Chapter 3
Thermal Infrared Remote Sensing and Sea Surface Temperature of Marine and Coastal Waters Around Africa

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Abstract Owing to satellite-derived Thermal Infrared (TIR) data, it is possible to derive large basin scale view of Sea Surface Temperature (SST) around the African continent over the last 2 or 3 decades. This may form the baseline against which future changes can be measured. Measurements of SST also serve as an entry point to characterize the water dynamics along the African coast and to understand where and when changes have taken place, such that possible short- to medium term scenarios can be developed and used as management tools for precautionary measures. Significant advances in TIR technology have been achieved to build the necessary confidence in satellite-based SST measurements for research, as well as for operational and commercial purposes. An effective dissemination of these EO value added products to African institutions and policy-makers is a key condition for long-term sustainability of coastal and marine resources. The chapter presents a variety of applications using TIR images and SST data that have contributed to develop the necessary knowledge and competences that are critical for the implementation of conservation and management strategies at continental, regional and national scales.

3.1 Introduction

With *ca*. 35,000 km of coastline, the African continent expands across 35° of latitude on either side of the equator and across similar distance in longitude from 50°E to 20°W. As a result of this geographical cover, Africa is surrounded by a complex system of ocean currents maintained by typical wind patterns, namely the north- and southeasterly trade winds, interacting with the shape of the coastline and bathymetry to create at regional and local scales some peculiar ocean surface dynamics that directly influence the distribution of the organisms and the ecosystem functioning at the coast. Among well-known features, the western African coast includes two

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of the four major upwelling areas of the world ocean, the Benguela system in the south and the Morocco-Mauritanian system in the north (Hill et al. 1998). These are sites of economical importance due to high water productivity sustaining large biodiversity and valuable fish resources. Also, a number of mesoscale structures and oceanic fronts are recurrent e.g. along the eastern coast of Africa molding to a large extent the pelagic ecosystem and species distribution.

Due to this dynamic, coastal and marine environments play a vital role in the economy and society of many African countries (Odada 2010), contributing significantly to reducing the national balance of payments deficit, creating employment and meeting the protein needs of the local population. Fish products provide more than 60 % of the dietary proteins in many countries, such as Ghana and Gambia, stressing the need to develop fisheries management strategies to ensure efficient exploitation while keeping the stocks sustainable on the long-term. Given that marine physics can determine to a large extent the rate and distribution of the biological resources across a range of scales (Gargett 1997), monitoring the dynamics of water masses at appropriate resolution in the time-space domain will considerably facilitate the formulation and implementation of these strategies, as well as the mitigation of an increasing human impact on marine and coastal resources around Africa.

Earth Observations (EO) from satellite enable the provision of environmental information at low cost (to the users) and unprecedented time scales over large and distant areas of the oceans, complementing expensive, hence scarce, field campaigns using research vessels. Thermal Infrared (TIR) sensors on-board satellites, depicting changes in Sea Surface Temperature (SST) over large marine areas, are instrumental to monitor variations in the water masses at the ocean surface resulting from long or short-term atmospheric processes, as well as water column dynamics.

In the following, the applications of TIR to monitor and assess different marine issues around Africa are reviewed. A first section summarizes the fundamental basis to measure TIR signal over the ocean from space, listing the main sensors and databases available, and outlining the current status with the use of TIR data for accurate retrieval of SST. Other sections are referring to different applications of TIR over African coastal and marine waters, using SST as a single indicator of changes in water masses or in combination with other platforms to assess important processes such as fisheries. Finally, some concluding remarks are presented, providing a forward perspective in the use of TIR imagery to meet the societal needs of the African population in the context of international aid initiatives.

3.2 Sensors and Data Repositories

Quantitative information about the oceans is transferred from the sea surface to the satellite sensor through the atmosphere via electromagnetic radiation. This information transfer has some constraints, which are set by the relationship between the radiation emitted from the sea surface, and the atmosphere it travels through before reaching the satellite sensor. Thermal Infrared (TIR) sensors usually passively collect radiations at wavelengths between *ca*. 10 to 15 μm, although some instruments have additional bands in the visible and near-infrared parts of the spectrum for specific purposes, complementing information given by the far-infrared bands.

The strength of the infrared radiation emitted by the ocean is a function of the temperature at its surface: the higher the temperature, the greater is the radiant energy. Sea surface temperature is therefore the main product retrieved by these sensors, after correcting the water surface-emitted signal from the contribution due to the atmosphere. Note that a complete description of the retrieval of SST in terms of the physics of the signal and atmospheric effects is outside the scope of this paper. Details on these issues are available through a number of technical publications (e.g. Kilpatrick et al. 2001; Merchant et al. 2008) and books (Robinson 2004 and references therein).

The reliable calibration of the instruments, coupled with the regular validation exercises with field observations, allow SST measurements from TIR sensors to reach high levels of absolute accuracy, e.g. $< 0.2\,°C$ with the Advanced Along-Track Scanning Radiometer (AATSR) instrument (O'Carrol et al. 2008). In addition, polar-orbiting satellites can provide SST measurements twice daily at a spatial resolution of *ca*. 1 km. Alternatively, radiometers on-board geostationary satellites—e.g. the Meteosat Second Generation (MSG) satellites of the European Space Agency (ESA)—have coarser ground resolution (3–5 km) but much higher temporal sampling frequency (every 15 min or half-hourly) within its large but constant field of view.

Thermal sensors operating onboard satellite have been in orbit for the last 30 years, providing multi-decadal observations of the marine and ocean dynamics through SST measurements at global and regional scales. The Advanced Very High Resolution Radiometer (AVHRR) series operated by the US National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite, Data, and Information Service (NESDIS) represent undoubtedly the longest time series of SST measurements collected from space. The data are distributed operationally and globally through the AVHRR Pathfinder programme[1] (Kilpatrick et al. 2001) from 1981 to present, at spatial resolution of 4 km and daily daytime and nighttime fields. The processing and validation of Pathfinder SST are outside the scope of this work, but have been the focus of several publications (Kearns et al. 2000; Kumar et al. 2003; Marullo et al. 2007; Nykjaer 2009).

In addition to AVHRR, many other satellite missions equipped with thermal infrared bands to measure SST have been launched since 1999 in a variety of orbits (Donlon 2010). Such a multitude of available SST datasets derived from sensors with different characteristics and processed in slightly different ways called for an international effort to harmonize these data in order to provide users with consistent long-term data stream of SST products. As part of Global Ocean Data Assimilation Experiment (GODAE), the Group for High Resolution SST (GHRSST) provides a wide variety of SST data[2] (Donlon et al. 2007), including a multi-sensor merged product and uncertainty estimates for each of the products (e.g. Level 4 K10 SST

[1] The link http://www.nodc.noaa.gov/SatelliteData/pathfinder4km provides access to Pathfinder through the present, adding observations by the NOAA-19 sensor.

[2] Available at https://www.ghrsst.org.

data produced the Naval Oceanographic Office at 0.1° grid). Data is made available through both regional and global Data Assembly Centers, all of which offering the same interoperable metadata models, file format structures and access methods (Donlon et al. 2009).

In spite of the availability of multiple datasets from satellite, there are several obstacles that prevent African countries to make full use of this technology. These obstacles include the lack of appropriate infrastructure and data communication systems that would limit the diffusion of the data and subsequent use of these data by the African scientists. Also the level of technical expertise may not be sufficient or appropriately targeted to manipulate satellite data and promote their applications in the marine sector. A number of specific programs and projects and/or initiatives have been established to overcome these difficulties.

The information system GEONETCast is part of the Global Earth Observation System of Systems (GEOSS) established by the Group on Earth Observations (GEO) to provide environmental satellite data to users on a worldwide basis. It relies on the EUMETSAT's broadcast system for meteorological and environmental data, named EUMETCast, a multi-service dissemination system using standard Digital Video Broadcast technology and commercial telecommunication satellites (Jungbluth et al. 2011). Owing to a number of projects and European initiatives such as the Preparation for Use of MSG in Africa (PUMA) and its follow-up the African Monitoring of the Environment for Sustainable Development[3] (AMESD), more than 100 receiving stations have been deployed in sub-Saharan Africa countries collecting environmental information, including sea surface temperature from TIR sensors, through the EUMETCast system (see e.g. Clerici et al. 2009).

The Europe-Africa Marine EO Network[4] (EAMNet) has been established specifically in the marine and coastal domain to link Earth Observation (EO) data providers with centers of excellence in Europe and Africa to support sustainable development in Africa. Its data portal regroups several information systems providing the African user community with a set of EO-derived bio-physical variables, of importance to conduct water quality monitoring and resource assessment in their marine and coastal waters.

For example, the Global Marine Information System[5] (GMIS) has simple and easy-to-use mapping tool applications, created for the publication and dissemination of marine information via the web. GMIS relies on best quality EO data, including sea surface temperature from the Moderate Resolution Imaging Spectometer (MODIS)—available in two versions, the first onboard the Terra orbital platform (MODIS Terra), the second onboard the Aqua orbital platform (MODIS Aqua)—and AVHRR series, to generate indicators for regional diagnostic of the coastal state and analyses of changes in marine ecosystems. A specific window for Africa has been predefined in the system with five regional sub-windows corresponding to African Large Marine Ecosystems[6].

[3] See http://www.amesd.org for details.

[4] See http://www.eamnet.eu for details.

[5] Available at http://gmis.jrc.ec.europa.eu.

[6] See http://odin.ioc-africa.org/index.php/african-large-marine-eco-systems for details.

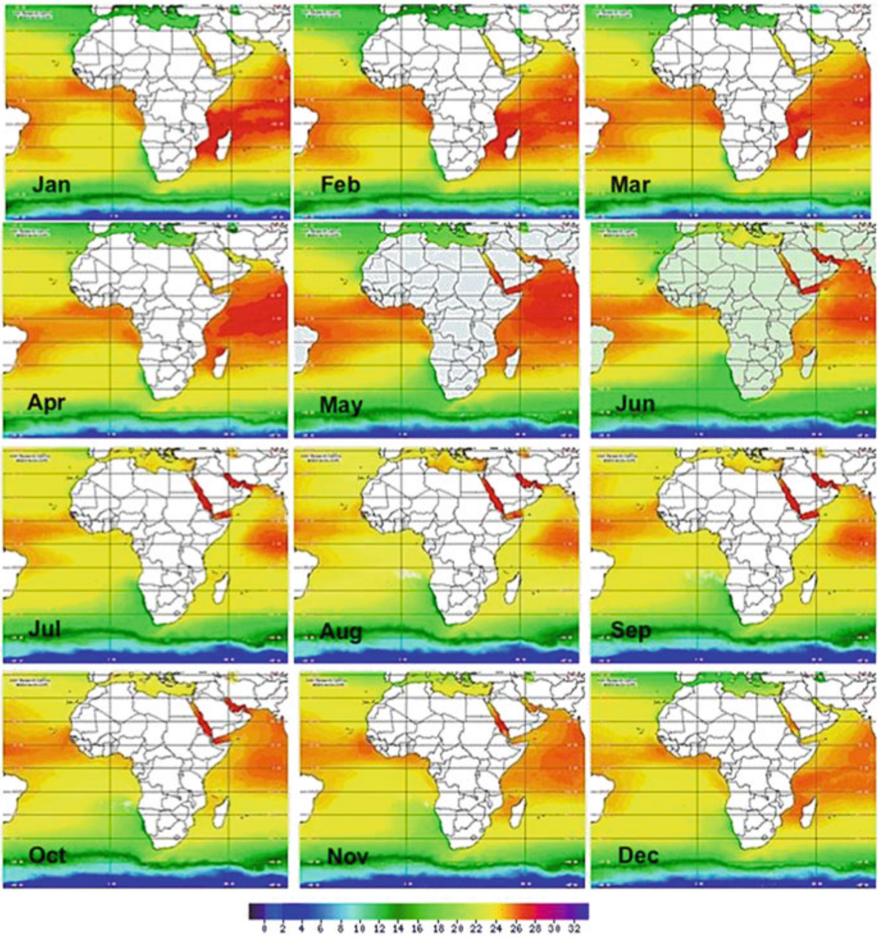

Fig. 3.1 Monthly climatologies of sea surface temperature (in°C) around Africa from MODIS Terra instrument (2000–2011). Images extracted from http://gmis.jrc.ec.europa.eu

3.3 Characterizing Water Masses Around Africa

Monthly SST climatology from MODIS (Fig. 3.1) illustrates the variety of the water masses around Africa under the influence of large-scale atmospheric processes such as the Trade Winds on the Atlantic Ocean side and the monsoon wind patterns on the Indian Ocean side. The oceanic circulation along the coast of Africa can be depicted from the SST images with the eastern Atlantic boundary currents on either side of the equator, i.e. southward Canary Current and northward Benguela Current feeding respectively the North and South Equatorial currents as part of the mid-Atlantic gyres.

All together, these currents contribute to a large extent to shape the global climate through exchange of heat/temperature and salt with adjacent waters (Tyson et al. 2002). Along the eastern coast of Africa, the seasonally-reversing monsoon winds over the Indian Ocean translate into the SST fields with a strong South Equatorial Current (22–23 °C) flowing westward from June to September (southwest monsoon) and feeding both the southward currents on either side of Madagascar and the northward Somali current. During the northeast monsoon (December–February), the flow reverse in the northern Indian Ocean carrying colder water westward and flowing south along the Somali and Kenya coast until it mixes with the warmer South Equatorial Current.

The benefit of satellite TIR data was exploited as early as the late 70's and early 80's to provide synoptic views of these strategic and dynamically-complex regions, and in particular the Aguhlas Current system (Lutjeharms 1981; Lutjeharms and Roberts 1988; see also references in Lutjeharms 2007). A large number of peer-reviewed publications and books (e.g. Lutjeharms 2006) were specifically dedicated to the Agulhas Current in which TIR images have an important role to describe the surface dynamics. Basically, the current flows southwestward along the southern African coast carrying warm waters from the Mozambique Channel and eastern Madagascar down to the southern tip of South Africa, where it get trapped within the Antarctic Circumpolar Current creating some spectacular mesoscale dynamics eastward along the Subtropical Convergence (Olson and Evans 1986). In Fig. 3.2, a monthly time series of MODIS SST data for 2005 has been analyzed using a threshold value in order to mask temperatures below 20 or 22 °C depending on the season. As a result, the sequence of images show the variability of the Agulhas flow, collecting waters from the South Equatorial Current on either side of Madagascar into a jet-like structure flowing along the South African coast until it retroflects to the east offshore Port Elizabeth, creating meanders and eddies as it collides with the south Atlantic waters.

Using TIR data from Meteosat II, Lutjeharms (1988) was also able to observe the shedding of a warm eddy detached from the Agulhas Current and crossing the Sub-Tropical Convergence and contributing to meridional heat transport at the border of the Southern Ocean. The TIR images also revealed some Agulhas eddies formed at the tip of South Africa and propagating into the Atlantic ocean. The variability of this so-called Agulhas leakage could have an important impact on the overall Atlantic overturning circulation (Whittle et al. 2008; Beal et al. 2011).

The stability of the Agulhas Current along the steep continental shelf is occasionally perturbed by transient events, so-called Natal pulses, generated by slight changes in the shelf width off Natal Bight (Lutjeharms and Roberts 1988; Lutjeharms et al. 2003; Bryden et al. 2005; Lutjeharms 2006). These instabilities are described as large solitary meanders associated with cold-water core readily observable within the warmer Agulhas Current from satellite TIR images. Using 6 years of data collected from the Spinning Enhanced Visible and Infra-Red Imager (SEVIRI), onboard the MSG geostationary satellite, Rouault and Penven (2011) provided a detailed analysis of these features occurring on average at a rate of 1.6 pulses per year, i.e. significantly less than previous estimates based on field observations and/or

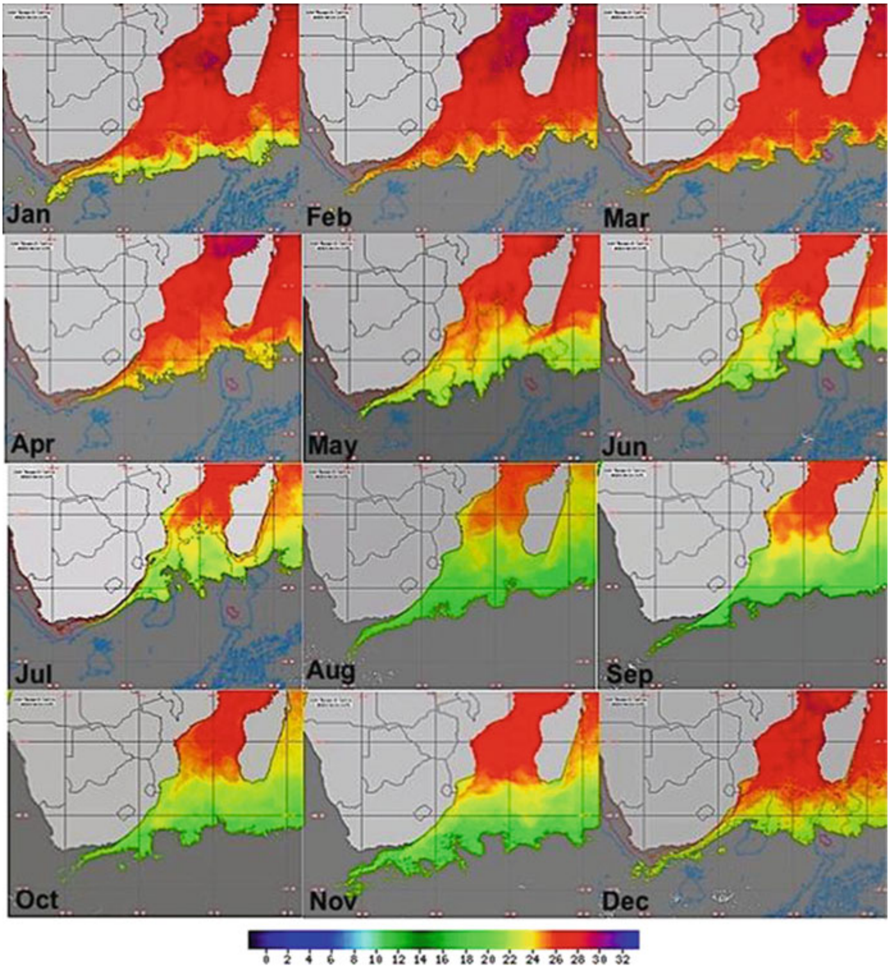

Fig. 3.2 SST monthly composites [°C] from MODIS Terra for 2005 in the Southern African area. SST lower than 22–23 °C have been masked out (dark grey) to highlight the extent of the Agulhas Current. Data extracted from http://gmis.jrc.ec.europa.eu using the 'threshold' analysis tool

numerical studies. Nevertheless, Natal pulses and associated eddies are critical in the life cycle of marine organisms and migration of commercial fishes (Fréon et al. 2010; Roberts et al. 2010), underlining the importance to monitoring these features on an operational basis using high-resolution TIR sensors.

North of the Agulhas Current, the hydrography in the Mozambique channel also show great spatio-temporal variability with a number of anti-cyclonic eddies propagating southward and directly affecting the Agulhas Current system and the variability of Natal pulses (De Ruijter et al. 2002; Schouten et al. 2003; Lutjeharms 2006; Swart et al. 2010).

Further north, during the southwest monsoon, the strong and northeasterly flowing Somali Current is responsible for high marine productivity along the Somali coast, while low biomass and phytoplankton production is commonly observed in the Gulf of Aden. The situation reverses during the northeast monsoon in winter (Veldhuis et al. 1997). Southwest winds during the boreal summer generate upwelling cells that represent important fishing zones for northeast African countries. MODIS image from June 2004 (Fig. 3.3) show typically two upwelling events respectively centered at 5°N and 10°N, starting in May and fading out late September. These features were already observed and analysed in the early 80’s by Brown et al. (1980) and Evans and Brown (1980). At both locations, colder and nutrient-rich waters extend ca. 200 km offshore as filaments with a temperature difference of 4 to 5 °C compared to surrounding waters. A large anti-cyclonic ring known as the Great Whirl (Schott 1983) separates the upwelling cells, whereas other gyres can be observed southeast of the Socotra Island. Mafimbo and Reason (2010) used satellite data including thermal imagery to describe the mechanism of these upwelling events showing a strong covariability between SST and changes in mesoscale winds. This area represents an important fishing ground for the eastern African countries. A better understanding of its dynamic is essential to establish an ecosystem approach to fishery management in this part of the ocean currently under severe overfishing threats.

3.4 Upwelling Dynamics

Upwelling events are driven by alongshore wind stress inducing offshore transport of surface waters, replaced then by deeper cold water enriched in macronutrients, iron and inorganic carbon. This oceanographic feature yields optimal conditions to sustain growth of organisms at all level of the food chain (Cury et al. 2000). A satellite-based TIR can readily spot changes in the temperature signature resulting from an upwelling process, which makes SST product an optimum indicator to assess the variability and strength of such oceanographic phenomena. In particular, satellite TIR-derived SST has revealed the complexities and spatial extension of the mesoscale structures associated with upwelling, with off-shore streamers or narrow filaments that could reach few hundreds km offshore.

Van Camp et al. (1991) have described the upwelling variability off Northwest Africa using AVHRR data, observing filaments and meanders of cool coastal water extending well beyond the shelf break, and coupled with the large-scale seasonal variations of the trade winds (Fig. 3.4a). Hagen et al. (1996) and Barton et al. (1998) reported recurrent filaments from TIR imagery off Cape Ghir and north of Cape Bojador, respectively. These features resulting from a strong interactions between wind and local topography (Troupin et al. 2012) are quasi-permanent and extend few hundreds km offshore, significantly influencing the hydrodynamics and ecosystem behavior in the vicinity of the Canary Islands (Pelegri et al. 2005). An analysis of the temperature gradients on MODIS SST images through edge detection algorithm (Nieto et al. 2012) confirmed the intense mesoscale dynamics in this region with

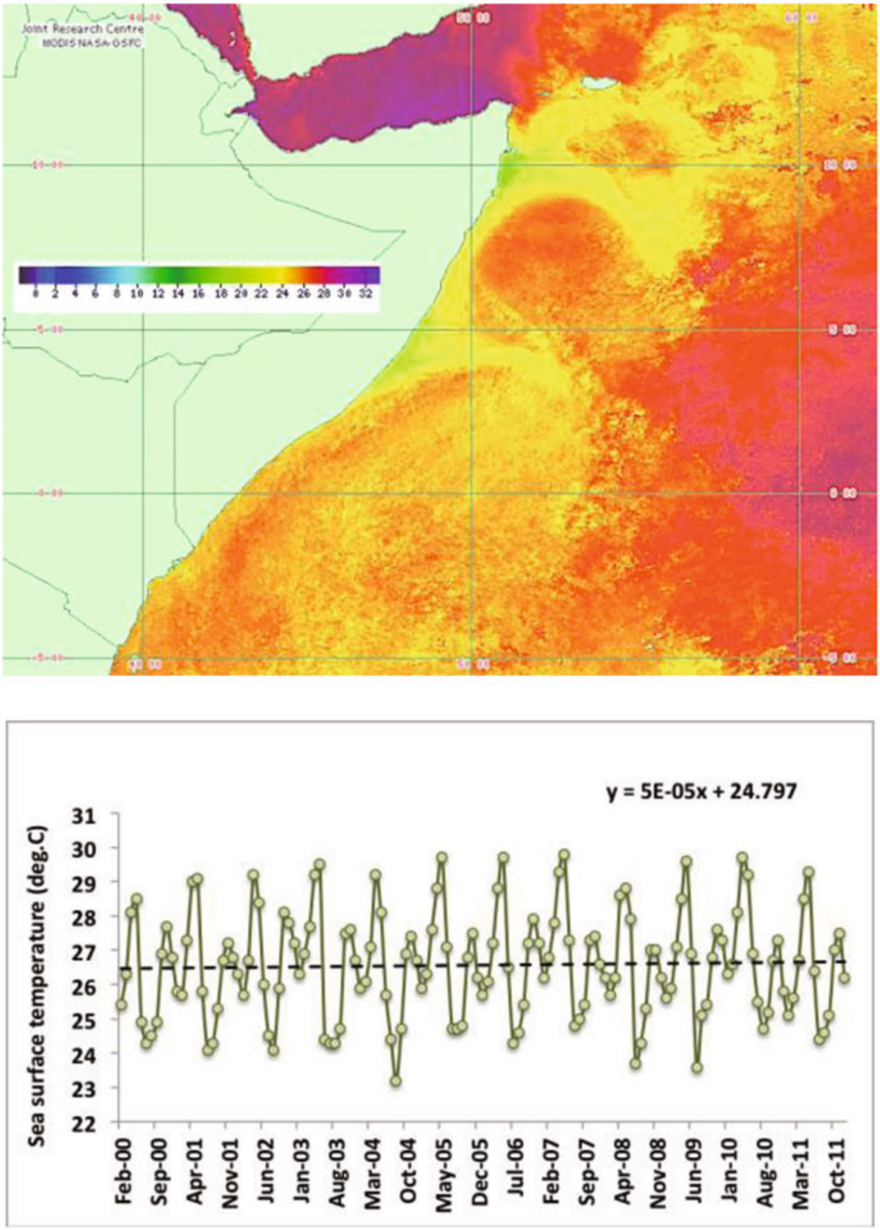

Fig. 3.3 Sea surface temperature (in°C) from MODIS Terra instrument for July 2004 showing filaments of upwelled waters along the coast of Somalia. The MODIS time series (January 2000–December 2011) reveals a clear seasonal cycle of the upwelling process with coldest temperature observed in July during the southwest monsoon. A second minimum temperature is observed in January as a result of the northeast monsoon and the reversal of the Somali current direction and cooler SST flowing south from the northern Indian Ocean. In spite of some inter-annual variability in the seasonal signal, no significant trend is observed over this MODIS decade. Image and plots are extracted from http://gmis.jrc.ec.europa.eu/using the 'timeseries' analysis tool

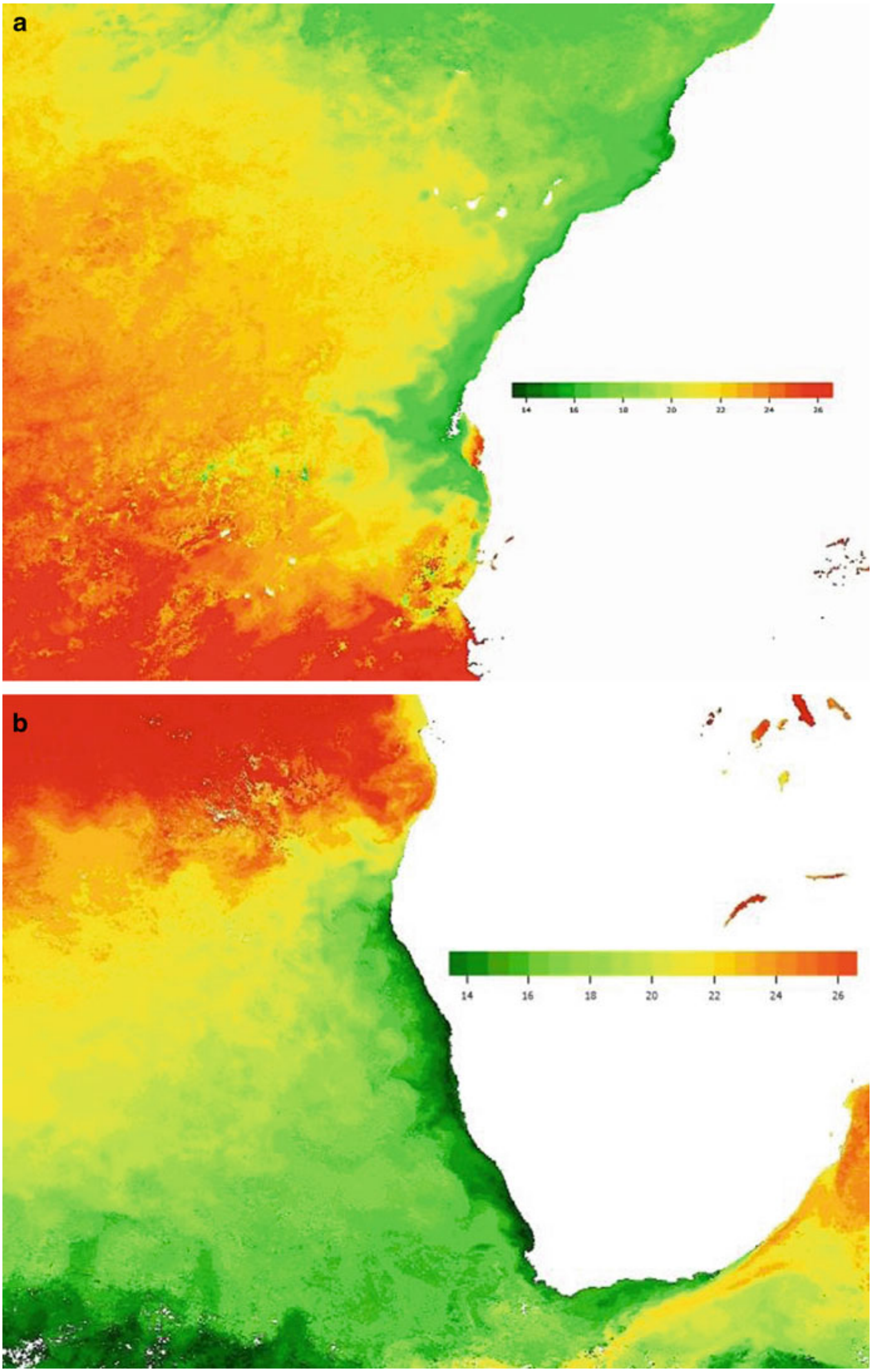

Fig. 3.4 SST (in°C) monthly composite (June 2004) from MODIS Terra instrument showing the extension and mesoscale features of coastal upwelling systems in northwest Africa (**a**) and the Benguela Current (**b**)

highest filament activities associated with Cape Bojador (26.1°N), Cape Ghir (30.5°N), and Cape Blanc (21°N).

In the south, Meeuwis and Lutjeharms (1990) also used AVHRR data set to investigate surface thermal characteristics of the Benguela upwelling system, showing similar permanent feature with seasonal variations depending on the location. The Benguela upwelling (Fig. 3.4b) extends from the southern tip of South Africa to the Angola front, with maximum intensity observed off Luderitz (Namibia). Owing to TIR satellite sensors, Lutjeharms et al. (1991) showed evidence of a complex structure of filaments exceeding 1000 km in length. Obviously, the spatial extent and time evolution of these filaments could not have been made using traditional ship surveys. Similar filaments and eddies are clearly observed in Fig. 3.4a (a MODIS SST monthly composite) along the coast of South Africa and Namibia with colder temperature extending several hundreds of km offshore.

In addition to map the spatio-temporal variability of upwelling events through sequential SST images, TIR data have been extensively used to estimate an upwelling index consisting in most cases of the temperature difference observed between coastal water and water further offshore at a given latitude (Nykjaer and Van Camp 1994). Figure 3.5 illustrates the seasonal cycle of the upwelling index in Northwest Africa as observed with AVHRR SST for the 1981–1989 period. Upwelling process is persistent throughout the year between 20°N and 26°N, with maximum intensity during the summer. South of 20°N, upwelling of lower intensity would mostly occur in winter, whereas north of 28°N, upwelling cells of significant intensity would take place during summer and autumn.

A similar scenario was observed using AVHRR SST data for the 1987–2006 period (Marcello et al. 2011), together with some evidence of an upwelling intensification during this period along the whole northwest African coast as a result of an increase in the water temperature offshore with respect to coastal waters. A direct link to meteorological forcing would expose upwelling systems to higher sensitivity to climate disturbances. Warming is associated with a stronger pressure gradient between land and ocean, which in turn, would reinforce alongshore geostrophic wind, hence coastal upwelling (Bakun 1990). The previous observation and this latter theory is somehow contrasting with another study showing a significant decrease in upwelling intensity within the Canary upwelling system between 1967 and 2006 as calculated from wind-derived Ekman transport (Gomez-Gesteira et al. 2008). A similar weakening of the upwelling intensity in the Iberian/Canary system is observed in the NCEP/NCAR time series resulting from hindcast modeling using observations from different platforms, including TIR satellite data, over the last 4 decades (Pardo et al. 2011). The same data, on the other hand, would show an enhancement of upwelling in the Benguela region. The impact of climate change on upwelling systems still relies on divergent indications. Santos et al. (2005), for example, argued that the variability of AVHRR-derived SST over 2 decades (1980s and 1990s) in the Canary Current is better explained by a breakpoint in the upwelling regime intensity as opposed to a linear long-term trend. Such a debate underlines the importance of maintaining a long-term continuity of satellite TIR data, and their subsequent combination with numerical models to get a better understanding of the processes in place.

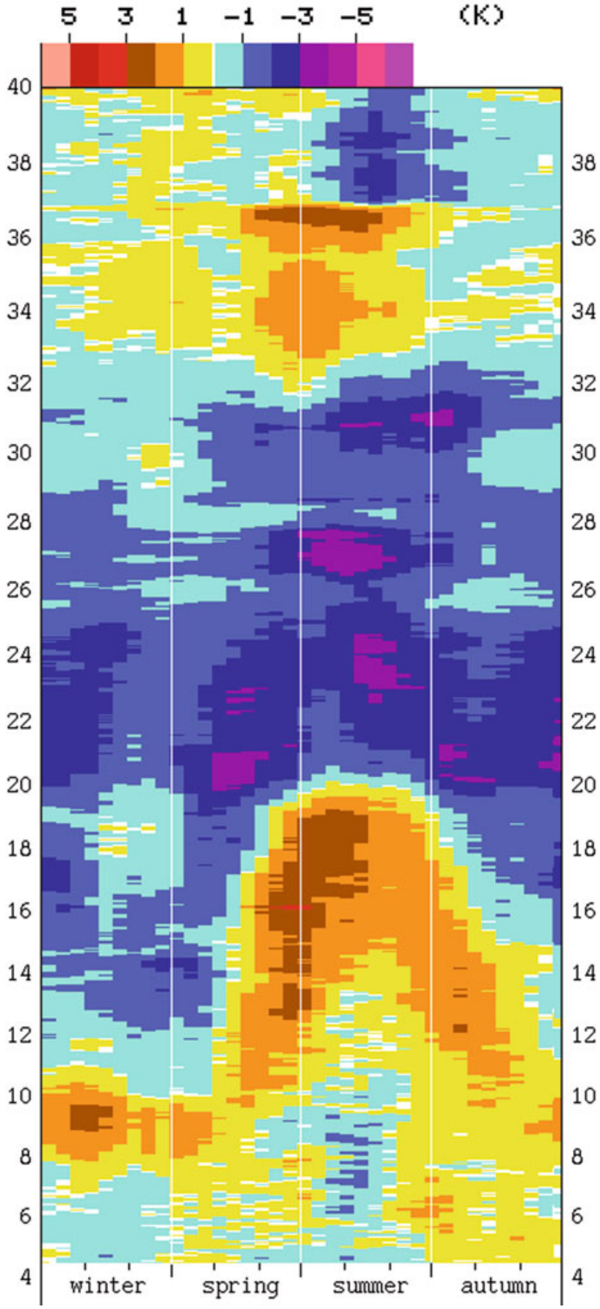

Fig. 3.5 Latitudinal-time section of SST upwelling index as defined by the zonal difference in TIR data for the period July 1981 to August 1989 (adapted from Nykjaer and van Camp 1994). Negative values refer to coastal temperature lower than 500 km offshore at given latitude

3.5 Applications to Fisheries & Marine Resources Management

Sustainable fisheries management practices are high priority on the development agenda for coastal African countries because they directly affect food security for the local population. Recent advances in data acquisition systems, analysis methods and communication technologies have considerably promoted the use of satellite data in the field of fisheries for both, near-real-time support of the day-to-day fishing activities and in the analysis of long-term variability in fish populations. Such synoptic observation of the sea surface is useful in several ways for the fisheries and aquaculture industries: for resource management, optimization of harvesting strategies, better understanding of the resource behavior and its spatial/temporal variability, site protection against recurrent phenomena (e.g. harmful algal blooms) and safety precautions. Chassot et al. (2011) have compiled a comprehensive review showing the importance of satellite remote sensing, including TIR images, to characterize the habitat and ecosystem properties that influence marine resources at large temporal and spatial scales, thus contributing to the development of an ecosystem approach to fisheries management.

As mentioned in the previous section, upwelling systems on the west coast of Africa support large populations of pelagic and demersal fish of considerable economic importance to regional and global fisheries. According to Pauly and Christensen (1995), coastal upwelling systems represents less than 1 % of the world oceanic area but accounts for ca. 20 % of the global fish catch.

In the Benguela-Angolan system, the catch of small pelagic fishes fluctuated greatly after 1980, including a dramatic collapse of the Namibian sardine from 1994 to 1996, despite the application of sound management principles. The observed variability was to a large extent due to the environment and not to fishing activities, as it is often the case in other modern fishery grounds. One of the key objectives of the EU ENVIFISH project (1998–2002; see Barange and Nykjaer 2003) was the identification and quantification of major environmental conditions that influence the recruitment and distribution of small pelagic fish stocks in the Benguela-Angola system. A substantial part of the scientific research in this project relied on TIR imagery derived for the period 1982–1999, starting with a synoptic-scale description of the South East Atlantic (Hardman-Moutford et al. 2003), and detailed SST pattern recognition using neural network method (Richardson et al. 2003).

Following the success of the ENVIFISH project, a similar analysis of the small pelagic fisheries was performed in the North West African upwelling system through the EU project NAT-FISH carried out between 2002 and 2005. As for its southern counterpart, NAT-FISH objectives was to identify and quantify environmental variability related to significant changes in abundance and distribution of small pelagic fish stocks, but also to investigate the potential of using models in combination with satellite SST data as a tool for suggesting precautionary measures to be implemented into responsible fishery management strategies. The project gave the opportunity to scientists in developing countries to gain insight into the use of long time-series of satellite-derived oceanographic variables otherwise not available at the level of their institutions.

Taking advantage of the high spatial and temporal resolution of thermal sensors, the detection and monitoring of thermal fronts from composite SST fields can contribute to develop forecasting capabilities of fish population and their movements (Agenbag et al. 2003), and subsequently, improve the harvest of the stocks in an effective and sustainable way. Temperature is indeed an important factor determining the distribution of fishes, as many of them tend to migrate along preferred temperature ranges. Lan et al. (2011) observed maximum aggregation of yellowfin tuna in equatorial Atlantic waters with temperature above 24–25 °C. According to Zainuddin et al. (2008), the distribution of albacore tuna in the northwestern Pacific is narrowly associated with a combination of environmental parameters, which can be described from thermal imagery, ocean colour, and altimetry. Specific isopleths in the sea surface temperature coincide with highest catch per unit efforts, underlining the benefit to monitor these temperature gradients to generate maps of potential fishing ground and predict spatial patterns of albacore habitats.

Also frontal structures associated with meanders and eddies are potential sites for fish aggregation due to increasing productivity at lower trophic levels (Bakun 2006). Consequently, TIR images are often used to identify so-called Potential Fishing Zones (PFZs) through the detection of SST gradients as generated by these oceanic features. The maps are then disseminated to fishermen in real time to help in reducing search time for fishing grounds, in saving on fuel and, thus, in reducing operational costs (Dwivedi et al. 2005). Moreover, the system could improve the quality of the catch and the sustainability of the stocks, targeting on adults populations rather than juvenile and nursery grounds, otherwise endangered by a blind and unsupervised harvesting process. This operational process to support fisheries is not yet very much used in Africa when compared to Asian countries where the benefit-to-cost ratio of fishing activity largely improves when using satellite data, combining thermal and visible imagery.

As part of the AMESD programme, a Thematic Action related to ‘Coastal and Marine Management’ was recently implemented through the Mauritius Oceanography Institute (MOI), thus acting as AMESD regional Implementation Centre. The main objective of this Action is to support the governments and institutions of the Indian Ocean Commission (IOC) and eastern African countries to make better use of Earth Observation data in their marine and coastal policies. Accordingly, following an agreement with EUMETSAT, MOI is regularly receiving daily chlorophyll and SST data at 1 km resolution to provide IOC users with oceanographic charts for the detection of Potential Fishing Zones. Figure 3.6 is an extract of such operational service showing sequential daily maps of MODIS SST in the Mozambique Channel. The data were further analysed to identify frontal structures favourable to aggregations of important commercial fishes. Using TIR data and other satellite sensors, Tew Kai and Marsac (2010) underlined the importance of eddy boundaries to monitor the distribution of top predators in this region.

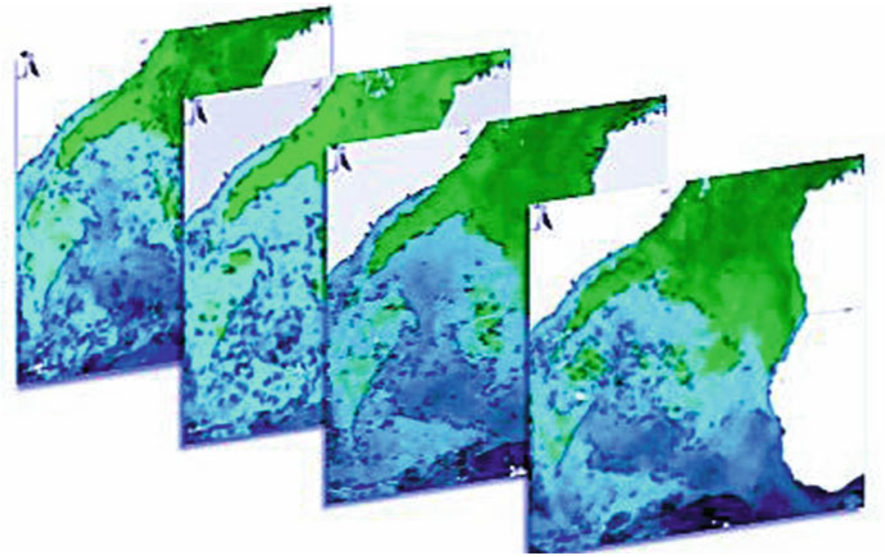

Fig. 3.6 Daily maps of SST (5 to 8 July 2012) as retrieved from MODIS Aqua instrument. Frontal features have been identified using an edge detection algorithm specifically adapted to SST images (Cayula and Cornillon (1992) further improved by Belkin and O'Reilly (2009). The images (courtesy: Vimal Ramchandur, MOI) are part of an operational service to be implemented within a sustainable management framework under the authority of Ministries of Fisheries of countries within the Indian Ocean Commission and nearby eastern African countries

3.6 Conclusion

Data from the thermal-infrared sensors based on satellite have been essential to characterize the complex and highly dynamic marine water properties around Africa. According to the Intergovernmental Panel on Climate Change (IPCC 2007), Africa is considered as one of the most vulnerable continents to climate change and climate variability with a large range of consequences for the environmental and social sectors. Over the last 2 or 3 decades, the continuing measurements of sea surface temperature from space represent by itself a simple and effective indicator of climate variability, identifying 'hot-spots' where SST changes are more pronounced than the average condition. Other derived information such as upwelling frequency and intensity, variability of mesoscale eddies, frontal structures are particularly important to assess the alterations of ecosystems and the impacts on biodiversity. Integrating TIR SST data in fisheries information system in relation to the spatial distribution of fishing grounds, spawning areas, nursery areas, represents thus an immediate step to take in order to move toward an ecosystem-based approach of ruling fisheries, with the possible identification and monitoring of additional Marine Protected Areas.

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References

Agenbag JJ, Richardson AJ, Demarcq H, Fréon P, Weeks S, Shillington FA (2003) Estimating environmental preferences of South African pelagic fish species using catch size- and remote sensing data. Prog Oceanogr 59: 275–300

Bakun A (1990) Global climate change and intensification of coastal ocean upwelling. Science 247(4939):198–201

Bakun A (2006) Fronts and eddies as key structures in the habitat of marine fish larvae: opportunity, adaptive response and competitive advantage. In: Olivar MP, Govoni JJ (eds) Recent advances in the study of fish eggs and larvae. Scientia Marina 70S2: 105–122

Barange M, Nykjaer L (2003) ENVIFISH: an EU/Southern African collaborative project investigating environmental causes of pelagic fisheries variability. Prog Oceanogr 59:177–179

Barton ED, Aristegui J, Tett P, Canton M, Garcia-Braun J, Hernandez-Leon S, Nykjaer L, Almeida C, Almunia J, Ballesteros S, Basterretxea G, Escanez J, Garcia-Weill L, Hernandez-Guerra A, Lopez-Laatzen F, Molina R, Montero MF, Navarro-Perez E, Rodriguez JM, van Lenning K, Velez H, Wild K (1998) The transition zone of the Canary Current upwelling region. Prog Oceanogr 41(4):455–505

Beal LM, De Ruijter WPM, Biastoch A, Zahn R, SCOR/WCRP/IAPSO WG136 (2011) On the role of the Agulhas system in ocean circulation and climate. Nature 472:429–436

Belkin IM, O'Reilly JE (2009) An algorithm for oceanic front detection in chlorophyll and SST satellite imagery. J Mar Syst 78:319–326

Brown OB, Bruce J, Evans RH (1980) Sea surface temperature evolution in the Somali basin during the southwest monsoon 1979. Science 209:595–597

Bryden HL, Beal LM, Duncan LM (2005) Structure and transport of the Agulhas current and its temporal variability. J Oceanogr 61:479–492

Cayula J-F, Cornillon P (1992) Edge detection algorithm for SST images. J Atmos Ocean Tech 9:67–80

Chassot E, Bonhommeau S, Reygondeau G, Nieto K, Polovina JJ, Huret M, Dulvy NK, Demarcq H (2011) Satellite remote sensing for an ecosystem approach to fisheries management. ICES J Mar Sci. doi:10.1093/icesjms/fsq195

Chen Z, Yan X-H, Jo Y-H, Jiang L, Jiang Y (2012) A study of Benguela upwelling system using different upwelling indices derived from remotely sensed data. Cont Shelf Res, in press

Clerici M, Hoepffner N, Diop M, Ka A, Kirugara D, Ndungu J (2009) SST derivation from MSG for PUMA Pilot Porject in Fisheries. Int J Remote Sens 30(8):1941–1959

Cury P, Bakun A, Crawford RJM, Jarre A, Quiones RA, Shannon LJ, Verheye HM (2000) Small pelagics in upwelling systems: patterns of interaction and structural changes in "wasp-waist" ecosystems. ICES J Mar Sci 57:603–618

De Ruijter WPM, Ridderinkhof H, Ltujeharms JRE, Schouten MW, Veth C (2002) Observations of the flow in the Mozambique channel. Geophys Res Let 29:1401–1403

Donlon CJ (2010) Sea surface temperature measurements from thermal infrared satellite instruments: status and outlook. In: Barale V, Gower JFR, Alberotanza L (eds) Oceanography from Space. doi:10.1007/978-90-481-8681-5_13. Springer, Science + Business Media B.V, pp 211–227

Donlon CJ, Casey KS, Robinson IS, Gentemann CL, Reynolds RW, Barton I, Arino O, Stark J, Rayner N, LeBorgne P, Poulter D, Vazquez-Cuervo J, Armstrong E, Beggs H, Llewellyn-Jones D, Minnett PJ, Merchant CJ, Evans R (2009) The GODAE high resolution sea surface temperature pilot project (GHRSST-PP). Oceanography 22(3):34–45

Donlon CJ, Robinson IS, Casey KS, Vazquez-Cuervo J, Armstrong E, Arino O, Gentemann C, May D, LeBorgne P, Piollé J, Barton I, Beggs H, Poulter DJS, Merchant CJ, Bingham A, Heinz S, Harris A, Wick G, Emery B, Minnett P, Evans R, Llewellyn-Jones D, Mutlow C, Reynolds R, Kawamura H, Rayner N (2007) The global Ocean data Assimilation Experiment (GODAE) high resolution sea surface temperature pilot project (GHRSST-PP). Bull Amer Meteor Soc 88(8):1197–1213

Dwivedi RM, Solanki HU, Nayak S, Gulati D, Sonvanshi VS (2005) Exploration of fishery resources through integration of ocean colour and sea surface temperature. Indian J Mar Sci 34(4):430–440

Evans RH, Brown OB (1980) Propagation of thermal fronts in the Somali current system. Deep-Sea Res 28A(5):521–527

Fréon P, Coetzee JC, Van der Lingen CD, Connell AD, O'Donoghue SH, Roberts MJ, Demarcq H, Attwood CG, Lamberth SJ, Hutchings L (2010) A review and tests of hypotheses about causes of the Kwazulu-Natal sardine run. Afr J Mar Sci 32(2):449–479

Gargett AE (1997) Physics to fish: interactions between physics and biology on a variety of scales. Oceanography Mag 10(3):128–131

Gomez-Gesteira M, de Castro M, Alvarez I, Lorenzo MN, Gesteira JLG, Crespo AJC (2008) Spatio-temporal upwelling trends along the Canary Upwelling System (1967–2006). Trends Dir Clim Res: Ann NY Acad Sci 1146:320–337

Hagen E, Zulicke C, Feistel R (1996) Near-surface structures in the Cape Ghir filament off Morocco. Oceanol Acta 19(6):577–598

Hardman-Mountford NJ, Richardson AJ, Agenbag JJ, Hagen E, Nykjaer L, Shillington FA, Villacastin C (2003) Ocean climate of the South East Atlantic observed from satellite data and wind models. Prog Oceanogr 59(2–3):181–223

Hill AE, Hickey BM, Shillington FA, Strub PT, Brink KH, Barton ED, Thomas AC (1998) Eastern ocean boundaries coastal segment (E). In: Robinson AR, Brink KH (eds) The global coastal ocean, regional studies and syntheses, the sea, Vol 11. Wiley, New York, pp 29–67

Jungbluth G, Fulton R, Moodie L, Seymour P, Williams M, Wolf L, Zhang J (2011) GEONETCast: global satellite data dissemination and the technical and social challenges. GSA Spec Pap 482:77–85

Kearns EJ, Hanafin JA, Evans RH, Minnett PJ, Brown OB (2000) An independent assessment of pathfinder AVHRR sea surface temperature accuracy using the marine atmosphere emitted radiance interferometer (M-AERI). Bull Am Meteorol Soc 81:1525–1536

Kilpatrick KA, Podesta GP, Evans R (2001) Overview of the NOAA/NASA advanced very high resolution radiometer Pathfinder algorithm for sea surface temperature and associated matchup database. J Geophys Res C 106:9179–9197

Kumar A, Minnett PJ, Podesta GP, Evans RH (2003) Error characteristics of the atmospheric corrections algorithms used in retrieval of sea surface temperatures from infrared satellite measurements: global and regional aspects. J Atmos Sci 60:575–585

Lan K-W, Lee M-A, Lu H-J, Shieh W-J, Lin W-K, Kao S-C (2011) Ocean variations associated with fishing conditions for yellowfin tuna (*Thunnus albacares*) in the equatorial Atlantic Ocean. ICES J Mar Sci 68(6):1063–1071

Lutjeharms JRE (1981) Features of the southern Agulhas current circulation from satellite remote sensing. S Afr J Sci 77:231–236

Lutjeharms JRE (1988) Meridional heat transport across the sub-tropical convergence by a warm eddy. Nature 331:251–254

Lutjeharms JRE (2006) The Agulhas current. Springer, Berlin

Lutjeharms JRE (2007) Three decades of research on the greater Agulhas Current. Ocean Sci 3:129–147

Lutjeharms JRE, Roberts HR (1988) The natal pulse: an extreme transient on the Agulhas current. J Geophys Res C1(93):631–645
Lutjeharms JRE, Boebel O, Rossby HT (2003) Agulhas cyclones. Deep Sea Res II 50:13–34
Lutjeharms JRE, Shillington FA, Duncombe Rae CM (1991) Observations of extreme upwelling filaments in the South East Atlantic Ocean. Science 253:774–776
Mafimbo AJ, Reason CJC (2010) Air-sea interaction over the upwelling region of the Somali coast. J Geophys Res 115:1–11
Marcello J, Hernandez-Guerra A, Eugenio F, Fonte A (2011) Seasonal and temporal study of the northwest African upwelling system. Int J Remote Sens 32(7):1843–1859
Marullo S, Nardelli BB, Guarracino M, Santoleri R (2007) Observing the Mediterranean Sea from space: 21 years of Pathfinder-AVHRR sea surface temperature (1985 to 2005): re-analysis and validation. Ocean Sci 3:229–310
Meeuwis JM, Lutjeharms JRE (1990) Surface thermal characteristics of the Angola-Benguela front. S Afr J Mar Sci 9:261–280
Merchant CJ, Le Borgne P, Marsouin A, Roquet H (2008) Optimal estimation of sea surface temperature from split-window observations. Rem Sens Env 112(5):2469–2484
Nieto K, Demarcq H, McClatchie S (2012) Mesoscale frontal structures in the Canary Upwelling System: new front and filament detection algorithms applied to spatial and temporal patterns. Rem Sens Env 123:339–346
Nykjaer L (2009) Mediterranean Sea surface warming 1985–2006. Clim Res 30:11–17
Nykjaer L, Van Camp L (1994) Seasonal and interannual variability of coastal upwelling along northwest Africa and Portugal from 1981 to 1991. J Geophys Res 99:14197–14207
O'Carrol AG, Eyre JR, Saunders RW (2008) Three-way error analysis between AATSR, AMSR-E and in situ sea surface temperature observations. J Atmos Oceanic Technol 25:1197–1207
Odada EO (2010) Integration of coastal and marine areas into sustainable development strategies: A case study of Africa. J Oceanogr Mar Sci 1(3):40–52
Olson DB, Evans RH (1986) Rings of the Agulhas. Deep-Sea Res 33(1):27–42
Pardo PC, Padín XA, Gilcoto M, Farina-Busto L, Pérez FF (2011) Evolution of upwelling systems coupled to the long-term variability in sea surface temperature and Ekman transport. Clim Res 48:231–246
Pauly D, Christensen V (1995) primary production required to sustain global fisheries. Nature 374:255–257
Pelegri JL, Marrero-Diaz A, Ratsimandresy A, Antoranz A, Cisneros-Aguirre J, Gordo C, Grisolia D, Hernandez-Guerra A, Laiz I, Martinez A, Parrilla G, Perez-Rodriguez P, Rodriguez-Santana A, Sangra P (2005) Hydrographic cruises off northwest Africa: the Canary current and cape Ghir region. J Mar Syst 54:39–63
Richardson AJ, Risien C, Shillington FA (2003) Using self-organizing maps to identify patterns in satellite imagery. Prog Oceanogr 59:223–241
Roberts MJ, Van der Lingen CD, Whittle C, Van den Berg M (2010) Shelf currents, lee-trapped and transient eddies on the inshore boundary of the Agulhas Current, South Africa: their relevance to the Kwazulu-Natal sardine run. Afr J Mar Sci 32:423–447
Robinson I (2004) Measuring the oceans from space: the principles and methods of satellite oceanography. Springer/Praxis, Berlin. ISBN 3-540-42647-7, p 670
Rouault MJ, Penven P (2011) New perspectives on Natal Pulses from satellite observations. J Geophys Res 116:C07013. doi:10.1029/2010JC006866
Santos AMP, Kazmin AS, Peliz A (2005) Decadal changes in the Canary upwelling system as revealed by stallite observations: their impact on productivity. J Mar Res 63:359–379
Schott F (1983) Monsoon response of the Somali current and associated upwelling. Prog Oceanogr 12:357–381
Schouten MW, de Ruijter WPM, van Leeuwen PJ, Ridderinkhof H (2003) Eddies and variability in the Mozambique channel. Deep Sea Res II 50:1987–2003
Swart NC, Lutjeharms JRE, Ridderinkhof H, de Ruijter WPM (2010) Observed characteristics of Mozambique channel eddies. J Geophys Res 115:C09006. doi:10.1029/2009JC005875

Tew Kai E, Marsac F (2010) Influence of mesoscale eddies on spatial structuring of top predators' communities in the Mozambique channel. Prog Oceanogr 86:214–223
Troupin C, Mason E, Beckers J-M, Sangrà P (2012) Generation of the Cape Ghir upwelling filament: a numerical study. Ocean Model 41:1–15
Tyson P, Odada E, Schulze R, Vogel C (2002) Regional-global change linkages: Southern Africa. In: Tyson P, Fuchs R, Fu C, Lebel L, Mitra AP, Odada E, Perry J, Steffen W, Virji H (eds) Global-regional linkages in the Earth system. IGPB Series, Springer, Chapter 2 pp 3–64
Van Camp L, Nykjaer L, Mittelstaedt E, Schlittenhardt P (1991) Upwelling and boundary circulation off Northwest Africa as depicted by infrared and visible satellite observations. Prog Oceanogr 26(4):357–402
Veldhuis MJW, Kraay GW, Van Bleijswijk JDL, Baars MA (1997) Seasonal and spatial variability in phytoplankton biomass and growth in the northwestern Indian Ocean: the southwest and northeast monsoon, 1992–1993. Deep Sea Res I 44(3):425–449
Whittle C, Lutjeharms JRE, Duncombe Rae CM, Shillington FA (2008) Interaction of Agulhas filaments with mesoscale turbulence: a case study. S Afr J Sci 104:135–139
Zainuddin M, Saitoh K, Saitoh SI (2008) Albacore (*Thunnus alalunga*) fishing ground in relation to oceanographic conditions in the western north Pacific Ocean using remotely sensed satellite data. Fish Oceanogr 17:61–73