Observation of Whitecapping in the Hurricane Frances

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Abstract

The role of breaking waves in wave dynamics and air-sea fluxes is an area of significant interest in hurricane dynamics. Wave breaking is a source of aerosols and spray in the air, and bubbles in the water, which may be dynamically and thermodynamically significant, especially in the transition from a well-defined air-sea interface to the more diffuse two-phase flows on either side of the boundary. While aspects of these problems can not be studied in the laboratory or with numerical models, observations are necessary to measure the statistics of breaking especially their morphology and kinematics, and their relationship to the dynamics and thermodynamics. As part of the Coupled Boundary Layers/Air-Sea Transfer (CBLAST) experiment, a nadir-looking mega-pixel video camera, along with an inertial motion unit and laser altimeter was mounted on the NOAA/HRD P3 (N43RF) aircraft. The imaging system recorded images of the surface below the aircraft at a rate up to 30 Hz. Methods of image sequence analysis were used to identify breaking waves and measure their evolution in space and time. The striking qualitative differences between observations of the sea surface in hurricane force winds and more moderate winds were noted.

1 Introduction

Breaking waves play an important role in air-sea interaction: enhancing momentum flux from the atmosphere to the ocean; dissipating wave energy that is then available for turbulent mixing; injecting aerosols and sea spray into the air, and entraining air in the water. A better understanding of wave breaking kinematics and dynamics is important for wave modeling, remote sensing in the microwave and visible wavelengths, and furthering our understanding of surface waves. Surface wave and atmospheric boundary layer data were collected during the Coupled
Boundary Layers/Air-Sea Transfer (CBLAST) experiment from 2003 to 2004.

The purpose of CBLAST is to improve the understanding and parameterization of high-wind, air-sea fluxes and subsequently improve hurricane intensity forecasting. The experiment was sponsored by the Office of Naval Research, the NOAA Hurricane Research Division, NOAA Office of Atmospheric Research, United States Weather Research Program and the Ocean Winds program of the NOAA/NESDIS Office of Research and Applications. The experiment utilized two NOAA/Aircraft Operations Center WP-3D Orion aircraft flying in tandem. In each flight, two modules were flown: 1) a stair-step flight pattern was flown for the purpose of obtaining in-situ measurements of air-sea fluxes in gale force winds and 2) a multiple GPS dropsonde deployment was performed from the two WP-3D in the hurricane eyewall to obtain estimates via budget calculations of air-sea fluxes and exchange coefficients in extreme hurricane force winds.

A nadir-looking mega-pixel video camera, along with a scanning lidar, laser altimeter, and inertial measurement unit, was mounted onboard the NOAA/HRD P3 aircraft. The imaging and scanning system recorded digital videos of the breaking sea surface and corresponding surface wave heights during hurricane force wind. Boundary layer wind profiles were measured using GPS dropsondes, Stepped Frequency Microwave Radiometer (SFMR) and a pressure transducer array on the aircraft. The observed dependence of whitecapping on surface wind speed is discussed.

2 Data Acquisitions and Analyses

The flight started its measurement from about 1400UTC and ended at 2300UTC on Sep. 1 2004. Seventeen digital films of duration 297s or 543 s were recorded by a mega-pixel (1018x1004) CCD camera at the rate of 30 frames per second. The plane attitude measured both by DGPS and Inertial Motion Unit(IMU) were recorded synchronically. Single image frames of the sea surface could be subtracted from the films. About 150,000 frames were regarded as useable after primitive checks considering the cloud contaminations and vignette effects.

The airplane flew at the Altitude ranging from 250m to 2500m. The dimension of the image frame could be calculated based on the optical focus length. The width of the image is approximately half of the distance from the plane camera to the sea surface.

Due to the fact that the foams of whitecap has low emissivity and features bright in the visual light spectral band, the whitecapping could be identified and located by contouring the brighter portions of the images. The determination of the threshold of brightness is the crucial part of this research. The statistical characteristics of grey scale in images are strongly affected by lighting conditions, sun glitters, camera shutter and aperture setting and vignette effects. The threshold values are not fixed. Method of manually visual check was adopted by previous studies. Fig. 1 is an example of typical whitecapping image during hurricanes. Different values of threshold were applied to locate the area of whitecapping from the contour lines and the most appropriate one is chosen manually. In present study, however, the
amount of frames is huge, which makes it impossible to manually determine the thresholds. On the other hand, we would prefer that if the processes of thresholding could be repeated without subjectivity.

The image is first transformed into 8 bit resolution, using 256 levels of grey scales representing the brightness of each pixel. The vignette effects are then eliminated using the method that divides the matrix of the image by the matrix of averaged intensity over the filming period. Furthermore, the clouds are check by calculating the gradient of the brightness variations. Images with lower gradient, which usually infer the clouds effect, will not be used.

It is assumed that the probability distribution of the pixels brightness is composed of two distinguished parts, i.e. the pdf of sun glitters and sea surface (without whitecapping)and the whitecappings. It is supposed that the pixels of sun glitters and sea surface have lower mean and are distributed in the lower grey scale part, while the whitecapping has higher mean with narrower distribution. It is fortunate that a dip between the two pdf curves could be found in most cases if the amount of pixel sample is enough, say ten million or more. Fig. 2 is an example to find the ‘dip’ in the distribution curve using 3rd derivations of accumulative distribution curves. In this way, we developed algorithms which could automatically dealing with the images and find out the thresholds of the whitecapping brightness. The area occupied by whitecapping over the area of the images gives the WhiteCapping Coverage (WCC).

The measurements of sea surface wind speed U10 of Hurricane Frances were carried out by using GPS Dropsonde and SFMR (Stepped Frequency Microwave Radiometer). Fig. 3 illustrated the wind quivers of hurricane Frances on Sep.1 1930 UTC, where the blue line denotes the aircraft trajectory. GPS Dropsondes were launched from the same P-3 aircraft; the velocities calculated from mounted GPS gave the wind speed profile in the atmospheric boundary layer. The SFMR sensed the bright temperature, which infer the wind speed on the surface of ocean. These data were merged with atmospheric model. Data assimilated hindcast wind field data for hurricane Frances were adopted in present study. These re-analysis hurricane wind field data were provided every 6 hours. The grid size is about 6 km. As the ground speed of the aircraft was about 130m/s, the time it required to pass over one grid points is around 50 seconds. Therefore, we interpolate the re-analysis wind field into every minute, as illustrated in Fig.4. The moving hurricane method, that interpolates the wind components in both temporal and spatial domain was adopted. A WCC obtained from the images of one minute film indicates that the WCC is an averaged value over 1 square kilometres to 10 square kilometres depending on the flight altitude. Compared to previous studies using limited number of ship borne or air borne pictures, the variance of WCC estimated could be reduced significantly in present study.

3 Discussions

Fig. 5 is a S-S plot of the dependency of WCC to the wind speed. The left figure is the data digitized from previous study while the right figure is the data from present study. As we all know the wave breaks when the velocity of water particles on the
wave crest exceeds the wave celerity. In the swell, this criterion could be fulfilled as the wave steepness increases, such as wave evolutes to form a Stoke profile in the deep ocean or when it propagates to the shallow water in the nearshore region. In the windsea, the wave could break in less steepness due to the existing wind drifting surface shearing layer. Therefore, occurrence of wave breaking increases with stronger wind. Fig. 5 demonstrates the dependency of wave breaking induced WCC to the wind speed. The line in the left figure is the result of regression from all data points in previous studies. This line indicates that the WCC on the ocean surface will reach to 100% when the wind speed is more than 25m/s. This is absolutely not true as 100% WCC had never been observed on the sea. The unrealistic regression line may due to that the data points were measured only at moderated wind speeds. The WCC in the wind speed up to 50 m/s is first measured in present study. As indicated in the fig., these WCC data makes it possible to extend the regression line and thus could contribute to the better parameterize of WCC.

In the Fig. 6, it is obvious that the magnitude of WCC scattered a lot. At the same wind speed, say, 20m/s, the WCC scatters more than one order of the magnitude. The data points are then colored for the indication of where the images were filmed. It is found that as hurricane Frances moved toward northwest direction, the WCC of the data points on the right wind (the first quadrat) are much higher than those on the left wind (the second quadrat). These phenomena imply that the WCC is not only a function of wind speed. As indicated on Fig. 7, the film 12, 13, 14 were recorded in sequence. It is found that a trend exists that even for higher wind speed, the WCC decreases. The role of fetch, or wave properties play should be further discussed.

The P-3 aircraft flew into the hurricane eye and the corresponding films are 3 and 12. As demonstrated in Fig. 8 and Fig.9, it is found that as the wind speed reached to 40m/s, the increase of wind speed does not lead to the increase of WCC. We found that the streaks cover more area than active breakers. These streaks are not as bright as active breakers and results in less portion calculation of whitecapping. Fig. 11 is a typical image of streaks. These streaks are found to have nearly the same spacing between each other. And furthermore, the streaks lines are perpendicular to the crest of active breakers. This spatial periodicity makes it possible to use two dimensional FFT as a filter to separate the streaks and active breakers. Fig. 12 is the results of separating the streaks and active breakers. It is found that as the wind speed reaches to 40 m/s, the occurrence of active breaking reduced and on the other hand the streaks increase rapidly. However, it is a pity that due to the noisy 2D FFT spectrum, the spacing between streaks could be estimated. In Powell’s measurement of the Drag Coefficient during high wind speeds in tropical cyclones, he stressed out that the drag coefficient decreases as the wind speed reaches to 40m/s. As the Cd coefficient is widely used in numerical ocean models, the Cd coefficient dominates the estimation of momentum flux between ocean and atmosphere, the drifting current, the storm surges and so on. The study of the relationship between the occurrence of whitecapping induced streaks and the decrease of Cd coefficient would be a very interesting and awaiting issue.
4 Future Works

Wave breaking induced whitecapping plays important role not only on the wave energy dissipation, but also on the air-sea interactions. It is found recently that the traditional parameterized descriptions of atmospheric and ocean boundary layer could not be applied to the sea surface properties in high wind speed. In order to improve the numerical modeling of ocean circulations and waves and get better understanding of hurricane dynamics, it is an important research topic for both the engineers and scientists. The difficulties of this study lay on the lack of observations. As the extreme weather seldom lasts long, the strategy of integrations of latest in-situ and remote sensing technology should be taken. Taiwan situates in the midway of most of the typhoons in eastern Pacific. Recent deployed deep ocean data buoy, which is capable of measuring the turbulence in the sea surface, and the development of X-band radar provide the practical tools for further investigations of wave breaking. It is hoped that more field data of high wind speeds could be observed in the near future.

5 References


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Fig. 1 An example of air-borne image in Hurricane Frances 2004. The contouring of pixel intensity is used to indicate the spatial coverage of whitecaps.

Fig. 2 This figure shows the determination of threshold of grey scale for the whitecaps in each image frame. It is developed base on the characteristics of the cdf of brighter pixels.
Fig. 3 The re-analysis wind field of Hurricane Frances on Sep. 1 2004 1930UTC. The blue line denoted the path of aircraft.

Fig. 4 17 digital films were recorded with durations of 297s or 543s. The blue wind quivers indicate the location where the films were taken.
Fig. 5 Right: The S-S plot of averaged WCC to the U10. The range of U10 is higher than any previous studies comparing to the dots in left fig,

Fig. 6 The min-averaged WCC in the right wing of the hurricane is larger than those in the left wing.

Fig. 7 The change of WCC during the plane flew through hurricane eyewall.
Fig. 8 WCC in extreme wind speed (U10>40m/s)

Fig. 9 Corresponding U10 and WCC in the hurricane
Fig. 10: An example of streak in extreme wind condition (U10>50m/s)

Fig. 11: The dependence of spatial coverage of active breakers and streaks to U10.