A SUMMARY OF RESEARCH ADVANCES ON TROPICAL CYCLONE INTENSITY CHANGE FROM 2014-2018

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ABSTRACT

This contribution summarizes key research advances on tropical cyclone (TC) intensity change from 2014-2018 from the Ninth International Workshop on Tropical Cyclones (IWTC-9). Research advances on intensity change have occurred on many fronts, including improved understanding of the role of vertical wind shear (VWS) and its impact on convection, surface fluxes, ocean eddies, dry/dusty air intrusions, eyewall replacement cycles (ERCs), spiral rainband dynamics, eyewall instability and inner-core mixing, and the mechanisms by which TCs intensify. This summary highlights a number of these important advances. Additionally, some new and emerging topics on TC intensity change have recently been elucidated: the important role of vortex structure on the subsequent intensification rate, the maximum potential intensification rate (MPIR), and the role of upper level outflow on TC intensity change.

Keywords: tropical cyclone, intensity change, external influences, internal influences

1. Introduction

A summary is given of two rapporteur reports on research advances on TC intensity change from IWTC-9, held in Honolulu, Hawaii, from Dec. 3-8, 2018. These two rapporteur reports by Vigh et al. (2018) and Braun et al. (2018) cover internal and external influences on TC intensity change, respectively. A detailed analysis of the third rapporteur report on operational perspectives is provided by Courtney et al. (2019a, b). The research advances summarized herein have occurred since IWTC-8, or from 2014-2018. This summary report is organized as follows. Sections 2 and 3 highlight important research advances on internal and external influences to TC intensity change, respectively. Section 4 provides an overall summary and the IWTC-9 intensity change recommendations.

2. Intensity Change: Internal Influences

A number of advances have occurred in the understanding of internal influences on TC intensity change. The main internal influences on TC intensity change are eyewall instability and inner-core mixing processes, ERCs, spiral rainband dynamics, and interaction of the TC with the ocean through surface fluxes. This section also includes a summary of the following special focus topics: internal processes contributing to rapid intensification (RI), fundamental mechanisms by which TCs intensify, and some recent new emerging ideas on internal influences on TC intensity change.

The hurricane eyewall can be become dynamically unstable when the radial potential vorticity (PV) gradient changes sign, satisfying the Charney-Stern necessary condition for combined barotropic-baroclinic instability. When the eyewall becomes unstable, it can break down into polygonal structures and mesovortices, and mixing can ensue between the eyewall and eye. Recent research on this topic has extended the previous idealized adiabatic and inviscid studies to more realistic frameworks (three-dimensional and with more complicated diabatic and frictional forcing). Wu et. Al (2016) showed that the secondary circulation can help maintain the annular ring structure and make it

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less susceptible to instability. Menelaou et al. (2016) emphasized the importance of the vortex Rossby wave-inertia gravity wave instability in destabilizing three-dimensional PV rings.

New research on secondary eyewall formation and ERCs has focused on improved understanding of wind-pressure relationships and intensity changes during ERCs, and improved prediction of ERCs and associated intensity changes. A new intensity change guidance model called the ERC climatology model (E-SHIPS) has been developed and is being used by operational centers. State-of-the-art numerical weather prediction models still have difficulty predicting the onset time of the ERC, the location and contraction speed of the outer eyewall, the dissipation rate of the inner eyewall, and the total duration of the event. With regard to wind-pressure relationships (WPRs), Kossin et al. (2015) showed that the migration of the WPR is quite different for weak versus strong hurricanes undergoing ERCs (Fig. 1). While the classic ERC is associated with weakening, some recent studies have shown that subtle intensity changes can also occur with ERCs where the outer eyewall is maintained for a long time or the inner eyewall does not dissipate.

Spiral rainbands have significant effects on TC structural and intensity change. Recent studies have shown that the outer rainbands are dominated more by ice-phase processes than the inner rainbands (especially over land), and also have high lightning flash densities. Convective heating in inner rainbands have been shown to increase intensity, while stratiform cooling in these bands promotes weakening. Evaporative cooling in the outer rainbands tends to reduce intensity, while this process has a minimal effect for inner rainbands.

The following are the important advances in understanding the role of surface fluxes on TC intensity change. Recent studies have shown that sea spray effects can aid intensification, through enhancing thermodynamic disequilibrium and thus the surface fluxes from the ocean into the boundary layer. New theories were developed to include the effect of TC-induced cooling of the sea surface on TC maximum potential intensity (MPI). New studies were performed on understanding the impact of surface fluxes on the TC boundary layer, including boundary layer recovery. With regard to the sea-surface-temperature (SST), it was shown that radial variability of SST across the storm is important, as this modifies the convective available potential energy inside and outside the radius of maximum winds (RMW), thereby affecting the intensity change. Uncertainties still remain with regard to the wind-speed dependence of the surface drag and enthalpy coefficients, and more observations of surface fluxes in high wind speeds are needed.

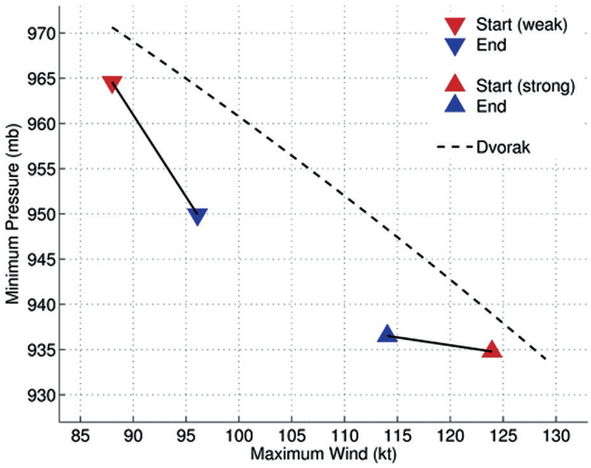

FIG. 1. Mean WPR changes for TCs that begin an ERC as a weaker hurricane (Vmax < 100 kt (51.4 m/s) and as a stronger hurricane (Vmax > 100 kt (51.4 m/s)). Reproduced from Kossin (2015).

Many recent studies focused on improved understanding of the processes responsible for RI. Studies have shown the RI events usually last longer than 24 h, and that the storm structure (convection, precipitation, and thermodynamic parameters) often becomes more symmetric prior to RI episodes. The degree of axisymmetry in the development stage has been shown to be strongly related to intensification rates (Shimada et al. 2017). Although the axisymmetric pathway is common, studies have also shown that RI can occur with asymmetric convective bursts and hot towers in the inner-core. RI events depend on the nature of the precipitation (deep convective versus stratiform) and the shear-relative distribution of the convection. Tao et al. (2017) showed that the onset of RI was marked by a significant increase in stratiform precipitation in all shear-relative quadrants, especially upshear left (Fig. 2). Further research is needed on whether deep convective bursts are a symptom or cause of RI. Additionally, a consistent definition of RI is needed globally, as different basins have different thresholds based on observed intensity change cumulative distribution functions.

A summary was provided on four main intensification mechanisms for TCs. The first two mechanisms are well known, while the second two mechanisms are newer and have had more active research in recent years. The first mechanism is the well-known balanced symmetric intensification mechanism. Using the quasi-balance equations, diabatic heating drives a secondary circulation in a linear Sawyer-Eliassen sense, which draws isosurfaces of absolute angular momentum (AAM) inward to spin up the vortex. If the heating occurs inside the RMW, the heat energy is more efficiently converted into kinetic energy and thus spins up the vortex faster. The second mechanism is the wind-induced surface heat exchange (WISHE), which is a finite amplitude instability with a positive feedback between the surface winds and speed-dependent surface moist entropy flux. Recent modifications to WISHE include the role of small-scale turbulence in the outflow layer and capping of

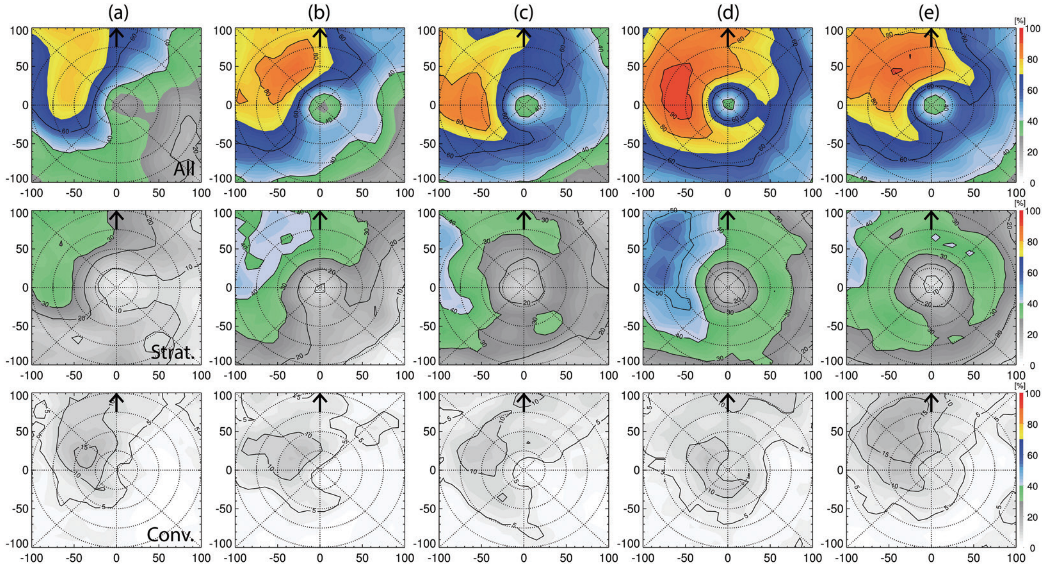

Fig. 2. Composite shear-relative distribution of the rainfall coverage from (I) all precipitation, (II) stratiform precipitation, and (III) convective precipitation. From left to right: (a) 12–24 h before RI onset, (b) 0–12 h before RI onset, (c) RI onset, (d) RI continuing, and (e) 12–24 h before RI ends. Dotted range rings represent the 25-, 50-, 75-, and 100-km radii. Reproduced from Tao et al. (2017).

the winds in the surface enthalpy flux. The third mechanism is newer and is a rotating convective framework. This framework explicitly recognizes the importance of localized, rotating deep convection, whose vorticity is amplified several times that of the broad scale vortex circulation via stretching and tilting processes. The parent vortex is then intensified through upscale growth of these localized vorticity anomalies. Also, more recent, the fourth and final mechanism is the boundary layer spin-up mechanism. This mechanism emphasizes the critical importance on unbalanced processes in the nonlinear boundary layer, where strong radial convergence can lead to spin-up even though AAM is diminished in the boundary layer.

Finally, three new emerging topics on internal influences on TC intensity change have been identified in recent years. In the first topic, the critical role of vortex structure on the subsequent intensification rate (IR) is discussed. In these studies, the IR is shown to depend critically on the radial and vertical structure of the parent vortex. In the second topic, the concept of the MPIR of a TC was identified and discussed from observational and energetic perspectives. MPIR is similar to the well-known MPI, except that it is an upper bound on the IR rather than the intensity. Development of a rigorous MPIR theory could eventually lead to better prediction of RI events. Finally, the role of TC outflow on TC intensity change is discussed. Recent field campaigns have had targeted measurements in the outflow region, which may lead to an understanding of outflow's precise role in intensity variability in the future.

3. Intensity Change: External Influences

There were a number of recent advances in the understanding of external influences on TC intensity change, which are summarized below. The main external influences on TC intensity change are the interaction of the TC with the underlying ocean, VWS, trough interactions, and dry or dusty environmental air intrusions. While there exists an understanding of the impact of each of these processes separately on TC intensity change, when multiple external factors act in concert, there is less understanding of dynamical and thermodynamic processes causing intensity changes.

With regard to ocean influences, research in the past four years has focused on the influence of mesoscale warm- and cold-core ocean eddies on TC intensity change. The complicated structure of these ocean eddies is shown in the Gulf of Mexico during Hurricane Isaac (2012) in Fig. 3, reproduced from Jaimes et al. (2016). When a TC moves over a warm-core ocean eddy, increased enthalpy fluxes ensue due to moisture disequilibrium, contributing to intensification. When a TC nears a coastal region, it may interact with fresh water which tends to reduce TC-induced cooling. SST displays a complicated relationship with TC intensity change, varying from basin to basin. During strong El Niño events, ocean heat content (OHC) and SST anomalies can contribute to extreme intensification rates (which occurred in the environment of Hurricane Patricia in 2015). Finally, under global warming conditions, upper ocean thermal stratification may increase leading to stronger TC self-induced cooling, partially offsetting the increased intensifi-

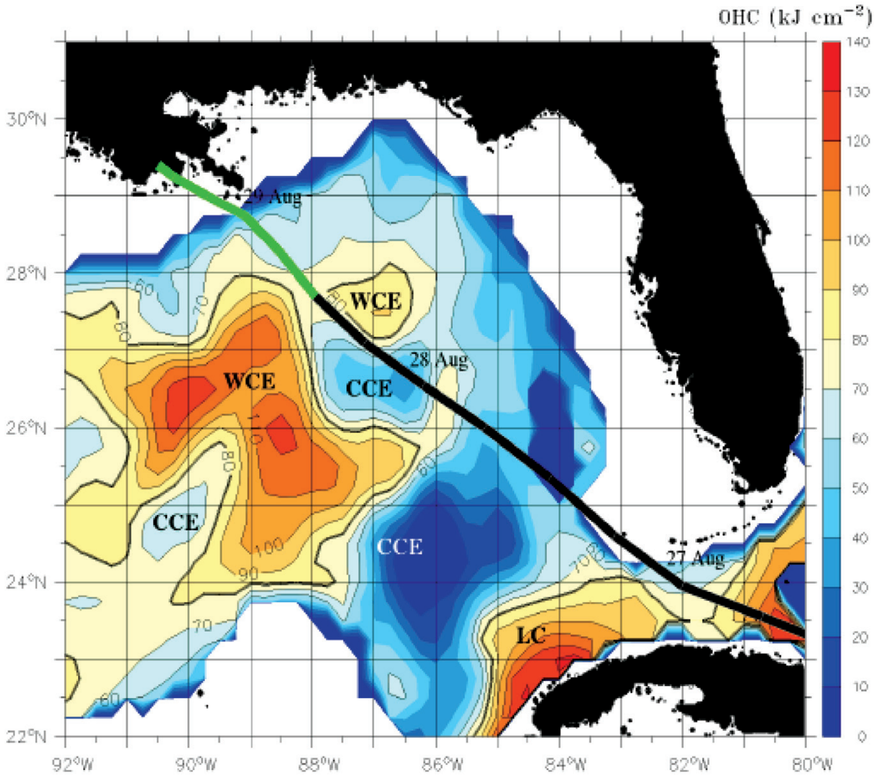

FIG. 3. Best track of Isaac (black: Tropical storm; green: Cat 1 Hurricane) relative to the complex ocean circulation and ocean heat content in the Gulf of Mexico for 25 August 2012 (WCE: Warm core eddy; CCE Cold core eddy; LC: Loop Current). Reproduced from Fig. 1 of Jaimes et al. 2016.

cation rates expected under warming scenarios.

VWS is one of the most important external influences on TC intensity change. VWS usually causes a reduction in intensity, however the pathway of this reduction can be quite complicated and is also highly dependent on the VWS magnitude, vertical profiles, and horizontal variability around the TC. With regard to its impact on convection, VWS modulates the azimuthal and radial distribution of the inner-core convection which then affects intensity. While VWS typically produces a wavenumber-one asymmetry in convection with an enhancement downshear, recent work has shown that VWS can also organize deep convection in the upshear left quadrant, favoring intensification. The vertical profile of VWS is important for intensity change, with positive TC-relative environmental helicity favoring intensification. Due to this interaction with convection, Tao and Zhang (2015) showed that the predictability of TC intensity is lower when the TC exists in moderate VWS (Fig. 4).

Dry environmental air often inhibits TC intensification, especially when it occurs coincident with VWS, since VWS disrupts the inertial stability of the vortex allowing the dry air to be more easily entrained. The location of the dry air and how it interacts with the TC circulation are critical; merely having dry air in the environment near a TC is not a sufficient condition for interaction and weakening. When dry air is ingested in a TC, the TC weakens as the vertical mass flux is reduced due to a reduction of deep convective activity.

Aerosols affect TC intensity change through their indirect effects with the microphysical processes and radiation. Aerosols can act as cloud-condensational nuclei, and if more condensation occurs, column latent heating will be increased. Invigoration of convection in the eyewall would typically lead to intensification, while invigoration of convection in the outer circulation and rainbands would lead to weakening. Aerosols are often present in dry air masses (e.g., the Saharan Air Layer) which generally inhibit intensification.

With regard to TC-trough interactions, recent studies have shown that troughs can both aid and hinder intensification. As an example, Leroux et al. (2016) showed that the interaction depends on the TC vortex depth, with intensification being more likely for deeper TCs. Peirano et al. (2016) demonstrated that the positive eddy-flux-convergence effect is often dominated by the negative VWS effects, causing weakening. The geometry of the TC-trough system was also shown to be important for intensity change. An interesting linkage between external and in-

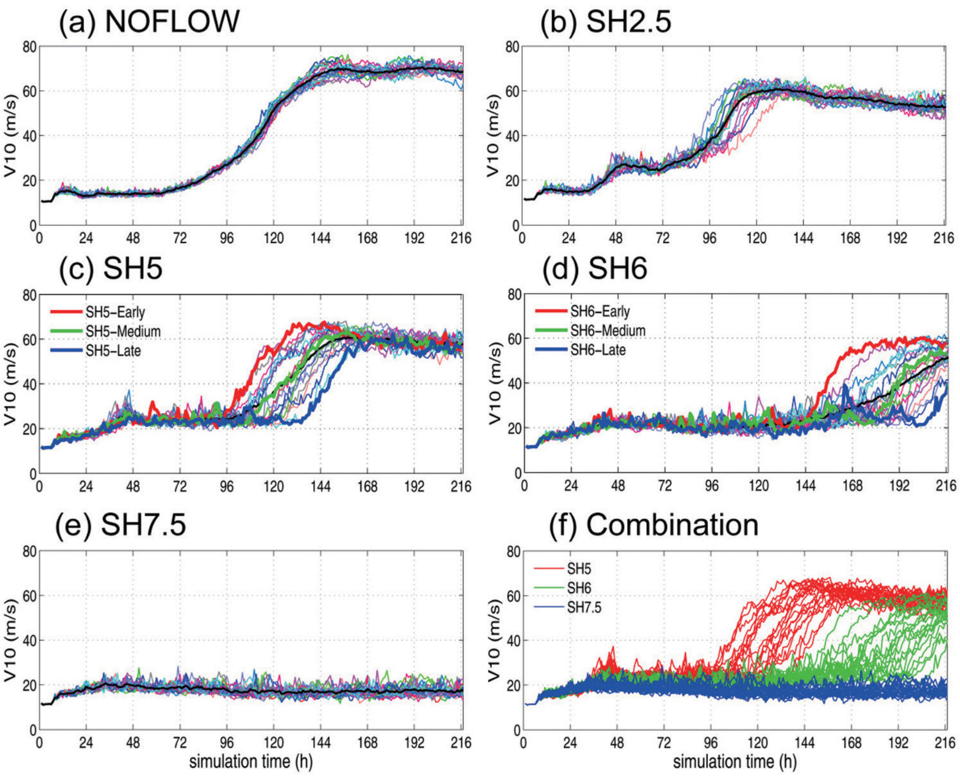

Fig. 4. Time evolution of the TC intensity in terms of the 10-m maximum wind speed (m s^{-1}) for all ensemble members of (a) NOFLOW, (b) SH2.5 (shear of 2.5 m s^{-1}), (c) SH5, (d) SH6, (e) SH7.5, and (f) combination of SH5, SH6, and SH7.5. All under SST = 27 C. Reproduced from Fig. 2 of Tao and Zhang 2015.

ternal processes was found where an upper-level jet streak (associated with a trough) can externally force an ERC in certain circumstances (Dai et al. 2017).

When multiple external factors act in concert, the predictability of the timing of (RI) is low. In particular, the external factors act in complicated ways with the internal processes during RI events. Rapid weakening events were found to occur when TCs cross sharp SST gradients, move into regions of higher VWS, and entrain drier air.

Finally, the storm environment is modulated by the Pacific Decadal Oscillation, El Niño-Southern Oscillation, and the Madden-Julian Oscillation, and therefore these large-scale, low-frequency, modes of variability affect TC intensity change.

4. Summary and recommendations

A brief summary has been provided of the rapporteur reports by Vigh et al. (2018) and Braun et al. (2018) from IWTC-9, describing research advances on TC intensity change by internal and external influences, respectively. The reader is referred to these rapporteur reports for a more detailed analysis than can be provided by this short summary. While research advances have occurred on many fronts on various internal and external influences to TC intensity change, further research is clearly needed on understanding RI, particularly when multiple factors act in concert.

Based on the rapporteur reports and the breakout sessions at IWTC-9, the following main recommendations for future research on TC intensity change were obtained. Although this summary has focused on the main research advances on intensity change over the past four years, these recommendations include both the recommendations from research and operational perspectives. In brackets, the community to which the recommendation is directed is given. These are not the final IWTC-9 recommendations; however, these recommendations were submitted to the recommendations committee at IWTC-9, and portions of them were used in the final IWTC-9 recommendations.

- New strategies should be considered to observe the TC inner-core with high spatial and temporal resolution from the upper ocean to the stratosphere in order to improve understanding of the various internal influences (including ERCs, eyewall instability and mixing, spiral rainband dynamics and surface fluxes) on TC intensity change. The observations should be used to diagnose and improve numerical weather prediction models for better predictions of these processes and associated intensity changes. [RESEARCH COMMUNITY]

- Further research studies should be conducted for improving the understanding of the conditions and precursors to RI through symmetrical and asymmetric processes. A holistic approach should be used, recognizing the potential role of multiple internal and external factors acting in concert. To aid these studies, RI should be defined as an event, rather than a 24-h case-based definition. [RESEARCH COMMUNITY]
- Scientists with competing intensification mechanism theories and frameworks should team up together in a larger collaborative effort to resolve some of these long-standing debates. We recommend that funding agencies recognize this potential approach and design funding calls specifically toward this purpose, and that World Meteorological Organization (WMO) sponsor an international workshop to bring leading researchers together to review the issues involved in the controversy. [WMO]
- Improved representation is needed of ocean pre-storm conditions and coastal processes in current coupled TC forecasting models. This improvement will likely require that simultaneous and coincident measurements of oceanic and atmospheric profiles be made before, during, and after a storm and be assimilated into the models. [RESEARCH AND OPERATIONAL COMMUNITY]
- Further research is needed on the intensity impacts of the interaction of complex spatially (horizontal and vertical) and temporally varying environmental VWS, including during TC-trough interactions, with TC vortices having a wide range of horizontal and vertical structures and intensities. Key foci include how these interactions impact vortex tilt and precession, synoptic- to convective-scale vertical motion, the distribution of convection in the inner-core region, and the corresponding impacts of dry-air intrusion and/or downdraft cooling of the boundary layer. [RESEARCH COMMUNITY]
- Advance intensity forecast guidance development, visualization, and integration into operational centers, including: diagnostics (especially VWS); dynamic models; statistical-dynamical techniques; machine learning approaches; and ensembles to promote probabilistic intensity output. [RESEARCH COMMUNITY]
- Improve the knowledge transfer into operational centers of research outcomes, model and technique developments, and best practice in handling difficult cases. Strategies include online documentation (e.g., the European Center for Medium Range Weather Forecasts user guide); online training (e.g. virtual laboratory seminars); Tropical-Storms e-mail listserv; and workshops (WMO regional training; recordings at American Meteorological Society conferences). [RESEARCH COMMUNITY AND WMO]
- Operational centers should expand verification in line with WMO guidelines to identify difficult cases and for such cases to be collated and stored on a community-based database for subsequent investigations and research (this can apply to track, structure and impacts). [OPERATIONAL COMMUNITY AND WMO]

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