P2.7 SCATTEROMETER INFERRED WINDS IN THE VICINITY OF THE GULF STREAM

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1. INTRODUCTION

The NOAA/NWS Ocean Prediction Center (OPC) is responsible for issuing wind warnings and forecasts of winds and seas for the High Seas and Offshore waters of the Atlantic and Pacific Oceans. The OPC Atlantic Offshore zones extend from 46 km to roughly 460 km of the coast and include the complex sea surface temperature (SST) gradients of the Gulf Stream, slope, and shelf waters. Wind warning categories are: GALE (17 to 23.5 m $s^{-1)}$, STORM (24 to 31.5 m $s^{-1)}$, and HURRICANE FORCE (32 m s^{-1} or higher). These warnings are broadcast by a variety of methods to mariners at sea. OPC wind warnings have both an economic and safety impact.

In the past, OPC forecasters have relied primarily on wind observations from merchant and government ships of opportunity and moored meteorological buoys for short-term warning decisions. Remotely sensed surface winds from the Special Sensor Microwave Imager (SSM/I) aboard the DMSP series satellites has helped to fill the gaps between conventional observations. However, the SSM/I wind retrievals are quite limited in areas of liquid cloud and precipitation as discussed by Atlas et al. (1996). Also, the upper limit of wind retrievals is at the top of the GALE category, therefore, SSM/I does not help forecasters differentiate between the stronger wind warning categories.

Scatterometer derived winds have been available to OPC forecasters for periods of time over the last ten years. ERS-1 and ERS-2 winds were used with minimal success as the swath width was limited. NSCAT data was used routinely by forecasters for its short life. Seawinds scatterometer (aboard the NASA QuikSCAT satellite) winds have been used by OPC forecasters in their warning decision process since 1999 and have been available in their operational workstations since 2001(Atlas et al., 2001). The 1800 km wide swath, all weather capabilities, and large retrievable wind range (well into HURRICANE FORCE)(Von Ahn et al., 2003) have made QuikSCAT winds a heavily used tool by OPC forecasters. A key to the utility of the QuikSCAT winds is their availability in the operational workstations. Forecasters can compare the winds to other data sets including: model forecast fields, visible and infrared satellite imagery, and SST analyses.

Seawinds scatterometer (referred henceforth as QuikSCAT) is an active radar in the ku band and directly measures the ocean surface roughness on the cm scale (Atlas et al.,2001). The small-scale ocean roughness has been shown to have a direct relationship to the near surface wind speed (Atlas et al.,2001)). In essence the instrument measures wind stress on the ocean surface and wind speed is then inferred from the wind stress.

The effect of the Gulf Stream and the warm and cold rings on local weather were documented by Sweet et al. (1981). Near calm conditions were observed over cooler slope waters with rougher seas over the Gulf Stream itself. Also, Sweet at al., (1981) observed a dramatic change in wind speed from the cooler waters (5-10 m s^{-1}) to 13 to 18 m s^{-1} over the warm Gulf Stream waters. Glendening and Doyle (1995) in a theoretical modeling study showed the signature of large-scale Gulf Stream features in the marine atmospheric boundary layer (MABL). Desjardin et al. (1998) investigated the impact of the Gulf Stream meanders and cold and warm rings on the atmospheric boundary layer during the March 1993 Superstorm using the MC2 non-hydrostatic model. They found that in advance of the strong cold front the wind speed pattern was shaped by the Gulf Stream features. It was found that a shallow unstable well mixed boundary layer was present over the Gulf Stream meanders and warm rings allowing for increased vertical momentum transfer and enhanced wind speed. Statically stable conditions and minimized momentum transfer occurred over the colder waters with lower wind speeds. Recently, Young and Sikora (2003) related changes in mesoscale cloud structures to Gulf Stream meanders again reinforcing the link of the marine atmospheric

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boundary layer (MABL) to the underlying sea surface. Since scatterometers infer wind speed by measuring surface roughness and thus wind stress one would think that the observations of Sweet et al. (1981) and modeling results of Desjardin et al. (1998) would be evident in the scatterometer derived wind fields across the Gulf Stream features. In fact, by combining data sets such as SST analyses, infrared imagery, and scatterometer winds OPC forecasters have observed significant wind gradients across SST fronts. This paper will focus on pre-frontal, low-level southerly flow events. Examples of wind changes across SST fronts will be shown in section 2. Guidance for forecasters will be discussed in section 3. Summary and conclusions will be given in section 4.

2. EXAMPLES

The first example to be discussed is from March 04, 2002. Figure 1 shows the corresponding OPC surface analysis from 0000 UTC 4 March, 2002. A cold front was just moving off the Mid-Atlantic Coast of the United States with

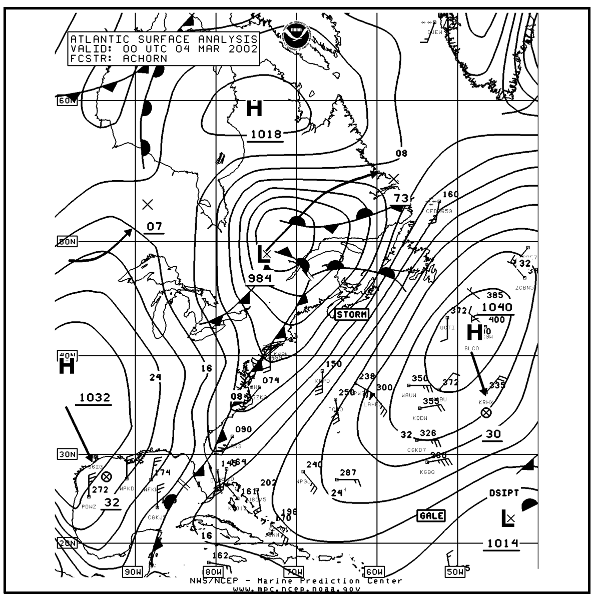

Fig. 1. OPC operational surface analysis for the western North Atlantic from 0000 UTC 4 March 2002.

high pressure situated near 42°N 49°W. A prolonged southerly surface flow existed from the subtropics to the Gulf of Maine. Figure 2 shows the corresponding SST AVHRR composite (a) and (b) the QuikSCAT 25 km resolution surface winds. Wind barbs in red indicate GALE force strength with winds from 17 to 20 m s^{-1}. The corresponding QuikSCAT winds show a sharp decrease in wind speed across the North Wall of the Gulf Stream with winds lowering to 7 to 10 m s^{-1}. Interestingly, these values correspond very well with those discussed by Sweet at al. (1981). The SST composite shows a warm ring to the north of the Gulf Stream as indicated by the arrow in (a). Over the warm water of the warm ring we see an area of increased winds to GALE force (17 to 20 m s^{-1}).

In this example we see higher wind speeds over the Gulf Stream and associated warm ring and lower wind values over the cooler waters.

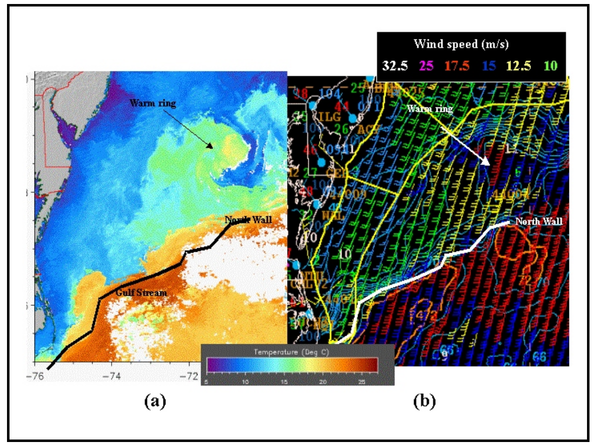

Fig. 2. SST AVHRR 3 day composite (a) and 25 km QuikSCAT winds (b). In (b) wind speeds are colored as indicated in the table in the upper right hand corner. The location of the North Wall of the Gulf Stream is shown by a darl line in (a) and white line in (b). Contours in (b) are SST in degrees F from the NESDIS 14 km resolution SST analysis.

SSTs were estimated at 22 to 23°C over the Gulf Stream, 18°C over the warm eddy and 12 to 15°C over the slope and shelf waters. This represents a 10°C difference from the Gulf Stream to the shelf waters.

Example 2 is from June 2002 as a cold ring began to pinch off south of Nova Scotia at approximately 59°W longitude. A uniform pressure gradient with southwest winds existed over the forming cold ring. Wind speeds drop from 10 to 12.5 m s^{-1} over the warmer water to 5 to 7.5 m s^{-1} over the forming cold ring. There is no change in synoptic scale pressure gradient across these waters. SST lowered approximately 5 to 7 °C over the forming cold ring. In this example we see a 50% reduction in wind speed over the cooler waters. The winds downwind of the cold pool increase again to similar speeds as upstream of the cold pool (10 to 12.5 m s^{-1}).

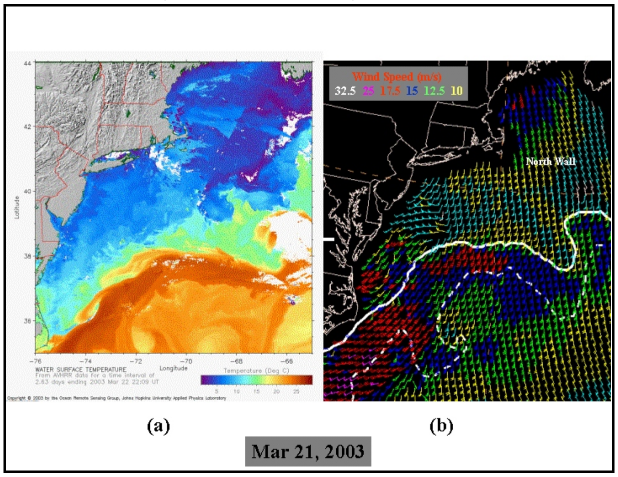

Fig. 4. 3-day SST composite from AVHRR (a) and QuikSCAT winds from March 21, 2003 (b). The U.S. Navy OFA Gulf Stream North Wall (white solid line)and South Wall (white dashed line) analyses are shown in (b).

Example 3 shown in Figure 4 is another spring example from March 21, 2003. Similar to example 1, southerly flow dominates the western North Atlantic waters from the subtropics to the Gulf of Maine. In this case GALE force winds of 17.5 to 22 m s^{-1} were observed by QuikSCAT over the Gulf Stream core. To the north of the Gulf Stream southerly winds dropped to 7.5 to 10 m s^{-1}. The shape of the wind maxima follow closely the contours of the North Wall. A cool ring can be seen in (a) to the east of Cape Hatteras centered on 71.5°W longitude. A minimum in wind speed of 7.5 m s^{-1} can be seen in this location in (b).

3. GUIDANCE FOR FORECASTERS

Accurately forecasting the wind conditions described in section 2 is a very difficult challenge for OPC forecasters. Operational numerical guidance from global models do not typically handle the changes in wind speed we have observed across the Gulf Stream north wall. This can result in wind warning areas being too large and possible economic losses. The NCEP Global Forecast System uses a 50 km SST that does not contain the warm and cold rings observed across the western North Atlantic. The Gulf Stream SST gradients are highly smoothed. The bias of the western North Atlantic (WNA) NOAA Wavewatch III (Tolman et al. 2002) 10 m winds as compared to altimeter derived winds is shown for the western North Atlantic. These winds are derived from the NCEP Global Forecast System. The time period shown is March

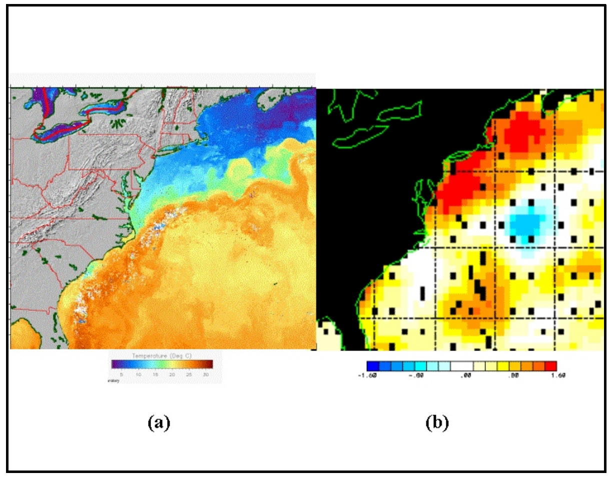

Fig. 5. Seven day AVHRR SST composite from April 15, 2002 in (a). Bias of 10 m winds from the NOAA Western North Atlantic Wavewatch III Wave Model as compared to altimeter derived winds (b).

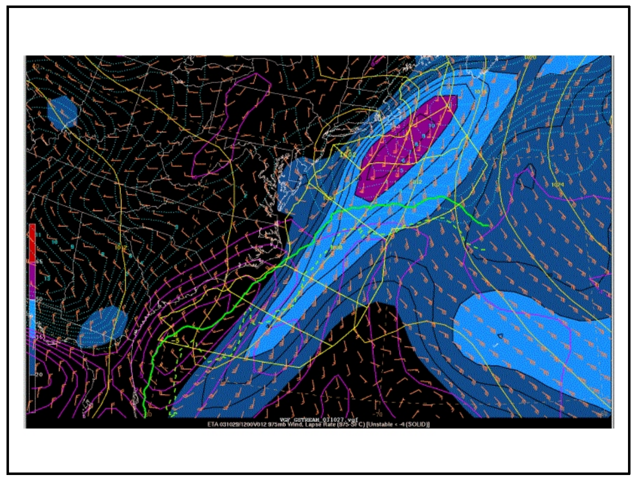

Fig. 6. Eta model forecast from 29 Oct 2003 of 975 hPa-surface lifted index as purple solid lines where negative and cyan dashed lines where positive. Contours are 975 hPA isotachs. Yellow lines are surface isobars at a 4 hPa spacing. Wind barbs are 975 hPa winds. The green solid line is the north wall of the Gulf Stream from the U.S. Navy OFA analysis.

through May 2002 and was a spring season dominated by southerly flow across the Gulf Stream and to the New England waters. The left panel shows the SST 7 day AVHRR composite from mid April 2002. The red areas in (b) show clearly that there is a high bias in the numerical guidance over the cooler shelf and slope waters.This bias over cooler water points to an inability of the model (the NCEP GFS) to reduce wind speeds over cooler waters. In essence it appears that low-level static stability does not have as significant an impact on the low level winds in the model forecasts as we have observed with QuikSCAT.

OPC forecasters have several guidance tools based on numerical model output to help forecast the complexity of the surface wind field off the mid Atlantic Coast. Some of these have strengths and weaknesses. An early attempt to define areas of static stability with the NCEP Eta model was to calculate a lifted index from the surface or skin temperature to the 975 hPa level. Areas of potential mixing are unstable with a negative lifted index (LI) and are magenta. Statically stable areas have a positive LI and are shown as dotted cyan contours. Winds displayed are the 975 hPa winds. This gives the forecaster some indication about potential for winds in well mixed areas but significantly over forecasts winds over the stable MABL.

In this example in Figure 6, we see that the area of instability in southerly flow parallels but is farther south than the North Wall of the Gulf Stream. This may be due to the coarseness of the 14 km SST field used by the Eta. A large stable layer with lifted indices to +11 can bee seen over the outer New England waters. This guidance is

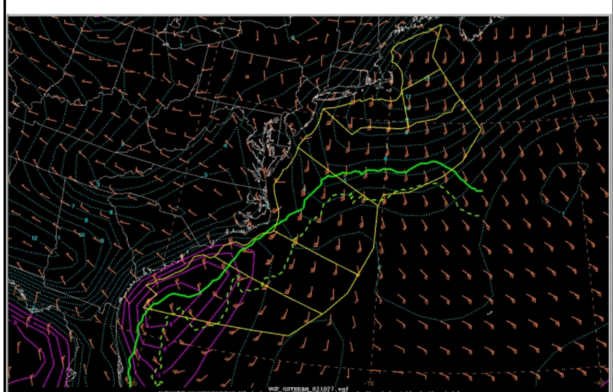

Fig. 7. GFS based surface to 925 hPa lifted index with magenta contours negative indicating instability. Cyan dashed contours are positive and indicate areas of stability. Plotted winds area mix of 40 m high winds in unstable areas and 10 m winds in stable areas. The Navy OFA Gulf Stream analysis is shown as in Fig. 6.

useful for estimating areas of low-level mixing and mixing inhibition but does not aid the forecaster in deciding the strength of winds over the stable cold waters.

Figure 7 shows a 12 hour forecast of a mix of 40 m and 10 m winds from the NCEP GFS model for 1200 UTC 29 Oct 2003. Winds displayed are a function of the 925 hPa to surface LI. The 40 m winds are displayed in areas of instability and 10 m in stable conditions. In part because of the coarseness of the underlying SST field this guidance does not always show shallow areas of instability over the Gulf Stream. In comparing the Eta guidance in Figure 6 and GFS in Figure 7 there are significant differences across the area of the Gulf Stream. Forecasters have found this guidance useful but is still limited due to the low resolution.

The RUC (Rapid Update Cycle) model (Benjamin et al., 2002) offers short term guidance

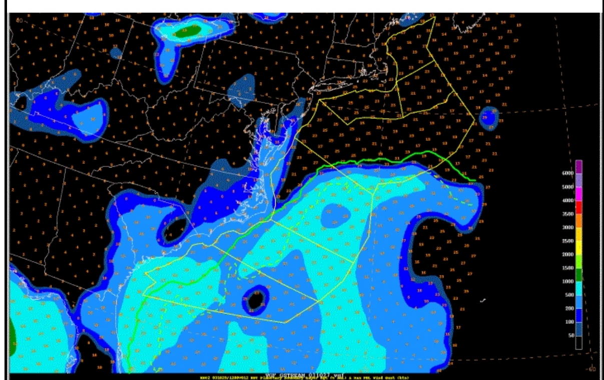

Fig. 8. NCEP RUC model height of the MABL (colored contours) and maximum MABL wind gust (numeric values) in knots for 1200 UTC 29 Oct 2003.

for forecasters for the U.S. and adjacent offshore waters. Figure 8 shows the RUC height of the MABL and maximum wind gusts as discussed by (Benjamin et al., 2002). The Gulf Stream north wall parallels the higher MABL heights northeast of Cape Hatteras. The MABL height varies from less than 50 m over the shelf and slope waters to nearly 1 km over the Gulf Stream. Maximum wind gusts vary from 25 to 27 knots (12.5 to 13.5 m s^{-1}) over the shallow MABL to 16 to 18 m s^{-1} over the well mixed deep Gulf Stream MABL. The maximum MABL gusts are shown in Figure 9 as colored contours along with the 10 m wind barbs. In comparing Figure 9 to Figure 8, it is clear that the maximum gusts of 17.5 m s^{-1} are forecast over the Gulf Stream and deeper mixed MABL. Oddly the 10 m winds show no significant difference between the slope waters and Gulf Stream. To date these RUC fields are the best guidance OPC

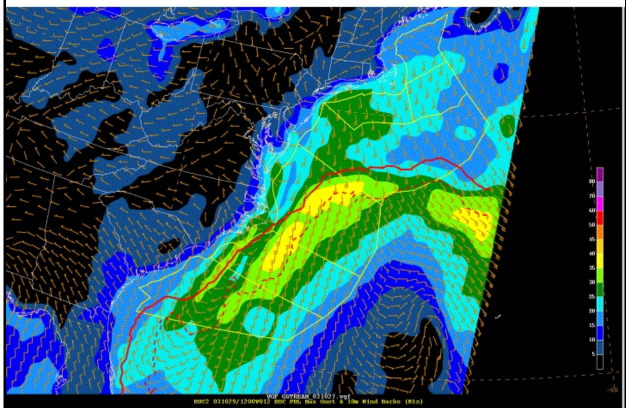

Fig. 9. RUC 10 m winds (barbs) and maximum gust value (in knots) as colored contours for 1200 UTC 29 Oct 2002.The Gulf Stream North Wall is shown as a solid red line.

forecasters have to both determine mixing depth and maximum wind speed potential across the complex SST gradients of the Gulf Stream. This guidance is being adapted to the NCEP Eta model and should be available within the next six months.

4. SUMMARY AND CONCLUSIONS

Scatterometer derived winds have shown significant wind speed gradients across the north wall of the Gulf Stream, warm and cold rings and adjacent cool slope waters. Typically, a sharp decrease in wind speed is observed over the cooler slope and shelf waters as compared to winds over the warm well mixed Gulf Stream MABL. As discussed in earlier papers the decrease in wind speed is due to an increase in low-level static stability over the cooler shelf waters (Sweet et al. 1981 and Desjardins et al. 1998). In fact a 50% reduction in wind speed was observed by QuikSCAT across the Gulf Stream SST front. The 50% reduction matches well with the aircraft observations discussed by Sweet et al. (1981). The examples shown in this paper are all spring or early summer cases when SST gradients are a maximum. The climatology of Gulf Stream wind events needs to be examined.

Forecasting the winds conditions across these dynamic waters is a very difficult task for OPC Offshore and High Seas forecasters. The impact is beyond the wind forecasts as the winds generate waves. Model biases in wind fields as shown earlier do indeed carry over to wind wave forecasts. Numerical forecast guidance typically over forecast 10 m winds over the cooler waters under stable conditions and under forecasts winds over the well mixed Gulf Stream MABL. The OPC has attempted to create guidance using existing NCEP models for forecasters to anticipate changes in MABL stability and make educated adjustments to wind speeds and wave forecasts. Some of these have been discussed in Section 3. All have strengths and weaknesses. The most positive to date is the height of the MABL from the RUC and the associated maximum MABL gust values. These parameters are being added to those available from the NCEP eta model within the next 6 months.

To accurately forecast wind and sea conditions, it is clear that a high resolution and timely SST analysis is needed. This will require combining SST data from multiple sources and factoring in the strengths and weaknesses of each instrument. Currently OPC forecasters have available hourly 24 hour composites from the GOES-12 satellite. This data has proven valuable but suffers like all thermal images from contamination from clouds. The high temporal resolution (48 looks per day) and relatively short compositing time (24 hours) of the GOES-12 SST product is a good starting place. Beyond SST analyses, there is a need for accurate forecasts of ocean features. The NCEP is currently adopting the HYCOM Model (Bleck, 2002) and expect to be operational in several years.

Wind forecasts off the Mid-Atlantic Coast need to be improved. Empirical studies comparing forecast wind speeds with observed winds from buoys and QuikSCAT under different flow regimes need to be done. The results of these studies need to be in the hands of the OPC forecasters to help make educated adjustments to numerical model wind fields. Perhaps the numerical wind guidance and boundary layer assumptions within numerical models need to be examined.

5. REFERENCES

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