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Satellite images suggest a new *Sargassum* source region in 2011

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In the summer of 2011, a major '*Sargassum* event' brought large amounts of seaweed onto the beaches of the islands of the eastern Caribbean with significant effects on local tourism. We present satellite observations showing that the event had its origin north of the mouth of the Amazon in an area not previously associated with *Sargassum* growth. A significant concentration of *Sargassum* was detected in April, when it was centred at about 7° N latitude and 45° W longitude. By July it had spread to the coast of Africa in the east and to the Lesser Antilles and the Caribbean in the west. We have previously used images from MERIS (Medium Resolution Imaging Spectrometer) and MODIS (Moderate Resolution Imaging Spectroradiometer) to show the value of satellite observations in tracking patterns of *Sargassum*. For the years 2003–2010, we were able to determine the seasonal distribution over the range of 20°–40° N latitude and 100°–40° W longitude covering the 'Sargasso Sea' region of the North Atlantic and the Gulf of Mexico. In 2011, satellite data showed a large shift in the distribution, whose cause is unclear.

1. Introduction

A major '*Sargassum* event' was widely reported in the Caribbean during the summer of 2011 when large amounts of pelagic *Sargassum* (*Sargassum natans* or *Sargassum fluitans*) washed ashore on beaches. These two species grow and divide without contact with shore or sea floor (Butler *et al.* 1983), making them distinctly different from *Sargassum* species such as *Sargassum muticum*, which grow rooted in shallow water, but may be observed adrift after storms. *S. muticum* has spread round the world in ships' ballast water and is now becoming a problem in many areas (Rueness 1989).

After a long history of discussion (Krummel 1891, Winge 1923, Parr 1939), it is now agreed that pelagic *Sargassum* survives and grows in the oligotrophic waters of the North Atlantic, but the reasons for its distribution and large and variable biomass remain unclear (Ryther 1956). The distribution of pelagic *Sargassum* was used to define the 'Sargasso Sea' as the area of the North Atlantic subtropical gyre, with the approximate latitude range of 20°–40° N and longitude range of 40°–80° W, from the eastern edge of the Gulf Stream to about the longitude of the Azores and the mid-Atlantic ridge. Lapointe (1995) found that the productivity of *S. natans* is nutrient-limited in oceanic waters and is significantly enhanced in the coastal waters of North America. He suggested that nutrient inputs from land, for example, from

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the Mississippi River, may be a factor in determining the distribution of pelagic *Sargassum*.

In 2011, large amounts of *S.natans* or *S.fluitans,* unprecedented even to older inhabitants, washed ashore in the islands of the Lesser Antilles, well to the south of the above-noted latitude range. A typical message, from Tanya Clovis of ‘Save our Sea Turtles’ (www.sos-tobago.org), reported unusually high levels for the months of May to July on the Atlantic coast of Tobago, saying, ‘It is common for a pile of it to wash up once a year for a relatively short period, but we have never in recent memory had so much of it for so long and seen such huge mats or lines of it from the air’. Initial suggestions as to the origin of the weed were the Sargasso Sea or the Gulf of Mexico, based on historical records. However, satellite images suggest a new and a different source in this case.

During April to August 2011, images from the European Space Agency’s MERIS (Medium Resolution Imaging Spectrometer) instrument on the ENVISAT (Environmental Satellite) satellite (see details below) showed a significant increase in *Sargassum*-like detections in an area off northern Brazil, centred at about 7° N, 45° W, where we have detected only small amounts in the past. Increased detections started in April 2011 and reached a peak in July, returning to background levels by October. The total amount (summed over the area 0°–15° N, 60°–10° W) at the time of the peak was about three times higher than the maximum total amount ever recorded by MERIS for the Gulf of Mexico. The maximum amount in the Gulf of Mexico occurred in June of the ‘*Sargassum* Year’ of 2005 (Gower *et al.* 2006).

With the failure of ENVISAT in early April 2012, the time series of *Sargassum* observations with MERIS is now interrupted until launch of the follow-on OLCI (Ocean Land Colour Instrument) on Sentinel 3 in about 2014. In the meantime, NASA’s MODIS (Moderate Resolution Imaging Spectroradiometer) and VIIRS (Visual Infrared Imaging Radiometer Suite) also give images that can be used to detect and track *Sargassum*. Between them, these instruments provide a higher frequency of coverage from three sensors presently in orbit, each covering a wider swath than MERIS, but with less suitable spectral bands for discriminating floating vegetation from cloud, haze, foam or sunglint.

2. Detection of *Sargassum* by satellite

In searching for these slicks, we use the maximum chlorophyll index (MCI) derived from MERIS level 1 radiances (Gower *et al.* 2008). Level 2 data are less suitable for this work because the target *Sargassum* interferes with atmospheric correction by increasing radiances in the near infrared. MCI is a measure of the radiance peak at 709 nm, that is, the radiance at 709 nm in excess of a baseline radiance which is linearly interpolated to 709 nm from radiances measured at 681 nm and 753 nm. Curvature of the level 1 spectra (red and green in figure 3) results in negative values for MCI in clear water.

We also use a similar index from MODIS (MODIS Red Edge, MRE). MODIS has a wider swath, giving more frequent coverage, and two instruments in orbit, though one is of lower quality. However, for MODIS, the 709 nm band is not available. MRE measures an increase in radiance at 748 mn above a linearly interpolated baseline between bands at 678 and 870 nm. The range of wavelengths used in computing MRE is therefore significantly larger than the range used for the MCI of MERIS (about 200 nm compared to 75 nm). This larger range leads to increased errors caused by radiance from atmospheric scattering and to the MRE having a stronger negative bias than the MCI. The MRE is similar to the Floating Algae Index (FAI), proposed by Hu (2009), which uses partial atmospheric correction and bands at 645, 854 and 1240 nm to achieve higher spatial resolution, but covering an even larger range of wavelengths (600 nm).

3. Surface and satellite *Sargassum* observations in 2011

Figure 1 shows a photo of *Sargassum* on a beach on the east coast of Barbados on 2 August 2011, provided by a local photographer. *Sargassum* on beaches is a major problem for tourist areas, since it starts to decay after a few days. Such large masses, as shown in figure 1, overwhelm the capability of most communities to remove it, either by trucking to landfill or by towing out to sea.

Figure 2 shows MODIS satellite images of this *Sargassum*, moving towards Barbados from the north-east, a few days earlier in late July. We did not obtain suitable images from MERIS. In figure 2, colour-coded (pseudo-colour) images show values of the MRE index. High (less negative) MRE values over water indicate the presence of floating vegetation. The sequence of images from 20 and 29 July (figure 2) to 2 August (figure 1) combine to confirm the floating slicks as *Sargassum*.

Figure 3 shows a MERIS satellite image of the area off Brazil, north of the mouth of the Amazon River, about a month earlier on 29 June 2011, with spectra of the dense slicks. The spectra are computed from 'level 1' radiances (as measured at the satellite) in the spectral bands of the MERIS instrument. They show the 'chlorophyll red edge' signature, a strong increase in radiance as wavelengths increase through 700 nm, here seen as a radiance increase between measurements in MERIS bands at 681 and 709 nm. For *Sargassum*, absorption by water reduces radiances at longer wavelengths, resulting in a peak at 709 nm.

Figure 1. *Sargassum* washed ashore and on an east coast beach of Barbados, Lesser Antilles on 2 August 2011 (photo by Richard Roach, Barbados). Huge quantities of decaying *Sargassum* need to be removed from beaches to avoid impacts on tourism.

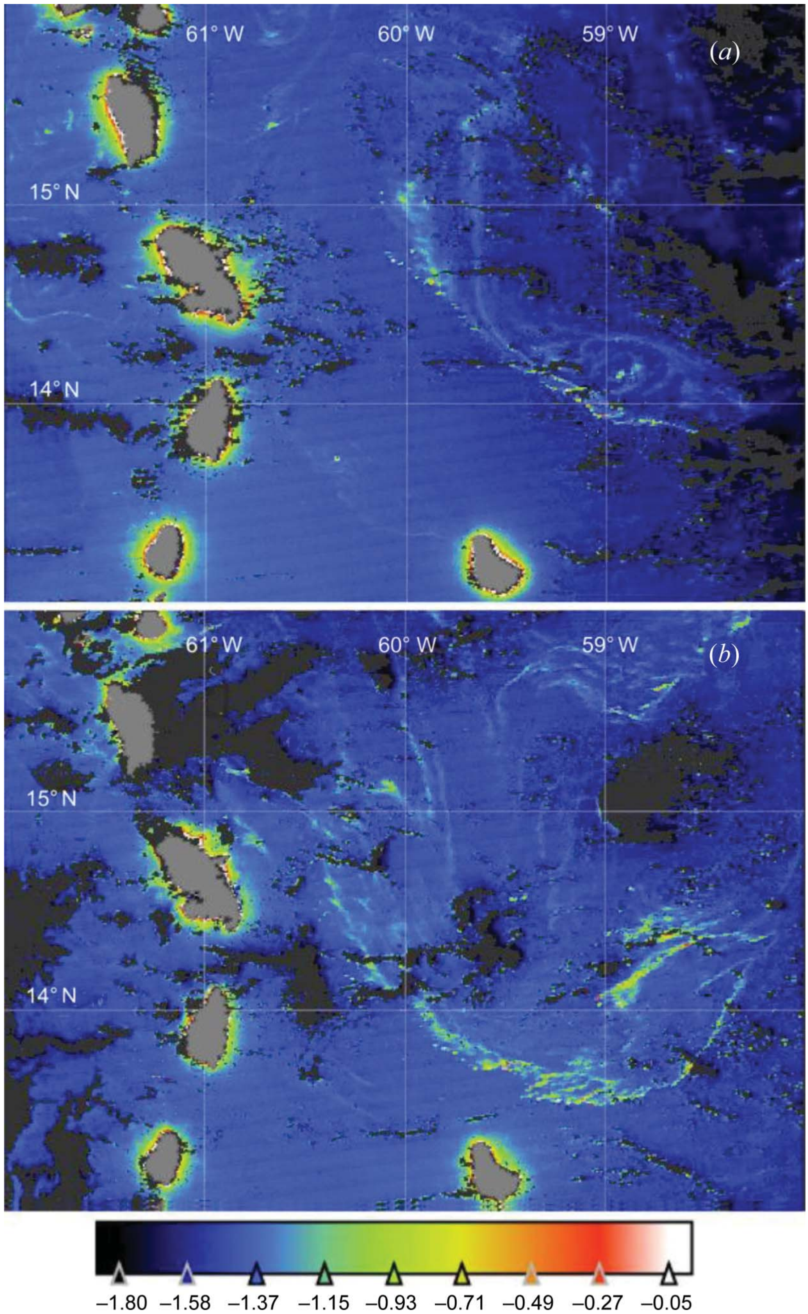

Figure 2. MODIS 'Red Edge' (MRE) satellite images for 20 July 2011 (top, (*a*)) and 29 July 2011 (bottom, (*b*)) showing lines of *Sargassum* approaching Barbados (bottom, right of centre) and other islands of the Lesser Antilles. Clouds are masked to dark grey and land to light grey. The colour bar at bottom shows the MRE value in units of $mW.m^{-2}.nm^{-1}.ster^{-1}$. Increased signal near land is due to scattering in the atmosphere. Figure 1 shows that large amounts of *Sargassum* had washed ashore by 2 August.

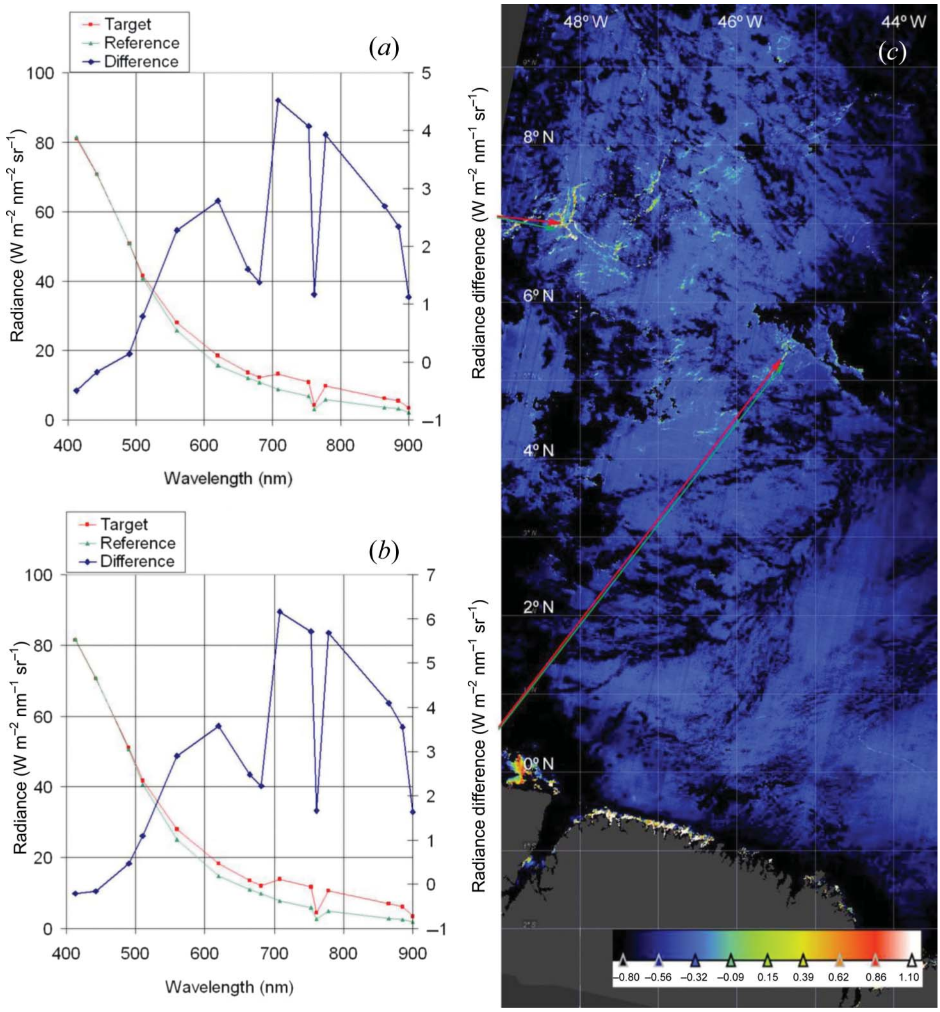

Figure 3. Spectra ((*a*) and (*b*)) and MCI 1.2 km resolution image (*c*) of floating vegetation north of the Amazon River mouth on 29 June 2011, showing the chlorophyll 'red edge' in slick spectra (red, positions indicated by red arrows, radiances measured at the satellite) and clearly visible in difference spectra (dark blue line, values on right-hand y-axis) after the reference spectrum (green) of nearby clear water is subtracted. Image colour sequence is as for Figure 2.

4. *Sargassum* time series

MERIS imagery at 1.2 by 1.2 km spatial resolution is processed by European Space Agency's (ESA) Grid Processing on Demand (GPOD) system to give global, daily composite images at a spatial resolution of 5 by 5 km recording the maximum MCI value for any 1.2 km pixel in each 5 km area (Gower *et al.* 2008). This record of the maximum value preserves detections of high-MCI targets. The daily images are then combined into monthly products at the same 5 km spatial resolution, keeping the maximum MCI per pixel for the month. The resulting monthly composites have more complete coverage, with data gaps only in areas with very frequent cloud, and

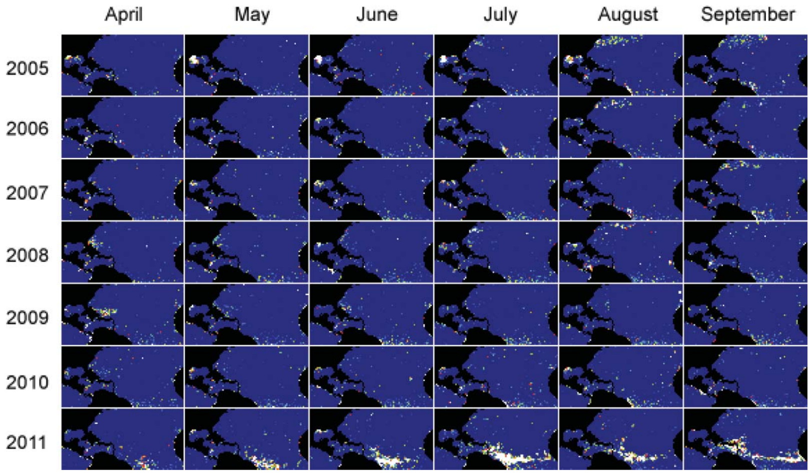

Figure 4. Monthly time series of MERIS MCI for 2005 (top row of small images) to 2011 (bottom row) and April (left column) to August (right column) of *Sargassum* detection counts in 1-degree squares for the area 0°– 45° N and 100°–10° W covering the Gulf of Mexico, Caribbean and north and tropical Atlantic across to the west coast of Africa. Land is masked to black. Colour sequence as for Figure 2. The large area of high signal off northern Brazil shows white at the bottom of the lowest row and extends from the Caribbean to Africa in July and September 2011.

are useful for recording floating vegetation and other high chlorophyll events, such as intense, surface phytoplankton blooms (Gower *et al.* 2008). Distributions and their seasonal and interannual variability can then be monitored using the monthly composites. Detected events can also be studied in more detail with MERIS level 1 or 2 data which give radiances with higher spatial resolution, 300 m for full resolution (FR) and 1200 m for reduced resolution (RR) in all MERIS spectral bands.

In the present case, part of the MCI time series of spatial distribution is shown in figure 4 as monthly sub-images at one-degree spatial resolution covering the latitude range of 0°–45° N and longitude range of 100°–10° W for the years 2005 to 2011 (rows top to bottom) and months April to September (columns left to right). This includes the area of the Sargasso Sea in the North Atlantic, the Gulf of Mexico and Caribbean and the tropical Atlantic off northern Brazil and eastwards to the west coast of Africa. The top row of images shows the sequence for 2005, in which strong growth in the Gulf of Mexico resulted in *Sargassum* being advected into the north Atlantic at about 40° N latitude by the Gulf Stream (top right images), before being blown back in a southeast direction by the trade winds (Gower and King 2011). Gower and King (2011) show similar images for all months of years 2003 to 2008 in which *Sargassum* is almost entirely in the range of 20°–40° N latitude. In figure 4, the high signal in 2011, well outside this range off Brazil at about 10° N latitude, is shown in the bottom row. This signal increased in July and moved slightly further north in the months shown. In July, it extended westwards to the Caribbean. In September, it showed two areas of highest abundance, one near the Caribbean and a second off the coast of Africa.

MERIS data extend back to 2002 and can be used to produce time series for specific areas. Figure 5 shows the monthly total signal and fraction clear of cloud in the area 5°–9° N latitude and 35°–50° W longitude, corresponding roughly to the area

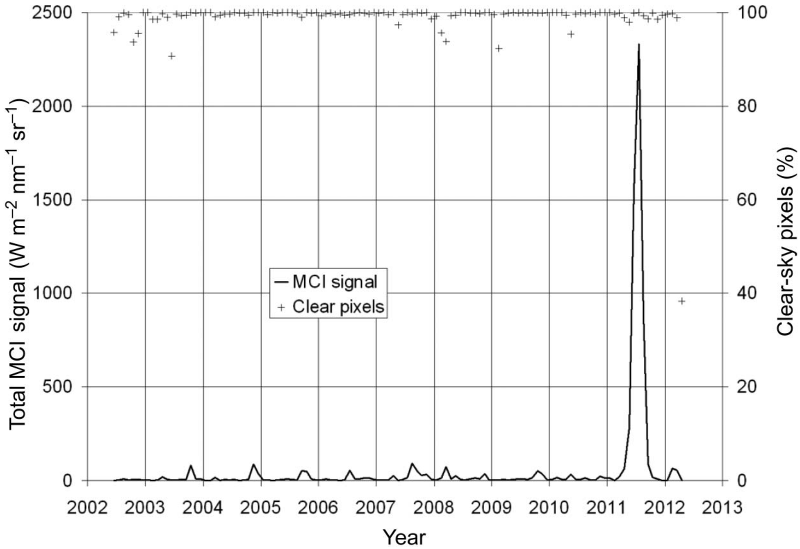

Figure 5. Monthly time series of MERIS MCI signal integrated over the rectangular area 5°–9° N, 35–50° W. The high signal in July 2011 is about a factor 200 larger than any signal previously observed in July. The plot of clear sky pixels shows that 90% of months have better than 98% coverage, and only April 2012, for which MERIS provided only 4 days of data before ENVISAT failed, has less than 90%.

of maximum signal, which figure 4 shows to have occurred in July 2011. The time series clearly shows the peak in 2011, with much smaller signals in other years.

5. Discussion

Using satellite data alone, we cannot prove that the slicks imaged by satellite are of *Sargassum*. However, in the present case, we have strong confirmation from shoreline reports. Timing and locations agree well both in the Caribbean and in Sierra Leone, Africa. Figure 1 is one example. We also have numerous media and personal communications, including pictures similar to figure 1, in late August from Sierra Leone, West Africa, where Sargassum is extremely rare.

A common confusing target is the buoyant cyanobacterium *Trichodesmium*, which forms similar sinuous surface slicks. These slicks also show the chlorophyll 'red-edge' signature. However, water surrounding *Trichodesmium* slicks tends to show increased brightness at 560 nm (examples not shown) due to high concentrations of *Trichodesmium* trichomes in the water. In this sense, the spectra in figure 3 are consistent with *Sargassum*, rather than *Trichodesmium*. Also, *Trichodesmium* blooms tend to be much shorter-lived. The persistence of signal over many months, as in figure 4, suggests a larger organism, like *Sargassum,* rather than a small phytoplankton which is much more sensitive to wind mixing. Phytoplankton events appear in other areas in images similar to figure 4, but for 1 or 2 months only, reflecting a lifetime of 1 to 3 weeks.

We should also note a very different confusing signal which has an effect on MCI data for all months of figure 4, due to cosmic rays impacting the image sensor arrays of MERIS and MODIS, when satellites are in the area of the South Atlantic Anomaly

(NASA 2002). This anomaly is centred over southern Brazil, but extends far enough towards the north to cause the sparse background signal near the southern edge for all months in figure 4. In the present case, this is not a significant source of error, since the *Sargassum* event of 2011 gave a much stronger MCI signal than the cosmic rays in this area, and the two spectral signatures are very different.

The present observations broaden considerably the area over which pelagic *Sargassum* is known to grow and form rafts, even though this growth may occur only rarely. Previously, *Sargassum* was thought to be limited to the area of the North Atlantic, known as the Sargasso Sea, though many early reports showed the importance of the Gulf of Mexico (Winge 1923). Our first satellite detections (Gower *et al.* 2006) were in the Gulf of Mexico in 2005, and data for the years 2003–2005 emphasized this as an area of growth (Gower and King 2011). The later observations reported by Gower and King (2011) show relatively more growth in the Sargasso Sea area of the Atlantic, but no sign of major growth off northern Brazil.

The variability indicated by this event and shown by figure 4 is probably characteristic of many pelagic ocean species for which similar images are not available. Pelagic *Sargassum*, *Trichodesmium* and *Coccolithophores* are probably the only ocean species easily visible to satellites, with spectral signatures that allow discrimination from confusing targets and a good chance for their identification. *Sargassum* has the added advantage of being robust and long-lived, with individual plants being large enough to be easily recognizable, making identification from ships and on beaches much easier, and hence providing the needed validation of satellite image data.

It is possible that significant populations of pelagic *Sargassum* may occur sporadically in other oceans. We have heard reports of *Sargassum* in the Indian Ocean off Madagascar, but the lines or patches in this area, shown by our satellite observations, have the signature of *Trichodesmium*. There is no clear reason for the lack of pelagic *Sargassum* in the South Atlantic or in the Pacific and Indian Oceans. There is a large literature on the association of *Sargassum* with other species, especially young sea turtles, which appear to find food and shelter in *Sargassum* mats in the Atlantic (Carr 1986, Bolten 2003, Putman *et al.* 2010). However, turtles exist in all tropical and temperate oceans and appear to thrive without *Sargassum.* Perhaps, in past millennia, turtle evolution was aided by *Sargassum* mats in other oceans.

6. Conclusions

Satellite data clearly show a new area of origin for the 2011 *Sargassum* event, well to the south of the area discussed in historical reports (Krummel 1891, Winge 1923, Parr 1939, Ryther 1956) and by Gower and King (2011). Lapointe (1995) noted a possible connection between *S.natans* and nutrient inputs from land, for example, from the Mississippi River. Figures 3 and 4 suggest a possible similar influence from the Amazon, though the actual link remains unknown.

The increasing trend of global sea level shows a distinct dip centred in early 2011, which Boening *et al.* (2012) ascribe to anomalous rainfall associated with La Nina, transferring water out of the oceans on to the land. Their figure 3 shows Australia and the north coast of South America as the two areas where most water had accumulated by the spring (March–May) of 2011. Above-normal run-off would have started earlier and could have been a significant source of nutrients to the equatorial Atlantic. Floods were reported from the Amazon area in 2011 and 2012, but no link has been made to *Sargassum*.

Our observations now cover the entire lifetime of the MERIS imager on the ENVISAT satellite, from June 2002 to April 2012. This instrument provided spectral bands, especially at 709 nm, well suited for identifying *Sargassum*. Future tracking of this *Sargassum* will be hindered by lack of this sensor and the associated GPOD data processing, but should still be possible with MODIS. The approximately 1 km by 1 km spatial resolution of MERIS or MODIS limits detection to relatively extensive mats or rafts of aggregated floating algae. This bias needs to be considered when interpreting satellite observations. The full resolution of the MERIS sensor (300 m) is also available, but the large data volume is a problem in large-area studies and was not available as an input to GPOD. MODIS also has two bands with 250 m resolution, but spectral discrimination is limited and again data volume is large.

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