

ABSTRACT

Tropical cyclone translation speed (TCTS) strongly influences the duration and severity of cyclone-related hazards, yet the mechanisms governing its variability over the North Indian Ocean (NIO) remain poorly understood. In this study, we examine the climatology, variability, and dynamical controls of TCTS over the NIO considering data for past 44 years (1981–2024). TCTS shows a weak, statistically non-significant, basin-wide slowing tendency, but the frequency and residence time of slow-moving (TCTS < 15 km h⁻¹) cyclones have increased significantly, whereas moderate (15 km h⁻¹ < TCTS < 25 km h⁻¹) and fast-moving TCTS ≥ 25 km h⁻¹) cyclones show no significant trend. Slow-moving phases dominate over the central Bay of Bengal and the parts of Arabian Sea, whereas fast-moving phases are rare and largely confined to near-coastal and higher-latitude regions. The TC composite analysis shows the presence of mid-latitude Rossby wave during pre-, monsoon and post-monsoon season (except post monsoon season in Arabian Sea), and the strength of the meridional wind (mid-latitude Rossby wave) modulates the TCTS. During the post-monsoon season, fast-moving cyclones are associated with a more organized equatorial Rossby wave environment over Arabian Sea.

INTRODUCTION

- Translation speed determines the duration and spatial extent of cyclone-induced rainfall, flooding, and storm-surge impacts.
- TC movement is governed by large-scale atmospheric circulation, including monsoon flows, subtropical ridges, and mid-latitude troughs.
- Long-term trends vary regionally, highlighting the need for basin-specific investigations.
- Despite its high socio-economic vulnerability, TC translation speed and its controlling mechanisms remain insufficiently explored.
- Equatorial and mid-latitude Rossby waves can modify convection, steering flow, and upper-level circulation, potentially influencing TC movement.

This study investigates TC translation speed over the NIO during 1981–2024, focusing on its climatology, long-term variability, and links with steering flow and Rossby wave activity.

METHODS

- Data Source: JTWC best-track data (6-hourly) for named cyclones of CS intensity and above over the North Indian Ocean (1981–2024).
- Translation Speed: Calculated at 6-hour intervals using a 24-hour running window and expressed in km h⁻¹.
- Seasonal Classification: Pre-monsoon (March–May), monsoon (June–September), and post-monsoon (October–December).
- Speed Categories (IMD-based):
 - Slow: Below 15 km h⁻¹
 - Moderate: 15–25 km h⁻¹
 - Fast: more than 25 km h⁻¹
- Reanalysis Data: ERA5 pressure-level winds and geopotential height (1981–2024) used to analyse environmental steering flow.
- SST Data: NOAA OISST data (1981–2024) used to examine sea-surface temperature conditions.

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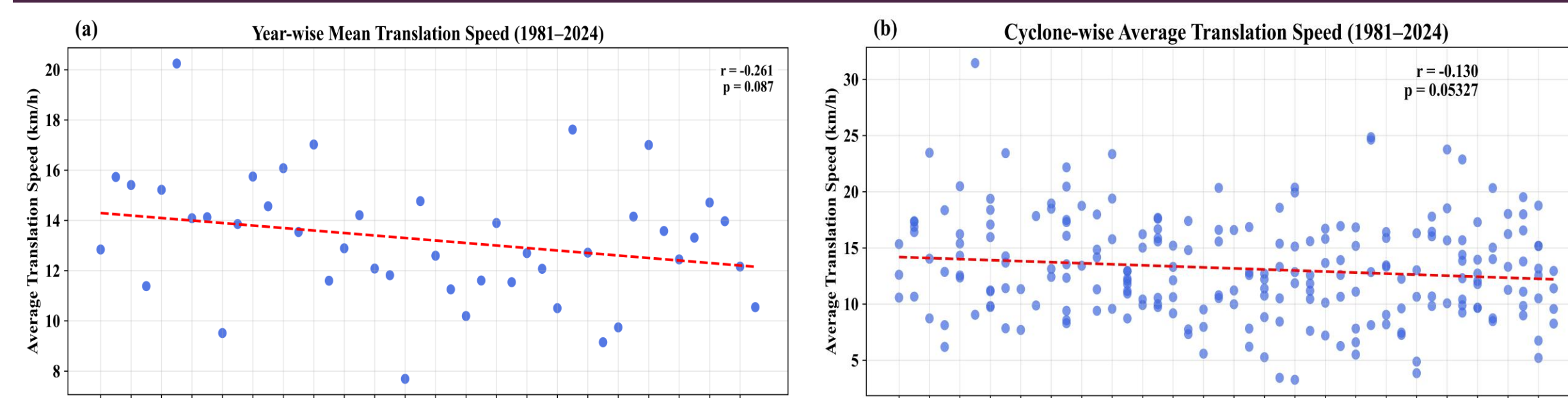
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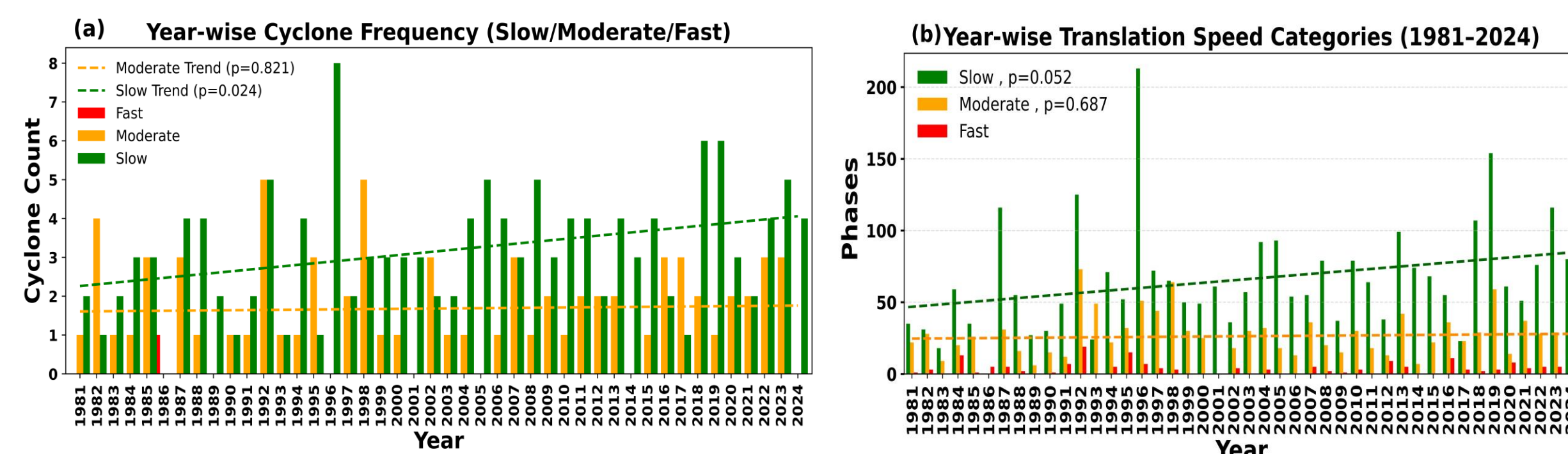
- Most cyclone phases occur between 10–15 km/h, with very few exceeding 25 km/h.
- Mean cyclone translation speed shows a decreasing trend, with annual averages mostly between 12 and 14 km/h.
- Slow-moving cyclone numbers show a significant increasing trend ($p = 0.02$), while moderate-moving cyclones show no significant trend.
- Slow-moving cyclone phases are increasing, indicating a shift towards slower cyclone movement.
- Slow-moving cyclones have the longest track lengths, with an increasing trend ($p = 0.061$).
- Residence time increases for slow-moving cyclones ($p = 0.052$) and moderate-moving cyclones ($p = 0.0687$), suggesting greater potential for prolonged rainfall.

- Slow- and moderate-moving cyclones dominate both basins. ARB tracks are denser, while higher-latitude BoB TC tend to move north-eastward at moderate to fast speeds.
- Slow-moving phases dominate the central/eastern BoB and north-central AS, reaching 60–80% and locally exceeding 90%.
- Moderate-moving phases are more frequent over central India, northeastern BoB, the North Andaman Sea, and southern AS.
- Fast-moving phases are concentrated over the northern BoB, Himalayan foothills, and southwestern AS, with probabilities below 10% across most of the AS and peninsular India.

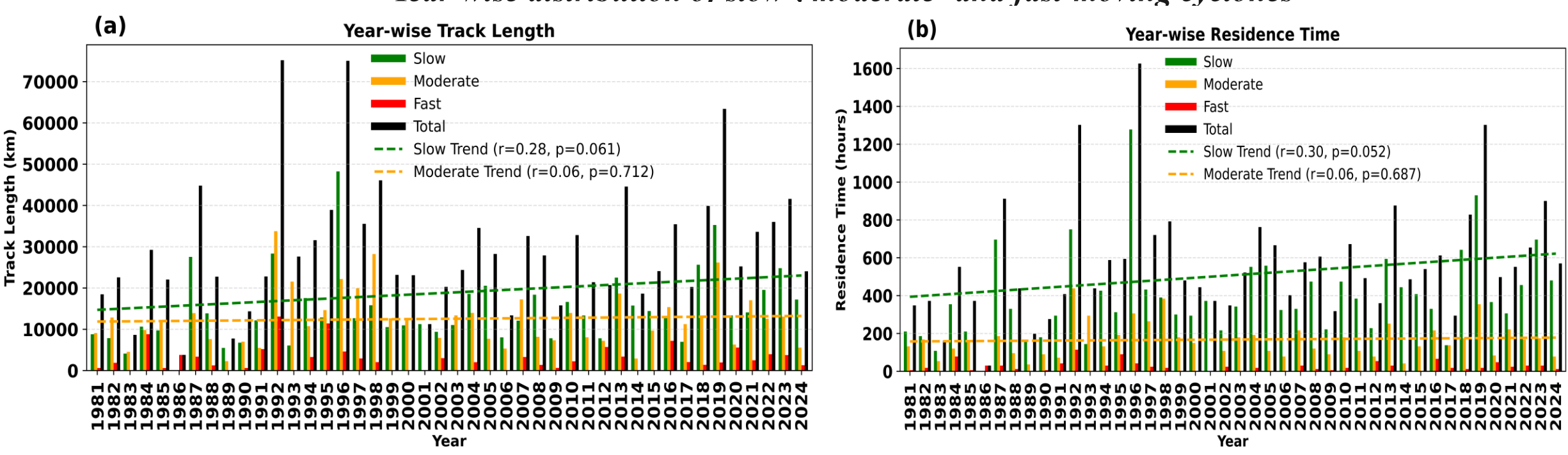
RESULTS AND DISCUSSION



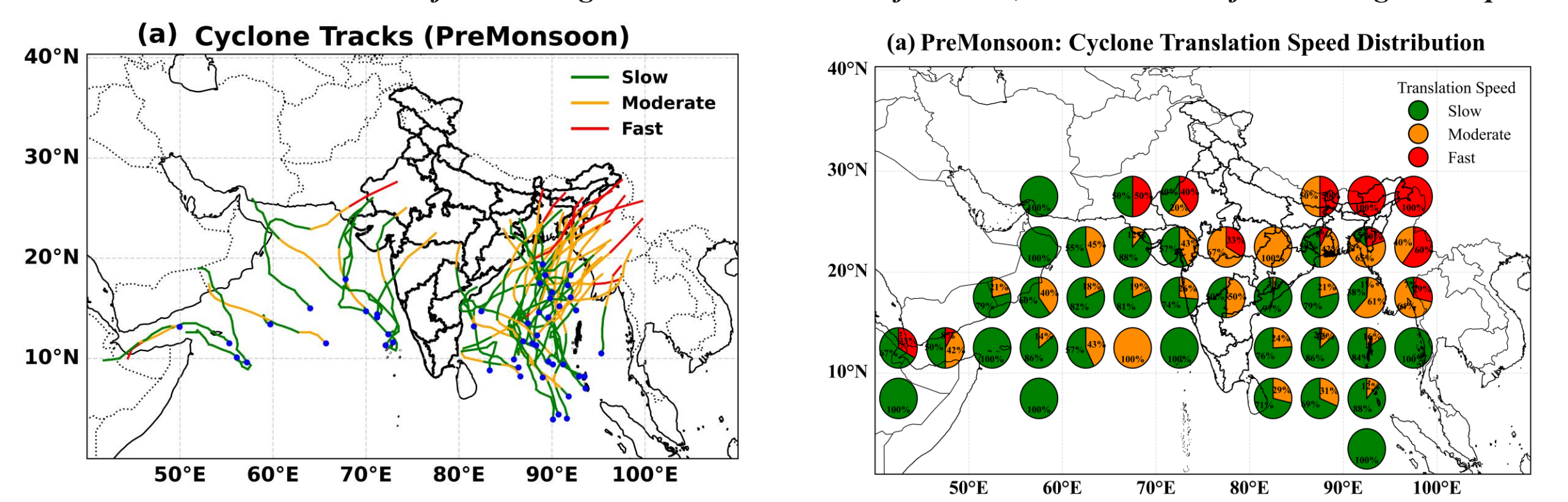
Long-term variability of TCTS over NIO a) Mean annual translation speed of all cyclones. b) Mean translation speed of each individual cyclone



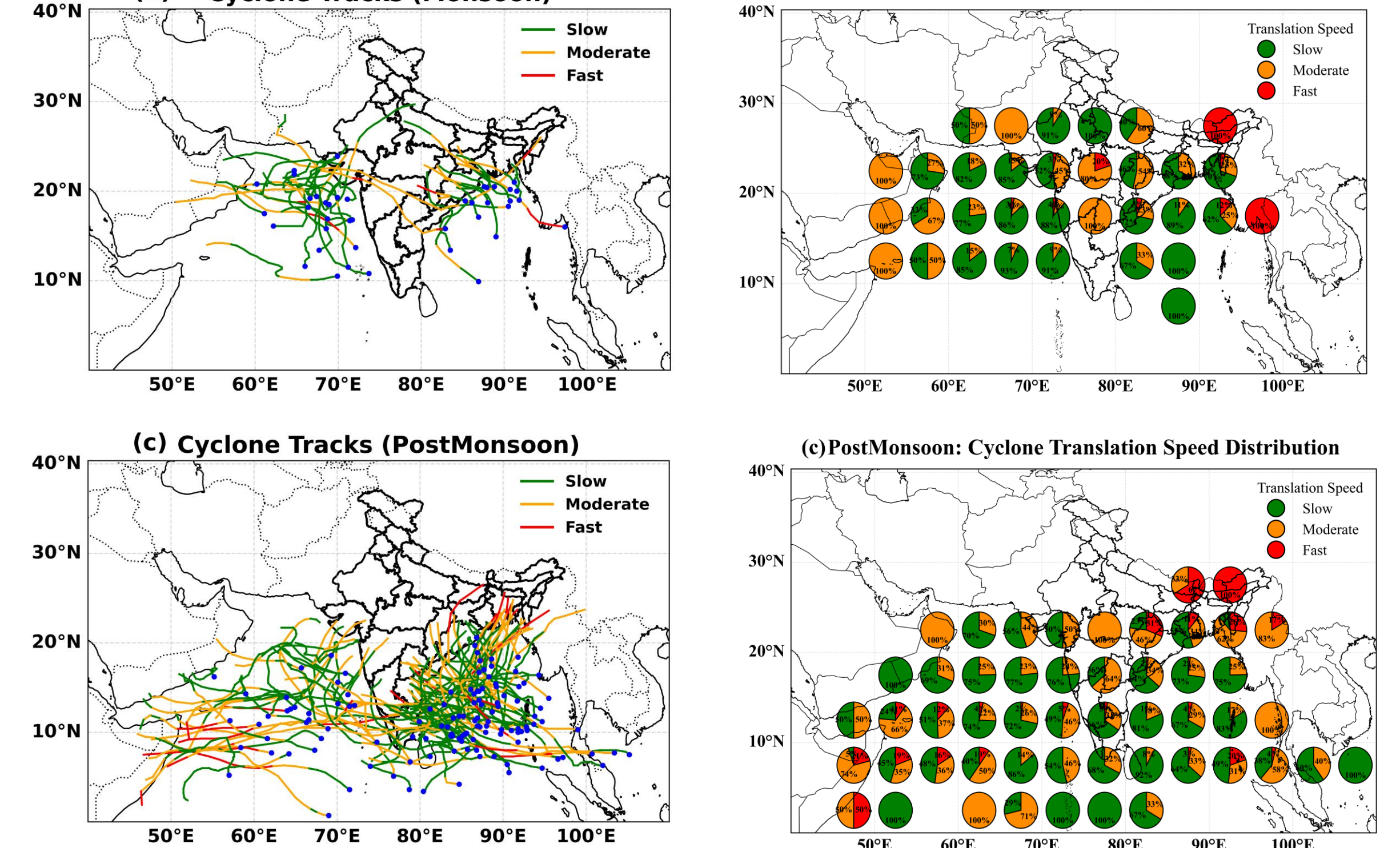
Year-wise distribution of slow-, moderate- and fast-moving cyclones



Year wise distribution of track length and residence time for slow-, moderate- and fast-moving TCTS phases

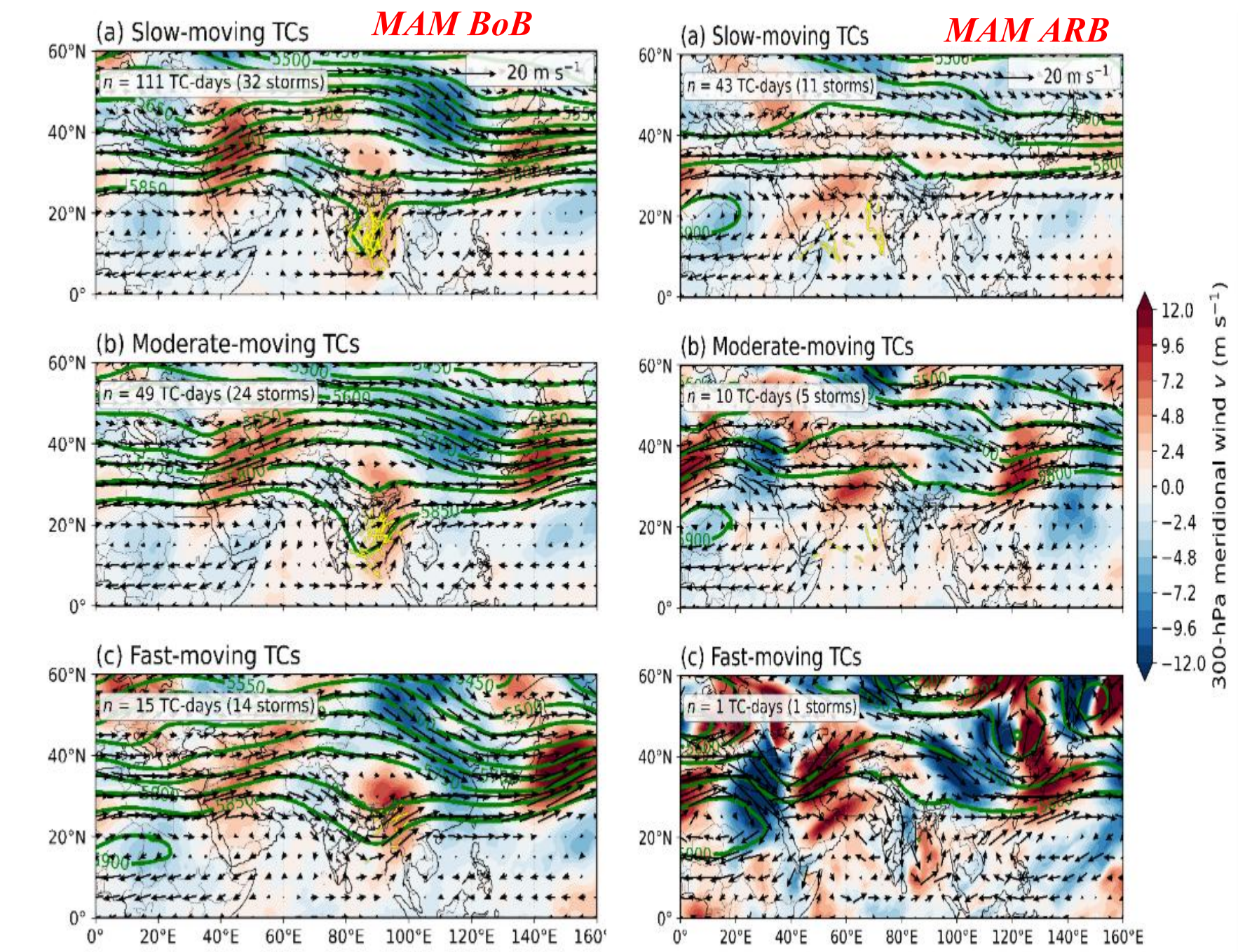


Tracks of cyclones during the a) pre monsoon c) post-monsoon season with Spatial probability (%) of TCTS phases over the North Indian Ocean (NIO)



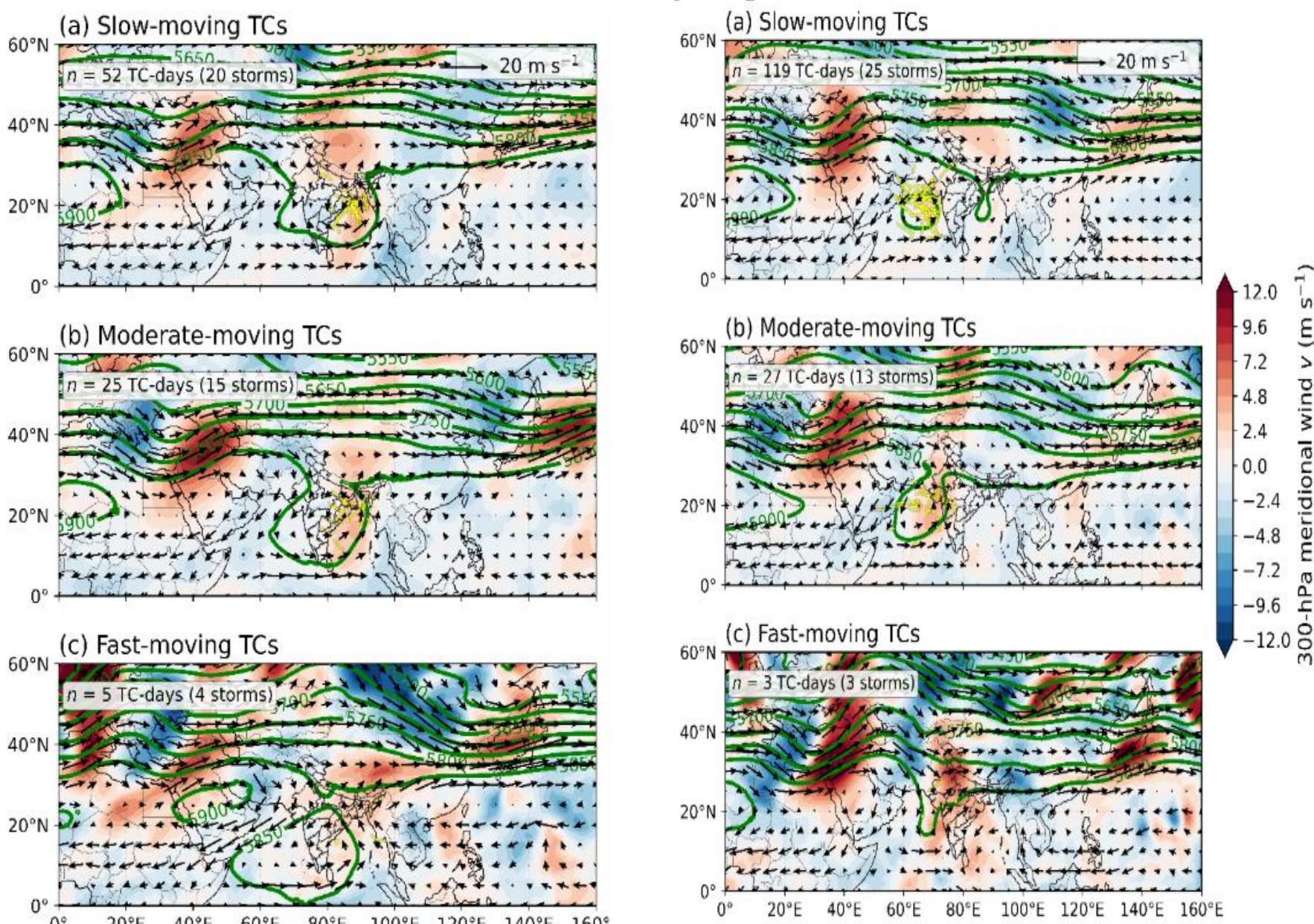
Role of Equatorial Rossby wave in controlling the TCTS in lower latitudes over Arabian Sea

Factors controlling the slow, moderate and fast TCTS



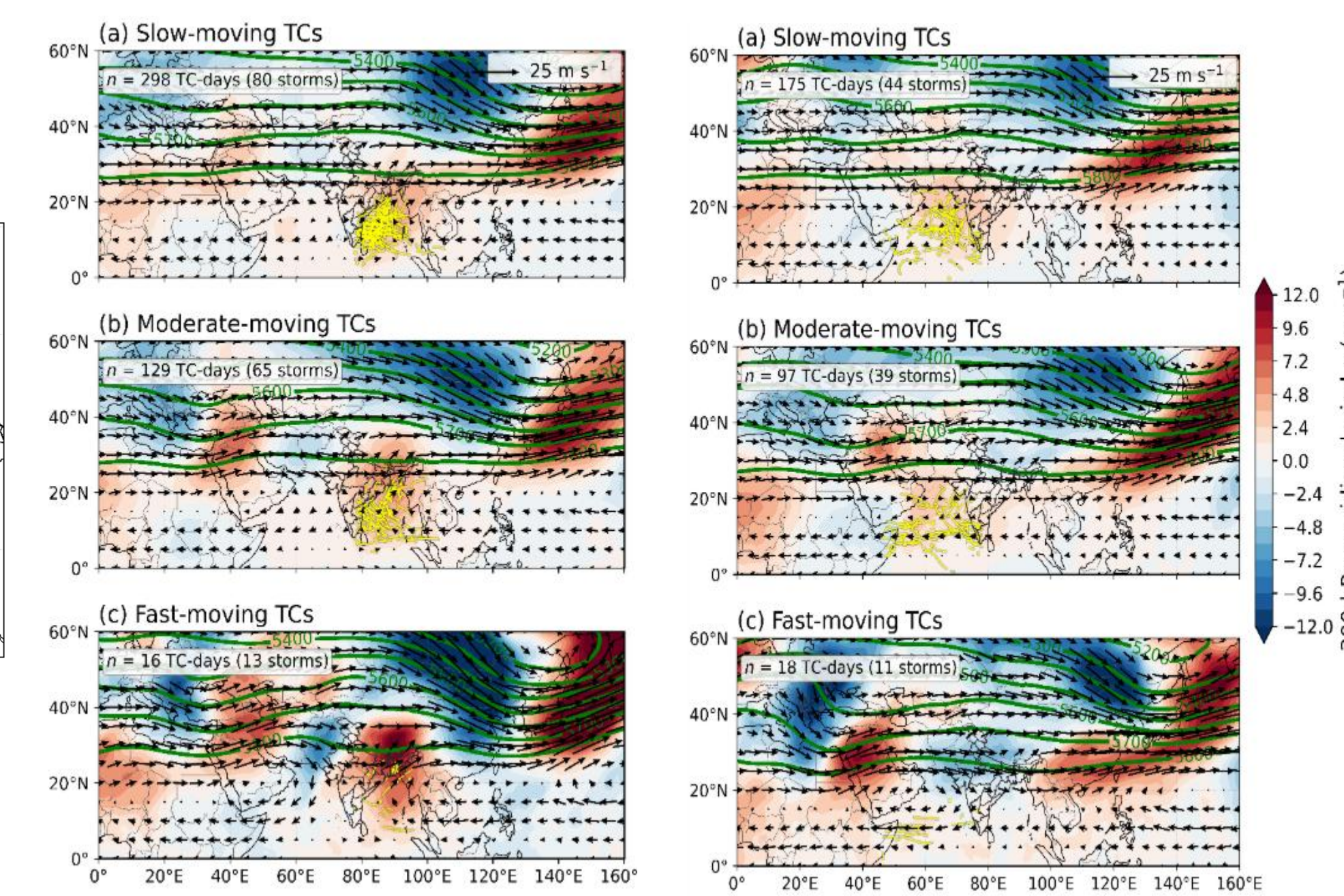
- Slow moving TCs are associated with weak Rossby wave activity and weaker 500-hPa steering flow over both basins.
- Moderate moving TCs shows more organized Rossby wave patterns and moderately enhanced steering flow.
- Fast moving TCs are associated with amplified mid-latitude Rossby wave trains, pronounced trough ridge patterns, and stronger steering winds.

Rossby wave and steering-flow signals are more organized over the Bay of Bengal than the Arabian Sea during the pre-monsoon season.



- Slow moving TCs are associated with weak upper-level steering and weak v_{300} signals.
- Moderate moving TCs show more organized midlatitude wave patterns but relatively weak steering flow.
- Fast moving TCs are associated with prominent Rossby wave trains and stronger steering winds.

The monsoon trough is well established over the Bay of Bengal but weak or absent over the Arabian Sea.



- Slow moving TCs remain south of the strongest upper-level winds and experience weaker steering.
- Moderate moving TCs show a clearer trough ridge pattern around the storm tracks.
- Fast moving TCs are associated with strong Rossby wave trains, enhanced steering winds, and poleward movement or re-curvature.

Arabian Sea TCs may be influenced by additional factors, as fast-moving systems often follow westward tracks.

CONCLUSIONS

- Examines tropical cyclone translation speed over the North Indian Ocean (NIO) during 1981–2024.
- The overall decreasing trend in translation speed is weak, while slow-moving cyclone phases have increased significantly.
- Slow-moving cyclones show longer residence times, increasing the risk of prolonged rainfall and flooding.
- Fast moving cyclones are associated with stronger Rossby wave activity and enhanced steering flow.
- Slow moving cyclones generally experience weaker steering flow.
- Seasonal and Basin Variability: These relationships differ between the BoB and ARB and across seasons.

Importance: Understanding Rossby wave patterns can improve cyclone-motion prediction, impact-based forecasting, and disaster preparedness. Westward-propagating Equatorial Rossby (ER) wave patterns are observed across all cyclone-speed categories.

- Slow moving cyclones show weak, diffuse ER-wave anomalies and less organized 300-hPa zonal winds.
- Moderate moving cyclones exhibit clearer ER-wave structures and more organized upper-level zonal flow.
- Fast moving cyclones are associated with stronger ER-wave anomalies and enhanced 300-hPa zonal winds.