We (authors) appreciate all the comments and suggestions provided by the reviewer. In response to the reviewer's comments, the manuscript has been revised. We have listed our answers and the changes made to the manuscript below. The reviewer's comments (in red) have been listed followed by our response (in black).

Interactive comment on "The Effects of Sea Spray and Atmosphere-Wave Coupling on Air-Sea Exchange during Tropical Cyclone" by Nikhil Garg et al.

C. Fairall (Referee)

chris.fairall@noaa.gov

Received and published: 27 October 2017

1. The major advance in this paper is the use of Anguelova and Hwang's whitecap parameterization that is based on wave properties (taken from the wave model)

Ans: We do not use the whitecap parameterisation described in Anguelova and Hwang (2016), rather, we use the parameterisation for estimating whitecap fraction given in Kraan et al. (1996).

2. One major flaw of this work is the use of the Andreas approach for sea spray. It is based on questionable assumptions – COARE2.6 is purely interfacial so any residual is due to spray. Furthermore, the data used to arrive at the coefficients has essentially no observations past 20 m/s. Thus the actual differences in observed vs COARE2.6 fluxes is mostly noise.

Ans: In our study, we used COARE2.6 as Andreas's model uses COARE2.6 also. Also, this parametrization has been used in numerous publications by Andreas and his co-authors. We do understand reviewer's concern, however, we would like to mention that this is in-line with the standard practice. Besides using HEXOS data (DeCosmo, 1991), we have also conducted further tests (not presented in the paper) using FASTEX data (Persson et al., 2005) and found little effect on the value of coefficients.

Furthermore, as described in Andreas et al. (2008), we note that although the Tropical Ocean-Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (COARE) version 3.0 bulk flux algorithm (Fairall et al., 2003) has been tuned with flux data collected in wind speeds up to 20 m/s and is therefore operationally useful in this wind speed range, however, as argued by Andreas et al. (2008), it is based strictly on interfacial scaling and thus may not be reliable if it is extrapolated to wind speeds above 20 m/s. Andreas (2010) argues that the version 2.6 of COARE algorithm is used because its calculations of temperature (z_T) and humidity (z_Q) roughness lengths, which are used in computing sensible heat flux (H_S) and latent heat flux (H_L), are based on surface renewal theory of Liu et al. (1979). Because this algorithm is theoretically based and proven to be accurate for treating the interfacial sensible and latent heat fluxes in winds up to 10 m/s (e.g. Fairall et al. (1996), Grant and Hignett (1998)), it should still be accurate when extrapolated to higher wind speeds.

3. The formulation of the feedback coefficients might be ok, but the values are non-physical. There are more physically based formulations of feedback – Bao et al 2011 or Mueller and Veron 2014. So the results given here lack credibility.

Ans: We do concur with the reviewer that these values need to be revisited, however, due to the lack of measurements data in wind speed beyond 18m/s, it is rather difficult at this point of time. Furthermore, we would like to add that these coefficient terms are used due to the uncertainties associated with the sea spray generation function, and the values of these coefficient terms hold little meaning, besides the fact that they are used as correction for the "nominal" sea spray fluxes obtained from the microphysical model. The values used in Bao et al. (2011) and Mueller and Veron (2014) are also equally non-physical because of the aforementioned reason.

4. Another thing that is not explained is the difference between Expt1 and 2. Why does this change lead to a stronger hurricane. On 26 they claim the change from 1 to 2 'increases the surface roughness, which results in intensification of the hurricane'. I find that strange – it is the opposite of conventional wisdom and needs to be explained. Also, the modest increases in windspeed lead to a doubling of sensible and latent heat flux (fig 15) for Expt 1 to 2. I don't understand that. This aspect needs a lot more explanation.

Ans: We would like to bring reviewer's attention to Table 1, where the differences between the different experiments have been summarized. Furthermore, we describe the different experiments in Section 4.2. With respect to the conventional wisdom, it can be argued that there is some evidence that increasing coefficient of drag (or roughness length) results in intensification of hurricane. There are some studies investigating idealized hurricanes, where it was found that up to a certain value of coefficient of drag, the hurricane intensifies. The aforementioned results are reported by Montgomery et al. (2010), Kilroy et al. (2017). The increase in sensible and latent heat flux in our view is also due to the formulation of the heat flux parameterization used in the present study. This can be further realized from the parameterization of momentum and heat fluxes used in WRF model. The bulk formulas for momentum, sensible heat and latent heat can be written as:

$$\tau=\rho\overline{(w'u')}=\rho C_d(U_{ref}-U_0)^2$$

$$H_s=\rho c_p\overline{(w'\theta')}=\rho c_p C_h U_{ref}(\theta_{ref}-T_s)$$

$$H_l=\rho L_v\overline{(w'q')}=\rho L_v C_q U_{ref}(q_{ref}-q_s)$$

where $\overline{(w'q')},\overline{(w'\theta')},\overline{(w'u')}$ are covariance terms for humidity, potential temperature and velocity respectively. These covariance terms are more commonly written using friction velocity u_* where the terms for humidity, potential temperature and velocity become $u_* q_*, u_*\theta_*, u_*^2$ and using Monin Obukhov similarity theory, the terms q_*,θ_*,u_* are given as

$$q_*=\frac{\kappa(q_{ref}-q_s)}{\ln\left(\frac{z_{ref}}{z_Q}\right)-\psi_h\left(\frac{z_{ref}}{L_0}\right)}$$

$$\theta_*=\frac{\kappa(\theta_{ref}-T_s)}{\ln\left(\frac{z_{ref}}{z_T}\right)-\psi_h\left(\frac{z_{ref}}{L_0}\right)}$$

$$u_*=\frac{\kappa U}{\ln\left(\frac{z_{ref}}{z_0}\right)-\psi_m\left(\frac{z_{ref}}{L_0}\right)}$$

here $z_{0,}z_T,z_Q$ are the roughness length for momentum, temperature and humidity. Now, using above equations and for neutral stratification, the coefficient of drag, heat and humidity can be written as

$$C_{d,N}=\left(\frac{\kappa}{\ln(\frac{z_{ref}}{z_0})}\right)^2$$

$$C_{h,N}=\frac{\kappa C_{d,N}^{1/2}}{\ln\left(\frac{z_{ref}}{z_T}\right)}$$

$$C_{q,N}=\frac{\kappa C_{d,N}^{1/2}}{\ln\left(\frac{z_{ref}}{z_Q}\right)}$$

From these expressions, It can be deduced that increasing the coefficient of drag affects the coefficient of heat and humidity. Furthermore, from the bulk formulas, it can also be realized that this change in coefficient terms affects the sensible and latent heat fluxes, besides the effects of increasing wind speeds on the heat fluxes. Lastly, we would also like to point out that the parameterization used for the roughness length of temperature and humidity in the coupled and uncoupled experiments presented in our study are set equal to 0.95×10^{-4} m, thus giving constant values for the denominator in the computation of coefficient of heat and humidity.

5. The examination of the sensitivity to spray focusses on heat fluxes, which have never been measured in hurricanes and therefore can't be verified. I suggest they could focus on the near-surface air temperature and humidity, which have been measured (e.g., we Zhang et al. 2017).

Ans: We would like to thank the reviewer for the suggestion. We would like to request more information on the study mentioned by the reviewer. Our search for the aforementioned study didn't lead to any useful results.

6. Comparisons of sensible and latent heat flux for Expts 2,3,4 suggest that spray has negligible effect on the thermodynamics. However, it is clear from fig 12b that much less spray is produced by the author's model compared to MOM80 in Andreas. I think it would be interesting to see a comparison of the total spray mass flux as a function of wind speed (this paper vs MOM80)

Ans: It is possible to infer it from the Figure 12b, where Figure 12b shows that the whitecap fraction is 25% of the whitecap fraction as opposed to the whitecap fraction obtained from MOM80. Because, in this study, we do not modify the SSGF, just use whitecap fraction from wave model instead of an empirical relation. As the whitecap fraction is merely used for scaling sea spray generation function for different wind speeds, therefore, in our view the effects of changing whitecap fraction should be applicable as a scaling parameter to the volume (or mass) flux of sea spray as well.

7. On a more editorial subject, I think the description of whitecap fraction and spray function parameters (sections 5.1.1 and 5.2.1) should be moved to section 2 since they are not part of the hurricane simulations.

Ans: Done. The two subsections are relocated to the section 2. Thank you for the suggestion.

References:

Andreas, E. L.: Spray-Mediated Enthalpy Flux to the Atmosphere and Salt Flux to the Ocean in High Winds, J. Atmospheric Sci., 40(3), 608–619, 2010.

Andreas, E. L., Persson, P. O. G. and Hare, J. E.: A Bulk Turbulent Air-Sea Flux Algorithm for High-Wind, Spray Conditions, J. Phys. Oceanogr., 38, 1581–1596, 2008.

Anguelova, M. D. and Hwang, P. H.: Using Energy Dissipation Rate to Obtain Active Whitecap Fraction, J. Phys. Oceanogr., 46(2), 461–481, 2016.

Bao, J. W., Fairall, C. W., Michelson, S. A. and Bianco, L.: Parameterizations of sea-spray impact on the air-sea momentum and heat fluxes, Mon. Weather Rev., 139(12), 3781–3797, 2011.

DeCosmo, J.: Air-sea exchange of momentum, heat, and water vapor over whitecap sea states, PhD Thesis, University of Washington, Seattle., 1991.

Fairall, C. W., Bradley, E. F., Rogers, D. P., Edson, J. B. and Young, G. S.: Bulk parametrization of air-sea fluxes for Tropical Ocean-Global Atmosphere Coupled-Ocean Atmosphere Response Experiment, J. Geophys. Res., 101, 3747–3764, 1996.

Fairall, C. W., Bradley, E. F., Hare, J. E., Grachev, A. A. and Edson, J. B.: Bulk Parameterization of Air–Sea Fluxes: Updates and Verification for the COARE Algorithm, J. Clim., 16(4), 571–591, doi:10.1175/1520-0442(2003)016<0571:BPOASF>2.0.CO;2, 2003.

Grant, A. L. M. and Hignett, P.: Aircraft observations of the surface energy balance in TOGA-COARE, Q. J. R. Meteorol. Soc., 124(545), 101–122, doi:10.1002/qj.49712454505, 1998.

Kilroy, G., Montgomery, M. T. and Smith, R. K.: The role of boundary-layer friction on tropical cyclogenesis and subsequent intensification, Q. J. R. Meteorol. Soc., 143(707), 2524--2536, doi:10.1002/qj.3104, 2017.

Kraan, G., Oost, W. A. and Janssen, P. A. E. M.: Wave energy dissipation by whitecaps, J. Atmospheric Ocean. Technol., 13(1), 262–267, 1996.

Liu, W. T., Katsaros, K. B. and Businger, J. A.: Bulk Parameterization of Air-Sea Exchanges of Heat and Water Vapor Including the Molecular Constraints at the Interface, J. Atmospheric Sci., 36(9), 1722–1735, doi:10.1175/1520-0469(1979)036<1722:BPOASE>2.0.CO;2, 1979.

Montgomery, M. T., Smith, R. K. and Nguyen, S. V.: Sensitivity of tropical-cylone models to the surface drag coefficient, Q. J. R. Meteorol. Soc., 136(653), 1945--1953, doi:10.1002/qj.702, 2010.

Mueller, J. A. and Veron, F.: Impact of sea spray on air–sea fluxes. Part II: Feedback effects, J. Phys. Oceanogr., 44(11), 2835–2853, 2014.

Persson, P. O. G., Hare, J. E., Fairall, C. W. and Otto, W. D.: Air-sea interaction processes in warm and cold sectors of extratropical cyclonic storms observed during FASTEX, Q. J. R. Meteorol. Soc., 131(607), 877–912, 2005.