Research on Enhancing the Meteorological Support Capacity of Civil Aviation Air Traffic Control Based on Intelligent Technology

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Abstract: With the growth of civil aviation flight volume and the frequent occurrence of extreme weather, air traffic control meteorological support is facing higher requirements such as precise forecasting, real-time early warning, and multi-departmental collaboration. Based on the meteorological business practice of civil aviation air traffic control, this paper analyzes the pain points in the monitoring and forecasting of complex weather conditions such as thunderstorms, low-altitude wind shear, and icing. It introduces intelligent technologies such as machine learning and big data analysis to construct an integrated meteorological service system of "precise monitoring - intelligent forecasting - dynamic decision-making". And in response to the challenges such as data security, model generalization and talent gap faced in its practical application, strong countermeasures and suggestions are put forward from the dimensions of technology, management and talent cultivation, aiming to provide technical support and management reference for the operational safety of civil aviation.

Key words: Civil Aviation Air Traffic Control Thunderstorm Low-altitude wind shear Freezing; Meteorological guarantee Intelligent technology

DOI:10.69979/3041-0843.25.02.035

Introduction

In the current era of vigorous economic and technological development, air transportation, with its advantages of being fast, convenient, comfortable and safe, has become the preferred mode of transportation for passengers. However, civil aviation transportation is closely related to meteorological conditions. The impact of bad weather on civil aviation operations is even more severe. According to the relevant data statistics of the Civil Aviation Administration's safety report, the proportion of adverse weather in civil aviation safety accidents is as high as 30% to 40%. In actual operation, bad weather can, at the very least, cause flight delays or cancellations, disrupting passengers' normal travel plans. At worst, it can severely disrupt the operational order of civil aviation and even seriously threaten the lives and property of passengers and crew members. Especially in recent years, with the abnormal global climate change, extreme weather phenomena such as thunderstorms, low-altitude wind shear and icing have occurred frequently and severely, and their impact on civil aviation operations cannot be underestimated.

Against this background, the meteorological support work of civil aviation air traffic control has attracted high attention. To promote the high-quality development of the civil aviation industry, the civil aviation department has successively introduced a series of plans and policies. 2025 is a crucial year for the successful conclusion of the 14th Five-Year Plan and the strategic planning of the 15th Five-Year Plan. It is also an important convergence point for the air traffic control system to transition from "Asia-Pacific first-class" to "world-class", and strict requirements have been put forward for precise weather forecasting and collaborative decision-making. However, when dealing with complex weather phenomena, the existing meteorological services still expose drawbacks such as blind spots in monitoring, information silos, and insufficient forecast accuracy. They are difficult to meet the demand for precise meteorological information in civil aviation operations and also pose many potential threats to the safe flight of aviation.

With the rapid development of technology, intelligent technologies represented by machine learning and big data analysis have emerged and demonstrated outstanding advantages in fields such as data processing and pattern recognition. Introducing the above-mentioned intelligent technologies into the meteorological support field of civil aviation air traffic control and building an advanced meteorological service system can effectively solve the drawbacks faced by traditional meteorological services in the past. It is of great practical significance to enhance the reliability and safety of civil aviation operations in complex weather scenarios and promote the sustainable and healthy development of the civil aviation industry.

1 Difficulties in monitoring and forecasting complex weather conditions

For a long time, civil aviation meteorological monitoring and forecasting have always been the core issue that the civil aviation industry pays close attention to. In recent years, with the intensification of global warming, complex weather conditions such as thunderstorms, low-altitude wind shear and icing have been increasing and strengthening at Delingha Airport in Qinghai Province, posing a significant threat to the normal operation of civil aviation and flight safety. Therefore, it is extremely urgent to strengthen the civil aviation meteorological monitoring and forecasting work under complex weather conditions. However, when dealing with complex weather phenomena, many drawbacks of traditional aviation meteorological monitoring and forecasting have become increasingly prominent.

1.1 Monitor blind spots

Complex weather conditions have a small scale but change rapidly, making it difficult for traditional monitoring methods to achieve full coverage in the past. Take thunderstorms as an example. They develop rapidly and on a small scale. Conventional meteorological observation stations, due to the large distance between stations, are unable to comprehensively monitor the occurrence and development of thunderstorms. Especially in some mountainous areas or regions with complex terrain, due to the obstruction of the terrain, some meteorological elements are difficult to be effectively detected, resulting in blank areas for monitoring. In addition, low-altitude wind shear is also one of the frequent complex weather phenomena at Delingha Airport, which poses a huge threat to aircraft take-offs and landings. This phenomenon often occurs in the low-altitude areas around airport runways. Conventional observation equipment has difficulty accurately capturing the dynamic changes of the devices, resulting in blind spots in monitoring and being unable to provide comprehensive and accurate meteorological information for aviation operations.

1.2 Information Island

Civil aviation meteorological monitoring and forecasting is not only the responsibility of the civil aviation meteorological department, but also cannot do without the mutual cooperation between air traffic control and airlines. Multiple data sources are bound to be generated in this process. However, due to the imperfect information sharing mechanism among various departments and the non-uniformity of data formats and standards, the information flow is not smooth, and the phenomenon of "information islands" is widespread. This not only makes it difficult for various departments to form effective synergy when dealing with complex weather phenomena, but also significantly reduces the efficiency and accuracy of meteorological monitoring and forecasting.

1.3 The prediction accuracy is insufficient

The formation mechanism of complex weather is complicated, involving the interaction of multiple meteorological elements and complex physical processes. The existing numerical weather prediction models have certain limitations in dealing with complex weather conditions. Firstly, for the key physical processes such as convection, turbulence, and water vapor phase change of weather phenomena like thunderstorms, low-altitude wind shear, and icing, their parametric processing is not precise enough, making it difficult to accurately simulate their occurrence and development processes. Secondly, the resolution of numerical models is not high, making it difficult to capture some small-scale features and subtle changes of complex weather, resulting in significant deviations between the forecast results and the actual situation, and failing to meet the high-precision requirements of civil aviation for meteorological forecasting.

2 Construction of Civil Aviation Air Traffic Control Meteorological Support System Based on Intelligent Technology

In recent years, China's civil aviation industry has developed rapidly, with the number of flights constantly increasing, and the demand for meteorological information in the aviation industry has also been growing day by day. The meteorological department of Qinghai must closely focus on the new demands of aviation meteorological services, target the key and difficult issues in complex weather monitoring and forecasting at airports, actively explore an integrated aviation meteorological service guarantee system of "precise monitoring - intelligent forecasting - dynamic decision-making", enhance the capabilities of precise monitoring, accurate forecasting and meticulous services, and assist the aviation industry in achieving stable flights.

2.1 Multi-source Data Fusion and Intelligent Monitoring

Explore and promote the integration of multi-source data and intelligent monitoring, and drive precise monitoring and forecasting with technological upgrades. On the one hand, fundamentally innovate the meteorological data structure to achieve a leap from "single data source" to "multi-source three-dimensional perception". By integrating multi-source heterogeneous data such as satellite remote sensing, meteorological radar networking, wind profile radar networking, airport ground encrypted automatic stations, laser wind measurement radar, and lightning positioning and early warning systems, a land-air integrated data resource library is constructed. Massive data inevitably brings about the problem of transmission rate. In this regard, technologies such as parallel computing and distributed storage are actively applied to optimize network links, improve data flow, and reduce transmission delays, significantly enhancing the timeliness of short-term and imminent monitoring, forecasting and early warning. On the other hand, actively introduce high-resolution numerical forecast data to achieve hourly and precise weather forecasts for the next 72 hours, significantly enhancing the near-field forecast capability for complex weather conditions. At the same time, we should actively promote the exploration and application of cutting-edge technologies such as artificial intelligence, optimize the evolution path of thunderstorms and the prediction of extreme events like heavy precipitation through AI-driven models, and inject "intelligent energy" into the civil aviation disaster prevention and mitigation and complex weather response system.

2.2 Optimization of Refined Forecasting Model

Optimize the refined forecast model, enhance the refined service quality with the help of machine learning, and empower the development of civil aviation air traffic control. Firstly, taking the airport runway as the grid unit, a Long Short-Term Memory Network (LSTM) model is constructed to give full play to its advantages in processing time series data. The LSTM model can effectively learn the variation law of the runway surface temperature over time and accurately predict the runway surface temperature in the next hour, thereby reducing the icing prediction error. Secondly, a low-altitude wind shear early warning model is constructed based on the XGBoost algorithm. This model integrates multi-source information such as Doppler radar radial velocity and radiosonde data, and utilizes the powerful feature processing and model training capabilities of XGBoost to sensitively identify wind shear risks 40 minutes in advance. Compared with traditional methods, the timeliness and accuracy of early warning have been greatly improved, which has bought precious time for the air traffic control department and the crew to deal with low-altitude wind shear and enhanced the meteorological support capacity of civil aviation air traffic control under complex weather conditions.

2.3 Dynamic Decision-making and Collaboration Mechanism

Dynamic decision-making and collaborative mechanisms are important supports for enhancing the meteorological support capacity of civil aviation air traffic control. On the one hand, build a meteorological - control - crew linkage platform to break down the information barriers among various departments. With the help of this platform, meteorological data can be collected in real time. Based on the analysis results, "Suggestions on the impact of weather on Flight Operations" can be automatically generated, providing a strong reference for the reasonable planning of detour routes and the timely adjustment of aircraft takeoff and landing periods. In addition, the "Suggestions on the Impact of Weather on Flight Operations" is integrated into the air traffic control automation system, enabling civil aviation controllers to obtain it quickly and make scientific decisions accordingly. This avoids flight chaos caused by poor information transmission or delayed decision-making, ensuring the safe and orderly operation of flights under complex weather conditions. On the other hand, the "Weather Impact Index (WII) Model" was developed to quantify the risk levels of flight operations under different weather scenarios. Highly targeted traffic management strategies were provided for different risk levels, enabling control workers to flexibly adjust response strategies in combination with the degree of weather risks, and improving the scientific decision-making and collaborative efficiency of civil aviation air traffic control under complex weather conditions. Provide a strong guarantee for the safe operation of civil aviation.

3 Challenges and Countermeasures

At present, the civil aviation air traffic control meteorological support system based on intelligent technology has achieved remarkable results in improving the timeliness of early warnings, optimizing decision-making efficiency, and saving costs. However, it also faces many challenges. In-depth analysis of the prominent problems it faces and the proposal of practical countermeasures and suggestions are of great significance for promoting the continuous development and improvement of this system.

3.1 Existing Problems

3.1.1 Data Security Risks

Data is the core element of the intelligent civil aviation air traffic control meteorological support system. Although multi-source data fusion provides strong support for precise monitoring and forecasting of complex weather, it also increases data security risks. Civil aviation meteorological data is abundant, covering flight operation information, sensitive meteorological parameters and many other contents. In the process of cross-departmental and cross-system sharing, due to the lack of a complete encryption and permission management mechanism, civil aviation meteorological data is facing huge risks. On the one hand, the existing encryption technologies are unable to effectively resist increasingly complex cyber attack methods, resulting in the illegal acquisition, tampering or leakage of meteorological data during transmission and storage. On the other hand, the chaotic permission management leads to ineffective supervision of data access. Some personnel may obtain sensitive data beyond their authority, resulting in information leakage. This seriously threatens the safety of civil aviation flights and the privacy of passengers, which is extremely unfavorable for the long-term development of the civil aviation industry.

3.1.2 Model Generalization Challenge

The geographical environments where different airports are located vary, ranging from mountainous areas with complex terrain to coastal areas with diverse climates, all of which pose strict requirements for the adaptability of intelligent models. However, at present, intelligent models are facing the problem of generalization in the application of various airports. In order to enable the intelligent model to accurately simulate the meteorological conditions of each airport, it is urgent to carry out localized training. However, this process must invest a large amount of computing power resources. The existing computing power resources are limited and unevenly distributed, resulting in poor application effects of intelligent models at various airports and inability to provide accurate weather forecasts and decision support for flights at each airport.

3.1.3 Talent Gap

The construction of the civil aviation air traffic control meteorological support system based on intelligent technology cannot do without a large number of compound talents who are proficient in meteorological professional knowledge and intelligent technology. However, in practical applications, such highly specialized talents are extremely scarce. In the traditional education system, the meteorology major is relatively independent from majors such as computer science and data analysis. Students in each major master the knowledge of their respective professional fields, resulting in meteorological professionals being proficient in basic meteorological knowledge and business processes, but having only a superficial understanding of big data analysis and processing, AI algorithms, etc. Although AI technical talents are proficient in advanced algorithms and programming skills, they have no understanding of meteorological professional knowledge. They have great difficulties in developing related model operations, which seriously restricts the technological innovation and promotion and application of the civil aviation air traffic control meteorological support system.

3.2 Suggestions for Improvement

3.2.1 Technical Aspect

To effectively address the issue of data security risks, the following measures can be taken. Firstly, build a civil aviation meteorological data middle platform to uniformly access and standardize the processing of multi-source data from meteorological satellites, radars, automatic weather stations, etc. When accessing data, strictly standardize the data format and transmission protocol to ensure that data from different sources can be smoothly integrated. In the standardization processing stage, a series of operations such as data cleaning, transformation and integration should be carried out to remove noisy data, unify data coding, and lay the foundation for subsequent data storage, analysis and model training, etc. Moreover, the data middle platform must have powerful data management functions, monitor the entire data life cycle throughout, and ensure the security and reliability of the data. Secondly, introduce federated learning technology. Federated learning enables airports to achieve collaborative training of data without sharing the original data. Each airport only needs to encrypt and process the local data, extract the data features, and upload them to the federated learning platform to participate in the aggregation training. During this process, the model parameters are encrypted and exchanged among the participants, and finally a general model is obtained to effectively protect the data privacy of each airport and improve the generalization ability of the model.

3.2.2 Management Level

Promote the implementation of the "Civil Aviation Air Traffic Control Meteorological Information Sharing Specifications", clarify the responsibilities and authorities of each department in the process of meteorological information sharing, and detail the procedures and standards for data collection, transmission, storage and use. At the same time, a strict data access control mechanism should be established, clearly stipulating that only authorized personnel can access specific data to prevent illegal acquisition and abuse of data. Furthermore, a data security audit system should be established to regularly review the data sharing process, promptly identify and correct potential data security issues, and ensure data security. In addition, joint emergency drills of "meteorology - control" are carried out. Regular simulations of flight operation conditions under complex weather scenarios such as thunderstorms, low-altitude wind shear, and icing are conducted to enhance information communication and collaborative cooperation between the meteorological department and the control department, and improve their collaborative response capabilities to complex weather emergencies. Meanwhile, constantly summarize the experiences and lessons learned from practical drills, promptly optimize the emergency response process and coordination mechanism, and enhance the overall efficiency and scientific nature of decision-making in dealing with complex weather conditions.

3.2.3 Strengthen talent cultivation

Strengthening talent cultivation is the fundamental strategy to solve the problem of talent gap. In response to this, relevant departments can collaborate with universities to establish an interdisciplinary subject called "Intelligent Meteorology for Civil Aviation", integrating knowledge from multiple disciplines such as meteorology, computer science, and machine learning, and cultivating professional talents with the ability to conduct meteorological modeling and data analysis in a targeted manner. Meanwhile, enterprises are encouraged to carry out industry-university-research cooperation with universities, providing students with practical opportunities and cultivating compound talents who are proficient in both theory and practical ability, so as to meet the high-quality requirements of the civil aviation air traffic control meteorological support system for talents.

4 Conclusions and Prospects

4.1 Main Conclusions

To sum up, civil aviation meteorological monitoring and forecasting have always been a core issue of high concern in the civil aviation industry. When dealing with complex weather phenomena, traditional aviation meteorological monitoring and forecasting have exposed drawbacks such as monitoring blind spots, information islands and insufficient forecasting accuracy. To enhance the meteorological support capacity of civil aviation air traffic control under complex weather conditions, it is crucial to strengthen the deep integration of intelligent technology and civil aviation air traffic control meteorological business. Based on multi-source data fusion and intelligent monitoring, optimization of refined forecast models, dynamic decision-making and collaborative mechanisms, this paper constructs an intelligent civil aviation air traffic control meteorological support system, achieving remarkable results in terms of improving the timeliness of early warnings, optimizing decision-making efficiency, and saving costs. However, the challenges faced, such as data security, model generalization and talent gap, cannot be ignored either. To this end, it is urgent to take targeted improvement measures at multiple levels such as technology, management and talent cultivation, so as to gradually improve the civil aviation air traffic control meteorological support system and provide solid support for ensuring civil aviation flight safety and promoting the sustainable development of the civil aviation industry.

4.2 Outlook

In the future, efforts should be made to actively explore the global air route meteorological forecast technology that combines satellite remote sensing and AI. By leveraging satellite remote sensing to obtain meteorological information on a global scale, and at the same time, by integrating AI algorithms to efficiently process and analyze the data, more accurate meteorological forecast services can be provided for long-distance flights of flights. In addition, airport weather impact simulation based on data twins is also an important research direction. It can build a digital twin model of the airport to simulate the operation status of the airport under different weather scenarios, and assess in advance the impact of weather on flight take-offs and landings, airport facilities and other areas, providing comprehensive meteorological support for airport planning, operation and the construction of smart civil aviation.

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