SURFACE STRESS IN TROPICAL CYCLONE OBSERVED BY SCATTEROMETER

W. Timothy Liu, Wenqing Tang, and Xiaosu Xie
Jet Propulsion Laboratory, California Institute of Technology

1 INTRODUCTION

Ocean surface wind (U) is air in motion and stress (τ) is the turbulent transport of momentum between the ocean and the atmosphere. While the strong wind of a tropical cyclone (TC) causes destruction at landfall, it is the surface stress that drags down the TC. There was almost no stress measurement except in dedicated field campaigns and the stress we used was almost entirely derived from wind through a drag coefficient (C_D), as defined by $C_D = \tau / (\rho U^2)$. In TC, there is difficulty in measuring strong wind and large uncertainty in the drag coefficient.

The scatterometer is the most established spacebased instrument to measure ocean surface stress and wind vectors (Liu 2002, Liu and Xie, 2006). The difficulty of retrieving strong winds from the scatterometer is obvious in Fig. 1. Data from North Atlantic hurricanes in four seasons (2005-2008), excluding those with over 10% chances of rain, were examined. The normalized radar cross section (σ_o) from the two beams (with different incident angles and polarizations) of QuikSCAT are plotted against collocated H*wind speed (Powell et al. 1998), at bin size of 1 m/s. In moderate winds (U<30 m/s), the logarithm of σ_o (in dB) increases almost linearly with the logarithm of wind speed. At strong winds (U>30 m/s), however, σ_o increases at a much slower rate with increasing wind speed. Strong efforts have been made to adjust the model function (slope in Fig. 1) in strong winds but there are not sufficient in situ measurements available to give credible results.

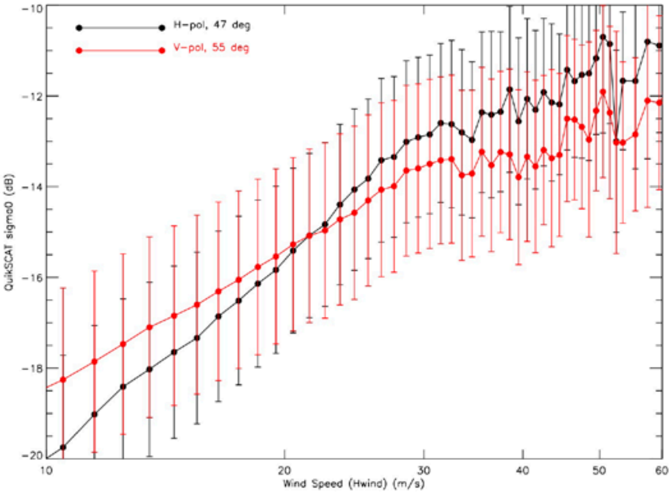

Fig. 1Backscatter coefficient for two beams measured by QuikSCAT collocated with H*wind along all reported hurricanes paths in North Atlantic from 2005 to 2008. QuikSCAT data with more than 10% chance of rainfall are excluded.

Liu et al. (1979) first postulated that, in a rough sea, under a moderate range of winds (between 3 and 20 m/s), the transfer coefficients of sensible and latent heat do not increase with wind speed because of molecular constraint at the interface, while C_D may still increase because momentum is transported by form drag. Emanuel (1995) argued, from theoretical and numerical model results, that the scenario of Liu et al. (1979) could not hold at the strong wind regime of a TC. To attain the wind strength of a TC, the energy dissipated by drag could not keep increasing while the energy fed by sensible and latent heat does not increase with wind speed. His argument puts limit on the increase of C_D as a function of wind speed. The postulation that the increase of C_D with wind speed will level off or decrease at TC scale winds was supported by the results of many subsequent studies. In Fig. 2, examples of C_D for strong winds in TC as a function of wind speed (Donelan et al. 2004; Powell et al. 2003; Jarosz et al. 2007; Holthuijen et al. 2012) are shown together with the extension of C_D established for moderate winds (Large and Pond 1981; Smith 1980). The big spread of the values in the figure shows clearly the unsatisfactory stage of our present knowledge. The problem is the lack of stress measurements under the strong wind condition of TC (see Liu and Xie 2013, for a review).

2 HYPOTHESIS

We assume that ocean surface roughness that causes the backscatter is in equilibrium with surface stress. There is no distinct physics governing radar backscatter from ocean surface for different weather phenomenon including TC. Initial development of the relation between backscatter and surface roughness through artificially generated waves or from theory did not consider weather change, and the general relation should apply to the TC. The changes in wind retrieval algorithm under TC, as shown in Fig. 1, is not a remote sensing problem, but an air-sea interaction problem caused by flow separation as manifested in the change of the drag coefficient in TC.

3 STRESS ALGORITHM

To develop an algorithm to retrieve stress from σ_o, we first derived a set of stress from wind data under a moderate range of wind speed, where wind measurements coincident with satellite observations are abundant, and the drag coefficient is well established. We collocated WindSat (Gaiser et al. 2004) wind vector with QuikSCAT σ_o. The drag coefficient by Large and Pond (1981) was used to

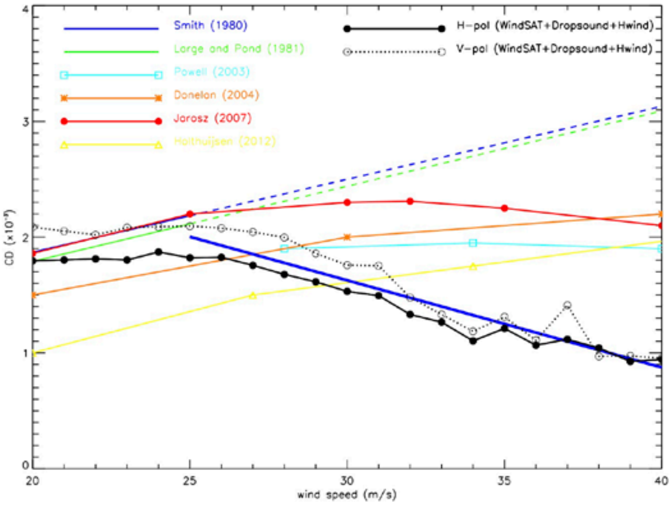

Fig. 2 Drag coefficient as a function of wind speed for strong winds determined in several previous studies with various methods to estimate stress. They are compared with the drag coefficient computed from stress measured by QuikSCAT with a linear regression of combined bin averages of the two beams.

derive stress from WindSat winds. Four linear regressions of the bin-averages are obtained, for the two beams of forward and backward looking data, The difference between forward and backward looking data is almost negligible. The number data pairs decreases from 10,000 to 500 at a range equivalent to wind speed from 12.6 m/s to 25 m/s. We tried to average out the variations caused by directional (azimuth angle) dependence with the large amount of data,

4 RESULT

We have assembled a set of strong wind data in tropical cyclones with wind speed above 20 m/s by combining WindSAT, H*wind, and dropsonde measurements (Chou et al. 2013). They are collocated with stress retrieved from QuikSCAT for each beam using the algorithm. The total number of collocated pairs of wind and stress are 39759 and 47093 for the two beams. They various from 10,000 at 20 m/s, decrease to 1000 at 30 m/s and to 100 at 40 m/s. There are too few data above 40 m/s and are not included in our analysis. The stress retrieved from QuikSCAT increases with wind speed up to wind speed of 30 m/s and the increase is much slower at higher wind speed.

The same set of collocated stress retrieved from the scatterometer and wind speed are used to computed the drag coefficient. They are shown in Fig. 2 as a function of wind speed and compared with the drag coefficients of previous studies. Between 20 and 25 m/s winds, the drag coefficients from scatterometer stress are enveloped by the past values. The values decrease significantly with wind speed at stronger winds at a rate larger than those of past formulations. A linear regression combining both beams of data is shown. The formulation our data suggest is $C_D=(3.89+0.075U)\times10^{-3}$.

5 DISCUSSION

The results confirm that the scatterometer is a unique stress rather than a wind sensor; the difference is accentuated under the strong wind of tropical cyclones. We show that, for the centimeter surface waves that governs the ku-band backscatter, stress increase at much slower rate, and the drag coefficient decreases at much faster rate, with increasing wind speed, than demonstrated in past studies that used much less stress measurements. That implies less drag by the ocean and less inhibitation of cyclone intensification. Stress also causes ocean mixing and brings up colder water from below, reducing sea surface temperature that determines the energy supply (sensible and latent heat fluxes) to the TC. In light of the reduced stress under intensification of winds, from what we previously expected, renewed assessments of ocean's influence TC destruction potential and the effect of global warming on TC are warranted.

Acknowledgment

This study was performed at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautic and Space Administration (NASA). It was supported by the Physical Oceanography and CYGNSS programs of NASA. We are deeply grateful to Kun-Hsuan Chou for providing the dropsonde data and for the advice of I-I Lin on typhoon studies. Windsat data were obtained from Remote Sensing System. © 2016 California Institute of Technology. Government sponsorship acknowledged.

References

Chou, K.-H., C.-C. Wu, and S.-Z. Lin, 2013: Assessment of the ASCAT wind error characteristics by global dropwindsonde observations, J. Geophys. Res. Atmos., 118, 9011–9021, doi:10.1002/jgrd.50724.

Donelan, M. A., B. K. Haus, N. Reul, W. J. Plant, M. Stiassnie, H. C. Graber, O. B. Brown, E. S. Saltzman, 2004: On the limiting aerodynamic roughness of the ocean in very strong winds. Geophys. Res. Lett., 31, L18306, doi:10.1029/2004GL019460.

Emanuel, K., 1995: Sensitivity of tropical cyclones to surface exchange coefficients and a revised steady state model incorporating eye dynamics. Journal of Atmospheric Sciences, 52, 3969–3976.

Gaiser, P.W. et al., 2004: The WindSat spaceborne polarimetric microwave radiometer: Sensor description and early orbit performance. IEEE Trans. Geosci. Remote Sens., 42, 2347-2361.

Holthuijsen, L. H., L.H., M. D. Powell, and J. D. Pietrzak, 2012: J. Geophys. Res., 117 C09003, doi:10.1029/2012JC007983

Jarosz, E., D. A. Mitchell, D. W. Wang, and W. J. Teague (2007), Bottom-up determination of air-sea momentum exchange under a major tropical cyclone, Science, 315, 1707–1709, doi:10.1126/science.1136466.

Large, W.G., and S. Pond, 1981. Open ocean momentum flux measurements in moderate to strong winds. J. Phys. Oceanogr., 11, 324-336.

Liu, W.T., 2002: Progress in scatterometer application, J. Oceanogr., 58, 121-136.

Liu, W.T. and X.Xie, 2013: Sea surface wind/stress vector. Encyclopedia of Remote Sensing. E. Njoku (ed), Springer-Verlag, DOI:10.1007/SpringerReference_327232.

Liu, W.T. and W.G. Large, 1981: Determination of surface stress by Seasat-SASS: A case study with JASIN Data. J. Phys. Oceanogr., 11, 1603-1611.

Liu, W.T., and X. Xie, 2006: Measuring ocean surface wind from space. Remote Sensing of the Marine Environment, Manual of Remote Sensing, Third Edition, Vol. 6, J. Gower (ed,), Amer. Soc. for Photogrammetry and Remote Sens., Chapter 5, 149-178.

Liu, W.T., K.B. Katsaros, and J.A. Businger, 1979: Bulk parameterization of air-sea exchanges of heat and water vapor including the molecular constraints at the interface. J. Atmos. Sci., 36, 1722-1735.

Powell, M. D., S. H. Houston, L. R. Amat, N. Morisseau-Leroy, 1998: The HRD real-time hurricane wind analysis system. J. Wind Engineer. Ind. Aerody., 77&78, 53-64.

Powell, M. D., P. J. Vickery, and T. A. Reinhold, 2003: Reduced drag coefficient for high wind speeds in tropical cyclones. Nature, 422, 279–283.
Quart. J. Royal Meteorol. Soc., 135, 2046-2066.

Smith, S. D., 1980: Wind Stress and Heat Flux Over the Ocean in Gale Force Winds. J. Phys. Oceanogr. 10, 709–726.

Soloviev, A., R. Lukas, M. Donelan, B. Haus, and I. Ginis, 2014: The air-sea interface and surface stress under tropical cyclones. Nature Scientific Reports, DOI: 10.1038/srep05306.

Wright, J.W., 1968: A new model for sea clutter. IEEE Trans. Antennas. Propagat., AP-16, 217-233.