基于改进的 GNSS-PWV 三因子阈值的降雨预报研究

摘要：大气可降水量（PWV）在研究大气水汽含量与降雨之间关系的研究中发挥着越来越重要的作用。基于 GNSS PWV 的三因子（PWV、PWV 变化量和 PWV 变化率）阈值的降雨预报方法已经在一些场景中取得了不错的效果，但该方法目前仍存在一些问题，包括部分场景下无法有效反映 PWV 的变化、预测因子的阈值确定不够合理。本文对传统方法进行了改进，以 PWV 为主要预测因子、PWV 增量和 PWV 增率为辅助预测因子，并采用定量选取月阈值的方法进行降雨预报。改进后的方法能够充分利用 PWV 的季节特征和实时信息，有效反映 PWV 和降雨之间的关系。基于 SuomiNet 网的试验验证结果显示，与传统三因子算法相比，改进方法的降雨预报正确率更高，误报率更低，且命中率处于相同水平。

关键词：GNSS；大气水汽；降雨预报；预测因子；阈值确定

The Rainfall Forecasting Research Based on Improved GNSS-PWV Three-Factor Threshold Method

Abstract: **Objectives**: Precipitable water vapor (PWV) plays an increasingly significant role in the quantitative study of the potential meteorological factors that cause rainfall. The PWV-based three-factor (PWV, PWV change and rate of PWV change) threshold method for the rain forecast has been established, empirically proving its effectiveness in some scenarios. However, an apparent issue is that not fully using real-time information restricts performance. Our study proposed an improved monthly threshold method to tackle this problem. **Methods**: The basic idea is to refine the predictors. In this paper, the three-factor monthly threshold method based on PWV, PWV increment and rate of PWV increment is used to realize the short-term rainfall forecast within 6 hours, in which PWV is used as the main predictor, and PWV increment and PWV increase rate are used as secondary factors to assist in the prediction. We offer a quantitative standard for picking the threshold based on maximizing Critical Success Index (CSI). The specific prediction steps are as follows: (1) Get the time series of the three predictors from the raw data. Set a sliding window length of 6 hours, after calculating the PWV increment and rate of PWV increment under the current window, slide the window backwards for 30 minutes. By repeating the operations, we obtain the PWV increment sequence and the rate of PWV increment sequence; (2) Select the monthly threshold based on the data from 2015 to 2018. Set the optimal threshold for PWV according to CSI every month, then fix the threshold of PWV, and use the CSI maximum principle to select the optimal thresholds for PWV increment and the rate of PWV increment jointly; (3) Use the optimal threshold set on the 2019 data to predict the rainfall in the next 6 hours. If the PWV exceeds the threshold at a certain moment, predict rainfall; if the PWV does not exceed the threshold at a certain moment, but both the PWV increment and the rate of PWV increment exceed the threshold, predict rainfall; otherwise, predict no rainfall. Finally, the forecasted rainfall and actual rainfall are counted to calculate the correct rate (CR), false alarm rate (FAR) and CSI. Meanwhile, we explain that compared with using Probability of Detection (POD), it is more reasonable to use CR to evaluate the proportion of predicted rainfall events. **Results**: We apply our method to 11 different stations of SuomiNet. The CR of the improved method is above 89%, while the FAR is controlled below 73%. Among them, the CR of the three stations P031, P047 and CN00 is about 95%, and the FAR is not higher than 65%. In general, the proposed method can predict more than 92% of rainfall on average, and the average FAR of each forecast is about 63%. Compared with the traditional three-factor algorithm, the average CR of the improved three-factor algorithm is increased by nearly 6%, the average FAR is reduced by more than 4%, and the average POD is at the same level. **Conclusion**: Using PWV increment and the rate of PWV increment, the new predictor can better reflect the characteristics of the rising phase of PWV and keep updating synchronously with PWV. Compared with the traditional method, our algorithm can predict rainfall more effectively and has higher applicability.

Keywords: GNSS; PWV; rain forecast; prediction factor; threshold selection

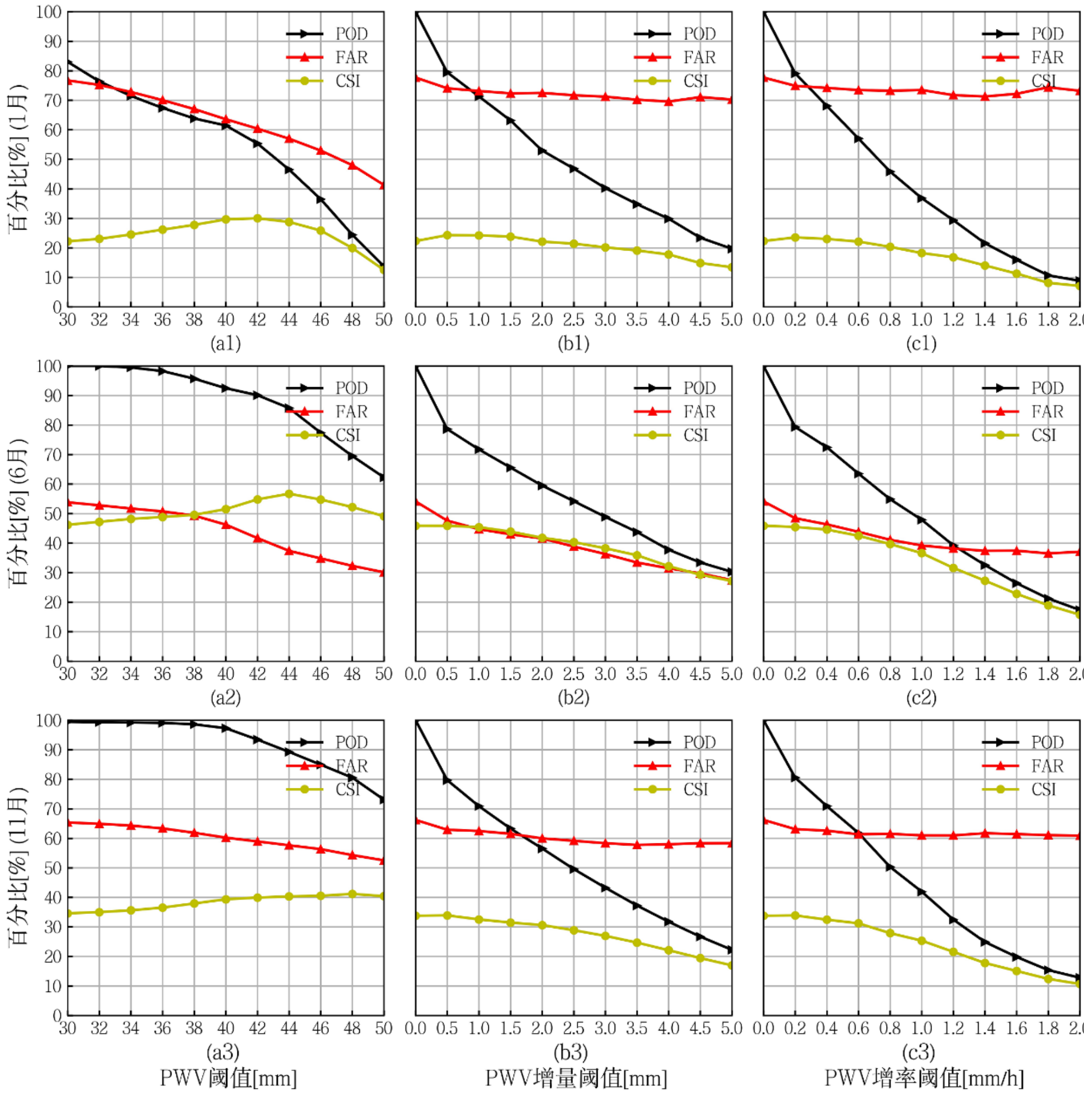

图 3. TTUW 测站阈值-评价指标图

Fig.3 The Threshold-Index Variations of Three Months of TTUW Station

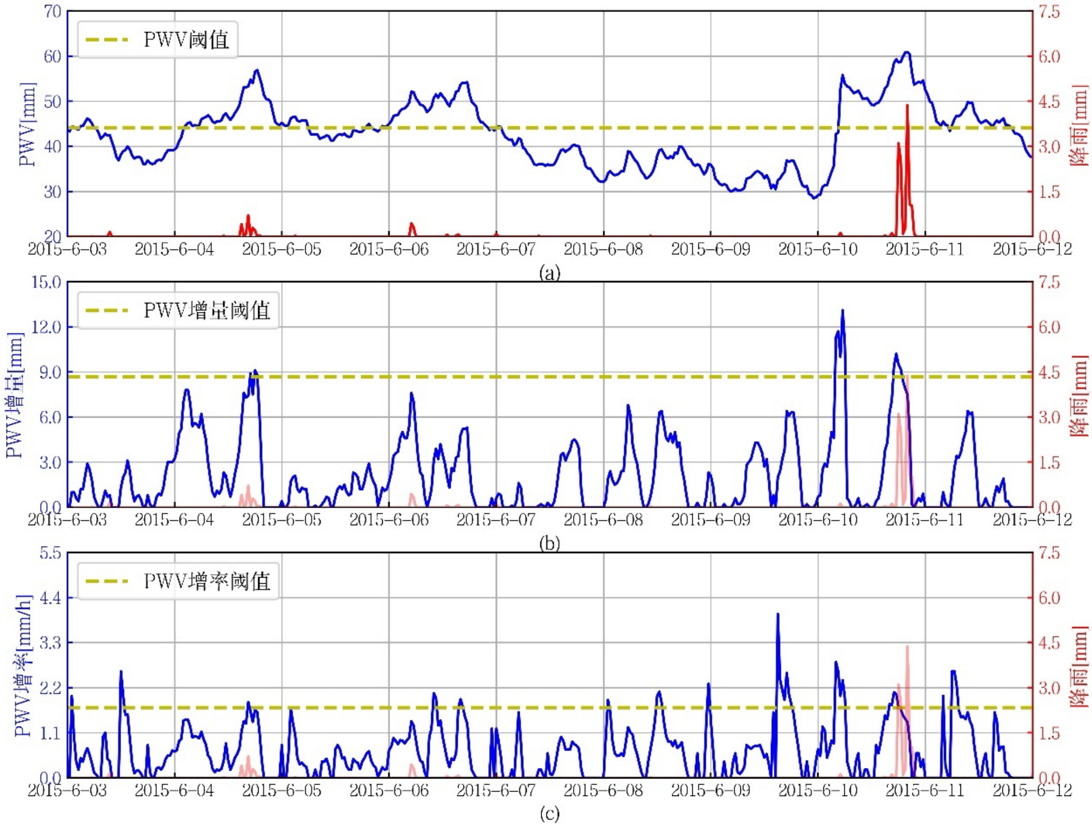

图 4. TTUW 测站最优阈值-预测因子图

Fig.4 Optimal Threshold-Predictor Map of TTUW Station

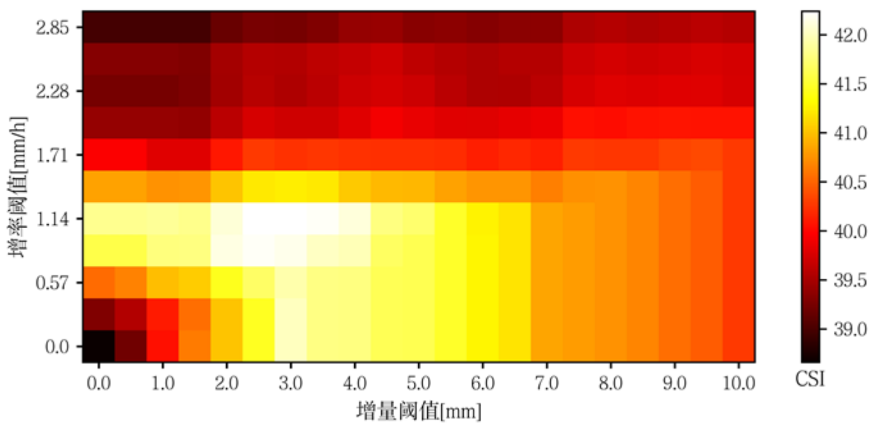

图 5　TTUW 测站 8 月份增量阈值和增率阈值与 CSI 分布关系的热力图

Fig.5 The Heat Map of the CSI Distribution with Respect to the Thresholds of the PWV Increment and the Rate of PWV Increment

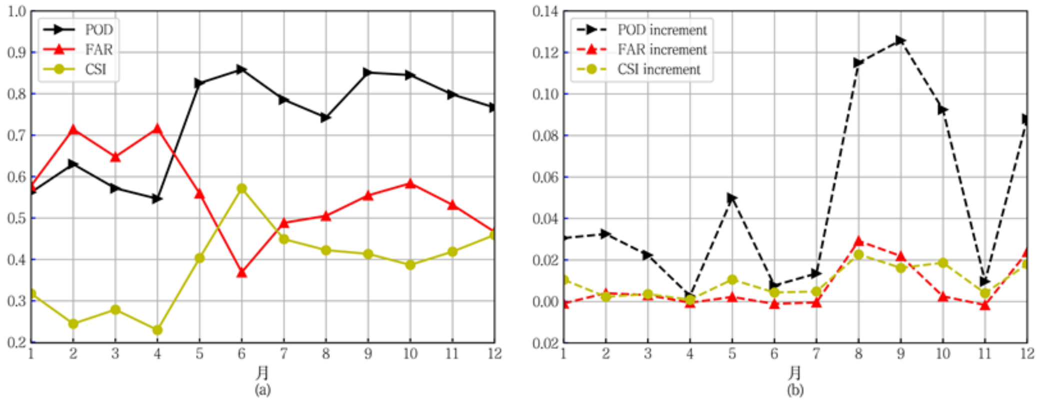

图 6. 三因子预测效果较单因子(PWV)预测的变化：(a)三因子预测最优阈值对应的 POD，FAR 和 CSI；(b)三因子预测较单因子预测 POD，FAR 和 CSI 的增加量

Fig.6 The Effect of the Three-Factor Model Compared with the Single-Factor(PWV) Model: (a) The POD, FAR and CSI to the Optimal Threshold of Three Factors; (b) The Increase of POD, FAR and CSI of the Three-Factor Model Compared With the Single-Factor (PWV) Model

表 3. 模型预测结果统计：New 代表本文提出的改进三因子阈值算法，Old 代表传统三因子阈值算法

Table 3 Statistics of the Model Prediction: New and Old Denote the Proposed Model and Traditional Model

测站	模型	N_{pred}	N_{total}	POD[%]	FAR[%]	CR[%]
P031	**New**	**889**	**931**	**85.23**	**58.38**	**95.49**
	Old	856	931	83.07	58.74	91.94
P047	**New**	**1122**	**1181**	**78.70**	**62.59**	**95.00**
	Old	1084	1181	81.92	62.95	91.79
P805	**New**	**691**	**767**	**65.47**	**60.03**	**90.09**
	Old	628	767	66.20	64.77	81.88
CN00	**New**	**741**	**781**	**73.94**	**64.44**	**94.88**
	Old	721	781	78.92	66.45	92.32
CN12	**New**	**547**	**585**	**62.79**	**63.75**	**93.50**
	Old	508	585	59.05	71.02	86.84
CN25	**New**	**589**	**652**	**54.16**	**57.55**	**90.34**
	Old	529	652	55.68	64.12	81.13
TNCM	**New**	**357**	**387**	**56.07**	**63.24**	**92.25**
	Old	327	387	60.27	67.92	84.50
LVEG	**New**	**589**	**642**	**68.95**	**72.07**	**91.74**
	Old	563	642	72.29	75.95	87.69
ECSD	**New**	**830**	**920**	**73.60**	**68.44**	**90.22**
	Old	776	920	70.56	70.56	84.35
SROD	**New**	**441**	**495**	**48.09**	**65.29**	**89.09**
	Old	395	495	42.23	76.47	79.80
TTUW	**New**	**792**	**852**	**68.70**	**54.54**	**92.96**
	Old	769	852	70.38	59.98	90.26
平均	**New**	**7588**	**8193**	**66.88**	**62.76**	**92.32**
	Old	7156	8193	67.32	67.18	86.59