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**THIRD INTERNATIONAL WORKSHOP ON TROPICAL CYCLONE LANDFALL PROCESSES**

# 6.1: Summary of Previous Research related to Track, Intensity, and Structure Changes at Landfall

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Abstract: The recent advances in the research on tropical cyclone track, intensity and structure changes at landfall are reviewed in this report. Based on the well-developed theories on TC motion, further understanding on how TC tracks are influenced by the existence of land and topography, mainly through land-induced motion and generation of asymmetric convection, has been obtained. Moreover, trends of the impacts from TCs such as heavy rainfall on climatic timescale have been re-assessed based on the enhanced understanding of land effect to TC motion. Substantial advances have been obtained in dynamical modeling of TC landfall processes with contributions from data assimilation of surface observations over land. A large number of studies, both idealized and based on real cases, have been conducted to investigate TC structure changes due to the surface friction of land, moisture availability and topography. Observations in the boundary layer have enhanced understanding of the near surface TC landfall processes. Extensive numerical modeling studies have largely clarified how the near-surface processes induce structure changes at the mid or even upper levels. In addition, when there are critical factors in the synoptic-scale environmental, such as vertical wind shear, for structure changes, studies have demonstrated the relative contributions from land-sea contrast versus such environmental factors to the subsequent TC structure at landfall.

# 6.1.0. Introduction

This report reviews and summarizes the advances in research on the track, intensity and structure changes of tropical cyclones (TCs) during their landfall phase, with a focus on those performed since the last Workshop (IWTCLP-II) in 2009. Studies based on observations, numerical modeling of real historical TC cases and theoretical approaches such as application of idealized modeling can be found in this summary report. The forecast challenges associated with this Topic will be addressed in a companion report.

The major contrasts between land and ocean surface are friction and moisture availability. Moisture availability is manifested in parameters such as the surface evaporation rate and latent heat fluxes. When a TC moves over land, dry air usually found at near surface can easily intrude into the storm’s circulation and affect its development. All these factors are the focus of research in TC landfall processes and we have seen substantial advances in some of them in the last few years. Depending on the size of a landfalling TC, its interaction with land is as early as when the outer rainbands touch the coastal area, followed by the core circulation. In this early period or even before that, the TC motion might have changed already due to interaction with land, as seen in the following reviews. This exactly reflects the point in the Introduction of the forecast challenges companion report that the critical time window for forecasters is often way before the cross point of the TC center to land.

The theme of this Workshop “Quantifying and Communicating Forecast Uncertainties” emphasizes the needs of communications between researchers and forecasters. When a TC undergoes rapid intensification or weakening during landfall, forecasters face both uncertainties in the storm development as shown by observations and numerical models, and at the same time issues related to the downstream impacts to the public from their decision making. Advances in science should serve to provide guidance and raise the confidence of forecasters during this process. Corresponding to the associated research disciplines as reviewed in the IWTC-VIII, the TC aspects of track, intensity and structure are discussed in this review, although it will be shown in the following review that these aspects are highly connected to each other dynamically. Nevertheless, this separation is practically convenient to identify the main foci in the associated publications and categorize them.

# 6.1.1. Track

The motion of TCs is one of the aspects in the science of tropical storms that has been well studied since the 1970s. The current understanding of TC motion is based on the theory of potential vorticity (PV) tendency (Wu and Wang 2000; Chan et al. 2002). In the PV tendency approach, TC motion as measured by the rate of change of PV is budgeted according to horizontal advection, vertical advection, diabatic heating and friction. Condensation heating associated with convection is able to modify the diabatic heating term in the PV tendency equation, and subsequently the TC motion. Therefore, theoretical studies on TC landfall processes often concentrate on how the steering flow and barotropic beta effect may be modified (through the advection terms in the PV tendency equation) by the existence of land surface, including topography, in the vicinity of a TC and how the pattern of convection changes the diabatic heating contribution to PV tendency.

Kuo et al. (2001) was a theoretical study on why TC motion often rotates when it approaches high topography such as the island of Taiwan with its Central Mountain Range (CMR) exceeding 3000 m. Calculations on both the *f* plane and spherical geometry without a mean flow were performed. It was found that the idealized TC vortex was trapped by the topography and followed a clockwise (for this Northern Hemisphere example) island-circulating path, which the authors termed the “topographic *β* effect”.

While the vortex trapping in Kuo et al. (2001) increases with the peak height, length scale of topography as well as latitude, another idealized study of Wong and Chan (2006) identified land-induced TC motion from their fifth-generation mesoscale model (MM5) simulations of land and ocean surfaces without topography and mean flow. On an *f* plane, the simulated TC vortex was drifted to land with an average speed of 1 m s-1 when the roughness length is 0.5 over land. It was found that the friction-induced asymmetry in the TC system-scale flow was the primary mechanism responsible for causing the TC drift. Diagnosis of the budget terms in the PV tendency indicated that while the horizontal advection term was dominated by the advection effect by the system-scale asymmetric flow, the diabatic heating and vertical advection terms have to be considered in determining the vortex land drift. Apparently, the latter two terms are related to strong asymmetries in the surface fluxes of heat, moisture and momentum between land and ocean surface, and in turn asymmetry in vertical motion and convection.

As a follow-up to what has been mentioned in the Introduction, accurate track prediction is of obvious importance to the subsequent estimation of impacts from the landfalling TC. In essence, the timing of when the eye of TC moves over land controls the regions affected by the high winds in the TC core. The speed of TC motion during landfall also determines the duration of severe weather experienced in those regions. The following studies on typhoons in the South China and Taiwan area well illustrate the interplay between TC motion, land effect and asymmetries in the storm.

## 6.1.1.1 Impacts from asymmetric convection

The annual precipitation of Taiwan is approximately 2500 mm with most of the heavy rainfall resulting from landfalling typhoons. The typhoon rainfall pattern is phase-locked with the CMR, with its southwest slope receiving especially large amounts (Chang et al. 1993). Taiwan has experienced a dramatic increase in typhoon-related rainfall, with nine of the top twelve rain-producing typhoons occurring since 2001. This record-breaking increase has led to suggestions that they are the manifestation of the effects of climate change, including global warming.

In Hsu et al. (2013), the effect of topographically phase-locked convection on the motion of typhoons across the island of Taiwan is studied.  Data for 84 typhoons that reached Taiwan’s east coast from 1960 to 2010 are analyzed, with motions compared to the long-term average overland translation speed. For the 61 typhoons with continuous track, 77% of the slow-moving TCs made landfall on the northern end of Taiwan’s east coast, while 60% of the fast storms had southeast coastal landfalls (**Fig. 1**). This geographic asymmetry with respect to typhoon translation speeds widened after landfall, as the slow movers typically decelerated during the overland period while the faster TCs sped up (**Fig. 2**). In particular, the average overland duration was 16 hours for the slow class, compared to only 3 hours for the fast-moving typhoons. The combination of slower translation with longer duration for the northern class of TCs led to large rainfall on the southwest slope of the island’s CMR (not shown).

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|  | **Fig 1.** Tracks of the typhoons subdivided by landfall latitude relative to 23.5N and overland translation speed. Overlaid pie chart shows numbers and relative proportions of northern landfall and southern landfall cases – fast (red), medium (black), and slow (green) speed classes – based on overland translation speed (adapted from Hsu et al. 2013). |

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|  | **Fig 2.** The 3 hourly mean translation speeds from 12 hours before landfall (“l”) to 12 hours after departure (“d”) for the east coast landfall cases subdivided with respect to: (a) landfall latitude, for continuous (NLT, SLT) and discontinuous (DIS) cases, one standard deviation before departure is also added for NLT and SLT; and (b) overland translation speed class (fast, medium north, medium south and slow) for the continuous cases. In (b), the average of cases having CWB gauge rainfall amounts over 1000 mm while overland is also shown for comparison (adapted from Hsu et al. 2013). |

Experiments with the Weather Research and Forecasting (WRF) Model, developed by the U.S. National Center for Atmospheric Research (NCAR), are used to study the effect of convection on storm motion over a mountainous island resembling Taiwan. Hsu et al. (2013) found that the topographically phase-locked convection acts to slow down (speed up) the northern (southern) landfalling typhoons. Their model results also suggested a positive feedback mechanism for the slow storms, in which the convective heating pattern forced by topography acts to reduce the TC motion, leading to even more prolonged precipitation and heating, and yielding further speed reductions.

The following case studies are quite consistent with the theory developed in Hsu et al. (2013). Wang et al. (2012) simulated Typhoon (TY) Morakot (2009), the most devastating storm to hit Taiwan in the past five decades that brought an unprecedented 4-day maximum total rainfall of nearly 3000 mm (Chanson 2010; Hendricks et al. 2011; Wang et al. 2012). As expected, multiple factors across a wide range of scales interacted and worked in synergy to produce this extreme event. These factors include the background large-scale monsoon gyre that contributed to Morakot’s large size and slow speed near Taiwan (Hong et al. 2010; Nguyen and Chen 2011; Wu et al. 2011), strong interaction with southwesterly monsoon that caused long-lasting rainbands (Chien and Kuo 2011), and of course the steep and complex topography of Taiwan (Ge et al. 2010). In this event, however, the unusually slow speed upon departure from Taiwan on 8 August (~5 km h−1) was a key factor for the disaster since the rainfall over southern Taiwan was the heaviest during this period (especially over 0600-1800 UTC), and the interplay between TC motion and asymmetric convection was particularly intriguing. Wang et al. (2012) hypothesized that the deep-layer steering flow, although indeed slow, still remained at ~10 km h−1 and exceeded the TC moving speed on 8 August (**Fig. 3**). Furthermore, through sensitivity tests with reduced moisture using the Cloud-Resolving Storm Simulator (CReSS, Tsuboki and Sakakibara 2002, 2007) at 3-km horizontal grid spacing, they demonstrated that the asymmetric latent heating (LH) effect on 8 August, which was strongest to the southeast of the TC center (i.e., to the rear of the TC) and arising due to interaction with the monsoon, was responsible for the further slowdown of the storm.

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| *Strongest rainfall*  *Steering flow*  *LH effect*  *Combined*  *motion vector*  • | **Fig 3.** Schematic of the hypothesis of Wang et al. (2012), overlaid on the radar Vertical Maximum Indicator (VMI) reflectivity composite (dBZ) at 0800 UTC 8 Aug 2009. The arrows represent TC motion vectors induced by the steering flow and other effects (purple), by the LH (black), and the combined effect (red). The red dot marks the center of Morakot upon leaving Taiwan, and the thick dotted and dashed lines enclose the area of asymmetric rainfall, mostly to the south and east of the TC center. |

Using a similar approach, Wang et al. (2013) also examined Fanapi (2010), a compact and westward-moving typhoon that suddenly slowed down from 22 to 14 km h−1 for 12 h upon leaving Taiwan and led to heavy rainfall (>800 mm) that seriously flooded the coastal city of Kaoshiung in southwestern Taiwan. It was found that the rainfall of Fanapi shifted from an axisymmetric to an asymmetric pattern after it moved across the terrain of Taiwan (**Fig. 4**), with deep convection mostly to the south and southeast, and the asymmetric LH rather than environmental flow was again responsible for the sudden speed reduction (**Fig. 5**). Thus, while the asymmetric rainfall of Fanapi was induced for a reason different from Morakot, it affected the track and prolonged the heavy-rainfall period and increased the total amount in both cases (Wang et al. 2012, 2013).

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| **(a)**  **(b)**  **(c)**  **(d)**  **(e)**  **(f)** |
| **Fig 4.** Radar VMI reflectivity composites (dBZ) and 850-hPa horizontal winds (m s−1) in NCEP analyses at (a) 1800 and (b) 2300 UTC 18, and (c) 0600, (d) 1100, (e) 1800, and (f) 2300 UTC 19, September 2010. For winds, the analyses at 0000 and 1200 UTC are plotted in (b),(f) and (d), and pennants, full barbs, and half barbs represent 50, 10, and 5 m s−1, respectively. The TY symbol depicts the TC center (adapted from Wang et al. 2013). |

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| **(a)**  **(b)** |
| **Fig 5.** Deep-layer mean flow (300-700 hPa, inside 450 km from TC center) computed from NCEP analyses (gray symbols) and TC motion from the CWB best track (“x”, all in km h−1) at indicated times or periods, the mean TC motion vectors in run R01 (control, with moisture not reduced) and R03 (with 50% moisture) over 0600-1500 UTC 19 September (arrows), and their difference vector (dashed arrow, labeled as LH). (b) Further estimates on various effects from LH in TC motion (km h−1, note the difference in scale of circles) shown in (a). The abbreviations ALH, VWS, and FADV denote effects from asymmetrical LH, the vertical wind shear associated with vortex decoupling, and the advection of planetary vorticity, respectively (adapted from Wang et al. 2013). |

Because the TC-terrain interaction so strongly constrains the potential climate change of TC rainfall, it is concluded that most of the recently observed large increase in typhoon rainfall is the result of slowly moving TCs and their tracks relative to the high mountains. If these factors are taken into account, the apparent large increase in TC-related rainfall disappears. Another factor contributing to increased TC-related rainfall is associated with interaction between the typhoon circulation and southwest monsoon wind surges. This southwest monsoon factor, which only contributes after the typhoon center exits Taiwan and becomes apparent only during the last decade, may suggest potential decadal or longer-term changes through monsoon-TC interactions.

## 6.1.1.2 Impacts from topographically induced wind flow

Tang and Chan (2013) carried out idealized numerical simulations using the WRF model on a beta plane, with no mean flow but the actual topography of the Taiwan island and the Philippines to investigate the underlying physical mechanisms associated with deflection of TC motion by such topography. By comparing the results from experiments with and without terrain, the barotropic beta effect was largely removed. The initial TC vortex was placed far from any land and then land-induced motion and eventually TC landfall was simulated.

By analyzing the asymmetric flow in the simulated TCs, terrain-induced gyres were identified over both the CMR of Taiwan and the mountains of Luzon. These gyres were then advected cyclonically around the TC center by the symmetric circulation of the TC and the flow associated with the gyres started to steer the TC northeastward. Later when the TC was about to make landfall at Taiwan, the anticyclonic gyre was located north and the cyclonic gyre south of the TC (**Fig. 6**). Similar terrain-induced gyres were found in the all-Philippines-terrain and Luzon-only experiment, however, the westerly flow between the gyre pair was weaker in these experiments because the mountains in Luzon are lower than the CMR in Taiwan.

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| **Fig 6.** Three-hour averaged asymmetric flow between the simulations with Taiwan terrain and without within the model η levels 0.860-0.620 during 62-64 h (left panel) and 84-86 h (right panel). Thin lines with arrows represent the streamlines of the difference between the two simulations and shadings show the wind-speed difference in m s-1. The solid straight line represents the overall direction of the TC in the Taiwan experiment and the dotted line that in the no-Taiwan case (adapted from Tang and Chan 2013). |

Nevertheless, in PV tendency consideration of these idealized experiments it was found by Tang and Chan (2013) that diabatic heating could not be ignored in explaining the TC track during landfall, which is similar to the conclusions in the Taiwan area case studies presented in 6.1.1.1. Three different mechanisms have been identified to determine the diabatic heating distribution, which include intrusion of dry air from the mountain, low-level convergence induced by the terrain-induced wind field in the southwestern part of the TC and development of convergence cyclonically inward from the eastern side of the mountain to the TC core. These mechanisms lead to asymmetric divergence within the boundary layer and vertical motion, and in turn asymmetric vertical advection of water vapor and condensation heating (**Fig. 7**).

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|  | **Fig 7.** A schematic diagram summarizing the three mechanisms for the enhancement of diabatic heating when a TC approaches the South China coast with possible influences from the Taiwan island and the Philippines topographies. Dashed lines are used to distinguish the process of Mechanism 1 from the others (adapted from Tang and Chan 2013). |

# 6.1.2. Intensity

When TCs develop over the oceans, influences on intensity include inner-core characteristic, large-scale atmospheric flow especially the vertical wind shear (VWS), ocean processes and interactions between air and sea (e.g., Kaplan et al. 2010). When TCs make landfall, ample observational and theoretical evidence show that TCs decay rapidly and finally dissipate as they move over land, because they are primarily maintained by the latent heat release of water vapor extracted from the oceans (Wong et al. 2008; Cheung et al. 2013). However, a lot of factors affect how the intensities of TCs vary before and after landfall. For TCs that made landfall at the U.S. Gulf coast, statistical results show that on average the weakest TCs strengthen at most before landfall, and the strongest hurricanes weaken the most, with the threshold of intensity separating the two groups about 85–100 kt (1 kt = 0.514 m s-1; Rappaport et al. 2010). Previous studies show that the decay rate of TCs is related to their respective central pressures at landfall, and the wind speed decays to a small but nonzero background wind speed (Kaplan and DeMaria 1995; Wong et al. 2008; Ramsay and Leslie 2008). Based on the data of U.S. landfalling TCs during the period 1967–1993, Kaplan and DeMaria (1995) developed an empirical model for predicting the maximum wind of landfalling TCs. In the model, the wind speed is determined from a simple two-parameter exponential decay function. An optional correction can also be added that considers storms that move inland slowly or rapidly. This model from Kaplan and DeMaria can explain 91 % (93 % if the motion speed correction is made) of the variance in intensity change after landfall. On the other hand, Wong et al. (2008) developed a similar model for South China coast landfalling TCs based on a dataset during 1975–2005. Besides the landfall intensity and landward speed, it was found that the excess of 850-hPa moist static energy has significant influence on the intensity decay rates.

Similar to the impact of asymmetric convection to TC motion, the connections between TC intensity and structure are even closer. When asymmetric structures develop in a TC during landfall, the single value of intensity may not be a thorough measure of the potential impacts from the storm. Fortunately, a number of observational and numerical modeling studies in the past few years have extensively clarified our understanding of TC structure change during landfall from boundary layer processes to those at the upper levels. Therefore, the more direct impact of dry air from land to TC intensity is first reviewed in this section. While statistical models are able to capture a large part of the variance of intensity change after landfall, estimation of the impacts on regional scale depends heavily on dynamical models, and in this aspect there have been many advances in research. These advances will also be reviewed in this section.

## 6.1.2.1 Dry-air intrusion

Using idealized numerical modeling, Kimball (2008) explored the effects of dry air intrusion on hurricane structure during landfall. The model allowed an evolving land surface temperature (LST) but the sea surface temperature (SST) was held constant. The idealized hurricanes approached a straight, flat coastline in weak, uniform south-westerly steering flow. The land-use category of the land surface is uniform and cases with different moisture availability (MA) and roughness length (RL) are compared. About 3-10 hours prior to the storm center crossing the coastline, a strong left-right asymmetry appeared with enhanced rainfall to the right of the storm track forced by intrusion of dry, or low equivalent potential temperature (θe) air (**Fig. 8**) illustrates the process. Because the southwesterly background flow is slightly stronger than the forward motion of the vortex (thick black arrow in **Fig. 8**), dry environmental air entrains into the outer circulation of the vortex in the right-rear (RR) quadrant of the storm. The dry air wraps cyclonically around the outer edge of the front half of the eyewall annulus and branches out into an upper level and lower level intrusion. Weak outflow above 850 hPa prevents the upper branch of dry air (black arrow) from entering the eyewall and it continues to circle around to the rear where weak inflow allows the air to enter the eyewall in the RR quadrant. It finally reaches the inner edge of the eyewall in the right-front (RF) quadrant between the 700 and 750 hPa levels. A channel of low θe air from land (light grey arrow) enters the vortex in the LR quadrant, rises, and joins the environmental dry air in the RR and RF quadrants. Once in the RF quadrant, both sources of low θe air are located above high θe over the water surface, leading to slantwise static instability in the RF quadrant. Cumulus towers lean into wind with height because the tangential wind decreases with height in a tropical cyclone. Hence, large amounts of cloud and rainwater exist in between the RR and RF quadrants (on the right side of the storm track). The lower branch of the environmental dry air (dark grey arrow) experiences inflow at the front of the vortex and reaches the inner core at left-front (LF) quadrant. An additional source of low θe air from land enters the front of the vortex, below 850 hPa (light grey arrows in **Fig. 8**), encounters low-level inflow, and also reaches the inner eyewall in the left-front (LF) quadrant of the vortex. This low θe air at low levels leads to stabilization and a lack of rainfall on the left side of the vortex track.

The landmass to the north of the landfalling hurricane is a significant source of low θe air because the LST cools as the hurricane approaches. The approaching storm cloud canopy blocks solar radiation and the limited heat capacity and conductivity of the soil surface lowers the LST (Tuleya 1994). Additional cooling occurs by 1) enhanced friction forcing air to flow towards the lower pressure center of the storm, which expands and cools as it do so and 2) evaporation of falling rain. Cases with land-use categories with lower MA values cause the θe of the air over land to decrease further, enhancing the pre-landfall left-right rainfall asymmetry.

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|  | **Fig 8.** Schematic of dry air intrusion before TC landfall. The thin black circles represent the storm  eyewall. The thin solid black arrow indicates the direction of motion of the storm; motion relative quadrants are shown using abbreviations LF, RF, LR, and RR. The thick black arrows show dry air intrusion above 850 hPa, the dark gray arrows show dry air intrusion below 850 hPa but above the surface, and the light gray arrows indicate dry air originating at the surface over land (adapted from Kimball 2008). |

As the storm center crosses the coastline, the rainfall asymmetry flips with enhanced rainfall now occurring on the *left* side of the vortex track. Differences in surface friction between land and sea cause a region of low-level speed convergence of the tangential wind and enhanced convection on the right side of the vortex and divergence and decreased convection to the left. In Kimball (2008) a similar dipole in speed divergence of the tangential wind is seen. However, directional convergence of the radial wind (vr/r where vr is the radial wind, and r the radius), forced by increased frictional turning of the winds towards low surface pressure (leading to larger values of vr over land), drives an even larger convergence maximum in the half of the vortex that is located over land (**Fig. 9**). With the vortex moving to the east-northeast at the time of landfall, this region is located to the left of the vortex track. Large speed convergence of the radial wind seen on the left side of the storm is most likely driven by the convection on that side of the storm instead of vice versa. Cases with 1) high RL combined with low to medium MA and 2) high MA combined with low RL show larger left-right rainfall asymmetries at landfall. On the west side of the vortex, high RL drives the low-level directional convergence of the radial wind, while in the moist cases, sufficient MA provides fuel for convection.

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|  | **Fig 9.** Schematic of the two surface convergence (green) and divergence (yellow) zones when the TC center crosses the coastline. The dipole at the coastlines is due to speed retardation and acceleration by surface friction, respectively. The large convergence zone over land is due to directional convergence of the radial wind caused by increased frictional turning toward the central low pressure (source: S. Kimball). |

After landfall mean inner-core rainfall rates decrease but do not show much difference between land-use cases. Outer-core rainfall rates and coverage, on the other hand, increase for land-use cases with higher MA values. High MA cases have more active rainbands and convection in these bands retriggers in response to surface convergence forced by differential friction between land and sea.

There is considerable disagreement in both observational and modeling studies about the location of the rainfall maximum before and during landfall. However, factors not considered in Kimball (2008) potentially play an important role. These include VWS, irregularly shaped coastlines, topography, and the formation of mesoscale features. Some of these factors will be discussed in depth in the next section on TC structure.

## 6.1.2.2 Modeling intensity change during landfall

A better representation of surface and near-surface atmospheric conditions through data assimilation of surface observations is essential for accurate forecasting of landfalling TCs. Nevertheless, in many numerical weather prediction practices, assimilation of surface observations is still a challenging problem. In a recent study, Pu et al. (2013) demonstrated that the traditional three-dimensional variational (3DVAR) data assimilation has difficulties in assimilating surface observations due to its use of static background error covariances. In contrast, an ensemble Kalman filter (EnKF) could better assimilate the surface observations. In addition, Ha and Snyder (2014) showed that EnKF could produce promising mesoscale weather analyses with the assimilation of surface observations.

In light of recent progress in advanced data assimilation methods, Zhang and Pu (2014) examined the impact of ensemble assimilation of surface observations on the prediction of a landfalling hurricane. Considering that it was one of the deadliest disasters in U.S. history and that it had two consecutive major landfall events, the study used Hurricane Katrina (2005) for case study. An advanced research version of the WRF model (Skamarock et al. 2008) and an EnKF system, developed by the NCAR Data Assimilation Research Testbed (DART; Anderson et al. 2009), were employed.

A specific initial time (0000 UTC 25 August 2005), which led to poor prediction of Hurricane Katrina in several previous studies, was selected to begin the data assimilation experiments. QuikSCAT ocean surface wind vectors and surface Mesonet observations were assimilated with the minimum central sea level pressure and conventional observations from the National Center for Environmental Prediction (NCEP) into the WRF model using the EnKF method. Impacts of data assimilation on the analyses and forecasts of Katrina’s track, landfalling time and location, intensity, structure, and rainfall were evaluated.

It was found that the ensemble-based data assimilation resulted in improvement in Katrina’s track forecasts (**Fig. 10**). Compared with a baseline experiment that assimilates only Katrina’s position and minimum sea level pressure, assimilation of QuikSCAT and Mesonet surface observations (SFC experiment) led to significant improvements in predictions of Katrina’s track. Assimilation of NCEP ADP conventional observations also led to better hurricane track forecasts compared with BASE and SFC. However, with assimilation of both surface observations and NCEP ADP conventional observations, an additional 10-29% improvement in track forecast was found when predicting Katrina’s second landfall in Louisiana.

Further examination showed that assimilation of surface observations has an influence on the hurricane vortex structure through modifying thermal and dynamical fields such as wind, humidity, and temperature and enhancing low-level convergence and vorticity due to the evolution of model dynamics during the data assimilation cycles. However, single-level surface observations do not enable the model to predict reasonable intensities due to their lack of impact in the middle to upper troposphere (**Fig. 11**). When surface observations were assimilated with other conventional data, obvious enhancements were found in the forecasts of track and intensity, realistic convection and surface wind structures. More importantly, surface data assimilation resulted in significant improvements in representation of the surface wind structure and quantitative precipitation forecasting (QPF) during the landfall events. Since surface wind and QPF are the key factors that determine the degree of damages from a landfalling TC, assimilation of surface observations has great potential for improving TC landfall forecasting.

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| **Fig 10.** Comparison of the simulated and best track (black) between 0000 UTC 25 August and 0000 UTC 30 August 2005. (Left panel) ensemble means by assimilating SFC, ADP and ADP\_SFC. (Right panel) individual ensemble members in the ADP\_SFC ensemble (adapted from Zhang and Pu 2014). |

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|  | **Fig 11.** Time series (at 6-h intervals) of (a) minimum central sea level pressure (hPa), and (b) maximum surface wind speed (kt) between 0000 UTC 25 Aug and 0000 UTC 30 Aug 2005. The simulations of BASE, SFC, ADP and ADP\_SFC are compared with best track data (adapted from Zhang and Pu 2014). |

In the North Indian Ocean (NIO), TCs in the post monsoon season are more devastating than the premonsoon season (Mohanty 1994). Indian seas of Bay of Bengal (BoB) and Arabian Sea (AS) contribute about 7% of the world’s TCs and are relatively moderate in intensity as compared to those of other basins. The BoB (AS) contributes about 75% (25%) to the total number of TCs over the NIO (Mohanty et al., 2011). Although the frequency is relatively less over Indian seas, out of 10 recorded deadliest TC cases with very heavy loss of life (ranging from about 40,000 to well over 200,000) over the world, 8 cases were formed in the BoB and AS in the past 300 years. For example, the world’s highest recorded storm surge of 45 feet occurred due to BoB-Bakherganj cyclone in 1876 near Meghna Estuary, Bangladesh (WMO technical report 2008). Mohanty (1994) explained that the region between 15°N–20°N and 87°E–91°E over the BoB is a favorable region for the formation of cyclonic disturbances. Further observational study by Mohanty et al. (2011) revealed that the severe cyclonic storms are increasing in the current warming environment.

Over the past 20 years, significant advances have been made in the numerical prediction of TCs in terms of track, intensity and inland rainfall due to increase in model resolutions, physical and microphysical parameterizations, and improved mesoscale data assimilation techniques. Pattanayak et al. (2008) studied the relative performance of high-resolution mesoscale models to predict TCs over the Indian seas. Mohanty et al. (2010) demonstrated that better the initial and boundary conditions better the TC rainfall prediction. They conducted experiments with available initial and boundary conditions from different sources of agencies like GFS, FNL from the U.S. and the National Center for Medium-range Weather Forecast (NCMRWF), India. FNL data stood better for the prediction of rainfall with higher skill scores. Recent studies highlighted the significance of physical parameterization in the models in simulation of track, intensity and associated rainfall of TCs (Pattanayak et al. 2012, Osuri et al., 2011a, b). A recent study by Mohanty et al. (2013) showed skillful performance of three high-resolution mesoscale (NCAR version of ARW, NCEP version NMM and Hurricane WRF) models for the simulation of TCs over the BoB. The study demonstrated that the better initial TC vortex position is important in order to improve the track and intensity forecast, thereby, the rainfall prediction.

Osuri et al. (2012) and Singh et al. (2008) made a comprehensive study on the impact of satellite-derived wind products in the simulation of TCs over the Indian seas. The study Osuri et al. (2012) considered the equitable threat score (ETS) and bias at different thresholds of rainfall. The improved analyses with the 3DVAR assimilation of QuikSCAT and SSMI sea surface winds performed far better with higher ETS with minimum bias (up to 9 cm of 24-h accumulation during landfall day) for all the thresholds compared to that without data assimilation. Mandal et al. (2006) evaluated the impact of sea surface temperature in modulating TC movement and intensity over the Indian seas. Further, when Doppler Weather Radar (DWR) reflectivity and radial wind observations were assimilated into the ARW model initial conditions, the position and structure of rain bands were improved and the rainfall intensity was well corrected when compared to no-data assimilation experiment. For example, in the case of TC Jal (4-7 Nov 2010), the convective clouds were sheared to the west causing more rainfall inland than in the coastal regions during landfall (RSMC 2010, **Fig. 12**). No-assimilation runs predicted the rainfall along the east coast of India, while, the DWR data-assimilated run predicted a rainfall zone of 40–120 mm in agreement with the TRMM-observed rainfall over the interior parts (near 15°N and 76°E).

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| **Fig12** |
| **Fig 12.** Simulated 24-h accumulated rainfall from three experiments (CNTL, GTS and DWR) along with TRMM observed rainfall in case of TC Jal (valid for 48-h forecast). The CNTL run had no additional observations assimilated. GTS data was assimilated in the GTS run. Doppler weather radar observations along with GTS were assimilated in the DWR run (Source: U. C. Mohanty). |

The state-of-the-art cloud resolving model Hurricane WRF (HWRF) model has been used to predict the recent very severe cyclonic storms (VSCS) Phailin (2013), Lehar (2013) and Madi (2013) over BoB. This model clearly showed overall superiority at longer range forecast (4-5 days) in terms of track, intensity, size and inland rainfall structure. In all the cases, HWRF showed significant improvements in intensity evolution (**Fig. 13**). The rainfall amount and structure was improved significantly in case of TC Phailin showing peak rainfalls activity over Northern parts of Odisha as observed (**Fig. 14b**). **Fig. 14a** provides the wind swath of TC Phailin demonstrating that the system made landfall with very severe cyclonic storm intensity in advance of 3 days. In case of TC Lehar, model highlighted the role of land in the intensification process. When TC Lehar started interacting with the land, model showed dry air incursion into the TC environment, which caused weakening of Lehar over the BoB before making landfall.

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| Fig13aFig13b  Fig13c | **Fig 13.** HWRF intensity prediction in terms of 10-m maximum wind speed in knots for (a) Phailin (b) Lehar and (c) Madi, along with IMD observed intensity (Source: U. C. Mohanty). |

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| Fig14 |
| **Fig 14.** HWRF forecast of (a) 10-m maximum wind speed in m s-1 and (b) rainfall swath in cm during the life-cycle of TC Phailin from 00 UTC 10 October 2013. The black and grey lines represent the JTWC best and HWRF model track respectively. Rainfall swath accumulated over 126 hr of forecast is zoomed over the rectangular region highlighted in (a) and the numbers in (b) represents the IMD station-observed accumulated rainfall for the landfall day (03UTC 12–13 Oct 2013) period (Source: U. C. Mohanty). |

# 6.1.3. Structure

As follow up to the intensity section, the advances in the studies of TC structure during landfall are reviewed in this section. Substantial improvements in our understanding of TC structure changes have been obtained through new observations and applications of high resolution numerical models in both real-case and idealized setting.

## 6.1.3.1 Observed boundary layer processes

The importance of turbulent processes in the atmospheric boundary layer (ABL) to TC intensification and maintenance is well-known (e.g., Smith et al. 2009; Bryan 2012; Kepert 2012; Zhang et al. 2012). However, the ABL structure in TC conditions remains to be understood, largely because of the lack of observational data. In particular, turbulence observations in the TC boundary layer are scarce. Direct measurements of turbulence structure of the TC boundary layer over the ocean were only conducted by research aircraft with advanced turbulence sensors between the outer trainbands (Black et al. 2007; Drennan et al. 2007; French et al. 2007; Zhang et al. 2008; 2009). Few eyewall penetrations within the boundary layer from early field experiments into Hurricanes Allen (1980) and Hugo (1989) provided the useful information for momentum flux (Zhang et al. 2011a). Lorsolo et al. (2010) presented a novel technique to map turbulent kinetic energy (TKE) in several hurricanes using Doppler radar measurements. Turbulence observations over land in hurricane conditions are even more limited than those over the ocean. Almost all the previously reported turbulence observations during landfalling TCs are based on tower observations, which are thus typically within the surface layer below 10 m (Yu et al. 2009; Zhu et al. 2010; Zhang et al. 2011b). These studies pointed out that momentum fluxes in the surface layer over land are generally larger than those over the ocean due to larger surface roughness. The variability of the drag coefficient is the largest in low to moderate (<10 m s-1) wind conditions. Dissipative heating is found to be much smaller than that calculated based on similarity theory. Recently, Kosiba and Wurman (2014) presented dual-Doppler analyses of the fine-scale structure of landfalling Hurricane Frances. They estimated the momentum flux and TKE following Lorsolo et al. (2010), and found that vertical momentum fluxes caused by individual roll-like structures are much larger than values employed in turbulence parameterization schemes, in agreement with the findings of Zhu et al. (2010). They also found that the estimated TKE values are comparable to those reported in previous observational studies over the open ocean but with more variability. Till now, there is no direct observation of heat or moisture fluxes in landfalling TCs. The vertical structure of momentum flux is not observed either. These are the important topics to be explored in the future.

The mean ABL structure in TCs has been investigated more than the turbulence structure, especially after 1997 when Global Positioning System (GPS) dropsonde data are available (e.g., Franklin et al. 2003; Kepert 2006; Barnes 2008; Bell and Montgomery 2008, Zhang et al. 2011c). However, GPS dropsonde data are mainly collected over the ocean so that observations of the mean ABL structure in TCs over land are mainly based on remote sensing instruments. Land-based Doppler radar has been used to measure the vertical distribution of wind velocities although the resolution is limited (e.g., Marks 2003; Morrison et al. 2005; Schroeder et al. 2009; Hirth et al. 2012; Giammanco et al. 2013). Recently, mobile Doppler radar (e.g., WSR-88) data have provided observations of relatively fine-scale linear features or rolls in the lowest several hundred meters of the ABL in landfalling TCs (e.g., Wurman and Winslow 1998; Geerts et al. 2000; Lorsolo et al. 2008; Kosiba and Wurman 2013). Doppler wind profilers have also provided useful but limited information of the boundary layer structure of landfalling hurricanes (Knupp et al. 2000; Knupp et al. 2006; Kim et al. 2009). Most of these studies agreed that the mean wind profile is close to logarithmic through the depth of the wind speed maximum given its variability. The boundary layer wind profiles at landfall are found to change with radial distance to the storm center (Giammanco et al. 2013), supporting a general reduction in boundary layer depth with decreasing radial distance, which was firstly pointed out by Zhang et al. (2011c) who analyzed dropsonde data over the ocean. Giammanco et al. (2013) also found that composite wind profiles from landfalling hurricanes has a distinct low-level wind speed maximum in the eyewall region with significant differences between the onshore and offshore flow regimes. Studies on boundary layer rolls mainly focused on the distribution of their wavelengths and their roles on modulating mean wind profiles and momentum fluxes. While the above mentioned studies have shed important insight on the kinematic structure of the ABL in landfalling TCs, thermodynamic structure of the ABL in landfalling TCs remain poorly understood. Ming et al. (2014) presented analyses of data from multiple platforms and studied the boundary layer structure of the outer rainbands of Typhoon Morakot (2009). Their limited GPS radiosondes suggested that the thermodynamic mixed layer depth decreased after convection and equivalent potential temperature recovered during the post-convection period that is supported by surface fluxes (**Fig. 15**). Their result also indicates that convective downdrafts may play an important role in modulating the turbulence transport. Above all, future research to focus on investigating the thermodynamic structure of the boundary layer in landfalling TCs and their linkage to the kinematic structure and interaction with vortex-scale and convective structures is recommended.

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| **Fig 15.** Schematic diagram summarizing the evolution of BL structures observed and speculated based on data collected during the landfall of Typhoon Morakot (2009) for two periods: (a) convective and (b) postconvective. The cloud areas represent the principle rainband and convection. The circle with an X within a circle depicts tangential flow (adapted from Ming et al. 2014). |

## 6.1.3.2 Changes in wind flow

Yang et al. (2011a) investigated the landfalling characteristics of Typhoon Nari (2001) as it moved across Taiwan Island by performing a series of cloud-resolving simulations with or without Taiwan topography. Various kinematic and precipitation features prior to and after landfall have been examined with a focus on the dynamic effects of Taiwan’s high topography upon the generation of Nari’s asymmetric structures. It was found that tangential winds weaken, whereas the low-level inflows and midlevel outflows increase after landfall due to the increased friction and terrain blocking (**Fig. 16**). The eyewall updrafts exhibit more cellular structures and tend to tilt more outward with height over the high topography on Taiwan. Nari’s primary and secondary circulations are stronger in the presence of Taiwan terrain than those without terrain. The radii of the maximum winds and the eyewall updrafts contract further after landfall, with more pronounced contraction occurring in the portion of the eyewall where more terrain retardation and blocking are present. In particular, the high topography of the Taiwan Island allows the elevated low equivalent potential temperature air over the rugged terrain to intrude into the inner-core region, causing the breakdown of the eyewall.

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| **Fig 16.** Vertical cross sections for the simulated storm-relative tangential flow (brown, contoured at 10 m s-1), radial flow (black, contoured at 5 m s-1) and vertical velocity (colored) of (a) full-terrain and (b) no-terrain averaged in the along-track direction at time of landfall (22 h and 21 h, respectively) for Typhoon Nari (2001) (adapted from Yang et al. 2011a). |

Yang et al. (2011b) conducted the absolute angular momentum (AAM) and radial wind budgets of Typhoon Nari by analyzing high-resolution simulation results (with 2-km horizontal grid spacing and 2-min output interval). The AAM is nearly conserved outside the eyewall and above the boundary layer while Nari is over ocean; after landfall, the enhanced surface friction and turbulent mixing produces mostly negative local tendencies of AAM above terrain. For the landfall storm, both the radar observation and model simulation indicate that the radial inflows at lower levels become thicker and stronger over land, and the sloping radial outflow jet is maximized at the midlevel above the rugged topography. The enhanced imbalance accelerations imply that the gradient wind balance is no longer appropriate to describe the tangential winds over terrain. Near the eyewall, the supergradient winds can be as strong as 9 m s-1 above terrain and subgradient winds up to –21 m s-1 are found at the surface on the lee side (**Fig. 17**). The stronger force imbalances of the landfall Nari produce larger local changes of AAM and radial momentum, leading to more quickly-evolved vortex flows and secondary circulations over Taiwan’s steep terrain.

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|  | **Fig 17.** The time-radius cross section of azimuthally averaged fields of vertical velocity (solid line, contoured at 1 m s−1) near 700 hPa (s = 0.7), and storm-relative tangential (shaded, m s−1) and radial wind speeds (dashed line, contoured at 3 m s−1) near the surface (s = 0.9985). The thick dashed line denotes the RMW near the surface (adapted from Yang et al. 2011b). |

## 6.1.3.3 Feedbacks from asymmetric convection to TC circulation

Li et al. (2013) examined the landfall processes of five TCs in the northwestern Australian region. Asymmetries in rainfall distributions of these TCs have been identified and attributed to TC motion, land-sea contrast and VWS. In particular, changes in VWS during the landfalls have been identified. Although for these real TC cases the VWS changes were found mostly due to the large-scale synoptic flows, it was suspected that storm-scale dynamics also played a role.

As a follow up, Li et al. (2014a) performed idealized numerical simulations of landfalls for TCs on a *f* plane of the Southern Hemisphere. Asymmetric rainfall distribution developed when the simulated TC approached land, which consisted of enhanced rainfall on the onshore flow side and a local maximum on the offshore side. It was found that such asymmetry in rainfall was consistent with the convergence pattern at the top of the boundary layer, which was resulted from advection from the surface convergence when friction increased on the onshore side and the offshore radial wind accelerated due to reduced friction. Nevertheless, VWS developed during the landfall process associated with the system-scale low- and upper-level asymmetric flows (**Fig. 18**). The low-level wavenumber-1-like flow was attributed to asymmetric geopotential height field generated by frictionally induced convergence (divergence) on the onshore (offshore) side, while that at the upper level was due to asymmetric convection and associated diabatic heating (**Fig. 19**). Vortex tilting was found minimal in the simulations and thus contributing little to such internally generated VWS.

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|  | **Fig 18.** Time series of the average wind from 900 hPa to 150 hPa and the VWS within 400 km from the simulated TC center for an idealized experiment on a *f* plane with no mean flow in the Southern Hemisphere. The simulated landfall time is at 219.5 h (adapted from Li et al. 2014a). |

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| Fig19 | **Fig 19.** Asymmetric winds (vector) and height anomaly (shaded, unit in m) at 850 hPa (left panel, 216-h simulation) and 200 hPa (right panel, 264-h simulation). The simulated landfall time is at 219.5 h (adapted from Li et al. 2014a). |

Li et al. (2014b) further investigated the interaction between such internal VWS and that originated from the synoptic-scale environment by imposing a weak environmental VWS of 4 m s-1 to their idealized simulations, again with no mean flow. Surface convergence patterns due to change in surface friction during landfall similar to that discussed in Li et al. (2014a) were found, and the effect to rainfall was particularly large in the outer band where convection was shallow. Modification to the vertical stability of air due to advection of cold and dry air from land also played a role, as has been discussed in Kimball (2008). When the smooth and wet (for land, SW) and dry and rough (RD) sets of experiments were compared in Li et al. (2014b), a consistent component of VWS pointing from the offshore to onshore side due to the land-sea contrast has been identified to develop before the landfall (**Fig. 20**), which is similar to that identified in Li et al. (2014a).

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|  | **Fig 20.** Differences in VWS vectors between the rough and dry (RD) and smooth and wet (SW) experiments for various environmental VWS directions (ES, NS15 and SS05). The landfall times in the RD experiments for these three sets of environmental VWS are 35, 41 and 51 h respectively (adapted from Li et al. 2014b) |

The sets of experiments with environmental VWS imposed to idealized experiments showed a distinct contrast between convection developments in the inner core versus the outer band, and the effects from moisture availability have been masked by the shear effect. In the inner core, environmental VWS dominates the convection and rainfall locations (**Fig. 21 left panel**). In the outer band, however, internal VWS generated by vortex dynamics dominates the pre-landfall period while the effect from environmental VWS takes over the dominance after landfall (**Fig. 21 right panel**). It should be noted that such conclusion was for moderate environmental VWS with magnitude comparable with the internal shear due to land-sea contrast. Moreover, these idealized experiments had no topographic effect, which will lead to further asymmetry in convection.

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| **Fig 21.** Simulated radially averaged rainfall mixing ratio (g kg-1) at sigma level 1.0 in the inner-core (left panel) and outer-band (right panel) region for the RD experiment in Li et al. (2014b) with imposed easterly external VWS. The shaded internal is 0.2 (0.02) and red color indicates mixing ratio 1.6 (0.06) and above in the left (right) panel. |

## 6.1.3.4 Formation of fronts in landfalling TCs

Knupp et al (2006) analyze surface and remote sensing data collected during the landfall of Tropical Storm Gabrielle (2001). The storm was embedded in VWS forcing a distinct asymmetry in the storm as it approached the west Florida peninsula coastline near Venice. A broad stratiform precipitation region preceded the storm center as it made landfall, extending over much of central and northern Florida. Unusually cool air (T ≤ 22ºC) existed over land, generated by overcast conditions and evaporative cooling of stratiform rain. The presence of mesoscale downdrafts was supported by a decreasing surface θe and surface mesoscale divergence under the overcast area. Just before landfall, time series show a rapid rise in θe followed by a drop about 2 hours later. The temperature changes are accompanied by wind shifts, pointing to a warm and cold frontal passage respectively. Surface analyses confirm this.

The warm front was hypothesized to have formed when environmental northeasterlies brought the cooler air toward the center of Tropical Storm Gabrielle still located over warm (28ºC) Gulf of Mexico water. As a result, surface sensible heat fluxes over the Gulf increased, warming the air before being entrained into the storm-scale flow and being wrapped around the center toward the front of the storm. This caused the formation of a thermal gradient in the front half of TS Gabrielle. As environmental northeasterly and cyclonic storm-scale flow created a region of enhanced convergence, a warm front formed (**Fig. 22**). Knupp et al. (2006) also pointed out that the development of cold air may have contributed to the rapid decay of Gabrielle just before landfall.

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|  | **Fig 22.** Schematic showing the basic elements within the boundary layer that promote frontogenesis. These include the source of cool air from land, surface heat fluxes over the water producing a horizontal temperature gradient, and the convergent forward flank of Gabrielle, perhaps enhanced in this case by the east-northeasterly airflow that existed on a scale larger than that of Gabrielle’s core cyclonic circulation. Dashed lines are isotherms near the surface (adapted from Knupp et al. 2006) |

Neugent and Kimball (2014) observed similar frontal structures in Hurricane Ida (2009) as it made landfall on the Alabama coast. The time series in **Fig. 23** clearly shows an increase in temperature and dew-point and a shift in wind direction from northeasterly to southeasterly at about 2:30 CST on 10 November 2009, marking the passage of a warm front. A cold front passes about 6 hours later. Strong VWS caused the formation of an extensive stratiform cloud deck over land preceding the storm center which crossed the coastline at around 6:00 CST on 10 November 2009. Solar radiation values remained well below 100 W m-2 throughout the daytime hours of 9 November 2009 at the South Alabama Mesonet station in Robertsdale, Alabama (**Fig. 23**). As the sun rose around 6:00 CST that morning, the air temperature began to rise slowly until stratiform rain began to fall at 10:30 CST. This caused a sudden drop in temperature and rise in dew-point, suggesting evaporative cooling occurred. The air temperature remained near 18ºC for the remainder of the day and night until the warm front came through.

Increased rain rates are observed just before the warm front passes (**Fig. 23**). Time series from other South Alabama Mesonet sites and KMOB WSR-88D radar imagery indicate strong convection occurred ahead of the front. This was forced by the overrunning of warm, moist air as it encountered the dense cooler air mass approaching from the northeast. Rapid weakening of the storm occurred just before landfall. Similar to Hurricane Gabrielle (Knupp et al. 2006), the formation of a cold air mass ahead of the storm may have contributed to storm weakening in addition to colder water and strong VWS.

Knupp et al. (2006) surmised the formation of small-scale fronts in hurricane may be a common phenomenon and with the advent of finer resolution surface observing networks and mobile remote sensing tools, such features may be observed more often allowing them and their impacts to be studied in more detail. Cold air formation ahead of sheared storms may contribute to storm weakening, while overrunning of warm, moist air can lead to localized heavy precipitation.

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|  | **Fig 23.** Time series of station pressure (light blue), temperature (dark blue), dew point temperature (purple), wind speed (cyan), solar radiation (yellow), precipitation (light green), and wind direction (magenta dots) at the South Alabama Mesonet station at Robertsdale, Alabama from 00:00 CST on 9 November 2009 to 12:00 CST on 10 November 2009. Temporal resolution is 1 min (adapted from Neugent and Kimball 2014). |

## 6.1.3.5 Outer rainbands

Spiral rainbands in TCs can be classified into inner and outer rainbands, according to their characteristics and locations. Inner rainbands occur in the rapid filamentation zone, whereas outer spiral rainbands are defined as those rainbands that occur outside the inner core. More recently, behavior and structures of outer spiral rainbands and their effects on TC intensity and structure changes have been getting more and more attention. When a TC is about to make landfall, the outer rainbands will first affect the coastal regions, and depending on the rainband structure the regions experiencing hazardous weather could be extensive. Thus, it is important to understand the convective cell structures within the rainbands.

Convective-scale downdraft structures are affiliated with cellular convective cells embedded in outer rainbands of TCs. Two types of downdraft features, referred to as the inner-edge downdraft and the low-level downdraft, are often observed (**Fig. 24 left panel**; Hence and Houze 2008; Didlake and Houze 2009). The former tends to originate at 6–8-km altitude, producing a sharp reflectivity gradient along the inner boundary of the outer rainband and being forced aloft by pressure perturbations formed in response to adjacent buoyant updrafts. The later originates as radial inflow in lower layers and is likely forced by precipitation drag and subsequent evaporative cooling (**Fig. 24 right panel**). The downdrafts with low entropy air can penetrate into the boundary layer, contributing to the formation of surface cold pools. Mesonet observations reveal that prominent cold pools extend 40–80 km behind the rainband’s leading edge (Eastin et al. 2012). Convergence of storm-relative inflow along the cold pool leading edge is coincident with a modest high pressure anomaly, while inflow divergence prevails through the cold pool and rainfall maxima. As outer rainbands pass, wavelike pressure perturbations with low (high) pressure located inside the outer (inner) edge of the rainband can be seen (Yu and Tsai 2010; Yu and Chen 2011; Yu and Tsai 2013), resulting in part from the presence of surface cold pools.

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| **Fig 24.** (a) Schematic of the vertical convective motions within a convective cell in an outer rainband. The clear arrow indicates the in, up, and out convective circulation, passing through a low-level convergence, vertical convergence of vorticity flux, and midlevel divergence regions indicated. The circled region labeled ‘‘J’’ indicates the rainband tangential wind jet, with the associated low-level shear. Dashed arrows in the background indicate the low-level downdraft and the upper-level downdraft as a part of the three-dimensional flow (adapted from Hence and Houze 2008). (b) Schematic of the vertical structure of another mature convective cell within an outer rainband. The black and thick arrow indicates the in-up-out transverse circulation across the rainband. The circled region labeled “Jet” indicates the tangential wind jet. The regions labeled “L” are the places where low equivalent potential temperatures are found. Grey and dashed arrows suggest the low-level and upper-level downdrafts (adapted from Li and Wang 2012b). |

It has been believed that the activity of outer rainbands and their interaction with the eyewall convection as well as the storm-scale circulation are key to the structure and intensity changes of TCs. Wang (2009) demonstrated that cooling in outer rainbands maintains both the intensity of a TC and the compactness of its inner core, whereas heating in outer spiral rainbands decreases the intensity but increases the size of a TC, which was also confirmed in other studies (Sawada and Iwasaki 2010; Xu and Wang 2010; Li and Wang 2012a; Fang and Zhang 2012; Li and Duan 2013; Chen et al. 2014). From the hydrostatic adjustment perspective, heating in outer rainbands would reduce the horizontal pressure gradient across the radius of maximum wind and thus the storm intensity. Diabatic heating in outer rainbands contributes positively to the spinup of the outer-core primary circulation (namely the storm size) by the mean vertical and radial transport of angular momentum (Pendergrass and Willoughby 2009; Fudeyasu and Wang 2011).

Strong downdrafts triggered by active outer rainbands are also regarded as an inhibiting factor to TC intensity. Subsidence brings low θe air from the mid-troposphere into the inflow boundary layer. The air is advected to the core region and entrained into the eyewall, thereby suppressing eyewall convection and reducing the TC intensity. On the other hand, the dry and cool air becomes trapped between the eyewall and the outer rainband, reducing both mass and moisture convergence into the eyewall, and thus restraining the eyewall updrafts and convection, and limiting TC intensity. Such suppression of TC intensity becomes more notable if cloud condensation nuclei are increased in the outer-rainband region because of the enhanced evaporative cooling from the increased precipitation (Carrio and Cotton 2011; Krall and Cotton 2012).

Another unique role of outer rainbands in affecting TC structure and intensity is their contributions to formation of concentric eyewalls. Judt and Chen (2010) deemed that the shape of outer rainbands plays an important role in the formation of a secondary eyewall. The more circular the rainbands are, the better is the projection onto the azimuthal mean with more concentrated PV generation.  The convectively generated PV alters the wind field by generating a jet at and below the level of maximum heating, enhancing surface fluxes and thereby further strengthening convection in the outer rainbands, which eventually become a secondary eyewall. Zhu and Zhu (2014) further addressed the crucial roles of outer rainband heating in governing the formation and development of the secondary tangential wind maximum and demonstrated that the outer rainband convection must reach a critical strength relative to the eyewall convection before secondary eyewall formation can occur. Qiu and Tan (2013) also found that descending radial inflow in the downwind portion of outer rainbands could penetrate into the inner-core region, sharpens the gradient of radial velocity, and reinforces local convergence as well as enhances convergence and convection on the other side of the TC by producing strong supergradient winds. These processes favors convection enhancement during the early phase of secondary eyewall formation.

# 6.1.4. Discussion and conclusions

As can be seen, most of the studies on TC landfall reviewed in this report focused on how the changes in the environmental factors, such as increased surface friction and reduced moisture availability from land, influence the track, intensity and structure of TCs. This focus on the physical processes related to the land-sea contrast can be taken as the fundamental definition of the TC landfall process. However, it is well known that from a preparedness of impacts perspective, the duration of up to days before the TC makes landfall is when the forecasters are facing great challenges. How the landfalling TC changes in its track, intensity and structure mostly determines the subsequent impacts not only to the core region near the TC center but could be tens of kilometers away. Therefore, from a broader sense TC landfall process should take into account this preparedness period for impacts, in which rapid changes in TC track, intensity and structure often occur. These changes may be due to topography in the vicinity, oceanic influences, internal TC dynamics such as the eyewall replacement cycle and changes in the environmental conditions. Thus, how well we are able to mitigate the hazardous impacts from TC landfalls depend on the forecast skills of various aspects of TCs even before the land-sea contrasts are considered.

Although the rate of improvement has not been as fast as in TC track, forecast of TC intensity is indeed improving in the past two decades at a rate that is statistically significant (DeMaria et al. 2014). This improvement was mostly attributed to advances in numerical modeling and data assimilation techniques. The studies on TC intensity forecasts during landfall reviewed in section 6.1.2.1 are consistent with this forecast trend. However, it should be emphasized that most of these studies are based on case studies, and the results suggest that data assimilation of both the land-based observations (e.g., station observations and radar reflectivity) and conventional upper-level observations are essential to the successful simulations of TC track and intensity. There are several issues that determine how well we are able to apply these advances in numerical models and data assimilation systems to forecasts of landfall processes. First, the density of observations including the availability of radar platforms may not be good enough to provide advantages to the numerical models in some coastal regions under possible TC impacts. For example, many regions do not have the high-density land-based observational network such as the Mesonet in the U.S and some offshore facilities. Second, when these observations are available the TC landfalling process has commenced already with possible impacts from the outer rainbands, and will impose a great pressure to the timely provision of numerical guidance taking benefits from the observations. Lastly, studies show that the best numerical modeling results come from the advanced data assimilation systems such as the EnKF system and applications of high-resolution models (Davis et al. 2008). These systems require much computational resources that may not be available in every forecast region. Nevertheless, these numerical studies are encouraging in that clear directions for improving TC intensity forecast during landfall have been identified.

As emphasized in the report, structure changes during TC landfall largely determine the patterns of impacts, and studies since the last IWTCLP Workshop have clarified many structure-related problems. These problems include the factors that determine the distribution of convection before and after landfall, those for the areas of near-surface strong winds when the boundary layer adjusts to the changes in land-surface properties and the dynamics governing such high-wind areas, thermodynamics due to changes in moisture availability and feedbacks of near-surface processes to the mid and upper levels. **Fig. 25** is a summary on the latter point. While asymmetries developed at surface and in the boundary layer are more due to the roughness and moisture differences between land and sea, the resulted asymmetric vertical motion will induce changes in the mid to upper levels, which generate VWS of the storm scale that will affect the subsequent convective development. On the other hand, asymmetric convection, together with possible asymmetries in the TC circulation due to land and topography, will modify the TC motion before landfall. All these issues reflect the critical role of the guidance on structure change during landfall in order to estimate well the downstream impacts, which represent a major challenge for forecasters in the coming years.

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|  | **Fig 25.** Schematic diagram showing the dynamical and physical processes involved in the development of asymmetric structures in landfall TCs from the surface to the upper levels. The dash line indicates the potential feedback from the VWS to the structure of further convection development (adapted from Li et al. 2014a). |

As in the studies focusing on modeling the intensity change during landfall, those on structure changes have also demonstrated the capabilities of the modern numerical models in capturing the details of structure changes during landfall. However, many of these studies, especially the idealized ones, have isolated the factors influencing the landfall processes in order to investigate their individual effect. For example, environmental factors have not been considered in **Fig. 25** and there was no topography. With environmental factors such as synoptic-scale VWS, results from Li et al. (2014b) indicated that such environmental factors would dominate the convection distribution after landfall. To add to the matrix of complexity, existence of high topography will introduce additional dynamical processes that modify the winds and convection distribution within the TC. It is the capability of the numerical models to simulate the interactions between land-sea contrasts, boundary-layer processes, internal structure changes due to vortex dynamics and environmental factors that will determine the future success in simulating real TC landfalls. In particular, the question on whether thresholds exist for these parameters (e.g., friction, moisture, environmental VWS, etc.) to become dominating in terms of structure changes has not been examined thoroughly.

How to transform the advances in science to quantitative forecasts and via effective communication is in accord with the main theme of this Workshop. Based on the state of the science in regard to TC landfall processes surveyed in this report, the following future research directions are recommended:

* Whereas current numerical guidance from global models on TC track is mostly satisfactory, studies should be conducted on whether land effects on TC motion, which determines the landfall position, have been well captured by numerical models, and whether high-resolution regional models have advantages in this aspect.
* Extended land-based observations to be assimilated into numerical models have the potential to improve TC intensity forecast during landfall, and should be planned.
* A cost-effective numerical system with balance between forecast details and economic computational resource should be identified.
* The complexity associated with factors determining TC structure changes during landfall require systematic studies, based on historical cases or real-time demonstration projects, to obtain further knowledge on the circumstances under which one or more factors play the critical role in certain structure changes.

# Acronyms used in the report:

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| 3DVAR | Three Dimensional Variational (data assimilation) |
| ABL | Atmospheric Boundary Layer |
| AAM | Absolute Angular Momentum |
| ADP | Automated Data Processing |
| ARW | Advanced Research WRF |
| AS | Arabian Sea |
| BoB | Bay of Bengal |
| CMR | Central Mountain Range |
| DART | Data Assimilation Research Testbed |
| DWR | Doppler Weather Radar |
| EnKF | Ensemble Kalman Filter |
| ETS | Equitable Threat Score |
| FNL | GFS Final (analysis) |
| GFS | Global Forecast System |
| GPS | Global Positioning System |
| HWRF | Hurricane WRF |
| LF | Left Front |
| LH | Latent Heating |
| LR | Left Rear |
| LST | Land Surface Temperature |
| MA | Moisture Availability |
| MM5 | Fifth-generation Mesoscale Model |
| NCAR | National Center for Atmospheric Research |
| NCEP | National Center for Environmental Prediction |
| NCMRWF | National Center for Medium-Range Weather Forecast |
| NIO | North Indian Ocean |
| PV | Potential Vorticity |
| QPF | Quantitative Precipitation Forecast |
| RD | Rough and Dry |
| RF | Right Front |
| RL | Roughness Length |
| RR | Right Rear |
| SST | Sea Surface Temperature |
| SW | Smooth and Wet |
| TC | Tropical Cyclone |
| VSCS | Very Severe Cyclonic Storms |
| WRF | Weather Research and Forecasting |

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