

Variations in the inorganic carbon components in the thermal fronts during winter in the northeastern Arabian Sea



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ARTICLE INFO

Article history:

Received 30 October 2014

Received in revised form 26 December 2014

Accepted 29 December 2014

Available online 5 January 2015

Keywords:

Carbon dioxide

Fronts

Air-sea exchange

Arabian Sea

ABSTRACT

In order to examine the variations in inorganic carbon components in the thermal fronts, seven fronts have been sampled in the northeastern Arabian Sea during winter. The sea surface temperature (SST) was cooler by 0.2 to 1.03 °C within the fronts sampled and three out of seven fronts were relatively saltier (by 0.04 to 0.10) and others were fresher (by 0.03 to 0.13) compared to outside the front. Increase in chlorophyll-a (Chl-a) was observed by 0.05 to 0.6 mg m⁻³ in the four fronts and marginal decrease was noticed in other fronts (0.02–0.23 mg m⁻³). The increase in Chl-a within the front from that of outside showed linear relation with magnitude of difference in temperature and salinity suggesting that enhanced vertical mixing brought nutrients to surface to support phytoplankton biomass in the fronts. Dissolved oxygen was relatively under-saturated by ~1.6% in the frontal zone compared to outside suggesting that dominant heterotrophy in the former region due to availability of high phytoplankton biomass. Dissolved inorganic carbon (DIC) was higher in the frontal zone by 3 to 41.5 μM than outside. The salinity normalized DIC displayed linear relation with Chl-a and inverse correlation with dissolved oxygen saturation suggesting that both auto and heterotrophic activities may be responsible for changes in DIC in the frontal zone. The higher levels (by 3 to 50 μatm) were noticed in the frontal zone compared to outside, however, the magnitude of difference was linearly correlated with difference in SST and Chl-a between within and outside fronts. Based on the simple model, it was noticed that biological and mixing effects were dominant controlling factors for pCO₂ followed by thermal and flux effects. The biological effect was dominant at fronts 1 and 3 while mixing effect controls at fronts 2, 4 and 6. This study suggests that fronts act as a source or sink depends on the strength of the mixing process associating with biological response and also age of the front.

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1. Introduction

Ocean fronts are generally defined as an interface among two or more water masses with different characteristics. Frontal zones are known to hinder the exchange of material between inshore and offshore (Brink, 1987) and therefore they are important zones to arrest spreading of pollutants. Frontal regions are rich in nutrients and highly productive (Franks, 1992; Fiala et al., 1994; Pitcher et al., 1998; Basterretxea and Aristegui, 2000; Jacquet et al., 2002; Brown et al., 2008; Munk et al., 2003; Nammalwar et al., 2013). Thus, fronts represent enriched habitats that contribute disproportionately to regional productivity, nutrient cycling, trophic ecology, carbon fluxes and sequestration. Hence these regions are attracted by several marine researchers to study mechanisms associated with frontal formation and material cycling (Chen, 1983; Liu et al., 2003; Zhao, 1985; Lu et al., 2010; Li et al., 2000).

Several studies have been conducted to examine the physical and biogeochemical characteristics of the frontal zones in the temperate region. For instance, Borges and Frankignoulle (2003) observed thermal front (Ushant front) in the Western English Channel. This front is formed between the warm stratified northern waters and the colder permanently well-mixed southern waters of the Eastern Channel (Pingree et al., 1979). The thermal fronts were also noticed between destratified and stratified waters along the Armorican Shelf and Western English Channel. Very low pCO₂, high dissolved oxygen and chlorophyll-a were found in the warmer waters and vice versa on the colder waters suggesting high DIC fixation by phytoplankton in the warmer waters of the frontal structure in the western English Channel (Jordan and Joint, 1984; Borges and Frankignoulle, 2003; Harlay et al., 2010) and shelf break of Bay of Biscay (Suykens et al., 2010). Loggerwell et al. (2001) suggested that recruitment success of Pacific sardine may be related to climate-related variability in mesoscale eddies. Subduction at fronts is a possible explanation for the massive imbalance of new versus export production that arises when only contemporaneous processes in homogeneous water parcels are considered (e.g., Stukel et al., 2011). Recently, it was noticed that high CO₂ fluxes were associated with subtropical frontal zone in the Southern

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Ocean using drifters and it has important implications on sequestration of atmospheric CO₂ (Boutin et al., 2008; Resplandy et al., 2014). The studies on fronts in the tropical region, such as Indian Ocean, were mainly concentrated on identifying potential fishing zone (PFZ). Since more than a decade, satellite based sea surface temperature (SST) and chlorophyll features have been used to differentiate water masses in the northeastern Indian Ocean in context of understanding PFZs (Solanki et al., 1998, 2000). Intensive ground truth data have been collected and found that 70–80% of success was achieved on identifying PFZ using remote sensing data (Solanki et al., 1998, 2000; Nammalwar et al., 2013). However, no efforts have been made so far to quantify biogeochemical processes in the frontal zone in the Indian Ocean.

The northern Arabian Sea (northwestern Indian Ocean) is a highly productive zone during winter (November to March) due to injection of nutrients to surface through convective mixing (Madhupratap et al., 1996). Despite high nutrients (nitrate >2 μM), primary production is significantly lower during winter than summer (Bhattathiri et al., 1996; Barber et al., 2001) and was attributed to deeper mixed layer than euphotic depth during former season. As a result, phytoplankton experiences both dark and light cycles which lead to decrease in phytoplankton growth. On the other hand, several fronts form in the northeastern Arabian Sea due to advection of low saline waters from the near-shore by offshore winds along the Indian peninsula. Recently first ever observations were carried out on frontal zone to characterize the chemical and biological features. They noticed that fronts are associated with high nutrients and phytoplankton biomass compared to outside and was attributed to enhanced vertical mixing in the frontal zone (Vipin et al., in review; Rajdeep et al., 2015). Such increased mixing and nutrient input not only enhance biological production but also impact air–sea exchange of CO₂ at the interface. However, no efforts have been carried out so far to understand the influence of fronts on pCO₂ levels in the Indian Ocean.

The Arabian Sea is known for perennial source of CO₂ to the atmosphere (Goyet et al., 1998; Sarma et al., 1998; Sarma, 2003). Most of these measurements were carried out at seasonal time-scale with coarse resolution (1° interval) along the selected transects (Sarma et al., 1998; Millero et al., 1998) or extrapolation to entire basin using remote sensing SST and chlorophyll-a (Chl-a) based on regression equation developed for pCO₂ with SST (Goyet et al., 1998), SST and Chl-a (Sabine et al., 2000) or dissolved inorganic carbon (DIC) and total alkalinity (TA) with SST, salinity and Chl-a (Sarma, 2003; Bates et al., 2006). Recently Sarma et al. (2013) estimated fluxes of CO₂ from the Indian Ocean between 1990 and 2009 using interpolated data, biogeochemical models, ocean and atmospheric inversions and noticed that the seasonal variations in the CO₂ fluxes were ill simulated by all these models in the northern Indian Ocean compared to observations. This was attributed to problems associated with simulations of monsoon circulation in this zone. It was noticed that the measured pCO₂ was significantly lower than simulated during winter and vice versa during summer in the Arabian Sea. It is also possible that observations might have missed meso-scale features that might lead to underestimation of CO₂ flux. In order to examine the same, an experiment was conducted to understand how pCO₂ levels varied in the frontal zone in the northeastern Arabian Sea and how important these meso-scale features on exchange at the air–water interface during northeast monsoon. In this experiment we would like to test the hypothesis that all fronts will have high chlorophyll-a (Chl-a) and efflux CO₂ to atmosphere due to intensive vertical mixing.

2. Material and methods

In order to identify the fronts, near real time, sea surface temperature (SST) data from various sensors (AVHRR) were used to identify possible locations of fronts. The fronts have been identified as gradient in temperature by 0.25 °C. This information was immediately transmitted to the

onboard research vessel to gear the ship towards the identified location. The details of the identification of fronts were given elsewhere (Vipin et al., in review).

Surface water samples were collected onboard research vessel R/V Sindhu Sankalp (#SSK 60) from 22nd January to 3rd February, 2014 in the northeastern Arabian Sea (Fig. 1). During the cruise, samples were collected on seven selected fronts representing open ocean region, which is influenced by winter convective mixing with relatively higher Chl-a (fronts 1, 2 and 5), coastal region (fronts 3 and 4) and oligotrophic region (fronts 6 and 7) where relatively low Chl-a was noticed (Fig. 1). The interest of selecting fronts from different regions is to examine how different physico-chemical characteristics of the water in the frontal zone from that of outside with different background values. Fifty nine samples were collected in 7 transects covering both frontal and non-frontal regions in each transect.

Water sampling was carried out using a Seabird Conductivity–Temperature–Depth–rosette system fitted with 10 l Niskin bottles. Chl-a was measured using fluorescence sensor (Wet Labs, USA) fitted to the CTD rosette. The fluorescence sensor was calibrated using measured Chl-a following acetone extraction method given in the JGOFS protocols (Department of Energy (DOE), 1998). Dissolved oxygen (DO) was estimated using Winkler's method following automated potentiometric end point detection (Carritt and Carpenter, 1966). The pH and total alkalinity (TA) were measured by potentiometric (Metrohm, Zofingen, Switzerland) Gran titration method following standard operating procedures suggested by the Department of Energy (DOE) (1998). Dissolved inorganic carbon (DIC) was measured using a Coulometer (UIC Inc., Joliet, Illinois, USA) attached to an automated subsampling system (Sarma, 1998). The precisions for pH, TA and DIC were ± 0.002, ± 2.0 and ± 1.8 μmol l⁻¹, respectively. The accuracy of the measurements of

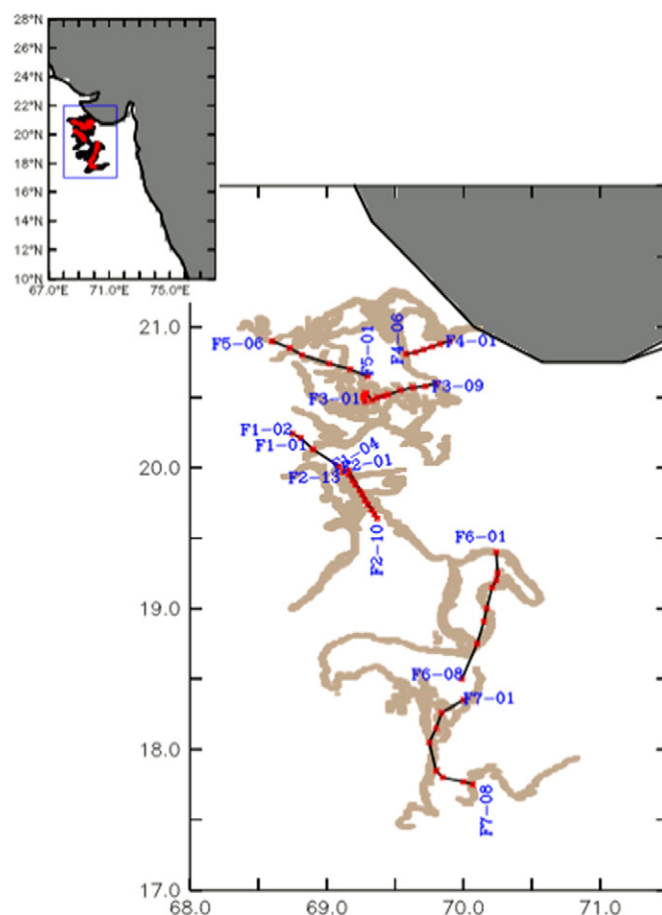


Fig. 1. Thermal fronts during the sampling period and cruise track.

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