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SIXTH INTERNATIONAL WORKSHOP on TROPICAL CYCLONES

Topic 2 : **Tropical Cyclone Formation and Extratropical Transition**

Topic Chair: Patrick A. Harr
Naval Postgraduate School
Monterey, CA 93943-5114 USA

E-mail: paharr@nps.edu
FAX: 01.831.656.3061

2.0.0 **Introduction**

In this section, summaries of recent progress in observations, forecasting, and research of tropical cyclone formation and extratropical transition are provided. Furthermore, requirements that remain for advancements in these topics are identified. During the period since IWTC-V, there have been improvements in observational capability, new research results into important physical processes, and forecast improvements with respect to tropical cyclone formation and extratropical transition. However, further requirements have also been identified. A partial list of these requirements includes improved definitions of formation and extratropical transition, validating theories of tropical cyclone formation, identifying the role(s) of the large-scale environment in tropical cyclone formation and extratropical transition, sensitivities in formation and extratropical transition to important physical processes, and the impact of an extratropical transition event on the downstream midlatitude circulation.

The tropical cyclone formation and extratropical transition remain challenging complex problems because they involve interactions among physical processes that vary over multiple space and time scales. Therefore, progress in all aspects of tropical cyclone formation and extratropical transition will be realized via a collaboration of forecasters, observationalists, modelers, and theoreticians.

In this summary, the external and internal influences in tropical cyclone formation are examined. Then, the forecast challenges associated with tropical cyclone formation are examined. The summary of extratropical transition is based on observational and forecast challenges followed by factors related to physical processes and downstream impacts.

2.0.1 **External Influences on Formation**

For some time, the large-scale, climatological conditions favorable for the formation of tropical cyclones have been known as a combination of dynamical and thermodynamic factors. These include a sea-surface temperature above 26^{o}C, a deep ocean mixed layer, cyclonic low-level vorticity, and weak vertical wind shear. Furthermore, there is often a region of organized deep convection that exists in a region of low- and mid-level moisture.

Over recent years, there has been increased attention on the roles of tropical wave activity on the organization of deep convection as a pre-cursor to tropical cyclone formation. While tropical easterly waves over the North Atlantic and eastern North Pacific have long been identified as pre-cursor disturbances to tropical cyclone formation over those regions, there has been increased focus on tropical wave activity over additional ocean basins that contain tropical cyclones. Some of this focus is directly attributable to the availability of new data sources that allow identification of wave characteristics over a variety of spatial and temporal scales.

Overall, tropical wave activity may be placed in the context of basic modes of circulation associated with special dynamic and thermodynamic characteristics over equatorial latitudes. Often, the basic structural features of the basic tropical wave modes are not conducive or consistent with large-scale characteristics known to be favorable for tropical cyclone formation (i.e., latitude, rotational flow), However, over several ocean basins, interactions between tropical waves and large-scale, basic-state flow characteristics may alter the wave structures such that its potential for evolution into a tropical cyclone becomes more favorable. Recent research has reinforced the roles of basic tropical circulation modes on climatological factors such as rainfall, cloud distribution, and tropical cyclone formation.

Beyond the roles of individual modes of tropical circulation, the interactions among modes are important for altering circulation characteristics that may be favorable for tropical cyclone formation. Furthermore, the interaction among modes may be responsible for changes in storm frequency that could vary from synoptic time scales to intraseasonal time scales.

While tropical wave activity has been investigated as an influence on tropical cyclone formation characteristics, it is important to examine factors that impact the evolution of a circulation from a wave-like feature to a tropical cyclone vortex. Many of these factors are external to the wave activity. These include vertical wind shear, and increased baroclinicity that may result from trough intrusions from the midlatitudes to the subtropics or tropics.

Finally, there are indications that the relationships among large-scale factors and tropical cyclone formation may change as climate changes. Therefore, the relative importance of individual dynamic and thermodynamic factors may change over future years.

Because of the availability of several new data sets, which include reanalysis fields and remotely-sensed parameters such as outgoing longwave radiation, it is recommended that studies make use of these data sets to assess the impacts of variability in tropical circulation modes on tropical cyclone formation. It is also recommended that the impacts of external factors (i.e., vertical wind shear) be assessed relative to tropical cyclone formation from basic tropical modes of circulation. If clear relationships between tropical cyclone formation and tropical circulation modes exist, then it is recommended that the potential for prediction of tropical cyclone formation be explored by utilizing statistical relationships between known tropical circulation characteristics (i.e., periodicity, vertical variation in amplitude) and tropical cyclone formation. Relationships that would lead to statistical predictive skill require identification of many factors such as the role of basin-scale circulation changes, impacts of vertical wind shear, and sea-surface temperature variations.

2.0.2 **Internal Influences on Tropical Cyclone Formation**

For a variety of reasons, the tropical cyclone formation has remained one of the least understood phases of the tropical cyclone lifecycle. This is typically related to the lack of conventional observations over oceanic regions in which tropical cyclones form. However, increased satellite sensors and improved analysis techniques of remotely-sensed data have provided better representation of the tropical cyclone formation process. The coverage of satellite data in conjunction with some specialized observation campaigns, has led to two primary theories for the organization of a precursor tropical disturbance into a tropical cyclone. These theories of tropical cyclone formation have been advanced using detailed modeling studies that allow examination of the sensitivity of tropical cyclone formation to a variety of mechanisms.

Since IWTC-V, the primary theories of tropical cyclone formation have been argued from the viewpoint of bottom-up or top-down development of a low-level cyclonic vorticity maximum. In the bottom-up scenario, pre-existing low-level cyclonic vorticity is increased due to convergence and stretching associated with regions of deep convection. Observational evidence exists that define vortex intensification following periods of intense deep convection. In the top-down scenario, a precursor tropical disturbance may contain one or more mesoscale convective systems (MCSs) with an accompanying mesoscale convective vortex (MCV). Merger of MCSs within the original disturbance results in a more intense MCV that may eventually extend downward to increase the cyclonic vorticity at low levels.

There are crucial internal elements to each theory of tropical cyclone formation. For example, the bottom-up theory requires some pre-existing cyclonic vorticity at low levels while the top-down scenario requires sustained precipitation to saturate the relatively dry and cold lower levels beneath the stratiform region of the MCS/MCV complex.

While the definition of tropical cyclone formation generally focuses on the presence of low-level cyclonic vorticity and a warm-core vertical structure, the differences in the bottom-up and top-down theories of formation often lead differences in the development of these features. Therefore, a specific definition of tropical cyclone formation is still required, which was also identified as a requirement during IWTC-V.

Research of internal influences on tropical cyclone formation should be guided by several remaining over-arching questions on key physical mechanisms. These mechanisms include the requirement of a saturated or nearly saturated profile associated with a downdraft-free convective environment. Furthermore, it is recommended that a widely-accepted definition of tropical cyclone formation that concentrates on the evolutionary process. There is a continued requirement for detailed investigations via high-resolution numerical modeling of the processes that lead to increases in low-level vorticity in tropical disturbances. Finally, null cases or non-developing tropical disturbances should be investigated to determine sensitivities to various physical processes.

2.0.3 **Operational Forecasting of Tropical Cyclone Formation**

Many factors contribute to challenges in operational forecasting of tropical cyclone formation. Because tropical cyclones tend to form in regions with relatively few conventional observations, forecasters must rely heavily on satellite data and global operational numerical weather prediction models. Furthermore, there are specialized issues associated with the operational forecasting of tropical cyclone formation in each ocean basin in which tropical cyclones form. For example, over the southern West Pacific and eastern South Indian Ocean tropical cyclones may form very near coastal locations. Therefore, there is very little time between formation and a potential landfall. Even if the tropical cyclone does not make landfall, formation of a tropical cyclone near the coast of Eastern or Western Australia is often associated with periods of heavy rainfall.

Over recent years since IWTC V, much emphasis has been placed on identifying the ability of global operational numerical prediction models. Although a large amount of variation in skill among the operational models exists, it is generally recognized that skill in prediction of tropical cyclone formation has increased. Although special cases of rapid cyclogenesis or cyclogenesis in high vertical wind shear conditions are not forecast well, many factors seem to contribute to the increase in skill. Tropical cyclone formation in conjunction with well defined large-scale conditions is one instance when numerical forecasts exhibit some skill. Specific favorable large-scale conditions include the presence of the convectively-active phase of the Madden-Julian Oscillation (MJO). Although it is generally agreed that operational global models do not exhibit predictive skill associated with the MJO, in basins such as the western North Pacific and regions of the Australian monsoon trough, well represented MJO conditions in the initial conditions do seem to persist long enough into forecast sequences to reflect favorable conditions for tropical cyclone formation.

There has been some documented success of predictive skill associated with tropical cyclone formation during periods of other favorable large-scale circulation modes (i.e., equatorial Rossby waves). In particular, several instances of multiple outbreaks of tropical cyclones related to Rossby wave dispersion of pre-existing tropical cyclones have been documented.

There is a need to transition conceptual models that develop from validated theories of tropical cyclone formation to operational practice. This transition should utilize new satellite data sources and increased skill from numerical prediction models. Tools for systematic evaluation of the distribution and evolution of deep convection in pre-cursor circulations based on satellite data should be developed. It is recommended that the skill associated with each global operational numerical model be evaluated with respect to forecasts tropical cyclone formation in each ocean basin in which tropical cyclones form. Knowledge of the model performance traits can alert forecasters to increase monitoring of disturbances likely to intensify into tropical cyclones. Finally, it is recommended that conceptual models of factors related to basic tropical modes of circulation be organized for operational use.

2.0.4 **Observing and Forecasting of Extratropical Transition**

In recent years, the difficulty in operational forecasting the extratropical transition of tropical cyclones has been highlighted relative to diagnostic analysis of observations and numerical prediction. Often, extratropical transition is associated with maintenance of tropical cyclone force winds, precipitation, and ocean waves 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 the damaging weather elements to the public. Therefore, a requirement for a precise definition of extratropical transition is required such that the continued threat may be conveyed to the general public. Furthermore, the definition should encompass the needs of operational and research communities for a common framework on which to examine the physical processes that occur during extratropical transition.

In recent years, several cases of extratropical transition have been observed with aircraft such that new data sets have been available for analysis of the complex physical processes that occur during extratropical transition. While these studies have provided new insights into changes of the remnant tropical cyclone structure there are still requirements for increased forecast skill associated with many of the impacts of extratropical transition such as the expansion of the surface wind distribution, the distribution of heavy precipitation, occurrence of tornadoes, and the generation of extreme ocean wave conditions.

One particular forecast issue associated with extratropical transition has been identification of the timing of the extratropical transition process and the likely structural characteristics associated with the extratropical cyclones that result from the extratropical transition process. Operational forecasting of these factors has improved with the use of the cyclone phase space for summary and display of analyzed and forecast structural characteristics of a tropical cyclone as it proceeds through the extratropical transition process. Furthermore, detailed numerical simulations of the extratropical transition process have been instrumental in identifying sensitivities to tropical cyclone characteristics and the midlatitude circulation into which the decaying tropical cyclone is moving. In conjunction with numerical simulations, diagnostic analyses of extratropical transition events have led to specification of factors important for increasing forecast skill of many attributes of an extratropical transition event. While some diagnostic analyses have been performed on conventional atmospheric fields, others have been based on the cyclone phase space, which provides a compact framework for assessing the dynamic and thermodynamic characteristics of the extratropical transition process.

Specific recommendations for improvements in forecasting of extratropical transition events revolve around the timing of the evolutionary processes and the sensitivity of the process to various physical characteristics. These improvements are ultimately connected to observations of critical processes such that appropriate diagnosis of the extratropical transition may be conducted and the processes may be accurately depicted in the initial conditions of operational numerical forecast models. Critical to these improvements is the increased utility of satellite data and in particular microwave imagery from polar-orbiting platforms that will identify thermodynamic and moisture distributions during the extratropical transition event. Ultimately, the development of a satellite-based extratropical transition diagnostic should be developed.

2.0.5 **Physical Processes and Downstream Impacts of Extratropical Transition**

Since IWTC-V, one of the primary realizations associated with extratropical transition has been the importance of extratropical transition on influencing the multi-scale dynamics associated with the midlatitude circulation far downstream of the extratropical transition event. The downstream impacts may be related to a variety of physical processes associated with the extratropical transition and the midlatitude circulation in which the extratropical transition is occurring.

Physical processes associated with the extratropical transition involve the transport of anomalous amounts of moisture and heat into the midlatitudes in conjunction with the presence of a positive potential vorticity (PV) anomaly. Therefore, diabatic processes often play a critical role in altering the distribution of PV and may modulate the impact of the PV anomaly associated with the decaying tropical cyclone on the pre-existing midlatitude PV distribution. Additionally, the transport of heat and moisture has important implications on boundary layer contributions to the re-intensification of the decaying tropical cyclone as an extratropical cyclone.

Often the movement of the tropical cyclone into the midlatitudes imposes significant perturbation to the midlatitude flow that may rapidly extend downstream and to a lesser degree upstream of the location of the extratropical transition event. The large amount of variability in the downstream response to an extratropical transition suggests that there are important sensitivities to a variety of physical mechanisms associated with the forcing on the midlatitude flow. These mechanisms may include basic baroclinic energy conversions, forcing of diabatically-forced Rossby wave-like circulations, and enhancements to downstream jet streaks. All of these factors would exhibit sensitivity to a variety of interactions with a decaying tropical cyclone. Finally, use of ensemble prediction systems indicate that the downstream forcing due to an extratropical transition is typically associated with reduced predictability.

Not only is extratropical transition 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.