A Simplified Approach to Understanding Boundary Layer Structure Impacts on Tropical Cyclone Intensity

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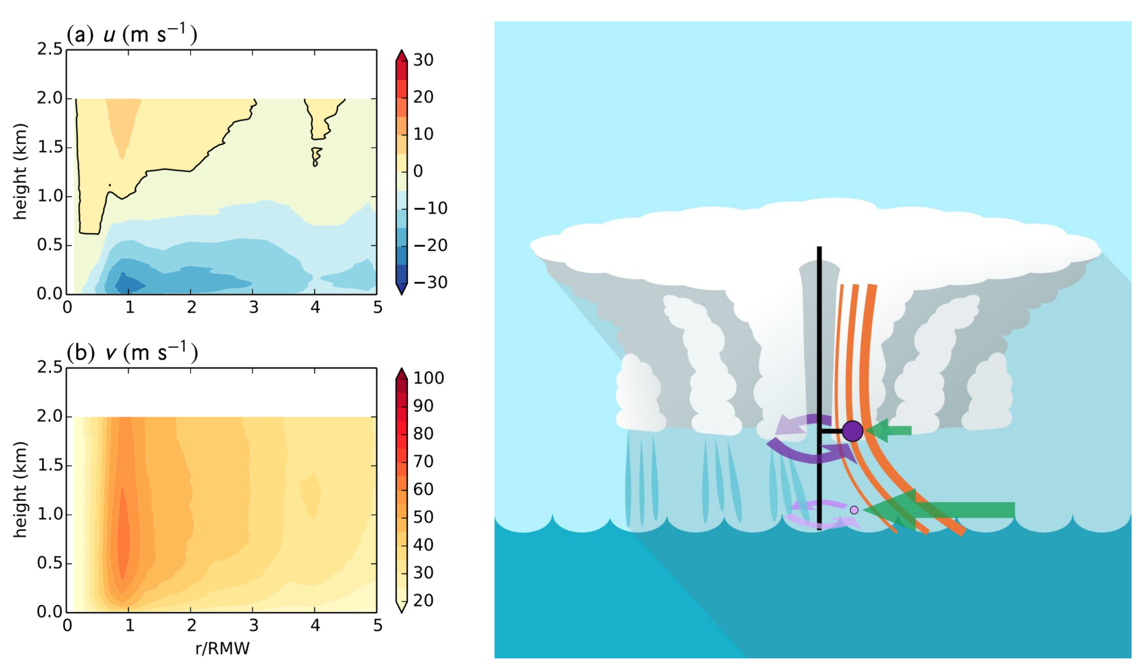
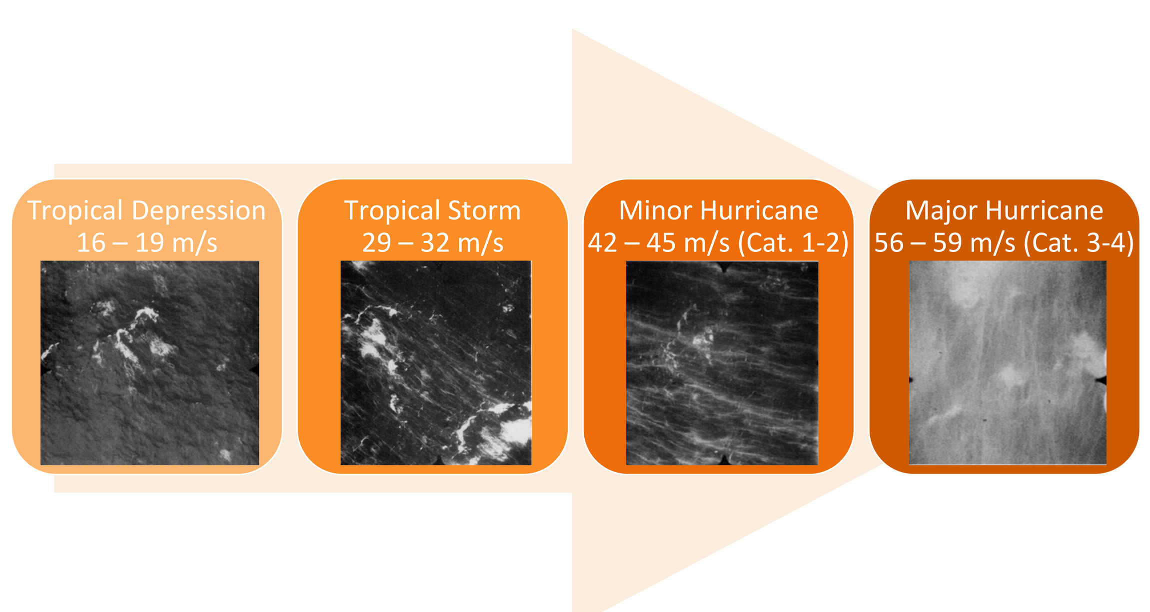
Introduction

The TCBL is approximately the lowest 1 km of a TC (Fig. 1), and it is known to be important for TC intensification because it is the primary: source of enthalpy; sink of momentum; and region that converges angular momentum via frictionally forced radial inflow. However, the complex, linear interactions between TCBL structure and TC intensity are not well understood due to limited observations of the TCBL.



▲ Fig. 1: (left) Dropsonde composite TCBL structure adapted from Kepert et al. (2016), where the parameters are: (a) radial velocity (m s^{-1}) and (b) tangential velocity (m s^{-1}). (right) Idealized TC illustration depicting typical TCBL structure of tangential velocity (purple), radial velocity (green), and angular momentum (orange).

While surface friction is known to be important for TC intensity change, the exact magnitudes of the drag coefficient (C_D) in the TCBL are not well known due to the non-linear relationship between the changing ocean surface structure with increasingly large surface wind speeds (Fig. 2). Additionally, the effects of C_D on TC intensity change are also uncertain.



▲Fig. 2: Ocean surface images captured from research aircraft within TCs and adapted from Black et al. (1986).

This study seeks to simplify these complex, non-linear interactions between surface friction, TCBL structure, and TC intensity change through a new conceptual framework. This new framework is developed from first principles in the form of a logistic growth equation (LGE), and it can be adapted to retrieve C_D from TCBL structure.

Research Questions

- How does TCBL structure relate to current and potential TC intensity?
- How does TCBL structure quantitatively relate to the drag coefficient?
- Can this LGE framework retrieve the drag coefficient from observations?

Methods

Part 1: Derive the Framework

Start with the tangential wind component of the momentum equation:

$$\frac{\partial \bar{v}}{\partial t} + \bar{u}\frac{\partial \bar{v}}{\partial r} + 0 + \bar{w}\frac{\partial \bar{v}}{\partial z} + \frac{\bar{u}\bar{v}}{r} + f\bar{u} = F_\lambda$$

Eulerian Tendency, Radial advection, ~~Tangential advection~~, Vertical advection, Centrifugal acceleration, Coriolis, Friction

End with:

Logistic Growth Equation (LGE)

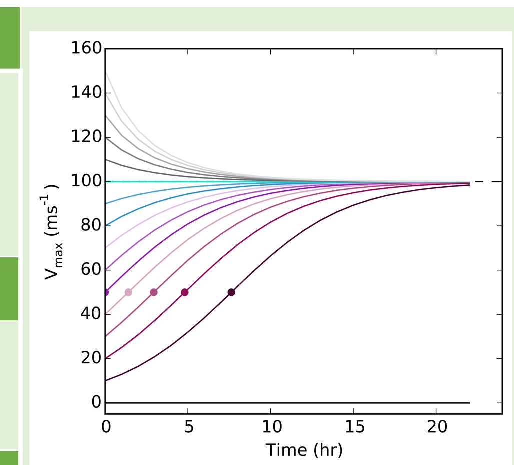
$$\frac{\partial v_{max}}{\partial t} = \left(\frac{-u_m}{r_m}\right) v_{max} - \left(\frac{\alpha^2 C_D}{z_m}\right) v_{max}^2$$

Instantaneous Logistic Potential Intensity

$$ILPI \equiv \frac{(-u_m) z_m}{\alpha^2 r_m C_D}$$

Differential Form of C_D

$$C_D \approx \frac{(-u_m) z_m}{\alpha^2 r_m v_{max}}$$

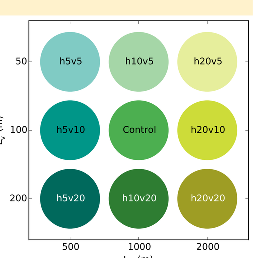


▲ Fig. 3: (solid) Sample logistic growth curves computed from the LGE. (dashed) The ILPI for all of the solid curves.

C_D = drag coefficient, v_{max} = maximum tangential wind speed, v_{10} = 10-m tangential wind speed, u_m = radial wind speed at the location of v_{max}, r_m = radius of v_{max}, z_m = height of v_{max}, and $\alpha = v_{max}/v_{10}$.

Part 2: Test the Framework with a Simplified Model

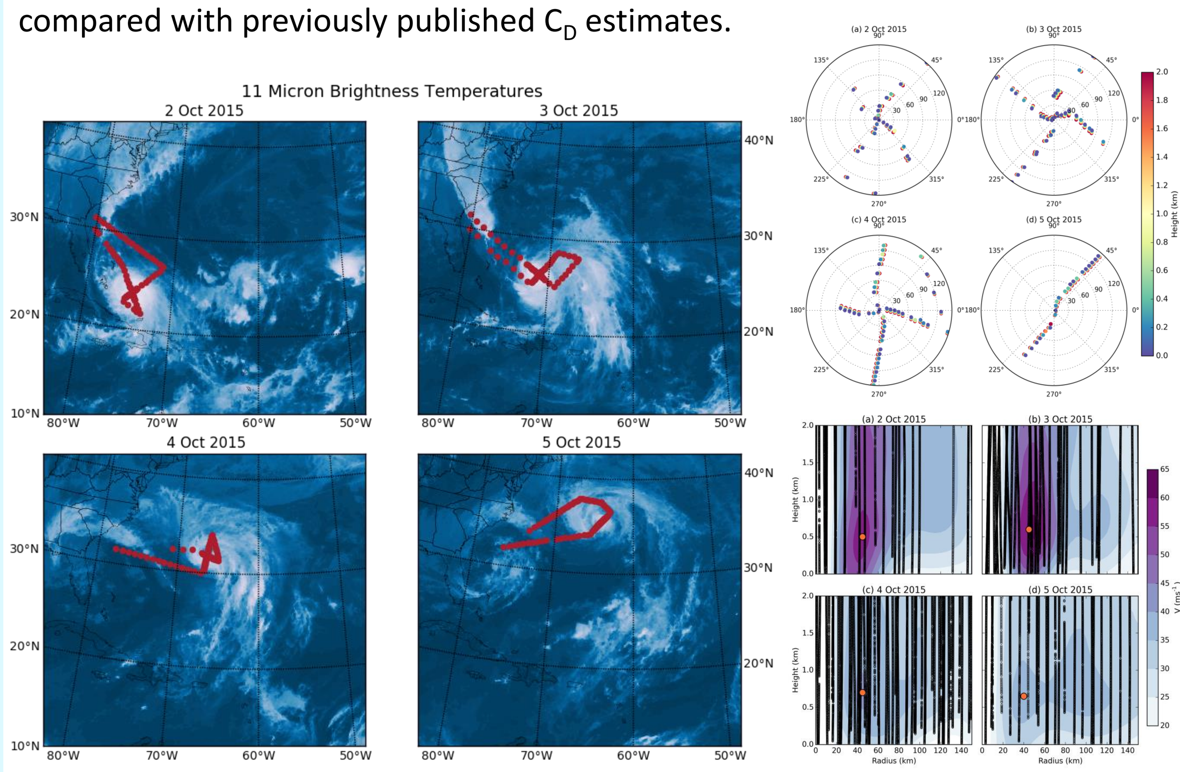
Experiment 1	Experiment 2	Experiment 3
"Control Run"	"Fixed Drag Experiment"	"Sensitivity Study"
Run the axisymmetric version of CM1* with all default settings	Run the axisymmetric version of CM1 eight more times, but now holding C_D constant at values ranging from 0.5 - 4.5 x 10^{-3} to test a greater range of values	Run the axisymmetric version of CM1 eight more times, but now holding C_D constant at 2.5 x 10^{-3} and changing the size and shape of turbulence



*Cloud Model 1, Bryan and Fritsch (2002)

Part 3: Test the Framework with Observations

Test with the published analyses of Hurricanes Fabian and Isabel (2003) from Bell et al. (2012), as well as with new analyses of Hurricane Joaquin (2015) that are developed from the Tropical Cyclone Intensity Experiment (2015) dropsondes (Fig. 4). Results of C_D from Hurricanes Fabian and Isabel are then compared with previously published C_D estimates.

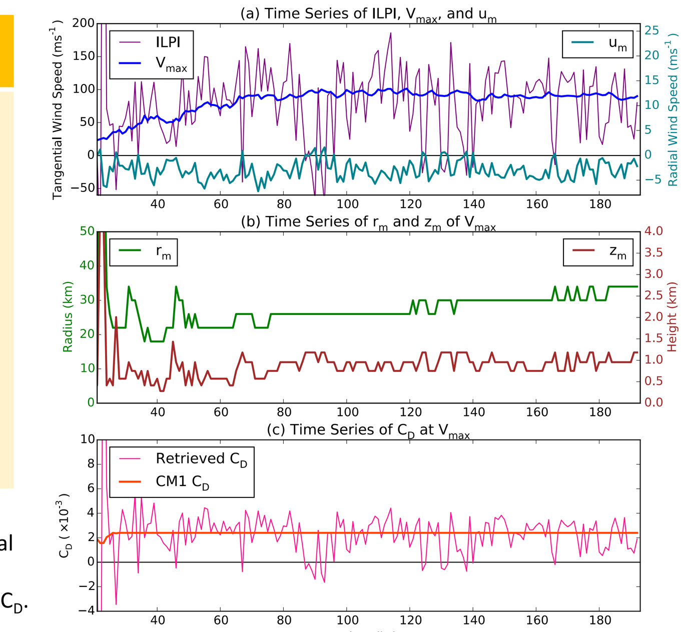


▲ Fig. 4: (left) Infrared satellite imagery showing: Hurricane Joaquin (2015), its environment, and dropsonde data from the Tropical Cyclone Intensity Experiment on 2-5 October 2015. (upper right) Azimuthal and (lower right) radial data locations of dropsonde data.

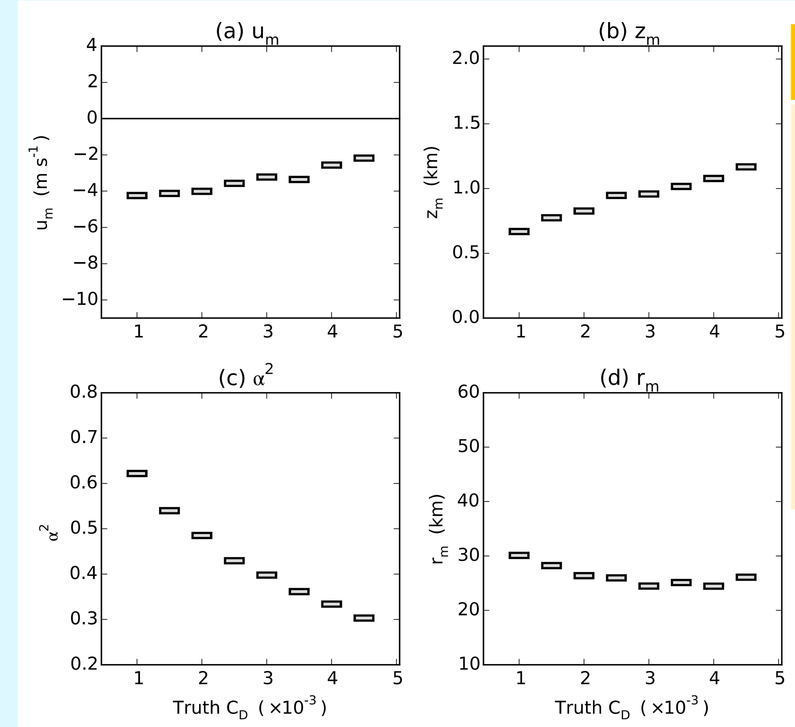
Part 2 Results: Modeling

Experiment 1

- The wind speed-dependent C_D reaches its model-prescribed maximum very quickly (Fig. 5)
- This suggests that we can set C_D to being a constant without significantly degrading the modeled TC structure



▶ Fig. 5: (Top) ILPI, tangential wind, and radial wind. (Middle) Radius and Height of v_{max}. (Bottom) Model (orange) and retrieved (pink) C_D.

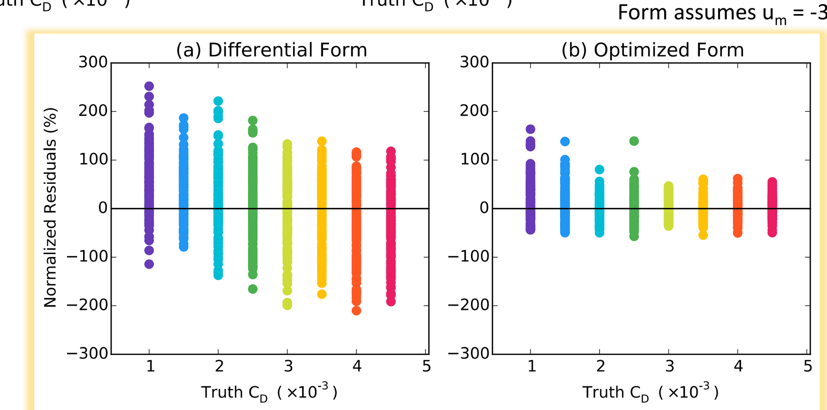


Experiment 2

- The CM1 TCBL changes structure as both ILPI and the Differential Form of C_D predict (Fig. 6)
- Skill can be increased if the radial flow at the location of v_{max} can be assumed to be -3 m s^{-1} (Fig. 7)

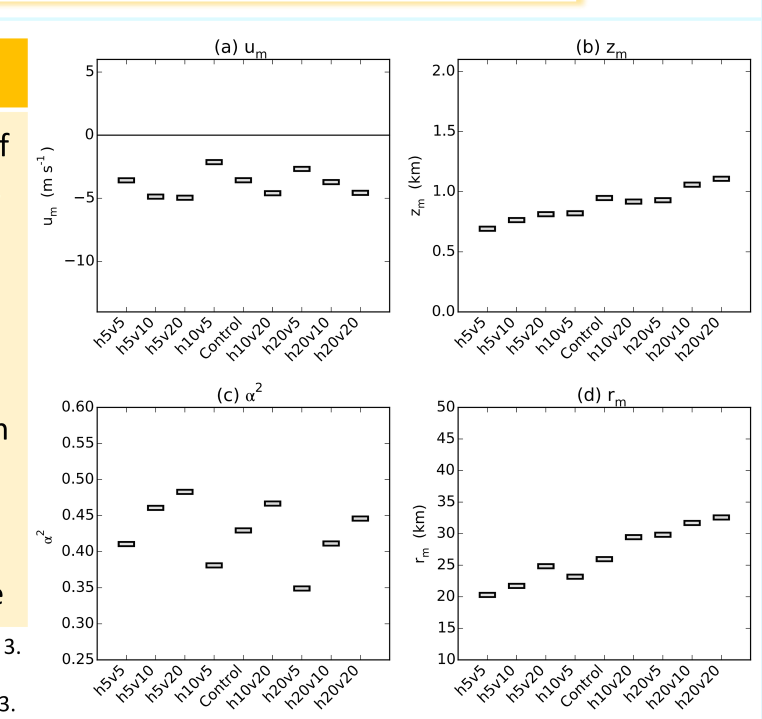
◀ Fig. 6: CM1-output variables of ILPI and C_D retrievals, and their average values after model spin-up.

▼ Fig. 7: Normalized residuals of Differential and Optimized Forms of C_D retrievals, where the Optimized Form assumes u_m = -3 m s^{-1}.



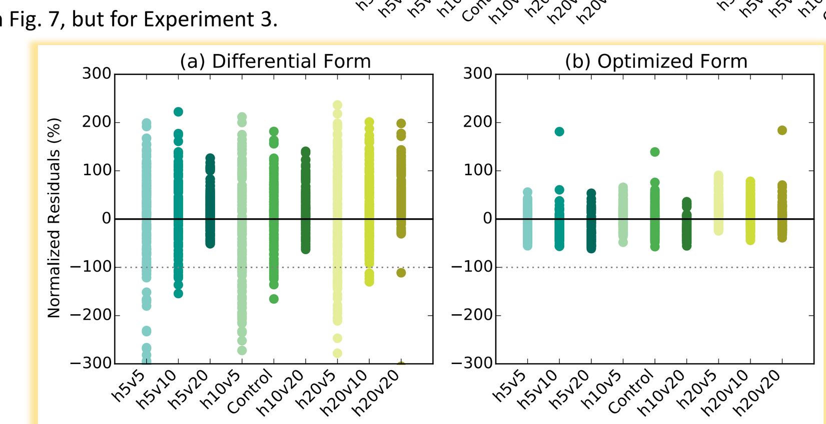
Experiment 3

- Both the shape and size of turbulence do affect TCBL structure (Fig. 8)
- C_D retrievals are dependent on turbulence size and shape (Fig. 9)
- While the Optimized Form in this study is not a general solution, it is not strongly dependent on turbulence size and shape



▶ Fig. 8: As in Fig. 6, but for Experiment 3.

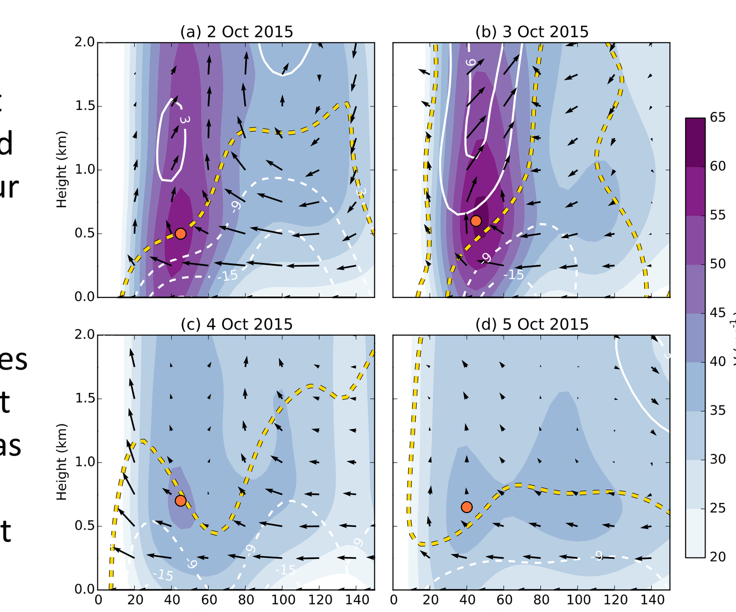
▼ Fig. 9: As in Fig. 7, but for Experiment 3.



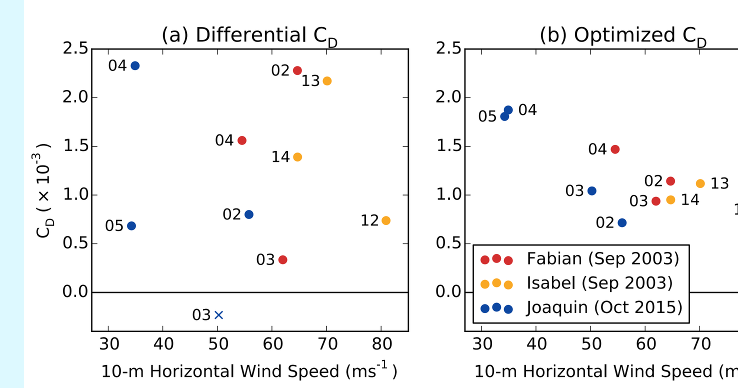
Part 3 Results: Observations

Axisymmetric Hurricane Joaquin analyses show that v_{max} does tend to be located near the u = -3 m s^{-1} contour for all four observed days (Fig. 10).

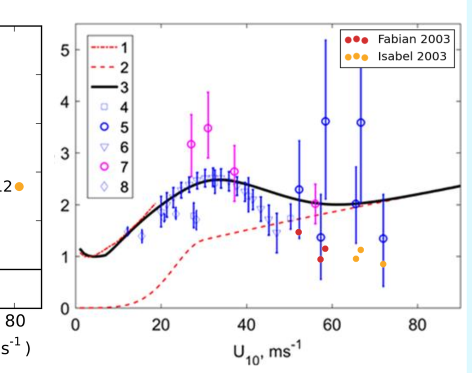
Retrievals of C_D in Hurricanes Fabian and Isabel show that this method has a lower bias than Bell et al. (2012) (Fig. 11), but magnitudes are not unrealistic when compared to other retrieval methods (Fig. 12).



▲ Fig. 10: Axisymmetric analyses of Hurricane Joaquin's TCBL from 2-5 Oct 2015.



▲ Fig. 11: Differential and Optimized Forms of C_D retrievals for Hurricanes Fabian, Isabel, and Joaquin.

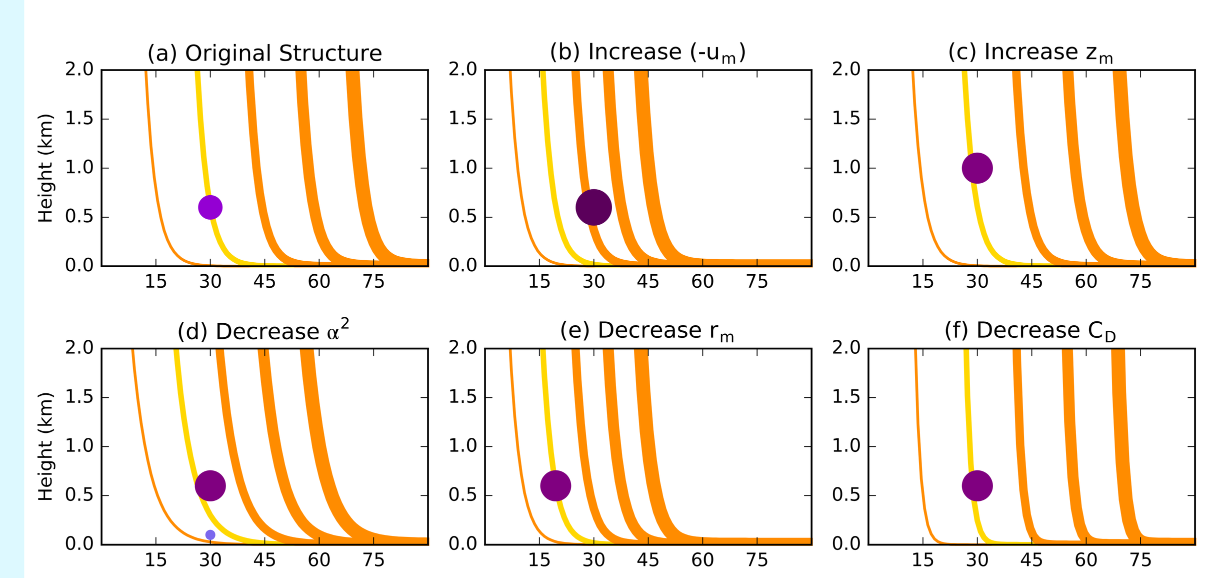


▲ Fig. 12: Reprinted from Soloviev et al. (2017), with Hurricanes' Fabian and Isabel's Optimized C_D overlaid.

Conclusions

The new conceptual relationships between surface friction, TCBL structure, and TC intensity proposed in this study are shown to exist in the simplified, axisymmetric version of CM1. The direct, individual relationships are summarized below (Fig. 13).

Applying this conceptual framework towards C_D retrievals from observations shows promise, but future work quantifying error is needed. Preliminary tests with CM1 show that individual errors can be optimized to within 100% if an appropriate constant u_m can be assumed. Testing with observations show a low bias for Hurricanes Fabian and Isabel (2003) compared to the method proposed by Bell et al. (2012), but retrievals are within the range of overall C_D uncertainty.



▲ Fig. 13: Summary schematic illustrating the ways TCBL structure can affect TC intensity. Purple points denote v_{max}, green arrow denotes u_m, and orange and yellow exponential curves denote arbitrary angular momentum contours.

Acknowledgements

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