

Time Series Based Air Temperature Forecasting Based on the Outlier Robust Extreme Learning Machine [†]

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Abstract: In this study, an Improved version of the Outlier Robust Extreme Learning Machine (IORELM) is introduced as a new method for hourly air temperature forecasting in multi-steps ahead. The proposed method was calibrated and used to estimate hourly air temperature for one to ten hours in advance after finding its most optimum values (i.e., orthogonality effect, activation function, regularization parameter, and the number of hidden neurons). The results showed that the proposed IORELM has an acceptable degree of accuracy in predicting hourly temperatures ten hours in advance ($R = 0.95$; $NSE = 0.89$; $RMSE = 3.74$; $MAE = 1.92$).

Keywords: Extreme Learning Machine (ELM); hourly air temperature forecasting; Machine Learning; Outlier Robust Extreme Learning Machine (ORELM); Quebec; Real-time forecasting; Water Resource Management

1. Introduction

One of the most significant challenges facing humanity is climate change mitigation. Despite the existing challenges in forecasting climate change effects on Earth, there is scientific agreement on its detrimental consequences. The climate change effects have been identified as adversely affecting ecosystems, soil erosion, reducing biodiversity, rising sea levels, extreme temperature changes, and global warming. Additionally, a significant impact is expected on food security, human health, energy consumption, and economy. Forecasting air temperatures, in particular, has become an increasingly crucial climatic aspect in various fields, including tourism, energy, agriculture, industry, and so on [1,2]. There are several applications for air temperature forecasting, including forecasting cooling and energy consumption for residential buildings [3], controlling greenhouse temperatures adaptively [4], and predicting natural hazards [5]. As a result, there is a need to reliably anticipate air temperature since they would assist in a planning horizon for constructing a business development, an energy policy, an insurance policy, and infrastructure upgrades when combined with the study analysis of additional elements in the topic of interest.

Machine Learning (MA) helps improve several types of systems so that their use is overgrowing. Although Feed-forward Neural Network (FFNN) is the most well-known and widely-used MA-based technique in modeling complex systems, it has some weaknesses, such as overfitting, trapping in local minima, lengthy training process, and slow convergence [6–9]. Huang et al. [10] proposed a single-layer FFNN (SLFFNN) known Extreme

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Learning Machine (ELM) to overcome the mentioned limitations. Compared to conventional FFNN methods, ELM requires minimal user involvement, provides rapid training, and has high generalizability [10,11]. Although this method has many advantages, it has several limitations, one of which is its low performance in the presence of outliers. Zhang and Luo [12] proposed Outlier Robust ELM (ORELM) to improve the model performance by increasing sparsity. Moreover, the second limitation of the ELM is the random determination of two main matrices (i.e., input weights and bias of hidden neurons), which account for at least 66% of all tuned parameters of the final model [13]. It was suggested by Ebtehaj et al. [13] that by introducing a simple iterative process, the random initialization of the two matrices would be reduced to a minimum. To the authors’ best knowledge, there is no study on applying the ORELM in hourly air temperature forecasting.

This research aimed to develop a novel technique and explore the potential of new data intelligent models by integrating the ORELM and iterative process defined by Ebtehaj et al. [13] to forecast hourly air temperature in Quebec City, Canada. The parameters of the developed Improved version of the ORELM (IORELM), including the activation function, regularization parameter, and the number of hidden neurons, were optimized by defining different models. Moreover, the performance of the IORELM was evaluated for multi-step ahead forecasting of the hourly air temperature.

2. Materials and Methods

2.1. Study Area

A time series of hourly air temperature data has been collected at the station of Sainte-Catherine-de-la-Jacques Cartier (Latitude: 46.8378 & Longitude = -71.6217) from 1 January 2001 to 30 November 2022 for the present study (Figure 1). A 50:50 ratio was used to split the collected data into training and testing stages (i.e., 95376 samples were collected for each stage). It has a minimum, an average, a standard deviation, and a maximum of -36.37, 1.6, 11.455, and 23.5 °C, respectively. Measurements of the dataset were conducted by the “Ministère de l’Environnement et de la Lutte contre les changements climatiques, de la Faune et des Parcs” [14] of Québec, Canada.

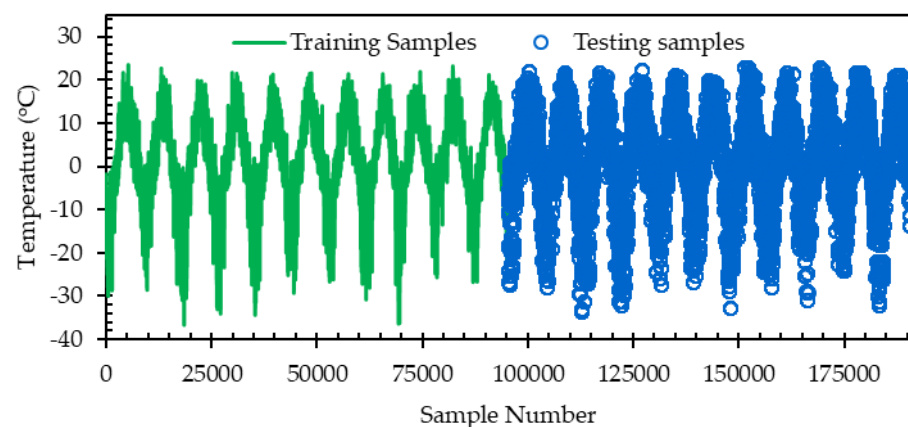


Figure 1. Time series of historical temperature for both training and testing stages.

2.2. Improved Outlier Robust Extreme Learning Machine (IORELM)

Considering several k random samples as (x_i, t_i) and $A(x)$ as the activation function, the general form of the SLFFNN is defined as:

$$\sum_{j=1}^L W_j f(\mathbf{In}W_j \cdot \mathbf{x}_i + S_j) = y_i, \quad i = 1, 2, \dots, k \quad (1)$$

where k is the number of samples, \mathbf{x}_i and y_i are the input and output variables, respectively, S_i is the bias of hidden neurons, $\mathbf{In}W_j$ is the input weight matrix, $A(x)$ is the activation function, W_j is the vector of the output weight, and L is the number hidden neurons.

A matrix representation of the above-mentioned equation, which is composed of L equations, is given below:

$$\mathbf{HW}=\mathbf{y} \tag{2}$$

$$W = [W_1, \dots, W_k]^T \tag{3}$$

$$\mathbf{y} = [y_1, \dots, y_k]^T \tag{4}$$

$$\mathbf{H} = \begin{bmatrix} A(\mathbf{InW}_1 \cdot \mathbf{x}_1 + S_{A_1}) & \cdots & A(\mathbf{InW}_h \cdot \mathbf{x}_1 + S_L) \\ \vdots & \ddots & \vdots \\ A(\mathbf{InW}_1 \cdot \mathbf{x}_k + S_1) & \cdots & A(\mathbf{InW}_h \cdot \mathbf{x}_k + S_L) \end{bmatrix}_{k \times L} \tag{5}$$

The matrix H could be calculated easily due to the random definition of bias of hidden neurons (i.e., S) and the output weight (i.e., InW). Consequently, the only unknown variable in the matrix form of the equations provided in Equation (2) is W (i.e., Output weight matrix). Ebtehaj and Bonakdari [15] mentioned that the number of tuned parameters through modeling must be less than the number of training samples. Therefore, Eq. (2) is not square in most cases and solving it to find the unknown variable is not simple. Thus, the lost function defined for IORELM is as follows:

$$E_{\text{ORELM}} = \min_{\mathbf{W}} \|\mathbf{e}\|_1 + \frac{1}{C} \|\mathbf{W}\|_2^2 \text{ subjected to } \mathbf{y} - \mathbf{HW} = \mathbf{e} \tag{6}$$

where C is the regularization parameter. Due to solving this equation results in a constrained convex optimization problem, the augmented Lagrange of Equation (6) is defined as follows:

$$L(\mathbf{W}, \mathbf{e}, \lambda) = \|\mathbf{e}\|_1 + \frac{1}{C} \|\mathbf{W}\|_2^2 + \lambda^T (\mathbf{y} - \mathbf{HW} - \mathbf{e}) + \frac{\mu}{2} \|\mathbf{y} - \mathbf{HW} - \mathbf{e}\|_2^2 \tag{7}$$

where μ is a penalty parameter defined as $\mu = 2k / \|\mathbf{y}\|_1$ and λ is the Lagrange multiplier vector. The explicit solution of Equation (6) using the defined augmented Lagrange vector in Equation (7) is:

$$\beta_{k+1} = (\mathbf{H}^T \mathbf{H} + 2 / C \mu \mathbf{I})^{-1} \mathbf{H}^T (\mathbf{y} - \mathbf{e}_k + \lambda_k / \mu) \tag{8}$$

where

$$\begin{aligned} \mathbf{e}_{k+1} &= \text{shrink}(\mathbf{y} - \mathbf{HW}\beta_{k+1} + \lambda_k / \mu, 1 / \mu) \\ &\cong \max \{ |\mathbf{y} - \mathbf{HW}_{k+1} + \lambda_k / \mu| - 1 / \mu, 0 \} \circ \text{sign}(\mathbf{y} - \mathbf{HW}_{k+1} + \lambda_k / \mu) \end{aligned} \tag{9}$$

(“ \circ ” is the element-wise multiplication and I is the identity matrix).

For all defined iteration numbers by the user, the output weight was calculated, and the value of the samples in both training and testing was computed using the three matrices (i.e., input weights, bias of hidden neurons, and output weights) and the activation function. Finally, the optimized values of the mentioned matrices related to the model with the lowest testing error were stored as the final model.

3. Results and Discussions

In this section, the IORELM-based model is discussed in detail in terms of finding the optimal parameters, including the regularization parameter, the activation function, and the number of hidden neurons (NHN). Using the most optimum values of the NHN, the regularization parameter, and the best activation function, the performance of the IORELM in multi-step ahead forecasting of the hourly air temperature was assessed.

The performance of the IORELM is evaluated in Figure 2 by considering NHN in the range of [2,20]. The performance of NHN = 1 was also evaluated, but its use in a figure prevented the observation of the differences between other values, so it was not included in this figure. Figure 2 provides information on some statistical indices, including Corrected Akaike Information Criteria, Root Mean Square Errors (RMSE), Mean Absolute Errors (MAE), Nash–Sutcliffe efficiency (NSE), and correlation coefficients (R). The mathematical definition of these indices can be found in recent publications [16,17]. To forecast hourly air temperatures, the following inputs have been taken into consideration:

$$T(t) = f(T(t-1), T(t-2), T(t-3)) \tag{10}$$

where $T(t)$, $T(t-1)$, $T(t-2)$, and $T(t-3)$ are the air temperature at time t , $t-1$, $t-2$, and $t-3$, respectively.

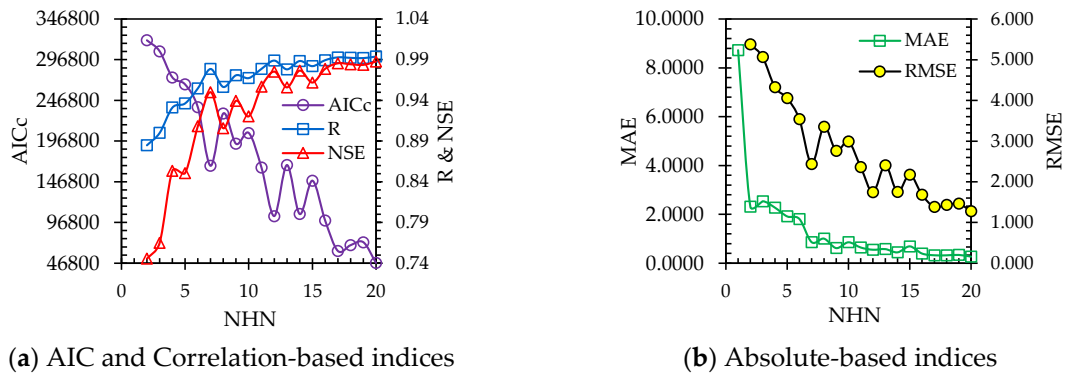
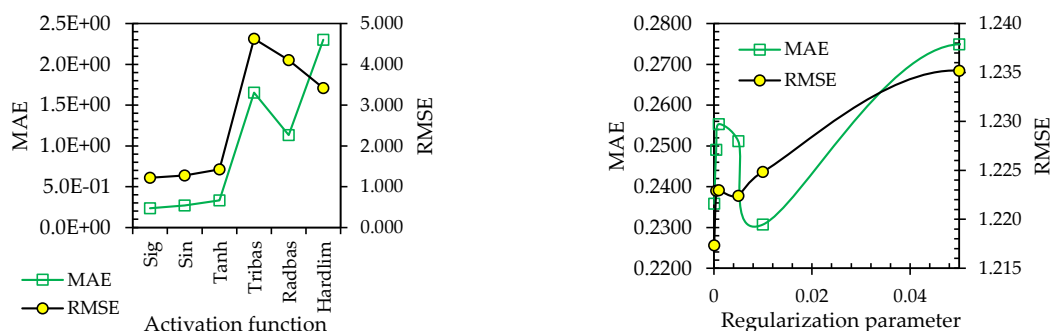


Figure 2. Performance evaluation of the IORELM with the different number of hidden neurons.

The general trend presented in Figure 2 shows that the increase in the number of neurons in the hidden layer has a direct relationship with the modeling accuracy. However, there are some exceptions for some indices. For example, all indices for the models with $NHN = 8, 12, 14, 17,$ and 18 have higher values than those for $NHN = 9, 13, 15, 18,$ and 19 , respectively. It should be noted that as NHN increases, the differences between the presented models decrease. There could be explained by the fact that the input weights and biases of hidden neurons are determined randomly, which accounts for more than 66% of the total number of optimized values [13]. Based on this knowledge, the number of iterations increased to 100,000 and the best solution is presented in Figure 2. It can be seen that increasing NHN by more than 17 does not significantly change the values of $R, NSE, RMSE,$ and $MARE$ indices. Nevertheless, the $AICc$ index, which considers the accuracy and simplicity of the model, should also be evaluated. Considering that the lowest value of $AICc$ was observed in $NHN = 20$ and there is an insignificant difference between other indices in the high value of NHN , $NHN = 20$ was chosen as the optimal number of neurons.

The optimal activation function was found using the optimal number of hidden layer neurons and the functional equation presented in Equation (10). The results presented in Figure 3a show that among the six functions given in this figure (i.e., Sigmoid (Sig), sine (Sin), tangent hyperbolic (Tanh), radial basis function (Radbas), triangular basis function (Tribas), and hard limit (Hardlim)), the performance of tribas, radbas, and hardlim functions is much weaker than the others. The statistical indices indicated that the Sigmoid function ($R = 0.994; NSE = 0.989; RMSE = 1.217; MAE = 0.236$) outperformed the others. The RMSEs of the IORELM modeling using Sig are more than 4.9%, 17%, 280%, 236%, and 180% lower than those for Sin, Tanh, Tribas, Radbas, and Hardlim, respectively. For MARE, these ratios are 14%, 41%, 601%, 380%, and 876%, respectively. Therefore, the Sigmoid was selected as the most optimum activation function.



(a) Activation function (b) Regularization parameter

Figure 3. Investigation of the effects of (a) Activation function, and (b) regularization parameter, on the IORELM performance.

To find the optimum regularization parameters (i.e., 0.0001, 0.0005, 0.001, 0.005, 0.01, 0.05, 0.1, 0.5) were considered in Figure 3b. The trend of changes presented in this figure shows that there is no clear relationship between the regularization parameter and the model’s accuracy, so it can be seen that the MAE at $C = 0.01$ is better than the value of this index at $C = 0.005$ and 0.5 . The RMSE and MAE ranges for all regularization parameter values are [1.217, 1.235] and [0.231, 0.275], respectively. Although the difference between the presented values is significant, the best performance of IORELM was obtained at the lowest value of the regularization parameter (i.e., $C = 0.0001$).

Figure 4 illustrates the statistical indices of IORELM in forecasting hourly air temperatures one to ten times ahead. Three lags were considered as input variables for developing these models, as described in Equation (10) for one hour ahead (1HA). Two to ten hours ahead, the first inputs are $T(t-2)$ to $T(t-10)$, the second inputs are $T(t-3)$ to $T(t-11)$, and the third inputs are $T(t-4)$ to $T(t-12)$, respectively. The increase in forecast time (i.e., from 1HA to 10HA) decreases the values of two correlation-based indices (R and NSE), while increasing the values of RMSE and MAE. The relative differences of the value of one index for 2HA to 10HA compared to the 1HA indicated that this ratio for R, NSE, MAE, and RMSE are [0.56%, 4.48%], [1.13%, 10.04%], [82.84%, 714.7%], and [40.87%, 207.53%], respectively. However, it can be seen that the results of hourly air temperature for 10HA ($R = 0.95$; $NSE = 0.89$; $RMSE = 3.74$; $MAE = 1.92$) are acceptable. It should be noted that this model has predicted 95,376 different samples with only 20 neurons in the hidden layer, which confirms the model’s simplicity.

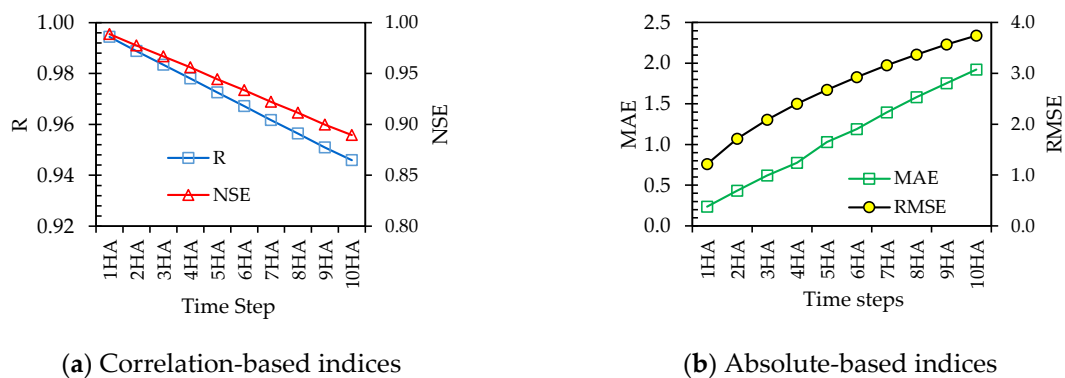


Figure 4. Assessment of the IORELM capacity in multi-steps ahead precipitation forecasting.

4. Conclusions

This study suggests the Improved Outlier Robust Extreme Learning Machine (IORELM) for forecasting air temperature hourly up to ten hours in advance. The most optimal values of hidden neurons (e.g., 20), the most efficient activation function (e.g., Sigmoid function), and the regularization parameters (e.g., $C = 0.0001$) were determined by calibrating this model for one hour in advance ($R = 0.994$; $NSE = 0.989$; $RMSE = 1.217$; $MAE = 0.236$). Model performance was assessed for one to ten hours in advance using the most optimal values of the different parameters. The more the time ahead increases, the more the accuracy of the model decreases. Nevertheless, the model’s performance ten hours ahead of precipitation forecasting was acceptable ($R = 0.95$; $NSE = 0.89$; $RMSE = 3.74$; $MAE = 1.92$). Since the effect of input variables has not been assessed, it is recommended that future studies use feature selection and compare the model’s performance with optimal inputs.

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Data Availability Statement: All data used during the study were provided by a third party. Direct requests for these materials may be made to the provider, as indicated in the Acknowledgements.

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Conflicts of Interest: The authors declare no conflict of interest.

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