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Topic 2.0: Tropical cyclone formation and extratropical transition

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**SEVENTH INTERNATIONAL WORKSHOP ON TROPICAL CYCLONES**

**Topic 2.0: Tropical Cyclone Formation and Extratropical Transition**

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**2.0.1 Introduction**

In this section, progress since ITWC-VI on research, observations, and forecasting of tropical cyclone formation and extratropical transition is summarized. While tropical cyclone formation and extratropical transition are stages at opposite ends of the tropical cyclone lifecycle, significant lack of understanding remains in relation to processes associated with each stage. Formation and extratropical transition involve interactions among physical processes that vary over multiple space and time scales. Additionally, relatively few, consistent in situ observations of each stage exist. Tropical cyclone formation often occurs over remote regions that do not contain standard observation capabilities or are out of range of typical tropical cyclone observation program assets. While extratropical transition may occur downstream from data rich continental regions, the stage is rarely targeted for in situ observations as the storm is no longer a landfall threat.

In IWTC-VII, this topic contains sections devoted to forecasting tropical cyclone formation and extratropical transition. These sections were also part of IWTC-VI and their continuation points to the importance of these two stages of the tropical cyclone lifecycle to operational entities. In IWTC-VI, the process of tropical cyclone formation was divided into two sections devoted to internal and external influences on formation. Recommendation from IWTC-VI pointed to the need for an increase in understanding of the relative roles of these influences. Since IWTC-VI, several major field campaigns have been designed and implemented with specific objectives related to an increase in understanding of scale interactions during the formation process. Therefore, in IWTC-VII there is a section devoted to review of recent advances in theoretical and idealized modeling of tropical cyclone formation and a section to detail the field work that has objectives to increase understanding and forecast skill of tropical cyclone formation. Similar evolution has occurred in relation to the extratropical transition stage of the tropical cyclone lifecycle. In IWTC-VI, the section on physical processes and downstream impacts of extratropical transition lead to recommendations of increased observations and understanding of these processes. Again, field campaigns were implemented to address these issues and a section in IWTC-VII will report on the accomplishments related to the studies conducted since IWTC-VI.

During the period since IWTC-VI, there have been improvements in observational capabilities, dedicated field campaigns, and new research results into key physical processes associated with tropical cyclone formation and extratropical transition. However, new
requirements have been identified. These include continued exploration of the need for a formal definition of formation or extratropical transition, validation of theory and idealized model results, and examination of sensitivities in the formation and extratropical transition processes to large-scale and internal factors. These are summarized in this topic report and followed by an initial set of recommendations associated with continued advancement in understanding of tropical cyclone formation and extratropical transition.

2.1 Tropical Cyclone Formation: Theory and Idealized Modeling

The lack of observations over remote tropical oceans where tropical cyclones typically form has contributed the uncertainty in understanding processes related to tropical cyclone formation. While some operational and research observation campaigns do exist, they typically focus on mature storms or storms that threaten landfall. Research since IWTC-VI has continued with respect to formation of a surface vortex that is able to self amplify under favorable large-scale and mesoscale conditions.

The “top-down” and “bottom-up” paradigms to formation have continued to be studied via observation-based and numerical model-based research. Since IWTC-VI, the “bottom-up” way of thinking has been placed into the marsupial paradigm that encompasses the multi-scale nature of tropical cyclone formation from synoptic to cloud scales. The process by which deep convection that develops in an environment of vertical vorticity and amplifies the local vorticity via stretching is fundamental to the unified theory. Additionally, the vorticity remnant is sustained beyond the lifetime of the originating deep convection. Throughout the process, vortical remnants combine and undergo additional intensification via continued convective development, in a manner that corresponds to an upscale cascade of energy. The amplification and combination of vorticity represents an increase in the relative circulation over a contained area that encompasses the deep convection. This unified view of tropical cyclone formation is put forward in contrast to theories related to finite amplitude disturbances and the role of a “trigger” mechanism that contributes to the evolution of a tropical wave to a tropical depression. In this view, the process of formation is often described as undergoing stages of development. The initial stage is one in which deep convection forms due to low-level moisture in a region of mean ascent due to decreased radiative cooling. There is some similarity between stage one and the aggregation process defined in the unified view. The second stage is related to the pre-existing circulation and embedded deep convection contracts into a tropical cyclone. While the definition of tropical cyclone formation is often focused on the presence of a low-level self-sustaining circulation and a warm-core vertical structure, the primary views of tropical cyclone formation are consistent with the existing specification of the multi-stage process of formation.

Future research on the theory and idealized modeling of tropical cyclone formation should be guided by several remaining over-arching questions on key physical mechanisms. A priority should be to analyze recent field program data to document the lifecycle of vortical convection and the contribution to amplification of the relative circulation in the re-tropical depression system. As the data become analyzed in detail, there is a likely role for idealized numerical simulations to complement observational studies. There are documented cases in which operational global numerical models successfully predict tropical cyclone formation days in advance. These cases should be examined to determine characteristics associated with these successful forecasts and compare with unsuccessful forecasts. Finally, it would be useful to examine the limits of predictability with respect to tropical cyclone formation.
2.2 Field Experiment Formation Studies

In the period since IWTC-VI, several major field campaigns have been undertaken with specific objectives related to tropical cyclone formation. During 2008, the combined THORPEX Pacific Asian Regional Campaign (T-PARC) and Tropical Cyclone Structure-2008 (TCS-08) program was conducted over the western North Pacific. A specific goal of TCS-08 was to examine the relative role(s) of mesoscale processes in organizing a pre-tropical cyclone disturbance such that it may begin to intensify as a tropical cyclone. Specifically, aircraft missions were designed to examine processes associated with relative contributions of low-level vorticity in deep convective towers versus mid-level circulations embedded in stratiform regions of mature mesoscale convective systems. This objective addresses the predictability associated with the location, timing, and rate of tropical cyclone formation over the western North Pacific.

Perhaps the most significant T-PARC/TCS-08 case with respect to tropical cyclone formation was that of TY Nuri during August 2008. The pre-Nuri disturbance was an easterly wave that tracked across the western North Pacific over a period of days prior to intensifying to a tropical depression. Several aircraft missions in the pre-depression disturbance collected unique Doppler radar, dropwindsonde, and surface wind measurements over the course of the development. Analyses of the data continue and are leading to new insights relative to basic paradigms of tropical cyclone formation.

During 2010, several field programs were conducted over the tropical North Atlantic. The PRE-Depression Investigation of Cloud systems in the Tropics (PREDICT) program was conducted between 15-30 September 2010. Several hypotheses were investigated during the field phase. The experiment design was set to address many of the factors discussed with respect to the unified view of tropical cyclone formation summarized in Section 2.1. Additional objectives focused on the role of the Saharan Air Layer with respect to the protected region of deep convection and aggregation of vorticity. Additional experiments have been conducted over the North Atlantic in 2010. The Genesis and Rapid Intensification Processes (GRIP) project had similar objectives to PREDICT with respect to tropical cyclone formation. However, GRIP utilized a different set of observing platforms. Also the Intensity Forecast Experiment (IFEX) had a tropical cyclone formation component that utilized the U.S. National Oceanic and Atmospheric Administration (NOAA) research P-3 aircraft.

The occurrence of a concentrated set of field programs since IWTC-VI holds promise for increased understanding and forecast skill related to tropical cyclone formation. Continued comprehensive and detailed analysis of all collected data is strongly recommended.

2.3 Tropical Cyclone Formation Forecasting

A theme in the IWTC-VI report on tropical cyclone formation forecasting was a degree of optimism in that formation forecasting was becoming a solvable problem. This was based on an upward trend in formation forecast skill, increased understanding of the role(s) of large-scale factors in tropical cyclone formation, and increased skill in guidance supplied from operational numerical models. However, it was noticed that there remain a significant number of instances in which formation is not well forecast. These missed
forecasts are often associated with rapid formation, small circulations, hybrid circulations, or cases in which mesoscale factors dominate.

In the period since IWTC-VI, the optimism with respect to tropical cyclone forecasting has continued and is expected to increase. Much of the expected increase in forecast skill may be due to increased skill exhibited in operational numerical model forecasts of formation. The increase is generally attributed to increased resolution, improved use of observations, and improved physical parameterizations. While, operational global models do not typically have horizontal resolution capable of correct representation of mesoscale factors in formation, the increased skill with respect to large-scale factors that impact formation influences the capability to correctly identify formation cases at lead times that may extend beyond five days.

Tropical cyclone formation forecasts at extended ranges (i.e., 1-2 weeks) are becoming increasingly available and reliable. It is clear that planners for a wide variety of maritime activities have a demand for extended range forecasts of tropical cyclone formation. The increase in skill of predictions at extended ranges is due to increased understanding of synoptic-scale tropical wave activity that contributes to organization of convection. While initial forecast techniques at extended ranges were primarily statistical, numerical forecasts at extended ranges are now routine and exhibiting increased skill.

As the actual formation of a tropical cyclone likely involves a continuum of processes that act over space and time scales, there is a continuum of strategies being applied to tropical cyclone forecasting. These strategies range from purely statistical, mixed statistical and numerical, purely numerical, and diagnostic with respect to satellite analysis. Furthermore, there has been an increased use of probabilistic forecast techniques with respect to tropical cyclone formation.

Several recommendations are provided to ensure continuation of the optimistic view toward tropical cyclone formation forecasting. There should be an increased examination of the systematic combination of operational numerical forecast products. It is clear that consensus of operational track forecasts have lead to increased skill and a similar and systematic approach should be applied to construction of consensus formation forecasts. As the number of forecast products increases, there is a critical need for a systematic verification data base. Additionally, standard verification techniques should be employed. The pathways to formation should be clearly examined and defined in a systematic manner that is consistent with forecast practices. Finally, a formal specification of a threshold intensity that signifies formation should be examined.

2.4 Extratropical Transition Research and Field Experiments

While the extratropical transition of a tropical cyclone is often associated with severe local weather conditions, the impact of an extratropical transition on the midlatitude flow has been shown to be directly linked to high-impact weather events far downstream of the original extratropical transition event. Therefore, there is a strong requirement to assess the extent of the sensitivity to various physical mechanisms during extratropical transition. These mechanisms include the impact of sensible and latent heat fluxes, precipitation distribution, frontogenesis, and baroclinic energy conversions. Finally, the character of the downstream response to extratropical transition should be placed in the framework of the mean.
environmental conditions (i.e., baroclinic wave guides) across the entire ocean basin in which the extratropical transition is occurring.

An extratropical transition event often represents a period a decreased predictability over a large downstream region. The impact of extratropical transition on predictability of downstream flow patterns is placed in a framework that addresses; i) the mechanisms associated with the excitation of Rossby wave trains, ii) critical forecast errors associated with the decaying tropical cyclone and upstream midlatitude trough, iii) critical forecast errors downstream of the extratropical transition, iv) appropriate initial perturbations relative to extratropical transition in ensemble prediction systems, v) observations required to reduce forecast errors associated with downstream impacts of extratropical transition, and vi) impacts to data assimilation systems from new or increased observations in the environment of an extratropical transition event.

Following IWTC-VI, the THORPEX Pacific Asian Regional Campaign (T-PARC) was conducted to examine the lifecycle of a tropical cyclone over the western North Pacific. During the field phase of T-PARC, several tropical disturbances moved poleward to undergo a transition into the midlatitudes. The character of these disturbances included a weak circulation associated with widespread deep convection, a midget tropical cyclone, a typhoon, and a super typhoon. Corresponding to the variety of tropical disturbances was a wide range of forecast and actual structural changes and downstream developments, which provide a broad spectrum of forcing and downstream impacts to be investigated. These observations will provide a basis for examining the impact of the tropical circulations on the region of the midlatitudes into which they are moving and their downstream impacts through a variety of physical mechanisms.

A key recommendation to be carried forth from IWTC-VI is the need for increased understanding of factors that explain the variability associated with extratropical transition events and their impact on local and downstream high-impact weather. Continued analysis of data obtained during T-PARC is strongly encouraged to examine the rapid evolution of factors that have tropical and midlatitude origin respectively. While T-PARC provided the first capability to obtain in situ observations of an extratropical transition event, continued efforts to obtain observations of complex physical processes is recommended.

### 2.5 Forecasting Extratropical Transition

During the poleward movement of a tropical cyclone, tropical cyclone force winds, rainfall, and ocean waves are often maintained far into the midlatitudes. Since official forecasts of the tropical cyclone may have been terminated, it is often difficult to convey the continued threat of severe weather elements.

A new topic of study related to the extratropical transition of tropical cyclones has examined the development of predecessor rainfall events (PREs). There are two primary factors that contribute to PRE development. The first is the advection downstream of deep tropospheric moisture from the poleward-moving tropical cyclone. The moisture is then able to interact with other forcing mechanism for vertical motion and contribute to heavy rainfall in a region remote from the tropical cyclone. The second factor is the interaction of the near tropical cyclone environment with a mid-tropospheric trough or midlatitude front. The interaction contributes to enhanced vertical motion and rainfall over a region near the tropical
cyclone. Furthermore, due to the enhanced effect from the midlatitude forcing the rainfall may be more extreme that what would have occurred from the tropical cyclone alone.

Since IWTC-VI, forecasting of extratropical transition events has benefited from development of new techniques and understanding of several factors. The use of potential vorticity as a measure by which tropical-extratropical interactions could be identified has been examined with respect to juxtaposition of lower- and upper-tropospheric features. The radial expansion of tropical cyclone force winds has also been examined with respect to two primary factors that are related to changes in the radial gradients of temperature and geopotential and the increase in vertical tilt of the tropical cyclone inner core. Increased use of ensemble prediction systems has also increased to allow identification of uncertainty in downstream impacts. In the context of ensemble predictions, an increase in variability among ensemble members is identified with an increase in forecast difficulty or uncertainty. The impact of initial condition sensitivity with respect to numerical forecasts of extratropical transition has been examined. Experiments have indicated that initial condition errors are a primary source of forecast error and the initial conditions may be extremely sensitive to key observations. Finally, new understanding of the role of vertical wind shear has bearing on the forecasting of structural changes as a tropical cyclone moves into the midlatitudes.

Recommendations that would contribute to improved skill in forecasting extratropical transition and its downstream impacts include increased understanding of factors that impact the extratropical transition process. There is a need for improved observation capability with respect to the rapidly-moving tropical cyclones that undergo extratropical transition. Even though an event is occurring without threat of landfall, the impact on the midlatitude flow can be significant and influence weather patterns over downstream populated regions. The communication of warnings to the public should be enhanced. There is a tendency for complacency once the public perceives that the threat of a tropical cyclone has ended. New graphical forecast products are needed that could define and communicate weather parameters and regions in probabilistic framework that would communicate uncertainty to the public.