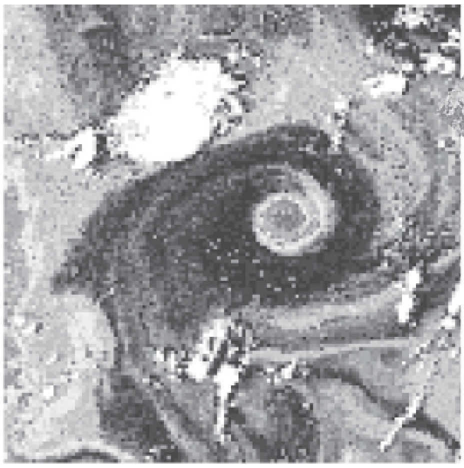
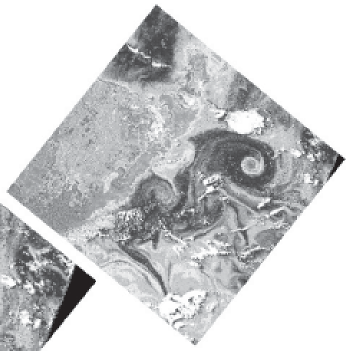
# A PLANKTON GUIDE TO OCEAN PHYSICS





## *Colouring in the currents round South Africa and Madagascar*

Graham D. Quartly and Meric A. Srokosz

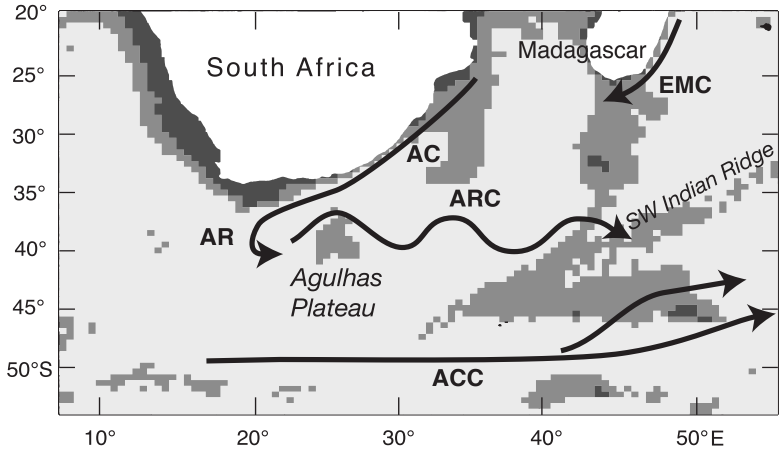
The ocean colour sensor SeaWiFS,* launched in August 1997, has been a great boon to those researching large-scale oceanic biological productivity. The sensor can detect variations in the colour of the water due to the presence of chlorophyll in phytoplankton, which essentially changes the water colour from blue to green. SeaWiFS has provided measurements of chlorophyll concentration over nearly all the world's oceans, and because of their association with fronts, eddies and regions of upwelling, these records of phytoplankton abundance reveal much about physical processes occurring within the ocean.

The long data record from SeaWiFS has engendered a number of studies of physical ocean processes. Here, we will describe a number of examples taken from the Agulhas Current system around South Africa (Figure 1). Typically, the waters in this region show an annual cycle in the quantity of phytoplankton, with highest values around July and August (Figure 2, overleaf). This so-called 'spring bloom' is triggered by the increase in light levels and the enhanced stratification due to surface warming and the abeyance of storms. A secondary bloom occurs in the Madagascar Basin to the east of Madagascar. This is due to the seasonal deepening of the mixed layer coupled with strong eddy activity mixing up nutrients into the surface layer. Here, we are not concerned with the absolute values of chlorophyll concentration, but in the ability of chlorophyll to act as a tracer of water motion.

Clearly, we are dealing with a non-conservative quantity: growth, mortality, and grazing by zooplankton all affect the abundance of phytoplankton present. Additionally, any processes that raise or lower the depth of the biota will affect the value in the surface layer that the satellite 'sees'. The sensor can only detect phytoplankton near the sea-surface. However, it is often valid to assume that the near-surface chlorophyll concentration is homogeneous within a given water body (for example, a current or an eddy), and so changes in chlorophyll concentration can be used to delineate the boundaries of features and enable their temporal evolution to be studied.

***Figure 1*** *The main oceanographic features in the Agulhas Current system. Light shading indicates waters deeper than 3000 m; dark shading indicates those shallower than 1000 m. The poleward-flowing Agulhas Current (AC) 'retroflects' (turns back) to the south of South Africa forming the Agulhas Retroflection (AR), and the resulting eastward-flowing Agulhas Return Current (ARC) has north–south meanders, partially forced by topography, such as the Agulhas Plateau at 26° E. The Antarctic Circumpolar Current (ACC) is much further south in this region. The East Madagascar Current (EMC) flows poleward along the coast of Madagascar and then, guided by the bathymetry, flows round the southern tip of that island.*

***Bottom topography plays an important role in guiding ocean currents around South Africa and Madagascar***




*SeaWIFS = Sea-viewing Wide Field of View Sensor.

## Observing upwelling

Most of the waters in the Indian Ocean are oligotrophic, that is, low in nutrients, and so phytoplankton growth is limited by nutrient supply. The major exceptions to this are in regions where subsurface nutrient-rich waters are being upwelled into the euphotic zone. The most pronounced examples in our area of interest are the Benguela Upwelling, the Delagoa Bight, and regions to the south-east and south of Madagascar, which all stand out as areas of high biological productivity (Figure 2). These features continue to be noticeable in the ocean colour images even when the annual cycle of phytoplankton concentration is at its maximum.

***In July and August, high plankton productivity occurs throughout the mid-latitudes, especially where fed by upwelling***

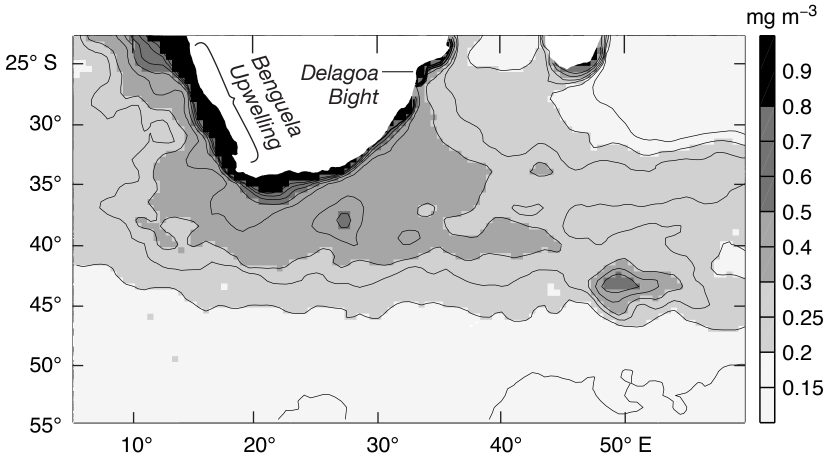
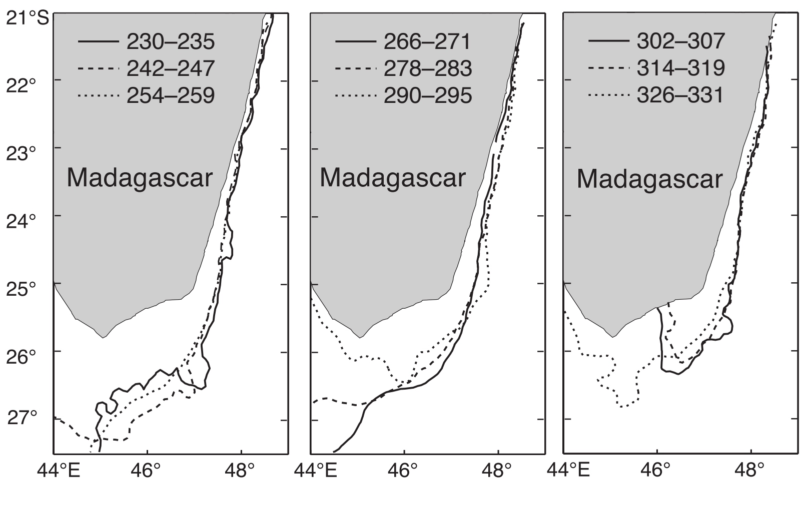



***Figure 2*** *Mean chlorophyll concentration for August (averaged over 1998 to 2001), showing high productivity in the Benguela Upwelling region and the Agulhas Current system, with much lower chlorophyll concentrations [than] in the regions to the south or in the central Indian Ocean (top right). As well as high productivity to the south of Madagascar, there is increased chlorophyll concentration year-round to the north of Crozet Plateau, near 50˚E, 44˚S.*

***Ocean colour images show that the extent of upwelling to the south of Madagascar is very variable, whereas that to the east of the island is more constant***

***Figure 3*** *Boundary of the upwelling region in late 1998 for a series of six-day composites. Numbers correspond to Julian Day (230 = 18 Aug. etc.) and the contour represents 0.2 mg m*$^{-3}$*. North of 25.5˚S the boundary between upwelled waters and the East Madagascar Current (EMC on Figure 1) remains fixed, but south of that latitude, the boundary changes much more rapidly (especially between days 266 and 290) in response to shifts in the path of the EMC.*




The dynamics of the various upwelling regions are very different. Persistent upwelling had already been noted in the Delagoa Bight, despite the frequent easterly onshore winds; this implied that it was the alongshore current rather than the winds that was the motive force for the upwelling. The predominant winds over Madagascar are also from the east, and upwelling along the east coast of Madagascar can be explained in terms of the poleward flow of the East Madagascar Current (EMC) together with the broadening of the shelf to the south of Madagascar.

As the waters of the East Madagascar Current are low in nutrients and thus in chlorophyll, we may characterise the edge of this upwelling region by the contour corresponding to a chlorophyll concentration of 0.2 mg m$^{-3}$. Little short-term variability (days to weeks) is observed in the boundary of the upwelling to the east of Madagascar (Figure 3), except during January–February (not shown). Neither is there much long-term variability, nor any clear seasonal signal. As the upwelling is predominantly current-induced, this in turn suggests that there is little seasonality or shorter term variability in the flow of the EMC, in agreement with the limited *in situ* observations which have been made of the current.

South of Madagascar the behaviour of the current is very different: here, the EMC is much less constrained and often lies much further offshore, and the winds, varying from south-easterly to north-easterly, make a variable contribution to the upwelling. The productive upwelled shelf waters may at times be entrained and advected westwards by the EMC, which is itself low in chlorophyll (Figure 4). The picture is further complicated by the presence of eddies in this area (see below).

## Imaging fronts

Fronts may also be marked by locally high levels of phytoplankton, when the mixing between two adjacent water masses provides the optimal ingredients for growth (nutrients, light, warmth, remnant plankton, and enhanced mixing and upwelling) that neither water mass contains alone. A particular example is the region just to the south of the Agulhas Return Current (Figure 5), where there are three major fronts – the so-called Agulhas Return Front, the Subtropical Front and the SubAntarctic Front – in close proximity. The latter front is associated with the eastward-flowing Antarctic Circumpolar Current, which lies to the south of the Agulhas Return Current (Figure 1). In this frontal zone the phytoplankton distribution is extremely inhomogeneous, with many small patches of enhanced productivity, some transitory, others longer lasting. The surface waters to the south are all richer in nutrients than the more northern waters, but the increased primary productivity lies mainly along the Subtropical Front. This is because the interaction of colder nutrient-rich waters with warmer, more stratified ones provides the right conditions (enhanced

***The East Madagascar Current draws out 'blobs' of more productive water***

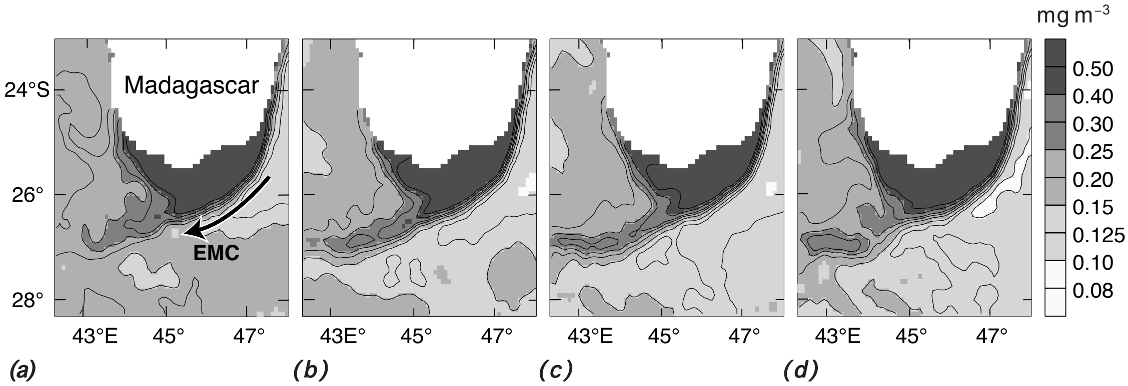



***Figure 4*** *Successive six-day composites from late 2000 for the region to the south of Madagascar, showing rapid evolution in patterns of chlorophyll concentration. The EMC, distinguished by water with low chlorophyll concentrations (and marked by an arrow in (a)), draws the productive upwelled waters south-westwards away from Madgascar. In successive pictures, this strand is seen to separate forming a 'blob' of high chlorophyll concentration water.*

nutrient and light levels) for phytoplankton growth. This region of enhanced growth is bounded to the north by the Agulhas Return Front, which enables the front to be detected in ocean colour imagery. Monitoring changes in this front using SeaWiFS gives results that agree very well with satellite observations of changes in sea surface temperature (SST), again demonstrating the close link between physical and biological processes.

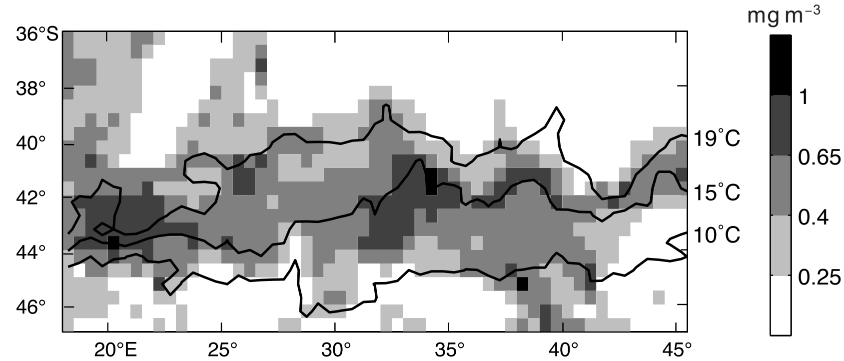



***Figure 5*** *Chlorophyll concentrations for February 1999. The isotherms are from ATSR (Along-Track Scanning Radiometer, a space-borne infrared sensor for sea-surface temperature). At this time of year, the 19˚C, 15˚C and 10˚C isotherms typically correspond to the positions of the Agulhas Return Front (marking the position of the Agulhas Return Current), Subtropical Front and the SubAntarctic Front. The highest chlorophyll concentrations lie along the Subtropical Front, especially where the strength of the front (inferred from the SST gradient) is greatest.*

***The Subtropical Front (between the Agulhas Return Front and the SubAntarctic Front) is highlighted in SeaWIFs images by its high primary productivity***

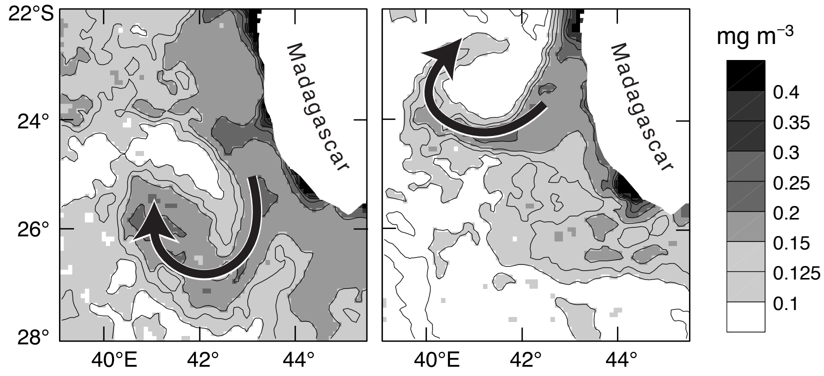
## Revealing eddies

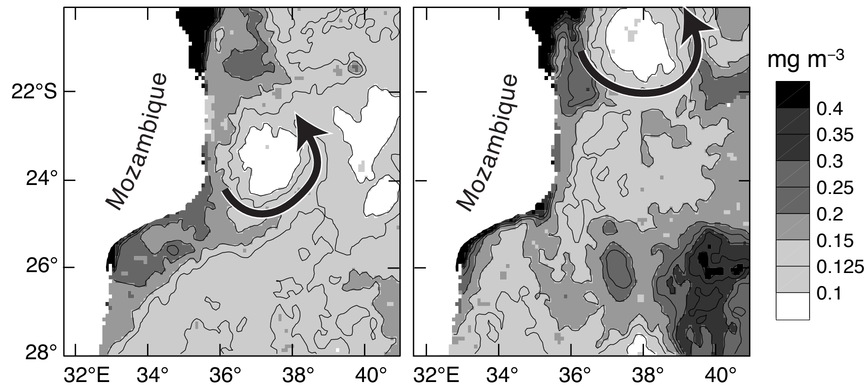
The flow field associated with eddies can affect the amount of plankton growth because the dynamics associated with the eddies can bring nutrients from deeper in the water column into the euphotic zone. However, in the Agulhas region, eddies are more commonly revealed by wrapping themselves in a 'Cloak of Visibility', as they entrain chlorophyll-rich surface waters from upwelling regions (see Figure 6). From single images it is not always clear what the eddies' sense of rotation might be, but by looking at a sequence of images (or better still, an animation of such a sequence) it is easy to deduce whether their sense of rotation is cyclonic or anticyclonic. From the chlorophyll patterns these particular eddies appear to be cyclonic.

It is not apparent whether the cyclonic eddies in Figure 6 form in the lee of Madagascar or have been generated elsewhere, and only become apparent when they entrain more productive waters. This acquired 'green mantle' provides a means of tracing the movement of the eddies. In an animation of the SeaWiFs data for this region, a number of such features can be discerned moving westwards or west-south-westwards towards the African coast and the Agulhas Current. This interpretation is consistent with the progression of anomalies in sea-surface height seen from space in radar altimeter data, thus confirming the more indirect observation of their dynamics using the chlorophyll patterns. The advantage of chlorophyll distributions over altimeter data is that (in cloud-free conditions) they provide much higher resolution (1 km) observations of the features.

***Two cyclonic eddies off south-western Madagascar are revealed by the 'Cloak of Visibility' provided by high-chlorophyll coastal waters***

***Figure 6*** *Cyclonic (clockwise) eddies to the south-west of Madagascar revealed by enhanced chlorophyll-rich waters. The high chlorophyll concentration waters had originated from coastal upwelling of nutrients, and were subsequently entrained around the eddies.*






***Two examples of anticyclonic eddies sweeping polewards along the coast of Mozambique***

***Figure 7*** *High-productivity waters off the coast of Mozambique are dragged into mid-channel by southward-moving anticyclonic eddies; however the cores of these two eddies continue to be marked by low chlorophyll concentrations.*

A different situation is found on the western edge of the Mozambique Channel, where there is a train of poleward-heading anticyclonic eddies (see Figure 7). These reveal themselves by a scarcity of phytoplankton, for although phytoplankton-rich waters are swept from the coast into the centre of the channel, they do not penetrate into the cores of the eddies. Examination of a sequence of composite images reveals about five of these southward-moving anticyclonic features per year, in agreement with observations from current meter moorings in the channel.

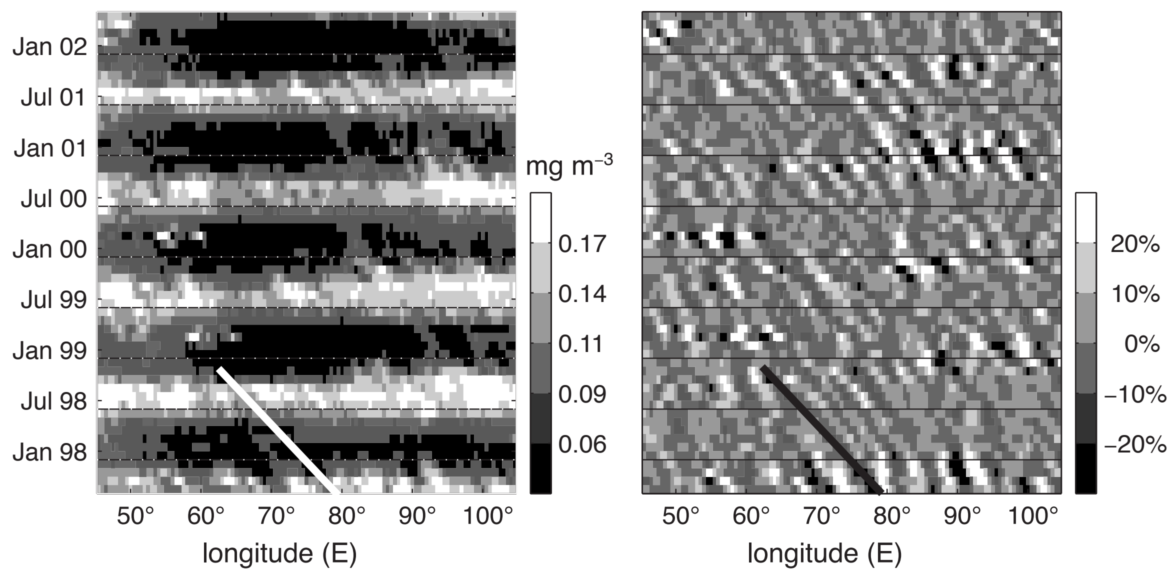
Such techniques for tracking eddies have been used elsewhere; for example, rings (eddies) shed by the North Brazil Current have been tracked by high-chlorophyll waters entrained from the Amazonian outflow region

## Colouring waves

Rossby waves are important for linking events in the east and west of an ocean basin, as they are propagating disturbances their motion may also have weaker north–south components). As they propagate, the Rossby waves displace water to the north and south due to the geostrophic currents associated with the wave motion. Given their near-zonal propagation, the evolution of Rossby waves can be revealed by Hovmöller diagrams (longitude–time plots) at a given latitude. A portrayal of the absolute chlorophyll values (Figure 8(a)) mainly shows the strong annual cycle in chlorophyll concentration, with the westward-propagating Rossby waves only occasionally apparent. A filter can be applied to produce chlorophyll anomalies (values relative to local spatial mean); a Hovmöller diagram of these anomalies (Figure 8(b)) reveals the Rossby waves much more clearly. In many locations the Rossby wave phytoplankton signal is consistent with north–south displacements across a meridional gradient; that is, the chlorophyll concentration changes with latitude but is uniform in the east–west direction and this pattern is distorted by the wave motion and so detected by SeaWiFS. However, in the centre of the South Indian Ocean gyre, Rossby waves are revealed by ocean colour in a region where there is no obvious latitudinal variation of chlorophyll concentration. Candidate explanations for a visible signatures involve either significant raising of the deep chlorophyll maximum, or real phytoplankton growth due to upwelling of nutrient-rich water induced by the Rossby wave. A quantitative explanation of these moving waves of colour is a topic of current research.

***Figure 8*** *Hovmöller diagrams showing chlorophyll signature of Rossby waves at 32° S in the Indian Ocean: note that time progresses* ***up*** *the diagrams.* ***(a)*** *Absolute values of chlorophyll concentration.* ***(b)*** *Results after filtering to give anomalies with respect to a local spatial mean (expressed as fractional change in chlorophyll concentration). An example Rossby wave trajectory has been marked on both plots to indicate the size and speed of the propagating features (many others can be seen). Propagation speed is ~10° in a year, corresponding to ~3 km day$^{-1}$.*

***Filtered SeaWiFS data reveal the passage of Rossby waves through their effect on chlorophyll concentration***




***(a)*** ***(b)***

## End of the rainbow

The examples described in this article demonstrate that a satellite sensor designed for one purpose – ocean colour measurements of biological processes – can reveal much about physical processes. The technique exploits the intimate relationship between ocean biology and physics to enhance our understanding of both. Through the ages, writers have referred to the sea in poetic terms, with Homer's 'wine dark sea' in the Odyssey being one of the most evocative descriptions. SeaWiFS might not have shown the sea to be 'wine dark', but through its spectrum of colour measurements, it has illuminated some aspects of the endlessly fascinating oceans.

## Acknowledgements

We are very grateful to Orbimage for the development of such a high quality instrument, to NASA Goddard Space Flight Centre for the efficient distribution of data, and to Rutherford Appleton Laboratory for the precise SST data.

## Further Reading (with annotations)

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