Upwelling signals: a comparison of sea surface temperature products in the Benguela

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**Abstract**

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**1. Introduction**

Sea surface temperature (SST) are regarded as one of the most important parameters within the global ocean-atmosphere system, and is particularly useful research tool in the scientific fields of meteorology and oceanography (Mesias et al., 2007). For over 150 years, SST data has been collected using *in situ* measurement techniques (Rayner et al., 2003); with satellite measurements of SST being available since the 1970s. Furthermore, over the past decade, techniques have been developed to allow a combination of different SST datasets available from the various in situ and satellite platforms. These are referred to as the Level-3 and Level-4 high resolution gap-free products. Previous studies demonstrated that satellite-based SST data are less accurate than *in situ* data due to the complexity of the oceanic and atmospheric conditions that need to be accounted for in deriving satellite SST products(Robinson et al., 1984; Brown et al., 1985; Minnett, 1991). These errors vary both regionally and temporally (Wick, 1992). In comparison to *in situ* SST measurements established from ships, or buoys, a major advantage of satellite SST is their reliable global coverage and near real time availability. SST datasets with a high level of accuracy, spatial completeness and fine resolutions are necessary for weather and climate forecasting and is of great importance for reliable climate change monitoring (Reynolds and Smith, 1995; Smith and Reynolds, 1998; Reynolds et al., 2002; Chao et al., 2009)

Long-term SST data have been obtained from two kinds of satellite remote sensors; specifically, thermal infrared (TIR) and microwave (MW) remote sensors, which show different weather sensitivity characteristics and accuracies (Li et al., 2013). Infrared remote sensor SST products have high spatial resolution ranging at approximately a 4km grid as well as having a long history; however, they are unfortunately affected by the presence clouds and significantly large amounts of aerosols in the atmosphere. This is known to result in spatial discontinuity. MW SST products have a lower resolution than infrared SSTs at approximately a 25km grid, with a much lower accuracy near coastlines(Li et al., 2013; Hain et al., 2011, Parinussa et al., 2008). However, by combining these SST products, it is possible to take advantage of the strengths within both of these data types, and each sensor type could help produce an SST dataset with more spatial and temporal coverage and higher resolution.

For many applications, SST data are not used or provided at the full resolution of the sensors but are averaged over defined areas in order to produce a gridded product. For datasets with long time series observations, this approach is often necessary to reduce the volume of the data produced; however, gridding in this way destroys more detailed information and as a result a gridded SST measurement is taken as an estimate of the average SST across a specific grid cell over a certain time period. Spatial sampling uncertainty and temporal averaging is present in gridded products as the full gridded cell is often not being observed as a result of interference due to the presence of clouds or aerosols, as previously mentioned. In existing daily global SST analysis products, typical grid resolution ranges from 0.05°×0.05° to 0.25° ×0.25°, or from approximately 5 to 25 km (e.g., Reynolds and Smith, 1994; Brasnett, 2008; Donlon et al., 2012). However, due to spatial and temporal averaging applied for interpolation, the actual resolution of the physical features can be substantially coarser than grid resolutions (Reynolds and Chelton, 2010; Reynolds et al., 2013) In some cases, the SST analysis fields may be smoothed to satisfy the operational requirements. Small scale features can evolve during the course of the day, but the sensor sampling during this time is not dense enough for the sub-daily global analyses at a high spatial resolution (Reynolds and Chelton, 2010; Reynolds et al., 2013). To capture these small-scale features in a gridded analysis, it is suggested that the development of an improved analysis would have high resolution at small-scale features in regions of good coverage and lower resolution in areas of poor coverage (Reynolds et al., 2013).

In order to assess the suitability of a range of SST products for coastal application, this study aimed to observe patterns and trends in upwelling signals in the Benguela Upwelling System (BUS) across a range of localities and spatial scales off the South African West Coast. We selected an upwelling system because this physical process provides a strong signal of increasing and decreasing SST that is strongly localised to known centres of upwelling, and which relates to the coastal wind field that drives the offshore advection of water mass. Because upwelling is a well characterised oceanographic process, the resultant fluctuating SST signal should be observed across independent SST products – here we assess blended SST products covering a range of spatial grid resolutions from 0.05°×0.05° to 0.25° ×0.25°. We hypothesized that the higher resolution data should have a better fidelity at detecting these upwelling signals, some of which might only be confined to smaller spatial scales or localised closer to the shore.

The BUS is one of the four major Eastern Boundry Upwelling Systems (EBUS) (Bakun et al., 2015). EBUS are characterised as vast regions of coastal ocean occuring along the western shores of continents bordering the Pacific and Atlantic Oceans (Bakun, 1990; Pauly and Christensen, 1995; Bakun et al., 2015; Bakun et al., 2010). Coastal upwelling associated with EBUS is known to have a large influence on the associated ecosystem’s primary priductivity, and hence the abundance, diversity, distribution and production of marine organisms at all trophic positions (Bakun et al., 2010; 2015). Climate change associated trends in the coupled atmosphere-marine climate that drive the BUS affect both economic and socio-economic important sub-systems, which in turn affect many residents inhibating the coastline as well as those who derive their livelihoods and resources from the BUS.

In order to resolve signals that may be indicative of climate change, a long time series of spatially and temporally complete SSTs are important. Anthropogenic climate change has become an issue of global concern as it has been shown to have negatively affected marine and terrestrial ecosystems (Hoegh-Guldberg and Bruno, 2010; IPCC, 2015) by largely influencing coastal species such as corals, muscles and oysters (Hoegh-Guldberg and Bruno, 2010). The consequences of these changes are shown to have had direct effects on the functioning of marine ecosystems, with consequences across all trophic positions (Doney et al., 2011). According to the ‘Bakun hypothesis,’ an increase in greenhouse gases will result in an increase in day-time warming and night-time cooling and ultimately cause an increase in temperature gradients which will form stronger atmospheric pressure gradients (Bakun, 1990). It should be noted pressure gradients modulate the winds which ultimately affect the intensity and duration of upwelling (Bakun et al., 2010; Hsieh and Boer, 1992; Lima and Wethey, 2012; Mote and Mantua, 2002). Furthermore, it should also be understood that changes in sea surface temperatures indirectly affects coastal communities, and bears considerable, often far-reaching economic impacts as well (Murawski, 1993; Murawski et al., 2000, Bakun et al., 2010).

It is hypothesised that the higher resolution data should be able to detect gradients better than the coarser resolution data.

**2. Methods**

*2.1 Site Selection*

The South African coastline exhibits a large variation in seawater temperature and is divided into four bioregions (Smit et al., 2013; Mead et al., 2013). The western region of the coastline is dominated by the Benguela Current forming an Eastern Boundary Upwelling System (EBUS) (Hutchings et al, 2009), which provides a natural laboratory for this study. Annual mean coastal seawater temperatures within this region have a range of 12.3 ± 1.2°C at the Western limit near the Namibian border. Seasonal upwelling is controlled, with intense upwelling occuring throughout the summer months, by south-easterly trade winds and as a result reflects distinct temperature variations representing much lower temperatures within the upwelling cells over a fairly narrow continental shelf found from the Cape Peninsula to Cape Columbine. In order to examine upwelling patterns along the coastline, several sites from the SACTN dataset (Schlegel et al.,, 2016; 2017) along the west coast of South Africa (i.e. sites influenced by the Benguela current) were selected. Since temperature data were not evenly recorded for each of the sites (Schlegel et al.,, 2016; 2017) , the entire dataset was narrowed to only those sites with a time series of longer than 30 years. This yielded a total of four sites within the Benguela region (Fig 1).

*2.2 Datasets*

This study incorporates four Level-4 remotely sensed temperature datasets; complied by a number of organisations. The AVHRR-only Optimally-Interpolated Sea Surface Temperature (OISST) dataset has been providing global SSTs for more than four decades (Reynolds et al., 1994). OISST is a global 0.25° × 0.25° gridded daily SST product that assimilates both remotely sensed and *in situ* sources of data to create a gap free product (Banzon et al., 2016). The CMC dataset constitutes the second dataset. It is a version 3.0 Group for High Resolution Sea Surface Temperature (GHRSST) dataset with a 0.2° × 0.2° global grid resolution constructed by the Canadian Meteorological Center (CMC). It combines infrared satellite SST at numerous points in the time series from the AVHRR, the European Meteorological Operational-A (METOP-A) and Operational-B (METOP-B) platforms, as well as the microwave SST data from the Advanced Microwave Scanning Radiometer 2 in conjunction with *in situ* observations of SST from ships and buoys from the ICOADS program (refs for CMC). The Multi-scale Ultra-high Resolution (MUR) Sea Surface Temperature Analysis is produced using satellite instruments with datasets spanning 1 June 2002 to present times. MUR provides SST data at a spatial resolution of 0.01° × 0.01° and is currently among the highest resolution SST datasets available. The final dataset used is the Group for High Resolution Sea Surface Temperature (GHRSST) analysis produced daily using a multi-scale two-dimensional variational (MS-2DVAR) blending algorithm on a global 0.01° grid known as G1SST. G1SST uses satellite data from a variety of sensors, with some of the popular sensors being the Advanced Very High Resolution Radiometer (AVHRR), the Advanced Along Track Scanning Radiometer (AATSR), the Spinning Enhanced Visible and Infrared Imager (SEVIRI), the Moderate Resolution Imaging Spectroradiometer (MODIS) to mention a few, and in addition *in situ* data from drifting and moored buoys. We see that not all products are completely independent as they share the use of AVHRR SST data, but the amount of subsequent blending, the incorporation of other SST data sources, the different blending and interpolation approaches used, and the differing final grid resolutions make them comparable in this study.

Additionally, this study sought to incorporate the South African Coastal Temperature Network (SACTN) data served as the *in situ* temperature dataset used in this study. This dataset consists of coastal seawater temperatures obtained from 129 sites along the South African coastline, measured daily from 1972 until 2017 (Schlegel et al., 2016, Schlegel and Smit, 2017). Of these, 80 were measured using hand-held thermometers and the remaining 45 were measured using underwater temperature recorders (UTRs). For this analysis, the data were combined and formatted into standardized comma delineated values (CSV) files which allowed for a fixed methodology to be used across the entire dataset. Prior to data analysis, all data points exceeding 35°C and/or below 0°C were removed as these were considered as outliers. These data points were then changed to NA (not available) so as to not interfere with analysis.

An advantage to using *in situ* data over satellite data is that they may provide a more accurate representation of the thermal properties closer to the coast, whereas satellite data often fails to accurately capture and represent temperature properties within the same spatial context; the result being *in situ* data can therefore more accurately explain upwelling signals within the coastal inshore environment. Further evidence by Smit et al. (2013) has shown that satellite data collected along the South African coastline represents a warm bias reaching as high as 6°C over *in situ* temperatures within the nearshore environment.

In order to create a time series of each of the remotely sensed SST data products and to determine whether the same upwelling patterns exist on the broad-scale against the *in situ* time series. Shore-normal transects of all Level-4 products were extended at West Coast stations where the *in situ* data in the SACTN database were available. Time series of SSTs were extracted at 10, 30, 50km along these shore-normal transect from the coast shown as black boxes in Fig. 1. Time series represent the mesoscale temperature features associated with upwelling.

*2.3 Wind data*

Wind was an important variable in this study as wind direction and wind speed may have a direct influence on the intensity and duration of upwelling, consequently, wind data were investigated for its impact on upwelling at the specific sites for which we extracted SST time series. Wind data was obtained from the South African Weather Service (SAWS), and were provided at a 3-hour temporal resolution. The wind data variables used here were wind direction and wind speed. Since the wind data were modelled at three-hour resolutions, they were converted into daily data points in order to compare them with the temperature data.

*2.4 Defining and determining upwelling*

In order to determine the change in upwelling signals at various distances from the coast, and to test which datasets showed a clear, and visible representation of these signals, it was first necessary to define when upwelling was occurring; however, to accomplish this a set of threshold values for identifying when the phenomenon was taking place was required. Given that upwelling is primarily caused by alongshore, equatorward winds, both SST and wind data were used. The wind data were used to inform an upwelling index calculated using the formula presented in the work by Fielding and Davis (1989).

Upwelling Index = μ(cosθ − coastal angle)

where μ represents the wind speed (m/s), θ represents the wind direction in degrees, and coastal angle is the angle in degrees of each of the transects perpendicular to the coastline. The index relies heavily on wind speed and direction data in order to determine the presence of upwelling and its intensity. The above equation produces a value called the *upwelling index*: *upwelling index* < 0 represents downwelling whilst *upwelling index* > 0 represents upwelling (Fielding and Davis, 1989).When the upwelling index is greater than 0, SST usually dropped, as expected, suggesting that upwelling was occuring. It was found that the drop in SST that coincided with a positive upwelling index was close to the seasonally varying 25th percentile threshold for SST. With the bottom threshold set for temperatures that must be exceeded to qualify as an upwelling signal it was then necessary to determine the number of consecutive days that must be exceeded for an upwelling signal to qualify as a dicrete event., Here it must be noted that upwelling is known to vary on a seasonal basis and may also occur hourly (sub-daily). Therefore, the minimum duration for the classification of an upwelling signal was set as 1 day. The rationale being that data from the SACTN dataset as well as the satellite remotely sensed SST data are collected only at a daily resolution, preventing a temporally finer definition. With the upwelling index, temperature threshold, and duration for an upwelling signal established, the *detect\_event()* function from the *heatwaveR* package (Schlegel et al. 2018) was used to calculate metrics for the upwelling signals. Because upwelling signals were calculated relative to percentile exceedances, rather than an absolute definition, such as temperatures above a fixed temperature threshold, upwelling signals could occur any time of the year; however, upwelling was shown to be more dominant during spring and summer months, as expected. It must also be stated that due to irregular sampling efforts in the SACTN dataset the spatial and temporal distributions of upwelling is not necessarily even.