the First Inter-Monsoon (May) and Second Inter-Monsoon (November). During the SW monsoon, the Southwest Monsoon Current (SMC) flows from west to east transporting higher salinity water from the Arabian Sea (Figure 2a) whilst during the NE monsoon the currents reverse in direction with the Northeast Monsoon Current (NMC) transporting lower salinity water originating from the Bay of Bengal from east to west (Figure 2b). During the SW monsoon, increased chlorophyll concentrations (> 5 mg m^{-3}) have been recorded around Sri Lanka, particularly along the southern coast (Vinayachandran *et al*., 2004; de Vos *et al*., 2014) which appears to be a major upwelling region.

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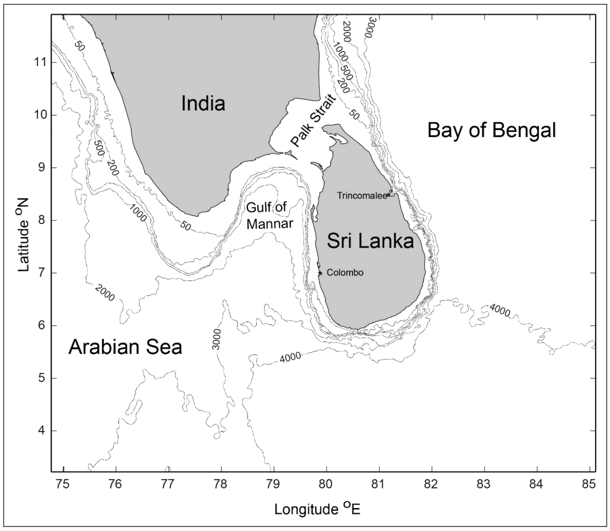

Figure 1: Study area showing bathymetry and model domain

The continental shelf around Sri Lanka is narrower, shallower and steeper than is average for the world (Wijeyananda, 1997). Its mean width is 20 km, and it is narrowest on the southwest coast where it is less than 10 km (Shepard, 1963; Swan, 1983; Wijeyananda, 1997). The continental slope around Sri Lanka is a concave feature that extends from 100 m to 4,000 m in depth. The continental slope on the southern and eastern coasts has an inclination of 45° which is one of the steepest recorded globally (Sahini, 1982). The abyssal plain around the island is 3,000–4,000 m deep (Swan, 1983).

The seasonal difference of sea surface salinity (> 2 ppt) around Sri Lanka is highly significant compared to other regions (Levitus *et al*., 1994). Salinity in the Bay of Bengal is generally lower (< 33 ppt), whilst salinities in the Arabian Sea are higher with maxima up to 36.5 ppt due to high evaporation and negligible freshwater input. The exchange of these waters occur along the southern coast of Sri Lanka with the reversing currents due to the monsoon winds.

There is significant seasonal variation in sea level in the north-eastern Indian Ocean with a range in the inner Bay of Bengal of ~0.80–0.90 m decreasing to the south (Wijeratne, 2008), hence mean sea level is 0.05 m lower in January compared to July, due to the inverse barometric effect. The seasonal sea level variability around Sri Lankan waters is around 0.2-0.3 m with maxima during June through the action of the SW monsoon (Wijeratne *et al*., 2008). The tides around the Island are mixed semidiurnal with a maximum spring tidal range of ~0.70 m.

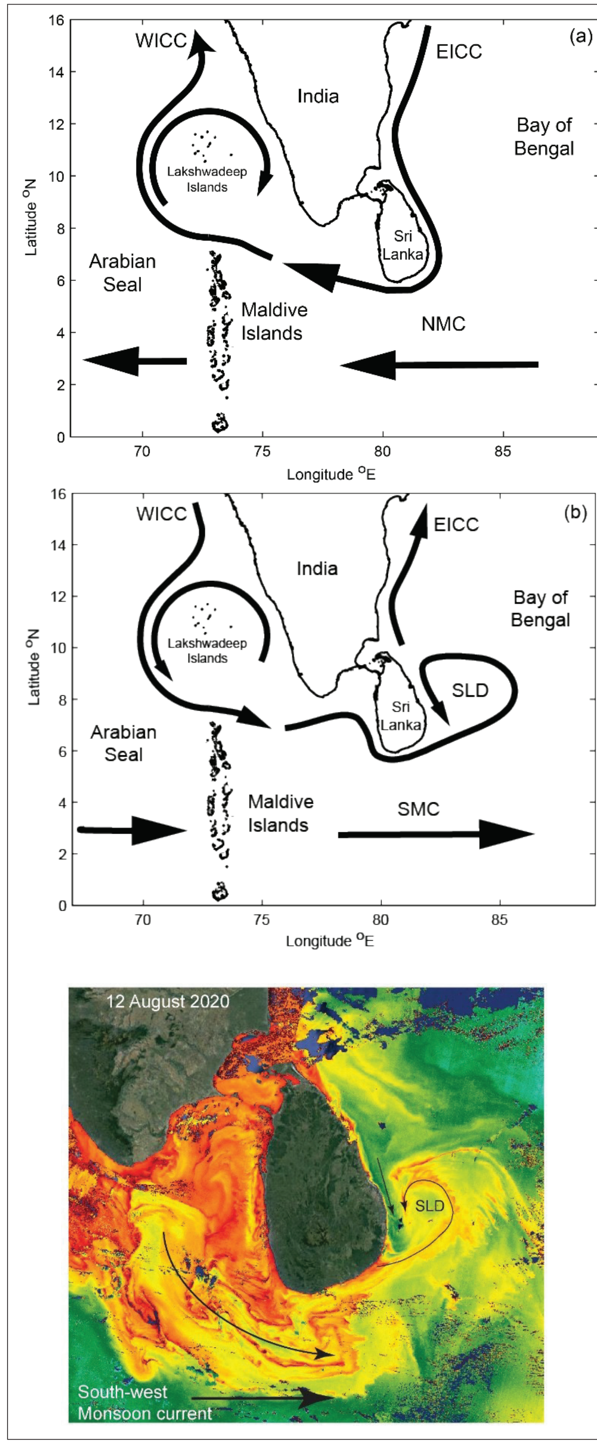

Figure 2: Circulation patterns around Sri Lanka and southern India for (a) Northeast monsoon; (b) Southwest monsoon; (c) ocean colour image from 12 August 2020 showing surface chlorophyll concentration. WICC – West Indian Coastal Current; EICC – East Indian Coastal Current; SMC – South Monsoon Current; NMC – North Monsoon Current; SLD– Sri Lanka Dome.

A schematic of the circulation in the northern Indian Ocean, in the vicinity of Sri Lanka is shown in Figure 2 (Schott & McCreary, 2001; de Vos *et al*., 2014; Su *et al*., 2021). During the SW monsoon along India and Sri Lanka (Figure 2b), the eastern boundary current or West Indian Coastal Current (WICC) in the Arabian Sea flows southwards along the West Indian coastline and joins the eastward flowing Southwest Monsoon Current (SMC). The presence of the anti-clockwise Lakshadweep eddy off the southwest coast of India modifies the current flow in this region. The SMC flows along the south coast of Sri Lanka from west to east transporting ~11.5 Sv (1 Sv = 10^6 m^3s^{-1}) between the equator and Sri Lanka (de Vos *et al*., 2014). After passing the coast of Sri Lanka, the currents form an anti-clockwise eddy defined as the Sri Lanka Dome (SLD) centred around 83° E and 7° N (Vinayachandran & Yamagata, 1998; de Vos *et al*., 2014; Su *et al*., 2021). The western arm of this eddy drives a southward current along the east coast of Sri Lanka (Figure 2c) whilst the remainder flows northward along the eastern Indian coast as the East Indian Coastal Current (EICC).

During the NE monsoon the currents reverse in direction (Figure 2a). Along the eastern Indian coast, the EICC flows southward past Sri Lanka and joins the Northeast Monsoon Current (NMC) flowing from east to west transporting ~9.6 Sv (de Vos *et al*., 2014). The currents then flow around the clockwise Lakshadweep eddy and northward along the western Indian coastline as the West Indian Coastal Current (WICC). One of main features to note from this description from the perspective of Sri Lanka, is the reversal of currents along the western and southern coasts and the north to south flow along the eastern coast.

Sri Lanka is a relatively large island (length 440 km; width 225 km), extending offshore into the Indian Ocean, similar to a headland. This allows for the Island to interact with the seasonally reversing monsoon. Many studies have reported the influence of flow interaction with islands and headlands leading to enhanced primary production – termed the island mass effect (IME) by Doty and Oguri (1956). These studies have included different spatial scales using laboratory and field experiments to understand circulation and enhanced productivity (Su *et al*., 2021).

The upwelling off the south coast of Sri Lanka usually appears and intensifies during the summer months when the SW monsoon prevails. Monthly satellite image composites of chlorophyll analysed by Yapa (2009) show high productivity waters with mean chlorophyll concentrations > 5 mg m^{-3} along the southern and western regions during the months of June-August that are accompanied by a 2° to 3° C decrease in sea surface temperature (SST) corresponding to regions where high chlorophyll concentrations are detected.

This paper is brief review of the circulation around Sri Lanka with an emphasis on the seasonal changes in circulation and upwelling patterns along the southern coast of Sri Lanka using satellite imagery and a high-resolution numerical model (ROMS).

METHODOLOGY

The main approach for the study is the use of satellite imagery and a numerical model to describe the mean circulation patterns and upwelling around Sri Lanka. Meteorological information from ECMWF ERA interim data which were also used for model forcing have been used to define the seasonal wind climate.

ROMS configuration and validation

The Regional Ocean Modelling System (ROMS) is a three-dimensional numerical ocean model based on the nonlinear terrain following coordinate system of Song and Haidvogel (1994). ROMS solves the incompressible, hydrostatic, primitive equations with a free sea surface, horizontal curvilinear coordinates, and a generalized terrain-following s-vertical coordinate that can be configured to enhance resolution at the sea surface or seafloor (Haidvogel *et al*., 2008). This model set-up is an extension of the same configuration used in de Vos *et al*. (2014) and Pattiaratchi *et al*. (2022).

The model grid (Figure 1) configured for this study included the continental shelf and slope waters surrounding Sri Lanka as well as the deeper ocean and consisted of a horizontal grid with resolution < 2 km with 30 vertical layers in a terrain-following s-coordinate system. The model was driven by direct air-sea heat and freshwater fluxes, momentum fluxes, inverted barometric effect, tide/sea level, transport and tracers at open boundaries. The forcing data were interpolated onto the corresponding model grid points to create initial and forcing files. The model was driven with 3 hourly atmospheric forcing and daily surface heat and freshwater fluxes using ECMWF ERA interim data. The heat and freshwater fluxes were also specified using ECMWF ERA data. The net heat flux at air-sea interface was estimated based on the balance of incoming solar radiation, outgoing long wave, sensible and latent heat fluxes, respectively. Freshwater fluxes were estimated using precipitation and evaporation data from ECMWF ERA data and the river inputs were ignored.

Satellite imagery

Suspended material (such as sediment, chlorophyll etc) in the surface waters may be used as a passive tracer to follow flow patterns using satellite imagery (Pattiaratchi *et al*., 1987). In regions of upwelling (for example see Figure 3), there is also a correspondence between regions of higher surface chlorophyll concentrations (SCC) and lower sea surface temperatures (SST). Thus, ocean colour imagery may be used to qualitatively validate numerical model outputs. Comparison between predicted SST and satellite derived SCC indicate that the model reproduced observed patterns, particularly the higher chlorophyll 'tongue' feature, and sharp fronts. Satellite imagery acquired by the Sentinel-3 satellite was used to supplement the ROMS model output. Here, the surface chlorophyll concentrations estimated using the OLCI algorithm was used (*https://ovl.oceandatalab.com*).

RESULTS

The wind field

The monsoon and inter-monsoon periods occur at similar times during the year. However, there is an inter-annual variability in the onset of these climatic events and thus the timing of each monsoon can vary by up to 1-2 months. In addition to the seasonal changes in the wind field there is also significant spatial distribution as revealed by the ECMWF ERA interim data (Figure 3). One of the factors influencing the spatial wind field is the local land topography of Sri Lanka and southern India. Coastal regions around Sri Lanka are relatively flat and surround the elevated central region that increases to a maximum elevation of 2,500 m. Similarly, southern India consists of elevated terrain that exceeds 1,000 m (Luis & Kawamura,

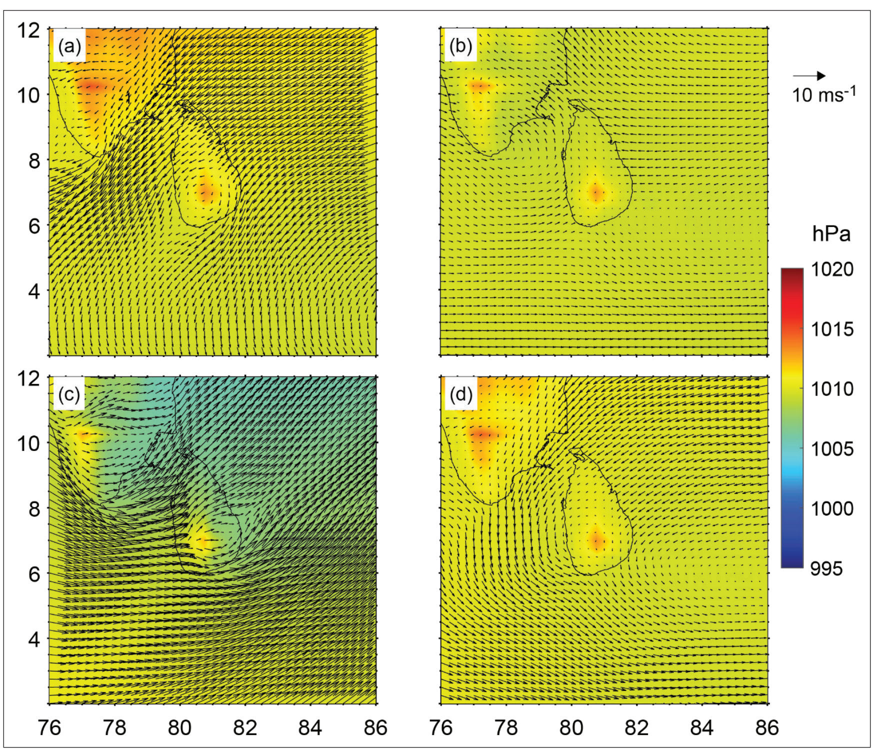

Figure 3: Seasonal mean wind speeds and directions for 2021 from ECMWF ERA interim data. Each plot represents a bi-monthly average with the length of arrow correlating with speed. (a) January-February (northeast monsoon); (b) April-May (first inter-monsoon); (c) July-August (southwest monsoon); (d) October-November (second inter-monsoon). The higher surface atmospheric pressure reflects the higher topography in the center of Sri Lanka and southern India.

2000). These are highlighted by the relatively higher surface atmospheric pressure at the centre of Sri Lanka and southern India (Figure 3). During the NE monsoon (Figure 3a), winds are predominantly from the northeast across the study region with stronger winds in the Gulf Mannar (Figure 1). Here, the north-easterly winds are funnelled through the elevated topography between southern India and Sri Lanka resulting in strong winds over the Gulf of Mannar (Luis & Kawamura, 2000). Off the southern coast of Sri Lanka, the winds are weaker and are mainly offshore during the NE monsoon (Figure 3a). The interaction between the NE monsoon winds and the central highlands of Sri Lanka results in a region of lower wind speeds ('wind shadow') off the south-west coast (Figure 3a). During the first inter-monsoon, the east coast of Sri Lanka experiences onshore winds (easterly) with weaker winds off the south coast remaining offshore (Figure 3b). Along the western and southern coasts of Sri Lanka, during the SW monsoon, the winds are stronger and are westerly (Figure 3c) and, due local topography, they veer northwards off the eastern side of the island (south-westerly winds). The influence of the central highlands is more pronounced with the wind shadow extending significantly offshore (Figure 3c). During the second inter-monsoon, the east coast of Sri Lanka experiences weaker north-easterly winds with winds off the southern coast remaining offshore and northerly (shore parallel) along the west coast (Figure 3d).

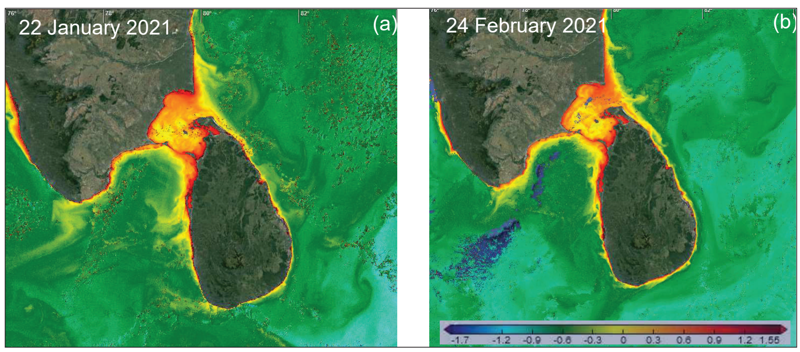

Figure 4: Weekly mean surface chlorophyll concentration (SCC) from Sentinel-3 satellite during the north-east monsoon in 2021: (a) 22 January 2021; and, (b) 24 February 2021. The SCC scale in (b) is logarithmic and has units mgm^{-3}.

Seasonal circulation

Satellite imagery

The seasonal circulation around Sri Lanka was examined through the use of surface chlorophyll concentration (SCC) for north-west (2021) and southwest monsoon periods. The SSC is used as a passive tracer to follow flow patterns using satellite imagery.

In January, the Northeast Monsoon Current (NMC) flows from east to west (Figure 2a) with offshore winds along the west coast (Figure 3a). In general, the weekly mean SCC was low around the Island and relatively higher values were restricted to the narrow coastal region (Figure 4). This is reflected in the SCC data with slightly higher concentrations to the west of Sri Lanka. There is evidence of offshore advection of SCC along the west coast.

In May, during the onset of the SW monsoon (Figure 2b) the flow is mainly from west to east along the south coast and a band of higher SCC (~2.0 mgm^{-3}) water was present along the south coast of Sri Lanka and is advected to the east (Figure 5a). The low SCC concentrations along the east coast of Sri Lanka was due to the southward flow of water (see Figure 2b, c). In the time series of images between 7 May and 26 June 2019, we follow the development of a very narrow band of higher SCC advecting to the east (Figure 5). This band is formed through the convergence of the eastward flowing water advecting higher SCC water from the south coast to the east and the southward flowing lower SCC water along the east coast (see also Figure 2c). On 14 May the only a small feature may be seen along the south coast (Figure 5b) and over the following weeks (to 10 June) the narrow band is a consistent feature (Figures 5c–e). On 26 June the band has contracted to the west and is now wider than the previous weeks (Figure 5f).

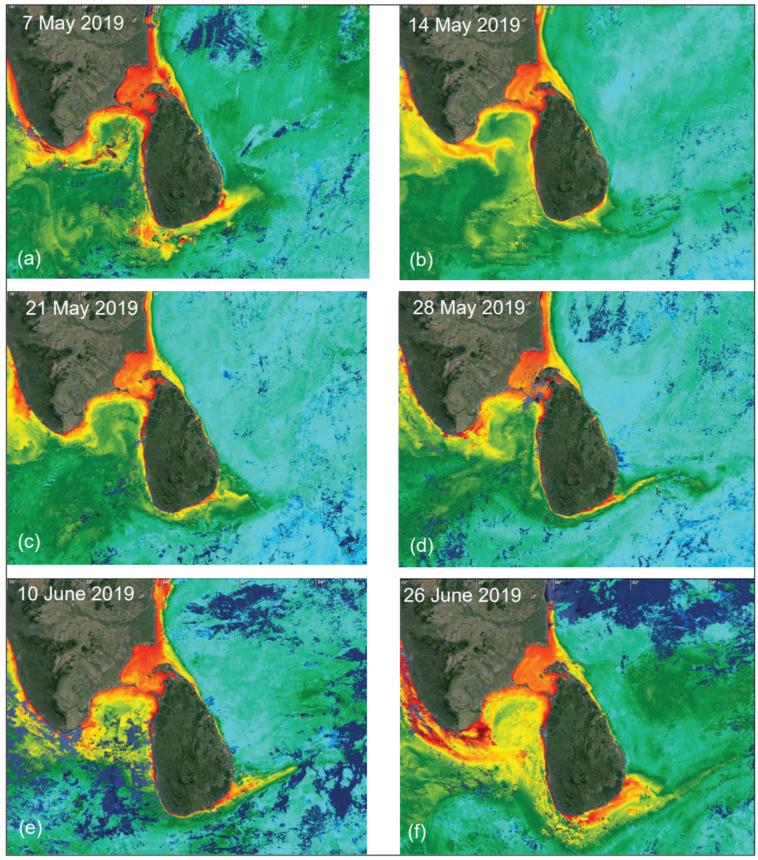

Figure 5: Weekly mean surface chlorophyll concentration from Sentinel-3 satellite during the onset of the south-west monsoon in 2019: (a) 7 May 2019; (b) 14 May 2019; (c) 21 May 2019; (d) 28 May 2019; (e) 10 June 2019; and, (f) 26 June 2019. Colour scale of SCC is shown on Figure 4b.

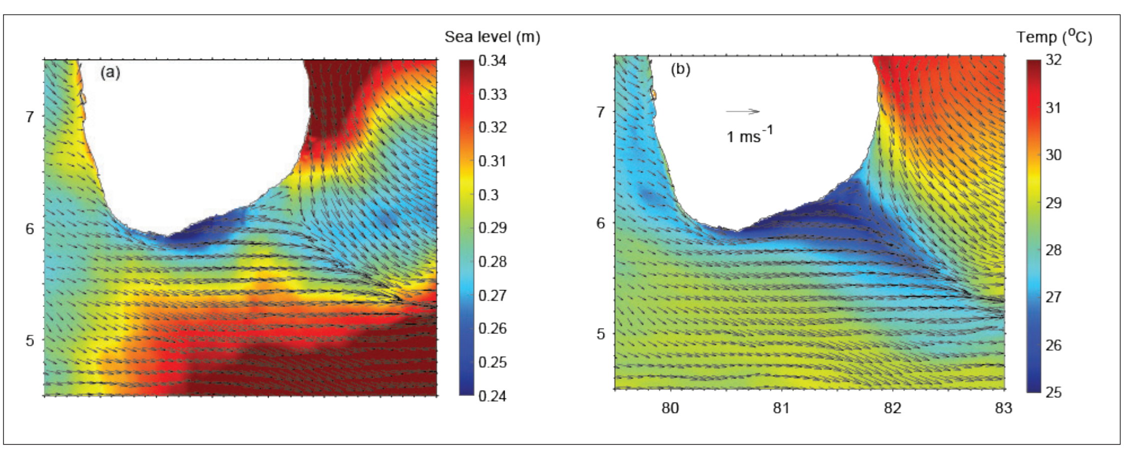

Figure 6: Predicted near-surface current vectors superimposed (a) sea level; and, (b) sea surface temperature along the southern coast during the south-west monsoon

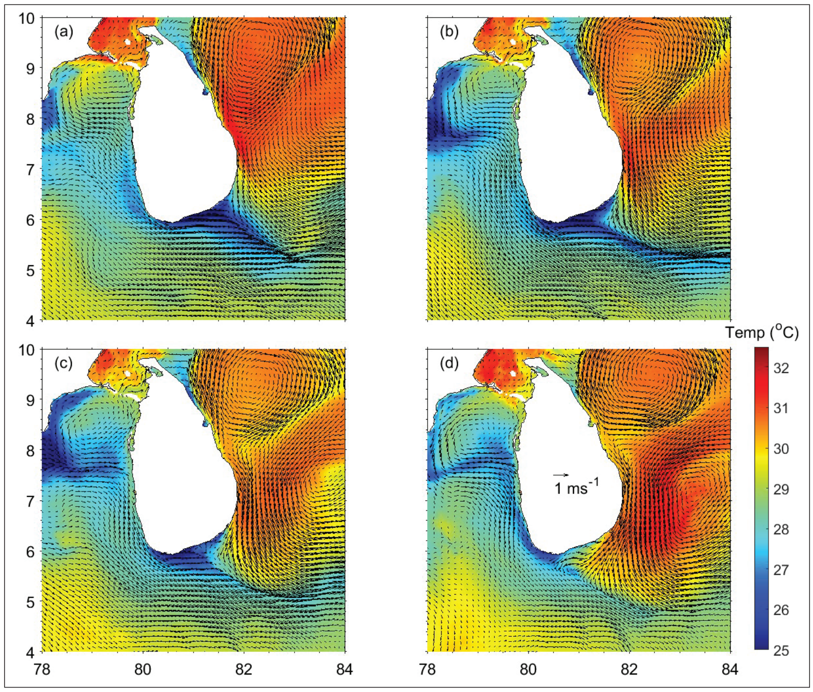

Figure 7: Predicted near-surface current vectors with sea surface temperature around Sri Lanka during south-west monsoon. (a) 11 June 2021; (b) 14 June 2021; (c) 17 June 2021; and, (d) 20 June 2021.

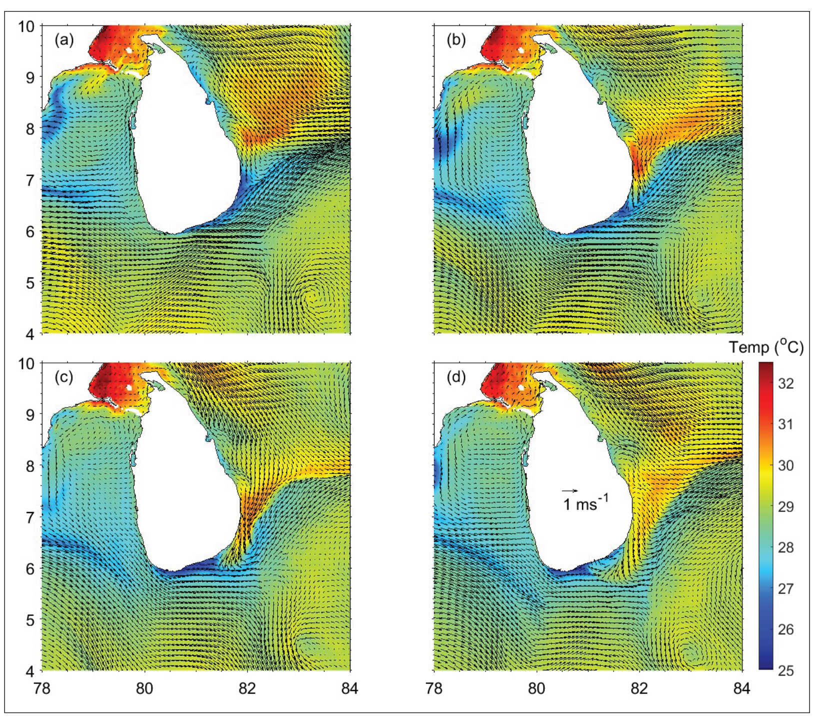

Figure 8: Predicted near-surface current vectors with sea surface temperature around Sri Lanka during late north-east monsoon and first inter-monsoon. (a) 09 Oct 2021; (b) 11 Oct 2021; (c) 13 Oct 2021; and, (d) 15 Oct 2021

Numerical modelling

Numerical model results provide additional information on the general patterns identified in previous studies (Figure 2) and ocean colour imagery (Figure 5). These were fully described in de Vos *et al*. (2014) and for the larger scale by Su *et al*. (2021). The numerical model results presented here are limited to flow features along the southern coast of the Island during the south-west monsoon: the formation of a cold-water tongue extending from the coast to offshore that was also present identified in the ocean colour imagery (Figure 5). We define the 'cold water tongue' as the cold-water patch that begins at the coast and extends offshore, narrowing with distance similar to a triangle (e.g. Figure 6b). This cold-water tongue is present due to the convergence of two current streams (Figure 2b, c): (1) eastward flow along the south coast as part of the south-west monsoon current; and, (2) the southward flow along the east coast of Sri Lanka as part of the Sri Lankan dome. As part of this convergence feature the mean sea level is depressed along the south coast with higher sea levels along the east coast and offshore (Figure 6a). The decreased sea level at the coast results in upwelling of colder water that is advected offshore by the convergent currents (Figure 6b). The colder water originates from water depths of 80–100 m (Figure 11; Su *et al*., 2021).

The ocean is dynamic and changes at time scales of order days reflect changes in atmospheric forcing. De Vos *et al*. (2014) identified changes occurring over 10-day cycles. The model predicted daily mean sea surface temperature (SST) and flow fields were examined at shorter timescales over a 10-day period during the south-west monsoon period (Figures 7 and 8). From 11–14 June 2021 (south-west monsoon) – the cold-water tongue was extending in a south-east direction and the convergence of the currents along the south coast (from the west) and east coast (from the north) can be readily identified (Figure 7a, b). On 17 June, the currents along the east coast has strengthened mainly due to the formation of an anti-clockwise eddy centred at 83.5°E 7.5°N and the cold water tongue has moved slightly to the west (Figure 7c). By 20 June, the eddy has strengthened further, and stronger southward currents are present along the east coast of the Island and this has resulted in the cold water tongue being moved further to the west and becoming weaker in terms of the colder water (Figure 7d). On 9 October, due to the stronger currents along the southern coast, the cold-water tongue with converging currents evident is now present further to the east, along the southern section of the east coast (Figure 8a). Over the period 11–15 October, the currents along the east coast have strengthened and the cold water tongue shifted to the east (Figures 8b–d). These daily model outputs confirm the observations through ocean colour imagery (e.g. Figure 5) and those reported by de Vos *et al*., 2014).

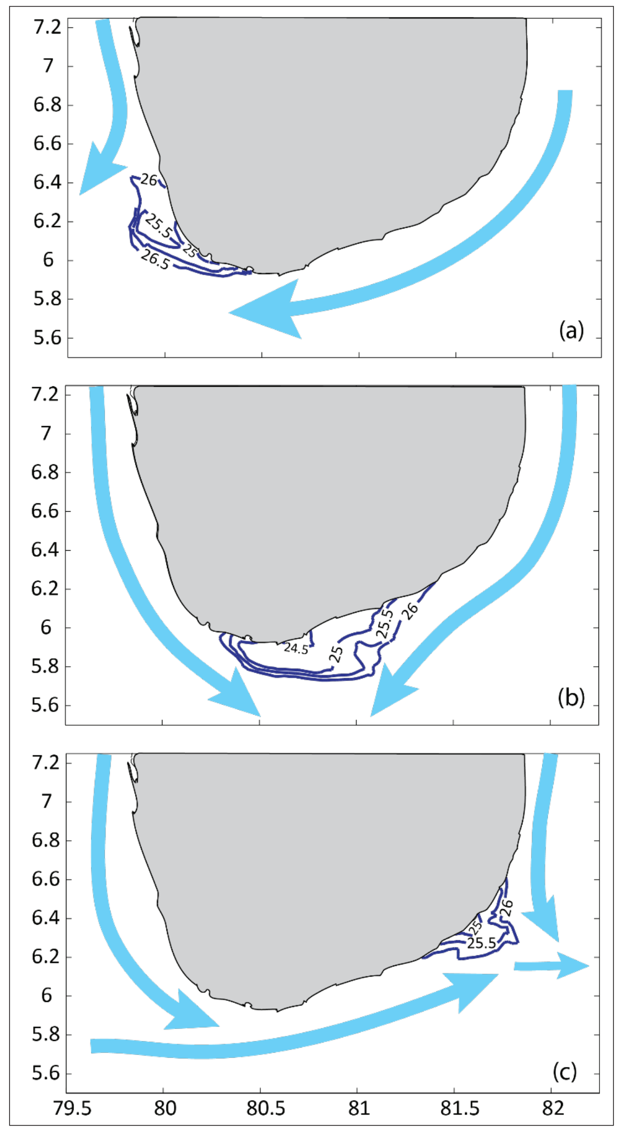

Figure 9: Predicted locations of the convergence region and associated upwelling region with respect to different current strengths along each coast (modified from de Vos *et al*., 2014).

The model results and ocean colour imagery indicated that the upwelling and associated colder, higher chlorophyll water along the southern coast of Sri Lanka during the south-west monsoon was due to flow convergence from currents flowing in different directions along the coast: to east along the south coast and to the south along the east coast. It was not due to direct wind driven upwelling through Ekman dynamics. Location of the upwelling centre depends in the relative strength between the two current systems and is shown schematically in Figure 9. When the currents from the west are stronger, the centre of cold-water tongue is located in the south-east (Figure 9a; see also Figure 3; de Vos *et al*., 2014). When the current strengths are comparable, the upwelling centre is located along the central part of southern coast (Figure 9b) and when the currents from the east are stronger, the centre of cold-water tongue is located in the south-west (Figure 9c).

DISCUSSION AND CONCLUSIONS

The seasonal and shorter term (< 10 days) changes in the surface circulation and upwelling patterns around Sri Lanka were examined using satellite imagery (mainly ocean colour) and a high spatial resolution numerical model (ROMS) configured to the study region and forced with ECMWF interim data. The emphasis was on the southern coast of Sri Lanka. The model reproduced all of the documented major circulation features in the region (de Vos *et al*., 2014; Su *et al*., 2021): reversing monsoon currents in response to the changing wind field and the Sri Lanka Dome. During both the SW and NE monsoons, the model results indicated southward flow along both east and west coasts converging and then moving offshore along the south coast. As the water is flowing offshore, there is divergence of water at the coast which results in upwelling of colder water from depth. This was confirmed by the numerical model output which indicated a lower sea surface height at the centre of upwelling.

Knowledge of ocean circulation and upwelling patterns are critical for managing anthropogenic impacts in the oceans. Upwelling regions are high primary production regions due to supply of nutrients from the sub-surface and therefore are important for the fishing industry. In many regions globally, the productive fishery grounds are located along ocean fronts that separate colder and warmer waters. Knowledge of these regions and how they move are critical for the fishing industry and for the prediction of potential fishing zones (e.g. *http://www.nara.ac.lk/?page_id=14683*). The surface ocean circulation is critical for the prediction of dispersion of buoyant material such as oil and plastics. These were highlighted by recent maritime accidents in Sri Lankan waters associated with the MT *New Diamond* and MV *X-Press Pearl* incidents.

MT *New Diamond*, was a large crude oil carrier transporting approximately two million barrels (~270,000 tonnes) of crude oil from Mina al Ahmadi in Kuwait to Paradip refinery along the east coast of India. On 3 September 2020, a fire broke out in the engine room of the ship. At this time, the ship was ~65 kilometres off Sangaman Kanda Point along the east coast of Sri Lanka. After burning intermittently for almost a week, the fire was finally extinguished on 11 September 2020. However, a diesel oil spill that was ~1 km long was observed during this period. During this time the winds and currents were directed offshore and thus there was no impact at the coast. Interestingly, when the accident occurred the ship was located close to the convergence region of the cold-water tongue (Pattiaratchi & Wijeratne, 2020).

The container ship, MV *X-Press Pearl*, was transporting cargo from Jebel Ali (United Arab Emirates) to Colombo (Sri Lanka) via Hamad Port (Qatar) and Hazira (India). The ship departed the port of Hazira on 15 May 2021 and arrived in Colombo on 19 May and was anchored off Colombo Port ~9.5 km offshore in a water depth of 21 m. On 22 May, a fire started in the cargo hold and by 24 May fire had intensified burned for 13 days. On 2 June, efforts to move the ship into deeper waters failed, with the aft portion sinking to the seabed. The vessel was transporting 1,486 containers, with a mixed variety of cargo but included 78 tonnes of plastic nurdles (low-density polyethylene pellets) in three containers that were released to the ocean (Pattiaratchi & Wijeratne, 2021). Nurdles are small plastic pellets used as raw materials for the manufacture of virtually anything that is plastic (e.g., from plastic bags and bottles to automobile parts) and are by definition classified as microplastics as their size is < 5mm (Pattiaratchi *et al*., 2022). During the period of the incident, there were strong onshore winds (> 10 ms^{-1}) and swell waves (height ~2 m) and was associated with the beginning of the south-west monsoon with the currents flowing to the south along the west coast of Sri Lanka at the location of the accident and to the east along the south coast. The numerical model simulations (using the same model as described in this paper) indicated movement of the nurdle plume southwards with the prevailing currents and by 27 May the plume had extended to the south-west corner of the Island. On 29–31 May, the nurdle plume had detached from the coast and was moving offshore to the south-east (Pattiaratchi *et al*., 2022).

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