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Comparison of chlorophyll in the Red Sea derived from MODIS-Aqua and *in vivo* fluorescence

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ABSTRACT

The Red Sea is a unique marine environment but relatively unexplored. The only available long-term biological dataset at large spatial and temporal scales is remotely-sensed chlorophyll observations (an index of phytoplankton biomass) derived using satellite measurements of ocean colour. Yet such observations have rarely been compared with *in situ* data in the Red Sea. In this paper, satellite chlorophyll estimates in the Red Sea from the MODIS instrument onboard the Aqua satellite are compared with three recent cruises of *in vivo* fluorometric chlorophyll measurements taken in October 2008, March 2010 and September to October 2011. The performance of the standard NASA chlorophyll algorithm, and that of a new band-difference algorithm, is found to be comparable with other oligotrophic regions in the global ocean, supporting the use of satellite ocean colour in the Red Sea. However, given the unique environmental conditions of the study area, regional algorithms are likely to fare better and this is demonstrated through a simple adjustment to the band-difference algorithm.

1. Introduction

The Red Sea sustains a diverse coral reef ecosystem that resides in one of the warmest and most saline seas in the world (Belkin, 2009; Longhurst, 2007). It has been clustered as a fast warming large marine ecosystem (Belkin, 2009) with evidence of an abrupt temperature increase since the mid-90s, which persists till present (Raitsos et al., 2011). Oceanic warming may have a direct or indirect impact on marine entities and ecosystems (Edwards & Richardson, 2004); thus, there is a need to assess past biological data to closely monitor the relatively unexplored and fragile Red Sea ecosystem.

Long-term *in situ* biological datasets at large spatiotemporal scales are not available in the Red Sea, making satellite remote-sensing of ocean colour a vital necessity for any marine ecological studies (Acker et al., 2008; Raitsos et al., in press), such as validation and assimilation of biological data into ecosystem models. Over the past two decades remote-sensing observations of ocean colour have provided unique information on the surface biomass of phytoplankton in the Red Sea, as indexed through the chlorophyll concentration. Yet, with the exception of a comparison between satellite and lidar fluorescence-derived chlorophyll conducted as part of a transect between New Zealand and Italy (Barbini et al., 2004), the performance of these satellite-chlorophyll algorithms has, to our knowledge, never been compared with *in situ* data in this region. Using datasets from three recent research cruises, covering an extensive part of the study area, the performance of two ocean-colour chlorophyll algorithms is evaluated using *in vivo* fluorometric chlorophyll measurements collected over large spatial scales in the Red Sea.

2. Methodology

2.1. In situ data

Oceanographic data were collected from three research cruises during 2008, 2010, and 2011, as part of the Research Cruises expedition programme of the Red Sea Research Center of KAUST (Fig. 1). The R/V "Oceanus" collected data from 35 stations during October 2008 from the east coast of Saudi Arabia (21°N). In March 2010 and September to October 2011, the R/V "Aegaeo" sampled a substantial part of the Red Sea (from 17°N to 28°N). It is the first time that the Red Sea has been sampled in depth at such large spatial and temporal scales.

Continuous fluorescence vertical profiles were collected at each station using a WET Labs ECO-FLNTUs (FLNTURTD-964) fluorometer attached to a CTD. The fluorometer was laboratory calibrated prior to each cruise. However, the fluorometer was not field calibrated as no independent measurements of chlorophyll (e.g. from High Performance Liquid Chromatography (HPLC) or from *in vitro* fluorometry)

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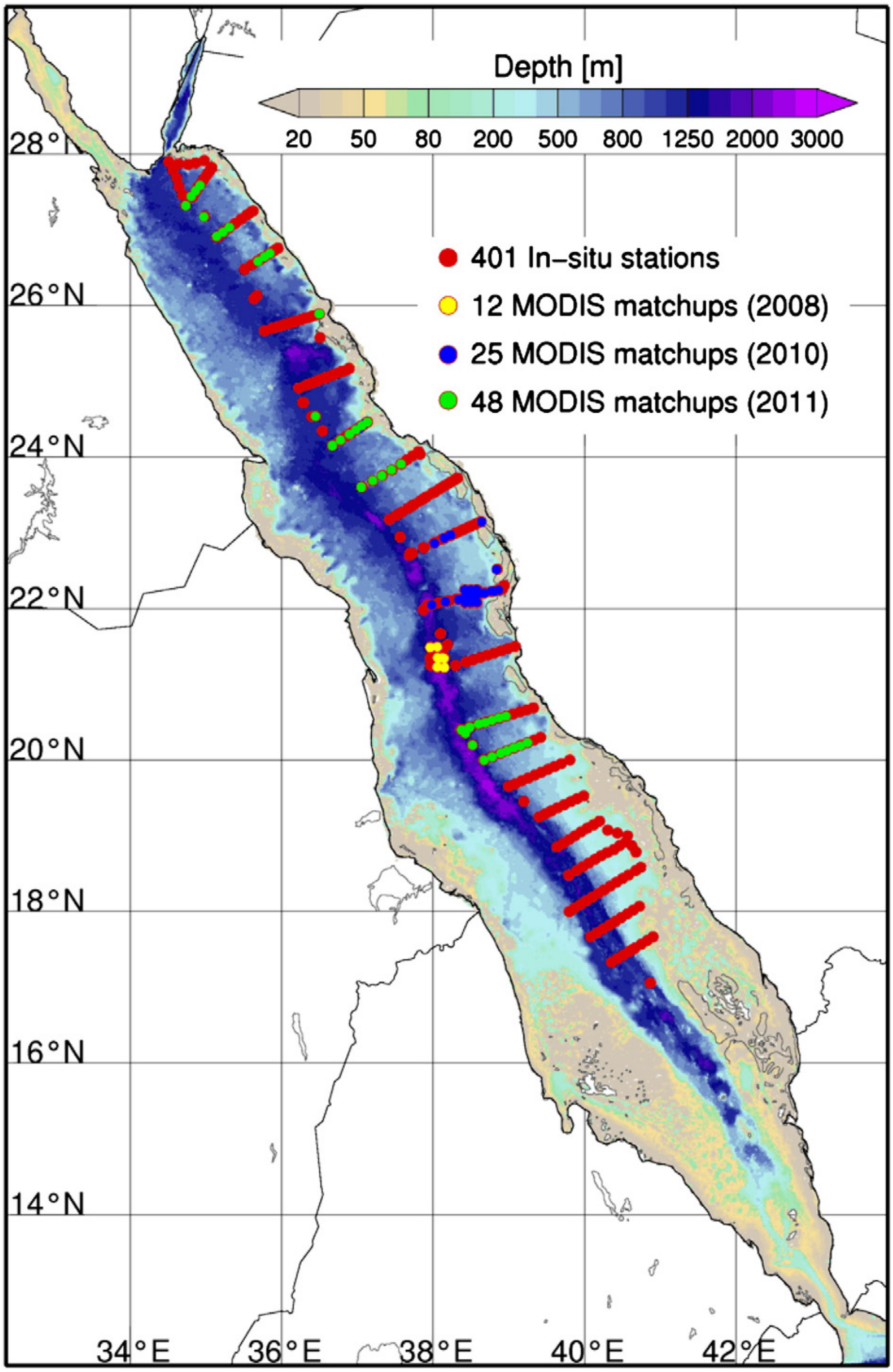

Fig. 1. The distribution of the *in situ* and satellite match-up data used in the study.

were taken during the cruises. The *in situ* chlorophyll concentrations used in this study are therefore likely to have higher uncertainty than those derived by HPLC or by using a field calibrated fluorometer. For the 2010 and 2011 cruise, a consistent bias in all fluorescence profiles was initially observed. After consultation with the sensor manufacturer, Sea-Bird Electronics, the bias was removed using out-of-water fluorescence data, which resulted in recalibrated data within the accuracy limits of the sensor (pers. comm. Leah Trafford, Woods Hole Oceanographic Institution). Any measurements with chlorophyll concentrations unrealistically low (<0.01 mg m^{-3}) were excluded from the analysis.

For each *in situ* chlorophyll profile the approximate depth to which the satellite signal is likely to penetrate was estimated. This involved the following: (i) estimating the euphotic depth from the surface chlorophyll concentration of each profile (top five measurements of the chlorophyll profile, representing ~5 m depth) using the model of Morel et al. (2007); and (ii) dividing the euphotic depth by 4.6 to approximate the 1st optical depth which was assumed to be the average penetration depth of the satellite signal over the spectral range. The *in situ* profiles in which the depth of the profile did not exceed the 1st optical depth, and profiles in which the 1st optical depth was not computed (e.g. all chlorophyll concentrations at the surface were <0.01 mg m^{-3}),