Estimation of sea-surface temperature around southern Africa from satellite-derived microwave observations

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Sea-surface temperatures may give strong indications of the location of fronts, currents, eddies and other components of ocean circulation. This has been recognized in particular for the seas around southern Africa.[1] Almost all studies using this property have employed measurements of thermal infrared radiation from orbiting satellites. This has distinct disadvantages due to the shading effect of persistent cloud cover. Another option is to use microwave observations, which are not affected by cloud cover. Until recently, however, the spatial resolution of microwave data was far too coarse for the purpose of studying ocean circulation in detail. We describe here a new set of microwave data that does not have this disadvantage, and show how useful it is by describing examples of local applications.

Introduction

Sea-surface temperature (SST) is used by commercial businesses as well as government agencies for many purposes. It is a key parameter for studying ocean circulation, ocean–atmosphere interaction, the radiation budget of the planet, and gaseous transfer between air and sea. It is an important factor and reference condition for many numerical models used for weather prediction. The accuracy of SST estimates by satellite remote sensing has become increasingly important for reliable climate and weather studies. Nevertheless, usual estimates of SST made with devices such as the Advanced Very High Resolution Radiometer (AVHRR) or the Along-Track Scanning Radiometer (ATSR) cannot estimate SST through clouds and have serious calibration problems due to atmospheric aerosols. Satellite remote sensing of sea-surface temperature with the Microwave Imager (TMI) of the Tropical Rainfall Measuring Mission (TRMM) can, however, be performed during cloudy conditions.

Sea-surface temperatures from TRMM TMI

The TMI is a passive microwave sensor that was designed to provide quantitative rain rate over a swathe 760 km wide. The instrument measures the microwave energy emitted by the Earth and its atmosphere and is able to quantify water vapour, cloud water and rain rate intensity in the atmosphere. The imager has nine channels, which measure the intensity of radiation, both vertically or horizontally polarized, at frequencies of 10.7, 19.4, 37.0 and 85.5 GHz, and of vertically polarized radiation at 21.3 GHz. The 10.7-GHz channel can be used for SST retrievals. An important feature of microwave retrievals is that SSTs can be measured at a quarter-degree resolution through clouds, which are nearly transparent to radiation of 10.7 GHz.

Stammer *et al.*[2] compared Reynolds SST[3,4] and TMI SST to validate the TRMM SSTs. The monthly and weekly Optimal Interpolation Reynolds SST (OI SST) for 1982–2001 has been derived from *in situ* and infrared satellite observations (by AVHRR). Although AVHRR observations can be obtained globally with a resolution of 9 km, Reynolds SST has only a 1-degree latitude/longitude resolution because of the algorithm used to produce that dataset in near real time. Globally, the mean difference between the two products is 0.18°C with a standard deviation of the difference of 0.54°C. TMI standard deviation is 0.45°C versus 0.55°C for Reynolds SST. Off Angola and over a large part of the South Atlantic, the data return is about 40%.[2] For the Indian Ocean, data return is between 40% and 80%. For the Agulhas Current region, cloudy conditions can persist for a month or more above the core of the current.[5] This may be largely due to the well-known process of cloud generation above the current.[6,7]

Figure 1 compares the weekly mean Reynolds SST and weekly mean TRMM SST south of Africa for the third week of May 2001. Although the Reynolds SST distribution correctly shows warmer water off the east coast of South Africa, the core of the Agulhas Current is adequately represented only in the TMI SST. This is mainly because of the different resolution of the two products. This does not mean that the infrared observations on a clear day would not portray the location and characteristics of the current as well as those from the microwave sensor. Overall, however, cloud interference will be responsible for a very confused picture from thermal infrared for the week as a whole.

Figure 2 compares OI SST and TRMM SST averaged in a box (corresponding to 35–38°S; 19–24°E) for 2000 and 2001. The mean difference is about 0.3°C with a maximum of about 1°C between

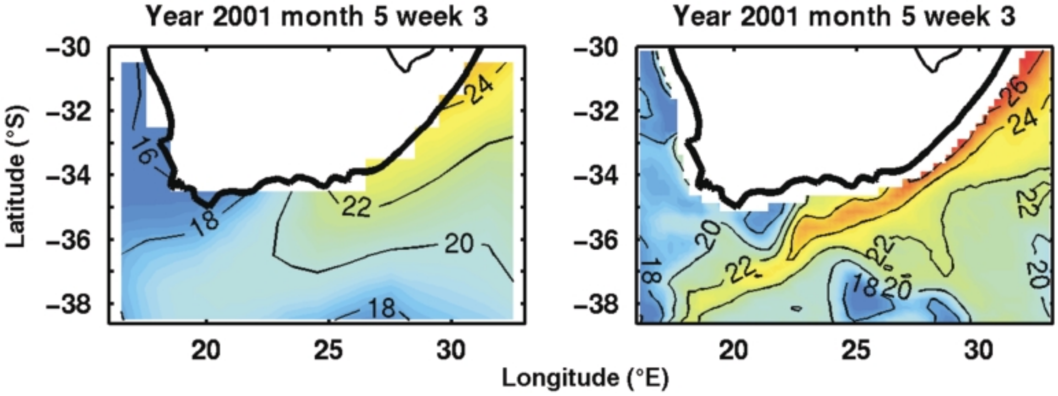

Fig. 1. Optimal interpolation (1 × 1-degree resolution) of weekly mean sea-surface temperature (SST) (left) for the third week of May 2001 compared with TRMM TMI weekly mean SST (0.25 × 0.25-degree resolution). The core of the Agulhas Current, shown in orange, is well represented only by the TRMM TMI results (right). Contours in °C. Colder water shown in blue.

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the two products. The Agulhas Current is usually found in this area (see Fig. 1) and the unusual behaviour of the current in late 2000 and early 2001 is clearly evident from this curve. By examining all weekly charts since 1997, it is clear that the Agulhas Current started to behave abnormally in December 2001 and adopted an upstream retroflection mode,[8] farther eastward than normal — at about 25°E — causing the below-normal temperatures for this period that can be seen in Fig. 2 from December 2001 compared with 2000. It is interesting to note from Figs 1 and 2 that even if the Reynolds SST does not represent the Agulhas Current well, it still indicates the SST anomalies created by the abnormal behaviour of the current on this occasion. The usefulness of TRMM SSTs for this type of research has not gone unnoticed elsewhere. Their applications have started to emerge.

Chelton *et al.*[9] combined surface wind stress measurement from the Quickscat scatterometer and TRMM SST for a three-month period in 1999 in the eastern tropical Pacific. They were thus able to study tropical instability waves, oceanic features with periods of 20 to 40 days and wavelengths of 1000–2000 km. They were also able to show the response of surface wind to SST associated with tropical instability waves. Xie *et al.*[10] used surface wind stress measured with the Quickscat scatterometer, TRMM SST and an oceanic general circulation model to study the effect of the Hawaiian Islands on ocean currents and SST in the Pacific. They showed that the wake of the islands creates an air–sea interaction that has an effect as far away as the coast of Asia, 8000 km from Hawaii. Rouault *et al.*[11] used TRMM SST and rainfall observations to study the influence of the Agulhas Current on an extreme weather event in South Africa in December 1998. Others[2] have developed a feature-tracking system based on TMI SST with which they studied the Agulhas Current and the East Madagascar Current. It has even been demonstrated that the accuracy of TRMM SST is sufficient to resolve the diurnal variation of SST.[12] Based on this broad consensus for the usefulness of TRMM SSTs, we now apply it to some local phenomena to demonstrate this utility for southern Africa.

Agulhas early retroflection

From Fig. 2 it was suggested that the southern Agulhas Current behaved in an abnormal fashion during 2001. This can be investigated more directly by using the TRMM images for that period. Figure 3 shows a sequence of six weekly SST charts

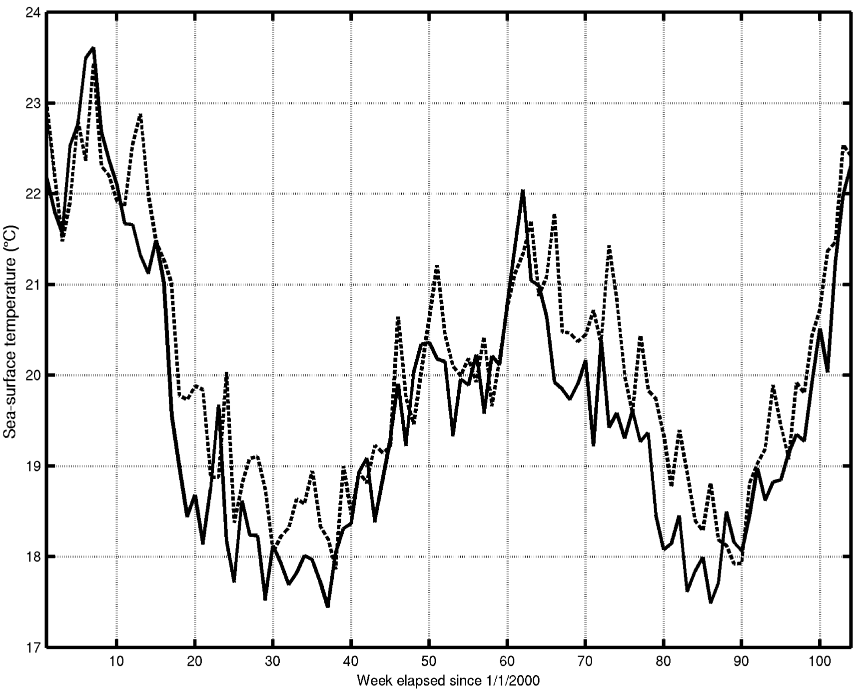

Fig. 2. Comparison between weekly Optimal Interpolation sea-surface temperature (SST) (solid line) and weekly TRMM TMI SST (dashed line) in the Agulhas retroflection area for 2000 and 2001 (104 weeks). SST is averaged in the box delineated by 35–38°S, 19–24°E. Mean difference between TMI and OI SST is 0.3°C.

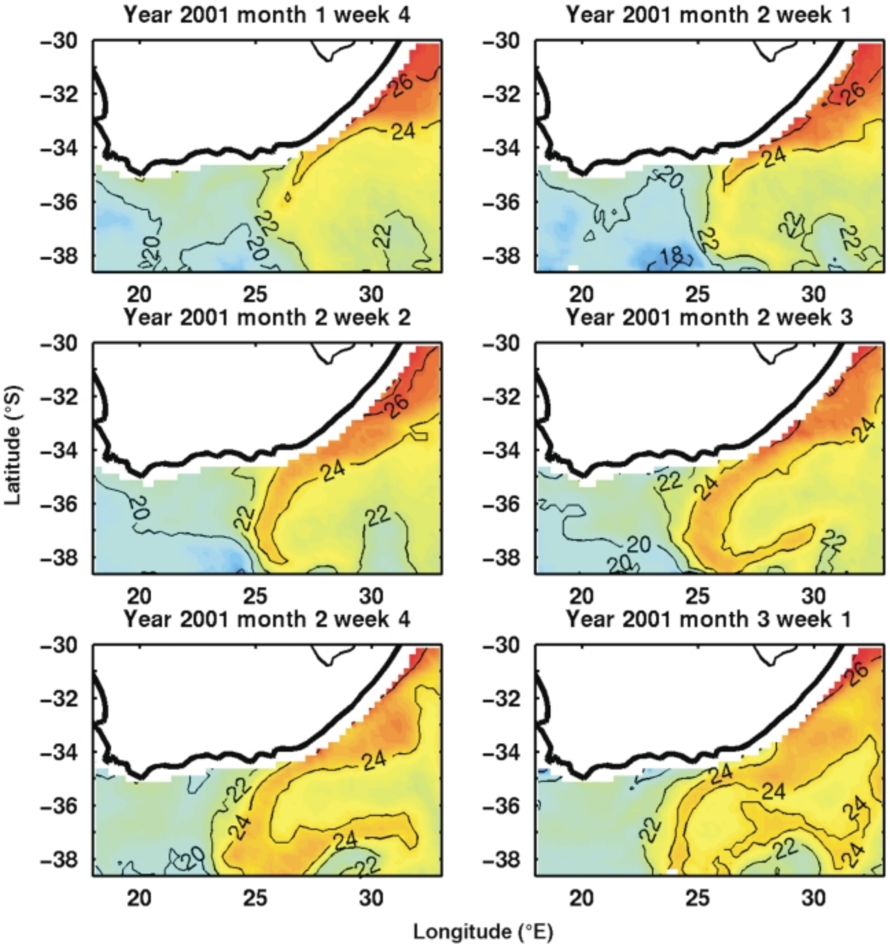

Fig. 3. Sequence of weekly mean TMI sea-surface temperatures showing a retroflection of the Agulhas Current at a position more eastward and northwards than normal. Warm Agulhas water, shown in orange, eventually re-enters the current. Data are shown for each week from the last week of January 2001 to the first week of March 2001. Contours in °C.

from the end of January 2001 to the beginning of March 2001 for the ocean region south of Africa. It clearly indicates a retroflection of the Agulhas Current. Examination of TRMM SST charts since 1998 for the region indicates that the retroflection that occurred at the beginning of December 2000 at about 24°E was quite far east from the usual area of the retroflection. A sequence of events shows a retroflection at 24°E at the end of November 2000 followed by a large pulse of warm water forcing retroflection at 28°E, four degrees eastward of the preceding retroflection. The next pulse of warm water is shown on Fig. 3. It seems that it took about 6 weeks for this pulse to complete the sequence of events, retroflecting at 25°E. It is noteworthy that the SST of the Agulhas Current did not seem to decrease over this period in spite of a substantial loss of energy to the atmosphere. Rouault *et al.*[13] have measured high latent heat fluxes and low incident shortwave radiation due to cloud cover over the Agulhas Current. This should have caused the SST to fall. Strong turbulent, vertical mixing in the Agulhas Current probably contributed to maintaining the SST at about 24°C. Following this abnormal upstream retroflection event, the Agulhas Current started to behave more normally from April 2001. Indeed, by July 2001 the current was lying even more westward than usual, creating warm anomalies to the southwest of the Western Cape, the winter rainfall region of South Africa. Reason[14] has argued that these positive SST anomalies that persisted until the end of 2001 could have affected the 2001 winter rainfall season, which was the wettest in about 40 years.

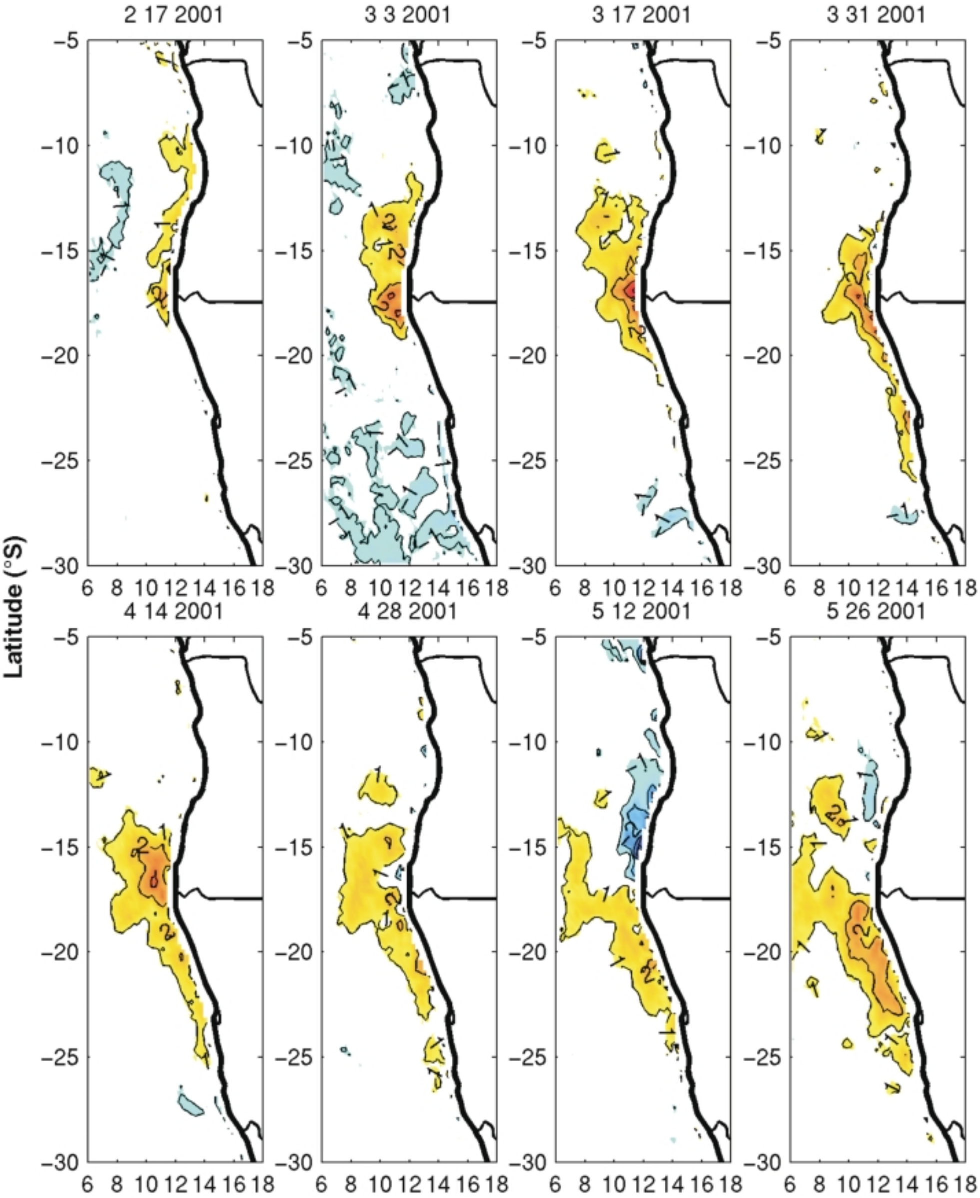

Fig. 4. Benguela Niños in 2001. Poleward propagation of warm SST anomalies (yellow–orange areas) from Angola to Namibia from February 2001 to May 2001. From left to right and top to bottom, the data are indicated every two weeks. Weeks are centred on the date shown above each caption.

These preliminary results show conclusively that data from the TRMM microwave sensor are of substantial benefit for investigating phenomena in the Agulhas Current system. This also holds true for the Benguela upwelling system on the west coast of southern Africa.

The 2001 Benguela Niño

Figure 4 shows the poleward propagation of a warm SST anomaly along the coasts of Angola and Namibia, based on a chart of weekly TRMM SST, starting in February 2001 and continuing until May 2001. Positive SST anomalies (warm water) first appeared in February along the Angolan coast between 5°S and 17°S, raising the water temperature to about 30°C. It seems that this warm water propagated mostly poleward along the coast, crossing the Angola–Benguela Front and reaching 27°S in April. The warm water remained for about 3 months, regardless of local wind conditions. It is changing wind conditions that usually rule SST variability in that upwelling region. These anomalous, but persistent, thermal conditions are known as Benguela Niños.

This particular warm event (Fig. 4) is unique in the TRMM SST record with data available from 1998 (Fig. 5). A short-lived pulse of warm water propagated poleward in April 1999 but the anomaly did not last more than a month. Mohrholz *et al.*[15] studied the 1999 pulse of warm water at sea during a scientific cruise in April 1999 and verified its existence *in situ*. Several investigators[16–18] have noted that some of the warm events along the Angolan coast were preceded by reduced trade winds in the tropical and equatorial Atlantic Ocean. When warm events occur off the Namibian coast in late summer, during the peak in the annual march of SST, they amplify the local effects on atmospheric instability, rainfall,[16,19] fisheries off Angola and Namibia[17,20] and moisture fluxes onto the adjacent land mass.[21] Similar warm events occurred in 1984[17] and 1995[22] and both were

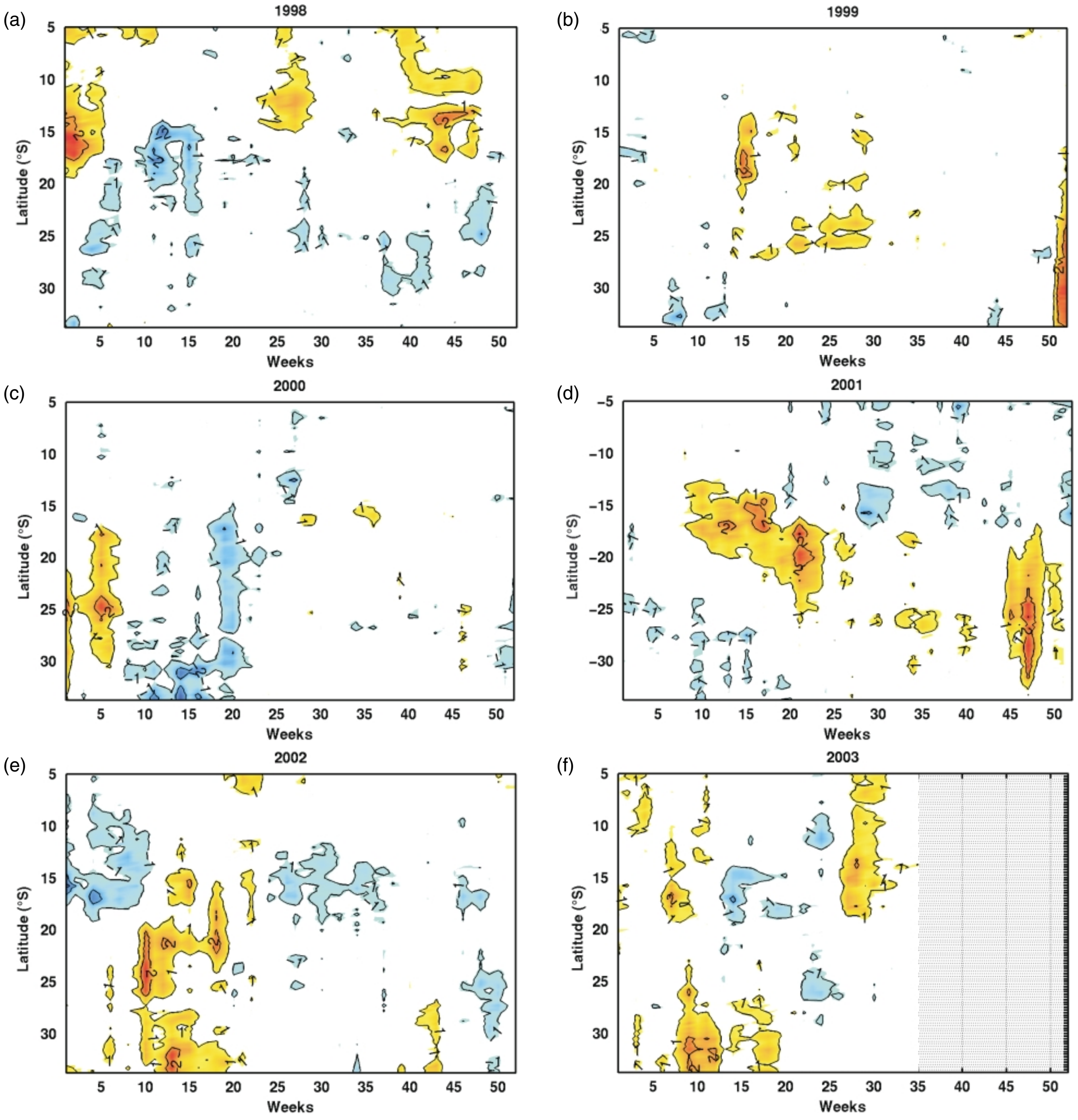

Fig. 5. (**a**) Time–latitude Høvmoller diagrams of weekly TMI sea-surface temperature (SST) anomalies (yellow–orange, warm; blue, cold) off the coasts of Angola, Namibia and South Africa (5°S to 33°S) for 1998. SST anomalies were averaged from the coast to about 3 degrees offshore; (**b**) corresponding results for 1999, (**c**) 2000, (**d**) 2001, (**e**) 2002 and (**f**) 2003.

linked to the equatorial Atlantic Ocean.[18]

The 2001 warm event shown in Fig. 4, based on TRMM SSTs, is similar to that of 1995. It probably was a coastal Kelvin wave that followed an equatorial Kelvin wave triggered by reduced trade winds along the equator.[18] Ocean model output, Topex/ERS sea-level heights, ERS and Quickscat wind speed data all show that the origin and propagation of the 2001 warm event had its source in the equatorial Atlantic, with reduced wind stress from the trade winds arising one month before the warm event off the Angolan coast (Rouault *et al.*, in prep.).

Monitoring the Angola/Benguela upwelling system

Figures 5a–f show time/latitude Hovmøller diagrams of SST anomalies off the Angolan and Namibian coasts, between 5°S and 27°S, for the 52 weeks of 1998–2003 inclusive. SST anomalies were based on the TRMM SSTs and ranged from the coast to about 3 degrees of longitude offshore. Positive (warm water) and negative (cold water) anomalies in the Benguela upwelling system are well represented in spite of there being no data near the coast. Wind-related thermal anomalies can be identified as a vertical line in the diagrams as they appear simultaneously over an extended domain whenever the wind drops or accelerates. The main cold events can be identified by vertical blue lines of variable width. For instance, in week 20, the first week of May 2000, negative anomalies appeared from 15°S to 27°S and lasted for 2 weeks (Fig. 5c). Analysis of the SST charts shows that those anomalies extended offshore by 2 or 3 degrees of longitude.

The year 1998 (Fig. 5a) started with warm water off Angola extending about 10 degrees of longitude offshore with the strongest anomalies (3°C) at the Angola–Benguela Front. Nevertheless, that warm event disappeared in February and subsequent warm water events did not propagate poleward towards Namibia. Cold water anomalies started to develop from 27°S to 20°S in February and from 14°S to 23°S in March and April. The next major warming happened at the beginning of September north of Angola and subsequently propagated quickly poleward. Maximum anomalies of 3°C were found at the Angola–Benguela Front in October and the warm event dissipated by the end of November.

The year 1999 (Fig. 5b) seems to have been normal except for a short warming at the Angola–Benguela Front and south of the domain at the end of the year. The warming south of 17°S extended towards Cape Town (33°S) and has been discussed by Roy *et al.*[23] The pulse of warm water identified by Mohrholz *et al.*[15] can be seen (Fig. 5b) between 15 and 20°S as warm anomalies and lasted for 3 weeks. Intense warming happened at the end of January 2000 (Fig. 5c) off Namibia, extending from 17°S with positive anomalies of up to 3°C, a spatial extension of about 2 to 5 degrees of longitude offshore and lasting about 3 weeks.

For 2001 (Fig. 5d), the warm events described above can be seen spreading diagonally in the figure from February to April. This signifies poleward propagation along the coast. In May we see the superimposition of a wind-related warm event on the poleward propagation of positive anomalies. In November 2001 wind-related positive anomalies appeared off Namibia, spreading 10 degrees of longitude offshore and lasting for a month. Some of the warm events extended to Cape Town.

The year 2002 (Fig. 5e) started with negative anomalies off Angola with the highest and most durable (2 months) anomalies at the Angola–Benguela Front. Warming started in February off Namibia and lasted for a month. Another warming happened in May at the Angola–Benguela Front. Positive anomalies developed from 15°S to 27°S at the end of 2002. In 2003 (Fig. 5f) there were anomalies off Angola, especially during February and June/July, nevertheless the situation was quite different from the 2001 Benguela Niño discussed above. A warm anomaly associated with a decrease in wind speed arose in March and April 2003 off South Africa. Figure 5f shows data collected up to 16 August 2003.

Accurate monitoring of anomalies in the Benguela upwelling system is of importance not only to the associated fisheries, but also local rainfall.[21] It is clear from the above that the TRMM SSTs give a reliable and practical means of monitoring this region.

Discussion

The value of using reliable and accurate SST information for climate studies based on atmospheric general circulation models has been stressed in particular by Hurell *et al.*[24] The above examples suggest that the TRMM SSTs can encompass the Agulhas Current and its behaviour, as well as the Benguela upwelling system, accurately. How important is this for weather and climate studies, particularly locally?

As mentioned above, the high heat and moisture fluxes from the Agulhas Current can lead to cumulus cloud formation.[25,26] Furthermore, it has been demonstrated that the high latent heat fluxes from the current influence regional climate[27] and may have a significant effect on the intensity of some local storms.[28] It is therefore important to include accurate values of the Agulhas Current SST as boundary conditions for weather prediction models and atmospheric or coupled general circulation models. Rouault *et al.*[29] have shown that NCEP (National Center for Environmental Prediction) and the ECMWF (European Centre for Medium-range Weather Forecasting) re-analyses underestimate by about 50% the latent and sensible heat fluxes for the Agulhas Current, due largely to the poor spatial resolution of the SST used. They have shown that Reynolds SST does not adequately represent either the core of the Agulhas Current or the mesoscale SST gradients of the region. The TRMM SSTs are altogether more useful.

Conclusion

For southern African countries with limited financial resources, the low cost and ready availability of remotely sensed microwave data on the Internet make satellite-retrieved precipitation datasets an ideal research tool and the necessary complement of the ground measurements.[11] Moreover, the data are available within a week. TRMM SSTs furthermore provide a practical and inexpensive way of monitoring the oceans surrounding southern Africa and are an improvement on infrared SST observations used as boundary conditions for numerical modelling or climate studies. Combining microwave and infrared SSTs will overcome the lack of data at the coasts from the Microwave Imager.

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