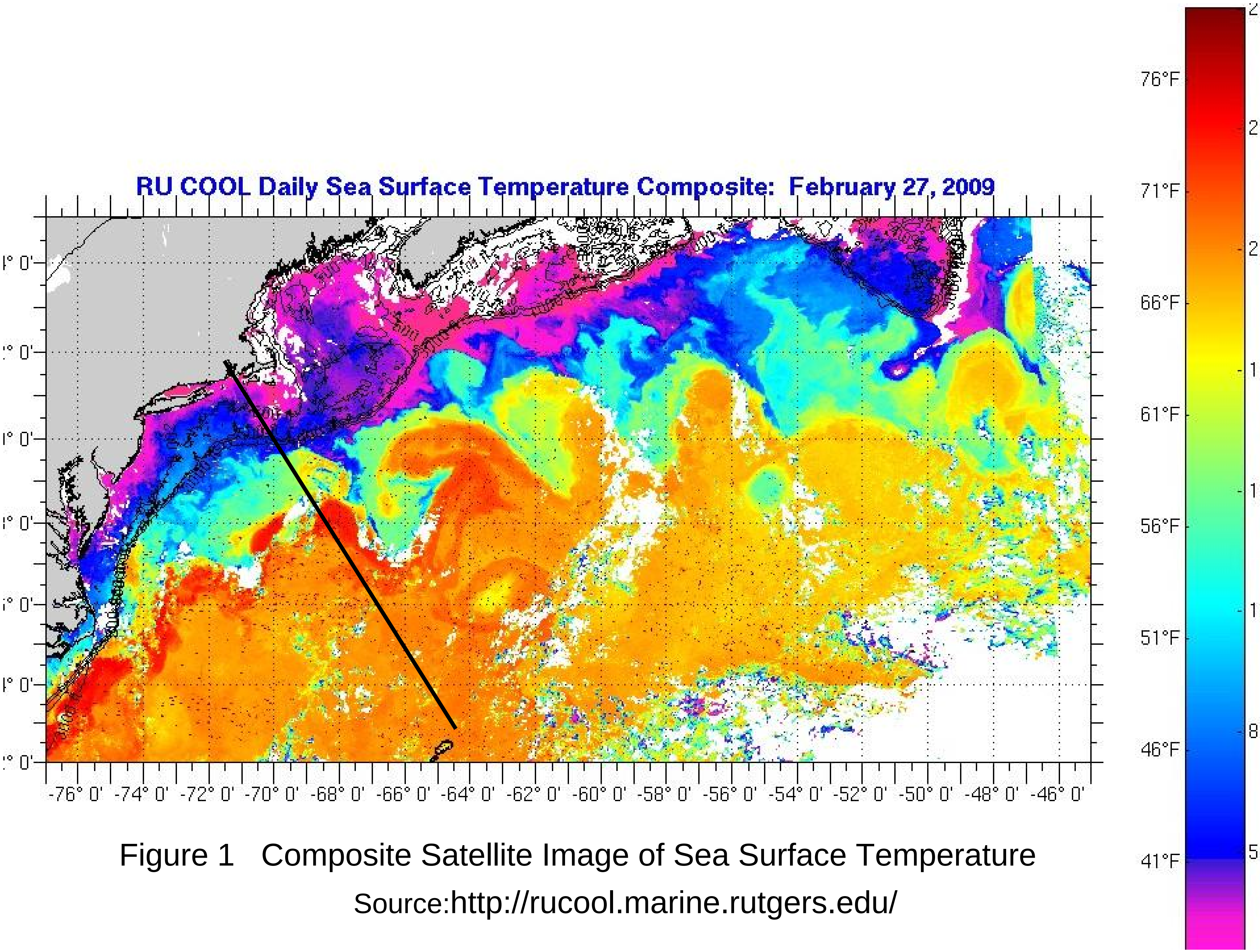

Figure 1 Composite Satellite Image of Sea Surface Temperature

Source:http://rucool.marine.rutgers.edu/

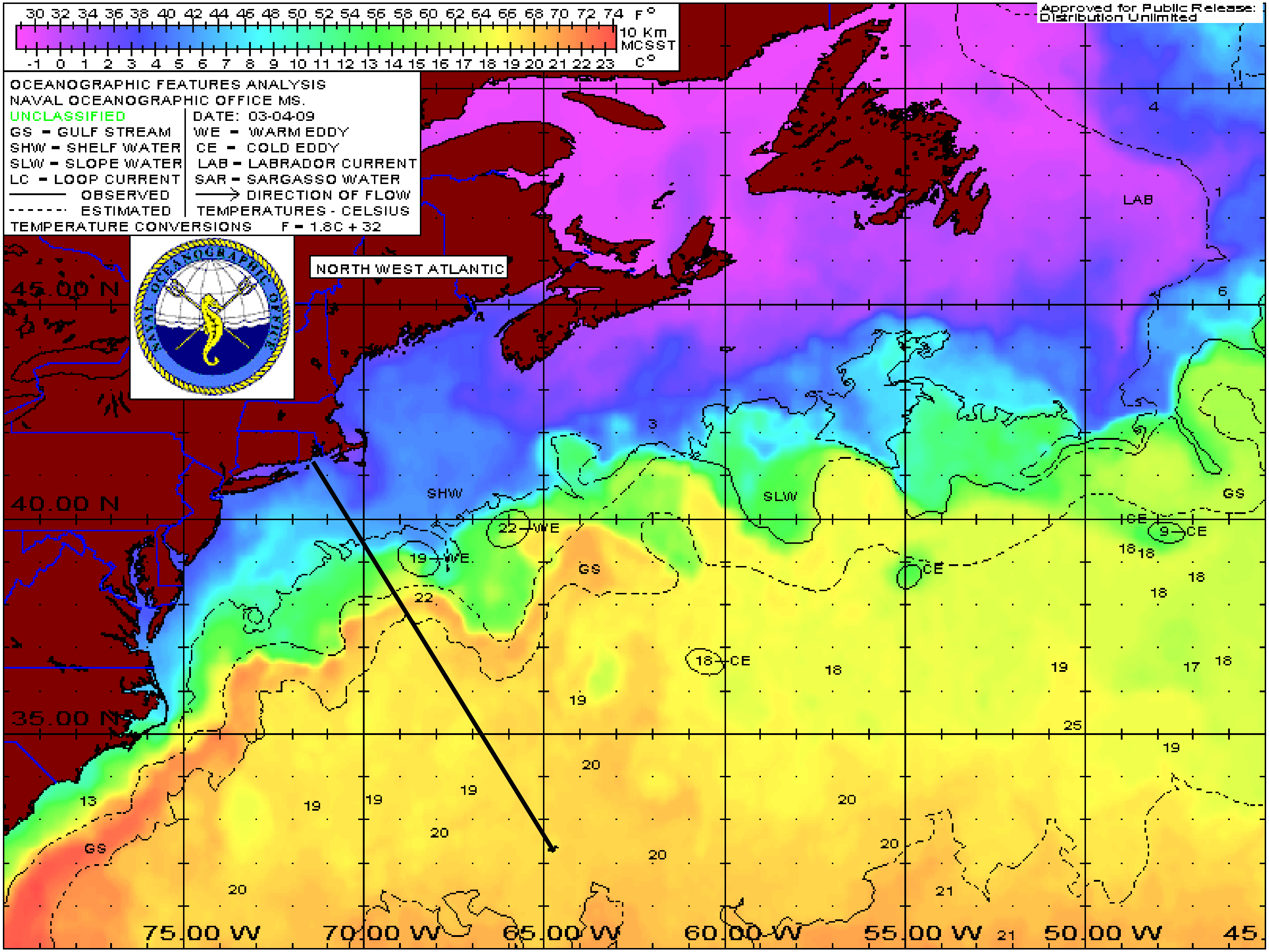

Figure 2 USN Sea Surface Temperatures NW Atlantic Region

Source:http://www.nlmoc.navy.mil/home1.html

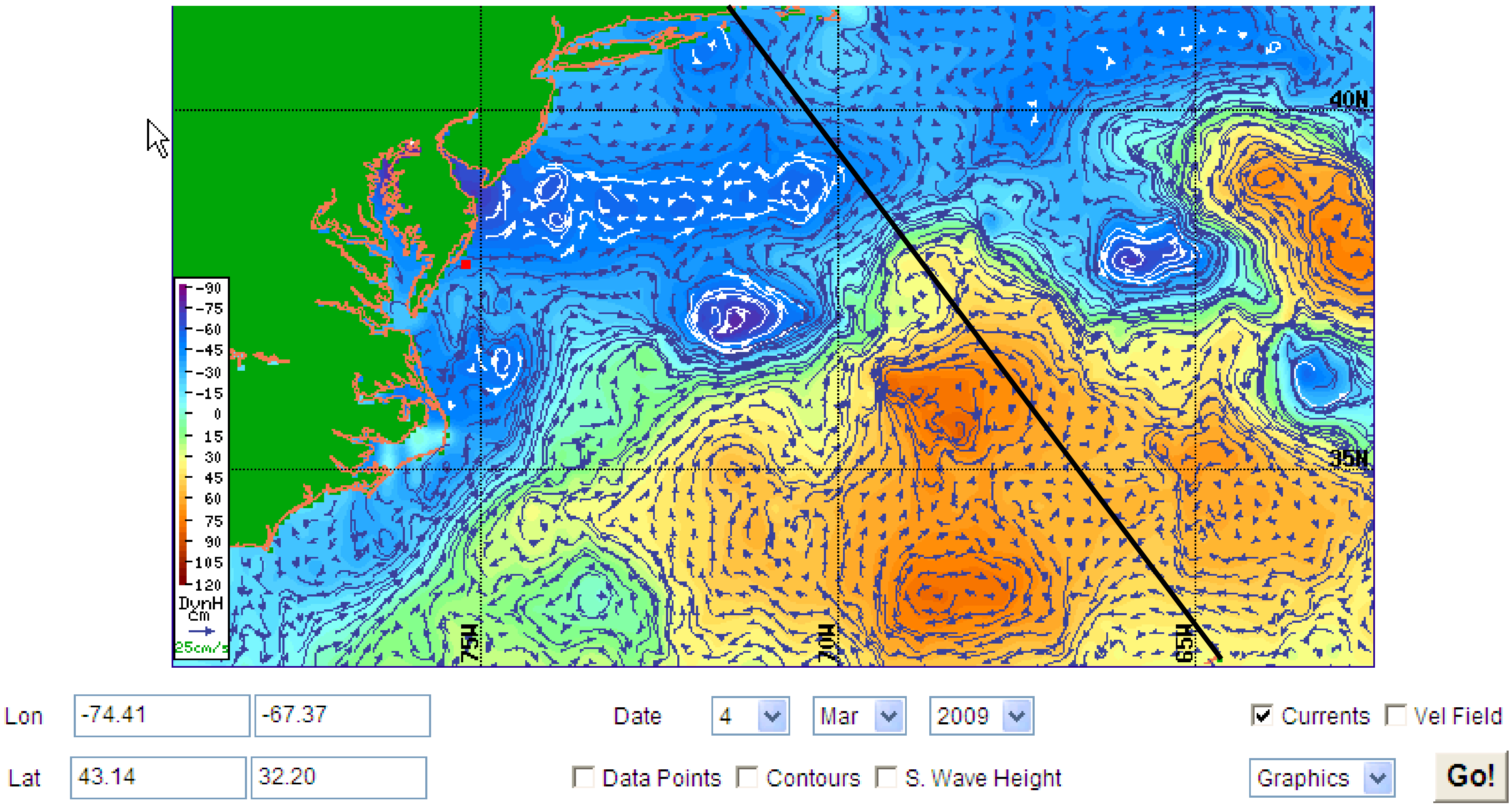

Figure 3 Satellite Altimetry Derived Surface Currents – NW Atlantic Region

Source:http://www.aoml.noaa.gov/phod/dataphod/work/trinanes/INTERFACE/index.html

Gulf Stream Characteristics

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Notes for the Bermuda 1-2

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Over the next few months before the start of the Bermuda 1-2 I will, on three or four occasions, be posting some thoughts on Gulf Stream structure to introduce racers to the range of information available on the Stream and its interpretation. In contrast to conditions encountered less than 30 years ago, racers to Bermuda in 2009 will have available to them a variety of data detailing long and short term weather patterns as well as the position, shape and form of the Gulf Stream. These data are easily accessible via the web and in combination with low cost graphics programs can be displayed in multi colors both afloat and ashore. Despite this ease of accessibility however, the conversion of these raw data to information sufficient to provide a basis for tactical decisions requires at least an elementary understanding of the behavior of weather and/or ocean current systems, their interactions, and the factors affecting change. Most sailors believe that they possess this understanding when it comes to weather and many often develop their own forecasts using Federal or private service surface analyses and model results received via radiofax or the WEB. All of us, sailor and non-sailor alike, seem to be keen observationalists and to some extent weather addicts as evidenced by the popularity of the Weather Channel and Website weather. Ocean currents however, seem to be a different matter. Few would claim to understand the governing factors and even fewer would have the temerity to make predictions regarding future flows. Until recently these beliefs would have been entirely understandable. In the case of the Gulf Stream, for example, despite a long history of observation, quantitative understanding and the beginnings of dynamic modeling date from the early 1950' s. Oceanographic surveys detailing its dynamic nature followed shortly thereafter. But it was the addition of satellite observations in the 1960' s and 70' s and their ability to "put a face" on this large, and rather remote, ocean feature that really facilitated a quantum leap in understanding of Stream structure and dynamics. With some understanding of the factors controlling the makeup of the Stream and its velocity field in combination with daily satellite images we are now presented with a range of data similar to that available to the meteorologist. This provides the opportunity for each of us to develop analyses of Stream behavior sufficient for most tactical decision making.

The understanding necessary to allow analyses of available Gulf Stream data for the purposes of optimum routing is rather rudimentary. We first need to understand that the Gulf Stream is a northeast tending boundary current formed between the warm waters of the Sargasso Sea and the colder waters of the east coast U.S. continental shelf. The <u>spatial gradient(s) in water temperature</u> provides a key indicator of Gulf Stream location, structure, and velocity. Next we need to recognize that this feature, particularly in the region north and east of Cape Hatteras, <u>varies significantly in space and time</u>. On occasion, this variability leads to instabilities and the breaking off of segments of the

Stream forming discrete nearly circular "rings" or "eddies" both inshore and offshore of the main body of the current. Rings formed to the north of the Stream are typically classed as warm core and display a clockwise rotation. Rings found south of the Stream generally display a cold core and counterclockwise rotation. Each of these rings displays its own unique temperature signature and well defined , if localized, velocities often equal in magnitude to those observed within the core of the Stream. Following formation, the rings tend to develop a characteristic drift, generally to the west at speeds of 0.1 knot if free of direct Stream influence. In addition, each ring has a finite life with warm core features generally persisting for 4-5 months before re-entrainment or dissipation due to contact with the adjoining continental shelf. Cold core rings survive for significantly longer periods due to reduced Stream and/or shelf influence with individual rings tracked for more than 1.5 years. The formation and movements of these features in combination with the meandering main body of the Stream and the resulting interactions or other flows proceeding along the bordering continental shelf often favors the formation of a flow regime in the vicinity of the rhumb line with all the qualities of a "patch-work quilt". Detailing the patterns associated with this quilt represents the challenge of Gulf Stream analysis.

Although it may appear to be a daunting task, much of the data required to define the flow characteristics and structural features of the Gulf Stream sufficient for navigational purposes are now available to us and easily accessible. Realization of their ultimate utility however, requires care in interpretation and an understanding of the errors inherent in each data set. These are precisely the same requirements encountered in the analysis of meteorological data so they come as no surprise. In both cases they are best satisfied by study extending over a period of time long compared to the time scales of variability. For the Gulf Stream this time scale is on the order of months. That is to say that Stream variations in structure and position as well as in the drift and trajectory of rings and the resulting velocity patterns may vary significantly over the course of a week or so. To detail this variability sufficient to predict future evolution requires observations extending over a period of time that is long relative to a week i.e. weeks to months. With this time scale in mind the Bermuda racer anticipating departure in June would be well advised to begin systematic study of the Gulf Stream regime no later than early April.

Although a few years ago I might have started my Gulf Stream studies with the USN sea surface temperature data (see: http://www.nlmoc.navy.mil/home1.html) today I generally begin by obtaining satellite SST images provided by one of several sites (see e.g. marine.rutgers.edu/mrs/, or fermi.jhuapl.edu/sat_ocean.html). These images are colored to more clearly illustrate temperature gradients and indexed geographically allowing the overlay of navigational data such as track lines or routes. The images generally are provided in one of two forms, instantaneous, or composite. The instantaneous image represents the view from a single satellite pass taken at some discrete time. The composite (Fig.1) represents what might be considered an average of multiple passes over an extended period of time (typically one day to a week). The instantaneous-single pass image tends to provide higher spatial resolution and more accurate detailing of Stream features and/or structure but is often subject to the presence of clouds. By focusing on selected features (e.g. the warmest picture element) over a number of passes, compositing is able to reduce this sensitivity to cloud cover. The matter of cloud interference is another reason why early study is recommended. There have been years when clouds prevented a clear view of the Stream for weeks during May and June.

An examination of a composite satellite image of the Gulf Stream region on February 27th, the last time that the area was reasonably cloud free, shows the main body of the Stream crossing the rhumb line to Bermuda (the black line) at a point approximately 240nm from Newport. The crossing proceeds from the southwest to the northeast and is part of a large amplitude series of meanders affecting much of the northern limits of the Stream between 74 W and 56 W. Maximum currents will typically be found along a line approximately 30 nm to the south of this point. A warm core ring with a diameter of approximately 60-80nm appears located to the east of the rhumb line centered near 39N 68 30'W. Recall that currents associated with this feature should display a clockwise rotation implying that there may be at least some amount of adverse (flow to the northwest) current along the rhumb line just before entry to the main body of the Stream. The image indicates that the ring is in close contact with the Stream, a factor that will tend to influence its future trajectory.

Cloud cover has limited satellite views for the past week. With this in mind we view the Navy representation of sea surface temperatures (Fig.2) with some degree of skepticism. The amount of dotted line in the figure indicates that it's likely that much of this image is the result of an analyst's interpretation of Stream evolution based on earlier observations during periods of limited cloud cover. Fortunately today there are alternatives to the use of raw interpretation. One of the most promising techniques is based on a combination of computer models and satellite observations of sea surface height. Such observations can proceed with minimal interference during periods of intense cloud cover. Sea surface heights vary as a function of water temperature. Since water temperature is one of the primary determinants of water density, and water density affects pressure, a map of heights may be used to estimate the spatial distribution of pressure producing a product that is similar to a chart of atmospheric pressures i.e. a weather map. And, just as the atmospheric pressure distribution is used to estimate wind speeds and directions, an ocean map of sea surface heights will provide a basis for the estimation of ocean currents, speeds and directions. The conversion however, is not without some amount of error since temperature is not the only factor affecting sea surface height (e.g. winds) and density/pressure is not the only factor affecting current speed and direction. These complicating factors however, do not negate the utility of the height data indicating only that they must applied with care.

Sea surface heights are presented at a number of web sites including one developed by the Delft University of Technology (http://rads.tudelft.nl/gulfstream/) and another by our National Oceanic and Atmospheric Administration (NOAA) at (www.aoml.noaa.gov/phod/dataphod/work/trinanes/INTERFACE/index.html). Of these, the NOAA site appears to provide data of most value to the Bermuda racer. Their analysis results in a daily representation of surface currents (Fig.3) with features similar to those shown by the Navy thermal plots and the earlier satellite SST images (compare to Figs 1 and 2). In all figures the main body of the Stream crosses the rhumb line at a point approximately 240nm from Newport. There is no indication in the altimetry of a warm core ring to the north of the Stream as shown in the earlier SST data (Fig.1). The complex of currents immediately SE of the northern limit of the Stream suggests that the ring may have been entrained during the first week in March. Proceeding south along the rhumb line the altimeter data show favorable southerly currents apparently associated with a large clockwise flow around an area of higher elevations centered around 36 N 68 30'W. The sense of rotation indicates that this is a warm core feature. As previously noted such features are usually to be found north of the Stream. These data suggest that this strict division may be oversimplified.

The influence of the clockwise ring on the rhumb line extends to 35 N. Beyond that point south to 33 N currents are generally weak. To the south of 33 N a west going current is encountered which continues to Bermuda.

The extent to which these altimeter based currents will actually affect a small boat passage to Bermuda is difficult to accurately assess. These are model based estimates subject to some amount of averaging and time delays. However, experience based on direct observations during the 2008 Newport to Bermuda Race suggests that the model reasonably simulates the actual flows and may represent the most effective all-weather planning tool presently available to the navigator. It clearly warrants careful consideration and continuing comparison with direct observations. We'll seek to further evaluate the accuracy of these data and continue this discussion in subsequent notes.