The impact of limiting ocean roughness on GEOS-5 AGCM tropical cyclone forecasts

Andrea Molod,[1,2] Max Suarez,[2] and Gary Partyka[3,2]

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[1] Global climate models have been shown to simulate tropical cyclone-like behavior even at relatively coarse resolution, and recent higher resolution simulations more accurately capture the intensity, structure, and interannual variability. Even the highest resolution global models, however, continue to underestimate the intensity of the strongest tropical cyclones. The simulated cyclone intensity has been shown by many studies to be greatly influenced by the fluxes at the air-sea interface. A simple modification has been implemented in the GEOS-5 atmospheric general circulation model (AGCM) based on existing theory and laboratory experiments, which demonstrated that the ocean roughness does not increase with surface stress beyond some threshold. A series of strong tropical cyclone simulations were performed with the GEOS-5 AGCM to evaluate the impact of imposing a limit on ocean surface roughness at high wind speeds. The results demonstrated clear improvements in cyclone intensity and structure in the simulations with limited ocean roughness. **Citation:** Molod, A., M. Suarez, and G. Partyka (2013), The impact of limiting ocean roughness on GEOS-5 AGCM tropical cyclone forecasts, *Geophys. Res. Lett.*, *40*, 411–416, doi:10.1029/2012GL053979.

1. Introduction

[2] Strong tropical cyclones have an important impact on the atmosphere and the ocean and on local population and economies. The necessity for accurate short-term forecasts of these events is therefore apparent, and forecasts of the tracks of these extreme events have significantly improved in the last 10 years, primarily due to increases in horizontal resolution and improved physical parameterizations. The ability to properly forecast cyclone intensity, however, even at grid spacings on the order of 1–5 km, has lagged [*Marchok et al.*, 2009]. Improvements have also been made in the simulation of strong tropical cyclones in the coarser resolution models used for global data assimilation and even for the coarse resolutions used for climate studies, motivated primarily by the desire to predict future trends in tropical cyclone frequency and intensity. All of these applications of atmospheric models for tropical cyclone simulations suggest the need for accurate depiction of the spatial scale and intensity of individual storm events in these models across a wide range of resolutions.

[3] Recent studies based on multiyear simulations with high-resolution climate models show that the interannual variability of tropical cyclones is well captured by models at 20 to 50 km resolution but that simulated storm intensities are still weak [e.g., *Manganello et al.*, 2012; *Knutson et al.*, 2007]. The study of *Knutson et al.* [2007] in particular found that at 18 km resolution the storm track, hurricane eye definition, and warm-core structure are all well simulated. They found, however, that the intensity of the strongest storms is weaker than observed and that the weak intensity is exacerbated in the wind field relative to the pressure field. They attributed this characteristic of the simulations to excessive surface drag.

[4] The estimate of surface turbulent exchange processes in most climate and forecast models is calculated using a bulk scheme. Estimates of the exchange coefficients for the bulk formulations contain an underlying functional relationship between the ocean surface roughness and the surface stress. The relationships used are generally empirically based, derived either from laboratory experiments or localized ocean measurements [*Charnock*, 1955; *Large and Pond*, 1981; *Fairall et al.*, 2003; *Edson*, 2008], and all describe a roughness that increases with wind speed for all but near-calm wind regimes. Although these relations were not developed for winds of tropical cyclone strength, they are nevertheless extrapolated to compute the exchange coefficients at those high wind speeds.

[5] At high wind speeds, however, near the upper end of the Beaufort scale, physically based arguments and laboratory and field observations suggest that roughness does not continue to increase with wind speed. For example, the study of *Emanuel* [2003] showed that cyclone intensity is related to the ratio of the surface exchange coefficient of enthalpy to the exchange coefficient of momentum. He suggests that the air-sea exchange undergoes a regime transition at tropical storm strength wind speeds, where it becomes dominated by sea spray mechanisms, and argues that the transition to this regime can be adequately captured in an ocean roughness parameterization by imposing a threshold beyond which the surface roughness does not increase with increasing winds. Although some recent modeling and laboratory studies [*Montgomery et al.*, 2010; *Haus et al.*, 2010] raise questions about the details of the relationship between the cyclone intensity and the ratio of enthalpy to momentum exchange coefficients proposed by *Emanuel* [2003], the existence of a threshold for the drag coefficient (which is a function of surface roughness) at high winds has been confirmed by many laboratory, observational, and modeling studies. The laboratory study of *Donelan et al.* [2004] and the field study of *Powell et al.* [2003] found that the drag does not increase with winds beyond approximately 30–35 m/s. Studies of

[1]Earth System Science Interdisciplinary Center, University of Maryland, College Park, Maryland, USA.
[2]Global Modeling and Assimilation Office, Goddard Space Flight Center, Greenbelt, Maryland, USA.
[3]Science Applications International Corporation, Beltsville, Maryland, USA.

Corresponding author: A. Molod, Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD 20740, USA. (Andrea.Molod@nasa.gov)

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Table 1. List of Tropical Cyclone Cases[a]

Name	Simulation Start Date	Obs Max Wind	Model Max Wind	Δ Max Wind	Obs Min SLP	Model Min SLP	Δ Min SLP
Danielle	24 August 2010	60.3 (117.2)	55.0	3.8	942.0	949.7	−2.1
Megi	13 October 2010	79.7 (154.9)	59.9	6.1	885.0	957.1	−5.6
Chaba	25 October 2010	59.2 (115.1)	43.9	1.2	935.0	957.5	−2.3
Malakas	22 September 2010	46.9 (90.1)	58.0	5.1	955.0	933.3	−3.6
Fanapi	15 September 2010	54.0 (104.9)	45.1	1.8	930.0	958.7	−1.4
Jal	04 November 2010	36.0 (70.0)	28.1	0.6	988.0	989.9	−0.05
Tomas	29 October 2010	43.7 (85.0)	35.1	2.2	982.0	982.2	−5.3
Otto	07 October 2010	38.6 (75.0)	31.4	0.4	985.0	972.0	−1.8

[a]Each row contains the information about the modeled (Model) and observed (Obs) winds in per second and sea level pressure (SLP) in millibars for each cyclone. Numbers in parenthesis are winds in knots. Model results are from the THR25 experiment. The columns that refer to a Δ reference the increase in wind or decrease in sea level pressure of the THR25 experiment relative to the CTL experiment.

results from the more recent Coupled Boundary Layer Air-Sea Transfer Hurricane field program [*Black et al.*, 2007; *French et al.*, 2007] also show the existence of a "roll off" of the drag coefficient beyond some wind threshold but suggest that the threshold may occur at lower wind speeds (closer to 23 m/s) than previous studies suggest. Modeling studies by *Moon et al.* [2004a, 2004b] and *Zhou et al.* [2008], for example, using an ocean wave model coupled to a wave boundary layer model, also found that the surface drag coefficient levels off and even decreases at wind speeds larger than approximately 35 m/s.

[6] A surface layer turbulence scheme incorporating a threshold of surface roughness or surface drag coefficient has been used in several general circulation models for forecasts of idealized and realistic tropical cyclones. For example, *Davis et al.* [2008] showed the increase in wind speed in very high resolution (4 km) simulations of hurricane Katrina in 2005 when a threshold is imposed, and *Nolan et al.* [2009] showed a similar impact on the intensity of a simulation of hurricane Isabel in 2003. *Moon et al.* [2007] developed a surface layer parameterization based on results from a coupled wave and wave boundary layer model that limits the drag coefficient at high wind speeds. Based on typhoon forecasts at 8 km resolution, they found that the new scheme increased surface wind speeds but did not impact the minimum sea level pressure.

[7] The impact of limiting the modeled surface drag on the highest resolution tropical cyclone forecasts motivates the study of the impact of limited surface drag in forecasts of individual storm events at the coarser resolution typical of climate simulations. The present study examines the impact of imposing a threshold on the surface drag at high wind speeds in a set of short-term forecasts of strong tropical cyclones with an atmospheric general circulation model (AGCM) developed for use at a wide range of horizontal resolutions and a wide range of applications. The model and the experiments are described in the following section. Results of the forecasts follow, along with a description of the connection to tropical cyclone intensity. The study is summarized in the final section.

2. Model and Experiments

[8] The GEOS-5 AGCM was developed at NASA's Global Modeling and Assimilation Office for use in a range of applications including data assimilation, weather and seasonal forecasting, and climate simulation. The AGCM was therefore developed for use in simulations at a wide range of horizontal resolutions, from 2° (approximately 200 km) for coupled climate simulations to 0.25° × 0.33° (approximately 25 km) for data assimilation and weather prediction, and to 10 km for global mesoscale simulations. The GEOS-5 AGCM suite of physical parameterizations are described in *Rienecker et al.* [2008] and *Molod et al.* [2012], and a brief description of the GEOS-5 surface layer parameterization is provided here. The scheme to describe the flux of heat, momentum and tracers at the land-, ocean-, or sea-ice interface is the Monin-Obukhov similarity scheme described in *Helfand and Schubert* [1995]. The scheme accounts for the difference between the roughness lengths for enthalpy and momentum through the presence of a viscous sublayer inhibiting enthalpy transfer. The presence of the viscous sublayer is based on the premise that enthalpy transfer is predominantly due to diffusivity, whereas momentum transfer is predominantly due to the form drag of the roughness elements. Over the oceans, the surface roughness used for momentum and enthalpy transfer is computed using the relationship between the ocean surface stress and ocean surface roughness of *Large and Pond* [1981], modified by the relation of *Kondo* [1975] for weak winds and by the relation described in *Garfinkel et al.* [2011] for higher wind speeds (hereafter referred to as the LPG scheme). The equation to describe the enthalpy transfer in the viscous sublayer is based on *Yaglom and Kader* [1974] and describes a resistance to enthalpy transfer that increases with surface roughness.

[9] A series of 5 day forecasts at a horizontal resolution of 0.25° × 0.33° × 72 levels were run to examine the impact of a decrease in ocean surface roughness at high wind speeds. Present-day climate simulations are typically performed at coarser resolution (approximately 1° or 100 km), but the next generation of climate simulations are expected to be performed at the resolution of the experiments described here. A sample of eight Atlantic, Pacific, and Indian Ocean basin tropical cyclones from the year 2010 was chosen for this study, all of which developed into hurricanes or typhoons. They are listed in Table 1. For inclusion in this study, each tropical cyclone had to be "reasonably represented" in the GEOS-5 data assimilation system fields used to initialize the forecasts. For a tropical cyclone to meet this standard, it had to be represented at the initial time as a warm-core low pressure system whose strongest winds were close to the pressure minimum and near the surface, and the maximum tropical cyclone winds had to be at least at or near 25 m s^{-1}. The initial time of each simulation was chosen to be approximately 2 days prior to the cyclone's peak intensity, as gauged by wind speed. The forecast thus would span

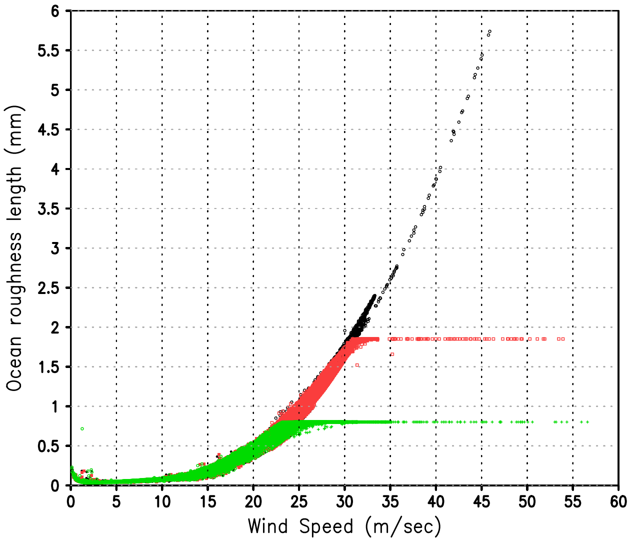

Figure 1. Scatter plot of ocean roughness in millimeters as a function of surface wind speed in meters per second. The black points represent the CTL experiment, the red are from the THR30 experiment, and the green points are from the THR25 experiment.

the rapid cyclone deepening, cyclone peak intensity, and cyclone filling stages of the storm. As seen in the third column of Table 1, the maximum wind speed attained by the different tropical cyclones ranges from approximately 40 to 80 m s^{-1}, a wide range in values chosen to examine the impact of the decreased roughness in storms of varying intensity.

[10] Three forecasts were performed from each initial state, a control and two experiments. The models used for all three forecasts were identical except for the change in the functional relationship between the ocean surface roughness and the wind stress. Scatter diagrams for the behavior of the ocean roughness as a function of surface wind speed for the control and the two experiments are shown in Figure 1. The suite of experiments for each tropical cyclone case included a control in which the LPG formulation was valid for all wind speeds, shown as the black curve in the figure and referred to here as CTL, a simulation in which the ocean roughness did not increase with wind stress beyond surface wind speeds of approximately 30 m s^{-1}, shown as the red curve in the figure and referred to here as THR30, and a simulation in which the ocean roughness was held constant beyond approximately 25 m s^{-1}, shown in the green curve and referred to here as THR25. The choices for the roughness cutoffs for the two experiments were based on *Emanuel* [2003], *Donelan et al.* [2004], and *Black et al.* [2007].

3. Results

[11] Results of the experiments to limit surface roughness are shown in Figure 2 and are summarized in Table 1 using winds and sea level pressure estimates from the Joint Typhoon Warning Center (http://www.usno.navy.mil/JTWC/) and the National Hurricane Center (http://www.nhc.noaa.gov/index.shtm) for reference. Table 1 indicates that with the exception of one tropical cyclone (Malakas), the observed winds are underpredicted by all the model experiments and that the change in speed due to the limit on the surface roughness represents an improvement in the modeled winds. In addition, the table shows that the impact on the tropical cyclone intensity is larger for more intense storms (again, with the exception of the Malakas experiments). The case with the strongest wind speeds, Megi, shows an increase in maximum surface winds of just over 6 m s^{-1} and also a decrease in minimum sea level pressure of just under 6 mb. This increase in cyclone maximum wind speed shown here is smaller than the increase of near 10 m s^{-1} reported in *Davis et al.* [2008] and *Nolan et al.* [2009] for the single case each study examined with stronger simulated winds using model resolutions ranging from 1 to 4 km.

[12] Figure 2 shows the surface wind speed from each experiment as compared to the observational estimates. As expected, the modeled winds are generally lower than the observed winds, given the spatial and temporal resolution of the GEOS-5 AGCM used for these experiments. The points which lie above the (blue) one-to-one line are from Typhoon Malakas, which all model simulations developed too quickly into an overly intense cyclone. The linear curve fit for the THR25 experiment (green points and line) shows the higher winds relative to the THR30 and CTL experiments, which are closer to the observed winds.

[13] Details of the change in tropical cyclone structure and evolution associated with the increase in intensity in experiments THR30 and THR25 relative to CTL are illustrated based on results from the strongest case in terms of maximum wind speed (Megi). Figure 3a shows the time series of maximum wind speed (open circles) and minimum sea level pressure (plus symbols) in the cyclone's domain. The black curves are from CTL, and the red and green curves are from the THR30 and THR25 experiments, respectively. Near the mature stage of the storm, both of the threshold experiments simulate sea level pressure values that are up to 5 mb deeper than the control, and maximum surface wind speeds that are up to 5 m s^{-1} stronger than the control, both indicating the simulation of a stronger typhoon. Figures 3b

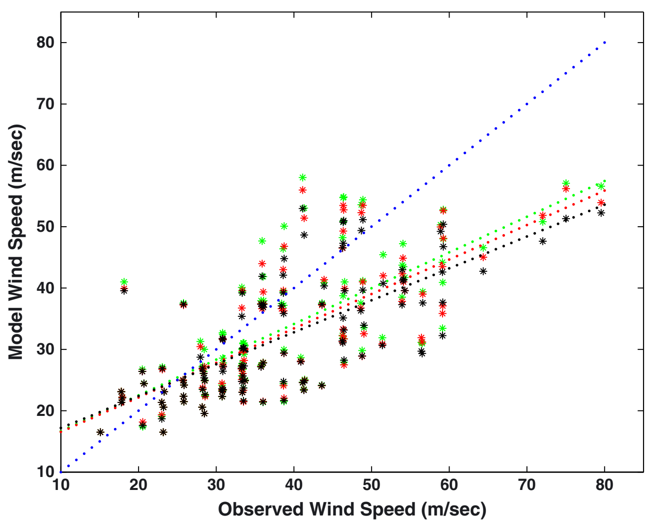

Figure 2. Scatter diagram and linear curve fit for observed versus modeled surface wind speed in meters per second from the CTL (black), THR30 (red), and THR25 (green) experiments. Results are shown throughout all tropical cyclone cases.

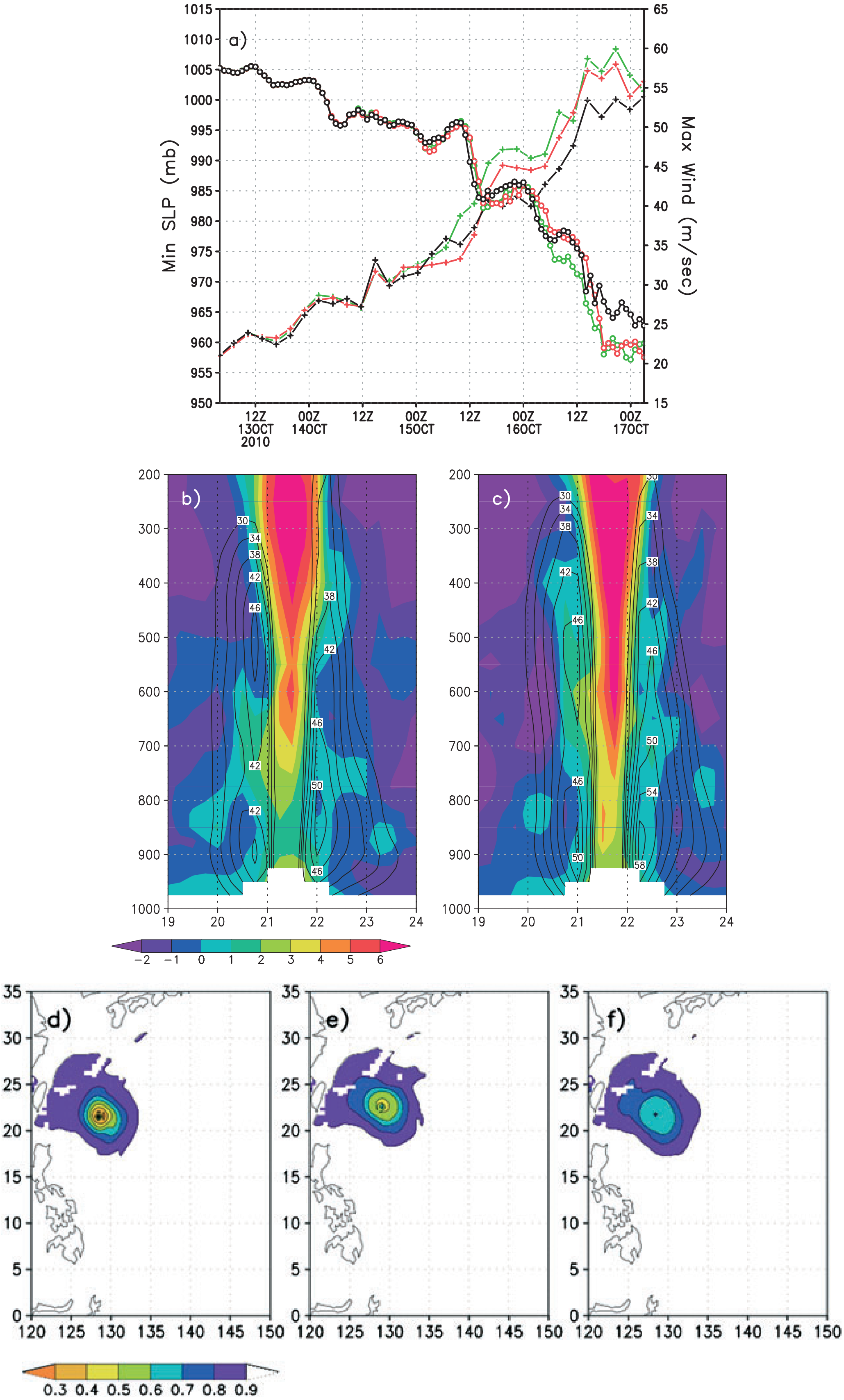

Figure 3. Results from the experiments simulating typhoon Megi. (a) Time series of minimum sea level pressure in millibars and maximum surface wind speed in meters per second from the CTL (black), THR30 (red), and THR25 (green) experiments. (b) Latitude-height cross-sections of temperature anomaly (shading) and winds (contours) at the time of maximum storm intensity from the CTL experiment. (c) Same as Figure 3b but for the THR25 experiment. (d) Ratio of C_t to C_m for the CTL experiment. (e) Same as Figure 3d but for THR30 experiment. (f) Same as Figure 3d but for THR25 experiment.

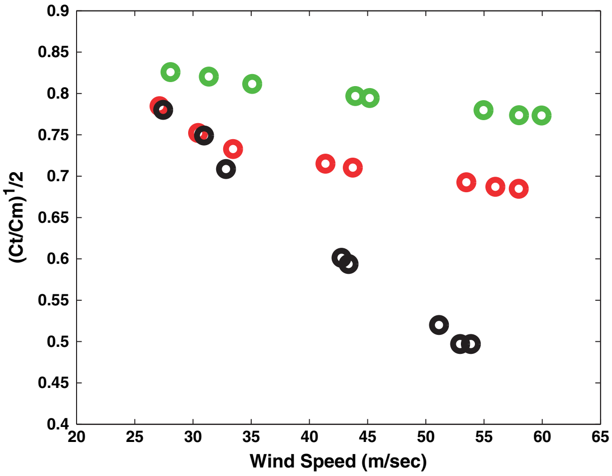

Figure 4. Scaling relationship between $(C_t/C_m)^{1/2}$ and the maximum surface wind speed in meters per second for each experiment suite for all the tropical cyclone cases. CTL experiments in black, THR30 in red, and THR25 experiments in green.

and 3c show latitude-height cross-sections of the typhoon at full maturity from the CTL experiment (Figure 3b) and from the THR25 experiment (Figure 3c). The contours are the zonal wind component, and the shading is the temperature anomaly from the domain averaged mean. Both panels show the expected elevated temperatures in the core and highest winds near the eye wall at about 900 mb, but Figure 3c shows the higher temperature anomalies and wind speeds, indicating the simulation of a stronger cyclone in the THR25 experiment.

[14] The presence of a viscous sublayer that increases in strength with surface roughness suggests that as the ocean surface roughness increases, the resistance to enthalpy transfer will increase as well. The expectation, therefore, is that limiting the surface roughness beyond some wind speed threshold will cause the momentum transfer to decrease and cause the enthalpy transfer to increase. The ratio of the transfer coefficients of enthalpy to momentum, C_t/C_m, are shown in Figures 3d–3f and reflects the expected increase with limits on the roughness. The figure shows the ratio C_t/C_m in the core of typhoon Megi at the time of maximum surface wind speed. For the CTL experiment (Figure 3a), the ratio is near 0.3 in the core, for the THR30 experiment the ratio increases to near 0.4 (Figure 3b), and for the THR25 experiment the ratio increases further to a value of near 0.65 (Figure 3c). The ratios found in the THR30 and THR25 experiments are both below the 0.75 threshold for the development of strong tropical cyclones proposed by *Emanuel* [2003].

[15] A summary of the relationship between C_t/C_m and tropical cyclone intensity is shown in Figure 4. The scaling relationship proposed by *Emanuel* [1986] states that the maximum wind speed of a tropical cyclone is linearly related to $(C_t/C_m)^{1/2}$, and so Figure 4 shows $(C_t/C_m)^{1/2}$ as a function of storm maximum wind speed for each experiment from each suite of Table 1. The figure shows that the relationship is nearly linear for each experiment suite beyond the wind speed at which the roughness threshold was imposed. Other modeling studies [*Montgomery et al.*, 2010] and laboratory studies [*Haus et al.*, 2010] have found low values of C_t/C_m associated with intense storms and even found the ratio to decrease with storm intensity, but the findings here are consistent with the earlier scaling relationship.

4. Summary and Conclusions

[16] A series of experiments were performed with the GEOS-5 AGCM at horizontal resolutions of approximately 25 km to examine the impact of imposing a threshold of ocean surface roughness on tropical cyclone intensity. The study was motivated by the need for global climate models to accurately capture intense individual tropical cyclones. The results of three suites of eight strong tropical cyclone simulations demonstrated improvements in cyclone intensity when the ocean surface roughness is held steady beyond its value at approximately 25 m/s. The experiments spanned a wide range of storm intensities, and the strongest storms showed the largest impact.

[17] The results presented here demonstrated an increase in intensity of approximately 10% in simulations of individual strong tropical cyclones by imposing a limit on ocean surface roughness. The experiments were performed at a horizontal resolution of 25 km, which is comparable to the expected resolutions for the next generation of long-term climate predictions. The model improvements reported here, along with continued development related to the handling of deep convection, will add fidelity to climate projections of potential changes in tropical cyclone behavior with the evolving climate.

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