Sea surface temperature trends around Southern Africa.

(Focusing on the Benguela Current system and the Agulhas Retroflection area)

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Minor dissertation submitted to the Department of Oceanography at the University of Cape Town in partial fulfilment of academic requirements for MSc Ocean and Climate Dynamics.

PLAGIARISM DECLARATION

I know the meaning of plagiarism and declare that all work contained in this minor dissertation is my own. I have acknowledged work I received from literature. The only support I got was from my supervisor in a form of guidance.

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Abstract

Sea surface temperature (SST) fluctuations and changes around southern Africa have important consequences on regional weather, climate and the marine ecosystem. SST is a good indicator for upwelling strength in the Benguela Current system and therefore is linked to biological activity in that region. SST is an important driver of the air-sea exchange of moisture and energy, especially in the Agulhas Current where high latent and sensible heat fluxes occur. It is important to quantify SST trends with accuracy for the long term monitoring and characterisation of weather, climate and marine ecosystem in southern Africa, especially in the context of climate change. Here various 1^o x 1^o SST datasets are used to calculate yearly time series, inter-annual fluctuations and trends in key oceanic regions of southern Africa. OI SST, Hadley SST, NOCS SST and ER SST (which has 2^o x 2^o resolution) are used in this study. I start calculating trends and inter-annual fluctuations for various domains and dataset in the recent satellite era since 1982 to compare the non-satellite products NOCS SST and ER SST with the satellite products Hadley SST and OI SST. The idea is to validate the non-satellite products since 1982 and then use them to calculate trends around southern Africa before 1982. Trends and inter-annual fluctuation in the Angola Benguela Current system and the Agulhas Current retroflection system are therefore presented for all datasets for the 1982 – 2012 period. The datasets show different trends and different timing or amplitude of inter-annual variability. This prevents the estimation of changes in the region with confidence before the satellite era which was the initial objective of the study. The main reason is that ER SST is a 2^o x 2^o dataset and maybe not adequate for upwelling region and the Hadley SST 1^o x 1^o dataset include satellite data from 1980 which creates some non-homogeneity in

time and probably an artificial cooling at the coast from the 1980's when satellite data is introduced in the dataset to patch the observational gaps. It is therefore not advisable to use Hadley SST for trend studies including 1982 onwards. From 1982 to 2012 in the Benguela upwelling system, whereas OI SST and HadIey SST show mainly cooling trends of different magnitude, NOCS SST and ER SST show warming trends with NOCS showing significant ($p < 0.05$) warming trends which is suspicious. In the Northern Benguela and Retroflection all datasets show warming trends for the 1982 - 2012 period except from NOCS SST.

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1. Introduction

There are many applications for sea surface temperature (SST). SST applications range from commercial to government agencies. SST is a key parameter for the study of ocean-atmosphere interaction, gaseous transfer between air and sea, ocean circulation and the radiation budget of the planet. In weather prediction study or climate study models are forced with SST, therefore plays an important role (Rouault & Lutjeharms, 2003). Regional weather and climate is greatly affected by changes in SSTs around southern Africa and the strength of upwelling is mirrored by SST. The uniqueness of oceans surrounding southern Africa plays a role in weather and climate of coastal regions and possibly further inland as well. On the western boundary of the southern Indian Ocean basin we have the warm, saline and fast flowing Agulhas Current. West of southern Africa we have the cold Benguela Current which is the eastern boundary current of the southern Atlantic Ocean basin. The overlaying atmosphere is sensitive to SST changes around southern Africa especially the warm Agulhas Current where high latent heat fluxes occur. SST often mirrors changes in wind speed, Ekman pumping and wind stress curl and is therefore a good integrator of the effect of climate change in the region of southern Africa. SST measurements have been taken over a long period of time via observation and satellite remote sensing and various gridded datasets have now been established, so it makes sense to look at trends of this parameter to help characterize coastal climate change in southern Africa. Different methodologies of acquiring SST might have led to different results with regards to the SST products. Only two trend studies exists in this region, one only covers the satellite era (Rouault, et al., 2010) from 1982 to 2010 and the other one (Santos et al, 2012) covers from 1960 to 2000 using Hadley

SST 1x1 degree a dataset based on ICOADS observation, with gaps filled up with statistical technics that also uses AVHRR since 1980

The objective of this dissertation was to determine and quantify SST trends around southern Africa before the Satellite era and to extend in time the results of Rouault et al (2010) established from 1982 starting with a validation and comparison of various gridded datasets. The products that are being compared are: OISST (Optimum Interpolation Sea Surface Temperature), HadISST1 (Hadley Centre Sea Ice and Sea Surface Temperature), NOCS SST and ER SST, the only 2x2 degree product. To compare products I compute trends and calculate yearly time series with each product and evaluate the results from 1982 first. There are not many 1 x 1 degree gridded SST datasets which are available globally. The satellite era (since 1982) provides a reference to evaluate products that do not make use of satellite remote sensing (Hadley SST, NOCS SST and ER SST) but use observation patched by statistical methods. The products which do not make use of satellite data once validated could then be used to estimate trends for the last 50 to 100 years and go further back in time than the study of Rouault et al (2010) who looked at trends since 1982 only.

In this study we used the OI SST which is a globally complete dataset that is extensively used globally for a number of study or real time monitoring. OI SST is available in a spatial grid of 1^{o} x 1^{o}. The data is available since December 1981 and produced operationally. OISST is generated from different data sources, i.e. SST from Advanced Very High Resolution Radiometer (AVHRR) and Advanced Microwave Scanning Radiometer (AMSR), sea-ice data, and in situ data from ships and buoys (Reynolds, et al., 2002). We also use the HadISST1 (Rayner, et al., 2003) data set which is based on Voluntary Observing Ships (VOS) observations patched with statistics to fill the gaps. The resolution of the data set is a grid of 1^{o} x 1^{o} and the period of data is 1871 - 2012. AVHRR data is also included in the dataset since 1980 according to the dataset paper (Rayner, et al., 2003).

A 2-staged reduced-space optimal interpolation procedure is used in constructing the data, to restore local details quality-improved gridded observations were superimposed immediately after the two-staged reduced-space optimal interpolation procedure. However, AVHRR satellite estimate of SST seems to have been integrated in the product which could make the product inadequate for long term trend detection as will be discussed below. The NOC SST is also used in the study and is available from 1973 to 2006. NOCS Flux Dataset v2.0 is purely an in situ dataset, it is not blended with satellite but obtained from in situ measurements made from Voluntary Observing Ships (VOS). NOCS SST has a spatial resolution of a 1^{o} x 1^{o} grid and a monthly temporal resolution. It also uses the optimal interpolation technique to fill the gaps. The agreement with other independent measurements from research mooring is improved by the bias adjustment. When the dataset is cross-validated it is suggested that the uncertainty estimates are realistic, but also that the uncertainty estimates are underestimated in regions of high variability and overestimated in low variable regions. The ERSST 3b (Extended Reconstruction Sea Surface Temperature, version 3b) is the only data set beside Hadley SST that goes before 1973. However it has a lower resolution from the study, it has a 2^{o} x 2^{o} grid spatial resolution. On this version of ERSST 3b, the satellite dataset was removed to curb the cold bias it introduced. The main source of the data for ERSST, Hadley SST and NOCS is ICOADS (International Comprehensive Ocean–Atmosphere Dataset) I therefore do not choose to look at ICOADS dataset available at 1x1 or 2x2 degree resolution in the latest version.

The research questions addressed in this dissertation are the following:

- Are changes in the Benguela Current system and Agulhas Current system (Rouault, et al., 2010) established with OI SST also present to other datasets for the 1982 – 2012 period?
- Do all products show the same trends and inter-annual fluctuations in the region?
- What are the changes estimated since 1960 in the region when the number of routine SST observations were increased globally ?
- What are the changes estimated since 1850 start of global SST dataset used by IPCC and are those trends reliable?

In the next chapter a comprehensive literature review is presented. In this section we describe the importance and the role SSTs play in the region of southern Africa and to the global climate change at large. The brief description of the two main current systems influencing regional weather and climate is presented. In Chapter 3, we describe the different datasets used, namely Hadley SST, ERSST, OI SST and NOC SST and the methodology employed in the study. In Chapter 4, we present the results of the study, through time series in specific domain and charts showing trends. The Discussion takes place in Chapter 5. In Chapter 6 we conclude and recommend future work.

2. Literature Review

2.1. The Agulhas Current System

The Agulhas Current system is divided into three main regions, the Agulhas Current, the Agulhas Retroflection and the Agulhas Return Current. The Agulhas Current is relatively a fast, narrow and warm current which flows down African east coast (Penven & Lutjeharms, 2001). At the Agulhas Retroflection region, Agulhas Current termination happens and the Agulhas Current turns on itself. Considerably high latent heat flux due to considerable evaporation and turbulent mixing occurs above the Agulhas Current which has a marked effect on the overlaying atmosphere Rouault et al (2000, 2003)The Agulhas rings and filaments leak into the South Atlantic Gyre, thereby injecting warm salty south tropical water into the South Atlantic Ocean. Rings and filaments injected into the South Atlantic Ocean will have an effect on the Atlantic Meridional Overturning Circulation (AMOC). Some of these rings join the North Brazil Current and transport this Indian Ocean water into the North Atlantic Subtropical Gyre, a very important mechanism on the AMOC (Biastoch, et al., 2008). The AMOC plays an important role in global climate modulation (Tor & Jan Even, 2013). SSTs in southern Africa have been measured for more than 50 years by voluntary observing vessels mostly. In the past 30 years SST estimates improved a lot with the introduction of estimations from space. However cloud cover in the Agulhas current system is an important problem for Infrared SST estimates. This is due to the fact that over and above the core of the Agulhas Current there's close to 5 times evaporation as compared to its neighbouring waters and this leads to cloud formation (Rouault, et al., 2000). SST monitoring in this region is therefore of profound importance, because short-term and long-term changes to SSTs in this region can have a huge effect on regional weather, climate, marine ecosystems and also global climate change via AMOC.

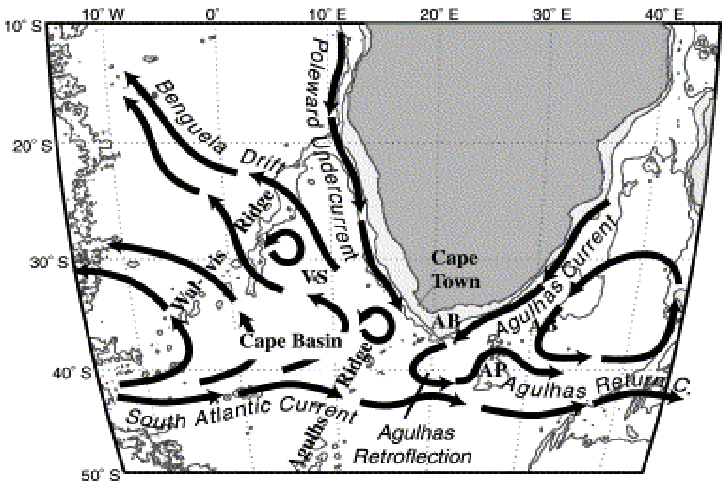

Figure 1: A schematic representation of southern African current systems (Beal & Bryden, 2003).

2.2. *The Benguela Current*

The Benguela Current is an eastern boundary current of the South Atlantic Ocean Gyre. It is a cool, shallow and broad surface current, characterised by a lot of primary production. The Benguela Current is wind-driven and is coupled by upwelling brought about by the Ekman Pumping and Ekman Transport (Wedepohl & Lutjeharms, 2000).Ekman Transport refers to the displacement of surface water in a net perpendicular direction to wind forcing in response to Coriolis Effect. The south-western Indian Ocean SST's influence on southern African rainfall has been studied extensively, but the role of moisture flux between South Atlantic Ocean and southern African rainfall has been less documented (Vigaud, et al., 2009). SST variability and changes in the Benguela Current system has also not been extensively studied. SST fluctuations in the northern Benguela are said to be greatly influence by the seasonal intrusion of tropical Angola Current water and

Benguela Ninos (Rouault, 2012) which impact considerably the marine ecosystem. The Benguela Current is one of the strongest upwelling systems in the world and therefore is a very productive marine ecosystem. SST here mirror wind strength and so they could be used as a proxy for upwelling strength and to measure the health of this very productive marine ecosystem. Fisheries in this region provide considerable economic values and the effect of climate change could lead to an economic disaster if the wind were to drop here. Because there are no homogeneous wind records in the region, we are only left with SST to study changes in upwelling intensity in the Benguela region. North of the Benguela there is a strong meridional SST gradient of 1^{o}C per 34 km where the warm tropical Angola Current water interacts with the cold upwelled Benguela Current system, the Angola Benguela Front (ABF) situated around 17^{o}S (Veitch, et al., 2006). The relaxation of the easterly winds along the equator deepens the thermocline off Angola and interact with the Angola Current. This permits the warm tropical surface water to propagate southwards across the front thereby mixing with the northern Benguela waters off the Namibian coast, leading to warm SST anomalies in the northern Benguela Current region (Rouault, 2012). This thermal sharp ABF acts as the northern boundary of the Benguela upwelling system. This feature is absent from other eastern boundary currents like the Canary, the California and the Humboldt Currents. The marine ecosystem, hypoxia, fisheries, rainfall of the region are greatly affected by warmer than usual ocean events in Angola and northern Namibia, warm events such as Benguela Ninos (Rouault, 2012).

2.3. SST variability and temporal trends around southern Africa

Geographically southern Africa is partly surrounded by a marine environment. Southern African weather and climate is therefore greatly affected by changes to physical characteristics of these marine environments especially changes to SSTs. The exact effect and the mechanisms that bring these changes to regional weather and climate are not yet fully understood especially on the eastern Atlantic Ocean side (Reason & Jagadheesha, 2005). Studies which looked at the relation between SSTs in the eastern Atlantic Ocean and rainfall variability over southern Africa mainly focused on austral summer, but most of SSTs influence in this region is said to be in winter whereby South-western Cape of South Africa receives mainly winter rainfall due mostly to mid-latitude cold fronts (Mason, 1995) & (Walker, 1990). South-eastern Atlantic SSTs relations to South-western Cape region of South Africa's rainfall variability and to regional large-scale ocean-atmosphere has been demonstrated in previous studies and SSTs in this region are usually warmer than climatological values during wet winter years. Mechanisms that could be associated with winter rainfall variability in this region were explored using atmospheric general circulation model experiments which contained varying idealized SST anomalies in the South Atlantic. During winter months the sensitivity of the atmosphere in terms of convergence of moisture and latent heat flux to subtropical-mid-latitude SST anomalies were discovered in the experiments (Reason & Jagadheesha, 2005). From increased frequency of severe thunderstorms and high variability in general rainfall patterns, SST and other weather variables, it is almost certain that locally the changes in marine weather are a reality and will therefore affect the marine ecosystem, terrestrial temperature and climate. In the experiment where sensitivity of a tropical-temperate trough to sea-surface temperature anomalies in the Agulhas retroflection region were investigated it was proven using a Regional Atmospheric Modelling System's (RAMS) that positive change to SSTs in this region has a distinguishable effect on convective precipitation, and this result was proven to be consistent with the expectations in reaction to high SSTs in this region (Crimp, et al., 1998). Since the observations of SSTs dates back for more than a century and improved through the introduction of satellite remote sensing in 1980’s, it makes sense to particularly take a closer look at SST as key role players in oceanic climate change and eventually the terrestrial weather and climate around southern Africa. SST is a great integrator of wind stress effect. In bulk formulae for calculating ocean-atmosphere heat fluxes SSTs play a key role because they affect evaporation rates, hence incidental on precipitation and to the overlaying air temperature. The Ocean’s thermal inertia is far greater than that of atmosphere and land, and for this reason looking at SST trends will give us an indication on how the climate has been changing through time. However, inhomogeneous measurement practices and poor temporal and special sampling hamper the accurate determination of long term SST trends (Deser, et al., 2010). There’s a lot of uncertainty in the 20th century SST trends which is due to the inaccurate determination of long term SST time series. This limits the utility and physical interpretation and may affect the affirmation of climate model simulations. Nevertheless long term SST trends are important in the discrimination of naturally-occurring multi-decadal variability and secular climate change (Deser, et al., 2010).

3. Data and Method

For this study different SST data sets were used to analyse and validate SST trends around southern Africa. The main focus areas for the study are coastal Benguela Current system and the Retroflection region which forms part of the Agulhas Current system. The Benguela Current is divided into four smaller domains, the Southern Benguela, the South Central, the Northern Central and the Northern Benguela. All these smaller regions are along the coast. The coastal domains extend 1° offshore and are 3° wide except for the domain which marks the northern Benguela which is 4° wide. For the Retroflection domain we averaged from 17° E to 21°E and 36°S to 40°S. We use as reference product the optimally interpolated SST (Reynolds, et al., 2002) OI SST data set. The OI SST is a product attained from merged daily, *in situ*, infrared satellite observations of high resolution (9 km) from the instrument AVHRR (advance very high resolution radiometer) boarded on NOAA (National Oceanic and Atmospheric Administration) satellites. The OI SST has been validated (Rouault and Lutjeharms, 2003) and used successfully in many studies in the region of southern Africa. Such research studies include Benguela Ninos (Rouault, et al., 2003a) (Rouault, 2012) and the description of the 1999/2000 southern Benguela warm event (Roy, et al., 2001). It is used in one of the few comprehensive study of trends in the region (Rouault et al, 2009, 2010). (Rouault & Lutjeharms, 2003) And (Rouault, et al., 2003a) argued that even though the 1° x 1° latitude-longitude grid data sets (e.g. OISST) are not resolving some features of the coastal area and the core of the Agulhas Current system due to the interpolation scheme and the data resolution, by averaging over a large area the data sets can be used quite satisfactory. We also used the HadISST1 (Rayner, et al., 2003), which is a blend of satellite and in-situ monthly data that uses a 2-step reconstruction technique.

The HadISST1 has a spatial grid of 1^{o} x 1^{o}. The dataset starts in 1871 on. The satellite data that is used to construct HadISST1 is from ARC (ATSR Reprocessing for Climate, 1996 on) and AVHRR (Advanced Very High Resolution Radiometer, 1981 on) Pathfinder. The ARC is stable, has a high accuracy; however it has a short record and a lower coverage. AVHRR Pathfinder has a lower accuracy with an excellent coverage and a long record. The in-situ data is mostly from VOS and ICOADS and it dates back from 1850 on. The in-situ data has a long record with a poor coverage and a low accuracy. The level of uncertainty in HadISST is very high due to the use of 2-step technique in the construction of dataset. The NOCS SST (Berry & Kent, 2009) from the NOCS Flux Dataset v2.0 is a new product. The NOCS Flux dataset v2.0 is derived from VOS *in situ* weather reports, the data covers the 1973 – 2006 period. Known biases of the reports were adjusted, with estimation of residual uncertainties. The optimal interpolation technique is also employed in the NOCS dataset by using random uncertainty estimate in observations. The resolution of the dataset is 1^{o} x 1^{o} latitude-longitude grid and the monthly fields have been calculated from daily fields using simple statistical averages. There are also uncertainty estimates for each grid point and time step. The NOCS dataset has been used in the northern hemisphere successfully where the Mediterranean Sea SST relation to atmospheric variability were studied (Skliris, et al., 2011), however there seem not be a study where the dataset is used in our regions of interest probably because of its novelty. The Extended Reconstructed Sea Surface Temperatures (ERSST) is also used as a reference for the study. The ERSST v3b is the same as ERSST v3, the only difference between the two is the exclusion of satellite data on the former (Smith, et al., 2008). The ERSST v3b is also constructed using in situ data from VOS. The special grid of this dataset is 2^{o} grid box and it could be too sparse to adequately resolve our regions of interest, however it is used as a reference in the open ocean because it is the only product with Hadley SST that goes back to 1900. All the above datasets analyses except OI SST are based on International Comprehensive Ocean-Atmosphere Data Set (ICOADS). Therefore it is expected that a certain level of agreement between the data sets should exist.

Table 1: Characteristics of the datasets

	OISST	**HadISST1**	**NOCS SST**	**ERSST 3b**
Start time	1982	1871	1973	1854
End time	2012	2012	2006	2012
Duration	30 years	141 years	33 years	158 years
Time step	Monthly	Monthly	Monthly	Monthly
Spatial resolution	1^0 x 1^0 Grid Globally	1^0 x 1^0 Grid Globally	1^0 x 1^0 Grid Globally	2^0 x 2^0 Grid Globally
Source of data	In situ and satellite	In situ and satellite	ICOADS	ICOAD
Method of error checking	Optimal interpolation	2-step reconstruction technique	Optimal interpolation	2-step reconstruction technique
Reference	(Reynolds, et al., 2002)	(Rayner, et al., 2003)	(Berry & Kent, 2009)	(Smith, et al., 2008)

Methods

The least-square method was used to calculate linear trends from monthly SST fields. On each grid box the basic polyfit function was used to determine the trend polynomial. To determine the significant levels the Student t-test was used which is contained in statistical toolbox of Matlab. Matlab was the programme used for the overall statistical analysis to read netcdf files of the original datasets, to extract time series along the coast or in a box and to produce charts or compare products. Monthly anomalies were calculated by subtracting monthly data with monthly climatology.

Domain

The coastal domains extend 1^{o} offshore and are 3^{o} wide except for the domain which marks the northern Benguela which is 4^{o} wide. For the Retroflection domain we averaged from 17^{o} E to 21^{o}E and 36^{o}S to 40^{o}S.

4. Results

In this section we present results obtained from time-series analyses and calculation of trends around southern Africa. The domain used for time-series analyses is shown in **Figure 2**. Regions which were used for the study were: (1) Southern Benguela (**X**), (2) South Central Benguela (**O**), (3) North Central Benguela (**<**), (4) Northern Benguela ([]) and (5) Retroflection region (**□**).

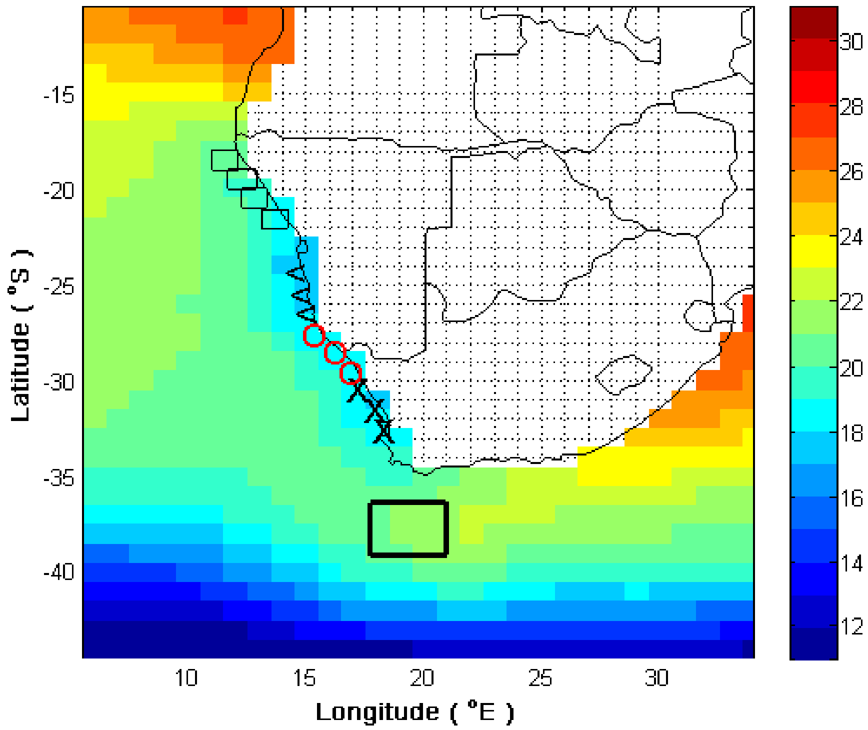

Figure 2: The study domains. Monthly time series were constructed by averaging all SST fields from 1982 to 2012 in Southern Benguela (X), South Central Benguela (O), North Central Benguela (<), Northern Benguela ([]) and the Retroflection region (□). NOCS dataset is only available till 2006.

For the coastal and the Retroflection time series we averaged the domains indicated in **Figure 2**. The coastal domains extend 1° offshore and are 3° latitude wide except for the domain which marks the northern Benguela which is 4° wide. For the Retroflection domain we averaged from 17° E to 21°E and 36°S to 40°S.

4.1. Climatology

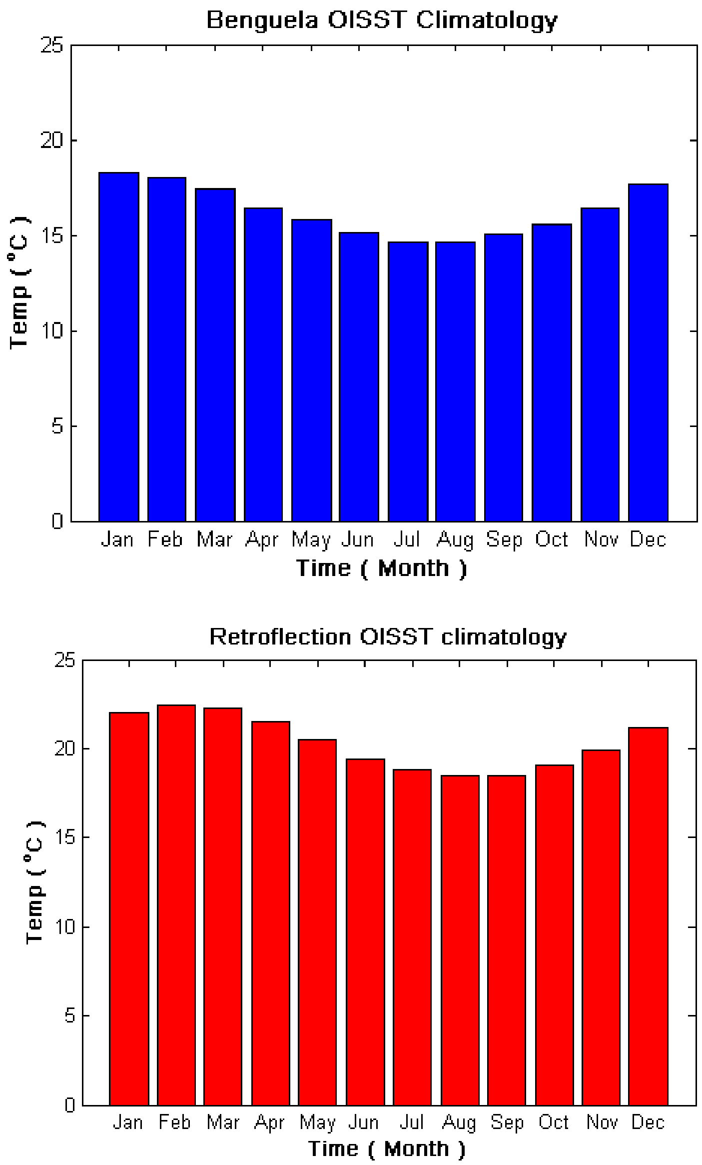

Figure 3: Climatological means of the greater Benguela and Retroflection.

The climatology (1982 – 2012) of coastal Benguela and Retroflection is shown in **Figure 3**. The climatology was constructed using OI SST which contains high resolution morning and evening AVHRR satellite estimates together with the vast available observations. Because of the resolution of OISST (1x1 Degree) and the interpolation scheme used as well as averaging over large area, the time series does not reproduce the summer minimum that occurs in the Benguela upwelling system and seems to overestimate the SST (Dufois & Rouault, 2012), (Weeks, et al., 2006) and (Demarcq, et al., 2003). Due to the interpolation scheme used (Cf chapter 3), open Ocean can influence the coastal data nearest to the coast. The cold upwelled water is underestimated due to the resolution of dataset. The Benguela current is generally cooler in the summer months when southerly/south easterly winds are strongest and warmer in the winter months following weaker southerly/south easterlies and SST at the shore can be as cold as 9 to 10 ^{o}C (data not shown) (Dufois & Rouault, 2012), (Weeks, et al., 2006) and (Santos, et al., 2012). However we expect the product to represent trends properly due to the sheer size of the upwelling and its offshore extension as discussed previously. Moreover the dataset seems to represent properly warm and cold events due to ENSO in the region (Rouault et al, 2010). The Retroflection climatology shows warmer SSTs during summer months and cooler SSTs during winter months typical of open ocean climatology and also of Agulhas Current temperature (Rouault & Lutjeharms, 2003).

4.2. Time series analysis for the period 1982-2012

Figure 4, shows time series of yearly SST of the Southern Benguela domain for all data sets spanning the 1982 – 2012 period, because of data availability the NOCS time series period is only 1982 - 2006. The immediate observable features present in this figure are decreasing yearly temperature means for the OISST and HadISST and increasing yearly temperature mean for NOCS and ERSST. Slopes have different magnitude in OISST and HadISST

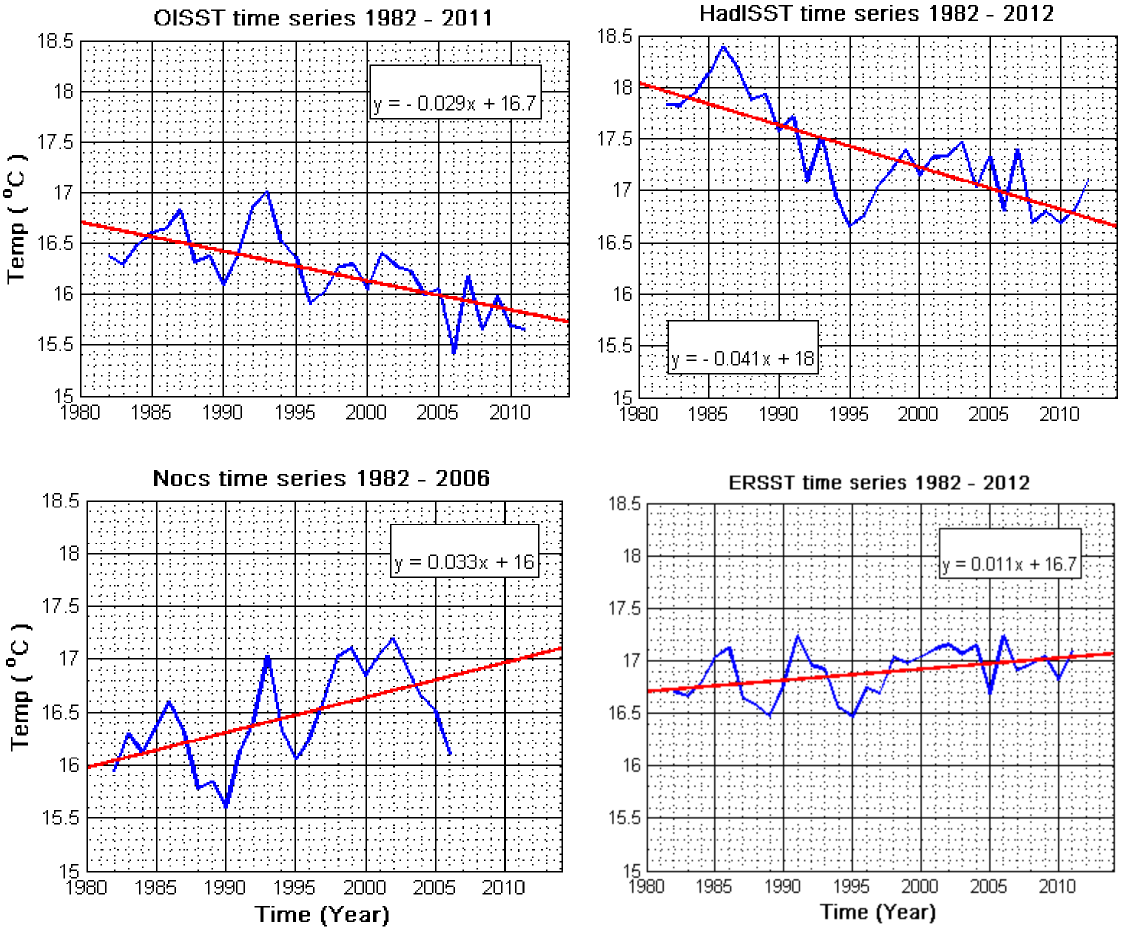

Figure 4: Southern Benguela time series for different SST products (OISST,HadISST, NOCS & ERSST) for the 1982 - 2012 period. Plotted in blue are the yearly means, a linear fitting in red with trend in ^{o}C/year in white windows. All trends significant at 95% based on a two tailed Student's t test.

These are not good results and they do not give us confidence in NOCS and ERSST products that could be used to estimate trends prior to 1982. The pure SST from pathfinder SST shows similar trends as Reynolds SST (Rouault, et al., 2011). The observed cooling trends in OI SST and HadISST are of -0.029 ^{o}C/year and –0.041 ^{o}C/year respectively in magnitude. The warming in NOCS and ERSST are 0.033 ^{o}C/year and 0.011 ^{o}C/year respectively. A difference of up to 2 ^{o}C of the HadISST when compared with OI SST is clearly visible in the southern Benguela region. Inter-annual variability is represented with mixed success, for instance lower than normal SST in 1995 is present in NOCS, ERSST and HadISST but not in OI SST, another cause of concern.

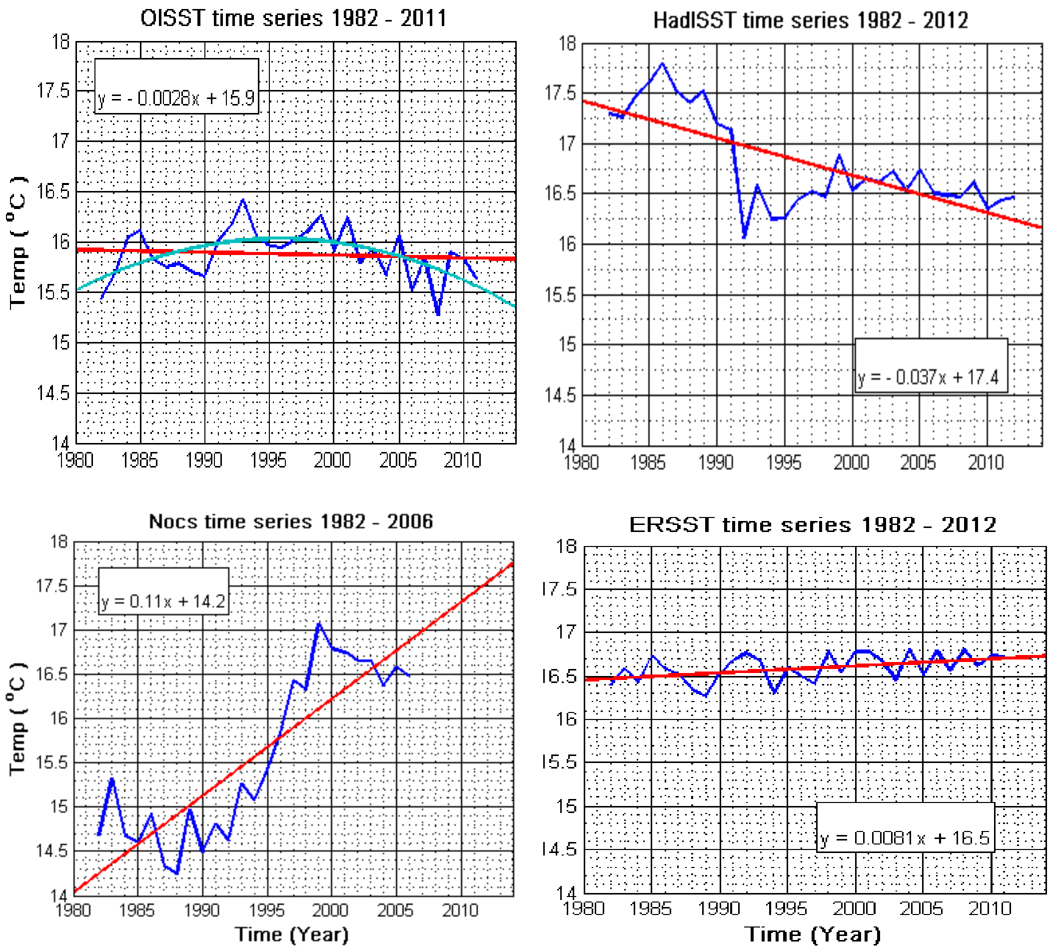

Figure 5: South Central Benguela time series and trend for all data sets, 1982-2012. Plotted in blue are the yearly means, a linear fitting in red, and a parabola in light-blue for the OISST data with trend in °C/year in white windows. All trends significant at 95% based on a two tailed Student's t test.

The peak in 1986 seems to be present in most dataset but occurs in 1987 in OI SST. We will come back to that point later (Fig 9 to 13). In **Figure 5**, the time series of yearly SST and trend is presented for South Central Benguela and shown for the period 1982 – 2012, for all SST fields. The OISST time series shows an increase trend for the first decade and a decreasing trend thereafter, but a general trend for the entire period is a slight cooling trend of 0.0028 °C/year. Difference between dataset is also present. A general cooling trend of 0.037 °C/year is observed in the HadISST. However there seems to be serious cooling in the first decade, and thereafter the SSTs seem to be stable. The NOCS SST show a robust warming in this region of 0.11 °C/year but this seems suspicious when compared with OI SST. The ERSST time series indicates a very slow warming rate of 0.0081 °C/year with high frequency inter-annual variability. The warm bias of the HadISST compared to OI SST is also visible in the south central Benguela.

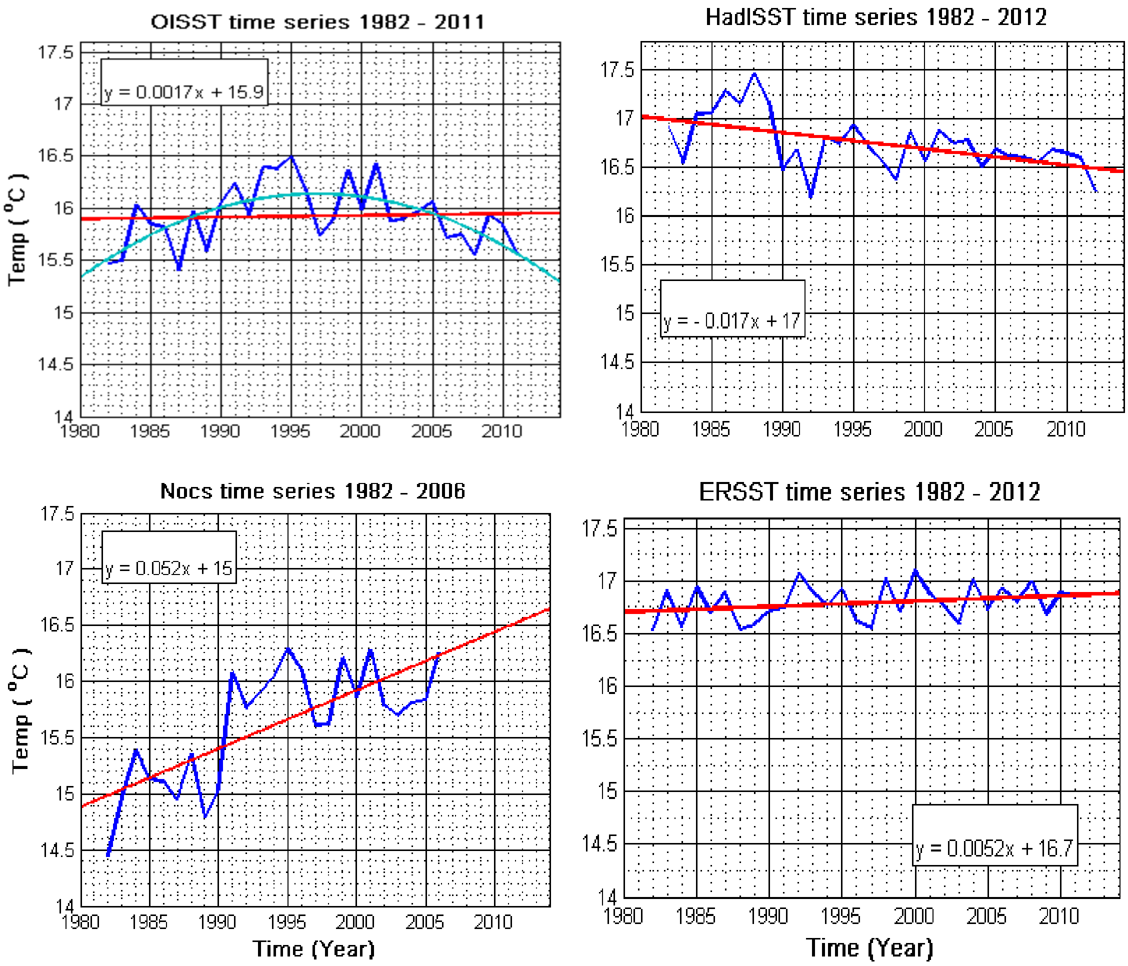

Figure 6: North Central Benguela time series with general trends for the 1982 - 2012 period. Plotted in blue are the yearly means, a linear fitting in red and a light-blue parabola for OISST data with white windows showing trend in °C/year. All trends significant at 95% based on a two tailed Student's t test.

Figure 6, shows time series yearly SST and trends for the north central Benguela domain. The OISST time series general trend follows a quadratic polynomial pattern with a typical parabola shape. There is warming trend from 1982 – 1997 and a cooling trend from 1998 – 2011. The general trend for the whole period is a small warming trend of 0.0017 °C/year. The HadISST exhibits a general cooling trend of 0.017 °C/year with 3 – 5 year cycles of inter-annual variability. The NOCS still shows a strong suspicious warming trend of 0.052 °C/year. The notorious Benguela Ninos of 1995 (Rouault et al., 2003, Rouault 2012) is represented in all dataset but ER SST. HadlSST still has a warm Bias. There is wide range of temperatures changes in NOCS. ERSST shows trend line which is almost flat, but there is some slight warming trend observed, 0.0052 °C/year.

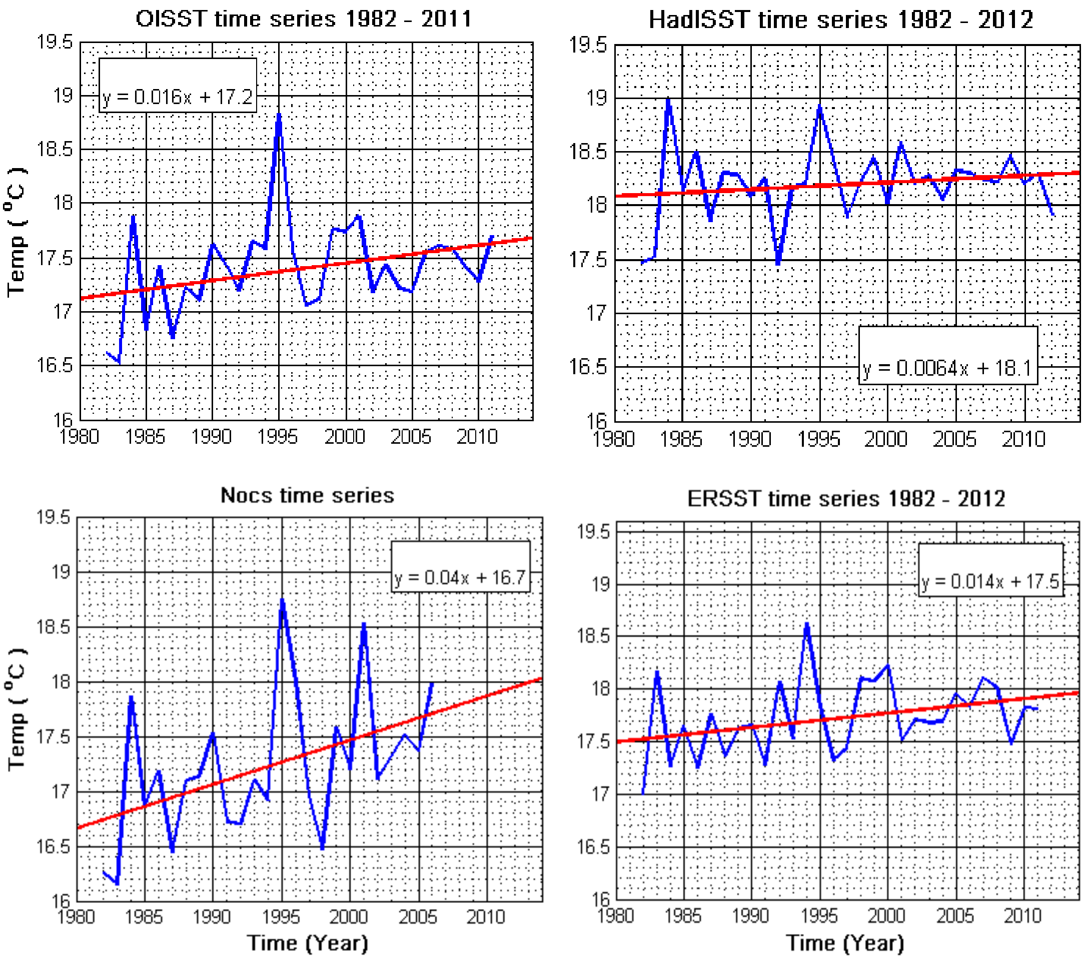

Figure 7: Northern Benguela time series for different SST products (OISST,HadISST, NOCS & ERSST) for the 1982 - 2012 period. Plotted in blue are the yearly means, a linear fitting in red with trend in °C/year in white windows. All trends significant at 95% based on a two tailed Student's t test, except for ERSST which is has 85% significant level.

In **Figure 7,** the northern Benguela time series trends are shown for the 1982 – 2012 period. Generally this region is characterized by warming trends shown in all data sets. The magnitude of these trends ranges from 0.0064 °C/year to about 0.04 °C/year. For this domain we have a warming agreement between dataset as well as absolute maybe due to the large geographical extension of the warming in this region as shown later. HadlSST still has a warm Bias. The northern Benguela is greatly influenced by the position of ABF, which acts as the northern boundary of the Benguela Current system, by allowing the warm Angola Current tropical water to reach far south thereby influencing SSTs in that domain. This domain seems to have stronger agreement between datasets. It is also the strongest change in the Benguela system which could explain the agreement. Benguela Ninos of 1995 and 19984 seem to be properly reproduced, except for ERSST. Changes in northern Benguela SST are crucial to rainfall variability in southern Africa. Warmer SST anomalies in this region are prone to wetter conditions in southern Africa. The Angola Benguela Front is also very sensitive to SST anomalies in the eastern south Atlantic SSTs. Weakening of the easterly winds along the equator causes deepening of thermocline off Angola and allow warm tropical water to propagate southwards across the ABF thereby warming northern Benguela Current significantly and this warming of Benguela surface water has a negative effect on the productivity of the upwelling system and therefore inhibits the marine ecosystems. **Figure 8**, show time series the Agulhas Current system, the Retroflection region. The trend results on this figure for these data sets agree with literature in that there has been a warming of the Agulhas Current system since 1982. This warming is said to be forced by wind driven augmentation of Agulhas Current transport in the southern West Indian Ocean((Wu, et al., 2012); (Rouault, et al., 2009)). The OISST shows a warming general trend of 0.033° C/year, the HadISST's general warming trend was 0.0095 °C/year, NOCS general warming trend was 0.0022° C/year and the ERSST general trend was 0.0093° C/year. Even though the data sets all show a warming trend, the difference in trends is a cause of concern.

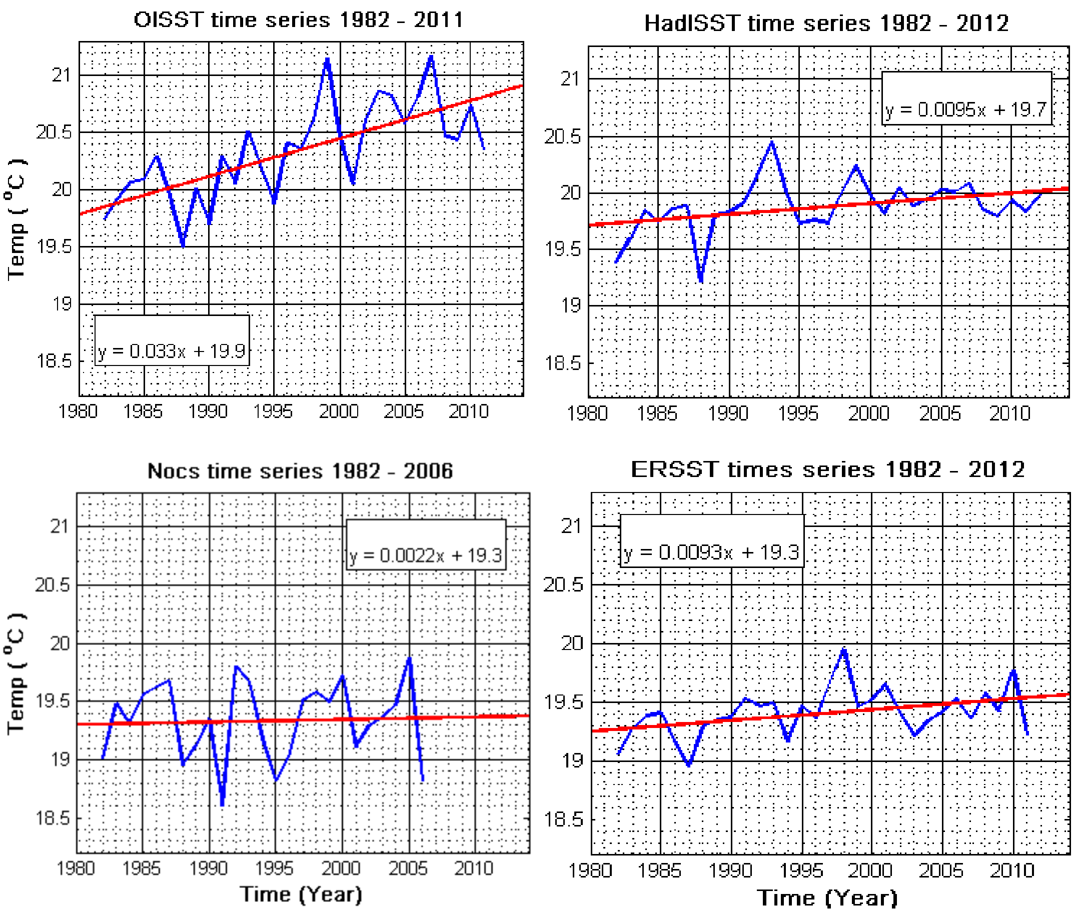

Figure 8: Retroflection time series general trends for the 1982 - 2012 period. Plotted in blue are the yearly means a, linear fitting in red with the white windows showing trends in °C/year. All trends significant at 95% based on a two tailed Student's t test.

In light of the above it seems that the NOCS dataset has the most problems. There are also important differences between all datasets. To compare these dataset we detrend the data and look at inter-annual variability in all domains using the 4 datasets. This is shown in Figure 9 to 13.

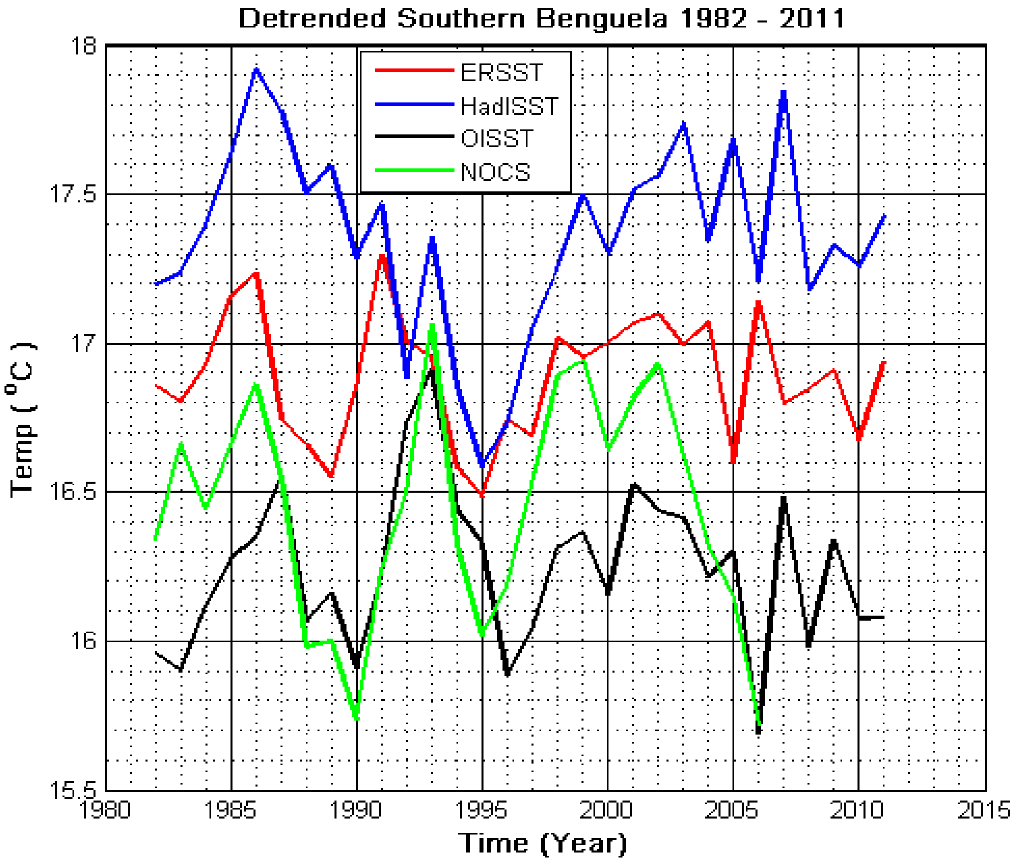

Figure 9: Detrended time series for the Southern Benguela area. Calculated for all SST data sets. The white window shows the legend for different colour plots.

Detrended southern Benguela SST yearly SST time series for the 1982 - 2011 period are showed in **Figure 9.** Data are averaged yearly. The inter/multi-annual variability in this area is clearly visible. There are 3-6 year cycles in most data sets. Most data sets show warm events in 1986, 1993, 1999, 2007 and also a broader warm period between 2000 & 2005. There are also cool events shown by data sets in the Southern Benguela area. The most noticeable ones are the 1995 and 2006 cool events. In 2000 again we observe a cool event of a lesser intensity. However some peaks do not correspond to the same year. The 1987 peak in OISST, our reference dataset is not reproduced a year earlier than the other datasets. The 1993 event is reproduced by all datasets except the NOCS. The 2000 cold event is not reproduced by ERSSST. The 2007 warm event is reproduced by OISST and

Hadley SST but not by the others. There are considerable biases and differences between all datasets which of course can be attributed to the various methods and the resolution of datasets but could also indicate some problems in the datasets themselves that are beyond the scope of the study. The same problems occur in other domains as well which further limit our confidence to establish trends before the satellite era in the region. If inter-annual variability is not described with confidence, how can one establish trends? Moreover the difference in SST trends is a cause of concerns if one need to use NOCS SST for trends since 1973 or HadlSST and ER SST for trends before 1982.

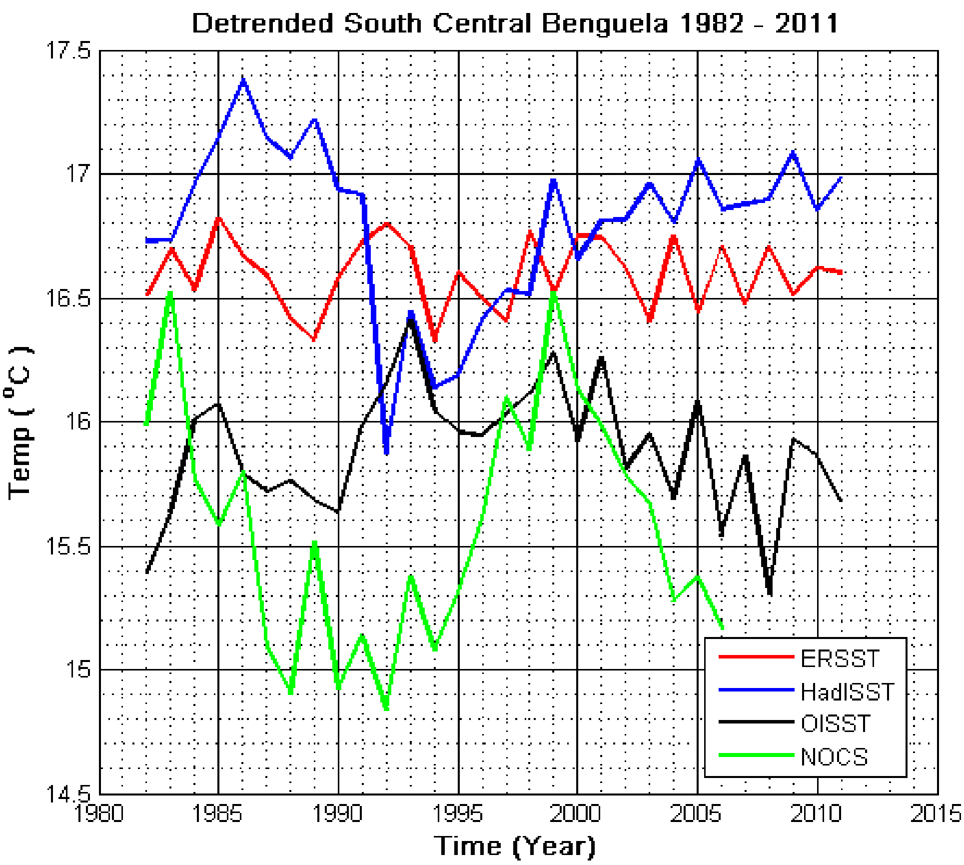

Figure 10: Detrended time series for the South Central Benguela area. Calculated for all SST data sets. The white window shows the legend for different colour plots.

Figure 10, shows detrended SST time series of yearly means for the South Central Benguela for the period 1982 – 2011. In this area it seems that there is no obvious agreement between the datasets except for some years where we observe events of similar nature, warm events in 1986, 1993, 1999 and 2005. The frequency of the variability in this area differs from each data set. NOCS SST shows the most range of variability. The ERSST seems to be the most stable in this area with the least range of variability, this however might be due to its spars resolution which may smooth out smaller scale variability. However ERSST seems to lag by a year.

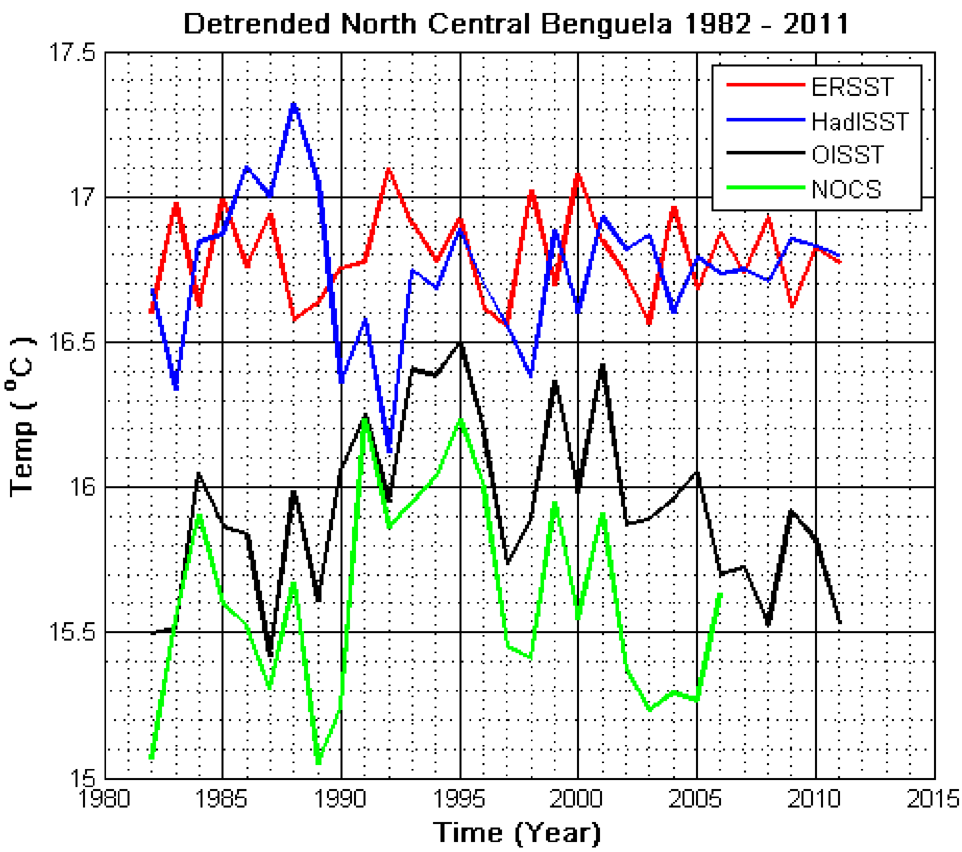

Figure 11: North Central Benguela detrended time series for the 1982 – 2011 period. The legend for different SST plots is given on the white window.

A significant agreement between dataset's warm and cool years seems to be observable throughout the 1982 - 2011 period in **Figure 11**. The ERRSST seems to be in agreement with HadISST, even though the ERSST shows some sign of legging the HadSST by a year. The NOCS SST and OISST seem to agree from year to year especially for the 1982 - 2002 period and they have greatest ranges in this area. The ERSST also indicates some level of stability based on the range of SST year to year variability. Bias between dataset is still a cause of concern. The HadISST shows multi-annual temporal variability of two to seven years for the first 16 years (1982 – 1998) and is more stable thereafter. Most data sets show warm years in 1984, 1988, 1991, 1995, 1999 and 2001. The multi-annual cycles are present in all data sets.

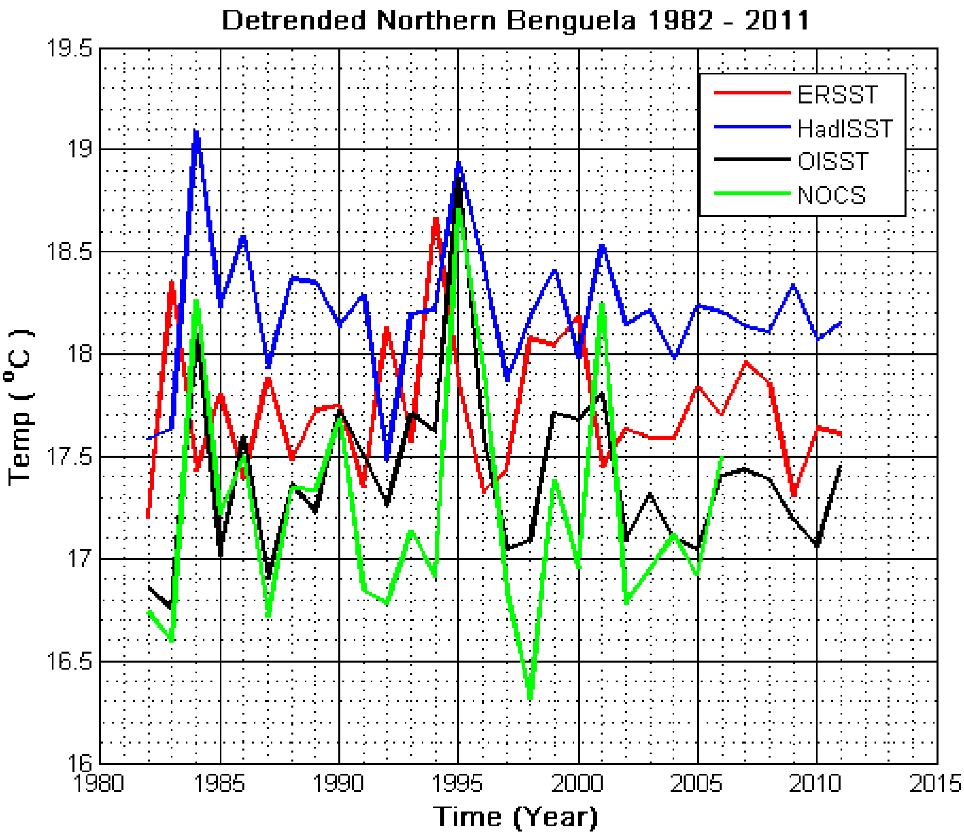

Figure 12: Northern Benguela detrended time series for the 1982 - 2011 period. In the white window the legend which shows data products for the plots is shown.

De-trended SST time series calculated for the Northern Benguela domain are shown in **Figure 12**. There are five main warm peaks where most of the data sets agree to a certain extent, 1984, 1986, 1990, 1995 and 2001. There are also observable cool events in this area of Benguela, the cool events were seen in, 1985, 1987, 1992 and 1997. The NOCS SST agrees with OISST in most of warm events. All data sets show a high frequency inter-annual variability, however the range of variability differs from data set to data set. The 1995 warm event linked to Benguela Nino is interesting in that it is the only peak where all data sets show an almost equal amount of variability, and the range of that variability seem to agree in all data sets.

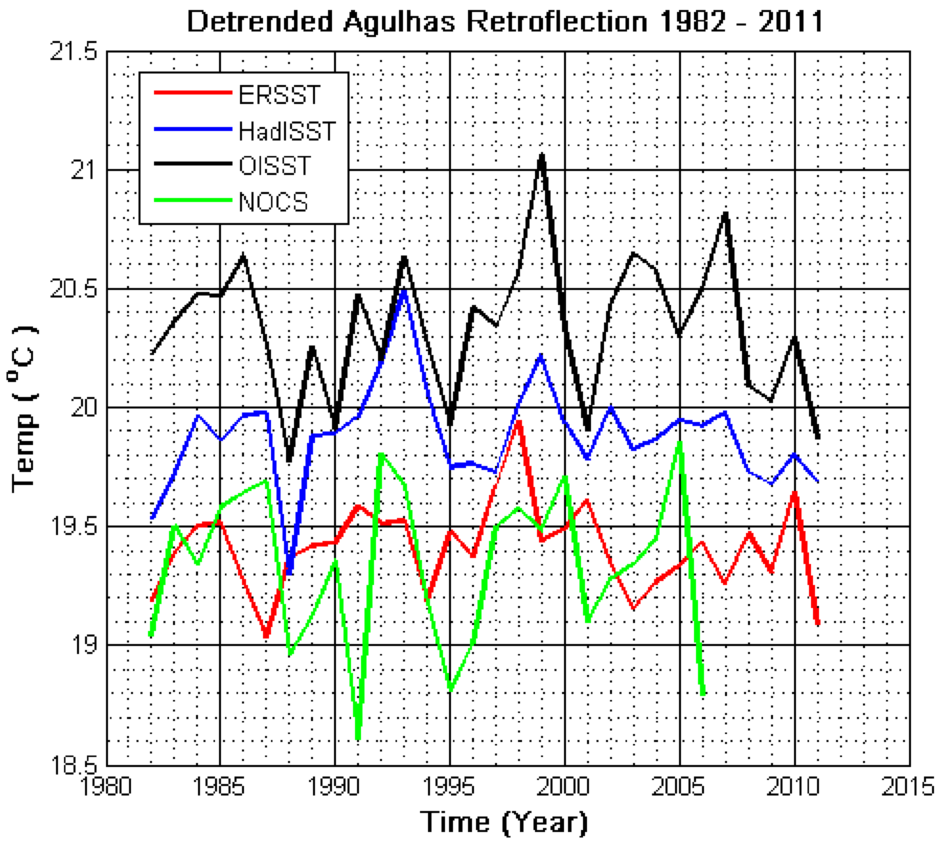

Figure 13: Detrended time series for Agulhas Retroflection area. Calculated for all SST data sets. The white window shows the legend for different colour plots computed with different data products.

The Retroflection area is very variable and is dominated by eddies and filaments, we expect a high level of inter-annual variability. Because of the abundance of small scale features in this area SST data sets are prone to differ especially due to resolution and the statistical techniques used in the reconstruction of data sets. In **Figure 13**, detrended SST time series of different data products are shown. There is a strong cool event in 1988 and two more cool events of lesser amount in 1995 and 2001. The strong warm eventsare observed in 1993 and 1999. The amount of warm and cool events differ in each data sets with some peaks occurring on the same year and others of different years depending on the type of data set we looking at.

4.3. Long period SST trends

While the former chapter give us little confidence in Hadley and ER SSST SST for the study of trend in the region, it is still interesting to look at results using those dataset because it is all we have and some authors have used those datasets to propose cooling trends in the Benuela or warming trends in the Agulhas Current. Looking at longer SST time series of HadISST and ERSST for the Benguela domains gives interesting results also because both data sets are derived from ICOADS data set. In **Figure 14,** the time series for HadISST and ERSST are presented. The HadISST warm bias is also evident in the long period time series, this might be due to the differences in resolutions of these two products. The HadISST has a higher resolution and therefore represent the upwelling much better than ERSST. In the southern and south central Benguela the two SST fields seem to agree to a certain extent. There seem to be a general warming from 1900 up until 1990, and thereafter there seem to be a radical cooling in these regions, in the HadISST. The HadISST uses remote sensing satellite data (AVHRR) since the 1980's onwards which is probably arise as a result of introducing satellite measurements. The ERSST shows a general consistent warming for all periods in southern and south central Benguela.

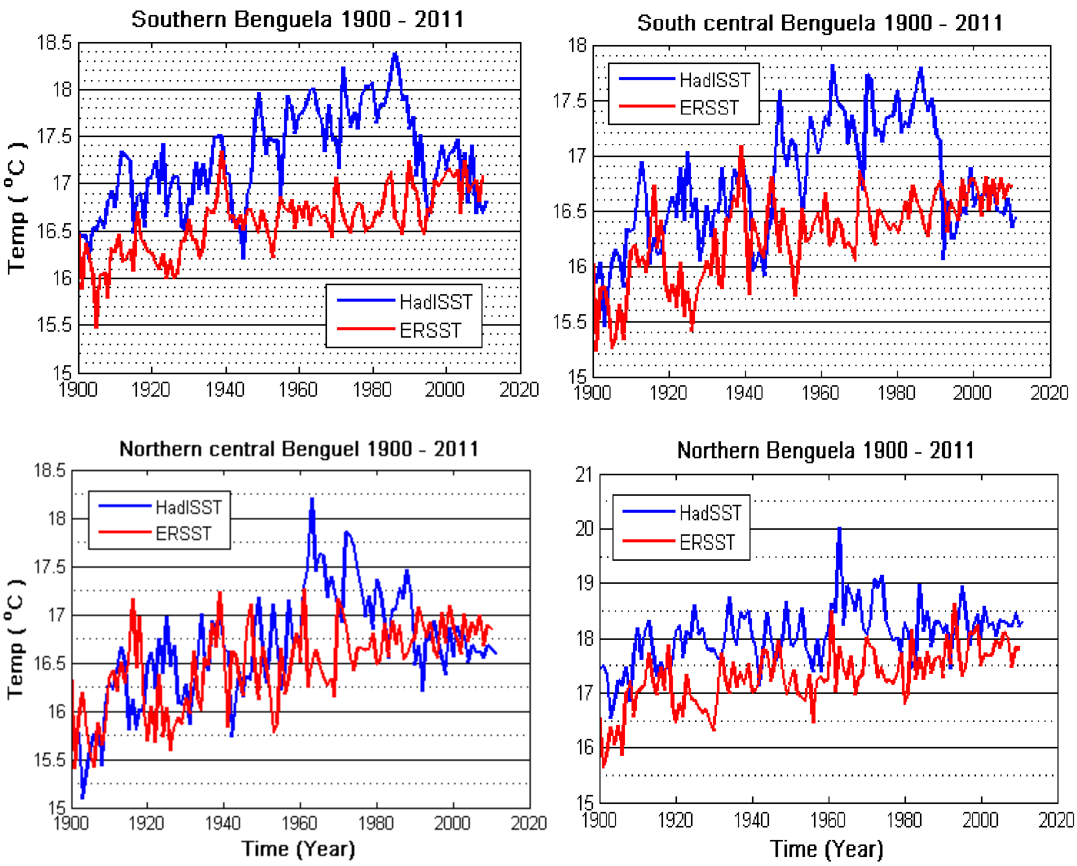

Figure 14: Long period time series for all Benguela domains. Plotted in blue are HadISST SST means and ERSST SST yearly means are plotted in red. Using a Student t test we found at least 80% significant level for the long term time series.

The HadISST northern central Benguela time series shows a warming between 1900 & 1960, and a cooling after the 80's until 2011. This cooling could correspond to the introduction of AVHRR satellite estimate in the data and therefore be an artefact of the dataset. The ERSST shows a warming in both the north central and northern Benguela, in fact in all the Benguela domains the ERSST depicts a warming coupled with high inter/multi-decadal variability. The northern Benguela HadISST shows a general warming throughout the century, with high frequency of inter/multi-decadal variability. Looking at the HadISST data set the Benguela Current system seems to have started cooling down in the 1970's before the satellite era. From the late 1970's onwards the ERSST and HadISST seem to agree. One of the reasons ERSST doesn't show the observed cooling might be attributed to its resolution and the fact that the area of interest which is dominated by a wind driven upwelling cell is much closer to shore for it to be represented well in the ERSST.

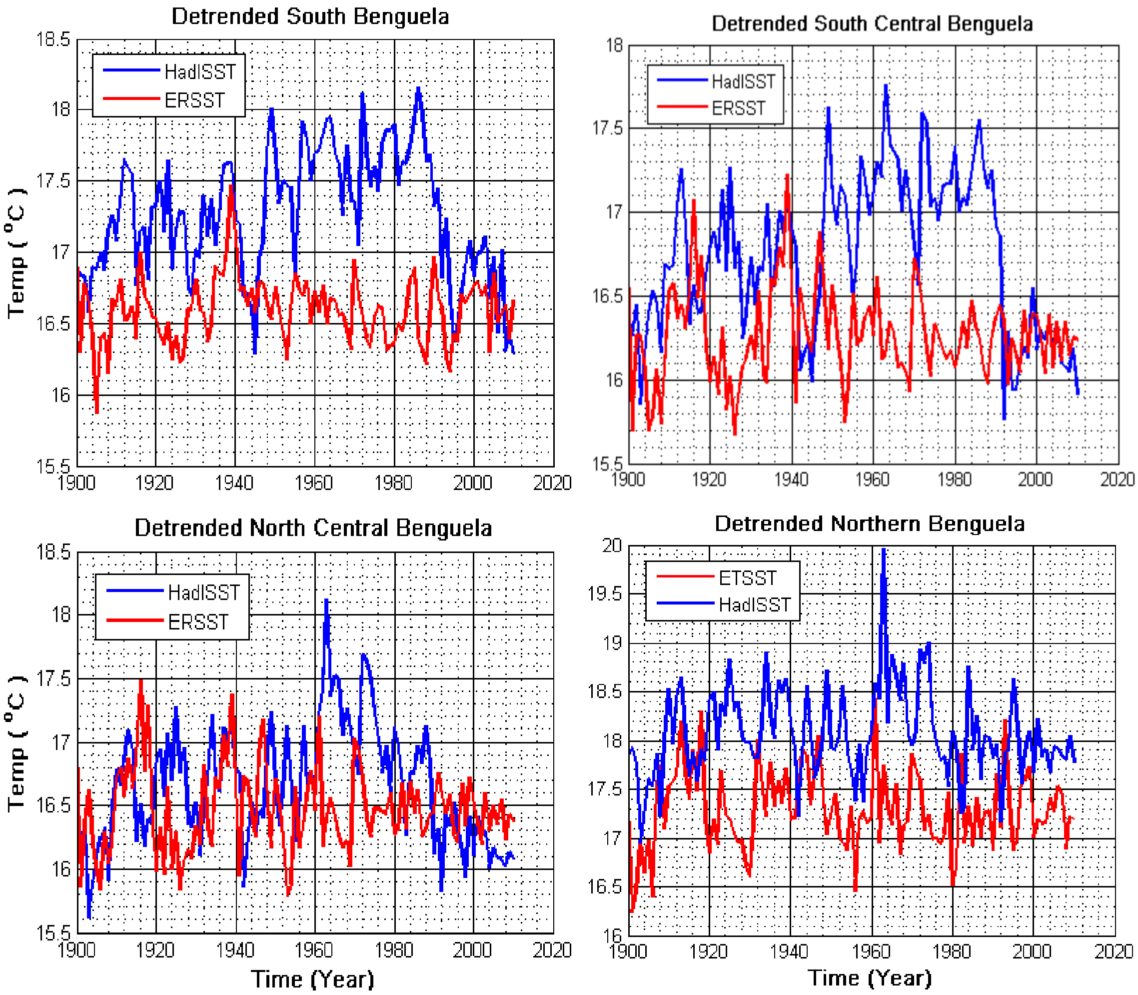

Figure 15: Detrended SST time series for the 1900 - 2011 period. The time series calculated for all the Benguela domains. The white window contains the legend of the data set used.

In **Figure 15**, we take a closer look to the inter/multi-annual to decadal/multi-decadal variability of the long period SST time series. The long period time series is detrended so as to flatten the time series around the mean but not removing the mean. Generally the ERSST seems to be more stable with some exceptions where we observe high range of low frequency variability in peaks throughout the 1900 - 2011 period from all the Benguela domains. The HadISST generally shows most of variability with great range of inter/multi-annual to decadal/multi-decadal variability throughout the given period of the study. The HadISST in the South and Southern Benguela show a similar pattern of variability, and the sudden deep after 1982 is clearly captured in both domains. The deepening of HadISST after the 1980's is due to the inclusion of AVHRR satellite data in the original HadISST. This resulted to the cold bias of the satellite in this region of interest. In the Northern and North Central domains the HadISST shows similar pattern to ERSST but out of phase for the first 60 years. In 1961 there seem to be some phenomenon which alters HadISST peak and thereafter the peaks deepen considerably. This is a further problem and using Hadley SST 1x1 degree for trend after 1982 is not advisable.

2.1. Spatial field rends

SST trends vary spatially. Field trends are much more visible and make the examination of overall trend spatial variability easy to visualise. Southern Africa exhibit temperature trends which are heterogeneous spatially. The OISST decadal field trend shows clearly the warming and cooling trends in the Agulhas and Benguela regions respectively in **Figure 16**.

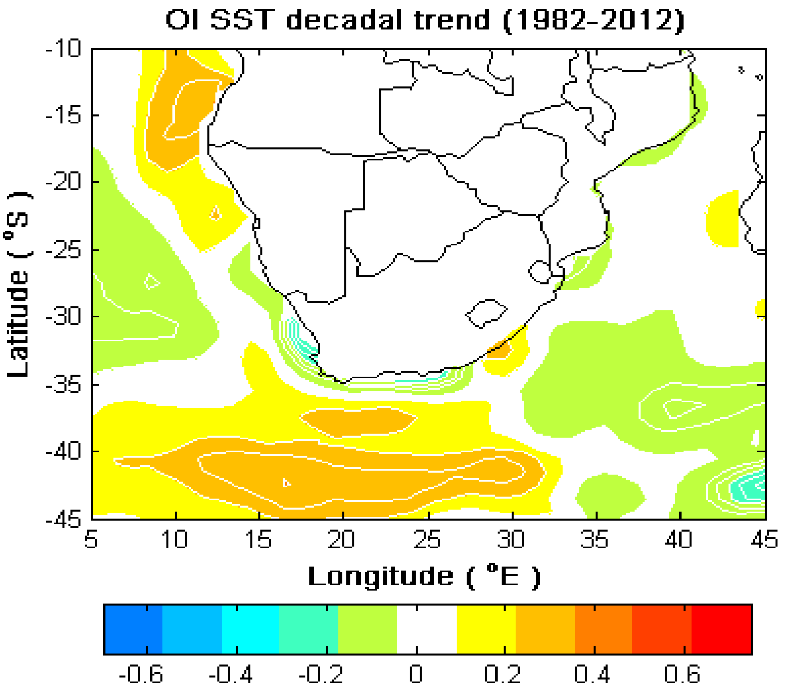

Figure 16: Spatial SST trends (°C/decade) around southern Africa (1982 - 2012), derived from OISST data set. Red signifies a warming trend and blue is cooling. 95% significant level SST spatial trends shown in colour shading.

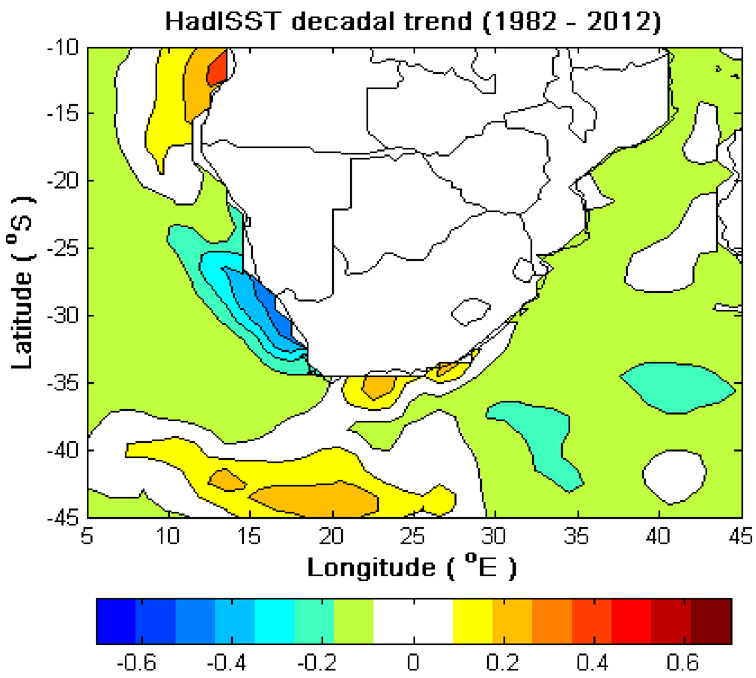

Figure 17: Spatial temperature trends (°C/decade) around southern Africa (1982 - 2012), derived from HadISST data set. Red signifies a warming trend and blue is cooling. 95% significant level SST spatial trends shown in colour shading.

Generally SSTs have been warming by 0.4 ^{o}C/decade around southern Africa since the 1980's with the exception of the south western and southern coastal areas where we observe cooling trends of up to -0.4 ^{o}C/decade. The northern Benguela warming trend (0.2 ^{o}C/decade) is clearly articulated on the OISST trend figure. **Figure 17,** shows general warming and cooling trends around southern Africa constructed using the HadISST for the 1982 – 2012 period. Heterogeneity of trends is quite eloquently portrayed with a general warming trend around the Agulhas Current system and the northern Benguela and cooling trends in central and southern Benguela. The warming trends range from 0.1 – 0.3 ^{o}C/decade and the cooling trends range from -0.1 – (-0.4) ^{o}C/decade. The south coastal cooling trend is not present in the HadISST data set. When compared with OI SST otherwise both dataset show the same pattern which could be due to the introduction of AVHRR in HAdlSST. **Figure 18 & 19**, show general temperature trends derived from NOCS and HadISST respectively for the 1973 – 2006 period, which is the commun period for both dataset, NOCS starting in 1973. The NOCS SST is characterised by a strong warming trends everywhere in the Benguela Current system which is at odd with Hadley SST. This further indicates that NOCS dataset is problematic and should be dismissed. The 1973 -2006 trends in HadlSST are similar to the 1982 -2012 trends. Except for the northern Benguela and Angola Coast this dataset seems at odds with the other and should be used with caution. The Agulhas Current system has a warming trend but there is a cooling trend in the Retroflection area. However, the HadISST shows oposite results to the NOCS. The HadISST is characterised by cooling trends in the Benguela Current system and general warming trends in the Retroflection region of the Agulhas Current system in the 1973 – 2006 period.

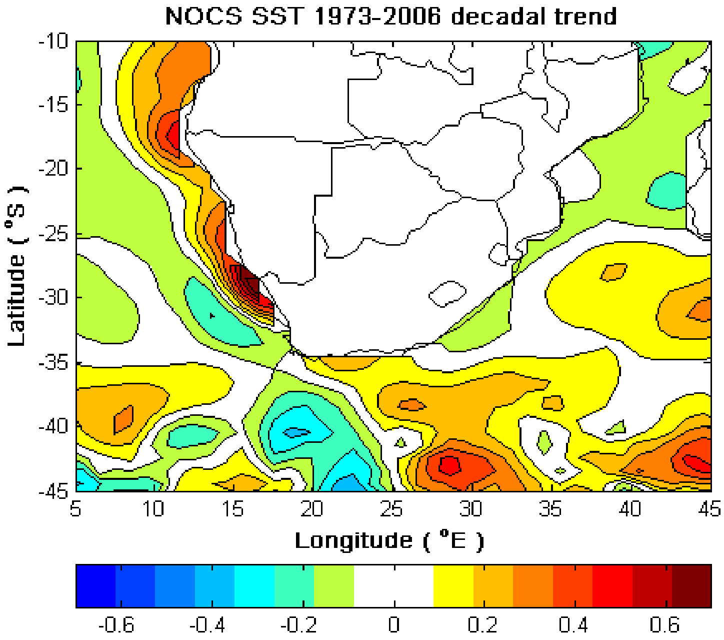

Figure 18: Spatial temperature trends (°C/decade) around southern Africa (1973 - 2006), derived from NOCS data set. Red signifies a warming trend and blue is cooling. 95% significant level SST spatial trends shown in colour shading.

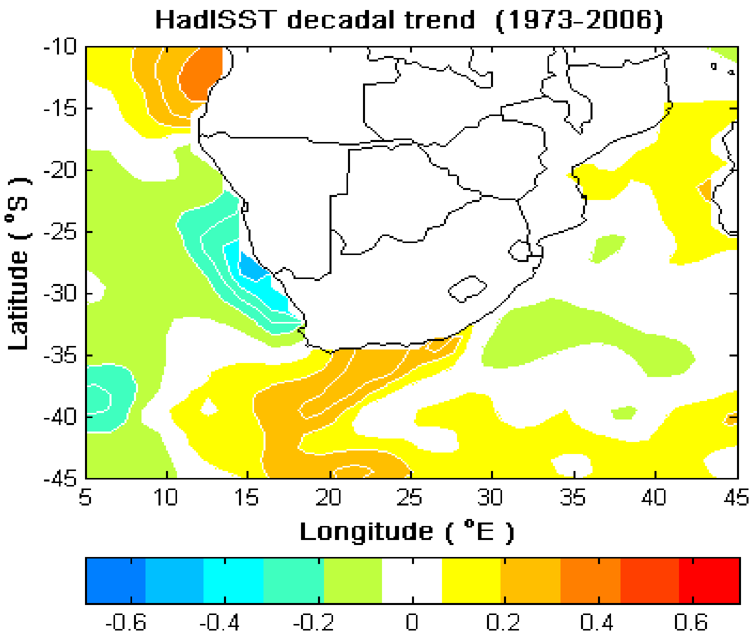

Figure 19: Spatial temperature trends (°C/decade) around southern Africa (1973 - 2006), derived from HadISST data set. Red signifies a warming trend and blue is cooling. 95% significant level SST spatial trends shown in colour shading.

This is quite similar when considering the 1982-2012 period. For that reason we are dismissing the use of NOCS for the study of regional trend in the region.

2.2. Seasonal SST trends

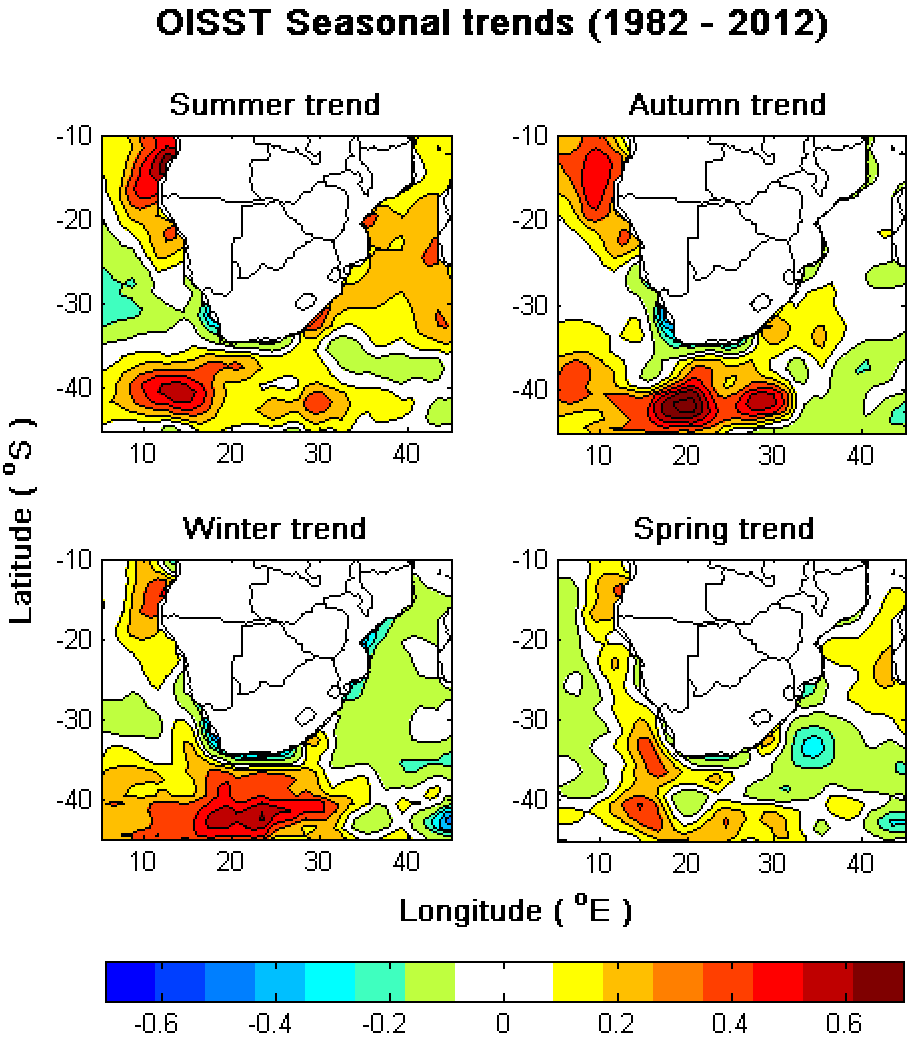

Figure 20: Seasonal trends around southern Africa derived from OISST for the 1982 – 2012 period. Summer (DJF), Autumn (MAM), Winter (JJA) and Spring (SON). 95% significant level SST spatial seasonal trends shown in colour shading.

Figure 20, shows seasonal trends around southern Africa for the period 1982 – 2012. The Agulhas Current system generally shows warming trends of differing magnitude in all season with some patches of cooling in spring. The strongest warming rate is found at the Retroflection during the autumn season and the least warming rate is observed during spring season at the Retroflection region. The south coast shows cooling trends in all season with the strongest cooling trend in winter. In the southern Benguela cooling trends between -0.4 & -0.1 ^{o}C/decade are observed for summer, autumn and winter and a warming trend of up to 0.2 ^{o}C/decade is observed in spring. The spring season is the only season that shows a warming trend in the southern Benguela. The central Benguela shows trend amounts of -0.1 ^{o}C/decade for for summer, autumn and winter and a of 0.2 ^{o}C/decade warming trend in spring. All seasonal trends in the northern Benguela show a warming trend with trend rates between 0.2 & 0.6 ^{o}C/decade. The warmest trends in the northern Benguela are found during summer and autumn seasons and the least warm trends are found during winter and spring season. **Figure 21** shows seasonal trends around southern Africa for the period 1982 – 2012. The seasonal trends have been constructed using HadISST. Warming trends of differing magnitude were observed in the Agulhas Current system for all seasons with less significant ($p < 0.05$) warming trend in spring. Contrary to what we observed in **Figure 20** in the south coast where strong cooling trends were depicted, **Figure 21** shows warming trends in the south coast region for all seasons. The southern Benguela in **Figure 21** shows strong cooling trends for all seasons and the strongest cooling found during autumn season and the least cooling found in spring season, and the strong cooling trends were up to -0.6 ^{o}C/decade with the least cooling trend of -0.2 ^{o}C/decade. This is contrary to what we observe in **Figure 20** where cooling trends were only observed for summer, autumn and winter season and a warming trend in spring season. The cooling trends in central Benguela in **Figure 21** are clearly visible for all season. The autumn season has the strongest cooling trend in the central

Benguela and the least cooling trend is found during spring season. The northern Benguela shows warm trends of varying amounts in all seasons. This result is similar to what we found in **Figure 20** where OISST data was used, but the magnitude of the rates of warming differs from figure to figure and from season to season. The warmest trends are found in summer and spring and least warm trends found in autumn and winter in the northern Benguela.

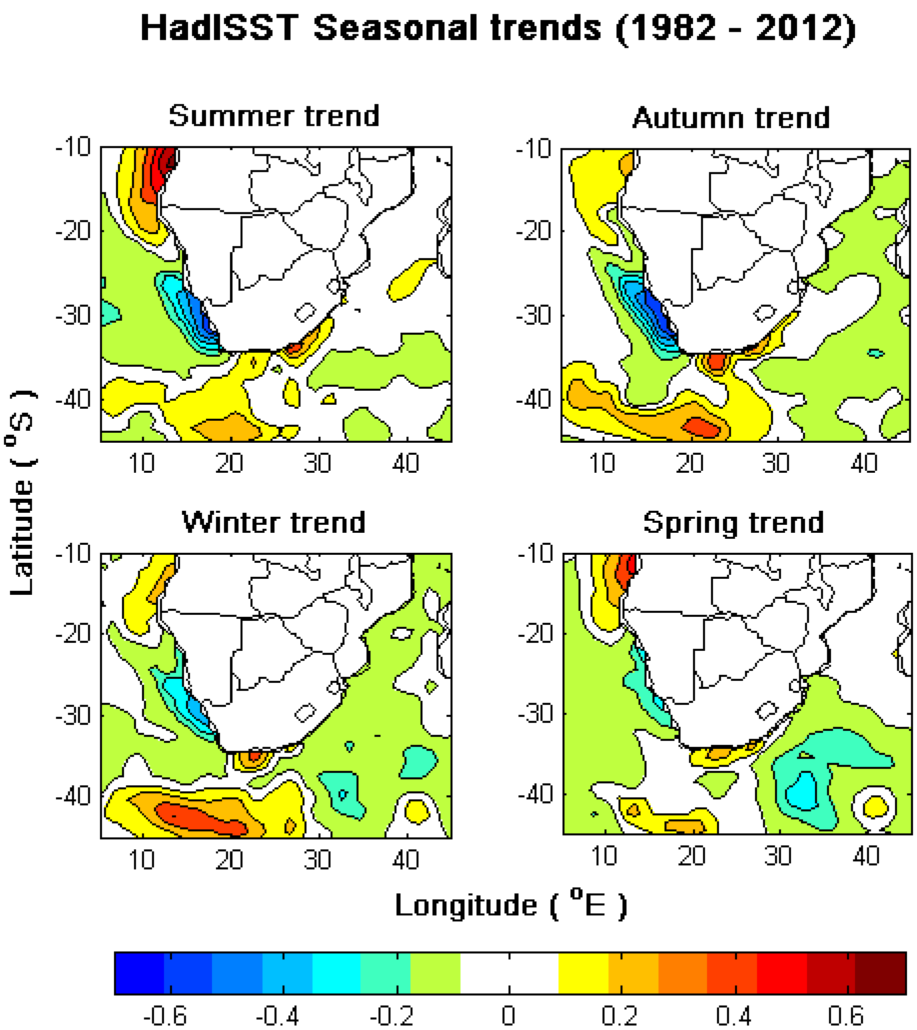

Figure 21: Seasonal trends around southern Africa derived from HadISST for the 1982 – 2012 period. Summer (DJF), Autumn (MAM), Winter (JJA) and Spring (SON). 95% significant level SST spatial seasonal trends shown in colour shading.

Figure 22, shows seasonal trends of ERSST for the 1854 – 2012 period. Generally we observe warm trends throughout the seasons. However the rate of warming differs from season to season and within different domains. The summer and autumn seasons show similar trends in the Benguela domain. The Retroflection warming is also similar for the summer and autumn season. The Southern and Central Benguela are warming by up to 0.03 °C/decade. The autumn and winter seasonal trends have the least amount of warming in the Southern and Central Benguela. The Retroflection in these seasons' trends has up to 0.06 °C/decade warming rate. Overall ER SST shows an interesting trend in the upwelling and along the coast of Southern Africa which could indicate that wind has increased along the coast leading to less warming than the surrounding open ocean and maybe a stronger upwelling.

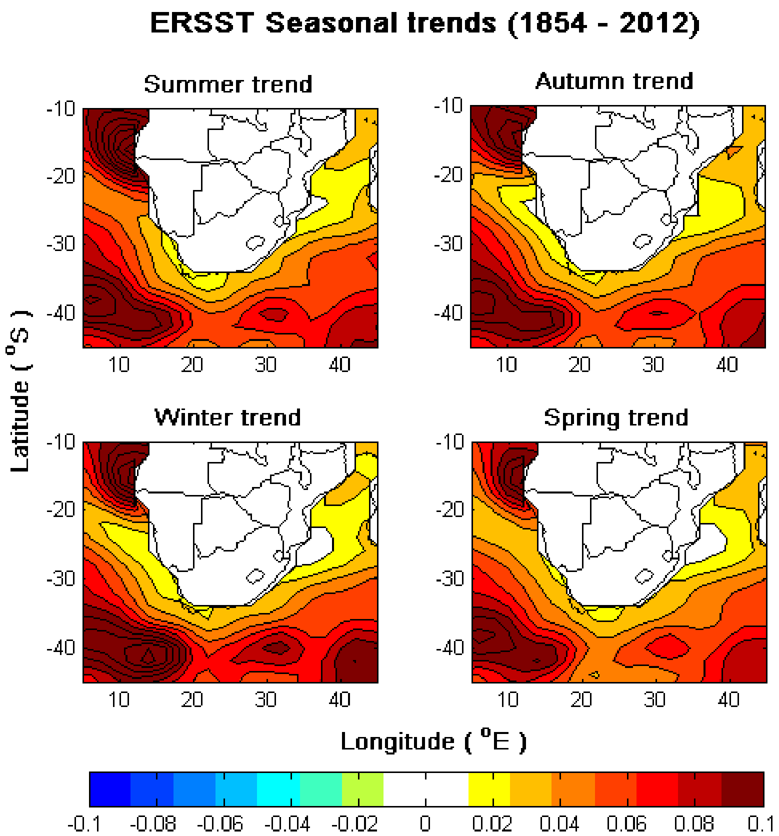

Figure 22: ERSST seasonal trends for the 1854 - 2012 period. To compute season we averaged three months, Summer (DJF), Autumn (MAM), Winter (JJA) and Spring (SON). 80% significant level SST spatial seasonal trends shown in colour shading.

Northern Benguela shows a warming of 0.8 – 0.1.ºC/decade. The summer seems to be the season with most warming in the Northern Benguela.

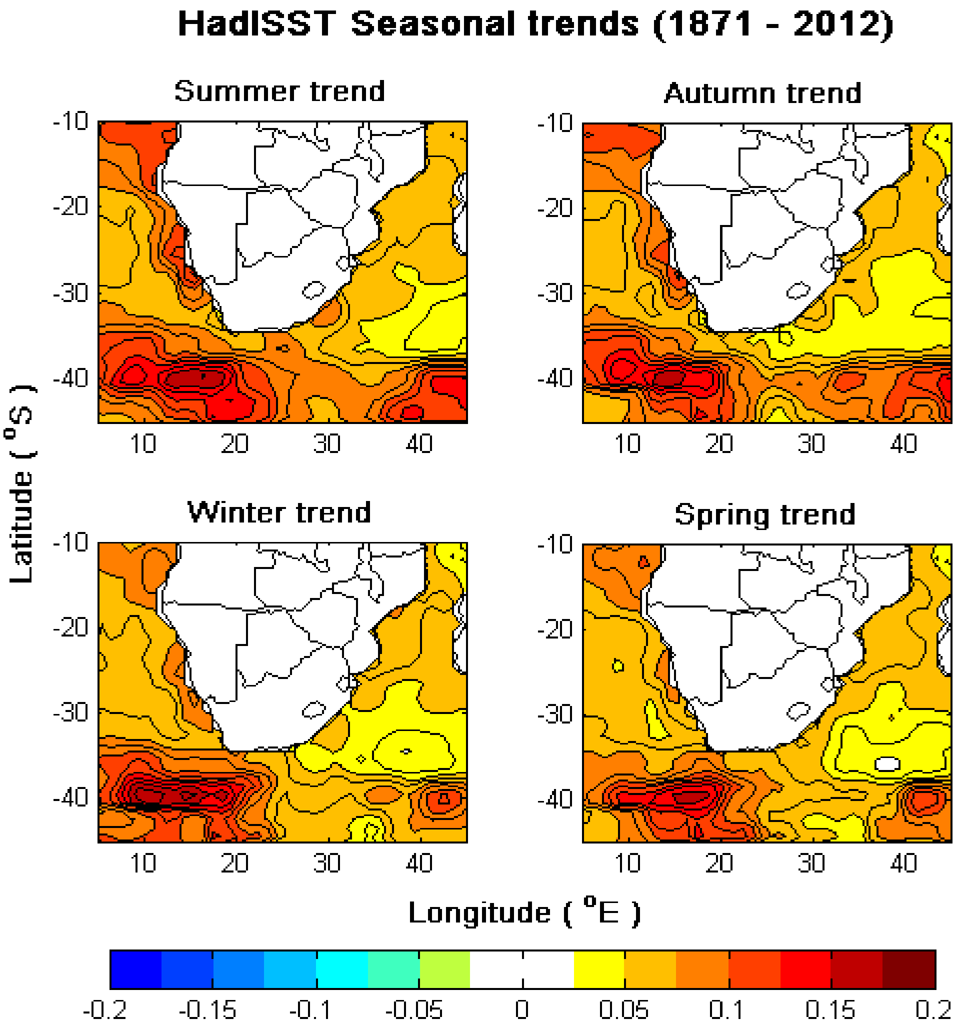

Figure 23: HadISST seasonal trends for the 1871 - 2012 period. To compute season we averaged three months, Summer (DJF), Autumn (MAM), Winter (JJA) and Spring (SON). 80% significant level SST spatial seasonal trends shown in colour shading.

The HadISST seasonal trends are shown in **Figure 23** for the 1871 – 2012 period. They are quite different from Er SST. All seasons show warm trends around Southern Africa. The Retroflection area shows the most amount of warming in all seasons. The summer and autumn seasons show most warming in the Benguela region and the least amount of warming is observed in spring season. The Northern Benguela shows most warming in the Benguela region. The seasonal trends since 1960 for ERSST and HadISST are shown in **Figure 24 & 25** respectively. In **Figure 24,** generally summer and autumn seasons show warmest amounts of trends, with least amount of warming trends in winter and spring seasons. The Agulhas Current system is characterised by significant ($p < 0.05$) warm trends in summer and autumn seasons. There is lesser warming of Agulhas Current system in winter and spring seasons. The range of trends from winter to summer is between 0.05 – 0.25 °C/decade. There is not much trend change in Southern Benguela.

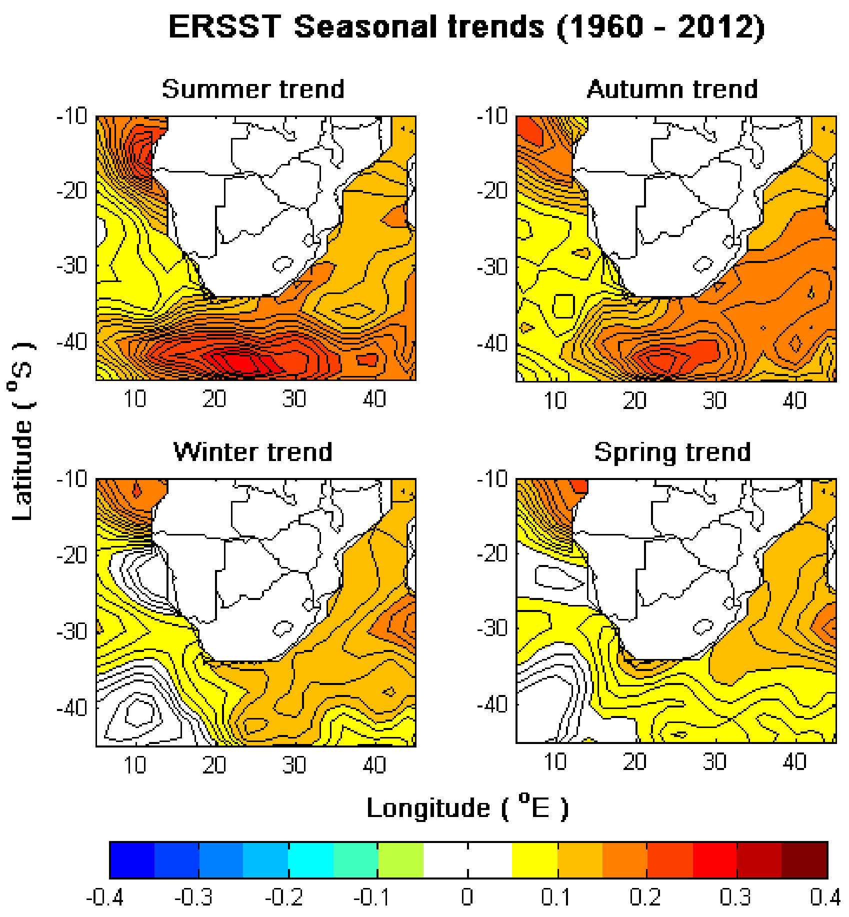

Figure 24: ERSST seasonal trends, 1960 - 2012. The black areas are a result of contours being too close to each other. Top left - Summer (DJF) trend, top right - Autumn (MAM) trend, bottom left-Winter (JJA) trend and bottom right - Spring (SON) trend. 90% significant level SST spatial seasonal trends shown in colour shading.

The Central Benguela also shows minimal trend change through the seasons with the exception of winter and spring seasons where less than 0.5 °C/decade trends are observed. The Northern Benguela's distinct warming trends are eminent in **Figure 24**, and there is a sharp trend rate change in Central-Northern Benguela in winter.

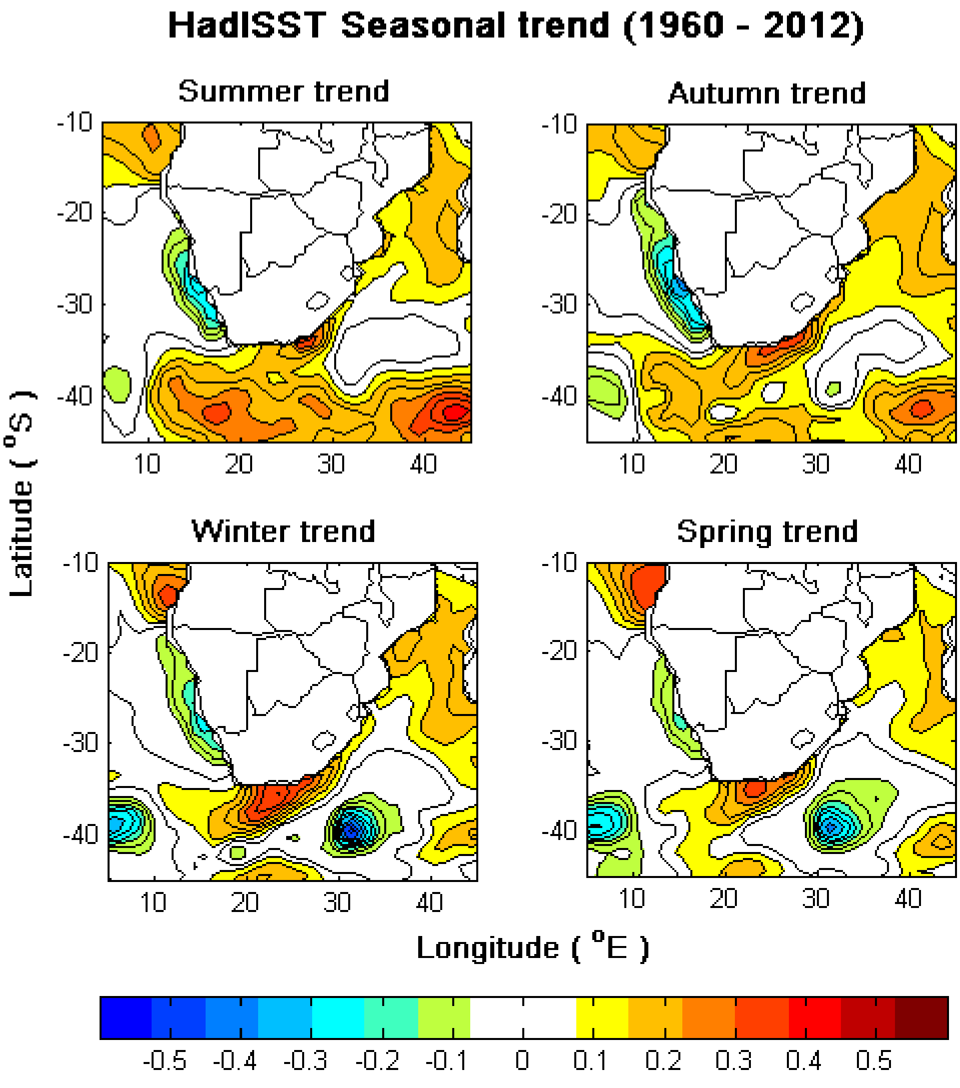

Figure 25: HadISST seasonal trends, 1960 - 2012. The black areas are a result of contours being too close to each other. Top left - Summer (DJF) trend, top right - Autumn (MAM) trend, bottom left-Winter (JJA) trend and bottom right - Spring (SON) trend. 90% significant level SST spatial seasonal trends shown in colour shading.

The HadISST in **Figure 25** shows much spatial variable trends for all seasons. The Benguela Current system generally shows cooling trends and the Agulhas Current system shows warming trends for the 1960 – 2012 period for all seasons. Autumn has the highest amount of cooling trend, with a significant ($p < 0.05$) cooling trend of up to -0.4 °C/decade and the least cooling trend is observed during spring with a cooling trend of up to -0.1 °C/decade. The strongest amount of warming is also observed in summer in **Figure 25**. The warming trends for HadISST Retroflection area are in the range of 0.1 – 0.3 °C/decade. The spatially close opposite trends of the Benguela and Agulhas Retroflection are clearly observed in this period of years. The Benguela trends seem to be warming up moving off shore.

2.3. HadISST – OISST difference

To check the bias between OISST and HadISST for the 1982 -2012 period, we took difference between the two data sets (OISST – HadISST) and the results were plotted.

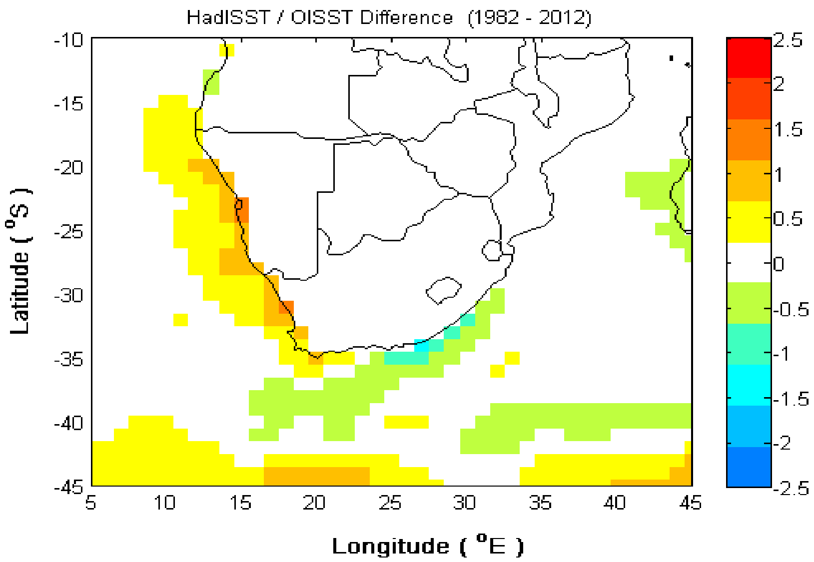

Figure 26: Field differences in SST for HadISST and OISST for the 1982 - 2012 period.

Figure 26 shows the difference between HadISST and OISST in the southern Africa. In the Agulhas Current system the OISST warm bias is clearly visible especially closer to shore in the Eastern Cape coast where we observe an OISST bias of up to 1.5 ^{o}C. In the Benguela Current system the HadISST warm bias is prominent. The HadISST is up to 1.5 ^{o}C warmer than OISST especially closer to the coast. This might be due to the scheme and the interpolation techniques used in the reconstruction of these two widely used SST data set. Care must be taken when using these data sets especially when dealing with small features closer to shore.

5. Discussion

In this Chapter we discuss and synthesise the objectives and results of the study. This dissertation's main goal was to investigate whether changes in the Benguela Current system and Agulhas Current system (Rouault, et al., 2010) are also present to other data sets for the 1982 – 2012 period, and to also check whether all datasets show the same trends? Having this in mind, the discussion is mainly focused on the trends and inter-annual variability for all dataset in the region of southern Africa by intending to answer the research question. All datasets showed significant ($p < 0.05$) trends except in the Northern Benguela where ERSST significance level was 85% for the 1982 – 2012 period. The significance level decreased with an increase in period and was 80% & 90% for the 1800's and 1960's respectively.

Research questions

Are changes in the Benguela Current system and Agulhas Current system (Rouault, et al., 2010) **established with OI SST also present to other datasets for the 1982 – 2012 period and are all products showing the same trends?**

The changes in the Benguela Current and Agulhas Current system are present in other datasets. However, in the Benguela Current system the results are not consistent. Whereas OISST and HadISST show mainly cooling trends of different amounts the NOCS and ERSST show warming trends with NOCS showing significant ($p < 0.05$) warming trends. In the Northern Benguela and Retroflection all datasets show warming trends for the 1982 - 2012 period with some cooling patches in spatial trends in the Agulhas Current system. The spatial trend and multi/inter-annual variability is observed in all datasets in southern Africa with difference in the timing of events.

Can we use these products to estimate changes before the satellite era and what are the estimated changes since 1950 when SST observations were increasing globally, and are these changes estimated since 1850 start of global SST dataset used by IPCC?

The ERSST and the HadISST are both derived from the same ICOADS dataset, therefore some agreement in terms of periodical peaks, multi/inter-decadal variability and long term trends was expected. It is important to mention that the HadISST's use of AVHRR in the 80's produces very high uncertainties in trends in this period as the satellite cold bias is clear observable when looking at long term time series. Therefore using HadISST to calculate trends after the 80's is strongly not advisable due to the inclusion of AVHRR data in HadISST. The latest version of ERSST does not include satellite estimate and therefore can be used for the whole period of dataset to estimate trends. However the ERSST resolution is not really adequate when looking in trends nearer to the coast.

The ERSST warming trend estimate for the 1960 – 2012 period in the Southern Benguela is 0.1 ^{o}C/decade, for the Central Benguela the warming trend is 0.1 - 0.2 ^{o}C/decade and for the Northern Benguela and Retroflection area the warming trends of up to 0.3 ^{o}C/decade are observed. For the ERSST 1854 – 2012 period in the Southern and Central Benguela I estimate trends of 0.02 – 0.04 ^{o}C/decade, the Retroflection and Northern Benguela trends of up to above 0.1 ^{o}C/decade are estimated. The HadISST trend estimates for the 1960 – 2012 period in Southern Benguela was -0.25 ^{o}C/decade and for the Central Benguela the trend range is -0.1 – 0.2 ^{o}C/decade. The Northern Benguela showed cooling trend estimate of between -0.05 and -0.1 ^{o}C/decade and the Retroflection shows trend estimates of 0.3 – 0.4

^{o}C/decade. For the 1871 – 2012 period the warming trend estimates were 0.075 ^{o}C/decade for the Southern and Central Bengula. In the Northern Benguela and Retroflection I observe warming trend estimates of 0.1 and 0.15 ^{o}C/decade respectively. Full interpretation of the datasets has limitations because of the interpolation schemes employed, resolution of data and the use of AVHRR in some products which proves to be problematic when sampling in conditions where there are clouds present or when there's too much sunlight facing the sensor. Therefore small scale oceanic features are absent from 1^{o} x 1^{o} datasets. Rouault, et al., (2003a) showed that the core of Agulhas Current is not represented in OISST dataset because of its resolution, and also the small upwelling cells around South Africa are not present in the OISST. Each 1^{o} grid influences the next one to it because of the interpolation scheme. If the OISST is problematic because of its resolution and interpolation, then other datasets (HadISST & NOCS) might also be problematic due to the fact that they are of the same resolution as OISST. However the resolution of the datasets was adequate enough to be used in the study. Extreme caution must be employed when dealing with these datasets especially if one seeks to investigate small coastal processes in smaller domains. In the time series and spatial trends analysis it was observed that the NOCS product produced results which were not related whatsoever to the results obtained using OISST and HadISST.. The OISST and HadISST show similar results to a certain extent (e.g. Benguela) and they differ in certain areas (e.g. South coast) but the general trends of our domains of interest were resolved quite satisfactory, but probably due to the fact that common use of AVHRR in both datasets was employed. In the Southern Benguela both the OISST and HadISST showed cooling trends. In the Southern and Northern Central Benguela cooling trends were observed for both OISST and HadISST. The warming trends of the Northern Benguela were also captured in all datasets. The

Retroflection region also showed warming trends in both OISST and HadISST. Looking at long dataset (HadISST) it was observed that the Benguela Current system started showing signs of cooling in mid-1970s, and also the time series shows significant ($p < 0.05$) multi/inter-decadal SST variability. Further studies need to be done in order to quantify for certainty the variability observed in this region of Southern Africa. To fully compare OISST with HadISST further studies need to be done, where the inter/intra-annual variability will be looked into with great depth.

6. Conclusion

The inclusion of AVHRR satellite estimate in 1980 to the HadISST is an artefact of data which clearly lead to the cooling trends observed since the 60's in Southern and Central Benguela. The HadISST has a warm bias of up to 2 ^{o}C in the 1982 – 2012 period when compared with OI SST. Therefore trend calculation is not advisable for the HadISST before 1980. The NOCS SST was the only 1^{o} resolution dataset which showed warming trends in the Benguela area for the 1982 – 2006 & 1973 – 2006 periods and therefore seems to be problematic. The long term trends (HadISST and ERSST) showed warming trends of up to 0.2 ^{o}C/decade everywhere around southern Africa. There is high multi/inter-annual variability in this region. Warm and cold events are captured by most datasets, however timing is not consistent. Only ER SST can be used for trends before the satellite era but resolution is not adequate for upwelling. Extreme care must be taken when using low resolution datasets locally, and each dataset has its own limitations, it therefore depends on the user's discretion on which dataset to use for a particular study.

Recommendation for future work

Since this region is dominated by small scale oceanic features a higher resolution SST dataset derived from ICOADS which will also give light to small scale features of interest might need to be employed for future studies. Further study would also need to look at the original SST data from ICOADS or voluntary observation ship and re-grid the data in domain closer to the coast. This study illustrates the difficulty to establish reliable trends at the regional scale before the satellite era. As for satellite further study should use higher resolution SST data such as Pathfinder SST, OI AVHRR or ATSR SST

Acknowledgements

This study was funded by the Applied Centre for Climate & Earth Systems Science (ACCESS). The research leading to these results received funding from the EU FP7/2007-2013 under grant agreement no. 603521. Special thanks is extended to my supervisor Dr Mathieu Rouault for his guidance and patience throughout the study and to my colleagues, the Taught Masters class of 2013 for their support and fun time we shared in the office. I dedicate this dissertation to my parents Matoto and Nowakhe Dlomo who are both unemployed but managed through thick and thin to support me throughout my studies by selling fruit and veg on the streets of Queenstown. Special thanks to Assoc Prof Bette Davidowitz (Dr D with the flow diagrams), Asso Prof Saalih Allie (Bugs), Prof Nic Heideman, Mr Ken Rafel ('Life is hard, people are difficult MATHS is easy') and Dr Riashna Sithaldeen for their outstanding work they did on the GEPS programme. You all made an impact in my life. Gratitude to UCT.

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