Article Title: Monsoon meteorology and agricultural phenology structure atmospheric transport of aerial biomass across the Indian subcontinent

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Abstract: The movement of organisms through the atmosphere is a fundamental but under-observed ecological process that redistributes biomass, genes, and ecological interactions across continents. Aeroecology has revealed that such movements are strongly determined by synoptic and mesoscale atmospheric dynamics, which jointly determine when, where, and at what altitudes animals initiate, sustain, and terminate flight. However, current understanding is derived largely from temperate climatologies, leaving tropical aeroecology, where atmospheric circulation regimes are fundamentally different, poorly resolved. Here, I synthesize existing literature on radar observations, migration studies, and atmospheric dynamics to examine how monsoon-dominated tropical atmosphere structures aerial movement across the Indian subcontinent at inter-continental (>1000 km) and intra-peninsular (100 – 500 km) scales.

Across trophic levels, long-distance migratory movements are jointly organized by synoptic-scale monsoon flow and its seasonal reversal, orographic channeling and uplift along the Himalayan barrier, and spatial constriction at coastal bottlenecks along the western coast of the peninsula. These processes generate a common set of migration corridors for both, birds and insects, including trans-Himalayan, circum-Himalayan, Indo-African, and Indo-East/Southeast Asian pathways. At regional scales, evidence from the limited but critical radar observations indicates that aerial dispersal is tightly coupled to intraseasonal active–break phases of the monsoon, the stability and intermittency of diel boundary-layer transitions (including the strength of nocturnal low-level jets), and – particularly for insect pests – cropping cycles and agricultural phenology.

Despite these distinctive dynamics, radar aeroecology in the tropics remains sparse. India’s rapidly expanding weather-radar network, especially its dual-polarization X- and C-Band coverage across the western coast and the western Himalayan arc, provides an exceptional but underutilized platform for strengthening tropical aeroecology. By explicitly integrating monsoon meteorology, ecology, and radar aeroecology, this synthesis provides a framework for advancing a mechanistic, globally representative understanding of tropical aeroecology.

Keywords: aeroecology, birds, bats, insects, migration, monsoon, weather radar

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1. Introduction

More than a million animal species enter the lower atmosphere at some point in their lives to disperse, migrate, mate, or perform other essential life-history functions (Drake & Gatehouse 1995; Alerstam 2009; Chapman et al. 2015). Aeroecology conceptualizes this aerosphere not as a passive physical medium, but as an important ecological system structured by dynamic atmospheric processes, within which animals must sense, navigate, and interact while occupying an energetically costly niche (Kunz et al. 2008). Because wind velocity, turbulence, and convection govern the energetic costs of flight and the displacement potential of airborne organisms, a mechanistic understanding of aerial movement requires explicit consideration of atmospheric dynamics (Shamoun-Baranes et al. 2010; Shamoun-Baranes et al. 2017; see **Box 1** for a glossary of key atmospheric terms).

Broadly, aerial animal movement is structured by three interacting atmospheric controls operating across spatio-temporal scales (**Figure 1**): (i) large-scale (synoptic) circulation that establishes the background wind field, including pressure gradients and frontal dynamics (Shamoun-Baranes et al. 2017), (ii) mesoscale and boundary-layer processes that regulate the vertical structure and diel evolution of the lower atmosphere, including boundary-layer growth and collapse, low-level jets (LLJs), and convection (**Figure 2**; Reynolds et al. 2005; Wainwright et al. 2020), and (iii) topographic forcing, whereby mountains and coastlines modify airflow through channeling or orographic acceleration resulting in migration bottlenecks and corridors (Ranjan et al. 2023; Hawkes et al. 2024; Ram et al. 2024). Together, these processes determine the speed, direction, stability, and vertical stratification of winds, thereby shaping when, where, and at what altitudes animals initiate, sustain, and terminate flight (Westbrook & Isard 1999; Shamoun-Baranes et al. 2010; Potter et al. 2018; Wainwright et al. 2020; Jentsch & Weidinger 2022; Mikkola et al. 2023).

Modern radar systems – especially Doppler Weather Radars (DWRs) – have emerged as powerful tools in aeroecology, uniquely capable of simultaneously observing atmospheric structures and the movement of vast assemblages of flying animals embedded within them (Holleman et al. 2008; Dokter et al. 2011; Bauer et al. 2019). However, despite the advantages, they remain underutilized in ecological research across most tropical countries (but see Drucker et al. 2025). Unlike dedicated biological radars, DWRs are designed for meteorological monitoring rather than animal detection[1]

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[1] Purpose-built biological radars are typically deployed as single, study-specific systems (e.g., entomological Vertical Looking Radars or Robin and MERLIN™ bird radar systems), whereas Doppler Weather Radars (DWRs) operate as extensive national-scale networks. Crucially, DWRs are government-operated infrastructures that substantially reduce the financial barriers associated with acquiring, deploying, and maintaining dedicated biological radars (Drake et al. 2020; Bauer et al. 2024). Given that a modern biological radar unit can cost USD $150,000–$250,000, with substantial annual operating expenses, access to national DWR networks represents a particularly important opportunity for researchers in the Global South.

(Chapman et al. 2003; Chilson et al. 2012; Chilson et al. 2017; Drake et al. 2020; Long et al. 2020; see also Bauer et al. 2024). Their scanning strategies, widening beam geometry with distance, and the frequent overlap between biological and meteorological echoes complicate ecological interpretation (**Figure 3**; Gauthreaux et al. 2020). Interpreting biological backscatter often requires independent validation through aerial sampling using drones (Löcken et al. 2020), helikites, aerial nets, or suction traps (Chapman et al. 2002; Chapman et al. 2004; Mungee et al. 2025), ecological expertise on the known occurrence or emergence of animals (Frick et al. 2012; Stepanian et al. 2020; Anjita et al. 2024), or the application of advanced post-processing and machine-learning techniques (Lin et al. 2019). While hundreds of studies in Europe and North America have leveraged operational DWR networks to quantify migration magnitude, vertical stratification, and wind coupling (e.g., Dokter et al. 2011; Hu et al. 2016a; Hu et al. 2016b; Shamoun-Baranes et al. 2017), comparatively few have examined tropical systems (Rogers et al. 2020; but see Kearsley et al. 2022; Anjita et al. 2024; Drucker et al. 2025). As a result, much of modern aeroecological inference has been shaped by atmospheric conditions typical of mid-and high-latitude regions (Gauthreaux et al. 2003; Shamoun-Baranes et al. 2010; Dokter et al. 2011; Shamoun-Baranes et al. 2017).

However, atmospheric structure varies systematically with latitude (Rife et al. 2010; Sandeep et al. 2015; Luiz et al. 2024). Differences in seasonality and circulation regimes can fundamentally alter the ecological context in which aerial movement evolves and operates (Drucker et al. 2025). For instance, shorebird departure timing and migration trajectories were closely associated with seasonally reversing monsoon circulation along the East Asia–Australasian Flyway (Lei et al. 2025), while the bird migration in Colombia was temporally more diffuse and uniform across the season as compared to the strongly pulse-driven migration of temperate North America (Drucker et al. 2025). Although still relatively few, these studies suggest that differences in atmospheric structure between tropical and temperate climates, often interacting with regional topography, can generate distinct aeroecological dynamics (Rogers et al. 2020).

Despite these indications, empirical studies explicitly examining aerial movement within tropical atmospheric systems remain scarce, leaving a major gap in our understanding of how aerial movement ecology. Here, I synthesize existing evidence to examine how monsoon-driven tropical atmospheric processes structure aerial movement, using India as a focal case. The Indian subcontinent provides a particularly compelling system for examining these dynamics at lower latitudes. The region lies at the intersection of a seasonally reversing monsoon circulation (**Figure 4**), major orographic barriers, and multiple large-scale migratory networks, including the Central Asian Flyway of birds and the Himalayan insect flyway (Miyabayashi & Mundkur 1999; Boere & Stroud 2006; Hawkes et al. 2025). The steep elevational gradients of the Himalayas intersect the monsoon circulation to channel, lift, trap, or accelerate aerial fauna, producing movement dynamics that differ fundamentally from those described in temperate systems. Yet these complementary sources of information – ecological observations, atmospheric climatology, and weather-radar infrastructure – remain largely unintegrated.

To address this gap, I pursue three objectives. First, I review the development of radar-based research on aerial fauna in India – from early entomological radar campaigns to recent DWR applications – focusing on how these observations reveal coupling between aerial organisms and synoptic and mesoscale atmospheric structure. Second, I synthesize the country's principal migratory corridors and aeroecological hotspots across birds and insects, examining how aerial movement is organized by three interacting atmospheric controls: large-scale monsoon circulation, mesoscale and boundary-layer dynamics, and topographic forcing across major mountain systems and coastlines. Third, building on this synthesis, I identify key gaps in our understanding of how aerial fauna interact with monsoon-driven atmospheric structure across scales, and outline how these gaps can be addressed using the spatial coverage, temporal continuity, and observational capabilities of India's rapidly expanding DWR network.

2. Methods

I conducted a structured literature search to synthesize existing knowledge on radar-based aeroecology and atmospheric drivers of aerial fauna movement in India. Literature searches were performed in the Web of Science Core Collection database without temporal restriction using two main search strings: (i) Radar-based studies: TS=((radar* OR "weather radar*" OR "vertical looking radar*" OR "entomological radar*") AND (bird* OR avian OR insect* OR arthropod* OR bat* OR chiroptera* OR "biological echo*" OR bioscatter*) AND (India OR "Indian subcontinent")), and (ii) Atmospheric determinants of aerial movement and migration: TS=((migrat* OR dispers* OR flyway* OR "windborne movement" OR emergence) AND (bird* OR avian OR insect* OR arthropod* OR locust* OR aphid* OR planthopper* OR bat* OR chiroptera*) AND (atmospher* OR monsoon OR "boundary layer" OR "low-level jet" OR "synoptic wind*") AND (India OR "Indian subcontinent")) NOT TS=("emerging disease" OR zoonos* OR virus* OR rabies OR "nipah" OR pathogen*).

Titles and abstracts were screened for relevance to radar observations, aerial movement, and atmospheric drivers of aerial fauna in the Indian subcontinent. Because several foundational radar–entomology studies conducted in India between 1960 and 1990 are incompletely indexed in international databases, supplementary manual searches were undertaken to retrieve archival publications, institutional reports, and regionally published journals. Citation chaining was used to identify additional relevant sources.

3. Radar Observations of Aerial Fauna in India

Radar-based studies of aerial fauna in India remain limited in number and historically sporadic. The available literature is characterized by campaigns linked to technological experiments (Ramana Murty et al., 1964; Mazumdar et al., 1965; Riley & Reynolds 1997), opportunistic observation of bioscatterers by meteorologists (Suresh et al. 2005), or to specific agricultural pest outbreaks (Riley & Reynolds 1997; Amarjyothi et al. 2021; Anjita et al. 2024), rather than as a sustained research discipline at the intersection of ecology and meteorology.

The earliest documented radar study of aerial fauna in India used a 3.2-cm (X-Band; **Figure 3**) meteorological radar to track Desert Locust (*Schistocerca gregaria*) around New Delhi, demonstrating predominantly wind-driven transport within the lower boundary layer (~ 1 to 1.5 km) and a clear diel cycle of convective ascent and evening descent (Ramana Murty et al., 1964; Mazumdar et al., 1965; **Figure 2;** also see **Box 1**). Crucially, the swarm arrival and activity was tightly linked to the phase structure of the southwest monsoon; invasion followed an anomalously wet 15-day period, but peak aerial activity occurred during a subsequent temporary break in monsoon conditions, when rainfall subsided and lower-tropospheric winds were well organized. With the return of active monsoon conditions and a shift in wind direction, swarm activity rapidly diminished and locusts disappeared from the region. These early observations already illustrated how insect movement in the region is strongly coupled to the alternating active and break phases of the monsoon circulation (**Box 1**).

A major phase of development occurred between 1985 and 1995, when the UK Overseas Development Administration tested prototypes of the first nutating vertical-looking entomological radar near Hyderabad, southern India, in collaboration with the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), as part of a programme on the ecology and management of the cotton bollworm (*Helicoverpa armigera*; King et al. 1990; Riley et al. 1990; Riley et al. 1992; Reynolds et al. 1999). This represented the first sustained effort in India to quantify aerial insect assemblages using coordinated radar observations, mark–recapture, and aerial sampling using helikites. The studies showed that adult bollworms emerged at dusk (~20 min after sunset), with peak densities about one hour later, followed by declining but sustained nocturnal activity. Early peaks were dominated by ovipositing females, with mate-searching males appearing later in the night. Most individuals remained within ~10 m of the surface, and no mass high-altitude ascents were observed, indicating predominantly local dispersal rather than long-distance migration (Riley et al. 1992).

From the same campaign, Reynolds & Wilson (1989) showed that during the winter agricultural season (early *rabi*; November–December), large numbers of Hemiptera undertook nightly windborne flights at ~100 m above ground. Aerial catches were dominated by rice planthoppers, leafhoppers, and aphids, alongside high densities of predatory mirids. Radar observations documented mass dusk take-off events and secondary nocturnal density peaks later in the night after 23:00 IST, potentially representing long-distance migrants. Back-trajectory wind-field analyses suggested source regions 100–200 km away, often from irrigated rice landscapes along the Krishna River basin. In some cases, insect invasions coincided with synoptic disturbances that strengthened and veered low-level winds, including cyclonic systems moving inland from the Arabian Sea.

Riley et al. (2013) extended this work to eastern India, using elevated aerial nets – rather than radar per say – in West Bengal to examine long-distance migration of aphids and associated small insects. Samples were similarly dominated by planthoppers, leafhoppers, aphids, and predatory mirids. In contrast to the ICRISAT study, substantial activity occurred during both day and night; however, peak activity and movements still occurred after dusk. Wind-field analyses indicated displacement distances of 300–500 km overnight, with migrants typically originating in Bangladesh or northern

West Bengal and advected southwest under post-monsoon north-easterlies (**Figure 4**). The study also highlighted the role of nocturnal temperature inversions in sustaining passive flight by enabling insects to remain within stable, fast-moving nocturnal wind layers, including LLJ-like flows developing above the inversion. These atmospheric conditions substantially increased potential displacement distances during warm tropical nights.

Because birds produce stronger radar returns than most insects, they are generally easier to detect with traditional S- and C-band DWR (**Figure 3**). Nevertheless, the first explicitly bird-focused radar study in India appeared only later. Suresh et al. (2005) used the S-band DWR at the Cyclone Detection Radar Station (Chennai, South India) to investigate strong reflectivity returns (28–38 dBZ) observed during morning and evening twilight between December and April. After ruling out clouds, particulates, and refractive turbulence, the authors attributed these signals to mass departures and arrivals of wetland birds commuting between coastal roosts and foraging areas. Several lines of evidence supported this interpretation: reflectivity enhancements occurred exclusively over land, peaked precisely at civil dawn and dusk, formed expanding and contracting horizontal "biological fronts" between ~200–600 m a.g.l., and exhibited radial velocities exceeding background winds by up to ±10 m s^{-1}, consistent with powered flight rather than passive drift. Thus, despite their capacity for powered and directional flight, vertebrate commuting behavior remained structured by boundary-layer transitions and low-level wind organization. Importantly, Suresh et al. (2005) provided one of the only quantitative demonstrations in India of using DWR reflectivity to estimate bird densities: ~2,400 birds km^{-3}, implying 8,000–13,000 individuals within the sampled 5 × 7 km region, values broadly consistent with independent roost counts. To the best of my knowledge, till date this remains the only study in India to explicitly quantify aerial vertebrate densities using DWR.

The 2020 desert locust upsurge across West and Northwest India marked a renewed application of the national DWR network for biological monitoring, representing the first coordinated use of DWR for this purpose since the early opportunistic studies of Ramana Murty et al. (1964) and Mazumdar et al. (1965). Rao et al. (2020) used data from radars in Jaipur (S-Band) and New Delhi (C-Band) to resolve fine-scale swarm morphology, including swarm fronts, internal density gradients, and leading-edge movement, enabling reliable mapping of swarm progression across heterogeneous terrain. Subsequent studies demonstrated that locust swarms produce distinct reflectivity signatures (10–30 dBZ) and Doppler velocity fields closely aligned with near-surface winds (Amarjyoti et al. 2021). Anjita et al. (2024) further showed that swarms can be detected at distances of 40–80 km as coherent non-meteorological echo patches forming shallow layers within the lowest 1–1.5 km of the atmosphere, and are often embedded within LLJ regimes associated with monsoon onset or dryline boundaries.

Despite these advances, radar-based investigations of aerial fauna in India remain remarkably sparse and episodic, spanning only a handful of campaigns over more than five decades. However, a substantial body of ecological and observational research – largely independent of radar – already documents major migration routes, dispersal pathways, and seasonal aggregation zones for alate organisms across the Indian subcontinent, often in close association with prevailing wind systems and atmospheric structure. Synthesizing these patterns provides the much needed framework for understanding how atmospheric processes organize aerial movement across the region and for advancing radar aeroecology.

4. Atmospheric Controls of Aerial Movement Across the Indian Subcontinent

Birds, as powered fliers, exercise strong control over heading, altitude, and airspeed, and can often compensate for moderate to strong crosswinds (Sinelschikova et al. 2020). Their navigation integrates multiple sensory systems including magnetoreception, solar and stellar compasses, and orographic landmarks (Emlen 1975a, 1975b; Pennycuick 1975; Alerstam 1979a; Alerstam 1979b; Schmidt-Koenig et al. 1991; Green 2003; Newton 2008; Pennycuick 2008; Goto et al. 2017; Aschwanden et al. 2019; Wiltschko & Wiltschko 2019). In contrast, most migratory insects are windborne and rely primarily on synoptic-scale wind fields, boundary-layer structure (including LLJs), and temperature thresholds to determine activity and movement (Schaefer 1976; Westbrook & Isard 1999; Reynolds et al. 2005). While directional orientation occurs in many taxa, long-distance movement is achieved predominantly through selective ascent into favorable wind layers rather than sustained course correction (Achtemeier 1991; Chapman et al. 2010; Chapman et al. 2015; Hu et al. 2016a; Hu et al. 2016b; but see Menz et al. 2011). Because these two groups differ fundamentally in their degree of aerodynamic control and atmospheric coupling, their interactions with monsoon-driven wind regimes and boundary-layer dynamics also differ, and so I consider them separately in the following subsections.

4.1 Avian Movement Systems

Migratory birds provide the clearest framework for understanding how large-scale biological movements interact with atmospheric circulation and regional topography across the Indian subcontinent. The majority of long-distance migrants in India are embedded within the Central Asian Flyway (CAF), with fewer species across the East Asia–Australasian Flyway (EAAF) and the West Asia–East African Flyway (WAEAF) (Miyabayashi & Mundkur 1999; Boere & Stroud 2006; **Figure 5**).

CAF links high-latitude breeding areas across northern Eurasia – including Arctic Russia and Siberia – with wintering regions across the Indian subcontinent and few parts of South Asia and Middle East. Southbound autumn migration coincides with the development of the Siberian High – a large cold-season continental anticyclone that intensifies the Asian winter monsoon, generating persistent northerly low-level flow from the Eurasian interior toward South Asia and Indian Ocean (Zhang et al. 2025). In spring, the mid-latitude westerlies and the Western Disturbances interact with the Himalayas to provide tailwinds and uplift that help migratory birds gain altitude to cross the mountains more efficiently (Lang & Barros 2004; Dimri & Dash 2012; Dimri et al. 2015; Koll et al. 2015; Puranik & Karekar 2017; Hunt et al. 2018). While the Asian monsoon system establishes the large-scale atmospheric context for seasonal migration (**Figure 4 & 5**), the specific routes and movement dynamics of migrants are ultimately shaped by regional mesoscale processes and complex topography that modulate wind assistance and barrier permeability at finer spatial scales (Kumar et al. 2020a). Accordingly, CAF is increasingly viewed as an umbrella system comprising distinct, nonoverlapping corridors, each characterized by different atmospheric, orographic, and ecological conditions (Kumar 2019; Kumar et al. 2020a).

The Western circum-Himalayan corridor is used predominantly by species capable of obligate or facultative soaring flight (e.g. Black Kites, Greater and Indian Spotted Eagles, Tawny Eagles, Western Marsh Harriers, Montagu's Harriers, Pallid Harriers, and the Common and Demoiselle Cranes; Terraube et al. 2012; Kumar et al. 2020a; Baraiya et al. 2022; Mi et al. 2022; Ram et al. 2024; Baraiya et al. 2025; Kannan et al. 2025). This association suggests that thermal uplift likely plays an important role in structuring this route, as the arid and semi-arid landscapes of Central Asia and Pakistan generate strong daytime thermal convection that can facilitate energetically efficient soaring flight. The Trans-Himalayan corridor within the CAF is used by a smaller number of species with specialized, high-altitude powered flight (e.g. Bar-headed Goose, Brown-headed Gull, Eurasian Wigeon, Northern Pintail, Garganey, and Ruddy Shelduck; Bishop et al. 2015; Palm et al. 2015; Prins & Namgail 2017; Li et al. 2020; Kannan et al. 2025; Panagoda et al. 2025), and finally the Eastern circum-Himalayan route supports a few circum-navigating species such as the Himalayan Vultures and Northern Shovelers (Palm et al. 2015; Ummee et al. 2025) and partially overlaps with the EAAF (but see Palm et al. 2015).

Some species, however, change corridors, e.g. Black Kites (Literák et al. 2022) and Himalayan Vultures (Ummee et al. 2025), although the drivers of such switching remain poorly understood, and are likely influenced, at least in part, by atmospheric conditions. Ruddy Shelducks, Common Cuckoo, and Siberian Rubythroat circumnavigate the Himalayas along either the western or the eastern corridors (Miyabashi & Mundurkar 1999; Trierweiler et al. 2014; Palm et al. 2015; Cheng et al. 2024; Zhao et al., 2024), while Demoiselle Cranes take the western detour in spring but cross the high-altitude Himalayas and Qinghai−Tibet Plateau during autumn (Galtbalt et al. 2022; Mi et al. 2022). The circum-Himalayan detours can be up to 36% longer than the shortest trans-Himalayan trajectory (Baraiya et al. 2025), and thus most likely reflect the trade-off between wind assistance and migratory distance and/or time (Khacher 1978; Hawkes et al. 2011, Hawkes et al. 2013; Delany & Namgail 2017; Parr et al. 2017; Prins & Namgail 2017).

In contrast to the Himalayan-centered migration systems of the CAF, large-scale movements across eastern Asia occur within a more open coastal atmospheric corridor associated with the EAAF, which similarly links high-latitude breeding areas across Arctic and temperate East Asia with wintering regions extending through Southeast Asia, Indonesia, and Australasia (Yong et al. 2015; **Figure 5**). CAF and EAAF also overlap meteorologically in that both are embedded within the seasonal monsoon circulation (Yong et al. 2015). However, the dominant physical controls shaping migration differ between the two systems: with stronger roles of topographic barriers and uplift dynamics of the Himalayan–Tibetan region along the CAF and predominance of coastal wind systems and maritime atmospheric circulation across the EAAF. Crucially, along the EAAF, tailwind support associated with the strengthening East Asian winter monsoon circulation during autumn appears particularly important for southbound migration, whereas temperature gradients, emerging productivity and resource availability along the flyway, play a greater role during spring movements (Zhang et al. 2025).

The western margin of the Asian continent supports a third major migration system that intersects the Indian subcontinent: the WAEAF (Newton 2008). WAEAF is among the most poorly documented flyways in the world and is frequently omitted from global syntheses due to the paucity of tracking data (Guilherme et al. 2023). Amur Falcons and Common Cuckoos represent the best-studied migrants along this route (Ganpule 2011; Cheng et al. 2024; Kaur et al. 2024), migrating from Northeast Asia to South and East Africa and using Northeast India as a major staging region where large congregations refuel before undertaking transoceanic flights across the Arabian Sea and western Indian Ocean (**Figure 5**). These movements suggest that migration along WAEAF is closely linked to seasonal transitions in the Asian monsoon system and the displacement of the Inter-Tropical Convergence Zone (ITCZ; **Figure** 4). During autumn, migrants arriving in Northeast India typically stage during October–November before departing toward Africa under the post-monsoon circulation regime. At this time, the establishment of continental anticyclonic circulation across West Asia and the Arabian Peninsula generates coherent easterly flow across the northern Arabian Sea, providing favorable tailwind support for long-distance transoceanic flights toward East Africa. In contrast, spring return movements occur during the pre-monsoon transition, when atmospheric circulation over the Arabian Sea becomes increasingly influenced by strengthening southwesterly flow associated with the developing Somali Jet and the northward displacement of the ITCZ. Importantly, many migrants appear to time their movements to precede the peak Somali Jet phase, which typically develops during the mature southwest monsoon (June–August).

Across all three flyways, autumn migration is closely aligned with the development of continental high-pressure belt (ITCZ) and the strengthening of monsoon outflow, which generate persistent tailwinds: northerlies along the CAF, easterlies across the Arabian Sea along the WAEAF, and coastal northeasterlies along the EAAF, and facilitate southward displacement. In contrast, spring migration occurs under transitional circulation regimes, where westerlies, pre-monsoon flows, and Western Disturbances interact with the Himalayan barrier to wind assistance and access to high-altitude crossing routes. The Himalayas act as both a major barrier and a dynamic filter, structuring corridor selection through a combination of orographic uplift, channeling, and energetic constraints, while coastal and oceanic margins enable alternative, wind-mediated pathways, particularly along the eastern and western flanks of the subcontinent. This framework also provides important context for understanding the movement ecology of aerial insect migrants in the region.

4.2 Insect Movement Systems

Insect migration typically occurs as multi-generational, wind-assisted movement across regional and continental scales, in which successive generations track shifting seasonal resources rather than completing closed individual migratory circuits (Brown & Chippendale 1974; Drake & Gatehouse 1995; Chapman et al. 2015; Satterfield et al. 2020). Unlike vertebrate migrants, these movements are often mediated by developmental and physiological adaptations such as diapause and migratory morphs that synchronize dispersal with seasonal environmental conditions. Because each generation relies heavily on atmospheric transport and makes independent movement decisions, migratory connectivity between breeding and non-breeding populations is generally weak, resulting in extensive population mixing across large spatial scales (Drake & Gatehouse 1995; Chapman et al. 2013; Gao et al. 2020).

Despite their ecological importance, substantial knowledge gaps persist and the diversity of migratory taxa and the spatial extent of their flyways remain largely unknown (Prakash et al. 2022). Across the globe, only a small fraction of insect taxa, e.g. brown planthopper (*Nilaparvata lugens*), globe skimmer dragonfly (*Pantala flavescens*), monarch butterfly (*Danaus plexippus*), Silver-Y moth (*Autographa gamma*), have been studied in detail (Drake & Reynolds 2012; Chapman et al. 2015; Wu et al. 2019; Hu et al. 2024). Unlike birds, for which complete migratory routes have been reconstructed through satellite and GPS tracking, no insect species has yet been tracked along its full migration pathway (but see Menz et al. (2011) for a partial route analysis of the Death's-head hawkmoth *Acherontia atropos*). Therefore, the coupling between insect migration and atmospheric circulation must largely be inferred indirectly from radar observations, wind trajectory analyses, and population-level genetic evidence. Below, I synthesize the best-resolved insect migratory systems within the Indian subcontinent and their atmospheric coupling.

The Himalayan insect flyway, analogous to the CAF, was recently formalized by Hawkes et al. (2025) based primarily on evidence from migratory Diptera. However, field evidence for traffic along this flyway is extensive even beyond Diptera. Gatter (1980) recorded continuous northward spring migrations of butterflies, noctuid moths, syrphid flies, and bumblebees at elevations >5,000 m, with hoverfly fluxes reaching ~19 individuals per minute at Thorong La in Nepal (5,416 m). These rates are comparable to migratory traffic recorded at substantially lower temperate mountain passes, such as the Pyrenees (2,263 m; Hawkes et al. 2024), highlighting the remarkable vertical extent of aerial migration in lower-latitude systems. Observations from Nepal also corroborate high-altitude spring crossings (~3,600 m) by hoverflies and butterflies (Westmacott & Williams 1954; Reynolds et al. 2024). Isotopic analyses of the globe skimmer dragonfly (*Pantala flavescens*) reaching the Maldives indicate origins in Nepal, implying long-distance, potentially trans-Himalayan trajectories consistent with flight records up to 6,300 m (Hobson et al. 2012). More recently, Chandra et al. (2019) documented 2,261 insect species in the Indian Trans-Himalaya, including recognized migrants from Odonata, Lepidoptera, Hemiptera, Diptera, and Hymenoptera.

Collectively, these observations indicate that the Indian Himalayas support a recurrent, atmospherically structured migratory corridor. The broad seasonal direction of autumn and spring movements suggests a role for monsoon-driven synoptic circulation analogous to that documented for migratory birds, although the mesoscale, vertically stratified atmospheric mechanisms shaping these migrations remain unexplored due to the absence of complete-route tracking data for insects. Nevertheless, earlier entomological studies have noted that Himalayan insects frequently exploit diel wind systems of the valley–pass topographic accelerators (along-valley wind circulation regimes; **Box 1**; Westmacott & Williams 1954; Mani 1968; Gatter 1980; Reynolds et al. 2024).

A second major insect movement system linked to the Indian subcontinent appears to occur along the Afro–Asian corridor analogous to the WAEAF for birds. The proposed trans-Himalayan migratory pathway of the globe skimmer dragonfly, considered the longest regular non-stop migration relative to body size (Hedlund et al. 2021), extends from northern India across the subcontinent and onward toward East Africa (Anderson 2009; Hobson et al. 2012; Ranjan et al. 2023). Offshore records of the painted lady (*Vanessa cardui*) across the northern Indian Ocean (Ecuador 1992), together with its recently demonstrated 4,200 km trans-Atlantic migration (Suchan et al. 2024), indicate that large Lepidoptera are capable of monsoon-assisted Indo–African crossings, even though population-level connectivity remains unresolved. The fall armyworm (*Spodoptera frugiperda*) has also been proposed to have reached the Indian subcontinent from Africa (Johnson 1987). The same atmospheric corridor has been confirmed for desert locusts with rapid trans-Indian Ocean transport found tightly coupled to monsoon dynamics and Indian Ocean Dipole–driven rainfall anomalies (Feng et al. 2025). Energetic modeling and wind trajectory analyses indicate that such transoceanic movements depend critically on favorable tailwinds and are unlikely to be achieved through self-powered flight alone (Hedlund et al. 2021). Smaller insects, which often rely more heavily on passive atmospheric transport, may be capable of similar long-distance dispersal across this corridor, although the mechanisms remain poorly understood. Genetic studies support an Indian origin for several Drosophilidae and Tephritidae species now established in East Africa, implicating seasonal wind-driven dispersal as the underlying mechanism (Tsacas 1984; Jacquard et al. 2013; also see Johnson 1987). Large offshore arrivals of blowflies in the Maldives also support mass transoceanic transport (Hawkes et al. 2024). Large-scale wind assisted migrations of Culicoides are also known to occur on the movements of the ITCZ (Sellers 1980). Taken together, these observations indicate a recurring monsoon-mediated aerial corridor between India and East Africa, with insects transported toward India by south-westerly monsoon winds and potentially redistributed westward or southward during the winter monsoon, likely via the Maldives and Seychelles (Anderson 2009; Hobson et al. 2012). These bidirectional exchanges are driven by seasonal shifts in the ITCZ and associated wind-field reversals, which establish synoptic-scale pathways linking South Asia, the Arabian Peninsula, East Africa, and the central Indian Ocean.

Another large-scale migratory system links Southeast and East Asia and partially intersects the Indian subcontinent, broadly coinciding with the EAAF for birds. Populations of brown planthoppers from India (primarily Assam and West Bengal) and the Malay Archipelago act as donor populations for the larger Southeast and East Asian cluster, with net gene flow directed toward Southeast Asia (Wu et al. 2019; Hu et al. 2024). The Bay of Bengal branch of the southwest monsoon transports large swarms from Northern Indochina into East India at altitudes of ~500–1,500 m, where boundary-layer convergence can concentrate migrants before westward dispersal across the Indo-Gangetic Plain. These winds transport insects across hundreds to over a thousand kilometers in a single night (Drake & Reynolds 2012; Otuka et al. 2012; Chapman et al. 2015; Hu et al. 2024). Autumn migration occurs during the weakening monsoon and the establishment of continental northerly flow, enabling southward return transport toward subtropical wintering regions. Trajectory modeling and long-term monitoring indicate that the common cutworm (*Spodoptera litura)* undertakes seasonal cross-border migrations along the southern Himalayan margin, moving from Northeast India, Bangladesh, and Northern Myanmar into Southwestern China during spring and returning toward South Asia in autumn, with these movements facilitated by monsoon-driven airflow across the region (Song et al. 2024). Although India lies just outside the formal East Asian insect flyway (Hu et al. 2025), many agricultural pests remain genetically and demographically linked to Indochinese source populations, making India integral to the wider Asian migratory system.

Beyond trans-boundary flyways, windborne insect movement within India at shorter scales (~100–500 km) is increasingly recognized as an important ecological phenomenon (Ramesh et al. 2012; Jyothi et al. 2021; Vinayan et al. 2023). In the Indian subcontinent these pathways frequently coincide with the inland penetration of the Arabian Sea monsoon LLJ, which extends across peninsular and central India during the southwest monsoon (Viswanadhapalli et al. 2020; **Figure 4**). Monsoon LLJ is often associated with a strongly stratified nocturnal boundary layer that can concentrate aerial organisms within relatively thin atmospheric layers (Desamsetti et al. 2010; Dwivedi et al. 2020), creating favorable conditions for wind-assisted drift and the formation of coherent insect layers detectable by radar. Recent studies indicate that migratory insect abundance can be comparable to or even greater during daytime (e.g. windborne dispersal of mosquitoes in northeast India; Reynolds et al. 1996) than nighttime, particularly under warmer atmospheric conditions, suggesting that daytime boundary-layer convection and thermal uplift may also contribute to large-scale insect transport across India (Gao et al. 2025).

Several experimental and observational studies support the plausibility of wind-assisted dispersal across the Indian subcontinent. Flight-mill experiments show that *H. armigera* can sustain flights exceeding eight hours under still-air conditions, suggesting that moderate wind assistance could result in substantial downwind displacement (Pedgley et al. 1987; Vaishampayan & Singh 1996; Jyothi et al. 2021). Field observations have linked sudden increases in moth abundance to synoptic wind regimes, especially southeasterly flows during February–April and occasionally during October–December when cyclonic systems develop over the Arabian Sea (Pedgley et al. 1987). In the teak defoliator (*Hyblaea puera)*, dispersal occurs primarily during April–July when high population densities trigger migration from early-flushing to later-flushing teak stands, producing short-range wind-assisted movements of ~5–10 km and occasionally longer atmospheric transport (Nair & Sudheendrakumar 1986). Seasonal wind reversals also structure aphid dispersal across the Indo-Gangetic Plain, where mustard aphids ascend hundreds of metres into the boundary layer and can be transported tens to hundreds of kilometres within a single night (Ghosh et al. 2019). Flight activity of red flour beetle (*Tribolium castaneum)* and lesser grain borer (*Rhyzopertha dominica)* peaks during the warm monsoon and post-monsoon months but declines sharply during cooler periods (Rajan et al. 2018), highlighting the role of temperature thresholds along with monsoon cycles. Collectively, these observations indicate that regions lying beneath the inland extension of the monsoon LLJ, particularly across Maharashtra, Madhya Pradesh, and Rajasthan, may function as major corridors for drift-dominated insect transport during stable monsoon nights.

Species capable of sustained powered flight migrate primarily in response to ecological cues while still interacting with atmospheric structure. Butterfly migrations provide the most well-documented example. Large swarms dominated by *Catopsilia* and *Papilio* species have been recorded along the Kalpakkam coastline of South India, moving predominantly northward during October and southward during July (Ramesh et al. 2012). These movements frequently occur across or even against prevailing winds, indicating that migration is driven largely by seasonal rainfall patterns, host-plant phenology, and reproductive cycles rather than passive atmospheric advection alone. Nevertheless, migration timing remains closely coupled to diel atmospheric conditions. Peak flight activity occurs during periods of strong solar heating but relatively weak convective turbulance. Large butterfly movements often occur near transitions in monsoon rainfall regimes, implying sensitivity to intraseasonal variability such as active–break phases of the monsoon (Ramesh et al. 2012). Similar atmospheric coupling has also been demonstrated in the transcontinental spread of desert locust swarms, whose rapid redistribution across the Indian Ocean region has been shown to be tightly phase-locked to intraseasonal variability in the monsoon circulation (Feng et al. 2025). Danaine butterflies likewise undertake large-scale seasonal migrations across Southern India, moving westward toward the Western Ghats following the southwest monsoon (October–November) and returning toward the eastern plains during the pre-monsoon period (April–May; Vinayan et al. 2023). Evidence further suggests that populations breed alternately between the Western Ghats and the eastern plains, implying a multi-generational migration cycle in which successive generations undertake the reverse movement (Kunte 2005; Bhakare & Ogale 2018). Together, these observations indicate that even actively flying migrants remain strongly constrained by atmospheric structure, with ecological drivers interacting with diel atmospheric and synoptic monsoon dynamics to shape migration timing and direction.

5. Tropical Aeroecology: Knowledge Gaps and Observational Opportunities

Although the available literature remains sparse compared with better-studied regions such as Europe and North America, and many migratory pathways within the Indian subcontinent remain poorly resolved (Tyagi et al. 2022), it nevertheless provides strong evidence for a convergence of large-scale, intercontinental migratory routes across taxa. Both birds and insects utilize the same three principal corridors intersecting the Indian subcontinent (Trierweiler et al. 2014; Chapman et al. 2015; Hu et al. 2016a; Anderson 2009). This indicates that these international flyways are not taxon-specific but are instead emergent properties of the underlying atmospheric system and synoptic monsoon circulation: both groups exploit favorable tailwind assistance at large scales, even though the mechanisms by which they maintain heading and regulate movement differ (Alerstam 1979a; Chapman et al. 2010; Chapman et al. 2015; Hu et al. 2016a).

Additionally, intra-peninsular movement is tightly coupled to agricultural phenology[2] and spatiotemporal shifts in resource availability. Seasonal cropping cycles, host-plant dynamics, and resource availability associated with monsoon progression structure the timing, magnitude, and direction of dispersal in many taxa, including major agricultural pests and migratory butterflies (Kunte 2005; Ramesh et al. 2012; Rajan et al. 2018; Ghosh et al. 2019; Vinayan et al. 2023). Aerial transport operates on populations whose emergence, abundance, and distribution are themselves seasonally structured, linking atmospheric transport processes with ecological and phenological dynamics. This coupling is especially important within the Indian subcontinent, where the inland penetration of the monsoon LLJ gives rise to recurrent transport corridors that redistribute these seasonally generated populations. From an observational perspective also, this presents a critical opportunity: the relative predictability of agricultural phenology, together with extensive agronomic datasets, provides a powerful but underutilized framework for interpreting radar signals in terms of species composition and ecological function, potentially making tropical aeroecological systems more tractable than their temperate counterparts. The sparsity of literature therefore reflects limited integration of meteorological and atmospheric processes with ecological research, rather than the absence of large-scale insect movement systems, suggesting that India likely hosts far more extensive and structured migratory dynamics than currently documented. In the sections that follow, I first synthesize the key distinctions that emerge between temperate and tropical aeroecological systems, and then outline how these differences can be explicitly investigated using the expanding network of Doppler weather radars.

5.1 Tropical vs. Temperate Aeroecology: Emerging Contrasts

In temperate regions, aerial migration is typically organized around transient synoptic events, producing discrete, pulse-like movements that are tightly coupled to passing weather systems (Gauthreaux & Belser 2003; Liechti 2006; Van Doren & Horton 2018). In contrast, tropical monsoon systems are defined by persistent but seasonally reversing circulation. Over the Indian subcontinent, strong and spatially coherent southwesterly low-level jets (LLJs) during the summer monsoon transition to weaker, more heterogeneous northeasterly flows in the post-monsoon period (Gadgil 2003; Goswami 2005; Roxy et al. 2015). This fundamental difference shifts aerial movement from episodic transport windows to sustained, seasonally structured displacement where the same atmospheric corridors can be reused under reversing wind regimes. During the summer monsoon, LLJs can facilitate rapid, long-distance transport, with insects such as planthoppers routinely advected over >1000 km within a single night within highly stratified flow (Otuka et al. 2012; Hu et al. 2024). By comparison, post-monsoon movement becomes weaker and more intermittent, often relying on localized synoptic enhancement and favorable nocturnal boundary-layer conditions (Reynolds & Wilson 1989; Riley et al. 2013).

A second key contrast lies in the diel structure of the atmospheric boundary layer (ABL), which governs the formation and accessibility of transport layers. Much of temperate aeroecology is

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[2] In the Indian subcontinent, agricultural phenology is structured around three primary cropping seasons: the monsoon-driven *kharif* season (June–October; e.g. rice, maize, cotton), the winter *rabi* season (October–March; e.g. wheat, mustard, pulses), and the short pre-monsoon *zaid* season (March–June; e.g. cucurbits, fodder crops, and some pulses)

interpreted within a relatively canonical ABL cycle: a deep daytime convective boundary layer (CBL; ~1–3 km) transitions rapidly after sunset into a shallow, strongly stratified stable boundary layer (SBL; typically <0.5–0.6 km). This predictable collapse provides a consistent temporal window at dusk, gating take-off, ascent, and altitude selection, and enabling migrants to exploit coherent, low-turbulence nocturnal layers for efficient transport (Hu et al. 2016). In monsoon-dominated tropical systems, however, this structure is far less consistent. Although the CBL similarly deepens during the day, nocturnal stabilization is frequently delayed or weakened. Cloud cover, wet surfaces, and persistently warm nighttime temperatures suppress radiative cooling, often delaying surface decoupling by several hours after sunset (Sandeep et al. 2015; Mehta et al. 2017a,b). As a result, a fully developed SBL is not a reliable nocturnal state, and the lower atmosphere may remain weakly mixed or only partially stratified well into the night. Consequently, access to these transport layers is contingent rather than guaranteed, and coherent vertical layering may only emerge under specific combinations of stability and wind shear (Sandeep et al. 2015; Mehta et al. 2017; Algarra et al. 2019). This results in greater spatio-temporal variability in aerial density, vertical structuring, and radar detectability across both diel and synoptic scales. These differences fundamentally alter both the predictability and vertical organization of aerial movement.

A third distinction, largely absent from temperate systems, is the strong influence of intraseasonal variability. The Monsoon Intraseasonal Oscillation (MISO), expressed through active–break cycles, imposes a dominant ~10–20 day modulation on atmospheric structure. During active phases, enhanced convection, deep cloud cover, and precipitation disrupt boundary-layer stratification, increase turbulence, and suppress organized aerial movement. In contrast, break phases are characterized by reduced convection, clearer skies, and the development of more stable and vertically stratified nocturnal conditions, favoring the formation of concentrated bioscatter layers and enhancing radar detectability. These cycles also modulate LLJ strength and inland penetration, as well as boundary-layer depth and stability (Krishnamurti & Bhalme 1976; Sikka 2006), thereby structuring migration across taxa, from locust redistribution under strengthened flow to episodic hemipteran transport across the Indo-Gangetic Plain (Reynolds & Wilson 1989; Amarjyothi et al. 2021). Unlike temperate systems, where migration is primarily organized around short-lived synoptic events, tropical movement dynamics are therefore embedded within a hierarchy of interacting timescales, with intraseasonal variability exerting a dominant control on when and where movement can occur.

Overall, these atmospheric differences translate into a stronger coupling between aerial movement and ecological production in tropical systems. Tropical aerial transport operates on populations whose emergence, abundance, and spatial distribution are themselves structured by monsoon-driven resource dynamics. In intensively cultivated tropical landscapes, agricultural phenology, particularly the timing of sowing, crop growth, and harvest cycles, further amplifies this coupling by synchronizing pulses of aerial biomass with favorable transport conditions. As a result, atmospheric flows do not simply redistribute organisms, but repeatedly connect temporally shifting source populations with distant sink regions across the subcontinent.

5.2 India’s Weather Radar Network: Observational Capacity and Research Frontiers

Globally, advances in dual-polarization and signal processing now enable routine separation of biological and meteorological scatterers and, increasingly, discrimination among biological targets (Stepanian et al. 2016; Dokter et al. 2019; Matthews et al. 2025). Opportunistic observations have been largely replaced by mechanistic inferences such as relating migration intensity to boundary-layer stabilization, quantifying concentration of migrants within LLJs, and forecasting migration timing and routes (Shamoun-Baranes et al. 2010; Chilson et al. 2017; Van Doren & Horton 2018; Horton et al. 2020). National mosaics of density, migration intensity, ground speed and flight direction are available for birds and insects (Dokter et al., 2011; Chilson et al. 2017; Nilsson et al. 2019; Horton et al. 2020; Mungee et al. 2025). Standardized products such as vertically integrated reflectivity and migration traffic rate have enabled cross-site and cross-season synthesis (Shamoun-Baranes et al., 2014; Dokter et al. 2019; Lin et al. 2019; Nilsson et al., 2019).

India is uniquely positioned to support comparable advances. The India Meteorological Department (IMD) currently operates a network of 51 weather radars, comprising 22 S-band, 19 X-band, 9 C-band, and 1 Ka-band systems, of which 33 are dual-polarization (**Figure 6**). The network spans almost the full climatic breadth of India, and the coverage is particularly dense along the western coastline (to monitor the inland penetration of Arabian Sea monsoon flow), and across the western Himalayan arc (to resolve high-elevation atmospheric processes). These regions coincide with major migratory corridors and with strong gradients in elevation, habitat, and agricultural phenology, creating unusual opportunities to examine how atmospheric transport, topographic forcing, and source-sink population dynamics interact across both plains and complex terrain. The network is expanding rapidly under the Government of India’s *Mission Mausam* initiative, which aims to increase aerospace coverage to >95% through ~120–130 radars by 2026–2027.

The chain of dual-polarized X-band radars along the western Himalayan arc is particularly well suited to resolving insect movement within complex terrain, which currently remains almost entirely uncharacterized in the region. Owing to their shorter wavelength and higher sensitivity to small targets, X-band systems can detect dense fluxes of even small-bodied insects, offering a largely untapped opportunity to examine windborne insect transport across mountain passes, valleys, and orographically structured airflow from Jammu and Kashmir through Ladakh to Uttarakhand. By contrast, avian migration across the Himalaya has been relatively well studied, particularly with respect to large-scale crossings and flight strategies. However, the organization of movement within the Indian subcontinent, especially post-entry redistribution across the peninsula (e.g., the contrasting east- and west-coast routes in Brown-headed Gulls (Panagoda et al. 2025)), remains poorly resolved. Existing studies linking movement to habitat, temperature, and precipitation (Urfi 2011; Komal et al. 2017; Gupta 2023; Bhagwat et al. 2025) rarely incorporate atmospheric structure explicitly, limiting inference about regional-scale redistribution and its drivers. The dense network of C- and S-band radars along the coastlines and major wetland systems (**Figure 6**) offers a clear pathway to resolving these dynamics, building on early demonstrations of radar-based migration detection (Suresh et al. 2005).

These intra-peninsular radars also provide a critical opportunity to resolve the coupling between atmospheric transport and ecological production, particularly the role of agricultural phenology in structuring the timing, composition, and magnitude of aerial biomass entering monsoon-driven flow. Integrating radar observations with trajectory modelling, ground-based sampling, and emerging tools such as genomics and isotopic tracing can enable the identification of source populations, sink regions, and recurrent migration corridors across the subcontinent, providing a mechanistic basis for understanding redistribution processes across both ecological and agricultural systems. These challenges extend across taxa and highlight the need for systems that allow direct calibration of radar-derived biological signals.

Another underexplored opportunity lies in integrating bat movement ecology with India's radar network. Although bats constitute a substantial component of aerial biomass, they remain underrepresented in radar-based studies in the tropics, where long-distance migration is less prevalent than in birds or insects (Frick et al. 2012a,b; Moussy et al. 2013; Sangavi et al. 2021; Murugavel et al. 2023). However, bat emergences from large colonies generate some of the most intense, spatially coherent, and temporally predictable vertebrate fluxes within the nocturnal boundary layer (Horn and Kunz 2008; Chilson et al. 2012; Meade et al. 2019). These tightly constrained events produce compact, high-density reflectivity plumes that are readily distinguishable from birds, insects, and precipitation in weather radar data (McCracken et al. 2008; Frick et al. 2012; Vanitharani et al. 2013; Werber et al. 2023). Globally, such systems have been central to calibrating and validating radar-based aeroecological inference (Kunz et al. 2008; Chilson et al. 2012; Horn & Kunz 2008). In India, several well-documented colonies fall within the footprint of the expanding IMD radar network, presenting immediate opportunities to integrate radar observations with telemetry and colony-based counts to quantify diel and seasonal variability in vertebrate aerial flux.

Despite this expanding infrastructure, a critical bottleneck remains access to and standardization of radar data. Volumetric data are not consistently archived, and access to raw scans is often restricted, limiting biological applications (Bhat et al. 2025). In the United States, the expansion of aeroecological research followed the public availability of long-term Next Generation Weather Radar (NEXRAD) archives, while in Europe the European Network for the Radar Surveillance of Animal Movement (ENRAM) has enabled continental-scale analyses of major flyways. Similar progress has recently emerged in Australia following open access to operational radar archives. India currently lacks a centralized, accessible repository of long-term datasets, and integration with auxiliary data (e.g., reanalysis winds, radiosonde profiles, ecological observations) remains limited.

India lacks a centralized, accessible repository of long-term raw datasets. In addition, there is limited integration between radar data and auxiliary datasets such as reanalysis winds, radiosonde profiles, and ecological observations, constraining mechanistic interpretation. Addressing these limitations will require coordinated efforts to (i) establish open-access radar archives with standardized formats, (ii) develop reproducible workflows for biological signal extraction and classification, (iii) integrate radar data with atmospheric and ecological datasets, and (iv) build interdisciplinary capacity linking meteorology and ecology. Given the scale and diversity of India’s radar network, such developments would enable unprecedented insight into the organization of aerial movement across monsoon-dominated tropical systems.

6. Conclusion

By synthesizing multiple lines of evidence, this study shows that aerial movement across the Indian subcontinent is structured by monsoon-driven atmospheric dynamics operating across scales. Aerial movement across taxa is governed by the interaction of the same three globally fundamental sets of processes: large-scale circulation, boundary-layer dynamics, and topographic forcing (Kunz et al. 2008; Shamoun-Baranes et al. 2010). However in monsoon-dominated tropical systems, their meteorological and hence ecological expression differs in important ways. Seasonal wind reversals, strong intraseasonal variability, and pronounced diel boundary-layer transitions create a distinct set of ecological opportunities and constraints for dispersal, migration, and biomass transport. Recognizing these differences is essential for developing a truly global understanding of aerial life. India’s aeroecology is fragmented across radar studies, natural history, agriculture, ornithology, entomology, and meteorology. A national weather-radar-based aeroecology system would integrate these disjointed bodies of knowledge and transform our understanding of aerial biodiversity. For ecologists and meteorologists seeking to interpret biological signatures in Indian radar data, the current literature therefore provides a useful spatiotemporal scaffold, identifying key corridors, broad seasonal windows, and likely diel structure.

Conflict of Interest

The author declares no conflicts of interest.

Author Contributions

M.M. conceived the study, carried out the analyses and literature synthesis, interpreted the results, wrote the manuscript, and takes responsibility for the content of the work.

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Data Availability Statement

This article is a synthesis of previously published literature and publicly available datasets. No new data were generated or analyzed for this study. The locations of Doppler Weather Radars (DWRs) used to illustrate the Indian radar network were obtained from the India Meteorological Department (IMD) website (https://mausam.imd.gov.in/) though an RTI Application. All other sources used in the preparation of this manuscript are cited in the reference list.

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Box 1. Glossary of atmospheric terms

Along-valley wind circulation: A diurnal mountain-flow system with daytime upslope and up-valley winds and nighttime downslope and down-valley drainage flows, which can align with or oppose aerial movement.

Active–break monsoon phases: Intraseasonal (~10–20 day) shifts in convection and rainfall associated with MISO/BSISO variability:

- **Active phase:** Enhanced convection and widespread rainfall over the Indian subcontinent.
- **Break phase:** Suppressed convection, clearer skies, and more coherent low-level winds.

Atmospheric boundary layer (ABL): Lowest layer of the troposphere directly influenced by surface fluxes of heat, moisture, and momentum on timescales of hours or less.

- **Convective boundary layer (CBL):** Daytime ABL driven by surface heating, characterized by buoyant turbulence and strong vertical mixing.
- **Stable boundary layer (SBL):** Nocturnal ABL driven by radiative cooling, characterized by weak turbulence, strong stratification, and limited vertical mixing.

Dryline boundary: A mesoscale boundary separating moist and dry air masses, characterized by sharp humidity gradients and often acting as a zone of convergence and uplift.

Indian Ocean Dipole (IOD): A coupled ocean–atmosphere mode defined by an east–west sea surface temperature gradient across the tropical Indian Ocean, modulating monsoon circulation, winds, and rainfall.

Inter-Tropical Convergence Zone (ITCZ): A seasonally migrating zone of low pressure and deep convection where trade winds converge; shifts northward over India during summer and southward during autumn.

Low-level jet (LLJ): A horizontally coherent wind maximum in the lowest ~1–2 km of the atmosphere (typically ~10–25 m s^{-1} in the monsoon region), enabling rapid and concentrated atmospheric transport.

Mid-latitude westerlies: Prevailing west-to-east winds in mid-latitudes associated with synoptic disturbances and large-scale atmospheric transport.

Monsoon Intraseasonal Oscillation / Boreal Summer Intraseasonal Oscillation (MISO/BSISO): Northward-propagating (~10–30 day) intraseasonal variability in tropical convection and circulation that modulates monsoon intensity, low-level jet strength, precipitation patterns, and boundary-layer structure across the Indian subcontinent.

Nocturnal monsoon inversion: A stable temperature inversion that develops within the nocturnal boundary layer during monsoon conditions, often co-occurring with the LLJ and suppressing vertical mixing, thereby maintaining coherent transport layers.

Northeast monsoon (October–November): Post-monsoon reversal to weaker northeasterly flow, restructuring windborne transport pathways across the subcontinent.

Somali Jet (Findlater Jet): A strong cross-equatorial low-level jet over the western Indian Ocean that drives southwesterly monsoon flow into India.

Southwest monsoon (June–September): Season of strong, persistent southwesterly low-level flow over India, often organized into high-speed transport corridors associated with the monsoon circulation.

Western Disturbances (WD): Eastward-propagating mid-latitude low-pressure systems embedded in the westerlies, originating over the Mediterranean region and influencing winter precipitation and synoptic flow over northern India.

Vertical wind shear: Change in wind speed and/or direction with height; in stable conditions, shear is associated with the formation and maintenance of jets and thin, stratified transport layers.

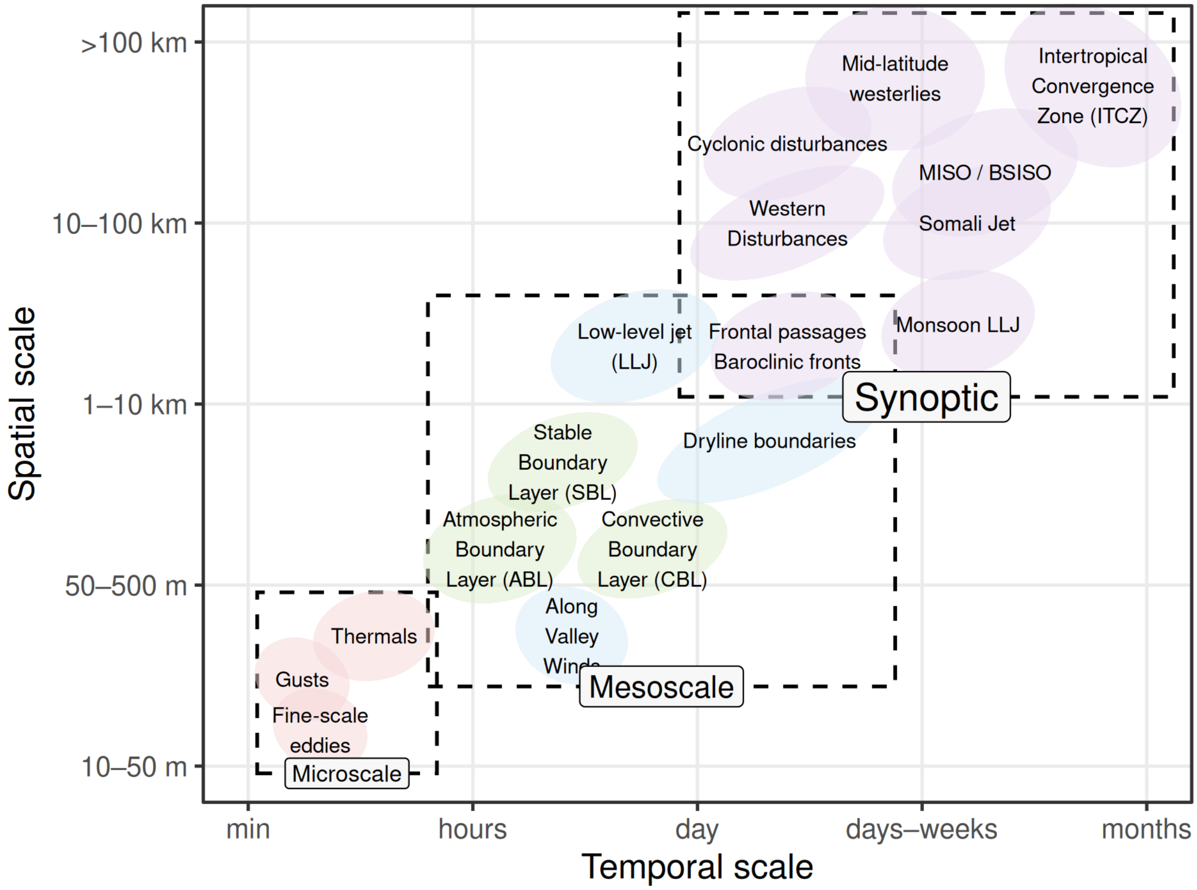


Figure 1. Spatio-temporal organization of atmospheric processes relevant to aerial movement of animals. Ellipses represent the typical temporal (x-axis) and spatial (y-axis) scales of key atmospheric processes pertaining to aerial movement of animals. Colors distinguish four conceptual groupings of processes (turbulence, boundary-layer, convective / shear systems, and large-scale circulation), while dashed boxes highlight three scale regimes: microscale, mesoscale, and synoptic. Mesoscale processes play a central role in governing take-off, departure, landing, and vertical stratification (flight altitude), whereas large-scale migratory routes are primarily structured by synoptic circulation. Microscale processes determine fine-scale behaviours such as foraging and local predator–prey interactions.

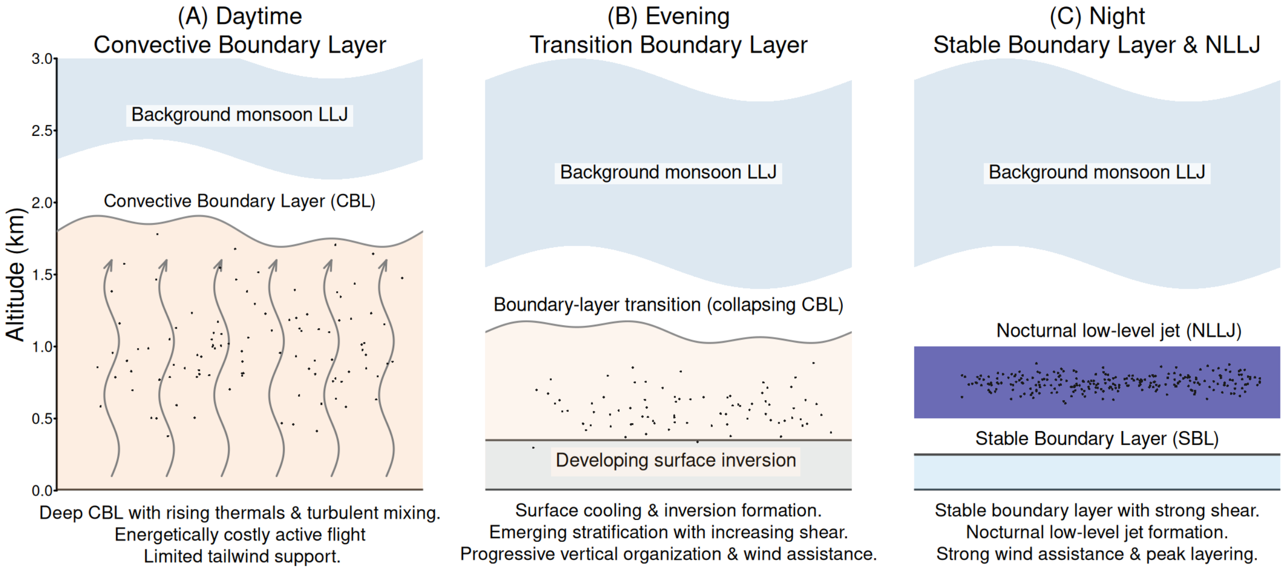
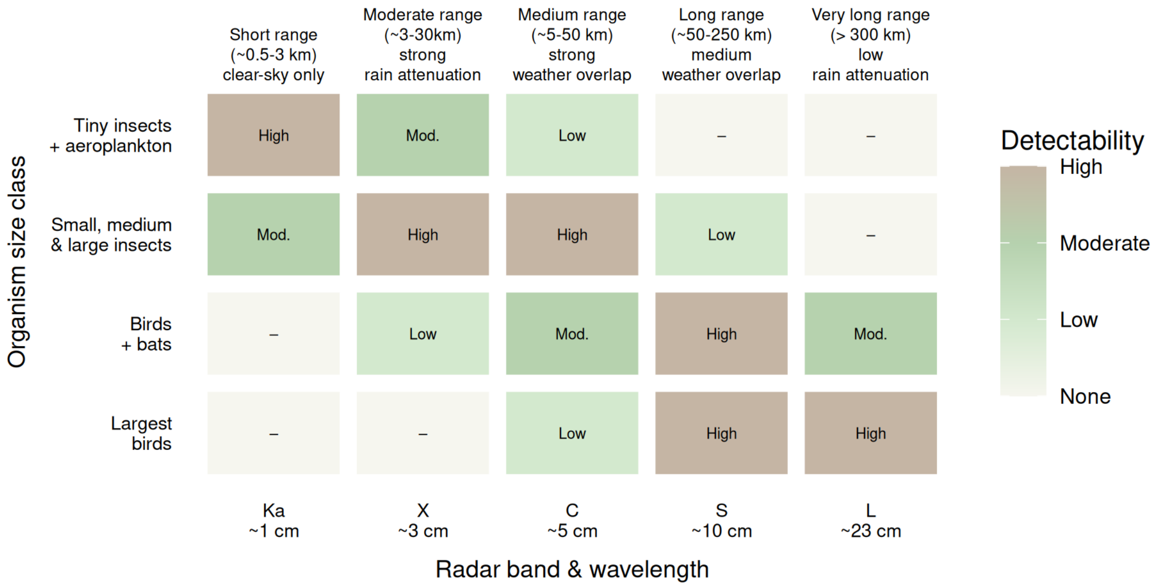


Figure 2. Diel reorganization of the troposphere and its aeroecological consequences. The structure of the lower atmosphere reorganizes predictably across the 24-hour cycle, generating distinct transport regimes for aerial fauna. **(A)** During daytime, a deep convective boundary layer (CBL) driven by surface heating produces strong turbulent mixing and weak vertical stratification. Under these conditions, aerial organisms are broadly distributed, wind assistance is diffuse, and radar returns are vertically widespread. **(B)** During the evening transition, surface cooling initiates inversion formation and boundary-layer collapse, increasing vertical shear and promoting the emergence of organized transport layers. **(C)** At night, a shallow stable boundary layer (SBL) forms near the surface, capped by strong shear and, frequently, a nocturnal low-level jet (LLJ). This regime generates coherent, wind-assisted transport layers above the inversion, leading to vertical stratification of migrants and the strongest radar-defined bioscatter signatures of the diel cycle. Diel transitions illustrate how boundary-layer physics governs not only flight energetics and directional alignment, but also the radar-detectability and vertical structure of aerial biomass.



Organism size class	Ka ~1 cm Short range (~0.5-3 km) clear-sky only	X ~3 cm Moderate range (~3-30km) strong rain attenuation	C ~5 cm Medium range (~5-50 km) strong weather overlap	S ~10 cm Long range (~50-250 km) medium weather overlap	L ~23 cm Very long range (> 300 km) low rain attenuation
Tiny insects + aeroplankton	High	Mod.	Low	–	–
Small, medium & large insects	Mod.	High	High	Low	–
Birds + bats	–	Low	Mod.	High	Mod.
Largest birds	–	–	Low	High	High

Figure 3. Radar wavelength and detectability of aerial organisms across major radar bands. Typical relationship between common weather radar wavelengths (x-axis) and the approximate size of biological targets detectable in the atmosphere (y-axis). Short-wavelength radars (Ka- and X-band; ~1–3 cm) are highly sensitive to small bioscatterers but operate over relatively short ranges and experience strong attenuation in precipitation. Intermediate wavelengths (C-band; ~5 cm) represent a trade-off between sensitivity and range, allowing detection of mixed bioscatter (insects, birds, and bats) while overlapping strongly with meteorological echoes. Longer wavelengths (S- and L-band; ~10–23 cm) experience little attenuation and enable long-range detection, but are primarily sensitive to larger birds (see Gauthreaux Jr et al. 2019), with weak to no sensitivity to small insects. Detection ranges shown are approximate and depend on radar power, beam geometry, atmospheric conditions, and target density.

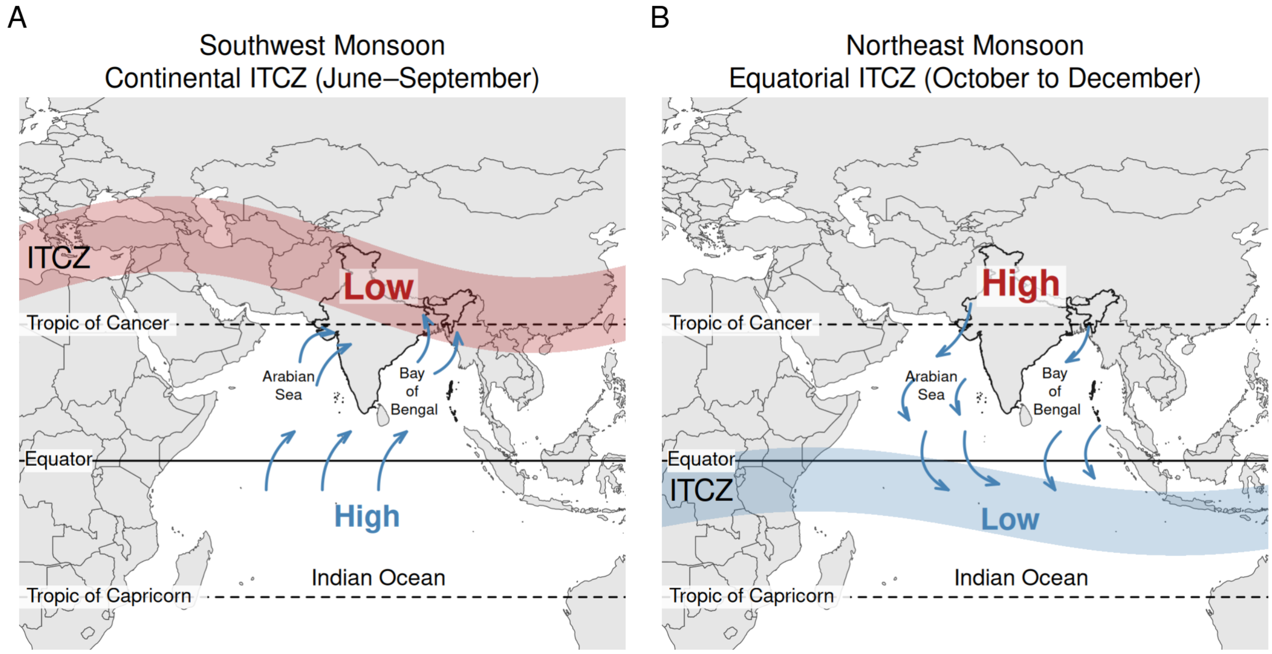


Figure 4. Seasonal reorganization of the Indian monsoon system. (A) During the Southwest Monsoon (June–September), strong cross-equatorial flow from the southern Indian Ocean intensifies into southwesterly low-level winds over the Arabian Sea and penetrates the subcontinent. The Inter-Tropical Convergence Zone (ITCZ) shifts northward over northern India, establishing a continental low-pressure belt (monsoon trough) across the Indo-Gangetic Plain. This configuration promotes sustained low-level transport pathways, particularly along the Arabian Sea and Bay of Bengal branches, and can concentrate aerial fauna within shear zones and monsoon low-level jets. **(B)** During the Northeast Monsoon (October–December), the circulation reverses. The ITCZ retreats southward toward the Indian Ocean, high pressure dominates over the subcontinent, and northeasterly surface winds prevail. This seasonal reversal alters both the direction and persistence of wind assistance for aerial transport, restructuring potential dispersal corridors for aerial movement of animals.

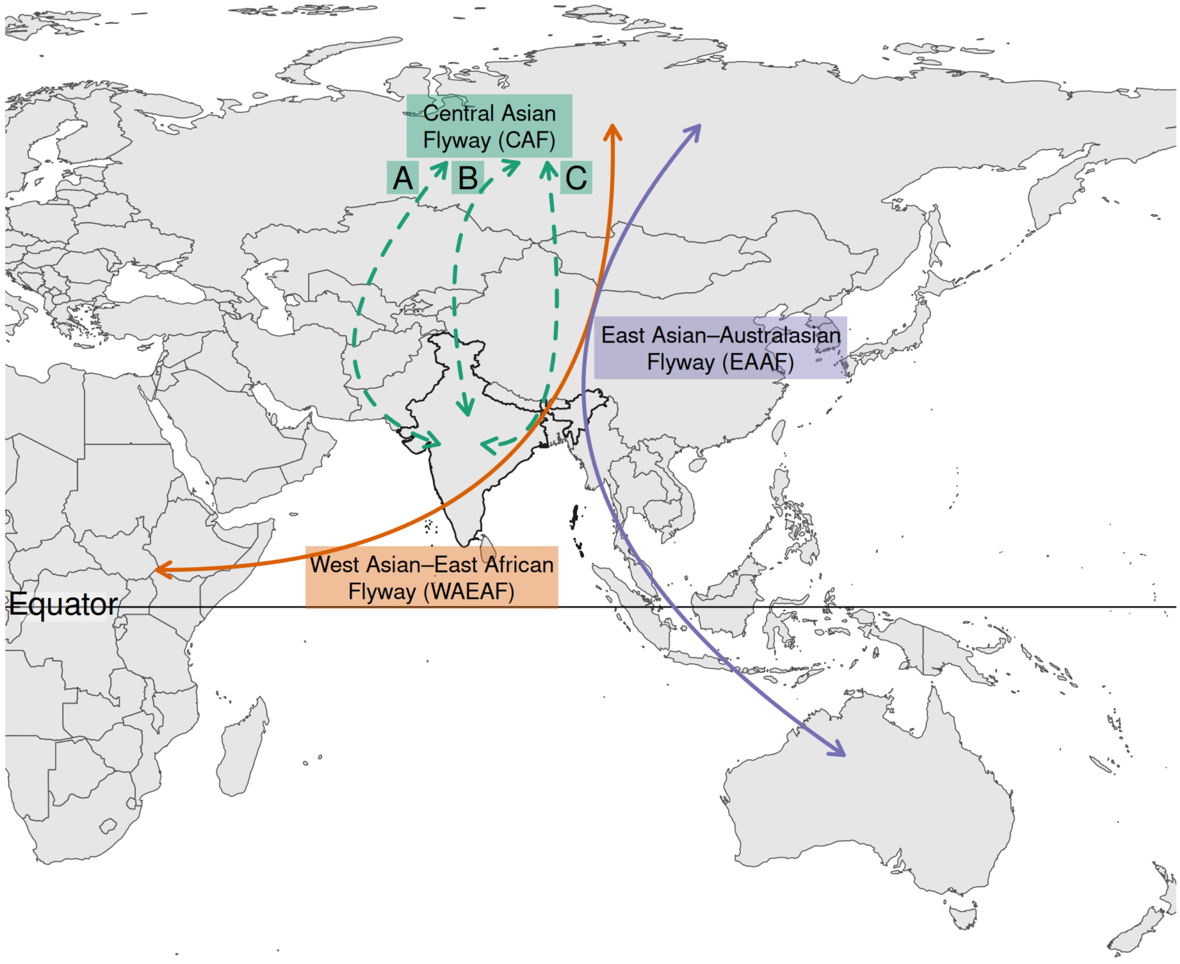


Figure 5. Monsoon-structured aerial migration corridors intersecting the Indian subcontinent. Three major avian flyways intersect the Indian subcontinent. The Central Asian Flyway (CAF) comprises three principal corridors: (A) the western circum-Himalayan route, associated with soaring migrants exploiting thermal uplift and arid convection; (B) the trans-Himalayan route, used by high-altitude powered migrants crossing the Tibetan Plateau under favorable wind and uplift conditions; and (C) the eastern circum-Himalayan route, linking South and Southeast Asia and partially overlapping with the East Asia–Australasian Flyway (EAAF). Autumn movements are facilitated by northerly and easterly flow associated with the winter monsoon, while spring movements are supported by westerlies and pre-monsoon circulation that enable uplift and tailwind assistance across the Himalayas. The EAAF is similarly shaped by the East Asian monsoon, whereas the West Asian–East African Flyway (WAEAF) reflects transoceanic connections between South Asia and East Africa mediated by post-monsoon easterlies and pre-monsoon southwesterlies linked to the Somali Jet and the seasonal displacement of the Intertropical Convergence Zone (ITCZ). Arrows indicate approximate migration corridors within broader flyway belts. Importantly, emerging evidence presented in this synthesis suggests that these same atmospheric pathways also structure insect migration and dispersal, pointing to a shared aeroecological framework across taxa.

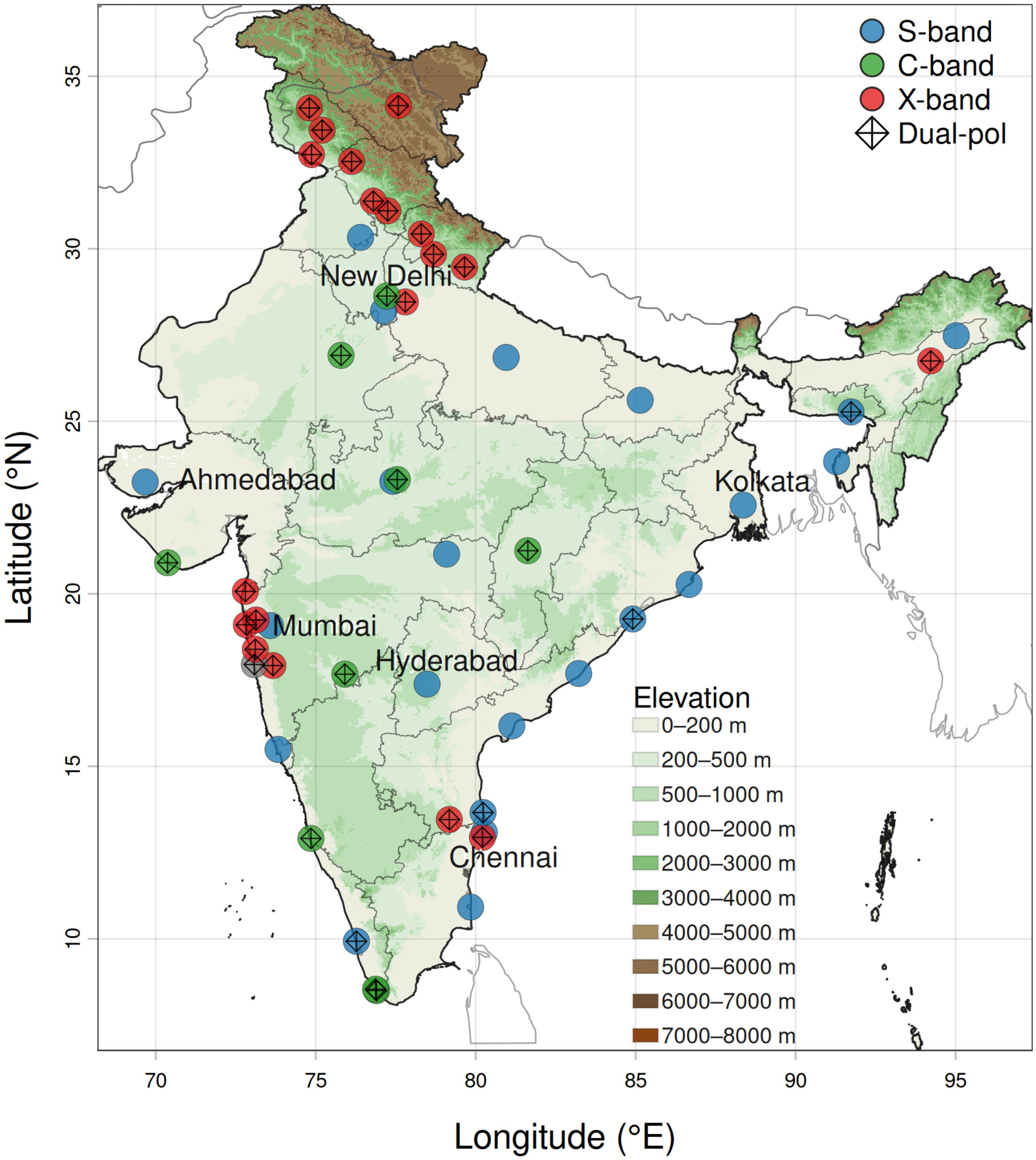


Figure 6. Spatial distribution of India's Doppler Weather Radar (DWR) network. Radar sites are coloured by frequency band (S-, C-, X-, and Ka-band), with dual-polarization systems indicated by additional central markers. The current network comprises 51 radars, including 22 S-band, 19 X-band, 9 C-band, and 1 Ka-band systems, of which 33 are dual-polarization. Coverage is particularly dense along the western coastline, especially across Maharashtra, and across the western Himalayan arc (Jammu & Kashmir, Ladakh, Himachal Pradesh, and Uttarakhand), where a chain of dual-polarized X-band radars provides unprecedented coverage of high-altitude passes and orographically structured airflow. These regions coincide with major migratory corridors and zones of strong atmospheric forcing, making them especially suitable for studying aerial movement. [Ministry of Earth Sciences, Indian Meteorological Department. (2026, March 5). *Details of operational DWR network across India* (RTI Application No. IMETD/R/E/26/00078). Central Public Information Officer, New Delhi.]