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Persistence of Cold Wedges in the Somali Current System

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Key Points:

- First observational evidence that the northward Somali Current and associated cold wedges may persist into the boreal fall intermonsoon
- Rapid breakdown of the Somali Current system after the onset of the winter northeast monsoon and the arrival of a cyclonic eddy
- Persistence of cold wedges and associated circulations may affect air-sea interactions and biogeochemical processes within the ecosystem

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Abstract

The Somali Current system in the western Arabian Sea reverses seasonally with the South Asian Monsoon and is associated with localized upwelling cells or cold wedges during the summer southwest monsoon. Drifter trajectories in boreal summer and fall 2014 provide rare observational evidence that the northward Somali Current and associated cold wedges can persist into the boreal fall intermonsoon period. The near-surface circulation and sea surface temperatures further suggest that the wedge-like surface signatures may intermittently be capped and then reappear at a later time. Our observations show that the northward Somali Current system rapidly decayed within 1 week after the onset of the winter northeast monsoon and the arrival of a cyclonic eddy at the coast in early November 2014. This eddy may not only have affected regional ocean-atmosphere interactions but also biogeochemical processes and the marine ecosystem through the transport of water properties and locally induced upwelling.

Plain Language Summary

The Indian Ocean rim countries are home to about one third of the global population and depend on rain-fed agriculture as well as fisheries supported by coastal upwelling systems, which are linked to monsoon variability. A better understanding of regional air-sea phenomena is therefore needed, and we report here on recent drifter observations in the western Arabian Sea that provide new insights into the persistence of upwelling cells or cold wedges and associated circulation patterns in the southern part of the Somali Current system, which reverses seasonally with the monsoon. Our observations during the 2014 drought year reveal that the northward Somali Current and associated cold wedges can persist into the intermonsoon period following the summer southwest monsoon. The wedge-like surface signatures in the surface circulation and sea surface temperature may intermittently be capped and then reappear at a later time. During our observational period, the northward Somali Current system of the summer southwest monsoon rapidly decayed within 1 week after the onset of the winter northeast monsoon and the arrival of a mesoscale feature at the coast in early November. The latter may not only have affected regional ocean-atmosphere interactions but also biogeochemical processes and the marine ecosystem.

1. Introduction

The Somali Current system in the western Arabian Sea reverses seasonally with the South Asian Monsoon and is associated with localized upwelling cells or cold wedges during the summer southwest monsoon. These cold wedges typically develop on the northern side of both the Southern Gyre and the Great Whirl; that is, where the flow turns offshore (e.g., F. A. Schott & McCreary, 2001; F. A. Schott et al., 2009). The southern cold wedge has been found to migrate northward in some years and then to coalesce with the Great Whirl suggesting a breakdown of the two-gyre system (e.g., Evans & Brown, 1981; F. Schott, 1983). The kinematics and dynamics of the Great Whirl have received much more attention over the years (e.g., Beal & Donohue, 2013; Fischer et al., 1996) than those of the Southern Gyre. During the early phase of the summer southwest monsoon, the southern Somali Current develops as a cross-equatorial extension of the northward East African Coastal Current and reaches to about 3°–4°N where it turns offshore and retroflects across the equator forming the Southern Gyre; a well-defined upwelling cell or cold wedge then occurs on its northern side (e.g., F. Schott, 1983; F. A. Schott & McCreary, 2001). North of this region, the local alongshore winds cause an upwelling regime as well as northward surface flow along the boundary (e.g., Swallow et al., 1983; F. Schott, 1983). During the late phase of the summer southwest monsoon when the two-gyre system breaks down, the Somali Current becomes a continuous northward western boundary current flowing northward to about 10°N (e.g., F. Schott, 1983; F. Schott et al., 1990). In the following intermonsoon period, the northward cross-equatorial flow continues up to about 2°–3°N where the surface current turns offshore again (e.g., F. Schott & Fieux, 1985; F. Schott et al., 1990). Observations have also corroborated the existence of Somali Undercurrent manifestations at various locations and times which generally flow southward/northward north/south of about 4°N where they turn offshore (e.g., F. A. Schott & McCreary, 2001).

While the Great Whirl has been observed to persist well into the boreal fall intermonsoon period (e.g., Beal & Donohue, 2013; Melzer et al., 2019) and subsurface remnants have even been found during the winter northeast monsoon (e.g., Bruce et al., 1981; Bruce & Volkmann, 1969), the persistence of circulation patterns associated with the southern cold wedge has largely been unknown before this study. Warren et al. (1966) inferred flow patterns in and around the Somali Current from hydrographic property distributions collected in August–September 1964 and pointed to an irregularity in its path near 4°N where the surface current appeared to have first turned abruptly eastward, moved offshore, and then looped back toward the coast north of that latitude. Similarly, Swallow et al. (1983) described sudden changes in the trajectory of a drifter upon encountering the frontal cold-wedge region during the 1979 summer southwest monsoon. It has been suggested that the observed anomalies of the Somali Current system around 4°N may be related to topographic effects (e.g., F. Schott, 1983; Warren et al., 1966) but model studies seem to contradict this explanation; that is, in simulations where the deep topography was artificially changed, the model circulation was not affected (Esenkov & Olson, 2002). On the other hand, layer-model solutions have indicated that the observed flow patterns may result from the structure of the upper layer consistent with geostrophy (e.g., McCreary et al., 1993).

Due to piracy in the Arabian Sea, new observations have been difficult to obtain for over 2 decades, hampering progress in understanding the regional ocean-atmosphere processes. However, the deployment of autonomous platforms such as Surface Velocity Program (SVP) drifters released as part of the Global Drifter Program (GDP) have provided a way to partially fill this observational gap (e.g., Maximenko et al., 2013; P. Niiler, 2001). Measurements of sea surface temperature (SST) and associated circulation patterns in the Arabian Sea are important because regional SST features such as the cold wedges in the Somali Current system have been found to co-vary with changes in the atmospheric boundary layer on the oceanic mesoscale during the summer southwest monsoon (e.g., Mafimbo & Reason, 2010; Vecchi et al., 2004). Therefore they may also affect the development of the South Asian Monsoon and ultimately feed back to rainfall over India (e.g., Izumo et al., 2008; Vecchi & Harrison, 2004).

This study provides new and rare observational evidence of the persistence of cold wedges and associated circulation patterns in the southern part of the Somali Current system during the 2014 drought year (i.e., weak monsoon), which co-occurred with both El Niño and a negative Indian Ocean Dipole (IOD) event (Roman-Stork et al., 2020, Table 1). Despite the complex influence of the El Niño-Southern Oscillation (ENSO) and IOD on the summer southwest monsoon, drought years have generally increased since the mid 1990s (e.g., Roman-Stork et al., 2020) and this study with its potential implications for regional ocean-atmosphere interactions as well as biogeochemical processes and the marine ecosystem (e.g., Hood et al., 2017; Wiggert et al., 2005) is therefore timely in view of a changing climate. Since coastal upwelling plays a vital role in the management of fisheries for several East African nations, anomalies in the system may further have consequences for food security and even lead to regional instabilities (Ochiewo et al., 2020).

2. Data and Methods

2.1. Surface Drifters

Within the framework of the GDP, drifter deployments in the Indian Ocean began in 1985 and recent research initiatives such as “Northern Arabian Sea Circulation—autonomous research” (NASCar; L. Centurioni et al., 2017) were designed to mitigate the regional data gap through regular bi-weekly deployments within the Somali Current system for approximately 5 years. In this study, we use quality-controlled 6-hr interpolated data from satellite-tracked Lagrangian SVP drifters (http://www.aoml.noaa.gov/phod/dac/index.php; Hansen & Poulain, 1996; Lumpkin & Centurioni, 2019) that provide observations of 15-m currents and SST in their basic configuration (e.g., L. R. Centurioni, 2018). The velocity observations are accurate to about 0.01 m/s for winds up to 10 m/s when a wind-slip correction is applied to drogued drifters (P. P. Niiler et al., 1995) but we also make use of undrogued drifter data after applying the correction by Pazan and Niiler (2001). The drogue presence is detected using a strain gauge inside the drifter's hull and SST is measured at about 0.2-m depth with an accuracy of 0.05°C (e.g., L. R. Centurioni, 2018).

Following Hormann et al. (2019), we further use an extended version of their gridded drifter/altimetry/wind synthesis covering the period 1993–2018 to describe the time-dependent near-surface currents in the Arabian Sea (cf. Shroyer et al., 2021) where the altimetry-based data were provided by the Copernicus Marine Environment Service (CMEMS: http://marine.copernicus.eu; e.g., Ducet et al., 2000) and winds were taken from the European Center for Medium-Range Weather Forecasts ERA-Interim reanalysis (ECMWF: https://www.ecmwf.int; Dee et al., 2011) with associated momentum fluxes derived from the COARE (Coupled Ocean-Atmosphere Response Experiment) 3.5 algorithm (Edson et al., 2013) as before.

2.2. Ancillary Data

Quality-controlled temperature profiles were obtained from an Argo float (WMO ID 1901046) in the western Arabian Sea and its 10-day cycle data are freely available at https://fleetmonitoring.euro-argo.eu/float/1901046 (Argo, 2022; Wong et al., 2020).

In addition, the daily Optimum Interpolation SST (OISST) v2.0 product is used which is available on a 1/4° spatial grid since late 1981. The analyses are produced by blending observations from various platforms (i.e., satellites, ships, and buoys) where gaps are filled by optimum interpolation after applying a bias correction to satellite and ship data with respect to moored and drifting buoys to account for platform and sensor differences (https://psl.noaa.gov/data/gridded/data.noaa.oisst.v2.highres.html; Reynolds et al., 2007).

We also use daily level-3 chlorophyll data from the GlobColour project, which are provided as 1/24° global maps through merging outputs from different satellite sensors. The derived chlorophyll concentrations for case-1 waters, used as a proxy for the biomass of phytoplankton, are here based on the GSM (Gram per Square Meter) method, which merges the normalized single-sensor reflectances at the original wavelengths without intercalibration (https://hermes.acri.fr; Maritorena & Siegel, 2005).

3. Results and Discussion

Analysis of the drifters deployed during NASCar from ships of opportunity reveals a pronounced surface signature of the southern cold wedge near 4°N in July 2014 as expected. However, we have found that the near-surface current signature of the cold wedge persisted until November 2014, thus suggesting that the northward Somali Current may have existed well beyond the demise of the summer southwest monsoon (Figure 1). The cold wedge was also observed by an Argo float and its upper-ocean temperature profiles show the progression of the near-surface cooling as well as shoaling of the cold wedge from the beginning of June to September 2014 (Figures 1c and 1d). Although drifter velocities are much slower during boreal fall compared to boreal summer, both selected tracks indicate that the Somali Current extends over the shelf north of about 5.5°N. This extension of the current may have been missed by other observational efforts and our observations appear to be among the first confirming the near-shore Somali Current extension during the summer southwest monsoon and following intermonsoon period just before the onset of the winter northeast monsoon. It should be noted that drifter SSTs are warmer by about 5°C in November than in July where the 2014 summer southwest monsoon has been classified as a drought year with anomalously low winds (e.g., Trott et al., 2017). Despite generally weak winds during the early intermonsoon period (cf. Figures 2d and 2e), the observed cold wedge in November could be due to upwelling-favorable winds and the warm drifter SSTs could be related to the upwelling of warmer than usual subsurface water. In recent decades, there has been a prevalence of weak monsoon seasons which may be linked to global climate change associated with an increase in both upper-ocean heat content and evaporation due to a warming ocean and a more moisture-holding atmosphere (e.g., Roman-Stork et al., 2020).

Since the individual drifter trajectories do not allow for a detailed description of the SST evolution in the Arabian Sea between July and November 2014, Figure 2 shows OISST maps with superimposed COARE wind stress fields. The southwest monsoon winds are generally upwelling favorable during the first 3 months after onset and coastal SSTs confirm the drifter-observed cold wedge in July; note that there are no indications of a northward cold-wedge propagation in 2014 (cf. Trott et al., 2017). During October, the winds are weak and more onshore with SSTs being warmer by about 2°C compared to September. Focusing on early November when the winds start blowing from the northeast, the SSTs indicate again a wedge-like signature near 4°N which decays within 1 week. To our knowledge, this is the first observation of a reappearing or persisting cold wedge during the boreal fall intermonsoon indicating an intermittent capping by, for example, remotely-forced downwelling Rossby waves (e.g., Chatterjee et al., 2019) or a possible surfacing of a Somali Undercurrent in this region (cf. F. A. Schott & McCreary, 2001). The model study by Anderson et al. (1991) has indicated that the cold wedge near 4°N is

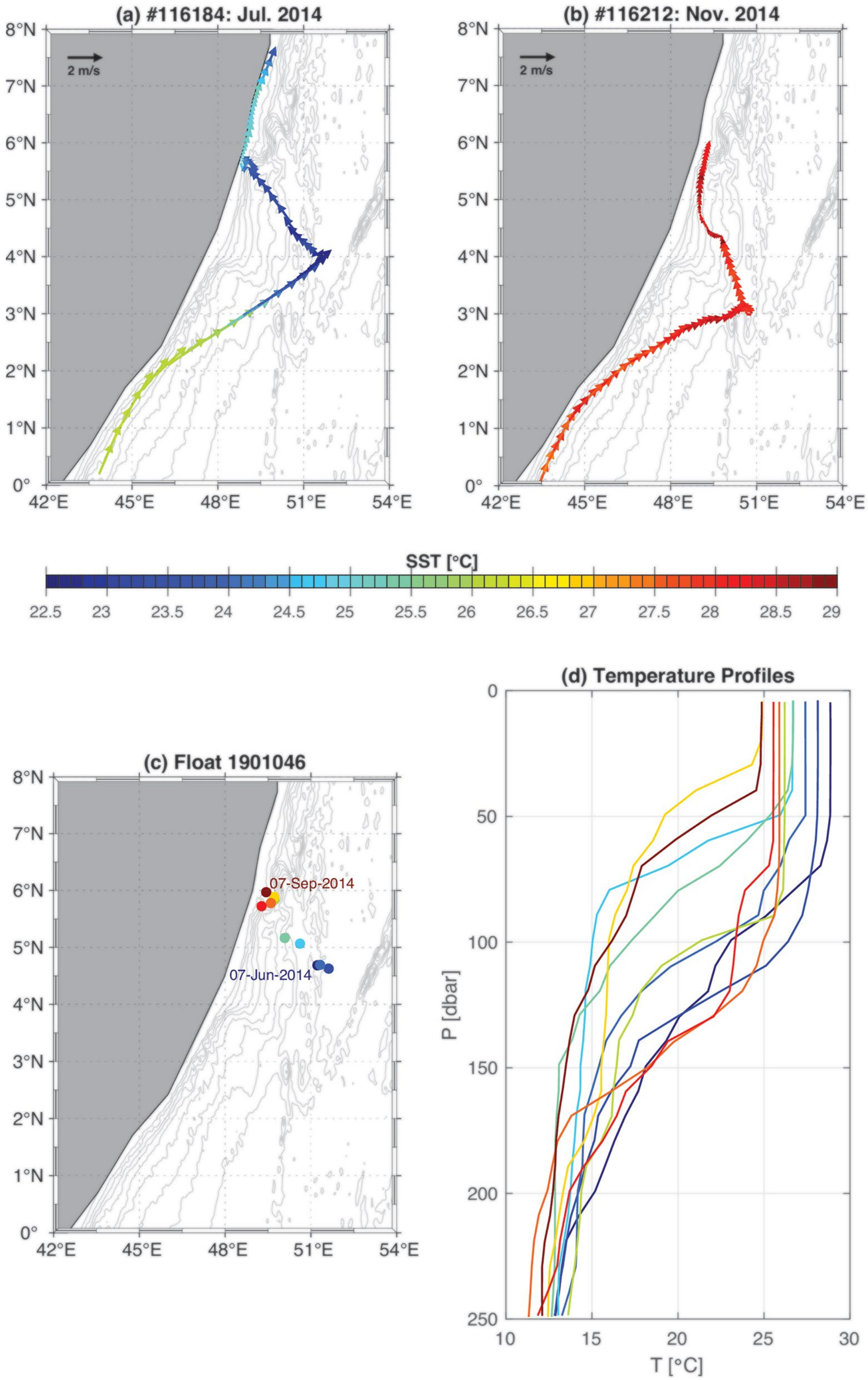

Figure 1. Surface currents as observed by (a) Drifter #116184 in July 2014 and (b) Drifter #116212 in November 2014 color-coded by their SST measurements; note, both drifters had lost their drogue during the shown time periods. (c) Positions and (d) corresponding upper-ocean temperature profiles from an Argo float in the northern part of the cold wedge from the beginning of June 2014 until the end of its lifetime 3 months later; temperature profiles are color-coded by positions.

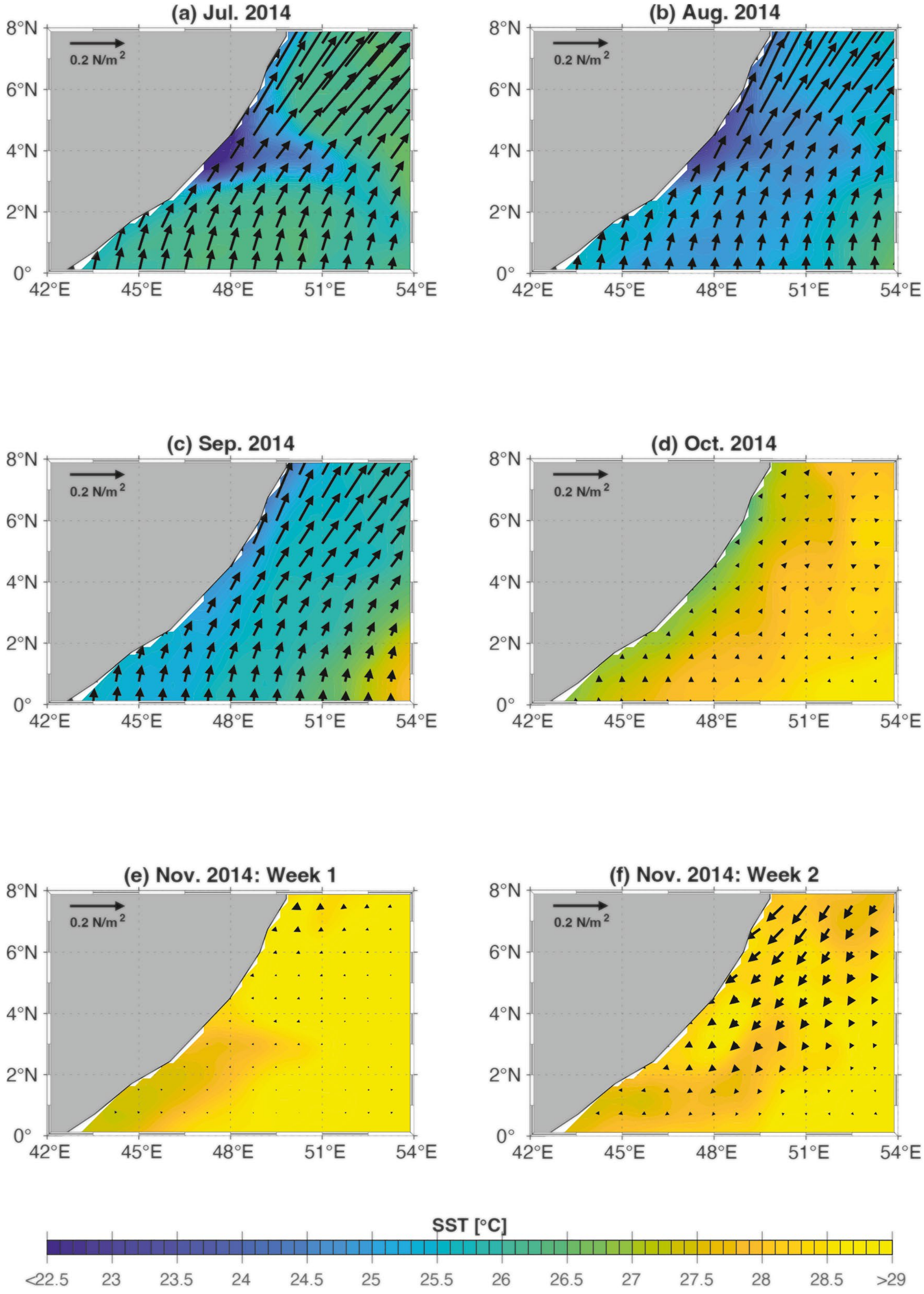

Figure 2. Monthly OISST maps with superimposed COARE wind stress vectors for (a) July 2014, (b) August 2014, (c) September 2014, and (d) October 2014 as well as (e)–(f) weekly OISST maps with superimposed COARE wind stress vectors for the (e) first and (f) second week of November 2014, respectively.

sensitive to the vertical temperature profile and only forms when there is cold water close to the surface; that is, processes affecting the regional stratification such as the above may explain our observation of a reappearing or persisting cold wedge.

Further insights into the developments in the Somali Current region between boreal summer and fall 2014 are provided by the drifter/altimetry/wind synthesis (Figure 3) that allows the computation of the near-surface currents and associated eddy kinetic energy ($\boldsymbol{EKE} = \frac{\acute{u}^2+\acute{v}^2}{2}$, where $\acute{u}$ and $\acute{v}$ are the zonal and meridional velocity anomalies, respectively). In July and August the Somali Current turns offshore at about 3°N, flows around the observed cold wedge (cf. Figure 2a), and then continues northward along the coast; however, there are no clear indications of the Southern Gyre in 2014 (cf. Trott et al., 2017). The area where the Somali Current turns offshore is associated with enhanced EKEs in both months, which also occur in September when the Somali Current becomes a continuous northward western boundary current in agreement with previous studies (e.g., F. Schott, 1983; F. Schott et al., 1990). The Somali Current continues to flow northward during October, but near-surface velocities and EKE levels are lower compared to September; note that there is an early manifestation of a cyclonic eddy located around 3°N, 53°E. This mesoscale feature becomes much more prominent in the first week of November when it is centered at about 4°N, 49°E. During this time, the Somali Current is still weakly northward along the southern boundary of the wedge and north of the eddy with offshore flow near 2°N. The progression of the wedge and currents associated with the coastal eddy are apparent in Figures 3e and 3f. The northward expression of the Somali Current finally dissipates in the following week when the eddy nears the coast and the winter northeast monsoon sets in (cf. Figure 2f).

The observed eddy in boreal fall 2014 may have played an important role in the breakdown of the northward Somali Current and to further investigate this, a corresponding longitude-time diagram of CMEMS sea level anomalies (SLAs) is shown in Figure 4a. The eddy, which is associated with negative SLAs due to its cyclonic character, appears to be generated near 54°E at the beginning of October and then propagates westward toward the Somali coast with a phase speed of about 0.2 m/s. Such mesoscale features typically form due to baroclinic current instabilities and can transport water properties trapped within them over long distances influencing heat and momentum fluxes as well as marine ecosystem dynamics (e.g., Chelton et al., 2011).

To further illustrate the importance of the above eddy for the Somali Current region, including its ecosystem, Figure 4b shows a GlobColour chlorophyll map at the beginning of November 2014. The eddy is clearly recognizable in the image, with particularly enhanced values in its core and southern periphery. Such chlorophyll anomalies have been linked to various biophysical mechanisms which include horizontal advection, vertical fluxes, and eddy-induced stratification/mixing (e.g., Gaube et al., 2014). Following Foltz et al. (2012), we have computed the linear Ekman pumping from the regional COARE wind stress fields for the first 2 weeks of November 2014 indicating upwelling in association with the observed cyclonic eddy (Figures 4c and 4d); that is, Ekman pumping can act on the upward displacement of the isopycnals within the eddy to move nutrients into the euphotic zone (cf. Chenillat et al., 2015). Through the absorption of solar radiation in the upper ocean, chlorophyll distributions can affect SSTs and their influence on the South Asian Monsoon has been demonstrated for the Arabian Sea (e.g., Nakamoto et al., 2000; Turner et al., 2012). The changes in water properties associated with the observed eddy may therefore not only have implications for regional biogeochemical cycles but also ocean-atmosphere interactions in the Indian Ocean (cf. Gera et al., 2020).

4. Conclusions

Drifter trajectories in the western Arabian Sea during boreal summer and fall 2014 have revealed that the northward Somali Current and associated cold wedges can persist into the intermonsoon period following the summer southwest monsoon. Monthly maps of the surface circulation and SSTs in this region have further indicated that the wedge-like surface signatures may intermittently be capped by processes affecting the vertical stratification such as remotely-forced downwelling Rossby waves (e.g., Chatterjee et al., 2019) suggesting that subsurface remnants can reappear at a later time as observed here. There have also been observations of Somali Undercurrents during boreal fall/winter (cf. F. A. Schott & McCreary, 2001) and their possible surfacing around 4°N may be another cause of the reappearing cold wedge during the boreal fall intermonsoon because the local SSTs have been found to be sensitive to the subsurface temperature profile (Anderson et al., 1991). Associated SST-induced changes in the lower atmosphere may further result in variations of the surface heat and moisture

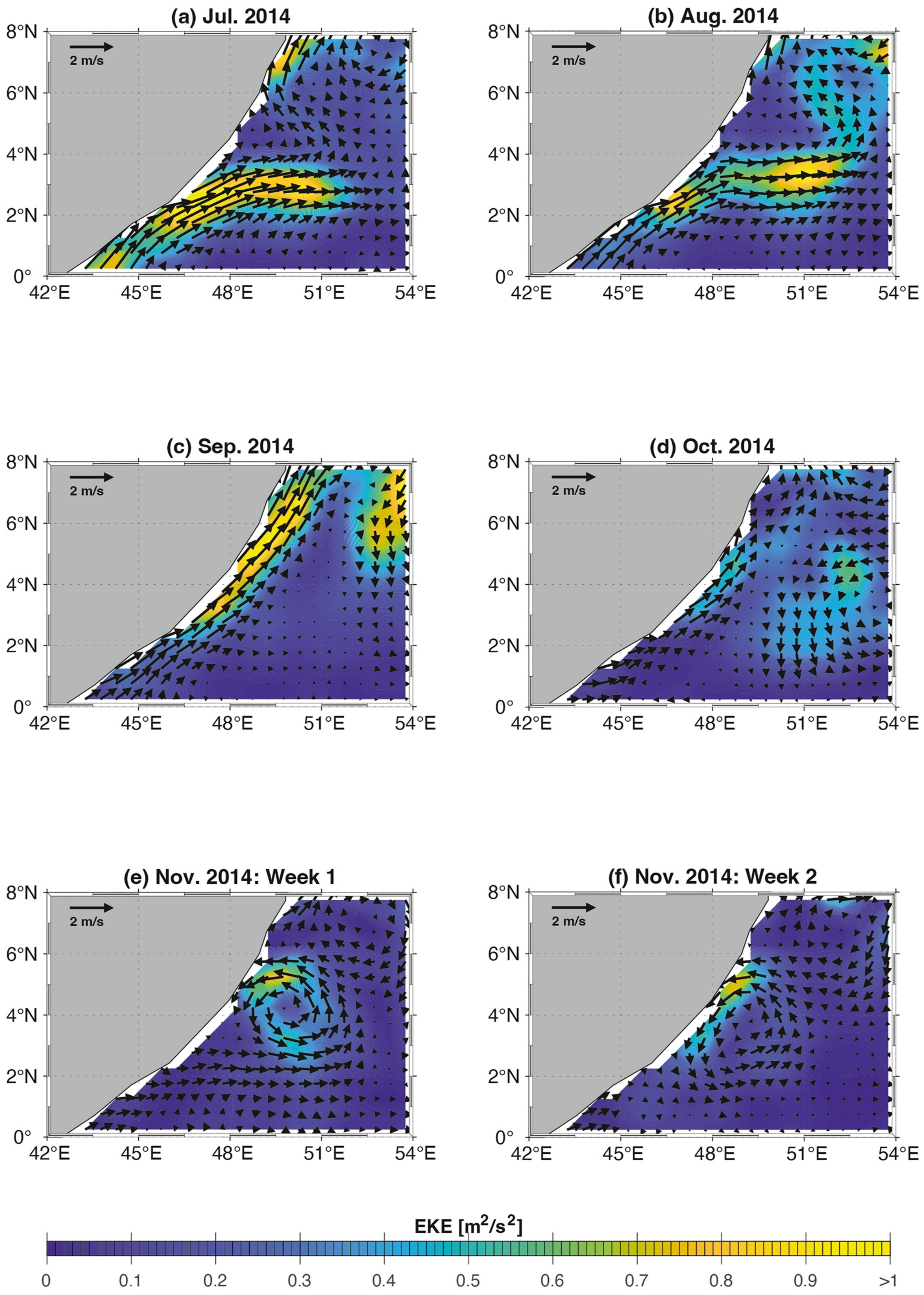

Figure 3. Same as Figure 2, but for EKE with superimposed surface currents as derived from the drifter/altimetry/wind synthesis.

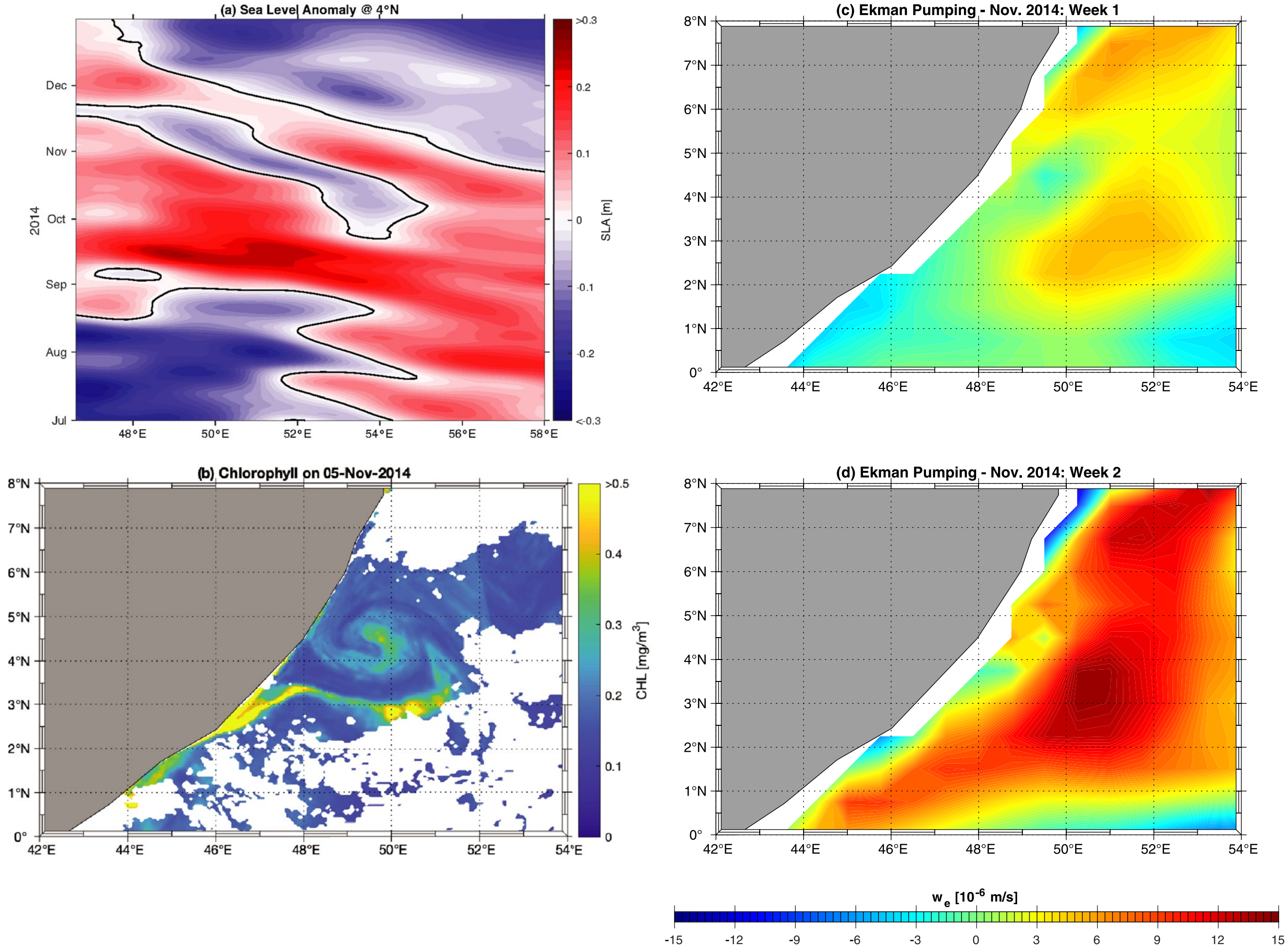

Figure 4. (a) Longitude-time diagram of CMEMS SLA averaged between 3°N and 5°N. (b) Distribution of GlobColour chlorophyll on 05 November 2014. (c and d) Ekman pumping velocity for the (c) first and (d) second week of November 2014, where positive/negative values indicate upwelling/downwelling.

fluxes (cf. Vecchi et al., 2004) and therefore be of importance for the developing winter northeast monsoon. The northward Somali Current system of the 2014 summer southwest monsoon finally dissipated within 1 week once winds started blowing from the northeast and a cyclonic eddy impinged on the coast. The propagation diagram in Figure 4a indicates that this mesoscale feature in early November is not formed locally due to the breakdown and consequent instability of the Somali Current, but rather from offshore circulation dynamics. This eddy may not only have contributed to the rapid disintegration of the surface circulation and associated features but also affected regional ocean-atmosphere interactions as well as biogeochemical processes and the marine ecosystem through its transport of water properties such as chlorophyll and locally induced upwelling. Further advances in understanding of climatic processes in the northern Indian Ocean will therefore rely on both sustained observations and coupled biogeochemical models and be of prime importance in view of a changing climate.

Data Availability Statement

All data used in this study are available from sources listed below (cf. Section 2).

- Drifter data: http://www.aoml.noaa.gov/phod/dac/index.php (Hansen & Poulain, 1996; Lumpkin & Centurioni, 2019)
- CMEMS altimetry-based data: http://marine.copernicus.eu (e.g., Ducet et al., 2000)
- ECMWF wind data: https://www.ecmwf.int (Dee et al., 2011)
- Argo float data: https://fleetmonitoring.euro-argo.eu/float/1901046 (Argo, 2022; Wong et al., 2020)

- OISST data: https://psl.noaa.gov/data/gridded/data.noaa.oisst.v2.highres.html (Reynolds et al., 2007)
- GlobColour chlorophyll data: https://hermes.acri.fr (Maritorena & Siegel, 2005)

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