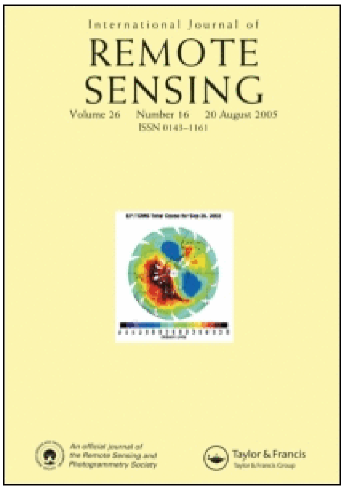

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J. Gower [a]; S. King [a]; P. Goncalves [b]
[a] Institute of Ocean Sciences, Fisheries and Oceans Canada, BC, V8L 4B2, Canada [b] Terradue Srl, Rome, Italy

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Global monitoring of plankton blooms using MERIS MCI

J. GOWER*†, S. KING† and P. GONCALVES‡
†Institute of Ocean Sciences, Fisheries and Oceans Canada, Sidney, BC, V8L 4B2, Canada
‡Terradue Srl, Via G. Peroni 442/444, 00131, Rome, Italy

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The MERIS maximum chlorophyll index (MCI), measuring the radiance peak at 709 nm in water-leaving radiance, indicates the presence of a high surface concentration of chlorophyll *a* against a scattering background. The index is high in 'red tide' conditions (intense, visible, surface, plankton blooms) and is raised when aquatic vegetation is present. A bloom search based on the MCI has resulted in the detection of a variety of events in Canadian, Antarctic and other waters round the world, as well as detection of extensive areas of pelagic vegetation (*Sargassum* spp.), previously unreported in the scientific literature. Since 1 June 2006, global MCI composite images, at a spatial resolution of 5 km, are being produced daily from all MERIS (daylight) passes of reduced resolution (RR) data. The global composites significantly increase the area now being searched for events, although the reduced spatial resolution may cause smaller events to be missed. This paper describes the composites and gives examples of plankton bloom events that they have detected. It also shows how the composites are affected by the South Atlantic anomaly (SAA), where cosmic rays impact the detectors of the MERIS instrument.

1. Introduction

The maximum chlorophyll index (MCI) shows the amplitude of a peak near 705 nm in the radiance spectrum of light reflected from the earth's surface, which several authors have associated with high levels of chlorophyll *a* in ocean, coastal and lake water targets, such as plankton blooms and floating or benthic plants (Gitelson *et al*. 1992, Yacobi *et al*. 1995, Gower *et al*. 1999, 2005). Among satellites for monitoring large ocean and coastal areas, the index is unique to MERIS in that a band covering 705 nm (for MERIS this is centred at 709 nm) is not present on either MODIS or SeaWiFS. We have been able to demonstrate use of the MCI to detect plankton blooms (Gower *et al*. 2005), floating *Sargassum* (Gower *et al*. 2006) and 'superblooms' of Antarctic diatoms (Gower and King 2007) associated with platelet ice (Smetacek 1992).

We present examples to show that global composites of this index provide an important new tool for the detection and monitoring of plankton blooms and other aquatic vegetation. Although the MCI will not detect all of the harmful algal blooms (HABs) that are causing increasing damage to aquaculture, tourism and coastal water quality, it clearly has a role in monitoring some of the surface, high-chlorophyll events, which are widely publicized as 'red tides'. Global composites will

*Corresponding author. Email: jim.gower@dfo-mpo.gc.ca

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allow us and others to extend the search for plankton blooms to the limits imposed by cloud cover, sun glint and MERIS data collection.

2. MERIS global MCI composite images

The global MCI composites were developed as an example of the GRID distributed computing capabilities at the ESA research centre at ESRIN. The composites are formed according to specifications provided the Institute of Ocean Sciences (Fisheries and Oceans Canada) in Sidney BC, Canada. These specifications were based on detection of MCI events in a number of locations around the world, including the coasts of Canada, the USA, India, Chile and Antarctica.

In figure 1, an example of the present form of the composite shows the 14 descending (daylight) passes that make up the MERIS coverage pattern for a single day in July 2006. For this day, the pattern shows one missing pass and another, shorter data gap. Land, cloud and sun glint areas are masked to black. In this season, coverage is shifted to northern latitudes, and there is adequate sunlight to collect data north of latitude 64° N, where adjacent swaths overlap. A cut-off at a minimum sun elevation prevents coverage over much of the Southern Ocean, and sun glint obscures the east side of image swaths between latitudes $-10°$ and $+50°$. MCI values are coded from dark blue (low), through light blue and yellow to red (high).

The MCI (Gower *et al.* 2005) is computed as radiance at 709 nm above a linear baseline defined by radiances at 681 and 753 nm. This is calculated only for pixels for which radiance at 865 nm is less than $15\,\mathrm{mW\,m^{-2}\,sr^{-1}\,nm^{-1}}$ to eliminate land pixels and areas of strong sun glint, haze or cloud.

$$\text{If } L_{865} < 15\ \mathrm{mW\ m^{-2}\ sr^{-1}\ nm^{-1}}, \text{ then MCI} = L_{709} - L_{681} - 0.389(L_{753} - L_{681}) \cdots, \quad (1)$$

where L_{865} represents level 1 radiances (as measured at the satellite) at a wavelength of 865 nm, and similarly for other wavelengths, and the factor 0.389 represents the wavelength ratio (709−681)/(753−681).

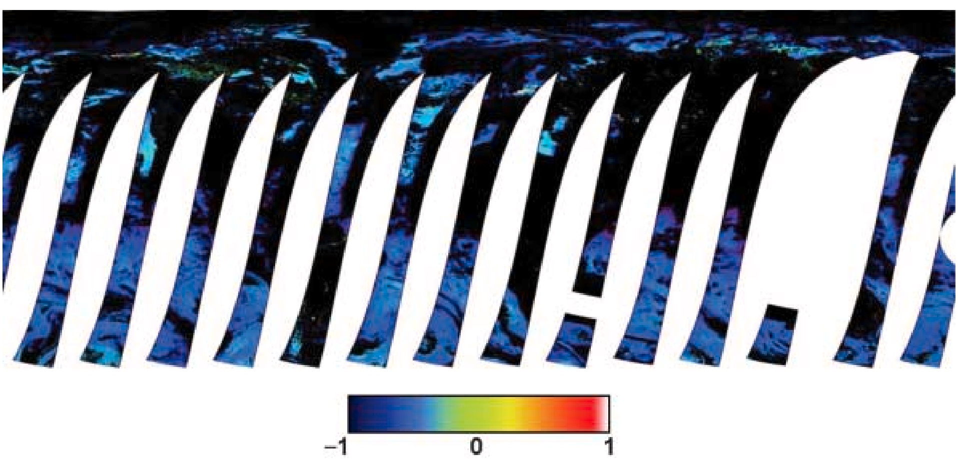

Figure 1. Example of a MERIS daily global composite showing the MCI for 7 July 2006. Full coverage would consist of 14 day-time passes. A major bloom event in the Baltic (figure 4) can be seen at top centre. The colour bar shows the MCI values in figures 1 to 4. Clear ocean waters give an MCI value of about $-0.5\,\mathrm{mW\,m^{-2}\,sr^{-1}\,nm^{-1}}$.

MCI values are computed from level 1 data before atmospheric correction, since the events we are studying typically give radiances outside the range that can be handled by atmospheric-correction algorithms. In the few cases where we have been able to compute MCI from atmospherically-corrected (level 2) data, reflectance values at each wavelength in equation (1) were used instead of radiances. The resulting images were nearly identical to the level 1 results, with values diverging from a mean linear transformation between reflectance and radiance by only a few percent. In most cases, however, the level 2 atmospheric correction fails over these events. The present prototype global composite includes a small bias correction as a function of local sun elevation, not shown in equation (1), which compensates an observed trend in the average MCI signal. Composites have a nominal 5 km resolution. Each composite pixel shows the maximum MCI value computed for any reduced resolution (RR) MERIS (1.2 km) pixel assigned to that composite pixel. The reduced spatial resolution compared to the 1.2 km of MERIS RR may result in smaller bloom events being missed, but the use of the maximum values in the composite tends to preserve high values.

Figure 2 compares the global composite data (left), with MERIS RR data (right) for a day and area when a bright surface bloom is detected inside Australia's Great Barrier Reef. The bloom is visible in figure 2 as an area of high MCI extending out of Repulse Bay in an area well away from the Reef. We have the reduced-resolution composite data for all parts of the world, and in this case, we also have the RR data that give higher spatial resolution (1.2 km) and the full MERIS spectral information. The right panel of figure 2 shows level 1 MERIS radiance spectra of pixels with high values of MCI (red), together with spectra of nearby pixels showing low MCI values

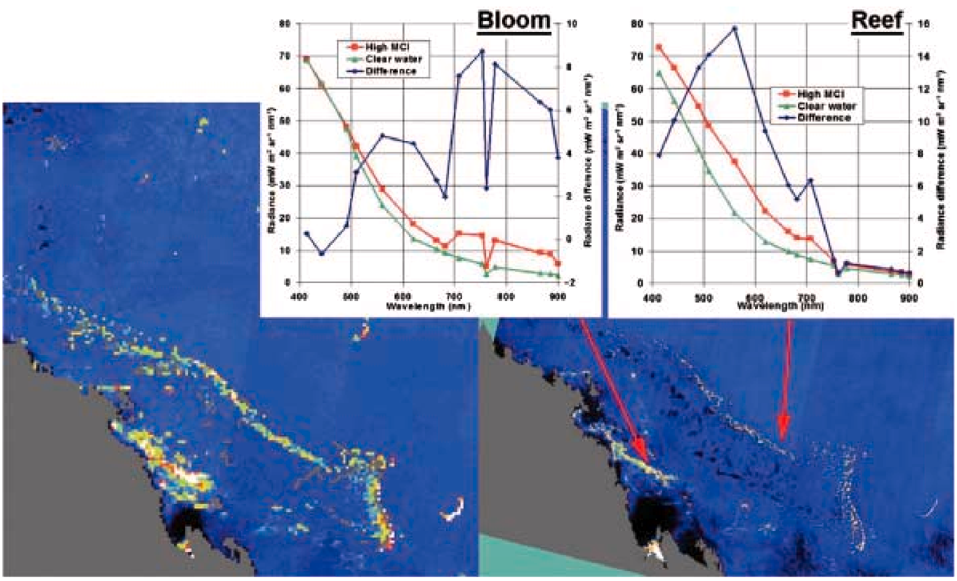

Figure 2. A bloom extending out of Repulse Bay, NE Australia, shown by the daily global MCI composite (left) for 21 August 2006, compared to higher resolution MERIS RR data (right), which gives spectra of level 1 (top-of-atmosphere) radiances from the bloom (left spectrum) and from an area of coral reef (right spectrum). In each case, red spectra are of high-MCI targets, green spectra are from nearby clear water and blue spectra (values on right axes) show the radiance differences between these.

typical of nearby 'clear' water (green). Spectra plotted in blue show differences between these pairs of spectra. The difference spectrum for the bloom shows that a significant fraction (about 10%) of the water surface is covered with algae buoyant enough to exhibit the 'red-edge' spectrum of land vegetation. The difference spectrum for the reef shows a bright ocean bottom at blue and green wavelengths, with an MCI signal that we interpret as being caused by submerged, chlorophyll-containing components (zooxanthellae) of the coral. Figure 3 compares figure 2 with earlier and later observations, showing no event (background MCI signals) in Repulse Bay on 5 August 2006, high signals on 21 August and lower values over a more extended area on 27 August. Figure 3 suggests an approximate lifetime for the event of 1 to 3 weeks.

Figure 4 shows the Baltic Sea on a series of days when patches of high MCI were detected. The bright bloom (high MCI) event starts on about 30 June and continues intermittently to about 17 July. Sudden disappearances of the bloom after 8 and 13 July may correspond to surface winds mixing buoyant cyanobacteria cells down into the water column. The Baltic blooms are confirmed by Swedish scientists to be intense surface blooms of cyanobacteria (E. Graneli, Kalmar University, personal communication), as observed in previous years. Blooms are at present being tracked using AVHRR satellite image data. These provide a single spectral band (band 1, 570 to 670 nm) for mapping the blooms, with a second band 2 (670 to 900 nm) that can be used to separate atmospheric effects, assuming that water-leaving radiances are low at these longer wavelengths. However, in many cases, this condition is not met. The additional spectral bands of MERIS can provide significant improvements in feature discrimination.

Figure 5 shows a composite image formed from a month of daily, global MCI imagery of Antarctica, using all the daily composites for the month of February 2007. This is in polar stereographic projection, at 5 km spatial resolution, and again preserves the maximum values of MCI observed in each pixel. Figure 5 shows high values of the index near land in the Weddell Sea, and in other areas close to the ice edge at the time of minimum ice extent. We interpret these high values as indicating a previously reported form of 'superbloom' (Smetacek *et al*. 1992) in which high surface chlorophyll concentrations are associated with platelet ice. Earlier observations from March 2006 (Gower and King 2007) detected high surface chlorophyll associated with ice on the west side of the Antarctic Peninsula. Figure 5

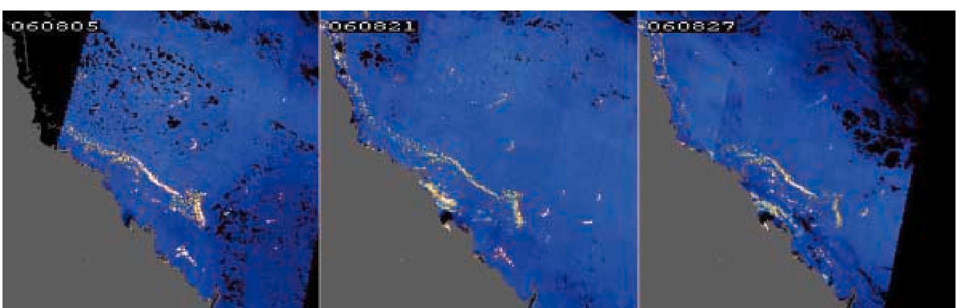

Figure 3. The bright bloom off Repulse Bay, Queensland, Australia, as shown by the daily global MCI composites for 5, 21 and 27 August 2006. The event started some time after 5 August (060805), peaking near 21 August.

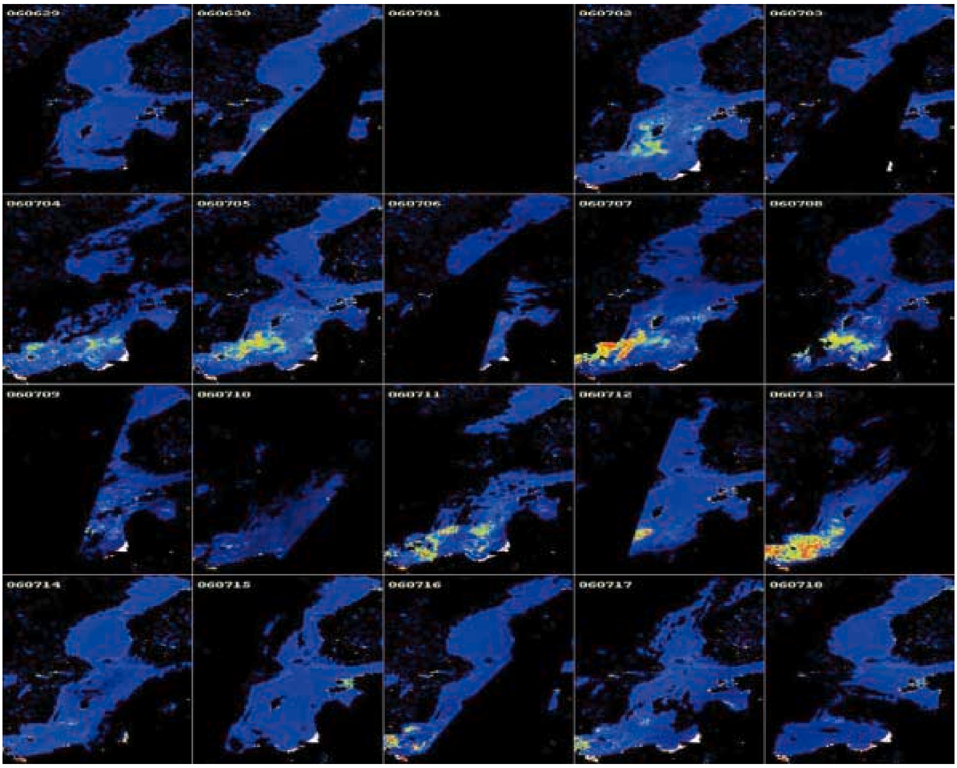

Figure 4. Segments of the daily global composites from 29 June (060629) to 18 July 2006 (060718) covering the southern Baltic, showing consecutive days of coverage from MERIS.

shows this phenomenon, covering a larger area in February 2007, including the locations in the Weddell Sea described by Smetacek (1992).

3. Discussion

Typically, we are finding an average of about one plankton bloom event somewhere in the world on any given day, not counting the 'false alarm' events discussed below. We feel this is a significant detection rate, especially as this is the first prototype of the global composite product, at present producing data at a reduced spatial resolution. Events in isolated areas are probably not detected by other means, and many events, even those close to civilization, are likely to go unreported. Comprehensive bloom detection is important for monitoring marine productivity. Detection and monitoring of the 'superbloom' events in Antarctica is an additional demonstration of the value of the MCI method.

There are a number of sources of false alarms that need to be taken into account when interpreting the composites in terms of algal blooms. High MCI values in shallow water will often be due to benthic vegetation and coral reefs (Gower *et al.* 1999, 2005). Many examples are shown in figures 2 and 3 associated with the Great Barrier Reef. Silty water will also tend to increase MCI values by increasing the backscattered radiances. However, the broad-band backscatter due to silt is easy to detect in the satellite data, and allowance can be made for the greater sensitivity with which blooms are then indicated by chlorophyll absorption near 670 nm and the

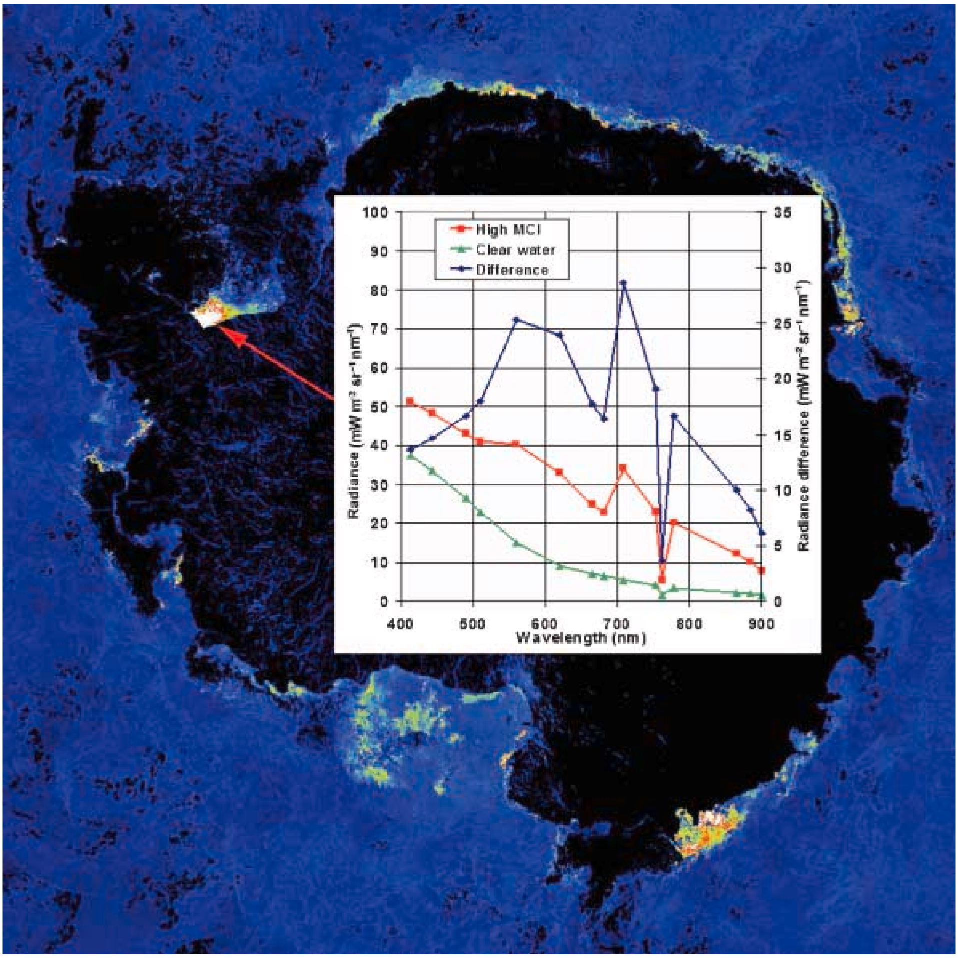

Figure 5. An area of high MCI index (upper left) in Antarctica, indicating high levels of chlorophyll *a* among ice in the Weddell Sea. The image is a monthly composite of daily global MCI composites for February 2007. The inset shows spectra in the high-MCI area (red) compared to a nearby open-water area (green). The difference (blue) is plotted using the right-hand axis and shows an MCI value of about $10\,\mathrm{mW\,m^{-2}\,sr^{-1}\,nm^{-1}}$. Other areas off Wilkes Land (bottom right) and along the ice edge off Queen Maud Land (top) also show high values of the index. The colour scale is as for figure 1, but here covers the larger radiance range -1 to $+5\,\mathrm{mW\,m^{-2}\,sr^{-1}\,nm^{-1}}$.

resulting peak near 709 nm. Floating *Sargassum* is a false alarm in the sense that this is not generally regarded as a phytoplankton bloom. *Sargassum* has scientific, practical and historical interest, and its detection using MCI is a significant 'first' for MERIS. In summary, in deep water, and in the absence of floating vegetation and cosmic ray hits (see below), we interpret the radiance maximum at 709 nm as due to the presence of high surface concentrations ($>$ about $30\,\mathrm{mg\,m^{-3}}$) of chlorophyll, indicating the presence of a bloom.

Events appearing to cover a small spatial area can also be due to cosmic ray particles impacting single elements of the CCD detectors of MERIS. Figure 6 shows the global spatial distribution of single pixel events shown by the MCI. Events are located by examining 3 x 3 pixel areas of the global daily composites and accepting

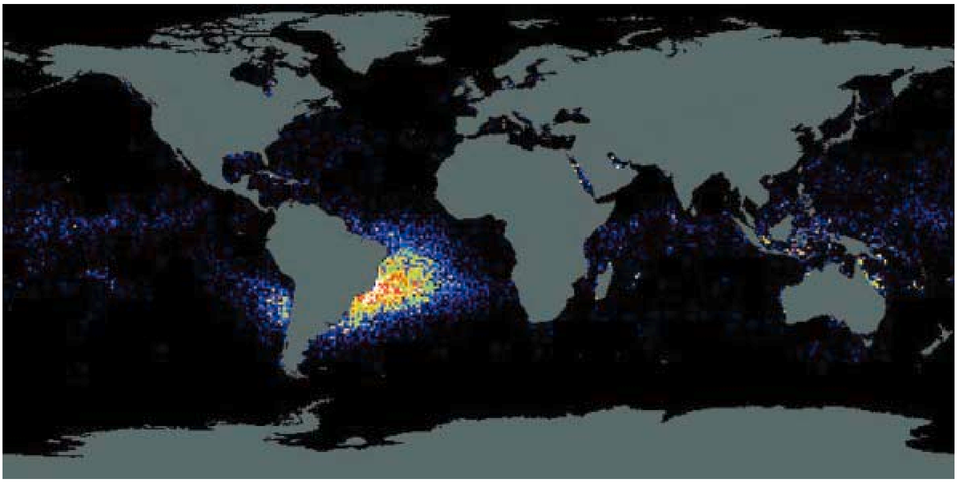

Figure 6. The global spatial distribution of single pixel events in MCI detected by MERIS suggests that most of these, occurring in the SAA off the coast of Brazil, are due to impacts of cosmic rays on the detectors of the MERIS instrument. The image uses the same colour sequence as figure 1, with black indicating zero counts, and colours blue, green, yellow and red to white indicating 1 to 20 counts per 1° square per month. The MCI will only indicate events recorded over cloud-free water. Land is masked to grey.

only areas where the 8 edge pixels all have valid MCI (i.e. excluding 'no-data', cloud or land), where the standard deviation of these eight edge pixels is below a threshold S, and where the centre MCI value exceeds the average of the eight edge pixels by more than a threshold V. For Figure 6, S=0.05 mW m^{-2} sr^{-1} nm^{-1} and V=0.3 mW m^{-2} sr^{-1} nm^{-1}. Due to the geometrical projection used for the composites, this algorithm will detect fewer events at higher latitudes, cutting off at about 60° N and S latitude.

Figure 6 was computed using all daily MCI composites for the month of July 2006. The large number of events over the South Atlantic off Brazil corresponds to the position of the South Atlantic anomaly (SAA) in cosmic ray intensity at the altitude of Envisat. This pattern is typical of observations of the SAA, for example using the SAA detectors on the US ROSAT satellite (NASA Goddard 2002). In other parts of the world in figure 6, most events are due to vegetation on isolated coral and other reefs. MCI values are computed only over cloud-free water, so that persistent cloud (e.g. off Peru) blocks detection of events.

4. Conclusions

The MCI composites produced by ESA allow a systematic and global search for plankton blooms and other aquatic vegetation using MCI. One measure of the value of the MCI is in the fact that it has successfully detected two phenomena, *Sargassum* (Gower *et al.* 2006) and Antarctic superblooms (Gower and King 2007), both reported to cover wide areas, but never before detected by satellites.

Wider distribution of the composites, once refinements are added, can involve a wider user-base in the detection and monitoring of blooms and in exploitation of MERIS data generally. Coverage is more frequent for events occurring at higher latitudes, such as the Baltic (figure 4), due to convergence of Envisat's near-polar orbits. Nearer the equator, the gaps between passes widen (figure 1) and coverage is also more limited by sun glint.

Although the MCI will not detect all of the HABs that are causing increasing damage to aquaculture, tourism and coastal water quality, we expect it to have a role in monitoring some of the surface, high-chlorophyll events, occurring under clear-sky conditions. It is also possible that other unexpected phenomena may add to the two new detections credited to MCI so far.

Acknowledgements

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