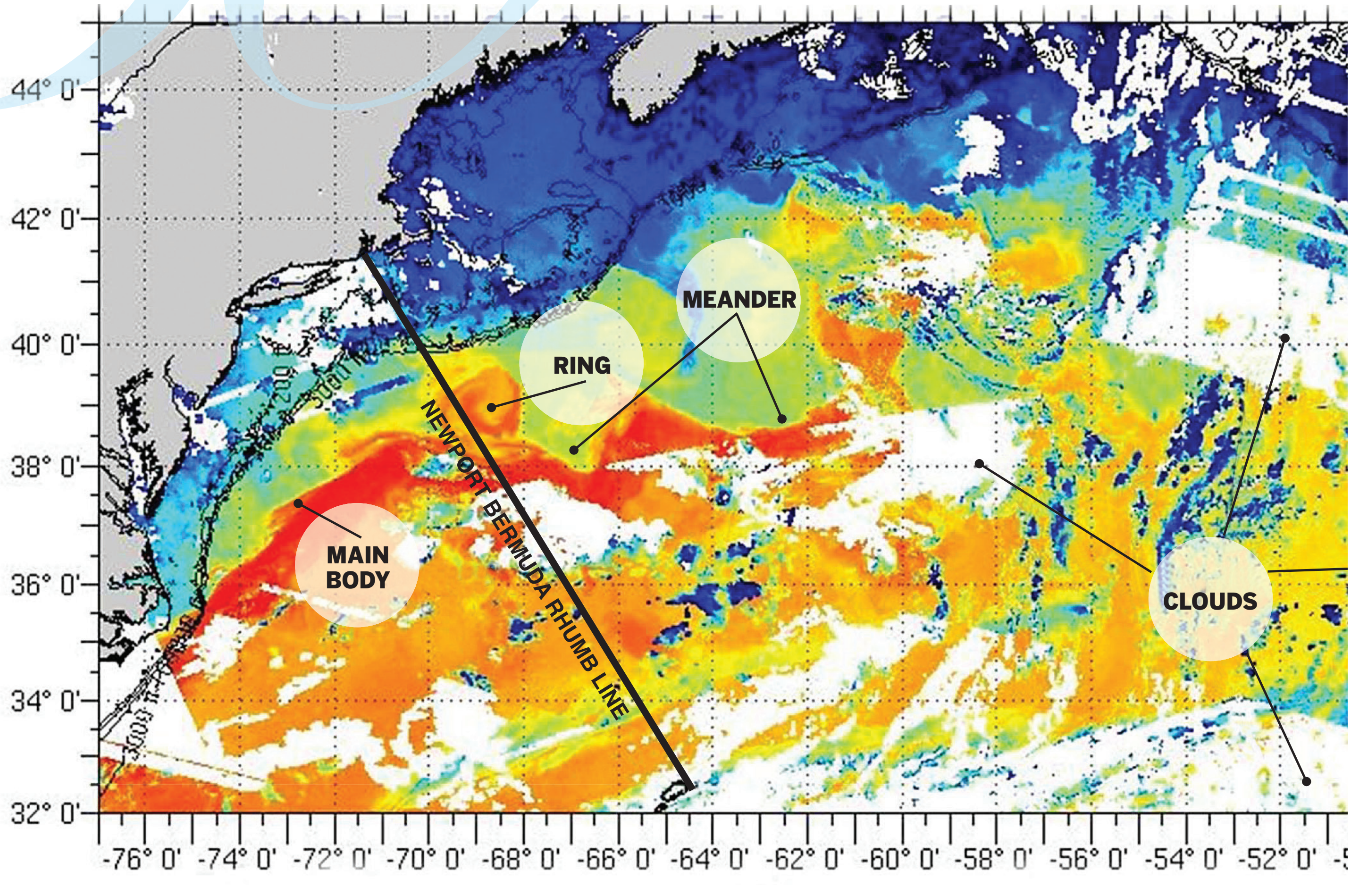
Gulf Stream Analysis



For many competitors the Newport-Bermuda Race (N-B) consists of three or four discrete segments each with its own dominant characteristics and challenges. Following the start there is, first, the segment past Block Island and across the continental shelf, usually dominated by sea breeze and tidal currents. Next comes the crossing of the main body of the Gulf Stream typically found approximately 250nm from Newport. After the Stream there is the relatively long crossing of the Sargasso Sea to the vicinity of Bermuda. Finally comes the approach to the island, made interesting by local weather and tidal effects, and on to the finish at St David's.

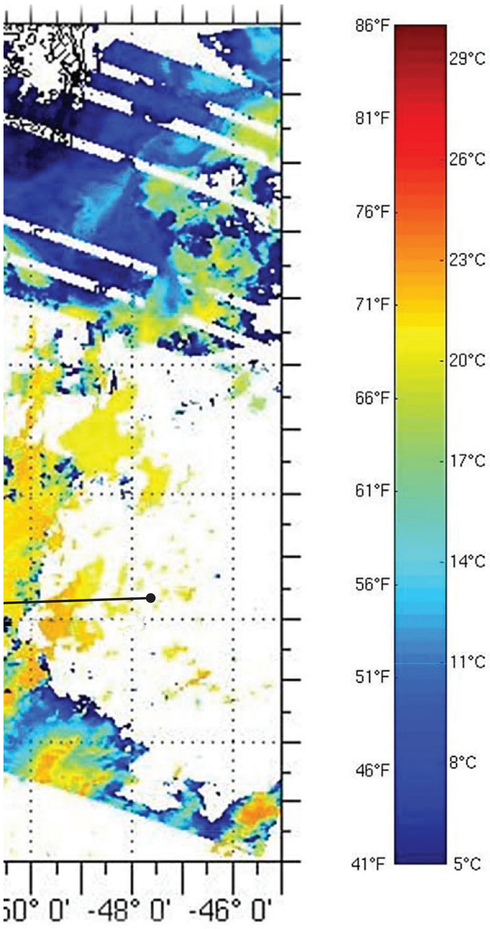
Of these, the Gulf Stream crossing is often considered the most challenging. There are several reasons for this.

The Gulf Stream is a portion of the large clockwise current system affecting the entire North Atlantic Ocean. Driven by a combination of winds and water column temperatures and salinity, the Gulf Stream is a portion of an energetic western boundary current which separates the warm waters of the Sargasso Sea surrounding Bermuda from the cooler continental shelf waters adjoining New England. This results in striking water temperature contrasts over a short distance favoring formation of a narrow region approximately 60nm in width where maximum currents can exceed 5kts (i.e. the main body).

From Florida to Cape Hatteras this current follows a reasonably well defined northerly track along the edge of the continental shelf. To the north of Hatteras, however, Stream-associated flows proceed along a progressively more northeasterly tending track with the main body of the current separating gradually from the shelf. Flow trajectories in this area, which includes the N-B rhumb line, be-

and Prediction

BY W. FRANK BOHLEN



NOAA

Figure 1. Composite satellite SST image and major Gulf Stream features Northwest Atlantic, December 12, 2015

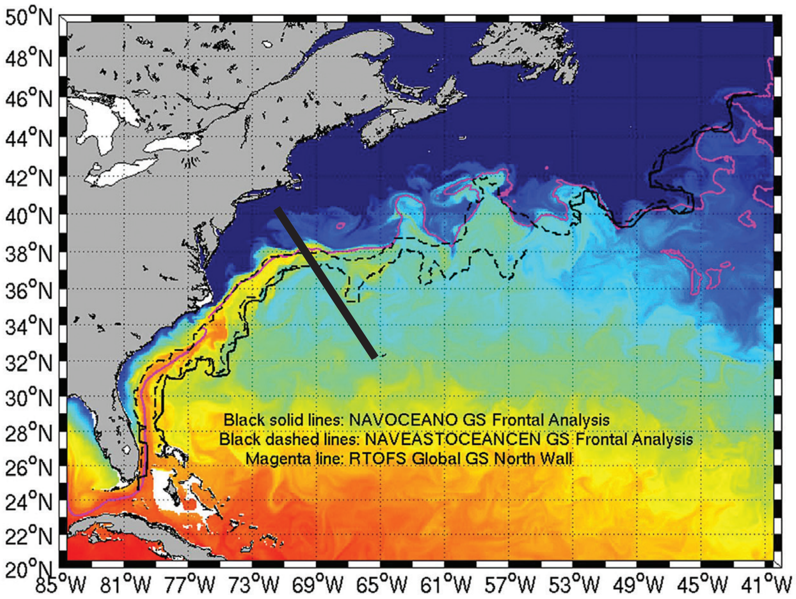
come increasingly nonlinear and wave-like with characteristics similar to those observed in clouds of smoke trailing downwind from a chimney. The resulting meanders in the main body of the Stream tend to propagate downstream towards Europe and grow in amplitude. On occasion these meanders will grow to a point where they will "pinch off," forming independent rotating rings or eddies in the areas north and south of the main body. This combination of time-variant features has the potential to affect a significant portion of the N-B rhumb line well outside of the main body of the Stream.

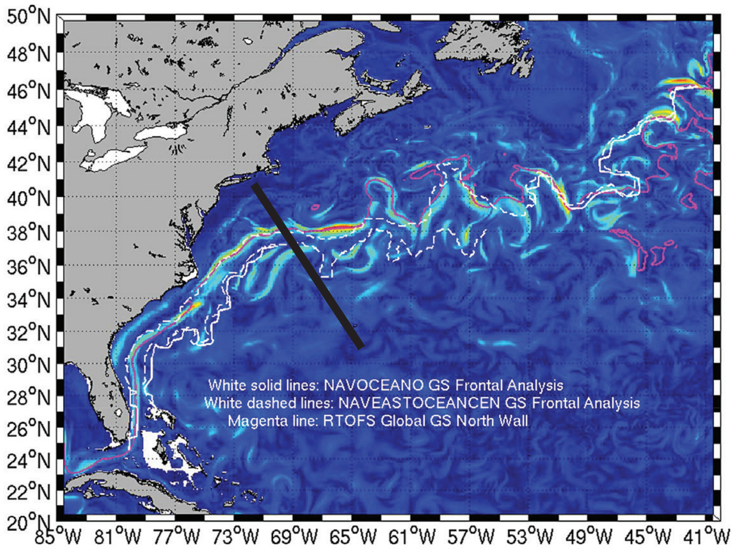
The extent of this influence necessarily varies in space and time. Add to this the fact that the warm waters of the Stream exert significant influence on local weather, and it's easy to understand why race navigators have historically found the Gulf Stream and its offshoots a unique challenge.

The extent to which the challenge of the Gulf Stream can be met depends entirely on our understanding of Stream dynamics and the methods available to define existing Stream structure and to predict future evolution. Although navigators have known of the Stream for centuries (it was mapped by Benjamin Franklin in 1769), systematic study of the Gulf Stream only began in the 1930s with the founding of Woods Hole Oceanographic Institution (WHOI). By the 1950s sufficient data had been compiled to provide clear illustration of the variability of the Stream and to define the primary governing factors. These results, however, were largely descriptive with the predictive yet to come. This fact was evident in the briefing prepared by WHOI for the N-B Skipper's Meeting in 1954, entitled "A Prediction of the Unpredictable," which addressed the variable nature of the Stream and the difficulties in defining its evolution. This briefing contained a disclaimer that "the Gulf Stream changes from week to week. Please…. Losers of Race do not hold us responsible!" Following this briefing John Nicholas Brown, owner of *Bolero,* was said to have referred to the Newport Bermuda Race as the "great Atlantic lottery."

To this day the inherent variability of the Gulf Stream, plus the extent of its influence on currents within and adjacent to the main body of the Stream and on local weather, remain the heart of the navigational challenge. These factors are fundamentally turbulent, making them to some extent random or chaotic, which complicates accurate determination and prediction. This turbulence displays a wide range of spatial (space) and temporal (time) scales from centimeters to 100's of kilometers, from seconds to months. As sailors we typically only care about times out to possibly a week and spatial effects on a 50 to 100ft patch of the ocean. Response resolution on these small scales is particularly difficult. It should not be surprising, then, that predictions of weather or currents may not always compare favorably with our observed conditions.

We have of course made significant progress since 1950 in observing the Gulf Stream and in the dissemination of the resulting data. Ship and aircraft surveys have been largely replaced by satellites with facsimile or radio displaced by the Internet. Infrared sensors on satellites now may provide synoptic views of the surface temperature distributions (SST) in the Stream (**Fig.1**) several times (4-6) each day, allowing analysis of Stream location and structure as well as evolution. Typically the images are provided in two forms, instantaneous or composite. Under clear sky conditions or minimal cloud cover, an instantaneous, or a photo taken at a particular time, can provide an excellent view of the Stream and adjoining waters with a spacial resolution of about 1km (0.5nm). Increasing cloud cover may require compositing of a number of instantaneous images to allow removal of cloud influence. This typically results in a single composite image for the day. This powerful procedure significantly extends the utility of satellite imaging





particularly over the Gulf Stream region where some amount of cloud cover is common throughout the year. The compositing process does result in some loss of spatial resolution, which should be considered during analysis. The amount, however, is generally inconsequential over a one-to two-day period.

Compositing, of course, does have its limitations and can do nothing for dense cloud cover. Under persistent conditions this may result in extended periods of time between usable satellite views of the Stream. Such conditions have prevailed through much of this past December and continue. Our last usable view of the Stream was December 12, 2015 (**Fig.1**). The potential for such conditions favors an early start to Stream evaluations in order to limit impacts if cloud cover were to form close to the start of the race. In addition, navigators are increasingly making use of a variety of numerical computer models of circulation to estimate Stream location and structure. These models provide the added benefit of detailed current velocity estimates not available from the satellite views and in a format (GRIB) that can be easily accommodated by optimum routing programs such as Expedition, Manseau, OpenCPN, and Sailfast.

Computer modeling of ocean circulation began almost as soon as computers came into general use in the 1960s. Early models provided coarse spatial resolution and failed to handle turbulence very well. As a result they were of little use to navigators. During the 1970s and 80s model sophistication increased rapidly due to both the development of analytical and numerical methods to handle turbulence and small scale flow interactions and improved computers. The resulting increase in model skill allowed study of Stream development and evolution and added significantly to our understanding of the factors governing the Gulf Stream and its role in the oceanic transport of heat and other properties. This transport is essential to the maintenance of the global climate and is central in many of the ongoing discussions of possible future climate change. It's important to realize this fact and to recognize that most available numerical models owe their existence to the need to address these global issues and not small boat navigation.

Figure 2, HYCOM derived SST patterns NW Atlantic Region

Gulf Stream Models

Of the variety of models that might be applied, two have found general application by Bermuda Race navigators over the past ten years. The first is the community developed model HYCOM (https://hycom.org/hycom) that is the basis of the Global Real Time Ocean Forecast System (RTOFS) developed and disseminated by NOAA (see http://polar.ncep.noaa.gov/global/monitor). This is a powerful model and incorporates a variety of data from other models, instruments (e.g. Argos drifters tracking currents), and satellites. It provides 1/12º (5nm) horizontal resolution and has been developed in close collaboration with the U.S. Navy (http://www7320.nrlssc.navy.mil/GLBhycom1-12/prologue.html). Model runs available on these sites provide indications of past conditions as well as those in the future typically out to eight days. The NOAA site also provides comparisons between the Navy's results and their own (**Fig.2**). It is particularly interesting to compare

Figure 3, HYCOM surface currents NW Atlantic region

NOAA

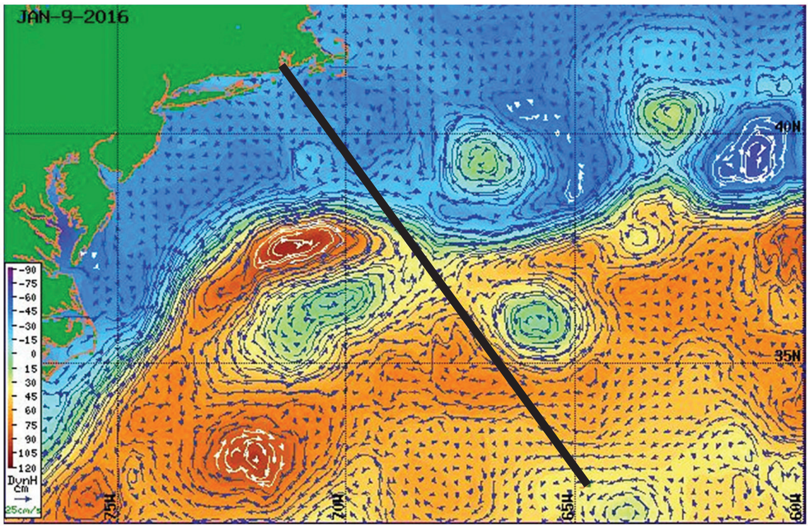


Figure 4, Satellite altimetry derived surface currents - NW Atlantic region Images, January 7-9, 2016

NOAA

these model results and the associated indicated Gulf Stream location to satellite sea surface temperature (SST) plots such as those available (cloud cover permitting) on the Rutgers site (http://rucool.marine.rutgers.edu/). Generally there are some evident differences between each of the model results and the direct satellite observations. These differences must be carefully considered when designing routes or race strategy.

In addition to the SST distributions and Stream location HYCOM (RTOFS) also provides plots of surface currents (**Fig.3**). These are of value within routing programs but often difficult to graphically interpret making them practically useless for old school "pencil and straight edge" plotting. Note should be made that the maximum speeds shown on these plots is approximately 3kts. Direct measurements have shown that maxima can approach 5kts (i.e. 250cm/sec), suggesting that not all of the factors affecting small area near surface flows are accurately simulated by the model. This model then should be considered to provide reasonably accurate indication of Stream location with set and drift provided by a routing program using HYCOM output somewhat less than what might actually be observed.

An alternative to HYCOM is provided by the second major model type, the altimetry-based hydrodynamic model. Altimetry refers to satellite measurements of sea surface elevations relative to a reference surface. While not apparent, the sea surface is not flat with highs and lows resulting from tides, winds, and differences in temperature and salinity. Across the Gulf Stream from Newport to Bermuda the average sea surface elevation rises by approximately 1m. Delft Technical University produced the first estimates of ocean circulation based on these measurements following the 1992 launch of the TOPEX/POSEIDON satellite. Subsequent work by NOAA has yielded an alternative model (http://www.aoml.noaa.gov/phod/dataphod/work/trinanes/INTERFACE/index.html) that has been tested in the last five Bermuda Races and proven to be accurate and easy to use. The ability to retrieve historical conditions, allowing comparisons with both HYCOM and satellite SST images, ease in the selection of a particular area of interest and the quality of the images makes the output of this model of particular value in analyses of Stream conditions. These qualities more than offset the absence of GRIB formatted output.

Comparing the output from HYCOM for January 7 (**Fig.3**) to that from the altimetry based model for January 9 (**Fig.4**) (two-day delay allowing for data reduction time) shows generally reasonable agreement. In both the main body of the Stream is encountered near 38º N 69º W with currents going from northwest to southeast. However, the magnification provided by the NOAA program provides a clearer image of the current structure on the altimetry based plot **(Fig.4)** than on the HYCOM product **(Fig.3)**. In addition, the altimetry based model shows features besides the main body of the Stream including a warm core (clockwise rotating) ring near 39º 30' N 67º W and several cold core rings (counter clockwise rotating) south of the main body. One of these latter rings near 36º N 66º W is in contact with the rhumb line and is likely to move west across the rhumb line over the next month. Due to their cool temperatures, which favor some sinking and subsequent covering by warmer waters, these cold rings are often difficult to see on satellite IR images. The fact that they are visible by altimetry makes these products particularly valuable for the navigator. Coverage of the entire region to Bermuda only adds to this value.

As in the case of HYCOM, the altimetry based model is best used to define Stream location and structure since the currents shown seldom exceed 1-2kts, clearly low relative to known current speeds. Again this is the result of model formulation and spatial resolution.

The above combination of satellite observations, computer models, and the Internet have significantly reduced the extent to which racing to Bermuda is a "lottery." The navigator in 2016 has an impressive array of tools not available in the 1950s. This has reduced but not eliminated the element of "chance" in the Race. The Stream and associated weather effects remain fundamentally turbulent which complicates prediction. As a result the Stream doesn't always behave as expected. Meanders change amplitude but fail to move. Rings don't follow a simple westerly track and may even display rotational patterns counter to those expected in areas north and south of the Stream main body. The unexpected can be reduced by early individual study using the above sources of information and others (see http://bermudarace.com/ Resources- Gulf Stream & WX) but not eliminated.

The Stream remains an intriguing phenomenon and something of a mystery. Using its energies to our benefit is the navigational challenge and one of the major attractions of the Newport Bermuda Race.