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Anomaly Weather Information Detection Using Wireless Pressure-sensor Grid

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Abstract: In recent years, we have witnessed an unprecedented rise in localized severe weather phenomena, such as tornadoes and heavy rain, that are not predictable by conventional weather forecasting systems. In spite of this, there are few observation posts for forecasting tornadoes and heavy rain. It is necessary to srastically increase such observation points in order to make accurate predictions using real data. We have developed a compact and low-cost pressure information acquisition system to detect signs of localized abnormal weather. This research proposes an algorithm to predict local weather by detecting anomalous pressure values in the time series of the pressure sensor information and to notify users of impending dangerous weather conditions.

Keywords: wireless sensor networks, anomaly detection, localized heavy weather

1. Introduction

In recent years, we have witnessed an unprecedented rise in localized severe weather phenomena, such as tornadoes and heavy rain, that are not predictable by conventional weather forecasting systems. Current weather forecasting systems cannot detect such localized abnormal weather. To do so, they must use local environmental data. However, conventional meteorological observation systems are generally more expensive, and the number of their locations is limited. Therefore, we have developed inexpensive environmental sensing nodes for local temperature and atmospheric pressure recording.

Our research proposes an algorithm to predict local weather by detecting anomalous pressure values in the time series of the pressure sensor information and to notify users of impending dangerous weather conditions.

This paper is organized as follows. Section 2 discusses previous studies and the relative position of our research. Section 3 describes the configuration of our system. We set forth our suggested algorithm in Section 4 and the experimental results in Section 5. Finally, we present our conclusions and discuss future challenges in Section 6.

2. Problem with Localized Anomalous Weather Forecasting

2.1 Weather Forecasting System

Weather forecasting is a major factor in our lives. Weather forecast information in Japan is provided by the Japan Meteorological Agency. In recent years, weather forecasting systems have been based on computer simulation. Weather forecast probability is calculated by environmental sensing posts, satellite images, and radar.

The accuracy of Japan's weather forecasting system regarding precipitation is about 85% [17], [18], which is quite high worldwide. In recent years, tornado observation sites based on measurement of environmental information by satellite and radar have been established all over Japan, with millimeter-wave radar [2] and Doppler radar observation [3] sites becoming mainstream. Doppler LiDAR uses a laser light system to receive reflected light from atmospheric dust and fine particles [4]. Additionally, weather forecasts using numerical simulation have been widely studied. For example, cloud-resolving model simulation research has created cumulonimbus clouds [5], and meteorological modeling simulation has been used to model cities and states [6]. However, in recent years, these systems have failed to predict localized torrential rain and tornadoes by localized pressure changes, which often occur. Japan in particular has had more than 100 observed tornadoes over the past 10 years [19], leading to an increase in research into their prediction [20]. Since tornadoes and torrential rainstorms are often caused by special cumulonimbus clouds called "supercells" [7] and occur due to a local front [8], [9], elucidation of the causes is desired. However, tornadoes can occur in a narrow range of 100–200 meters in width [21]. Therefore, for urban units, the observed data is not sufficient in current weather forecasting systems. The prediction of localized abnormal weather requires more high-density environmental data, such as atmospheric pressure, temperature, and humidity. However, the high cost of observation equipment for environmental sensing posts makes it burdensome to increase the number of environmental observation posts. Tornadoes, as a representative example of localized abnormal weather, have been studied extensively in the United States and one or two cases have acquired the pressure change just under the tornado [12]. In addition, it is difficult to forecast where and when tornadoes will occur. If we are able to measure the atmospheric pressure change just underneath

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a tornado, we may be able to determine the mechanism of the tornado [13], [14]. In the United States, a Doppler radar network is used for tornado prediction [10]. However, the accuracy ratio is only 5–10%, which is low [11].

Therefore, it is necessary to measure the atmospheric pressure in small intervals to detect change in the vicinity directly under a tornado in order to elucidate the mechanism of local abnormal weather or tornadoes. For this reason, we have developed inexpensive environmental sensing nodes for local temperature and atmospheric pressure. To this end, we propose an algorithm for localized anomalous weather prediction that uses many large wireless sensor nodes.

2.2 Regional Environmental Information Sensing System

Environmental information acquisition devices have been sold widely for both research and household use. For example, the "Eko" system [15] (MEMSIC Inc.) has been used in environmental research [1]. Eko is generally used in agriculture to record temperature, humidity, and wind speed. However, at $1,000 per unit, this system is expensive. An example of a general consumer product is the Vantage series by Davis Inc. [16]. The Vantage series records temperature, humidity, wind speed, and atmospheric pressure values. This unit is slightly lower in cost at $600 per unit, but it can only be used for stand-alone applications and is therefore not suitable for large-scale data collection. Therefore, we have developed an inexpensive and precise environmental information sensing system for detecting localized weather abnormalities.

3. Development of Environmental Information System

3.1 Localized Atmospheric Pressure Sensing System

Observation nodes measure the temperature and atmospheric pressure with a sensor and transmit sensing data to a server using a Zigbee and General Packet Radio Service (GPRS) module. Our system outline is shown in **Fig. 1**.

Cost and structure of the observation node consist of the following.

- Atmospheric pressure and temperature sensor: LP331AP $12
- Temperature and Humidity Sensor: SHT-25 $15
- Zigbee Module: TOCOS TWE-Strong $30
- 3.7 V 2,000 mAh Li-po battery $10
- Charging unit: Li-Po rider $10
- 3 W 80 mm × 100 mm solar cells $10

Our observation node runs on storage batteries that use a photovoltaic device, and thus it does not require an external power supply. Moreover, since the device is expected to be used outdoors, we have mounted it in a waterproof housing. And we installed 6 nodes in our university. This nodes collecting pressure, temperature, and humidity data every 1 minutes from Mar. 1, 2014. The prototype of our observation node is shown in **Fig. 2**, and the inside structure is shown in **Fig. 3**.

An observation node can be constructed using commercially available products. Our prototype node has a GPRS unit and its cost is about $600, which is rather inexpensive when compared to existing research equipment. Furthermore, if the GPRS unit is shared in wireless communication, such as Zigbee, it can be manufactured at a cost of about $100 per node. Therefore, large-scale observations that are much less expensive compared to other existing products and research are plausible. Temperature and

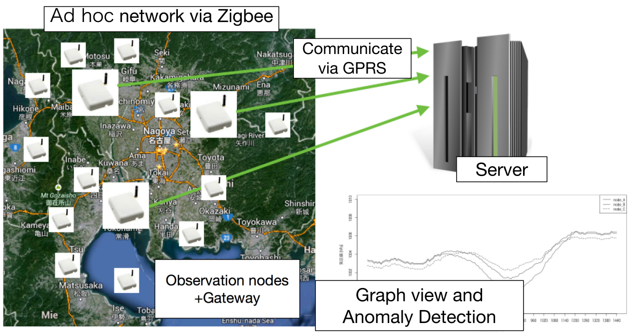

Fig. 1 Outline of our system.

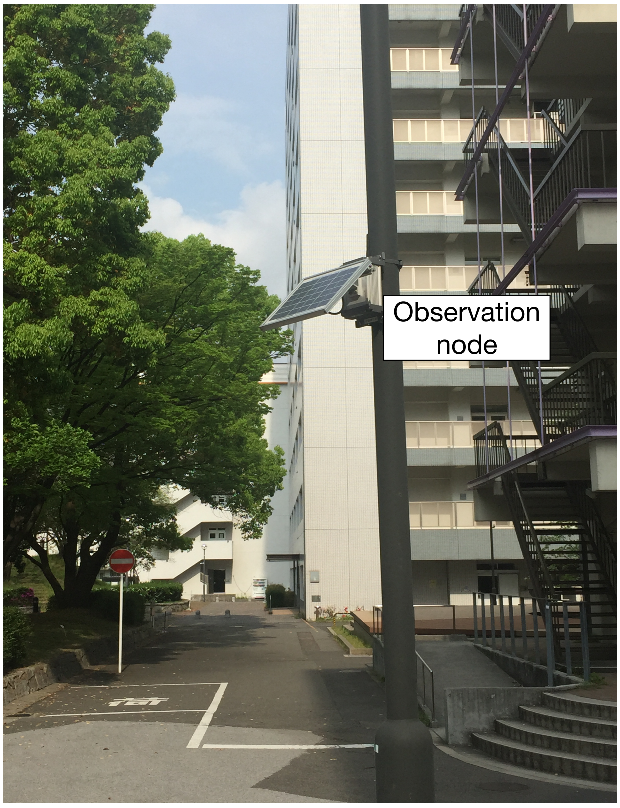

Fig. 2 Prototype of pressure observation node.

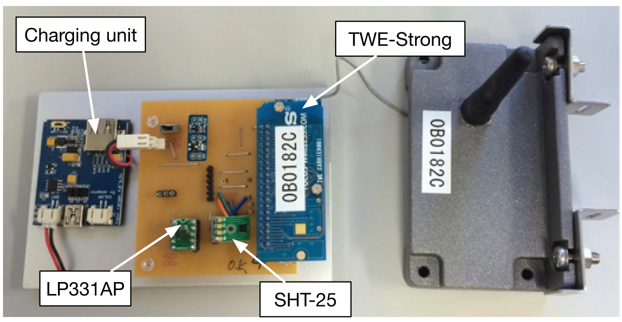

Fig. 3 Inside of observation node.

atmospheric pressure sensors are currently connected, and it appears possible to connect wind speed sensors, humidity sensors, and various other sensors. In addition, because our observation node uses a battery and solar cells, it is suitable for continuous outdoor use. We propose an algorithm for tornado prediction by detecting anomalous pressure values in the time series of the atmospheric pressure sensor information and for notifying users when such localized abnormal weather is detected.

3.2 Implementation of Server Application

The application server mainly consists of the following three functional components.

- User Interface: Manages the sensor name, such as graphs, and displays the time-series sensor data.
- Database: Stores the observation data, which can be exported in CSV format.
- Alarm module: Notifies users via SMS/e-mail whenever it exceeds the threshold setting.

Server applications are based on the web user interface. Users report destination e-mail addresses and SMS destination mobile phone numbers. Any of the sensor information can be inspected. Furthermore, by registering as a group of individual sensors, it is possible to compile data and compare it to the sensor information of another group. Moreover, a threshold can be set for each sensor. Currently, only notification functions triggered by a certain threshold are in use. In the future, it will be possible to implement the abnormal weather detection algorithm proposed in this research. Our goal is to quickly notify users of localized abnormal weather.

3.3 Accuracy Evaluation of Our System

In this section, we compare our observation node with the Japan Meteorological Agency's pressure data for evaluation of its accuracy. The Japan Meteorological Agency provides real-time environmental data that is updated every 60 minutes. The data for each observation point can be viewed freely on the agencys website. We used the data from Jan. 14, 17:00 to Jan. 15, 05:00, 2014 for Showa district, Nagoya in Aichi Prefecture for our accuracy evaluation experiment. We viewed this data every 10 minutes and compared the pressure data provided by the Japan Meteorological Agency with the data measured by our system. The results of the accuracy evaluation are provided in **Fig. 4**. The data measured by our system were approximately 3 hPa higher than the data provided by the Japan Meteorological Agency. This is due to the difference in altitude at which our measuring device and that of the Japan Meteorological Agency are placed. The Japan Meteorological Agency locates their measuring devices at approximately 25 m high. Therefore, the comparison of the measured values confirms that our system is equivalent in accuracy to the Japan Meteorological Agency installations.

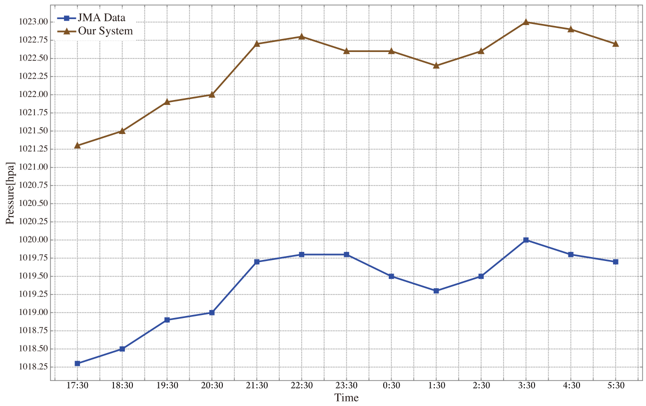

Fig. 4 Comparison of measured values with data provided by Japan Meteorological Agency.

4. Proposal of Abnormal Weather Detection Algorithm

4.1 Atmospheric Pressure Variations in Abnormal Weather

Our algorithm addresses atmospheric pressure change in order to detect early signs of localized abnormal weather situations and notifies users about these situations. We selected tornadoes, typhoons, and cold fronts as typical examples of localized abnormal weather events. The data is actual atmospheric pressure data provided by the Japan Meteorological Agency.

- **Figure 5** shows the data for typhoons in Ibaraki Prefecture occurring on Oct. 15, 2013 at 17:00.
  Meteorological data observation site: Meteorological station, Tsukuba, Ibaraki Prefecture.
- **Figure 6** shows the data of the passing time of a cold front in Ibaraki Prefecture occurring between March 31, 2013 and April 2, 2013.
  Meteorological data observation site: Meteorological station, Tsukuba, Ibaraki Prefecture.
- **Figure 7** shows the data of a tornado in Joso City, Ibaraki Prefecture occurring on May 6, 2012 at 17:00.
  Meteorological data observation site: Meteorological station, Tsukuba, Ibaraki Prefecture.

We used the actual atmospheric pressure data as provided by the Japan Meteorological Agency [22] to determine the locations of the observation points for tornado forecasting. Tornadoes often travel significant distances. For example, the tornado damage in Ibaraki Prefecture reached a length of 35 km [23]. Therefore, a wide range of observation points are required to obtain detailed pressure changes in order to accurately forecast tornado movement. To obtain such data, we increased the observation points for our system and arranged them on a grid. In addition, atmospheric pressure lowers slowly with the passing of fronts and typhoons. However, atmospheric pressure fluctuates wildly during tornadoes and the pressure plummets during reapproach. Our objective is to minimize human casualties caused by tornadoes and to monitor the atmospheric pressure fluctuations in a time series. Moreover, we propose an anomaly detection algorithm for detecting the early stages of localized abnormal weather. It shows the characteristics of the pressure change of each environmental change below.

Typhoons Slowly pressure change in a wide range occurs.
Cold front passes Slowly pressure change of trace amount.
Tornado Rapid pressure change in a small range occurs.

In addition, cases that capture the pressure change of directly under a tornado is rare. Very intense atmospheric pressure change is happening directly under tornado [13]. In Japan, is less at-

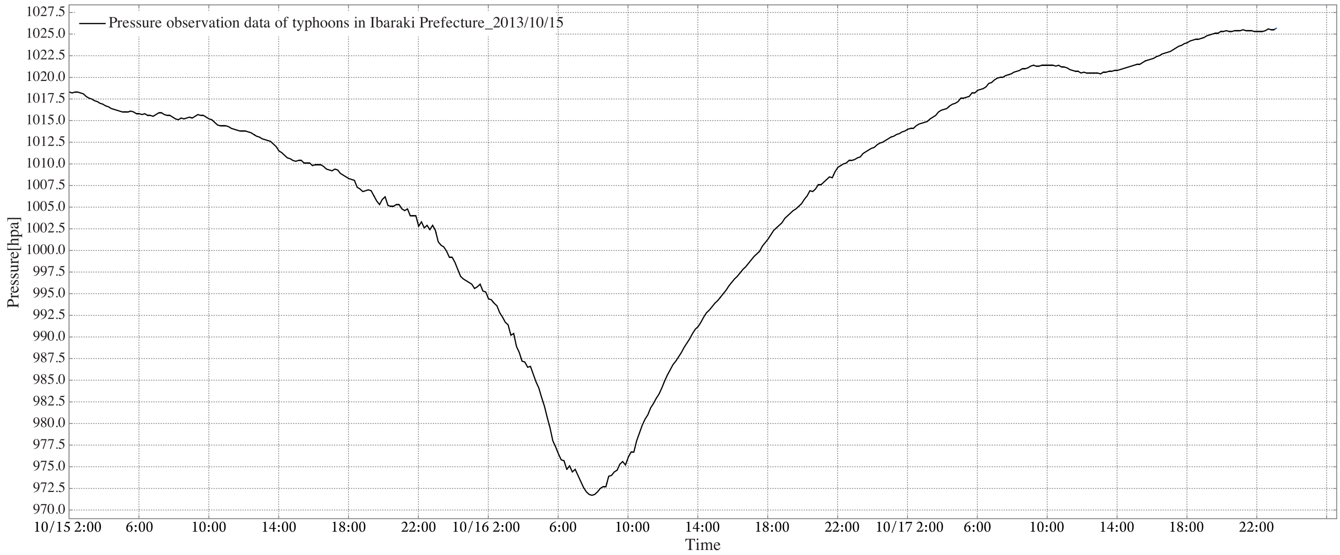

Fig. 5 Pressure observation data of typhoons in Ibaraki Prefecture.

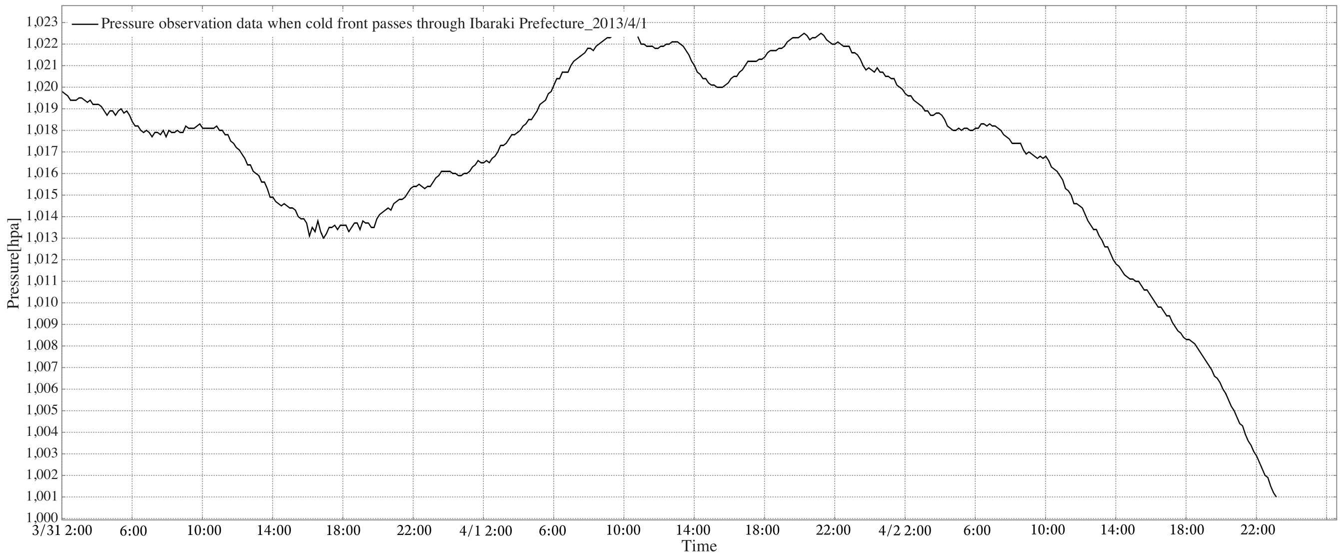

Fig. 6 Pressure observation data when cold front passes through Ibaraki Prefecture.

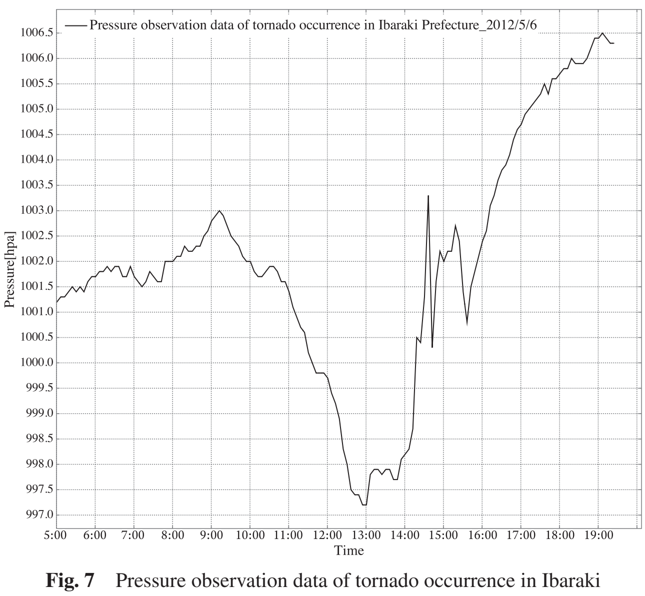

Fig. 7 Pressure observation data of tornado occurrence in Ibaraki Prefecture.

mospheric pressure measurement possible weather observation point. Therefore, in the tornado near, intense pressure change from observation data is expected. The actual data reveals that atmospheric pressure drops occur in the early stages of a tornado and afterward rapidly drops during its passage. The path of actual tornado movement, cited from the Japan Meteorological Agency reported material [21], is shown in **Fig. 8**. The actual data of shows atmospheric pressure drop occurs in the stage of early occurrence of the tornado, after a rapid drop in atmospheric pressure occurs in the passage of tornado. Our purpose is to minimize the human deaths and injuries from tornadoes, to monitor the atmospheric pressure fluctuations in the time series. Moreover, we propose an anomaly detection algorithms for detecting the early stages of localized abnormal weather.

4.2 Atmospheric Pressure Anomaly Detection in Time-series Data

As mentioned in the previous section, observing pressure change during the time series is important for detecting tornadoes

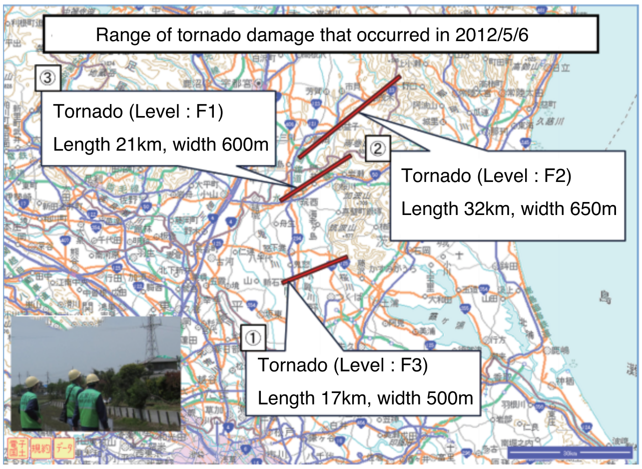

Fig. 8 Path of actual tornado movement (Reported by Japan Meteorological Agency).

in their early stages. In addition, knowing how close a tornado is will help users determine whether to stay indoors or evacuate. Therefore, we have designed our system to observe variations in localized atmospheric pressure by arranging the sensors of the observation nodes at intervals of 1,000 m. This will enable users to calculate their distance from the tornado, and the path of the tornado can be forecast by the atmospheric pressure data acquired by the individual nodes. Further, if only a particular observation node has detected an abnormal value, it is considered to be a problem with the atmospheric pressure sensor, rather than an actual pressure change. That is, we can determine whether atmospheric pressure values are true or false by comparing them to the atmospheric pressure values of neighboring nodes. From the above, it is possible to detect tornadoes in their initial stages by recording atmospheric pressure changes, which further allows us to determine the distance between the current position of the observation node and the tornado.

4.3 Detection Algorithm of Abnormal Atmospheric Pressure Data in Time Series

In this section, we describe the detection algorithm for abnormal atmospheric pressure values in a time series. Equation (1) is the atmospheric pressure data for each observation node, where X_{node} is the pressure data at the observation node and the time data is time = t, date = d, and year = y. The pressure data at the observation node is represented by

$$X_{node}(t, d, y). \qquad (1)$$

Using Eq. (2), we can score the pressure variation in the time series. We then calculate the average square error of past data to be specified in the *min* scores for each time of each observation node and output the score variation of the pressure data in the time series. It is currently set to $min = 10$, and, by comparing it with the pressure measurement data of the last 10 minutes, we can calculate the score. In this section, we show the effectiveness of the proposed method using actual pressure data for a tornado that occurred in Ibaraki Prefecture. In Section 5, we will conduct a comparison experiment regarding the difference of past data to be used for the score calculation.

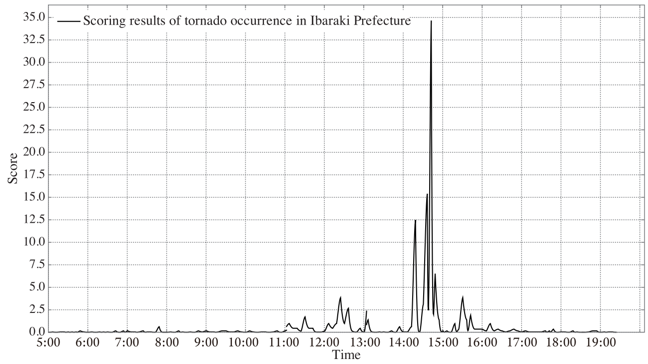

Fig. 9 Scoring results of tornado occurrence in Ibaraki Prefecture.

Table 1 Comparison of the maximum value.

Weather Environment	Maximaum Value
Cold front passing	1.36
Typhoon	3.32
Tornado	34.3

$$val_{node}(t, d, y) = \sum_{i=-1}^{min} \{x_{node}(t, d, y) - x_{node}(t - i, d, y)\}^2. \qquad (2)$$

We also ensure that the anomalies in the time series are scored based on the proposed algorithm. We confirm the algorithm by using the pressure for the actual tornado occurrence mentioned in Section 4.1 and scored with Eq. (2). The score approaches 0 if there is no change in atmospheric pressure. Increases in the value, such as in the last 10 minutes, indicate pressure fluctuations. We show the scoring results for the tornado occurrence in Ibaraki Prefecture in **Fig. 9**, those for the cold front in **Fig. 10**, and those for the typhoons in **Fig. 11**. We shown maximum score for each weather environment in **Table 1**.

The scoring results in these figures demonstrate that score values increase with atmospheric pressure change. In addition, significant changes in score values can be observed in atmospheric pressure when a tornado is approaching. We have shown that the present system can detect pressure variations in a time series. Furthermore, the scoring results for the tornado differ from those of the typhoon and the cold front. In addition, a higher number is output in the early stages of the tornado as compared with the typhoon, successfully demonstrating that early stage detection of tornadoes is possible.

5. Experimental Evaluation

5.1 Experimental Setting

In this section, we describe the experimental setup that was used for the evaluation experiment. In Section 4, with the scoring for the tornado, we demonstrated that early detection of tornadoes is possible using the past 10 minutes of data. In this section, we use the historical data to detect changes in localized abnormal weather sooner. Using the meteorological data of a tornado occurrence from each node, we calculate the score using the algorithm that was proposed in Section 4.3. In addition, we compare past data at 10 minutes, 30 minutes, and 60 minutes.

- Meteorological data observation site: Meteorological station, Tsukuba, Ibaraki Prefecture
  Data of tornado occurrence in Joso City, Ibaraki Prefecture occurring on May 6, 2012 at 17:00

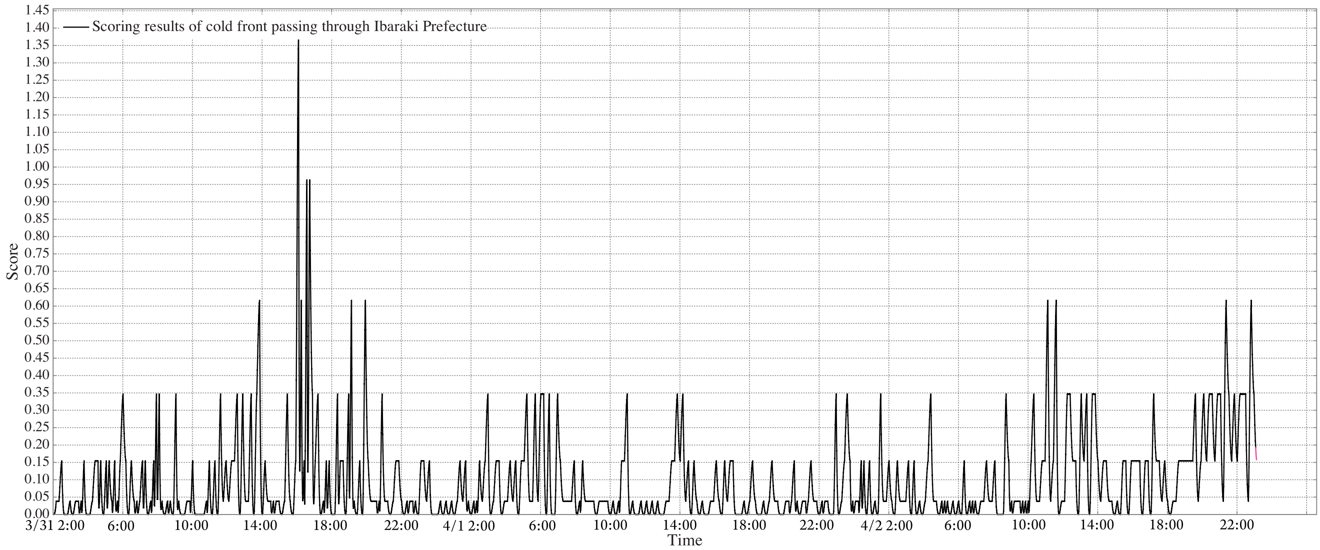

Fig. 10 Scoring results of cold front passing through Ibaraki Prefecture.

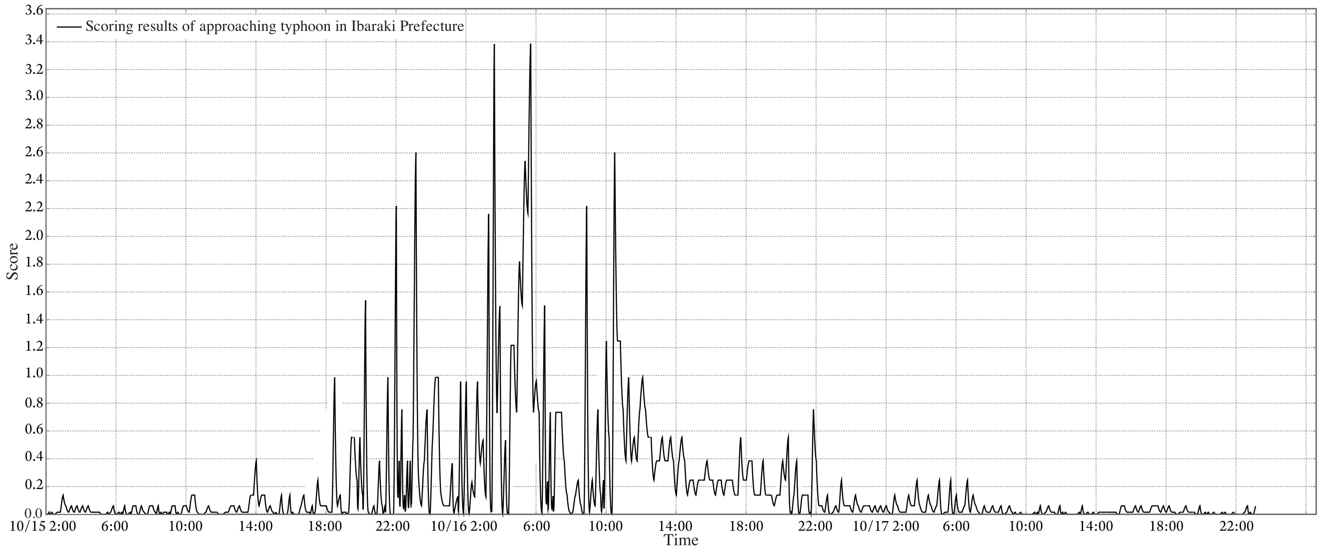

Fig. 11 Scoring results of approaching typhoon in Ibaraki Prefecture.

- Data of past 10 minutes: Use the data from the Japan Meteorological Agency for 10 minutes prior
- Data of past 30 minutes: Use the data from the Japan Meteorological Agency for 30 minutes prior
- Data of past 60 minute: Use the data from the Japan Meteorological Agency for 60 minutes prior

We calculated the scoring using these dummy atmospheric pressure data and successfully detected a tornado in its early stages.

5.2 Experimental Results

The score output results of our calculations using the experimental environment set for each observation node in Section 5.1 are set forth in **Fig. 12**. The score calculation results were normalized so that they were easy to compare.

The score calculation results show that, as in the case of the verification results of Section 4.3, an abnormal score is found in the early developmental stages of a tornado. These results confirm that, using changes in the atmospheric pressure value of each observation node, it is possible to detect pressure changes that indicate the initial stage of a tornado. This also allows us to measure the distance between the current node position and the tornado, which, consequently, can help reduce human casualties. Notably, when looking at the data of the past 60 minutes, the increasing score variation at 12:00 indicates the tornado's initial stage. As described above, by using the algorithm proposed in this paper, the detection of localized abnormal weather is possible. Moreover, we have also shown that, by comparing the values of the observation nodes, we can determine whether the observations indicate localized abnormal weather or an atmospheric sensor failure. In the future, we intend to improve the accuracy of our system by accumulating past data from the Japan Meteorological Agency and comparing it with measured values. In addition, we aim to miniaturize the environmental information observation node and implement certain low-cost nodes using Zigbee communication.

6. Summary

In this research, we implement a low-cost environmental information collection system for the purpose of predicting localized abnormal weather. By using the atmospheric pressure changes of an actual tornado occurrence, we demonstrated that it is pos-

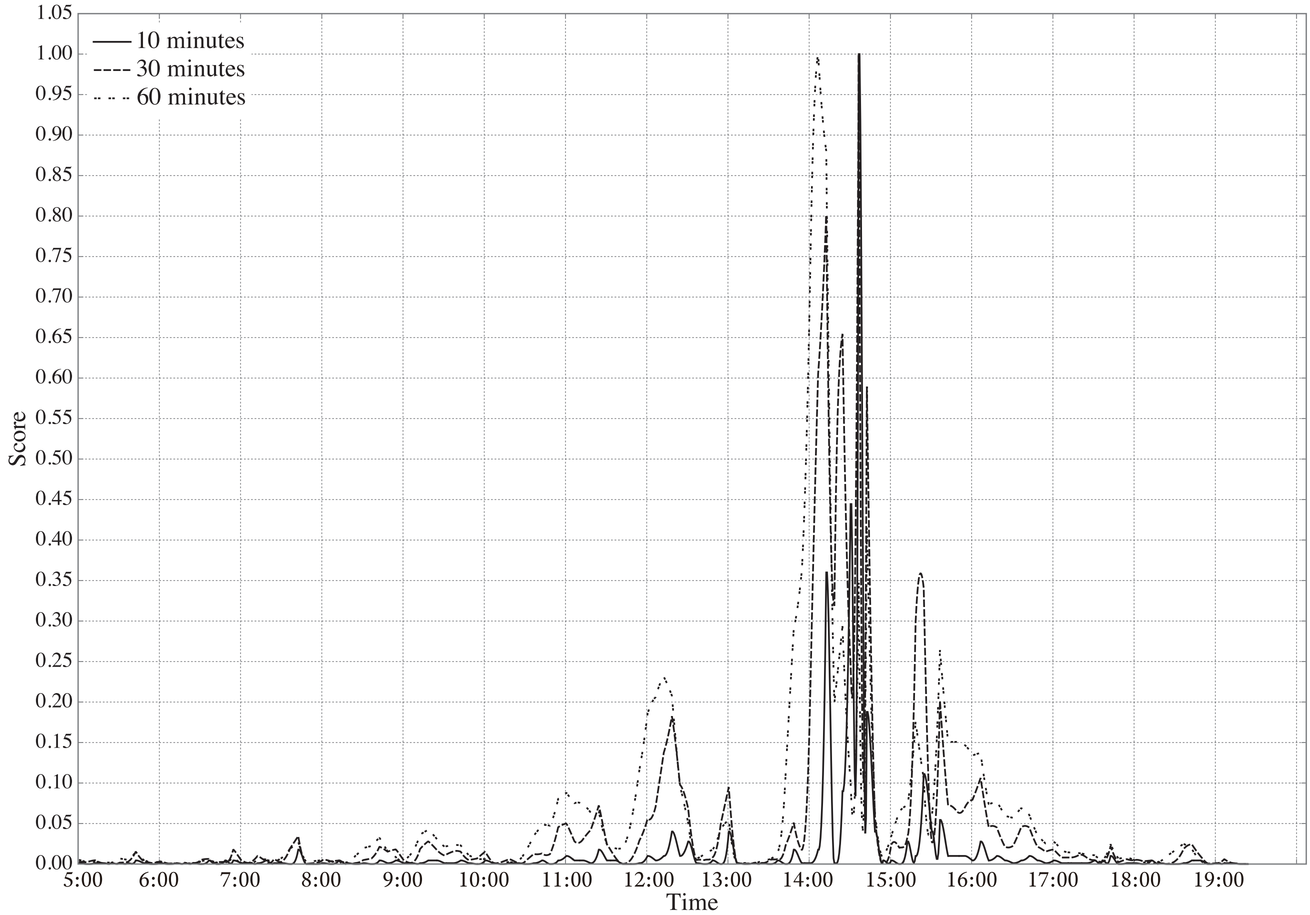

Fig. 12 Scoring results (Normalized).

sible to determine sudden changes in atmospheric pressure at the observation points, which can be used to detect abnormalities signaling the initial stage of a tornado. This information can also be used to calculate the distance between the current position and the tornado, thus helping to reduce human casualties. Moreover, by comparing the values of the observation nodes, we can determine whether changing values are the result of sensor failure or localized abnormal weather. In the future, we will develop observation nodes to collect data, including wind speed, temperature, and humidity sensors, and compare this data with comprehensive data, such as past data provided by the Japan Meteorological Agency. We present our prediction system. We continue to detect weather abnormalities with high accuracy. In addition, we performing long-term experiments with an increasing number of observation points. Recent years, the atmospheric pressure sensor is include smart phones. Because, it is possible to more data collection use by smartphones. Our algorithm is simple and has less computational cost. Therefore, by utilizing the large-scale information in the future, it is possible to highly accurate abnormality detection.

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