SEA SURFACE TEMPERATURES AROUND THE SOUHTERN AFRICAN COAST:

CLIMATOLOGICAL ASPECTS AND APPLICATIONS

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Thesis presented in fulfilment of the requirements for the degree of
Master of Science at the University of Stellenbosch.

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April 2003

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

ABSTRACT

The oceanic and meteorological systems that characterize the southern African coastline are well-documented. In this thesis, these characteristics have been considered in conjunction with the analysis of a unique set of sea surface temperature (SST) data, obtained from measuring sites around the southern African coast, to determine the variability of SSTs in the immediate coastal region of southern Africa, and to demonstrate how this variability impacts on marine-related economic activities. As part of the analysis process, various statistical techniques have been applied to the data over different time periods to establish the extent of the spatial variability of SSTs along the southern African coastline.

From the results it has been possible to identify three distinctly different 'climatological' regions around the southern African coast; *viz* a cooler west coast region with a low annual and seasonal SST variability and a higher variability from day-to-day, a warmer east coast region with a higher annual and seasonal SST variability and a lower variability from day-to-day; and a temperate south coast region with a highly erratic annual, seasonal and day-to-day SST variability. Furthermore, it has been possible to identify, *albeit* small, the existence of a high and a low frequency signal of 12-15 days and 40-60 days, respectively, in the three different regions. There is also evidence of the periodic occurrence of anomalously warm and cold SST events in all three regions, and a probability of <1.1% of a day-to-day SST anomaly of >3°C (+3°C or -3°C) occurring anywhere along the southern African coastline.

The general causes of SST change have been discussed within the context of the heat budget equation. Furthermore, the effects of the variability of SST on the climate and marine life around southern Africa and the resulting impact on the various marine-related economic activities (such as aquaculture, air-sea rescue and power stations) have been identified, and shown to be both positive and negative.

Finally, it should be noted, that economic information relating to marine activities is closely guarded due to inter-industry competition. It has therefore been difficult to quantify the exact impact of the effects of SST variability on these activities.

OPSOMMING

Die oseaniese en weerkundige stelsels wat die kuslyn van suidelike Afrika kenmerk is goed gedokumenteer. Die stelselkenmerke is in hierdie verhandeling ondersoek aan die hand van 'n unieke datastel van seeoppervlaktemperature (SST) afkomstig van meetplekke aan die kus van suidelike Afrika, ten einde die veranderlikheid van SST in die onmiddelike kusomgewing van suidelike Afrika vas te stel, asook om te demonstreer hoe hierdie veranderlikheid inwerk op see-verwante ekonomiese aktiwiteite. As deel van die proses van analise is verskeie statistiese metodes gebruik om die data oor verskeie tydperke te ontleed ten einde die omvang van ruimtelike veranderlikheid van SSTs langs die kus van suidelike Afrika te bepaal.

Uit die resultate was dit moontlik om drie duidelike onderskeibare 'klimatologiese' streke aan die kus van suidelike Afrika te identifiseer; te wete 'n koeler weskusstreek met 'n lae jaarlikse en seisoenale SST-veranderlikheid en hoër dag-tot-dag veranderlikheid, 'n warmer ooskusstreek met 'n hoër jaarlikse en seisoenale SST-veranderlikheid en laer dag-tot-dag verandelikheid; asook 'n gematigde suidkusstreek met 'n hoogs wisselvallige jaarlikse, seisoenale en dag-tot-dag SST-veranderlikheid. Dit was verder moontlik om, alhoewel klein, die bestaan van lae en hoë frekwensie seine van 12-15 dae en 40-60 dae onderskeidelik in die drie streke te identifiseer. Daar is ook tekens van die periodieke voorkoms van anomale warm en koue SST-gebeurtenisse in al drie streke en 'n waarskynlikheid van <1.1% van die voorkoms van 'n dag-tot-dag SST-anomaliteit van >3°C (+3°C of -3°C) op enige plek langs die suider Afrikaanse kuslyn.

Die algemene oorsake van veranderings in SST is bespreek binne die konteks van die formule vir die behoud van hitte-energie. Die invloed van SST-veranderlikheid op die klimaat en die seelewe om suidelike Afrika en die gevolglike effek op mariene-verwante ekonomiese aktiwiteite

(soos akwakultuur, lug-see-redding en kragstasies) is ook geïdentifiseer en is aangetoon om beide positief en negatief te wees

Ten laaste dien dit gemeld te word dat ekonomiese inligting met betrekking tot mariene aktiwitweite goed bewaar word as gevolg van kompetisie in die bedryf. Dit was derhalwe moeilik om die presiese impak van die gevolge van SST-veranderlikheid op sodanige aktiwiteite te kwantifiseer.

ACKNOWLEDGEMENTS

Sincere thanks and gratitude for the hours of advice and guidance given to me by my main supervisor, Dr. M L Grundlingh and Mr. B H A Schloms for his encouragement during the course of this study. The hours of assistance and access to resources provided by Mr. R van Ballegooyen of CSIR, Lt. Col. McCarthy of Southern Air Command, Mr. R Stroud of City of Cape Town, Mrs. M A Rolfes, Mr. J Spotten of City of Cape Town, Mr. A M Greenwood of Otter Environmental Mr. E. Schoeppe of City of Cape Town, Sea Fisheries Library and all other individuals and institutions not mentioned, has been greatly appreciated.

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NOAA-11 – 20/07/89 (cover image supplied by Dr. J J Agenbag: Dept. of Environment Affairs and Tourism: Marine and Coastal Management

CHAPTER 1: INTRODUCTION

The oceans are the largest and most prominent feature on Earth. When looking at a map of the world, a few features about the oceans are readily apparent. First of all, the oceans dominate the surface area of the globe. Second, the oceans are interconnected, and between about 55° and 65°S encircle the entire globe. Lastly, the oceans determine where the continents end, and have thus shaped political boundaries and human history. As a reservoir, the oceans contain an impressive 97.2% of all the water (including ice) in the world (Thurman & Trujillo, 1999). Compared to the atmosphere, the ocean is much denser and has a greater ability to store heat (Walker, 1990; Thurman & Trujillo, 1999).

The sun is the principal source of heat to the surface of the Earth, mainly through incoming visible radiation, most of which is absorbed by the oceans (Ross, 1978; Thurman & Trujillo, 1999). This radiation is redistributed by the oceans and the atmosphere with the excess radiated back into space as longer wavelength, infrared radiation (Year of the Ocean, 1998). Clouds and other gases, primarily water vapour and carbon dioxide, absorb the infrared radiation emitted by the Earth's surface and remit their own heat at much lower temperatures (Rodgers, 1995; Thurman & Trujillo, 1999).

Incoming solar radiation is mainly received in the tropical regions, while very little is received in the polar regions due to their oblique angle to the sun's rays and the reflectivity of snow and ice. Over time, winds in the atmosphere and currents in the ocean redistribute the energy absorbed near the equator to the colder regions of the globe (Ross, 1978; Year of the Ocean, 1998; Thurman & Trujillo, 1999; Couper-Johnston, 2000).

1.1 ROLE OF THE OCEANS

The ocean plays an important role in storing and transporting, via ocean currents, large amounts of heat around the globe, influencing the day-to-day changes in global weather patterns (Year of the Ocean, 1998, Thurman & Trujillo, 1999), and promoting long-term climate changes, such as droughts and profuse precipitation (Rodgers,1995). The long-term impacts of climate change, such as a rise in the sea level or storm surges, could result in the increased erosion of shores and associated habitats, increased salinity of estuaries and freshwater aquifers, altered tidal ranges in rivers and bays, changes in sediment and nutrient transport, and increased coastal flooding (Year of the Ocean, 1998, Thurman & Trujillo, 1999). Such changes could have considerable implications for the coastal areas, where populations and significant economic activities are concentrated (Year of the Ocean, 1998).

The ocean also plays an important role as a source of food for direct consumption as well as for fish meal and fertilizer. The total global catch of marine fish, including shell fish, has been estimated to be between 70 to 80 million tonnes per year (Year of the Ocean, 1998) with more than a billion people relying on fish as their main source of animal protein (Pacific Climate-Fisheries Workshop, 2001).

Furthermore, the ocean plays an important role as a form of transport, especially where maritime trade is concerned. Between 1945 and the 1980s total worldwide sea-borne tonnage increased from approximately 500 million tons to ten times that amount (Open University, 1991). Although air travel has reduced maritime passenger traffic since 1945, air transport remains uncompetitive for bulk cargo such as petroleum, coal, iron ore, grain and fruit.

1.2 OCEAN HAZARDS

The ocean is rarely perfectly calm. The most noticeable movement is that of waves traveling across its surface. The majority of these waves are driven by the wind and break in familiar fashion along the shore. For most of the time the energy produced in this way is released gently (Thurman & Trujillo, 1999). However, during a severe storm, wave formations can become hazardous when they are driven hard and fast against the coast, where damage often occurs as a result of high winds, storm surging, flooding and shoreline erosion. The well-documented North Sea storm surge of 1953 led to sea-levels up to three meters above normal and caused 1800 deaths in Holland and 300 in England (Open University, 1991). Tsunamis, or giant waves, whose destructive force is characterised by potentially devastating flood inundation, are unique coastal events resulting from offshore earthquakes, landslides or volcanic activity. A tsunami will remain undetected in the open ocean because its amplitude is less than one meter. However, on reaching shallow water, tsunamis rapidly build up into waves of up to 30 m (Year of the Ocean, 1998). The Hawaiian Islands, for example, experience severe tsunamis, on average once every 25 years (Open University, 1991).

Shipping vessels and platforms such as oil rigs are all too familiar with hazardous wave formations. For example, in September 1995 the Ocean Drilling Programme's research vessel – the *Resolution* – experienced a major hazard in the north Atlantic Ocean where two intense low-pressure systems to the north and to the east converged to form one powerful storm (Thurman & Trujillo, 1999). Gusts of 185 km/h (100 knots) were experienced and the ship was battered by waves that reached 21 m in height. In the winter of 1968 hazardous wave formations in Table Bay caused two French trawlers to be deposited on Woodstock beach (Bang, 1968).

Hazardous 'freak' or 'killer' waves are known to be generated, at times, off the east coast of South Africa, where strong south-westerly wind conditions can drive massive waves in a direction opposite to that of the current. This has the effect of shortening the distance between waves and accentuating their height. At times two or more waves become superimposed, creating a single wave of up to 25 m in height (Mallory, 1974; Branch & Branch, 1988). These waves periodically cause substantial damage to ships - the bows of the ship dipping down into the trough that precedes the wave and then being crushed as the oncoming mountainous wave breaks down onto the deck.

Other hazards impacting on the coastal region include biological events such as red tides and harmful algal blooms. These large concentrations of phytoplankton, which produce toxins, usually form when conditions at the sea surface are warm and calm (Brown & Hutchings, 1987). The mass mortality of the red tide organisms when conditions become unfavourable results in an increase in the number of bacteria. The effects on marine life mainly occur through the resultant depletion of oxygen levels in the water. However, animals such as oysters and mussels feed by filtering particles, including phytoplankton, from the water. As a result toxic phytoplankton accumulates in the digestive system of these filter feeders, which can be lethal to consumers such as birds, marine mammals and humans (Wong & Wu, 1987).

1.3 AIR– SEA INTERACTION STUDIES

The global atmosphere and ocean, both fluids, are continually in contact and interacting with each over approximately 70% of the Earth's surface. The manner in which air-sea interactions occur is critical to the understanding of the Earth's climate and have, therefore, been the subject of studies by oceanographers and climatologists throughout the 20th century.

For most of the 20th century air-sea interaction studies have been conveniently divided into two broad categories (Rodgers, 1995), i.e. small-scale surface process studies, which have involved investigating surface fluxes such as the exchange of heat, moisture, momentum and trace constituents across the air-sea interface, and large-scale circulation studies, which have involved investigating global climate change and ocean circulation.

1.3.1 Small-scale surface process studies

Small-scale surface process studies appear to have originated in the early 1900s, when G.L. Taylor developed a technique for computing energy fluxes across the air-sea interface in the form of bulk aerodynamic equations (Garsting, 1964). This technique, which makes the least demand upon observations - requiring measurements at one level in the atmosphere and the sea surface temperature (SST) only - was further developed by Rossby and Montgomery (Warsh *et al.,* 1970) during the mid-1930s, and later extensively applied by Jacobs (1951), Charnock (1951) and Budyko *et al* (1954). These results showed that the atmosphere-ocean system is intrinsically coupled, although feedbacks across the air-sea interface are often masked by temporal and spatial differences. For example, as indicated by Charnock (1951), the energy transmitted by the wind to the ocean is a small fraction of the radiation received at the surface, yet wind-driven currents largely determine the regions where the ocean energy is fed back into the atmosphere that sets the pattern of cloud cover, which in turn determines the radiation input.

By the late 1960s, as part of an instrument development programme (Garstang & LaSeur, 1968; Davidson, 1968; Kuettner & Holland, 1969), an instrumented deep-ocean spar buoy, Triton, suitable for energy flux measurements was developed at the Florida State University (Warsh *et al.,* 1970). Equipped to measure parameters such as SST, humidity, air temperature and wind speed, Triton was used in the Barbados Oceanographic and Meteorology Experiment (BOMEX), where the simplest type of flux measurement, the bulk aerodynamic method, was attempted (Garstang *et al.,* 1970). The results showed that it was possible to compute energy fluxes by the bulk aerodynamic method, and that energy fluxes across the air-sea interface vary in response to processes taking place in the free atmosphere by periods lasting minutes to days (Garsting *et al.,* 1970).

During the decades that followed a series of similar large-scale field programmes were initiated in a continued effort to understand the fundamental processes of energy exchange across the air-sea interface, for example, the Atlantic Trade Winds Experiment (ATEX), Global Atmospheric Research Program Atmospheric Tropical Experiment (GATE), Joint Air-Sea Interaction Experiment (JASIN), Marine Remote Sensing Experiment (MARSEN), Storm Transfer and Response Experiment (STREX), Humidity Exchange over the Sea (HEXOS) and the Frontal Air-Sea Interaction Experiment (FASINEX), which focused particularly on the effects of wind stress and SST on the exchanges of heat, moisture, momentum and trace constituents within the boundary layers of the upper ocean and the lower atmosphere (Rodgers, 1995). The reader is referred to Geernaert (1990) for a more detailed overview of these studies and their results, and to Rodgers (1995) for the more recent Surface of the Ocean Fluxes and Interactions and Atlantic Stratocumulus Transition Experiment (SOFIA/ASTEX), which focused specifically on air-sea interactions and cloud development in the Azores region of the Atlantic Ocean during 1992.

1.3.2 Large-scale circulation studies

Large-scale circulation studies appear to have originated in the 1950s, when the El Nino phenomenon (an ocean-warming event in the equatorial Pacific Ocean) was, for the first time, shown by J. Bjerknes to be a coupled process of atmospheric and oceanic changes (De Vries *et al.,* 1997; Couper-Johnston, 2000) – hence the new name, El Nino-Southern Oscillation (ENSO).

As a result of the 1972-73 ENSO event several independent studies and large-scale field programs, for example the Mid-Ocean Dynamics Experiment (MODE) and the North Pacific

Experiment (NORPAX), were initiated to investigate in more detail the variations in ocean currents such as the Gulf Stream, ocean eddies, changes in ocean circulation and temperature patterns, and in particular their effects on climate (Ross, 1978; De Vries *et al.,* 1997; Couper-Johnston, 2000). The results of these investigations showed the possible links between oceanic temperatures and climate, and demonstrated the shifts and changes in the ocean circulation, SST patterns and atmospheric conditions associated with events such as ENSO (Ross, 1978; De Vries *et al.,* 1997; Couper-Johnston, 2000). One of the more interesting results to emerge came from an independent study done by Streten (1983), who showed that dry years over Australia are associated with low SSTs over the eastern Indian Ocean and the south-west Pacific, particularly at low latitudes, and that wet years are associated with warm SSTs extending from the equator to middle latitudes in the same region.

However, it was the 1982/83 ENSO event that propelled air-sea interaction studies into the decades ahead, and highlighted the need to develop predictive models for the accurate forecasting of such events. As a result of the extensive damage - an estimated $8 billion worldwide (Couper-Johnston, 2000) – caused by this event and influence on global weather phenomena, a major study, the Tropical Ocean-Global Atmosphere (TOGA) programme, was initiated in 1985 to focus on unravelling the mechanisms behind ENSO events (Thurman & Trujillo, 1999). The objective of the TOGA programme was to monitor the equatorial South Pacific Ocean during the time when ENSO events occurred to enable scientists to model and forecast future events more successfully (*ibid*).

By 1995 the TOGA study had been completed and offered a wealth of additional data that enabled the development of more reliable models which link the combined atmosphere-ocean system (Thurman & Trujillo, 1999). These models have enabled ENSO events to be forecast up to a year in advance as was done for the 1987, 1992 and 1997 ENSO events. Since the completion of TOGA, the Tropical Atmosphere and Ocean (TAO) project has continued to monitor the equatorial Pacific Ocean with a series of 70 moored buoys (Elliot *et al.,* 2001).

The reader is referred to Couper-Johnston (2000) for a detailed overview of the more recently studied La Nina phenomenon (an ocean-cooling event in the equatorial Pacific Ocean). Although oceanographers and climatologists knew of La Nina for decades, its effects had generally been perceived to be nothing more than extensions of the norm, and therefore insignificant (Stevens, 1999; Couper-Johnston, 2000). However, this perception changed after the 1988-89 and 1997-98 La Nina events, which impacted more widely on climates (Stevens, 1999; Couper-Johnston, 2000). Nonetheless, it has been shown (Couper-Johnston, 2000) that the global bill of damages for these La Nina events did not in any way compare to that of the 1982-3 or 1997-8 ENSO events.

Current air-sea interaction studies by Krishnamurti *et al* (2000) and Elliot *et al* (2001), for example, have highlighted the importance of combining small-scale surface process studies with the large-scale circulation studies to determine the extent of the feedbacks between the ocean and the atmosphere, and the importance of SST.

1.3.3 Air-sea interaction studies in South Africa

Locally, air-sea interaction studies appeared to have originated during the 1980s, when it was recognised that the source of climatic change over southern Africa was not always attributed to changes in global atmospheric circulations, such as those associated with ENSO, but also to the variability of SST in the local ocean (e.g. Walker & Shillington, 1990; Lindesay & Vogel, 1990). Studies on the Agulhas Current (e.g. Jury & Walker, 1988) have shown that this has an immediate effect on the overlying atmosphere, even resulting in cumulus cloud formation (e.g.

Olivier, 1999). It has furthermore been shown that this effect has a direct influence on the rainfall along the East coast (Jury & Pathack,1991).

In the early 1990s a research project was initiated to study possible statistical correlations between SST anomalies of adjacent oceans and rainfall over the South African continent. The project had a high degree of success and the reader is referred to Jury (1995) for a detailed overview of this study and the results. Within the period 1995-98 a study to develop techniques for long-term rainfall prediction over South Africa showed that the best predictors of seasonal rainfall are based on the predicted phase of ENSO (Olivier, 1999). The study also showed that South African mid-summer rainfall correlates positively with the Southern Oscillation (SO) and negatively with SST anomalies over parts of the Indian Ocean (*ibid*).

During the same period, several cruises were undertaken by the University of Cape Town to collect data for the quantification of surface fluxes across the air-sea interface (Grundlingh *et al.,* 1999; Olivier, 1999). The results of the cruises, as summarised by Olivier (1999), showed that throughout the year the core of the Agulhas Current (approximately 50km wide) transfers approximately five times as much water vapour to the atmosphere as the surrounding water. It was also shown that the moisture content of the atmosphere intensified up to heights of 1000 m when winds blew parallel to the Agulhas Current and a clear line of cumulus clouds was formed over the current. However, when the wind is landward, all this moisture is advected over the adjacent landmass (Grundlingh *et al.,* 1999; Olivier, 1999). It was also within the period 1995-98 that an ongoing study was conducted involving the actual measurements of oceanic features in the South African region and their impact on the overlying atmosphere (Olivier, 1999),

A number of other oceanic features, for example eddies and the Agulhas Retroflection, in the region of the Agulhas Current have also been shown to affect atmospheric pressure systems over southern Africa. For example, it was recently demonstrated that changes of as little as 2°C in SST in the Agulhas Retroflection region can have a considerable effect on the synoptic systems over southern Africa (Grundlingh *et al.,* 1999).

Recently, a team of researchers at the University of Pretoria have been using the CSIRO-4 and CSIRO-9 Global Circulation Models (GCM) extensively to study the impact of SST anomalies on the general circulation, with the latest version of the CSIRO-9 GCM being used for various experiments, in particular the effect of SST fluctuations on the local atmospheric circulation (Olivier, 1999). Considerable progress has been made recently in the ability to do long-term forecasting of La Nina conditions (above-average rainfall usually) specifically, due to the development of a two-tiered forecasting system which forecasts SSTs for the western Indian Ocean and then uses them as input into a global climate model (*ibid*).

Current air-sea interaction studies by Rouault & Lutjeharms (2000), for example, have shown how Agulhas eddies of subtropical origin found in the subantarctic south of Africa can create unstable atmospheric conditions.

1.4 ROLE OF SEA SURFACE TEMPERATURES

Life in the marine environment is particularly dependent on, and adapted to, the behaviour of the sea temperature, how the temperature responds to external factors and, how the temperature influences other physical and chemical oceanographic parameters. Even small changes in the sea temperature in a particular area could have serious effects on local marine life, possibly to the extent that a whole ecosystem could be destroyed.

It is clear from the paragraph above and section 1.3 that the SST has the greatest impact on adjacent landmasses and life in the ocean. This, undoubtedly, makes SST a very important physical oceanographic parameter.

1.5 COASTAL GEOGRAPHY OF SOUTH AFRICA

The South African coastline is, from the Orange River to Ponta do Ouro on the Mozambique border, approximately 3000 km long (Dept. of Environmental Affairs & Tourism, 2002), and is bordered by two major ocean current systems: the Agulhas, flowing southwards past the east and south-east coasts, and the Benguela, flowing northwards past the west coast. The shallow continental shelf areas around South Africa form an important oceanographic region, with the Agulhas Bank the widest area extending to over 250 km from the land (Schumann, 1990).

Since the African continent terminates at a relatively low latitude (35°S), three oceans meet, i.e. the Atlantic, Indian and Southern Ocean (Schumann, 1990). Although their geographical boundaries are accepted to be somewhat arbitrary (Shannon, 1989), the interactions between the waters of these oceans can extend over distances of thousands of kilometers (Schumann, 1990). Considerable mixing of water from the Atlantic, Indian and Southern oceans takes place over the Agulhas Bank (Schumann, 1990).

The Agulhas Current is the principal oceanographic feature of the South African marine environment and dominates the circulation off the South African east and south-east coasts. It is responsible for transporting warm water from the tropics southward, and plays an important role in the heat balance of the planet (Shannon, 1990). The Agulhas Current is up to 160 km wide and flows at a speed of between 2 m^{-2} and 3 m^{-2} , transporting approximately 80 million tons of water per second (Grundlingh & Lutjeharms, 1990). The SST of the current core off Durban varies between 22 and 26°C (Grundlingh & Lutjeharms, 1990). South of the continent the Agulhas current meanders, fragments and injects subtropical water into the south-east Atlantic in the form of Agulhas rings, while the main part of the Agulhas current returns, or retroflects, eastwards into the interior of the Indian Ocean (*ibid*).

In contrast, the Benguela Current, not a strongly identifiable current in the sense of the Agulhas Current, is a broad, cooler and rather sluggish current in the eastern South Atlantic (Shannon, 1989). As the Benguela Current flows northwards up the west coast, it plays an important role in displacing the deeper colder water upwards into the shallower regions, thus priming the water mass for the upwelling process (Schumann, 1990).

1.5.1 Climate

The surface waters off the west and east coasts play key roles in determining the climate of southern Africa's coastal regions, i..e. summer rainfall and high humidity along the east coast, bimodal rainfall (peaks in autumn and spring) along the south coast, winter rainfall along the south-west coast and semi-arid conditions along the west coast (Walker, 1990). During summer condensation occurs at the sea surface, due to the air being warmer than the sea, and consequently fog is frequently formed along the west coast (*ibid*). A comparison of annual rainfall at Port Nolloth (61 mm) and Durban (1000 mm), which are approximately at the same latitudes, highlights the sharp contrast between the west and east coasts (Shannon, 1989). As the Agulhas Current moves southward the SST decreases by 1°C every approximately 500 km as heat is lost to the atmosphere (Grundlingh & Lutjeharms, 1990). It is this heat loss that is largely responsible for the subtropical climate of the coastal region along the east and south-east coasts.

1.5.2 Weather

To the south of the African continent the vast expanses of the Southern Ocean form productive spawning areas for a number of processes affecting southern Africa (Grundlingh, 1999). The atmospheric fronts of the region are drawn northward by the South Atlantic anticyclone to affect local weather conditions, while at the same time generating storm swell that impinges on the coast and interacts with the Agulhas Current (Grundlingh & Lutjeharms, 1990). The heat and water vapour transferred to the atmosphere within the Agulhas Retroflection region can intensify low pressure systems moving over the area (Lutjeharms & De Ruitjer, 1996). Cyclogenesis, the formation of low-pressure cells, is known to occur where the Agulhas waters encounter the cold waters of the Southern Ocean near 40°S, 15°-20°E (*ibid)*.

It is clear from the above that the climate and weather of southern Africa are affected by the SST of the surrounding oceans – as is shown by the numerous studies (e.g. Bang, 1970; Pearce, 1977a; Grundlingh, 1983; Grundlingh, 1992; Lutjeharms & De Ruitjer, 1996) which have focused on the characteristics of the Agulhas and Benguela systems on the east and west coasts respectively. Although studies (e.g. Walker, 1990; Jury & Courtney, 1995; Weeks *et al.,* 1998; Rouault & Lutjeharms, 2000) have been conducted on the relationships between these oceanographic phenomena, the weather and climate of the subcontinent, less emphasis has been placed on the economic impacts of anomalous SSTs.

1.5.3 Economic activity and SST in the Coastal Region

Worldwide, approximately 60% of all people live at or near the coast (Dept. of Environmental Affairs & Tourism, 2002). Presently South Africa has one of the highest coastal population densities in Africa with 80 people per square kilometre compared to the African average of 55 people per square kilometre (Dept. of Environmental Affairs & Tourism, 2002). The coastal regions in South Africa and the adjacent oceans are playing an increasingly more important role in the economy of the country. Recent research by the Department of Environmental Affairs and Tourism (2002) has revealed that the value of the direct benefits derived from coastal resources in South Africa could be as high as R168 billion annually, or approximately 35% of the Gross Domestic Product (GDP).

In the coastal areas, the reduced water depth (0 – 50m) focuses attention on the SST. It is in this area where the SST impacts most visibly and immediately on human related activities and the local economy. A number of economic activities, such as the fishing, aquaculture, shipping and tourism industries, air-sea rescue operations and power-stations, are influenced by the SST. For example, financial losses may be experienced by the fishing or aquaculture industries if mortalities occur as a result of a change in SST; similar losses may arise in the tourist industries if a decrease in SST occurs at a popular holiday resort. On the other hand, a nuclear-power-station making use of sea water as a coolant could benefit if a decrease in SST occurs. Therefore, sustainable development in the marine environment requires and depends on our insight into the behaviour of SSTs.

1.6 RATIONALE OF THIS STUDY

In 1993 the author initiated a project to study the behaviour of SSTs in the coastal region around southern Africa. There were three basic reasons for initiating this study. First, although a unique set of SST data (collected from several measuring sites around the southern African coast) was in existence, the analyses of the data both spatially and temporally have been generally neglected. Secondly, it was recognised that abrupt changes in the behaviour of SSTs can impact significantly on marine-related economic activities; and that a better understanding of the spatial and temporal behaviour of SSTs would be required before any advice could be offered on how best to manage these impacts.

The study is confined to the realm of the immediate coastal region, since it is here where marine-related human activities generally take place.

1.7 KEY QUESTIONS

This thesis attempts to give an overview of the available literature on ocean-atmosphere interactions in the southern African region. In addition, it focuses on the impact of SST on economic activities in the region. The following key questions will be addressed:

- What are the general characteristics of SST around the southern African coast?
- Are there significant spatial and temporal variations ?
- What are the general causes and effects of SST anomalies ?
- Which economic activities are dependent on SST and how are they affected by variations in SST?

1.8 SCOPE OF THESIS

In an attempt to answer the questions above, a unique data set, collected at several SST measuring sites around the southern African coast, will be used. After applying various statistical techniques to these data, the spatial and temporal variabilities are determined and anomalies identified. To identify the causes of SST change, meteorological data in the form of recorded observations are used. Throughout this study an understanding of the effect of SST on various economic sectors has been gained from personal communication with numerous marine-related role-players in the various economic sectors and through participation in relevant workshops.

1.9 THESIS LAYOUT

CHAPTER 2 - GENERAL OCEANOGRAPHIC AND METEOROLOGICAL CONDITIONS AROUND SOUTHERN AFRICA

To consider the oceanic environment of southern Africa in isolation would be short-sighted as this environment is continually being affected by forces acting on a larger scale. Through the use of published information this chapter endeavours to summarise the main oceanographical processes, meteorological conditions and physical factors which determine the state of the oceanic environment of southern Africa and, in particular, the characteristics of the coastal SST. In this way this chapter provides an introduction to, and sets the scene for, further discussion in the rest of the dissertation which is confined to the coastal regions.

CHAPTER 3 - DATA AND METHODS

This chapter contains a discussion on the collection of the SST data set used in this study. Particular emphasis is placed on the development of the Crawford bucket and its use in SST data collection. The chapter also indicates the characteristics of the measuring sites and the procedures involved in the processing of the data.

CHAPTER 4 - SPATIAL AND TEMPORAL CHARACTERISTICS

Sea surface temperatures, like any other physical data, have different time and space scales. In this chapter, statistical methods are applied to the data over selected time periods to identify the spatial and temporal characteristics of SSTs around the southern African coast.

CHAPTER 5 – SEA SURFACE TEMPERATURE ANOMALIES: CAUSES AND EFFECTS

This chapter identifies several SST anomalies and the probability of their occurrence. The causes and effects of such anomalies, and SST variations in general, are briefly discussed. Three case studies are presented.

CHAPTER 6 – ECONOMIC APPLICATIONS AND IMPACTS OF SEA SURFACE TEMPERATURES

Several marine-related economic activities are sensitive to the behaviour of SSTs in order to function successfully. In this chapter these economic activities (such as the aquaculture, fishing, tourism and shipping industries, air-sea rescue operations, power stations, thermal desalination systems, angling and surfing) are identified and the effects that SSTs have on them are discussed.

CHAPTER 7 - SUMMARY

This chapter serves as an overview of the climatological aspects of SSTs around the southern African coast and the impacts of SSTs on the various economic activities found in the coastal region.

CHAPTER 2: GENERAL OCEANOGRAPHIC AND METEOROLOGICAL CONDITIONS AROUND SOUTHERN AFRICA

An overview of the physical oceanographic environment and the offshore region around the southern African coast, is presented to establish an understanding of the physical processes and factors involved in determining the characteristics of SST.

2.1 RELEVANT OCEANOGRAPHIC CONCEPTS

2.1.1 Heat balance

The distribution of temperature in the atmosphere and in the surface layers of the ocean reflects the general dispersion of the heat supply from the sun. The global heat budget indicates that there is a surplus of heat between 0° and 38° latitudes - where more heat is gained than lost – and, a deficit from there to the poles - where more heat is lost than gained - (Oliver, 1973; Dring, 1986; Barry & Chorley, 1987). If there was no redistribution of heat from tropical to polar latitudes, the tropics would simply get hotter and the polar regions colder. However, this does not happen since the unequal latitudinal distribution of heat causes air movement (wind) which, in turn, causes ocean currents. This movement of air and sea masses is very complex due to the earth's rotation, the inclination of its axis to the plane of its orbit (which introduces a seasonality to the characteristics), the laws of fluid dynamics and the finite dimensions of the ocean basins. The end result is a generally circular movement of water within the individual oceanic basins. The term **gyre** is used to describe the rotating behaviour of water masses on a basin-scale (e.g. the Southern Indian Ocean Gyre, the South Atlantic Gyre, etc.). In the Southern Hemisphere these gyres rotate anticlockwise, while in the Northern Hemisphere the rotation is clockwise (Thurman & Trujillo, 1999).

2.1.2 Water Masses

The oceans are composed of different bodies, or masses, of water, defined as large volumes of water having common origins or source areas and distinct temperature-salinity (thermo-haline) characteristics (Pond & Pickard 1986). Water masses gain their temperature and salinity characteristics through interaction with the atmosphere at the surface (solar heating, evaporation) or by the mixing of two or more bodies of water.

Water masses mix very slowly with surrounding waters and their thermo-haline characteristics remain conservative over most spatial scales (Pickard & Emery,1982). Thus, the distinctive temperature-salinity relationships of these masses make it possible to identify them, and provide information of their place of origin, propagation paths and mixing rates. The density alone of water is not sufficient to identify a water mass, since a combination of various temperatures and salinities can result in the same density value (ibid). By using a number of temperature and salinity relationships rather than individual values of temperature and salinity, a reasonably small number of water masses are identified in the oceans (Pond & Pickard, 1986).

Vertically, water masses are classified as follows (Thurman & Trujillo, 1999):

- surface (0 - 100m);
- central (to base of main thermocline);
- intermediate (from below central water to 3000m); and
- deep and bottom waters (filling the lower portions of the ocean basins).

Generally it can be said that waters at greater depth originate from higher latitudes (lower temperature) and those closer to the surface nearer the equator (higher temperature).

Many marine organisms remain within a particular water mass because its physical characteristics are favourable to their life.

2.1.3 Currents

The ocean currents are generated by three factors – wind, tide and the differences in water temperature and salinity (density). Of these, the wind is the most important factor, since wind-driven currents impact on climate and have a profound effect on marine plants and animals (Thurman & Trujillo, 1999).

(a) Wind-driven currents

Wind-driven currents are caused by the force of the prevailing winds exerting pressure on the sea surface. As a result the water moves and the movement is transmitted to the underlying water to a depth dependent mainly on the strength and persistence of the wind, though this rarely extends further than 350 m in depth (The World Book Encyclopedia; 1999). The surface speed of a wind-driven current is approximately 2,5 – 3,5% of the wind velocity at the surface (*ibid)*. If the wind effect is local, the wind drift current is of short duration. However, the larger-scale wind field, for example the southeast trades, exerts a cumulative effect on the oceans, causing large masses of water to move (Pond & Pickard 1986) (see Appendix A for effect of the Coriolis Force). Some currents can flow at > 1m/s, and transport millions of tons of sea water per second (The World Book Encyclopedia; 1999).

On a global scale, the fast moving flow on the western and eastern sides of a gyre is referred to as boundary currents. The rotation of the earth causes the centres of the gyres to be located towards the western sides of their basins (Pickard & Pond, 1986). Currents on the western sides of these gyres, referred to as western boundary currents, are narrower and flow faster than those on their eastern sides (eastern boundary currents), and can extend to depths of 1000 m or more (The World Book Encyclopedia; 1999). Examples of western boundary currents are the Gulf Stream (northern Atlantic), Kuroshio (northern Pacific) and the Agulhas Current (southern Indian). The southward flowing Agulhas Current typically flows 3-4 times faster than the northward flowing Benguela Current (eastern boundary current) (Shannon, 1985;

Grundlingh,1983).

The Agulhas Current is the strongest western boundary current in the Southern Hemisphere and is capable of reaching speeds of more than 2m/s, transporting water at a rate in excess of 70 000 000m^3/s (Schumann, 1990).

Western boundary currents have their origins in the tropics and are, therefore warm. As this energy gets transported from the tropics to the higher latitudes, heat is lost to the atmosphere as soon as the air temperature becomes less than the SST. This heat flux, in turn, causes the warmed air to start moving towards an area of lower temperature. Consequently, western boundary currents usually have a significant effect on prevailing weather and climate conditions, while the dynamics of the flow has an impact on navigation.

(b) Tidal

Although tidal currents are common throughout the world, their effect is especially noticeable in narrow waterways and shallow waters. The common pattern of tidal currents is of a flood current in one direction as the tide is rising and an ebb current in the opposite direction as the tide is falling (Pond and Pickard, 1986). In the shallow and open waters of the continental shelf the speed of the tidal current varies significantly with the tidal cycle and the direction correspondingly changes. The dominant tidal period along the South African coast is semi-diurnal, i.e. one high tide and one low tide every 12 hours. Around southern Africa tides are mainly of importance to mariners at the entrances to harbours where currents can impact on vessel motion, for example Walvis Bay, Luderitz, Port Nolloth, Saldanha Bay and Durban. In contrast to the Bay of Fundy where tidal currents of 3.6 m/s occur (The World Book Encyclopedia; 1992), off the South African coast, these currents are in the order of only 0,1-0,5m/s (Captain Gibson, South African Navy, 1994, pers. comm).

(c) Density

Density currents originate when water masses of different densities mutually arrange themselves into a more stable juxtaposition (Pond & Pickard, 1986). Density, in turn, is related to the differences in the water temperature and salinity (*ibid)*. For example, the colder, denser and higher salinity water masses of Antarctic origin will tend to flow northwards along the sea bottom, while the warmer, less dense and lower salinity water of tropical origin, will tend to flow southward at the surface (Shannon, 1989).

In the ocean, salinity may often decrease with depth, but in these cases, almost invariably, the temperature decrease is such that the density still increases (Shannon, 1989). Should the temperature remain constant, increased salinity results in a greater density (*ibid)*. Reasons for the variation in salinity in seawater can be traced to the effects of, for example, evaporation and freezing, both which result in an increase in salinity of the remaining (or underlying) water (Shannon, 1989; Thurman & Trujillo, 1999). Other processes, such as high precipitation, river run-off and melting of ice, reduce salinity through dilution (*ibid)*.

Flow speeds of density currents are of the order of a few cm/s (Pickard & Emery, 1982; Thurman & Trujillo, 1999).

2.2 AGULHAS CURRENT

(a) General Characteristics

In the Southern Indian Ocean gyre (see Fig.2.1) the water is driven by the westerlies and trade winds (Duncan, 1970). The westward-flowing northern flank, the South Equatorial Current, splits into two parts on reaching Madagascar – a small part flows around the island and down the Mozambique coast to become the Mozambique Current. The other flows down the eastern side of the island as the East Madagascar Current. These parts recombine partially south of the Mozambique channel and extend southwestwards along the East Coast of Southern Africa as retroflects, back into the Indian Ocean (e.g. Bang, 1970; Gordon *et al.,* 1987; Lutjeharms & Valentine, 1988; Lutjeharms & van Ballegooyen, 1988; Duncombe Rae, 1991). It is here in this retroflection area of high shear where various independent features are generated (Section 2.2 (c) and (d)).

Between the current and the coast are trapped water masses which continuously respond to meanders and changes of the Agulhas Current (Pearce 1977b). The Agulhas Current can thus directly affect processes such as sediment transport (Flemming 1978) and dilution of effluent from rivers and pipelines (Grundlingh 1983). Meteorological conditions on the East Coast of southern Africa, from the long-term (for example the mild subtropical climate of the south coastal areas) to the short-term (diurnal, sea breeze characteristics), are partially a result of the heat source presented by the current (Schultze, 1965; Hunter, 1981). There is also an important economic link between the position of the current and shipping, in the form of transit times or the risk of 'freak' or 'killer' waves (Mallory, 1974; Schumann, 1976) (see section 1.2 para. 3, for explanation of these waves).

(b) Variability

Along with the increase in knowledge on the flow and dynamics of the Agulhas Current has come the realisation of the role of the current in the heat and mass balance of the Indian Ocean (Toole & Raymer, 1985). However, it is only with the advent of satellite technology and the quantifiable method of altimetry (Douglas *et al.,* 1987) that the quasi-synoptic and extensive coverage required to explain large scale variability has been obtained (Grundlingh, 1992). From global analyses (Zlotniki *et al.,* 1989; Sandwell & Zhang, 1989) which enable comparisons among the major western boundary currents of the world, the Agulhas Current has emerged as the one with the highest variability (Grundlingh, 1992). The variability derived from GEOSAT altimetry in 1986/87 clearly indicated the tributaries to the Agulhas (Mozambique and Eastern Madagascar currents) (Grundlingh, 1991), the Agulhas Current itself, its volatile retroflection region and the E-SE spread in variability in the Agulhas Return Current (Zlotniki *et al.,* 1989; Sandwell & Zhang, 1989). The reader is referred to Lutjeharms and Roberts (1988) for a detailed analysis of the Natal Pulse, an unusual, solitary meander on the Agulhas Current's trajectory, which can contribute significantly to the variability of the Agulhas Current.

The surface water of the Agulhas Current is warm, generally >21°C, however, fairly cooler in winter and typically >23°C during summer, and having the character of a narrow, deep, intense jet (Pearce, 1977a; Shannon, 1989) – typically a column of water approximately 1000 m thick and flowing at a speed of up to 2 m/s (Proff. G.B. Brundrit, University of Cape Town Oceanography Dept., 2002, pers.comm.). Figure 2.2 shows the average course of the core of the Agulhas Current as denoted by the heavy red line.

However, Pearce (1977a) has shown that the current core, which can exceed speeds of 1m/s (Shannon, 1989), is capable of changing its position by 30km from day-to-day and, Schumann (1988) has shown that the daily variability of the current can be such as to mask any seasonal variability that may be present - this variability allegedly to be associated with meanders.

1984; Lutjeharms & van Ballegooyen, 1988a, 1988b). These types of perturbations can affect the inshore shelf circulation and associated coastal phenomena (Pearce, 1977b; Pearce *et al.,* 1978; Schumann, 1981, 1982).

(d) Rings

When the Agulhas Current retroflects south of the African continent, the hairpin-like shape of the retroflection may lead to occlusion and trapping of water inside the 'hairpin'. The isolated body of water of 100-300km in diameter and rotating anticlockwise is referred to as a 'ring' (Harris, 1978; Lutjeharms *et al.,* 1992). These rings which carry vast amounts of heat (Lutjeharms *et al.* 1992) are responsible for injecting quanta of 'Indian Ocean water' into the southwestern Atlantic (Gordon & Haxby,1990). Through the proposed kinematic relation between the SST in the region and the rainfall variation over semi-arid Southern Africa (Shannon *et al.,* 1989; Mason, 1990), the anomalous presence of warm subtropical water here could impact upon the climate of the subcontinent (Lutjeharms *et al.,* 1992; Grundlingh, 1992). Agulhas rings are unique in the worlds' oceans both in terms of their intensity and in being introduced at the eastern boundary of an ocean basin (Olson & Evans, 1986). It has also been suggested that the rings entering the Atlantic represent one of two westward inter-ocean exchanges of mass and heat within the thermocline (Grundlingh, 1992) the other being the Pacific-to-Indian transfer off Indonesia (Gordon, 1990). The confined passage south of the African continent, thus, has significance far beyond its local and more direct sphere of influence in that it forms a unique link in the global thermodynamic balance (Grundlingh, 1992).

2.3 BENGUELA CURRENT

Due to the extent of the Benguela Current, a more detailed description of its characteristics and the region it characterises is presented in Appendix B

.

(a) General Characteristics

The Benguela Current found generally between 15° and 34°S within 185km of the coast and forms the eastern flank of the South Atlantic gyre (Shannon, 1966; Shannon, 1985). It has been defined by some authors in terms of generally northward moving currents. However, Bang (1971) defined the Benguela Current as the region '...east of the offshore divergence within which oceanic processes are controlled by short term atmospheric interactions...'.

Based on Defant's (1936) current charts it appears that the Benguela Current, in a band 200-300km wide, flows in a north northwesterly direction in close proximity to the coast at 34°S, moving gradually offshore northwards (Hart & Currie, 1960) and curving westwards north of 20°S (Shannon, 1985). Nelson and Hutchings (1983) have suggested that the current accelerates in areas of steep topography and meanders over the planes. Away from the coast and in the absence of strong gradient currents, surface currents have been shown (Harris & Shannon, 1979) to be influenced by the prevailing wind.

The seaward boundary of the Benguela Current is to some extent academic. However, a well-developed front, particularly south of Luderitz (27°S), generally exists over much of the area between Cape Point and Cape Frio and although spatially and temporally variable appears to approximate the coastal shelf (Shannon, 1985).

Because of changes in the wind component and orientation of the coastline around 15°S, the northern boundary of the Benguela Current is to a great extent debatible (ibid). According to

Shannon (1985), the wind component north of 15°S is not that favourable for upwelling and, according to Picaut (1981), if upwelling does occur it is not as a result of local winds.

The southern boundary of the Benguela Current appears to have been extended to include not only Cape Agulhas (Harris, 1978; Shannon *et al.,* 1983) but, the Agulhas Retroflection area thereby including the Agulhas Bank (Shannon *et al.,* 1981). It is consistently documented in the literature that during summer the upwelling zone can extend as far southeast as Cape Agulhas and that there is a notable change in the wind component south of approximately 35°S. Thus, the southern boundary of the Benguela appears to originate from the combination of meteorological, oceanographical and topographical factors.

Using a drifter Harris and Shannon (1979) were able to show the Benguela Current to be moving at an average velocity of 17cm/s. Several authors using different techniques such as drift cards, ships drift and satellite tracking drifters have deduced or measured surface currents and have been summarised by Shannon (1985) in Fig.2.3.

Since there are significant differences in the seasonal wind regime across the Benguela region (Hart & Currie, 1960) it has been divided into two distinct regions, the Northern Benguela region - north of Port Nolloth to the northern boundary - and the Southern Benguela region - Port Nolloth to the southern boundary.

The southern Benguela region volume transport fluxes for the equatorward shelf-edge jet, have been estimated by Bang and Andrews (1974) as being 7Sv (1Sv = $10^6 m^3/s$) and 10Sv respectively, which constitutes a large proportion of the gross transport in the South Atlantic.

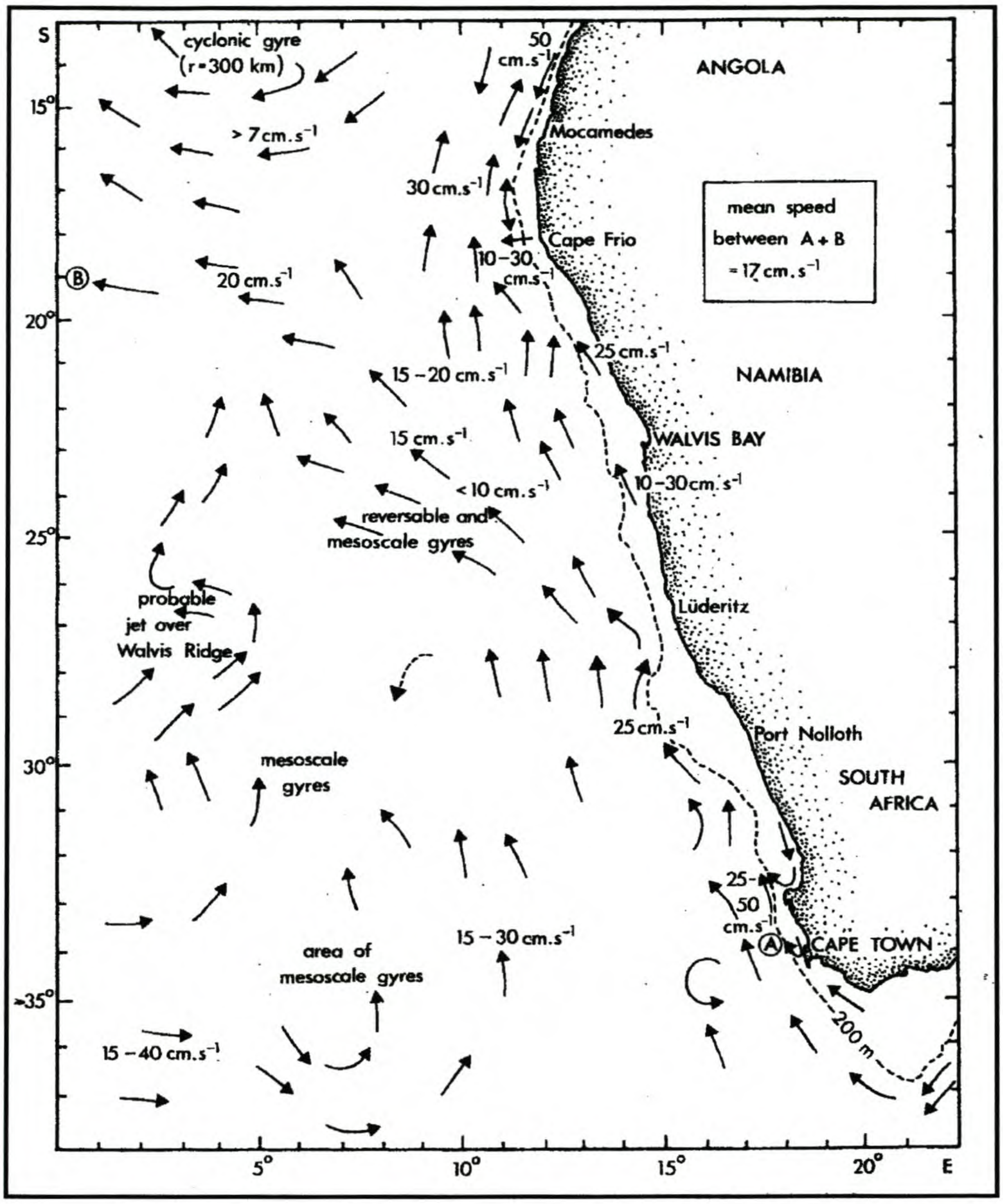


Fig.2.3 – Surface currents in the Benguela region (after Shannon, 1985)

(b) Variability

The average seasonal SSTs for the Benguela region are shown in Figure 2.4. The similarities between the winter and spring distribution, where temperatures are <16°C between Cape Frio and Cape Town with a range of upto 300km offshore (Boyd & Agenbag, 1984; Parrish *et al.*, 1984), are quite striking. Also as impressive are the similarities between the summer and autumn distribution where the area of cool water contracts meridionally and zonally (ibid). The seasonal differences evident in Figure 2.4 can be ascribed to changes in insolation, upwelling, vertical mixing and horizontal advection (Shannon, 1985).

Shannon (1985) showed that the lowest values occur during August and, the highest values during late summer to autumn, with a lag of two months (March and May respectively) between the two regions. Also, there is a definite seasonal signal off Namibia as opposed to off the Cape where, excluding May, there is hardly any change in temperature during the year (ibid).

Both Duncan (1964) and du Plessis (1967) have done studies on the occurrence of thermoclines in the Benguela region and have shown that, except during summer, thermoclines off Namibia tend to be shallower, infrequent and associated, on average, with warmer less stratified water than in the south.

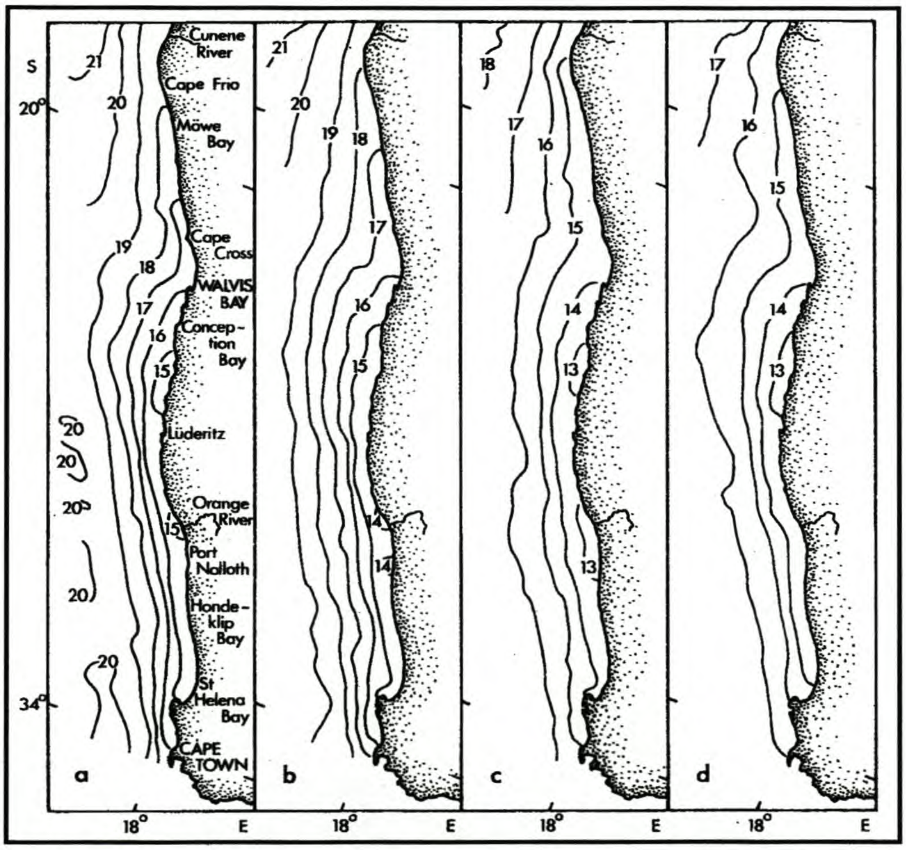


Fig.2.4 – Average Seasonal SST (°C) – a,summer; b,autumn; c,winter; d,spring (after Boyd & Agenbag, 1984)

2.4 SOUTHERN OCEAN

(a) Antarctic Circumpolar Current

The Southern Ocean, with its unique geography, is the only place where ocean currents run completely around the globe (Pickard & Emery, 1982). The West Wind Drift, so called because it was attributed to the prevailing easterly wind near the coast of Antarctica, flows westward in a narrow zone around the continent. Farther north the remainder of the Southern Ocean is dominated by a strong, deep, eastward-flowing current known as the Antarctic Circumpolar Current (ACC), also referred to as the West Wind Drift since the surface is primarily driven by the frictional pressure of the westerly wind (Pickard & Emery, 1982). A northward component of the West Wind Drift, as a result of the wind pressure and the Circumpolar Front, contributes to the surface current which leads to the formation of fronts, i.e. convergences within the APFZ (Antarctic Polar Front Zone) (ibid).

In its circuit round the continents the ACC is obstructed only in the narrow Drake Passage between South America and the Palmer Peninsula projecting north from Antarctica (Pickard & Emery, 1982). Generally the ACC is not very fast moving with surface speeds of 4cm/s in the Antarctic zone, increasing to 15cm/s north of the Polar Front and decreasing again toward the Subtropical Convergence (Pickard & Emery, 1982; Pond & Pickard, 1986). However, the current is very deep and measurements done in the late seventies have shown that the volume transport varies between 28×10^6 m^3/s and 290×10^6 m^3/s (Pond & Pickard, 1986). Typical time and space scales for variations were 2 weeks and 80km (compared with the 800km width of the Drake Passage (Pickard & Emery, 1982). Some of these variations are associated with the strong zonal jets at the major fronts - current speeds of 50 to 100 cm/s have been observed in these jets (ibid).

2.5 METEOROLOGY

(a) West Coast of Southern Africa

The three macroscale atmospheric features (van Ballegooyen, 1995) which determine the prevailing winds on the West Coast are the dominant quasi-stationary South Atlantic high (SAH) pressure system, the pressure field over the adjacent subcontinent and the mid-latitude cyclones traversing the southern regions, as well as a less extensive, but more important coastal low which is observed to move anti-clockwise around the Southern African coast (Nelson & Hutchings, 1983; Hunter, 1987, Reason & Jury, 1990) occurring at all times of the year (Reason & Jury, 1990). In particular, perturbations (sudden strengthening, weakening or reversals) of the dominant south/south-easterly alongshore winds associated with the SAH, are critical in determining the intensity of the upwelling or downwelling process. Andrews and Hutchings (1980) have suggested that the SE wind generated by the eastward ridging of the SAH constitutes more than 50% of the total winds for spring, summer and autumn.

The surface winds associated with the SAH are influenced by the coastline of the adjacent subcontinent. The desert-like nature of the area north of Cape Columbine with its weakly sloping topography landwards causes it to act as a thermal barrier to cross-shore winds near the surface, resulting in the winds along the West Coast to be predominantly south to south-easterly. Further, less significant modification of the nearshore winds occurs due to the land-sea breezes which are common over the whole coast north of Cape Columbine (Jackson, 1947). In the southern areas where there is considerable coastal topography, rapid variation and acceleration of the local winds are significant in generating local upwelling cells such as those described in Appendix B (B-4) – (B-6).

On the West Coast the development of the coastal low starts with the ridging of the SAH to the south or over the continent. As this ridging continues eastwards, offshore flow at the plateau coastal low just north or in the area of Luderitz (van Ballegooyen, 1995). Should the ridging strengthen or remain stationary south of the continent (Jury *et al* 1990a), the coastal low which develops to the north of Luderitz then remains stationary or moves even further northwards. However, generally, the coastal low migrates southwards down the West Coast and reaches Cape Town within approximately two to three days and acts as a 'leader-front' to approaching mid-latitude cyclones from the west. The sharp change in coastal topography near Cape Town tends to slow down the migration of the coastal low in this area (Jury *et al.,* 1990b). After the passage of the coastal low and the first cold front the SAH either ridges again to the south of the continent or a succession of mid-latitude cyclones follow the initial cold front and its associated coastal low. If the SAH ridges in immediately behind the coastal low and cold front, the weakening or reversal of the S/SE winds is of shorter duration (van Ballegooyen, 1995). However, if a succession of cyclones follow the initial front and coastal low, prolonged periods of NW to SW winds may occur in the southern regions (ibid). The sequence of events described above, associated with the ridging of the SAH results in a moderation of the winds on the West Coast every approximately 4,5 to 12 days (Preston-Whyte & Tyson, 1973; Coastal Low Workshop, 1984; Kamstra, 1987; van Ballegooyen, 1995).

Generally, the S/SE winds intensify as the coastal low approaches a site along the coast (Jury *et al.,* 1990b) and on passing, causes a sudden abatement or reversal of the wind. In the northern regions of the West Coast the changes or reversals in the S/SE winds associated with the coastal low are generally of shorter duration than in the southerly regions which are also strongly affected by the trailing mid-latitude cyclones (van Ballegooyen, 1995). Thus, the effect of these coastal lows on the surface wind component are best observed to the north and south during summer when the effects of the easterly-moving mid-latitude cyclones is normally weakest.

Modification of the winds by mid-latitude frontal systems have been observed as far north as the

Gariep, with the intensity increasing southwards towards Cape Point. In winter the effects of these frontal systems are severe with extreme instances resulting in NW to SW gales in the southern regions. However, in summer the effects on the West Coast are generally weak causing periodic slackening or abatement of the S/SE winds to the south. Thus in the southern regions, particularly during winter, it is difficult to determine the difference between the effect of the coastal low and the cyclones that follow. Generally, the coastal low is responsible for the abrupt changes or reversals in the wind component, while the one or more cyclones which may follow determine the duration of this change in the wind component in the southerly regions.

In winter, low pressure cells which move eastwards across the southern Cape province are continually being generated in the SW Atlantic. NW winds dominate (to a lesser extent than the SE winds) displacing warmer waters outside the coastal zone inshore, resulting in downwelling on the West Coast.

Jury (1985) has shown that airflow, particularly between Cape Town and Cape Agulhas, is modified by the coastal topography confining its effects to a relatively smaller area abutting the land. An example is the infamous Cape Doctor - a howling SE wind - which produces localised cold jets and upwelling plumes at Oudekraal and Gordons Bay. During periods of calm, when the SE wind is temporarily suspended, shallow thermoclines can quickly develop within the upwelled area as a result of solar radiation. At times the southeasterly wind system may be disrupted by eastward moving low pressure cells which initiate northwesterly and westerly winds, resulting in the termination of upwelling and movement of the oceanic thermal front shorewards (Walker *et al.,* 1984).

(b) South Coast of Southern Africa

The coastal lows formed on the West Coast propagate past Cape Town and rapidly traverse the Agulhas Bank (Reason & Jury, 1990) and are most obvious in summer when the effects of the mid-latitude cyclones are further offshore. Particularly strong wind conditions ('southwest buster') and rapid changes in wind direction are associated with the passing of coastal lows along the South coast (Hunter, 1987; Jury *et al.,* 1990b) with the strongest southwest buster conditions occurring within the vicinity of Port Elizabeth. The propagation of the coastal low and its lifespan on the South coast are primarily influenced by the intensity and proximity of the trailing mid-latitude cyclone. For example, in summer when the mid-latitude cyclone is relatively weak or lies far south of the landmass, the low migrates more rapidly along the South coast (Reason & Jury, 1990). Also having an influence on the propagation of the coastal low is the Agulhas Current, which tends to contribute to its rapid acceleration in the southeastern part of the South Coast (van Ballegooyen, 1995).

However, Jury *et al.*(1990b) and Schumann (1989) have found the propagation of atmospheric systems to be slowest on the South coast. Schumann (1989) has also found that the winds associated with these systems to be weakest along the South coast, strengthening towards Port Elizabeth and then decreasing as the coastal low migrates northwards up the East Coast.

At times the SAH ridges in over the land and westerly winds are experienced on the western side of the Agulhas Bank. Constant westerly or SW winds tend to generate downwelling between Cape Point and Cape Agulhas (Lutjeharms *et al.,* 1991). Eventually the ridge of high pressure elongates to such an extent that it separates to form a budd-off high which then moves up the East Coast. Easterlies are thus generated moving water in the upper layers offshore (Schumann *et al.,* 1988), resulting in upwelling on the southern and southeastern parts of the South Coast. Such winds are also generated when the region of maximum anticyclonic activity has moved south (Schumann *et al.,* 1982). Along this part of the coast Westerly winds are dominant throughout the year, however, with easterlies forming a significant component in summer (Schumann *et al.,* 1988).

Surface lows located to the south of Cape Agulhas, result in westerly winds at the Cape south coast. These often produce downwelling at the capes and upwelling in the bays along the south and SE coasts (Schumann *et al.,* 1988). East moving low pressure cells passing south of the Cape tend to result in strong variable winds thereby mixing Agulhas Bank waters between Cape Point and Cape Agulhas (Lutjeharms *et al.,* 1991). Schumann *et al* (1988) suggest that wind is the dominant force over the inshore shelf areas.

(c) East Coast of Southern Africa

The East Coast is also dominated by a quasi-stationary high – the South Indian High (Preston-Whyte & Tyson, 1973; van Ballegooyen, 1995) – situated to the east of Madagascar. The associated winds are NE and are periodically interrupted by coastal lows which as they migrate from west to east gradually decrease in strength north of Port Elizabeth and finally dissipate in the vicinity of Durban or, move out to sea (Jury *et al.,* 1990b). Its propagation and lifespan also primarily influenced by the intensity and location of the trailing mid-latitude cyclone.

(d) Wind Shadow Zones

Wind shadow zones are commonly caused by the local topography and are basically areas of calm. Off the southern African coast the wind shadow zone extends between 31°S and 33°S. In this area the diminished offshore transport allows the water to remain near the surface long enough to be heated by the sun (Jury, 1987). The warm water found between the latitudes mentioned extends the length of the wind shadow, and highlights the influence that topographic deflections in marine winds have on oceanic conditions over the shelf (ibid).

CHAPTER 3: DATA AND METHODS

The development of the Crawford bucket, its application to the collection of the SST data set presented and the origin of the measuring sites are discussed, followed by a description of the procedures involved with the processing of the data.

3.1 MEASUREMENT OF SST

Voluntary observing ships (VOS), or ships of opportunity, have in the past been recording SSTs along with other meteorological parameters such as air temperature and pressure, as part of the World Weather Watch system. This system was established in 1963 by the World Meteorological Organisation (WMO) (WMO, 1973) to provide an observation and data distributing network of global monitoring of the atmosphere.

Various methods of observing SSTs have been adopted by VOS for example, the intake method, the limpet method and the trailing thermistor method. All of these methods essentially measure the temperature of the water at 1-2m below the surface using the temperature dependency of some resistors. These methods are more fully described in the International Oceanographic Commission (IOC) (1975). Of these, the most common methods have been either to fit the ship with a thermograph to record the water temperature at the intake of the engine cooling system or simply measure the temperature of a water sample collected manually in a bucket between 1-5 m below the surface.

At a meeting in Geneva in 1964, the Commission for Marine Meteorology (CMM) - one of five applications commissions formed by the WMO between 1963 and 1969 (WMO,1973) - expressed its concern over the unsatisfactory methods and unreliable SST measurements from VOS.

The intake method has been and still is the most commonly used by ships (IOC, 1975, Hopkins, 1992). However, problems associated with this method include the following :

- The error of parallax introduced when reading the thermometer due to the inaccessibility in general, of instruments in engine rooms;
- coarse scale graduations of thermometers; and
- lack of calibration instruments.

(Sauer, 1963; Beetham, 1966; IOC, 1975; Hopkins, 1992):

In the mean time, in South Africa the challenge to produce a more suitable and inexpensive instrument for the measurement of SSTs was taken up by A. B. Crawford of the South African Weather Bureau (SAWB) in 1964, and he produced what was later referred to as the **Crawford bucket**. It was subsequently adopted by the CMM as a standard for comparison tests (Crawford, 1970). In the late 1960s during a study co-ordinated by a panel established by the CMM (of which Crawford was a member) the various methods and instruments used for measuring SSTs by VOS (WMO,1972), were evaluated. The Crawford bucket, among others, was reported to have performed satisfactorily but buckets made of canvas were viewed as being completely inappropriate. Several British vessels were known to have made use of the Crawford bucket method for a limited period at this time (Captain Gibson, South African Navy, 1994, pers. comm).

The Crawford Bucket, as shown in Figure 3.1, consists of a standard thermometer (see Fig.3.2) (a product of Zeal or Thermo Schneider) housed in a plastic tube, extended a few cm's on either end with radiator hose. This cushions the fall should the thermometer be dropped. The bottom end of the tube is sealed with a rubber stopper. Inside, the thermometer is held securly in position between three short pieces of laboratory piping, which are themselves tied to the plastic tube. A six meter length of nylon rope is tied tightly to the open end of the housing to enable the instrument to be 'tossed' out to sea and for the temperature to be measured between 1 - 5m below the surface. Temperatures are easily read from the window cut out of the tube.

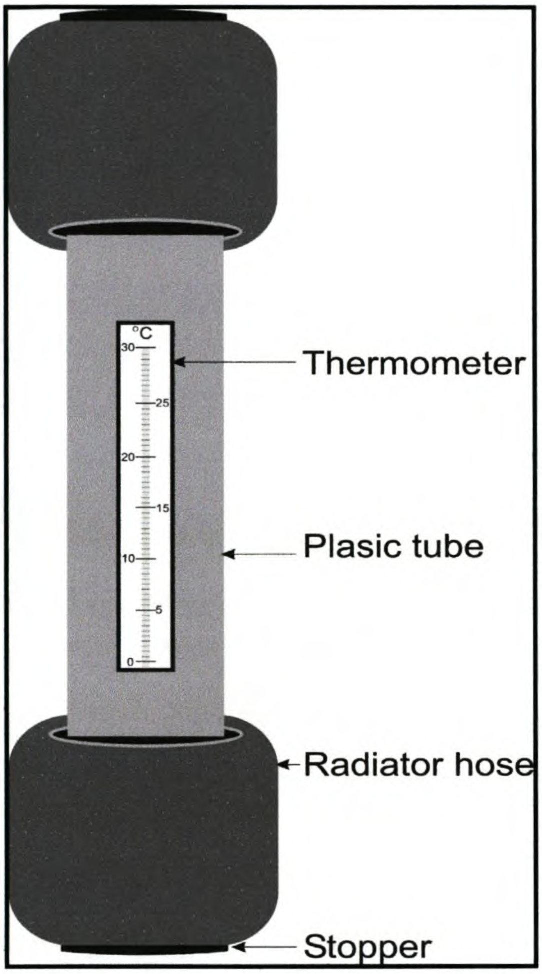


Fig.3.1 – The Crawford Bucket (after Crawford, 1965).

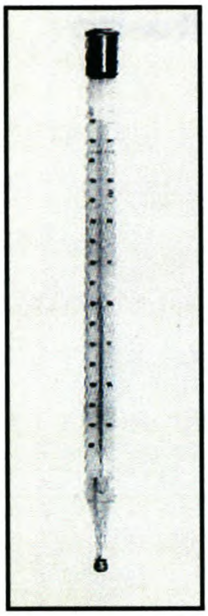


Fig.3.2 – The standard dry bulb thermometer.

During 1966, in response to Sauer's findings, the U.S. Naval Oceanographic Office developed a number of devices known as Near Surface Reference Temperature (NSRT) Systems (Beetham, 1966). Extensive tests done in the field and the laboratory revealed that the NSRT system has an accuracy of 0,3°C, is relatively free from observer errors and is not sensitive to ship speeds or weather conditions (Beetham, 1966; IOC,1975).

As a result of the difficulties experienced (see pp. 39) with the intake method the IOC, in 1975, designated it as the "least desirable". Generally, with the intake method, a temperature probe is fitted through a hole in one of the seawater intake pipes, which is located below the ship's deck in the engine room (IOC, 1975). Finally, to try and resolve the issues which had clouded the quality of VOS reports for decades, the CMM co-ordinated a study of different instruments and observing practices, between the summer of 1988 and the summer of 1990, known as the Voluntary Special Observing Programme - North Atlantic (VSOP - NA) (Hopkins, 1992). The results clearly identified the problems associated with the siting of instruments on board VOS, as well as the limited information available to assist observers.

Presently, a large number of VOS have been fitted with temperature probes located on the outside of the ship near the hull (Mr. I.T. Hunter, Manager: Maritime Forecasting Services, South African Weather Services, Dept. of Environmental Affairs & Tourism, 2003, pers. comm). These probes extend to approximately one meter and are accurate to 0.1°C. However, some VOS are still observing SSTs using the intake method and a handful of research vessels are making use of the NSRT method. (ibid)

3.2 SST MEASURING SITES

With the use of VOS data only, the first realistic isotherm charts of SSTs around the Southern African coast (between 6°E - 37°E and 17°S - 40°S) were produced in the late 60's (Crawford, 1969). These early charts were enthusiastically received by a diversity of organisations and individuals such as fishermen, scientists and tourists. They were, until recently, in the form of 10-day mean SST charts for the west and east coasts. However, although it is accepted that a 10 day analysis (recently reduced to a 7 day analysis) does not produce a synoptic pattern, the availability of near coast VOS data has never been adequate enough to enable the time period to be reduced. To augment the data with satellite imagery and data obtained by aircraft

These sites are still in operation, and the monitoring procedures for the 33 measuring sites originally established by the SAWB at Cape Town International Airport, remain unchanged. The SAWB has, since this study, been renamed to the South African Weather Service (SAWS) and will, henceforth, be referred to as such.

3.3 DATA COLLECTION AND PROCESSING

SSTs are measured on a daily basis at all the measuring sites and are collected by officials at the SAWS every seven days and stored on a database. These data are available from the SAWS and has also been incorporated into the Southern African Data Centre for Oceanography (SADCO) database (Grundlingh, 1991).

Except for the Natal Sharks Board, all SST observers are supplied with the relevant apparatus, i.e. the Crawford Bucket (see Fig.3.1), and the necessary training. Training involves general instruction with respect to the accurate measurement of SST, for example, keeping the bucket in the shade when not in use and keeping the thermometer in the bucket whilst reading the temperature. Also, volunteers are encouraged to read the temperatures to the nearest 0,1°C.

Common Errors:

- Temperature readings may not have been taken while the thermometer was still submerged in the bucket of water. They may, instead, have pulled the thermometer out of the bucket to read the temperature. Such a sample will have had a chance to react to local atmospheric effects (Walker *et al.,* 1984) through exposure to the sun (heating) or to the evaporating influence of the wind (cooling);
- Temperature readings may not have been taken from the open sea. They may, instead, have been taken from rock pools or from a bucket of sea water that may have been left standing for a while, or from within a harbour. All such samples will also have had chance

to be affected by the local atmospheric effects described above; and

- thermometers may have been retrieved too quickly, thereby not allowing time for the mercury level to reach the correct temperature.

Measuring sites at Koeberg, Cape Agulhas, Hondeklipbaai, Doringbaai and the Natal Sharks Board sites do not provide observations over weekends, since there is nobody available to make the observations. Occasionally other 'gaps' develop in the data sets from some of the measuring sites as a result of an observer being off sick or on leave. There are also times when weather and sea conditions are not conducive for the measuring of SSTs (observers are not expected to compromise their safety). It has been made clear to observers that they must not 'guess' temperatures but rather leave them blank.

3.4 SUPPORTING DATA

The following supporting data was introduced to assist with the checking of 'suspect' SSTs.

3.4.1 Weather Charts

Surface synoptic charts are drawn up every six hours i.e. (00h00, 06h00, 12h00, 18h00 GMT) by the SAWS and depict the prevailing synoptic weather patterns over southern Africa. Incorporated onto the charts are the offshore VOS and drifting buoy (DRIBU) weather data which are received locally at the SAWS through the ARGOS System (from Toulouse in France) and the Global Telecommunication System (GTS) of the WMO. Also included in the charts are the data received from various lighthouses and automatic weather stations (AWS) (referred to as SYNOPS) around the southern African coast. The primary function of these systems is to ensure that the exchange of data to scientists world wide is as rapid and reliable as possible (WMO, 1973; Rosso, 1983; ARGOS, 1988). The SAWS is the only organisation in South Africa that has direct access to these systems and which receives the data real-time. Data is transmitted approximately every hour via satellite to the ARGOS and GTS from any moving platform, for example, DRIBUs, VOS and ice buoys, from any fixed platform such as moored buoys and AWSs, (Rosso, 1983; ARGOS,1988). Infra-red images are used to help position the fronts and areas of high and low pressure.

3.4.2 VOS and DRIBU

Real-time reports for individual DRIBU, VOS, or SYNOPS can be accessed from the mainframe computer at the SAWS - through direct entry, via a Telkom digiline link if outside of Pretoria, and decoded to obtain the parameters required. However, only the previous 48 hours of data is kept at the SAWS for any particular DRIBU. Unlike all other data transmitted from southern Africa DRIBU data is not archived and historical data is therefore only available from the SAWS when the magnetic tapes from Toulouse have been obtained. Historical data for TOGA buoys can be obtained direct from National Aeronautical and Space Administration (NASA).

3.4.3 Satellite Data

Infrared images received at the SAWB were of use, with respect to SSTs, only when the areas concerned were not obscured by cloud or advection fog. Sea surface temperatures can be derived from SATEM data (satellite data in digital form). However, due to the sparsity of the data, especially near the coast, and because the data is received infrequently at the SAWS, this source proved to be disappointing and of little use. Thus, for these technical reasons satellite imagery was not incorporated into this study, although its advantages are acknowledged by the author.

3.5 DATA VERIFICATION

Since it was assumed that errors could exist in the data sets, either through the data capturing process or through incorrect temperature observations *per se*, a debugging procedure was introduced using the support data described above.

Firstly, a plot program was written to plot the daily changes in temperature over a month for a particular measuring site. This enabled the average conditions to be established at a glance and possible 'spikes' to be identified. Abrupt changes in temperature were considered valid if they were maintained on consecutive days while gradually returning to more average conditions.

Secondly, a program was written to establish the frequency of the daily temperature differences for a particular measuring site. Generally, the highest frequencies appeared to range between –3°C and +3°C. It was therefore decided that if an abrupt change in temperature beyond this range occurred and was not maintained on consecutive days while gradually returning to more average conditions, it would be considered as a possible 'spike'.

If a SST was considered a possible spike for a particular measuring site, the supporting data described above would then be used to establish previous and prevailing weather and sea conditions in the area concerned. If supporting data was not available or not sufficiently indicative of an error, the observer concerned was contacted for personal verification. Invariably, either an air temperature instead of a SST had been reported or the thermometer was faulty. If the SST in question could not be corrected in this way the entry was left blank. If it was considered to have been a typographical error the SST was corrected according to the SSTs on the days before and after it. For example, if Day1 = 14,5°C, Day2 = 25,3°C and Day3 = 14,9°C then Day2 would be amended to 15,3°C.

At the end of this rather tedious and meticulous process of checking and editing of each individual measurement, a unique data set was obtained that could be used for an analysis of the SSTs around the Southern African coast. The present study represents the first time that this data set is systematically analysed and interpreted.

3.6 DATA COVERAGE AND METHODS

Of the 33 SAWS measuring sites presently in operation, data for 29 are included in this study. Since the period covered by this study is between 1972 and 1992, the remaining four sites at Ichaboe and Mercury Islands, Kommetjie and Fish Hoek, established at the beginning of 1992, have been omitted because of a shortage of data. The longterm data for the Natal Sharks Board measuring sites were only adequate for three of the 20 sites namely - Southbroom, Durban and Zinkwasi. The remaining 17 measuring sites had very large gaps between observations with, for example, at times only four observations in a period of four months. It was therefore decided not to include these sites for this particular study. Thus, the 32 SST measuring sites around the southern African coast that were used for the purpose of this study are spatially shown in Figure 3.4.

The periods that were covered by the data for each of these measuring sites are shown in Table 3.1. The histograms in Appendix D show the total number of reporting days for the periods covered by the data for each measuring site.

Of the 32 measuring sites, 30 had one SST measurements a day. The remaining two, Tsitsikamma and Port Elizabeth, had two measurements a day. Unless otherwise stated, for these two measuring sites, the two observations were used to calculate an average for the day. Sea surface temperature measurements that were taken once a day were typically taken between 07h00 and 11h00. Where SSTs were measured twice a day, the second measurement was typically taken between 14h00 and 16h00.

Although day-to-day SSTs were not available for Stilbaai from 1973 – 1979, Durban from 1981 - 1989 and Nahoon, Eastern and Orient Beaches from 1973 – 1983, the monthly averages for

Table 3.1 – Periods that were covered by the data for each of the measuring sites around the southern African coast.

	SST MEASURING SITE	PERIOD OF DATA
1	Walvis Bay	1973 - 1980
		1983 - 1986
		1990 - 1992
2	Luderitz	1973 - 1992
3	Diaz Point Lighthouse	1990 - 1992
4	Port Nolloth	1973 - 1992
5	Hondeklipbaai	1990 - 1992
6	Doringbaai	1990 - 1992
7	Lamberts Bay	1973 - 1992
8	Saldanha Bay	1973 - 1981
		1990 - 1992
9	Yzerfontein	1991 - 1992
10	Dassen Island	1990 - 1992
11	Koeberg (Beach)	1990 - 1992
12	Koeberg (Basin)	1987 - 1992
13	Sea Point	1974 - 1992
14	Hout Bay	1972 - 1975
		1991 - 1992
15	Kalk Bay	1972 - 1976
		1990 - 1992
16	Muizenberg	1973 - 1992
17	Gordons Bay	1973 - 1992
18	Hermanus	1974 - 1981
		1989 - 1992
19	Gansbaai	1980
		1989 - 1992
20	Cape Agulhas	1986 - 1992
21	Stilbaai	1980 - 1992
22	Mossel Bay	1985 - 1992
23	Knysna	1972 - 1992
24	Tsitsikamma (a.m)	1990 - 1992
	Tsitsikamma (p.m)	1990 - 1992
25	Plettenberg Bay	1987 - 1988
		1990 - 1992
26	Port Elizabeth (a.m)	1973 - 1992
	Port Elizabeth (p.m)	1974 - 1992
27	East London: Eastern Beach	1984 - 1992
28	East London: Orient Beach	1984 - 1992
29	East London: Nahoon Beach	1984 - 1992
30	Natal: Southbroom	1978 - 1992
31	Natal: Durban	1974 – 1980
		1990 - 1992
32	Natal: Zinkwasi	1978 - 1992

3.6.1 Spatial Classification

The coastline was divided up according to Heydorn and Tinley, 1980, as shown in Figure 3.5 with the ***west coast region*** consisting of 19 measuring sites namely Walvis Bay, Luderitz, Diaz Point Lighthouse, Port Nolloth, Hondeklipbaai, Doringbaai, Lamberts Bay, Saldanha Bay, Yzerfontein, Dassen Island, Koeberg (Beach), Koeberg (Basin); Sea Point, Hout Bay, Kalk Bay, Muizenberg, Gordons Bay, Hermanus and Gansbaai, the ***south coast region*** consisting of 7 measuring sites namely Cape Agulhas, Stilbaai, Mossel Bay, Tsitsikamma, Plettenberg Bay, Knysna and Port Elizabeth and the ***east coast region*** consisting of 6 measuring sites namely East London Orient Beach, East London Eastern Beach, East London Nahoon Beach, Southbroom, Durban and Zinkwasi.

3.6.2 Seasonal Classification

The seasons were categorised according to the SAWS (Mr. K Moir, Manager: Forecasting Services: Cape Town, South African Weather Services, Dept. of Environmental Affairs & Tourism, 2003, pers. comm) :

- Summer: from December to February
- Winter: from June to August
- Autumn: from March to May
- Spring: from September to November

3.6.3 Statistical methods

By using all the available data from the measuring sites within the three coastal regions, the following statistical methods were applied.

(a) Distribution skewness (S_k)

The distribution skewness was calculated for a year and each season using the equation below.

$$S_k = (\sum x^3 / N) \ / \ (\sqrt{\sum x^2 / N})^3$$

Where **x** = SST

N = total number of observations

(b) Kurtosis (k_u)

The coefficient of kurtosis for a year and each season was calculated using the following equation:

$$K_u = ((\sum x^4 / N) / (\sum x^2 / N)^2) - 3$$

Where **x** = SST

N = total number of observations

(c) 95% Confidence Limits

The 95% confidence limits were calculated for the mean SSTs and the upper and lower confidence limits for each year and season using the equations below.

$$\text{95\% Upper limit} = \bar{x} + (t \ * (sd / \sqrt{N}))$$

$$\text{95\% Lower limit} = \bar{x} - (t \ * (sd / \sqrt{N}))$$

where $\bar{x}$ = arithmetic mean

t = degrees of freedom

sd = std deviation

N = total number of observations

Standard deviation:

$$Sd = \sqrt{\sum (x - \bar{x})^2 / (N-1)}$$

Where $\bar{x}$ = arithmetic mean

x = SST

N = total number of observations

(d) Probability

The probablitity of day-to-day changes in SST were calculated using the following equation:

$$P(x) = N! / x!(N-x!) * P^{x} * (1-P)^{N-X}$$

Where **P** = mean / N

mean = total number of occurrences where the day-to-day change is x / total number of observations

N = total number of days in a month; e.g. for January over a period of 10 yrs, N = 310

x = extent of the day-to-day SST change; e.g. a change of 1°C, or 2°C, or 3°C etc.

(e) Spectral Analysis

The following two methods were used to calculate the spectral energy of five randomly selected measuring sites namely, Luderitz, Lamberts Bay, Gordons Bay (West Coast), Port Elizabeth (a.m) (South Coast) and Durban (East Coast).

As part of a validation process to verify any signals found using the first method (*method 1*), *method 2* was used. For this method only, the 1993-1995 SST data was incorporated for these sites in order to have three near complete six year data subsets. Also, as part of this validation process, to obtain some clarity regarding the consistency of any signals found, Knysna (South Coast) was included since its dataset, from 1972 – 1995, is near complete. The total number of reporting days from1993 to 1995 for these six measuring sites are shown in Table 3.2.

Table 3.2 – Total number of reporting days for the six measuring sites from 1993 –1995

	TOTAL NUMBER OF REPORTING DAYS					
YEAR	**Luderitz**	**Port Nolloth**	**Lamberts Bay**	**Knysna**	**Port Elizabeth (a.m)**	**Durban**
1993	204	363	365	187	365	220
1994	231	354	364	252	365	195
1995	237	356	365	298	365	280

Method 1

For this method, a program developed in Microsoft C (Morrisson, 1995) was used to individually analyse the five measuring sites. In the program the data was smoothed by means of a weighted moving average filter. The filter has a 50% cutoff point at 10 weeks thus removing variations of period 7 or 8 weeks and less, while allowing those of periodicity greater than 12 weeks to pass. Small gaps of one day were linearly interpolated and gaps of several days were filled by obtaining an historical average for that particular day of the month. The residuals were defined by:

residual=observation - fitted value

and, also provided a means of checking that the residuals of a 'good' fit would be random and close to zero (*ibid)*.

Method 2

For this method, the MATLAB Signal Processing Toolbox (Krauss *et al*, 1995) - a well known commercial software package, with power spectral density routines – was used.

The data was divided into subsets of six years viz. 1974-1979, 1980-1985 and 1990-1995 and analysed independently. The years 1986-1989 were ignored because of the extent of the gaps in the data. The period 1980-1985 for Durban was not analysed as no day-to-day data was available.

Apart from using interactive interpolation software to remove any gaps, the filters applied were restricted to have as narrow a bandwidth as possible to avoid disproportionate loss of data. The power spectral density routine makes use of the averaged periodogram method of Welch (1967) (Rosen & Salstein, 1983) where the discrete time series $x(t)$ of length $N\Delta t$ is split up into a n_{win} subseries, each of length $m=N/n_{win}$. A window of length m is used in each of the subseries and the magnitude of the square of the FFT (Fast Fourier Transform) of each windowed subseries is calculated and normalised. The confidence interval of 80% was calculated directly by the MATLAB routines.

The intensity of the energy was measured by calculating the *rms* (route mean square) using the following equation:

$$rms = \sqrt{(°C)^2} \times \Delta F$$

where: ΔF = bandwidth (1/256)

$(°C)^2$ per cycle per day = average of the values corresponding to each peak, e.g. 40 days, in each of the subsets

CHAPTER 4: SPATIAL AND TEMPORAL CHARACTERISTICS OF SEA SURFACE TEMPERATURE

Sea Surface Temperatures, like any other physical data, exhibit variability over different timescales. In this chapter, various statistical methods are applied to the data over different time periods in order to determine the spatial variability of SSTs around the southern African coast .

4.1 DISTRIBUTION CHARACTERISTICS

To assist in obtaining an initial overall picture of the three coastal regions and, before making any comparisons between the coastal regions or even drawing conclusions, it was decided to establish how the data was distributed.

In a normal distribution, observational frequencies are a maximum at the mode of the variable and drop off at higher and lower values. When plotted, this distribution assumes a bell shape, with the degree of spread and the 'height' of the bell determined by the specific parameters of the distribution. If the distribution is completely symmetrical, the mode and the mean (average of all values) coincide. The variable is thus said to be both independent and random (Garvin, 1986).

Generally, SSTs cannot be referred to as independent variables since their variability depends on prevailing meteorological and oceanographical conditions. However, they can be referred to as random variables since observations are not restricted to the same sample of water.

Table 4.1 – Annual and seasonal S_K values for the three coastal regions.

		TOTAL NUMBER OF MEASURING SITES				
	S_K	YEAR	SUMMER	AUTUMN	WINTER	SPRING
WEST COAST	<0.55		1			
	0.55 - 1.0		2	1		3
	1.001 - 2.0	19	14	16	14	15
	2.001 - 3.0		2	2	5	1
SOUTH COAST	<0.55		2			
	0.55 - 1.0		2	2		2
	1.001 - 2.0	7	3	5	7	5
	2.001 - 3.0					
EAST COAST	<0.55					
	0.55 - 1.0		2			
	1.001 - 2.0	6	4	6	6	6
	2.001 - 3.0					

The positively skewed results for the West Coast region were to be expected. The reason is that this region is generally a cooler environment characterised by a cold Benguela Current (see Chap.2 section 2.3) and seasonal upwelling (see Appendix B).

The near approximation of the normal distribution at Gordon's Bay during summer (a period of maximum upwelling on the West Coast) would be expected. The reason is that this is an area particularly affected by 'deep southeast' wind conditions (see Appendix B section B-5 para. 3) and the resulting intensification of the upwelling process (see Chap.2 section 2.5(b) pg.34).

However, the results for the East Coast region would have been expected to have been negatively skewed. The reason is that, although the East Coast region is generally a warmer environment characterised by a warm Agulhas Current (see Chap.2 section 2.2), there are occasions, throughout the year, when SSTs are cooler as a result of disruptions to the Current (see Chap.2 section 2.5 (c)).

These results also bring to attention the consideration of where the observers were measuring the SST, which could effect the results. For example, SSTs at Orient Beach were measured ~500m away from the mouth of the Buffalo River and at Nahoon Beach ~10m away from the mouth of the Nahoon River. River water temperatures obtained from the South African Department of Environmental Affairs and Tourism for the Kei River mouth (unfortunately, the Buffalo and Nahoon Rivers' water temperatures were unavailable) during 1992 showed that temperatures on several occasions were between 24°C and 31°C. It would now appear that these high river water temperatures are not influencing the SST as much as it would have been thought.

The results for the South Coast region would have been expected to have approximated the normal distribution the closest. The reason is that, the South Coast region is generally a more moderate environment influenced by the oceanic systems that characterize the regions on either side of it (see Chap.2 section 2.2 – 2.3, 2.5(b)) and, experiencing localised upwelling and heating (see Chap.2 section 2.5(b)). Although near approximation of the normal distribution was shown in the results for Knysna (S_K = 0.4) and Tsitsikamma (S_K = 0.33) during summer, it appears that, generally, SSTs are cooler. This seems to imply that the oceanic system characterizing the east coast region is not having as great an impact on the south coast region.

4.1.2 Modality

On average, 65% of the total number of measuring sites on all sides of the coast showed some form of bi-modality/tri-modality (i.e. more than one mode) suggesting that there is more than one preferred SST value. The reason is that, as the oceanic and meteorological systems that characterise these three regions vary (see Chap.2 section 2.2, 2.3, 2.5) so do the SSTs, by responding with higher SST values as a result, for example, downwelling or lower SST values as a result of, for example, upwelling.

Table 4.2 – Annual and seasonal modality for the three coastal regions

	TOTAL NUMBER OF MEASURING SITES					
	MODE	YEAR	SUMMER	AUTUMN	WINTER	SPRING
WEST COAST	BI-MODAL	6	5	2	3	4
	TRI-MODAL	2	3			
SOUTH COAST	BI-MODAL	2	4	3	2	4
	TRI-MODAL	3	1			1
EAST COAST	BI-MODAL	2	1			1
	TRI-MODAL		1			

From Table 4.2 it can be seen that there was no form of bi-modality/tri-modality in autumn or in winter on the East Coast. Thus it would appear that, during these months the variability of the oceanic and meteorological systems that characterise this region only trigger the SST to respond with lower SST values.

4.1.3 Kurtosis

The degree of spread about the mean, or 'peakedness' is known as kurtosis and is an important characteristic since it gives some indication of the extent of the variability of a sample – in the case of this study a sample of SSTs. The three types of kurtosis are illustrated in Figure 4.3.

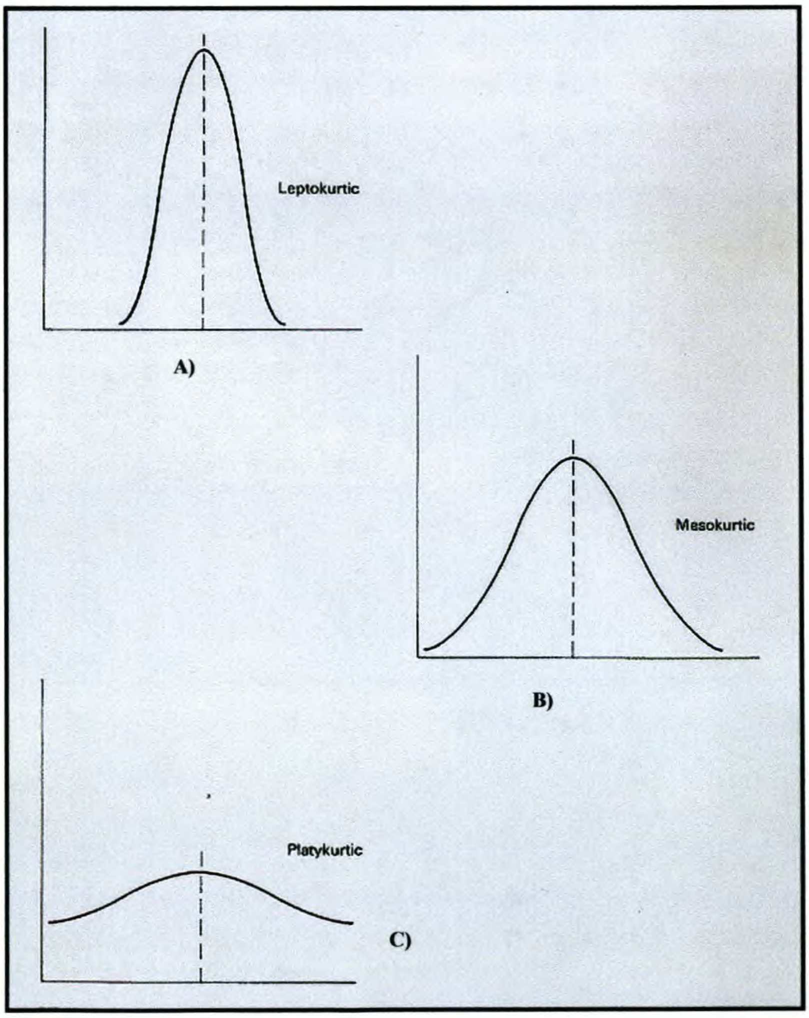


Fig. 4.3 – Types of Kurtosis – a, Leptokurtic; b, Mesokurtic; c, Platykurtic

If the distribution is distinctly more peaked than the normal distribution it is called *leptokurtic* and implies that the variability of the sample is low. If the distribution follows the normal distribution, or very close to it it is called *mesokurtic*. If the distribution is distinctly flattened relative to a normal distribution it is called *platykurtic* and implies that there is a high degree of variation in the sample (Larsen & Marx, 1986; Garvin, 1986).

The K_u values are shown in Table 4.3 and were calculated using the method presented in Chapter three (3.6.3(b)). (0 = *mesokurtic*; >0 = *leptokurtic*; <0 = *platykurtic*)

Table 4.3 – Annual and seasonal k_u values for the three coastal regions – 0 = mesokurtic; >0 = leptokurtic; <0 = platykurtic.

		TOTAL NUMBER OF MEASURING SITES				
	K_u	YEAR	SUMMER	AUTUMN	WINTER	SPRING
WEST COAST	0	2	11	18	12	15
	>0	16	1	1	2	
	<0	1	7		2	4
SOUTH COAST	0	2	3	4	5	6
	>0	4	2	2	1	1
	<0	1	2	1	1	
EAST COAST	0		5	3	4	5
	>0	6	1	4	1	
	<0					1

Generally over an entire year, it appeared that distributions were predominantly *leptokurtic*, indicating that there was little variation in SSTs at the various measuring sites. However, the seasonal distributions appeared to be predominantly *mesokurtic*. To a lesser degree, *platykurtic* distributions appeared to be mainly visible in measuring sites on the west coast, indicating that this was an area of higher SST variability.

4.1.4 Conclusion

Generally, it appears that in all three regions there is not much variation in the SST, and that there is a tendency for cooler SSTs to prevail.

4.2 MEAN TEMPORAL CHARACTERISTICS OF SSTs

To obtain a first-level insight into the steady–state temperatures around the coast, the overall mean values, the mean seasonal conditions and the mean day-to-day conditions were calculated using all the availabale data for the various measuring sites.

4.2.1 Annual Means

The long-term changes in SST are shown in Figure 4.4 (4.4.1(a), 4.4.2(a) and 4.4.3(a)) and indicate that, over a period of 20 years the West Coast decreased by approximately 1°C, the South Coast remained unchanged and, the East Coast increased by approximately 1°C.

To establish any degree of certainty regarding these findings it was felt that, a longer time series of similar data would be required to do further analysis. Since to the best of the author's knowledge there were no similar findings in the current literature, it was decided to leave these findings open to interpretation.

The mean annual SSTs for the three coastal regions are represented in Table 4.4.

Table 4.4 shows that the SST consistently increased around the coast from west to east, from an average of 14,3°C along the West Coast, to 17,8°C on the South Coast and 19,5°C along the East Coast region. The overall average difference between the East and West Coasts was 5,2°C. These average differences are primarily influenced by the meteorological and oceanographical factors that dominate these regions (see Chap.2 section 2.2-2.3 & 2.5). This pattern is to be expected in view of the fact that the West Coast, or Benguela region, is characterised by colder temperatures which are the result of the Benguela Current (see Chap.2 section 2.3 (a)) and wind induced upwelling (see Chap.2 section 2.3 (c) & 2.5) and, that the East Coast is characterised by warmer temperatures as a result of the Agulhas Current (see Chap.2 section 2.2).

The highest annual mean SST in each region appears to have occurred during different years (West coast during 1980, South coast during 1983 and East coast during 1992), whereas, the lowest annual mean SSTs appear to have occurred concurrently at the South and East coast sites during 1973 and in 1988 along the West Coast.

Table 4.4 - Annual mean SSTs (°C) around the Southern African Coast and average differences of SST between West and South Coasts, South and East Coasts and, overall, from West to East. The minimum and maximum temperature for each sector, and the minimum and maximum differences are indicated in bold

YEAR	WEST COAST	South - West	SOUTH COAST	East - South	EAST COAST	East - West
72			17.2			
73	14.5	**1.9**	**16.4**	1.1	**17.5**	**3.0**
74	14.7	2.9	17.5	1.6	19.1	4.5
75	14.7	3	17.6	1.2	18.8	4.2
76	14.7	3	17.6	1.4	19	4.4
77	14.9	3.5	18.4	**0.6**	19	4.1
78	14.5	3.9	18.4	1.3	19.7	5.2
79	14.4	3.5	17.9	1.5	19.4	5
80	**15**	3.1	18.1	1.6	19.7	4.7
81	14.2	3.6	17.8	1.9	19.7	5.5
82	14	4	18	1.7	19.7	5.7
83	13.9	**4.7**	**18.6**	1.3	19.9	6
84	14	3.5	17.5	2.1	19.6	5.6
85	14.5	3.4	17.9	2.1	20	5.5
86	14.2	4	18.2	1.6	19.8	5.6
87	14.1	4.2	18.3	1.4	19.7	5.6
88	**13.8**	3.9	17.7	2.1	19.8	6
89	13.9	3.6	17.5	2.3	19.8	5.9
90	14	3.4	17.3	**2.5**	19.8	5.9
91	14	4.2	18.1	1.9	20	**6.1**
92	14.2	4.3	18.4	1.8	**20.2**	**6.1**
AV.	14.3	3.6	17.8	1.7	19.5	5.2

The smaller difference between the East and South Coasts (1,7°C) than between the South and West Coasts (3,6°C) indicates that the East and South Coasts are more closely related climatologically. This suggests that the moderating influence of the Agulhas Current (Hunter, 1987) which injects quanta of warm water onto the Agulhas Bank, overshadows the effect of coastal upwelling (see Chap.2 section 2.2(d)) along the South Coast. Also having an effect, is the orientation of the landmass with respect to the prevailing meteorological conditions plays, for example, if the wind blows parallel to the coast upwelling will occur, and if the wind blows onshore downwelling will result.

It is also noticeable that the highest (4,7°C,1983) and lowest (1,9°C, 1973) average difference between the West and South Coast regions coincided with the occurrence of the highest and lowest average SSTs in the South Coast region respectively. Also, the SST on the West coast was very low (13,9°C) during 1983. Furthermore, the highest (6.1°C,1991/92) and lowest (3,2°C,1973) average difference overall, i.e. West to East, coincided with the highest and lowest mean SSTs in the East Coast region respectively.These occurrences are not surprising when considering that 1972/73, 1982/83 and 1991/92 have been identified (see, for example Philander (1983) and Schumann *et al* (1995)), as being El Nino years – the effects of this cyclical phenomenon on the behaviour of SSTs to be discussed in more detail section 5.2.

Since the highest (2,5°C,1990) and lowest (0,6°C,1977) average difference between the South and East Coasts and, the highest mean SST (15°,1980) for the West Coast region occurred independently, it was concluded that they resulted from meteorological and/or oceanographical perturbations on a more regional scale.

4.2.2 Seasonal Means

The mean seasonal SSTs for the three coastal regions are shown in Figure 4.4 (4.4.1(b-e), 4.4.2(b-e), 4.4.3(b-e)), and the following points are noteworthy:

- In the south and east coast regions mean SSTs were highest during summer, coinciding with the period of maximum insolation and, lowest during winter, coinciding with the period of minimum insolation. However, in the west coast region, although SSTs were highest during summer, SSTs were lowest during spring coinciding with the landward migration of the SAH.

- The SST consistently increases around the Southern African coast from west to east (see section 4.2.1) all year, with lower SSTs occurring on the West Coast in the Benguela region, higher SSTs occurring on the East Coast and, generally, moderate SSTs on the South Coast;

- Of interest, is that the South Coast temperatures approach those of the East Coast in summer, and those of the West Coast in winter. This suggests that, in summer, the Agulhas Bank is more under the influence of warmer water from the east, and in winter, more under the influence of colder water from the west. It can be interpreted that the meridional temperature gradient is displaced westward in summer, and eastward in winter.

Typically, the greatest differences in mean SSTs occurred between the West and South Coasts during summer (5,1°C) and spring (3,3°C) when upwelling favourable conditions are at their maximum (see Appendix B section B-3) along the West coast and, insolation is at its maximum over the Agulhas Bank, therefore, favourable for the development of seasonal thermoclines particularly during summer (Schumann & Beekman, 1984). This effect together with the influence of the Agulhas Current on the South Coast, appears to have noticeably 'diluted' the changes in mean SSTs between the South and East Coasts where, typically, the lowest differences were experienced during summer (0,2°C) and spring (1,6°C). Differences in mean SSTs between the South and East coasts were greatest during winter (2,5°C) and early spring (2.3°C) when the current tends to weaken in response to meteorological changes in the Northern part of the Indian Ocean, thereby, becoming a more variable component and having less of an influence on the South Coast region. Thus, the cooler SSTs experienced in winter and early spring on the South Coast as a result of the weakened effects of the Agulhas Current, and the development of a more homogeneous storm-mixed structure during winter particularly (see Appendix B pg.vii para.2), mean SST changes between the West and South Coasts were somewhat lower during winter (2,3°C) and early spring (2,8°C). Particularly noticeable is the 2°C increase in the mean SST difference from summer to autumn between the South and East Coasts when upwelling is most pronounced in areas located along the eastern side of the Agulhas Bank region, for example Port Elizabeth. Also, during summer/autumn the Agulhas Current takes on a different character which inhibits the current from spreading onto the shallow

Agulhas Bank region, except in the form of fragmentary eddies (see Chap.2 section 2.2(c)-2.2(d)) and unstable tongues of warm water (Hunter, 1987).

4.2.3 Day-to-day SST changes

As far as the applications of SSTs are concerned (see Chap.6), the **extent** of the day-to-day changes in SST are of primary importance because of the financial implications. For example, fishing fleets operating in the coastal regions could have their catch per unit of effort and consequently their financial returns negatively affected if, because of a sudden decrease in SST, the fish don't bite (the bait off the hook).

To establish the extent of the day-to-day changes of SST around the Southern African coast, the number of occurrences for a particular change in SST from day-to-day were calculated for the three coastal regions and for each month of the year using all the available data. The results are shown in Table 4.5. (where: TDIFF=day1-day2, TDIFF=day2-day3; if data was unavailable for day4 then, TDIFF=day5-day6 etc.).

These results appear to indicate that, for 74,8% of the total number of reporting days on the West Coast, 72,6% on the South Coast and 83.8% on the East Coast, no day-to-day changes in SST occurred and, imply that from day-to-day SSTs were more stable on the East Coast than the West and South Coasts.

The day-to-day SST changes for the three coastal regions were mainly +1°C or -1°C and represented 10,7% and 9,5%, respectively, of the total number of reporting days on the West Coast, 11,4% and 9,7% on the South Coast and, 5,7% and 5,3%, on the East Coast. To a lesser extent +2°C or -2°C (representing, for each occurrence, 1,8% of the total number of reporting days on the West Coast, 2,1% on the South Coast and, 1,7% on the East Coast) and,

+3°C or -3°C (representing, 0,3% and 0,5%, respectively, of the total number of reporting days on the West Coast, 0,5% and 0,6% on the South Coast and, 0,5% and 0,6% on the East Coast).

Changes in day-to-day SSTs >+3° and ,>-3°C represented 0,6% of the total number of reporting days on the West Coast, 1% on the South Coast and 0.8% on the East Coast and, at times were as great as +7°C on the West Coast and +8°C on the South and East Coasts and, as low as -8°C on the West and East Coasts and -9°C on the South Coast.

The wind component is the only factor affecting the SST that is common in all three regions (see Chap.2 section 2.5(a)-2.5(d); Appendix B). It is also a component in all three regions that is the most variable (strengthening, weakening or reversal) on a daily basis. Copenhagen (1953b) has shown that winds of, for example, 5-10 m/s are capable of causing a decrease in SST of between 3° and 4°C within a day. This renders the wind component a primary factor in initiating day-to-day changes in SST around the Southern African Coast. However, the position of the Agulhas Current core also has a tendency to experience daily variations (see Chap.2 section 2.2(b)) resulting in the movement of warmer water offshore and, the subsequent exposure of cooler subsurface water.

Table 4.5 – Number of occurrences for a particular change (TDIFF) in SST (°C) from day-to-day for the period of a year and for the three coastal regions

WEST COAST

TDIFF	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
-8	0	2	0	0	0	0	0	0	0	0	0	1
-7	1	4	2	0	0	0	0	1	0	0	0	4
-6	7	5	7	3	0	0	0	0	0	0	2	6
-5	16	20	13	7	0	1	0	0	2	2	4	22
-4	32	44	43	17	8	2	1	7	1	10	31	31
-3	106	108	101	50	24	17	15	10	20	49	68	106
-2	305	293	311	223	153	122	95	104	132	211	278	326
-1	1072	977	1108	1138	1188	1064	1040	1090	1081	1206	1123	1111
0	**8288**	**7513**	**8368**	**8328**	**9048**	**9077**	**9462**	**9397**	**8847**	**8882**	**8317**	**8360**
1	1267	1150	1287	1288	1166	1069	1041	1181	1279	1428	1377	1407
2	343	326	325	180	110	87	82	107	114	198	290	353
3	72	90	57	30	22	10	5	9	21	24	67	80
4	23	29	15	5	6	5	5	2	1	7	18	21
5	6	11	5	2	1	1	0	0	1	2	5	6
6	2	4	3	1	0	0	0	1	0	0	4	1
7	2	1	0	0	0	0	0	0	0	0	0	1

SOUTH COAST

TDIFF	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
-9	0	1	2	0	0	0	0	0	0	0	1	1
-8	2	7	1	1	0	0	0	0	0	0	0	0
-7	8	5	8	1	0	0	0	0	0	0	0	4
-6	6	15	7	3	0	0	0	0	0	0	0	6
-5	14	14	16	6	1	0	0	0	0	6	4	6
-4	13	37	24	15	3	2	2	2	0	8	14	13
-3	43	64	62	45	15	18	11	8	5	25	34	49
-2	138	156	167	117	90	78	64	66	54	97	135	136
-1	459	389	413	490	552	554	559	556	506	543	516	466
0	**3636**	**3212**	**3601**	**3592**	**3867**	**3793**	**3970**	**3965**	**3819**	**3808**	**3664**	**3643**
1	576	514	560	508	487	527	553	612	668	664	661	670
2	147	157	156	110	75	71	59	56	54	108	140	174
3	57	56	57	27	10	8	6	6	5	16	41	38
4	14	31	14	11	4	2	0	1	0	4	3	16
5	7	11	8	7	1	1	1	0	0	0	4	3
6	3	5	1	1	0	0	0	0	0	0	1	1
7	2	5	1	0	0	0	0	0	0	0	0	3
8	0	1	0	0	0	0	0	0	0	2	0	0

EAST COAST

TDIFF	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
-8	0	1	0	0	0	0	0	0	0	0	0	0
-7	0	0	1	0	0	0	0	0	0	0	0	1
-6	2	2	1	1	0	1	0	0	0	1	0	0
-5	7	5	2	2	0	0	1	1	1	0	1	5
-4	7	21	13	7	5	2	2	1	2	2	4	9
-3	35	29	28	23	16	22	13	9	10	10	12	29
-2	86	73	68	76	57	50	63	64	46	62	56	56
-1	177	157	189	184	220	191	203	193	189	184	190	171
0	**2942**	**2658**	**2988**	**2868**	**3032**	**2977**	**3100**	**3068**	**2955**	**3024**	**2914**	**2985**
1	222	214	197	179	202	187	198	196	213	211	208	191
2	86	82	72	78	52	38	52	56	38	64	57	74
3	27	24	33	14	13	15	15	11	11	13	11	29
4	5	15	3	9	2	8	4	5	3	1	5	9
5	2	5	4	2	2	1	0	0	0	1	1	1
6	1	0	0	1	0	0	0	0	0	0	0	1
7	0	0	1	0	0	1	0	0	0	0	0	1
8	0	0	1	0	0	0	0	0	0	0	0	0

4.2.4 Conclusion

Generally, it appears that the annual and seasonal SST variability is lower on the West Coast due to what appears to be a stable Benguela Current, but, are more variable from day-to-day as a result of the variability of the wind component. On the East Coast it appears that the annual and seasonal SST variability is higher due to an elusive Agulhas Current, but, are less variable from day-to-day due to the continual transport of warmer waters south from the equatorial regions and, a less variable wind component. On the South Coast it appears that the annual, seasonal and day-to-day SST variability is even higher due to its geographical location with respect to the South Atlantic and Indian Oceans and effects of the Agulhas Current.

4.3 SPECTRAL ANALYSIS

To investigate the possibility of any 'hidden periodicities' (apart from seasonal), the spectral density function, or spectrum, of a selected time series was determined. The highest frequency about which meaningful information from a data set can be obtained using spectral analysis, is known as the Nyquist frequency (Chatfield, 1989). Apart from Port Elizabeth and Tsitsikamma, all the measuring sites presented in this study have only one observation per day. Spectral analysis will therefore impart no information about the temperature variation within a day at any one of those sites. The Nyquist frequency, with only one observation per day, is $w_N =$ radians per day or $f_N = 1/2$ cycle per day or 1 cycle per two days) (ibid).

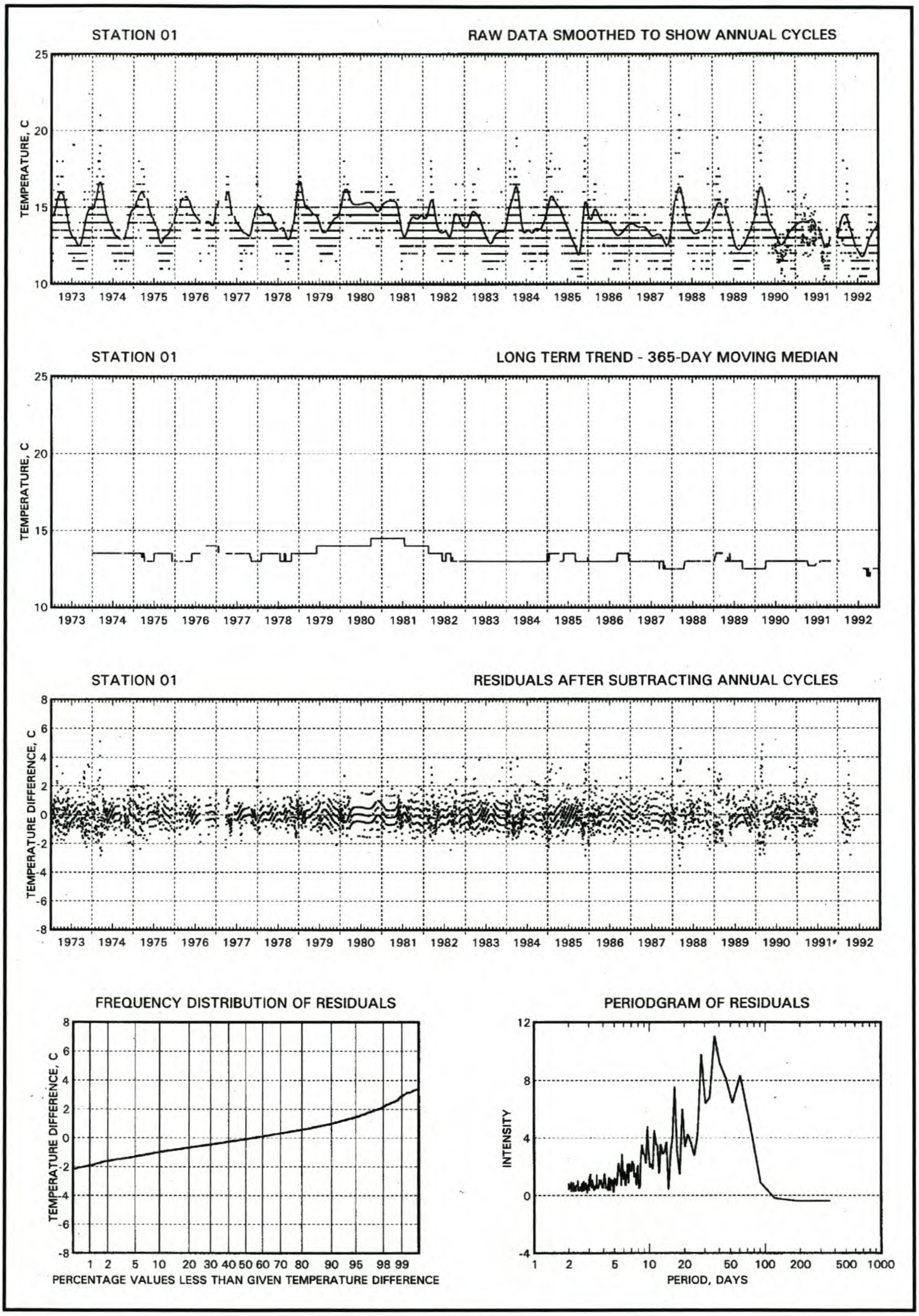
Finally, to make a comment about the lowest frequency that can be fitted to a set of data: if only six months of temperature observations from winter to summer were available for these measuring sites, it would not be clear if there was as upward trend in the observations or if winters are colder than summers. However, with one year's data it **would** start becoming clear that winters are colder than summers or vice versa. Thus, to determine variation at the low frequency of 1 cycle per year then more than one year's data must be available. Therefore the lower the frequency of interest, the longer the time period over which observations must be made, whereas the higher the frequency of interest, the more frequently the observations must be made.

4.3.1 Results

Figure 4.5(a) – 4.5(e) shows the standard output, using *method 1* (see Chap.3 section 3.6.3 (e)), of the analysis, namely the progression of each site from raw smoothed data to periodogram of residuals. The trailing off on the periodograms relates to the removal of the annual cycle as shown in the first graph of each figure.

At first, what is very striking from Figure 4.5(a) – 4.5(e) is the consistent appearance of a strong 40-60 day signal. To a lesser extent, there seems to be evidence of a 12-15 day signal in most of the periodograms. However, it is recognised that this represents only approximate bounds on the periods identified and, that the magnitudes of these signals at the various sites are clearly not the same.

Figure 4.6 (a) – 4.6 (c) shows the results of the validation process using *method 2 (*see Chap.3 section 3.6.3 (e)). As can be seen, the 12–15 day and the 40–60 day signal, identified in the periodograms of Figure 4.5 (a) – 4.5(e).



STATION 01 RAW DATA SMOOTHED TO SHOW ANNUAL CYCLES

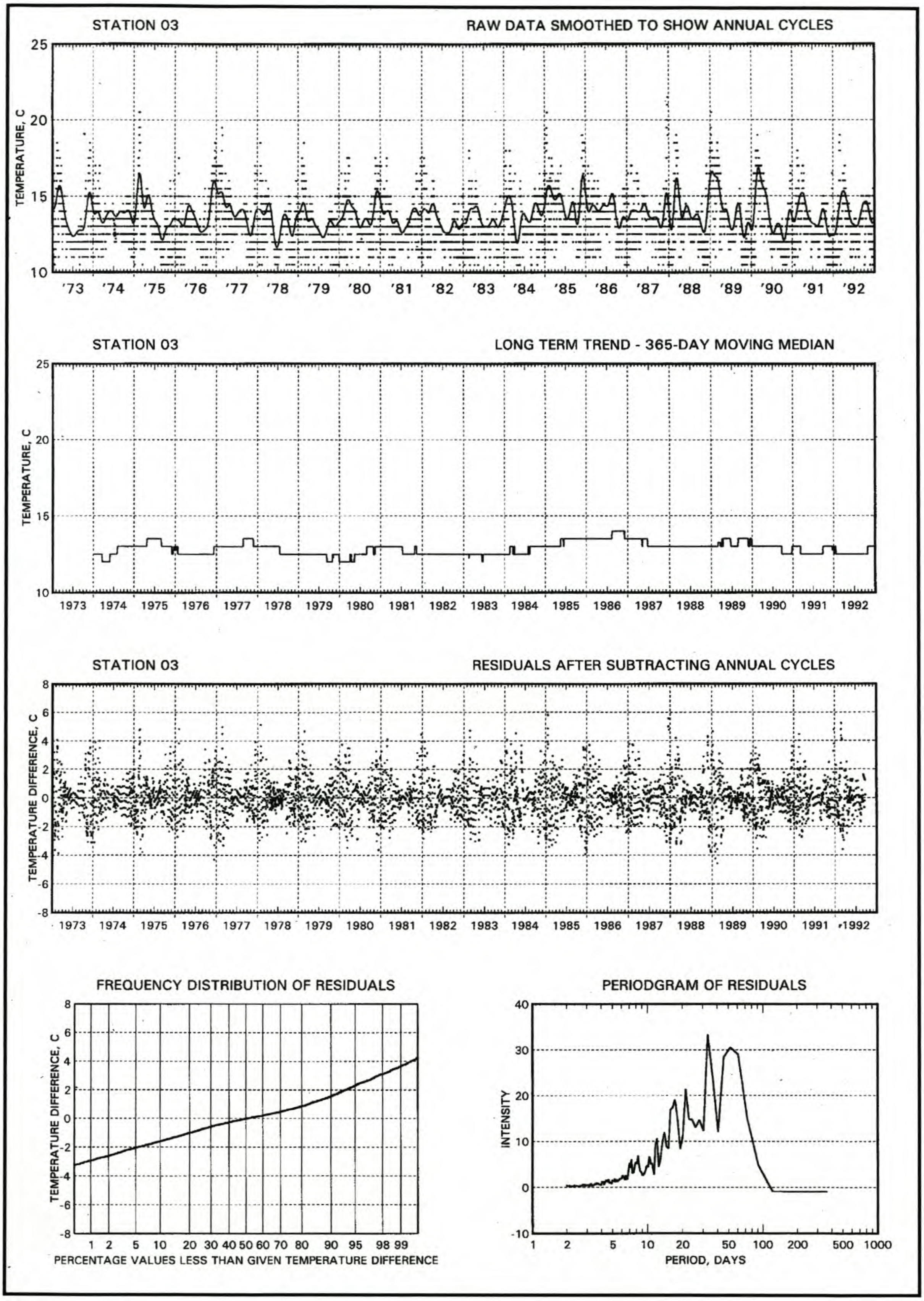
STATION 01 LONG TERM TREND - 365-DAY MOVING MEDIAN

STATION 01 RESIDUALS AFTER SUBTRACTING ANNUAL CYCLES

FREQUENCY DISTRIBUTION OF RESIDUALS

PERIODGRAM OF RESIDUALS

Fig. 4.5 – Standard spectral output *(method 1)* showing the smoothed raw SST data, longterm trend, residuals after subtracting the annual cycles, frequency distribution of residuals and periodogram of residuals; a, LUDERITZ



STATION 03 RAW DATA SMOOTHED TO SHOW ANNUAL CYCLES

STATION 03 LONG TERM TREND - 365-DAY MOVING MEDIAN

STATION 03 RESIDUALS AFTER SUBTRACTING ANNUAL CYCLES

FREQUENCY DISTRIBUTION OF RESIDUALS

PERIODGRAM OF RESIDUALS

Fig. 4.5 (continued) - b, Lamberts Bay.

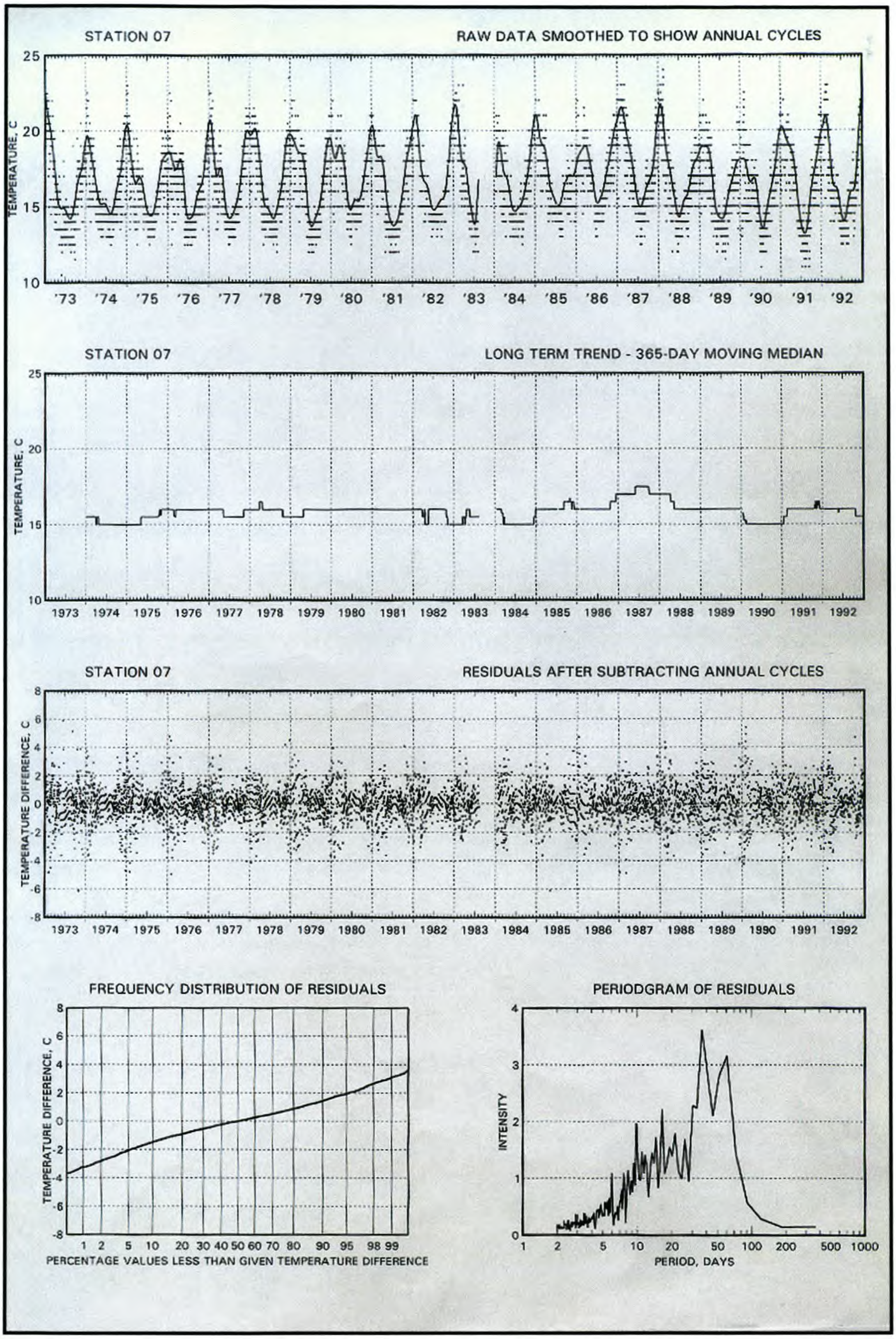


Fig. 4.5 (continued) - c, Gordons Bay.

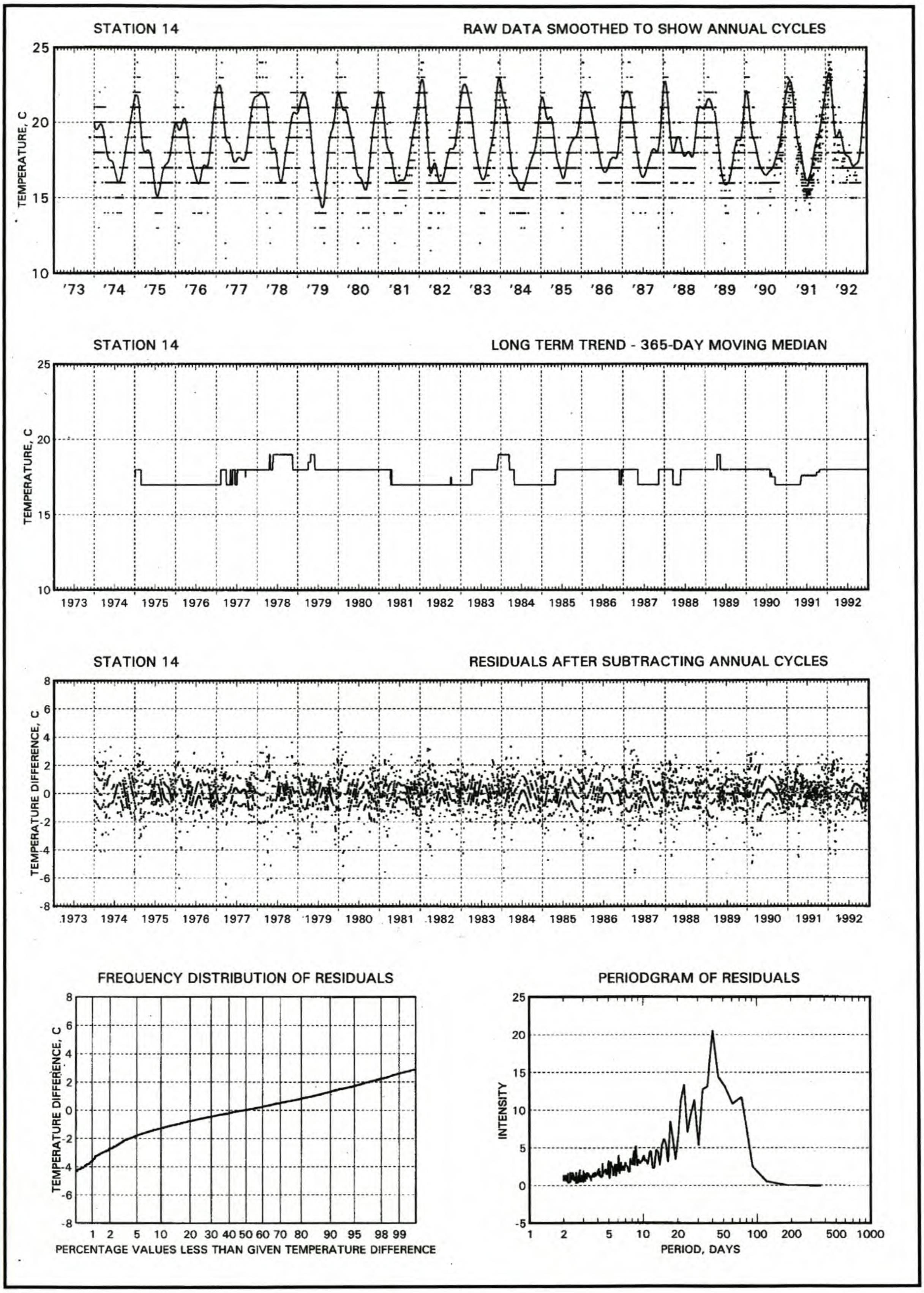


Fig. 4.5 (continued) - d, Port Elizabeth (a.m).

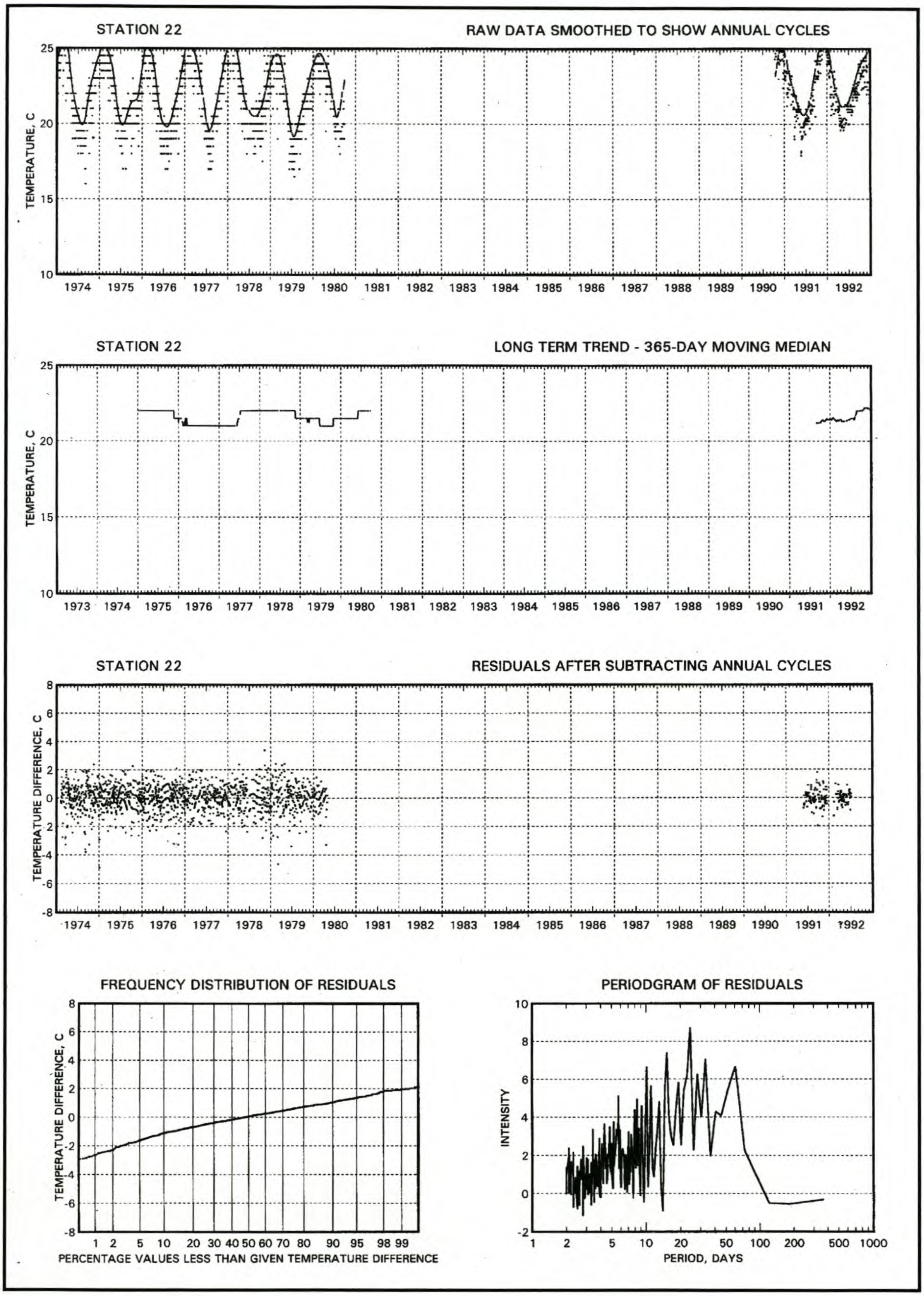


Fig. 4.5 (continued) - e, Durban.

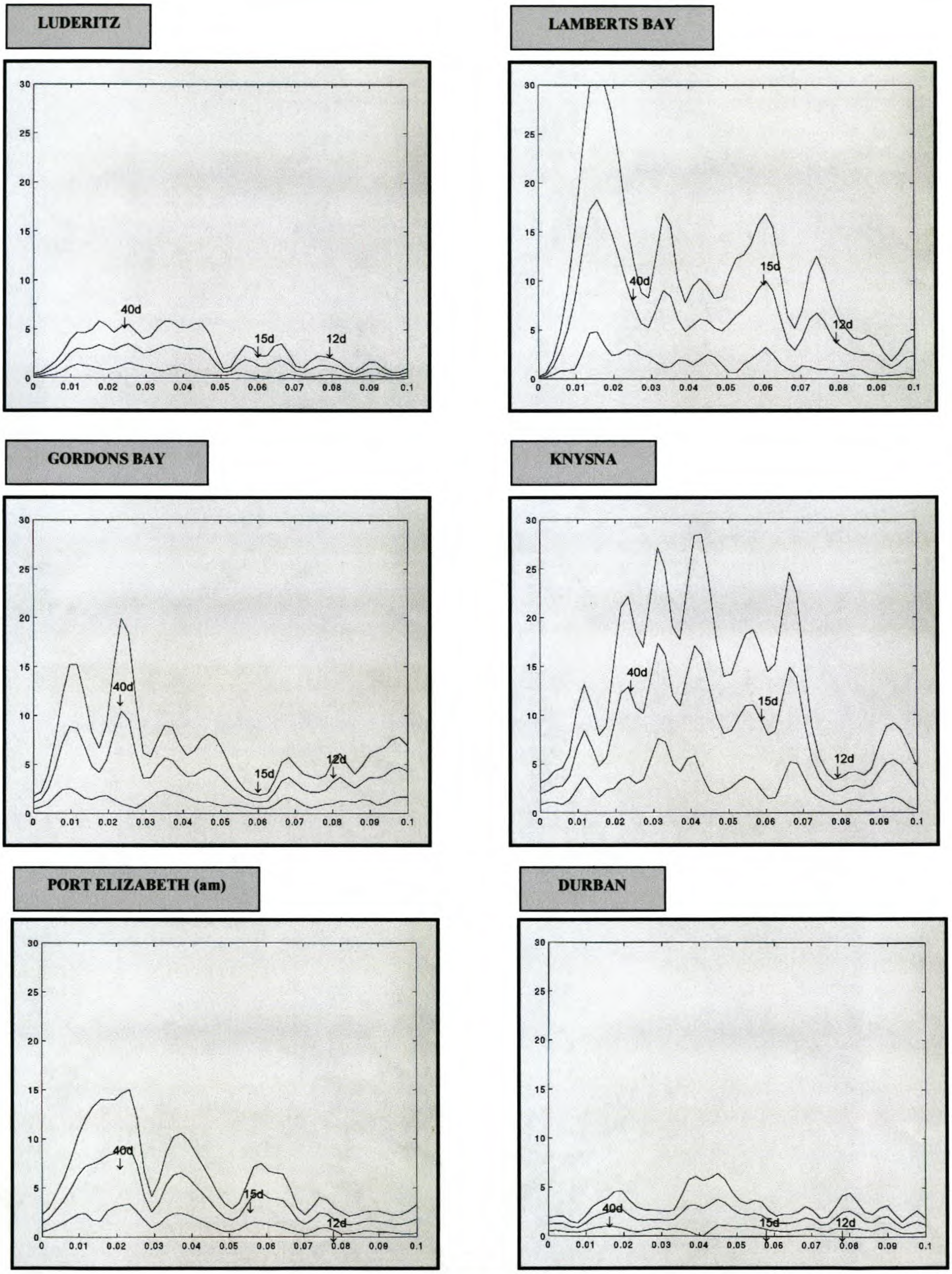
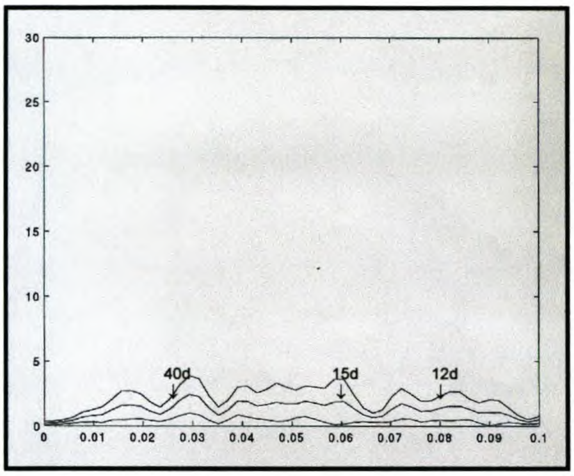
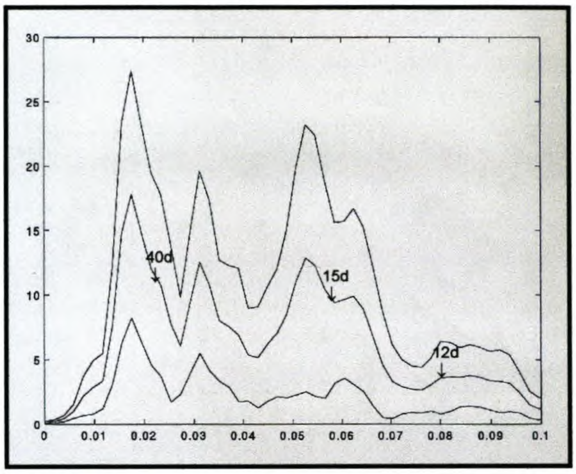


Fig.4.6 (a) – Power spectral density curves showing upper and lower 80% confidence limits for the data subset 1974-1979 - X-axis: cycles per day; Y-axis: (°C)^2 per cycle per day ;

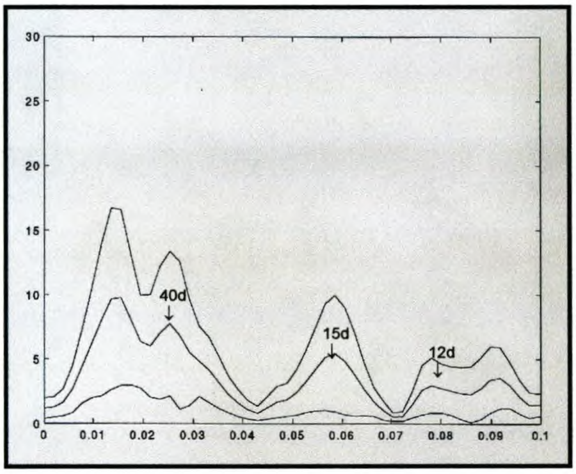
LUDERITZ



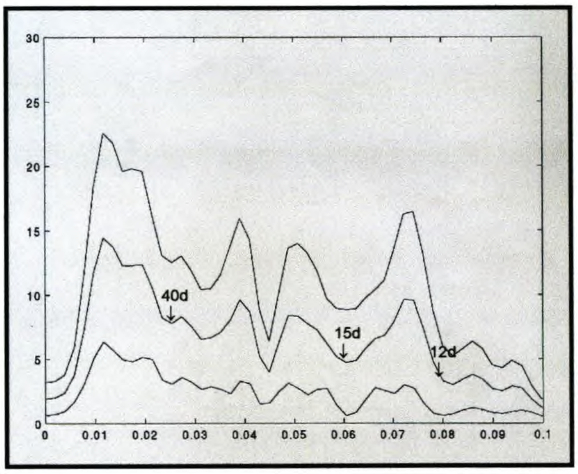
LAMBERTS BAY



GORDONS BAY



KNYSNA



PORT ELIZABETH (am)

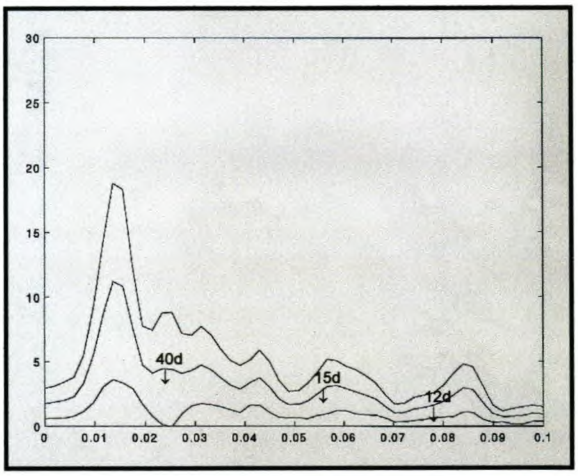


Fig.4.6 (b) – Power Spectral density curves showing upper and lower 80% confidence limits for the data subset 1980-1989 – X-axis: cycles per day; Y-axis: (°C)^2 per cycle per day

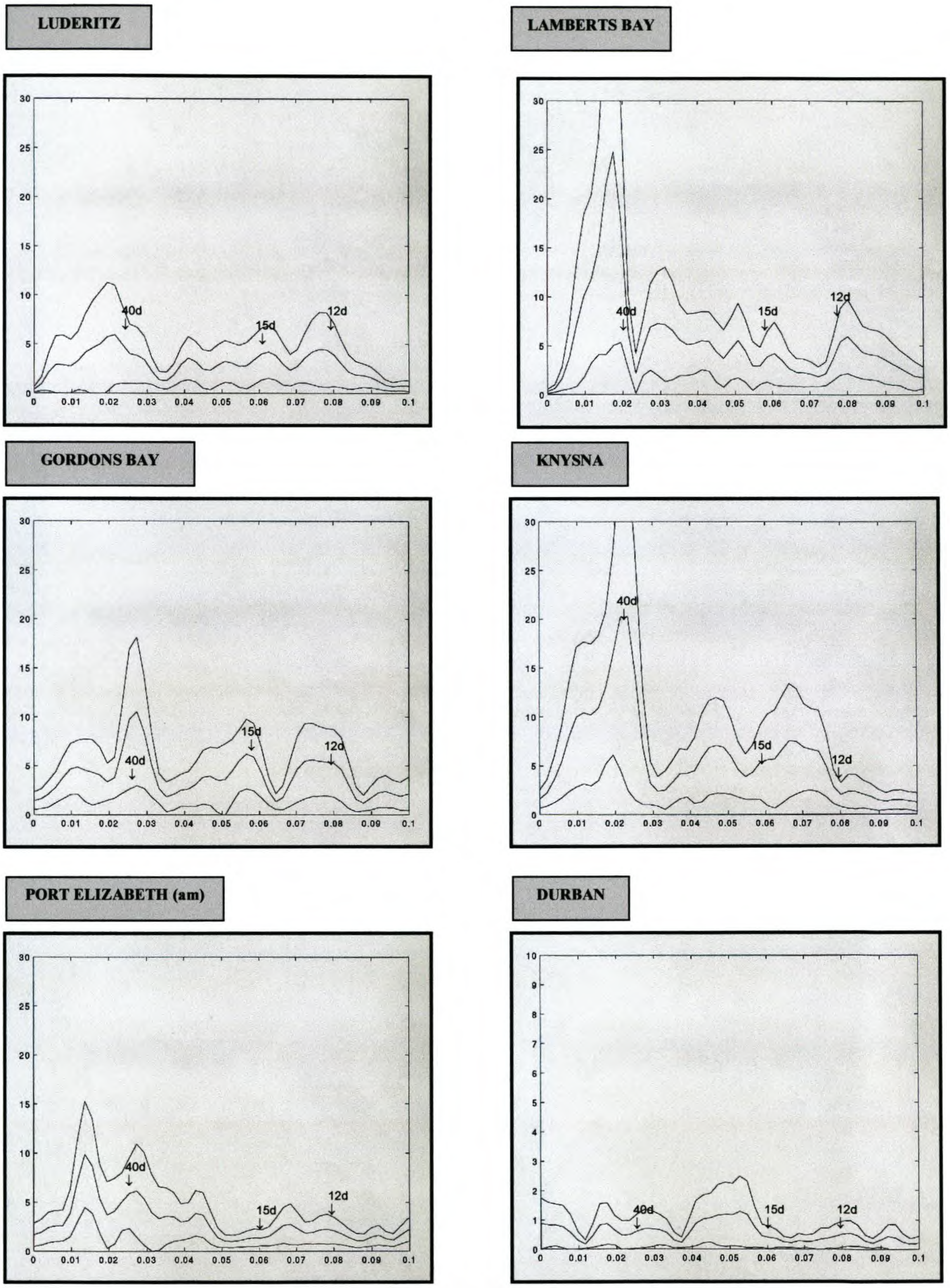


Fig4.6 (c) – Power Spectral density curves showing upper and lower 80% confidence limits for the data subset 1990 –1995 – X-axis: cycles per day; Y-axis: (°C)^2 per cycle per day

The intensity of the energy was measured by calculating the *rms* (see Chap. 3 section 3.6.3 (e)) value for the peaks at 40, 50 and 60days for the 40-60day signal and, 12, 13, 14 and 15days for the 12-15 day signal. The results are shown in Table 4.6.

Table 4.6 – ***rms*** values for the 12d,13d,14d and 15d peaks and, 40d, 50d and 60d peaks; d-days

	Luderitz	**Lamberts Bay**	**Gordons Bay**	**Knysna**	**Port Elizabeth**	**Durban**
12d	**0.01**	**0.02**	**0.01**	**0.01**	**0.01**	**0.01**
13d	**0.01**	**0.01**	**0.01**	**0.02**	**0.01**	**0.01**
14d	**0.01**	**0.01**	**0.01**	**0.02**	**0.01**	**0.01**
15d	**0.01**	**0.03**	**0.01**	**0.02**	**0.01**	**0.01**
40d	**0.01**	**0.03**	**0.03**	**0.05**	**0.02**	**0.01**
50d	**0.01**	**0.06**	**0.02**	**0.05**	**0.04**	**0.01**
60d	**0.01**	**0.08**	**0.02**	**0.04**	**0.03**	**0.01**

(a) 12-15day signal (high frequency)

This signal was particularly intense at Knysna (0,02 at 13d,14d and 15d) and Lamberts Bay (0,03 at 15d). However, Gordons Bay, Port Elizabeth, Luderitz and Durban the signal was less intense (0,01).

(b) 40-60day signal (low frequency)

This signal was particularly intense at Lamberts Bay (0,06 at 50d and 0,08 at 60d), Knysna (0,05 at 40d and 50d and 0,04 at 60d) and Port Elizabeth (0,04 at 50d). However, Luderitz and Durban the signal was less intense (0,01).

(c) High frequency versus low frequency

Except for Luderitz and Durban, there was a tendency for the intensity of the signals to increase from the high to the low frequency range. This was especially noticeable at Lamberts Bay and Knysna, where the increases in intensity were as high as 0,05 and 0,03 respectively. However, at Port Elizabeth (0.02) and Gordons Bay (0.01) the signal was less intense.

The greater intensities experienced in the low frequency range in comparison to those of the high frequency range at Lamberts Bay, Gordons Bay, Knysna and Port Elizabeth appear to be reflecting the differences between the absolute maximum and minimum SSTs experienced at each of these measuring sites.

(d) Spatial differences

Starting with Luderitz, and for both frequencies, the intensity alternated between an increase and a decrease in energy from one side of the Southern African Coast to the other, with Durban and Luderitz consistently experiencing the lowest intensities for both frequencies in comparison to the other five sites. This tends to suggest that the effects of the mechanism/s generating these signals and the resulting intensities were localised.

4.3.3 Discussion

A 40-50 day signal was found to be well documented by several authors and shown to exist in atmospheric and oceanographic data (Madden & Julian, 1972; Krishnamurti & Subrhmanyam, 1982; Anderson & Rosen, 1983; Rosen & Salstein, 1983, Madden, 1986; Dickey *et al*, 1991; Krishnamurti *et al*, 1992; van Ballegooyen, 1995).

Madden and Julian (1971, 1972) were the first to document a signal of this type in the atmosphere with respect to the behaviour of upper level winds at a number of tropical stations between 1957 and 1967 and, attributed it to a rather large (thousands of kilometers) circulation cell - similar to the Walker-type of circulation reported by Bjerknes (1969) - centered over the mid-Pacific.

Particularly interesting are the results produced by Krishnamurti *et al* (1988) on ocean fluxes of sensible and latent heat. These authors showed that the latent heat flux between 30 - 50 days could be as large as 10- 20 watts/m^2 which was about 5 - 10% of the total flux over the Pacific and Indian oceans. Furthermore, it was noted that wind and SST variations on this time scale were important contributors. Although the amplitude of the SST was only shown to be in the order of 0.9°C - 1°C on this time scale, the SST coupled with wind variations in the order of 3 - 5m/s contributed to significant latent heat fluxes of ~10 - 20 watts/m^2.

However, more locally, the approximate 40-60 day (low frequency) and 12-15 day (high frequency) signals have been identified to exist in oceanographic variables around the Southern African Coast by, for example, Jury *et al* (1990), Jury and Brundrit (1992) and van Ballegooyen (1995). All these authors attribute these signals, ultimately, to the influence of upper atmospheric Rossby waves in the mid-latitude westerlies on the shelf circulation, through coastal trapped waves in the atmosphere and ocean, which result in a pulsing of the physical environment (see below).

In general, the continental shelves are areas where a large number of physical phenomena occur with temporal scales of minutes to months and spatial scales of meters to thousands of kilometers (Huthnance 1975, 1981). Apart from these phenomena which all contribute to the variability of shelf waters, the greatest variability in many shelf regions, particularly those surrounding Southern Africa, is due to large scale wind-driven motions (van Ballegooyen, 1995). Several authors, for example, Jury *et al* (1990) and Nelson (1992a, 1992b), have shown how wind stresses over the West and South coast shelf regions produce energetic fluctuations at subinertial frequencies (although recently found to be significant in the wider shelf areas – R van Ballegooyen, CSIR, 2001, pers.comm) with the synoptic variability (2-20 days) being the most energetic. These subinertial motions may be characterised in terms of CTW (coastal trapped wave) theory (Brink, 1991; van Ballegooyen, 1995) which involves the relationship between the atmospheric pressure, sea level, wind stress and shelf topography. Schumann (1983) and van Ballegooyen (1995), for example, have indicated that wind stress is a prime generator of such trapped waves and consequently the periods involved correspond to those of the appropriate weather systems (Schumann, 1983).

By using sea level and atmospheric pressure data for the period 1980-1990, as part of a detailed study to analyse CTWs, van Ballegooyen (1995) identified the existence of an approximately 40-50 day and 10-15 day signal and, suggested that any observed CTW signal is generally a combination of a remotely or open-ocean forced and locally wind-driven response.

In the pressure-adjusted sea level data for 1985, large amplitude (10-15cm) low frequency sea level perturbations were found to propagate anticlockwise along the Southern African coastline from Walvis Bay to the East coast at approximately 2m/s particularly during autumn. Since there was no accompanying low frequency variability in the atmospheric pressures during this period it was suggested (van Ballegooyen, 1995) to have its origins near the equator. Also, particularly at that time of the year, there is often substantial movement of the Angolan Front and salinity intrusions into the Northern Benguela region (Boyd, 1987).

Thus, these 'remotely forced' CTW motions can travel several hundreds or even thousands of kilometres (in the case of low frequency CTWs) from remote sites to the area of concern and in so doing influence, for example, the upwelling dynamics in a local upwelling cell by imposing time-dependant boundary conditions on arrival.

Also, large amplitude (5-15cm), low frequency (40-60days) sea level perturbations, for the period 1985, were found to propagate clockwise along the coast from Durban to Port Elizabeth at approximately 20cm/s particularly during spring. This was suggested to be 'open-ocean' forced (van Ballegooyen, 1995) through the progression of a Natal Pulse (a large perturbation in the Agulhas Current) along the East Coast since, as mentioned in the previous paragraph, there was no accompanying low frequency variability in the atmospheric pressures during this period. Generally, these Natal Pulses cause strong reversals of the shelf circulation along the East Coast and their intensity varies with the size of each pulse (van Ballegooyen, 1995). Van Ballegooyen (1995) has tentatively indicated that there are about two large perturbations and a further number of smaller such perturbations each year.

Coastal trapped wave motions in the ocean along the Southern African Coast are mainly generated by rapid changes (strengthening, relaxation or reversals) in the direction of the wind, for example a sudden change in the predominant south or south-easterly alongshore winds associated with the SAH along the West Coast (van Ballegooyen, 1995). Generally, the coastal low, itself driven by the eastward movement of Rossby waves in the upper atmosphere, is responsible for these abrupt changes or reversals in the wind direction, while the one or more cyclones which may follow, determine the duration of this change in the wind direction in the southerly regions (ibid). The South Coast (Hunter, 1987, Jury *et al,* 1990b) experiences particularly rapid changes in wind direction and very strong wind conditions ('southwest buster") with the passing of coastal lows – the strongest southwest buster conditions experienced near Port Elizabeth.

Coastal lows, occurring at all times of the year (Reason & Jury, 1990), have been shown by several authors, for example Preston-Whyte and Tyson (1973), Kamstra (1987), Walker (1984) and the Coastal Low Workshop (1984), through spectral analysis of atmospheric pressure data, to have a high frequency signal of approximately 6-10 days. Jury *et al,* (1990a) and Jury and Brundrit (1992) have shown that pulsing events (upwelling/downwelling cycles) of >6 days can result in significant changes in SST – a range of 5°C being typical.

Although CTW motions in the ocean result in strong current fluctuations over the shelf in the high frequency range, the impact on environmental variables such as SST have been shown to be negligible (van Ballegooyen, 1995).

On the West Coast there is evidence of another open-ocean influence on shelf circulation – Agulhas rings. This appears to have a periodicity of approximately 40 days – Agulhas rings. Duncombe Rae (1991) and Duncombe Rae *et al* (1992) have described in detail the interaction of Agulhas rings with the shelf waters and suggest that if a ring moves more northwards than westwards from the retroflection, as a result of being steered by the topography of the West Coast shelf, it will probably affect the Benguela upwelling system. However, these rings have been shown (Lutjeharms & Gordon, 1987; Walker & Mey, 1988; Olson & Evans, 1986) to have high rates of heat loss. The effects would therefore be more confined to the lower atmosphere, where the additional source of heat would influence passing weather systems.

Apart from the effects of CTW events and open-ocean influences on the shelf circulation, another possible mechanism for producing the low frequency (40-60 day) signal in the data is based on the mathematical model according to Krishnamurti *et al* (1992) which involves air-sea interaction. Basically, solar heating enhances atmospheric convection which leads to increased surface winds, thereby enhancing the wind-induced mixing of the surface layer of the ocean. Mixing with the deeper cold water produces a drop in surface temperature, followed by a drop in convective activity, until solar heating restores the SST and convection starts once again. This process has been schematically represented in Figure 4.7.

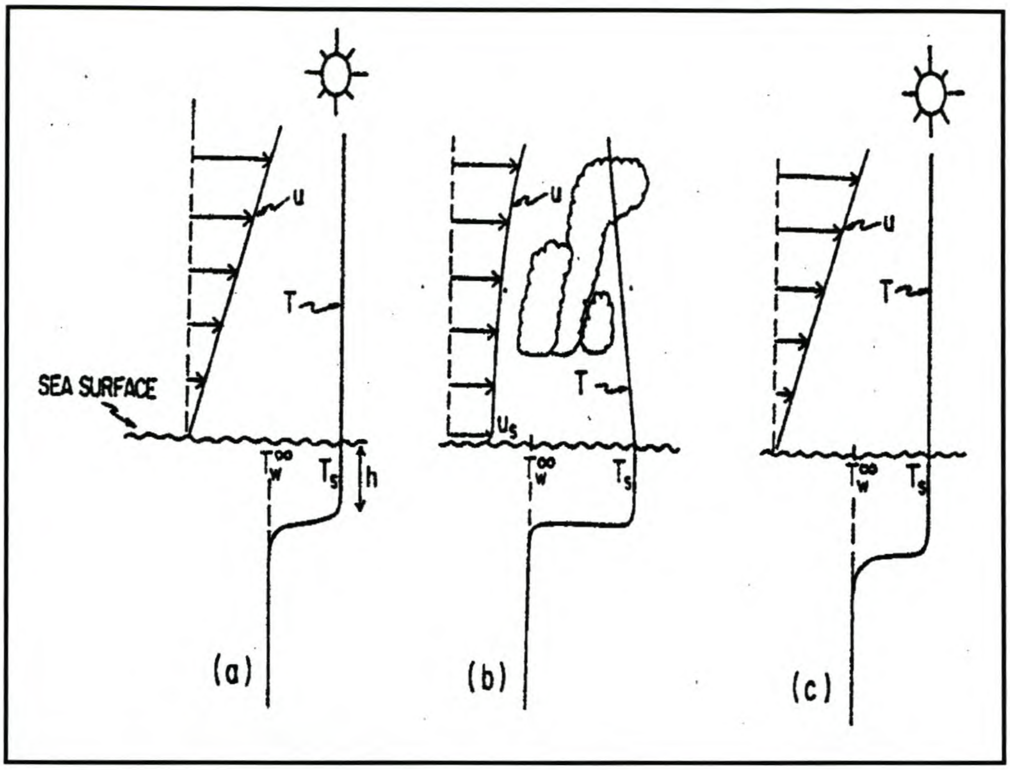


Fig. 4.7 – Three phases in one cycle of the low frequency oscillation – a, stable stratified atmosphere over an ocean with a warm mixed layer at temperature *Ts* and depth *h*, lying over cold deep water of temperature $T^{\infty}w$. Winds at the sea surface are weak; b, solar heating increases *Ts* leading to atmospheric convection with momentum transport and increased surface wind *Us*; c, increased *Us* deepens the mixed layer and lowered *Ts* by mixing with deep cold water. Solar heating of the sea surface will cause the cycle to repeat (after Krishnamurti *et al*, 1992)

The high and low frequency energy maxima experienced at Lamberts Bay and Knysna are consistent with the notion that shelf waters in these wider shelf regions respond more readily to changes in the wind parameter (van Ballegooyen, 1995). The noticeable low magnitudes at Durban for both frequencies are possibly attributed to the enhanced damping of CTWs due to the of the presence of the Agulhas Current as shown by van Ballegooyen (1995), and the negligible effects of the dissipated coastal low in this area.

4.3.3 Conclusion

In the low frequency (40-60 day signal) range three possible forcing mechanisms seem to present themselves: Firstly, the effects of CTW events by modifying vertical and horizontal circulation and correspondingly, the SST. Secondly, the effects of open-ocean influences on shelf circulation in the form of Agulhas rings (West Coast) and large perturbations in the Agulhas Current (East Coast) which cause strong reversals of the shelf circulation. Thirdly, the effects of air-sea interaction where the convection cycle results in the strengthening and weakening of the wind and a corresponding decrease or an increase in the SST.

However, in the high frequency range (12-15 day signal) only one possible forcing mechanism was identified i.e. the effects of the coastal low and the ensuing one or more cyclones. This results in a pulsing, or upwelling-downwelling cycles, of the environment by, for example, increasing upwelling-favourable winds over the shelf.

CHAPTER 5: SEA SURFACE TEMPERATURE ANOMALIES: CAUSES AND EFFECTS

Through the use of standard analytical techniques, variations in SSTs were identified around the Southern African Coast, and their possible causes discussed (see Chapter 4). In the present Chapter, a brief overview of the general causes of SST change is firstly presented to establish an understanding of how heat is lost and gained by the ocean.

The environmental effects of SST anomalies are illustrated with three case studies.

5.1 GENERAL CAUSES OF SST CHANGE

The nature and extent of SST characteristics at different localities depend on the net rate of heat transferred into or out of the water body in that region. Thus, the conservation of heat energy (or heat budget) is expressed as an equation in the form of (Laevastu, 1960; Pickard & Emery, 1982):

$$Q_T = Q_s + Q_p + Q_b + Q_e + Q_v + Q_h$$

where Q_T = total heat energy gained or lost by a body of water

Q_s = total incoming solar radiation

Q_p = heat transferred by precipitation

Q_b = total outgoing long wave radiation

Q_e = heat gained or lost by evaporation/condensation

Q_v = heat transported in or out of water body by currents (advection)

Q_h = net amount of heat transferred to the atmosphere by conduction across the air-sea interface

The following sections will briefly discuss these parameters and their effects on the heat budget.

5.1.1 Transfer of heat through insolation

The sun is the primary source of heat for the oceans (see Chap.2 section 2.1.1). However, only the top ~10m benefits from this direct warming effect since infra-red radiation is strongly absorbed by the water (Dring, 1986; Pickard & Emery, 1982). This upper 10m represents the near surface mixed layer and is the layer in which all SSTs, represented in the present study, were observed (Chap.3 section 3.1).

(a) Short-wave radiation (incoming energy) (Q_s)

An important aspect determining the amount of incoming radiation is the water-vapour content of the atmosphere (Pickard & Emery, 1982). Since the surface of the ocean is warmed by the amount of solar radiation it has been able to absorb, it can generally be said:

- that a calm sea on a clear and windless day will favour an increase in SST as the ability to absorb heat is at its greatest. Kindred (1985), showed these conditions could result in temperatures up to ~1m depth to be 5°-10°C higher than waters at 1-2m depth. Obviously the magnitude of the daily insolation on the ocean surface depends on the length of the day and the noon altitude of the sun;
- that a rough sea on a windy day will favour a decrease in SST due to vertical mixing of surface waters;
- that reduced amounts of insolation due to cloud cover, especially over a prolonged period, will also tend to favour a decrease in SST.

Laevastu (1960) showed how insolation decreased due to the increase of the relative humidity and the turbidity of the air. Laevastu also showed that when cloudiness was slight and scattered, insolation could be greater than if the sky were clear due to the reflection from the clouds. It has been suggested that insolation is less when clouds are at lower altitudes than at higher altitudes, even though they may be of the same type and amount (Drummond, 1958;

Laevastu, 1960). The passage of a cold front, for example, will reduce insolation because of the increased presence of cloud cover at lower altitudes and the higher relative humidity of the cold air immediately behind the front.

(b) Long-wave radiation (outgoing energy) (Q_b)

A small portion of the incoming radiation is re-radiated by the sea surface as long-wave radiation. The rate of the outgoing energy is determined by the temperature of the sea according to Stefan's Law namely at a rate proportional to the fourth power of their absolute temperature (Pickard & Emery, 1982). Cloud cover tends to reduce long-wave radiation, with thicker clouds,such as cumulus, being more effective than cirrus.

5.1.2 Transfer of heat through conduction (Q_h)

The amount of heat gained or lost by the sea surface through conduction is principally due to the presence of a temperature gradient in the air above the sea surface (Pickard & Emery, 1982). Heat is conducted away from the sea if the air temperature decreases upwards from the sea surface, and conducted down into the sea if the air temperature decreases downwards towards the sea (Pickard & Emery, 1982), as expressed in the following relation

$$Q_h = -C_p * K * dT/dZ$$

where: Q_h = heat conduction (rate of loss or gain of heat)

C_p = specific heat capacity of air at constant pressure

K = coefficient of heat conductivity

dT/dZ = temperature gradient of air

5.1.3 Transfer of heat through convection (Q_h / Q_e)

When air in contact with a warm sea is heated, it expands and rises taking the heat rapidly away with it in a process known as convection (Pickard & Emery, 1982). For the same temperature difference between sea and air, the rate of loss of heat when the sea is warmer is greater than the rate of gain when the sea is cooler.

5.1.4 Transfer of heat through evaporation (Q_e)

Water evaporation occurs as a result of a supply of heat from an outside source or, of heat being lost through some process - the latter being more common with respect to the sea (Pickard & Emery, 1982). Evaporation is greatest in the tropics as a result of the trade winds, lower near the equator where lower mean wind speeds are experienced and the seasonal heat input decreases due to greater mean cloud cover, and lowest in the cold polar regions (Pickard & Emery,1982). Factors affecting the removal of moisture saturated air above the sea surface -for example wind speed and thermal convection, and the water vapour deficit of the air above the water - determine the rate at which evaporation occurs (Laevastu, 1960). For example, where the air temperature is less than the SST, heat will be gained from the sea due to evaporation (Pickard & Emery, 1982). Wind speeds play an important role in determining the time it takes for temperatures to change. For example, winds at high speed will cause temperatures to change more rapidly (Laevastu, 1960), Mosby (1957) showed that temperatures change more rapidly in a warm wind than in a cold wind.

5.1.5 Transfer of heat through precipitation (Q_p)

The transfer of heat through precipitation only comes into effect if the quantity of rain and the difference between the temperature of the rain and the sea surface is large (Laevastu, 1960).

5.1.6 Transfer of heat through advection (Q_v)

As early as 1775 it was shown by Franklin that the distribution of currents and temperature are closely related.

Western Boundary Currents, such as the Agulhas Current (see Chap.2 section 2.2), play a vital role in the distribution of heat from the equator to the poles (Pinet, 1999). Warmer water advected inshore by such currents affect the SST measured in proximity of the beach. So, for example, higher SSTs are experienced on the East Coast than on the West Coast of Southern Africa (see Chap.4 section 4.3). The effect of the Agulhas Current on SSTs at the coast depends largely on the distance of the current from the coast, which in turn, is largely a function of the bottom topography, coastal shape and other effects.

5.2 IDENTIFICATION OF ANOMALOUS SST EVENTS

Firstly, monthly mean SSTs were calculated for each year using all the available day-to-day data within the three coastal regions. It was then decided to calculate the 95% confidence limits (see Chap.3 section 3.6.3 (c)) of these mean SSTs for each year and season for the three coastal regions as shown in Figure 4.4.1 – 4.4.3. These were then used to identify, for each year and season for the three coastal regions, day-to-day SSTs lying outside of the confidence intervals. This resulted in a number of SST departures of which the absolute maxima and minima are shown in Figures 5.1.1 - 5.1.3. It is these absolute maximum and minimum SSTs that were defined as consituting anomalous events. However, what was established during the process was that an anomalous event could occur instantaneously or gradually over a period of time. Thus, an anomalous event that was identified could either be a single departure or, a series of departures.

The magnitude of change for either a warm or cold anomalous event was calculated, within the predefined time periods and regions, as follows:

$$\Delta tw = SST_{\mathbf{abs\ max}} - \textit{upper 95\% confidence limit}$$

$$\Delta tc = SST_{\mathbf{abs\ min}} - \textit{lower 95\% confidence limit}$$

where $SST_{\mathbf{abs\ max}}$ = absolute maximim SST as shown in Figure 4.4.1 – 4.4.3

$SST_{\mathbf{abs\ min}}$ = absolute maximim SST as shown in Figure 4.4.1 – 4.4.3

upper 95% confidence limit = upper limit as shown in Figure 5.1.1 – 5.1.3

lower 95% confidence limit = lower limit as shown in Figure 5.1.1 – 5.1.3

Δtw = positive change in SST (warm)

Δtc = negative change in SST (cool)

5.2.1 Annual anomalous events

(a) Identification

These events were identified for each year as described on page 97 using Figure 4.4.1(a), 4.4.2(a) and 4.4.3(a), and Figure 5.1.1(a), 5.1.2(a) and 5.1.3(a). The magnitudes of change were calculated as described above and the years where Δtw and Δtc were found to have peaked, are shown in Table 5.1. Anomalously warm and cold events appeared to have peaked, respectively, approximately every 3,6 years and 4 years on the West Coast, every 2,5 years and 3,6 years on the South Coast and, every 3,5 years and 4,5 years on the East Coast.

Table 5.1 - Periods when Δ*tw* and Δ*tc* peaked around the Southern African Coast (°C).

	WEST COAST		SOUTH COAST		EAST COAST	
Year	***Δtw***	***Δtc***	***Δtw***	***Δtc***	***Δtw***	***Δtc***
73	10,5					
74				-6,3	6,8	-5,7
75			6,8			
76		-5,3			6,9	
77				-6,7		
78	8,6					
79		-5	7,3			-8,9
80					7,3	
81	9,7					
82			8,2			
83	8,6					
84		-4,4				-8
85				-6,3		
86			7,3		6,7	
87			7,2			
88	9,7		7,3	-7,2	6,9	
89						-9,2
90		-4,8	7,3	-6,9		
91						
92	9,3	-4,9		-6,9		-7,8

(b) Discussion

Generally, the anomalous events represented by the absolute maxima and minima in Figure 5.1.1(a), 5.1.2(a) and 5.1.3(a) tend to suggest that when these events occur, anomalously warm events are warmer on the West Coast with Δ*tw* ranging between 7,2°C and 10,5°C (as opposed to between 5,5°C and 8,2°C on the South Coast and between 5°C and 7,3°C on the East Coast), and anomalously cooler events are cooler on the East Coast with Δ*tc* ranging between –9,2°C and –4,1°C (as opposed to between –7,2°C and –4,4°C on the South Coast and between –5,0°C and –3,1°C on the West Coast).

Table 5.1 suggests that peaking alternated between anomalously warmer and cooler events on the West and East Coasts approximately every 4 years and on the South Coast approximately every 3 years. Thus these events appear to have been triggered by a cyclical phenomena on a more global scale, for example, ENSO. However, simultaneous peaking of anomalously warmer events between the three regions was only experienced in 1988, and of anomalously cooler events in 1992. Peaking of anomalously warmer and cooler events coincided on the West Coast during 1992, on the South Coast during 1988 and 1990 and, on the East Coast during 1974. This tends to suggest that these events were triggered by more than one mechanism on either a global and/or a regional scale.

It was assumed that ENSO (see Appendix C), triggered the anomalously warm events experienced on the West Coast during 1973, 1983, 1988 and 1992 and, on the South Coast in 1982 and 1987/88 – as shown in Table 5.1, since they correlated closely with ENSO events identified by Philander (1983), Walker *et al* (1984); Shannon *et al* (1990) and Schumann *et al* (1995).

During ENSO events on the South Coast an increase in the frequency of the westerly wind component is experienced and the frequency of the upwelling-favourable easterly wind component is interrupted with the result that coastal SSTs correspondingly increase (Schumann *et al* 1995). On the West Coast as a result of the northward shift of the westerly wind component SSTs correspondingly increase (Gillooly & Walker, 1984).

According to SAWS surface weather maps for the summers of 1979/80 - 1982/83, the effects of high pressure cells at the Cape Peninsula were weak during the summer of 1982/83 (Nelson and Walker, 1984) and eastward moving lows were more frequent (Walker *et al*, 1984) thus resulting in a predominantly westerly wind regime with correspondingly higher SSTs being experienced. Similar deviations in the wind regime during the warm event of 1976/77 were described by Bain and Harris (1977). Gillooly and Walker (1984) showed that for the summers of 1976/77 and 1982/83 the Subtropical Convergence Zone was displaced northwards thereby indicating an increased frequency of cold fronts at the tip of South Africa and a northward shift in the position of the SAH. It is interesting to note that in the 1982/83 summer period Hondeklip Bay (north of Cape Columbine) was shown by Nelson and Walker (1984) to experience a greater than average frequency of SE winds. This would imply that the 1982/83 warm event, in particular, was limited to the SW part of the West Coast region. Studies on the Southern Benguela warm event of 1982-1983 by Boyd & Agenbag (1984) and Walker, Taunton-Clark & Pugh (1984) suggest that the Northern and Southern Benguela regions are affected differently.

Since the West Coast region was defined as one region consisting of measuring sites from the Northern and Southern Benguela regions (see Chap.3 section 3.6.1), Benguela Ninos (see Appendix C) could not justifiably be identified. However, during a Benguela Nino both the Northern and the Southern Benguela regions are initially triggered by a switch in the normal wind patterns during the summer months, resulting in the advection of warmer waters into the respective regions - in the southern Benguela warmer water is advected eastwards from the surface thermal front adjacent to the region and in the northern Benguela, water is advected southwards from the Angola-Benguela front located north of the region.

On the other hand, La Nina, was assumed to be the mechanism triggering the anomalously lower SST events experienced on the South Coast, as shown in Table 5.1, since they correlated closely with La Nina events identified by Schumann *et al* (1995). During La Nina events there is a tendency for upwelling favourable winds to persist on the South Coast.

On the East Coast anomalously warmer and cooler SST events appeared to correlate closely to the variability of rainfall over South Africa (Walker, 1990). Where anomalously higher SSTs occurred, wetter years over the summer rainfall region of South Africa were found to coincided and, *vice versa* for anomalously cooler SSTs. Anomalously warmer SSTs throughout most of the Agulhas Current system and the Mocambique Channel are associated with wet conditions (ibid), as a result of anomalously high sensible and latent heat fluxes and, *vice versa* during dry conditions.

(c) Conclusion

It is evident, that anomalously warmer events experienced on the West and South Coasts are triggered by ENSO, which causes a shift in the normal wind patterns resulting in the advection of warmer waters into the respective regions. Also, that anomalously cooler events experienced on the west and south coasts are triggered by La Nina, which results in the intensification of upwelling in the respective regions. These anomalously warmer and cooler events appear to alternate approximately every four years on the West Coast and approximately every three years on the South Coast.

On the East Coast it is evident that anomalously warmer and cooler events are triggered by perturbations in the Agulhas Current system, and appear to alternate between anomalously warmer and cooler events approximately every four years.

5.2.2 Seasonal Anomalous events

(a) Identification

These events were identified for each season as described on page 101 using Figure 4.4.1(b)-4.4.1(e), 4.4.2(b)-4.4.2(e) and 4.4.3(b)-4.4.3(e), and Figure 5.1.1(b)-5.1.1(e), 5.1.2(b)-5.1.2(e) and 5.1.3(b)-5.1.3(e). The magnitudes of change were calculated for each season as defined on page 70 and where Δtw and Δtc were found to have peaked, are shown Tables 5.2 – 5.4.

Table 5.2 - Seasonal periods where Δtw and Δtc peaked on the west coast (°C).

	WEST COAST							
	SUMMER		AUTUMN		WINTER		SPRING	
Year	Δtw	Δtc	Δtw	Δtc	Δtw	Δtc	Δtw	Δtc
73	7,9				6,6			
76		-5,5		-4,6		-4,1		-3,7
78			6,6		6,6			
79				-4,6				
81			7,9					
83	7,4							
86					3.3			
88	7,9		7,7					
90						-3,9		
91	7,7							
92	7,7	-5,1		-4,3	6,2			-4

Table 5.3 - Seasonal periods where Δtw and Δtc peaked on the south coast (°C).

	SOUTH COAST							
	SUMMER		AUTUMN		WINTER		SPRING	
Year	Δtw	Δtc	Δtw	Δtc	Δtw	Δtc	Δtw	Δtc
75					-5,1			
77		-9,5		-6,7		-3,5		
82	4,9		5,6				5,5	
83							5,1	
85								-5,2
86	4,8							
88			5,9	-6,4			6,5	
90	4,4							-6,7
92		-9,4		-6		-3,9		

Table 5.4 - Seasonal periods where Δtw and Δtc peaked on the east coast (°C).

	EAST COAST							
	SUMMER		AUTUMN		WINTER		SPRING	
Year	Δtw	Δtc	Δtw	Δtc	Δtw	Δtc	Δtw	Δtc
74	6,8					-4,4		
76			6,9					
78					4,2		4,5	
79		-9,6		-5,8	4,3	-6,9		
80			5,7				4,6	
85							4,6	
86	4,8						4,7	
88	4,8							
89								-8,3
92		-8,3		-5,9				

(b) Discussion

Clearly, over the years, anomalously warm events appear to have peaked mainly during summer on the west and south coasts and during spring on the south and east coasts. Anomalously cooler events appear to have peaked mainly during autumn throughout the three coastal regions. Generally, Table 5.2 – 5.4 tends to imply that anomalously warmer events are warmer during summer and autumn on the west and east coasts (up to 7,9°C on the west coast and up to 6,9°C on the east coast), and anomalously cooler events are cooler during summer on the south and east coasts (up to –9,5°C on the south coast and up to –9,6°C on the east coast).

Of interest, is the occurrence of an inter-seasonal peaking of anomalously warmer and cooler events during winter on the east coast. This situation can arise on the East Coast as a result of the perennial easterly moving coastal lows, which, on approach cause the prevailing NE winds in this region to accelerate, with the Agulhas Current responding by moving further offshore. After the low has passed through, atmospheric pressure increases and the wind changes to an upwelling-favourable southwester (see Chap.2 section 2.5 (c)) with correspondingly cooler coastal SSTs being experienced. However, as a result of this change in wind direction eddies are sometimes generated in the surface water over the shelf and correspondingly warmer coastal SSTs being be experienced (see Chap.2 section 2.2 (c)).

Table 5.2 - 5.4 shows that, intra-annual peaking of anomalously warmer events occurred during 1973, 1978 and 1992 on the West Coast; during 1982 and 1988 on the South Coast, and in 1978, 1980 and 1986 on the East Coast. Also, intra-annual peaking of anomalously cooler events occurred during 1976 and 1992 on the West Coast, during 1977, 1979 and 1992 on the south coast, and 1979 and 1992 on the east coast. Inter-annual peaking of anomalously warmer events appeared to have occurred, particularly, during the summers of 1991-92 on the West Coast, in the springs of 1982-83 on the South coast and 1985-86 on the East Coast, and of anomalously cooler events in the winters of 1978-79 on the East Coast.

Except for the summer of 1986 and 1991 on the west coast, the spring of 1983 and 1985 on the south and east coasts respectively, and the winters of 1978 and 1979 on the east coast, the periods where Δ*tw* and Δ*tc* were shown to peak in Tables 5.2 – 5.4 coincided with those shown in Table 5.1 (section 5.2.1). It was therefore assumed that the trigger mechanisms of the events shown in Table 5.2 – 5.4 were the same as those identified and discussed in section 5.2.1 (b) for the events presented in Table 5.1. However, other more localized trigger mechanisms were considered for, for example, the anomalously warm event experienced on the west coast during the winter of 1986.

This particular anomalously warm event on the west Coast was found to correlate closely to a major perturbation in the retroflection of the Agulhas Current identified by Shannon *et al* (1990), and was presumed to be the mechanism triggering this particular event. However, this significant disturbance in the Agulhas retroflection started towards the end of 1985 and early 1986 (ibid). It was attributed to the abrupt moderation of the Indian Ocean trades and the westerlies south of Africa after August 1985 (see Figure 5.2), which then lead to a southward displacement of the zero wind stress curl and a decrease in the volume transport of the Agulhas - the Agulhas Retroflection being sensitive to the volume transport of the Agulhas Current. Figure 5.3 illustrates the pattern of this abnormal intrusion of Agulhas Current water along the west coast of South Africa which reached its maximum in the winter of 1986.

The anomalously warmest event was experienced on 02/01/1973 (25,5°C; Δ*tw* = 7,9°C) during summer on the west coast, on 08/01/1982 (27,0°C; Δ*tw* = 4,9°C) in summer on the south coast, and on 05/04/1980 (27,5°C; Δ*tw* = 6.9°C) during autumn on the east coast. The anomalously coolest event was experienced on 22/06/1976 (9,0°C; Δ*tc* = -4,1°C) during winter on the west coast, on 10/03/1988 (10,5°C; Δ*tc* = -6,7°C) in autumn on the south coast, and on 06/09/1989 (10,0°C; Δ*tc* = -8,3°C) during spring on the east coast.

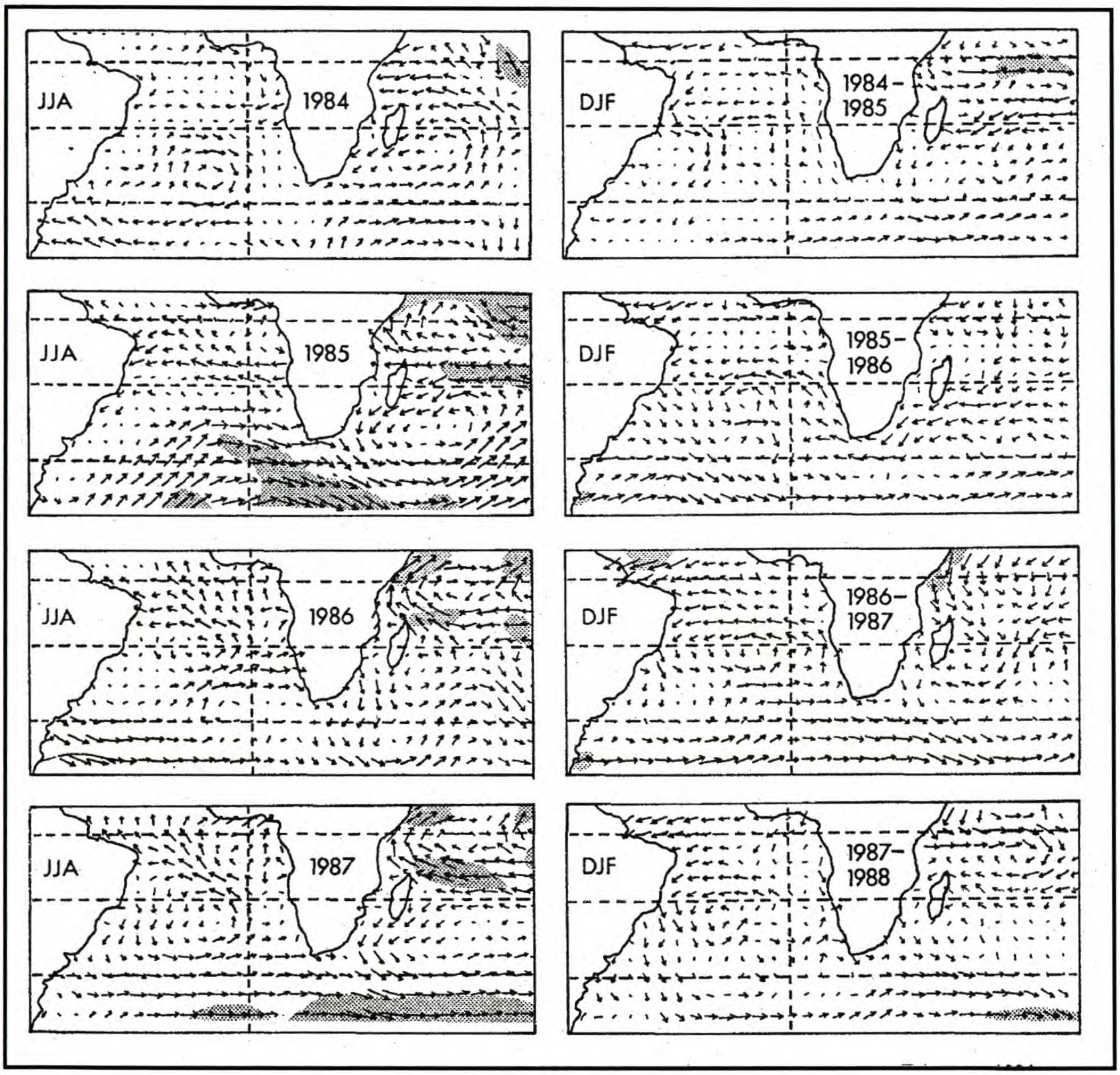


Fig.5.2 – Seasonal 850mb vector wind anomalies; vector length of 5° longitude represents wind speed anomaly of 3,1m/s. Areas where speed exceeds 5m/s are shaded (after Shannon *et al*, 1990)

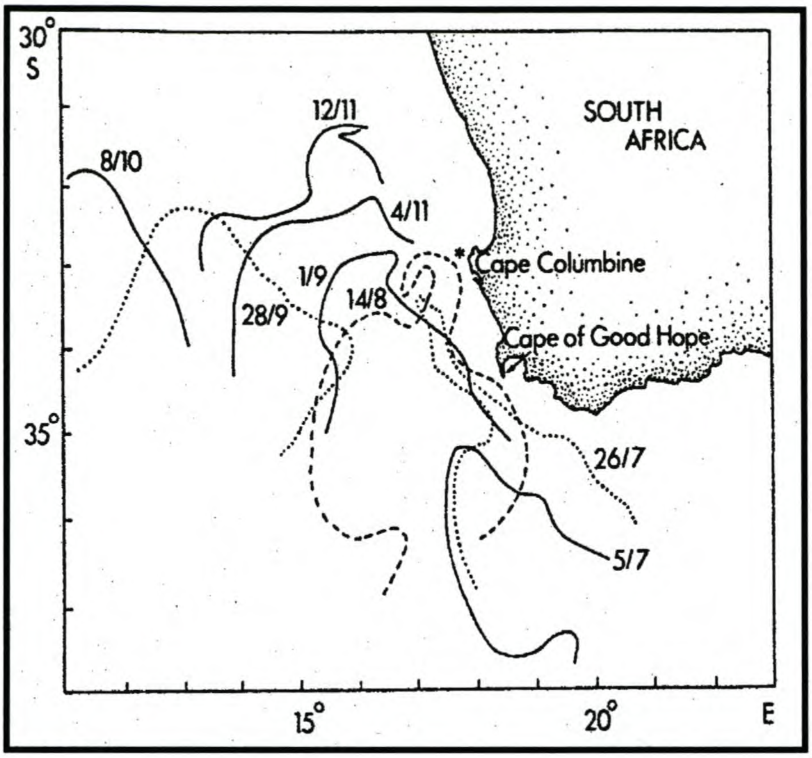


Fig.5.3 – Pattern of abnormal AC intrusion during winter 1986 (after Shannon *et al* 1990)

(c) Conclusion

It is apparent that a peaking of anomalously warm events can be expected during summer on the west coast and during spring on the east coast. However, on the south coast a peaking of anomalously warm events can be expected in both summer and spring. Also apparent, is that a peaking of anomalously cold events can be expected in all three regions during autumn. Since most of these anomalous events were identified to coincide with those events shown in section 5.2.1, it was presumed that the events in this section were triggered by the same mechanisms as those discussed in section 5.2.1 (b).

However, the variability of the Agulhas Current and its retroflection was found to also contribute to the triggering of anomalously warm events on the west coast in particular. On the East Coast, inter-seasonal anomalously warm and cool events were found to be triggered, in particular, by the effects of coastal lows on the prevailing winds, and the influence of the Agulhas Current.

5.3 PROBABILITY OF OCCURRENCE

In Table 4.5 (see Chap.4, section 4.2.3) it was shown that at most of the measuring sites around the southern African coast, several occasionally large increases and decreases in SST from one day to the next were experienced during a particular month. These instantaneous large SST changes are of major concern because of their devastating effects on marine life and economic activities related to the marine environment (see Chapter 6). However anomalous these changes may be, the question of their probability of occurrence arises.

Probabilities of the day-to-day changes in SST were calculated using the method shown in Chapter 3 (section 3.6.3(d)).

Table 5.5 shows the probabilities of a day-to-day change in SST for the three regions and indicates that on average, overall, there is a 70% probability that a change of at least 1°C, or -1°C, can occur anywhere along the southern African coast from one day to the next. Having already established the significance of the variability of the wind component in initiating a day-to-day change in SST (see Chap.4 section 4.3.3), these results are to be expected. However, this also tends to suggest that the measurements made by the observers at the different measuring sites around the southern African Coast were accurate.

On average, the probability of a day-to-day change in SST of >3°C (+3°C or -3°C) anywhere around the southern African coast appears to be ≤1.1% for any particular month. Although euryhaline marine species, for example Salmon, can tolerate a day-to-day increase or decrease in SST of up to 6°C (Landau, 1992), most fish species (Dr. L. Fernhead, Two Oceans Aquarium, 2001 pers.comm) and marine plants (Dring, 1986) can only tolerate a change of up to 3°C.

Therefore, day-to-day changes in SST >3°C (+3°C or -3°C) are regarded as anomalous and appear to have a higher probability of occurrence during summer on the west and south coasts.

The probability of no day-to-day SST change is lowest for all three regions during summer (25.4% - West Coast, 25.9% - South Coast and 28.2% - East Coast) than in winter (33.8% - West Coast, 32.3% - South Coast and 33.2% - East Coast). Thus, for all three regions, the probability of an increase or a decrease in SST is higher in summer than in winter when stormy conditions are more prevalent and, as a result the water is less stratified (see Chap.4 section 4.2.3).

Table 5.5 – The probabilities (%) of a day-to-day change in a particular SST (°C) for the three coastal regions

WEST COAST

SST	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
-6	0	0.025	0.008	0	0	0	0	0	0	0	0	0.017
-5	0.123	0.2	0.108	0.054	0	0.008	0	0.015	0.008	0.015	0.038	0.2
-4	0.757	1.121	0.793	0.436	0.129	0.093	0.029	0.193	0.1	0.214	0.471	1.057
-3	3.529	4.379	3.757	2.564	1.886	1.271	1.029	1.457	1.036	2.05	3.064	4.157
-2	10.85	11.414	11.043	9.779	9.621	8.357	7.271	7.929	7.979	9.35	10.486	11.057
-1	21.207	20.2	21.071	22.214	23.464	23.636	24.421	23.429	23.607	22.514	21.386	20.114
0	**26.486**	**24.657**	**26.486**	**29.621**	**30.9**	**33.471**	**35.1**	**33.014**	**33.357**	**30.45**	**27.479**	**25.1**
1	21.35	20.743	21.657	22.986	22.886	24.064	23.707	23.921	24.143	23.436	22.264	21.286
2	11.114	11.771	11.079	9.95	9.193	7.843	7.379	8.6	8.464	9.829	11.036	11.914
3	3.7	4.343	3.343	2.193	1.779	1.157	0.979	1.25	1.179	1.986	3.186	4.164
4	0.838	1.092	0.638	0.254	0.169	0.146	0.1	0.146	0.1	0.192	0.585	0.892
5	0.118	0.2	0.091	0.027	0	0.009	0	0.018	0.009	0.009	0.091	0.127
6	0	0.009	0	0	0	0	0	0	0	0	0	0.009

SOUTH COAST

SST	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
-6	0.06	0.12	0.08	0.02	0	0	0	0	0	0	0	0.06
-5	0.283	0.433	0.367	0.217	0.017	0	0	0	0	0	0.033	0.267
-4	1.1	1.386	1.257	0.8	0.186	0.071	0.057	0.1	0	0.086	0.4	1.014
-3	3.671	4.371	4.229	3.314	1.8	1.514	1.257	1.386	0.529	1.4	2.786	3.714
-2	10.371	10.857	10.943	10.586	9.343	9.314	8.486	8.657	5.386	8.386	10.229	10.429
-1	20.829	19.986	20.171	21.814	23.557	23.757	23.614	23.386	24.814	22.914	21.657	20.129
0	**26.643**	**25.343**	**25.414**	**27.614**	**31.586**	**31.657**	**33.114**	**32.243**	**36.829**	**32.471**	**28.129**	**25.843**
1	21.143	21.014	21.257	21.429	23.143	23.286	24.257	23.871	24.471	24.514	22.643	21.643
2	10.657	11.1	11.457	10.286	8.729	8.829	8.314	8.929	7.343	9.057	10.9	11.529
3	3.814	3.943	3.814	3.186	1.457	1.4	0.857	1.343	0.657	1.171	2.9	4.029
4	1.35	1.367	1	0.783	0.233	0.133	0.083	0.067	0	0.05	0.45	1.3
5	0.38	0.4	0.26	0.1	0	0.02	0	0	0	0	0.06	0.28
6	0.04	0.06	0.04	0	0	0	0	0	0	0	0	0.04

Table 5.5 (continued)– The probabilities (%) of a day-to-day change ina particular SST (°C) for the three coastal regions

	EAST COAST											
SST	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**
-6	0	0.05	0	0	0	0	0	0	0	0	0	0
-5	0.1	0.2	0.1	0.133	0	0.133	0	0	0.1	0	0	0.1
-4	0.575	0.75	0.8	0.75	0.2	0.55	0.075	0.1	0.575	0.025	0.2	0.575
-3	2.825	3.325	4	3.575	2.5	2.75	1.125	1.55	2.8	0.975	2.6	3.225
-2	9.4	10.4	11.475	10.85	10.225	8.525	8.675	7.375	9.475	6.675	10.775	10.6
-1	21.05	21.125	20.95	21.15	22.5	22.35	24.2	23.475	21.625	24.975	22.575	21.375
0	**30.25**	**27.225**	**25.525**	**26.85**	**29.45**	**32.125**	**32.725**	**34.925**	**30.475**	**35.025**	**28.05**	**27.225**
1	24.575	22.225	20.9	21.875	23.025	21.875	23.325	23.4	22.8	23.425	21.825	22.125
2	8.35	11.1	11.325	11.025	9.925	8.1	8.525	7.475	8.15	7.725	10.6	11.15
3	2.5	3.2	3.95	3.225	2	2.8	1.35	1.575	2.9	1.05	2.975	3.2
4	0.4	0.5	0.9	0.525	0.225	0.65	0.075	0.1	0.8	0.125	0.4	0.4
5	0.025	0.05	0.15	0.075	0	0.125	0	0	0.2	0	0	0
6	0	0	0	0	0	0.033	0	0	0.067	0	0	0

5.4 CASE STUDIES

The variation of SSTs in the three coastal regions have been shown in Chapter 4 and Chapter 5 to reflect the variations of some of the oceanic and meteorological systems that characterise these regions. However, there are occasions when variations in SST are caused by even more localised phenomena. The following case studies attempt to illustrate these localised effects.

This configuration, however, does not modify the coastline in any way. The coastline from Walvis Bay to Cape Cross is shaped in a west-facing arc. As is the situation off the Orange River, the spreading of the continental shelf in this region is also most pronounced (ibid).

(b) Meteorology

Boyd (1987) has provided a detailed study of the diurnal and seasonal wind regime along the Namibian coast. Generally, the diurnal variation of coastal winds includes the strengthening of southerly to SW components in the afternoon and evening and the incidence of light northerly winds in the early morning.

In most months northerly winds have a westerly component, but in June and July (i.e. mid winter) an intense east to northeasterly component (or Berg wind) develops (Boyd & Agenbag, 1984). In summer and early autumn (i.e. December - March) a general strengthening in westerly winds is experienced as well as a high percentage of calms. Wind speeds are often over 10 m/s per hour with southerly winds being more dominant. Generally, winds at Walvis Bay are predominantly longshore (Boyd, 1987).

(c) Data

The longterm monthly means as well as the smoothed SST values are indicated in Figure 5.5. Smoothing was done by way of a simple 7 point running mean. Gaps in the series reveal missing data.

Figure 5.5 shows that in Walvis Bay maximum temperatures occur during summer due to increased insolation (see section 5.1.1) as a result of the local summer wind pattern described above. In comparison with the other measuring sites in the West Coast region during summer, Walvis Bay is situated in an area of minimum upwelling (Boyd, 1987), resulting in an unreliable supply of nutrients. From what has been shown by Boyd (1987), upwelling in summer at Walvis

Bay is mainly retarded due to strong insolation coinciding with weaker equatorward winds and an inflated onshore component. These factors result in the setting up of permanent stratification which impedes the amount of water moved offshore. Minimum temperatures are shown in Figure 5.5 to occur during winter, coinciding with minimum insolation and maximum in upwelling winds. However, there does appear to be an absence of seasonality in upwelling at Walvis Bay when compared to other measuring sites on the West Coast (*sensu* Shannon (1985)).

Two warm events (1974 and 1984) and two cool events (1976 and 1985) occurred. The 1984 warm event has already been established as a major Benguela Nino event, resulting from a significant intrusion of tropical saline water from the north into the shelf zone off northern and central Namibia.

Its effects on the marine environment in this area are evident in the transitory collapse of the Anchovy stock from 1984-1986 (Boyd *et al*, 1985; Le Clus, 1986 and Boyd, 1987). The resulting nutrient conditions and low productivity levels during 1984 were similar to that of 1963 (Stander & De Decker, 1969) - also characteristic of the Pacific event. Although not as dramatic, Pilchard stocks were affected by the cool event of 1985 (Le Clus, 1986).

microscopic plants which secrete an external casing of silica. Due to their high specific growth rate they survive well where nutrient availability is unreliable. Upon death these skeletons accumulate on the sea floor to form a siliceous ooze which is commonly referred to as diatomaceous ooze (Copenhagen, 1953b; Rodgers & Bremner, 1991). Eventually, the dissolved oxygen diminishes, sulphate-reducing micro-organisms prosper and the production of H_2S ensues (Copenhagen, 1953a,b). If these conditions remain undisturbed the production of H_2S increases, thereby further diminishing dissolved oxygen levels in the lower layers of the water column (Copenhagen, 1953a).

This diatomaceous ooze amidst a 'bubbling sea' (Copenhagen, 1953a, De Wit, Fisheries Inspector: Walvis Bay Harbour, 1992, pers. comm), frequently appears at the surface in the form of an island ~100 m long (Copenhagen, 1953a,b, De Wit, Fisheries Inspector: Walvis Bay Harbour, 1992 pers. comm). These large areas of mud seen at the surface are forced up by the H_2S to a height of approximately 5-10 m above the surface of the sea (Copenhagen, 1953b; Rodgers and Bremner, 1991) and, after approximately 1-4 hours subside beneath the waves again (ibid; De Wit, Fisheries Inspector: Walvis Bay Harbour, 1992 pers. comm). It is of interest to note that Copenhagen (1953a) documented an individual who swam out to one of these islands as saying: 'the water around the island is very cold'.

At the start of 1992 it was decided by the author, in agreement with the volunteer observing the SST, that it would be an interesting exercise to monitor H_2S eruptions in conjunction with SSTs to determine if any relationship existed. The volunteer observer was advised to observe any H_2S eruptions at the same time the SST was measured.

The results have been summarized in Table 5.6 and indicate that for 50% of the occasions H_2S eruptions were observed, the day-to-day change in SST was between –3,2°C and -1°C. The prevailing meteorological conditions (see Table 5.6) suggest that the near gale force southerly winds could have contributed significantly to any upwelling observed, nevertheless another theory is also considered plausible which may have contributed to the decrease in SST.

(e) Conclusion

The results shown above tend to indicate that the H_2S eruptions could have contributed to the decrease in the day-to-day SSTs experienced at Walvis Bay on the days described in Table 5.6 Although upwelling favourable winds occurred on the days of observation, these results tend to suggest that as the mud island was forced up to a height h above the surface by the H_2S it, in turn, forced the colder bottom water up to the surface.

Table 5.6 – Days when H_2S eruptions were observed and Pelican Point wind data at 12h00 UT – observed SST (°C); TDIFF – day-to-day difference in SST; Wind direction; wind speed (knots)

DATE	SST	TDIFF	H_2S	WIND DIR	WIND SPEED
31/12/91	15.9			SW	21
01/01/92	16.3	-0.4	●	W	8
03/01/92	18.6			W	15
04/01/92	18.4	-0.2	●	SW	22
09/02/92	18.3			SW	23
10/02/92	16.2	-2.1	●	SW	16
26/02/92	15			SW	19
27/02/92	16	-1	●	SW	18
01/03/92	17.8			SW	12
02/03/92	16	-1.8	●	SW	14
22/03/92	17			SW	14
23/02/92	16.7	-0.3	●	SW	16
06/04/92	19.5			SW	10
07/04/92	16.3	-3.2	●	SW	23
26/07/92	15.1				
27/07/92	14.5	-0.6	●	SW	29
28/07/92	14.1	-0.4	●	SE	7
06/08/92	14			SW	25
07/08/92	13.9	-0.1	●	SW	27
11/12/92	19.6				
12/12/92	19.9	-0.3	●	SW	10
13/12/92	18.6	-1.3	●	S	21

5.4.2 Kalk Bay: Anomalous cold event – 24/02 - 26/02/1975 and 23/02-26/02/1992

(a) Location

Kalk Bay (see Fig 5.6) is a small yet active fishing village situated, if facing north, on the western side of False Bay - the largest bay in S.A. with an area of 900km^2 (Grundlingh & Largier, 1991) and flanked by impressive mountain ranges.

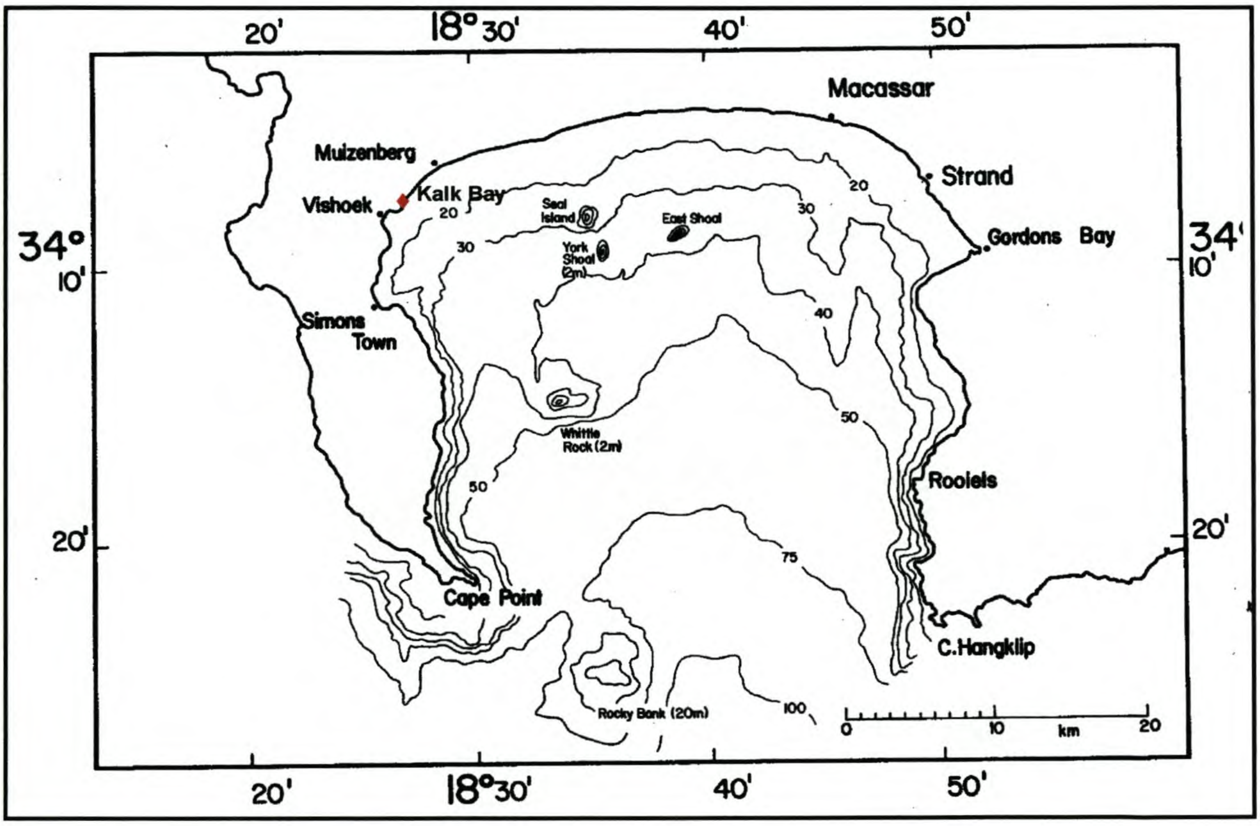


Fig. 5.6 – Chart showing Kalk Bay (red square) (after Grundlingh *et al.*,1989)

(a) Meteorology

Generally, the local winds in False Bay are controlled by the topography bordering both sides of the bay (Grundlingh & Lagier, 1991) and the disposition and time scale of synoptic weather systems that define the domain (Jury, 1984). The climate of the region is Mediterranean (Grundlingh & Lagier, 1991).

As a result of the local topography, Cape Point bears the brunt of the southeasters which are regularly of gale force strength (>30 knts, ~15 m/s) (Grundlingh, 1991). However, the Kogelberg on the eastern side is known to be responsible for projecting a wind shadow over the bay towards the end of a southeast wind condition (Grundlingh & Lagier, 1992).

The main physical aspects of False Bay were outlined at the 1968 and 1989 False Bay symposium (Jackson, 1991). Studies of the circulation in the bay under different wind conditions have shown (Atkins, 1970; Wainman *et al*, 1987; Grundlingh, 1991) that the bay is mainly characterised by a clockwise flow under easterly or southeasterly wind conditions and an anticlockwise flow under northwesterly wind conditions.

In summer, localised upwelling takes place in the northeasterly cornor of the Bay (Grundlingh, 1991) and is mainly attributable to the topographical enhancement of the southeaster (Grundlingh & Lagier, 1991). Generally, it appears that the presence of the high mountains along the eastern side of False Bay (Jury, 1987) affects the location of the downwelling area and, creates upwelling areas between the east coast (of False Bay) and the boundary of the wind shadow on the east coast (Grundlingh, *et al.,*1989).

(c) Data

The longterm monthly absolute maximum, mean maximum, means, mean minimum and absolute minimum SSTs are indicated in Figure 5.7 (a) – 5.7(b).

particularly striking as it is depicted in both graphs. On considering the 95% confidence limits shown in Figure 4.1.1(b) for the west coast region during summer, this SST clearly falls outside of the lower limit. After examining all the available day-to-day data for Kalk Bay more closely, it was found that a SST of 12°C was observed on 26/02/75 and on 24/02/92 – 26/02/92.

The decrease of the SST to 12°C for the period 24/02/75-26/02/75 was not instantaneous and occurred in two phases. During the first phase, the SST decreased by 5°C from 17°C (24/02/75) to 14°C (25/02/75). In the second phase, the SST decreased by 2°C from 14°C (25/02/75) to 12°C (26/02/75), recovering to 15°C on 27/02/75.

In contrast, for the period 24/02/92-26/02/92 the SST instantaneously decreased by 8°C from 20°C (23/02/92) to 12°C (24/02/92) where it remained for the next two days (25/02/92-6/02/92), recovering to 18°C on 27/02/92. Long-term temperature profile data (obtained from the Department of Environmental Affairs and Tourism: Marine & Coastal Management) shows that such water would have had to have been upwelled from at least 30 m depth.

(d) Anomalous cold event

After consulting SAWS synoptic weather charts (see Fig. 5.8 – 5.15) for the 24/02 – 26/02 of 1975 as well as for the same period during 1992, it was found that for the same period during 1975 and 1992 a strong to gale force northwesterly wind ahead of an unseasonably intense frontal wave was experienced. The strong to gale force winds experienced at Cape Point for 24/02-26/02 1975 and 1992 at 12h00 UT are shown in Table 5.7.

DATE	WIND DIR	SPEED
24/02/75	NW	25
25/02/75	NW	20
26/02/75	NW	20
23/02/92	NW	18
24/02/92	NW	15
25/02/92	NW	30
26/02/92	NW	16

Table 5.7 – Wind direction and speed (knots) at 12h00 UT at Cape Point for the period 24/02/75-26/02/75 and 23/02/92-26/02/92

Generally, the northwesterly wind conditions were stronger between 24/02/75 and 26/02/75 than between 23/02/92 and 26/02/92. An instantaneous, rather than a gradual, decrease in SST would therefore have been expected during the 1975 period.

It would appear that the gale force wind conditions experienced on 25/02/92 were responsible for sustaining the upwelling for the period 25/02/92-26/02/92.

Both these events were logged by the fisheries inspectors from Kalk Bay harbour who reported particularly high fish mortalities – estimated to be between 500kg and 1000kg - in the Kalk Bay area for 24/02/92. The type of fish identified were mainly Bank fish – so called because they inhabit the rocky shore and shallow reef areas, for example, steentjies , strepies (*Sarpa salpa)*, blacktail (*Diplodus sargus capensis)* and musselcrackers (*Sparodon durbanensis)*. The steenjie and strepie (typically about 45cm in size) are favoured bait species and, the musselcracker (typically about 1m in size) a sought-after rocky-shore angling species (Branch & Branch, 1988). These bank fish are regularly fished out by local fishermen trying to supplement their income and sold from Kalk Bay for either consumption purposes or as bait. Therefore, fish mortalities such as those experienced in the 1992 event could impact negatively on the local fishermen in Kalk Bay who fish mainly from the shore.

(e) Conclusion

The anomalous upwelling events experienced in Kalk Bay during the period 24/02/75-26/02/75 and 23/02/92-26/02/92 were triggered by unseasonably strong northwesterly wind conditions. Since the northwesterly wind intensified during the 1992 event the upwelling was prolonged.

Fish mortalities were reported for the 1992 event. However, although there might have been fish mortalities during the 1975 event, there are no records available which indicate whether there were fish mortalities or not.

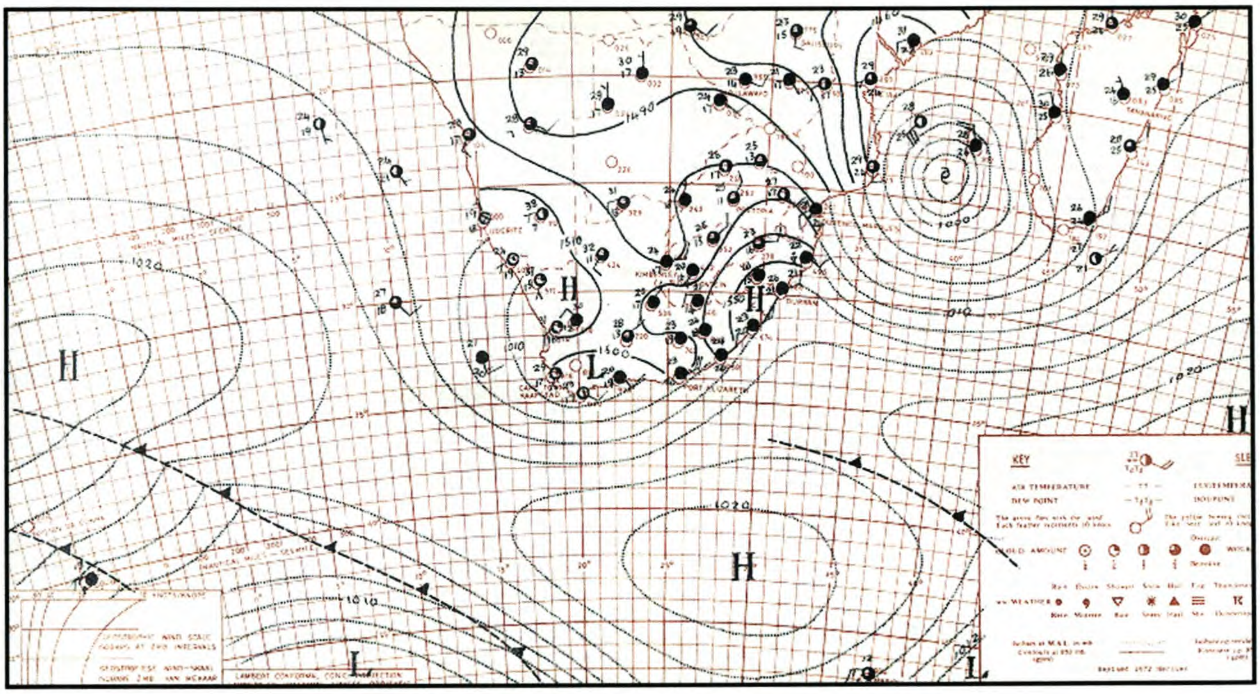


Fig 5.8 – SAWS Synoptic weather map for 23/02/75 12H00 UT

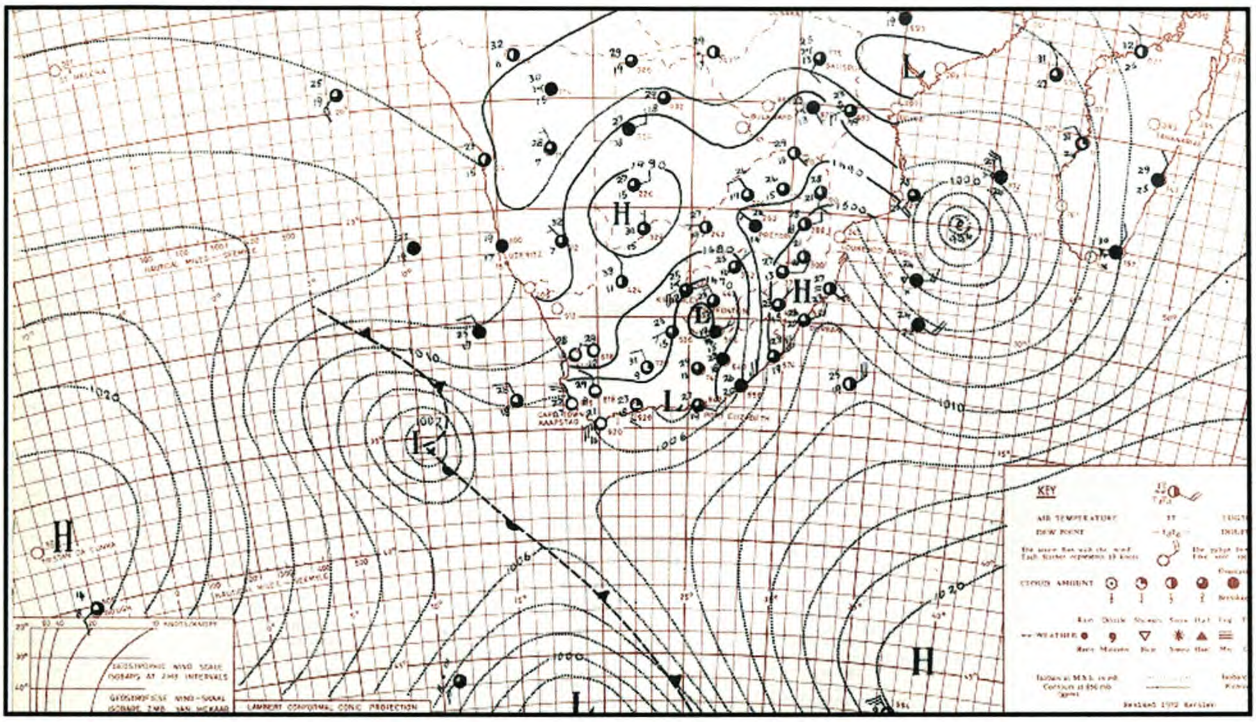


Fig 5.9– SAWS Synoptic weather map for 24/03/75 12H00 UT

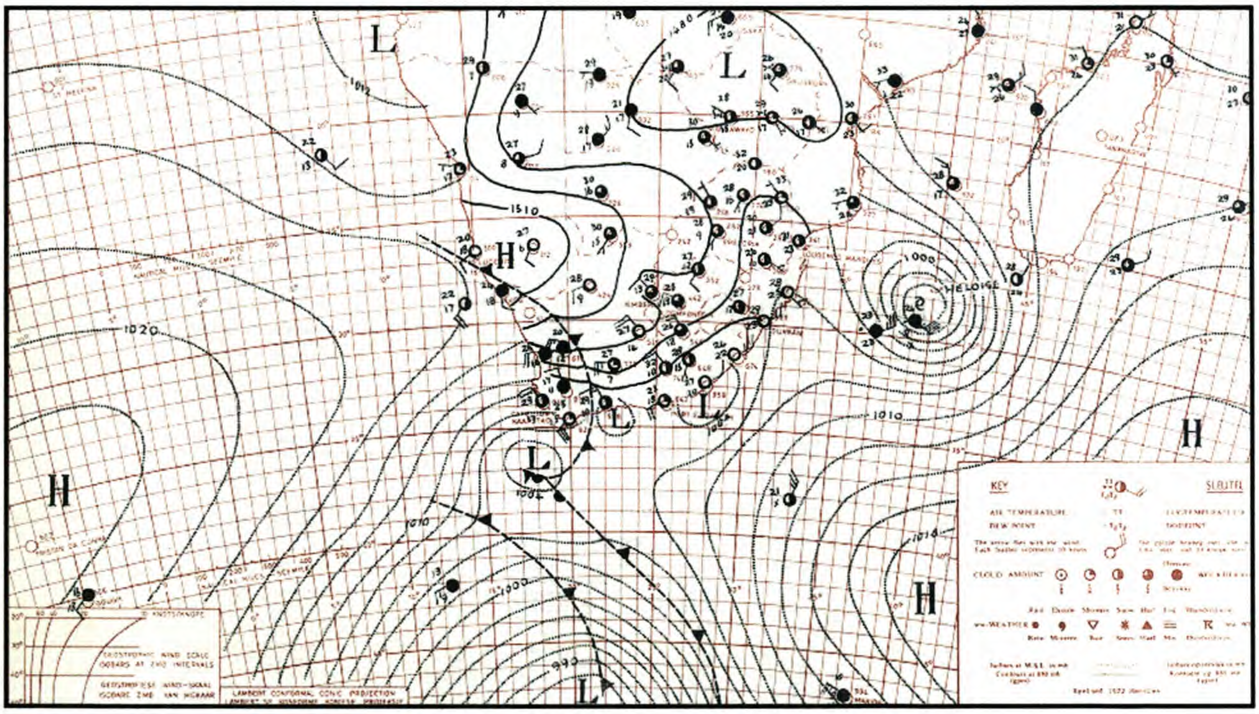


Fig 5.10– SAWS Synoptic weather map for 25/03/75 12H00 UT

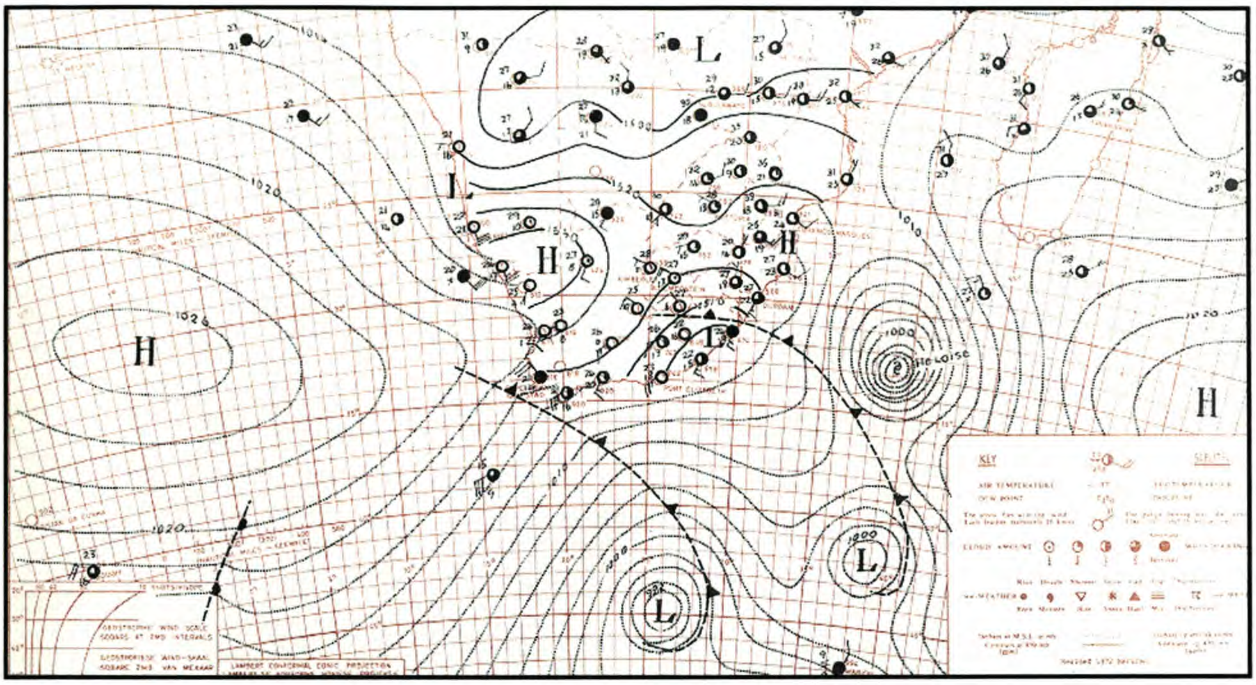


Fig.5.11 – SAWS Synoptic weather map for 26/02/75 12H00 UT

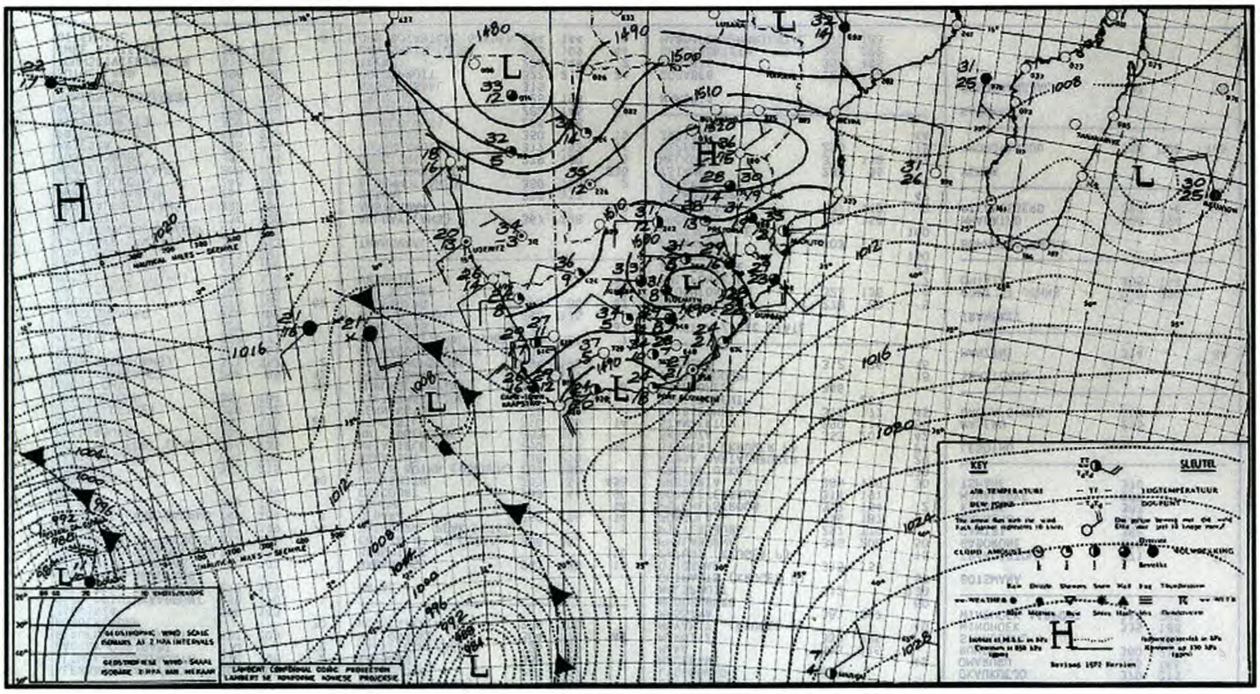


Fig 5.12– SAWS Synoptic weather map for 23/02/92 12H00 UT

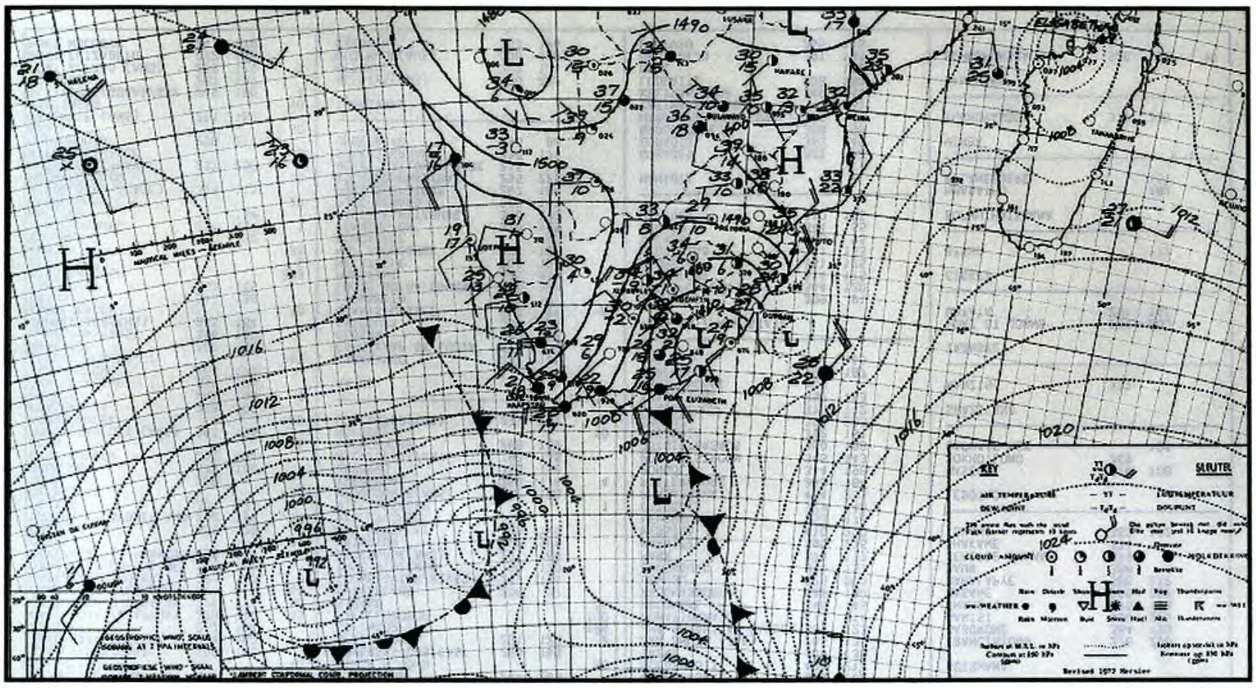


Fig 5.13– SAWS Synoptic weather map for 24/02/92 12H00 UT

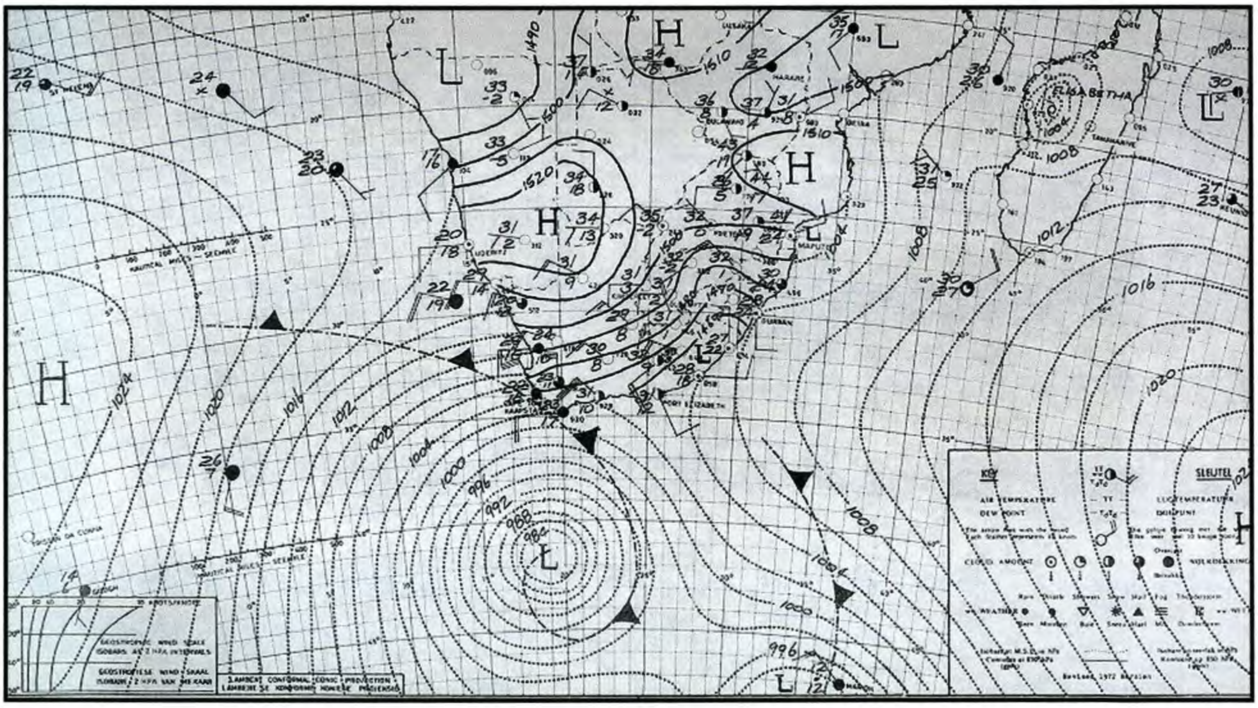


Fig 5.14– SAWS Synoptic weather map for 25/02/92 12H00 UT

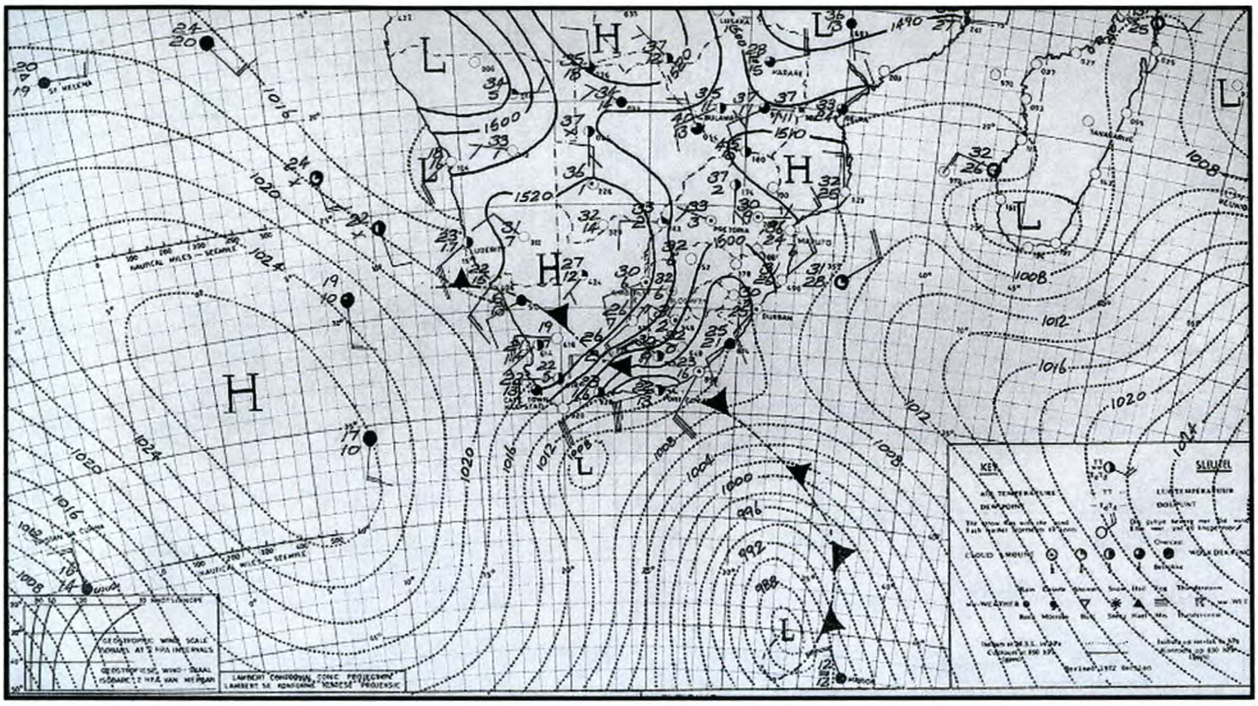


Fig.5.15 – SAWS Synoptic weather map for 26/02/92 12H00 UT

5.4.3 Tsitsikamma: Anomalous cold event – 16/03-19/03 1991

(a) Location

Tsitiskamma (see Fig.5.16) falls into the Cape South Coast regime which is approximately zonal (Schumann *et al*, 1995) and, where the continental shelf widens (up to 270km) to form the Agulhas Bank. Although observations for this measuring site are made close to the Storms River mouth, the freshwater outflow from the river does not appear to have much impact since the dominant intertidal invertebrates in this area are known to be strictly marine forms (Hanekom *et al,* 1989).

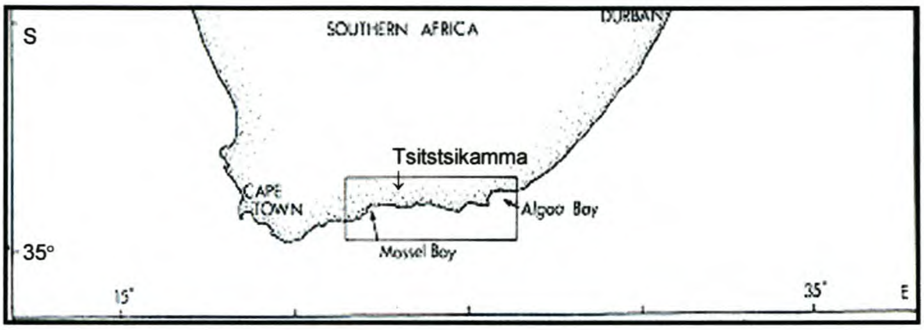


Fig. 5.16 – Chart showing Tsitsikamma (after Hanekom *et al*, 1989)

(b) Meteorology

The Cape south coast region appears to be characterised by a pulsed wind regime (Jury & Pathak, 1991). A pulsed wind regime is driven by a continual passage of upper level Rossby wave trains, so upwelling events tend to be intermittent and short lived (Schumann *et al,* 1995) such as those identified at Tsitsikamma (see Table 5.8). The easterly and westerly wind component dominate the region and have been extensively documented by Schumann *et al* (1982; 1988) and Beckley (1983). However, during summer the easterly component is particularly dominant (Heydorn and Tinley, 1980) – the percentage has been found by Schumann and Martin (1991) to be more than 40%. This is mainly because the area of maximum anticyclonic activity is displaced south (Taljaard, 1972; Schumann *et al*, 1982, 1988) of the Cape south coast at this time and the SAH begins to ridge southeastwards.

As a result of easterly conditions during summer, pronounced upwelling can be expected in this region (Hanekom *et al*, 1989; Schumann *et al*, 1995). The reverse process of downwelling occurs during westerly and southerly conditions (Schumann *et al*, 1982, Beckley, 1983). However, SSTs correlate poorly with westerly component winds (Schumann *et al,* 1995), implying that the downwelling process does not bring warmer water to the coast from further offshore.

Table 5.8 – Upwelling events identified between 1990 and 1992 at Tsitsikamma – SST (°C); TDIFF- day-to-day difference in SST

TSITSIKAMMA (a.m)			**TSITSIKAMMA (p.m)**		
DATE	**SST**	**TDIFF**	**DATE**	**SST**	**TDIFF**
04/09/90	15.5		27/10/90	17	
05/09/90	13	-2.5	28/10/90	12	-5
			07/11/90	18.5	
			08/11/90	10	-8.5
			16/02/91	17	
			17/02/91	13	-4
16/03/91	19		16/03/91	22	
17/03/91	13	-6	17/03/91	13.5	-8.5
18/03/91	11.5	-1.5	18/03/91	12	-1.5
19/03/91	11.5				
			21/10/91	16	
			22/10/91	13	-3
18/02/92	20.5				
19/02/92	13	-7.5			
20/02/92	13.8	-0.8			
21/02/92	11.5	-2.3	21/02/92	18	
			22/02/92	13	-5
05/03/92	18				
06/03/92	12	-6			
09/10/92	15		09/10/92	16	
10/10/92	11.5	-3.5	10/10/92	12	-4
11/10/92	11.5		11/10/92	12	

Clark and Kamstra, 1988). The profiles agree with those reported by Taunton-Clark and Shannon (1988) and Schumann *et al* (1995) for the Agulhas Bank.

It is of interest to note that, on average, the minimum temperatures at Tsitsikamma, as well as Knysna and Port Elizabeth, were observed in spring and autumn when the thermocline was either being established or broken down. These findings are in agreement with those of Swart and Lagier (1987), that the coldest bottom temperatures on the Agulhas Bank do not occur in winter.

The establishment of the summer thermocline (see Appendix B B-3 pg.vii) and the concurrent upwelling driven by easterly component winds dominates the temperature variability at coastal sites such as Tsitsikamma. It is here in summer, as well as at Knysna, that the largest deviations from the mean have been found (Schumann *et al*, 1995) in comparison to Port Elizabeth, for example. This is not surprising, as colder water is more likely to upwell at the coast over the more irregular bathymetry off the south coast than in the shallower water of Algoa Bay.

From Figure 5.17 the diurnal variation, on average, throughout the year appears to be between 1°C and 1.5°C and, on occasions between 0°C and 0.5°C. According to Laevastu (1960) these variations are not unusual. On no occasions were the p.m. SSTs found to be lower than the a.m. SSTs due simply to the effects of conduction and convection throughout the day (see section 5.1.2 - 5.1.3). After reviewing the tide tables for the Tsitsikamma area it appeared that high and low tide coincided with the diurnal change in SST. However, the effect of the tide would depend on calm conditions and whether the tide was low, high or ebbing at the time the SST was observed. For example, if the am SST was measured on a spring high tide the diurnal difference would be increased if the pm SST was measured on a spring low tide when the surface waters would have been affected by insolation.

Particularly striking for this site are the summer and late spring minima, evident in both the a.m and p.m charts and ranging, on average, between 4°C and 8°C . Although the average diurnal SST for summer, in particular, appeared to be warm (ranging between 19°C and 22°C), intermittent periods where the SST plummeted, for example –7,5°C, were identified (see Table 5.7). In some instances the SST decreased further by between 1°C and 2.5°C over a period of approximately 1 to 3 days before recovering to its average state. The hourly automatic weather station (AWS) wind data for Plettenberg Bay (see Table 5.8) showed that the easterly wind component coincided with each of the upwelling events identified.

Since the author arranged with the observer to record visibility as well, it appears that fog was recorded on each occasion when the SST decreased more than 3°C. This is not unusual and is simply the result of warmer moister air moving over a cooler sea surface. The air is cooled to below its dew point temperature, condensation takes place and, advection fog results.

Table 5.9– Hourly AWS wind data for Plettenberg Bay for the periods 04-05/09/90, 27-28/10/90, 07-08/11/90, 16-17/02/91, 16-19/03/91, 21-22/10/91, 18-22/02/92, 05-06/03/92, 09-10/11/92. First two figures multiplied by 10 is wind direction, second three figures divided by 10 is wind speed in m/s

	HOUR																							
DATE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
04/09/90	12059	11056	10067	10068	10067	9066	9062	10064	9074	9075	10070	11073	11071	11071	11076	11079	10077	9074	8078	9080	8075	7062	8051	5038
05/09/90	7038	5028	6031	6035	4029	4036	4036	1021	3016	4019	6024	6017	7024	4020	4023	5017	4028	3012	1023	27097	27098	27098	28070	28055
27/10/90	NO	DATA																						
28/10/90	NO	DATA																						
07/11/90	8044	6024	8026	7029	8040	7037	8055	9072	10076	10082	11096	12091	12103	11096	10113	11113	10108	10105	10101	9092	8083	7078	8067	7066
08/11/90	6052	6055	5044	5046	6055	5038	8012	36031	1023	34064	31050	28021	4026	3032	35025	17021	8022	34032	30035	35036	25052	26053	31025	28019
16/02/91	5026	*****	*****	*****	*****	10056	*****	*****	*****	10081	10078	11083	12075	*****	*****	*****	11087	8071	*****	*****	*****	6050	2021	25014
17/02/91	26027	*****	*****	*****	26075	26088	*****	*****	*****	27047	27047	25062	25055	*****	*****	*****	25058	*****	*****	*****	*****	27030	28027	28027
16/03/91	*****	*****	*****	34012	33024	33020	*****	*****	*****	*****	7034	*****	*****	*****	*****	9062	10063	10071	*****	*****	*****	*****	6050	7052
17/03/91	6043	*****	*****	*****	*****	6038	*****	*****	*****	8049	8060	8054	8051	*****	*****	*****	6037	6030	*****	*****	*****	1024	1015	33016
18/03/91	1018	*****	*****	*****	29011	23012	*****	*****	*****	22014	24021	20017	23027	*****	*****	*****	32014	*****	*****	*****	*****	32023	28038	26049
19/03/91	27033	*****	*****	*****	28045	*****	*****	*****	*****	27046	27052	27059	*****	*****	*****	*****	25041	25036	25033	*****	*****	*****	*****	21009
21/10/91	10048	10056	10057	10056	10056	11058	11059	9066	9074	10097	10092	10094	10090	10099	10107	10101	11096	11092	10082	10074	10071	9065	7043	7045
22/10/91	5025	4025	2033	2052	1051	31032	26024	25021	27039	25055	25061	25072	25070	25059	26054	36055	36065	36089	36081	36070	36056	36057	36052	36049
18/02/92	9021	11018	9017	5007	30014	27013	17011	20009	19013	16021	16027	14038	12049	12055	12059	12058	12063	12068	11068	10070	10073	10073	9071	8058
19/02/92	8058	7053	7044	9048	8041	9051	8051	8052	9042	9048	8045	11037	15028	11041	9047	9046	10050	11044	11032	10032	10033	11036	8039	10024
20/02/92	19013	28014	32012	4019	2012	16007	9012	6019	5028	8028	11031	15027	9040	8050	8055	8061	7054	7050	6053	5047	5049	5048	5038	4016
21/02/92	5016	2019	3016	5031	3034	2023	24014	23021	22025	24030	22036	22039	23035	22034	22034	21027	19022	18016	18013	4014	4024	3029	5029	35026
22/02/92	23017	21018	20019	23010	23017	20013	23009	25010	2011	6030	6036	8039	7042	8048	7046	7050	7052	6051	5046	5048	5054	7075	7075	7066
05/03/92	8072	8064	7053	7044	5032	5029	5023	5021	8041	9046	8058	8062	8053	8065	8066	8063	8061	8055	7041	7040	7044	8045	9044	9034
06/03/92	6037	6020	7021	6027	6020	8014	17006	9009	7016	15021	12030	8055	9048	8052	8048	9055	8051	8043	7029	8024	7012	2013	35024	1009
09/11/92	10077	11075	10082	10083	11086	10092	10090	10091	10093	10096	11095	11095	11097	11102	11108	10100	9093	9094	8076	7061	8066	8047	7031	6036
10/11/92	4038	2029	3024	28015	1015	2012	1027	36055	36095	35090	35080	33043	25040	27039	25032	26043	27090	26066	27052	26049	28029	27028	27026	30022

(d) Anomalous cold event

From Table 5.8 the period of 16/03/91-19/03/91 is of particular interest due to the intensity of the upwelling event which persisted for 3 days.

Initially, on 16/03 (see Fig. 5.18) the SST increased during the day from 19°C to 22°C due to weak (on average, 3.7 knots) northerly wind conditions which persisted for most of the day. By late evening the wind suddenly switched to a stronger (on average, 12 knots) more easterly wind which persisted until 18/03/91. As a result the SST decreased by 9°C from 22°C on 16/03 to 13°C on 17/03 a.m (see Fig. 5.19) and, remained low (13.5°) for most of the day. Although the wind switched to westerly (on average, 5 knots) on 18/03 (see Fig. 5.20), a further decrease in SST of 2°C was experienced during the morning and remained between 11,5°C and 12°C until late afternoon on 19/03 (see Fig. 5.21). It would appear that the downwelling, driven by the westerly winds, was insufficient to displace the resident cold surface waters. Similar instances of SSTs remaining at a minimum during westerly conditions have been found by Hanekom *et al* (1989) whilst analysing SST variations in Tsistikamma during the period January, March and April 1984.

As the wind gradually strengthened (on average, 9 knots) to a more westerly wind component from late afternoon on 18/03 the SST started gradually recovering to 15°C on 20/03 a.m. Since this SST was shown to fall outside of the lower 95% confidence limit (see Fig. 4.4.2(c)) for the South Coast region during autumn, and considering that in section 5.3 it was established that a decrease in SST >3°C is anomalous, this decrease of 9°C from 16/03-17/03 was regarded as an anomaly.

The implication, from briefly examining the relationship between the SST and the easterly wind component at this measuring site for the period 16/03/91-19/03/91, is that the upwelling process proceeds very rapidly after the onset of the easterly-component winds and that no further decreases in SST occur with stronger winds. The latter suggesting that upwelling had already progressed to the stage where the colder bottom water had reached the measuring site – a finding supported by Schumann *et al* (1995).

A consideration at this point is that of the mixed layer depth which has been reported to be, generally, between 10 and 20 m by, for example, Beckley (1983) and Schumann and Beekman (1984).

The classical cross-shelf Ekman transport U_E is given by

$$U_E = T_S / \rho f$$

Where T_S is the alongshore surface wind stress generally taken to be proportional to the square of the wind speed, ρ the density of the water and f the Coriolis force. For a wind of 3 m/s and an Ekman depth of 2 m, at a latitude of 34°S the offshore velocity is approximately 7 cm/s (Schumann *et al*, 1995). Lentz (1992), however, showed that a considerable proportion of the wind-driven transport occurs below the surface mixed layer, and in reality the velocity should therefore be less than 7cm/s. With such small velocities there would be a tendency to assume that it would take some time for an upwelling front to break the surface. However, in an idealised situation a front could move a few hundred meters offshore in a few hours at such low velocities. Goschen and Schumann (1995) have indeed found irregular SST changes occurring at the coast within a few hours of the onset of easterly winds with speeds of 10 m/s and less.

Another consideration is that of the time taken to establish the Ekman layer which according to Brink (1983) is approximately half an inertial period. At 34°S this is approximately 10 or 11 hours, however, from the results of Goschen and Schumann (1995) it appears that the response can be faster in terms of a decrease in SST at the coast.

Within the immediate area of the Tsitsikamma Coastal National Park (TCNP), large shoals, (~200-3000 individuals) of strepie and blacktail (respectively *Sarpa salpa, Deplodus sargus carpensis)*, sand steenbras (*Lithognathus mormyrus),* maasbanker (*Trachurus trachurus)* and mullet (*Mugilidae*) were found motionless, as well as about 30-80 large musselcracker (*Sparodon durbanensis)* and kob (*Argyrosomus hololepidotus*) (A. Riley, TCNP, 1991, pers.comm). It is of interest to note that three of these species, strepie, blacktail and musselcracker, have a distributional range which extends into the cooler waters of the western Cape (West Coast region) (Hanekom *et al*, 1989) and, were also identified in the fish kill of 24/03/92 at Kalk Bay (see section 5.4.2).

(e) Conclusion

The anomalous upwelling event experienced at Tsitsikamma during the period 16/03/91-19/03/91 has clearly demonstrated the affects of the easterly wind component in the South Coast region. Also, that an instantaneous decrease in SST from day-to-day of, for example, 9°C can occur at coastal sites situated in the South Coast region within <24 hours of the onset an easterly wind component with wind speeds of <10 m/s.

Since similar species of fish were identified during the fish kill of 1991 at Tsitsikamma as were as identified in the fish kill of 1992 at Kalk Bay, this tends to suggest that the rapidity of the temperature decline rather than the low temperature *per se* is responsible for fish mortalities.

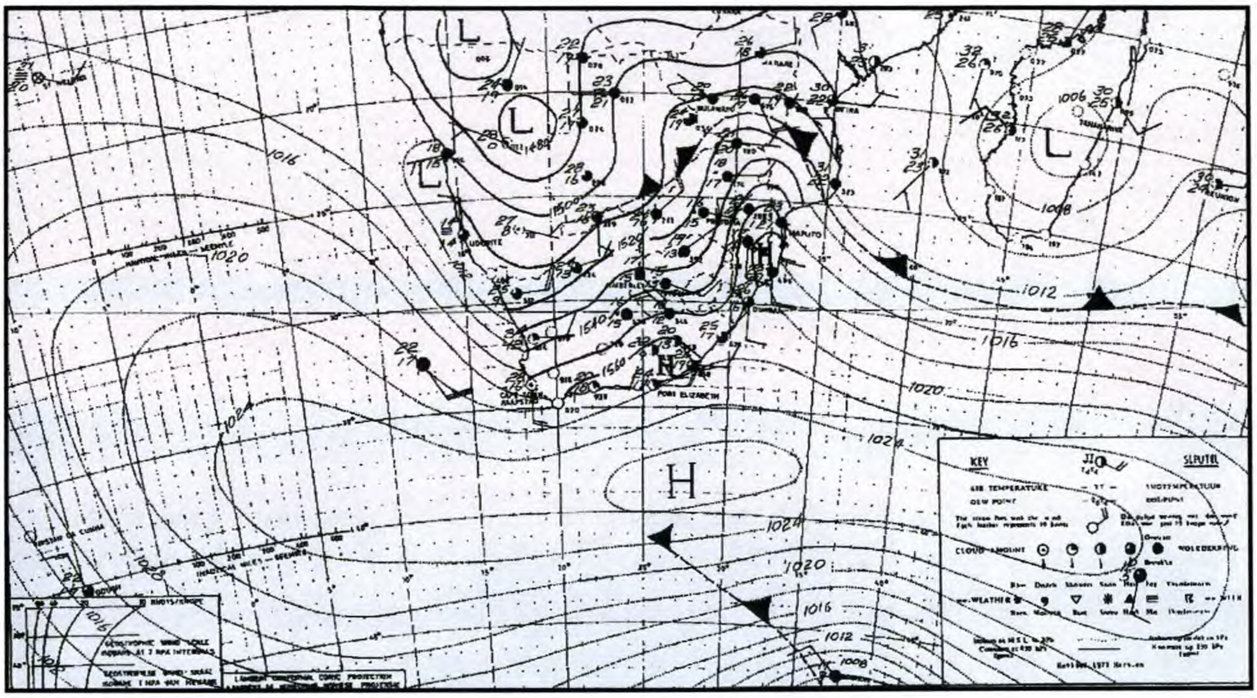


Fig.5.18 – SAWS Synoptic weather map for 16/03/92 12H00 UT

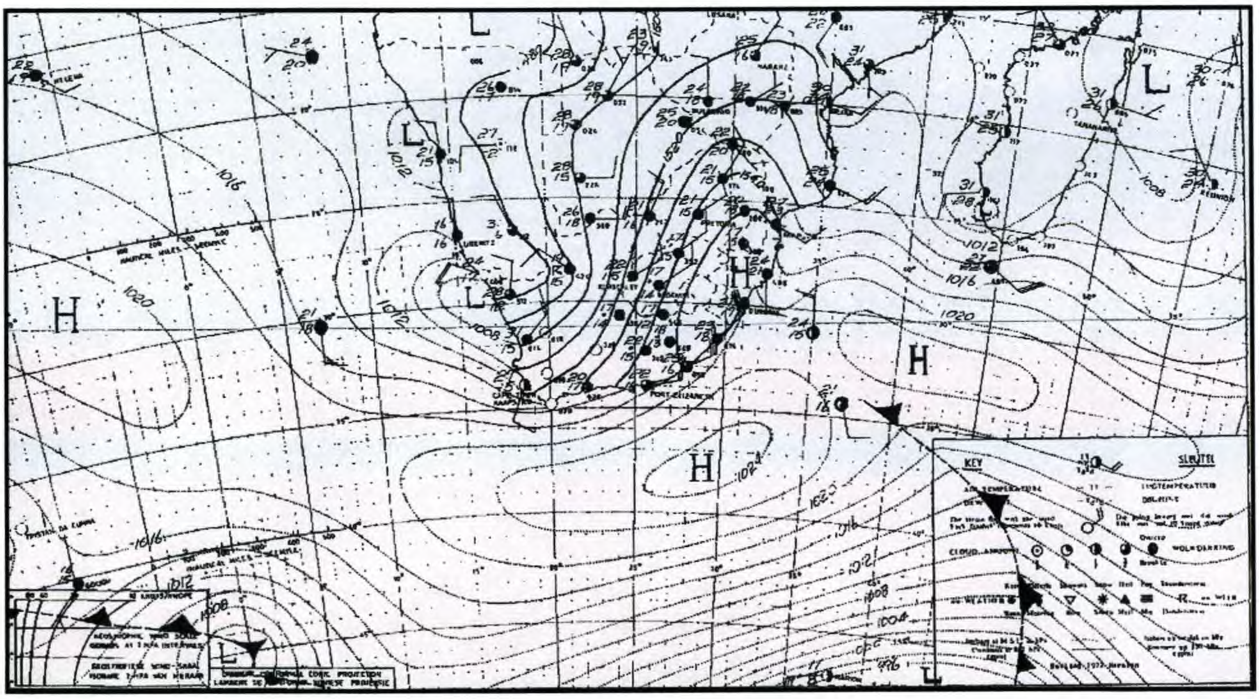


Fig.5.19 – SAWS Synoptic weather map for 17/03/92 12H00 UT

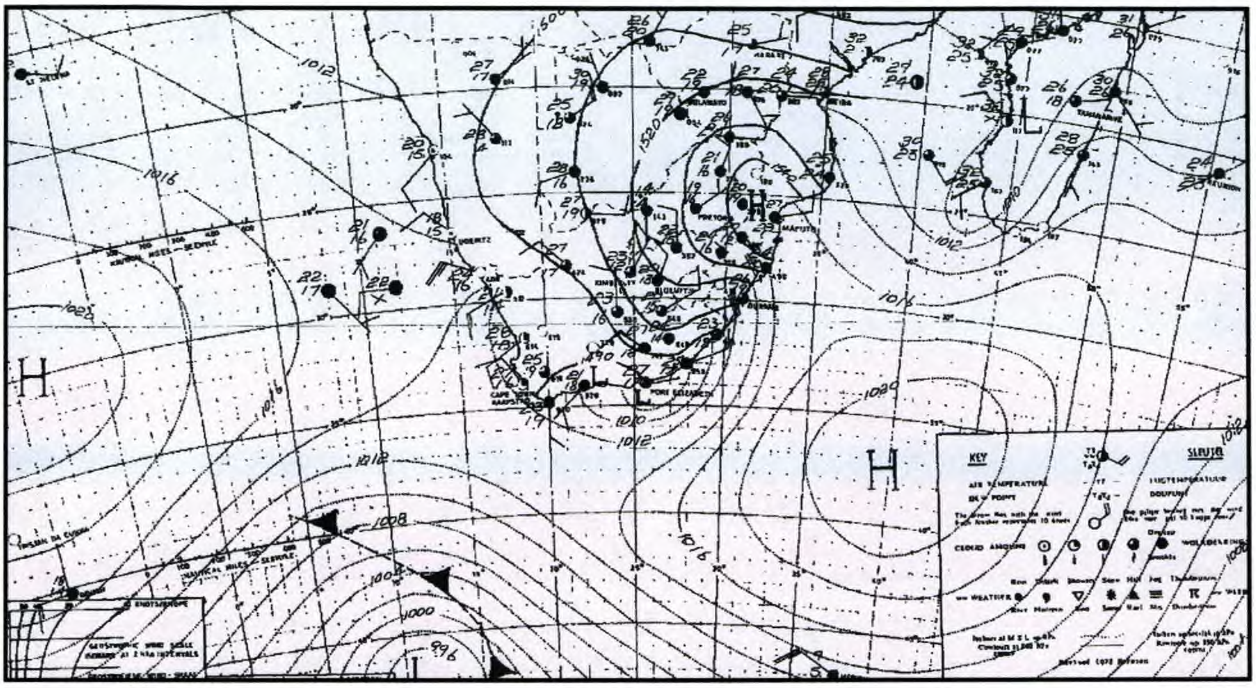


Fig.5.20 – SAWS Synoptic weather map for 18/03/92 12H00 UT

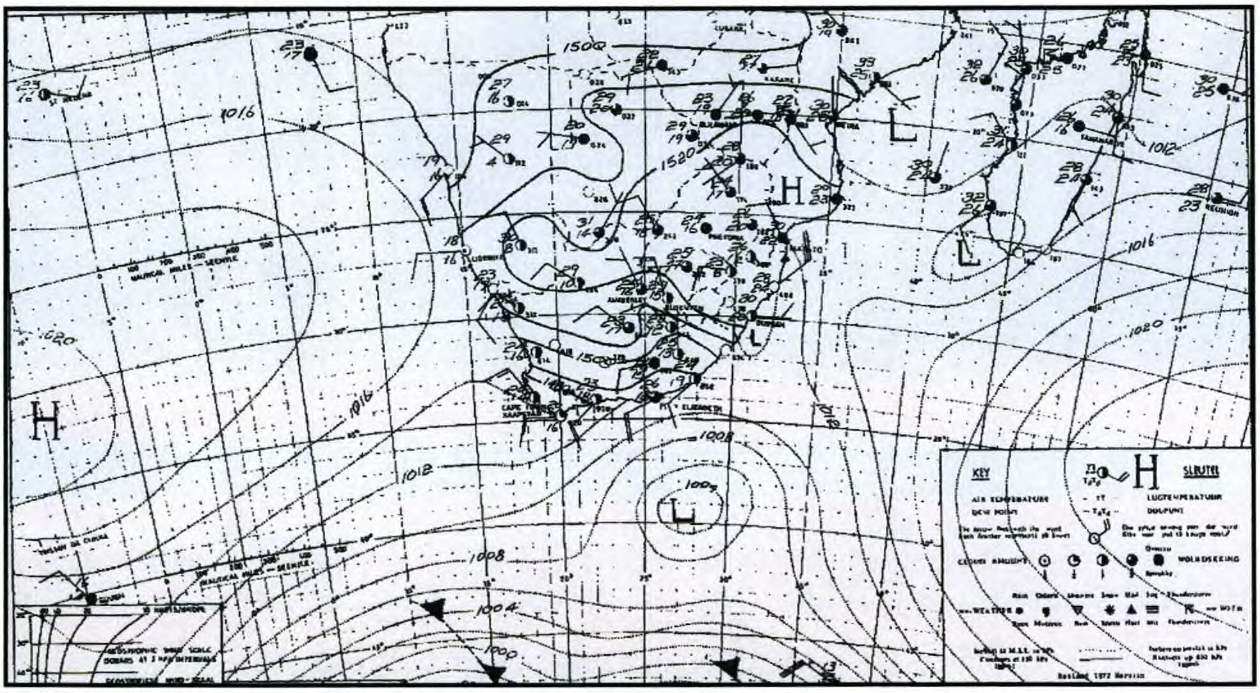


Fig.5.21 – SAWS Synoptic weather map for 19/03/92 12H00 UT

CHAPTER 6: APPLICATIONS OF SEA SURFACE TEMPERATURES

Apart from the climatological and biological effects of changes in SST, several economic activities are also affected by changes in SST. This Chapter attempts to firstly, highlight the general effects of SST on climate and marine life and secondly, to identify and describe some of the economic activities where SST plays an important role, and explain the effects of SST change on each of these activities.

6.1 CLIMATOLOGICAL AND BIOLOGICAL EFFECTS OF SST

As will be shown in the following sections, the effects of SST change are not always negative. For example, an extended upwelling season of nutrient-rich water can result in an abundance of commercially important fish.

6.1.1 Climatological effects

Sea surface temperature affects global climate change through the accumulation of surplus heat in the upper layer of the ocean (Schumann *et al*, 1995). The following are examples of studies done on climate variability with respect to SST. Walker (1990) has shown a positive correlation to exist between the interannual SST variations of the Southern Atlantic and Southern Indian Oceans, and rainfall patterns over Southern Africa (see Chap.5, pp.104, last para.). This has an important bearing on the local terrestrial environment. Jury and Pathack (1991) have shown a relationship to exist between SST and outgoing long-wave radiation which indicated that a decrease in SST within the cyclogenesis region of Madagascar brought summer rainfall to SE Africa. Conversely, an increase in SST to the NE of Madagascar in the preceding spring created conditions for more frequent cyclogenesis and increased rainfall over Madagascar. Schumann *et al* (1995) showed positive correlations to exist between the variation of the wind, SST and the Southern Oscillation Index (SOI) which indicated that when the SOI was low (ENSO situation-high SSTs and decreased easterly winds in the equatorial Pacific) the summer rainfall pattern over the South African plateau, decreased. The converse being true for La Nina.

The global ENSO cycle is an important component of climate variability and impacts significantly on local economics, for example, over the South African interior ENSO has been responsible for seven-fold fluctuations in the maize yield (Schumann *et al*, 1995). Also, the chokka catch appears to vary directly with the temperature (Sauer *et al* , 1991), and an extended upwelling season could result in a bumper chokka season.

6.1.2 Biological

Environmental stress endured by marine species is primarily through the effects of SST fluctuations. For example, during an ENSO event warm water appearing along the Peruvian and Ecuadorian west coast, causes large scale mortalities of fish and sea bird communities which are directly or indirectly dependent on the nutrient rich upwelled waters normally found along this coastline (Walker *et al*, 1984). Some fish escape fatality by disappearing below the abnormally warm surface layer (Pickard & Emery, 1982). On the occasions when sudden upwelling is experienced at Tsitsikamma, fish are often found taking refuge in the warmer waters of the Storms River mouth (Buxton, 1988). The 1963 winter warm event near Walvis Bay was coupled with continually low oil yields from pilchards and inconsequential reproduction activity (Walker *et al*, 1984).

The cold upwelled nutrient rich water along the west coast during spring and summer, is an important factor governing the growth of pilchard larvae and juveniles by ensuring sufficient food supplies (Crawford *et al*, 1990). The warm event of 1965 in this region was partially held responsible for the collapse in the South African pilchard industry in subsequent years (Walker *et al*, 1984).

(a) Cold Water Effects

Cold water events in a region can seriously affect biota and consequently top predators (Schumann *et al*, 1988), for example Cape Gannets and Jackass penguins, by altering the distribution of their prey (e.g. sardines). Prior to the dramatic cold water event of March/April 1987 in Algoa Bay 20 000 to 30 000 birds were estimated (Schumann *et al*, 1988) to have been feeding and resting in the region, only to be reduced to a few individuals (ibid) as the cold water penetrated and intensified in the region.

In 1983 and 1985 elf catches increased significantly off the eastern Cape and southern Natal (Crawford *et al*, 1990) as a result of the 1982 and 1984 cool period off eastern southern Africa. It was suggested that these cool conditions transferred elf eastwards, consequently reinforcing the species' annual migration to Kwazulu Natal in the following seasons.

Mass mortalities of fish, for example dageraad, roman, poenskop, musselcracker, hottentot and jan bruin, were experienced in February 1971 when Tsitsikamma experienced a day-to-day change in SST of -12°C (Winch, 1982). These mortalities of fish could be seen for up to 6 km along the Tsitsikamma coast. Hundreds more were found taking refuge in the warmer waters of the Storm River mouth and, gulleys and small bays into which ran sun warmed streams from the mountain.

(b) Warm Water Effects

Benguela Ninos appear to benefit the survival of early stages of some organisms, but may decrease the production of others by up to 50% (Crawford *et al*, 1990). It has been confirmed (ibid) that epipelagic species are favoured by warm conditions, and groundfish by cooler conditions. The migration intensities of recreational fish species from the NE and SW coasts to the SE coast of Africa have also been suggested (Crawford *et al*, 1990) to be influenced by SST conditions in the areas of their origin.

During Benguela Ninos when warm coastal waters prevail, species from warmer areas tend to broaden their extent poleward (ibid). For example, during the 1963 warm event Copepod species, characteristically found between Angola and Senegal, were found off Namibia (Stander & de Decker, 1969). In 1983 and 1984, *Sardinella aurita* was caught off Namibia, a species normally encountered off Angola and farther north (Thomas, 1984; Crawford *et al*, 1990).

Apart from displacing more tropical species southwards, Benguela Ninos also result in local fish populations being shifted further south. For example, during the 1963 event sardines were transferred as far south as Luderitz. In such abundance were the fish that a fish factory was opened in 1964 (Butterworth, 1983) and as the anomalously warm conditions passed and the sardines returned to the north the factory was closed in 1976 (Crawford *et al*, 1990). Again, during the 1984 warm event, sardines were migrated ~2°30' southwards (Thomas, 1984). At the same time snoek (*Thyrsites atun*) were also migrated southwards with detrimental consequences to the snoek catches off Namibia between 1984 and 1987 (Crawford *et al*, 1990). Benguela Ninos also decrease the productivity of many organisms. Plankton concentrations in the northern Benguela for 1984 were ~30% of mean values for the three prior years (Boyd *et al*, 1985).

Guano harvests from seabirds, such as gannets and cormorants, are also affected by Benguela Ninos which appear to indicate reproductive failure as a result of diminished availability of prey such as sardines (Boyd *et al*,, 1985). According to Crawford *et al* (1990) this tends to contradict earlier evidence of the southward transferral of sardines which would have produced an abundance of prey. Since Benguela Ninos are frequently accompanied by heavy rains, large quantities of guano are often washed into the sea (Shannon *et al*, 1986), thereby giving the impression that guano production was low. This could confuse the issue of relating actual guano production to guano harvests. What appears to emerge is that Benguela Ninos promote the sardine over the anchovy in the Northern Benguela. Although sardine and anchovy produce fewer eggs during Benguela Ninos (Crawford *et al*, 1990), the sardine survival rate is greater possibly due to the increased stability of the water column and reduced offshore transport of ichtyoplankton (ibid). Where hakes (Merluccius spp.) are concerned, they have been shown (Boyd *et al*, 1985; Schumacher, 1987) to have decreased during warm events, for example in 1982, and increased during cooler conditions, for example in 1981. It is interesting to note that the extent over which hake is dispersed off Peru increases during ENSO conditions (Crawford *et al*, 1990). This has a positive impact, since it reduces cannibalism by older hake and gives the younger hake a greater chance of survival (ibid).

Changes in the the upwelling process and in the amount of diatoms foraged by consumers can also affect the oxygen concentration of the water through modifications to the carbon-loading (Pollock & Shannon, 1987). For example, following the collapse of the Namibian sardine industry in the late 1960s and during the 1970s, increased carbon-loading occurred which resulted in an extended area of oxygen depleted water over the shelf between Luderitz and Port Nolloth (Crawford *et al*, 1990). In consequence this affected the domains appropriate for benthic organisms, for example the west coast rock lobster (*Jasus lalandii*) and the west coast sole (*Austroglossus microlepsis*) (Pollock & Shannon, 1987).

Hughes (1989) showed that higher SSTs off the SE coast resulted in a greater number of loggerhead turtles nesting in their southernmost nesting grounds, namely Maputaland. However, leatherback turtles were shown (ibid) to be totally unaffected by a reduction in SST, since they retain a generally constant body temperature of 31°C - and, appear not to rely on the higher SSTs off the SE coast for embarking on nesting migrations to Maputaland. When using marine organisms to establish the effects of anomalous SSTs it is difficult to quantify and qualify what is as a result of an environmental change, and what is simply a result of exploitation.

6.2 ECONOMIC ACTIVITIES AND THE EFFECTS OF SST

6.2.1 AQUACULTURE

Aquaculture can be described as man's effort to enhance the produce of useful aquatic organisms by controlling their rates of growth, mortality and reproduction (Pillay, 1990). Various terms have been used to describe the different practices, for example fish farming, fish cultivation, mariculture, aquafarming, fish culture and even aquaculture itself. From this point on aquaculture will be used as an all-incorporating term for both marine animal and plant culture.

Generally, in an increasingly hungry (and greedy) world aquaculture is used to provide food for direct human consumption and this should thus be considered as its dominant future function. Apart from this function, aquaculture is also used to produce organisms for animal feed, bait or sport (Reay, 1979) and where seaweeds are concerned, organic fertilizers and animal-feed supplements (Anderson *et al*, 1989). Seaweeds have this century become industrially important sources of colloids such as agar from red weeds and alginic acids from brown weeds. Some of the most valuable aquacultural products, for example, pearls and ornamental fish such as clown fish, are not intended for food whatsoever, and some cultured fish are used for biological control, for example grass carp and mosquito fish (Reay, 1979). Marine farms are of additional value in providing employment and utilizing waste (Anderson *et al*, 1989).

At present, aquaculture is one of the fastest growing industries in South Africa with production having been in the region of 4 000 tons (Fishing Industry Handbook, 2001) – attributable mainly to the production of mussels which has amounted to approximately 3 000 tons. In South Africa permits are mainly issued for the cultivation of oysters, abelone, mussels and prawns and several permits have been awarded to various companies for the cultivation of these products. However, according to Dr. J. Bailey (Dept of Environment Affairs and Tourism: Marine & Coastal Management, 2002, pers. comm) only 15 are currently producing commercially viable stock : (the production figures shown are for 2001)

- 11 - cultivating abelone at various localities between Port Nolloth and East London, collectively produced 188 tons;
- 2 - cultivating oysters at various localities between Port Nolloth and Port Alfred, collectively produced 97 tons;
- 1 - cultivating mussels at Saldanha Bay (although there are plans to start cultivation in Port Elizabeth during 2003), produced 600 tons; and
- 1 - cultivating prawns in KwaZulu-Natal, produced 249.5 tons.

Products such as abelone are cultivated mainly in hatcheries and nurseries situated on land. Seawater is pumped ashore where the temperature can then be regulated. However, products such as mussels, oysters and prawns are mainly cultivated using various raft and cage systems which are usually situated in or near the entrances of bays.

Currently, abelone is the only product being exported, mainly to Japan. Unfortunately, the waters off the Southern African coast have not, as yet, been graded by the European Union (EU) (Dr. J. Bailey, Dept of Environment Affairs and Tourism: Marine Coastal Management, 2002, pers. comm) which means that any product cultivated off the coast, for example mussels, cannot be exported. Apart from not having the facilities to cope with the production of large quantities of mussels, the notable drop in the production of mussels from approximately 3 000 tons to 600 tons in 2001 is because of the fact that the surplus cannot be sold on the international market.

There are essentially two types of aquaculture systems. The simplest type is the extensive or open system which requires minimal control and deviation from nature (Shepherd & Bromage, 1988). For example, moving oysters to preferential growing areas, and adding fertilizers to natural ponds. The other type is the intensive - high density production per unit area - or closed system, resulting in almost complete control over the organism and its environment (ibid).

6.2.1.1 Species selection

Choice of species is governed by the biological, technological, economic and marketing requirements that influence commercial viability (Webber & Riordan, 1976).

Marketability is generally considered to be the most critical, and the characteristics of particular species having an effect on this are ease of processing, texture, taste and appearance (Reay, 1979; Dr. J. Bailey, Dept of Environment Affairs and Tourism: Marine Coastal Management, 2002, pers. comm). To a certain degree these can (of course) be altered to meet the consumer's needs (Shepherd & Bromage, 1988). Cultural and social factors are sometimes more important than economic ones, and nutritional value is seldom a priority to the consumer. For example, in Japan dried abelone strips are used as offerings to shrines at festivities. In China the esoteric properties ascribed to eating abelone include delayed senility and increased fertility (Featherstone, 1995).

Of secondary importance to the marketability are the biological characteristics, for example growth-rate, conversion efficiency, availability of seed and tolerance to crowding, which will determine production costs and therefore choice of species (Reay, 1979). In the U.K. turbot has been chosen over plaice by aquaculturists due to its higher market value, greater tolerance to crowding, faster growth and inexpensive feeding costs. Initially turbot was considered disadvantageous to cultivate due to its unreliability of seed production. However, inspired by the high market value, funding was made available for research and the problem was solved.

6.2.1.2 Site selection and water quality

For several reasons SST is considered to be the most important water quality characteristic. Firstly, it has a direct effect on activity and metabolic processes, secondly, it has an indirect effect through dissolved oxygen level and thirdly, the high costs involved in controlling water temperature (Landau, 1992). Also, temperature allows the production capacity of the site to be determined and the growth rates predicted (Shepherd and Bromage, 1988). This is usually done obtaining detailed knowledge of the SST trends over several years at that site. As already established, (see Chap. 4 and Chap.5) the time-scale for fluctuations in SST vary considerably at different sites from hours to decades. For any fish or plant species the rate at which these fluctuations occur and their exposure time to the change are critical in determining their ability to adapt and thus, survive (Zoutendyk, 1989; Landau, 1992). Zoutendyk (1989) used the Cape rock lobster, *Jasus lalandii*, to illustrate how metabolic rates and enzyme activities of organisms fluctuate to compensate for changes in temperature. Lobsters were exposed to rapid temperature increases and decreases in 5°C intervals between 8°C and 19°C. When temperatures increased the lobsters' rate of oxygen consumption increased; *vice versa* for rapid decreases in temperature. At 19°C they appeared stressed and it was assumed that anything greater than 19°C would ultimately lead to coma and death. Thus, the Cape rock lobster are well adapted to the nearshore Benguela system where upwelling can result in temperature changes of up to 8°C within hours. On the other hand, downwelling which occurs at one third of the rate of upwelling (Andrews and Hutchings, 1980) results in an increase of temperature over several days (Field *et al*, 1981) and therefore the rate of oxygen consumption takes longer to stabilize (Zoutendyk, 1989). Shepherd and Bromage (1988) suggest that the rates of chemical reactions and processes within the bodies of fish show 50% increases for every 5°C rise in temperature between temperatures of 0°C - 20°C.

Temperature requirements for different species differ which makes this factor important in determining particular species for pre-established sites, or sites for pre-established species (Shepherd and Bromage, 1988). All species have maximum and minimum lethal temperatures which have to be avoided (Reay, 1979, Zoutendyk, 1989), but of equal concern is the need to provide optimum temperature for growth (Reay,1979; Shepherd & Bromage, 1988).

6.2.1.3 Fish/Shellfish culture

Aquaculture of this type is probably the most sensitive to changes in the environment and if these changes are destructive they could leave the company financially bankrupt (Shepherd and Bromage, 1988).

The direct and indirect effects of temperature are critical to the survival of any species. Generally, the main factors resulting in mortality are abiotic, diet, predators and pathogens (Reay, 1979). Because of continual interaction between these factors it is difficult to ascertain which is the main cause of mortality.

Not only do all species have tolerance limits in their response to absolute changes in temperature, but also to other abiotic factors, for example salinity, pH, dissolved gases, heavy metals and other chemical elements (Shepherd and Bromage, 1979).

6.2.1.3.1 Temperature effects

Landau (1992) has stated that "the optimal temperature is based on the sum of the internal chemical (mostly enzymatic) reactions that are taking place". For example, for fattening turbot the optimum temperature is 14°C which is only attainable at a certain time of the year in ambient seawater around U.K. coasts (Reay, 1979). To obtain this in tanks in the U.K. would mean pumping water and heating it, and the resulting heating costs would amount to more than five times the value of the fish at the end of its growth period.

In Hout Bay, a company by the name of South African Sea Products has been experimenting with culturing abelone in tanks. Sea surface temperatures in this area of South Africa have been shown to range on average between 12°C and 14,5°C during the year (Greenwood & Taunton-Clark, 1994). Although ideal for the cultivation of turbot, the water is heated to approximately 18°C which is the optimum temperature for cultured abelone (Featherstone, 1995). Thus, anywhere north of East London is not suitable for the cultivation of abelone since the SSTs are too warm, ranging on average between 19,5°C and 24,5°C during the year (Greenwood & Taunton-Clark, 1994). Although the water can be cooled, according to Engledow and Bolton (1992), this can be a cumbersome and costly process.

It has been suggested that the most cost effective way of increasing water temperature is to use the heated effluent (discharged water) from industries such as those which generate electricity (Shepherd and Bromage, 1988; Landau, 1992). It is of interest to note that an experimental oyster farm exists in the harbour basin of Koeberg nuclear power station (see section 6.2.3). Power stations considered fit for commercial aquaculture in Japan, Europe, U.S.S.R, U.S.A and U.K have an affiliation with fish farms (Reay, 1979). Lobsters, for example, take approximately six years to reach 450g in their natural environment, but just two years if kept in heated effluent of 22°C (ibid). Furthermore, the lobster, *Homarus*, normally inhabiting cold waters, has been shown by researchers not only to withstand higher temperatures, but also to grow more rapidly at these elevated temperatures (Landau, 1992) - suggesting the use of thermal effluent in commercial lobster culture.

One obvious disadvantage of using power station effluents is the existence of chlorine which is used as a biocide to inhibit spoiling of the condensers (Reay, 1979). However, chlorine is not always used in concentrations which are toxic to fish - the use of heat exchangers will avoid this problem if they are.

The mussel *Mytilus* is capable of rapidly filtering algal cells out of seawater at temperatures between 15° and 25°C (Landau, 1992). However, if the temperature decreases or increases, filtration will slow down substantially thereby affecting the growth rate of the mussel.

Problems associated with low temperatures are that they inhibit the growth rate, whereas higher temperatures tend to effect dissolved oxygen levels (Landau, 1992; Reay, 1979) and improve chances of diseases commonly associated with warm water (Landau, 1992).

A primary reason why fish perish is through lack of oxygen because of low dissolved oxgen concentration levels, or damaged gills, or because the haemoglobin-uptake mechanism is impaired (Reay, 1979; Shepherd and Bromage,1988; Landau,1992), or because the structures of the life-supporting enzymes have been changed and are no longer able to control the necessary reactions with the appropriate speed (Landau, 1992). Generally, death is instant and can only be avoided if the farmer happens to have prior knowledge and therefore, for example, boost dissolved oxygen levels (S. Web, University of Cape Town: Zoology Dept., 1996, pers. comm). An example of the relationship between oxygen supply and demand, and water flow and temperature is shown in Figure 6.1 for a trout system.

The levels of dissolved oxygen are affected by advection of water, by temperature, and the biomass and activity of the stock and other organisms (in particular plants). Biological oxygen requirements tend to increase when an algal bloom occurs, but more commonly, when bacterial populations increase as a result of an accretion of faecal matter or uneaten food.

stimulated during World War 2, when supplies of agar from Japan and Britain became unattainable. Only then was it recognised that local seaweeds have an intrinsic commercial value. In response to the interest shown by some local companies in cultivating *Gracilaria verrucosa* for agar, or as a possible feed for the more profitable abelone (ibid), two ongoing pilot aquaculture projects were started in Saldanha Bay and Luderitz, Namibia (B. Post - Sea Fisheries Industry Research, 1993 pers. comm). Both these projects have proved to be highly successful and are presently still in operation, yielding in the region of 270 tonnes (dry mass) at Saldanha Bay, and 160 tonnes (dry mass) at Luderitz (Fishing Industry Handbook, 2001). This currently has an export value of approximately R12 000 per tonne (ibid). In total, 2373 tonnes (dry mass) of seaweed, i.e. kelp gracilaria and gelidium, is currently being harvested, collected and cultivated around the southern African coast annually, and has an export value of approximately R28 million (Fishhing Industry Handbook, 2001). Due to the lack of a production plant, there is currently no agar being produced in southern Africa. Although, there is an agar production plant planned for St. Helena Bay in 2003, along with plans for the development of two 10 ha aquaculture farms for the cultivation of gracilaria (Beeld, 05/02/2002; (Dr. J. Bailey, Dept of Environment Affairs and Tourism: Marine Coastal Management, 2002, pers. comm). However, until then, all seaweeds will continue to be dried out only, before being exported mainly to the East.

6.2.1.4.1 Temperature effects

When any attempt is made to artificially cultivate stocks, it is essential to understand the environmental tolerances of the organism to be used. In the shallow sublittoral areas of the west coast of Southern Africa a remarkable combination of environmental conditions exists for the growth of seaweed, essentially as a result of the upwelling conditions which predominate throughout the summer months.

(a) *Gracilaria verrucosa*

Fluctuations in temperature affect the growth rate of plants. For example, Engledow and Bolton (1992) showed that the growth of *Gracilaria verrucosa* maximised at 25°C. At 5° and 10°C, growth rates were shown to be slow and at temperatures >27°C the plants perished after 14 days due to the development of pathogens (disease causing organisms) which thrive at these temperatures (Dring, 1986). It is interesting to note that this optimum temperature of 25°C is considerably higher than the ambient regime at Saldanha Bay, where the mean monthly temperatures range between 13° and 19°C (Greenwood & Taunton-Clarke, 1992 and 1994). A relatively high optimum temperature of 25°C, in the instance of *Gracilaria verrucosa,* is of course, advantageous to any aquaculturist, as cooling is a costly process (Engledow & Bolton, 1992). Not only does the temperature affect the growth rate of this particular red weed, but has also been found to be a significant factor in affecting the yield of agar (Bird, 1988; Lignell & Pedersen, 1989). Bird (1988) has shown that greater gel strength and yield is associated with increasing temperature.

(b) *Ecklonia maxima*

Ecklonia maxima is a slightly more complicated, although one of the fastest growing plants (*Ecklonia maxima* can grow 13mm a day and reach a height of 12m) (Branch, 1994), in that the vegetative growth and reproduction process are affected by temperature in different ways. For example, Bolton and Levitt (1985) have shown the optimum range of vegetative growth occurs between 17,5° and 20°C, and the optimum range of reproduction occurs between 15° and 17.5° C with an upper temperature limit (for reproduction) of 22.5°C. Furthermore, the main effect of sub-optimal temperatures was shown to progressively slow down the rate of egg release, and that of supra-optimal temperatures to increase the number of cells per female. It is of interest to note that the upper limit of 22.5°C is considerably higher than *Ecklonia maxima's* area of natural distribution.

What would seem to be influencing the distribution of *Ecklonia maxima* is the upper temperature limit for growth and/or reproduction of the sporophyte (spore-producing phase), since maximum temperatures of 22,5°C are seldom attained within the distribution limits of *Ecklonia maxima* (see Chap.4 & Chap.5), at which temperature the gametophytes (gamete (sperm and egg)-producing phase) are inclined to grow and reproduce (Bolton & Levitt, 1985, Dring, 1986).

Gracilaria verrucosa, has wider tolerance ranges, a high content of good quality agar (Engledow & Bolton, 1992) and a proven ease of growth in culture in comparison to *Ecklonia maxima*, and is therefore a more attractive option for aquaculture.

6.2.2 AIR-SEA RESCUE

In 1958, South Africa established an effective Search and Rescue organisation in terms of the International Convention for the Safety of Life at Sea and International Civil Aviation Organisation conventions to which it is a signatory (Lt. Col. M. M^{c}Carthy, South African Search and Rescue Organisation (SASAR), 2001 pers. comm). The function of SASAR is to search for, assist, and if necessary rescue survivors of aircraft accidents or forced landings and survivors of maritime accidents within the SASAR region of responsibility (see Fig. 6.4). Rescue operations are coordinated from The Maritime Rescue Co-ordination Centre located in Silvermine Cape Town and, the Aeronautical Rescue Co-ordination Centre located at Johannesburg International airport. From this point on only maritime SARs (search and rescue) will be considered.

In planning a successful SAR operation, which commences immediately from the time the incident is reported to the termination of the search, several weather and oceanographical factors are considered (IMO, 1993), for example, present and historical wind data, ocean current data, bathymetry and SST. SST is considered critical, since it is the primary factor determining the life expectancy of any one survivor. This, combined with currents and wind, Any individual submerged in water having a temperature of less than 33°C (i.e. 4°C below body temperature) will immediately start losing heat. As the temperature of the air and water decreases the rate of heat loss increases. The survival time in water temperatures >21°C depends predominantly on the fatigue factor of the individual and his/her ability to stay afloat and fight off sharks. It has been suggested that some individuals have survived more than 80 hours in SSTs >21°C. There is no doubt that during the sinking of the greek passenger liner *Oceanos,* just outside of Coffee Bay, on 4/08/91, warm SSTs ranging between 20° and 22°C were responsible for the survival of many of the people rescued from the water (Hunter *et al*, 1991) – some 10 hours later.

In water temperatures between 16° and 21°C, the temperature of the skin tends to decrease to near water temperature within 10 minutes of entry with shivering and discomfort immediately being experienced by the individual (IMO, 1993; M^{c}Carthy, 2001 pers.comm). With SST between 10°C and 16°C, the individual has a fair chance of surviving provided the rescue is completed within 6 hours (IMO, 1993; M^{c}Carthy, 2001 pers.comm). Only approximately 50% of human beings are able to survive for more than 1 hour in SSTs ranging between 4° and 10°C (ibid). At these temperatures fainting, disorientation, violent shivering, muscle cramps and intense pain in the feet and hands (until numbness takes over) will be experienced by the individual. Anything below 4°C is critical and will more often than not result in fatality due, primarily, to the loss of consciousness and subsequent drowning. M^{c}Carthy (2001) suggests that individuals who die within 10 to 15 minutes after entry into frigid water succumb as a result of the shock caused through the sudden entry into cold water and not the cold water *per se*.

6.2.3 POWER STATIONS

Nuclear Power stations generate approximately 17% of the world's electrical energy (Murray, 1995). Koeberg, South Africa's only nuclear power station, is located in the western Cape where its two reactors supply about 1840 MW of South Africa's electricity needs (Murray, 1995). Although the designs of nuclear power units differ, all create heat by nuclear reaction and use this heat to produce steam from water to drive the generators which produce electricity. The two 920MW units at Koeberg are of the design known as PWR (Pressurised Water Reactors). This means that the reactor core is cooled and moderated by light water and fuelled by enriched uranium dioxide. The PWR coolant is at a very high pressure and a seperate secondary system exists for generating steam to supply the turbine (ibid).

At Koeberg, seawater is used for the cooling process and the heated water discharged, as thermal effluent, back into the ocean via the outfall located south of the breakwater (see Fig. 6.8). It is not surprising that an experimental oyster farm has been sited at Koeberg (see section 6.2.1).

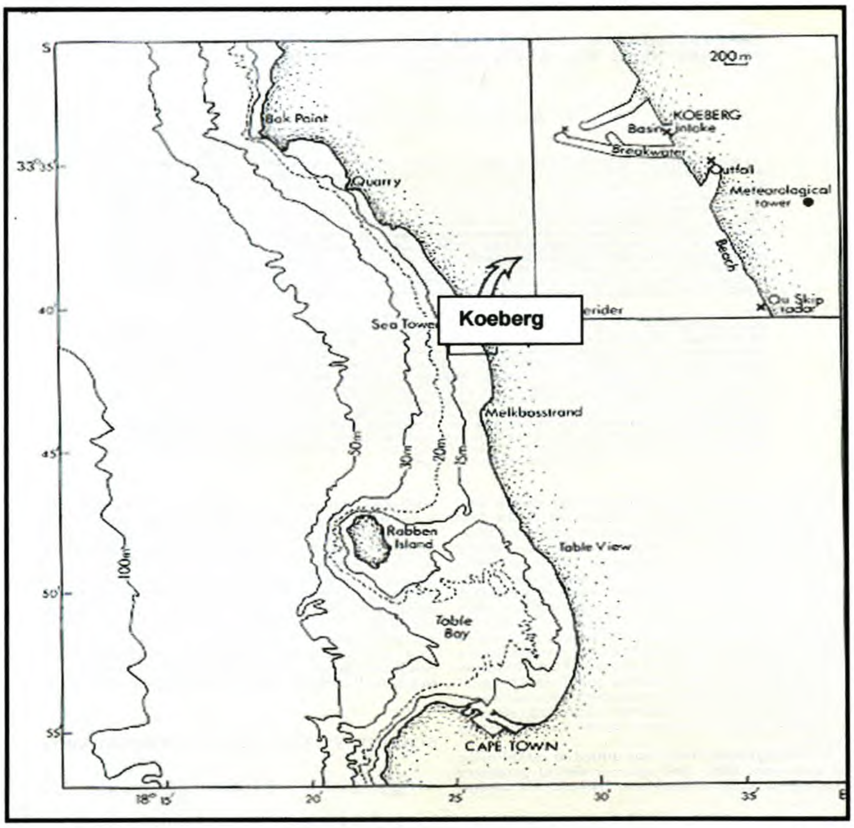


Fig. 6.8 – Chart showing position of outfall at Koeberg (after Jury and Bain, 1989)

6.2.4 FISHING INDUSTRY

This industry is extremely competitive and is constantly striving to maximise its catch per unit of effort. South Africa's fisheries sector contributes R2.5 billion to the economy, which is <0.5% of the GDP (Fisheries Industry Handbook, 2001). Direct employment in this sector is approximately 24 000. At an average of five persons per household, an estimated population of 120 000 is dependent on fishing (ibid). In 1998 South Africa exported 130 299 tonnes of fish products (26% of landings) valued at R1.4 billion (Fishing Industry Handbook, 2001). The trade in fish and fish products between South Africa and the rest of Africa is becoming a more viable option for many South African companies, as tariffs on trading have been reduced in terms of an agreement between SADC countries.

6.2.4.1 Temperature effects

In addition to the response of fish to SSTs, the behaviour of SSTs in response to environmental processes are critical to the success of this industry. The effects of a sudden decrease in SST can either result in the mortalities of fish, or a temporary migration of fish to a more suitable area. Both these scenarios impact negatively on the catch per unit effort.

However, another consideration to the fishing industry is the impact of red tide on fish stocks and therefore, catch per unit effort. Red tide is a well-known marine phenomenon in many parts of the world. The term implies unusually high concentrations of single-celled phytoplankton, in particular the group known as dinoflagellates, which result in a discoloration of the water where it occurs (Wong and Wu, 1987). In several instances red tide is responsible for mortalities of marine life mainly through the depletion of oxygen both directly (through suffocation due to gill clogging) and indirectly, through the detrimental activities of the increased number of bacteria.

Although red tides are common occurrences on the West and South Coasts of Southern Africa throughout the year, they occur more abundantly during late summer and autumn when there is a decline in the frequency of upwelling favourable winds (Brown & Hutchings, 1987). As a result warmer and calmer conditions prevail at the sea surface and, together with the high nutrient concentrations in the upwelled water, dinoflagellate numbers are able to rapidly increase (sometimes to millions of cells per liter of water) into a phytoplankton bloom (Brown & Hutchings, 1987). The concentration of the bloom by wind and currents, as well as the dinoflagellates' ability to swim to the surface result in the formation of a red tide.

Dense concentrations of red tide can suffocate fish by clogging or irritating their gills, so that they cannot extract sufficient oxygen from the water. During 1962, the mortality of more than 100 tons of fish in False Bay was attributed to gill clogging (ibid). Other forms of physical damage include the recently discovered feeding on fish tissue by certain dinoflagellate species resulting in the death of fish within a matter of hours (Wong and Wu, 1987). Such events are now thought to have been responsible for many unexplained fish kills in the past.

Red tides may also kill marine organisms indirectly by depleting the oxygen dissolved in the water. The mortality of the red tide organisms once the nutrients have been depleted results in an increase in the number of bacteria which are responsible for decomposition in the sea (Brown & Hutchings, 1987). The activities of this huge population of bacteria soon deplete the oxygen concentration in the water, leading to the death of other marine animals such as rock lobsters.

During March 1994, for example, SSTs increased from 13°C to 22°C and calm conditions prevailed on the West Coast between St Helena Bay and Dwarskersbos – 30km of coastline. Due to the intensity of the resultant phytoplankton bloom oxygen levels were extremely low in the near-shore zone resulting in mortalities of fish and crustaceans (see Fig.6.11). This "black tide" (so called because the water turns black from the hydrogen sulphide gases released by decaying of marine organisms) resulted in the mortality of between 10 and 12 tons of rock lobster and several tons of fish of all sizes, including sharks (The Argus, 17/03/94). The impact on the local fishing industry in the area was significant. Not only were hundreds of fisherman affected but a fish canning factory at St Helena Bay had to close down because of potential health hazards and another, Westpoint canning factory, had to sell off 60 tons of pilchards as fish meal instead of canning it for human consumption due to a potential health risk (Cape Times, 18/3/1994). The total damage was estimated to be in the region of R75 million (Fishing Industry Handbook, 2001).

At the time scientists from the Department of Environment Affairs and Tourism: Marine Coastal Management section described this event as one of the country's worst marine disasters and estimated that it would take one year for marine populations to recover.

6.2.5 OTHER

6.2.5.1 Angling

Rock and surf angling is a popular activity whether for sporting reasons, as a source of fresh food or to supplement daily income. It is estimated that there are in excess of 380 000 (Bennett, 1991) individuals taking part in this activity around the Cape Coast. The catch per unit effort has been shown (ibid) to be related to the behaviour of SSTs, which can result in anglers having to re-locate to other areas as a result of a lack of bites. For example, during the February 1971 upwelling event off Tsitsikamma (see section 6.1.2(a)), hundreds of anglers relocated to the Storms River mouth area where huge shoals of fish of all sizes and species were found taking refuge from the cold. Another example occurred several years ago, when large shoals of Yellowtail reportedly invaded False Bay and described by the press as "thick enough to walk on". However, at the time, the average SST in the Bay had increased from approximately 14°C to 17°C and as a result there were very few bites. Yellowtail are rarely caught when the SST increases to more than 15°C.

6.2.5.2 Tourism

For many coastal areas of South Africa, tourism provides an important source of income. The consequences of cold water unexpectedly occurring on the beaches for an appreciable time during a vacation period, are significant (Schumann *et al*, 1988). Tourists are always interested in the SSTs of bathing beaches and many plan their trips to the coast accordingly. The SST also plays a role in deciding what gear to take, for example whether to take a wetsuit or not. Indeed, both SATOUR and CAPTOUR include a SST field in their brochures, indicating the significance of this parameter in the tourist industry.

6.2.5.3 Surfing

According to the International Surfing Association, surfers competing in national/international events may not wear a wetsuit if the SST is >16°C. The reason is that a surfer in a wetsuit is more buoyant and streamlined and therefore able to perform better. Prolonged upwelling could, therefore, force the competition to be cancelled or relocated to another area. This can be costly.

6.2.5.4 Thermal desalination systems

In a simple still the heat of condensation is discarded immediately to a cooling system. However, in a multi-effect still, for example a 10 effect still or a 20 effect still, this heat of condensation is re-used in another 'effect' to evaporate more saline water (Dr. B Scheffler, Physics Department, University of Pretoria, 2001 pers. comms). The vapour on condensing can be used to evaporate additional saline water in yet another 'effect'- each 'effect' at a lower temperature than the preceding. The condensing vapour and evaporating saline water are separated by a heat transfer surface. Waste heat from a coastal power station is commonly used for the first 'effect' and seawater is the final coolant to condense the vapour formed in the last 'effect'.

Heat always flows from a higher to a lower temperature, so that each successive 'effect' is at a lower temperature than the previous. The smaller the temperature difference between 'effects', the more, 'effects', are possible for given initial (*highest*) and final (*lowest*) temperatures with more water being distilled per heat input.

6.2.5.5 Shipping

(a) Loadlines and density

Merchant ships often have to measure the density of seawater to determine displacement, draft and tons per centimeter immersion since the gross mass of the ship continually changes as thousands of tons of cargo are discharged or loaded. The loadline markings on a ship indicate the maximum depth to which a ship may be loaded. For example, if the density of the seawater increases the ship becomes more buoyant and can, therefore, carry more cargo. The density of seawater varies with temperature, salinity and pressure, increasing as temperature decreases and salinity and pressure increases. It is common knowledge that all processes that affect the distribution of temperature and salinity also affect the distribution of density. However, although temperature changes in the upper layers of the ocean are rapid, changes in the density are slower.

CHAPTER 7: SUMMARY AND RECOMMENDATIONS

7.1 SUMMARY

In this study an essentially unique set of SST data (collected at several SST measuring sites around the southern African coast) has been used to investigate the spatial and temporal variabilities of SST and the presence of any anomalies around the southern African coast. The investigation was centred on three regions, namely West Coast, South Coast and East coast.

In the analysis of the above data it was possible to determine three distinctly different 'climatological' regions:

WEST COAST REGION - a cooler region, characterised by a cold Benguela Current and seasonal upwelling. In this region the annual and seasonal SST variability was shown to operate within a narrow range (13°C-16°C) of variability due to a stable Benguela Current. However, the west coast region was shown to be more variable from day-to-day as a result of the variability of the wind component, with the occurrence of SST anomalies mainly as a result of shifts in the normal wind patterns.

EAST COAST REGION - a warmer region, characterised by a warm Agulhas Current. In this region the annual and seasonal SST variability was shown to operate within a broader range (17°C-21.5°C) of variability due to an elusive Agulhas Current. However, the east coast region was shown to be more stable and less variable from day-to-day due to the continual transport of warmer waters south from the equatorial regions, and a less variable wind component with the occurrence of SST anomalies as a result of perturbations in the Agulhas Current system.

SOUTH COAST REGION - a temperate region characterised by the South Atlantic and South Indian oceanic circulatory systems and the Agulhas Bank. In this region the annual, seasonal and day-to-day SST variability were shown to operate within an even broader and highly erratic range (15°C-22°C) of variability due to its geographical location, with the occurrence of SST anomalies as a result of the coastal lows.

In all three regions, *albeit* small, it was also possible to determine a high-frequency signal of 12-15 days (with *rms* values between 0.01 and 0.03) and a low-frequency signal of 40-60 days (with *rms* values between 0.01 -0.08). The high-frequency signal was attributed to the possible effects of the coastal low and the resulting cyclones, whereas, the low-frequency signal was attributed to the possible effects of CTW events, or the effects of air-sea interaction through the convection cycle. On the west coast, the low-frequency signal was also attributed to the possibility of Agulhas rings, and on the east coast to perturbations in the Agulhas Current which causes strong variations in the shelf circulation.

Anomalous warm and cold SST events were identified and found to alternate between warmer and cooler events approximately every 4 years. These events showed a tendency to occur particularly during summer and spring on the West Coast, in winter on the East Coast and, approximately every 3 years during summer and spring on the South Coast.

The probability of a day-to-day occurrence of SST anomalies >3°C or >-3°C anywhere along the southern African coast was found to be as low as <1.1%. A 70% probability was found that the SST will change by at least 1°C or -1°C from day-to-day anywhere along the southern African coast.

The effects of SST anomalies on marine life have clearly been shown to be (a) constructive, for example an extended upwelling season experienced on the south coast can result in an abundance of chokka, and (b) destructive, for example the occurrence of mass mortalities of fish and crustaceans as a result of a sudden day-to-day increase in SST, with a resultant red tide.

The applications of SST have been shown to cover a wide range of economic activities such as the aquaculture, fishing, tourism and shipping industries, air-sea rescue operations, power stations, surfing, angling and thermal desalination. The effects of the anomalous behaviour of SST on these economic activities have been shown to be detrimental in most instances. For the aquaculture and fishing industry, in particular, the physical component (SST) and the ecological component are inextricably linked through the amount of product available for harvesting.

7.1.1 Value of thesis

It is no secret that the fastest growing industry in South Africa is the aquaculture industry and that it has enormous economic potential. Recently, parliament approved the establishment of a salmon farm off the southern Cape coast, which clearly demonstrates the acknowledgement on the part of government of this potentially lucrative industry.

Sea surface temperatures are an important parameter where numerous economic activities are concerned. For example, SSTs are paramount in the eyes of aquaculturists. The first reason for this is that the more lucrative species such as abelone take four years before they are marketable. In this regard, and with respect to the SST, by choosing the wrong location for cultivation an aquaculturist could run the risk of becoming bankrupt. The second reason is that, in order for the aquaculturist to get the farm insured, a risk analysis report has to be approved of which SST is one of the main topics.

Therefore, the main value of this dissertation is in its ability to assist, for example, aquaculturists in selecting as secure a site as possible for the cultivation of their selected species. It can do so, firstly, by being able to show the variability of the SST around the southern African coast and, secondly, by being able to highlight the probabilities of change and the risks in the form of anomalous SST events.

7.2 RECOMMENDATIONS

The following recommendations stem from the experience gained in the collection and analysis of these data for this study:

- To generate additional SST measuring sites in the three coastal regions, particularly where measuring sites are sparse;
- To upgrade the existing SST measuring sites with more reliable electronic equipment such as the electronic devices installed at the Port Elizabeth and Koeberg measuring sites. In this way volunteers, who are often unavailable, will not need to be relied upon to measure the SST;
- To institute a system that properly documents the occurrence of fish mortalities; this will assist in obtaining a better understanding of the relationship between the behaviour of SSTs and the impact on marine life, especially their levels of tolerance;
- To generate a map showing the risks and resources around the southern African coast for use, in particular, by the aquaculture industry, which needs to make the correct choices regarding their selection of a site. However, it will be most important to keep the map up to date for it to be of any value. This was attempted by the author, but abandoned due to the difficulties in obtaining worthwhile data regarding the resources, the levels of tolerance of marine animals, and the tonnage produced and the value thereof.

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APPENDICES

APPENDIX A - Physical Factors

A-1 Coriolis force

Coriolis force is the behaviour of moving particles due to the earth's eastward rotation (Barry & Chorley, 1987). Thus, movement of air or water particles (or a bullet) are deflected to the left in the Southern Hemisphere and to the right in the Northern Hemisphere (NH). For example, due to the frictional stress, winds blowing over the surface of the sea drag the water along with it and, Coriolis Force displaces its direction of movement to the left or right. The amount of deflection depends on the velocity of the object and its latitude (ibid). There is no effect from this force between 10°S and 10°N, but polewards from these latitudes the effect varies from about 10° to the left or right of the direction of the wind in shallow water, to 45° in some polar regions of the open ocean. Therefore, the effect is greatest at the poles. Coriolis Force only alters the direction of movement and **not** the momentum.

An ocean current requires the balance of Coriolis Force and a pressure gradient force across it (Grundlingh 1983). In the Southern Hemisphere denser water collects on the right hand or cyclonic side of the current, the less dense water on the left or anticyclonic side (Grundlingh, 1983). Isotherms in the presence of a current are sloped whereas they remain horizontal if the water is motionless. This geostrophic relationship is used in meteorology and oceanography in the form of the thermal wind equation which relates the velocity and temperature fields (Grundlingh, 1983).

$$\partial u/\partial z = g\epsilon/f \times \partial T/\partial x$$

Where: $\partial u/\partial z$ is the vertical gradient of velocity in the downstream direction

$\partial T/\partial x$ is the thermal gradient across the current

ϵ is the co-efficient of thermal expansion

f is the Coriolis parameter

g is the acceleration of gravity

A-2 Ekman Spiral

The frictional force of the wind imparts motion to the surface water which is immediately deflected by the Coriolis Force. This layer in turn imparts motion to the water beneath, again with a deflection. As the movement is transmitted downwards the deflections form an Ekman Spiral. The deepest water may be moving at 180 to the surface flow but the bulk transportation of the ocean water mass, known as **Ekman Transportation**, is at right angles to the direction of the wind.

The Ekman Spiral causes the water of the oceans' current gyres to be piled up in their centres. The centres are offset to the west by the change of Coriolis Force with latitude. A combination of gravity flow down this 'hill' and the Coriolis deflection causes a resultant current flow around the hill called the geostrophic flow.

A-3 Venturi effect

When airflow is constricted in any way, for example, by a mountain barrier, it tends to accelerate (venturi effect) as it moves over the summit of the mountain (Barry & Chorley, 1987). However, friction with the ground also retards the flow compared with the free air at the same level. Over low hills there may be a considerable speed-up of the wind by comparison with the surrounding lowland (ibid).

Similarly, sea breezes (a thermally induced type of air movement) may be greatly increased where a well-marked low-level temperature inversion produces a 'venturi effect' by constricting and accelerating (Barry & Chorley,1987).

In the oceans the warm water is lighter and more viscous than cold water and as a result the warm water travels faster than the cold water. Since the colder water is in contact with the bottom, friction adds to the already retarded flow. Consequently, the faster travelling warm water sets up a vacuum (venturi effect) along the coast, thereby causing cold water to upwell.

APPENDIX B – Upwelling in the Northern and Southern Benguela regions

B-1 Upwelling

Upwelling is a process whereby warm, less dense surface waters diverge horizontally and are replaced by deeper, colder, denser and nutrient-rich waters. This has important consequences for a multitude of trophic systems. First a phytoplankton bloom (microscopic plants) occurs, followed rapidly by higher levels in the food chain (Schumann 1992). Biomass productivity is mainly centred around the upwelling front (Shannon, 1990) thus being of great concern to the fishing industry. Other centres of productivity include continental shelf-edge fronts (Marra *et al*, 1982), deep-sea fronts (ibid) and on the edges of features such as rings/eddies (Olson and Evans, 1986). Numerous studies (Shannon; 1985) have shown these centres of upwelling, in fact, exist. The upwelled water does not always reach the surface and the process may only be partial. This results in a complex water structure detrimenal to sonar operations. Conversely, downwelling is a process whereby surface waters converge and sink, resulting in an increase in SSTs. Dramatic fluctuations as a result of these processes may lead to mass mortalities of those marine organisms which are not able to adapt to such variable conditions.

In the Benguela region the predominant winds are governed by the SAH (South Atlantic High), the pressure gradient over the adjacent subcontinent and by eastward moving cyclones, produced by disturbances on the subtropical jet stream (SNelson & Hutchings, 1983), across the southern region. The SAH persists throughout the year but experiences seasonal shifts in position (centred around approximately 30°S:5°E in summer and 26°S:10°E in winter) and intensity (3-4mb) (Shannon, 1985).

Pressure over the African subcontinent changes profoundly from a well-developed low during summer to a weak high in winter as the ITCZ (Inter Tropical Convergence Zone) shifts northwards (Shannon, 1985). Consequently, the pressure gradient along the western coast is seasonally variable. The curled anticyclonic flow related to the South Atlantic High (SAH) is guided by the coastline due to the desert-like nature of the coastal plain acting as a thermal barrier to cross flow (Nelson & Hutchings, 1983) and by the orography of the continental escarpment. Therefore, winds along the western coast of Southern Africa are primarily southerly and upwelling favourable. Also on a large scale and a feature of virtually the entire Benguela region, is the occurrence of katabatic wind events during autumn and winter (Jackson, 1947). Commonly known as 'Berg winds' and of several days duration, they are related to the formation of a large high pressure system (a precursor to the coastal low) over or slighly south of the southern or southeastern part of the subcontinent. The anticyclonic circulation around the high results in a strong (upto 15m/s or more) east to northeast flow off the plateau of dry adiabatically heated air. Hart and Currie (1960) have suggested that Berg winds are of no consequence over the sea due to their divergence above the marine boundary layer. However, although Nelson and Hutchings (1983) have suggested that on the macroscale Berg winds appear to retard upwelling in the southern region of the Benguela, Shannon (1985) has intimated that they can generate localised upwelling within 10km of the coast.

Land-sea breezes have been found to be common along the coast north of Cape Columbine with the contrast between morning and afternoon winds to be particularly visible at Walvis Bay (Shannon, 1985). Hart and Currie (1960) have shown that there appears to be a marked intensification of the coastal winds during the day with a veering or backing of winds towards the south or southwest (depending on location and season). Jackson (1947) suggested that the sea breeze from its divergence from the southeast trade has a fetch of between 80 and 100 miles over the sea – a proposal supported by Hart and Currie (1960). This diurnal oscillation of winds and the seasonal variation therein appears to be important for the coastal upwelling dynamics for much of the region particularly the northern part (Shannon, 1985).

Hart and Currie (1960) showed how in winter the northward shift of the pressure systems has a pronounced effect in the south where the frequency of the winds with westerly components, i.e. non-upwelling favourable, is significant.

B-2 Northern Benguela

In the Northern Benguela Region (north of approximately 31°S), there's less of a seasonal variation in the wind component. Upwelling is experienced perennially but with a spring – summer maximum as far north as 25°S and, a late winter-spring maximum north of this latitude (Stander, 1964). While the wind off northern and central Namibia shows relatively little seasonal variation, there are nevertheless slight maxima in upwelling favourable winds during April to May and October (Stander, 1963; Boyd & Thomas, 1984,).

During prevalent wind conditions surface currents have been shown in the Northern Benguela, except near the boundary, by Boyd and Agenbag (1984) to be essentially longshore in a northwesterly direction. Their drogue studies around 21°S and 24°S, 46km offshore at a depth of 10m showed relatively constant movement between 10 to 30m/s northwestwards. Boyd (1987) did similar studies over the shelf at 22°S and proposed that currents within 5m of the surface are influenced by the diurnal effects of land-sea breezes, responding within a few hours. The average surface current was shown to be between 10 to 15cm/s and 1.7% of the wind speed. Boyd also noted an obvious shear between the surface currents and those at 20 and 30m. Hagen (1984) - who supported his study with data from four current meter moorings and a cross-shelf transect between 20°S and 21°S consisting of 15 stations 10km apart repeated 15 times at 36hr intervals during autumn 1979 - identified that within 100km of the coast, the longshore current and the appropriate baroclinic mass field behaved hydrostatically with less than a day lag to the variations in the longshore component of the local wind.

Generally, off central Namibia the maximum depth affected by upwelling is not much more than 200m (Hart & Currie, 1960; Stander, 1964). However, at 17°S it appears that the upwelled water originates from a depth of 100m or shallower (Shannon, 1985).

The interaction between the Benguela and warm Angola systems in the most northern region of Benguela is extremely complex and beyond the scope of this study. However, the flow in the upper 100m in this region of the Benguela is schematically illustrated in Figure B.1 as suggested by Boyd (1987).

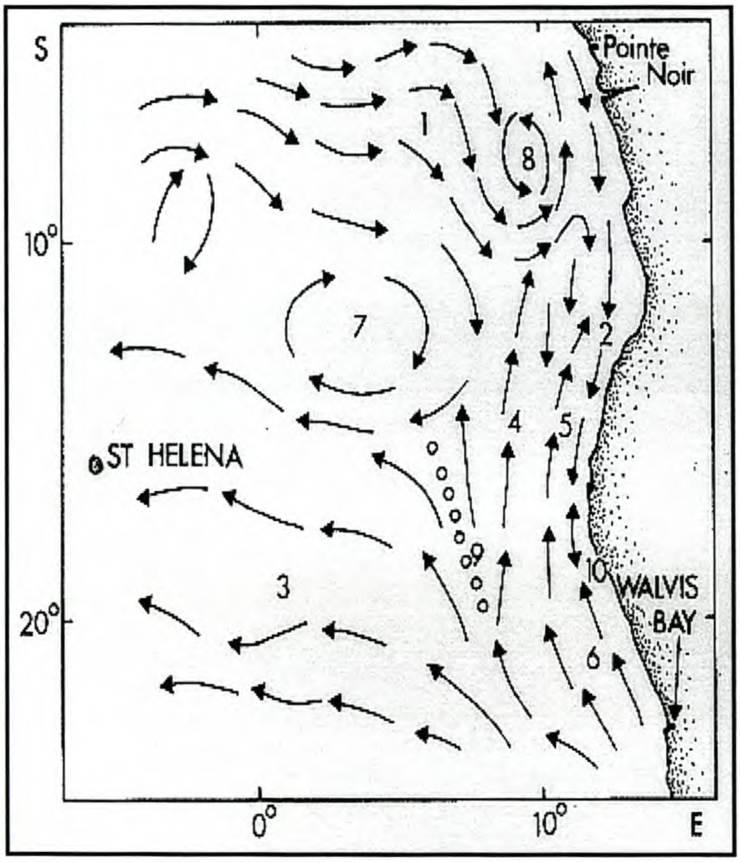

Fig.B.1 – Geostrophic water circulation between 0-100m off Angola and Namibia (after Boyd, 1987) – 1, South Equatorial Countercurrent; 2, Angola Current; 3, West branch of Benguela Current; 4/5/6, North branches of Benguela Current; 7, Eddies in inner region of cyclonic gyre; 8, Anticyclonic curl; 9, Benguela divergence; 10, merging zone of Angola Current and north littoral branch of Benguela Current

B-3 Southern Benguela

Wind induced upwelling in the Southern Benguela Region is highly seasonal and reaches a maximum during spring and summer (Shannon, 1966; Andrews & Hutchings, 1980) with the extent of the upwelling season is from September to March (Andrews & Hutchings, 1980). In the Southern Benguela the, on average, weekly passage of eastward moving cyclones south of the continent play an important role in regulating the wind component with an intensity which increases southwards from the Olifants River to Cape Point (Nelson & Hutchings, 1983). The possible effect in the summer months is a periodic weakening of the SAH and, therefore, a relaxation of southeast winds along the coast. However, the effect may possibly be strong to excessive gale force northwest to southwest winds of maybe hours duration in cycles of 3 – 6 days (ibid). In association with the approach of cyclonic systems, particularly in summer under conditions of a weakened SAH, is the development of low pressure cells near Luderitz (Taljaard *et al,* 1961) which migrate southward round the subcontinent as trapped waves at a speed of approximately 750km/day. Local upwelling in the areas affected by the migrating cells is retarded as a result of the cyclonic rotation of air about these cells (Nelson & Hutchings, 1983).

Generally, the Southern Benguela upwelling system is largely affected by three factors, *viz.* Mesoscale atmospheric perturbations, topography and the influence of the Agulhas Current system. Wind reversals are typically responsible for regulating the system with a period of approximately 6 days which are superimposed on the seasonal cycle being more defined in the Cape Peninsula and Agulhas Bank regions than in the north (Shannon, 1985) – the seasonal wind stress curl diagrams of Kamstra (1987) are a striking illustration of this.

In summer the divergent wind component dominates the southwest Cape particularly immediately west of the Cape Peninsula, whereas, in winter a broad convergence zone occurs south and east of the Cape Peninsula with subsidiary zones in Table and St. Helena Bays (Shannon, 1985).

The Southern Benguela Region is also characterised by an erratic coastline with several capes and bays, a marked change in general orientation at Cape Point (south of 34°S) and, in places, mountain ranges close to the coast. These topographic features shear the wind stress component resulting in the alongshore variability in the coastal upwelling (Jury, 1984). However, this is also regulated by the intrusions of Agulhas Current water which appear off the West Coast as either shallow tongues or advected eddies with time scales ranging from a few days to several months.

It is well established that the Cape Peninsula and Cape Columbine are important upwelling cells in the Southern Benguela, their tongue-like nature first noted by Andrews and Cram (1969). Like the northern extremity the southern extremity too is influenced by a warm water regime. Both these boundaries can be, in many ways, mirror images oscillating seasonally but out of phase by a few months (Shannon, 1985).

In comparison with the offshore temperature gradients which appear to be stronger, particularly in summer and autumn south of Walvis Bay, the longshore gradients are weak - 1°C or less per 1° latitude). Offshore in the southern most part of the Benguela the warmer surface waters (>16°C in winter, >20°C in summer at 20°E) have characteristics of South Atlantic and South Indian subtropical water (Shannon, 1985). These waters are advected around the Cape during the upwelling season (Shannon, 1966; Shannon, 1985) and can result in the magnification of the horizontal frontal thermal gradients in the Cape Peninsula and Cape Colimbine upwelling regions (Bang & Andrews, 1974; Lutjeharms & Valentine, 1988). While there appears to be uncertainty as to the contribution of the Agulhas Current water *per se* to the Benguela system there is consensus that, that of Agulhas Bank water is substantial and that the region is of great importance to the Benguela ecologically.

During winter the Agulhas Bank is characterised by very strong winds (Parrish *et al*, 1983) which coupled with diminshed stability assists mixing to a depth of at least 75m (Pugh, 1982) and, at times, throughout the water column. A strong thermocline at approximately 50m is established during summer and autumn which depends on wind speeds >20m/s to erode it (Pugh, 1982). Over the Bank net currents have been shown to be weak although, indicate strong diurnal activity (Shannon, 1985) with a suggested residence time of water on the Bank as long as several weeks.

During spring on the western side, cold water moves up onto the shelf (Nelson & Hutchings, 1983) and remains there until autumn when upwelling of central water occurring close inshore west of Cape Agulhas reaches, at times, as far east as Algoa Bay (Schumann, Perrins & Hunter, 1982). Therefore, as in the northern Benguela-Angola system region, the interactions between the Benguela and Agulhas systems can extend over a distance of approximately 1000km.

Numerous studies (e.g. Shannon, 1985) have shown upwelling cells to exist. However, only those identified as the most dominant upwelling cells have been described below.

B-4 Luderitz upwelling cell

Luderitz, situated in the middle of the Benguela region, has been identified by several authors (e.g. Parrish *et al, 1983*) as the predominant upwelling centre of the Benguela. Stander (1964) has shown that between the Orange River mouth and Luderitz, upwelling continues all year with a minimum during autumn and a maximum during summer. This is consistent with Bailey's (1979) study several years later on the mean monthly winds favourable for upwelling at Luderitz. Bailey showed how the southerly coastal winds blew constantly all year with a minimum between May and July and a slight maximum during the last quarter – the wind speed maximum located 50km, possibly more, offshore. Also, he reckoned that the Luderitz area experienced prolonged upwelling events similar to those off Peru and northwest Africa, as opposed to those off Oregon and in the Southern Benguela.

Characteristic of the Luderitz upwelling cell and related to a southward flow north of 25°S is a large eddy concentrated around 26°S to 27°S (Hart & Currie, 1960; Stander, 1964; Bang, 1971; Bailey, 1979). Using longterm wind data recorded at Luderitz Bailey (1979) observed that during certain years and subsequent to strong southerly winds in December to January warmer water appeared in January to March.

Figure B.2 shows the temperature distribution at 0, 200 and 400m off Namibia during January 1960 (from Stander, 1964). Immediately evident is the effect of the Luderitz upwelling cell on the Benguela system, its spatial scale and the convergence zone at 22°S to 24°S between the tongue and the northern Namibian region. Both Stander (1964) and, Nelson and Hutchings (1983) have inferred the possibility of wind induced upwelling being enhanced by the bottom topography in the area. However, off Namibia surface and subsurface flow patterns have been shown by Stander (1964) to differ significantly. Boyd and Agenbag (1984) have implied that the topography off Namibia is not a good indication of surface currents as the upper 20m has been consistently shown to be essentially wind driven (Boyd & Agenbag, 1984; Hagen, 1984). It has also been shown (Stander, 1963) that it is this surface layer where most of the short-term variability occurs. During winter and spring, the primary upwelling season (Stander, 1964; Shannon, 1985) the upper 50m is well mixed. However, in summer and autumn stratification is increased due to t slackening of the wind, insolation and advection.

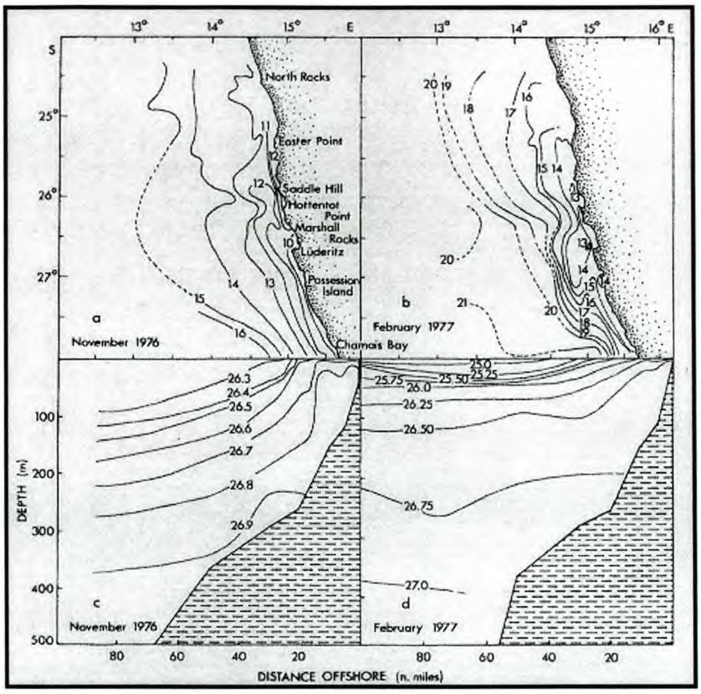

Fig. B.2 – Temperature at 0,200 and 400m off Namibia during January 1960 (after Stander, 1964)

It appears that the depth from where the upwelled water originates is between 200 and 325m (Hart & Currie, 1960; Stander, 1964; Bailey, 1979) with the strongest upwelling found to be close to the shelf break and in the order of 3.5 – 4.7 x 10^4cm/s (Shannon, 1985).

B-5 Cape Peninsula upwelling cell

By far the most impressive upwelling area in the world it is situated where the eastern boundary current system is bordered by a warm water regime on its poleward side (Shannon, 1985). It is a region where bottom topography and orographically induced wind curl is significant as Ekman divergence in determining the upwelling process. It is also a region where the wind component is regulated on a time scale of days as well as seasonally and, where upwelling occurs on spatial scales from >1km to tens of kilometers responding in a matter of hours to changes in the wind (Shannon, 1985).

The upwelling season off the Cape Peninsula extends from September to March (Andrews & Hutchings, 1980), with maximum upwelling favourable winds in November and March at Cape

Point. Particularly near Cape Point, cold water is 'ready' at subsurface depths close inshore as a result of the deep shelf break, which is convoluted by the Cape Point Valley, and the narrow nature of the shelf itself (Nelson, 1985). Local zones of strong wind curl and divergence are created by Table Mountain which stands secluded to the flow of southerly wind (Nelson, 1985). Nelson (1985) has proposed that there are four definable categories of atmospheric events, *viz,* deep southeaster, shallow southeaster, northwester and coastal low. The characteristics of the wind component around the Cape Peninsula have been described in detail by (Jury, 1980, 1984) who made extensive use of the data collected during the CUEX (Cape Upwelling Experiment) study and are briefly summerised below.

The onset of southerly winds with wind speeds at their maximum north of the Cape Peninsula, superseding the passage of a cold front, initiates upwelling off the northwestern Peninsula, entrains oceanic water and compresses the oceanic thermal front against the coast in the south. The moving anticyclones passing south of the region generate deep (2000m) air flow from 160° when they are supported by an upper air ridge. This 'deep southeaster' accelerates, due to the topography over the Cape Peninsula, resulting in the growth of upwelling and the formation of distinct tongues below the wind jets in Table Bay and, immediately south of the Table Mountain chain (e.g. Bakoven) as well as at other localities further south along the 60km Peninsula mountain range.

As the SAH ridges around south of the country the influences of the orography are magnified due to the effect of the depressed inversion layer which leads to the formation of a wind shadow zone north of the Peninsula and cyclonic wind vorticity. During this 'shallow southeaster' stage the upwelling tongue and thermal oceanic front progress westwards and southwards. The final stage is the formation of a coastal low and the approach of the next cold front resulting in wind reversals and northwesterly winds which cause a relaxation in the upwelling and compression of the thermal oceanic front over the shelf region (see Fig. B.3).

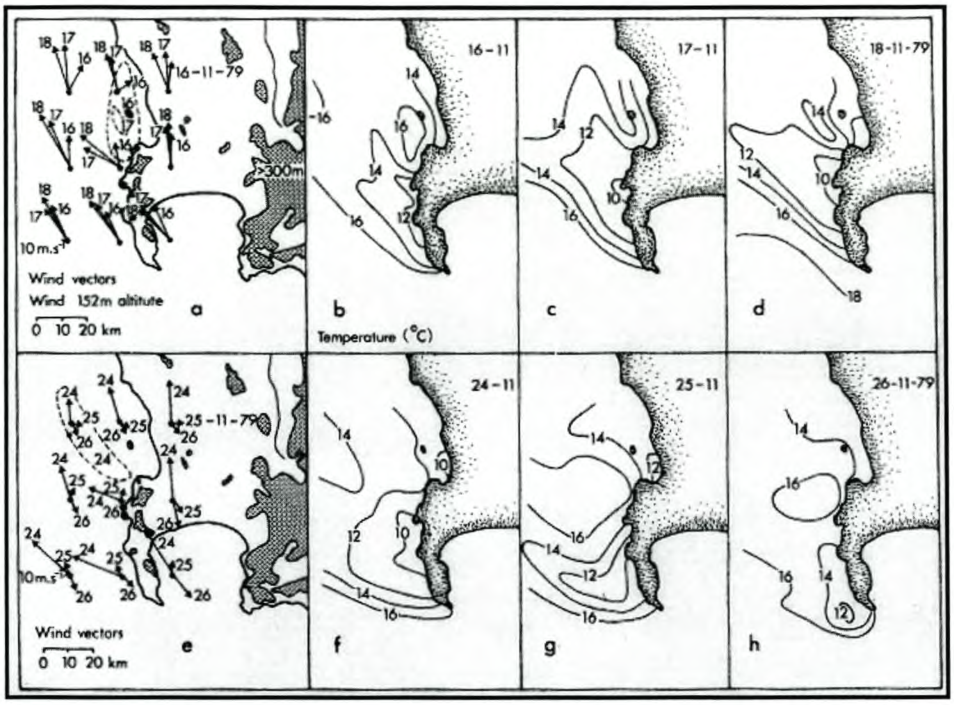

Fig.B.3 – Growth and decay of upwelling off the Cape Peninsula (after Jury, 1984)

It appears that within a five day period of vigorous upwelling (Shannon, 1985) a well-developed front establishes itself over the shelf break west of the Cape Peninsula, thereby, forming the seaward boundary of the coastal upwelling region (Duncan, 1964; Bang, 1973; Shannon *et al.*, 1981). Brundrit (1981) has suggested that once established, its main features could continue for the entire upwelling season, particularly at subsurface depths.

During the summer months the Cape Peninsula is characterised by a semi-permanent tongue or 'plume' (Andrews & Hutchings, 1980). Its surface features are obscured during northwesterly winds and during winter disappears completely (ibid). Some authors (e.g. Shannon *et al*, 1981) have shown that this surface front persists during winter and during periods of prolonged downwelling. At shallow depths (50 – 100m or less) off the Cape Peninsula temperatures of 9 - 10°C are nearly always present shorewards of the front even during winter, suggesting that upwelling can be switched on and off by the wind instantaneously (Shannon, 1985). The existence of an equatorward jet (approximately 50cm/s) appears to be a well established (confirmed during CUEX) feature over the shelf break.

The dynamics of False Bay which forms the eastern seaboard of the Cape Peninsula does not appear to have any major impact on the upwelling system (Shannon, 1985).

B-6 Cape Columbine upwelling cell

Similar to the Cape Peninsula, upwelling in the Cape Columbine region is to a large extent controlled by the bathymetry and the orographic impact on the wind component (Shannon, 1985). Kamstra (1987) has shown that during summer the winds around Cape Columbine, and into St. Helena Bay, are cyclonic with an area of strong divergence north of 31°S. Since the region between 31°S and 33°S is midway between the area of winter westerlies in the south and the perennial southerly winds north of 31°S it was not surprising that the winds during winter were somewhat confused.

The growth and decay of the Columbine tongue and coastalupwelling during a summer wind cycle is illustrated in Figure B-iv. The bending of the narrow tongue around the Peninsula is clearly evident. The characteristics of the surface layer (upper 20-30m) are influenced locally by the inflow from the Berg River during winter and in summer by insolation, however, studies have shown that the latter does not account for the rapid warming noted on occassions (Shannon, 1985).

It has been suggested that the rate of upwelling at Columbine is of the same order as off the Cape Peninsula *viz* a maximum of around 20m/day, the upwelled water originating from depths of 100-300m (Clowes, 1954).

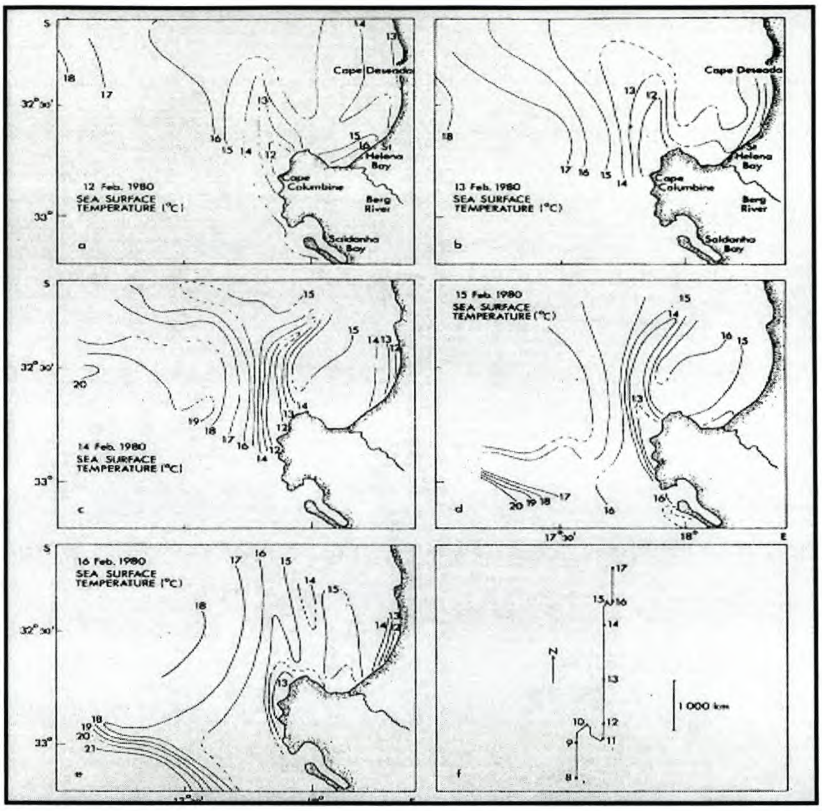

Fig.B-iv – Changes in the Columbine upwelling tongue in response to local winds (after Shannon, 1985)

Shannon (1985) has shown that there is a perennial net southward flow occurring at depths below 80m west of Cape Columbine over periods longer than 10 days – again, evidence of the existence of a **poleward** current. Also, his results depicted a maximum current speed during winter, 14cm/s on average with occassional bursts of upto 50cm/s, and a minimum of 6cm/s during summer. Current studies done during June 1975 (Shannon, 1985) showed southwrad or southwesterly flow of between 10-60cm/s throughout the water column under northerly conditions.

In view of the above, a study done during September 1974 (Shannon, 1985) in southerly wind conditions, the currents proved to be equatorward and barotropic at approximately 50cm/s, thus, showing **no** evidence of any poleward subsurface current. An experiment in November 1975 (Shannon, 1985) in strong southerly wind conditions, surface flow was typically >50cm/s northwards with the strongest jet (upto 135cm/s) immediately west of the Columbine tongue. Similar resluts were found by Clowes (1954).

Therefore, it appears that there is a northward acceleration of flow within 30km of Cape Columbine which is presumed to be strongest near the surface during summer, especially during strong southerly wind events, which, accelerate the development of the Columbine upwelling tongue (Shannon, 1985).

APPENDIX C – Cyclical Phenomena

C-1 ENSO (El Nino Southern Oscillation)

Every year in the eastern Pacific, starting at Christmas and lasting a few months (Shannon *et al*, 1990), trade winds from the east pile warm water in the western Pacific around Indonesia. As a result, the SST in this region increases by approximately 8°C (Pinet, 1999) while the SST off South America cools in response to the occurrence of upwelling, thereby, sustaining high levels of primary productivity, marine diversity and fisheries. In contrast to the eastern Pacific where conditions are dry, in the western Pacific in response to the rising air from the warmer waters rainfall is found. Sometimes the winds reverse and blow towards the east instead (Pinet, 1999) shifting warm waters towards the central Pacific. Every, approximately, three years (Shannon *et al*, 1990) enough water is moved to the east to cool the waters and lower the pressure in the west (Pinet, 1999). Consequently, winds blow less strongly towards the the west (ibid), more warm water advects east and upwelling along the South American coast is retarded. At this time a depression in the thermocline in the eastern Pacific and an elevation of the thermocline in the west is experienced.

This continuous action strengthens itself and at times persists into the next upwelling season (Shannon *et al*, 1990) - this being a well developed El Nino. Although the seasonal event was initially referred to as El Nino, it is now only these extreme events which are termed El Nino or ENSO (Shannon *et al*, 1990).

C-2 Benguela Nino

Shannon *et al* (1990) have suggested that the South Atlantic experiences an event analogous to the Pacific ENSO which manifests itself as an episodic extreme warming in the tropical eastern Atlantic and the advection of tropical water southwards along the coast of Namibia. Referred to as Benguela Ninos, various authors (Stander & De Decker, 1969; Boyd & Thomas, 1984; Shannon, 1990) have studied these events in detail which are superimposed on the normal annual cycle.