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An Investigation on Short-Term Prediction of Severe Weather Events Based on GNSS-derived Atmospheric Information

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Abstract

In recent years, the increasing frequency of natural disasters caused by various types of severe weather events (SWEs) has resulted in more and more damage and losses to properties and livelihoods. These phenomena highlight a pressing need to understand the intrinsic nature of these events and develop reliable and robust methods for the nowcasting and very short-range forecasting (VSRF) of SWEs, thus to prevent and mitigate the influences brought by all kinds of natural disasters. Facing with the high demand of the VSRF of SWEs, it is necessary to obtain and use various kinds of meteorological data with high accuracy and high spatiotemporal resolution in an effective way. Atmospheric water vapor (WV), which is recognized as an essential climate variable, greatly affects the atmosphere stability, the hydrological and energy cycles, and the formation of cloud and rainfall. As one of the most active components in the atmosphere, the evolution of WV has significant implications for determining the intensity, time and extent of potential SWEs. Therefore, to refine the service for the monitoring and detection of SWEs, it is of great importance to obtain the amount of WV contained in the atmosphere and capture its movements. However, the rapid change and dynamic characteristics of WV make it an extremely difficult task to obtain its accurate and timely spatiotemporal distributions in the troposphere using traditional observing techniques such as radiosonde, water vapor radiometers, and etc. With the rapid deployment and development for nearly four decades, the Global Navigation Satellite Systems (GNSS) has been widely used in the remote sensing of atmospheric variables, e.g., zenith total delay (ZTD) and precipitable water vapor (PWV). This is mainly due to the high accuracy, high spatiotemporal resolution and all-weather capability of GNSS observations. Hence, the availability of atmospheric information retrieved from GNSS has opened new avenues and new possibilities for GNSS meteorological applications of the detection of SWEs

This dissertation focuses on the retrieval of GNSS-derived atmospheric products with high accuracy and high spatiotemporal resolution, and then apply them to the nowcasting and VSRF of SWEs. The research include: the retrieval of atmospheric products from ground-based GNSS radio signals and their accuracy evaluation, the feature analysis of atmospheric variables and their responses

to SWEs, short-term prediction of SWEs using threshold-based models, anomaly-based models and back propagation neural network (BPNN) algorithm. The detailed research contents and major contributions are outlined as follows:

(1) The dissertation firstly illustrates the principles of atmospheric information estimation from ground-based GNSS, then clearly describes the theoretical algorithms, empirical models and various kinds of strategies about the whole processing procedure from GNSS signals to atmospheric delay, ZTD and finally to PWV. The Hong Kong region was selected as the experimental area, the ZTD series over the 10-year study period 2010-2019 at the 15 GNSS stations in the region were estimated using the Precise Point Positioning (PPP) technique based on the RTKLIB software with the near real-time (NRT) strategy. Then, with the incorporation of meteorological data and empirical models, PWV estimates over the same period can be obtained. Finally, the ZTDs provided by the International GNSS service (IGS) and the PWVs estimated from the sounding profiles were adopted to assess the accuracy of those products derived from GNSS observations.

(2) To more comprehensively take the atmospheric environment conditions into account, this study not only obtained the time series of ZTD and PWV over the study period, but also collected the temperature, pressure, relative humidity and the actual records of SWEs within the experimental area. In addition, the two variables of day of year (DOY) and hour of day (HOD), which represent the seasonal and diurnal variations of time-varying variables were also considered. Then, to investigate the correlation between each two of these variables, the Pearson correlation coefficient was adopted to conduct the cross-correlation analysis. Furthermore, this study also used the principal component analysis (PCA) method to figure out each variable's responses to the occurrence of SWEs and test their contributions and effectiveness in the detection of SWEs, which can be recognized as reference for selecting appropriate predictors in model development.

(3) In this study, severe rainfall event was chosen as an example of SWEs, thus the synoptic process for the formation of severe rainfall event was described in detail. Due to the threshold-based model is easy to operate and has simple principles, hence this study adopted this type of model to develop the 5-factor PWV-based model and the 7-factor ZTD-based model. The two types of new models used five and seven kinds of derivatives from PWV and ZTD series, respectively. It is noted that this study is the first to consider the predictors obtained from the descending trends in the PWV and ZTD series to detect the onset of severe rainfall events. The experimental results of the two types of models suggest that it is promising to use these model to obtain better prediction results and they can be used as effective complements to the operational models.

(4) Analyzing the anomaly series of a variable in response to a weather event is a common practice in the meteorological community, however, for variables derived from GNSS observations, this type of analysis has not been reported in the existing literature, let alone for the application of heavy rainfall detection. Hence, this study is the first to analyze the anomaly and cumulative anomaly time series of GNSS-derived atmospheric products to detect SWEs, and two kinds of new models using anomaly and cumulative anomaly series of GNSS-derived products were proposed. Compared with the threshold-based models, there is no need for those anomaly-based models to select a specific threshold value, thus the efficiency for model development can be greatly improved. However, due to the rapid temporal variation in the GNSS-derived tropospheric variables, their anomaly time series may contain a larger number of high-frequency noisy signals; hence, using the anomaly series of rapidly changing variables for severe rainfall detection is likely to result in poor performance. By using the cumulative anomaly series of these variables to detect severe precipitation events can effectively overcome this problem because those large noises can be effectively filtered out and the integrity of the information contained in the raw time series can be also ensured. In addition, the advantage of using cumulative anomaly series also lies in that the

formation of severe rainfall events is a timely response to the accumulated effects of weather parameters over a long period rather than instantaneous features, hence the prediction performance resulted from using cumulative anomaly time series can be further improved in comparison to that from using the anomaly series.

(5) Based on all the previous studies and discussions, this study also proposed a new method, which is a hybrid of threshold-based model and anomaly-based model, for the VSRF of severe rainfall events. The calculation of the anomaly series of a predictor is to minimize the data range for optimizing the threshold selection process; then, with the obtained anomaly series of a predictor, the improved percentile method was adopted to calculate its specific threshold. In addition, those state-of-the-art techniques proposed for each step contained in the development of a robust detecting model was also utilized in the new method. Consequently, it can be concluded from the experimental results that the anomaly-based percentile thresholds of predictors derived from the PWV/ZTD time series have the potential to be applied to the severe rainfall detection with a reasonably good accuracy.

(6) It can be clearly seen that the above models did not take the meteorological variables, e.g., temperature, pressure, and their impacts on the formation of the onset of SWEs into consideration. Therefore, this study also proposed a new model based on the improved BPNN algorithm, which has the ability of self-learning, nonlinear mapping and fast convergence. The predictors contained in the new model were PWV, ZTD, temperature, pressure, relative humidity, DOY and HOD. Prior to the model training phase, several factors that affecting the model's performance including the selection of hyperparameters, the length of training samples, and its time period were investigated, thus a principle for model development was formulated. While after the training and validation phases of the modelling were completed, the weight maps of the well-trained model were further investigated for the knowledge of the interior structure of the technique and for the determination of the most active variables.

Keywords: Global Navigation Satellite System (GNSS); GNSS meteorology (GNSS/MET); zenith total delay (ZTD); precipitable water vapor (PWV); very short-range forecasting (VSRF); severe weather events