Unique data set obtained in Hurricane Ellen (1973)

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Special research missions for the National Hurricane Research Laboratory (NHRL), carried out in Hurricane Ellen and Tropical Storm Delia in 1973, confirmed the presence of large amounts of supercooled liquid water in most of the convective cells within these storms and indicated the presence of internal gravity waves in the wake of Hurricane Ellen at the ocean thermocline. The missions were conducted for NHRL by NOAA's Research Flight Facility (RFF), with Mr. Billy Lewis and Dr. Robert Sheets as the NHRL onboard directors, and the rather unique cloud physics and air-sea interaction measurements were obtained under the direction of Mr. Paul Willis and Mr. Peter Black, respectively.

Studies of the micro-physical properties of hurricane clouds and of air-sea interactions within the hurricane aid in the design and evaluation of hurricane modification experiments and are necessary for the more sophisticated numerical models presently being developed for operational forecasting and experiment evaluations. The STORMFURY seeding hypothesis is based upon the premise that large amounts of supercooled water exist in hurricane clouds. The hypothesis states that seeding these clouds will cause these droplets to freeze, starting a chain reaction of ice particle growth and splintering processes which result in the release of large amounts of latent heat. These processes alter the thermal structure of the hurricane and result in changes in the pressure and wind fields. The NHRL has been attempting to make quantitative measurements of cloud particles in hurricane clouds to determine to what degree the basis for the hypothesis is valid. Measurements prior to 1973 agreed qualitatively with the supercooled water assumptions, but due to the lack of properly instrumented aircraft which could operate at the required altitudes, no quantitative measurements had been obtained. During 1973, however, the NOAA Research Flight Facility (RFF) C-130 aircraft (Fig. 1) was instrumented with a rather unique cloud physics measurement system. The system consists of an automatic ice particle counter, a continuous cloud particle replicator (Formvar), a continuous hydrometeor sampler (Foil), a liquid-water content instrument (Johnson-Williams), a total water content instrument (Lyman-Alpha), and a prototype constant temperature total liquid water content device being developed by Dr. Frank Merceret and Mr. Terry Schriker of NHRL. A minicomputer and analog and digital recorders are also on board for high rate sampling and some processing of the output signals from these instruments.

The RFF C-130 aircraft was also instrumented with a system for dispensing and recording the signals from airborne expendable bathythermographs (AXBT's). The transmitted signal was recorded on analog and digital tape

FIG. 1. Research Flight Facility (NOAA) C-130 specially instrumented aircraft.

with some intermediate processing, while simultaneously a minicomputer provided a hard copy of temperature versus depth. The printout was used to provide the U.S. Navy with real-time data. The AXBT system was integrated with an infrared radiometer, a vertical camera, and a laser wave height profileometer already installed on this aircraft under the direction of Mr. Duncan Ross of NOAA's Sea-Air Interaction Laboratory to form the nucleus of an air-sea interaction instrumentation system. In addition, the RFF C-130 was equipped with a T-13 dropsonde system, an LTN-51 inertial navigation system, and the more conventional instrumentation for measuring temperature, humidity, pressure, and altitude.

Tropical Storm Delia was located over the Gulf of Mexico approximately 200 n mi south of New Orleans on 3 September 1973, during a research mission into the system. The clouds in the western and northern portions of the storm were quite suppressed, but the low-level cyclonic circulation was quite evident. The outflow layer was also evident in the cirrus clouds generated by the convective activity located south and east of the storm center where radar echoes were observed to exceed 40,000 feet in height. Preliminary analyses indicated that large amounts of liquid water were present at temperatures of -5°C to -15°C in these convective cells. Most of this water appeared to be contained in medium size droplets and may have reached values of as much as 6 gm/m^3 . Ice particle concentrations of as much as 20 per liter also appeared to be present at these levels, but the major concentrations of these particles were generally observed in the layered clouds between the active updrafts. Exact values and details of the quantitative results must await further analysis and evaluation of instrument exposure and calibration.

Hurricane Ellen was located approximately 600 n mi ENE of Bermuda on 21 September 1973 when research flights were made into the storm by the RFF DC-6 and C-130 aircraft. A minimum central pressure of 962 mb and a maximum wind speed of 120 kt were recorded during the mission. A photograph illustrating the mature structure of Hurricane Ellen obtained during a simultaneous Skylab overflight is shown in Fig. 2. The DC-6 aircraft performed an X pattern at an altitude of 1500 ft, making two penetrations of the eye. A one minute sequence of the RHI radar presentation recorded on the first pass through the eye is shown in Fig. 3. The radar scans 360° in the vertical plane normal to the aircraft heading. The range markers are 5 n mi and the horizontal line is the sea surface. Therefore, the maximum radar echo heights are approximately 40,000 feet both left and right of the aircraft. A continuous hydrometeor sampler was also operated on the DC-6 aircraft along with an infrared radiometer measuring sea surface temperatures and the more conventional wind, temperature, pressure, and humidity measuring instruments.

During this mission, the C-130 aircraft was flown at temperature levels of approximately -5C and -15C in all quadrants of the storm and also at 400 ft to 1500 ft in the rear quadrants. The cloud physics data collected at the upper levels again indicated the presence of large amounts of liquid water in the convective clouds in all quadrants. Layered clouds were also present and concentrations of several ice particles per liter were observed (Fig. 4). Again, the exact quantitative values for these measurements must await further analysis and instrument calibration.

Drosondes were released from above 20,000 ft in all quadrants and in the eye. Some of the sensing elements became saturated making their reliability questionable.

However, large temperature gradients and horizontal asymmetries in the thermal structure of the storm were quite evident. The 500-mb to 700-mb layer temperatures in the eye of the storm were 10C to 15C warmer than those observed at the same levels 40 to 60 n mi from the storm center and some 8C warmer than the values recorded just outside of the eyewall.

The low-altitude portion of the flight consisted of a track across the rear of the storm some 60 n mi from the center and then a downwind and crosswind pattern into the hurricane eye. The flight altitude ranged from 500 ft to 2500 ft during this portion of the flight. A track was then flown toward the rear of the storm along its path for a distance of 100 n mi at an altitude of approximately 1500 ft.

A total of 18 AXBT's were dropped at intervals of 5 to 15 n mi along the low-level portion of the flight. Fourteen of these units operated to a depth of 500 ft or more while the remainder were only partially successful. The infrared radiometer and the SAIL laser profileometer failed to operate properly.

Preliminary analyses of the AXBT data appears to confirm theoretical predictions that fast-moving storms such as Ellen produce internal gravity waves in their wake at the ocean thermocline and produce only nominal cooling (0.5C to 1.5C) of the surface water. These conditions are reflected in Fig. 5 where the dash-dot line indicates the top of the thermocline and the solid lines are the actual AXBT traces. The vertical cross section extends from the storm center to 150 km to the rear. The undulations in the depths of the isotherms appear to be in phase with the undulations in the thermocline depth. Furthermore, the maxima and minima in thermocline and isotherm depths correspond with a relatively cool and warm mixed layer, respectively. This structure strongly

FIG. 2. Hurricane Ellen on 21 September 1973 taken from NASA SKYLAB.

FIG. 3. RHI radar sequence showing contoured eyewall. Range markers are 5 n mi.

suggests the presence of an internal wave with a wavelength of about 40 km.

Another portion of the NHRL hurricane-ocean interaction experiment, supported by the Office of Naval Research, was carried out from 26–30 September 1973, in the eastern Pacific. A Piper Twin Commanche operated by Dr. Mark Goldstein of International Business and Research, Inc. (IBR), carried out flights across the path of Hurricane Irah in the eastern Pacific on 27 and 29 September. This was 3 and 5 days after the storm had passed over the area with maximum wind speeds of 130 kt. About 30 IBR manufactured AXBT's were dropped at 10 n mi intervals across the path of the storm and simultaneous measurements of the sea surface temperature were obtained using an infrared radiometer.

Preliminary analyses indicated that less than 0.5°C cooling occurred in the wake of Irah. More cooling was anticipated because of the relatively slow moving storm (7–10 kt). Apparently, the stable stratification caused by the presence of extremely cold water (10°C) below the thermocline inhibits mixing or upwelling mechanisms from bringing cold water to the surface. Therefore, it appears that the generation of hurricane cold wakes is not only governed by the speed of movement of the hurricane but also by the thermocline stability.

The above-mentioned studies were just two of several inter-related observational studies of hurricanes which were planned for the 1973 season. However, prior to the com-

FIG. 4. Cloud particles replicated (FORMVAR) in layered clouds in Hurricane Ellen (temperature -7°C).

mencement of the season, the number of flight hours, personnel, etc., available for the project were reduced. A further reduction during the season and the lack of cooperation from mother nature prevented the collection of long term monitoring data for natural variability studies, additional data for the cloud physics and air-sea interaction studies, and data for the several other planned studies. It is anticipated that more data will be collected for these studies prior to the 1976 STORMFURY experiments.

FIG. 5. Analysis of AXBT data from the center to the rear of hurricane Ellen showing apparent gravity waves in the wake of the storm.

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