Extreme oceanographic events recorded in the Southern Benguela during the 1999–2000 summer season

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Two unusual oceanographic events occurred during the 1999–2000 summer season off the west coast of South Africa. The first was a strong and sustained warming that occurred in mid-December and lasted for two weeks. The second was an enhanced cooling that lasted from mid to late summer. These two events were the result of fluctuations in wind-induced upwelling. The spatial as well as the temporal extent of these conditions are analysed and the corresponding atmospheric setting is described. Using climatological data, the 1999–2000 summer season is placed in the long-term context of the climatic variability in the region. The influence of those two events on phytoplankton and anchovy recruitment may have contributed to a record high level of anchovy recruitment in 2000.

Background

During the summer season, holidaymakers visiting the Cape Peninsula are usually greeted on the beaches of the Atlantic coast by gusty southeasterly winds and icy waters with temperatures as low as 10°C. The presence of such cold surface water results from the well-known oceanographic process involving wind-induced divergence of surface water along the coast and upwelling of cold subsurface water over the continental shelf. Coastal upwelling off the Cape Peninsula and west coast is a seasonal process, active mainly from October to April, with a peak in intensity during the first quarter of the year. As a result of the sustained coastal upwelling, nearshore sea-surface temperature (SST) in summer is frequently as low as or even lower than that recorded in winter. Thus, the famous quote of the American novelist Mark Twain, 'The coldest winter I ever spent was a summer in San Francisco', which emphasizes the effect of summer upwelling off California on the local temperature, may be applied to Cape Town as well.

Off the west coast of South Africa, the pulsing pattern of the pressure field and consequent southeasterly wind, which is characterized by a 5–10 days' variability, induces a corresponding oscillation of the upwelling intensity.[1] This results in a succession of cold (10°C) and relatively warm (15°C) SST being recorded along the coast during the upwelling season.

Here, we document the 1999–2000 upwelling season off the west coast of South Africa, which was characterized by two unusual events. The first was a strong and sustained warming that occurred in mid-December and lasted for two weeks. The second was an unusual, sustained southeasterly wind which blew from mid to late summer, and which enhanced upwelling and lowered SST along the coast for an extended time. These two events were separated by a period of moderate upwelling intensity, extending from January to February. The spatial as well as the temporal extent of these two major oceanographic events are analysed and the corresponding atmospheric setting is described. Using climatological data, the 1999–2000 summer season is then placed within the long-term context of the climatic variability of the region.

Following highly successful reproduction of the anchovy population during the 1999–2000 summer season, anchovy recruitment increased sharply, reaching the highest level recorded over the last 16 years. Anchovy biomass for 2000 was estimated to be more than double the previous highest record. We present possible links between the anomalous oceanographic conditions during the 1999–2000 summer and the successful anchovy recruitment.

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Data

Three-hourly Meteosat infrared and visible images, NCEP/NCAR re-analyses of meteorological conditions,[2] and South African Weather Bureau (SAWB) raingauge synoptic charts were used to characterize the atmospheric variability during the study period and compare the anomalies with the mean values.

At Cape Columbine, wind is measured at a weather station, maintained by Marine and Coastal Management. The wind vector is recorded by an MC Systems automatic anemometer, minute samples being taken and vector averaged to hourly records. Comparison of data from satellites and from the weather station shows that the wind at Cape Columbine is representative of the whole west coast, in terms of the synopticity of upwelling winds.[3] Wind vectors were extracted for the period 1 October 1999 to 30 June 2000 and refined using a cosine-Lanczos filter with a half-power point at 36 hours. This suppresses the land–sea breeze and the effect of the travelling coastal low-pressure cell. The longshore wind coincides with the north–south line at this site and accounts for 98% of the variance in the filtered wind vector. Consequently, the principal component of the stress tensor lies on the north–south line, and its magnitude can be taken as

$$\tau = C_d \rho_a V_y^2$$

where C_d is the drag coefficient (taken as 0.0013), $\mathbf{V}_a$ is the density of air (taken as 1.22 kg m^{-3}) and V_y the alongshore wind component in m s^{-1}. The Ekman divergence in kg s^{-1} per metre of coast can then be estimated from the wind stress and the Coriolis parameter (f) as,

$$S = \frac{\tau}{f}.$$

Using the hourly time series of Ekman divergence, upwelling events are defined as being periods with continuous positive divergence. This corresponds to times of uninterrupted northward wind. For each upwelling event, the resulting divergence was calculated by accumulating the hourly divergence values.

High-resolution (1 km) NOAA AVHRR and Orbview-2 SeaWiFS data were acquired and processed locally. Daily images of AVHRR SST were generated using the Multichannel Sea-Surface Temperature (MCSST) algorithm,[4] mapped to a Mercator projection and composited to form weekly mean images for the period October 1998 to September 2000. NASA level-2 normalized water-leaving radiances were generated from the SeaWiFS data, and daily images of chlorophyll-*a* concentration produced. These were mapped to the same Mercator projection as for the SST imagery and similarly composited to form mean weekly images of chlorophyll-*a* concentration for the period July 1999 to June 2000. A simple 3 × 3 moving box filter was applied to both sets of images.

Weekly, optimally interpolated SST (OISST, source: http://ingrid.ldeo.columbia.edu/SOURCES/.IGOSS/.nmc/.weekly/) data were used to create weekly time series of SST anomalies from November 1999 to mid-May 2000 at three locations off the west coast. OISST data are a mixture of *in situ* and satellite SSTs and are available on a one-degree square grid from November 1981 to the present.[5] The locations of the three time series extracted correspond respectively to the coastal 1° squares adjacent to Cape Town (33°30′S), Cape Columbine (32°30′S) and Hondeklip Bay (30°30′S). Regional maps of monthly OISST anomalies for December 1999, March and April 2000, from the equator to 50°S and from 0° to 35°E, were also produced.

A monthly SST time series off the southern part of the west coast (a 2° square centred at 33°S, 17°E) and starting in 1970 was generated using surface meteorological data collected by merchant ships. The data were extracted from the COADS database release 1ab for the period 1970–1995, using an updated version of the CODE software and from the Public Climate Data Server of the Climate Diagnostics Centre (NOAA, Boulder) for the remaining period.[6,7] A monthly climatology was created using the monthly data from January 1970 to December 2000. A time series of SST anomalies from January 1970 to December 2000 was calculated by subtracting the monthly SST climatology from the monthly SST time series. This series will be referred to as Ship-SSTA.

Description of the 1999–2000 summer

The atmospheric setting

Analysis of Meteosat images, of NCEP/NCAR meteorological parameters as well as of SAWB synoptic charts showed that, at the beginning of December 1999, the high pressure system over the South Atlantic Ocean dominated the weather but that the pressure gradient between the high pressure regions over the ocean and the continent was quite weak. Consequently, southerly wind remained moderate. Early in December, a coastal low and a weak cold front disrupted this pattern. From 12 to 25 December, the influence of the high pressure conditions disappeared over a large area of the Southeast Atlantic. Interior low pressure spreading to the coast and offshore, weak cold fronts and coastal lows dominated the weather pattern. They generated weak northeasterly, northerly, northwesterly westerly and southwesterly winds. From 25 to 29 December, the high-pressure influence was re-established but the pressure gradient remained weak and moderate southerly winds were recorded off the west coast. At the end of the month, a weak cold front reached the Western Cape, with westerly winds disturbing the New Year's eve festivities.

During February and March 2000, the Southeast Atlantic high-pressure centre of action moved eastwards and affected the coastal areas for an extended period, generating strong southeasterly winds. In April and May 2000, high pressure conditions were still abnormally developed for the season and still spreading southward. This may have prevented cold fronts and cut-off lows with attendant westerly winds from disrupting the southerly circulation.

The wind at Cape Columbine

The atmospheric conditions described above altered the coastal wind regime during the 1999–2000 upwelling season. The time series of alongshore wind and of the cumulative divergence at Cape Columbine illustrate the succession of events that triggered the fluctuations of the upwelling off the west coast (Fig. 1).

There were 12 major upwelling episodes, unbiased by filter truncation, from November 1999 to April 2000. Episode 1 started on 22 October and ended on 16 November. During that period, there was uninterrupted upwelling for 20 days, injecting 1306 × 10^6 kg of water into the surface layer per metre of coast. This event was followed by episodes 2, 3 and 4, which had a smaller intensity and showed strong switching on and off of upwelling over comparatively short periods. Between 10 and 23 December, the divergence was close to zero because of the weakness of the upwelling-favourable wind. This calm period lasted for 14 days. Episode 5 started on 24 December and gradually led to a moderate divergence of 669 × 10^6 kg m^{-1} on 6 January. It was followed by a succession of upwelling events of moderate intensity (episodes 6 to 9). Episode 10 started on 3 March and lasted until 1 April. This episode, characterized by sustained upwelling-favourable wind for almost an entire month, was the most pronounced episode of the 1999–2000 upwelling season, with a cumulative divergence reaching 1689 ×10^6 kg m^{-1} on 1 April 2000.

The warm event of December

The impact on the surface thermal structure of the collapse of the upwelling-favourable wind in mid-December (after episode 4, see Fig. 1) is illustrated by a series of weekly composite images of high-resolution SST. These images allow the temporal as well as spatial fluctuations of SST to be observed off the west coast (Fig. 2).

During the first week of December 1999, upwelling was moderately active and cold waters (SST lower than 12°C) were recorded off the main upwelling cells: Cape Point, Cape Columbine and further north off Hondeklip Bay. Cold water extended over the shelf and warm water originating from the Agulhas region was encountered in the southern part of the area. Warming started to occur during the second week of December in the northern part of the region, while the cold SST associated

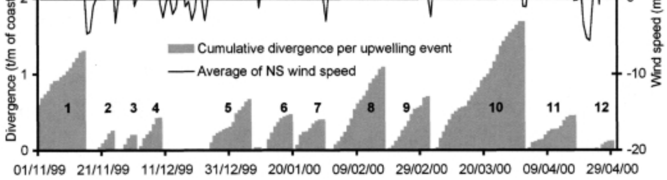

Fig. 1. Daily time series of north–south wind speed (m s^{-1}) at Cape Columbine from 1 November 1999 to 30 April 2000 (top) and cumulative divergence (t m^{-1}) per upwelling event (bottom) for the same time period. The episode number is indicated for each major upwelling event. The calculation of cumulative divergence was performed on the October–June time series, which explains why upwelling event number 1 does not start at 0 on 1 November 1999.

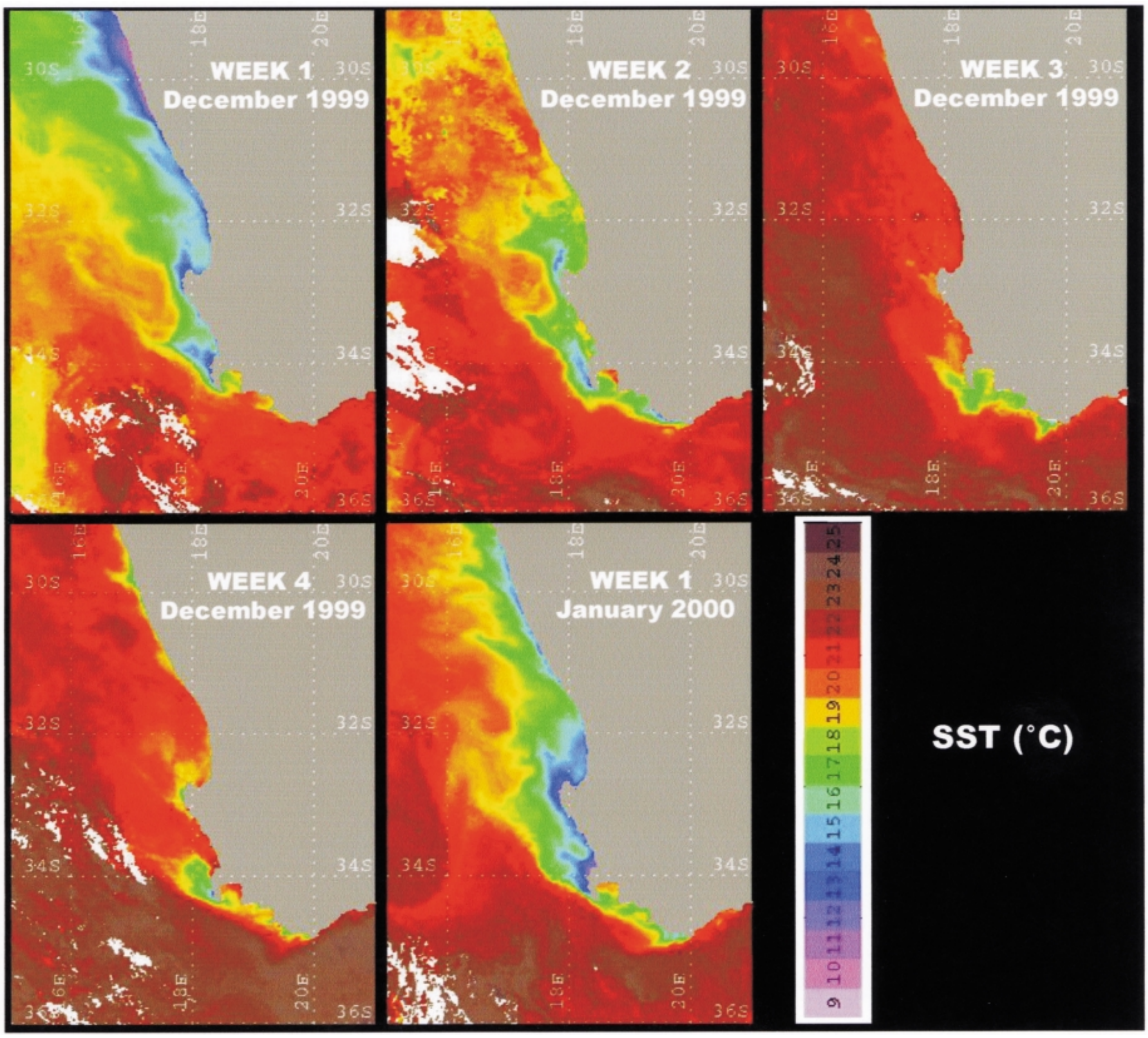

Fig. 2. Weekly composite of mean sea-surface temperature (°C) derived from high-resolution (1 km) AVHRR data from the first week of December 1999 to the first week of January 2000.

with the upwelling cells in the south was still noticeable. During the third week of December, the surface signature of the coastal upwelling cells had disappeared and the entire continental shelf north of the Cape Peninsula was covered with surface water warmer than 19°C. This confirmed the total collapse of the coastal upwelling process as suggested by the time series of Fig. 1. During the last week of December, similar conditions were encountered over most of the continental shelf, while an indication of a resurgence in upwelling was noticeable along the coastline. A week later (early January), the Cape Point and Cape Columbine upwelling cells were fully developed and cold water started to cover the entire continental shelf.

The regional map (Congo to South Africa) of OISST anomalies confirmed the existence of a warm event during December, with SST anomalies reaching more than 2°C (Fig. 3). The spatial extension of the 2°C anomaly isoline was limited to the broad continental shelf of the southern part of the region (south of 30°S).

The time series of Ship-SSTA for December from 1970 to 2000 allows comparison of oceanographic conditions recorded during early summer 1999 with the historical record (Fig. 4). It shows that the positive SST anomaly recorded in December 1999 was the second largest in the 30-year time series, with a value of +1.40°C (Fig. 4). The greatest anomaly was recorded in December 1992 (1.54°C).

In summary, there is supporting evidence from both wind data as well as local and regional SST observations that the oceanographic conditions in December 1999 were characterized by a collapse of the upwelling during the last two weeks of December. The disappearance of the upwelling resulted in an intense warm anomaly which affected the entire region.

The following cold anomaly

Regional maps of SST anomalies in March and April 2000 show a persistent negative anomaly centred along the west coast of

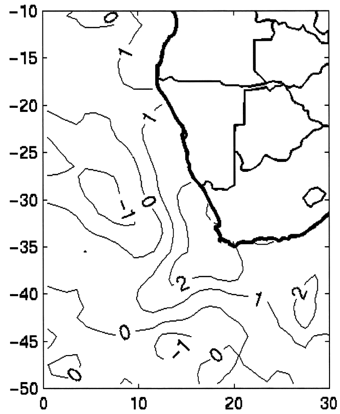

Fig. 3. Regional map of SST anomaly (°C) for December 1999 (source: OISST).

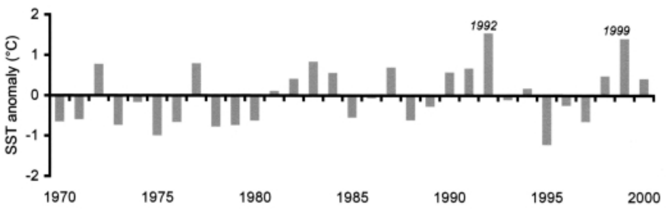

Fig. 4. Time series of the mean SST anomaly (°C) in December from 1970 to 2000 (source COADS dataset and Climate Diagnostics Center).

South Africa (Fig. 5). The core of the negative anomaly was located inshore. This suggests that a sustained coastal upwelling off the west coast, rather than advection from adjacent regions, was the mechanism leading to the observed negative SST anomalies. The persistent and intense upwelling episode 10, as well as the following episode 11 (Fig. 1), led to a sustained and almost uninterrupted upwelling from early March to mid-April, resulting in the persistence of cold water over the shelf. The weekly composite images of high-resolution SST during March and April 2000 confirm that the main upwelling cells off the Cape Peninsula and west coast were almost continuously active during this period (Fig. 6). As a result, these cells acted as a source of cold water originating from the coast and spreading over the continental shelf. In March and April 2000, SST weekly averages were below 14°C off the Cape Peninsula and off the west coast for an extended period (Fig. 6).

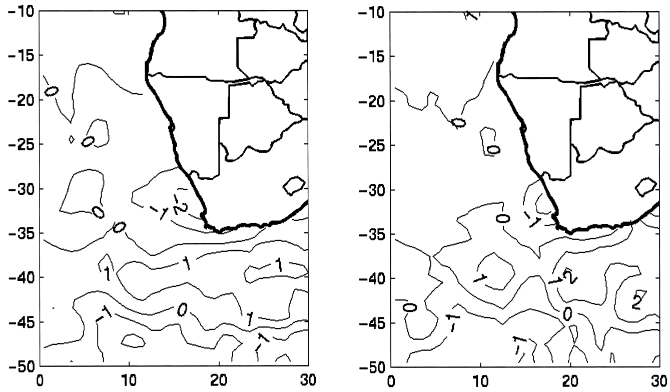

Fig. 5. Regional maps of SST anomaly (°C) for March and April 2000 (source: OISST).

The mean of Ship-SSTA during late summer (March to April) allows a comparison of oceanographic conditions recorded during late summer 2000 with historical records (Fig. 7). Late summer 2000 was characterized by a negative SST anomaly, reaching –1.9°C, by far the largest recorded over the last 30 years. The magnitude of this anomaly was more than twice the previous record of 1971.

In summary, there is supporting evidence from both wind data as well as local and regional SST observations that the oceanographic conditions during late summer 2000 were characterized

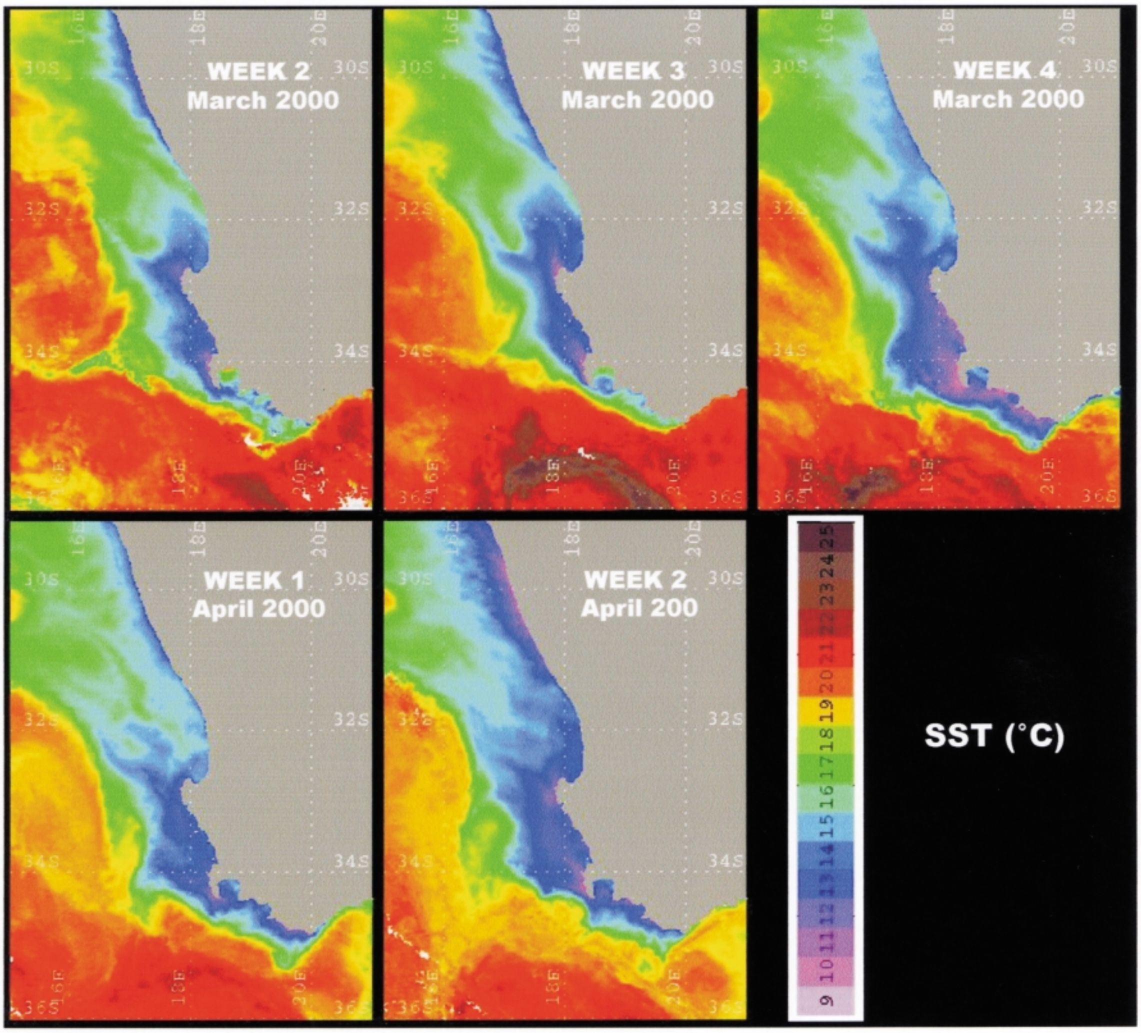

Fig. 6. Weekly composite of mean SST (°C) derived from high-resolution (1 km) AVHRR data from the second week of March to the second week of April 2000.

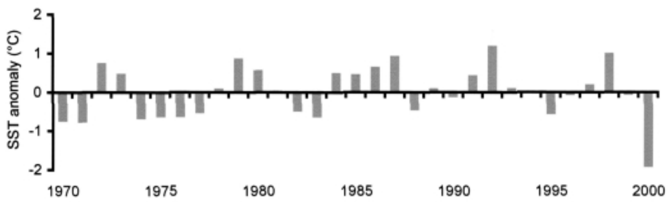

Fig. 7. Time series of the mean March–April SST anomaly (°C), from 1970 to 2000 (source: COADS dataset and Climate Diagnostics Center).

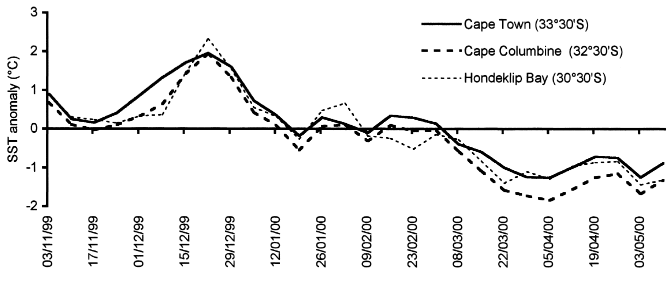

Fig. 8. Weekly SST anomalies (°C) at three locations off the West coast of South Africa from November 1999 to mid-May 2000 (source: OISST).

by sustained upwelling, which brought cold water onto the shelf from the Cape Peninsula up to 30°S.

A summary of the oceanographic conditions during summer 1999–2000

The chronology and magnitude of the two main oceanographic events that affected the water over the continental shelf of the Cape Peninsula and west coast during the 1999–2000 upwelling season are summarized in Fig. 8. These events affected the entire South African west coast, from Cape Point to Hondeklip Bay. The warm event had a comparable magnitude along the Cape Peninsula and west coast, with SST anomalies reaching 2.0°C during the third week of December, whereas the cold episode appeared to be more pronounced in the vicinity of Cape Columbine, where the SST anomaly in early April reached –2.0°C. From weekly time series of SST anomalies, it was not possible to observe any phase difference among the various locations in the occurrence of either the warm or cold events.

The 1999–2000 upwelling season in long-term context

The 1999–2000 upwelling season is placed in long-term climatic context by looking at the averaged Ship-SSTA from November to the following April for the last 30 years (Fig. 9). The 1999–2000 season appears to be 0.58°C cooler than the average conditions recorded over this timespan. The amplitude of this

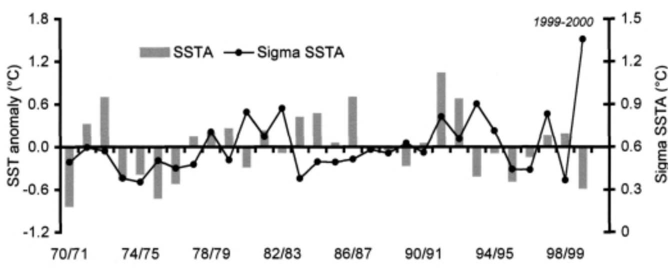

Fig. 9. Seasonally averaged (November to the following April) time series of SST anomaly (°C) for the summer seasons from 1970–71 to 1999–2000 (column) and standard deviation of ship-SSTA (°C) during the summer season (November to the following April) from the summer seasons 1970–1971 to 1999–2000 (line). Source: COADS dataset and Climate Diagnostics Center.

anomaly is significantly smaller than the principal anomalies recorded during the summers of 1970–71 (–0.83°C), 1975–76 (–0.72°C), 1986–87 (+0.74°C), and 1991–92 (+1.04°C). The 1999–2000 summer is also ranked as the third coolest over the last 30 years and as the seventh largest in terms of absolute magnitude of the anomaly. We conclude that, in using the mean SST anomaly over the entire summer season as a climatic index, the summer of 1999–2000 does not appear to be a major outlier.

By contrast, a different picture emerges from the time series of the seasonally averaged (November to April) Ship-SSTA standard deviation (sigma-SSTA). The standard deviation of Ship-SSTA can be interpreted as an index of the variability of the oceanographic conditions during the summer season. The value of sigma-SSTA recorded during the summer of 1999–2000 reached 1.36°C and was 50% higher than the previous maximum measured during the summer of 1993–94 (Fig. 9). The high standard deviation during the 1999–2000 summer is not unexpected considering the combination of both warm and cold events that occurred during this period and that are described above. However, it appears that the alternation of both extreme cold and warm events of such magnitude during the same summer is highly unusual and has not been recorded during the past 30 years. This succession of conditions of opposite sign was the main characteristic of the 1999–2000 upwelling season, whose amplitude identifies this summer as the most conspicuous outlier over the last 30 years.

Discussion

The global climatic context of the summer of 1999–2000 was characterized by a pronounced cold ENSO event (La Niña conditions over the Pacific Ocean), which started in winter 1998 and was in a mature stage during the austral summer of 1999–2000. Using NCEP/NCAR meteorological parameters at different levels of the atmosphere, we compared each month of the 1999–2000 summer with a composite of summer months since 1949 during which La Niña was present. It appears that the meteorological setting observed in the South Atlantic Ocean during the summer of 1999–2000 was similar to the atmospheric patterns observed during other La Niña episodes. The main characteristics are:

- a strengthened high-pressure system in the Atlantic and Indian oceans;
- a southward displacement of the Atlantic high-pressure condition associated with a low-pressure anomaly eastward of it extending to the Namibian and South African coastline;
- increased southeasterly wind along the coast of South Africa;
- abnormal northeasterly fluxes of humidity from the tropics towards the western part of southern Africa and above-normal rainfall over the summer rainfall areas (all areas except the Western Cape).

December seems abnormal in that context but could be explained by an even bigger southerly shift of the Atlantic high-pressure region and attendant eastwards low-pressure anomaly experienced during La Niña. Indeed, just south and east of the country anomalous southeasterly winds were experienced.

One expects that the extreme oceanographic conditions recorded during the summer of 1999–2000 had important ecological implications. An obvious one is the influence on the plankton abundance. Upwelling processes usually induce nutrient enrichment of the surface layers, with a consequent increase in primary production and abundance of phytoplankton over the shelf as illustrated in the SeaWiFS ocean colour image for the first week of December 1999 (Fig. 10). The decline in upwelling

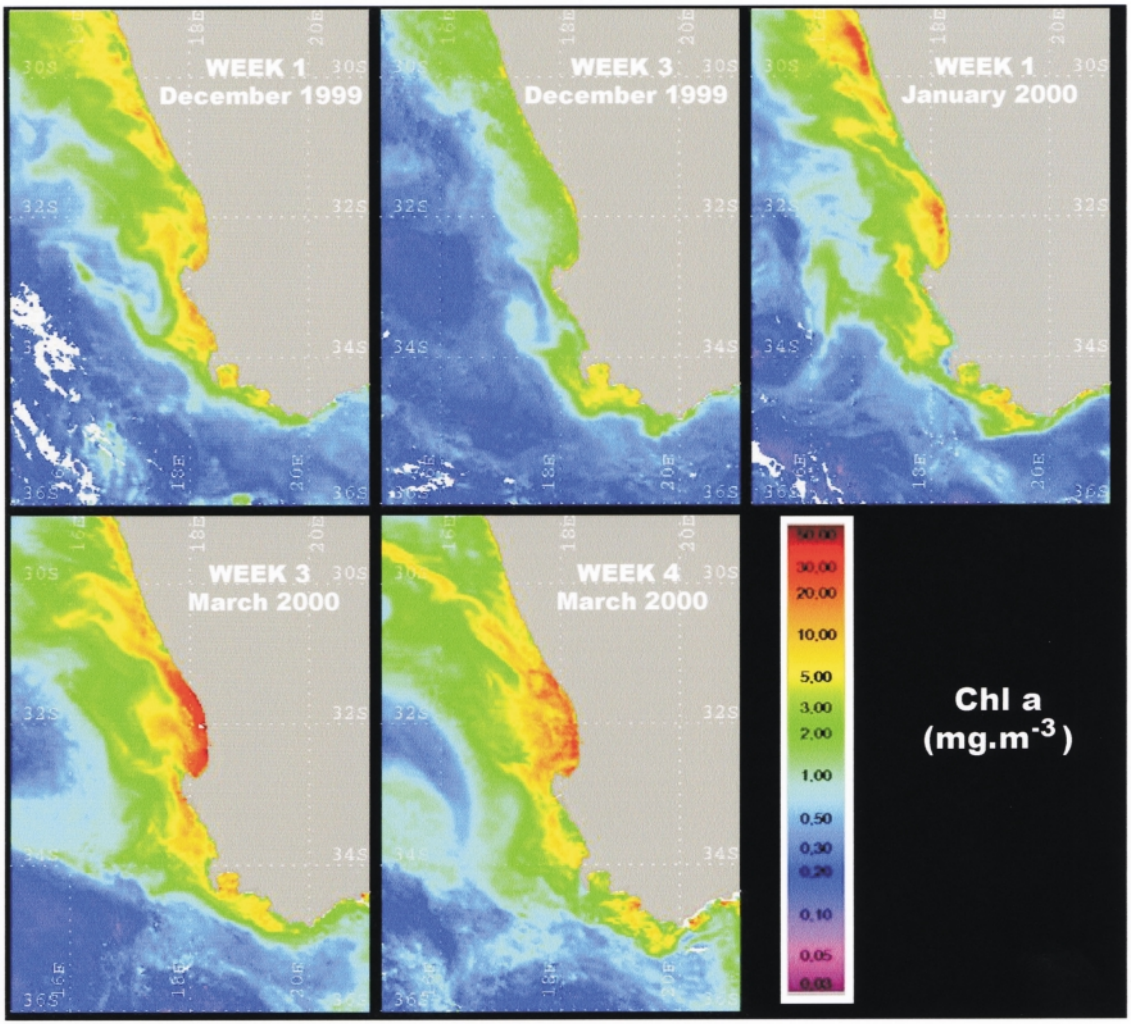

Fig. 10. Weekly composites of mean surface chlorophyll-*a* concentration (mg m^{-3}) derived from high-resolution (1 km) SeaWiFS daily data for selected weeks in December 1999, January 2000 and March 2000.

during the second and third weeks of December, and the associated warming events, resulted in a significant decrease in phytoplankton abundance during this period. As upwelling resumed again in the first week of January 2000, primary production increased on the shelf with an accumulation of phytoplankton biomass to 'normal' levels (Fig. 10). The onset of the cold anomaly, and sustained upwelling in March and April 2000, induced a continuous entrainment of nutrients onto the shelf and primary production appeared to be enhanced, with a particularly high accumulation of phytoplankton in the zone between Cape Columbine and Hondeklip Bay (Fig. 10).

One of the main ecological consequences of the unusual 1999–2000 upwelling season may be the record high level of anchovy recruitment observed in 2000 (the greatest recruitment recorded since the beginning of the time series in 1985). Previous investigations indicated a detrimental effect of enhanced upwelling in the summer on anchovy recruitment.[8] Both wind and SST data indicate that, when averaged over the whole season, the 1999–2000 upwelling was stronger than usual. Surprisingly, and in contrast to previous findings, the upwelling appears to have favoured anchovy recruitment in 2000. However, it may be possible to reconcile previous findings regarding the effect of upwelling on anchovy recruitment with the exceptional results of 2000, by noting the following:

- Anchovy spawning peaks in the late spring and early austral summer (October–December) over the Agulhas Bank. Eggs and larvae are then transported by a coastal jet from the spawning ground to the west coast nursery area. It is during this transport phase that enhanced upwelling is thought to affect the dispersal of eggs and larvae.[9] In late summer and autumn (January–April), larvae and juveniles are found over the west coast continental shelf. During this stage, one expects that upwelling can lead to increased food availability that would favour growth and reduce mortality. Recent modelling experiments have also indicated that intensified upwelling off the west coast favours retention within the coastal domain.[10]
- The collapse of the upwelling and of the associated offshore divergence during the last two weeks of December 1999 might have drastically reduced the advective loss of larvae and enhanced the number of larvae transported to the west coast by the jet. By averaging environmental conditions of a large temporal window, this beneficial effect is overridden by the enhanced upwelling conditions recorded during the remaining 1999–2000 summer season. Additionally, the elevated water temperature recorded in December 1999 would have resulted in more rapid larval growth, which is likely to have reduced mortality rates during the early life history stages.
- The moderate upwelling intensity that followed the December warm event could have favoured the development of the upwelling plume downwind of Cape Columbine and of the associated eddy which is thought to enhance transport to the coast and retention.[10]

- The moderate upwelling observed in January–February 2000 and the following sustained episodes recorded later in the season probably resulted in sustained primary and secondary production at a high level. This is supported by the high chlorophyll concentration observed in the SeaWiFS images. Then, rather than being detrimental to the larvae, the upwelling regime recorded during the mid and late summer season may have enhanced food availability to the group of larvae that previously reached the west coast nursery ground during the relaxed upwelling episode of December 1999. Enhanced food availability would have maximized the growth and reduced the mortality of anchovy post-larvae and young juveniles.

The unusual characteristics of the 1999–2000 upwelling season suggest that, when investigating the linkage between anchovy recruitment and environmental factors, it may be as important to take into account the temporal succession of events and their magnitude as to consider the mean conditions over the whole season.

Conclusion

The summer of 1999–2000 upwelling season was characterized by a marked weakening of upwelling in mid-December that lasted for two weeks. As a result, SST recorded in December reached anomalously high values. Later in the season, an unusual sustained southeasterly wind regime enhanced the upwelling divergence and lowered SST along the coast for an extended period. Those two events were separated by a period of moderate upwelling intensity, extending from January to February 2000. Owing to this extreme environmental variability, seasonally averaged values of factors such as SST give little indication of the oceanographic conditions that occurred. We recommend that new environmental indices be developed to incorporate the intra-seasonal variability.

There are indications of a direct response of plankton abundance to the alternation of weak and strong upwelling episodes. The chlorophyll-*a* concentration off the west coast, derived from SeaWiFS images, suggests that plankton abundance was low during the weak upwelling episode of December 1999 and significantly increased later in the season. The high-resolution wind data at Cape Columbine, in combination with the SST and cholorphyll-*a* satellite images, provides valuable information to investigate further the link between short-term upwelling variability and plankton population responses.

We have also shown that it is possible to reconcile previous findings regarding the effect of upwelling on anchovy recruitment with the exceptional recruitment recorded in 2000. The 16-year time series of anchovy recruitment can be used to test for the importance of the timing of upwelling events for anchovy recruitment, as observed in 1999–2000.

The extreme oceanographic events recorded during the summer of 1999–2000 provided us with useful clues on how the coupling between the physical and biological components of the Benguela ecosystem works. They show that, when investigating the linkage between fish recruitment and the environment, the temporal succession of events and their magnitude appear to be as important as the mean conditions over the entire season.

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1. Nelson G. (1992). Equatorward wind and atmospheric pressure spectra as metrics for primary productivity in the Benguela system. *S. Afr. J. mar. Sci.* **12**, 19–28 .
2. Kalnay E.M., Kanamitsu M., Kistler R., Collins W., Deaven D., Gandin L., Iredell M., Saha S., White G., Woollen J., Zhu Y., Chelliah M., Ebisuzaki W., Higgins W., Janowiak J., Mo K.C., Ropelewski C., Wang J., Leetmaa A., Reynolds R., Jenne R., Joseph D. (1996). The NCEP/NCAR 40-year reanalysis project. *Bull. Am. Meteor. Soc.* **77**, 437–471.
3. Johnson A. (2001). *Analysis of variable scatterometer wind fields in the Benguela upwelling region.* M.Sc. thesis, University of Cape Town, Rondebosch.
4. MacClain E.P, Pichel W.G. and Walton C.C. (1985). Comparative performance of AVHRR-based multichannel sea surface temperatures. *J. geophys. Res.* **90**, 11587–11601.
5. Reynolds, R.W. and Smith T.M. (1994). Improved global sea surface temperature analyses. *J. Climate* **7**, 929–948.
6. Woodruff S.D., Slutz R.J., Jenne R.L. and Steurer P.M. (1987). A comprehensive ocean-atmosphere data-set. *Bull. Am. Meteor. Soc.* **68**, 1239–1250.
7. Mendelssohn R. and Roy C. (1996). Comprehensive Ocean Data Extraction Users Guide. U.S. Dep. Comm., NOAA Tech. Memo. NOAA-TM-NMFS-SWFSC-228, La Jolla, CA.
8. Boyd A.J., Shannon L.J., Schulein F.H. and Taunton-Clark J.T. (1998). Food, transport and anchovy recruitment in the Southern Benguela upwelling system of South Africa. In *Global Versus Local Changes in Upwelling Systems,* eds M.H. Durand, P. Cury, R. Mendelssohn, C. Roy, A. Bakun and D. Pauly, pp. 195–209. Editions ORSTOM, Paris.
9. Hutchings L., Barange M., Bloomer S.F., Boyd A.J., Crawford R.J.M., Hugget J.A., Kerstan M., Korrubel J.L., De Oliviera J.A., Painting S.J., Richardson A.J., Shannon L.J., Schulein F.H., van der Lingen C.D. and Verheye H.M. (1998). Multiple factors affecting South African anchovy recruitment in the spawning, transport and nursery areas. *S. Afr. J. mar. Sci.* **19**, 211–225.
10. Penven P., Roy C., Colin de Verdière A. and Largier J. (2000). Simulation of a coastal jet retention process using a barotropic model. *Ocean. Acta* **23**, 615–634.

The call to explore

Pendant toute la traversée ils raisonnèrent beaucoup sur la philosophie du pauvre Pangloss. 'Nous allons dans un autre univers, disait Candide; c'est dans celui-là sans doute que tout est bien: car il faut avouer qu'on pourrait gémir un peu de ce qui se passe dans le nôtre en physique et en morale. — Je vous aime de tout mon coeur, disait Cunégonde; mais j'ai encore l'âme tout effarouchée de ce que j'ai vu, de ce que j'ai éprouvé. — Tout ira bien, répliquait Candide; la mer de ce nouveau monde vaut déjà mieux que les mers de notre Europe; elle est plus calme, les vents plus constants. C'est certainement le nouveau monde qui est le meilleur des univers possibles….'

During their entire voyage they spoke a great deal about the philosophy of poor Pangloss. 'We are going into another world,' said Candide, 'and no doubt it is in this new world that everything is good; for I have to confess that what's happened in the world that we've known, both physically and spiritually, has caused us to tremble a bit.' 'I love you with all my heart,' said Cunégonde, 'but nevertheless I'm still terrified to the depths of my soul by everything I've seen and experienced.'

'All will be well,' replied Candide, 'Look! The seas of this new world are already better than the seas of Europe. They are calmer, and the winds are steadier. It is for certain that this new world's the one that'll prove to be the best of all possible worlds.'

from chapter X of *Candide* by Voltaire (1694–1778)