Remotely Sensed Tropical Cyclone Structure

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LONG-TERM GOALS

Accurately map the three dimensional structure and intensity changes of tropical cyclones via satellite remote sensing data for both real-time analyses and as input to numerical weather prediction models.

OBJECTIVES

Develop techniques to map the three-dimensional (3-D) structure of tropical cyclones (TCs) in all-weather conditions. Enable the analyst to determine whether a tropical system has changed intensity via the organization of relevant cloud/rain bands and the formation of an eyewall or eye. Derive a methodology that will work well at night when Infrared (IR) data is typically poor and inadequate.

APPROACH

Passive and active microwave satellite data will be used to mitigate the current limitations of visible and infrared (vis/IR) data used to monitor tropical cyclone (TC) structure and intensity worldwide. Geostationary vis/IR data enable users to determine storm motion and intensity estimates, but the sensors are unable to see through upper-level clouds (cirrus shield created by vigorous convection in rainbands and eyewall). The inability to see through upper clouds degrades real-time warnings. Inaccurate nowcasts create poor initial conditions and then impair subsequent numerical model forecasts.

The Special Sensor Microwave/Imager (SSM/I) is a seven (7) channel passive microwave imager onboard the Defense Meteorological Satellite Program (DMSP) polar orbiter satellites. The SSM/I's 85 GHz channel is able to penetrate most non-raining clouds and the spatial resolution (12x15-km) can effectively map most rainbands and eyewall features. The ability to view TC internal 2-D structure around the clock is vital in knowing whether a system is intensifying, decaying, or remaining steady state and helps understand internal storm dynamics.

The Advanced Microwave Sounding Unit (AMSU) is a passive microwave sounder that has two functions that assist in TC monitoring; 1) mapping the upper-level warm core temperature anomaly via vertical temperature profiles, and 2) using the 89 GHz channel to assist in determining eye size for the intensity estimation algorithm. Tropical cyclones are a heat engine and create an anomalous pool of warm air above them that is directly related to their intensity. Therefore, if we can derive a method to map the warm core with satellite sounders, the community has an independent method to estimate TC intensities worldwide.

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WORK COMPLETED

SSM/I passive microwave digital imagery from over 6,500 tropical cyclone overflights has been processed at NRL-MRY. The data processing techniques utilize specific image enhancement methods to produce high quality outputs. The 85 GHz images and rainrate products are analyzed by both human analysts and provided as input to an automated computer vision technique. The computer vision method has been applied to over 2,000 TC samples meeting strict criteria and is now gearing up to incorporate near real-time data for additional tests. In addition, one season of total precipitable water products have been produced for the Atlantic basin.

AMSU passive microwave sounding data from the NOAA-15/16/17 polar orbiters have been processed for the past two (2) years over TCs in both the Atlantic and Pacific basins. Significant effort has been focused on the Atlantic basin due to the availability of high quality aircraft reconnaissance validation measurements. Near real-time processing is now online and providing the research team with invaluable insight on how to improve the algorithm and extend it to the western Pacific for eventual use at the Joint Typhoon Warning Center (JTWC).

RESULTS

This 6.2 effort has led the way in mining the wealth of TC organization information available in passive microwave imagery. The ability to use the 85 GHz imagery to see through non-raining clouds and remove the inherent limitations with vis/IR imagery has enabled researchers to better understand the time evolution of TC development and decay. Direct comparisons with coincident vis/IR data have proven time and again that passive microwave data can assist in both the nowcast position (relocations of 60-120 miles have occurred based on this data set) and intensity.

Passive microwave data is especially relevant at night when the analyst only has 4-5 km IR data to view and may follow cold cloud tops unrepresentative of the low-level circulation center (LLCC). Shear conditions remove many of the cold clouds, but low-level clouds associated with exposed LLCC are very hard to see in IR data. The Central Dense Overcast (CDO) and shear conditions come at critical times in a storm's timeline and need to be mapped in real-time for the warnings and model bogus to be accurate and effective. Examples are readily available on the NRL-MRY tropical cyclone web page:

http://www.nrlmry.navy.mil/tc-bin/tc_home

Internal eyewall cycles have been recently shown to occur much more frequently than previously realized due to inadequate sampling using vis/IR data. The passive microwave database reveals a process whereby; 1) single eye shrinks with time to small diameter (8-12 nm), secondary eyewall forms at much larger radii and proceeds to gain strength while limiting inflow of moisture and momentum to the inner-eye and eventually the inner eye collapses. The outer eyewall then contracts as the storm reintensifies. The eyewall replacement cycle process can occur over 12-36 hours, with time varying due to several unknown factors. The cycle is shorter when "environmental factors" are very favorable for rapid growth. The replacement cycle appears to lengthen as environmental conditions become hostile or less conducive (shear, dry air entrainment, lower SSTs). The double eye configuration occurred while sustained winds were less than 120 kts (105 kts), lower than that found from a six-year database.

A systematic review of passive microwave data during 1997-2002 in Figure 1 reveals that concentric eyewalls are highly correlated with storms reaching 120 kts or higher. Approximately two-thirds (66%) of Atlantic basin storms and over three-quarters (75%) of western Pacific typhoons reaching best track intensities of 120 kts or more exhibited concentric eyewalls. WPAC storms reaching Super Typhoon intensity typically form further east than normal and have favorable environmental conditions for many days that permit them to more closely attain the maximum potential intensity (MPI). In contrast, Atlantic-basin storms usually are well westward in their track when reaching Category 3,4, or 5 status and literally run into unfavorable wind shear, landfall, dry air entrainment or some combination of these factors that weaken the hurricane and do not permit double eyewalls to form. This correlation is important to: a) TC satellite analysts interpreting passive microwave imagery, b) understanding TC short-term intensity trends, and c) theoretical studies trying to understand inner core storm dynamics associated with eyewall evolution. Passive microwave data from SSM/I, TMI and AMSU were used to create the database.

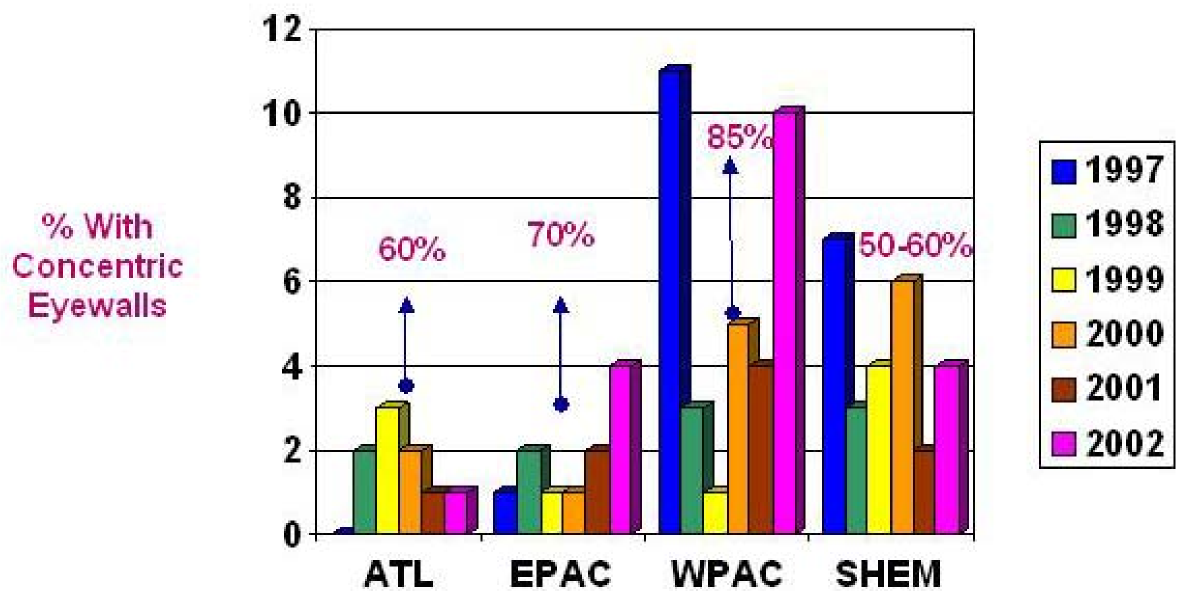

Figure 1: Number of tropical cyclones reaching a maximum sustained wind speed equal or greater than 120 kts for the Atlantic, Eastern Pacific, Western Pacific and southern hemisphere. The study time frame covers the years 1997-2002. Over 66% (two thirds) of all storms reaching 120 kts developed concentric eyewalls in the Atlantic and eastern Pacific, while the western Pacific statistics reveal 90%. Note the SHEM has more frequent concentric eyewall occurrences than the Atlantic or EPAC, while only a few storms actually reach > 120 kts.

The Atlantic basin is viewed by many as a "moist tropical belt" that is highly conducive to tropical cyclone development. Environmental factors such as wind shear, ocean heat content, surrounding surface pressures are closely monitored when attempting to figure which incipient tropical waves will double as they come off Africa. Evidence now reveals we need to spend considerably more effort mapping the very dry stable air associated with the Saharan Air Layer (SAL). SAL air is incredibly stable and maintains a rigid lid on convection due to a strong inversion at 850-900 mb. If SAL air gets too close to an existing system, the system's development can be arrested or delayed, depending on the extent of interaction. If SAL air is entrained, then rapid weakening can occur.

NRL teamed up with NOAA's Hurricane Research Division (HRD) during the summer 2003 Atlantic season to create a near real-time monitoring product. The three operational Special Sensor Microwave/Imagers (SSM/I) were used to map the total precipitable water (TPW) across the Atlantic basin every six hours. Very low values of TPW are used as a proxy for SAL air, since non-SAL air has a moisture profile extending well above the typical SAL inversion and contains considerably more total moisture in the vertical column. Figure 2 is a sample SSM/I TPW product for hurricane Isabel as it begins its journey. Dry SAL air is noted ahead and north of Isabel, while strong connections exist to the deep tropical moisture source to the southeast and southwest. The SAL air moved westward ahead of the storm, but some did entrain as the storm reached NE of Puerto Rico, possibly helping arrest the Category 5 intensity.

The SAL monitoring product was ftp'd and emailed to HRD field personnel and used to plan and make dropsonde measurements into potential SAL air around Isabel. These crucial aircraft data sets will be studied in FY-04 to understand our ability to map SAL air remotely and understand entrainment and its link to storm intensity changes.

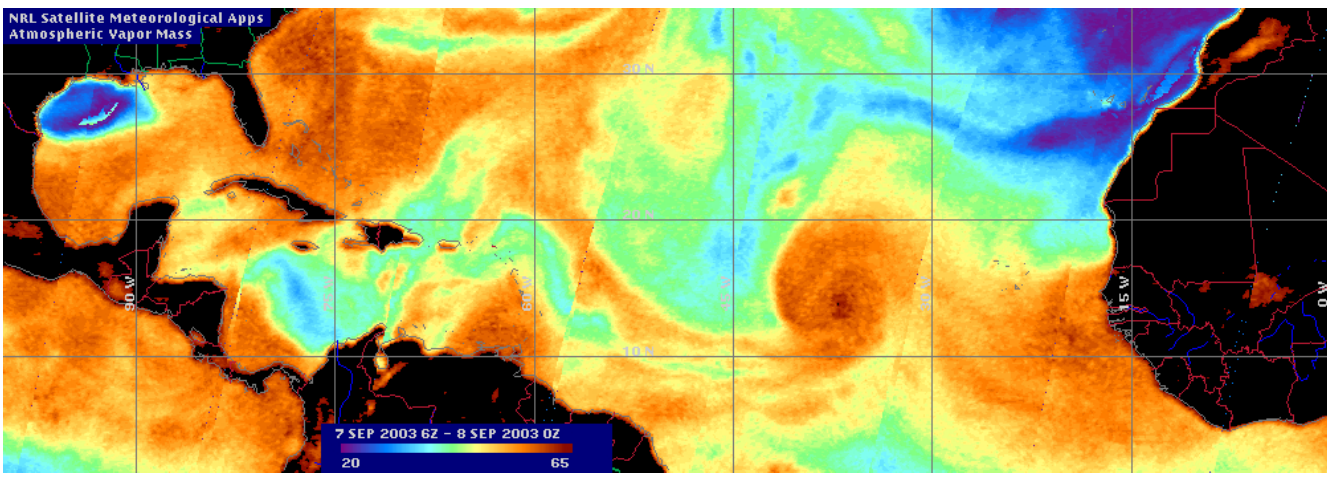

Figure 2. SSM/I produced total precipitable water (TPW) product for the Atlantic basin on Sept. 8, 2003 at 00Z. Data from three (3) SSM/Is are mosaiced over 18 hours to create this basin-wide view. The false color table has been selected to highlight moisture gradients and enable the user to readily discern boundaries between deep tropical air laden with moisture from much drier SAL air.

The AMSU TC intensity method using a warm core temperature anomaly module has proven very successful. Tests in the Atlantic revealed that accuracies similar to Dvorak errors (~ 12 mb) were achieved when compared to aircraft minimum sea level pressures. The main emphasis this year has been to incorporate the radius of maximum winds (a difficult parameter to measure). Operational values have been tested and discovered to work well most of the time, but poor values are entered that then directly impact the AMSU intensities. Efforts are underway to extract the Radius of Maximum Winds (RMW) automatically from a combination of passive microwave 85 GHz and IR imagery.

Statistics for Atlantic (N= 60) in hPa

	CIMSS	Dvorak
Mean Error	3.3	4.5
Std Dev	2.3	3.4
Bias	- 0.1	- 0.9
RMSE	4.0	5.6

Avg MSLP of sample 1002.4

Figure 3. AMSU derived tropical cyclone intensities validated with aircraft reconnaissance measured minimum sea level pressures (MSLP). The mean error, standard deviation, bias and root mean square error (RMSE) are calculated for 60 samples in the Atlantic. Comparisons are favorable when matched with coincident Dvorak IR.

IMPACT/APPLICATIONS

The passive microwave demonstrations have had a profound impact on our understanding of TC structure, intensity and evolution. The tropical cyclone theoretical and dynamical modeling communities are fascinated by the structural details now revealed by passive microwave data and are struggling to explain the mechanisms responsible to these short term changes that can have a profound impact on storm intensity. Understanding the reasons why TCs undergo eyewall replacement cycles will be a major plus for both forecasters and the modeling community trying to make inroads into TC intensity forecasting which woefully lacks the progress seen recently in track error reduction. Mapping SAL air accurately may directly improve our ability to predict TC intensity changes due to fluctuating interactions with this extremely dry and stable air mass.

TRANSITIONS

The capability to view and utilize passive microwave for TC reconnaissance has been transitioned to 6.4 and more recently to operations at Fleet Numerical Meteorology and Oceanography Center (FNMOC). FNMOC now creates and maintains a slightly modified TC web page 24/7. Both the AMSU warm core anomaly and SSM/I brightness temperature efforts have transitioned portions of their efforts to corresponding 6.4 SPAWAR 150 work units. A preliminary SAL mapping product will be transitioned to 6.4 in time for the summer 2004 season.

RELATED PROJECTS

This project is closely related to a 6.4 effort sponsored by the SPAWAR (PMW 150) entitled “Multi-Sensor Atmospheric Applications”, funded under PE 0603207N. The 6.4 project serves as the transition vehicle, works closely with JTWC, Naval Atlantic Metoc Center (NLMOC) and the National Hurricane Center, and currently has taken the software partially developed in this 6.2 task and produced near real-time intensity estimates. Feedback from JTWC, NLMOC and the NHC has been extremely positive.

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