Abstract

The marvelous transoceanic journey of the dragonfly species *Pantala flavescens*, spanning from India to Africa over multiple generations, presents a fascinating yet complex ecological-aerodynamic puzzle. The interplay of wind, precipitation, energy reserves, breeding habits, and life cycles in driving this migration makes this problem trans-disciplinary and challenging. We study the migration of *P. flavescens* using a three-pronged approach: (i) modeling the flight energetics, (ii) identifying optimal migratory routes, and (iii) conducting live force measurements of *P. flavescens* in wind tunnel. We propose the Dragonfly Energetics Model (DEM), a theoretical framework for assessing the energetics of dragonfly migration. We find that *P. flavescens* uses nearly half its initial mass to cover 1,400 kilometers in 90 hours, highlighting the critical role of favorable wind currents in assisting their open ocean crossing of 2,800 km from Africa to India.

Thereafter, we develop the Dragonfly Path-planning Model (DPM), integrating energetics, path-planning of micro-air vehicles (MAVs), and the wind field. Our model indicates that the migration from India to Africa typically starts in October, with stopovers at the Maldives and Seychelles, and the return from Africa to India is feasible from May onwards, aided by the Somali Jet. *P. flavescens* completes 4-5 breeding cycles across India, the Maldives, and Africa. These predictions align closely with numerous field observations and historical migratory records. Furthermore, our branched-network hypothesis links our field observation on 1^{st} and 2^{nd} November 2019 in northeast India (the origin) to the established migration route. It points to a more complex, branched migratory pattern and underscores the importance of using tailwinds and navigating crosswinds during migration.

A detailed analysis of forces and moments from live wind tunnel experiments provides insights into directional control and wind compensation mechanisms employed by *P. flavescens*. Our wind tunnel experiments reveal adaptive flapping mechanisms that enable these dragonflies to negotiate headwinds, tailwinds, and crosswinds. The thrust is the dominant force in tailwind flight, while lift generation is more significant in headwind conditions. We also discovered a novel mechanism of lift generation in tailwind flight. *P. flavescens* modulates its flapping frequency and wing kinematics to generate lift and thrust. The dragonfly generates side force to compensate for wind drift and yawing moment for heading correction, showing its sophisticated wind compensation capabilities. The force and moment generation become difficult with increasing crosswind angle. The dragonfly generates lift and thrust even in non-flapping phases, thus extending its flight time.

We aim to develop a holistic understanding of *P. flavescens*' transoceanic migration. The integration of energetics, path planning, and environmental factors, coupled with advanced force and moment measurements, sheds new light on the migratory behaviors of dragonflies; thus, we contribute to biological aerodynamics, ecology, and conservation by offering fresh perspectives on insect migration. Furthermore, the importance of the impact of climate change, particularly changing wind patterns and disappearing islands, on global ecological systems and the future of transoceanic migrations is highlighted in the present context.

Keywords: Transoceanic Migration; *Pantala flavescens*; Dragonfly Energetics; Migration Route; Branched Migration Network; Active Wind Compensation; Wind Tunnel Experiments; Live Force Measurement