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Remotely sensed variability of temperature and chlorophyll in the southern Benguela: upwelling frequency and phytoplankton response

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High-resolution (1km) satellite data from the NOAA AVHRR (Advanced Very High Resolution Radiometer) and OrbView-2 SeaWiFS (Sea-viewing Wide Field-of-view Sensor) are used to investigate the upper layer dynamics of the southern Benguela ecosystem in more detailed space and time scales than previously undertaken. A consistent time-series of daily sea surface temperature (SST) and chlorophyll *a* concentration images is generated for the period July 1998–June 2003, and a quantitative analysis undertaken. The variability in SST, upwelling and phytoplankton biomass is explored for selected biogeographic regions, with particular focus on intra-seasonal time scales. The location and emergence of upwelling cells are clearly identified along the length of the southern Benguela, being distinct on the narrow inner and the mid-continental shelves. Most notable is the rapidly pulsating nature of the upwelling, with intense warm/cold events clearly distinguished. The phytoplankton response to this physical forcing is described. Chlorophyll concentration on the inner shelf largely mirrors the pattern of SST variability, similarly dominated by event-scale processes. Over the mid-shelf, higher chlorophyll is observed throughout all seasons, although low biomass occurs during winter. The variability of the offshore extent of SST and chlorophyll is identified at locations of differing shelf width. Cooler upwelled water is confined primarily to the narrow inner-shelf, with event-scale pulses extending considerable distances offshore. Agulhas Current influences are readily observed, even on the Cape Peninsula inner-shelf. Chlorophyll concentrations vary considerably between the locations of differing shelf width. SST, upwelling and phytoplankton indices are derived for selected locations to quantify the intra-seasonal variations. The SST indices show marked temperature changes associated with rapid pulsation on the event scale. No strong seasonal signal is evident. In contrast, the upwelling indices display a strong seasonal signal, with most intense upwelling occurring in spring/summer in the south. The phytoplankton response to the seasonal upwelling index differs between the selected locations. This study concludes that, although low-resolution SST and chlorophyll data may be useful for investigating general patterns over large scales, higher resolution data are necessary to identify finer scale spatial and temporal variability, especially in the inshore coastal zones.

Keywords: Benguela, chlorophyll, phytoplankton, sea surface temperature (SST), SeaWiFS, upwelling

Introduction

The oceanography of the Benguela region is dominated by coastal upwelling, the extent and intensity of which is primarily determined by the wind and pressure field (Nelson and Hutchings 1983). This, together with the topography and orientation of the coast, results in the formation of a number of upwelling cells (Hutchings 1992, Shannon and Nelson 1996). The largest upwelling cell off Lüderitz is perennial in nature and effectively divides the Benguela into two regional ecosystems, the northern Benguela and the southern Benguela (Sherman 1999). The thermal characteristics of the Benguela ecosystem are illustrated in Figure 1.

Upwelling in the southern Benguela tends to be short-lived and seasonal. A frontal zone is usually well defined and, although variable, generally coincides with the shelf edge (Shannon and Nelson 1996). Upwelling filaments may occur with a lifespan of days to several weeks. These are generally orientated perpendicular to the coast and cause the front to become highly convoluted (Shannon and Nelson 1996). The southern boundary of the Benguela is considered to be the Agulhas retroflection, which is generally between 36°S and 37°S (Shannon 1985, Shannon and Nelson 1996). Warm subtropical Agulhas water ‘leaks’ into

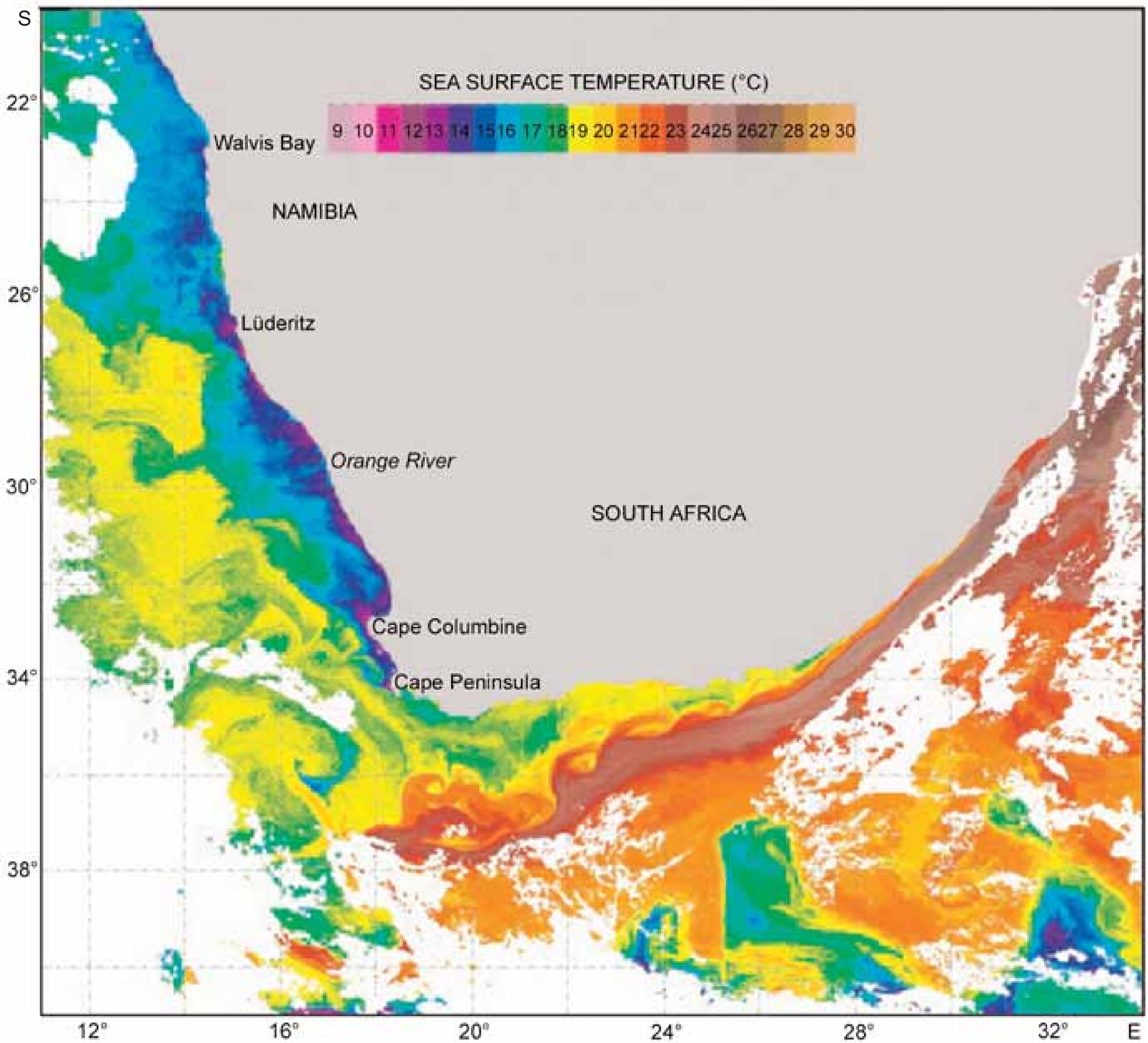

Figure 1: NOAA AVHRR sea surface temperature image for 15 May 2003 showing the cool Benguela ecosystem extending along the west coast of southern Africa, with the warm Agulhas ecosystem on the south-east coast

the south Atlantic, mostly in the form of Agulhas rings, eddies or filaments shed from the Agulhas Current as it retroflects to the east (Duncombe Rae 1991, Nelson *et al*. 1998, Garzoli *et al*. 1999). The Benguela system therefore displays substantial short-term seasonal and inter-annual variability that impacts significantly on its biological resources.

The high rate of upwelling in the Benguela is reflected in very high primary production. As the upwelled water moves offshore, it warms up and with a rich supply of nutrients in the surface layer, phytoplankton growth commences and blooms occur. Phytoplankton abundance is, however, highly variable, with low values around 27°–28°S at the base of the Lüderitz cell and high values downstream of upwelling cells. In the southern Benguela, maximum phytoplankton concentrations are considered to occur 20–80km from the coast, although blooms following periods of active upwelling can extend 100km or more offshore (Brown *et al*. 1991). Chlorophyll *a* concentrations in recently upwelled water, maturing upwelled water and aged water are documented as <1mg m^{-3}, 1–20mg m^{-3} and 5–30mg m^{-3} respectively (Barlow 1982). Average primary production estimates for the northern Benguela are 1.2g C m^{-2} day^{-1} and 2.0g C m^{-2} day^{-1} for the southern Benguela (Brown *et al.* 1991).

Present understanding of the functioning of the Benguela ecosystem is based on data collected mostly from research cruises and the use of low-resolution (4–18km) satellite data. Results of shipboard studies in the Benguela have suggested a varying response of phytoplankton to upwelling, but such investigations have been confined to microscale areas. Although *in situ* data may be of very high quality, synoptic coverage of the ecosystem is not achieved. Conversely, low-resolution satellite data may provide broad synoptic coverage, but exclude the detailed temporal and spatial variability of upwelling and of phytoplankton response that occurs in the Benguela. Higher resolution (1km) data from satellites that provide daily synoptic coverage of the ocean have been acquired locally since 1988. Exploitation of such data, in particular from the NOAA AVHRR (Advanced Very High Resolution Radiometer) and the OrbView-2 SeaWiFS (Sea-viewing Wide Field-of-view Sensor), offers the opportunity of investigating the upper layer dynamics of the Benguela ecosystem in more detailed space and time scales than has previously been undertaken. In particular, a study of the mesoscale upwelling events and consequent phytoplankton response in the Benguela using the higher resolution data would improve knowledge of the key processes that drive the Benguela ecosystem.

This study focuses on the quantitative analysis of 1km-resolution NOAA SST and SeaWiFS chlorophyll data within the southern Benguela ecosystem. The extent and frequency of upwelling during the period July 1998 through June 2003, and the response of the phytoplankton community, are examined. The particular focus is the spatial and temporal variability in SST, upwelling and chlorophyll *a* concentration on intra-seasonal time scales. These aspects are addressed by comparing the differences in variability of upwelling and phytoplankton biomass between various biogeographic regions in the southern Benguela, namely the Cape Peninsula, Cape Columbine and Namaqua shelf upwelling cells, St Helena Bay and the western Agulhas Bank (Figure 2a). Further to examining these dynamic variations in upwelling and phytoplankton is the development of appropriate indices to quantify the intra-seasonal variations. This is initiated by deriving indices of SST variability, upwelling intensity and chlorophyll variability for selected latitudinal lines in the southern Benguela.

Material and Methods

A study of the dynamic variations in upwelling intensity and phytoplankton biomass requires a consistent time-series of sea surface temperature (SST) and chlorophyll *a* concentration images from NOAA AVHRR and SeaWiFS satellite data respectively. High-Resolution Picture Transmission (HRPT) 1km-resolution data from these satellites are acquired locally by the Council for Scientific and Industrial Research (CSIR) Satellite Application Centre located close to Pretoria, South Africa. For the purpose of this study, HRPT NOAA AVHRR and SeaWiFS 1km data are referred to as 'high-resolution' data, although with the advent of even higher resolution commercial satellite imagery (e.g. Landsat, Spot or Ikonos at 30m, 20m and 4m resolution respectively), the data may well be more correctly referred to as being of moderate resolution. Both the commercial cost and the longer re-visit times of the higher resolution satellite data precluded these data from being suitable for a long-term study requiring daily synoptic coverage of the ocean.

The generation of high quality imagery was primary to this study. Daytime NOAA AVHRR SST images for the Benguela region were generated locally using the standard MultiChannel Sea Surface Temperature (MCSST) algorithm (McClain *et al*. 1985). Consistent parameters were applied, although a daily manual manipulation of Channels 2 and 4 was required for optimal cloud removal, and the minimum solar reflection angle was manipulated to limit sun glint in regional waters (Weeks 2005). The standard SeaWiFS bio-optical algorithms and processing parameters are not ideal for the high productivity waters of the Benguela, having been determined for application to the global dataset and generally open water 'Case 1' conditions. Hence, an intense study was undertaken, in close collaboration with the SeaWiFS Project at NASA, to determine optimal HRPT processing parameters for application to Benguela regional waters, both qualitative, for event-scale phenomena, or quantitative, for a long-term time-series study. Using the most recent operational parameters (algorithms, flags and masks) as a baseline, numerous conditions were tested, and control parameters and thresholds manipulated, to optimise SeaWiFS data quality and data retrieval. *In situ* chlorophyll data from Benguela waters were used to validate the determined processing parameters. This work is described in detail in Weeks (2005). Thereafter, a full reprocessing of local SeaWiFS HRPT data was undertaken.

Consistent HRPT time-series of both NOAA AVHRR SST and SeaWiFS chlorophyll *a* concentration were generated for the period July 1998 through June 2003. The products were projected to a cylindrical equirectangular projection such that each pixel represents 0.0104° of latitude and longitude. Southern Benguela SST and chlorophyll time-series were generated by extracting data from the daily five-year NOAA and SeaWiFS time-series to include the region 29°–36°S and 15°–21°E (672 lines by 576 pixels). Missing data do occur on some days owing to cloud, incomplete coverage of the region by the satellite, or data flagged for conditions as outlined in Weeks (2005). Data retrieval at such pixel locations is considered inaccurate and was hence omitted from further analysis. Additionally, there are occasional days in the extracted time-series (8.4% for SST, 11.7% for chlorophyll) where no high-resolution data are available for this region, owing to the position of the satellite zenith angle for a particular orbit swath of the day or because of problems with the satellite acquisition system. Therefore, limited spatial and temporal interpolation was applied to attain the minimum of data detail loss, while simultaneously filling in missing data where possible.

For the spatial interpolation, a spatial fill was applied to each individual daily image using a mean box function to fill missing data only. All original valid ocean data values were retained. For the temporal interpolation, alternative approaches were discussed and trials run wherein different temporal weightings were applied to images over running three- and five-day periods (for example, $^1/_7$, $^5/_7$, $^1/_7$, and $^1/_{24}$, $^3/_{24}$, $^{16}/_{24}$, $^3/_{24}$, $^1/_{24}$). The trials tested both interpolations (a) of missing data only and (b) of all ocean data. The interpolated time-series were assessed, both by image-to-image comparison and by animating alongside the original non-

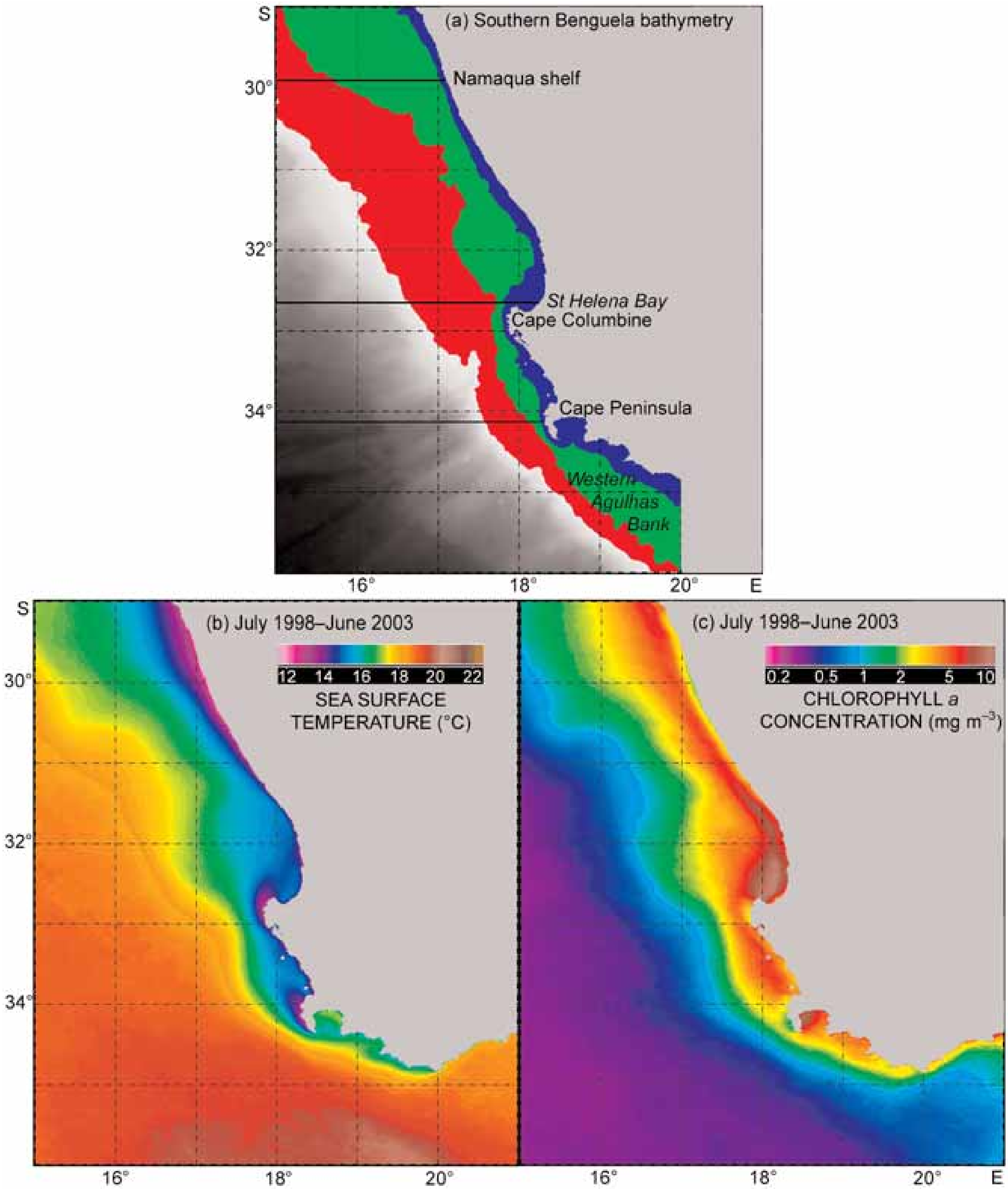

Figure 2: (a) Southern Benguela bathymetry: inner shelf: 0–100m (blue), mid-shelf: 0–200m (green), and outer shelf: 200–500m (red), (b) mean SST for July 1998–June 2003 and (c) mean chlorophyll for July 1998–June 2003. The three key latitudinal lines, for which the Hovmöller latitudinal plots were generated, are overlaid on the bathymetry map

interpolated data series, to ultimately select the result that most closely represents the expected value while optimally filling missing values. It was necessary to take into account both the rapid variation in physical dynamics and the associated phytoplankton response, particularly during periods of active upwelling. At such times, a temporal mean over the shortest time period appeared obviously preferable. On account of, in particular, the patchiness of the resultant high phytoplankton biomass, it was determined that a temporal interpolation over no longer than three days and for all the ocean data was optimal. The evaluation determined that optimal results were obtained by applying to the original daily images:

(1) a spatial fill per image for missing ocean data using a mean box function of size 7 x 7 pixels, requiring a minimum of 50% good valid pixels. All original valid ocean data values were retained, and then
(2) a three-day temporal interpolation on all ocean data using a $^1/_7$, $^5/_7$, $^1/_7$ weighting.

Thereafter, three- and five-day arithmetic means were generated from the daily interpolated time-series. There were two periods during which a number of daily images were missing, namely SST for 16–21 November 1998 and chlorophyll for 14–21 September 1998, and hence consecutive means could not be generated for these periods. Subsequent results obtained from these periods should therefore be considered with caution. Monthly, annual and five-year means were also generated. However, original non-interpolated data were used for the generation of these longer period means. The implication of the three-day sampling is such that the shortest period that can be adequately resolved is of the order of 10 days or more (Emery and Thomson 2001). Synoptic-scale three- to seven-day events are excluded and hence caution must be applied in interpreting the processes giving rise to any one signal. For the purpose of this study, the event scale refers to short-term intra-seasonal events.

Because the exploitation of high spatial and temporal resolution NOAA and SeaWiFS data are primary to this study, further work discussed in this paper focuses on using the three-day mean images. The relevant five-year time-series, extending from July 1998 to June 2003, comprised a total of 610 three-day mean files for each of the SST and chlorophyll parameters.

Results

The upwelling processes in the southern Benguela are influenced to a large degree by bottom topography — this is clearly illustrated by comparison of the bathymetry of the region (Figure 2a) with the five-year mean (July 1998–June 2003) SST and chlorophyll images (Figure 2b, c). Therefore, a first assessment of the dynamic variations in SST and chlorophyll in this region was undertaken by examination of these parameters over different depths of the continental shelf. Hovmöller (1949) shelf width-averaged plots were generated for the inner, mid- and outer continental shelves of the southern Benguela comprising latitudinal mean shelf width values of the parameters over time.

Bathymetric influence — Hovmöller shelf width-averaged plots

The bathymetric file for the region of interest (Figure 2a) was generated from the 2-Minute Gridded Global Relief Data (ETOPO2; http://www.ngdc.noaa.gov/mgg/fliers/01mgg04.html) at a 2nm resolution, and projected to a cylindrical equirectangular projection so as to exactly coincide with that of the SST and chlorophyll time-series. A high resolution (900m) continental outline (CIA Database, http://oceancolor.gsfc.nasa.gov/seadas/) was overlaid on the bathymetric data and the data manually corrected so as to accurately reflect the landmass outline. Coastal bays and islands were masked to exclude them from any computation. Similarly, data eastwards of 20°E were excluded from the analysis, 20°E being regarded as the eastern limit of the southern Benguela upwelling system. The 100m and 200m contours were then refined according to detailed local surveys (Marine and Coastal Management, Cape Town). The inner continental shelf was defined as the area with water depth at or <100m, the mid-shelf for depths of 100–200m, and the outer shelf for depths of 200–500m.

Latitudinal and temporal patterns of SST and chlorophyll variability for the inner, mid- and outer continental shelves are illustrated in Figure 3. These Hovmöller plots (hereafter referred to as shelf width plots) were generated from the three-day mean time-series to include data from 29.00°S in the north to 35.18°S, the latter being the southern tip of the 100m isobath. Note that each value in a shelf width plot represents the latitudinal mean of the particular shelf width for a three-day mean image in the five-year period. Missing values were minimal (<2%), being mostly on the inner continental shelf during winter. The missing values were interpolated by means of the Delaunay Triangulate procedure and a Trigrid function (Research Systems 2003).

The inner continental shelf (0–100m depth)

SST

The SST shelf width plot for the inner shelf (Figure 3a) shows two distinct bands of cold (9°–13°C) water from approximately 32.7°S to 33.0°S and from 33.9°S to 34.3°S, representing the upwelling cells of Cape Columbine and the Cape Peninsula respectively. These cold-water bands appear synchronous in nature and generally more intense in the spring/summer months, being most intense during summer 2000 (February–April) and spring/summer 2000/2001 (November–April). The pulsating nature of the cold upwelling events is evident, particularly when most intense, at which times cold upwelled water is also apparent along the length of the inner shelf between these capes. The intense upwelling of summer 2000 (Figure 3a; Roy *et al.* 2001) occurred following a distinct warm event in December 1999, at which time a band of warm (20°–22°C) water extended the length of the inner shelf of the southern Benguela. A second, but less intense warm event, is seen in February 2002.

In the north, cold water off the Namaqua upwelling cell extends over a much broader latitudinal range, from the northward extent of the analysis region (29.0°S) southward to, on average, 30.7°S, and appears more perennial in nature. Southward of this, and towards the broad inner shelf of St Helena Bay, SSTs largely reflect a seasonal insolation pattern, being warmest in summer (December–February) and coolest during winter (June–August). In the Cape Peninsula area, an abrupt change in SST pattern is notable at 34.35°S owing to the combined affects of (a) this

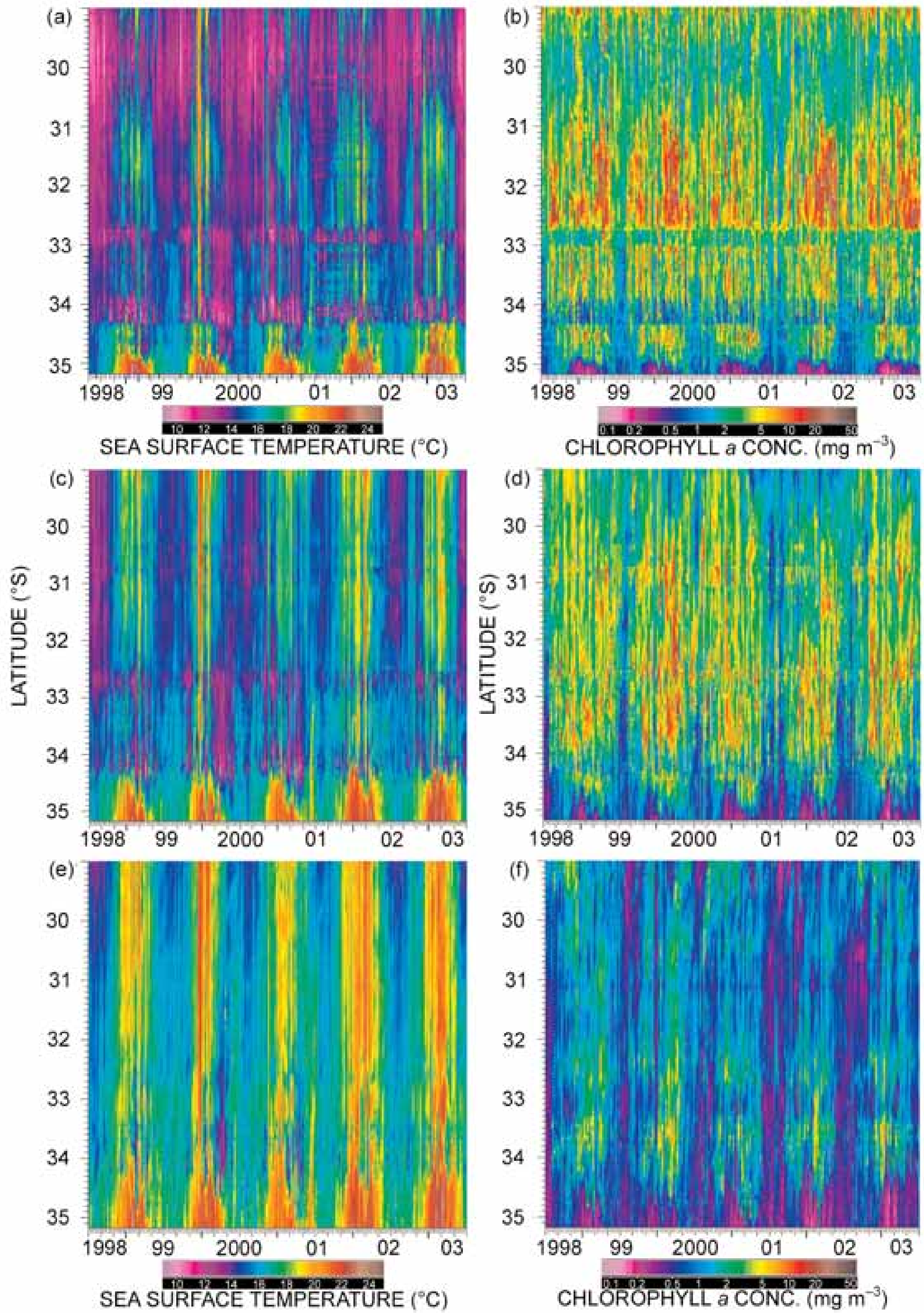

Figure 3: Hovmöller shelf width-averaged plots for the southern Benguela region from 29.00˚S to 35.18˚S for the period July 1998–June 2003 for the inner shelf (0–100m): (a) SST and (b) chlorophyll *a* concentration; for the mid-shelf (100–200m): (c) SST and (d) chlorophyll *a* concentration; and for the outer shelf (200–500m): (e) SST and (f) chlorophyll *a* concentration

being the southern limit of the Cape Peninsula upwelling cell and (b) the sudden broadening of the inner shelf immediately to the south of the Peninsula (Figure 2a). A strong seasonal signal is evident in the waters to the south thereof, on the western Agulhas Bank, owing to both insolation and the influence of warmer waters of Agulhas Current origin. However, intense upwelling events are seen (Figure 3a) to also manifest on the western Agulhas Bank, as far south as Cape Agulhas (35°S). At such times (February–April 1999, February–April 2000, February–April 2001), the cooler upwelled water signal dominates that of summer insolation and Agulhas Current influence.

Chlorophyll *a*

Chlorophyll concentration on the inner shelf of the southern Benguela (Figure 3b) to a large degree mirrors the pattern of SST variability (Figure 3a), similarly dominated by the event-scale processes. Two distinct bands of lower chlorophyll (<3mg m^{-3}) water coincide with the cold-water bands described above, at the locations of the Cape Columbine and Cape Peninsula upwelling cells, chlorophyll in the latter being even lower than that on the Cape Columbine inner shelf. The pulsation of the event scale is particularly evident in the Cape Peninsula band, where pulses of very low chlorophyll (<1mg m^{-3}) appear to correspond with very cold water (9°–12°C) events. Highest chlorophyll concentrations are apparent in St Helena Bay and the inner shelf extending to the north, with very high chlorophyll concentrations (>10mg m^{-3}) sustained during the late summer months (generally February–early May), with the exception of summer 2001. Comparison with the SST for this area (Figure 3a) reveals a relatively cool summer 2001 with typical warmer summer SSTs (>19°C) not experienced in the St Helena Bay area.

No clear seasonal chlorophyll signal is apparent along the inner shelf of the southern Benguela (Figure 3b), although lower biomass is somewhat evident in the July–August winter months. However, along the Namaqua inner shelf, the more perennial nature of upwelling appears to result in a corresponding biological response. In the south, an abrupt change in chlorophyll at 34.35°S again mirrors that of the SST pattern noted above. A seasonal chlorophyll signal is evident in the waters of the western Agulhas Bank, with warmer waters of Agulhas Current origin (Figure 3a) showing very low chlorophyll concentrations (Figure 3b).

Mid-continental shelf (100–200m depth)

SST

The marked Cape Columbine and Cape Peninsula cold water bands shown for the inner shelf (Figure 3a) are still clearly visible over the mid-shelf (Figure 3c), albeit less distinctly. The offshore extension onto the mid-shelf of cold upwelling events at these capes is less pronounced in the spring/summer of 2001/2002 and 2002/2003 than in the previous three years. Most distinguishable is the very intense cold event of summer 2000 (February–April), the upwelled waters again extending the length of the mid-shelf from Cape Columbine to Cape Peninsula, and preceded by the intense warm event of December 1999. Cold upwelled water is also clearly reflected on the mid-shelf in spring/summer 2000/2001 and 1998/1999, at times extending southwards towards Cape Agulhas. A second less intense warm event is noted north of Cape Columbine at the end of January 2000, with further warm events (>19°C) on the mid-shelf at the end of January and February 2002, whereas in 2003 warm water was fairly persistent from mid-February to early March.

SSTs northwards of the Cape Columbine plume reflect a broader mid-shelf mean and hence generally portray seasonal insolation. Namaqua cell upwelling extending onto the broad mid-shelf may therefore be masked. (The line breaks visible at 30.3°S and 30.7°S are a function of a rapid change in bathymetric contour orientation.) On the western Agulhas Bank, a strong seasonal signal is again evident owing to insolation and warmer waters of Agulhas Current origin. A warm water intrusion from the south is apparent in June 2001, extending northwards almost as far as Cape Columbine. This is clearly visible in SST imagery (Figure 4a) following the shedding of an anticyclonic ring from the Agulhas Current, and confirmed in Topex Poseidon/ERS2 altimeter data (not shown).

Chlorophyll *a*

In contrast to the SST distribution, chlorophyll distribution over the mid-shelf (Figure 3d) is more uniform from the Cape Peninsula northwards to the Namaqua shelf. No low chlorophyll band is obvious off Cape Columbine, whereas a somewhat lower chlorophyll band is discernable off the Cape Peninsula. The change in orientation of the 200m bathymetric contour (Figure 2a) just north of Cape Columbine does lead to some discontinuity, and also further to the north at 30.3°S and 30.7°S. In general, the pattern is of higher chlorophyll (>2mg m^{-3}) throughout, although concentrations of <1mg m^{-3} are observed along the mid-shelf during winter (June–August). High chlorophyll (>10mg m^{-3}) was also manifest on the event scale, being highest in summer 2000 (February–April) from north of the Cape Peninsula to 30.3°S, and most evident in the spring/summer of 2002/2003.

Very low chlorophyll (<0.5mg m^{-3}) is observed in the warmer Agulhas-conditioned waters on the western Agulhas Bank mid-shelf during summer, being particularly low (<0.2mg m^{-3}) during January–March 2003 coincident with very warm (>23°C) waters (Figure 3c). Very low chlorophyll is also noted in June 2001 coincident with the warm intrusion from the south (Figure 4a).

Outer continental shelf (200–500m depth)

SST

The dominant pattern of SST variability along the outer shelf (Figure 3e) is a seasonal one. Interannual variation is apparent, with comparatively cooler SST in spring/summer 2000/2001. North of 30.4°S, the averaged values are not representative of the mean outer shelf owing to the western boundary limit of the study area (Figure 2a). The warm event of December 1999 is prominent even along the length of the outer shelf, and the intense upwelling of summer 2000 evident as cool water (12°–14°C) extending from the Cape Peninsula to Cape Columbine. The slight

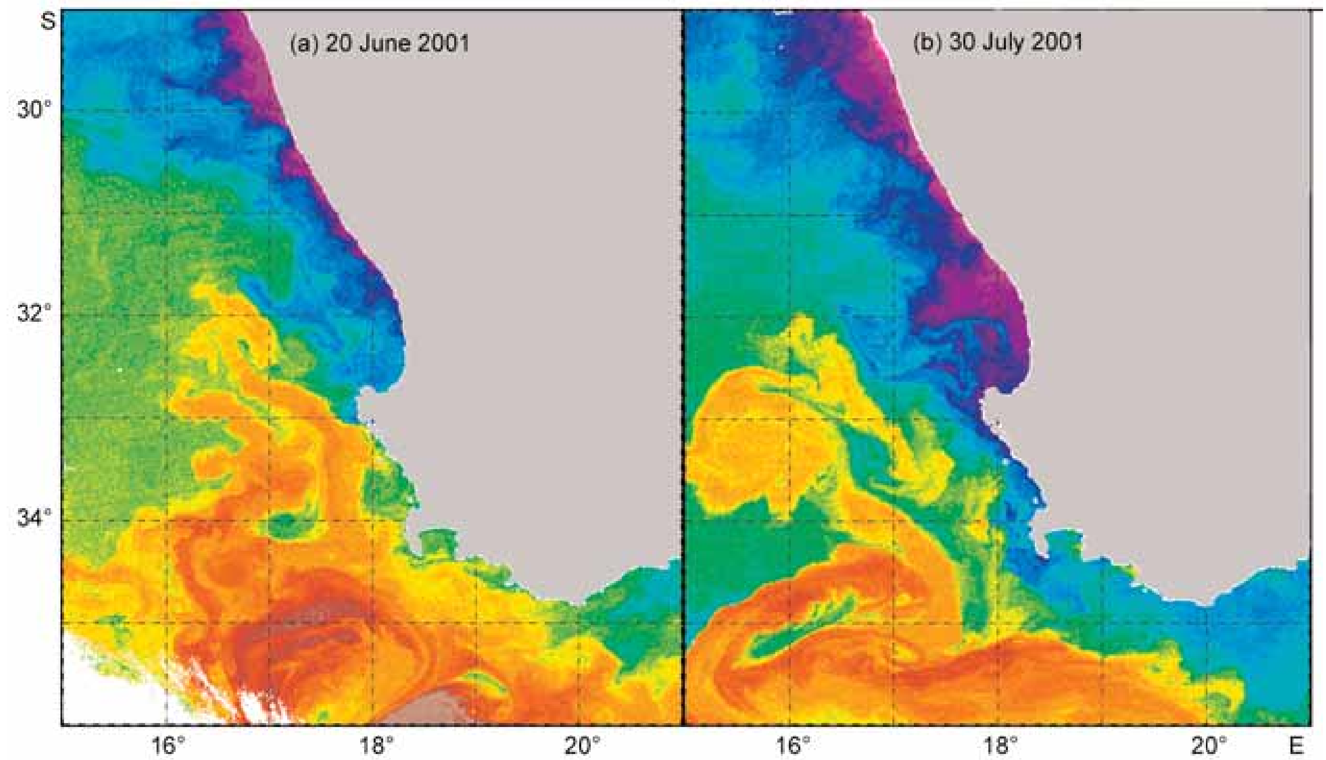

Figure 4: (a) SST image for 20 June 2001 showing the warm water intrusion following the shedding of an anticyclonic ring from the Agulhas Current; (b) SST image for 30 July 2001 showing enhanced offshore SST owing to the offshore location of the shed Agulhas ring

decrease in cool-water signal at 33.3°S is because of the rapid change in orientation and broadening of the outer shelf at this location (Figure 2a). Pulses of cold upwelled water onto the outer shelf are evident during spring/summer 2000/2001. Warmest waters are seen on the western Agulhas Bank as a result of the influence of the Agulhas Current, more pronounced during the summers of 2002 and 2003. The warm intrusion in June 2001 (Figure 4a) extended over the outer shelf as far north as Cape Columbine.

Chlorophyll *a*

Chlorophyll concentration over the outer shelf (Figure 3f) is generally low (<3mg m^{-3}), although a seasonal signal is evident. Somewhat higher chlorophyll is apparent during spring/summer, particularly south of approximately 32°S. Here, higher chlorophylls (>5mg m^{-3}) extend onto the outer shelf, generally coincident with cool water extended onto the outer shelf (Figure 3e). On the western Agulhas Bank, chlorophyll remained very low (<0.5mg m^{-3}), especially during the summers of 2002 and 2003, concurrent with warm Agulhas-modified waters.

Offshore extent — Hovmöller latitudinal plots

The Hovmöller shelf width plots provide a first evaluation of the dynamic variation in SST and phytoplankton biomass in this region. In order to better resolve the offshore extent of this variability along the varying shelf widths, a number of key latitudinal lines were selected (Figure 2a) for which Hovmöller latitudinal plots (hereafter referred to as latitudinal plots) were generated. The latitudinal plots were generated from the five-year SST and chlorophyll three-day mean time-series. Each line in a plot represents an average of five image data lines centred at the particular key latitude and extending 300 pixels (288km) offshore, after allowing for a landbuffer of two pixels (which are not included). For the purpose of this paper, latitudinal plots of only three key latitudes are shown, namely the Cape Peninsula, St Helena Bay and the Namaqua shelf (Figure 2a). These latitudinal lines represent varying widths of the inner, mid- and outer shelves. Owing to the western boundary of the study region (15°E), the Namaqua latitudinal plots are limited to extend only 200 pixels (192km) offshore, after the two-pixel landbuffer, and thus only partially include the outer shelf data values. As for the shelf width plots, missing values were interpolated by means of the Delaunay Triangulate procedure and a Trigrid function (Research Systems 2003).

The Cape Peninsula latitudinal line

SST

The Cape Peninsula latitudinal line (34.13°S; Figure 2a) represents a key latitude, having both a narrow inner and mid-shelf with an outer shelf of moderate width. Most dominant in the Cape Peninsula SST latitudinal plot (Figure 5a) is the cooler (<14°C) water confined primarily to a narrow band inshore, with a strong seasonal signal extending over much of the offshore distance. Event-scale pulses of cold (9°–13°C) water are seen extending offshore beyond the narrow inner shelf, being most intense during the spring/summer of 1999/2000 and 2000/2001, during which times

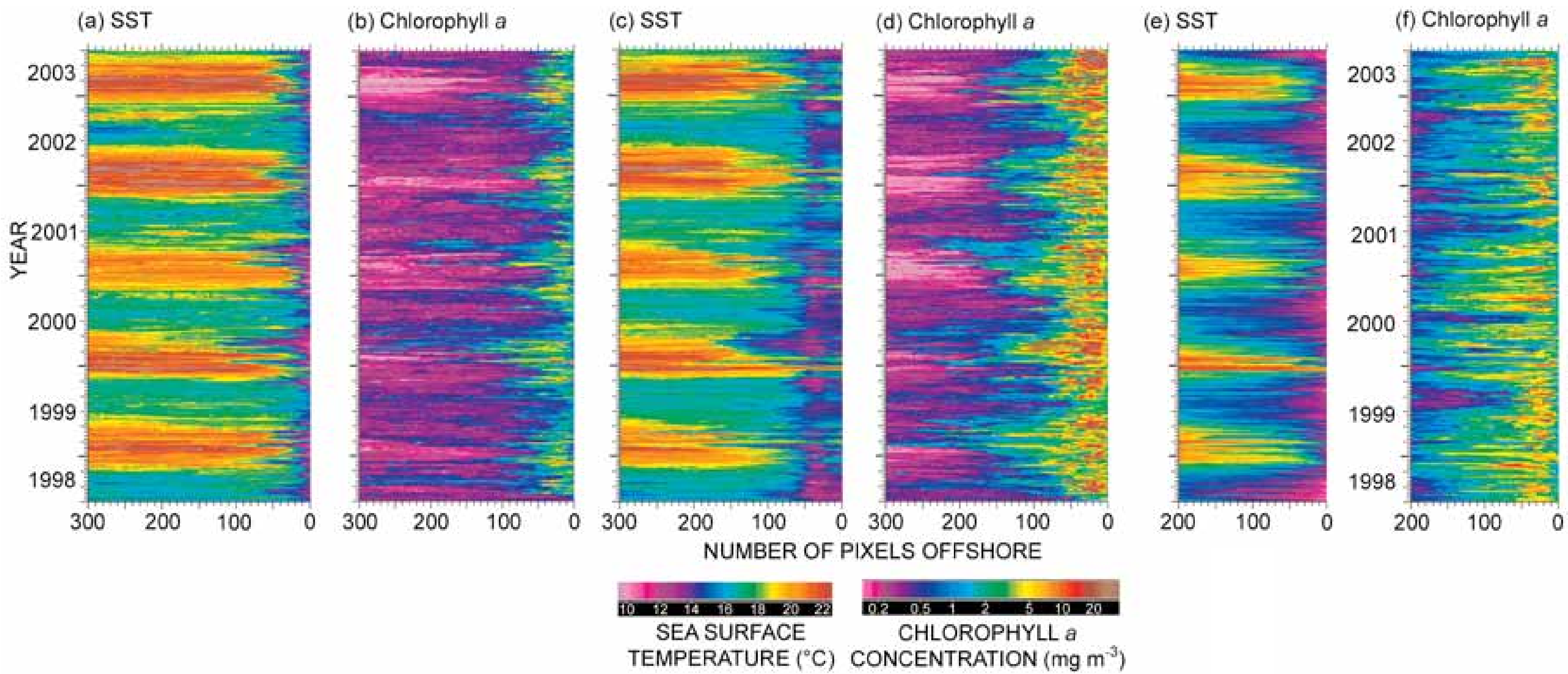

Figure 5: Hovmöller latitudinal plots for the period July 1998–June 2003. Three-day mean for (a) SST and (b) chlorophyll *a* concentration for the Cape Peninsula latitudinal line, extending 300 pixels (288km) offshore; (c) SST and (d) chlorophyll *a* concentration for the St Helena Bay latitudinal line, extending 300 pixels (288km) offshore; and (e) SST and (f) chlorophyll *a* concentration for the Namaqua Shelf latitudinal line, extending 200 pixels (192km) offshore

cold water extended up to 100km offshore. Interannual variability is noted in the offshore seasonal signal, with the coolest spring/summer occurring in 2000/2001.

The onshore movement of warm (19°–21°C) water in December 1999 is apparent but, although not reaching the coast, warm onshore movement is also evident each summer (December–March), interspersed between cold events. The most sustained warm event at this latitude occurred during winter 2001 (May/June) following the shedding of the above-mentioned anticyclonic ring from the Agulhas Current (Figure 4a). The subsequent anticyclonic entrainment of warm Agulhas waters impacted even the Peninsula inner shelf, as the Agulhas ring moved in a north-westerly direction, closely approaching the shore. Another such pronounced Agulhas ring passed farther offshore in October 2002, the warm (19°–21°C) waters approaching the outer Peninsula shelf. This event was preceded (September 2002) by an intrusion of cool water (14°C) 200km offshore (Figure 5a).

Chlorophyll *a*

Chlorophyll concentration off the Cape Peninsula (Figure 5b) shows a different pattern of variability to that of the associated SST (Figure 5a). The region beyond the outer continental shelf comprises generally very low chlorophyll (<1mg m^{-3}) with no strong seasonal signal. Inshore chlorophyll, although relatively low in concentration (<3mg m^{-3}), does exhibit a seasonal signal. Highest chlorophyll events (>5mg m^{-3}) with most offshore extension are seen primarily in spring/summer, especially when cold upwelled waters appear most intense (spring/summer of 1999/2000 and 2000/2001). At such times, the higher chlorophyll is displaced slightly offshore, low chlorophyll being coincident with freshly upwelled waters on the inner shelf. Slightly elevated chlorophyll (1–3mg m^{-3}) observed offshore at times (e.g. end of February and end of April 2001), is owing to the presence of filaments or eddies comprising the convoluted frontal boundary.

The St Helena Bay latitudinal line

SST

The continental shelf along the St Helena Bay latitudinal line (32.65°S; Figure 2a) comprises a broad inner shelf, narrow mid-shelf and broad outer shelf. The SST along this latitudinal line (Figure 5c) shows a very different trend to that off the Cape Peninsula (Figure 5a). Most notable is the strong cold-water signal along the boundary of the 100m isobath, approximately 40 pixels offshore (Figure 5c), where the core of the Cape Columbine upwelling plume extends northward from the Cape Columbine headland along the inner shelf boundary. When most intense (9°–13°C), the Cape Columbine plume appears to retain cold water inshore in St Helena Bay, while also limiting the onshore movement of warmer water (>17°C). However, strong onshore warm water events are seen to occur, being particularly intense in December 1999 and in February 2002. At other times in spring/summer, warmer water is apparent inshore of a moderate plume signal, probably as a result of retention and seasonal warming in the Bay. Offshore extension of cold water onto the outer shelf is strongest in February–April 2000, but also frequently evident at other times as cold event-scale pulses. Similar to the Cape Peninsula SST latitudinal line (Figure 5a), a strong seasonal signal dominates the region offshore beyond the continental shelf, also demonstrating some interannual variability.

Chlorophyll *a*

Chlorophyll concentration along the St Helena Bay latitudinal line (Figure 5d) is appreciably higher than along the Cape Peninsula line (Figure 5b). The offshore extension and distribution of higher chlorophyll (>3mg m^{-3}) over the broader continental shelf is seen as generally double that over the narrower Cape Peninsula shelf. High chlorophyll (>5mg m^{-3}) is apparent throughout the year, but with greater offshore extension in the spring/summer months (November–April). At such times, event-scale pulses of high chlorophyll appear to be associated with strong offshore cold water events. Retention of high chlorophyll concentrations on the inner shelf does seem generally apparent, with a lower chlorophyll signal visible at times along the inner shelf boundary (Figure 5d: 40 pixels offshore), coincident with the cold Cape Columbine plume. High chlorophyll may be visible on either side of this plume signal. Lowest chlorophyll (>0.2mg m^{-3}) is generally noted farthest offshore, coincident with warm water (>20°C) during the summer.

The Namaqua shelf latitudinal line

SST

The third key latitudinal line to be considered in this study, the Namaqua shelf line in the north (29.90°S; Figure 2a), comprises a narrow inner shelf, a broad mid-shelf but only partly represents the outer shelf. In contrast to the SST for the previous two key latitudinal lines (Figure 5a, c), a strong cold-water seasonal signal extends across the width of the Namaqua line (Figure 5e), being most intense during winter. Correspondingly, a strong onshore warm-water seasonal signal of equivalent extent is apparent, being most intense during the summer. Cold upwelled water is still evident on the event scale during summer, but confined primarily to the narrow inner shelf. Some interannual variability is apparent, the warmest winter being that of 2001, following the coolest summer. The strong warm event of December 1999 is clearly observed at this latitude, this signal thus appearing to be evident along the length of the southern Benguela.

Chlorophyll *a*

Although less concentrated than chlorophyll along the St Helena Bay line (Figure 5d), moderate to high biomass (2–10mg m^{-3}) extends along the width of the Namaqua latitudinal line (Figure 5f), across the broad mid-shelf and onto the outer continental shelf. This considerable offshore extent is apparent throughout the year despite the strong seasonal signal seen in the associated SST (Figure 5e). There appears to be no obvious correlation between the two parameters. Rather, it seems that moderate chlorophyll concentrations are generally spread across the width of the broad shelf, a slight offshore displacement coincident with very cold water (9°–12°C) on the inner shelf. Pulses of higher chlorophyll (>5mg m^{-3}) are observed at intervals throughout on the event scale.

Latitudinal line correlations

SST vs chlorophyll

In order to explore the relationship between SST and chlorophyll concentration in Figure 5, a correlation analysis was performed between these two parameters for the three key latitudinal lines. Only the non-interpolated values were used, and being in byte format, the output is therefore quantised. There is no strong correlation between SST and chlorophyll for the Cape Peninsula latitudinal line (Figure 6). The vast majority of points represent offshore values of chlorophyll concentrations <2mg m^{-3} across a range of temperature from approximately 11°–23°C. These low chlorophyll values are at the lower end of the temperature scale (<11°C), where they represent freshly upwelled waters on the inner shelf. Higher chlorophyll concentrations tend progressively towards SSTs of about 12.5°–20°C, values between 2mg m^{-3} and 7mg m^{-3} generally representing phytoplankton in recently upwelled waters. Highest concentrations (>7mg m^{-3}) are coincident with temperatures of 12.5°–17.5°C.

A very similar correlation (not shown) is observed for the Namaqua latitudinal line, except that chlorophyll concentrations are approximately double that of the Cape Peninsula line. Higher chlorophyll values (>5mg m^{-3}) relate to SSTs of 13°–17°C, representing biomass across the broad mid-shelf, with concentrations reaching 40mg m^{-3}. For the St Helena Bay latitudinal line parameters, the correlation (not shown) shows warmer offshore temperatures (>19°C) coincident with lower chlorophyll (<5mg m^{-3}). Higher chlorophyll across the range of 7–50mg m^{-3} is distributed between SSTs of 12°–17°C. Chlorophyll concentration along the St Helena Bay line appears almost four times higher than that of the Cape Peninsula line, and double that of the Namaqua line.

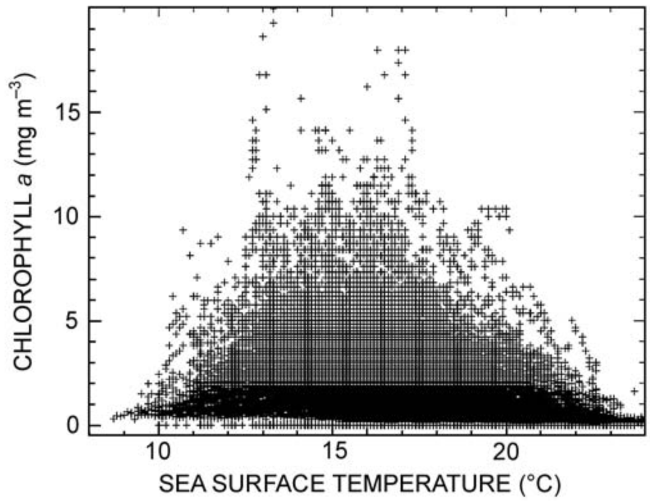

Figure 6: Correlation of SST and chlorophyll *a* concentration for the Cape Peninsula latitudinal line

SST, phytoplankton and upwelling indices

Further to examining the dynamic variations in upwelling and phytoplankton in the southern Benguela is the development of appropriate indices to quantify the intra-seasonal variability. This was initiated by selecting key locations along the length of the southern Benguela, for which the variation of SST and chlorophyll over the five-year time-series was examined, and upwelling indices generated. Only the key locations as per the Cape Peninsula and St Helena Bay latitudinal lines (Figure 2a) are discussed here. The mean value of a 5 x 5 pixel box at an inshore location along the latitudinal line was extracted from each SST image in the time-series. The upwelling index (UI) was generated by determining the difference in SST between an offshore reference location and the respective inshore location. This provides a measure of the temperature difference moving offshore, and may be considered a suitable index of upwelling strength — a positive index indicates colder water at the coast, inferring active upwelling (Carr and Kearns 2003). For the offshore reference point, the 5 x 5 pixel mean value at the most offshore extent (300 pixels) of the particular latitudinal line plot (Figure 5a–d) was extracted. Because chlorophyll *a* concentration may be considered a measure of phytoplankton biomass in 'Case 1' waters, this was used as an index of phytoplankton response to upwelling. As for SST, the mean value of a 5 x 5 pixel box at an inshore location along the latitudinal line was extracted from each chlorophyll image in the time-series.

The fluctuations of SST and indices of upwelling and phytoplankton for the Cape Peninsula and St Helena Bay key locations are shown in Figures 7 and 8 respectively. A low-pass filter was applied to the data such that the highest frequency component of the resultant dataset was 10% of the frequency spectrum of the original dataset. The low-pass filter was used merely as a visual aid — all the analyses were done on the unfiltered data.

The Cape Peninsula key location

Cape Peninsula SST

The Cape Peninsula SST latitudinal plot (Figure 5a) shows cooler upwelled water confined primarily to a narrow band inshore. Hence, the selected key location for the Cape Peninsula was sited on the narrow inner shelf (34.13°S, 18.28°E). Most notable in the fluctuation over time of SST at this location (Figure 7a) are the marked temperature changes associated with the rapid pulsation of the cold/warm events. Pulses of cold water (9°–13°C) are seen most frequently during spring/summer, the overall pattern of variation tending towards generally cooler temperatures in spring/summer, with generally warmer temperatures during autumn/winter. However, warmest events (18°–21°C) are also experienced in summer (January 1999, December 1999, January 2001, January/February 2002, January 2003) interspersed between cold events, as the strong summer SST frontal boundary moves shoreward under conditions of diminished upwelling.

Cape Peninsula upwelling index

The Cape Peninsula UI exhibits a strong seasonal signal (Figure 7b), with most intense upwelling in spring/summer. A ΔSST in excess of 10°C is attained each summer in the

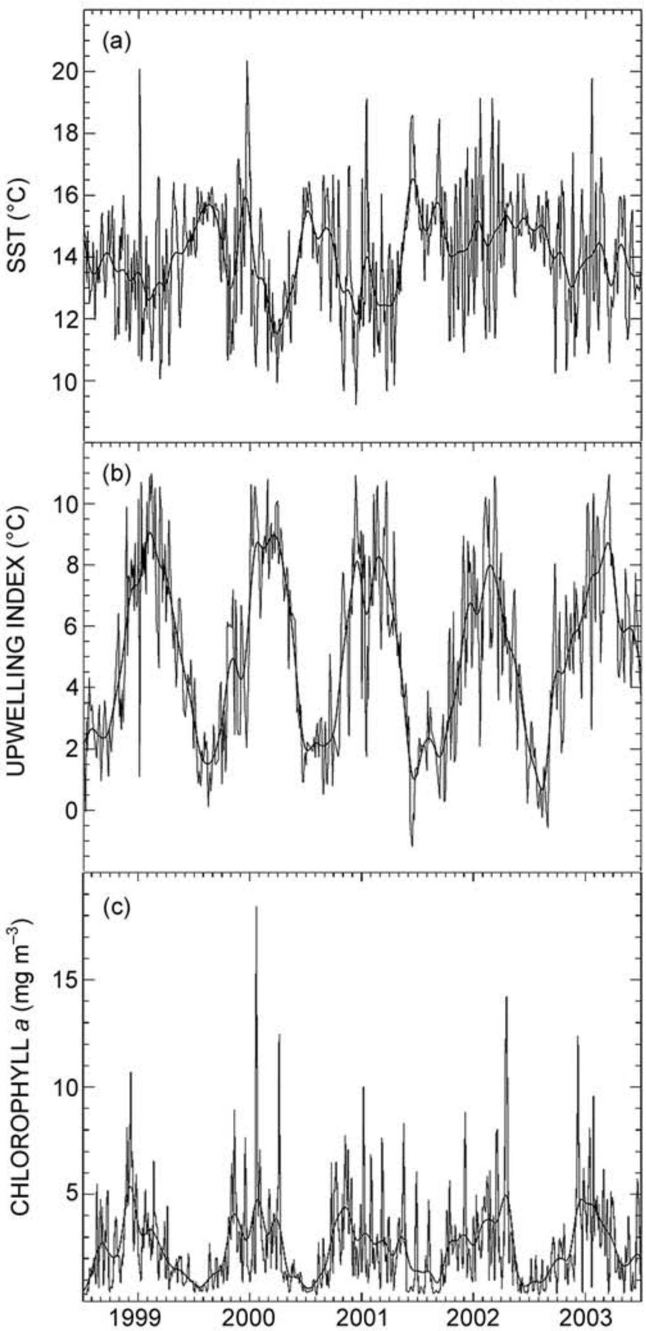

Figure 7: Variation of (a) SST at 18.28˚E, (b) upwelling index at 18.28˚E and (c) chlorophyll *a* at 18.10˚E on the Cape Peninsula latitudinal line for the period July 1998–June 2003. The dark line represents the applied low-pass filter

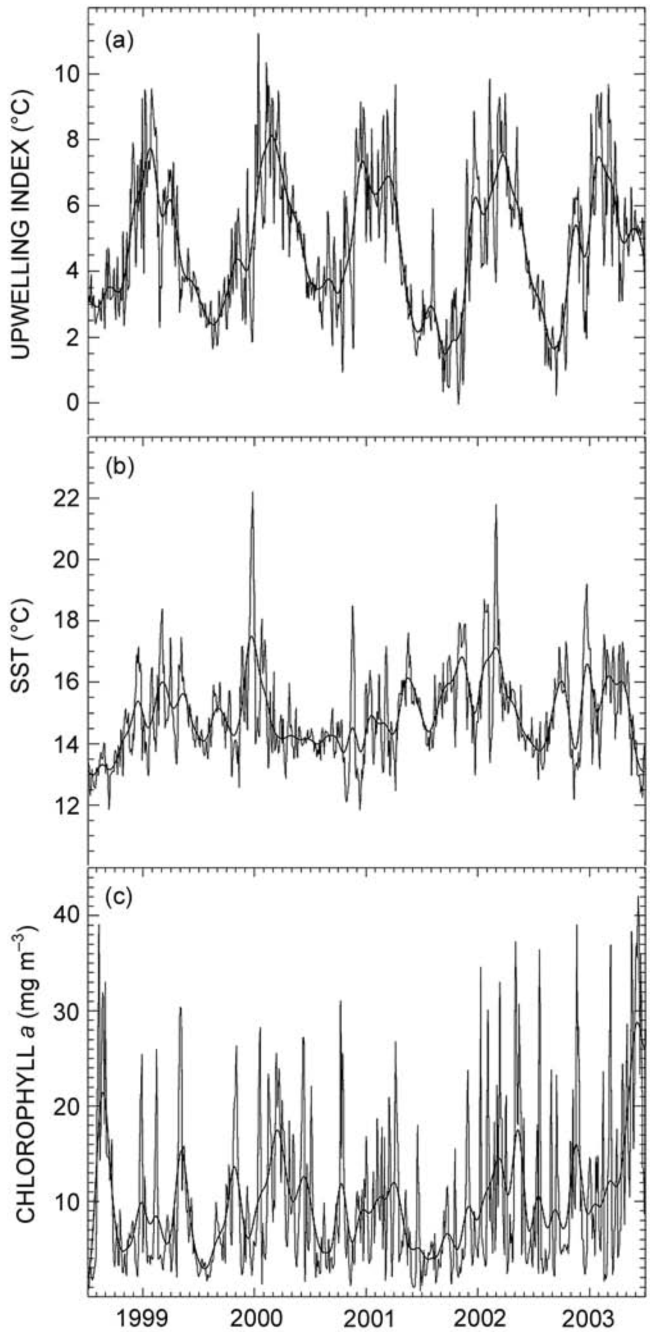

Figure 8: Variation of (a) upwelling index at 17.84˚E, (b) SST at 18.05˚E and (c) chlorophyll *a* at 18.05**˚**E on the St Helena Bay latitudinal line for the period July 1998–June 2003. The dark line represents the applied low-pass filter

five-year time-series. The intensity of upwelling varies rapidly on the event scale, interspersed with warm SST events, as demonstrated by a rapid decrease in the UI. During winter, the UI approaches zero. In fact, a negative UI (inner shelf SST exceeds that of 300 pixels offshore) is seen during June 2001, coincident with the effect of the above-mentioned Agulhas ring (Figure 4a), and again in September 2002. In the latter case, the negative UI is owing to cooler SST at the offshore reference point as a result of the cool water intrusion noted in Figure 5a, rather than the effect of warm Agulhas-conditioned waters on the inner shelf. Interannual variation in UI is seen in the Cape Peninsula, with a decreasing trend in UI from 1999 to 2002.

Cape Peninsula chlorophyll

The Cape Peninsula chlorophyll latitudinal plot (Figure 5b) shows higher chlorophyll displaced slightly offshore, lower chlorophyll being coincident with cold upwelled waters on the inner shelf. Therefore, a key location centred on the 200m isobath (34.13°S, 18.10°E; pixel 20 offshore in Figure 5b), was selected. Chlorophyll *a* (Figure 7c), a measure of phytoplankton response to the seasonal upwelling off the Cape Peninsula (Figure 7b), demonstrates an associated seasonal signal, also varying rapidly on the event scale. Higher chlorophyll concentrations (>5mg m^{-3}) are seen primarily in spring/summer, even though overall concentrations were relatively low. The highest chlorophyll concentration (18.5mg m^{-3}) is observed in January 2000, during the unusual summer of 1999–2000 (Roy *et al*. 2001). In contrast, the high chlorophyll (14.6mg m^{-3}) in April 2002 occurred during a period of quiescence. Concentrations during winter were low (<3mg m^{-3}), except for two peaks in June (6.2mg m^{-3}) and August (4.8mg m^{-3}) 2001, associated with the above-mentioned Agulhas ring and an Agulhas filament respectively.

However, phytoplankton biomass is often patchy, and the phytoplankton response to upwelling off the Cape Peninsula is generally upstream thereof. Hence, a better gauge would likely be a location farther northward of the upwelling latitude. A first selection was a location 40 pixels directly north (33.70°S, 18.10°E), on the somewhat broader mid-shelf. The chlorophyll at this location (not shown) displayed a similar seasonal response, but with concentrations double that of the location on the same latitude as the upwelling (34.13°S, 18.10°E).

The St Helena Bay key location

The most marked feature noted in the St Helena Bay SST latitudinal plot (Figure 5c) is the strong cold-water signal associated with the Cape Columbine upwelling plume. When intense, this upwelling plume appears to retain cooler water in St Helena Bay while limiting onshore movement of warmer water. Therefore, it may be expected that SST and phytoplankton biomass within St Helena Bay be influenced by the intensity of the Cape Columbine upwelling plume. For a measure of the relevant parameters in the St Helena Bay region, therefore, the appropriate upwelling index was considered as that of the Cape Columbine upwelling plume, and is examined first in the discussions below. For a measure of the SST and phytoplankton biomass, a key location centred within St Helena Bay was selected.

Cape Columbine upwelling index

The Cape Columbine UI was obtained by the difference in SST along the boundary of the 100m isobath (32.65°S, 17.84°E; 40 pixels offshore in Figure 5c) and the offshore reference SST. The UI (Figure 8a) shows a strong seasonal signal with most intense upwelling in spring/summer. This pattern is synchronous with upwelling off the Cape Peninsula (Figure 7b), also varying rapidly on the event scale. The strongest Cape Columbine upwelling (ΔSST of 11.2°C) is seen in January 2000, immediately preceded by the warm event (ΔSST of 1.9°C) of December 1999. The 'unseasonal UI' peak in July 2001 is a result of the offshore location at this latitude of the Agulhas ring (Figure 4b), shed in June 2001 (Figure 4a). In October 2001, cessation of upwelling, together with seasonal warming, led to a zero UI. The almost-zero UI seen in September 2002, however, is owing to a cooler offshore reference SST, as a result of the cold-water intrusion noted above (Figure 7b).

St Helena Bay SST

The SST for the selected location (Figure 8b) within St Helena Bay (32.65°S, 18.05°E; pixel 18 offshore in Figure 5c) appears to fluctuate largely between 13°C and 18°C, and is generally warmer in summer owing to seasonal warming of the shallow inner shelf bay. This contrasts somewhat with SST on the Cape Peninsula inner shelf (Figure 7a), and is despite strong spring/summer seasonal upwelling at Cape Columbine. Marked temperature changes are nonetheless apparent in St Helena Bay, associated with event-scale occurrences. Most notable of these are the two warm events in December 1999 and February 2002 when temperatures of 22°C were experienced within the Bay (also see Figure 5c). In contrast, large event-scale pulses are absent from March through October 2000. Generally, event-scale pulses are significantly reduced within St Helena Bay, relative to that on the Cape Peninsula inner shelf, both in extent and rate of SST fluctuation.

St Helena Bay chlorophyll

The chlorophyll concentration at the same location within St Helena Bay (pixel 18 offshore in Figure 5d) was used for a measure of the phytoplankton biomass. No seasonal signal is obvious (Figure 8c). Rather, chlorophyll appears to fluctuate rapidly throughout the year, from around 3mg m^{-3} to concentrations reaching 30–43mg m^{-3}. These levels are three- to fourfold greater than those observed at the Cape Peninsula latitude (Figure 7c, note the different y-axis scale). The two highest chlorophyll peaks occurred during autumn/winter of 1998 and 2003, both related to the accumulation of phytoplankton biomass inshore as a result of strong frontal boundary dynamics (deduced from daily NOAA AVHRR and SeaWiFS data — not shown). A trend towards increased chlorophyll is observed in 2002 and 2003, with particularly high chlorophylls from March to June 2003. During that period, an extensive coccolithophore bloom emerged from the core of the intense phytoplankton biomass, the detection and evolution of which was monitored by satellite ocean colour (Weeks *et al*. 2004b).

Discussion

The extent and frequency of upwelling during the period July 1998 through June 2003 and the biological response to this physical forcing have been addressed in this study by comparing the differences in variability between selected biogeographic regions in the southern Benguela. The shelf width plots allow identification of the location and emergence of upwelling cells as well as the spatial and temporal variation in chlorophyll along the length of the southern Benguela. The latitudinal plots show the offshore extent of SST and chlorophyll, allowing identification of this variability at locations of differing shelf width. The SST, upwelling and chlorophyll indices enable the intra-seasonal variations to be more comprehensively quantified and compared.

The Cape Columbine and Cape Peninsula upwelling cells are identified as two distinct bands of cold water (9°–13°C) on the inner and mid-continental shelves. Upwelling at these locations is synchronous in nature, and generally more intense in spring/summer. The Namaqua upwelling cell extends over a much broader latitudinal range, and is more perennial in nature. Most notable in the inner and mid-shelf SSTs is the rapidly pulsating nature of upwelling in the southern Benguela, with intense warm/cold events clearly distinguished. The dominant pattern of SST over the outer shelf is that of seasonal insolation. In the south, both the seasonal and event-scale influences of warmer waters (>20°C) of Agulhas Current origin are clearly identified.

Chlorophyll concentration on the inner shelf largely mirrors the pattern of SST variability, similarly dominated by event-scale processes. Two distinct bands of low chlorophyll (<3mg m^{-3}) coincide with the Cape Columbine and Cape Peninsula upwelling cells. Pulses of very low chlorophyll (<1mg m^{-3}) correspond with intense upwelling events. Highest chlorophyll concentrations (>10mg m^{-3}) are apparent in the St Helena Bay region, being most sustained during late summer. Over the mid-shelf, higher chlorophyll is observed throughout all seasons, although low biomass occurs during most winters. Chlorophyll concentrations over the outer shelf are generally low (<3mg m^{-3}). In the south, the seasonal and event-scale intrusions of warmer Agulhas-conditioned waters yield particularly low chlorophyll.

At the Cape Peninsula latitude, cooler upwelled water (<14°C) is confined primarily to the narrow inner shelf, with event-scale pulses extending up to 100km offshore. Offshore, a strong seasonal signal dominates, with onshore movement of warm water (>19°C) each summer, between upwelling events. Agulhas Current influences are readily observed, even on the Cape Peninsula inner shelf. Chlorophyll concentration off the Cape Peninsula shows a clear seasonal signal, with offshore extension primarily in spring/summer. Higher chlorophyll is displaced offshore when upwelling is intense. In the St Helena Bay region, the cold Cape Columbine upwelling plume (9°–13°C) causes retention of water on the inner shelf, while limiting onshore movement of offshore water. Event-scale pulses of cold water extending as far as the broad outer shelf are frequently evident. High chlorophylls (>5mg m^{-3}) are apparent throughout the year, with a greater offshore extension in spring/summer and generally double that off the Cape Peninsula. Upwelling in the Namaqua region is dominated by a seasonal signal of large offshore extent, most intense during winter, whereas a corresponding onshore warm water signal dominates in summer. Moderate to high chlorophyll (2–10mg m^{-3}) extends onto the outer shelf throughout the year, despite the seasonal signal in the associated SST. However, the warm summer SST signal across the broad Namaqua mid-shelf is likely a reflection of seasonal insolation, rather than diminished upwelling. Chlorophyll concentrations vary considerably between the three selected latitudes of differing shelf width, with chlorophyll along the St Helena latitude generally four times that of the Cape Peninsula latitude, and double that of the Namaqua latitude.

Marked temperature changes associated with rapid pulsation of the event scale dominate the Cape Peninsula and St Helena Bay SST indices, although the cold/warm pulses are significantly more reduced within St Helena Bay. Surprisingly, no strong seasonal signal is evident. This is unexpected, particularly at the Cape Peninsula, where cold pulses (9°–13°C) appear most frequently during spring/summer. However, both the Cape Peninsula and Cape Columbine upwelling indices show a strong seasonal signal, most intense in spring/summer, but varying rapidly on the event scale. During winter, the UI approaches zero. There appear to be three dominant modes of periodicity in the UI signal, viz. a high frequency, a seasonal and a long-term interannual mode. Single event-scale modes are evident, coincident with event-scale phenomena such as an Agulhas ring 'intrusion'.

Chlorophyll concentrations off the Cape Peninsula demonstrate a seasonal signal, in response to the associated seasonal upwelling, also varying rapidly on the event scale. Downstream of the Cape Peninsula, chlorophyll displays a similar response to Cape Peninsula upwelling, but with concentrations double that of chlorophyll at the latitude of the upwelling. Within St Helena Bay, no seasonal chlorophyll signal is apparent, despite a strong seasonal signal in the Cape Columbine UI. Rather, chlorophyll appears to fluctuate rapidly throughout the year, with concentrations three- to fourfold greater than levels attained at the Cape Peninsula. A trend toward increased chlorophyll is observed in 2002 and 2003, with especially high chlorophylls from March to June 2003. The unusual coccolithophore bloom that emerged from the core of the intense phytoplankton biomass (Weeks *et al*. 2004b) was confined between the Namaqua and Cape Columbine upwelling cells, where a broadening of the shelf favours stratification of the water column, conducive to the development of flagellate dominated blooms. This region is particularly susceptible to red tide formation and its negative impacts (Pitcher and Calder 2000).

Current research with remote sensing in the regional Benguela Environmental Fisheries Interaction and Training (BENEFIT) and Interactions and Spatial Dynamics of renewable resources in upwelling Ecosystems (IDYLE) programmes focuses on SST and SeaWiFS ocean colour, but has utilised primarily low (4.5km) resolution data. Low-resolution data were used to construct a climatology for SST and chlorophyll concentration for the Benguela ecosystem (Demarcq *et al*. 2003), and to describe the dynamic variations (H Demarcq, Institut de Recherche pour le Développement, unpublished data). Low-resolution (4.5km) SeaWiFS data were used to describe the temporal variation in chlorophyll concentration over five years (1997–2002) from 12°–34°S (H Demarcq, unpublished data). High-resolution (1km) SST data were, however, used to investigate the effects of environmental variability on the pelagic fish distribution in both the southern (Agenbag *et al*. 2003) and northern Benguela (CH Bartholomae, Namibian Ministry of Fisheries and Marine Resources, unpublished data).

A recent analysis of the physical and biological variability in the northern Benguela from October 1997 to October 2001 (Campillo-Campbell and Gordoa 2004) used monthly averaged one-degree resolution SST between the 200m and 500m isobaths as an index of upwelling strength. As a measure of biological variability, the best SeaWiFS chlorophyll image (4.5km resolution) per month was selected as representative of that month, and chlorophyll concentration estimated per one one-degree of latitude. Upwelling strength was determined as being strongest in the coolest (winter) months. North of the primary upwelling cell at Lüderitz, maximum chlorophyll was found in autumn and minima in winter, with no chlorophyll seasonality found at the latitude of the primary upwelling cell. No relationship was determined between upwelling strength and the biological response. However, using SST as a measure of upwelling strength does not account for additional processes such as seasonal insolation or advection, and hence the deduced seasonal upwelling is totally synchronous with the seasonal heating cycle. A better index of upwelling strength is attained by a measure of the difference in SST between a location adjacent to the coast and a location some distance offshore at the same latitude (Wooster *et al*. 1976, Parrish *et al*. 1983, Nykjaer and van Kamp 1994, Hill *et al*. 1998, Carr and Kearns 2003). Further, as shown by this study, chlorophyll concentration is highly variable and may be dominated by event-scale processes. Therefore, one chlorophyll image per month is unlikely to adequately represent biological variability in the Benguela region.

Carr (2002), in turn, found higher chlorophyll at the latitude of the primary Benguela upwelling cell (Lüderitz) than equatorwards. The author used 9km-resolution SeaWiFS data averaged monthly into latitudinal subregions extending 500km offshore, and distinguished meridionally by different seasonal cycles of wind forcing. Using 9km-resolution data for the southern Benguela, Carr and Kearns (2003) found peak offshore Ekman transport in spring and summer, with upwelling decreasing with increasing latitude. The local chlorophyll minimum was observed at 30°S (Namaqua shelf) with the maximum at 33°S (Cape Columbine). Seasonal variation was weak but winter minima were generally observed. The above findings differ considerably from those found in this study. However, the low (9km) resolution would preclude much of the detail observed in this higher resolution data study, with upwelling identified primarily on the narrow inner continental shelf.

Earlier studies (Weeks and Shillington 1994, Thomas *et al*. 2001) using Coastal Zone Colour Scanner (CZCS) data illustrated a clear minimum chlorophyll concentration in winter, but with no significant seasonality. That pattern of distribution is similar to that found in this study. A later study by Thomas *et al*. (2003) used 4.5km-resolution SeaWiFS data, composited monthly for each latitude, to calculate the mean chlorophyll for the first 100km from coast. In the Eastern Boundary Currents (EBCs) considered, maximum chlorophyll was both temporarily and latitudinally coincident with the seasonal maximum in upwelling. In the southern Benguela, the latitudinal region centred at 30°S (Namaqua shelf) exhibited elevated chlorophyll throughout most of year. South of this, chlorophyll variability was in phase with seasonal wind forcing. Those results are in agreement with the present findings. Thomas *et al*. (2003) concluded that the strong differences found between chlorophyll seasonality in the later study and previous studies using CZCS data (Thomas *et al*. 1994, Hill *et al*. 1998, Thomas 1999) were owing to the relative sparsity of CZCS data in the Southern Hemisphere.

Previous studies to address the relationship between environmental factors and biological production generally used Ekman transport, as deduced from wind data, as an indicator of upwelling. Cushing (1969) found increasing production for decreasing (but finite) Ekman transport, whereas Ware (1992) found a linear relationship between Ekman transport and primary production. Carr (2002) tested the linear relationship between environmental forcing (Ekman transport, SST) and production for EBC regions. Gridded 1° monthly European Remote-Sensing Satellite (ERS) wind data, 9km monthly SST, Japanese Ocean Colour and Temperature Sensor (OCTS) and SeaWiFS chlorophyll data were divided into subregions extending to 500km offshore. These were distinguished meridionally by different seasonal cycles of wind forcing. In the Benguela, production was most related to Ekman transport and was not correlated to SST.

The seasonal progression of chlorophyll biomass in the EBCs, as measured from SeaWiFS data, is driven to the first order by upwelling (Thomas *et al*. 2001). Wind forcing and biological response are in phase in relatively few regions with maximum amplitudes in Ekman transport not always corresponding to that in chlorophyll (Thomas *et al*. 2001). An upwelling index derived from ΔSST (the difference in SST between a location adjacent to the coast and a location some distance offshore at the same latitude), as used in this study, is based on the evidence of upwelling rather than on model assumptions linking the driving force to the upwelling. Carr and Kearns (2003) expanded previous work by quantifying the meridional and seasonal patterns of upwelling dynamics and the biological response in the EBCs, using a combination of hydrographic and nutrient climatology together with the satellite dataset of Carr (2002). ΔSST was included as an added variable. Low (9km) resolution monthly climatologies (1998–2000) of SST and chlorophyll were averaged to 1° bins. The only consistent relationship among the studied variables was between ΔSST and phytoplankton biomass, with all four EBCs presenting a linear relationship at an r of 0.6. In the Benguela, biomass was not correlated to SST, but, of all the four EBC regions, correlated most with ΔSST ($r = 0.8$).

In concluding this analysis of NOAA SST and SeaWiFS chlorophyll data, various studies published over many years have determined either low spatial or temporal resolution indices (Bakun 1973, 1975, Nykjaer and van Kamp 1994, Thomas *et al*. 2001, Carr and Kearns 2003). These studies show primarily the long-term mean seasonal cycles. Wind forcing varies seasonally and latitudinally in upwelling regions (Bakun and Nelson 1991). However, there are local factors within each upwelling region that impose additional spatial and temporal variability, including coastal orientation, the occurrence of headlands and the width of the shelf (Thomas *et al*. 2003). Although low-resolution SST and chlorophyll data may be useful for investigating general patterns over large scales, the finer-scale spatial and temporal variability is lacking, especially in the inshore coastal zones. High-resolution indices are required to examine patterns of change in more detail. Only three locations of differing biogeographic character within the southern Benguela have been explored in this study. Upwelling is a very dynamic three-dimensional process with strong resultant current flows, therefore, mesoscale dynamics are important. Also, it seems apparent from this study that phytoplankton biomass is not only often patchy, and perhaps inadequately represented by one location on the shelf, but the phytoplankton response to upwelling may be primarily downstream of the upwelling centre. Therefore, a next approach may be to subdivide the northern and southern Benguela into biogeographic provinces to further develop indices as useful input into the management of the ecosystem.

A key policy action within the regional Benguela Current Large Marine Ecosystem (BCLME) Programme is the assessment of environmental variability, ecosystem impacts and the improvement of predictability. Two cornerstones of this policy action are the development of an early warning system and the improvement of predictability of extreme events and their impacts in the BCLME. Fundamental to this is the requirement of an optimal satellite remote-sensing capability within the region, and the development of ecosystem indicators that can detect and monitor ecosystem changes. The application of satellite remote-sensing data to the Benguela ecosystem, both qualitatively and quantitatively, provides a firm foundation for this policy action. The qualitative application would include the detection and monitoring of specific event-scale phenomena, and their potential ecosystem impacts (Weeks *et al*. 2002, 2004a, 2004b). The processing of satellite ocean colour data should be modified accordingly (Weeks 2005). The quantitative application would encompass the development of a routine time-series of updateable ecosystem indicators, to serve as a measure of ecosystem function, for comparison with fluctuations in recruitment of exploited marine resources.

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References

Agenbag JJ, Richardson AJ, Demarcq H, Freon P, Weeks SJ, Shillington FA (2003) Estimating environmental preferences of South African pelagic fish species using catch size and remote sensing data. *Progress in Oceanography* **59**: 275–300

Bakun A (1973) Coastal upwelling indices, west coast of North America, 1946–71. US Dept of Commerce NOAA Technical Report *NMFS Special Scientific Report, Fisheries* **671**, 103pp

Bakun A (1975) Daily and weekly upwelling indices, west coast of North America, 1967–73. US Dept of Commerce NOAA Technical Report *NMFS Special Scientific Report, Fisheries* **693**, 114pp

Bakun A, Nelson CS (1991) The seasonal cycle of wind stress curl in subtropical Eastern Boundary Current regions. *Journal of Physical Oceanography* **21**: 1815–1834

Barlow RG (1982) Phytoplankton ecology in the southern Benguela current. I. Biochemical composition. *Journal of Experimental Marine Biology and Ecology* **63**: 209–227

Brown PC, Painting SJ, Cochrane KL (1991) Estimates of phytoplankton and bacterial biomass and production in the northern and southern Benguela ecosystems. *South African Journal of Marine Science* **11**: 537–564

Campillo-Campbell C, Gordoa A (2004) Physical and biological variability in the Namibian upwelling system: October 1997–October 2001. *Deep-Sea Research II* **51**: 147–158

Carr M-E (2002) Estimation of potential productivity in eastern boundary currents using remote sensing. *Deep-Sea Research II* **49**: 58–80

Carr M-E, Kearns EJ (2003) Production regimes in four Eastern Boundary Current systems. *Deep-Sea Research II* **50**: 3199–3221

Cushing DH (1969) Upwelling and fish production. *FAO Fisheries Technical Paper* **84**: 40pp

Demarcq H, Barlow RG, Shillington FA (2003) Climatology and variability of sea surface temperature and surface chlorophyll in the Benguela and Agulhas ecosystems as observed by satellite imagery. *African Journal of Marine Science* **25**: 363–372

Duncombe Rae CM (1991) Agulhas retroflection rings in the South Atlantic: an overview. *South African Journal of Marine Science* **11**: 327–344

Emery WJ, Thomson RE (2001) *Data Analysis Methods in Physical Oceanography* (2nd edn). Elsevier, Amsterdam, xvi + 638pp

Garzoli SL, Richardson PL, Duncombe Rae CM, Fratantoni DM, Goni GJ, Roubicek AJ (1999) Three Agulhas rings observed during the Benguela Current Experiment. *Journal of Geophysical Research* **104**: 20971–20985

Hill AE, Hickey BM, Shillington FA, Strub PT, Brink KH, Barton ED, Thomas AC (1998) Eastern boundary currents: a pan-regional review. In: Robinson AR, Brink KF (eds) *The Sea.* John Wiley, New York, pp 29–68

Hovmöller E (1949) 'The trough and ridge diagram'. *Tellus* **1**(2): 62–66

Hutchings L (1992) Fish harvesting in a variable, productive environment—searching for rules or searching for exceptions? In: Payne AIL, Brink KH, Mann KH, Hilborn R (eds) *Benguela Trophic Functioning. South African Journal of Marine Science* **12**: 297–318

McClain EP, Pichel WG, Walton CC (1985) Comparative performance of AVHRR-based multichannel sea surface temperatures. *Journal of Geophysical Research* **90**: 11587–11601

Nelson G, Boyd AJ, Agenbag JJ, Duncombe Rae CM (1998) An upwelling filament north-west of Cape Town, South Africa. In: Pillar SC, Moloney CL, Payne AIL, Shillington FA (eds) *Benguela Dynamics: Impacts of Variability on Shelf-Sea Environments and their Living Resources. South African Journal of Marine Science* **19**: 75–88

Nelson G, Hutchings L (1983) The Benguela upwelling area. *Progress in Oceanography* **12**: 333–356

Nykjaer L, van Kamp L (1994) Seasonal and interannual variability of coastal upwelling along northwest Africa and Portugal from 1981 to 1991. *Journal of Geophysical Research* **99**(C7): 14197–14208

Parrish RH, Bakun A, Husby DM, Nelson CS (1983) Comparative climatology of selected environmental processes in relation to eastern boundary current pelagic fish reproduction. In: Sharp GD, Csirke J (eds) *Proceedings of the Expert Consultation to Examine Changes in Abundance and Species Composition of Neritic Fish Resources*. *FAO Fisheries Report* **291**(2,3): 731–778

Pitcher GC, Calder D (2000) Harmful algal blooms of the southern Benguela current: a review and appraisal of monitoring from 1989 to 1997. *South African Journal of Marine Science* **22**: 255–271

Research Systems (2003) *IDL Reference Guide: Procedures and Functions*. Research Systems Incorporated, Boulder, Colorado

Roy C, Weeks S, Rouault M, Nelson G, Barlow R, van der Lingen C (2001) Extreme oceanographic events recorded in the southern Benguela during the 1999–2000 summer season. *South African Journal of Science* **97**: 1–7

Shannon LV (1985) The Benguela ecosystem. Part I. Evolution of the Benguela, physical features and processes. *Oceanographic and Marine Biology. An Annual Review* **23**: 105–182

Shannon LV, Nelson G (1996) The Benguela: large scale features and processes and system variability. In: Wefer G, Berger WH, Siedler G, Webb DJ (eds) *The South Atlantic: Present and Past Circulation*. Springer, Berlin, pp 163–210

Sherman K (1999) Large marine ecosystems: assessment and management. In: Sherman K, Tang Q (eds) *Large Marine Ecosystems of the Pacific Rim: Assessment, Sustainability and Management*. Blackwell Science, Malden, Massachusetts, pp 442–456

Thomas AC (1999) Seasonal distributions of satellite-measured phytoplankton pigment concentration along the Chilean coast. *Journal of Geophysical Research* **104**: 25877–25890

Thomas AC, Carr M-E, Strub PT (2001) Chlorophyll variability in eastern boundary currents. *Geophysical Research Letters* **28**(18): 3421–3424

Thomas AC, Huang F, Strub PT, James C (1994) A comparison of the seasonal and interannual variability of phytoplankton pigment concentrations in the Peru and California Current systems. *Journal of Geophysical Research* **99**: 7355–7370

Thomas AC, Strub PT, Carr M-E, Weatherbee R (2003) Comparison of chlorophyll variability between the four major global eastern boundary currents. *International Journal of Remote Sensing* **24**: 1–5

Ware DM (1992) Production characteristics of upwelling systems and the trophodynamic role of hake. In: Payne AIL, Brink KH, Mann KH, Hilborn R (eds) *Benguela Trophic Functioning. South African Journal of Marine Science* **12**: 501–513

Weeks SJ (2005) Specific applications of satellite remote sensing to the Benguela ecosystem. PhD Thesis, University of Cape Town, South Africa, 119pp

Weeks SJ, Currie B, Bakun A (2002) Satellite identification of massive hydrogen sulphide emissions in the southeastern Atlantic Ocean. *Nature* **415**: 493–494

Weeks SJ, Currie B, Bakun A, Peard K (2004a) Hydrogen sulphide eruptions in the Atlantic Ocean off southern Africa: implications of a new view based on SeaWiFS satellite imagery. *Deep-Sea Research I* **51**: 153–172

Weeks SJ, Pitcher GC, Bernard S (2004b) Satellite monitoring of the evolution of a coccolithophorid bloom in the southern Benguela upwelling system. *Oceanography* **17**(1): 83–89

Weeks SJ, Shillington FA (1994) Interannual scales of variation of pigment concentrations from CZCS data in the Benguela upwelling system and the subtropical convergence zone south of Africa. *Journal of Geophysical Research* **99**: 7385–7400

Wooster WS, Bakun A, McLain DR (1976) The seasonal upwelling cycle along the eastern boundary of the north Atlantic. *Journal of Marine Research* **34**: 131–141

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