Journal of Marine Systems 150 (2015) 1–11

Contents lists available at ScienceDirect

Journal of Marine Systems

journal homepage: www.elsevier.com/locate/jmarsys

Evolution and sub-surface characteristics of a sea-surface temperature filament and front in the northeastern Arabian Sea during November–December 2012

P. Vipin [a,b], Kankan Sarkar [a,b,1], S.G. Aparna [a,b,*], D. Shankar [a,b], V.V.S.S. Sarma [c,b], D.G. Gracias [a,b], M.S. Krishna [c], G. Srikanth [c], R. Mandal [a,2], E.P. Rama Rao [d], N. Srinivasa Rao [d]

[a] CSIR-National Institute of Oceanography, Dona Paula, Goa 403004, India
[b] Academy of Scientific and Innovative Research (AcSIR), CSIR-NIO, Goa, India
[c] CSIR-National Institute of Oceanography (Regional Centre), Visakhapatnam, India
[d] ESSO-Indian National Centre for Ocean Information Services, Hyderabad, India

ARTICLE INFO

Article history:
Received 6 February 2015
Received in revised form 8 May 2015
Accepted 9 May 2015
Available online 16 May 2015

Keywords:
Mesoscale processes
Frontal systems
Potential fishery zones
Indian Ocean
West India Coastal Current

ABSTRACT

We used satellite-derived sea-surface-temperature (SST) data along with in-situ data collected along a meridional transect between 18.85 and 20.25°N along 69.2°E to describe the evolution of an SST filament and front during 25 November to 1 December in the northeastern Arabian Sea (NEAS). Both features were ~100 km long, lasted about a week, and were associated with weak temperature gradients (~0.07 °C km^{-1}). The in-situ data were collected first using a suite of surface sensors during a north–south mapping of this transect and showed the existence of a chlorophyll maximum within the filament. This surface data acquisition was followed by a high-resolution south–north CTD (conductivity–temperature–depth) sampling along the transect. In the two days that elapsed between the two in-situ measurements, the filament had shrunk in size and moved northward. In general, the current direction was northwestward and advected these mesoscale features. The CTD data also showed an SST front towards the northern end of the transect. In both these features, the chlorophyll concentration was higher than in the surrounding waters. The temperature and salinity data from the CTD suggest upward mixing or pumping of water from the base of the mixed layer, where a chlorophyll maximum was present, into the mixed layer that was about 60 m thick. A striking diurnal cycle was evident in the chlorophyll concentration, with higher values tending to occur closer to the surface during the night. The in-situ data from both surface sensors and CTD, and so also satellite-derived chlorophyll data, showed higher chlorophyll concentration, particularly at sub-surface levels, between the filament and the front, but there was no corresponding signature in the temperature and salinity data. Analysis of the SST fronts in the satellite data shows that fronts weaker than those associated with the filament and the front had crossed the transect in this region a day or two preceding the sampling of the front.

1. Introduction

Ocean fronts are narrow zones of enhanced horizontal gradients of water properties (for example, temperature) (Belkin et al., 2009; Klein and Lapeyre, 2009). Filaments (also referred to as plumes, tongues, or squirts in the literature) are narrow elongated regions surrounded by water with different properties; the edge of a filament exhibits a curvature (Flament et al., 1985; Haynes et al., 1993). Gradients in water properties are observed at the edges of filaments, and these gradients are often so high that the edges form fronts. An example is seen on the Atlantic coast of the Iberian peninsula, where the edges of upwelling filaments form strong fronts (Haynes et al., 1993). Edges of all filaments need not, however, be fronts. Ramp et al. (1991) showed that a few filaments in the California Current System (Miller et al., 1999) are enclosed by density fronts, but there are filaments that are not bounded by fronts, and the properties change gradually at the edges of these filaments. Off northern California, cold-water filaments have sharp southern and diffuse northern boundaries (Randerson and Simpson, 1993). When we consider a transect across these mesoscale features, we find that gradients are observed only once across a front, implying a monotonic distribution of water properties, but twice across a filament, implying a non-monotonic distribution of properties.

In addition to the gradient in physical properties, both fronts and filaments have chemical and biological manifestations that are reflected

* Corresponding author at: CSIR-National Institute of Oceanography, Dona Paula, Goa 403004, India.
E-mail address: aparna@nio.org (S.G. Aparna).
[1] Present Address: Department of Mathematics, Malda College, Malda, India.
[2] Present Address: Hind Geophysical Pvt Ltd, Mumbai, India.

http://dx.doi.org/10.1016/j.jmarsys.2015.05.003
0924-7963/

in variations in nutrients and chlorophyll (Belkin et al., 2009; Brink et al., 1998). This biogeochemical signature of fronts makes them highly productive (Etnoyer et al., 2006; Klein and Lapeyre, 2009; Lendt et al., 1999; Mackas et al., 1991) and such frontal regions have been exploited for commercial fishing for decades (Alemany et al., 2014; Laurs et al., 1984). Satellite technology, particularly infrared sensors for remote sensing of sea-surface temperature (SST), makes it possible to track such fronts over time (Ba and Fablet, 2010; Shaw and Vennell, 2000), and remote sensing of chlorophyll adds a distinct advantage from the viewpoint of fisheries (Lanz et al., 2009; Solanki et al., 2003a, 2010).

The characteristics of fronts and filaments depend on the region in which they form. In the temperate oceans, the horizontal gradient of properties is high and so is the vertical extent of the feature (Dong et al., 2006; Moore et al., 1999). Cross-frontal differences in SST and sea-surface salinity (SSS) can be as large as 10–15 °C and 2–3 psu, respectively; typical differences are of the order of 2–5 °C and 0.3–1.0 psu (Belkin et al., 2009). For example, the Florida Current and the Gulf Stream are bordered by two perennial fronts, across which the SST difference ranges between 2–10 °C and 1.5–4.5 °C, respectively (Belkin et al., 2009). In the Atlantic, filaments off Cape Sao Vicente (Portugal) have a length (width) of about 250 km (50 km) and the temperature difference between the filament and surrounding waters is about 2–3 °C (Corré and Jesus, 2003; McCreary et al., 1991). Hickox et al. (2000) studied SST fronts in East China Sea, Yellow Sea, and Bohai Sea and found the cross-frontal SST range up to 4 °C, with the fronts exhibiting strong seasonal variability in this region. Apart from such high horizontal gradients, upwelling velocities tend to be higher in a frontal regime (Klein and Lapeyre, 2009; Mahadevan and Tandon, 2006) and enhanced vertical mixing and nutrient flux is observed in the filaments and frontal zones (Johnston et al., 2011; Niiler et al., 1989). Observations show that the vertical extent of the Kuroshio front is ~100 m (Park and Chu, 2006) and the Agulhas front is mainly a subsurface front, with high horizontal temperature gradients beneath 100–150 m (Belkin and Gordon, 1996).

In the tropical oceans, SST fronts or filaments with such high gradients are observed only in the regime of strong western-boundary currents and upwelling zones (Evans and Brown, 1981). In the north Indian Ocean (NIO), a long, persistent frontal system in the Gulf of Aden adjoining the Arabian Sea shows a cross-frontal temperature difference of ~5 °C during the summer monsoon (Belkin et al., 2009), when strong upwelling is forced off both Somalia (to the south of the gulf) and Oman (to the north of the gulf) (McCreary et al., 1993; Wyrtki, 1971). A temperature difference of ~6 °C was observed across an upwelling front along the west coast of India, during the summer monsoon in 1987 (Unnikrishnan and Antony, 1992). Often associated with such strong temperature fronts are long filaments (see, for example, Lierheimer and Banse (2002) and the review by Hood et al. (2009)). In general, the temperature gradients tend to be weaker in the tropics and the temperature difference was just 1 °C across cold-water filaments observed during the summer monsoon off Somalia in 1997 (Lendt et al., 1999) and Oman in 1995 (Barber et al., 2001). In the southeastern Arabian Sea (SEAS), Maheshwaran et al. (2000) observed SST fronts at the surface and at 50 m; the cross-frontal gradient was ~0.02 °C km^{-1}, an order of magnitude smaller than in the temperate oceans. A similar gradient was observed in a transect in the Bay of Bengal off the east coast of India (Hareesh kumar et al., 2013); the transect sampled across two fronts during December 1997 and January 1998, and the cross-frontal temperature gradient was just 0.07 °C km^{-1}. The vertical extent of these fronts was also smaller, ranging from 25 m to 40 m.

In spite of the much weaker temperature gradients observed across tropical fronts and filaments, the link between such mesoscale fronts or filaments and fisheries in the temperate oceans [see, for example,] (Alemany et al., 2014; Laurs and Burcks, 1985; Maul et al., 1984) has inspired their use for commercial fisheries in India (Mahadevan, 2014; Narendranath et al., 1991; Solanki et al., 1998, 2001a, 2003a, 2008), and SST fronts, along with satellite chlorophyll data, have been used to delineate potential fishery zones (PFZs) in the Indian Exclusive Economic Zone (EEZ) (Solanki et al., 2001b, 2005; Zainuddin and Saitoh, 2004). The PFZ advisories are issued by the Indian National Centre for Ocean Information Services (INCOIS; http://www.incois.gov.in/). Studies suggest that the fish catch in a PFZ is higher than in a non-PFZ (Choudhary et al., 2007; Deshpande et al., 2011; Solanki et al., 2003b). Economic analyses suggest that the PFZ advisories reduce the cost of fishing (Nayak et al., 2003), implying that the ephemeral SST fronts associated with these PFZs have a commercial value.

Most of the studies on such fronts in the NIO are either confined to the surface (owing to the use of only satellite data) (Belkin et al., 2009), or represent a few hydrographic sections that sampled across these features (Unnikrishnan and Antony, 1992), (Hareesh kumar et al., 2013; Maheshwaran et al., 2000), or report fish catch within and outside a designated PFZ (Choudhary et al., 2007; Deshpande et al., 2011; Solanki et al., 2003b, 2005). Yet, between the formation of an SST front or filament, which is a *surface* physical feature that can be discerned in satellite data, and the fish that lie at the apex of the marine food web is an intricate web of chemical and biological processes that determine the evolution of the complex marine ecosystem. In order to gain insight into the ecosystem dynamics underlying the PFZs, an inter-disciplinary programme called OCEAN FINDER was launched by the CSIR-National Institute of Oceanography in 2012. One task under this programme is collecting and analysing data, across a host of disciplines, on transects across such SST fronts. As noted by Hopkins et al. (2010), to capture the evolution of these mesoscale features as they “grow, merge, split, shrink, and disappear” over a short span of time, typically a week, is a challenge as fronts and filaments invariably represent nonlinear flows and processes over a range of different temporal and spatial scales. Our plan therefore was to determine the contour of a front or filament in satellite SST data and run a transect perpendicular to the front. Given that the cross-frontal spatial scale is small, the transect is expected to be short, of the order of just 100 km. Though these mesoscale features are seen practically all over the NIO, their concentration is not uniform in space and time.

A cruise in the eastern Arabian Sea was allotted to this programme during 23 November to 11 December 2012. Analysis of daily and 3-day averages of MODIS (Moderate Resolution Imaging Spectroradiometer) Aqua SST data (see Table 1 for the data sources) for November–December during 2008–2011 showed that fronts are more ubiquitous in the northeastern Arabian Sea (NEAS) during this period (Fig. 1). Obenour (2014) analysed 30 years of SST data and showed that the average probability of a clear pixel (no clouds) and of the existence of a front is also higher in the NEAS than in other regions of the NIO.

Hence, we decided to carry out the cruise in the NEAS, which is an interesting laboratory for studying the coupling between physics and ecosystem dynamics even on spatial scales much larger than those associated with the mesoscale SST fronts. This region is highly productive owing to surface cooling by dry continental winds that lead to convective mixing during the winter monsoon (Banse, 1968; Shetye et al., 1992). This winter cooling deepens the mixed layer, entraining nutrients into it, and leading to high productivity (Banse, 1984; Madhupratap et al., 1996; McCreary et al., 2009). As a result of the evaporation associated with this winter cooling, the salinity is higher at the surface in the NEAS. The vertical profile of salinity shows four salinity extrema (Rochford, 1964; Shenoi et al., 1993).

This paper describes the physical aspects of a Filament and a Front that were sampled during the cruise in November–December 2012. (Capitalisation, i.e., use of *Filament* or *Front*, implies a reference to *the* filament or front; when referring to other filaments or fronts, or to filaments and fronts in general, we use the small case.) We use satellite data to describe the evolution of the fronts in the region of interest during the cruise, and use data collected using a surface-sensor system and a CTD (conductivity–temperature–depth) to describe the variability of temperature, salinity, and chlorophyll. The paper is organised as follows. Section 2 describes the data and methods, including the cruise