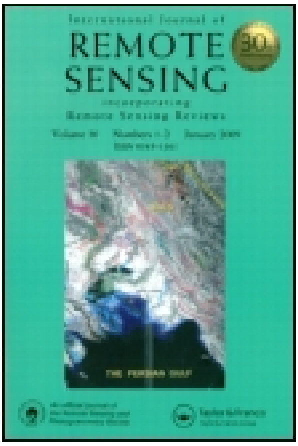

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Combined remote-sensing, model, and in situ measurements of sea surface temperature as an aid to recreational navigation: crossing the Gulf Stream

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Combined remote-sensing, model, and *in situ* measurements of sea surface temperature as an aid to recreational navigation: crossing the Gulf Stream

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Combined *in situ*, model, and satellite remote-sensing observations are used to determine the location of the Gulf Stream as an aid to safe navigation for small recreational vessels.

A field study was executed from Hamilton, Bermuda, to Virginia Beach, USA, over a period of 5 days, from 30 June 2010 to 4 July 2010 to test the feasibility of using remote-sensing products as an aid to cross the Gulf Stream from the point of view of a small, slow-moving ($\sim$6 knots, 3 m s^{-1}) sailboat. The *in situ* data collected were compared to NASA Moderate Resolution Imaging Spectroradiometer (MODIS) and Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) remote-sensing data, to the Global High Resolution Sea Surface Temperature (GHRSST) microwave and infrared blended data set, to the National Oceanic and Atmospheric Administration Real-Time Ocean Forecast System (NOAARTOFS) ocean model, and to selected NOAA buoy and ship measurements.

A spatio-temporal analysis was performed by comparing the *in situ* measurements with observations retrieved at the same time and location in each of the data sets. The least error (correlation coefficient $r = 0.94$) was obtained using MODIS data, and the largest error ($r = 0.78$) was obtained using the RTOFS model data. Overall, most observations agree with the general spatio-temporal trend of the *in situ* data, with 95% of the errors within ± 1°C and 98% of the errors within ± 2°C.

The study shows that MODIS data are particularly suited to identification of the location of the Gulf Stream, which can be used by small vessels to optimize the crossing route and to minimize the risks associated with the passage.

1. Introduction

The Gulf Stream is a mesoscale current that originates in the Gulf of Mexico and generally flows southwest to northeast, off the coasts of North America, into the Northern Atlantic Ocean to the coasts of northwestern Europe. It has been extensively studied for over 100 years due to its importance for ocean circulation and climate (e.g. Deser and Blackmon 1993; Taylor and Stephens 1998), and because it can pose significant risks to safe navigation (Pillsbury 1891). In specific conditions, high waves and strong winds quickly form and can pose life-threatening conditions to slow-moving sailboats.

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The core of the Gulf Stream is approximately 100 km long and has peak velocities exceeding 2.5 m s^{-1} ($\sim$5 knots) (Bower and Hogg 1996; Stammer et al. 2002). It plays an important role in transferring energy to higher latitudes, and it is responsible for the climate of Greenland and northern Europe (Seager et al. 2002; Haza et al. 2007). The speed of the current does not vary significantly on a daily basis, but does on a seasonal and annual scale (Fuglister 1951). However, the current's spatial location changes daily throughout the year (Frankignoul et al. 2001). Determining and predicting the exact location of the stream with high spatial and temporal accuracy is a complex task (Kelly 1991; Kontoyiannis and Watts 1994; Bower and Hogg 1996; Pena-Molino and Joyce 2008; McGrath, Rossby, and Merrill 2011).

Crossing the Gulf Stream in a small, slow-moving, recreational vessel is a challenging and often dangerous task because the speed of the current can be as large or larger than the spped of the boat, and it can be flowing in the opposite direction (Mapes 2009). The velocity of a displacement hull in knots is found using the mathematical formula $v = c\sqrt{\mathrm{LWL}}$, where c is a constant linked to the characteristics of the boat (e.g. weight and shape), ranging from 4.50 to 5.07 km^{-1} m$^{-1/2}$, and LWL is the length of the waterline in metres (Anderson 2003). Therefore, the maximum theoretical speed for a 9 m displacement boat is $\sim$7.4 knots and for a 13 m boat is $\sim$9 knots (1 knot is equal to 0.514 m s^{-1}). The maximum speed is usually achieved only in the best wind and sea conditions, and the normal cruising speed is usually between 60% and 80% of the maximum theoretical speed.

Small sailboats are particularly at risk when crossing the Gulf Stream, because they are usually displacement hulls sailing well below their maximum theoretical speed. Sailing in the Atlantic Ocean from east to west is particularly challenging because the route crosses the current in the opposite direction, drastically reducing the speed over ground (SOG) to only a few knots or less.

Therefore, knowledge of the exact location and extent of the Gulf Stream is paramount for a fast, safe, and comfortable crossing. Every year, thousands of small boats cross the Gulf Stream, as either a part of recreational navigation or competitive racing. In several races, crossing the Gulf Stream is considered to be one of the most (if not the most) dangerous parts of the race, and also one where great technical advantage can be gained.

Modern navigational aids such as global positioning systems (GPS), electronic charts, and model forecasts make it easier to navigate and plan an optimal route. However, most navigation systems rely only on meteorological forecasts and low-resolution data. Despite the recent advances in marine electronics and instruments, the availability of data when at sea remains very limited. Temperature sensors are ubiquitous on all offshore vessels, and their measurements can be used to identify the location of the Gulf Stream. However, *in situ* temperature data are of no use when planning an optimal crossing, since they cannot give early information on the exact spatial location of the current. It is therefore necessary to identify ways to combine the local measurements with reliable spatial information, derived through models, remote-sensing, and/or *in situ* observations

There are two main techniques that can be used to exactly determine the location of the Gulf Stream with high spatial and temporal resolution: using numerical modelling and remote-sensing satellite observations. The first approach is based on the use of numerical ocean models to simulate the real-time characteristics of the current (nowcast) and to predict its future behaviour (forecast). Numerical models are an important component for the improvement of safety of navigation at sea (Turner 2008). A big advantage of using numerical models is the high temporal resolution of data, which can be hourly of less. Additionally, model simulations are not prone to missing data due to cloud cover or atmospheric opacity, which is a common problem for certain types of remote-sensing measurements. Model data are the result of numerical simulations and a prediction of temperature values only partially based on observations.

The two most widely used models used to forecast the Gulf Stream are the National Oceanic and Atmospheric Administration (NOAA) Real-Time Ocean Forecast System (RTOFS)[1] and the US Navy Operational Global Ocean Model (NCOM).[2]

A second approach includes the analysis of real-time high-resolution remote-sensing data. High-resolution remote-sensing data of sea surface temperature (SST) and sea surface height (SSH) can provide accurate information on the location and strength of the current with high spatial and temporal resolution. SST is the water temperature at the surface as retrieved by remote-sensing or *in situ* data, and it can vary among data sets due to the different collection platform and the depth at which observations are made. The Gulf Stream is characterized by higher SST values than the surrounding waters, and therefore, accurate SST measurements can lead to an estimation of its location. High-resolution SST data can effectively capture the daily spatial variation of the current.

SST can be derived from satellite observations made in either the mid- and thermal infrared (IR) or microwave (MW) parts of the electromagnetic spectrum (Elachi 1987). IR observations have the highest resolution (up to 1 km at nadir) and have a long temporal coverage, dating back to the early 1980s. However, they are affected by atmospheric aerosols and cannot penetrate clouds. IR-based SST satellite products are usually the averages of 3 days, in order to minimize the number of missing pixels due to clouds or aerosols. MW observations have lower resolutions (usually 25 km), but do not require atmospheric correction and can penetrate most clouds (Elachi 1987).

It is also possible to blend SST observations from multiple sources to provide high-resolution cloud-free data (e.g. Castro et al. 2008; Reynolds and Chelton 2010).

This article studies the feasibility of using remote-sensing satellite data to determine the exact location of the Gulf Stream for a small recreational sailboat. Combining high-resolution temperature data from satellites and temperature measurements performed by the onboard sensors can provide the ability to (1) plan an optimal route in order to cross the Gulf Stream at its narrowest point (within a reasonable course change) and (2) know with less uncertainty when the effects of the stream can be expected in order to adjust the course and avoid navigating against the flow.

A field study was conducted to collect *in situ* measurements from Bermuda to the eastern coast of the USA over a period of 5 days, from 30 June 2010 to 4 July 2010. The goal was to collect SST measurements along the course and to determine whether it is possible to combine high-resolution measurements and *in situ* observations to optimize the crossing. The field study was designed to reproduce the typical conditions and challenges found onboard a recreational sailboat when crossing the Gulf Stream.

The data collected were compared to measurements from other buoys and ships, to the RTOFS ocean model, to the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) IR and NASA TMI MW SST products, and to the Global High Resolution Sea Surface Temperature (GHRSST)-blended SST product. The results show that MODIS data are particularly suited as an aid to navigation for crossing the Gulf Stream. The correlation coefficient between the MODIS data and the *in situ* observations made is in excess of 0.94.

The goal of this research is not to validate different data sets and discuss their accuracy, but to determine whether any of these data sets can be used as a navigation aid for a small sailboat.

2. Data

This research is based on *in situ*, model, and remote-sensing data collected between 30 June and 4 July 2010. The MODIS and TMI remote-sensing data were transformed from digital numbers to degrees Celsius using the published slope and intersection coefficients. No transformation was applied to the model or *in situ* observations. The comparisons between different data sets were performed between the closest points in space and time. All dates and times throughout the article are expressed in Eastern Daylight Time (EDT). The data analysis was performed using the open source 'R' statistical package.

2.1. Valkyrie *field study data*

Sea temperature data were collected from 30 June to 4 July 2010, on an average course of 330°, from Hamilton, Bermuda, to Virginia Beach, USA. This field study was conducted onboard *Valkyrie*, a production line Beneteau First 44.7 sailboat. Figure 1 shows *Valkyrie* on 29 June, being fitted with special equipment for the field study. A small sailboat was chosen for this research in order to collect data with the same instruments available to most recreational mariners and to reproduce the exact conditions of and understand the risks and challenges associated with crossing the Gulf Stream.

The data were collected using a Raymarine depth/speed transducer, calibrated at the factory, and connected to a Raymarine network. The measurements were recorded using a digital display that continuously reported the measured temperature, averaged over the past five minutes. The sensitivity of the instrument is ±0.1°C. A total of 48 measurements were made, each consisting of a date, time, location, and sea temperature, summarized in Table 1. The SST observations are also shown in Figures 4–7 as colour-coded segments.

Figure 1. The Beneteau First 44.7 *Valkyrie* in Hamilton on 29 June 20 being fitted by the author with special equipment for the field study.

Table 1. Summary of the sea temperature observations made.

ID	Date	Time (EDT)	Latitude (° N)	Longitude (° W)	SST (°C)
1	30 June	11:45	32.52	64.76	28.72
2	30 June	13:30	32.64	65.00	28.28
3	30 June	15:30	32.74	65.29	28.72
4	30 June	16:00	32.80	65.48	28.28
5	30 June	17:35	32.91	65.87	27.89
6	30 June	21:00	32.96	66.07	27.89
7	30 June	23:00	33.02	66.36	26.94
8	1 July	00:30	33.07	66.63	27.89
9	1 July	05:00	33.26	67.21	27.89
10	1 July	07:30	33.40	67.59	27.72
11	1 July	12:30	33.67	68.27	28.72
12	1 July	15:00	33.83	68.61	28.72
13	1 July	15:30	33.83	68.62	29.11
14	1 July	18:30	34.04	68.84	28.72
15	1 July	19:00	34.09	68.86	28.28
16	1 July	20:00	34.19	68.90	28.72
17	1 July	22:00	34.32	68.96	27.89
18	2 July	09:00	34.57	70.04	27.89
19	2 July	14:00	34.71	70.48	27.11
20	2 July	16:30	34.76	70.73	27.89
21	2 July	19:00	34.84	71.12	27.50
22	2 July	22:00	34.98	71.56	27.50
23	3 July	02:30	35.16	71.99	27.11
24	3 July	06:00	35.27	72.33	28.28
25	3 July	09:00	35.43	72.61	27.89
26	3 July	11:00	35.63	72.86	27.89
27	3 July	13:00	35.76	72.99	29.11
28	3 July	14:00	35.88	73.05	29.89
29	3 July	14:30	35.90	73.07	30.28
30	3 July	15:00	35.92	73.08	29.89
31	3 July	15:30	35.97	73.13	29.50
32	3 July	15:50	36.00	73.16	28.28
33	3 July	16:00	36.01	73.18	27.11
34	3 July	16:30	36.05	73.23	26.06
35	3 July	17:00	36.09	73.30	25.78
36	3 July	18:00	36.15	73.43	25.00
37	3 July	19:00	36.20	73.54	23.78
38	3 July	21:00	36.25	73.81	23.78
39	3 July	22:00	36.34	73.94	24.61
40	3 July	23:00	36.38	74.07	24.22
41	4 July	00:00	36.40	74.15	23.78
42	4 July	01:00	36.45	74.31	24.22
43	4 July	05:00	36.60	74.76	24.61
44	4 July	06:00	36.64	74.90	25.00
45	4 July	06:30	36.67	74.97	25.39
46	4 July	07:30	36.74	75.08	26.22
47	4 July	13:30	36.91	75.92	27.50
48	4 July	14:30	36.94	76.14	27.61

On the evening of 1 July, a strong squall with winds of up to 40 knots hit *Valkyrie* and caused considerable damage to the boom, electronics, and one of the headsails. SST measurements were not recorded for the following eight hours, while the crew manoeuvred to make temporary repairs and set emergency sails.

In addition to the reported data, additional measurements were made for wind velocity and direction, using an onboard anemometer, and wave height and direction, derived from GPS measurements. These data are not used in this study.

2.2. RTOFS SST data

RTOFS is a basin-scale ocean forecast system based on the Hybrid Coordinate Ocean Model (HYCOM) that concentrates on the northern Atlantic and a part of the southern Atlantic Ocean with a variable size grid resolution ranging from 4 to 17 km (Mehra and Rivin 2010).

Nowcast model data are provided at hourly intervals, but for this study data at 6 hour intervals were used, namely at 02:00, 08:00, 14:00, and 20:00. A total of 17 model outputs were used, from 30 June at 14:00 to 4 July at 14:00. The times were chosen to be closest to the *in situ* measurements made. Figures 2 and 3 show the 17 model outputs used and the SST observations made along the course taken by *Valkyrie*, shown using colour-coded circles. The colour scale for both figures is shown in Figure 2.

2.3. Buoy and ship in Situ *SST data*

The NOAA maintains a global network to continuosly retrieve meteorological parameters, including SST use of buoys, ships, and other installations such as oil rigs and research platforms. The data are available online through the Observing System Monitoring Center

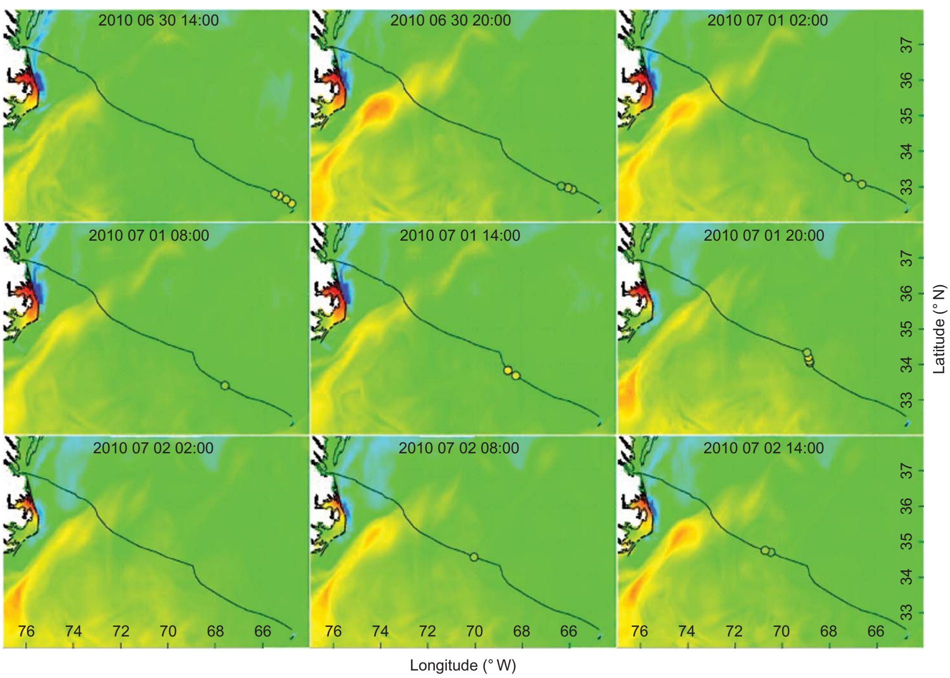

Figure 2. SST images from the RTOFS model from 30 June 2010 (14:00) to 2 July 2010 (14:00).

Note: The track of the field study is shown, and the sea temperature observations made are shown with colour-coded circles. Colour scale is shown in Figure 3.

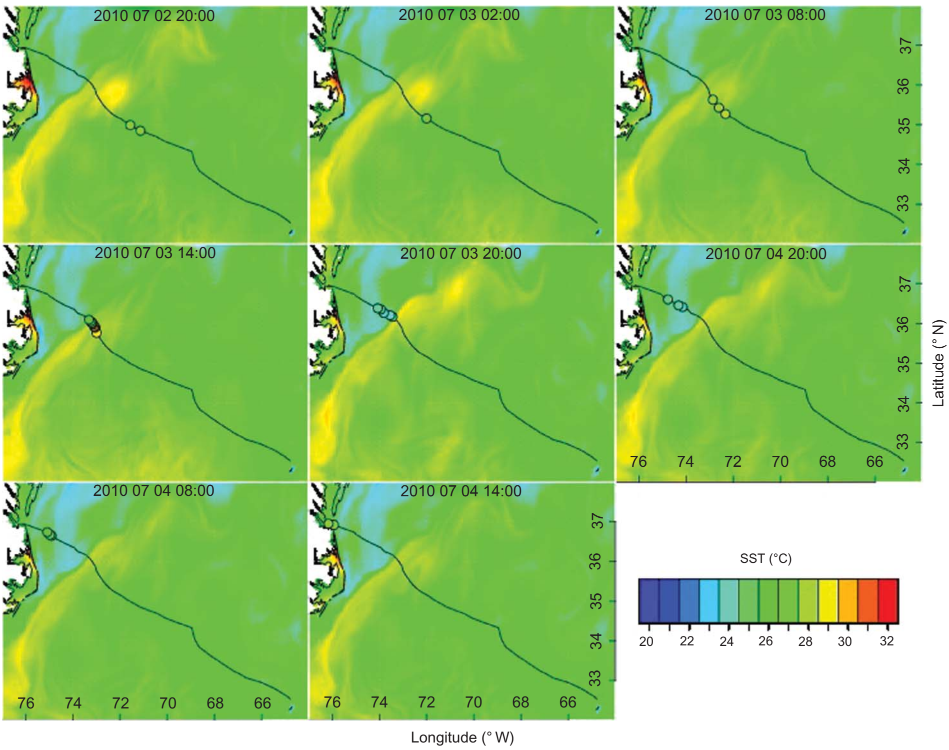

Figure 3. SST images from the RTOFS model from 2 July 2010 (20:00) to 10 July 2010 (14:00).

(OSMC),[3] an information gathering, decision support, and display system maintained by NOAA's Office of Climate Observations (OCO).

During the period of this study, five buoys (two drifting and three moored) and four ships collected SST data at times and locations in the vicinity of the observations made onboard *Valkyrie*. Table 2 summarizes the SST observations and their corresponding date, time, and location at which the measurements were made by each buoy or ship. Each vessel is identified by a unique international ID, and their characteristics can be retrieved at the NOAA's National Buoy Data Center (NBDC) website. Figure 4 shows the value and location of the buoy and ship measurements, and their relationship to the observations made

Table 2. Buoy and ship SST observations used in this study.

ID	Date	Time (EDT)	Latitude (° N)	Longitude (° W)	SST (°C)
BEPB6	30 June	12:00	32.37	64.70	28.00
PDBO	1 July	00:00	35.00	67.30	27.40
44834	2 July	22:00	35.63	70.83	27.20
H3VS	3 July	15:00	35.00	73.10	27.00
41001	3 July	02:50	34.70	72.70	26.40
WFKJ	3 July	18:00	35.40	73.30	23.90
PFBE	3 July	18:00	35.70	72.50	27.00
44014	4 July	05:00	36.60	74.80	24.70
CHYV2	4 July	14:30	36.93	76.01	27.10

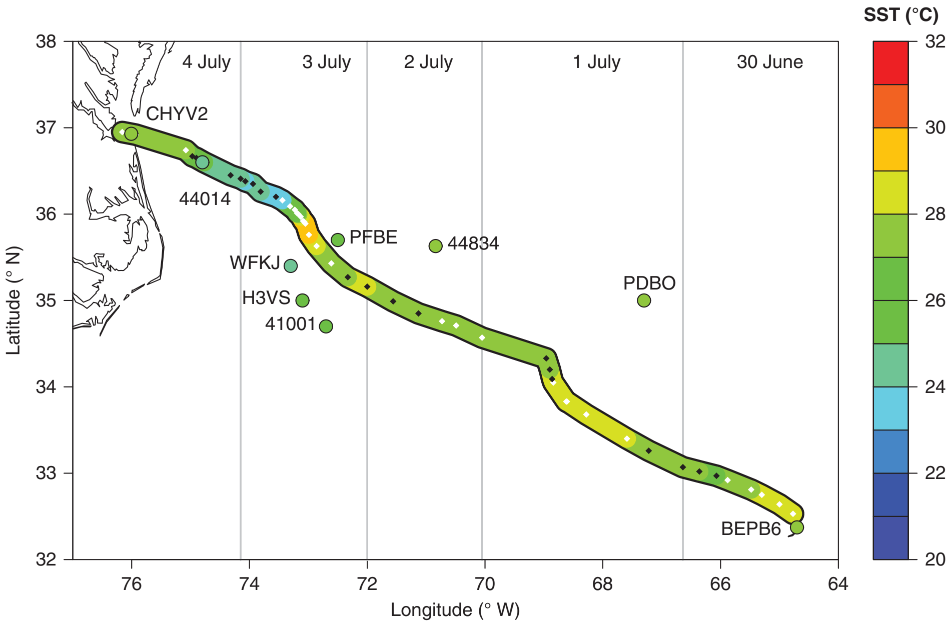

Figure 4. Composite buoys/ships and field study SST data.

Note: Each panel, delimited with vertical lines, corresponds to the SST data for a different day of the field study. The colour-coded diamonds indicate the location of the field study observations (white for daytime and black for night-time). The track is colour-coded according to the SST values observed at specific times and locations.

in the field study. The path of *Valkyrie* is indicated with a colour-coded segment, representing the value of the observations made. The locations of the observations are indicated with white diamonds for daytime and black diamonds for night-time.

The data are very important because, although sparse, they provide additional information regarding the validity of the observations made and their correlation with satellite data. Unfortunately, no buoy or ship collected data in the portion of the Gulf Stream crossed by *Valkyrie* on 3 July 2010, when very high SST values were observed.

2.4. MODIS SST data

Satellite remote-sensing observations from the NASA MODIS instrument can be used to derive SST with an accuracy of ±0.25°C. MODIS is a high-resolution multi-spectral sensor that is currently flying on two NASA satellites, Aqua and Terra. MODIS uses mid- and thermal IR for measuring the emissivity of the surface. MODIS SST products are corrected for atmospheric disturbances. A description of the MODIS SST products and their comparison with *in situ* measurements is discussed by Minnett et al. (2002).

This study is based on standard Aqua MODIS Level 3, 4.63 km gridded 3 day composite SST products, generated through surface emissions in the mid-IR region (4 μm) for night-time data and thermal IR region (11 μm) for daytime data. The gridded data are generated by binning and averaging the nominal 1 km swath observations, yielding ~4 km gridded global data. The data were downloaded from the NASA OceanColor website[4] and were processed using SeaDAS 6.1 software (NASA, http://seadas.gsfc.nasa.gov/), available

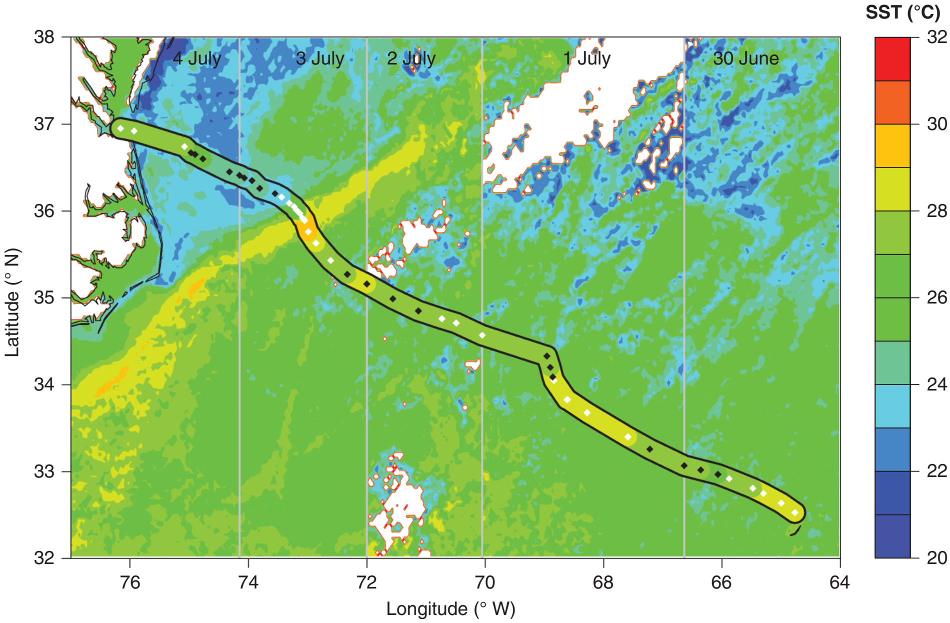

Figure 5. Composite MODIS and field study SST data.

from the same location. The data are distributed in Hierarchical Data Format Earth Observing System (HDF-EOS) format.

The use of MODIS data is limited in cloud-free conditions. Since MODIS is installed on both the Terra and Aqua satellites, four data points are available per day.

Figure 5 shows the spatial and temporal correlation between the field study observations and MODIS data. The figure is divided into five vertical panels, one for each day of the field study. Therefore, each vertical panel shows the spatial SST variation for a particular day. Both the MODIS data and the *in situ* observations are colour-coded using the same scale. A good spatial and temporal relation between the two data sets can be observed. The white areas in the image indicate missing MODIS data, due to land or cloud cover.

MODIS data can be freely obtained through direct broadcast, which requires an X-band antenna and its control equipment, or from the NASA MODIS website. The data are distributed in HDF5-EOS format, which is a proprietary format usually not supported by navigation equipment. However, the MODIS data can be easily converted without any loss of resolution into gridded binary (GRIB) format, which is supported by most devices.

2.5. TMI SST data

The Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) is a passive MW sensor flying onboard the TRMM spacecraft that can be used to retrieve nearly cloud-free SST data. One of the main advantages of the TMI sensor is that it has been flying for many years and is very well calibrated under different atmospheric conditions (Gentemann et al. 2004).

This study is based on TMI Level 3, 25 km gridded 3 day composite SST products, generated through passive sensing of the surface emissivity in the MW region (1–3 cm). The gridded data are generated by binning and averaging the swath data, yielding ∼25 km gridded global data. The data were downloaded from the Special Sensor Microwave/Imager

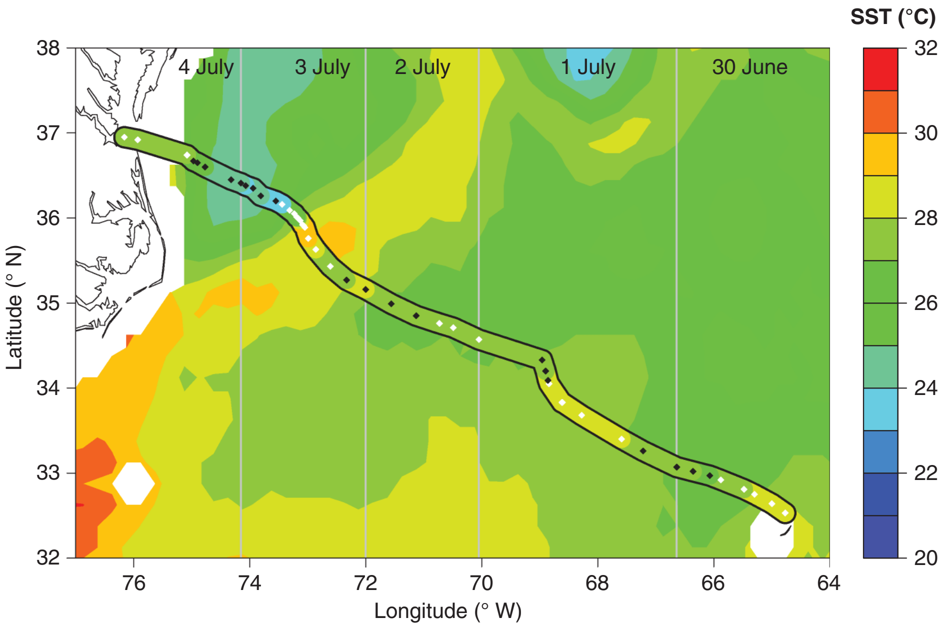

Figure 6. Composite TMI and field study SST data.

(SSMI) website[5] and were processed using R. The data are distributed in a proprietary binary format.

Figure 6 shows the spatial and temporal distribution of the TMI SST values and of the field study measurements, plotted using the same scale. The format of the figure is identical to Figure 5.

2.6. GHRSST SST data

The GHRSST is a global blended data set that fuses observations from IR and MW satellites and buoys. The data are distributed as a daily global gridded product with a resolution of ∼10 km.

This study is based on a GHRSST Level 4, global, 25 km gridded daily composite from the Operational SST and Sea Ice Analysis (OSTIA) (Stark et al. 2007). The data were downloaded from the NASA Jet Propulsion Laboratory (JPL) website[6] and were processed using R. The data are distributed in network common data format (netCDF).

Figure 7 shows the spatial and temporal distribution of the GHRSST SST values and of the field study measurements, plotted using the same scale. The format of the figure is identical to Figure 5.

3. Results

3.1. Spatial variation of the Gulf Stream

The location of the Gulf Stream varied significantly during the period of this study, consistent with the notion that the stream exhibits large daily fluctuations. Figure 8 shows contour lines for 28°C for the MODIS data used in this study, for the period ranging from 30 June 2010 to 4 July 2010. The contour lines correspond to the warmer water characteristic of the

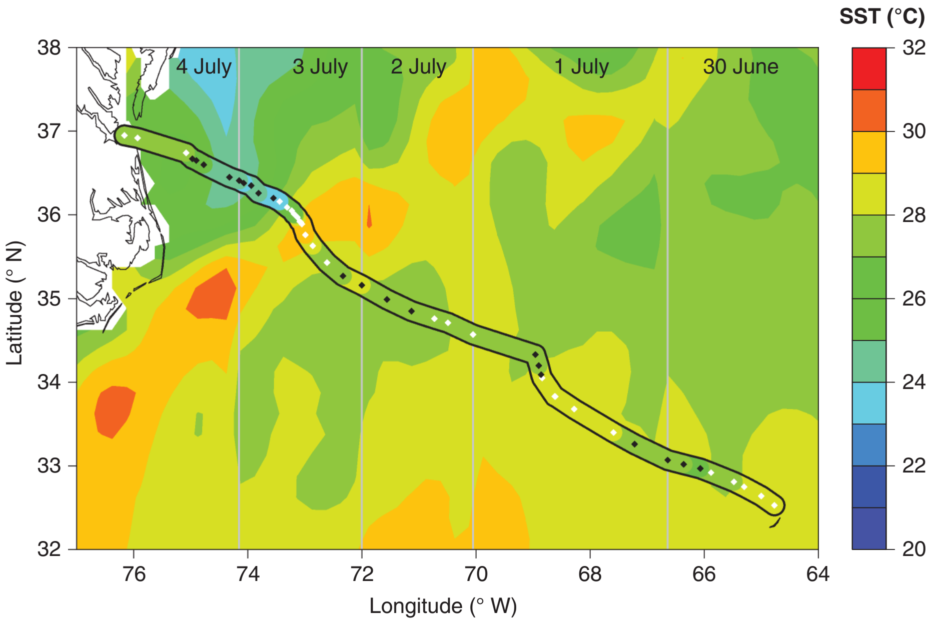

Figure 7. Composite GHRSST and field study SST data.

current and visualize its daily spatial fluctuations. In Figure 8, the solid segment indicates the track of *Valkyrie*, showing that the gulf stream was crossed during daylight hours on 3 July. The last panel shows the averaged data and the full route taken, along which *in situ* measurements were made. Figures 2 and 3 show the variation of the Gulf Stream as computed by the RTOFS model, at intervals of 6 hours. The Gulf Stream is easily identifiable as a very warm area off the coasts of North America. The solid black line in each image shows the path of the boat, along which *in situ* measurements were made. The figure shows that the Gulf Stream was crossed during daylight hours on 3 July. The location and value of the *in situ* measurements are shown with colour-coded circles. In both the MODIS and the model data, the spatial location of the Gulf Stream changes significantly, up to 50 km in the east–west extents, which translates into a very large uncertainty for a slow-moving sailboat.

3.2. Spatio-temporal analysis of the data

In order to assess the feasibility of using high-resolution data as an aid to navigation, the *in situ* measurements collected were compared with the SST data from the sources described in Section 2.

The comparison among the different data sets was performed by selecting the closest observations in both space and time. For MODIS data, the average value of a 3 × 3 pixel matrix centred at the longitude and latitude of the *in situ* measurements was used in the analysis. This was required because of missing data due to cloud cover. On 1 July, several MODIS pixels were missing in the daytime data due to clouds, and consequently, night-time data were also used for daytime observations.

A visual comparison between the data collected in the field study and the different model, buoys/ship, and remote sensing data is provided in Figures 2–7. Generally, there is a very good correlation between the data, indicating warm temperatures between Bermuda

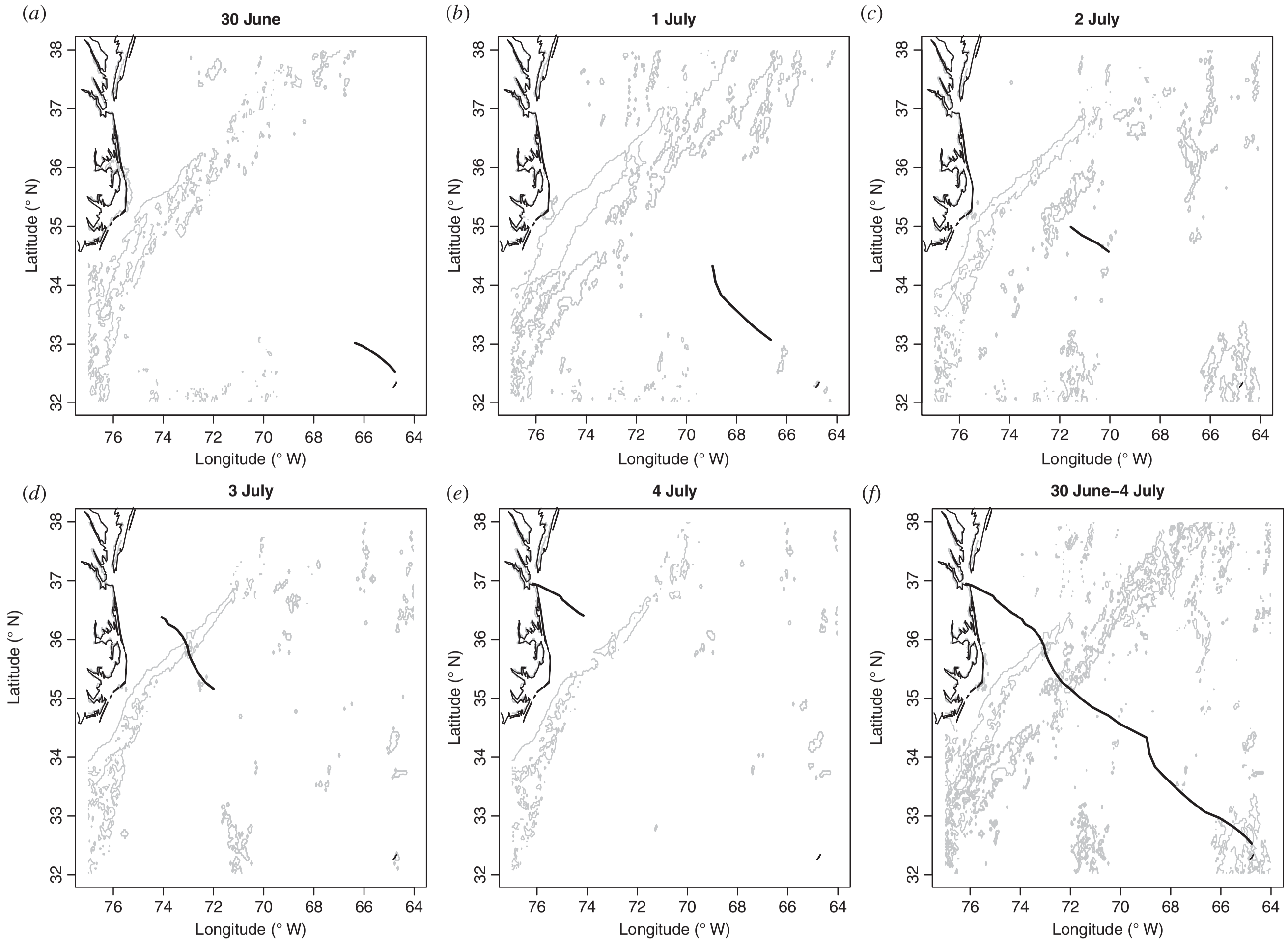

Figure 8. Contour lines for 28°C using MODIS data.

Note: The black line indicates the track of the boat, along which observations were made.

and the Gulf Stream, very high temperatures (up to 30°C) inside the Gulf Stream, and cooler temperatures (mid 20°C) between the western edge of the Gulf Stream and the eastern coast of the USA.

When the distributions are compared, discrepancies can be identified to the east and to the west of the Gulf Stream. Generally, the *in situ* observations made are between 1°C and 2°C higher. A statistical analysis of the distributions and variances showed that in deep and warmer waters, east of the Gulf Stream near longitude 71° W, the *in situ* measurements are higher than the MODIS data by approximately 2°C and higher than TMI and RTOFS data by approximately 1°C. In the shallower and colder waters, west of the Gulf Stream, the *in situ* measurements are higher than the MODIS data by approximately 1°C, but agree with both TMI and RTOFS. GHRSST data agree well with the *in situ* observations. For the correlation analysis, the data sets were transformed by adding 1°C or 2°C, as described previously. For the specific application presented, the discrepancy between the data sets is not important, since it is still possible to determine the location of the stream.

Figure 9 shows the correlation between each *in situ* measurement (vertical axis) and the corresponding observations from the other data sets used (horizontal axis). The oblique solid line indicates a 1:1 agreement, the dashed lines indicate a +1°C and −1°C relationship, and the dotted lines indicate a +2°C and −2°C relationship. Each data set is shown with a different symbol, and the buoy/ship observations are labelled with their platform ID. Most points lie between +1°C and −1°C, indicating a very good agreement. The largest discrepancies are found in the RTOFS data set for very large values, which roughly correspond to the exact location at which the Gulf Stream is crossed.

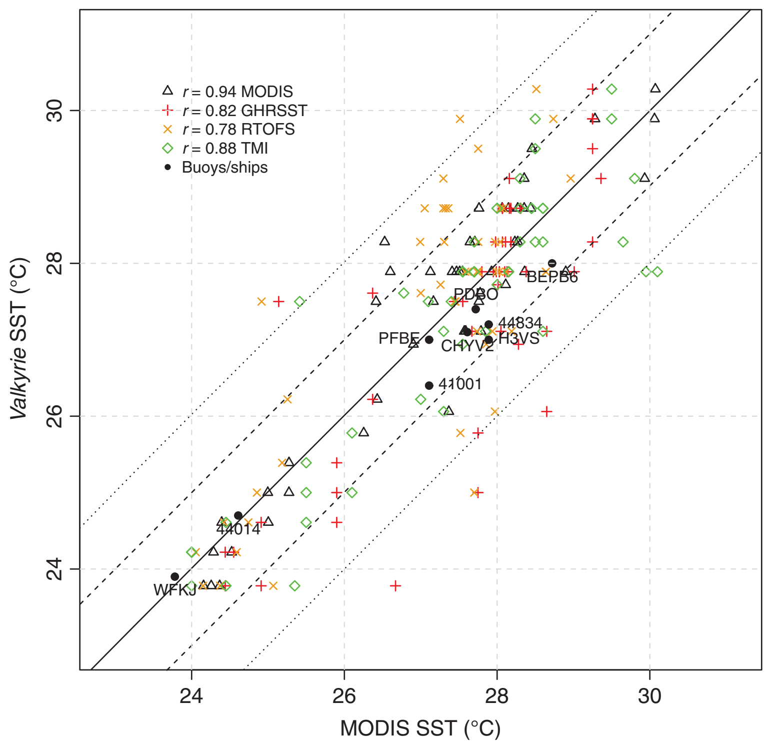

Figure 9. Correlation between *in situ* measurements and MODIS SST data.

The legend includes the *r* (correlation coefficient) values obtained using each of the data, namely 0.94 for MODIS, 0.82 for GHRSST, 0.78 for RTOFS, and 0.88 for TMI. All data sets have a very high correlation, MODIS being the best and RTOFS being slightly worse. Potentially, all of the data sets are good candidates for the purpose of the study.

However, in order to use one of these data sets for navigation, it is first necessary to determine whether the location of the Gulf Stream can be identified. Figure 10 shows the SST measurements for the *in situ* data and for all of the other data sampled at the same locations as a function of longitude. All time series show very good correlations (r = 0.78–0.94), indicating the reliability of the *in situ* measurements.

In the following discussion, the entry and exit points are defined as the locations in the *Valkyrie* SST measurements between longitudes 68.5° W and 72° W, whereas SST increases to above 27.5°C.

The best spatial and temporal correlation is obtained between the MODIS data and the *in situ* measurements, leading to an *r* value of 0.94. The spatio-temporal relationship is consistent throughout the time series, and in particular, it is possible to detect the sharp increase in surface temperature associated with the location of the Gulf Stream. Both of the data sets agree to a maximum SST value of about 30°C at longitude 70° W. The spatial error for the location of the Gulf Stream using the MODIS data is about 15 km east of both the entry and exit points. This discrepancy is likely to be caused by different acquisition times between the MODIS data and the *in situ* measurements. The error corresponds to about one and a half hours of navigation at 6 knots.

The TMI data also show a good correlation (r = 0.88), but the spatial error is much larger and corresponds to over 100 km east and 20 km east of the entry and exit points,

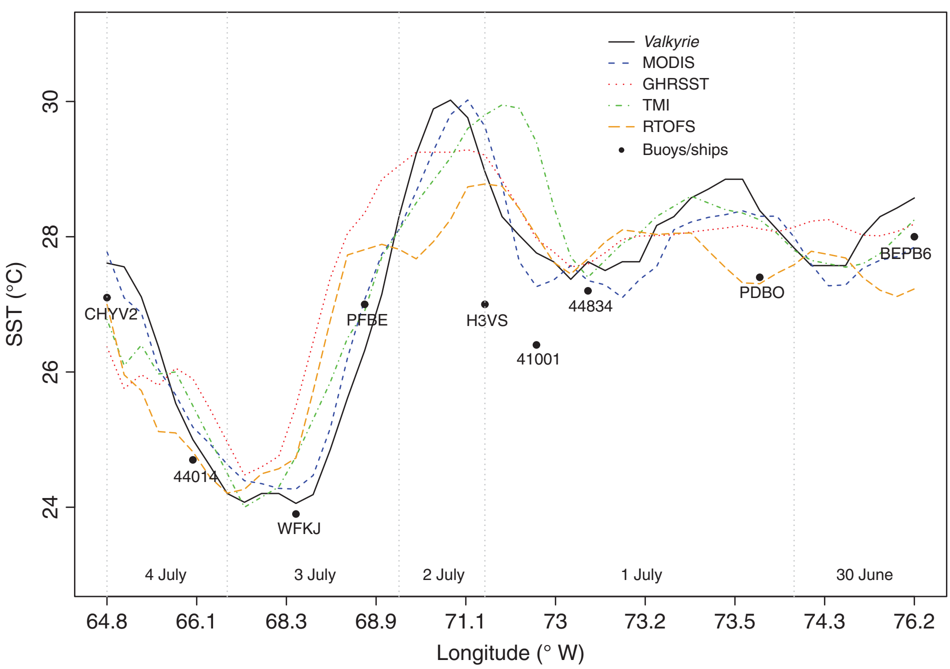

Figure 10. Comparison of *in situ* measurements and corresponding original and transformed MODIS SST data.

respectively. The GHRSST data, for which an r value of 0.82 is found, show a temperature peak slightly underestimated by about 1°C. The spatial error corresponds to 5 km east and 60 km west of the entry and exit points, respectively.

The RTOFS data obtained the worst correlation of the data sets used ($r = 0.78$) and also underestimated the peak temperature. A spatial analysis of the data shows a high SST-predicted value more west than those observed. The entry and exit points are predicted to be 30 km east and 50 km west, respectively, of the observed ones.

All data sets converge towards 24°C at longitude 66.2° W (−66.2), which corresponds to the colder waters found on the eastern coast of the USA, outside of the Gulf Stream. The buoy/ship measurements are indicated with their platform ID and are in general agreement with the data sets. Some variations are due to the different depth, time, and location at which the measurements are made.

3.3. *Optimization of the crossing route*

Due to the high correlation found between the *in situ* measurements and the MODIS data, it is possible to use the latter for both planning and real-time adjustment of the course to maximize the SOG and minimize the travel distance. Using MODIS SST data, it is possible to identify the location where the Gulf Stream can be crossed at its narrowest point, and when to apply course changes to maximize SOG without drastically increasing the distance.

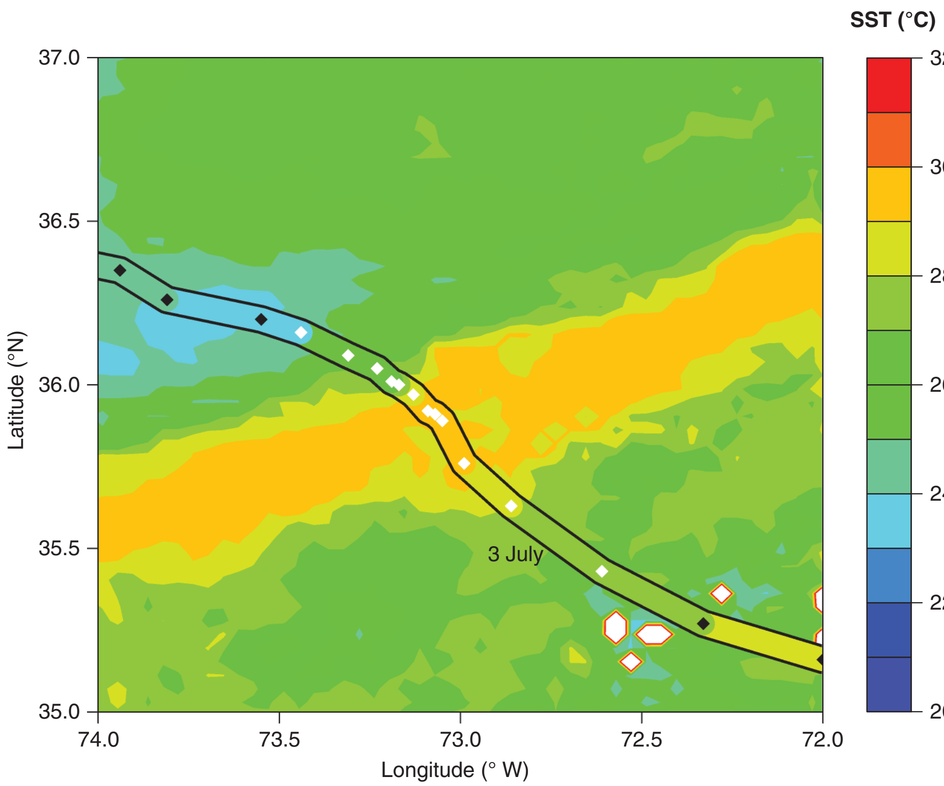

Figure 11. MODIS SST and *in situ* observations for 7 July, when the Gulf Stream was crossed east to west.

Once converted to GRIB format, the optimization procedure can be automated through navigation software that takes SST into account in the route optimization, or manually by imposing specific entry and exit points (as viewpoints) based on the SST data.

Figure 11 shows the *in situ* observations and the MODIS data relative to 7 July, when *Valkyrie* crossed the Gulf Stream at around 13:00. The spatio-temporal correlation between the MODIS data and the *in situ* measurements is very high, showing that the path taken by *Valkyrie* crossed the Gulf Stream in one of its narrowest points. A northerly course change to the otherwise SW–NE track was taken in order to cross the stream at a perpendicular angle, thus avoiding a drastic decrease in SOG.

4. Conclusions

The use of high-resolution satellite and model SST data is presented as an aid to small recreational vessels in the context of crossing the Gulf Stream. A field study was performed to collect *in situ* samples from Hamilton, Bermuda, to Virginia Beach, USA, from 30 June to 5 July 2010. A spatio-temporal correlation between the *in situ* data collected and the different data sets was computed. The best correlation was found between the *in situ* measurements and the MODIS SST data.

The MODIS SST data can give a good approximation of the exact location of the Gulf Stream, due to the sharp gradient of temperatures that can be observed around the stream edges.

Once converted to a format such as GRIB, which is normally used by navigation software, it is possible to use the MODIS data to identify the most optimal entry and exit locations to cross the Gulf Stream. By planning a more perpendicular crossing in a location where the Gulf Stream is narrow and lacking eddies, it is possible to maximize the SOG and minimize the distance.

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Notes

1. http://polar.ncep.noaa.gov/ofs/index.shtml.
2. http://www.opc.ncep.noaa.gov/OceanFcasts/image_viewer_Watl_sst.html.
3. http://www.osmc.noaa.gov.
4. http://oceancolor.gsfc.nasa.gov.
5. ftp://ftp.ssmi.com.
6. ftp://podaac.jpl.nasa.gov/OceanTemperature/ghrsst/.

References

Anderson, B. D. 2003. *The Physics of Sailing Explained*. Winchester: Sheridan House.

Bower, A. S., and N. G. Hogg. 1996. “Structure of the Gulf Stream and Its Recirculations at 55W.” *Journal of Physical Oceanography* 26: 1002–22.

Castro, S., G. Wick, D. Jackson, and W. J. Emery. 2008. “Error Characterization of Infrared and Microwave Satellite Sea Surface Temperature Products for Merging and Analysis.” *Journal of Geophysical Research* 113, no. C03010. doi:10.1029/2006JC003829.

Deser, C., and M. Blackmon. 1993. "Surface Climate Variations over the North Atlantic Ocean during Winter: 1900–1989." *Journal of Climate* 6, no. 9: 1743–53.
Elachi, G. 1987. *Introduction to the Physics and Techniques of Remote Sensing*. New York: John Wiley and Sons Ltd.
Frankignoul, C., G. de Coetlogon, T. M. Joyce, and S. Dong. 2001. "Gulf Stream Variability and Ocean-Atmosphere Interactions." *Journal of Physical Oceanography* 31: 3516–29.
Fuglister, F. G. 1951. "Annual Variations in Current Speeds in the Gulf Stream System." *Journal of Marine Research* 10: 119–27.
Gentemann, C. L., F. J. Wentz, C. A. Mears, and D. K. Smith. 2004. "In-Situ Validation of TRMM Microwave Sea Surface Temperatures." *Journal of Geophysical Research* 109: 9. doi:10.1029/2003JC002092.
Haza, A. C., A. J. Mariano, T. M. Chin, and D. B. Olson. 2007. "The Mean Flow and Variability of the Gulf Stream-Slopewater System from MICOM." *Ocean Modelling* 17, no.3: 239–76.
Kelly, K. A. 1991. "The Meandering Gulf Stream as Seen by the Geosat Altimeter: Surface Transport, Position and Velocity Variance from 73° W to 46° W." *Journal of Geophysical Research* 96: 16721–38.
Kontoyiannis, H., and R. Watts. 1994. "Observations on the Variability of the Gulf Stream Path between 74° W and 70° W." *Journal of Physical Oceanography* 24, no. 19: 999–2013.
Mapes, E. 2009. Crossing the gulf stream. *Sailing*, April 2009.
McGrath, G., T. Rossby, and J. Merrill. 2011. "Drifters in the Gulf Stream." *Journal of Marine Research* 68, no. 5: 699–721.
Mehra, A., and I. Rivin. 2010. "A Real Time Ocean Forecast System for the North Atlantic Ocean. *Terrestrial Atmospheric and Oceanic Sciences* 21, no. 1: 211–28.
Minnett, P. J., R. H. Evans, E. J. Kearns, and O. B. Brown. 2002. "Sea-Surface Temperature Measured by the Moderate Resolution Imaging Spectroradiometer (MODIS)." In *IGARSS 2002: Geoscience and Remote Sensing Symposium*, Toronto, Canada, June 24–28.
Pena-Molino, B., and T. Joyce. 2008. "Variability in the Slope Water and Its Relation to the Gulf Stream Path." *Geophysical Research Letters* 38, no. L03606, doi:10.1029/2007GL032183.
Pillsbury, J. E. 1891. *The Gulf Stream: Methods of the Investigation and Results of the Research*. Washington, DC: Government Printing Office.
Reynolds, R., and D. Chelton. 2010. "Comparisons of Daily Sea Surface Temperature Analyses for 2007–08." *Journal of Climate* 23: 3545–62.
Seager, R., D. S. Battisti, J. Yin, N. Gordon, N. Naik, A. C. Clement, and M. A. Cane. 2002. "Is the Gulf Stream Responsible for Europe's Mild Winters?" *Quarterly Journal of the Royal Meteorological Society* 128, no. 586: 2563–86. http://dx.doi.org/10.1256/qj.01.128.
Stammer, D., C. Wunsch, R. Giering, C. Eckert, P. Heimbach, J. Marotzke, A. Adcroft, C. N. Hill, and J. Marshall. 2002. "The Global Ocean Circulation during 1992–1997, Estimated from Ocean Observations and a General Circulation Model." *Journal of Geophysical Research* 107: 27.
Stark, J. D., C. J. Donlon, M. J. Martin, and M. E. McCulloch. 2007. "Ostia: An Operational, High Resolution, Real Time, Global Sea Surface Temperature Analysis System." In *Proceedings of Oceans '07. Marine Challenges: Coastline to Deep Sea*, IEEE Aberdeen, Scotland, June 18–21.
Taylor, A., and J. Stephens. 1998. "The North Atlantic Oscillation and the Latitude of the Gulf Stream." *Tellus A* 50, no. 1: 134–42.
Turner, A. C. 2008. *Evaluation of Environmental Information Products for Search and Rescue Optimal Planning System (SAROPS) – Version for Public Release*. Technical Report ADA479430. Groton, CT: Coast Guard Research and Development Center.