Understanding the helical evolution of tropical cyclones and their interaction with the upper ocean

A thesis submitted in

partial fulfillment of the requirement for the degree of

Doctor of Philosophy (Ph.D.)

by

Arpita Munsi

Department of Earth and Space Sciences,

Indian Institute of Space Technology, Thiruvananthapuram

August, 2022

ABSTRACT

Tropical cyclones (TCs) are violent meso-β scale convections occurring in the atmosphere. They are one of the most threatening natural hazards. Being marine events, they are poorly observed by conventional in-situ observations. Though TC track prediction has shown a satisfactory improvement with the advancement in remote sensing observational network and numerical weather prediction (NWP) model, the prediction of TC intensity, specially the rapid intensification (RI), is still now a challenging problem. One of the causes of this challenge is the lack of complete understanding of the TC dynamical and thermodynamical evolution. A special feature of a TC is its helical structure, quantified by helicity, which can be used to diagnose TC genesis and intensification. This dissertation aims to produce a quality mesoscale analysis by assimilating the available observations using an advanced data assimilation technique and using the downscaled analysis to understand the helicity evolution of TC intensity and their interaction with the upper ocean.

High-resolution analyses have been generated using the Advanced Research Weather Research and Forecasting model (WRF-ARW) and three-dimensional variational-Ensemble Kalman Filter (3DEnKF). This model has been used for dynamical downscaling the two-way nesting domain (18 km × 18 km, 6 km × 6 km, 2 km × 2 km) for three TCs, viz. Fani, Ockhi, and Luban over the north Indian Ocean (NIO). The available surface and upper-air observations, radiance data, and scatterometer/radiometer wind data have been assimilated. The simulated maximum surface wind (intensity), minimum sea level pressure (MSLP), and cyclone tracks have been compared to the International Best Track Archive For Climate Stewardship (IBTrACS) dataset. The variation of maximum surface level wind speed and MSLP is successfully simulated in the developed mesoscale analysis. The surface winds validated using the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) buoys observations showed a better correlation at the cyclonic stage and severe cyclonic stage compared to the very severe cyclonic stage. Comparing wind distribution at 850 hPa to the 5th Generation European Centre for Medium-Range Weather Forecasts Reanalysis (ERA5) showed that the analysis successfully captured more intense TC intensification stages. The significant features in the upper, middle and lower tropospheric circulations surrounding the TCs have been well simulated in the reanalysis as observed by

INSAT3D/3DR and Scatsat-1. The RI of TCs were successfully simulated in the mesoscale analysis. The simulated and the Global Precipitation Measurement (GPM) accumulated rainfall distribution was found to be collocated, especially over heavy rainfall regions.

The developed reanalysis has been used to understand the variation of atmospheric dynamic-thermodynamic parameters. Analysis showed that the release of CAPE in the presence of nearly saturated middle-level relative humidity (RH) causes intense diabatic heating, leading to an increase in low-level convergence, which triggered the RI. The increment in upper tropospheric divergence strengthened the vertical convection (TCs Fani and Luban). The first RI of TC Ockhi was associated with a decrease in upper troposphere divergence, which reduced the ventilation flow in the upper level. It caused moisture accumulation in the TC core region which increased the diabatic heating (through latent heat release) and strengthened the warm core leading to the second RI. The unorganized, weak, discontinuous vertical vortex columns became organized around the eye with intense vertical velocity throughout the column after RI. Spatial distributions of the Okubo-Wiess (OW) parameter show that the TC core portion began vorticity dominated by suppressing the strain-dominated surrounding from the DD stage. The evolution of dynamical and thermodynamical parameters indicated that the vortex stretching in the bottom-up mechanism and the developed positive feedback of diabatic heating, baroclinic instability, increased vertical velocity, and continuous vertical moisture transport and strengthening warm-core are responsible for the intensification of TCs.

The evolution of the helicity of the three TCs have been analyzed in this study. The analysis of kinetic energy density of primary (EP), secondary (ES) circulation and total helicity has shown that TCs showed helical features when the secondary overturning circulation knotted with primary tangential circulation in a moist convective situation. This condition can be considered a starting of the self-sustained helical feedback process. At this time, the core region became a rotation-dominated region that suppressed strain-dominated surroundings. The Okubo-Weiss parameter demonstrates the similar qualitative behavior of deep convection as total helicity. The local maxima in helicity time series are commensurate with the TCs' stages changes. Therefore, helicity analysis is essential to analyze the TC intensification and dissipation.

The importance of higher SST (above 26 °C) for the generation of TC is well established. The movement of TC towards warmer SST fuels RI and MI. The passage of TCs causes the cooling of ocean surface waters and a reduction in values of SST by about 2-3°C after RI is observed. However, the OMT is decreased by about 0.5 °C after RI because of the more ocean thermal energy available in the upper layers. The ultimate intensity of TC Fani was significantly impacted by OMT rather than SST. The reduction in the ocean thermal energy observed after the MI of TC Fani was non-conducive for further intensification. The energy input to the ocean due to wind stress is higher at the lower translational speed of TCs due to more time exposure. The study suggests that the upper ocean and TC interaction must be understood in greater detail to address the research problem of the prediction of TCs intensification.

The transfer of enthalpy through the air-sea interface fuels a TC and thus plays a role in its life cycle. The wind stress, ocean surface roughness, and moisture flux are strongly correlated to boundary layer (BL) helicity and showed a higher correlation at the intensified stages. The analysis indicated that TC and ocean interacted in a positive feedback mechanism at the genesis and development stages up to the ESCS stage for TC Fani, CS stage for TC Luban, and VSCS stage for TC Ockhi. After that, further intensification led to a reduction in moisture and heat flux, which countered the TC from intensification to higher intensities. TC-ocean interacted in a negative feedback mechanism at this duration and dissipated it consequently.