Developing Landfall Capability in Idealized HWRF for Assessing the Impact of Land Surface on Tropical Cyclone Evolution

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Background

Landfall is often the period during which a tropical cyclone (TC) presents the major hazard to life and property, and is also one of the major causes of the weakening of tropical cyclones. Understanding the changes that occur in the TC structure and its post landfall life cycle are therefore important.

Tropical systems typically weaken rapidly after landfall due to lack of surface moisture (SM) fluxes (Emanuel et al. 2004, 2008, Gopalakrishnan et al. 2011). Depending on surface and environmental conditions, some storms can sustain and even re-intensify over land (Dastoor and Krishnamurti 1991, Emanuel et al. 2004, 2008). Indeed, synoptic conditions are important in developing the storms and modulating their impact, and ongoing work continues to investigate the understudied role of land surface conditions on landfalling TCs (Tuleya 1994).

The availability of antecedent wet conditions and surface latent heat flux (LHF) has been thought to be the primary signatures for post-landfall TC intensification/ decay (e.g., Chang et al. 2009, Anderson et al. 2013). Evans et al. (2011) and Kellner et al. (2012) analyzed the re-intensification of Tropical Storm Erin (2007) over the U.S. Southern Great Plains (SGP) and concluded that anomalously wet land conditions can help sustain the storm inland. Similarly, it has been observed that monsoon depressions respond to high antecedent SM conditions and their intensity was maintained for a longer duration (Chang et al. 2009, Kishtawal et al. 2013). Subramanian et al. (2014) and Subramanian et al. (2016) studied the impact of soil temperature (ST) on TCs using an idealized version of HWRF and the results suggest that warm surfaces are crucial to post landfall intensification.

The use of idealized conditions conducive to intense TC development allows for model results to be viewed without the confounding of case specific conditions. Emanuel (1995), utilizing an idealized hurricane model, investigated the sensitivity of simulated TC intensity to the ratio of surface exchange coefficients of enthalpy and momentum (C_k to C_D). Montgomery et al. (2010) furthered the understanding of the role of C_D in hurricanes by using a threedimensional idealized MM5 model. While the former modeling study suggested that the intensity of TCs decreases with increase in frictional forces due to increase in C_D, the newer study points to a dual role that frictional forces play in hurricane dynamics. Gopalakrishnan et al. (2013) using the idealized version of HWRF studied the effect of the vertical diffusion coefficient on the structure and intensity of TCs and calibrated the HWRF modeled eddy diffusivities to best match flight level observation data gathered during Hurricane Allen (1980) and Hurricane Hugo (1989). Halliwell et al. (2015) used an idealized version of HWRF to obtain an improved understanding of the sensitivity of the HWRF model to ocean cooling and enhanced understanding of the dynamical processes that contribute to change in intensity of storms and resulting asymmetries. The Halliwell et al. (2015) study also stressed the importance of idealized studies in advancing the forecasting competencies in models.

While there are many studies involving the idealized model to deepen the understanding of the fundamental processes that affect TCs over the ocean, there are a relatively limited number of studies available to study the land impact. The availability of an idealized landfall modeling tool in HWRF will help the capability to study the processes involved in landfalling hurricanes and improve our understanding of post landfall TC dynamics.

This proposal was built on the recent and ongoing work by PI Dev Niyogi and his group related to the role of antecedent land surface conditions in impacting the structure, intensity, and longevity of landfalling tropical cyclones and its post-landfall characteristics. During this research, the team developed research capabilities to simulate idealized landfalling storm within HWRF modeling system.

The objective of this proposal was to work with the DTC in translating the work done in introducing the landfalling capability into the release version of the idealized HWRF and, to test the new capabilities by performing experiments and test cases to study the impact of land surface on TC evolution.

Methodology

In the previous version of idealized HWRF-v3.7a, the domain was over the ocean. The vortex was added to the center of the HWRF domain and was kept stationary. The conventional method to realize landfall is to introduce a wind and move the storm towards a predefined land surface in the domain. To avoid the spurious convection over land and instability due to gravity waves bouncing off the lateral boundaries, a moving land surface was incorporated. In this configuration, land is moved underneath the centered storm to realize relative landfall. A land/sea mask is used as a control variable to define the land points and the domain is redefined after every time step based on an input file to control how fast or slow the land moves underneath. Land characteristics are based on the land use, soil and vegetation table and different land use/land cover parameters, including SM ranges, surface roughness, emissivity, and albedo, defined and updated after every time step in the surface physics modules (Biswas et al. 2016a, Biswas et al, 2016b). A schematic of the land relative to storm motion is shown in Figs. 1a, b at different time steps.

The apparent speed at which landfall is realized can be altered in the source code and is explained in the HWRF Users Guide. Currently only the GFDL Slab land surface physics option is supported for landfall capability and efforts are underway to include other land surface physics options. A namelist file for land surface configuration introduces a switch for the landfalling capability, specifies the type of land surface, and the initial land surface temperature to be used over land. The default configuration introduces a homogeneous land surface but can be modified to account for heterogeneity through the source code. The direction of land motion can also be chosen. Two options are available – West to East or East to West. A complete explanation of the options and configurations available for the landfalling capability is available in the HWRF Users Guide.

Sample Results

Sensitivity to temperature:

Figure 2 is the Hovmöller diagram of axisymmetric winds azimuthally averaged around the center of the cyclone for different land surface temperature (LST). In all experiments, a steady state is achieved over the ocean at around 48 hours into simulation and when the storms make landfall at 56^{th} hour, there is a notable drop in intensity. The model results are for land surface temperatures ranging from 300 K to 314 K. As temperature increases, the intensity of the storm over land also increases. Re-intensification (gaining strength after initial drop in intensity post landfall) is seen with temperatures from 304 to 308 K and sustenance (maintenance post landfall) of storm's intensity is noted for land temperatures beyond 308 K. This trend is also noted in the time series plot for storm's central pressure and maximum wind speeds. The larger wind swaths of cyclones at over higher land surface temperatures enables the storm to bring in heat and moisture to maintain the circulation over land (Figure 2). Approximate values are 45 km for 302 K and 60 km for 308 K after landfall. Precipitation also increases with increase in temperature. Figure 3 shows the Hovmöller diagram of precipitation at different temperatures and we see that as temperature of land surface increases, the convection also increases. With warmer temperatures and stronger storms over land, the sensible heat flux also increases. Between 80-85 percent of the net radiative flux is contributed by sensible heat flux (Figure 4), leading us to believe that it maybe the total enthalpy rather than the contribution of latent heat fluxes that contributes to the maintenance of the cyclone structure over land. The enthalpy flux difference in the storm after landfall (56 -120 hours) is plotted in Figure 5 (See Halliwell et al. 2015 for methodology). It should be noted that the storm post landfall is never more intense than the storm over the ocean and thus the difference between the enthalpy fluxes after landfall (reference is Q(r, 56)) is always negative. It is also observed that the latent heat flux generated is higher for higher temperatures. This is possibly due to increased precipitation over land as the storm is more intense at higher land temperatures.

Summary

Results from temperature sensitivity experiments indicate that tropical cyclones can sustain or re-intensify after landfall at higher temperatures. Precipitation is also higher. With higher temperatures, sensible heat dominates the energy balance and it may be the total enthalpy of the system rather than the latent heat flux alone that is responsible for maintaining a storm's intensity over land.

Similar to temperature sensitivity experiments, impact of soil moisture, surface roughness (indicative of heterogeneity), size of storms, albedo and other land parameters could be tested and studied. This improvement to idealized framework for HWRF will further aid development in studying the impact of land surface and heterogeneity in land surface on the evolution of landfalling tropical cyclones.

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Figures

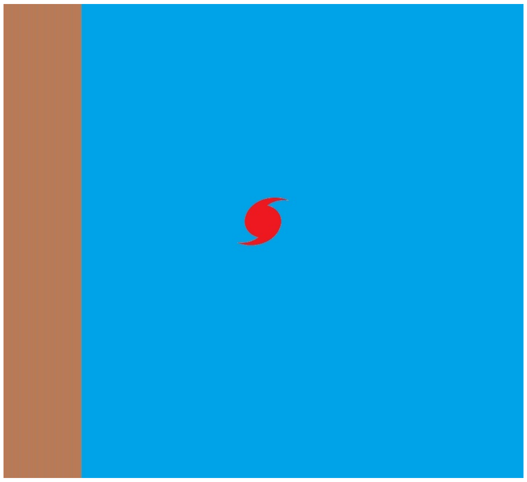


Fig 1a: Domain at T hours

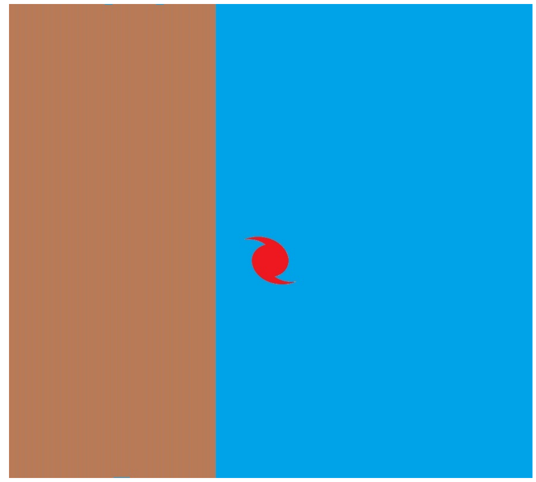


Fig 1b: Domain at T+ΔT hours

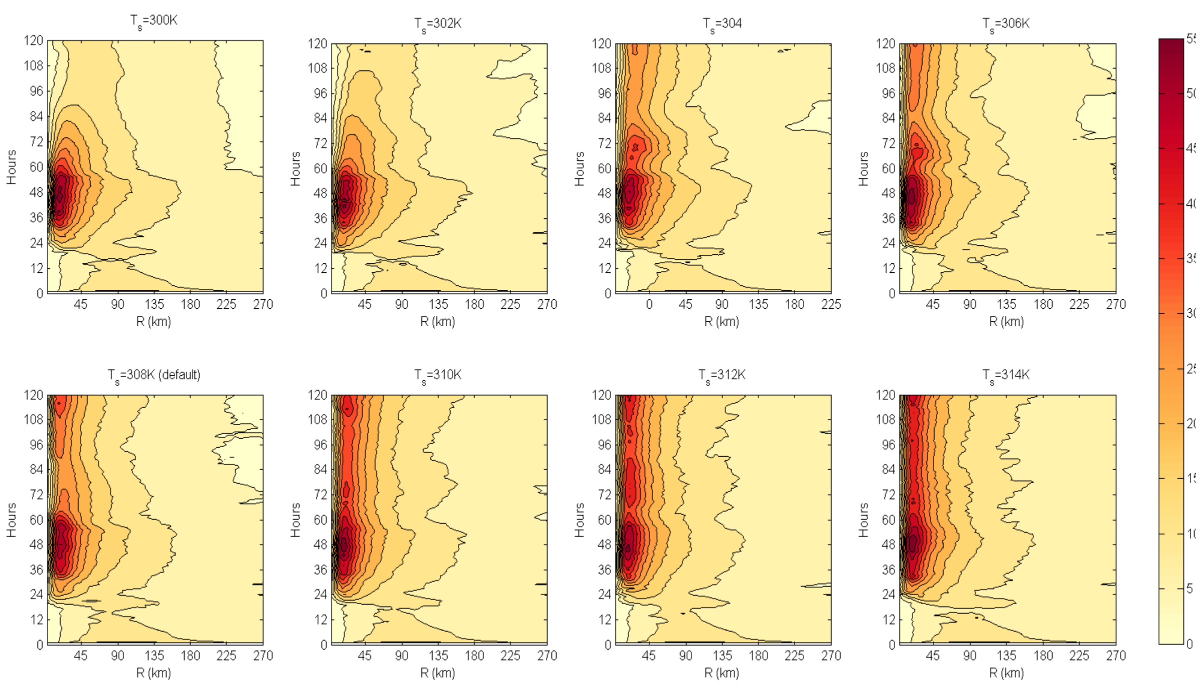


Figure 2: Time evolution (Hovmöller diagram) of azimuthally averaged axisymmetric 10-m winds (m/s) for different land temperatures (300 K to 314 K). The sea surface temperature was kept at a constant 302 K for all experiments.

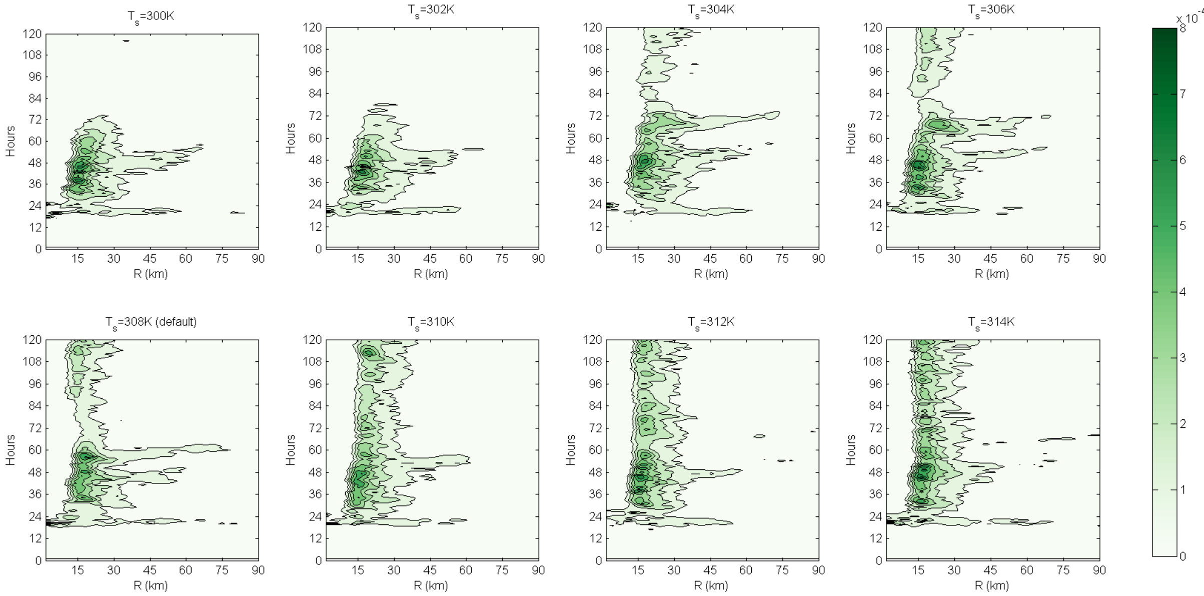


Figure 3: Hovmöller diagram of instantaneous precipitation in meters for different land surface temperatures.

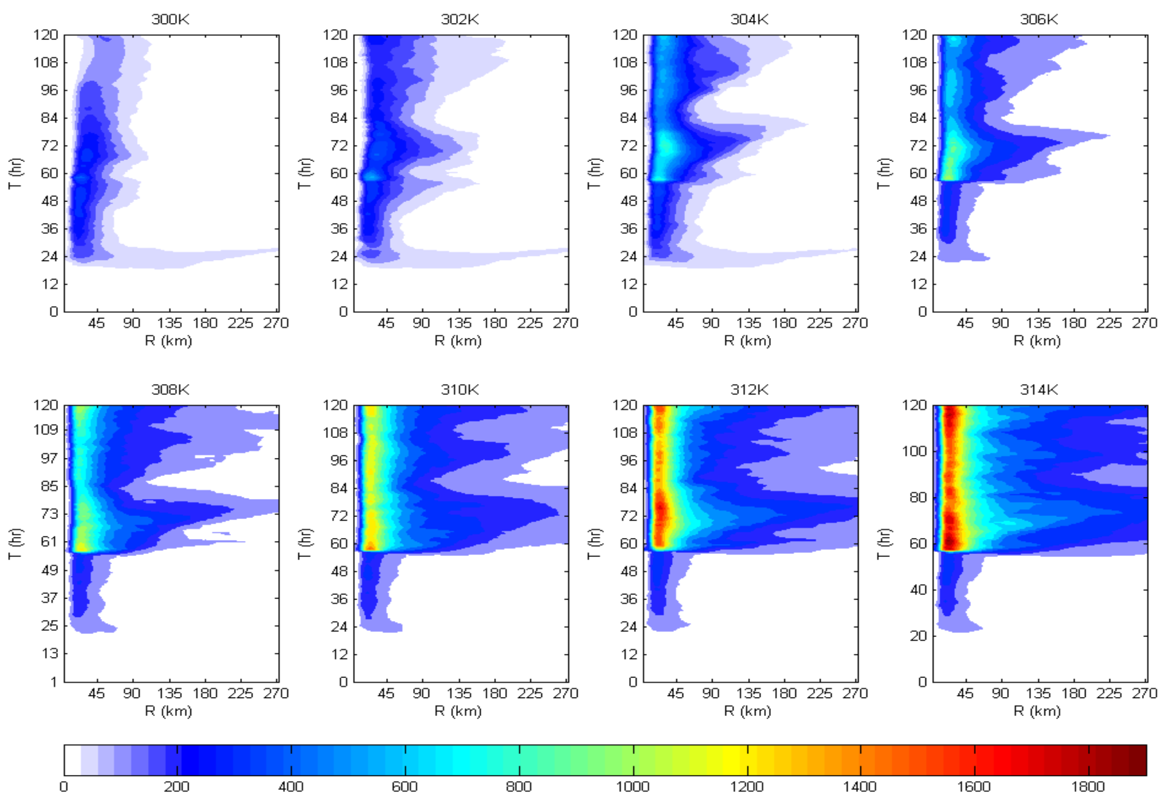
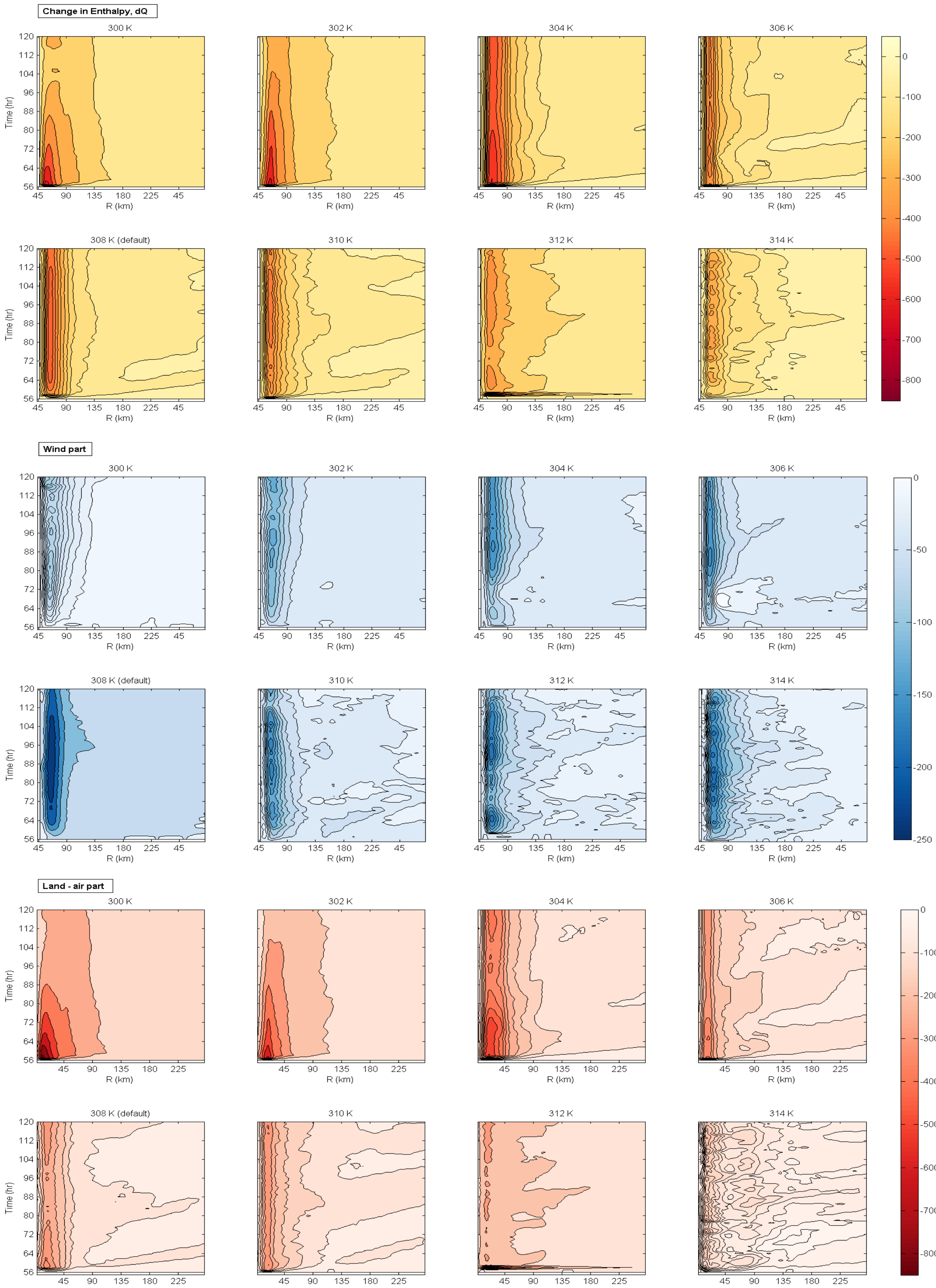


Figure 4: Hovmöller diagram of sensible heat flux (W/m^2) at different temperatures.



Change in Enthalpy, dQ
300 K
302 K
304 K
306 K
308 K (default)
310 K
312 K
314 K
Time (hr)
R (km)
Wind part
Land - air part

Figure 5: Hovmöller diagrams of $Q_E(r,t)$-$Q_E(r,56)$ in W m^{-2} (top panel) and its two primary components: the air-sea part due to changes in Δq and ΔT (middle panel) and the wind part due to changes in wind speed (bottom panel) for different land surface temperatures experiments (See Halliwell et al. 2015 for equations)