OCEAN-ATMOSPHERIC INTERACTIONS, HEAVY PRECIPITATION, AND HURRICANE PREDICTIVE INDEX (HPI) ASSOCIATED WITH LAND-FALLING HURRICANE IRENE OVER THE EASTERN COAST OF THE UNITED STATES

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ABSTRACT

Hurricane Irene's deepest strengthening occurred during August 24th-25th, as it passed over the warm waters of the Bahamas and Gulf Stream whose SST's reached 30.5º C. Irene reached category 3 status by August 24th. By August 27th, the storm made landfall over North Carolina [2]. eTRaP data provided estimated precipitation totals of 1" to 5" around the eye, however, using TRMM satellite data, precipitation totals were 5.9" to 8.9" over the northeastern coast of the US where the eye passed. The conditions that surrounded Irene's rainfall totals were surmised to be a result of strong ocean-atmospheric interactions over the Bahamas during its peak intensification period: August 23rd – 25th. To support this hypothesis, heat fluxes and vertical motions were derived over the entire period of Irene's existence, August 20th – 29th, using atmospheric data and soundings. Heat fluxes, HPI, and vertical motions were found to peak on August 23rd and remain consistently high.

1. INTRODUCTION

Hurricane Irene began as a tropical wave that developed off of the west coast of Africa on August 15, 2011. It made its way inexorably westward towards the southern end of the Cape Verde islands. As it traveled, the atmospheric pressure began to fall, strong sustained winds were measured around the area of low pressure, and cyclonic rotation became noticeable. The wave was upgraded to Tropical Storm Irene at 2300Z, August 20. Low amounts of wind shear and high sea surface temperatures (SST's) around Hispaniola allowed Irene to deepen its strength as well as organization, reaching hurricane status by August 22. It grew from a category 1 to a category 3 tropical cyclone. As Irene moved over the warm waters surrounding the Bahamas, the storm lost its eye, which it did not recover, after passing through a weak area in the subtropical ridge. Tropical cyclone Irene was then downgraded to a category 1 storm during August 26 as it approached the outer coast North Carolina (Fig. 1).

Fig. 1 GOES image of Hurricane Irene

Irene made landfall over North Carolina on August 27 at approximately 1200Z as a category 1 tropical cyclone and continued northward as a tropical storm along the east coast and through the New England region before dissipating as an extra tropical wave in the early hours of August 29. The storm released massive amounts of moisture over the east coast, upwards of 2" per hour to a total of 8" to 12" over an area stretching from North Carolina to Maine. This led to massive flooding over a region that was kept well saturated since April where massive amounts of snow-melt as well as rainfall had led to above average amounts of water, up to 8" above average, in the Northeast and along the Mississippi river [12].

In this study, we have investigated the processes including vertical motions, heat fluxes, and ocean-atmospheric interactions associated with tropical cyclone Irene's copious amounts of precipitation using remote sensing, atmospheric soundings, and satellite data. Ocean-atmospheric interactions play a dominant role in exchanging heat, momentum, and moisture fluxes associated with storm intensity and track changes. Air-sea interface supplies heat energy to the atmosphere and to the storm. The more heat exchange, the more evaporation and the greater the intensity of the storm.

2. MATERIALS AND METHODS

The heat fluxes were computed first using bulk formulae. Secondly, eTRaP and TRMM satellite data were analyzed to show the estimated as well as the exact amounts of fallen precipitation. Next, atmospheric sounding data is analyzed to show atmospheric stability associated with the storm. To accomplish this, the vertical motions within the storm were calculated using the computations shown below.

2.1 Computations

Computations for Convective Available Potential Energy (CAPE) and provides a measure of the maximum possible kinetic energy that a statically unstable air parcel can acquire. Therefore, it provides a guide to the strength of convection and instability in the atmosphere.

Vertical velocity is calculated from CAPE at the equilibrium level (EL). The vertical velocity of an air parcel by buoyancy is given by:

$$\frac{D_w}{D_t} = g\,\frac{T_{parcel} - T_{env}}{T_{env}} \qquad (1)$$

Where

w = vertical velocity

T_{parcel} = temperature of parcel

T_{env} = temperature of environment

g = acceleration due to gravity

CAPE may be computed as:

$$\text{CAPE} = \int_{LFC}^{EL} g\left[\frac{T_{parcel} - T_{env}}{T_{env}}\right] D_z \qquad (2)$$

An expression for computing the maximum vertical atmospheric velocity at the EL (w_{max}) may now be derived based on CAPE. Note that Dw/Dt in Eq. 1 may be written as:

$$\left(\frac{D_w}{D_t}\right) = \left(\frac{D_w}{D_z}\right) \times \left(\frac{D_z}{D_t}\right) \qquad (3)$$

Since, $\frac{D_z}{D_t} = w$:

Therefore, $\frac{D_w}{D_t} = w\frac{D_w}{D_z}$ (4)

If equation 4 is integrated vertically from the LFC to the EL following the motion of the parcel, the result is:

$$\frac{w^2}{2} = \int_{LFC}^{EL} g\left(\frac{T_{parcel} - T_{env}}{T_{env}}\right) D_z \qquad (5)$$

Note that the right hand side of Eq. 5 is just the definition of CAPE. Therefore, the expression for w_{max} is:

$$w_{max} = \sqrt{2CAPE} \qquad (6)$$

Finally, the Hurricane Predictive Index (HPI) is calculated using NOAA buoy satellite data to forecast severe weather including storm development and track (Table 1).

Date August	Sea Level Pressure (mb)	Wind Speed (knots)	Sea Temperature (ºC)	Air Temperature (ºC)	Heat Flux	Hurricane Predictive Index (HPI)
20	1006	43.4	28.9	27.8	96	-1.61
21	1007	43.4	28.5	25.2	287	-4.07
22	988	69.3	33.2	25.1	1128	-90.52
23	980	86.9	31.9	25.1	1184	-163.22
24	956	100	30.5	25.3	1041	-297.02
25	951	100	29.9	25.5	881	-278.92
26	946	91.2	29.2	26.7	457	-145.67
27	952	73.9	25.3	25.1	30	-7.98
28	966	52.3	21.9	20.1	188	-31.32
29	980	43.4	18.7	18.6	9	-0.66
30	1019	4.3	20.0	19.9	1	.002

Table 1 Buoy Data, Heat Flux, and Hurricane Predictive Index

3. RESULTS AND DISCUSSION

Buoy data (as shown in Table 1) gathered along Irene's track through the Atlantic, the amount of heat flux peaked at 1184 w/m^2, during August 22 through 25, as the storm passed over the warm waters of the Bahamas and a very warm gulf stream. The SST's ranged from 29.9º C to 33.2º C for these four days while the air temperature remained at a more subdued range of 25.1º C to 25.5º C. This high temperature differential led to quickly swelling winds and provided Irene with enough energy to grow from a category 1 to a category 3 tropical cyclone in two days. Measurements from the National Oceanic and Atmospheric Administration’s Office of Satellite and Product Operations also show a sea surface temperature anomaly in the Bahamas and Gulf Stream ranging from .5 to 2 degrees Celsius higher than normal during August 25. However, a sharp drop in available heat flux on August 26 forced the storm back down to a category 1. It no longer had the energy to support its constant growth.

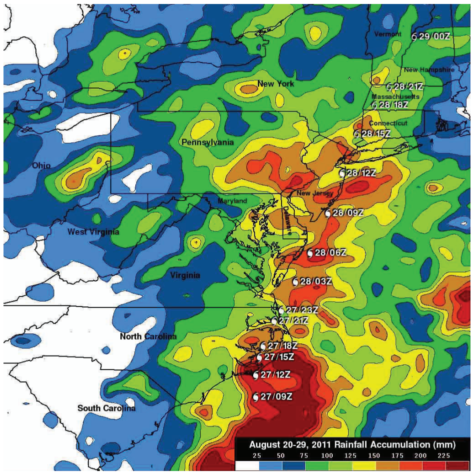

Fig. 2 TRMM Satellite Precipitation Totals

eTRaP (Ensemble Tropical Rainfall Potential) data provided estimated totals of rainfall for the storm as it moved over the Atlantic. Rainfall totals were predicted to be around 2” to 10” inches at first, while Irene was still passing the Cape Verde Islands and Cuba, but were reduced to less than the actual recorded rainfall, from approximately 1” up to 5” in the center of the storm, before and after landfall. NASA's TRMM (Tropical Rainfall Mapping Mission) shows Irene had beaten estimates and proceeded to dump from 5.9” to 8.9” of precipitation over coastal areas (where the eye had made landfall) and 2” to 5” farther inland in less than two days (as shown in Fig.2).

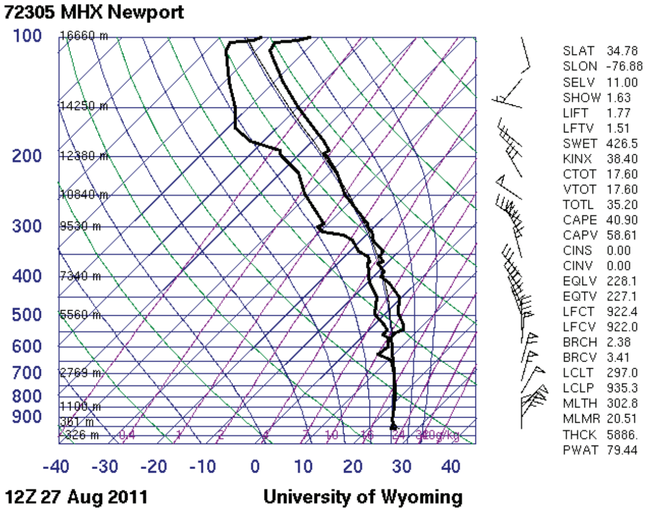

Fig. 3 Atmospheric Sounding for Coastal North Carolina on August 27

Atmospheric soundings help to explain how Irene could match and beat the precipitation predictions (Fig. 3). By looking at the storm's CAPE (Convective Available Potential Energy), PW (Perceptible Water), and LIFT. During the period of time between Aug 22 and 26, the same period of time during which the heat flux peaked and dropped, massive increases of CAPE and LIFT were observed. The storm's CAPE remained over 2000 for three days and peaked near 3781 (when it had also strengthened to a category 3) and its LIFT reached down to a value of -6 and stayed very low for those three days. Negative LIFT values show high amounts of atmospheric instability while positive values indicate the opposite; stable, non-lifting air. The CAPE may also be used to find the amount of vertical motions within the storm. The relationship between the CAPE value and vertical motion is proportional. The higher the CAPE, the more energetic the storm's vertical motions producing severe thunderstorms, tornadoes, heavy precipitation, and flooding. This helps to explain how Irene released as much precipitation as it did. Large amounts of LIFT allow the storm to gather the moisture and energy provided by the ocean's heat flux and the high amount of vertical motions help to disperse it throughout the storm as well as keep it aloft. That is the reason, when Irene made land-fall, it had 71.07 mm of Precipitable Water (PW) available, and how it was able to drop nearly 9” of rain on the east coast of the US.

The last tool used to analyze Irene's precipitation potential is the HPI (as shown in Table 1) as developed by Reddy et al, 1999. The HPI is another way of finding a storm's instability and uses a combination of several different buoy parameters; SST, air temperature, sea level pressure, and wind speed. By finding the HPI for each day of Irene's lifespan, plus a day, a pattern of constant instability shows itself. It peaks during the period of August 22 to 26 once more, reaching values as low as -297.02, but remains negative even through Irene's dissipation. The first time that the atmosphere could return to a stable state was on August 30, after the storm had even ceased to be an extra tropical wave.

The process by which a hurricane forms depends on warm water, moisture, and certain wind patterns at various altitudes. Ocean-atmospheric interaction is an important role in the behavior and strengthening of tropical disturbances. Momentum, heat, and moisture fluxes across the sea-air interface are needed for the context of large-scale ocean-atmospheric interactions.

The ocean gives up heat and moisture where the overlying atmosphere is colder and drier, and in turn, influences the development and evolution of the winds. The sea-air interface, heat flux, and momentum flux, fluctuate toward maximum values when the difference between the sea and air temperature is at its highest. This indicates that the high sea surface temperatures lead to a large exchange of heat and moisture (Emanuel 1988).

4. SUMMARY AND CONCLUSIONS

In conclusion, strong vertical motions and ocean-atmospheric interactions associated with high amounts of instability coupled with consistently large heat flux values, allowed Irene to absorb massive amounts of moisture. Even after its eye had collapsed and reformed, enough vertical motions were left to keep a majority of the moisture suspended until the storm made land-fall. Irene hit an area that was already quite saturated with moisture and exasperated the issue with another 2" to 9" inches of excess water as observed by NASA's TRMM Satellites. With precipitation falling at a rate of 1" to 2" per hour, the water had nowhere to run vertically through the saturated ground and was forced laterally instead, causing wide-spread flooding and inundation through-out the east coast. Although Irene was not a strong tropical cyclone, it was still force to be reckoned with.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

[1] *AHPS Precipitation Analysis*. *Http://water.weather.gov*. National Weather Service. Web. 1 Dec. 2011. <http://water.weather.gov/precip/>.

[2] Avila, Lixion A. and John Cangialosi. "Tropical Cyclone Report Hurricane Irene (AL092011)". National Hurricane Center. Web. 3 Jan. 2012.
<http://www.nhc.noaa.gov/data/tcr/AL092011_Irene.pdf>

[3] *Atmospheric Soundings*. *Wyoming Weather Web*. Web. 1 Dec. 2011. <http://weather.uwyo.edu/upperair/sounding.html>.

[4] Emanual, K. A., 1986: *An Air-Sea Interaction Theory for Tropical Cyclones*, J Atms. Sci., 45, 1143-1155.

[5] *Irene GOES LARGE*. Digital image. National Aeronautics and Space Administration. Web. 1 Dec. 2011.

[6] Reddy, Remata S. *Hurricane Predictive Index*. Web. 1 Dec. 2011.

[7] "Quick Review of the 2011 Atlantic Hurricane Season for the Rio Grande Valley and Beyond". United States. Department of Commerce. National Oceanic and Atmospheric Administration. *National Weather Service Southern Region Homepage*. Web. 1 Dec. 2011.
<http://www.srh.noaa.gov/bro/?n=2011event_hurricaneseasonwrap>.

[8] United States. Department of Commerce. National Oceanic and Atmospheric Administration. *Home Page - Satellite Services Division - Office of Satellite Data Processing and Distribution*. Web. 1 Dec. 2011. <http://www.ssd.noaa.gov/PS/TROP/DATA/ETRAP/2011/Atlantic/IRENE/archive.html>.

[9] United States. Department of Commerce. National Oceanic and Atmospheric Administration. *National Data Buoy Center*. Web. 1 Dec. 2011. <http://www.ndbc.noaa.gov/>.

[10] United States. Department of Commerce. National Oceanic and Atmospheric Administration. *Operational SST Anomaly Charts for the Year 2011*. Web. 3 Jan 2011. <http://www.ospo.noaa.gov/Products/ocean/sst/anomaly/2011.html>

[11] United States. National Aeronautics and Space Administration. *NASA - Home*. Web. 1 Dec. 2011. <http://www.nasa.gov/mission_pages/hurricanes/features/trmm-irene-study.html>.

[12] Xin Yang. *NERFC Departures from Normal, Water Supply and Water Resources*. *National Weather Service Eastern Region Headquarters*. Web. 1 Dec. 2011. <http://www.erh.noaa.gov/nerfc/watersupply.shtml>.