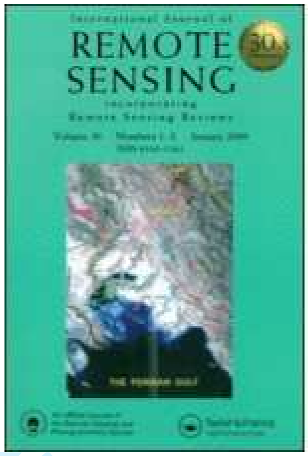

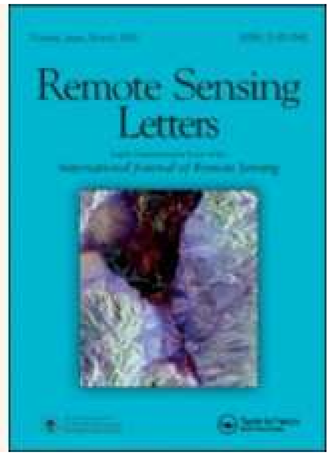

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Journal:	*International Journal of Remote Sensing*
Manuscript ID:	TRES-PAP-2009-0025.R1
Manuscript Type:	Research Paper
Date Submitted by the Author:	07-May-2009
Complete List of Authors:	Gower, Jim; Institute of Ocean Sciences King, Stephanie; Institute of Ocean Science, OSAP
Keywords:	MERIS, OCEAN COLOUR, PHYTOPLANKTON
Keywords (user defined):	Sargassum

Distribution of floating *Sargassum* in the Gulf of Mexico and Atlantic Ocean mapped using MERIS

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Abstract

We use satellite imagery from the European Space Agency (ESA) Medium Resolution Imaging Spectrometer (MERIS) optical sensor to make the first mapping of the full distribution and movement of the population of *Sargassum* in the Gulf of Mexico and western Atlantic. For most of the years for which we have data (2002 to 2008), the results show a seasonal pattern in which *Sargassum* originates in the northwest Gulf of Mexico in the spring of each year, and is then advected into the Atlantic. The *Sargassum* appears east of Cape Hatteras as a "*Sargassum* jet" in July and ends northeast of the Bahamas in February of the following year. This pattern is consistent with historical surveys from ships. MERIS provides a spectral band which greatly improves discrimination of floating vegetation from confusing signals such as cloud and sun-glint.

1. Introduction

Although the free-floating pelagic species of *Sargassum* (*natans* and *fluitans*) have been studied since at least the 1830's and have been acknowledged in marine lore by the naming of the Sargasso Sea, they have only recently been detected in satellite images (Gower et al., 2006). Observations from ships are hampered by the large and variable area over which *Sargassum* is dispersed. For satellites, this is not a problem since satellite coverage is almost global and is regularly repeated. Also, *Sargassum* should be an ideal target for optical satellite sensors. It is long-lived, buoyant and has a spectral signature which contrasts strongly with surrounding water. Aggregations are extensive enough to be detected by relatively low-resolution sensors. The major reason for its non-detection in the past has been the lack of a combination of sensor bands that provides a definitive signal in the presence of cloud, haze and sun-glint. This is now rectified by the ESA's (European Space Agency) Medium Resolution Imaging Spectrometer (MERIS) sensor (Rast et al., 1999, ESA, 2008).

Many sightings of *Sargassum* were recorded in the 19th century, especially by the German merchant marine, (Kruemmel, 1891), perhaps inspired by the early theory that *Sargassum* indicated presence of a vast undiscovered reef in mid-Atlantic. Winge (1923) in a historical summary, notes that the botanist Meyen, writing of "A journey round the world in 1830, 1831 and 1832" was the first to suggest that this *Sargassum* is truly pelagic. Winge also quotes Meyen as writing (in German) "Some sailors believe that this weed is collected by the Gulf Stream and that there are huge masses of seaweed in the Gulf of Mexico, an opinion that however, does not need to be considered further." It is not clear why Winge was so strongly against this idea. In fact, his summary shows that the idea of significant amounts of *Sargassum* originating in the Gulf of Mexico, as we propose here, was fairly common in the 19th century, but seems to have died out in the 20th.

The MERIS Imager on the Envisat satellite showed extensive areas containing long, narrow, meandering slicks in the north-western Gulf of Mexico in the early summer of 2005 (Gower et al., 2006). The same features are detectable in MODIS and SeaWiFS imagery. Gower et al.(2006) used the wider spatial coverage provided by MODIS to follow the seasonal pattern of *Sargassum* in the Gulf of Mexico between September 2004 and October 2005. In several cases the *Sargassum* affects sun-glint patterns by reducing surface roughness, showing that it should also be visible in SAR (Synthetic Aperture Radar) images (Grodsky et al., 2000, Ferraro et al., 2009). However, in none of these cases do the satellite data provide the more definitive spectral signature provided by MERIS.

In this paper, we extend our previous survey (Gower et al., 2006) using the global MERIS data set provided by ESA's G-POD (Grid Processing On Demand) system for the time period June 2002 to December 2008. Results show an annual cycle of *Sargassum* distribution in the Gulf of Mexico and North Atlantic, with considerable interannual variability. The satellite data do not show any sign of similar populations of long-lived pelagic *Sargassum* in other oceans of the world.

2. Methods

MERIS was launched on the European Space Agency's Envisat satellite in March 2002 and has provided systematic global coverage at 1200 m resolution since June of that year. MERIS also provides data at 300m resolution, but this is not usually available over offshore areas. To be detected with 1200m-resolution data, *Sargassum* therefore has to be dense enough, and to cover a large enough area, to affect the average colour (visible surface spectral reflectance) of an area of ocean surface 1200 m across.

We make use of an index, the MCI (Maximum Chlorophyll Index) available from MERIS, but not from MODIS or SeaWiFS, which provides good discrimination of floating and coastal vegetation, as well as intense surface plankton blooms (Gower et al., 2005). The index measures the local peak in water-leaving radiance near 705 nm, which has been identified as a measure of high concentrations of surface chlorophyll *a* (Borstad et al., 1985, Gitelson et al., 1992, Yacobi et al., 1995, Gower et al., 1999, 2005, Ryan et al., 2008) and is also shown to be a sensitive detector of the "shifted red-edge" characteristic of marine and floating vegetation (Gower et al., 2006, 2008). MCI is computed from the above-atmosphere spectral radiances (Level-1 data) measured for each pixel of the satellite image data to show excess radiance at 709 nm, above a baseline defined by linear interpolation between the neighboring spectral bands at 681 and 754 nm, as defined by equation 1.

$$MCI = L_{709} - L_{681} - (709 - 681)(L_{754} - L_{681})/(754 - 681) \qquad (1)$$

where L_{709} represents radiance at 709 nm, etc.. Pixels containing significant cloud, land or sun-glint are screened out by accepting only pixels for which L_{865} is less than a threshold value of 15 mW m^{-2} nm^{-1} sr^{-1}. This value was found in a series of trials as giving the best compromise between data volume (adding measurements in thin cloud and moderate sun-glint) and data quality (accepting errors due to these added sources of radiance).

In our previous paper on *Sargassum* in the Gulf of Mexico (Gower et al., 2006), we made use of MCI images at 1200 and 300 m resolution computed using equation 1 from Level-1 MERIS data. For the large-area tracking of *Sargassum*, in the present paper, we make use of global, daily composites of MERIS MCI values, provided by G-POD at 5 km spatial resolution. The value of each 5 km pixel in the composite is the maximum MCI of any 1200 m pixel assigned to that composite pixel. The daily composites are then combined into monthly images in which each pixel shows the maximum MCI recorded at that pixel on any day of the month. This fills areas missed due to cloud, sun-glint, and lack of MERIS coverage, while preserving any evidence of *Sargassum* occurrence. Changing sun elevations cause a small annual cycle (maximum amplitude 1.0 mW m^{-2} nm^{-1} sr^{-1}) in the "clear-water" background values of MCI computed in this way. This is compensated in the monthly compositing process.

The monthly composites of MCI signal at 5 km spatial resolution are analyzed by computing the frequency distribution (histogram) of MCI values in each one-degree square, and assuming that all MCI values exceeding the mean ocean background value in that one-degree square by a threshold amount, indicate presence of *Sargassum*. Squares that include coastlines and other fixed areas where MCI is observed to be high, such as coral reefs and areas with frequent coastal plankton blooms, are masked in all months.

We name the sum of the number of MCI values above threshold, multiplied by the amount by which MCI exceeds its background value (in mW m^{-2} nm^{-1} sr^{-1}) as “MERIS count.” That is:

$$\text{MERIS count} = \sum_{m=b+t}^{m=\infty}(m-b)n(m) \qquad (2)$$

where *n(m)* is the number of pixels in the one-degree square having an MCI value of *m, b* is the background value of MCI corresponding to open water and *t* is the threshold value, here 0.4 mW m^{-2} nm^{-1} sr^{-1}. We take this count as being proportional to the total amount of *Sargassum* in each one-degree square.

(Figure 1 about here)

3. MERIS image data and statistics

Since the first detection using satellite imagery, of *Sargassum* in the north-western Gulf of Mexico in May and June of 2005 (Gower et al., 2006), we have collected several images of dense aggregations in the Gulf Stream extension area of the western Atlantic east of Cape Hatteras, in October and November of 2006 and 2007, such as Figure 1(*a*). The *Sargassum* is collected into patches and long lines by surface convergence and shear. The difference spectrum (blue) in Figure 1(*b*) shows the "red-edge" characteristic of land vegetation, with a shift in wavelength of the effective “red-edge” position due to water absorption. This difference spectrum results in an MCI value of about 2.0 mW m^{-2} nm^{-1} sr^{-1}. The peak in the visible range (400 to 700 nm) at 620 nm is consistent with the brown colour of *Sargassum*. Interpretation as *Sargassum* is also based on the shape of the patches (especially the lines extending over 100 km in length), continuity of patterns over a several-month period, and lack of indication in the satellite data of any high background chlorophyll concentration, which would indicate a dense concentration of phytoplankton.

(Figure 2 about here)

For a systematic survey of *Sargassum* distribution and its variation with season and year, we require large-area composite satellite image data, of the type provided by G-POD, as described in the previous section. The 5-km data of the global composites are combined into one-degree squares, in which *Sargassum* concentrations are computed as MERIS counts. Figure 2 shows the spatial distributions of MERIS counts of *Sargassum* detected by MERIS MCI for the years 2002 to 2008 (top to bottom) and months January to December (left to right), in pixels measuring one degree in latitude and longitude. (image available at http://sargassumfromspace.org/research/Fig2_SargCounts.png) High concentrations of *Sargassum* are indicated in the northwest Gulf of Mexico for all years in March to June, except 2002 for which we have data only after June 12. *Sargassum* then appears in a broad area of the Atlantic to the east of Cape Hatteras (35 to 40N, 45 to 75W) in July and August, as best shown in 2005 to 2008. Little *Sargassum* is observed in the Gulf from September onwards. High count values in Canadian waters in the north of Figure 2 in January to April are associated with sea ice, and are not considered further here. Counts in the area immediately to the east of Figure 2 are relatively low.

(Figure 3 about here)

Figure 3 shows plots of estimated total amounts of *Sargassum* in the Gulf of Mexico (15 to 30N, 80 to 100W) and the western North Atlantic (22 to 40N, 20 to 80W), for each month from June 2002 to December 2008. MERIS counts are scaled to millions of tonnes by comparison with ship observations (Parr, 1939, Butler et al., 1983) as described below. Very little *Sargassum* was detected in 2002. Highest amounts are in May, June, July in the Gulf of Mexico, with values increasing through 2003 and 2004 to a maximum in 2005. Amounts in the Atlantic increase each year after July and drop back to low values in the spring of the following year, with the exception of the latest year, 2008.

(Figure 4 about here)

The average latitude and longitude of *Sargassum* detected in the Atlantic were computed using a simple linearly weighted average over the area 22 to 40N, 20 to 80W. Positions are plotted in Figure 4 for months in which *Sargassum* amounts in Figure 3 were greater than 700 000 tonnes. The seasonal variation shows considerable consistency from year to year in both latitude, Figure 4(*a*) and longitude, Figure 4(*b*). The statistical centre of *Sargassum* is first at about 37N, 67W in the Atlantic, moves eastwards until October and then moves southwest until February. Figure 5 summarizes the spatial distribution shown by Figure 2 and by the statistical results of Figures 3 and 4.

(Figure 5 about here)

4. Discussion

A significant feature of Figure 2 is the temporal continuity of the signal that we interpret as due to *Sargassum*. Movement of *Sargassum* over many months is consistent from year to year, and can be explained by prevailing surface currents and winds. The data clearly indicate strong growth early in the year in the Gulf of Mexico, with *Sargassum* advected by the Loop Current and Gulf Stream into the Atlantic each year in July and August. Data for the years 2003 to 2007 suggest that the Gulf of Mexico is the dominant source of *Sargassum*. Passive surface floats (MEDS, 2008) take about a month to travel from the north-east Gulf of Mexico near 27N, 85W to east of Cape Hatteras at 36N, 75W. This is a short enough time to be consistent with our interpretation of the movement of *Sargassum*.

The average spatial pattern of the annual cycle is shown schematically in Figure 5. In each year, *Sargassum* is first detected in a small area of the northwest Gulf of Mexico in March, which expands and spreads eastwards. In July *Sargassum* is present in both the Gulf and the Atlantic off Cape Hatteras, spread eastwards to about 45 W by the Gulf Stream in September. The north-east trade winds then move the *Sargassum* south and west over the fall and winter (October to February). Counts are very low in the Atlantic for the months of March, April and May in 2003 to 2007, though in 2008 significant *Sargassum* remained in the area northeast of the Bahamas at this season.

Our observations are consistent with earlier ship-based surveys. Parr (1939) reported on 194 surface net tows designed to collect *Sargassum* in the Sargasso Sea, Caribbean and Gulf of Mexico, in 1933, 1934 and 1935. Of these, 160 were in January, February or March, and the remaining 34 in April, July and August. Given the sparseness of his observations and lack of seasonal coverage, he used Kruemmel's (1891) estimates of the seasonality and average area of *Sargassum*. In late January of 1934 and early February of 1935, Parr measured *Sargassum* amounts on cruises from Cape Cod to Bermuda to the Caribbean. His observations were frequent enough, over a wide enough range of latitude to allow an estimate of the mean latitude (about 27 N) of the *Sargassum* at these times, letter P in Figure 4(*a*), which is in good agreement with the satellite data.

Between April 1977 and January 1982, Stoner (Butler et al., 1983) measured *Sargassum* density at 266 locations on a series of 15 cruises in the Sargasso Sea and Caribbean. The results were initially interpreted (Stoner, 1983) to show a drop in *Sargassum* biomass compared to Parr's earlier observations, but were later reinterpreted (Butler and Stoner, 1984) as showing a significantly lower value in only one area near 23 N, 65 W north of Puerto Rico, which Stoner visited in November of 1977 and 1980, and Parr visited in February/March 1933. Butler and Stoner (1984) suggested that this difference may be due to a seasonal variation. Our satellite data now confirm this, showing that the density at this location in November should indeed be lower than in February (Figure 5).

We select areas and months where Parr and Stoner measured significant amounts of *Sargassum*, and compare these with the satellite observations for the same areas and months. We are comparing ship and satellite observations made 70 and 25 years apart in time, but we know of no more recent surveys which would allow comparisons with a smaller time interval. The results for 11 different areas and dates give an average value of 1400 tonnes (wet weight) per square degree per MERIS count, with RMS (Root Mean Square) scatter of about a factor two among the 11 estimates of this value. We use this average value to compute the total amounts of *Sargassum* in Figure 3.

Our interpretation of significant amounts of *Sargassum* entering the Atlantic from the Gulf of Mexico in the summer is supported by the observations of Dooley (1972) who collected *Sargassum* passing Miami at semi-monthly intervals from April 1966 to May 1967, and noted "very low quantities in spring and winter, while tremendous quantities were available in summer and fall."

The satellite image data suggest that *Sargassum* amounts are regularly greater in the Gulf of Mexico than in the Atlantic (Figure 3). There have been few reported surveys of *Sargassum* in the Gulf, and no systematic surveys of seasonal variation, but sightings are common, especially washed up on beaches. In a single visit to Corpus Christi Texas on April 1 1935, Parr (1939) noted a "secondary maximum" of *Sargassum* in the northwest Gulf of Mexico, but observed it to be of "apparently deteriorating weeds." Wells and Rooker (2004), state that *Sargassum* occurred in the northwest Gulf from May to August 2000, a seasonal pattern confirmed by Figure 3.

Our interpretation of the satellite data for 2003 to 2007 is that *Sargassum* starts growing each year in the Gulf of Mexico in about March, and dies about a year later in the Atlantic in the area northeast of the Bahamas. The idea of new growth of *Sargassum* in the Gulf in March and April is contrary to Parr's conclusion that the weed there was "deteriorating." New growth is strongly suggested by the rapid increase in the amount of *Sargassum* in the northwest Gulf each year in March to July, which is very clear in the satellite data.

Our estimates for average total mass of *Sargassum*, derived by calibrating the satellite data with ship measurements in the same areas and months, is about 1 million tonnes (wet weight) in each of the Gulf of Mexico and the Atlantic, for a total of 2 million tonnes (averages of the data plotted in Figure 3). This is less than the 7, 11 and 4 million tonnes estimated by Parr (1939) for each of the three years of his observations (1933, 1934 and 1935).

There are several possible sources of error in our satellite estimates of *Sargassum* amounts. The possibility of confusion with surface slicks of *Trichodesmium* was discussed by Gower et al. (2006), with the conclusion that the spectra are sufficiently different in the cases we have examined in detail, and that this should not be a problem. Another species group commonly seen in satellite images are coccolithophorids, but in this case the difference in spectra is much more significant. Coccolithophores give no detectable MCI signal, and such blooms will not confuse the present observations. We note that benthic vegetation and coral reefs in shallow water (Gower et al., 1999) can cause false positive signals, but these are limited to fixed and known locations.

We noted a single example of a transient, high-MCI patch just outside the south-east corner of Fig 2 near the Azores in October 2003. This appears in the count data for a single month only, strongly suggesting that it represents a more transient phytoplankton event, rather than *Sargassum*. Parts of the patch were imaged on 8 different days of October, between the 2nd and the 22nd. Small wisps are seen on 26 and 30 Sept, but nothing was seen in November. The spectrum shows the chlorophyll red-edge, consistent with either *Sargassum* or a floating plankton bloom. The patch shows some tendency to form linear structures, but not the characteristic thin, curving lines that we consider to be a signature of *Sargassum*. On the other hand, the "thin, curving lines" may show the relative influences of the surface wind and mesoscale eddies that shape the floating patterns. We have not extended the statistics of our survey (Figures 3, 4 and 5) so far to the south-east as to include this patch.

MERIS covers only about half the earth's surface each day in the tropics, and the area of useful observations is further reduced by cloud and sun-glint, but the global composite data show that the area hidden from the satellite on all days of a month average only about 1% of the total. The coverage provided by MERIS therefore appears adequate for this survey. A more significant problem may be if the satellite detects only *Sargassum* that is to some extent "aggregated," while missing *Sargassum* that is evenly distributed, especially if a smaller fraction of this is on the surface. We do not detect *Sargassum* in the strongly-flowing areas of the Loop Current and Gulf Stream, but detect it in the slower-moving regions of the Gulf of Mexico and North Atlantic at either end of these flows.

MERIS can detect *Sargassum* using MCI only when it is at or just below the sea surface. At the wavelength of 709 nm, absorption by water is 1.0 per meter, so that *Sargassum* at a depth of 35 cm will give an MCI reduced to about half its value at the surface. Aging *Sargassum* loses buoyancy and will be subject to an increasing tendency to be mixed down by wind, waves or currents (Stoner, 1983). Woodcock (1993) showed that Parr's counts tended to be lower at wind speeds above 4 m.s^{-1}, and a similar effect may be expected for the satellite observations. Our statistical analysis preserves the largest MCI signal in a month, so that even if wind is a significant factor, a patch of *Sargassum* needs to be observed on only one low-wind day in the month to be detected.

Cosmic ray hits on the sensors of the MERIS instrument will give sporadic high MCI values which will be preserved in our statistics. These are probably responsible for some of the isolated MERIS counts in Figure 2 and may be responsible for a significant fraction of the low-value counts in Figure 3. Hits on the sensor are much more common in the South Atlantic Anomaly, which affects an area about 2000 km across, centered off the coast of Brazil. We are not aware of any publications on the effects of cosmic rays on earth-observing sensors, but the problem is well known in space astronomy (e.g. Salzberg et al., 1995).

The above errors are cause for concern, but are mostly unavoidable. Many are the same for all months and locations, and will distort the relative values only if processes such as mixing and surface aggregation are regionally or seasonally dependent. The conversion of the MERIS counts to tonnes of *Sargassum* makes use of a statistical comparison with available ship data, which compensates for some of these errors.

In areas of the world outside the region shown in Figure 2 (and near the Azores in October 2003 as already discussed), high values of MCI occur in shorter-lived patches which we interpret as intense surface plankton blooms of the type commonly referred to as "red tides." We hope to eventually identify the species responsible for these patches with the help of in-situ observers. We have not found features with the longer temporal continuity evident in Figure 2, which is characteristic of at least the Gulf of Mexico/Atlantic pelagic *Sargassum* population. We have found evidence of shorter-lived *Sargassum*-like patterns, for example in the Mozambique Channel between Madagascar and Africa. Further work is needed to locate and quantify possible other pelagic *Sargassum* populations.

5. Conclusions

Our observations for the period 2003 to 2008 show growth of *Sargassum* in the northwest Gulf of Mexico between March and June each year, with *Sargassum* appearing in the Atlantic, north and east of Cape Hatteras, starting in about July. In all years except 2008, we observe low total *Sargassum* amounts in the Atlantic before this annual injection from the Gulf of Mexico. Observations for 2003 to 2007 suggest that most *Sargassum* has a life-time of one year or less, with the major "nursery area" being in the northwest Gulf of Mexico. If *Sargassum* were longer-lived, we would expect to observe more evidence of *Sargassum* in the Atlantic northeast of the Bahamas, in February to May in these years. Only in 2008 do observations show significant concentrations in this area, with circulation back into the Gulf Stream. This circulation would be consistent with the traditional picture of the Sargasso Sea as being the main repository of *Sargassum* biomass.

MERIS shows large amounts of *Sargassum* in the Gulf of Mexico in the years 2003 to 2005, compared to the Atlantic, but smaller amounts in 2006 to 2008. The average of all years suggests that the Gulf of Mexico is the dominant *Sargassum* "nursery area," but clearly a longer time-series is required to better determine its relative importance. The observation of a significant average flow of about one million tonnes of *Sargassum* out of the Gulf of Mexico in most years implies a carbon flux which needs to be accounted for in productivity and carbon models.

The motion of the *Sargassum* in the Atlantic follows a consistent pattern from year to year. The observed distributions are consistent with earlier ship observations, and explain many of the apparent discrepancies found in them.

Satellite images based on appropriate spectral bands are clearly a valuable source of data for surveys of *Sargassum*, but with limitations due to spatial resolution, cloud cover and sun-glint. We note that the satellite may miss significant quantities of *Sargassum* if it is too evenly distributed or mixed beneath the surface by wind. We plan to expand our study to include correlation with observed wind speed. In the future, satellite observations can continue to provide a lengthening time series of data of the type we present here. Satellites can also play an important role in selecting the sampling pattern for any future ship survey.

Future observations of *Sargassum* depend on maintaining the capability provided by MERIS. The present US sensors SeaWiFS and MODIS and the planned future sensor VIIRS lack the band at 709 nm which make possible the computation of MCI, used here for detection of *Sargassum*. The major limitation of MERIS, especially when compared to MODIS, is in its relatively narrow swath width, which at 1150 km is about half that of MODIS. This is not wide enough to allow daily coverage of all areas. Also, there are at present two MODIS instruments in orbit, on the Terra and Aqua satellites, again increasing coverage. Ideally, future versions of the MERIS sensor would image over an increased swath width, and would also have two sensors in orbit at all times.

Acknowledgements

This work was supported by Fisheries and Oceans Canada, and by the Canadian Space Agency (CSA) under the GRIP (Government Related Initiative Program). Image data are supplied by the European Space Agency (ESA). Processing of the global composite data is by ESA's G-POD (GRID Processing On Demand) system.

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Figure Captions

Figure 1(*a*). Floating *Sargassum* in the Gulf Stream near 63W, 37N imaged as MCI on October 22, 2007 by ESA's ocean sensor, MERIS at its full spatial resolution of 300 m. Colours indicate MCI value as shown by the colour bar.

Figure 1(*b*). Top-of-atmosphere radiance spectra for a pixel of Figure 1(a) containing high *Sargassum* concentration (red) and for nearby clear water (green). The difference spectrum (blue, values on right axis) shows the "red-edge" of land vegetation, but shifted to a shorter wavelength.

Figure 2. MERIS counts of *Sargassum* for the years 2002 to 2008 (top to bottom) for months January to December (left to right) for the area 10 to 50 N, 38 to 98 W. Pixels measure one degree in latitude and longitude. The background dark blue colour corresponds to no detections. Increasing amounts are indicated by the colour sequence shown in Figure 1. One-degree squares where MCI gives strong signals from coral reefs and other benthic vegetation are masked to black. Land at 0.25° spatial resolution is shown in grey.

Figure 3. Plots of total amounts of *Sargassum* for the Gulf of Mexico (15 to 30N, 80 to 100W) and the western Atlantic (22 to 40N, 40 to 80W), for the period June 2002 to December 2008. Values are MERIS counts converted to tonnes (wet weight) by comparison with ship observations.

Figure 4. Average latitude (a) and longitude (b) of *Sargassum* in the Atlantic from 22 to 40N, 40 to 80W for months in which amounts plotted in Figure 3 were greater than 700 000 tonnes. The letter "P" in Figure 4a shows the average latitude (27.2 N) deduced from Parr's (1939) measurements in late January 1934 and early February 1935 along roughly 68 W.

Figure 5. Simplified outline diagram showing the average extent of *Sargassum* in March, May, July, September, November and February, based on MERIS count distributions by month as shown in Figure 2. Only in 2008 does MERIS detect significant *Sargassum* in the Atlantic between March and June (dashed outlines).

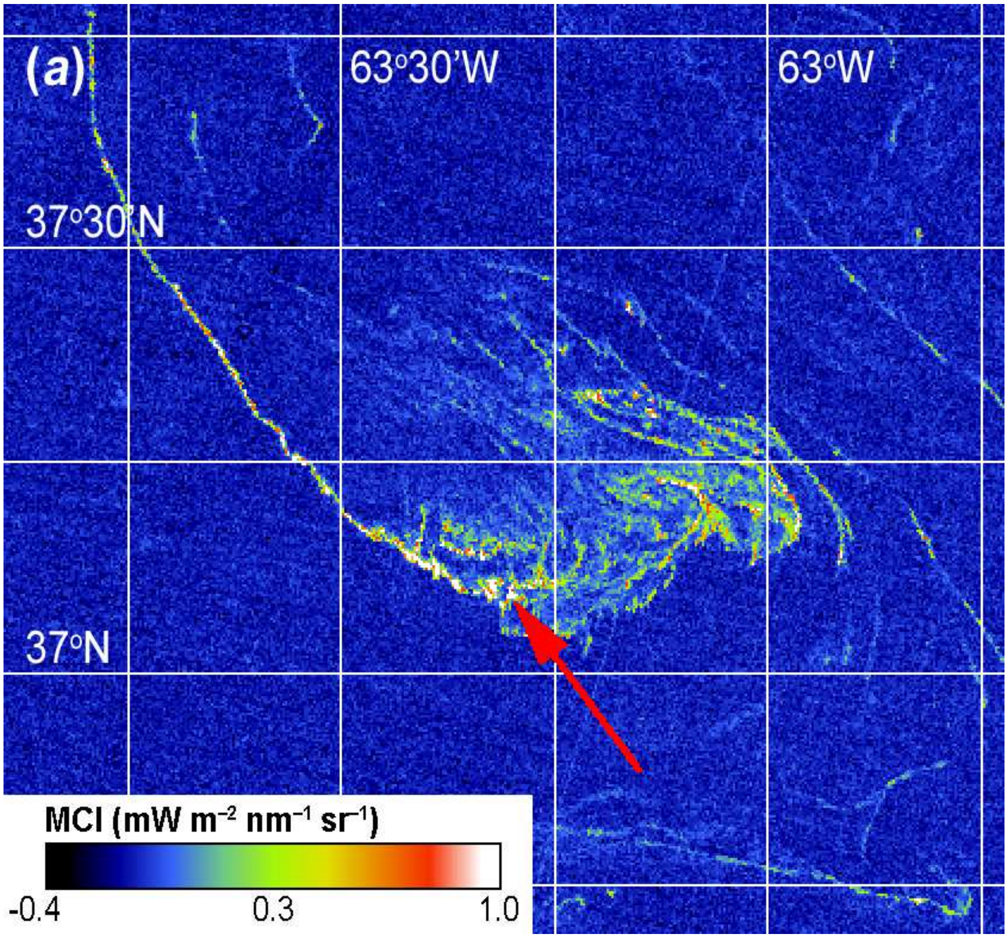

Figure 1(a)
106x99mm (200 x 200 DPI)

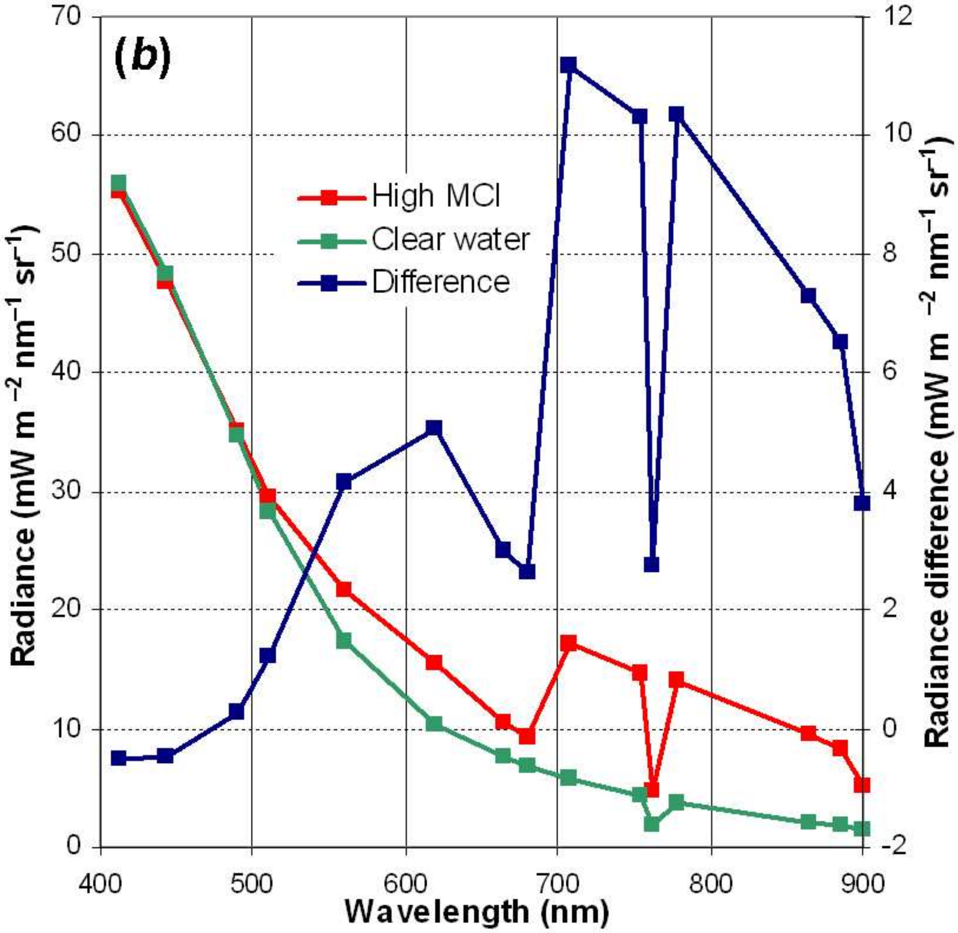

Figure 1(b)
299x291mm (72 x 72 DPI)

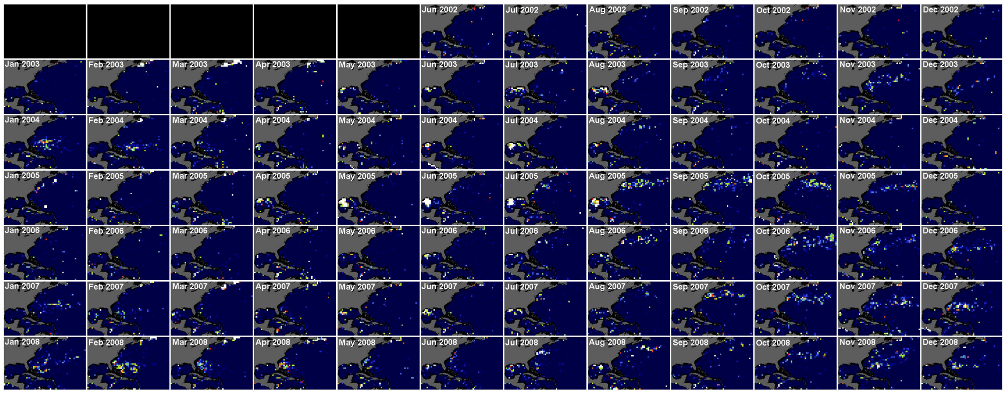

Figure 2
365x142mm (200 x 200 DPI)

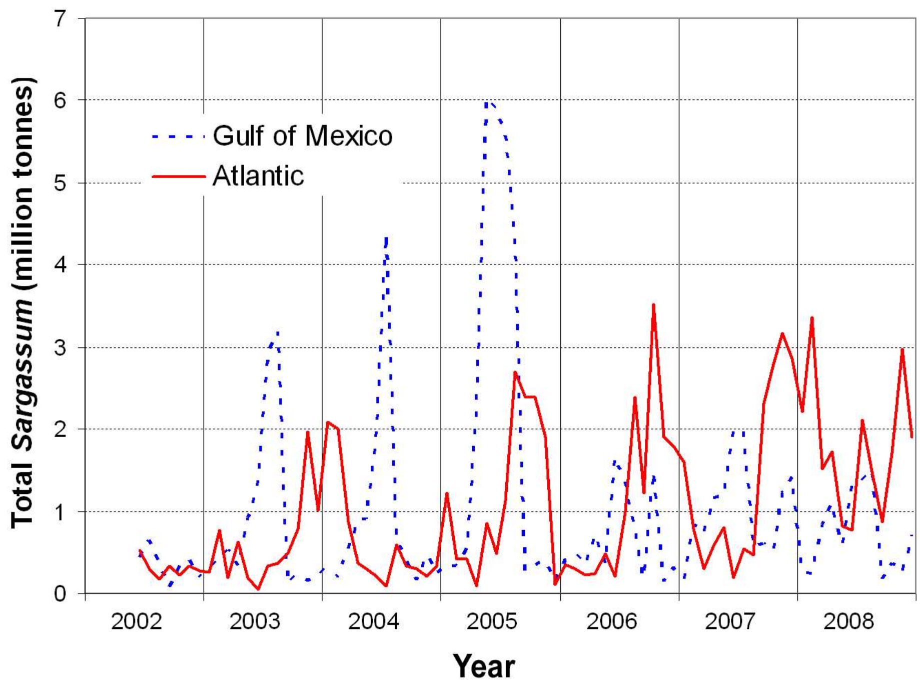

Figure 3
184x140mm (200 x 200 DPI)

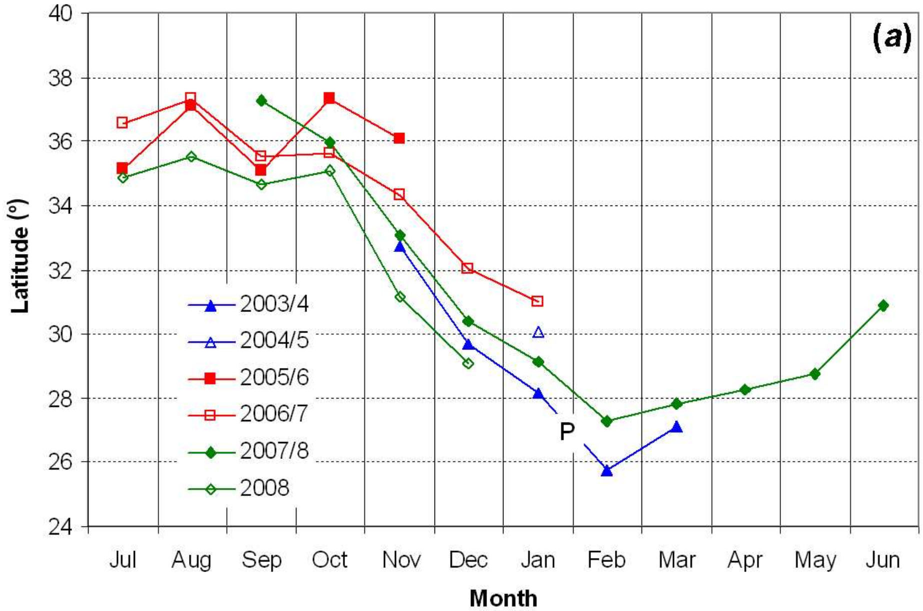

Figure 4(a)
150x101mm (200 x 200 DPI)

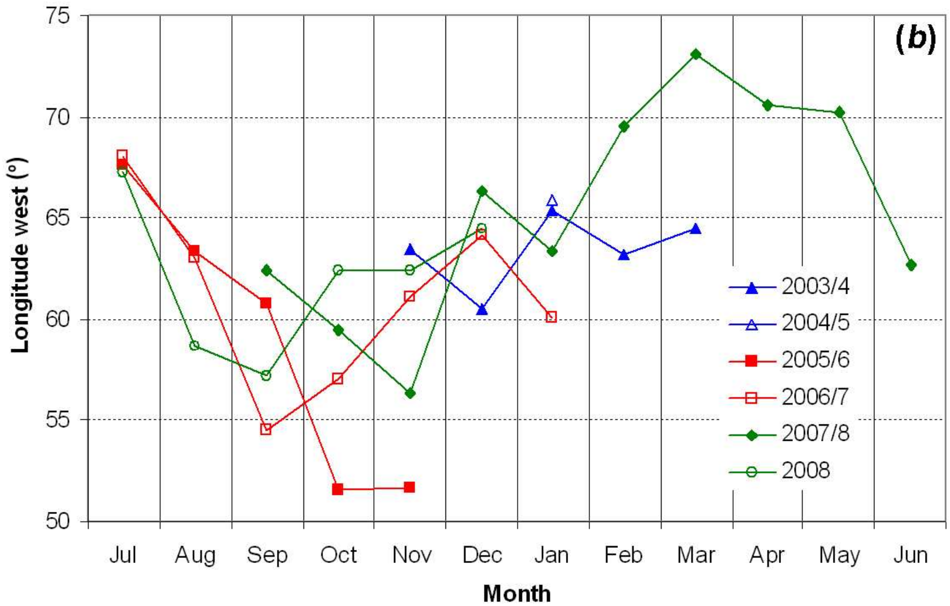

Figure 4(b)
150x101mm (200 x 200 DPI)

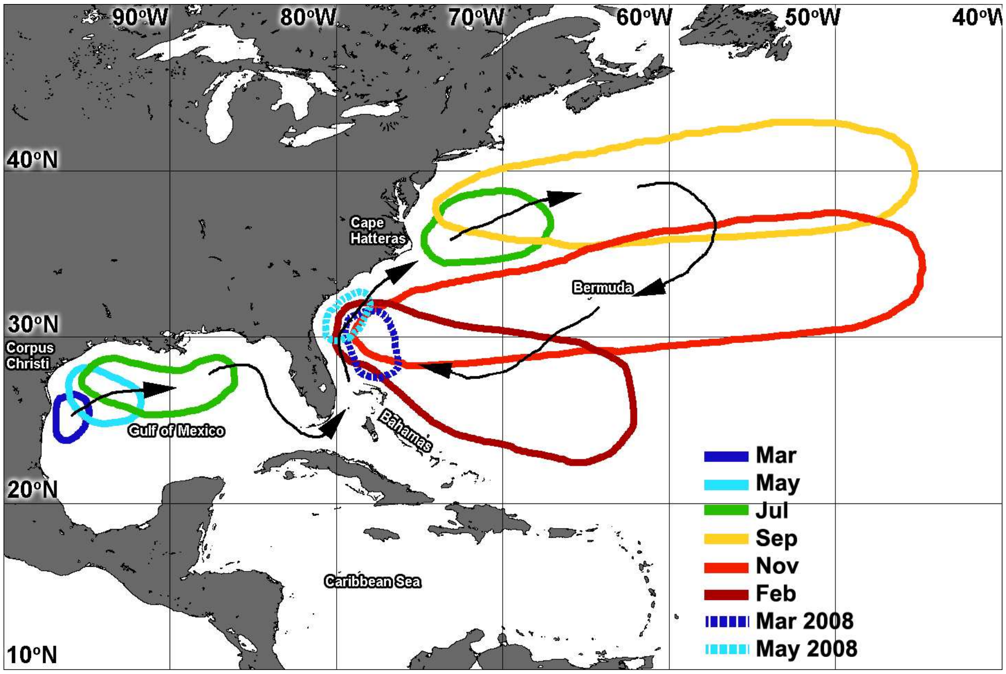

Figure 5
183x122mm (200 x 200 DPI)