Case Study 15

Biological Response Associated With a Coastal Upwelling Event

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15.1 Introduction and Background

This case study deals with one of the most powerful coastal upwelling regions on Earth. Upwelling is a physical phenomenon that sustains very high levels of marine life and diversity. The area of interest is the southern part of the Benguela upwelling region, particularly the west coast of Southern Africa, from 28 to 34°S. The Lüderitz upwelling cell, situated a little further north (at 27.5°S), where the trade winds blow strongly all year round, is one of the largest upwelling cells in the world, making this area a quasi-physical barrier, even for some small pelagic fish populations. At this location, the wind speed is very high (always >5 m s^{-1}) and the high turbulence level, associated with a relatively low water clarity and a strong offshore component of the currents, makes this particular area relatively unfavourable for the survival of ichthyoplankton (eggs and fish larvae) compared with the rest of the system, where the upwelling is less intense.

NASA's MODIS (Moderate Resolution Imaging Spectroradiometer) sensor, on board the Terra and Aqua polar orbiting satellites, offers a unique opportunity to study physical and bio-chemical processes occurring near the sea surface, by providing simultaneous views of both sea surface temperature (SST) and ocean colour (most common product is chlorophyll-*a* concentration). We use simultaneous synoptic views of SST and surface chlorophyll-*a* concentration (SCC) to describe and interpret the main spatio-temporal processes that occur in this highly dynamic coastal area. More precisely, the goal of this case study is to use spatially explicit, instantaneous information from both variables to explore the enrichment mechanisms that occur in the euphotic layer (i.e. the layer of the sea surface illuminated by sun light where photosynthesis can take place), in terms of mesoscale activity and algal growth. The availability of both SST and SSC from the same satellite is of crucial

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importance to understanding the links between the physics and the biology, and therefore to obtain an insight into the dynamics of the next trophic level, composed of zooplankton and ichthyoplankton which are highly sensitive to the environmental forcing that contributes to their survival, and ultimately to the success of their recruitment. Consequently pelagic fish species have developed specific strategies that take advantage of the richness of this region while minimizing the impact of the high level of environmental variability.

15.2 Materials and Methods

15.2.1 Information about image data

SST and ocean-colour data was acquired by the MODIS sensor on board the Aqua platform. MODIS data is disseminated via NASA's Ocean Color web site (http://oceancolor.gsfc.nasa.gov/) from where the SST and chlorophyll-*a* data for this case study can be downloaded. These data can be processed using the dedicated SeaDAS software freely available at http://oceancolor.gsfc.nasa.gov/seadas/. MODIS detects emitted and reflected radiance in 36 channels spanning the visible to infrared (IR) spectrum. Further information about the instrument can be found on the NASA MODIS web site at http://modis.gsfc.nasa.gov/about/specifications.php. The standard MODIS Chlorophyll-*a* algorithm (OC3; O'Reilly et al., 2000) relies on reflectance ratios at channels at 443, 488 and 551 nm.

The SST data used in this case study originates from the infrared part of the spectrum, between 11 and 12 μm. A second SST measurement (not used here) is also recorded at three wavelengths between 3.7 and 4.0 μm in the near infrared part of the spectrum. The electromagnetic radiation emitted from the sea surface can be inverted (using Planck's law, see http://en.wikipedia.org/wiki/Planck's_law) to deduce the surface temperature of the target. For remote sensing applications, the 11–12 μm spectral window is used most frequently because of its relatively low sensibility to the Earth's atmosphere. The nominal image resolution of the data (at the satellite nadir) is 1 km and its effective radiometric resolution for SST is 0.1°C. The chlorophyll concentration is displayed using a chlorophyll scale with values ranging from 0.01 to 58 mg chl-*a* m^{-3}. Both parameters are extracted from "Level 2" data i.e. in orbit form, including geolocation and atmospheric correction.

Wind data from the SeaWinds scatterometer, on board the QuikSCAT satellite, was also used in this case study. QuikSCAT was launched in June 1999 after the unexpected failure of the NASA scatterometer (NSCAT) satellite. The SeaWinds instrument is a specialized microwave radar that measures both the speed and direction of winds at the sea surface, at a spatial resolution of 25 km. This mission ended operation on 21 November 2009 due to an antenna rotation failure. The wind data used in this study are "Level 3" i.e. gridded and spatially and temporally combined.

15.2.2 Description of physical processes

The coastal upwelling principle was determined by physicist W.K. Ekman (1905) who examined the frictional effects of wind moving over the ocean surface. The net effect is that the current flow induced by the wind friction is deviated to the right of the wind direction in the northern hemisphere, and to the left of the wind direction in the southern hemisphere (Figure 15.1a). At the surface, the current moves at an angle of about 45 degrees to the wind direction. The net transport of water through the entire wind-driven water column is approximately 90 degrees to the direction of the wind. This movement of water is called **Ekman transport** or **Ekman flow**. Figure 15.1b shows the simplified cross-shore section of the water flow.

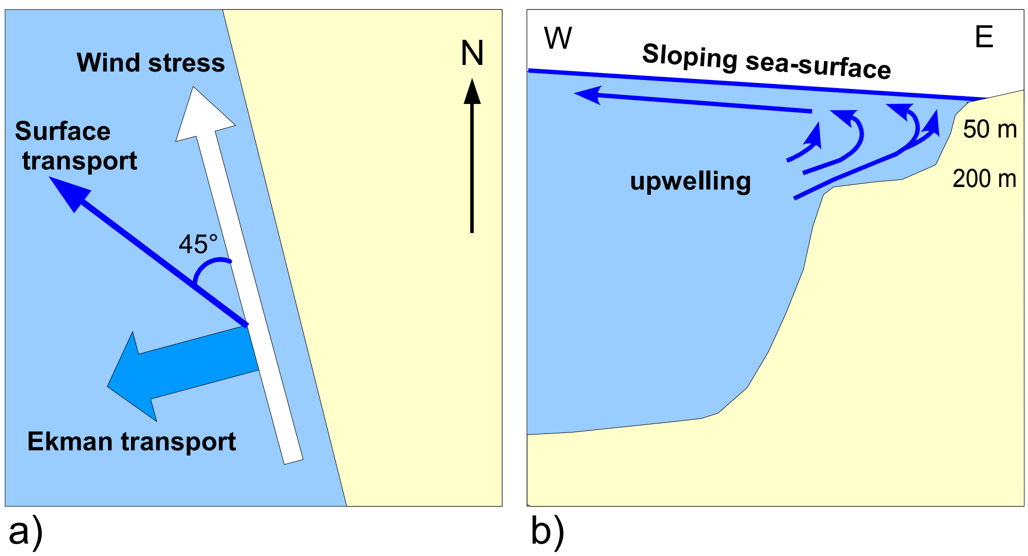

Figure 15.1 Schematic illustration of wind-driven, coastal upwelling in the southern hemisphere due to Ekman transport (adapted from Ocean Circulation, by The Open University).

Winds and currents thus combine to bring cold water from below the seasonal thermocline (50-200 m) to the surface, especially near the coast where the upwelling flow is maximum. Because of the temperature difference between the the coastal and offshore water masses, the surface temperature is a very good descriptor of coastal upwelling (Figure 15.2a), the dynamics of which can be studied from space. Furthermore, ocean-atmosphere interactions make these regions less cloudy than many other coastal regions. The presence of cold surface water decreases the evaporation, and therefore lowers the water vapor content of the atmosphere (one of the major absorbing components of the remote sensing reflectance signal, together with clouds and aerosols). Figure 15.2a shows that the coldest water (in white) is very close to the coast, a primary physical characteristic of a coastal upwelling region, and the most visible from space. Figure 15.2b shows the corresponding concentration of chlorophyll-*a* (the main photosynthetic pigment of most unicellular algae). The comparison between the SST and SCC images shows that, at first glance, there is a strong spatial link between both parameters. The mechanisms responsible for this relationship are the focus of this case study.

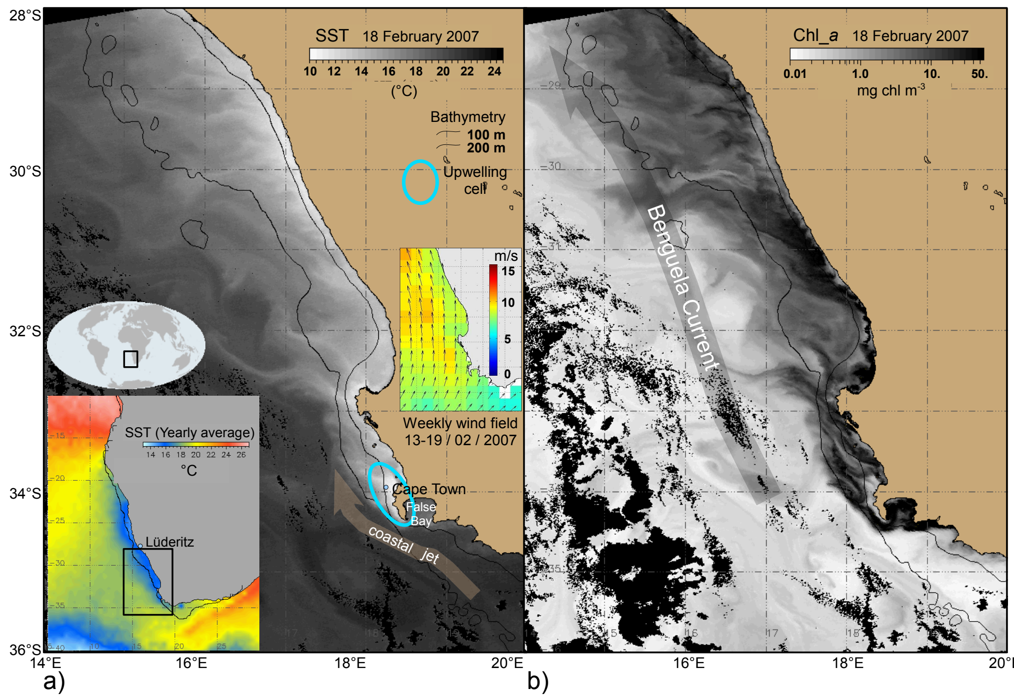

Figure 15.2 Region of interest showing (a) SST (°C) and (b) chlorophyll-a concentration (mg m^{-3}) computed from MODIS satellite data for the southern Benguela upwelling system, on 18 February 2007, during the upwelling season. The spatial resolution is 1 km. The left colour insert is the yearly average SST for the whole Benguela region, and the right insert is the average wind field during the week preceding the MODIS observation. The black patches in the offshore part of the chlorophyll image are due to lack of data because of the presence of clouds. MODIS data provided by NASA/GSFC.

Satellite images provide a synoptic view that allows a precise description of the spatial extent of the superficial upwelled waters. More precisely, the SST difference between the coastal and the offshore water allows a semi-quantification of the upwelling intensity based on the surface cooling. Such differences have been used to compute a SST-based coastal upwelling index (see Demarcq and Faure, 2000). The intensity of the coastal cooling is not homogeneous along the coast, but is reinforced in some locations where the vertical surface flux is stronger. These areas are called upwelling "cells". One in particular is clearly visible at the southern part of the region, between Cape Town and the Cape of Good Hope, the southwestern tip of the Cape Peninsula.

Fronts, eddies, plumes and filaments are the main signatures of mesoscale activity at the sea surface, and are primarily visible from satellite SST images because the water masses involved in frontogenesis (the formation or strengthening of a front) are generally of different temperatures. These features can also be observed through the "colour" of the sea, from maps of surface Chlorophyll-*a* concentration, the most widely used ocean colour product. In coastal upwelling areas, fronts and filaments are useful tracers of marine productivity and of the retention processes associated with the coastal circulation of water masses. Retention processes allow eggs and larvae of many pelagic species (or demersal and benthic species which have a pelagic early life stage) to be retained in favourable coastal areas, instead of being advected offshore.

Bakun's triade hypothesis (Bakun, 2006) provides a conceptual scheme for this mechanism. Bakun proposed that biological success is only possible in a marine environment if a satisfying balance is preserved between three fundamental physical processes: enrichment, concentration and retention. In coastal areas, enrichment processes are represented by the nutrient-rich, upwelled waters that enter the euphotic zone. The "concentration" term represents the vertical and horizontal advection of water masses that result in the concentration of biological matter, primarily phytoplankton. Last, but not least, the retention processes represents the ability of surface currents to keep the planktonic portion of the marine life (phytoplankton, zooplankton and ichthyoplankton) in particular areas where they will be more protected from predators and/or unfavourable environmental conditions. Marine species that have evolved in such a variable environment, have developed strategies that minimize the negative impacts while maximizing the favourable ones. For example, anchovies in the study region have developed a strategy to spawn in warmer waters (the extreme southern part of the system) which are physiologically more adequate for spawning. The eggs and larvae then drift away, pushed westward (but maintained close to the coast) by the coastal jet, where they are then passively transported to favourable retention areas where food is abundant. Naturally, over 90% of the released eggs are lost, but the survival of the species is preserved. Upwelled waters have high nutrient concentrations as a result of the sinking of organic matter (decaying phytoplankton blooms) from the sunlit surface layers into the deep ocean, where the cells are decomposed by bacteria. This process enriches the deep waters with nutrients (mainly nitrate, silicate and phosphate) which cannot be used at depth because the light levels are too low for photosynthesis.

Biologically, the newly upwelled water becomes progressively richer in chlorophyll and the maximum phytoplanktonic growth is reached when the uptake of nutrients becomes a limiting factor. The spatial heterogeneity of the surface currents, due to the complexity of the bathymetry combined with the heterogeneity of the wind field, creates mesoscale structures, visible on both the temperature and chlorophyll fields (Figure 15.2a,b). The intensity of these surface currents, as well as their induced retention effect on passive particles (or inversely their dispersal effect) are of primary importance in fisheries biology because they can cause the ichthyoplankton to drift far away from the coast where the feeding conditions are much less favourable for their survival. Consequently, the recruitment of these species could be impacted strongly by the natural variability of these currents. For example, it has been shown from satellite imagery that the length of the "pathway" associated with the meanders of the coastal jet in the southern Cape (Figure 15.2a), where both SST and chlorophyll gradients are very strong, is positively related to larvae survival, and therefore to the recruitment of the anchovy populations (Van der Lingen, 2006).

Note about colour palettes: The main images in Figure 15.2 are displayed in gray scale, the most objective way to represent a spatial continuum of a two-dimensional field for a single geophysical parameter. The disadvantage of a colour scale is the risk of artificially "contrasting" some parts of the image because a colour scale is always a compromise between smooth colour changes and a continuous light gradient. In a gray scale image, the light gradient is perfect and the eye is not influenced by the brightness of some colours. This is the best way to evaluate the global gradient of the image values. On the other hand, the determination of the local values is not as precise as for a colour scale (which is better in this respect), but far less objective for gradient estimation. Figures 15.3 and 15.4 show these two images using a false colour palette.

15.3 Training and Questions

Q1: Considering the physical principle of coastal upwelling (see Figure 15.1), how could it be characterized from a thermal point of view? What is the thermal contrast with the offshore oceanic water?

Q2: What mesoscale structures are visible in the SST and Chlorophyll images, either related to coastal upwelling processes, or not?

Q3: What is the main relationship between SST and SCC in the study area? In particular, how can you interpret the spatial information in terms of temporal history?

Q4: What are the main characteristics of the upwelling cells from the information available in the images, and what explanations can you give compared to the rest of the upwelling area?

Q5: What could be a suitable place for fish larvae to feed and survive in reasonably good conditions, with a low probability of being driven offshore where the predation pressure is higher? Look at the direction of the currents and topographic opportunities.

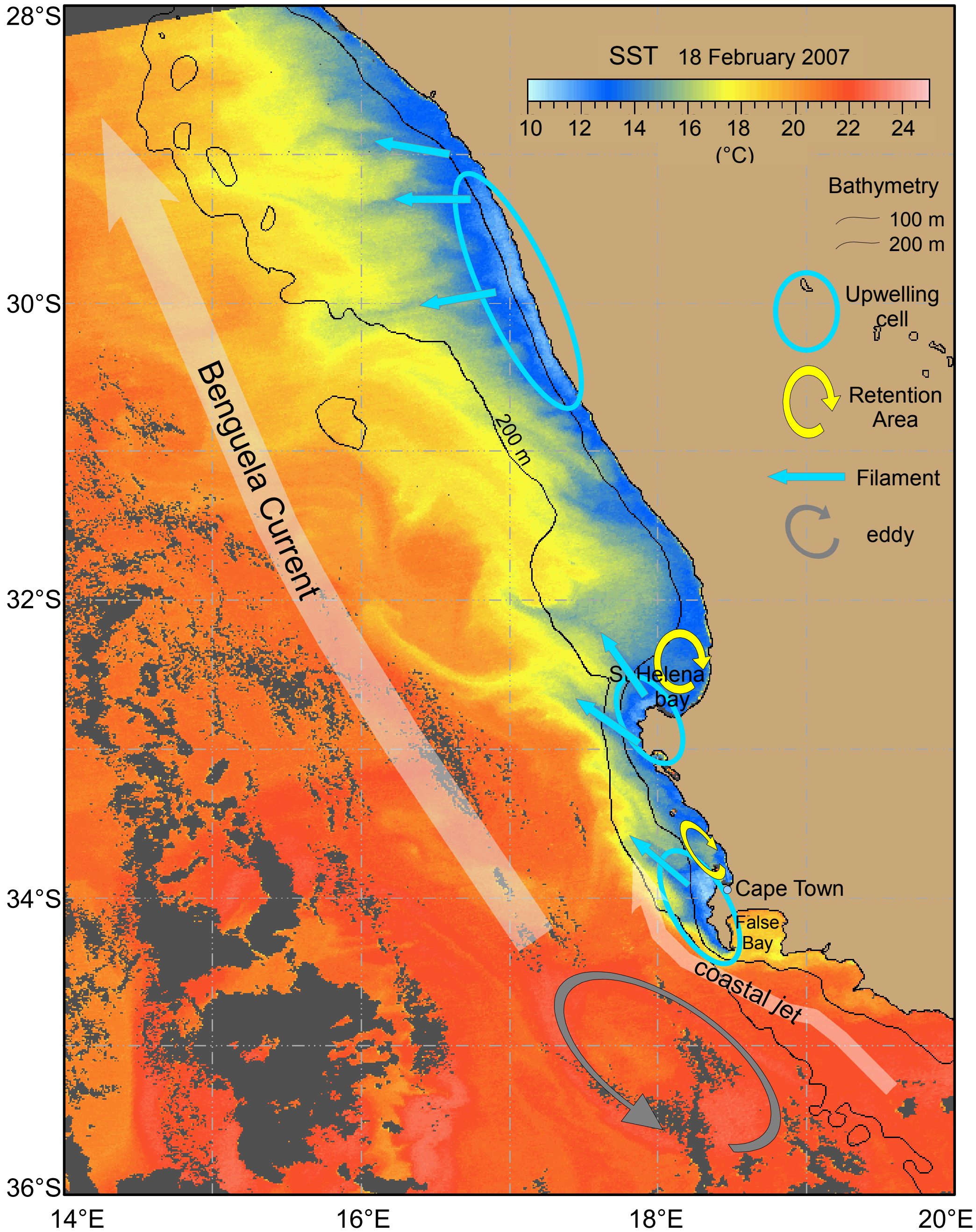

Figure 15.3 Same as Figure 15.2a (SST) but using a colour palette. Upwelling cells, associated filaments and retention areas are superimposed. MODIS data provided by NASA/GSFC.

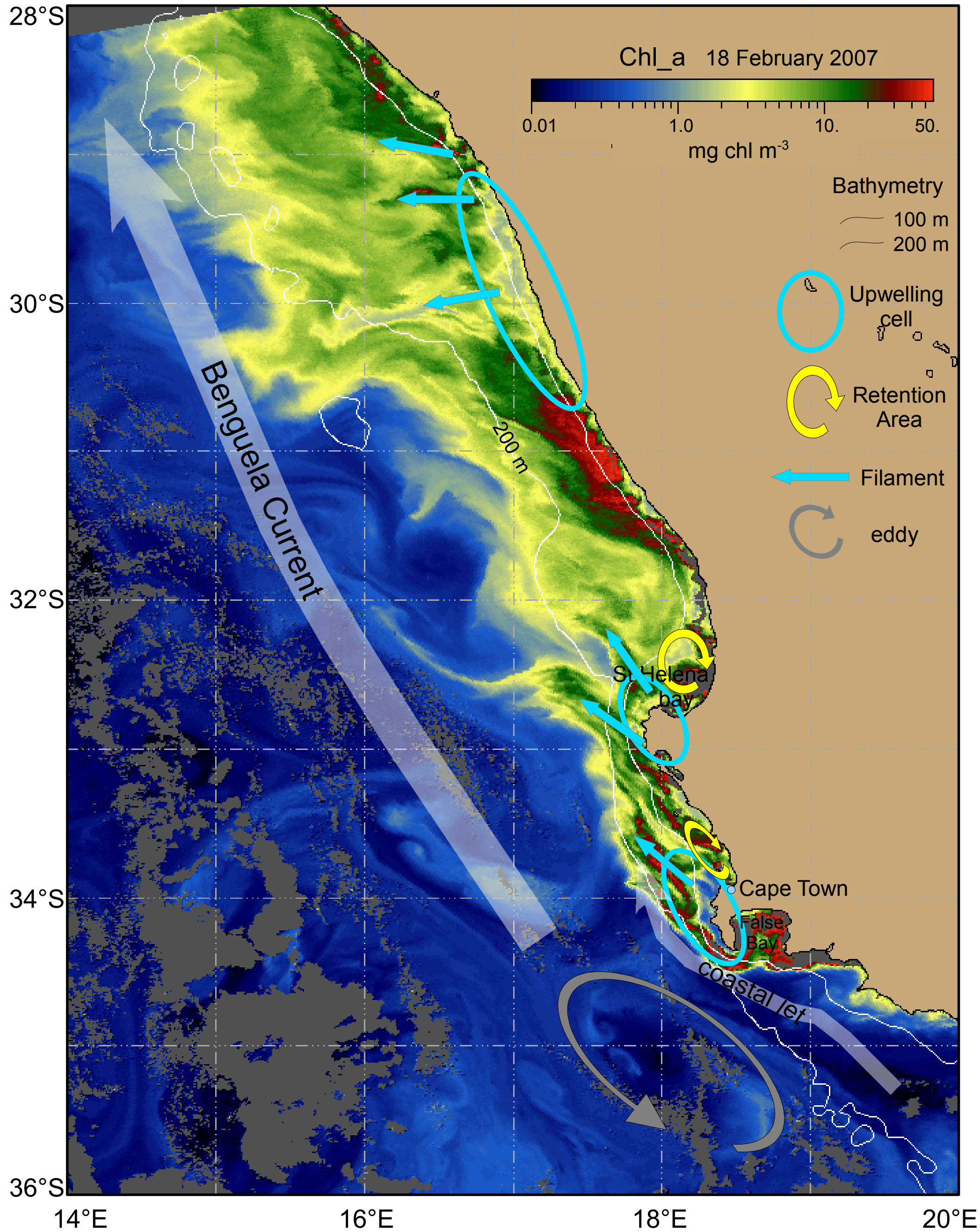

Figure 15.4 Same as Figure 15.2b (Chl-*a*) but using a colour palette. Note the logarithmic scale that accounts for the irregular distribution of the chlorophyll values. MODIS data provided by NASA/GSFC.

15.4 Answers

A1: The SST field (Figure 15.3) provides a synoptic view of the near surface dynamics, where upwelled waters are much colder than the surrounding waters. The minimal

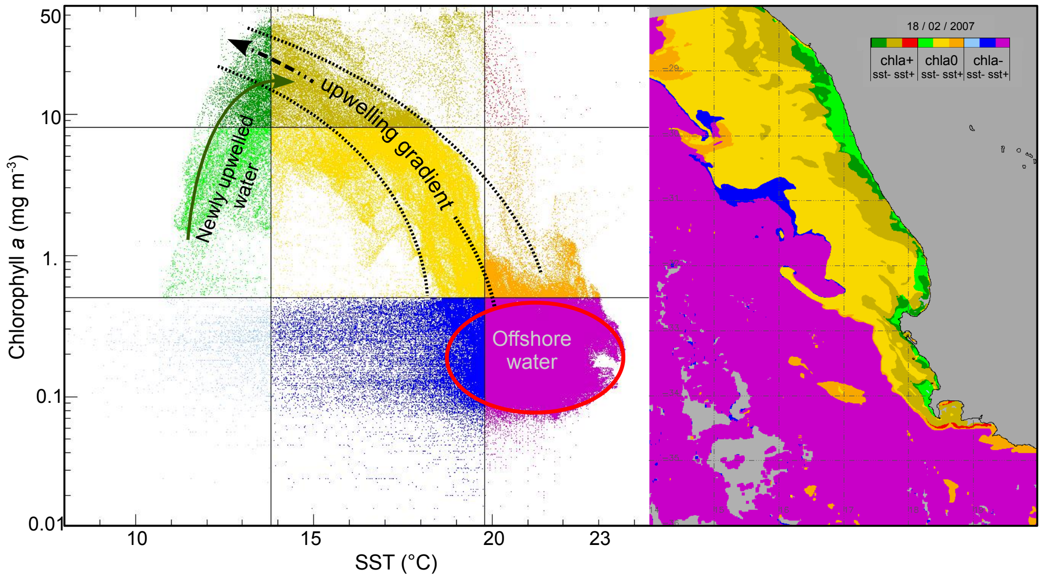

Figure 15.5 Cluster plot of the SST and SCC values showing a general negative relationship between the two parameters, as well as the intermediate chlorophyll and low temperature values of the newly-upwelled waters. MODIS data provided by NASA/GSFC.

temperature at the centre of the most active upwelling cell is close to 10°C, a temperature that is usually found at a depth of >100 m (data not shown), suggesting that the origin of the upwelled water is close to the continental slope. Several distinct upwelling cells occur at specific locations where the wind component parallel to the coast is maximum, according the Ekman pumping theory. The SST difference between the cool upwelled water and the warm offshore water is close to 10°C. This temperature difference can also be used as a proxy to estimate the intensity of the coastal upwelling, or at least its thermal impact at the sea surface, complementing the Ekman upwelling index, a measurement of the upwelling intensity computed from Ekman theory. A closer look at the concomitant weekly wind field (insert in Figure 15.2) shows that the location of the three identified upwelling cells matches exactly with those coastal portions parallel to the wind direction, where the upwelling process is maximal, according the Ekman theory (Figure 15.1a).

A2: The location, intensity and shape of the thermal fronts associated with these coastal waters supplies a lot of information on the mesoscale circulation features and the influence of the coastline. Knowledge of the bathymetry (100 and 200m isobaths) is essential to study the effects of the continental shelf and to understand the forcing effects of the large scale circulation (the westward coastal jet in the southern part of the area). A long upwelling filament (~200 km), situated between 32 and 33°S is clearly visible on the SST image, as well as the chlorophyll image (Figures 15.3 and 15.4). Many other filaments are visible, all associated with the various upwelling cells identified. Outside the coastal upwelling area, a warm anticyclonic eddy is clearly visible (grey arrow), partly generated by the frictional forces of the coastal jet current. Its central region, situated at 35°S and 18°E, is characterized by very low chlorophyll concentrations. This characteristic can be attributed to the deepening of the isotherms as a result of the surface convergent field associated with the "spinning up" of the eddy. An excellent description of eddies, as well as their importance as a temporary habitat for marine fish larvae, can be found in Bakun (2006).

A3: The surface chlorophyll field (Figure 15.4) provides an informative view of the biological response to surface enrichment resulting from coastal upwelling. At first glance, we observe a clear inverse relationship between SST and SCC, which is called the "upwelling gradient". Figure 15.5 summarize what we can deduce from a careful observation of both the SST and SCC fields from Figures 15.3 and 15.4. The colours in Figure 15.5 represent 9 partitions of the relationship between the two variables, as well their spatial correspondence. The warm "offshore waters" are easily identified by temperatures >20°C and low chlorophyll concentrations (< 0.5 to 0.6 mg m^{-3}). When moving towards the coast, the main category of water is that associated with the "upwelling gradient", where we can observe the progressive transformation of the recently-upwelled water (shown in green) as it reaches the euphotic layer. The chlorophyll concentration in this water mass increases progressively as photosynthesis takes place and the phytoplankton cells increase in number. The maximum chlorophyll values are extremely high (close to signal saturation). Chlorophyll concentration generally decreases as the water drifts offshore because of the "dilution" of the upwelled water. This upwelling gradient is maximum in the coastal area for high chlorophyll values > 10 mg m^{-3} (dark green and brown-green colours) before nutrients start to become a limiting factor for algae growth. To fulfill the view of this ecological gradient we may imagine the role of the zooplanktonic grazers (mainly large copepod species) that feed actively on the large diatom cells commonly found in upwelling areas. Similarly, small pelagic fish such as anchovies feed on the copepods. This chain of events evolves both in time and space, along a cross-shore gradient of progressively more mature waters.

A4: A closer look at the centre of the upwelling cells (particularly those off the Cape coast, indicated by blue rings) shows very low values of SCC as opposed to the previously observed negative relationship between SCC and SST. This surprising result can be explained by the residence time of the water masses in the euphotic layer, which is too short (less than a few days) to allow for a significant multiplication of the algae (diatoms in our case). Effectively, the time for cell division to take place is about 5 days. Further offshore, where the residence time at the surface becomes higher, photosynthesis takes place, the cells multiply and the chlorophyll concentration increases. A typical time period for a chlorophyll increase from 1 mg

m^{-3} to 10-20 mg m^{-3} in this area is 6-7 days (Brown and Hutchings, 1987).

A5: Any particle (e.g. phytoplankton cell, fish larvae) close to an upwelling cell has a high probability of being driven rapidly far offshore, especially if it is retained in an upwelling filament. In contrast, certain areas in this region make it possible for the same particles to be retained in a favourable environment for days or even weeks. The coastal complexity and the presence of capes induce such privileged areas. This is the case in St Helena Bay (indicated as a "retention area" in Figure 15.3) as well as the bay of Cape Town. Further south, False Bay provides a good retention area, combining relatively warm water associated with a strong enrichment, horizontally advected from coastal counter currents. This area is known for its high species diversity, including seals, white sharks, and even surfers!

15.5 References

15.5.1 Information for downloading data used in this case study

- MODIS data general access (ordering "Level 2" data): http://oceancolor.gsfc.nasa.gov/cgi/browse.pl
- Direct access to 1-km full orbit "Level 2" MODIS chlorophyll and SST data: http://oceandata.sci.gsfc.nasa.gov/MODISA/L2/
- SeaWinds data and "browse" images can be downloaded in various formats from http://podaac.jpl.nasa.gov/DATA_CATALOG/quikscatinfo.html
- "Level 3" gridded data in HDF4 format, along with various decoding software in C, Fortran, IDL and MATLAB: http://aspera.jpl.nasa.gov/download/pub/ocean_wind/quikscat/L3/

15.5.2 Information for related data and documentation

- Aqua sensor: http://aqua.nasa.gov/
- MODIS ocean colour products: http://picasso.oce.orst.edu/ORSOO/MODIS/code/Table1Products.html (see also http://oceancolor.gsfc.nasa.gov/DOCS/MSL12/master_prodlist.html/ for more detailed information)
- EOS products: http://eospso.gsfc.nasa.gov/eos_homepage/for_scientists/index.php
- The Earth Science Reference Handbook: (291 pages, 7.5 MB, PDF document) http://eospso.gsfc.nasa.gov/ftp_docs/2006ReferenceHandbook.pdf
- SeaWinds products: http://podaac.jpl.nasa.gov/DATA_CATALOG/quikscatinfo.html
- Ready to use data series: some of the data included in this case study was extracted from the AOOS web site (http://aoos.mpl.ird.fr/), a satellite image series finder, developed at IRD, Institut of Research for Development by the CRH (Centre de Recherches Halieutiques).

15.5.3 References and Suggested Reading

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