Satellite Images Show the Movement of Floating _Sargassum_ in the Gulf of Mexico and Atlantic Ocean

Article *in* Nature Precedings · May 2008

DOI: 10.1038/npre.2008.1894.1 · Source: OAI

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Summary

The question of the origin, distribution and fate of the floating seaweed *Sargassum* has fascinated sailors and scientists from the time of Columbus. Observations from ships are hampered by the large and variable area over which *Sargassum* is dispersed. Here we use satellite imagery to present the first mapping of the full distribution and movement of the population of *Sargassum* in the Gulf of Mexico and western Atlantic in the years 2002 to 2008. For the first time, we show a seasonal pattern in which *Sargassum* originates in the northwest Gulf of Mexico in spring of each year, is advected into the Atlantic in about July, appearing east of Cape Hatteras as a "*Sargassum* jet," and ending northeast of the Bahamas in February of the following year. This pattern appears consistent with historical surveys. Future satellite observations will show whether this pattern repeats in all or most years.

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[1]. Observations from ships are hampered by the large and variable area over which *Sargassum* is dispersed. For satellites, this is not a problem since the area of 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) MERIS sensor[2].

The MERIS Imager on the Envisat satellite showed extensive areas of long, narrow, meandering slicks in the north-western Gulf of Mexico in the early summer of 2005[1]. We have now extended the survey to global coverage for the time period June 2002 to April 2008. Results show an average annual cycle in *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 pelagic *Sargassum* in other oceans of the world.

Satellite image data

The Medium Resolution Imaging Spectrometer (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. To be detected, *Sargassum* therefore has to be dense enough, and to cover a large enough area, to affect the average color (visible surface spectral reflectance) of an area of ocean surface 1200 m across.

We make use of an index, MCI (Maximum Chlorophyll Index), which provides good discrimination of floating and coastal vegetation, as well as intense surface plankton blooms[3]. MCI is computed from the above-atmosphere spectral radiances 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 two neigbouring bands at 681 and 754 nm, as defined by equation 1.

$$MCI = L_{709} - L_{681} - (709 - 681)*(L_{754} - L_{681})/(754 - 681) \quad \ldots. \quad (1)$$

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.

For large-area tracking of *Sargassum*, we make use of global, daily composites of the MERIS data at 5 km spatial resolution. The value of each pixel in the composite is the maximum MCI of any RR image pixel assigned to that composite pixel. The daily composites are 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.

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 (here 0.4 mW/(m^2.nm.sr)), 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 number of MCI values above threshold, multiplied by the amount by which MCI exceeds its background value (in mW/m^2.nm.sr) as "MERIS count." We take this count as being proportional to the total amount of *Sargassum* in each one-degree square.

Satellite observations of *Sargassum* distribution

Since the first detection using satellite imagery of *Sargassum* in the north-western Gulf of Mexico in May and June of 2005, 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. The difference spectrum in the inset (blue) shows the "red edge" characteristic of land vegetation, with a shift in wavelength due to water absorption that results in a value of MCI of about 2.0 mW/(m^2.nm.sr). The peak in the visible spectrum (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 population of phytoplankton.

Figure 2 shows images of MERIS counts of *Sargassum* detected by MERIS MCI for the years 2002 to 2007 (top to bottom) and months July to September (left to right), in pixels measuring one degree in latitude and longitude. 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, 2006 and 2007.

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 April 2008. MERIS counts are scaled to millions of tons by comparison with ship observations[4,5] as described below. 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.

The data clearly indicate strong growth early in the year in the Gulf of Mexico, with *Sargassum* moving from there into the Atlantic each year in July and August. Passive surface floats[6] take about a month to be advected by the Loop Current and Gulf Stream 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 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. Values are plotted in Figure 4 for months in which *Sargassum* amounts in Figure 3 were greater than 700,000 tons. The seasonal variation shows considerable consistency from year to year. The statistical centre of *Sargassum* is first at about 37N, 67W in the Atlantic, moves eastwards until October and then moves southwest until February.

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, spreading eastwards to about 45 W by September, then drifting south and west. Counts are very low in the Atlantic for the months of March, April and May, though observations to April of the present year show for the first time at this season, significant *Sargassum* northeast of the Bahamas.

Comparison with observations from ships

Many sightings of *Sargassum* were recorded in the 19th century, especially by the German merchant marine, summarized by Kruemmel[7], perhaps inspired by the early theory that *Sargassum* indicated presence of a vast undiscovered reef in mid-Atlantic. Winge[8] 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." In fact, Winge's summary shows that the idea of *Sargassum* originating in the Gulf of Mexico, as we propose, was fairly common in the 19th century, but seems to have died out in the 20th.

Parr[4] 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[7]'s 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 on the left panel of Figure 4).

Between April 1977 and January 1982, Stoner[5] measured *Sargassum* density at 266 locations on a series of 15 cruises in the Sargasso Sea and Caribbean. The results were initially interpreted[9] to show a drop in *Sargassum* biomass compared to Parr[4]'s earlier observations, but were later reinterpreted[10] 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[10] suggested that this difference may be due to a seasonal variation. Our satellite data now confirms 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[4] and Stoner[5] measured significant amounts of *Sargassum*, and compare these with the satellite observations for the same areas and months. This means 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 tons per square degree per MERIS count, with r.m.s. scatter of about a factor two among the 11 estimates of this value. We use this average value to compute the total amount 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[11] 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[4] noted a "secondary maximum" of *Sargassum* in the northwest Gulf of Mexico, but observed it to be of "apparently deteriorating weeds." Wells and Rooker[12], 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 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," but a rapid increase in the amount of *Sargassum* in the northwest Gulf each year in March to July 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 tons in each of the Gulf of Mexico and the Atlantic, for a total of 2 million tons (averages of the data plotted in Figure 3). This is less than the 7, 11 and 4 million tons estimated by Parr[4] for each of the three years of his observations (1933, 1934 and 1935).

Errors in satellite estimates of *Sargassum* amounts

There are several possible sources of error in our satellite estimates of *Sargassum* amounts. The satellite 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. On the other hand, areas that remain hidden from the satellite on all days of a given month are relatively rare. *Sargassum* that is evenly distributed may not exceed our detection threshold, so that the satellite may be detecting only *Sargassum* that is to some extent "aggregated." 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 metre, 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[9]. Woodcock[13] showed that Parr's counts tended to be lower at wind speeds above 4 m/s, 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 only one low-wind day in the month to be detected.

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

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 count values in Figure 3. Hits on the sensor are much more common in the South Atlantic Anomaly, which affects an area about 2000km across, centred off the coast of Brazil.

In areas of the world outside the region shown in Figure 2, high values of MCI[3] show shorter-lived patches which we relate to intense surface plankton blooms of the type commonly referred to as "red tides." We do not observe patterns with the longer temporal continuity of *Sargassum* in any other ocean areas, confirming that a major population of pelagic *Sargassum* is found only in the Gulf of Mexico and western Atlantic. We note that benthic vegetation and coral reefs in shallow water[14] can cause false positive signals, but these are limited to fixed and known locations.

Conclusions

Our observations show a large increase in *Sargassum* in the northwest Gulf of Mexico between March and June each year, and low total *Sargassum* amounts in the Atlantic before the annual injection from the Gulf of Mexico in July. This suggests 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 there to be some circulation of the *Sargassum* observed northeast of the Bahamas in February, back into the Gulf Stream and then to the area northeast of Cape Hatteras. This would be consistent with the traditional picture of the Sargasso Sea as being the main repository of this biomass, however, we have not observed this *Sargassum* in satellite imagery for May and June.

This observation of a significant average flow of about one million tons of *Sargassum* out of the Gulf of Mexico each year implies a carbon flux which needs to be accounted for in productivity and carbon models.

Satellite images clearly provide greatly improved data coverage compared to ship 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. 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*.

Acknowledgements

This work was supported by Fisheries and Oceans Canada, by the Canadian Space Agency (CSA) under the GRIP (Government Related Initiative Program).

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Figure Captions

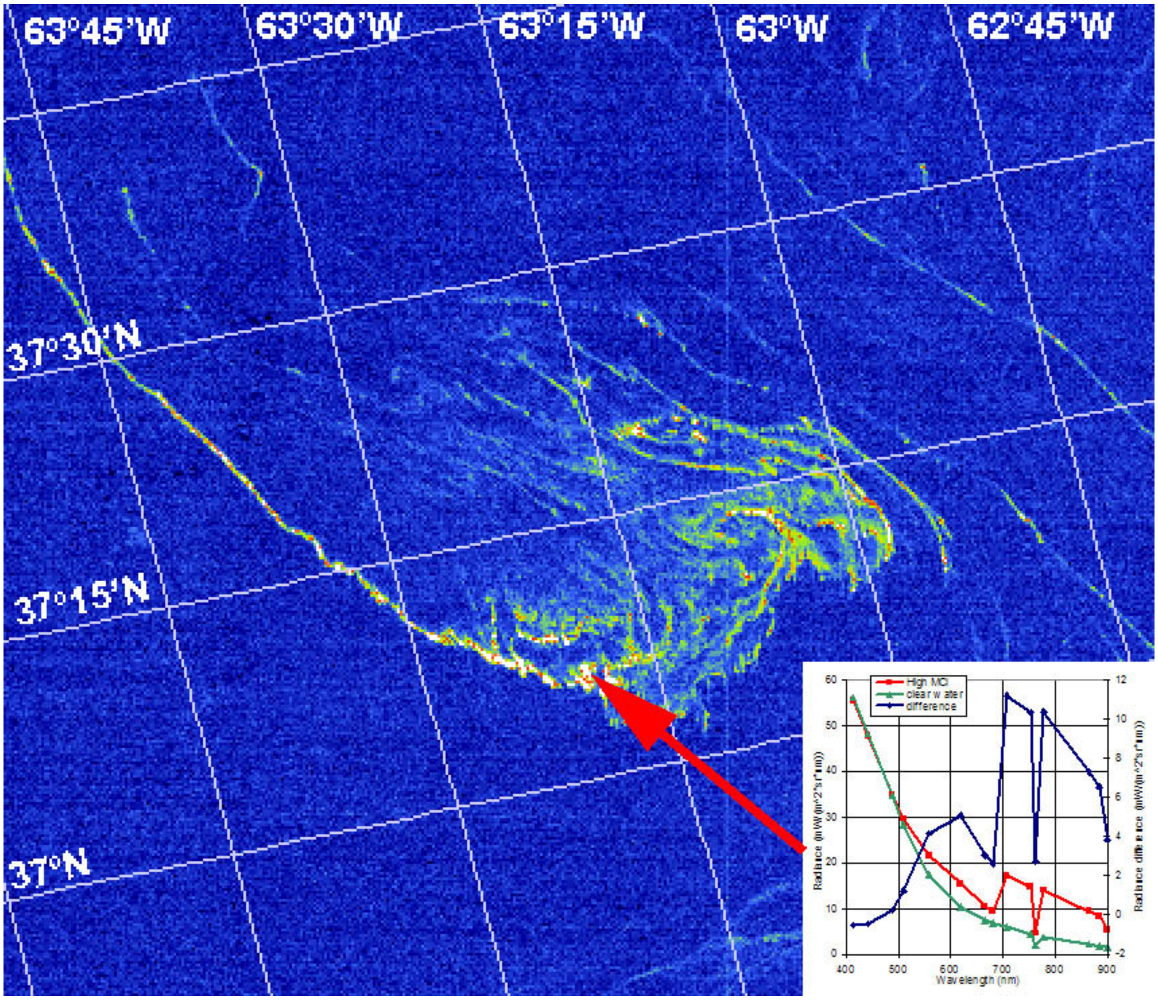
Figure 1. Floating *Sargassum* in the Gulf Stream near 63W, 37N imaged as MCI on October 22, 2007 by ESA's ocean sensor, MERIS at its full spatial resolution of 300 m, available for some areas. The *Sargassum* is collected into patches and long lines by surface convergence and shear. The inset shows top-of-atmosphere radiance spectra for an area containing *Sargassum* (plotted in red) and for nearby clear water (plotted in green) in the region indicated by the arrow. The difference spectrum (blue, values on right axis) shows the "red edge" characteristic of land vegetation, with the apparent red edge position shifted to a shorter wavelength.

Figure 2. MERIS counts of *Sargassum* for the years 2002 to 2007 (top to bottom) and months June to August (left to right), in pixels measuring one degree in latitude and longitude. The background dark blue colour corresponds to no detections. Increasing amounts are indicated by the colour sequence green, yellow, red to white. One-degree squares where MCI gives strong signals from coral reefs and other benthic vegetation are masked to black. Land at 0.25 degree spatial resolution is shown in grey. High concentrations of *Sargassum* are indicated in the northern Gulf of Mexico in all years except 2002, with the *Sargassum* appearing in the Atlantic to the east of Cape Hatteras along about 37N in August and September, especially in 2005, 2006 and 2007. Little *Sargassum* is observed in the Gulf starting in September.

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 April 2008. Values are based on satellite counts calibrated with a mean value derived from ship observations. Highest amounts are in May, June, and July in the Gulf of Mexico, with a maximum *Sargassum* year in 2005. Amounts in the Atlantic increase after July and usually drop back to low values by March. Very little *Sargassum* was detected in 2002.

Figure 4. Average latitude and longitude of *Sargassum* in the Atlantic (22 to 40N, 40 to 80W) for months in which amounts plotted in Figure 3 were greater than one million tons. The average positions show a consistent pattern in which *Sargassum* is injected into the Atlantic near 37N, and spreads initially eastwards and then south west. The spatial patterns are shown schematically in Figure 5. The letter "P" on the left panel shows the average latitude (27.2 N) deduced from Parr[4]'s 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 MERIS count distributions by month (as shown in Figure 2 for June to August) averaged over the years 2002 to 2007. In each year, *Sargassum* is first observed in the Gulf of Mexico in about March, by July it is still present in the Gulf, but has also appeared off Cape Hatteras. It then moves east and then south west, as shown. In the period 2002 to 2007, MERIS sees relatively little *Sargassum* in the Atlantic between March and June (Figure 3).



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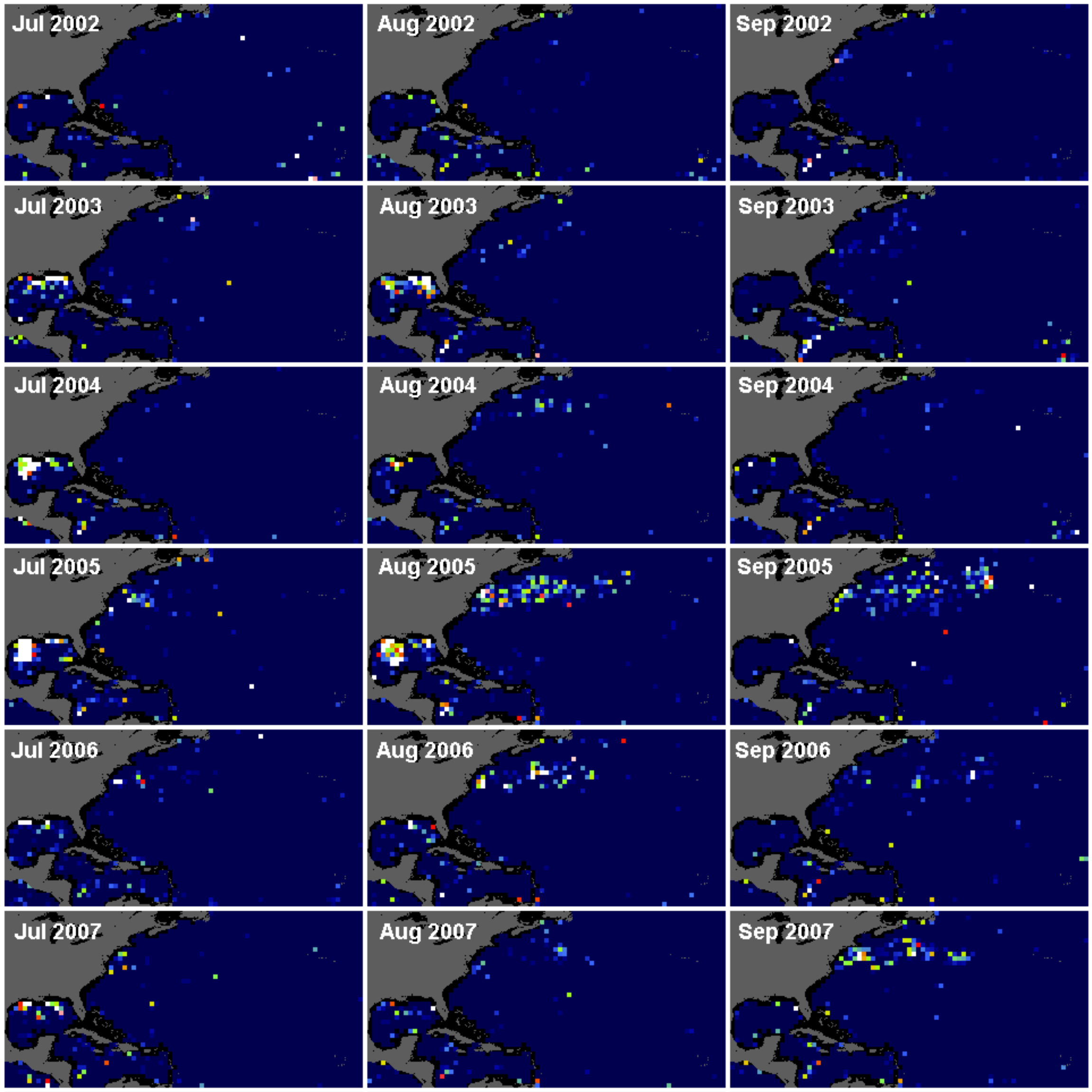

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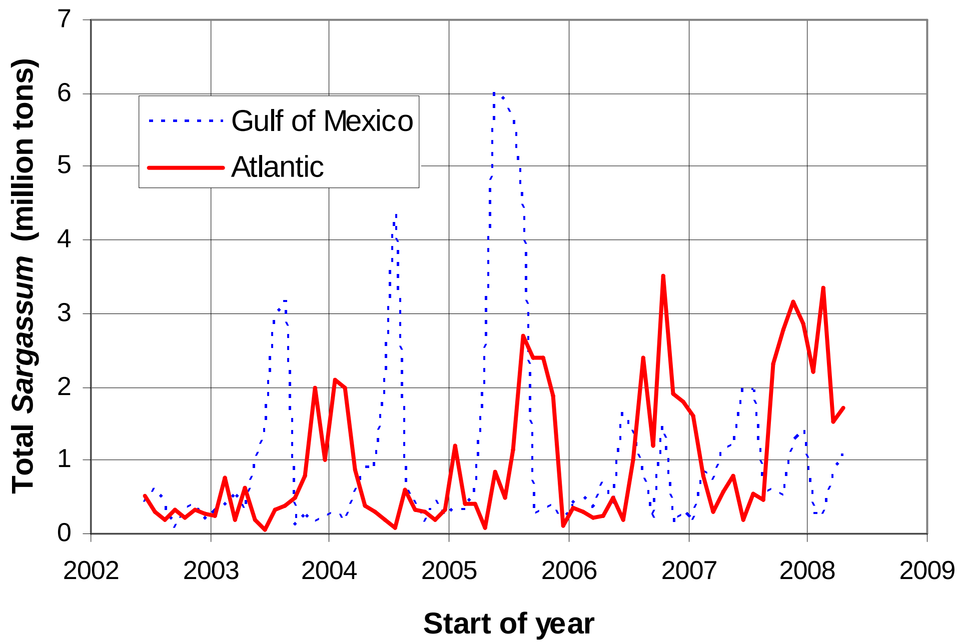

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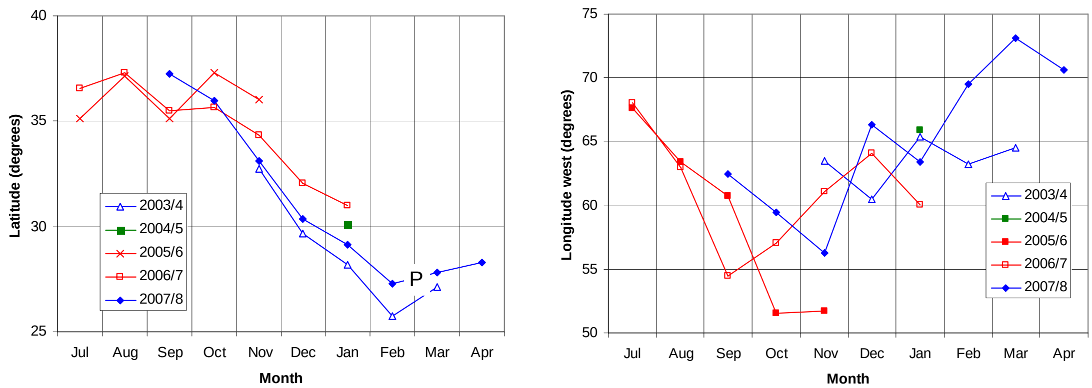

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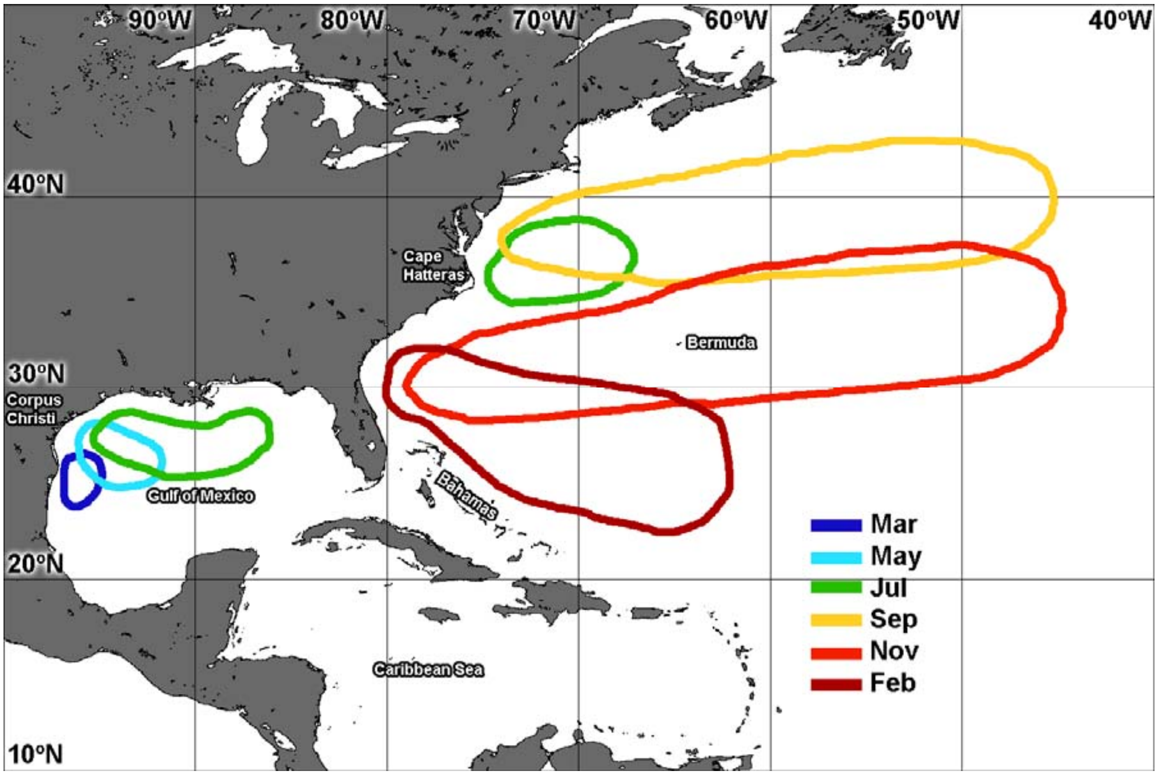

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