Construction and Application Practice of the Data-driven Comprehensive Management Platform for Regional Air Quality

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Abstract To address the severe challenges of $PM_{2.5}$ and ozone co-control during the "14^{th} Five-Year Plan" period and to enhance the precision and intelligence level of air environment governance, it is imperative to build an efficient comprehensive management platform for regional air quality. In this paper, the specific practice in Zibo City, Shandong Province is as an example to systematically analyze the top-level design, technical implementation, and innovative application of a comprehensive management platform for regional air quality integrating "perception monitoring, data fusion, research judgment of early warnings, analysis of sources, collaborative dispatching, and evaluation assessment". Through the construction of an "sky-air-ground" integrated three-dimensional monitoring network, the platform integrates multi-source heterogeneous environmental data, and employs big data, cloud computing, artificial intelligence, CALPUFF/CMAQ, and other numerical model technologies to achieve comprehensive perception, precise prediction, intelligent source tracing, and closed-loop management of air pollution. The platform innovatively establishes a full-process closed-loop management mechanism of "data – early warning – disposition – evaluation", and achieves a fundamental transformation from passive response to active anticipation and from experience-based judgment to data driving in environmental supervision. The application results show that this platform significantly improves the scientific decision-making ability and collaborative execution efficiency of air pollution governance in Zibo City, providing a replicable and scalable comprehensive solution for similar industrial cities to achieve the continuous improvement of air quality.

Key words Comprehensive management of air quality; Big data; Internet of Things; Closed-loop management; Data driving; Off-site supervision
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With the continuous advancement of China's ecological civilization construction and the sustained development of industrialization and urbanization, regional and complex problems of air pollution have become increasingly prominent, and the control of air pollution has become a major issue related to people's livelihood and sustainable development[1]. The outline of the "14^{th} Five-Year Plan" clearly requires that it is needed to strengthen the management of urban air quality according to the standard, and promote the coordinated control of fine particulate matter ($PM_{2.5}$) and ozone (O_3)"[2-3], marking that the control of air pollution has entered a new stage of reducing pollution and carbon emissions, and achieving synergistic benefits. In this context, the traditional single and decentralized control model has been unable to meet the practical needs of precise pollution control and scientific haze reduction.

Zibo City, as an important industrial city on the transmission channel of air pollution in the Beijing – Tianjin – Hebei region, has a biased industrial structure and a large base of pollutant emissions, facing dual pressures of internal emission reduction and external input. The traditional environmental management model relying on manual inspections and decentralized decision-making is unable to cope with complex and variable air pollution processes, and it is urgently needed to utilize modern information technology means to build a comprehensive control platform that can integrate multiple resources and achieve intelligent decision-making and efficient execution.

To completely address the structural problems such as "inconsistent information sources, multiple alarms from different parties, multiple handling processes, and low management efficiency" in traditional environmental management, the Zibo Ecological Environmental Bureau, as well as technical support units, jointly developed and implemented a comprehensive control platform of regional air quality. This platform is based on the concept of "all-round environmental protection" and uses data driving as its core, aiming to create a "smart brain" that covers the entire chain of air environment management by integrating multiple sources of information and reengineering business processes. In this paper, the overall architecture, core construction contents, application of key technologies and implementation results of this platform were analyzed to provide solid case references for promoting the improvement of the environmental control system and capability.

1 Design of overall architecture

This platform adopts advanced cloud computing and big data technology architectures, and adheres to the principles of "data integration, business collaboration, and intelligent application". Meanwhile, it has constructed an overall framework centered

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around "data aggregation, monitoring and early warning, analysis and judgment, and collaborative dispatching", achieving intelligent and schedulable management of the entire ecological environment process (Fig. 1).

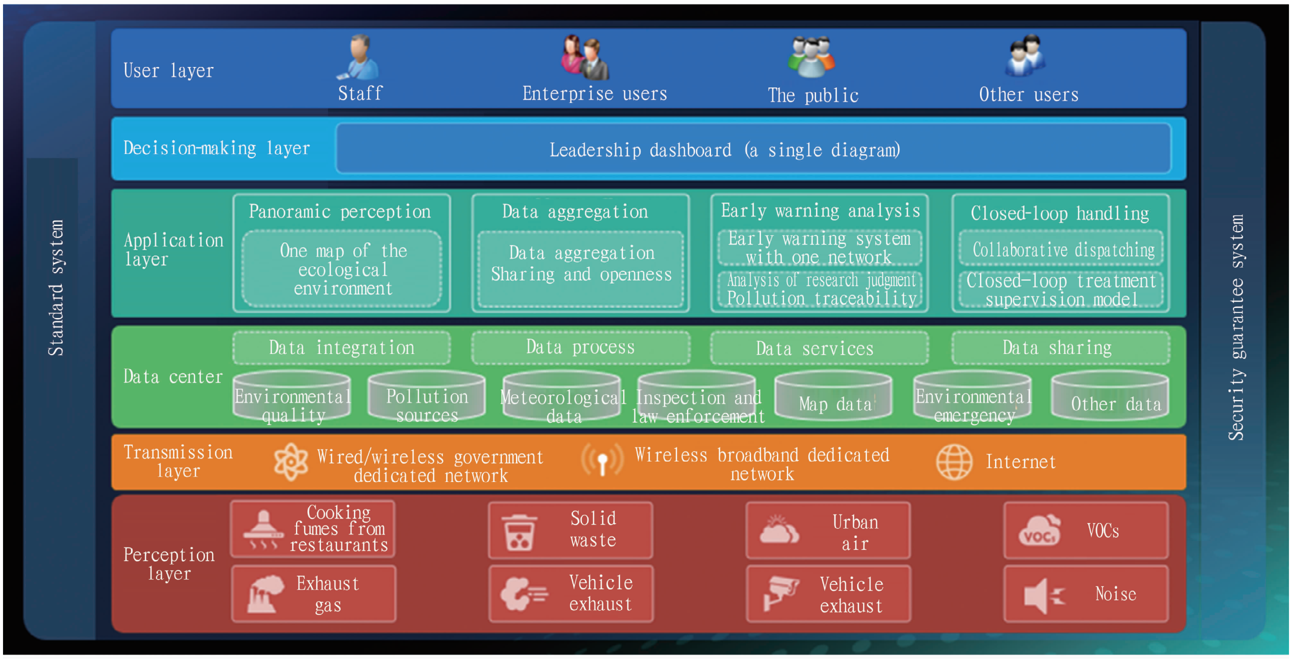

Fig. 1 Overall framework

1.1 Data aggregation center As the data foundation of the platform, data aggregation center is responsible for the comprehensive access and integration of various environmental data (Fig. 2). The data are from the monitoring networks of environmental air quality (national control, provincial control, municipal control, town offices, micro stations, super stations, component stations, *etc.*), monitoring networks of pollution sources (online monitoring of industrial waste gas, electricity supervision and control, VOCs monitoring, dust monitoring, OBD, *etc.*), video monitoring networks (high-altitude observation, enterprise video, and station video), and mobile monitoring data (drone, unmanned aerial vehicle, laser radar, *etc.*). By establishing unified data standards and ETL (extract, transform, and load) tools, it cleans, governs, and integrates multi-source heterogeneous data, builds an integrated and open thematic data warehouse for atmospheric quality control, effectively breaks down data barriers, and provides a unified and reliable data support platform for upper-level monitoring and early warning, analysis and judgment, and collaborative scheduling.

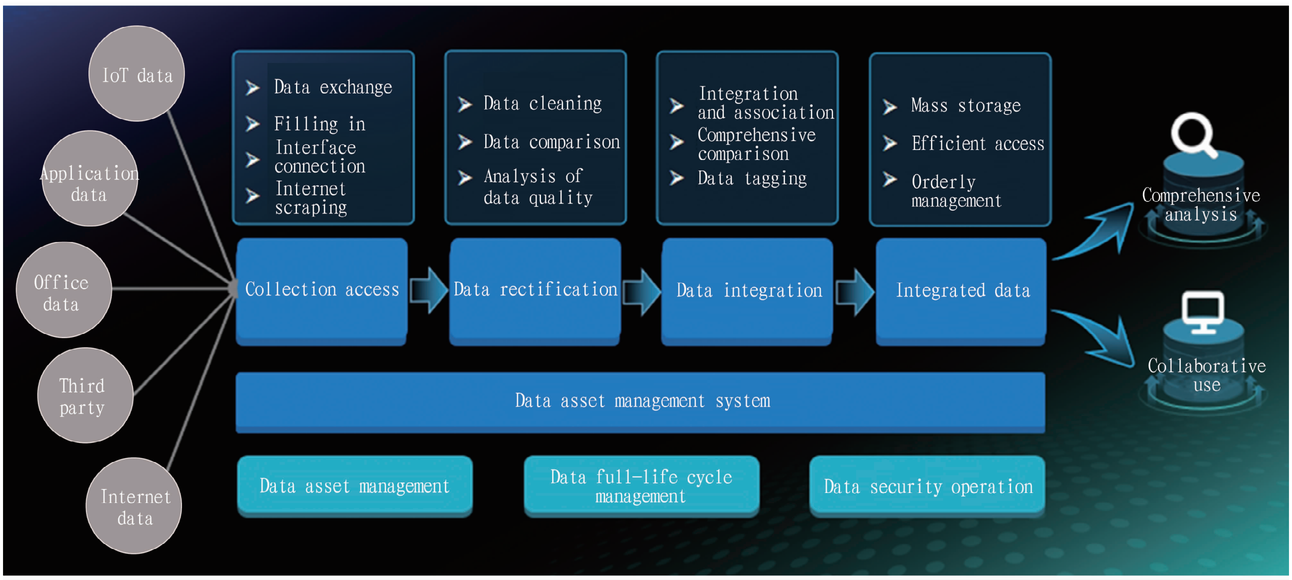

Fig. 2 Data aggregation

1.2 Monitoring and early warning center This center serves as the "perception nerve" and "early warning sentinel" of the platform. Based on the established "sky – air – ground" integrated monitoring network, it conducts real-time scanning and analysis of the aggregated standardized data products through the warning model rule library and intelligent algorithm model library (including machine learning algorithm library and statistical analysis algorithm library) (Fig. 3). When the data reaches the preset threshold or is abnormal, the system automatically triggers warnings (such as high values at air stations, abnormal emissions from enterprises), generates warning events according to the warning level, and pushes them to the subsequent processing flow. The warning method has gradually evolved from the transactional "single warning" to the analytical "comprehensive warning", and ultimately to the AI-based "intelligent warning", providing pre-processing support for quickly identifying problems.

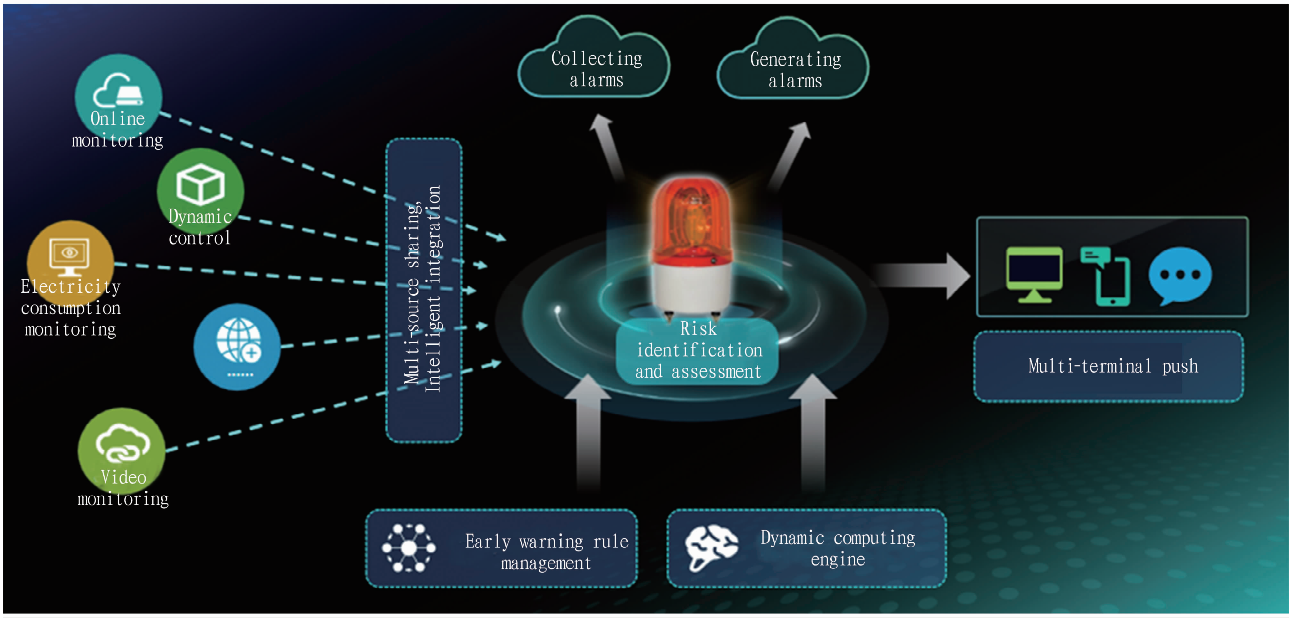

Fig. 3 Warning center

1.3 Analysis and research judgment center This center serves as the "decision-making engine" of the platform. Its core is a GIS-based visual system for atmospheric environment mapping, which presents the air quality situation of the entire city, the distribution of pollution sources, and warning information comprehensively, as well as the dynamic emissions of pollution sources at a micro level. Based on this, it integrates powerful analysis and research judgment functions as follows.

(1) For overall situation, it continuously monitors the current status of air quality, compliance rates, and city ranking, and comprehensively presents the changing trends of the city's environmental air quality.

(2) In terms of prediction and forecasting, numerical models and AI algorithms are used to predict future air quality, supporting pre-event research judgment.

(3) According to meteorological conditions and data of emissions of pollution sources, key pollution areas and emission sources are accurately identified to analyze pollution causes through local traceability, air chain query, source analysis, *etc.*

(4) The components and tracers of VOCs are analyzed to identify key sources.

1.4 Collaborative dispatch center This center serves as the "command center" of the platform, achieving the closed-loop management of the process and the regular evaluation of efficiency. On the one hand, it integrates the entire business process from the generation of warnings, task dispatching (including platform clue assignment and WeChat high-value reminder "dual push"), and on-site handling to result feedback and review and cancellation. Through customized configuration of the process, it can flexibly adapt to the requirements of different scenarios such as early warning verification, petition and complaint handling, and environmental protection supervision, ensuring "horizontal coverage from all sides and vertical implementation throughout the entire process" for coordinated scheduling. On the other hand, a scientific assessment and evaluation system is established to quantitatively evaluate data quality, handling efficiency (such as completion rate of work orders), and control effect (such as improvement of regional pollution) from the dimensions of departments, positions, and personnel. Through multi-dimensional statistics (alarm types, regional rankings, *etc.*), it provides objective basis for management optimization and performance assessment, implements "one post, dual responsibilities", ensures the smooth operation of the closed-loop management process, and promotes the transformation from "target-driven supervision" to "data-driven supervision".

2 Core functional modules and application of key technologies

Focusing on the core business of atmospheric environment management, the platform integrates and collects information on atmospheric environmental elements, and builds a smart supervision system based on the current situation of atmospheric environment and key requirements for pollution control and management in Zibo City. The platform consists of four functional modules as follows.

2.1 Panoramic sensing Based on a three-dimensional monitoring network covering the entire city, the platform integrates multi-source real-time data to build a GIS one-map visualization system, enabling panoramic perception of the environmental situation. This system connects 23 national, provincial, and municipal air monitoring stations, 787 town-level stations, 44 micro-stations, 1 011 fixed online monitoring points for waste gas pollution sources, 367 VOCs monitoring points, and 12 619 electricity monitoring points of 2 056 enterprises. It also integrates 7 000 sets of OBD, 5 000 sets of non-road machinery monitoring equipment, VOCs component stations and super stations in 15 chemical industrial parks, and other multi-dimensional monitoring data (Fig. 4 – Fig. 6). With the continuous improvement of the monitoring network, the platform has gradually achieved comprehensive perception of atmospheric environmental elements in the city.

Fig. 4 Environmental quality data access system

Fig. 5 Pollution source data access system

The platform also integrates 100 sets of high-altitude video surveillance, 2 440 channels of video surveillance of pollution sources, and 7 sets of laser radar monitoring data. Regular ship-borne monitoring, unmanned aerial vehicle flight patrols and other auxiliary monitoring methods are used to establish a comprehensive and all-weather environmental and pollution source monitoring system with a three-dimensional structure, thereby continuously enhancing the "sky – air – ground integrated" comprehensive monitoring capability for precise positioning and rapid response.

Fig. 6 Video data access system

Through two-dimensional and three-dimensional GIS and visual charts, the system dynamically presents the spatial distribution of air quality, the emission status and changing trend of pollution sources, supports spatial operations such as buffer analysis and interpolation analysis, quickly identifies high-value areas and diffusion trends, achieves the combination of grasping macro trends and tracking micro pollution sources, and provides comprehensive and intuitive data support for making decisions.

2.2 Data collection To break down data barriers and optimize data management, the platform is committed to building an environmental data center that covers the entire area, is managed in an integrated manner, and is open and shared. It comprehensively integrates multi-source data from key business systems of environmental air, surface water, drinking water sources, pollution sources, and motor vehicles, including visual data from video surveillance (*e. g.* air stations, pollution sources, and aerial observation), as well as front-end sensing data from sensors at air quality monitoring stations and fixed online monitoring points of pollution sources (Fig. 7).

Fig. 7 Data aggregation system

In response to the problem of inconsistent data standards among various business systems and the difficulty of effective connection in the past, the platform has continuously promoted the standardization governance and integrated cleaning of data resources, and has carried out step-by-step standardization construction of global business data, so as to build a unified database. Through these measures, the foundation of data information resources is effectively consolidated, and solid support is provided for subsequent big data correlation analysis and the precise capture and efficient utilization of data information, thereby effectively serving the decision-making needs for scientific and precise pollution control.

2.3 Early warning research judgment and traceability analysis Early warning research judgment and traceability analysis are the core capabilities of the platform, aiming to achieve early perception of pollution situations and precise responses (Fig. 8). The platform builds a complete chain of "prediction – early warning – traceability – research judgment" through the following mechanisms.

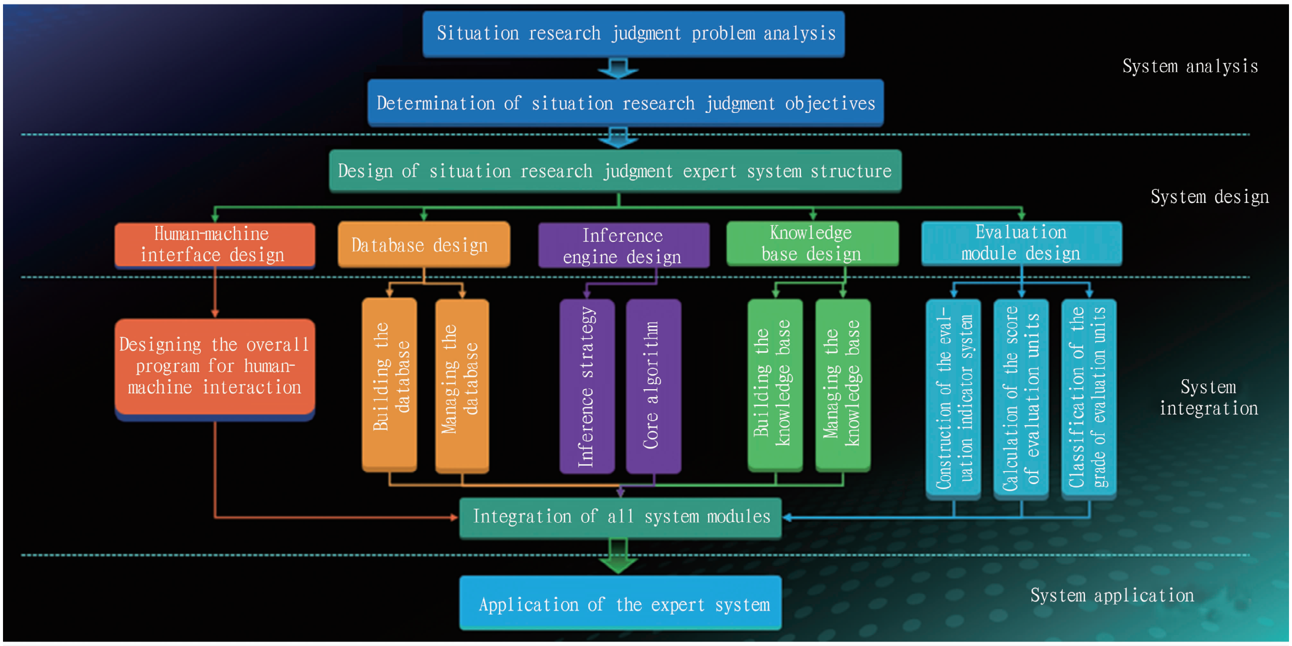

Fig. 8 Early warning and analysis

2.3.1 Precise prediction and intelligent early warning.

2.3.1.1 Long-term precise forecast. The platform integrates the WRF meteorological model, the CMAQ/CALPUFF atmospheric dispersion model, and machine learning algorithms[4] to achieve precise and detailed forecasts of air quality in different time periods and for different pollutants in the next 7 days (Fig. 9), providing scientific basis for making macro-level decisions.

Fig. 9 Forecast system of air stations

2.3.1.2 Real-time high-value warning. It dynamically scans the data of hourly concentration at monitoring stations, intelligently identifies sudden increases in concentration, promptly triggers high-value alerts, and supports the "early detection and early response" of pollution processes.

2.3.1.3 Automatic push loop. The platform supports the automatic generation of warning information at night and pushes it to relevant work groups hourly through intelligent robots, thereby achieving unattended real-time warning system and significantly improving response efficiency.

2.3.2 Multidimensional dynamic analysis of traceability. The platform builds a traceability system integrating multiple technologies, and forms a three-dimensional and precise portrait of pollution causes.

2.3.2.1 Dynamic and rapid traceability. Based on real-time data of wind field, it automatically identifies potential pollution sources in the upwind direction of the monitoring sites, and quickly identifies the suspected targets according to online monitoring and power consumption monitoring data of enterprises.

2.3.2.2 Depth analysis of numerical models. CMAQ/CALPUFF and other models are used to simulate the processes of pollutant transport, diffusion and transformation, and quantitatively assess the contribution rate of different regions and industries to pollution sources.

2.3.2.3 Fingerprint analysis of VOCs components. Based on the monitoring data from super stations and component stations, the specific source characteristics of chemical processes, solvent usage, mobile sources, *etc.* are precisely interpreted through the analysis of VOCs component spectra and tracer identification.

Fig. 10 Traceability analysis system

2.3.3 Data fusion and research judgment support.

2.3.3.1 All-region perception network. Based on a "four-level" monitoring network covering the entire city (including 23 standard stations, 787 township-level stations, 44 micro-stations, and over one thousand online monitoring points for pollution sources), integrated data from sky, air and ground sources such as video surveillance, lidar, and drifting monitoring are used to achieve panoramic perception of environmental situations.

2.3.3.2 Intelligent analysis engine. Through AI models, it can automatically identify abnormal emissions, analyze related sites, and integrate meteorological conditions for comprehensive research judgment, providing a multi-dimensional evidence chain for the determination of pollution causes.

2.3.3.3 Collaborative decision support. The platform has established a multi-level consultation mechanism of "daily consultation, weekly research judgment, and monthly assessment", and integrates intelligent report generation functions, significantly enhancing the scientificity and efficiency of making environmental decisions. The "routine consultation" module in the system can automatically generate a structured *Report on Control Measures* based on the results of real-time monitoring, prediction and analysis of sources. The report content covers key information such as the current state of the atmospheric environment, emission characteristics of pollution sources, air quality predictions, conclusions of traceability analysis, and comparisons between historical control measures, achieving a rapid transformation from data to decision support.

Through template-based and automated report generation, the consultation preparation time has been significantly shortened, so that experts and management personnel can focus on research judgment analysis and strategic formulation. Meanwhile, the platform has also established a closed-loop management process of "pre-event research judgment – in-event supervision – post-event assessment", and has a "historical control measure library" for accumulating and reusing expert experience. The effective strategies formed during each consultation are all entered into the knowledge base to support the system's continuous self-learning and optimization, thereby continuously improving the accuracy and practicality of subsequent control suggestions and enhancing the iterative enhancement of consultation decision-making capability. The platform has cumulatively supported over 500 consultation and analysis sessions, significantly improving the accuracy and response efficiency of pollution control[5].

2.4 Closed-loop disposal and process management The platform has established a closed-loop collaborative scheduling mechanism, and achieved the digitalized management of the entire process of environmental issues from discovery to cancellation. This mechanism has established a standardized disposal process of "monitoring – warning – pushing – disposal – feedback – review – cancellation". When the system identifies high values of air quality, abnormal emissions from pollution sources, smart power consumption alarms, aerial or unmanned vehicle patrols, and other multiple clues, task work orders are automatically generated, and synchronously pushed to corresponding responsible units and law enforcement officers through both the platform and mobile terminals.

During the process execution, the system uniformly gathers and intelligently screens multiple alarm information, and precise hourly push of tasks are achieved by the "platform assignment + WeChat reminder" method. The disposal personnel need to go to the site for verification and then feedback handling results on the platform. After review and confirmation, the cancellation can be made. The entire process realizes online trace and dynamic traceability, and is equipped with a reminder and supervision function to ensure closed-loop implementation.

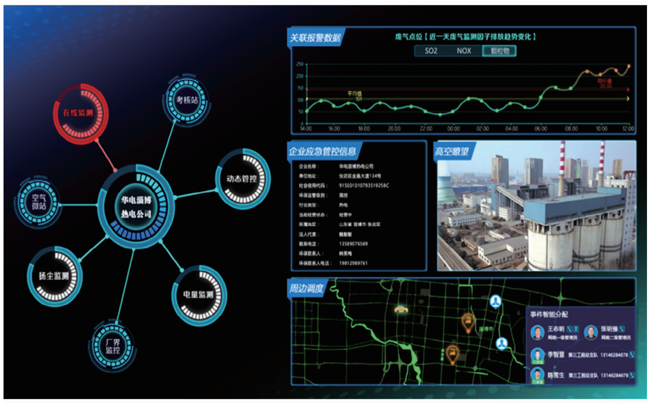

Fig. 11 Closed-loop disposal system

This mechanism effectively connects the monitoring, supervision and law enforcement processes, forming an efficient synergy between off-site supervision and on-site law enforcement. The system integrates multiple sources of clues such as high values of environmental monitoring data, abnormal data of excessive emissions from pollution sources, smart alarms of electricity usage, drifting monitoring, and unmanned aerial vehicle inspections into the early warning, verification, disposal and dispatching management center. After analysis and judgment, the platform has cumulatively pushed and handled more than 16 000 problem clues, including over 6 000 problem clues from the online monitoring system, over

1 000 problem clues from grids at micro stations, over 700 first-level alarms of smart electricity, and over 8 300 hourly high-value clues of air quality from town offices. Through the entire process of digital management, the systematic and refined level of environmental supervision has been significantly enhanced, and the profound transformation of the governance model from passive response to active intervention has been promoted.

3 Implementation results

The construction and application of this platform have systematically promoted three major transformations: First, the regulatory framework has shifted from the "single effort" of environmental protection departments to the collaborative and joint governance approach involving all parties. Secondly, the regulatory model has changed from a reactive approach to an active anticipation and investigation-oriented approach. Thirdly, the law enforcement method has evolved from a broad and random enforcement approach to a precise and non-site enforcement approach. Ultimately, through information and intelligent means, the environmental governance efficiency and environmental quality have been effectively enhanced, and the happiness and satisfaction of the people have been increased. Since the platform was put into operation, the regulatory efficiency of air environment in Zibo City has significantly improved, and substantial achievements have been made in regulatory efficiency, scientific decision-making, precise law enforcement, and collaborative governance.

3.1 The regulatory efficiency has achieved a leapfrog improvement The platform integrates various sources of data from the monitoring networks of air quality and pollution sources in the city, builds a unified IoT perception system covering the entire area, forms a unified thematic data warehouse for air quality management, and initially achieves data integration and business collaboration. Through unified scheduling on a "single platform", the problems of scattered information sources, multiple alarms, and low disposal efficiency in the past are effectively solved. Up to now, the platform has triggered over 34 300 alerts, completed 29 000 closed-loop dispositions, achieved the uninterrupted monitoring of the atmospheric environment and pollution sources during 7 × 24 hand, and significantly improved regulatory response speed and disposal efficiency.

3.2 The scientific nature of decisions has significantly improved The platform can achieve the precise prediction and traceability analysis of pollution trends based on big data analysis and intelligent models. Through methods such as comparative analysis, trend prediction, and site correlation, the system can infer the emission and diffusion patterns of pollutants, providing data support for daily consultations and emergency control. In response to severe pollution weather, the platform helps formulate differentiated plans for emission reduction, and minimizes the impact on economic and social activities to the greatest extent while ensuring the improvement of air quality.

3.3 The accuracy of law enforcement has significantly enhanced The platform has adopted a closed-loop mechanism of "one clue, and multiple sets of evidence" to transform the law enforcement model from a "massive force tactic" to a "targeted" and precise enforcement approach. Based on multi-dimensional data of electricity monitoring, hotspots grids, and online monitoring, the system automatically identifies abnormal behaviors and generates a list of suspects, realizes the rapid identification and precise crackdown of illegal pollution activities, and significantly enhances the efficiency and deterrent power of law enforcement.

3.4 Comprehensive optimization of governance coordination Through reengineering of business processes, the platform establishes a closed-loop management mechanism of "monitoring – warning – pushing – handling – feedback – cancellation", clearly defines the responsibility of each department, and forms a coordinated governance pattern across levels and businesses. Relying on the data-driven concept, it promotes the regulatory model to shift from passive response to active discovery and from single department management to all-staff governance, and gradually builds a systematic environmental governance system "from points to categories, and from categories to areas".

In summary, through data integration, process reengineering and intelligent application, the platform has comprehensively enhanced the refinement, intelligence and coordination level of air environment management in Zibo City, providing solid technical support for the continuous improvement of regional air quality.

4 Conclusions and prospects

The construction and application of the comprehensive control system of air quality in Zibo City is a successful practice of the deep integration of information technology and environmental management business. Through constructing the overall architecture of four centers, this platform deeply integrates key technologies such as big data, AI, and numerical models, and innovatively establishes a full-process closed-loop management mechanism. It effectively solves the pain points of traditional environmental management such as "data islands, delayed analysis, inaccurate warnings, and poor coordination", and realizes the digitalization, intelligence, and collaboration transformation of air environment governance.

In the future, the platform can further develop in the following aspects. Firstly, it integrated with the "carbon neutrality" goal to explore new paths for the coordinated control of air pollutants and greenhouse gases. Secondly, the research on model accuracy and uncertainty is strengthened, and the accuracy of simulation and prediction of secondary pollutants such as ozone is improved. Thirdly, it evolves towards the "digital twin" direction, build a digital twin of the urban atmospheric environment that interacts with the physical world in real time, and achieve higher-level simulation, deduction, and strategy optimization. The experience of this case indicates that the comprehensive control system centered on data driving is the key support for improving the efficiency of regional air environment governance in the current and future periods, and has a broad promotion value and application prospects.

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(From page 20)

low-level westerly jet stream of southerly wind at 700 hPa, and the strengthening of the cold cushion at 850 hPa, the mesoscale cloud masses further moved eastward and developed into mid-α-scale cloud masses (the inverted trough in Hetao area was affected by cold air and retreated southward). Along with the eastward movement of the heavy snowfall, the snowfall intensity in the southeast of Ordos weakened. At 15:00 (Fig. 5d), cloud mass A moved to Beijing, and cloud mass C moved to the junction of Ulanqab and Datong. From 15:00 to 16:00, the maximum snowfall occurred at Zhongning Station, up to 6.5 mm. As the cold air carried by the westerly airflow at 700 hPa infiltrated the cloud masses, gradually weakened and moved eastward, cloud mass D moved to the south of Ulanqab, and cloud mass C moved to the north of Hebei Province at 17:00. The intensity weakened significantly, and the lowest brightness temperature on the top of clouds was −56 ℃. Afterwards, the snowfall weakened, and significantly decreased at 20:00. The blizzard in the southeast of Ordos was caused by the mid-β-scale cloud mass generated above the low-level southerly airflow, while the blizzard in other areas was caused by the continuous merging and eastward movement of mid-β and mid-α cloud masses, and the TBB of the cloud masses causing the blizzard was ≤ −56 ℃. The blizzard occurred in the the edge gradient and large-value area of TBB.

7 Conclusions

(1) During this process, the presence of low trough at 500 hPa, the southerly wind jet stream at 700 hPa, easterly airflow at 850 hPa, cold high pressure and inverted trough on the ground provided favorable background conditions for this blizzard. The transportation of warm and humid air by the southerly wind jet stream at 700 hPa and intense water vapor convergence provided sufficient water vapor conditions for the blizzard. From the ground to 300 hPa over the blizzard area, there was a deep moist layer with relative humidity ≥90%, and the area of heavy snowfall corresponded to the low-level water vapor flux convergence zone.

(2) The blizzard occurred in the lower area with MPV <0, and the atmosphere was in a conditionally symmetric unstable state. The heavy snowfall ended with the release of the conditionally symmetric instability.

(3) The strong interaction between weather systems and the strong updraft induced by the low-level jet were one of dynamic factors contributing to the occurrence of the blizzard. With the invasion of cold air, a low-level cold pad was formed, so that the warm and humid air tilted upward along the cold pad. The secondary circulation updraft triggered by the wet Q vector system released the conditional symmetric instability energy, so that the sloping motion was more intense, and the heavy snowfall happened. At the same time, there was a good correspondence relationship between the blizzard area and the large-value area of low-level wet Q vector divergence.

(4) The blizzard in the southeast of Ordos was caused by the mid-β scale cloud cluster generated above the low-level southerly airflow, while the blizzard in other areas were caused by the continuous merging and eastward development of mid-β and mid-α cloud clusters, and the TBB of the cloud clusters was ≤ −56 ℃. The blizzard appeared in the the edge gradient and large-value area of TBB.

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