Summer Institute in Earth Sciences 2010

Hurricane Induced Sea Surface Temperature Changes

Kamila Wisniewska
Department of Geography, Hunter College
City University of New York

Research project conducted at NASA
Goddard Space Flight Center

Mentors: S. Daniel Jacob and Paolo de Matthaeis
Goddard Earth Sciences and Technology Center
Code 614.1

Abstract

Tropical cyclones, hurricanes as they are called in the Atlantic ocean basin, are one of the most destructive natural disasters known to mankind. Strong winds and heavy rain are associated with these weather systems which produce large waves in the ocean. The landfalling tropical cyclones cause disastrous damage to the coastal infrastructure and the natural environment, extensive flooding due to storm surge and very often loss of life. As hurricanes depend on the ocean for energy for intensification, investigation of hurricane-ocean interactions leads to better understanding of the evolution of these storm systems and allows for more accurate forecasting of intensity change in land-falling hurricanes. The main objective of the current research project was to use optimally interpolated, remotely sensed microwave and infrared Sea Surface Temperature (OI SST) data to document the SST changes resulting from storm forcing. SST changes for 19 hurricanes in the Atlantic basin, classified as Category 3 and above, were stratified according to storm characteristics such as the translation speed and maximum observed winds and the mean SST change composites were generated. The mean maximum cooling for hurricanes with intensity below Category 3 and translation speeds: below 3 m/s, between 3 and 6 m/s and above 6 m/s was -1.16^{o}C, -1.5^{o}C and - 0.76^{o}C, respectively. The mean maximum cooling for hurricanes with intensity of Category 3 or greater and for the above mentioned translation speed categories was -2.25^{o}C, -1.69^{o}C and -0.94^{o}C. The reported results for less intense hurricanes are counterintuitive, since we expected that the magnitude of SST changes would decrease with increasing translation speed as for the more intense cases. Additionally, the overall magnitudes of mean SST changes are not as large as documented by in situ observations. Therefore, more research on the subject is required to explain these results.

Introduction

Tropical Cyclones

Tropical cyclones are non-frontal, synoptic scale low-pressure systems that develop over large bodies of warm water, mainly in the tropical or sub-tropical regions. They are characterized by a 'warm core' and an organized convection. The primary energy source driving these storms is the latent heat released in clouds, which ultimately is extracted from the underlying ocean. The formation and evolution of tropical cyclones, based on the climatology of tropical cyclone genesis by Gray (1968, 1975, 1979) is related to six environmental factors:

1. Warm ocean waters of at least 26°C (80°F) throughout a sufficient depth at least on the order of 50m (150 ft).
2. An atmosphere which cools fast enough with height such that it is potentially unstable to moist convection. The thunderstorm activity allows the heat stored in the ocean waters to be liberated for the tropical cyclone development.
3. Relatively moist layers near the mid-troposphere (5 km, 3 mi).
4. A minimum distance of at least 500 km (300 mi) from the equator. For tropical cyclogenesis to occur non-negligible amounts of Coriolis force are necessary to provide for near gradient wind balance.
5. A pre-existing near-surface disturbance with sufficient vorticity and convergence. The development of tropical cyclones requires a weakly organized system with stable spin and low level inflow.
6. Low values of vertical wind shear between the surface and the upper troposphere (less than about 10 m/s (20 kt, 23 mph)). Large values of vertical wind shear can prevent genesis or weaken and destroy the tropical cyclone by interfering with the organization of deep convection around the cyclone's center.

According to the classification provided by the National Hurricane Center (NHC), tropical cyclones with maximum sustained winds of less than 17 m/s (34 kt, 39 mph) are called 'tropical depressions'. Once the tropical cyclone reaches winds of at least 17 m/s they are typically called 'tropical storms' and assigned a name. When the winds reach 33 m/s (64 kt, 74 mph) then they are called:

- 'hurricanes' (the North Atlantic Ocean, the Northeast Pacific Ocean east of the date line, or South Pacific Ocean east of 160E)
- 'typhoons' (the Northwest Pacific west of the dateline)
- 'severe tropical cyclones' (the Southwest Pacific Ocean west of 160E or Southeast Indian Ocean east of 90E)
- 'severe cyclonic storms' (the North Indian Ocean)
- 'tropical cyclones' (the Southwest Indian Ocean).

Hurricanes can be further classified based on their maximum sustained wind speeds into five categories. This classification is referred to as the Saffir-Simpson Hurricane Scale (SSHS) and it is summarized in Table 1.

SSHS Category	Maximum Sustained Wind Speed		
	m/s	mph	kt
1	33 - 42	74 - 95	64 - 82
2	43 - 49	96 - 110	83 - 95
3	50 - 58	111 - 130	96 - 113
4	59 - 69	131 - 155	114 - 135
5	70 +	156 +	136 +

Table 1. Saffir-Simpson Hurricane Scale.

The official Atlantic Tropical Cyclone season lasts typically form June 1st to November 30th, with the greatest storm activity starting in the middle of August and lasting through the middle of October. However, once every few years tropical cyclones occur also out of the season. For instance, Tropical Storm Ana inaugurated the 2003 season in late April. On average each year we expect about 11 tropical storms, 6 of which would be hurricanes and two of which would be Category 3 or greater (major hurricanes). The record breaking 2005 hurricane season was the most active since 1933, with 31 tropical cyclones of which 15 were classified as hurricanes.
At sea tropical cyclones cause strong winds, large waves and heavy rain. The international shipping industry, cruise vessels and private boats are often damaged or lost under such weather conditions. The landfalling tropical cyclones cause disastrous damages to the coastal infrastructure and natural environment, extensive flooding due to storm surge and loss of life. The NHC reports that the total number of deaths in the United States due to hurricanes since 1900 to 2005 exceeded 18,500 and the total cost of the damage adjusted to the 2005 dollars is estimated at $350 billion (Pielke et al. 2008). Taking into account the frequency with which hurricanes occur each year, the death toll and the cost of the damage, hurricanes are thought of as one of the most destructive natural disasters know to mankind.

The analysis of observational data, the theoretical and numerical models have greatly increased our understanding of the mechanisms governing the formation and evolution of tropical cyclones. These efforts ultimately contributed to more advanced prediction techniques. Early and accurate warnings issued to coastal populations and civil authorities threatened by an approaching hurricane are crucial in making necessary preparations to protect property and life.

Even though numerous observational and numerical studies have shown that tropical cyclones produce significant SST changes, all of the aspects of ocean's response to storm forcing are not well understood. The use of hurricane heat content derived from satellite radar altimetry measurements of Sea Surface Height (SSH) has been shown to improve intensity prediction.
Yet, in most research and operational dynamical models conditions of fixed SST in time are assumed. (WMO/TD-No. 693)

Upper Ocean Response to Tropical Cyclones
Strong wind forcing exerted on the ocean surface by hurricane strength tropical cyclones produces turbulent mixing of the upper oceanic layer, mixed layer deepening and entrainment of colder water form below. This is the primary mechanism responsible for the SST decrease during the tropical cyclone passage. (Price 1981; Black 1983).

Thermal Response
The analysis of observational data from hydrographic surveys suggests that the maximum cooling occurring after passage of tropical cyclone ranges between -1 and -6 ^{o}C. This response increases with decreasing hurricane translation speed and with increasing hurricane intensity (Price 1981). Black (1983) conducted an extensive review of 10 years of ocean temperature observations obtained from airborne infrared radiation thermometers (AIRTs) and aircraft-expendable bathythermographs (AXBTs). His analysis revealed a crescent-shaped pattern for the SST decrease underneath a tropical cyclone. The largest decrease was located in the right-rear quadrant between 1 and 2 RMW, where RMW is the radius of maximum winds.

Momentum Response
The forced stage response during the actual storm passage is mainly a local (depth and time dependent) response of the ocean to the very strong wind stress of the hurricane. The time scale of the forced stage is the storm residence time, which is typically half a day.
The relaxation stage response following a hurricane passage is inherently a nonlocal (three-dimensional and time dependent) baroclinic response to the stress curl of a hurricane. The time scale of the relaxation stage response is typically 5-10 days (Price et al., 1994).

Data

The following data sources are used in this study.
Best Track Data: The position of the storm's center as well as the observed maximum winds in six hour increments were obtained from the National Hurricane Center's storm reports. (www.nhc.noaa.gov).

Radii of Maximum Winds (RMW): The daily radii of maximum winds for the selected storms were obtained from the formation structure analysis available from the following Colorado State University web page. (http://euler.atmos.colostate.edu/~vigh)

Microwave Satellite OI SSTs: The Optimally Interpolated daily microwave and infrared Sea Surface Temperature (SST) data was obtained from the Remote Sensing Systems website. (http://www.remss.com). The SST product used in this research project was created by combing the microwave SST measurements taken by the TRMM Microwave Imager (TMI), carried on NASA's Tropical Rainfall Measuring Mission satellite, the Advanced Microwave Scanning Radiometer for Earth Observing System (EOS)(AMSR-E) and the infrared SST measurements captured by Moderate-resolution Imaging Spectroradiometer (MODIS), carried on NASA's AQUA satellite. The TMI data at 0.25 degree (~ 25km) spatial resolution, covering latitudes between 40S and 40N is available since 1998 to present. The combined microwave (TMI and AMSR-E) and infrared (MODIS) data at 0.09 degree (~ 9km) spatial resolution, which provide global coverage (90S to 90N) are available since 2007 to present.

Method

Nineteen tropical cyclones in the Atlantic Basin, classified on the Saffir-Simpson Scale as major hurricanes (Category 3 and above), were selected for a 10 year period from 1998 to 2008. The list of selected hurricanes is shown in Table 2. The daily positions of storm center at 12.00Z given by the Best Track data were used to calculate latitude and longitude of the points constituting the cross-track profile. Since, the fundamental scale on which moving hurricane affects the underlying ocean (the area of the strongest forcing) is determined by the Radius of the Maximum Winds (RMW), the distance between the cross-track points was normalized by the daily RMWs in 0.5 (between 0 and 3) and in 1 (between 3 and 6) RMW increments to the left and right side of the storm center relative to its motion. The translation speed (U) for each storm was calculated in six hour increments based on the change in position of the storm's center and the corresponding change in time. The daily SSTs were linearly interpolated at the cross-track profile for the duration of the storm, one day before the storm and four days after the storm (Wake I - IV). The hurricane induced SST changes were computed as the difference between SSTs for each day of the storm and the SSTs one day before the storm. The ΔSST were then stratified according to hurricane's translation speed and its intensity, given by the maximum observed wind speed (MWS). For the translation speed three groups were selected: storms with translation speeds less or equal to 3m/s, storms with translation speed greater than 3 and less or equal to 6 m/s and storms with translation speed greater than 6 m/s. Then, the above groups were further divided into two more categories: storms with MWS less than 50 m/s (below Category 3) and storms with MWS equal or greater that 50 m/s (Category 3 and above).
The mean storm composites of the change in SST were computed for the storm day and up to four days after the storm passage. A schematic diagram summarizing the procedure followed to compute mean storm composites of hurricane induced SST changes is shown in Figure 1. The results of the analysis will be discussed in the following section.

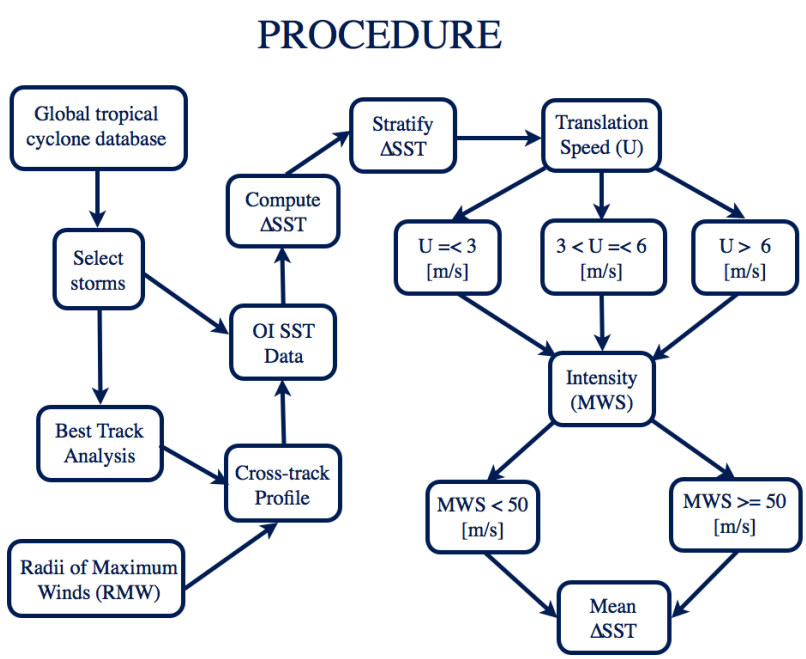

Figure 1. Schematic representation of the procedure used to analyze hurricane induced SST changes.

Name	Date	Category
GEORGES	Sep 15 - Sep 29 1998	4
MITCH	Oct 22 - Nov 05 1998	5
FLOYD	Sep 07 - Sep 17 1999	4
GERT	Sep 11 - Sep 23 1999	4
LENNY	Nov 13 - Nov 21 1999	4
ISSAC	Sep 21 - Oct 01 2000	4
ERIN	Sep 01 - Sep 15 2001	3
MICHELLE	Oct 29 - Nov 06 2001	4
LILI	Sep 21 - Oct 04 2002	4
ISABEL	Sep 09 - Sep 19 2003	5
FRANCES	Aug 25 - Sep 09 2004	4
IVAN	Sep 02 - Sep 24 2004	5
KATRINA	Aug 23 - Aug 31 2005	5
RITA	Sep 18 - Sep 26 2005	5
WILMA	Oct 15 - Oct 25 2005	5
HELENE	Sep 12 - Sep 24 2006	3
DEAN	Aug 13 - Aug 23 2007	5
GUSTAV	Aug 25 - Sep 04 2008	4
IKE	Sep 01 - Sep 14 2008	4

Table 2. List of storms selected for the analysis.

Discussion

The mean storm composites of hurricane induces Sea Surface Temperature changes (ΔSST) were computed based on the stratification explained in the Method section. The results of the analysis are presented and discussed below. Figure 2, illustrates the time evolution of the cooling caused by a passage of a hurricane strength tropical cyclones stratified according to the selected translation speed (U) and intensity (MWS) thresholds. Panels on the left side show mean cooling for storms with intensity below the Category 3 (MWS < 50 m/s) and the panels on the right show the mean cooling for storms with intensity equal to Category 3 or greater (MWS >= 50 m/s). The horizontal axis denotes the time evolution of the cooling, for storm day denoted by 0 to 4 days after storm passage. The vertical axis on the left side of each figure is the cross-track distance normalized by the daily RMW of every analyzed storm. The storm's center is located at 0 RMW and the positive and negative values represent the the distances to the right and left side of the storm center, respectively.

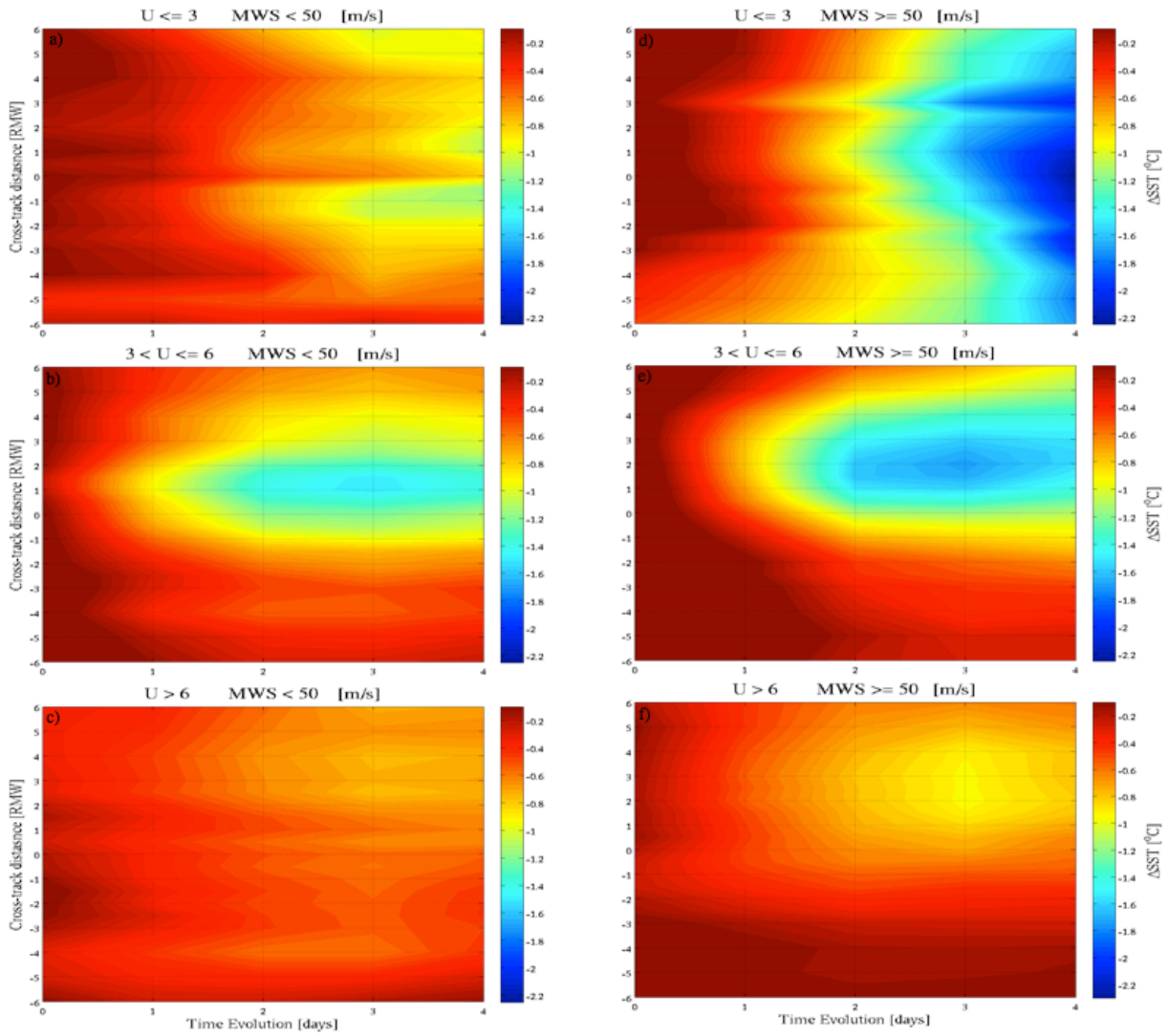

Figure 2. Time evolution of mean storm composites of hurricane induced ΔSST.

Panels (a) and (d) illustrate the mean ΔSST caused by slow moving storms (U =< 3m/s) for the two intensity categories. The ocean's thermal response is almost symmetric along the cross-track profile and its magnitude is greater for more intense storms. The mean ΔSST for storms moving with translation speeds between 3 and 6 m/s is shown in panels (b) and (e). The cold wake caused by these storms appears on the rightward side of the storm center and has wedge-like shape. This is due to the currents that propagate as near-inertial gravity waves and turn right along the wake causing dynamic instability on the right side, such that cooler deeper water mixes with the near surface water. This wave response is absent for storms moving with translation speeds less or equal to 3 m/s, therefore the cooling is almost symmetrical. Storms which have translation speeds greater than 6 m/s (panes (c) and (f)) and therefore shorter residence time at each location have smaller thermal response than the slower moving storms.For storms with translation speeds less than or equal to 3 m/s, the maximum mean cooling occurs on the fourth

day after storm passage. For storms with translation speeds above 3 m/s, the maximum mean cooling occurs three days after storm passage. Based on the in situ observations, it is well known that the maximum cooling occurs 1 to 2 days after storm passed over given location. The time delay in the cooling may be attributed to the daily temporal resolution and the averaging techniques used to create the OI SST products. The values of the maximum mean cooling according to storm intensity and translation speed are shown in Table 3.

Wake	MWS < 50			MWS >= 50		
	U =< 3	3 < U =< 6	U > 6	U =< 3	3 < U =< 6	U > 6
0	-0.3995	-0.2167	-0.3472	-0.4722	0.0419	-0.2534
1	-0.4540	-0.9225	-0.4625	-0.6879	-0.7800	-0.5380
2	-0.7452	-1.4122	-0.6492	-1.0464	-1.5989	-0.7883
3	-1.0691	-1.5023	-0.7575	-1.7721	-1.6886	-0.9411
4	-1.1598	-1.3876	-0.7256	-2.2452	-1.5442	-0.8245

Table 3. The maximum mean ΔSST [^{o}C] for the six storm composites, U and MWS are in [m/s].

Looking at panels (a) and (b) of Figure 2 as well as columns 2 and 3 of Table 3, it can be seen that the magnitude of cooling is greater for the storms with translation speeds between 3 and 6 m/s. Additionally, this can be seen in Figure 4, which illustrates the mean ΔSST on the fourth day after the passage of the storms (Wake IV) for the different storm composites. The vertical axis and horizontal axis are the mean ΔSST and the cross-track profile, respectively. The green, blue and red curves represent the the mean ΔSST for storms moving with the selected translation speed thresholds as shown in the legend. The mean ΔSST shown in panel (b) were expected to have similar pattern as the mean ΔSST shown in panel (a). In other words the expected thermal response should decrease with increasing translation speed for both intensity categories. Therefore, these results are not consistent with the findings based on in situ observations. Further analysis is required to identify the factors leading to this result.

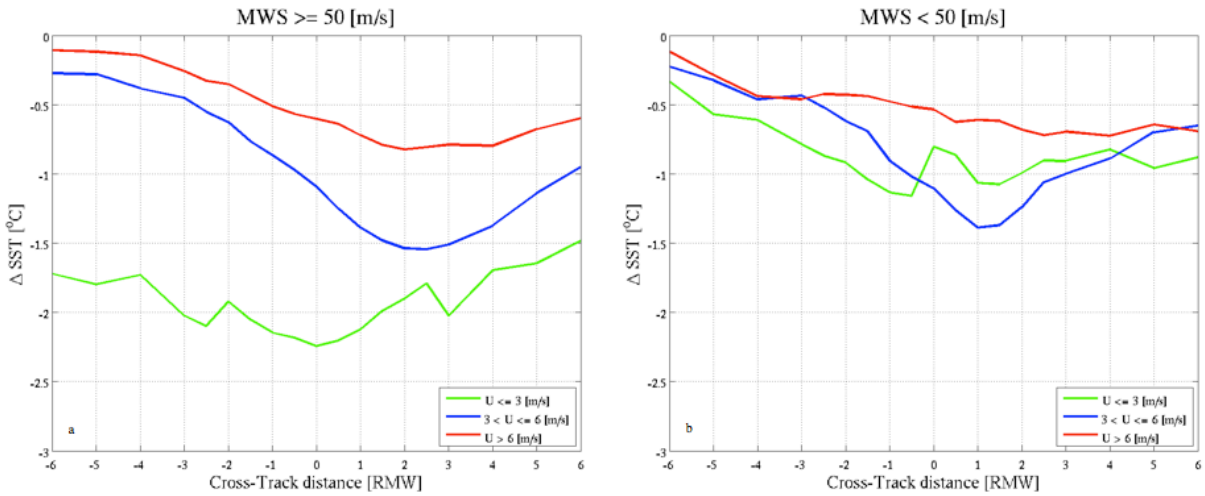

Figure 4. The mean ΔSST composites on the fourth day after storm passage (Wake IV).

The analysis of the ΔSST at the cross-track profile for the individual storms confirms that the ranges of the thermal response are more consistent with the in situ observations. Figure 5 illustrates the time evolution of the ΔSST (panel (c)) caused by hurricane Isabel on September 16, 2003, as well as the storm's translation speed (panel (b)) and intensity (panel (a)) throughout its duration. Although, the maximum cooling occurs on the third day after storm's passage (time delay), the magnitude of the cooling is more realistic. The maximum ΔSST reaches -5 °C.

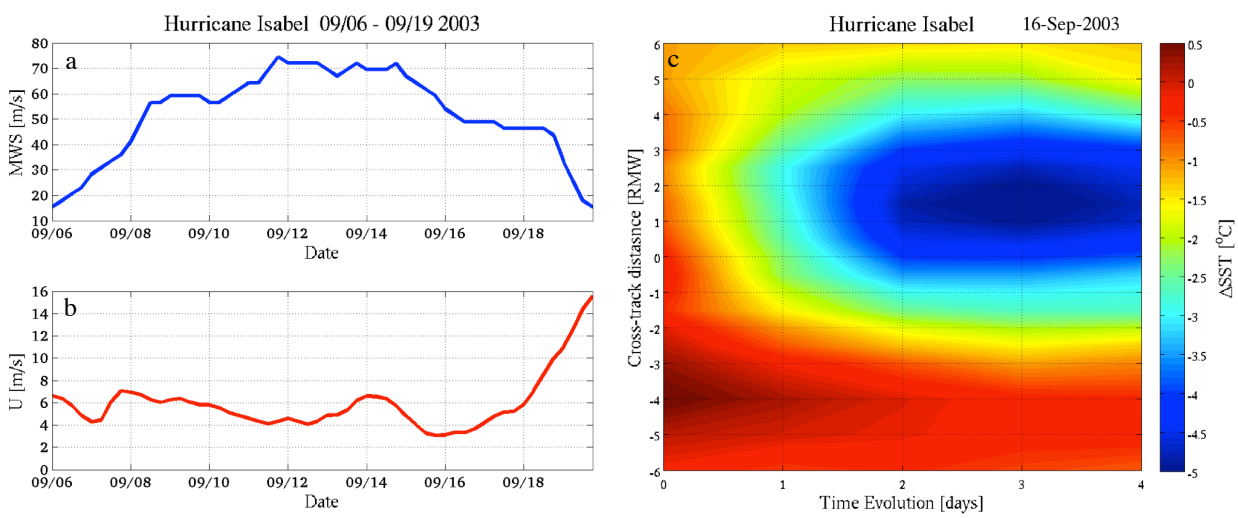

Figure 5. The ΔSST caused by Hurricane Isabel September, 2003.

The inconsistencies in the obtained results may be attributed to several factors. The number of analyzed storms is most likely insufficient and the analysis should include as many hurricanes as possible. The intraday variability of the SSTs is difficult to asses due to the daily temporal resolution of the OI SST data. Additionally, the averaging methods used to create the OI SST

products may result in smoothing of the SST ranges. Figure 6 illustrates the cold wake produced by hurricane Katrina on August 30, 2005. The larger black dots connected with lines represent the location of the storm each day at 12.00Z. The perpendicular dots to the storm's location on August 28 represent the cross-track profile. It is important to notice that since the OI SST are available only once per day the greatest area of cooling just north of the cross-track profile, shown in blue was not included in the analysis. Moreover, the degree of cooling depends also on the thermocline structure, in particular the depth of mixed layer. Therefore the deeper the mixed layer, the stronger forcing is required to cause the dynamic instability and entrainment of colder waters from below.

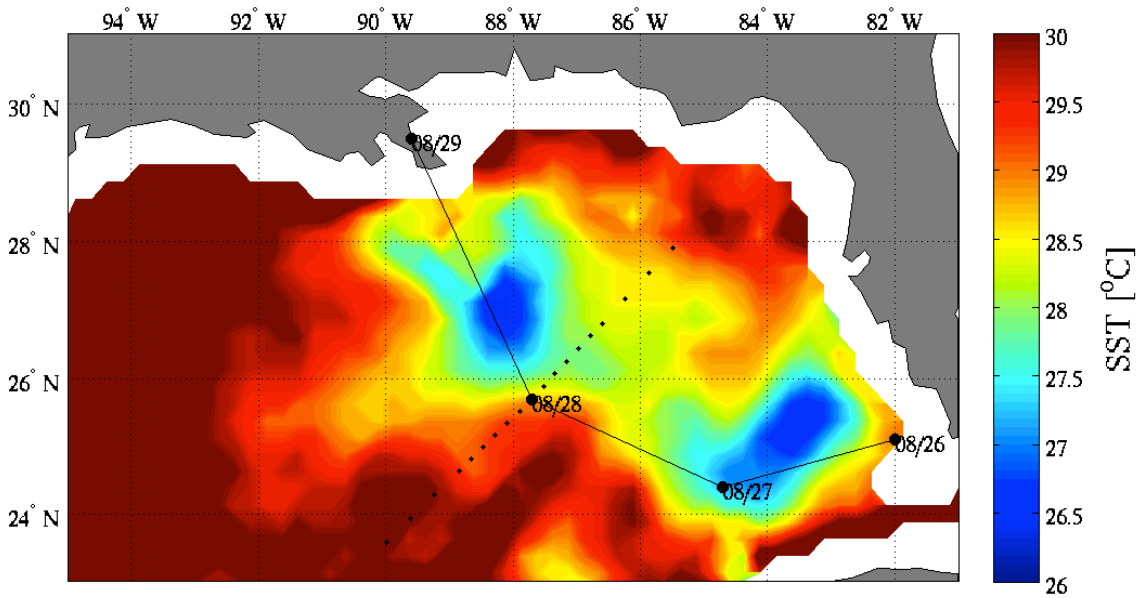

Figure 6. Cold wake due to the passage of hurricane Katrina on August 30, 2005.

Summary

The remotely sensed Sea Surface Temperature (SST) data were used in this project to document the hurricane induced SST changes. The SST changes for 19 hurricanes in the Atlantic basin were analyzed and stratified based on storm translation speed and intensity. The mean ΔSST composites were constructed. Not all of the obtained results were consistent with the in situ observations, therefore more research in this area needs to be done. In addition, by adding more storms to the analysis from the Atlantic and other ocean basins, a more complete composite construction will be needed to improve confidence in the results.

Acknowledgments

I would like to extend a special thanks to the Summer Institute in Earth Sciences program for providing this research opportunity. In particular, I would like to thank my mentors, Dr. S. Daniel Jacob and Dr. Paolo de Matthaeis for their support and guidance during this research project.

References

Black, P. G., 1983: Ocean temperature changes induced by tropical cyclones. Ph.D. dissertation, Pennsylvania State University, 278 pp.

Gray, W. M., 1968: Global view of the origin of tropical disturbances and storms. *Mon. Wea. Rev.*, **96**, 669-700.

Gray, W. M., 1975: Tropical cyclone genesis. Dept. of Atmos. Sci. Paper No. 323, Colorado State University, Ft. Collins, CO 80523, 121 pp.

Gray, W. M., 1979: Hurricanes: Their formation, structure and the likely role in the tropical circulation. *Meteorology Over the Tropical Oceans*. D.B. Shaw (Ed.), Roy. Meteor. Soc., James Glaisher House, Greenville Place, Bracknell, Berkshire, RG12 1BX, 155-218.

Pielke, Jr. R.A., J. Gratz, C.W. Landsea, D. Collins, M.A. Saunders, R. Musulin 2008: Normalized Hurricane Damages in the United States: 1900-2005. *National Hazards Review,* **9**, 23-48.

Price, J. F., 1981: Upper ocean response to a hurricane. *J. Phys. Oceanogr.*, **11**, 153-175.

Price, J. F.,T. B. Sanford, and G. Z. Forristall, 1994: Forced stage response to a moving hurricane. *J. Phys. Oceanogr.*, **24**, 233-260.

Shay, L. K., P. G. Black, A. J. Mariano, J. D. Hwakins, and R. L. Elsberry, 1992: Upper ocean response to hurricane Gilbert. *J. Geophys. Res.*, 97, 20227-20248

World Meteorological Organization, 1995: Global Perspective on Tropical Cyclones, Technical Document No. 693. Geneva, Switzerland. Chap. 5.