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Study on Low Air Meteorological Characteristics and Meteorological Service Application Strategies in Guangxi from the Perspective of Low Air Economy

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I. INTRODUCTION

As a crucial track for Chinas new productive forces, the low-altitude economy has been incorporated into the national strategic planning. China has explicitly proposed to develop general aviation and the low-altitude economy. This marks another clear policy signal from the Party Central Committee and the State Council regarding the development of the low-altitude economy, following the Central Economic Work Conference elevating it to a national strategy and the first mention of "low-altitude economy" in the 2024 National Two Sessions Government Work Report. Facing this trillion-yuan new track, meteorological departments leverage their unique operational foundations, technological advantages, and resource strengths to play an irreplaceable role in propelling the low-altitude economy to greater heights.

As the forefront and window of Chinas opening-up cooperation with ASEAN, Guangxi possesses unique geographical advantages for developing the low-altitude economy. The Peoples Government of Guangxi Zhuang Autonomous Region proposed to "lead with innovative R&D and scenario applications to accelerate the development of a low-altitude economic industry hub facing ASEAN." The plan sets clear development goals: By the end of 2026, low-altitude flight infrastructure will be continuously improved, application scenarios will achieve large-scale operation, the low-altitude equipment industry chain will be basically formed, the scale of the low-altitude economy will continue to grow, and Guangxi will become a supplier of low-altitude scenario service solutions and a base for low-altitude equipment R&D and manufacturing facing ASEAN.

Under this strategic context, the project is based on Guangxis strategic positioning as a China-ASEAN low-altitude economic hub. It constructs a three-in-one research framework of "meteorological mechanism-economic efficiency-service application", aiming to analyze the low-altitude meteorological characteristics in Guangxi, study the impact mechanisms on low-altitude economic activities, and ultimately propose meteorological service application strategies tailored to Guangxis low-altitude economic development. This provides meteorological technological support for the high-quality development of Guangxis low-altitude economy.

II. MULTI-TEMPORAL AND SPATIAL CHARACTERISTICS OF LOW ATMOSPHERIC ELEMENTS IN GUANGXI

2.1 Analysis of low temperature and humidity characteristics

2.1.1 Temporal and spatial distribution characteristics of temperature

The spatial and temporal distribution of low-level temperatures in Guangxi, along with extreme temperature events, exhibits distinct characteristics. Spatially, the horizontal distribution shows a decreasing trend from south to north. Coastal areas in southern Guangxi maintain higher annual average temperatures (22-24°°C), while mountainous regions in northern Guangxi experience lower temperatures (18-20°°C). Vertically, temperatures decrease at an average rate of 6.5°°C per kilometer, though this rate diminishes during temperature inversion layers or even increases with altitude. Specialized terrain areas demonstrate complex temperature patterns influenced by topography and local circulation, often forming unique thermal distributions. Temporally, seasonal variations show summer (June-August) as the warmest period, winter as the coldest, and spring-autumn as transitional seasons. Diurnal variations exhibit regional differences: smaller daily temperature ranges in summer compared to winter, with mountainous areas showing greater fluctuations than plains. Interannual trends indicate an overall upward trend in low-level temperatures across Guangxi, particularly in minimum temperatures, aligning with global climate change patterns. Extreme temperature events predominantly occur in summer, with southern Guangxi experiencing frequent hot days and extreme highs reaching 38-40°°C, while northern mountainous regions mainly see cold spells.With frequent occurrences, extreme minimum temperatures in Guangxi can reach-2 to 0°C. Analysis of temperature abrupt changes shows that the frequency of extreme temperature index mutations in Guangxi between 1987 and 2009 exhibited randomness, with higher mutation rates observed after 2009. However, indicators such as daily maximum minimum temperature, warm days, warm nights, and hot nights showed no significant abrupt changes.

2.1.2 Spatiotemporal distribution characteristics of humidity

The spatiotemporal distribution of low-level humidity in Guangxi exhibits significant regional variations and temporal regularities. Spatially, the horizontal distribution generally shows a decreasing trend from south to north. Coastal areas in southern Guangxi have relatively high annual average relative humidity (80-85%), while mountainous regions in northern Guangxi experience slightly lower levels (75-80%). Vertically, humidity decreases with increasing altitude, predominantly concentrated near the surface, particularly during summer when moisture becomes more concentrated in the lower atmosphere. Specialized terrain areas like the karst region in western Guangxi show marked variations in humidity distribution influenced by topography and vegetation, often forming localized high-humidity zones. Temporally, seasonal variation peaks in summer and troughs in winter, with spring and autumn serving as transitional periods. Summers humid conditions are driven by abundant moisture from the southwest monsoon. Diurnally, relative humidity typically reaches its maximum in the early morning and minimum in the afternoon, contrasting with daily temperature fluctuations. Interannual trends reveal a slight overall decline in low-level humidity across Guangxi, though variations exist regionally and seasonally. Extreme humidity events predominantly occur during rainy seasons, especially during prolonged heavy rainfall, when low-level humidity remains above 90% for extended periods. Conversely, dry spells mainly appear in drought seasons, particularly during strong cold air invasions.During the southward journey, the low altitude humidity can drop below 40%.

2.2. Characteristics of low-level wind field

The spatiotemporal variations of low-level wind speed and direction in Guangxi demonstrate distinct regularities and regional differences. In terms of spatial distribution, horizontal wind speeds generally decrease from coastal to inland areas. Coastal regions in southern Guangxi experience higher annual average wind speeds (3-4 m/s), while central and northern inland areas have lower values (1-2 m/s). Vertically, wind speeds increase with altitude, reaching peak levels at 500-1000 meters where gusts can reach 10-15 m/s. Canyon and mountain passes show significantly intensified winds due to the funneling effect, whereas basin and valley areas experience relatively weaker winds. Seasonal variations reveal maximum wind speeds in spring followed by autumn, with moderate levels in summer and winter. Daily variations differ across seasons and regions, typically peaking in the afternoon and subsiding at night, though coastal areas with maritime or valley wind circulation exhibit more complex patterns. Interannual trends show a slight downward trend consistent with the global "calm wind phenomenon". Extreme wind events predominantly occur during typhoon impacts and strong cold air southward movement, with frequent windy days along southern Guangxis coast where extreme maximum wind speeds reach 25-30 m/s. Wind direction patterns show marked seasonal shifts: northwesterly winds prevail in winter under the influence of the Asian continental high-pressure system, while summer sees...The southwest monsoon and southeast monsoon systems dominate the region, bringing prevailing southerly and southwest winds. Spring and autumn mark monsoon transition periods characterized by variable wind directions and frequent seasonal reversals. Diurnal variations show distinct patterns: coastal areas experience a pronounced sea-land breeze circulation—shore breezes during daylight hours and inland winds at night, while mountainous regions exhibit valley breeze circulation—valley breezes during daytime and mountain breezes at night. Urban areas, influenced by urban heat island circulation, often see southerly winds blowing from suburban areas toward cities at night. During typhoon impacts, wind direction rotates counterclockwise with the typhoons movement,

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showing most dramatic directional changes near its center. Before severe convective weather develops, significant wind direction shifts and sudden increases in wind speed typically occur, serving as crucial precursors to intense weather events.

2.4 Analysis of low altitude precipitation characteristics

The spatiotemporal distribution, intensity, and typological characteristics of low-level precipitation in Guangxi demonstrate significant regional variations and temporal regularities. In terms of spatial distribution, the horizontal pattern generally shows a decreasing trend from south to north. Coastal areas in southern Guangxi receive higher annual precipitation (up to 2000-2500 mm), while mountainous regions in northern Guangxi have slightly lower amounts (approximately 1500-2000 mm). Vertically, precipitation is predominantly concentrated near the surface, with heavy summer rainfall occurring mainly at elevations between 500-1500 meters. Specialized terrain areas exhibit distinct patterns: windward slopes of mountain ranges form rainbands due to enhanced elevation-induced precipitation, whereas leeward slopes become rain shadow zones with reduced rainfall. Temporally, seasonal variations are most pronounced during flood seasons. Daily variations show decreasing nighttime rainfall frequency from northwest to southeast, with mountainous areas experiencing significantly higher rates than plains. Interannual variations generally show slight increases but show marked regional and seasonal differences. Extreme precipitation events primarily occur during flood seasons, with coastal areas in southern Guangxi experiencing more frequent heavy rainfall days (extreme daily precipitation reaching 300-500 mm). Persistent heavy precipitation events average 1.2 occurrences annually, peaking at 4 times in 1994, with 12 years showing no occurrences between 1979 and 2019. The extreme precipitation index showed higher frequencies around 1991 and 2001 before stabilizing. Regarding precipitation intensity and typology, overall precipitation intensity shows an increasing trend.The intensity and frequency of heavy rainfall in Guangxi have shown more pronounced increases with uneven spatial distribution. Coastal areas in southern Guangxi experience heavier precipitation than mountainous regions in northern Guangxi, while temporal patterns reveal higher intensity during the afternoon to evening hours compared to early morning. Precipitation types are dominated by frontal rain, convective rain, and orographic rain: Frontal rain predominantly occurs in spring and autumn, formed by the convergence of cold and warm air masses, characterized by wide coverage and prolonged duration but relatively low intensity; Convective rain concentrates in summer, triggered by intense convective activities, featuring smaller coverage, shorter duration, and higher intensity often accompanied by thunderstorms and strong winds; Orographic rain mainly develops in mountainous areas due to topographic uplift, with intensity and coverage significantly influenced by terrain. Additionally, six major types of persistent heavy rainfall during Guangxis flood season include North China troughs, South branch troughs, low-pressure vortex shear, subtropical high edges, tropical cyclones, and monsoon low-pressure systems. Among these, North China troughs occur most frequently, while South branch troughs exhibit the longest average duration and widest impact range. The locations of persistent heavy rainfall zones show some correlation with frontal positions, though significant differences exist between different types of frontal structures.

2.5 Mechanism analysis of low air meteorological element variation

The variations in low-level meteorological elements in Guangxi are influenced by multiple factors including large-scale circulation patterns, terrain and underlying land surfaces, weather systems, and climate change, each with distinct mechanisms. Regarding large-scale circulation, monsoon circulation serves as a core driver: the East Asian summer monsoon transports abundant moisture and heat, contributing to the regions high temperatures and humidity during summer, while the winter monsoon brings dry cold air leading to low temperatures and aridity in winter. The intensity and timing of monsoon activity directly affect seasonal and interannual variations in low-level meteorological elements. The position and strength of the Western Pacific Subtropical High play a crucial role in precipitation distribution and temperature changes. When this high extends westward and northward, Guangxi experiences frequent hot spells with scarce rainfall; when it retreats eastward and southward, it becomes more susceptible to low-pressure troughs and tropical systems that increase precipitation. In mid-to-high latitude circulation, southward-moving cold air serves as a key trigger for winter cold spells and heavy rainfall. Variations in upper-level jet stream positions and intensities significantly influence vertical distribution patterns of low-level meteorological elements. Regarding terrain and underlying land surfaces, topographic dynamics manifest through mountain ranges blocking and uplifting air currents to form orographic clouds and precipitation. For instance, the uplift of the Ten Thousand Mountain Range enhances precipitation along southern Guangxis coast by raising the southeast monsoon. The narrow tube effect in valleys intensifies wind speeds, creating localized gale zones, while the "cold lake effect" in basins and river valleys triggers...Local cooling and temperature inversion; Under the influence of terrain thermal effects, the thermal difference between mountainous areas and plains forms valley wind circulation, affecting local wind direction and speed diurnal variations. The sea-land wind circulation formed by thermal differences between land and water impacts meteorological elements distribution in coastal regions. Differences in underlying surface characteristics are equally critical. Forests, farmlands, cities, and water bodies exhibit variations in albedo, heat capacity, and roughness, leading to differences in energy and moisture exchange processes that influence lower-level meteorological elements. Urbanization-induced urban heat island effect further intensifies urban temperature and humidity, altering local circulation and precipitation distribution. At the weather system level, tropical cyclones are the primary source of heavy rainfall and strong winds in summer, with their path and intensity directly affecting lower-level meteorological elements. Peripheral circulation also transports water vapor and energy to promote convection and precipitation formation. Low-pressure systems and shear lines are major contributors to heavy rainfall during flood seasons, often combining with monsoons or cold air masses to create persistent heavy precipitation. Their location and movement direction significantly influence lower-level meteorological element distribution. In frontal systems, cold fronts are the main cause of springtime heavy rainfall, frequently accompanied by strong winds, temperature drops, and precipitation. Prolonged maintenance of quasi-stationary fronts tends to lead to continuous low-temperature rainy weather. Regarding climate change impacts, Guangxis lower-level temperatures have shown an overall upward trend over the past 59 years.The temperature drop became more pronounced, with higher frequency and intensity of heatwaves while cold spells decreased. Precipitation showed a slight overall increase, though its distribution and intensity underwent significant changes: fewer days with light rain, more heavy downpours, and heightened precipitation extremes. Wind speeds generally weakened, aligning with the global "wind-still phenomenon", accompanied by fewer windy days and reduced daily wind speed variations.

III. STUDY ON THE INFLUENCE OF LOW ATMOSPHERE ON LOW LEVEL ECONOMIC ACTIVITIES

3.1 Analysis of the impact of low weather on UAV logistics

As a vital component of the low-altitude economy, drone logistics heavily depends on meteorological conditions for operational efficiency and safety. When it comes to weather sensitivity, wind speed and direction are the primary factors: when wind exceeds a drones maximum wind resistance (typically 10-15 m/s), flight stability drops significantly. Headwinds increase energy consumption and flight duration, while tailwinds may reduce energy efficiency but compromise landing precision. Crosswinds often cause course deviations, particularly during takeoff and landing phases. Precipitation not only raises air resistance and aircraft weight but can also infiltrate electronic equipment, causing malfunctions and reducing visibility for navigation. Temperature and humidity indirectly affect flight safety through battery performance (high temperatures accelerate aging, low temperatures increase internal resistance) and equipment stability (high humidity may lead to icing or condensation). Extreme risks emerge from low visibility conditions (fog, haze) and severe convective weather like thunderstorms and hail, which severely threaten a drones flight control and obstacle avoidance capabilities.

In terms of cost impacts, adverse weather conditions elevate operational expenses through multiple channels: headwinds and crosswinds increase energy consumption, shorten delivery ranges, and reduce single-shipment capacity; detour routes or altitude adjustments further raise energy costs. Extreme temperature and humidity accelerate equipment aging, while precipitation and sandstorms damage sensors and mechanical components, leading to increased maintenance frequency and costs. Weather-induced delays or cancellations decrease operational efficiency, and network re-planning increases management costs. Additionally, heightened meteorological risks drive up insurance premiums and potential claim expenditures.

In terms of safety impacts, meteorological factors directly threaten flight safety: Strong winds, turbulence, and powerful vertical currents reduce flight stability, increasing risks of loss of control and collisions; low visibility and electromagnetic interference (such as lightning) compromise navigation accuracy; extreme temperatures and precipitation impair equipment performance, raising the probability of malfunctions; severe weather also restricts emergency response capabilities, challenging critical functions like automatic return and emergency landings, thereby complicating accident handling.

3.2 Analysis of the impact of low atmosphere on low altitude tourism

The meteorological requirements for low-altitude aerial tourism vary by project type: Paragliding and powered paragliders require wind speeds below 10 m/s, side winds under 3 m/s, and stable airflow. Hot air balloons face the strictest conditions, needing wind speeds below 5 m/s, no precipitation or convection, good visibility, and typically operating during sunrise or sunset. Light aircraft and helicopters demand cloud bases above 500 meters, visibility over 5 kilometers, and avoidance of severe convection. Drone aerial photography places greater emphasis on lighting conditions compared to conventional drone logistics operations.

Weather conditions directly affect safety: strong winds reduce stability, heavy precipitation and lightning pose a direct threat, low visibility increases collision risk, turbulence affects control and reduces comfort; bad weather also limits emergency rescue capacity, and may lead to tourists underestimate the risk or panic due to sudden weather changes.

In terms of economic benefits, adverse weather reduces the number of effective operating days and increases temporary cancellations and complaints; turbulence flights and limited visibility reduce tourist experience, affecting reputation and repeat purchases; weather uncertainty increases marketing difficulties, resulting in obvious off-peak seasons; extreme weather also accelerates equipment aging and increases maintenance costs.

3.3 Analysis of the impact of low weather on agricultural aviation

Low atmospheric conditions exert multifaceted impacts on agricultural aviation operations, including their implementation efficiency and crop growth. Meteorological requirements vary across operational types: Agricultural pest control demands wind speeds below 3 m/s, temperatures between 15-28°℃, relative humidity of 50-80%, and at least 6 hours without rainfall post-operation, while crosswinds increase contamination risks in non-target areas. Sowing and fertilization require slightly more flexible wind speed thresholds but must maintain appropriate soil moisture levels. Low temperatures hinder seed germination while high temperatures cause fertilizer volatilization. Agricultural monitoring should avoid heavy rainfall and thunderstorms, as low visibility degrades remote sensing data quality. The optimal observation window spans from 10:00 AM to 3:00 PM.

In meteorological conditions affecting agricultural aviation operations, adverse weather directly reduces effective working hours. Seasonal weather variations lead to uneven workloads, decreasing equipment utilization rates. Excessive wind speeds, high temperatures, dryness, and low humidity cause uneven distribution of materials, ineffective pesticide fertilizers, and reduced spraying efficiency, thereby compromising operational quality. Flying against wind increases energy consumption and unit operation costs, while weather uncertainties may trigger repeated patching operations, driving up overall expenses. Additionally, severe weather and high temperatures heighten flight safety risks and increase the likelihood of pilot errors.

Furthermore, adverse meteorological conditions indirectly affect crop growth. Key factors like temperature, precipitation, and sunlight directly determine crop yields and quality, while extreme weather events can severely damage crops. These conditions also regulate the occurrence, development, and spread of pests and diseases. Climate change may alter pest patterns, making control efforts more challenging. Additionally, precipitation and temperature influence soil moisture, nutrient cycling, and erosion rates, which further impact soil quality and the growing environment for crops.

3.4 Dynamic response model construction of meteorological elements and economic efficiency

3.4.1 Data collection and preprocessing

To develop a dynamic response model linking meteorological elements with economic performance, the process begins with multi-source data collection and rigorous preprocessing. For meteorological data, it is essential to obtain key parameters covering low-altitude economic activity zones—including temperature, humidity, wind speed, wind direction, precipitation, and visibility—ensuring their temporal and spatial resolutions align with economic activities. Economic performance data should include operational metrics from drone logistics, low-altitude tourism, agricultural aviation, and related sectors, all rigorously synchronized with meteorological data across spatiotemporal dimensions. The preprocessing phase requires quality control, standardized normalization, and time series decomposition to establish a robust foundation for model construction.

When developing modeling approaches, researchers should scientifically select models based on their research objectives and data characteristics. Multivariate linear regression effectively captures linear relationships, time series models excel at analyzing dynamic lag effects, machine learning models can handle complex nonlinear relationships, while dynamic panel data models reveal regional heterogeneity impacts. By comparing and combining these models, we can fully leverage their respective strengths to enhance model interpretability and prediction accuracy.

After model construction, rigorous validation must be conducted using methods such as cross-validation to evaluate predictive performance, followed by residual analysis and significance testing. In practical applications, this model can be used for short-term forecasting, scenario analysis, and optimization decisions (guiding resource allocation). Additionally, it is essential to establish a model update and maintenance mechanism to ensure continuous optimization as data accumulates and environments change, thereby providing stable and reliable meteorological decision support for low-altitude economic activities.

IV. STUDY ON THE ADAPTABILITY OF LOW AIR METEOROLOGICAL CHARACTERISTICS TO LOW ECONOMIC ACTIVITIES

4.1 Development of airworthiness airspace and time domain resources recommendations

Based on low-altitude meteorological characteristics and economic activity requirements, Guangxis low-altitude airspace can be categorized into three risk levels: low, medium, and high. Low-risk areas primarily include the central Guangxi Plain and eastern Guangxi hilly regions, where wind speeds remain below 5 m/s year-round, precipitation is minimal, and visibility remains good. The optimal flight period occurs during spring and autumn. Medium-risk zones cover the southern coastal areas of Guangxi and northern mountainous regions influenced by monsoons and complex terrain, with particular challenges in the southern coastal areas requiring avoidance during typhoon seasons from June to October. Northern mountainous areas should conduct flights between 10:00 AM and 4:00 PM when air currents are relatively stable. High-risk areas encompass karst mountainous regions in western Guangxi and frequent strong convective weather zones. Non-essential flights should be strictly restricted, while those necessary must avoid peak convection periods and implement additional safety measures.

Regarding temporal resource optimization, the spring season (March-May) is the golden period for low-altitude economic activities. Summer (June-August) requires avoiding afternoon strong convection and typhoon periods. Autumn (September-November) is generally suitable but requires vigilance against cold dew winds in northern Guangxi. Winter (December-February) should shift activity focus to southern Guangxi. Daily variations show: The optimal flight period is 8:00-11:00 AM. Avoid mountainous operations from 12:00-16:00 due to intense convection. The second-best period is 17:00-19:00, though visibility may drop. Nighttime activities are generally unsuitable except under special circumstances. Special periods like 24-48 hours before/after typhoons, 12-24 hours after typhoon passage, 6-12 hours before/after severe convection events, and during heavy fog/haze weather require suspending or restricting low-altitude economic activities.

In terms of airspace dynamic management, it is essential to establish a real-time monitoring network for low-altitude weather conditions, including ground-based meteorological stations, radar systems, satellites, and drones. This network should continuously track critical parameters such as wind speed, direction, precipitation, and visibility while issuing timely risk alerts. Based on real-time meteorological data, airspace risk levels and airworthiness conditions should be dynamically adjusted. Priority mechanisms for airspace usage and conflict coordination must be implemented to ensure priority support for high-value and urgent missions. Additionally, emergency response protocols should be established for sudden weather changes, specifying measures like emergency landings, flight returns, and detours with clear responsibility assignments. A post-disaster assessment and recovery mechanism must also be created to ensure swift restoration of normal operations.

4.2 Airline and aircraft control programmes

In air route planning and optimization, solutions must be closely aligned with low-altitude meteorological characteristics. Meteorological condition-based route planning should consider the spatiotemporal distribution of wind speed, direction, temperature, and humidity. Drone logistics routes should avoid strong winds and heavy rainfall zones, while low-altitude tourism routes balance weather stability with scenic views. A dynamic adjustment mechanism should be established to promptly reroute around hazardous areas or optimize routes according to real-time weather changes, thereby enhancing efficiency. Additionally, a safety assessment model should be developed to identify high-risk sections through comprehensive analysis of meteorological conditions, terrain features, and human factors, with regular optimization of existing routes.

The selection and meteorological adaptability evaluation of aircraft must align with Guangxis climatic characteristics: Light drones are suitable for stable urban weather conditions, medium drones excel in complex meteorological environments due to their wind resistance and endurance advantages, while heavy drones are ideal for long-distance operations under adverse weather. An assessment system should be established based on indicators such as wind resistance, rain tolerance, and temperature adaptability to provide decision-making support. Additionally, customized recommendations for aircraft waterproofing, wind resistance, and thermal management upgrades are proposed for Guangxis climate. The implementation of adaptive flight control technologies should be promoted, along with encouraging the development of specialized aircraft models.

Flight activity management must prioritize meteorological safety through three key measures: First, establish a weather condition approval system with clear minimum safety standards for all operations. Non-compliant flights shall be prohibited or postponed, while strictly reviewing high-risk special flights. Second, implement real-time flight plan adjustments based on dynamic weather updates, establishing expedited approval channels for emergency situations. Third, deploy a real-time monitoring system to track aircraft positions, operational status, and weather conditions, complemented by early warning and emergency response protocols to ensure efficient handling of abnormal weather scenarios.

4.3 Technical pathways for low-altitude weather services

To support the development of low-altitude economy, low-altitude meteorological services require establishing technical pathways through three core components: monitoring, forecasting, and service provision. In constructing low-altitude meteorological monitoring systems, efforts should focus on optimizing ground-based observation networks by densifying weather stations in areas with dense low-altitude economic activities and complex meteorological conditions. Existing equipment should be upgraded to enhance detection capabilities for wind profiles and turbulence at lower altitudes, while establishing socialized meteorological observation networks that encourage corporate and individual participation to expand coverage. Additionally, low-altitude wind profiler radars should be deployed in key cities like Nanning, Guilin, and Beihai to achieve continuous monitoring of wind fields at altitudes from 0 to 3,000 meters. Drone-based meteorological detection technologies should be developed for vertical exploration of low-altitude meteorological elements, while millimeter-wave cloud radars and lidar systems will improve detection capabilities for low clouds and precipitation. Furthermore, a comprehensive low-altitude meteorological data processing and analysis platform must be established to integrate multi-source observational data with numerical model forecasts. Element fusion technologies should be developed to enhance spatiotemporal resolution and accuracy of data, supported by database construction and historical archives to facilitate research and service provision.

In the development of low-altitude meteorological forecasting technologies, three breakthroughs must address economic demands: First, advancing refined numerical prediction systems with horizontal resolution of 1-3 km and vertical resolution of 50-100 m. This involves optimizing parameterization schemes for boundary layers, convection, and cloud microphysics processes, while establishing ensemble forecasting systems to enhance prediction reliability and uncertainty assessment capabilities. Second, improving short-term forecasting techniques by leveraging radar, satellite, and ground observation data to strengthen severe convective weather warnings. This includes developing extrapolation methods for low-altitude meteorological elements to achieve 0-6 hour precision forecasts, along with probabilistic forecasting technologies that provide element distribution information. Third, innovating AI-driven forecasting systems through machine learning and deep learning to build intelligent prediction models for low-altitude meteorological elements. By mining complex relationships between elements using big data, we aim to establish AI-powered low-altitude meteorological disaster warning systems that improve both accuracy and timeliness of alerts.

In the construction of low-altitude meteorological service platforms, it is necessary to establish comprehensive service carriers to meet diverse needs: Build a low-altitude flight meteorological service system to provide customized forecasts, warnings, and consulting services; develop flight meteorological risk assessment tools to support plan formulation and decision-making; establish safeguard mechanisms to provide full-process meteorological support for critical flight activities; construct meteorological data sharing and exchange platforms to achieve data sharing between meteorological authorities, low-altitude economy-related departments, and enterprises; formulate data exchange standards to promote system interoperability and collaboration; establish cross-border data sharing mechanisms to support China-ASEAN low-altitude economic cooperation; simultaneously develop specialized meteorological service products, launch exclusive index products for scenarios such as drone logistics, low-altitude tourism, and agricultural aviation; develop GIS-based service products to enable meteorological information visualization and spatial analysis; and create mobile applications to provide convenient real-time meteorological services for low-altitude economic activities.

4.4 ASEAN-oriented cooperation on low-altitude economic meteorological services

To support the high-quality development of Guangxis low-altitude economy, it is essential to establish an integrated "monitoring, forecasting, and service" technical system for low-altitude meteorology. In constructing the low-altitude meteorological monitoring system, the first priority is to optimize the ground-based meteorological observation network by densifying monitoring stations and upgrading equipment in low-altitude economic clusters and meteorologically complex areas to enhance detection elements such as wind profiles and turbulence. Simultaneously, we will collaborate with social organizations to build a community-based observation network. The second phase focuses on advancing vertical sounding systems through deploying low-altitude wind profiler radars in key cities like Nanning, Guilin, and Beihai, utilizing drones for vertical profiling, and developing millimeter-wave cloud radars and lidar systems to improve detection capabilities for low clouds and precipitation. Finally, we will establish a comprehensive data processing and analysis platform that integrates multi-source observational data with numerical forecast products. Through data fusion technology, this system will enhance spatiotemporal resolution while creating databases and historical archives to support future research.

In the development of low-level atmospheric forecasting technologies, three key technological breakthroughs will be prioritized: First, advancing refined numerical prediction systems by establishing high-resolution models with horizontal resolution of 1-3 kilometers and vertical resolution of 50-100 meters. This includes optimizing parameterization schemes for physical processes such as boundary layers and convection, while developing ensemble forecasting systems to enhance prediction reliability. Second, improving short-term forecasting capabilities through data integration from radar and satellite sources, particularly enhancing severe convective weather warnings by developing 0-6 hour extrapolation forecasts and probabilistic prediction techniques for low-level meteorological elements. Third, innovating artificial intelligence-driven forecasting systems by applying machine learning and deep learning to build intelligent prediction models that analyze complex correlations between meteorological factors, ultimately establishing AI-powered early warning platforms for low-level meteorological disasters.

In the construction of low-altitude meteorological service platforms, we focus on creating comprehensive service carriers to meet diverse needs: Establishing a low-altitude flight meteorological service system to provide customized forecasting and warning services, risk assessment tools, and full-process support for critical flights; Building a meteorological data sharing and exchange platform by formulating data exchange standards to achieve data interoperability between departments and enterprises, while simultaneously establishing cross-border data sharing mechanisms to support China-ASEAN low-altitude economic cooperation; Developing specialized meteorological service products, including exclusive index products tailored for scenarios such as drone logistics, low-altitude tourism, and agricultural aviation. By integrating GIS technology to enable visualized meteorological information, mobile applications are developed to provide convenient real-time meteorological services for low-altitude economic activities.

V. CONCLUSIONS AND OUTLOOK

5.1 Key findings

This study conducts multidimensional analysis on the correlation between low-altitude meteorology and low-altitude economy in Guangxi, with core conclusions as follows: From the spatiotemporal distribution characteristics of low-altitude meteorological elements, temperature, humidity, wind speed, wind direction, and precipitation in Guangxis low-altitude areas are influenced by monsoon circulation, terrain, and underlying surface conditions, exhibiting significant spatiotemporal variations. Specifically, temperatures generally rise, precipitation slightly increases, and wind speeds weaken overall. The mechanisms driving these element changes are comprehensively driven by large-scale circulation, terrain effects, and weather systems. Regarding the impact of low-altitude meteorology on economic activities, meteorological conditions directly affect the safety, efficiency, and cost of drone logistics, low-altitude tourism, and agricultural aviation. Different activities demonstrate varying sensitivities ——: drone logistics is most sensitive to wind speed and precipitation, low-altitude tourism focuses on wind speed and visibility, while agricultural aviation prioritizes wind speed and temperature. Through constructing dynamic response models, we can quantitatively analyze the complex nonlinear relationship between meteorological elements and economic performance. In terms of adaptive matching, Guangxis low-altitude airspace is classified into three risk categories (low, medium, high) based on meteorological features and economic demands, each with different airworthiness conditions. Optimal flight periods are morning and evening in spring and autumn, while summer afternoons should avoid severe convective weather and adverse conditions. Additionally, improving monitoring systems, developing forecasting technologies, and establishing service platforms are crucial., is the key technical path to support the development of low-altitude economy, and strengthening China-ASEAN low-altitude meteorological cooperation provides an important guarantee for cross-border low-altitude economy.

5.2 Policy recommendations

To promote the high-quality development of Guangxis low-altitude economy, four policy recommendations are proposed based on research findings: First, strengthen the construction of low-altitude meteorological infrastructure by incorporating it into the development plan for the low-altitude economy, increasing fiscal investment and establishing a diversified investment and financing mechanism while coordinating planning to avoid redundant construction; Second, improve the low-altitude meteorological service system by perfecting service standards and norms, promoting market-oriented industrialization of services, and strengthening regulatory safeguards for meteorological safety; Third, facilitate the integration of low-altitude economy with meteorological services by establishing a collaborative development mechanism, supporting enterprises, meteorological departments, and research institutions in joint technological R&D, and encouraging enterprises to apply advanced meteorological technologies to enhance risk prevention capabilities and economic efficiency; Fourth, deepen China-ASEAN low-altitude meteorological cooperation by incorporating it into regional cooperation frameworks, enhancing policy communication and technical exchanges, supporting Guangxi enterprises in participating in ASEANs meteorological infrastructure construction and services, and expanding international markets.

5.3 Future research prospects

Although this study has achieved phased results, further exploration is still required in four aspects: First, research on low-altitude meteorological observation technology should focus on developing higher precision and spatiotemporal resolution observation techniques, exploring the application of new platforms such as drones and airships, and improving remote sensing inversion technology to enhance monitoring capabilities under complex conditions; Second, research on low-altitude meteorological numerical simulation should prioritize the development of higher-resolution numerical models, improve physical process parameterization schemes, and advance ensemble forecasting technology to enhance simulation prediction reliability and uncertainty assessment capabilities; Third, research on low-altitude meteorological service technologies should leverage artificial intelligence and big data to elevate service intelligence and personalization levels, deepen risk assessment and early warning technologies, and explore market-oriented business models and operational mechanisms; Fourth, research on coordinated development between low-altitude economy and meteorology should analyze the feedback effects of low-altitude economy on meteorological conditions, study the impacts of climate change on the low-altitude economy and adaptation pathways, and explore new models for China-ASEAN cross-border low-altitude economic and meteorological cooperation to facilitate regional low-altitude economic integration.

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