An Integrated System for Regional Environmental Monitoring and Management Based on Internet of Things

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***Abstract*—Climate change and environmental monitoring and management have received much attention recently, and an integrated information system (IIS) is considered highly valuable. This paper introduces a novel IIS that combines Internet of Things (IoT), Cloud Computing, Geoinformatics [remote sensing (RS), geographical information system (GIS), and global positioning system (GPS)], and e-Science for environmental monitoring and management, with a case study on regional climate change and its ecological effects. Multi-sensors and web services were used to collect data and other information for the perception layer; both public networks and private networks were used to access and transport mass data and other information in the network layer. The key technologies and tools include real-time operational database (RODB); extraction–transformation–loading (ETL); on-line analytical processing (OLAP) and relational OLAP (ROLAP); naming, addressing, and profile server (NAPS); application gateway (AG); application software for different platforms and tasks (APPs); IoT application infrastructure (IoT-AI); GIS and e-Science platforms; and representational state transfer/Java database connectivity (RESTful/JDBC). Application Program Interfaces (APIs) were implemented in the middleware layer of the IIS. The application layer provides the functions of storing, organizing, processing, and sharing of data and other information, as well as the functions of applications in environmental monitoring and management. The results from the case study show that there is a visible increasing trend of the air temperature in Xinjiang over the last 50 years (1962–2011) and an apparent increasing trend of the precipitation since the early 1980s. Furthermore, from the correlation between ecological indicators [gross primary production (GPP), net primary production (NPP), and leaf area index (LAI)] and meteorological elements (air temperature and precipitation), water resource availability is the decisive factor with regard to the terrestrial ecosystem in the area. The study shows that the research work is greatly benefited from such an IIS, not only in data collection supported by IoT, but also in Web services and applications based on cloud computing and e-Science platforms, and the effectiveness of monitoring processes and decision-making can be obviously improved. This paper provides a prototype IIS for environmental monitoring and management, and it also provides a new paradigm for the future research and practice; especially in the era of big data and IoT.**

***Index Terms*—Big data, climate change, cloud computing, enterprise systems, environmental monitoring and management, e-Science, geoinformatics, industrial informatics, Internet of Things (IoT), system integration.**

I. Introduction

ENVIRONMENTAL issues such as climate change have received much attention in recent years, and environmental monitoring, modeling, and management enable us to gain a deeper understanding of natural environmental processes. Environmental monitoring and management is a broad area focusing on using scientific and engineering principles to improve environmental conditions. How to effectively monitor, model, and manage environmental processes is a critical task for both scientists and engineers.

Environmental informatics has experienced a very rapid development and wide application in monitoring, modeling, and managing environmental processes in the past decade. Environmental informatics involves specific environmental problems related to the applications of computer science and systems engineering techniques, management information system (MIS), and environmental information system (EIS), which were designed to collect, process, and exchange data and information since the 1980s. Automatic data acquisition has been accelerated by a variety of technologies, such as remote sensing (RS), geographical information system (GIS), global positioning system (GPS), and so on. From the 2000s, the proliferation of automatic data acquisition technologies, such as radio frequency identification (RFID) and sensor technologies, was introduced to create decision support systems (DSSs) and integrated environmental information systems (IEISs), and also brought new vitality to environmental monitoring and management.

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The rapid development and wide application of environmental informatics has significantly improved environmental monitoring, management efficiency, and effectiveness. However, both the DSSs and enterprise information systems (EISs) (or IEISs) were implemented to help locate and analyze environmental problems rather than to solve any environmental problems in reality. In the last decade, the Internet of Things (IoT), a concept describing how the Internet extends into people's everyday lives through a wireless network of uniquely identifiable objects [1], is predicted to be able to promote the entire process of environmental monitoring, modeling, and management, as well as to support sustainable decision-making. This paper focuses on the IoT application in the new generation of environmental informatics, and provides a new paradigm for environmental monitoring and management in the future.

II. Related Work

Integrated environmental monitoring and management based on IoT is an enduring and active topic, not only for the scientists and engineers, but also for the public and the administrators, and it covers broad issues and involves many technologies in the computer and information sciences. In this section, existing environmental monitoring and management issues are discussed with a focus on environmental informatics, corresponding EISs [2], and integrated information systems (IIS), as well as IoT, are also reviewed to clarify the essence of this work.

A. Environmental Informatics

Environmental informatics is an interdisciplinary field involving environmental science, computer science, information science, and industrial information integration engineering (IIIE). It formally started developing in the early 1990s in Europe to integrate and coordinate various informatics technologies and facilitate decision-making to intimately link the territory knowledge with expected social, economic, ecological, and environmental objectives [4], and it can help handle various kinds of environmental problems with more cost-effective and forward-looking solutions.

The spectrum of environmental informatics can be classified into five categories: 1) database system (DBS) [3]; 2) GIS; 3) DSS [4]; 4) expert system (ES); and 5) IEIS [5]. In China, Professor Jiulin Sun (academician of the Chinese Academic of Engineering) leads the development of Res-informatics, with topics on mechanism of resources information, development and application of Geoinformatics, information integration, information sharing, ES, data bank, visualization, modeling of resource environment, and establishment of simulated research environment of resource sciences [6], [7]. From the late 2000s, IoT represents how the Internet extends into people's everyday lives through a wireless network of uniquely identifiable objects [5] and it is predicted that IoT will promote the entire process of environmental monitoring and management in the near future. However, challenges remain in the proper handling of "Big Data" [8] in both scientific and industrial areas, which need effective mechanisms for the acquisition, processing, transmission, storing, and management of massive data and information, and new paradigm of integrated EIS is expected to provide good solutions for them.

B. Integrated Information System

A specific kind of EIS (i.e., DBS, GIS, DSS, and ES) in general has its own merits and limitations. DBS is the basic component of various EISs, but it is limited to spatial analysis and decision-making. The strength of GIS lies in spatial analysis and information visualization, but it falls short of data management and utility modeling. DSSs usually excel in extracting relational knowledge from multidimensional data comparison and organizing the interactions among users and models, but they are vulnerable to decision-makers' experiences and preference [1]. ESs are excellent in knowledge management but almost all of them are limited in knowledge acquisition.

Fortunately, IISs, which involve multiple types of technologies and tools of information and computer sciences, provide a good solution to the complex tasks in environmental monitoring and management. IIS is an array of multiple information sets linked together in an organized way [9], [10]. IISs and tools have been widely used in practicing environmental monitoring and management including ecosystem assessment and resources management. The core technologies of IIS and typical application cases have been discussed in literature [11]–[13]. Studies on environmental sustainability incorporating the information systems have been initiated for improving environmental and economic performance [14]. There are numerous studies on the applications of IISs in different areas within the framework of IIIE [15], [16], which is a set of foundational concepts and techniques that facilitate the industrial information integration process and comprise methods for solving complex problems when developing IISs [17], [18]. The applications of IIIE have covered areas such as business analytics [19], supply chain management [20], [21], resources and environment management [22], public health service [23], [24], integrated medical supply systems [25], knowledge management, and ERP in enterprise management [26], automated assembly planning system [27]–[29], service workflow management [30]–[33], and human-machine system design [34]. Furthermore, Web services and integrated models were used to create accessible interfaces and manage the integrated data sets in IISs [35].

C. Internet of Things

The IoT refers to uniquely identifiable objects and their virtual representations in an Internet-like structure [36]. The term "Internet of Things" was first used by Kevin Ashton in 1999 [37], and became popular through the Auto-ID Center and related market analysis publications [38]. RFID tags, sensors, actuators, and mobile phones are often seen as prerequisites for the IoT [39]. Key technologies of IoT include RFID technology, sensor network and detection technology, Internet technology, intelligent computing technology, and so on; however, technical challenges must be tackled before these systems can be widely applied [40].

The concept of IoT has been proposed more than 10 years, and it is not just staying at the concept level but is becoming a reality with the rapid development and wide application of wireless sensor network (WSN) [41] and cloud computing. Ongoing investments and specific work have been initiated to solve challenging research problems, to develop the necessary hardware and software, and to deploy the infrastructure required [42]. The combination of the Internet and the emerging technologies such as near-field communications, real-time localization, and embedded sensors could help us transform everyday objects into smart objects that can understand and react to their environment [43]. Furthermore, some technologies that have been widely used in resource management and environmental science are technical components of IoTs, such as RS, GIS, GPS, and so on.

In IoT systems, multi-sensor data fusion issues such as node signal processing, WSN localization, anti-collision, and information-aggregation are often formulated as optimization subjects [44]; data fusion of multi-sensor for IoT precise measurement based on improved PSO algorithms have been discussed [45]. The combination of sensors, WiFi, 3G, RFID, near field communication (NFC), and Bluetooth will allow significantly improved measurement and monitoring methods of vital functions of health (temperature, blood pressure, heart rate, cholesterol levels, blood glucose, etc.) [46]. Fueled by the recent adaptation of a variety of enabling wireless technologies such as RFID tags and embedded sensor and actuator nodes, the IoT has stepped out of its infancy and is the next revolutionary technology in transforming the Internet into a fully integrated Future Internet [47]. A naming, addressing, and profile server (NAPS) as a middleware to bridge different platforms in IoTs sensory environments has been presented for widely used standards and protocols [48]. A software framework architecture for mobile devices that aims to facilitate the development process of embedded RFID applications and the integration process of business applications and Electronic Product Code (EPC) Network instances has been introduced to provide a common communication interface to abstract different devices and reading protocols as well as functions to process and distribute data [49].

Application fields of IoT include smart product management, waste management, intelligent shopping, urban planning, continuous care, sustainable urban environment, smart meters, emergency response, smart events, home automation, and so on [50]. IoT technologies can be suitably applied to environmental monitoring applications with the ability of sensing, in a distributed and self-managing fashion, as well as to seamlessly integrate such heterogeneous data into global applications [51], [52]. The IoTs can offer people with disabilities the assistance and support they need to achieve a good quality of life and allow them to participate in the social and economic life [53]. IoT is also used in detailed fields of environmental monitoring and management including underwater resources management [54], wetland monitoring system [55], emergency management community [56], food supply chain [57], urban public safety emergency management early warning system [58], in-home health care devices and services [59], [60], pre-alarm system in mines [61], and planning, construction, and management toward sustainable cities [62].

Furthermore, a number of large-scale initiatives on IoT are active in the US, Europe, Japan, China, Korea, and other countries. There are also many research projects funded by various governments, such as the program on Cyber-Physical Systems in the US, the HYDRA project, the RUNES project, the IoT-A project, and the iCORE project in the European Commission [53].

D. Motivations of This Paper

From the previous reviews of related work, there has been much important progress in both the environmental informatics and their applications in environmental monitoring and management, and the development and broad application of a variety of EISs (i.e., DBS, DSS, GIS, ES, and IIS) have effectively improved the efficiency of processes simulation and decision-making in environmental monitoring and management.

However, both the architectures and applications of previous EISs have some apparent shortcomings. First, multisources of data and information are constantly expanding from multi-sensors, such as mobile devices, RS, software logs, cameras, RFID, and WSNs, and therefore, acquisition, processing, and management of big data is a severe challenge in IISs for environmental monitoring and management. Second, the effective association and fusion between IISs and data acquisition is another important topic to be further concerned, which has been rarely studied in the existing literature. Third, how to adapt multidimensional and multi-scale applications under deferent tasks and cloud services is another challenge in the next generation IISs [63].

Accordingly, high-level integrated, smart, and sustainable information systems should be developed for practices in the context of industrial environment and sustainable engineering, and it is obvious that IoT reflects the trends of informatics in the near future. Based on this, a novel IIS for regional environmental monitoring and management based on IoT has been introduced for improving the efficiency of environmental monitoring and management tasks, and the results from case study demonstrate that the IIS based on IoT is valuable and efficient for complex tasks in environmental monitoring and management in big data and cloud services.

III. System Architecture

The explosion of information technologies in the last decade has laid the foundation for integrative information architecture of the IIS for environmental monitoring and management, a novel IIS for regional environmental monitoring and management based on the framework of IoT has been developed in this work, and Fig. 1 presents the architecture of this IIS in detail.

The architecture of the IIS for regional environmental monitoring and management based on IoT contains four layers: perception layer, network layer, middleware layer, and application layer.

A. Perception Layer

The perception layer is mainly used for collecting data and other information of detailed factors of physical world (targets or tasks) in environmental monitoring and management, usually including real-time datasets, models/methods, knowledge, and others. The real-time data collection based on IoT is related to multi-sensors, including RS platforms (i.e., satellites, balloons, aircrafts, and radar), situ instruments (i.e., situ observation instruments for meteorological, hydrological, and ecological factors), mobile (i.e., 2G, 3G, and LTE), IEEE 802.X (i.e., WiFi, Bluetooth, and ZigBee), RFID, and other sensors. The

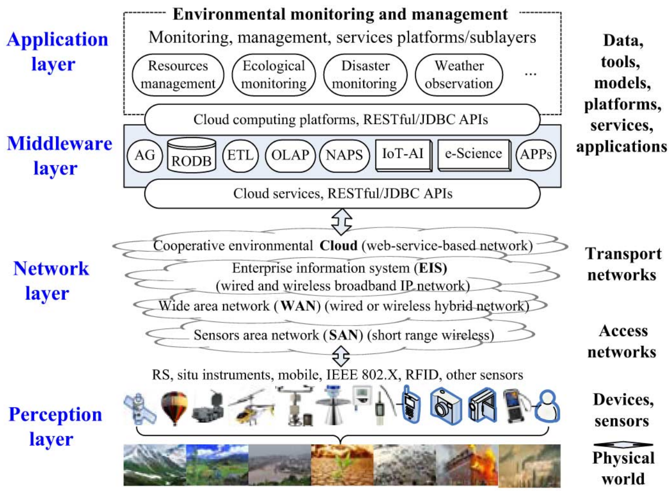

Fig. 1. Overall architecture of the IIS based on IoT.

perception layer makes masses of sensors and devices connected; the core and base of the layer is where the rapid development and wide application of sensor technologies in IoT will occur.

B. Network Layer

The network layer performs basic functions of data and information transmission as well as the interconnection of systems and platforms. The network layer mainly consists of access networks and transport networks. Access networks are short-range wireless networks, usually consist of Sensors Area Network (SAN), 2G, 3G, WiFi, and ZigBee are common components to support the connection of things (i.e., sensors, devices, and users) in environmental monitoring and management. In transport networks, various Wide Area Networks (WANs) of wired or wireless hybrid network are usually subsystems of EIS with wired and wireless broadband IP network, and EISs could be connected to the cooperative environmental cloud with Web-service-based global network [64]. European Telecommunications Standards Institute (ETSI), Machine to Machine (M2M) services architecture [65], 3rd Generation Partnership Project (3GPP), Machine-Type Communications (MTC) [66], the EPC-global architecture, transport protocols [HyperText Transfer Protocol/Transmission Control Protocol (HTTP/TCP) and Constrained Application Protocol/User Datagram Protocol (CoAP/UDP)], and Internet Protocol version 4/Internet Protocol version 6 (IPv4/IPv6) are common technologies or standards for the transport networks.

C. Middleware Layer

The middleware layer is a set of sub-layers for the management of data, software/tools, models and platforms, and interposed between the network layer and the application layer. Real-time operational database (RODB) is used for efficiently managing massive data generated by sensors and devices, and it is also used for storing and management of models, knowledge, and other information. Extraction–transformation–loading (ETL) is used to extract, transform, and load the demand information from the RODB in the IIS. Once the needed information is extracted and transformed to the required format, on-line analytical processing (OLAP) is realized through relational OLAP (ROLAP) and execute operations including slicing, dicing, roll up, drill-down, and pivoting. The NAPS is used to bridge different platforms in IoT sensory environments. Application gateway (AG), application software for different platforms and tasks (APPs), and IoT application infrastructure (IoT-AI) were introduced in the middleware layer for services and applications. Furthermore, GIS is used for temporal analysis of datasets, and e-Science platforms consist of Infrastructure as a Service (IaaS), Data as a Service (DaaS), Platform as a Service (PaaS), and Software as a Service (SaaS), which were used for computing and analysis in the IIS.

The middleware architectures proposed in the IIS based on IoT often follow the service-oriented architecture (SOA) approach, which allows for decomposing complex systems into simpler and well-defined applications and components, with common interfaces and standard protocols. Interactions between components, interfaces, applications, and protocols were implemented by representational state transfer (RESTful) APIs or Java database connectivity (JDBC) APIs.

D. Application Layer

The application layer of the IIS based on IoT mainly consisted of application support platforms, cloud computing platform, and e-Science platforms. The application layer provides the functions of storing, organizing, processing, and sharing the environment data and other information obtained from sensors, devices, and Web services, as well as the functions of taking professional applications in environmental monitoring and management, such as resources management, pollution monitoring (i.e., solid waste, noise, air quality, etc.) ecological monitoring, disaster monitoring and prediction, weather observation and forecasting, and so on.

The application layer is the top level and represents the final task of IIS for environment decision management and planning service. As the monitoring task is becoming more and more complex and more refined, more data coming from sensors and devices, and more information coming from Web services, processing, and management requires much powerful computational ability than before, and the technology for efficiently processing mass data and scientific models is necessary. Cloud computing that is based on virtualization technique and using networks as the carrier has merits of high reliability, extensity, and flexibility, thus providing a new technology for data processing and computation in the IIS, and it can integrate extensible data processing, information storage, and other distributed resources to make them work together.

IV. Case Study

IISs based on IoT has broad prospects in both scientific and industrial areas, as IISs are not only good solutions but also integrated platforms for complex tasks, and the features of IoT are exactly suitable for data collection and processing in the perception layer of IISs. Among the application fields where IISs and IoT solutions can provide competitive advantages and play important roles, environmental monitoring and management would be one of the most representative areas. This paper focuses

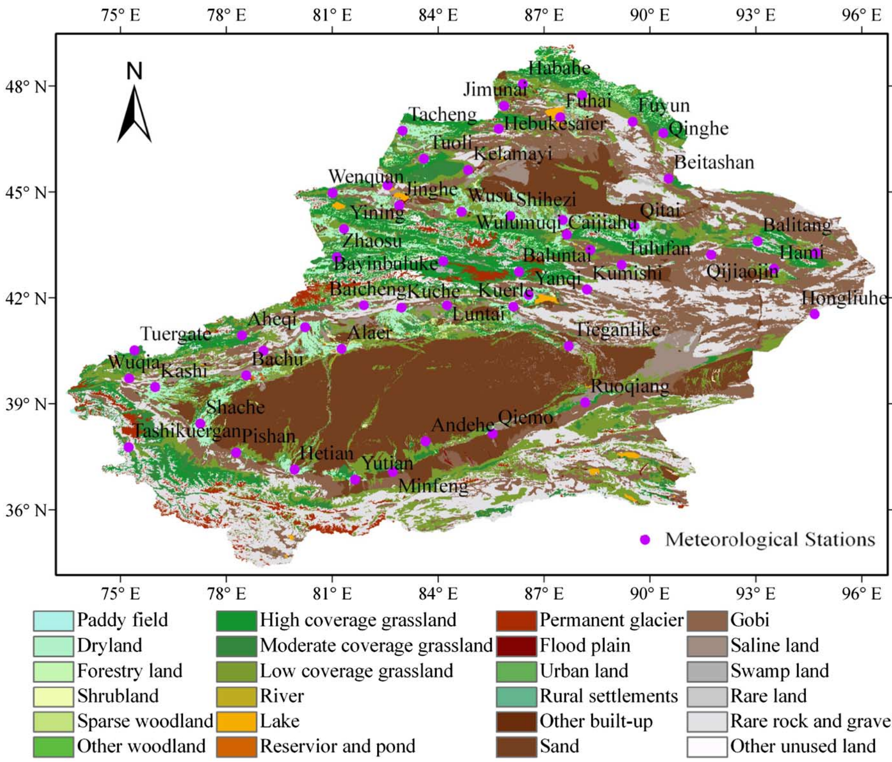

Fig. 2. Study area with land use types and meteorological stations distribution.

on the integration of key technologies from both IIS and IoT in typical environmental monitoring and management task, taking the regional climate change (i.e., air temperature and precipitation) and its ecological responses [i.e., gross primary production (GPP), net primary production (NPP), and leaf area index (LAI)] as an example, providing a paradigm for research in environmental sciences.

A. Study Area

The paper focuses on Xinjiang, which is located in the northwest of China and the center of Eurasia, as the typical study area (Fig. 2). Being far from the sea, and with alpine surrounds, it belongs to one of the typical arid and semi-arid areas in the world. The natural environment in this region is vulnerable and sensitive to climate change and human activities, and the temporal and spatial evidence of climate change over the past decades and its ecological responses has been discussed in existing literature [67]. Water resources and climatic conditions are decisive factors for restricting the sustainable development in Xinjiang [68], so understanding the intensity of climate change and its ecological responses is very important for the regional sustainable development in the area.

B. Data Collection

In order to analyze and present the climate change and its ecological responses in the study area, multisources datasets were collected from sensors and Web services under the framework of IIS based on IoT, which include: 1) 50 years (1962–2011) of hourly observational data of meteorological elements (i.e., air temperature and precipitation) from situ instruments and sensors distributed in the study area; 2) coupled Model Intercomparison Project, Phase 5 (CMIP5) multiple model simulations, and predictions data of meteorological elements (i.e., air temperature and precipitation) from Web services; 3) 10 years (2000–2011) of MODIS GPP/NPP datasets from Web services; and 4) 30 years (1981–2011) of AVHRR BU LAI products from Web services.

C. Models and Tools

The processing and analysis of multidimensional datasets need a set of models and tools, which are integrated in the middleware layer of IIS, datasets from both sensors and Web services, as well as models and tools are stored and managed in the RODB; extraction, transformation, and loading of the required information from the RODB are based on the ETL, when the needed information is extracted and transformed to the required format, OLAP (ROLAP) is used to execute operations including slicing, dicing, roll up, drill-down, and pivoting. AG, APPs, and IoT-AI are introduced in the middleware layer for detailed services and applications. Furthermore, GIS is used for temporal analysis of datasets, and e-Science platforms were used for computing and analysis in the IIS.

The results of GPP/NPP were calculated from the MODIS imagines based on the MOD17 algorithm, which is based on the original radiation use efficiency logic of Monteith (1972), which suggests that productivity of annual crops under well-watered and fertilized conditions is linearly related to the amount of absorbed solar energy specifically and the amount of absorbed photosynthetically active radiation (APAR). The translation of APAR to an actual productivity estimate is conducted via a conversion efficiency parameter ε, which varies by vegetation type and climate conditions. In consequence, MOD17

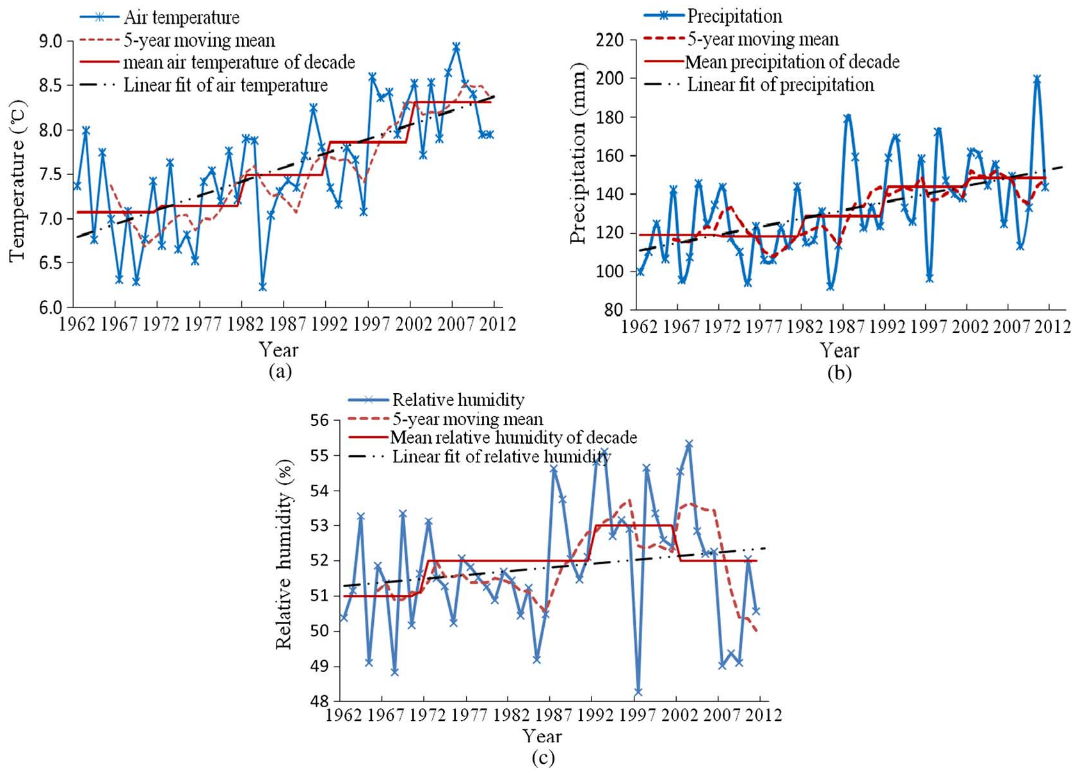

Fig. 3. Trends of meteorological elements in Xinjiang based on in situ observations from 1962 to 2011: (a) annual precipitation, (b) mean annual air temperature, and (c) mean annual relative humidity.

incorporates differences in maximum ε among vegetation types, and also lowers ε under water-stressed and/or cold temperature conditions

$$\mathrm{GPP} = \varepsilon \times \mathrm{APAR} \tag{1}$$

where ε is the radiation use efficiency, and absorbed photosynthetically active radiation (APAR) depends upon the geographic and seasonal variability of day length and potential incident radiation.

$$\mathrm{APAR} = \mathrm{PAR} \times \mathrm{FPAR} \tag{2}$$

where PAR is the incident radiation above the canopy (μ mol $\mathrm{m^{-2}s^{-1}}$) and FPAR is the fraction of incident PAR absorbed by the surface.

$$\mathrm{PAR} = \mathrm{SWRad} \times 0.45 \tag{3}$$

where SWRad is the incident shortwave radiation, which is provided in the dataset from NASA Data Assimilation Office (DAO).

$$\mathrm{FPAR} = 1 - \rho_a(\theta_s) - (1 - \rho_b(\theta_s))e^{(-G_t(\theta_s)\Omega \mathrm{LAI}/\cos\theta_s)} \tag{4}$$

where θ_s is the solar zenith angle; $\rho_a(\theta_\mathrm{s})$ and $\rho_b(\theta_s)$ are Albedo from above and below the canopy, respectively; $G_t(\theta_s)$ is the projection of the blades in the direction of θ_s; and Ω is the foliage clumping index, a parameter determined by the spatial distribution pattern of foliage

$$\varepsilon = \varepsilon_{\max} \times \mathrm{TMIN\_scalar} \times \mathrm{VPD\_scalar}. \tag{5}$$

The two parameters of daily minimum air temperature ($T_{\min}$) and vapor pressure deficit (VPD) are used to calculate the scalars that attenuate $\varepsilon_{\max}$ to produce the final ε (kg C $\mathrm{MJ^{-1}}$). Values of $T_{\min}$ and VPD are obtained from the DAO (http://polar.gsfc.nasa.gov/index.php) dataset, whereas the value of $\varepsilon_{\max}$ is obtained from the Biome Parameter Look-Up Table (BPLUT), http://www.ntsg.umt.edu/project/mod17.

To calculate NPP, MOD17 also estimates daily leaf and fine root maintenance respiration (R_lr), annual growth respiration (R_g), and annual maintenance respiration of live cells in woody tissue (R_m)

$$\mathrm{PSNet} = \mathrm{GPP} - \mathrm{R\_lr} \tag{6}$$

$$\mathrm{NPP} = \mathrm{PSNet\_Sum} - \mathrm{R\_g} - \mathrm{R\_m} \tag{7}$$

$$\mathrm{R\_lr} = \mathrm{Leaf\_MR} + \mathrm{Froot\_MR} \tag{8}$$

$$\mathrm{Leaf\_MR} = \mathrm{Leaf\_Mass} \times \mathrm{leaf\_mr\_base} \times \mathrm{Q10\_mr}^{[(T\mathrm{avg}-20.0)/10.0]} \tag{9}$$

where $\mathrm{leaf\_mr\_base}$ is the maintenance respiration of leaves (kg C kg $\mathrm{C^{-1}}$ $\mathrm{day^{-1}}$) as obtained from the BPLUT, and T_{avg} is the average daily temperature (°C) as estimated from the DAO meteorological data.

$$\mathrm{Froot\_MR} = \mathrm{Fine\_Root\_Mass} \times \mathrm{froot\_mr\_base} \times \mathrm{Q10\_mr}^{[(T\mathrm{avg}-20.0)/10.0]} \tag{10}$$

where $\mathrm{froot\_mr\_base}$ is the maintenance respiration per unit of fine roots (kg C kg $\mathrm{C^{-1}}$ $\mathrm{day^{-1}}$) at 20 °C as obtained from the BPLUT.

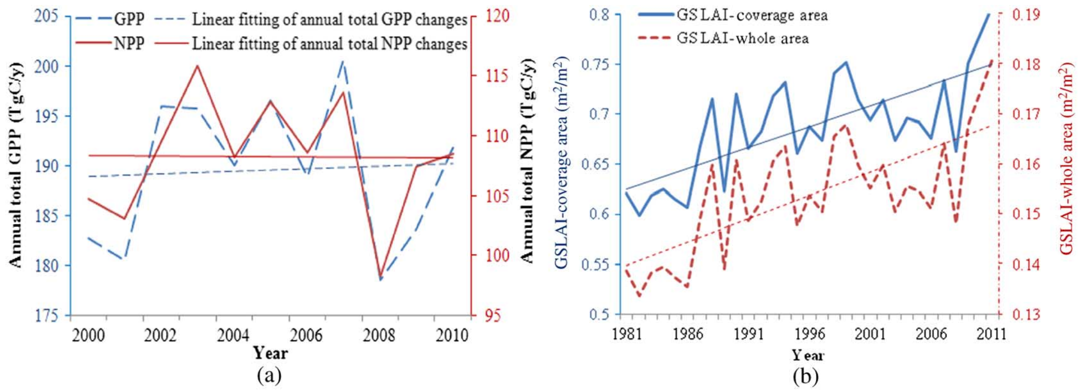

Fig. 4. Trends of GPP/NPP/LAI changes in Xinjiang: (a) annual total GPP/NPP; and (b) annual mean LAI in grow season (GS) of vegetation coverage area and whole area.

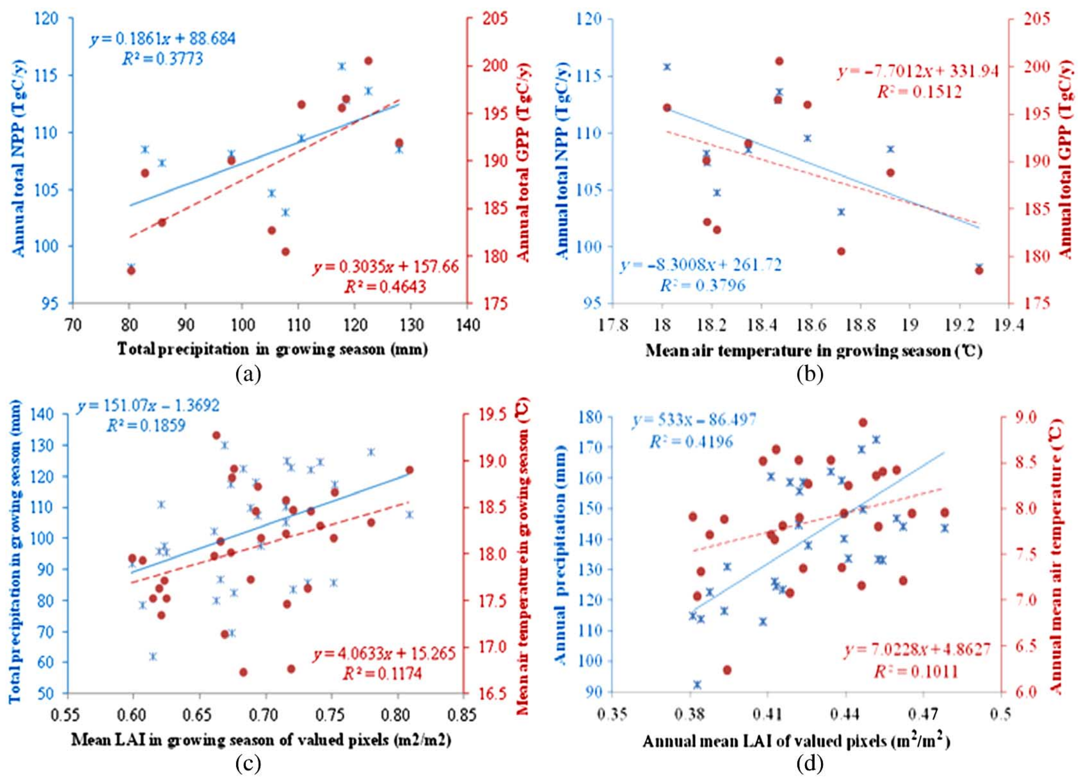

Fig. 5. Correlation between GPP/NPP/LAI and precipitation/air temperature: (a) annual total GPP/NPP versus total precipitation in growing season, (b) annual total GPP/NPP versus mean air temperature in growing season, (c) total precipitation/mean air temperature in growing season versus mean LAI in growing season of valued pixels, and (d) annual precipitation/annual mean air temperature versus annual mean LAI of valued pixels.

$$\mathrm{R\_g} = \mathrm{Leaf\_GR} + \mathrm{Froot\_GR} + \mathrm{Livewood\_GR} + \mathrm{Deadwood\_GR} \tag{11}$$

where $\mathrm{Leaf\_GR}$, $\mathrm{Froot\_GR}$, $\mathrm{Livewood\_GR}$, and $\mathrm{Deadwood\_GR}$ are growth respirations ($\mathrm{kg\ C\ day^{-1}}$) of leaf, fine roots, livewood, and deadwood, respectively.

$$\mathrm{R\_m} = \mathrm{Livewood\_Mass} \times \mathrm{livewood\_mr\_base} \times \mathrm{annsum\_mrindex} \tag{12}$$

where $\mathrm{Livewood\_Mass}$ is the mass of livewood (kg C), $\mathrm{livewood\_mr\_base}$ ($\mathrm{kg\ C\ kg\ C^{-1}\ day^{-1}}$) is the maintenance respiration per unit of livewood carbon per day from the BPLUT, and $\mathrm{annsum\_mrindex}$ is the annual sum of the maintenance respiration term $\mathrm{Q10\_mr}[(T_{avg} - 20.0)/10.0]$. More details about the algorithm could be obtained from the MOD17 User's Guide (http://www.ntsg.umt.edu/sites/ntsg.umt.edu/files/modis/MOD17UsersGuide.pdf).

D. Results

The evidences of climate change with trends of meteorological elements (i.e., annual precipitation, mean annual air temperature, and mean annual relative humidity) in Xinjiang-based on in situ observations from 1962 to 2011 are displayed in Fig. 3. The results showed the following.

1) There is an apparent increasing trend of air temperature in Xinjiang from 1962 to 2011; the mean annual air temperature in the last five decades is 7.07 °C (1962–1971), 7.15 °C

(1972–1981), 7.49 °C (1982–1991), 7.87 °C (1992–2001), and 8.31 °C (2002–2011); and the mean annual air temperature has increased by 1.24 °C in the past 50 years at a rate of 0.25 °C/decade.

2) There is a visible increasing trend of precipitation in Xinjiang from 1962 to 2011; the mean annual precipitation in the last five decades is 119.13 mm (1962–1971), 118.03 mm (1972–1981), 128.66 mm (1982–1991), 144.01 mm (1992–2001), and 148.68 mm (2002–2011); and the annual precipitation has increased by 29.45 mm in the past 50 years at a rate of 5.89 mm/decade.
3) The decade trend of relative humidity in Xinjiang is stable from 1962 to 2011 and the mean annual relative humidity in the past five decades is 51% (1962–1971), 52% (1972–1981), 52% (1982–1991), 53% (1992–2001), and 52% (2002–2011).

Compared with the obvious increasing trends of precipitation and air temperature, the trend of mean annual relative humidity in the past five decades is not significant on decade scale in Xinjiang, though there are severe fluxes of the mean annual relative humidity on annual scale, especially there are intense annual changes in the last 30 years.

The annual total GPP/NPP of the terrestrial ecosystem in Xinjiang from 2000 to 2010 was calculated from the annual 1-km improved GPP/NPP results (MOD17A2/MOD17A3) derived from MODIS. The results [Fig. 4(a)] showed that the annual trends of both GPP and NPP are fluctuating in the past decade; however, the linear fit of the total annual GPP changes was slightly positive, but the NPP was slightly negative in the period. Furthermore, the mean LAI of the growing season (from May to October) from 1981 to 2011 was calculated to present the long-term ecological responses to the climate changes in Xinjiang, and the results [Fig. 4(b)] showed that there is an obvious growth trend in the past decades.

The correlations between ecological indicators (GPP, NPP, and LAI) and meteorological elements (air temperature and precipitation) were analyzed to evaluate the effects of climate change on the ecosystems in Xinjiang, and the results showed the following.

1) Both the annual total GPP and NPP were closely tied with the annual precipitation [Fig. 5(a)], and the GPP had a higher correlation coefficient.
2) There is no insignificant correlation between mean air temperature and annual GPP, but there is a negative correlation between mean air temperature and annual NPP [Fig. 5(b)].
3) There is no visible correlation between the meteorological factors and the mean LAI in growing-season of the valued pixels (the areas covered with vegetation) [Fig. 5(c)].
4) There is a remarkable correlation between the annual precipitation and the annual LAI of the valued pixels [Fig. 5(d)].

V. Conclusion

This paper introduces a novel IIS for regional environmental monitoring and management based on IoT for improving the efficiency of complex tasks, the proposed IIS combines IoT, Cloud Computing, Geoinformatics (RS, GIS, and GPS), and e-Science for environmental monitoring and management with a case study of regional climate change and its ecological responses, which is one of the most hot topics in the scientific world. The results showed that it is greatly benefited from such an IIS, not only in data collection supported by IoT but also in Web services and applications based on cloud computing and e-Science platforms, and the effectiveness of monitoring processes and decision-making can be improved obviously. The integrative system introduced in this work is valuable for the perception, transformation, processing, management, and sharing of multisource information in environmental monitoring and management, and it also provides a new paradigm for the future work, especially in the era of big data and IoT.

It is a novel attempt on the development and application of IIS based on IoT for environmental monitoring and management, but there are also several issues needed to be addressed in the future. A number of challenges limit the implementation of fully fledged IISs, such as the complexity of the IIS [15], the standardized processing and management of multisource data from multi-sensors, security and privacy challenges [69], efficient heterogeneous sensing [51], people centric sensing platforms, quality of service in cloud computing, new protocols and APPs, and so on.

In conclusion, this paper provides a prototype IIS for environmental monitoring and management with a case study on regional climate change and its ecological responses in Xinjiang, China, and the results showed that water resource availability is the decisive factor with regard to the primary production of the terrestrial ecosystem in the area. The integrated approach introduced in this work would serve as a paradigm for resource and environment management in the near future.

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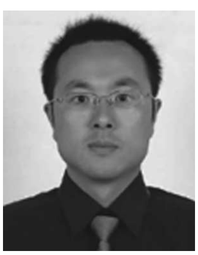

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