Development of an Instant Correction and Display System of Numerical Weather Prediction Products in China

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Abstract: This paper presents the development of numerical prediction products (NPP) correction and display system (NPPCDS) for rapid and effective post-processing and displaying of the T213 NPP (numerical prediction products of the medium range numerical weather prediction spectral model T213L31) through instant correction method. The NPPCDS consists of two modules: an automatic correction module and a graphical display module. The automatic correction module automatically corrects the T213 NPP at regularly scheduled time intervals, while the graphical display module interacts with users to display the T213 NPP and its correction results. The system helps forecasters extract the most relevant information at a quick glance without extensive post-processing. It is simple, easy to use, and computationally efficient, and has been running stably at Huludao Meteorological Bureau in Liaoning Province of China for the past three years. Because of its low computational costs, it is particularly useful for meteorological departments that lack advanced computing capacity and still need to make short-range weather forecasting.

Keywords: numerical prediction products (NPP); SharpMap; post-processing; instant correction method (ICM); numerical prediction products correction and display system (NPPCDS)

1 Introduction

Numerical prediction products (NPP), that is, outputs from numerical weather prediction (NWP) models, are widely used in weather forecasting around the world. The models simulate future atmospheric systems by solving fluid mechanical and thermodynamic equations which describe weather processes based on certain initial values and boundary conditions (Kimura, 2002). In China, weather forecasters make daily and short-range weather forecasts mainly based on the T213 NPP (nu-

merical prediction products of the medium range numerical weather prediction spectral model T213L31). The accuracy of their forecasts mainly depends on the accuracy of NPP. In order to improve the accuracy of weather predictions, it is necessary to reduce the NPP errors.

Although NWP models have been advancing rapidly along with the development of modern monitoring and computing technologies, NPP errors are still inevitable (Lorenz, 1982; Bengtsson and Hodges, 2006; Liang *et al.*, 2007). Many methods have been proposed to reduce

the NPP errors (Bennett and Leslie, 1981; Qiu and Chou, 1987; 1988; 1990; Kang, 1995; Chou and Xu, 2001). Generally, these methods can be divided into two classes. One class reduces the NPP errors ′from the front side′ (Chou and Xu, 2001), which means that these methods improve the representation of the dynamic framework and the physical processes of the atmosphere in the NWP models through theoretical and experimental research (Qiu and Chou, 1987; 1988; 1990; Kang, 1995). However, it is difficult to implement this type of methods in forecast offices that lack relevant expertise and advanced computing systems. Another class of methods reduces the NPP errors through post-processing the NPP. For example, some post-process the results of single realization of the NWP model, such as model output statistics (Glahn and Lowry, 1972), Kalman filtering (Fertig *et al.*, 2007), analog methods (Monache *et al.*, 2011), neural network based on back propagation algorithm (Xu *et al.*, 2007), variational method (Zupanski, 1993; Trémolet, 2007), ensemble calibration (Hamill and Colucci, 1998), and Bayesian model averaging (Raftery *et al.*, 2005). Other methods run multiple realizations of the same NWP model and then post-process the ensemble results (Molteni *et al.*, 1996; Toth and Kalnay, 1997).

Generally, these post-processing methods are applied to establish relationships between the large scale NPP and the weather elements at local stations, and these relationships are subsequently used to forecast local weather elements. However, these methods do not correct the large scale NPP (Nott *et al.*, 2001; Libonati *et al.*, 2008). A new correction method, the instant correction method (ICM), was proposed in this study, aiming to improve the accuracy of the large scale NPP through post-processing. A unique feature of this method is that it makes use of the continuity of the forecast errors. That is, it utilizes forecast errors that are known from immediately previous times to correct the subsequent forecast errors after the original NPP are created.

In this study, the instant correction method has been applied to correct the T213 NPP from the National Meteorological Center (NMC) of China. As the computation of the ICM is huge, it is necessary to correct the T213 NPP automatically and at the same time, spatially display the correction results over the study area.

Currently, a few correction systems are available, but can not display the T213 NPP (Toth and Kalnay, 1997; Raftery *et al.*, 2005; Shang, 2010). While there are systems available to display the NPP (Dyras and Serafin-Rek, 2005), only Meteorological Information Comprehensive Analysis and Process System 3.0 (MICAPS 3.0) is configured to display the T213 NPP. The MICAPS, however, is complicated and expensive. Additionally, it can not display the T213 NPP and the correction results simultaneously. Thus, it is essential to develop such a system that is simple, inexpensive, user-friendly, easily transferable, and integrates both auto correction module and spatial display module to facilitate applications of the ICM.

In this study, the numerical prediction products correction and display system (NPPCDS) has been developed based on the open-source software. The NPPCDS consists of two modules: an automatic correction module and a graphical display module. The automatic correction module was written in Fortran and automatically corrects the T213 NPP at regularly scheduled time intervals. The graphical display module was developed based on C sharp and open source software—SharpMap. It interacts with users to display the T213 NPP and its correction results. The NPPCDS is described in detail in the following sections.

2 Instant Correction Method

2.1 Theory of instant correction method

The instant correction method assumes that the NWP models are initialized at time $t = T$ to predict weather to $t = T + t_n$. In the intervening time period, new observations become available. However, the models do not make use of these observations until the next forecasting cycle. The instant correction method makes use of these new observations to correct the NPP through post-processing.

The T213 NPP, which is the most popular NPP in China, was used to apply the instant correction method. The T213 model is initialized at 1200 UTC (Universal Time Coordinated) every day. The forecast times of the T213 NPP are 12-h, 24-h, 36-h, 48-h, 60-h, 72-h, 96-h, 120-h, 144-h, 168-h, 192-h, 216-h and 240-h. The forecast variables are geopotential height, temperature, U-wind, V-wind, vertical velocity, and specific humidity at grids on different standard isobaric surfaces. After the T213 NPP is available, the NMC of China immediately sends it to all the provincial and local forecast units in the country. Subsequently, the forecasters in their respective locations around China use the T123 NPP as guidance to make forecasts.

If the T213 model starts at T, for each standard isobaric surface, we denote the forecasts whose forecast time is t_x as t_x forecasts at T and their corresponding forecast errors as t_x forecast errors at T. Here, t_x is a forecast time of the T213 NPP (12-h, 24-h, and so on).

For convenience, we denote the daily starting time of the T213 model, 1200 UTC, as T. Then we denote 00 UTC of the next day as $T+12$, and 1200 UTC of the previous day as $T-24$. We also denote the 12-h forecast errors at T as $\Psi e_T^{12\text{-h}}$, the 24-h forecast errors as $\Psi e_T^{24\text{-h}}$, the 36-h forecast errors as $\Psi e_T^{36\text{-h}}$, …, and the 240-h forecast errors as $\Psi e_T^{240\text{-h}}$. Therefore, all the forecast errors of the T213 NPP at T can be expressed as $\{\Psi e_T^{12\text{-h}}, \ \Psi e_T^{24\text{-h}}, \cdots, \ \Psi e_T^{240\text{-h}}\}$.

For a specific NWP model, the forecast errors should be continuous in time. According to our statistical analysis of the T213 NPP, there are correlations between the forecast errors at different forecast times.

At initialization of the T213 model, the 24-h forecast errors of the T213 NPP at $T-24$ can be obtained, which is denoted as $\Psi e_{T-24}^{24\text{-h}}$. The first observation corresponding to the forecasts is at 00 UTC of the next day. Then, we would get two actual forecast errors: $\Psi e_{T-24}^{24\text{-h}}$ and $\Psi e_T^{12\text{-h}}$.

Since a correlation exists between $\Psi e_T^{24\text{-h}}$ and both $\Psi e_{T-24}^{24\text{-h}}$ and $\Psi e_T^{12\text{-h}}$, then $\Psi e_T^{24\text{-h}}$ can be obtained by using $\Psi e_{T-24}^{24\text{-h}}$ and $\Psi e_T^{12\text{-h}}$:

$$\Psi e_T^{24\text{-h}} = \gamma_0 + \gamma_1 \Psi e_{T-24}^{24\text{-h}} + \gamma_2 \Psi e_T^{12\text{-h}} \tag{1}$$

where γ_0, γ_1, and γ_2 are the coefficients.

Then, the subsequent forecast errors can be corrected by using $\Psi e_T^{12\text{-h}}$ and $\Psi e_T^{24\text{-h}}$. Suppose the correlations between the forecast errors at different forecast times can be described as Equation (2):

$$Y = \beta_0 + \beta_1 \Psi e_T^{12\text{-h}} + \beta_2 \Psi e_T^{24\text{-h}} \tag{2}$$

where Y represents the forecast errors $\{\Psi e_T^{36\text{-h}}, \cdots, \Psi e_T^{240\text{-h}}\}$, β_0, β_1, and β_2 are the parameters.

When we get enough NPP and its corresponding observations, the coefficients of equations (1) and (2) can be established by statistical analysis. Using the new observations after the NWP model starts at T, forecast er-

rors $\{\Psi e_T^{12\text{-h}}, \ \Psi e_T^{24\text{-h}}, \cdots, \ \Psi e_T^{240\text{-h}}\}$ can be calculated according to equations (1) and (2). Thus, the NPP can be immediately corrected.

Making use of the continuity of the forecast errors, the instant correction method reduces the NPP errors at very low computational costs.

2.2 Application of instant correction method in China

The ICM has been applied to correct the T213 NPP at Huludao Meteorological Bureau in Liaoning Province of China. The study area (10°00′–70°00′N, 65°00′–152°30′E) of this paper is East Asia.

As there are no T213 NPP data that could be used as the reference dataset at 00 UTC, the National Centers for Environmental Projection (NCEP)/National Center of Atmospheric Research, USA (NCAR) reanalysis dataset, which has been used widely as the benchmark for assessing the accuracy of weather forecast products in China (Kalnay et al., 1998; Xie et al., 2007; Zhao and Fu, 2009; Zhao et al., 2010), is used instead in this study. Thus, the T213 NPP of the initial time (1200 UTC) and NCEP/NCAR reanalysis dataset of 00 UTC are used as the reference datasets to determine the forecast errors. Though there are three kinds of resolution of the T213 NPP (0.5° × 0.5°, 1.0° × 1.0°, and 2.5° × 2.5°), the 2.5° × 2.5° resolution is the one used by all the weather forecast offices in China. Thus, in this study, the spatial resolution of both datasets is global 2.5° latitude by 2.5° longitude, with 900 grids covering the entire study area.

The ensemble equations are established by using data from 2003 to 2008. Through the ensemble method combining both stepwise regression method and Kalman Filter method, the coefficients of the correction equations (1) and (2) were determined for all the meteorological variables on each standard isobaric surface. As the correction coefficients are calculated for each of the 900 grids, there are 340 equations on each grid ({1(specific humidity) × 8(isobaric surfaces) + 5(the other meteorological variables) × 12(isobaric surfaces)} × 5 (forecasting times) = 340) (Table 1), and the total number of equations is 306 000 for the entire study area.

The implementation of the ICM includes two parts: training and validation. The training period was from 2003 to 2008 (the data used to establish the equations) and the validation period was from 2009 to 2010. The improvements of the ICM T213 NPP (the results of the

Table 1   Number of correction equations for one grid

Meteorological variable	Standard isobaric surface	Forecasting length
Height	100hpa, 150hpa, 200hpa, 250hpa, 300hpa, 400hpa, 500hpa, 600hpa, 700hpa, 850hpa, 925hpa, 1000hpa	24-h, 36-h, 48-h, 60-h, 72-h
Temperature	100hpa, 150hpa, 200hpa, 250hpa, 300hpa, 400hpa, 500hpa, 600hpa, 700hpa, 850hpa, 925hpa, 1000hpa	24-h, 36-h, 48-h, 60-h, 72-h
U-wind	100hpa, 150hpa, 200hpa, 250hpa, 300hpa, 400hpa, 500hpa, 600hpa, 700hpa, 850hpa, 925hpa, 1000hpa	24-h, 36-h, 48-h, 60-h, 72-h
V-wind	100hpa, 150hpa, 200hpa, 250hpa, 300hpa, 400hpa, 500hpa, 600hpa, 700hpa, 850hpa, 925hpa, 1000hpa	24-h, 36-h, 48-h, 60-h, 72-h
Vertical velocity	100hpa, 150hpa, 200hpa, 250hpa, 300hpa, 400hpa, 500hpa, 600hpa, 700hpa, 850hpa, 925hpa, 1000hpa	24-h, 36-h, 48-h, 60-h, 72-h
Specific humidity	300hpa, 400hpa, 500hpa, 600hpa, 700hpa, 850hpa, 925hpa, 1000hpa	24-h, 36-h, 48-h, 60-h, 72-h

T213 NPP corrected by the ICM) are evaluated by three popular indices: correlation coefficient, climate anomaly correlation coefficient, and root-mean-square-errors (RMSE). The results clearly indicate that the ICM T213 NPP is much more accurate than the T213 NPP within 72 hours of the forecast initialization (Figs. 1 and 2). Thus, the instant correction method is stable, reliable and effective.

Comparing with the similarity correction method (SCM) proposed by Shang (2010), the correlation coefficients between the ICM T213 NPP and the reference datasets are higher than those between the SCM T213 NPP and the reference datasets. Similarly, the climate anomalies correlation coefficients are also higher, and the RMSE, except vertical velocity, are lower between the ICM T213 NPP and the reference datasets than those between the SCM T213NPP and the reference datasets, respectively. For the two main variables (height and temperature) of the T213 NPP forecasts, the ICM performed much better than the SCM within the first 72 hours of the forecasts as demonstrated by the higher correlation coefficients and lower RMSE (Figs. 3 and 4).

3   Numerical Prediction Products Correction and Display System (NPPCDS)

Currently, forecasters have to correct the NPP manually. Moreover, spatial display of the correction results by MICAPS 3.0 is complicated, and MICAPS 3.0 can not display the T213 NPP and its correction results at the same interface. Therefore, we developed an integrated system, the NPPCDS, to make the application of the instant correction method user-friendly for end users. It can automatically correct the T213 NPP and display both the NPP and its correction results. The details of the NPPCDS are described below.

3.1   Structure of NPPCDS

There are two modules in the NPPCDS: an automatic correction module and a graphical display module. The automatic correction module was developed in Fortran. It is a background program that automatically corrects the T213 NPP at the fixed time intervals. After the correction, the T213 NPP and its correction results can be displayed by the graphical display module. The graphical display module is developed based on C sharp and open source software—SharpMap. It is a foreground program that interacts with users. The graphical display module displays the T213 NPP and its correction results according to the needs of the end users. The structure of the NPPCDS is shown in Fig. 5.

3.2   Functions of NPPCDS

Every day, when observations at 00 UTC are obtained, the automatic correction module is automatically running to correct the T213 NPP at 1200 UTC of the previous day.

The resolution of the T213 NPP in practical applications around China is global 2.5° latitude by 2.5° longitude. Therefore, there are 900 grids in the study area. As shown in Fig. 6, for each point, there are three steps to correct. First, the module calculates actual forecast errors $\Psi e_{T-24}^{24\text{-h}}$ and $\Psi e_T^{12\text{-h}}$. Then, the module determines the forecast errors { $\Psi e_T^{12\text{-h}}$, $\Psi e_T^{24\text{-h}}$, ⋯, $\Psi e_T^{240\text{-h}}$ } by the corresponding equations. Finally, the NPP are corrected by using errors { $\Psi e_T^{12\text{-h}}$, $\Psi e_T^{24\text{-h}}$, ⋯, $\Psi e_T^{240\text{-h}}$ }. For easy processing and compatibility, the output is written in *text* format.
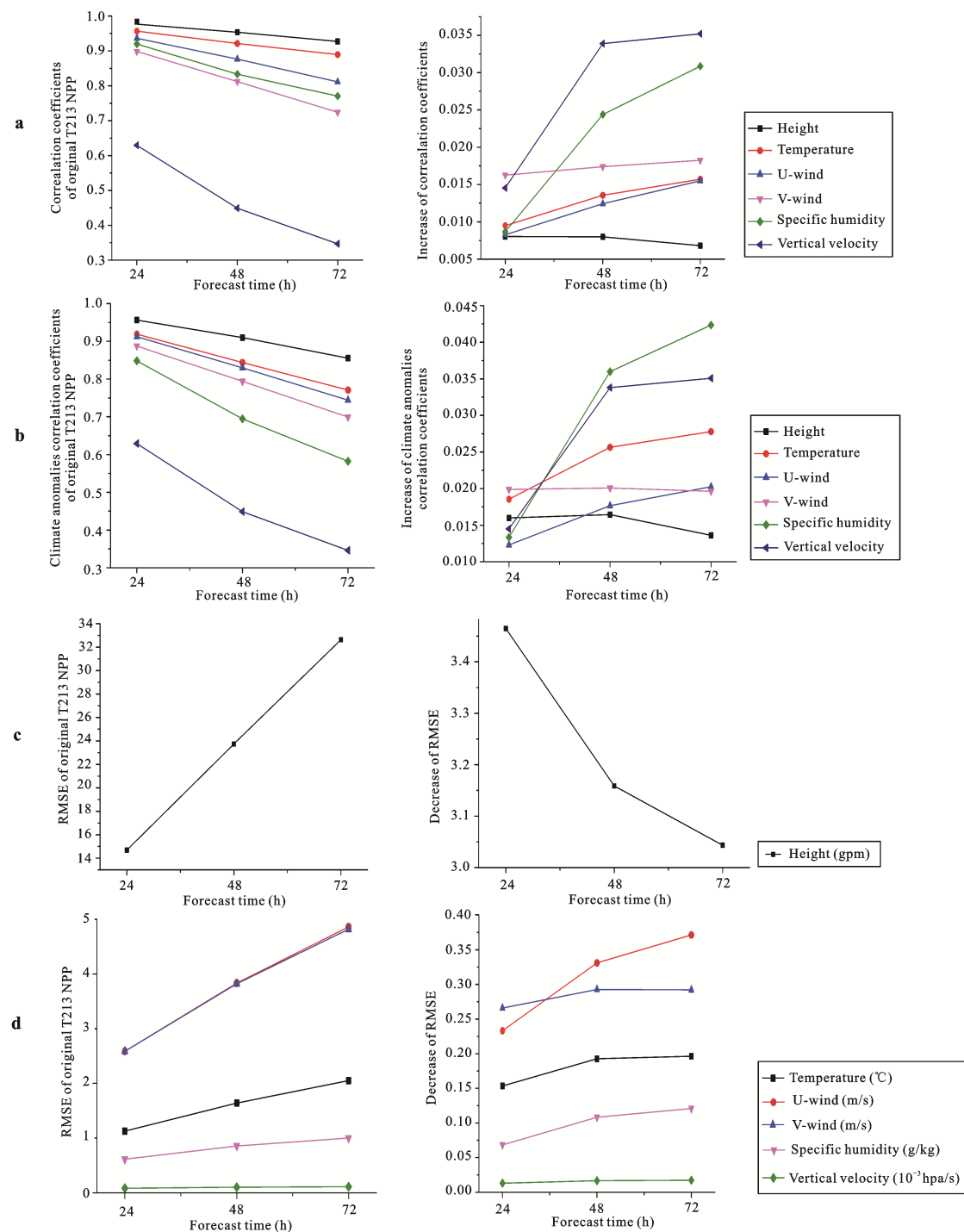
Fig. 1 Three indices after correction through ensemble equations in training period (mean values of all the points on all the isobaric surfaces for each forecast variable). a, correlation coefficients of original T213 NPP and increase of correlation coefficients after correction; b, climate anomalies correlation coefficients of original T213 NPP and increase of climate anomalies correlation coefficients after correction; c, RMSE (root-mean-square-errors) of original T213 NPP and its decrease after correction of height field; d, RMSE of original T213 NPP and its decrease after correction of other fields. Three indices (correlation coefficient, climate anomaly correlation coefficient, and RMSE) are calculated for each forecasting variable at each grid between the original T213 NPP and reference datasets (T213 NPP and NCEP reanalysis). Similarly, they are calculated between the ICM T213 NPP and reference datasets. Due to limited space, the differences of the mean value of three indices are listed in Fig. 1 and Fig. 2
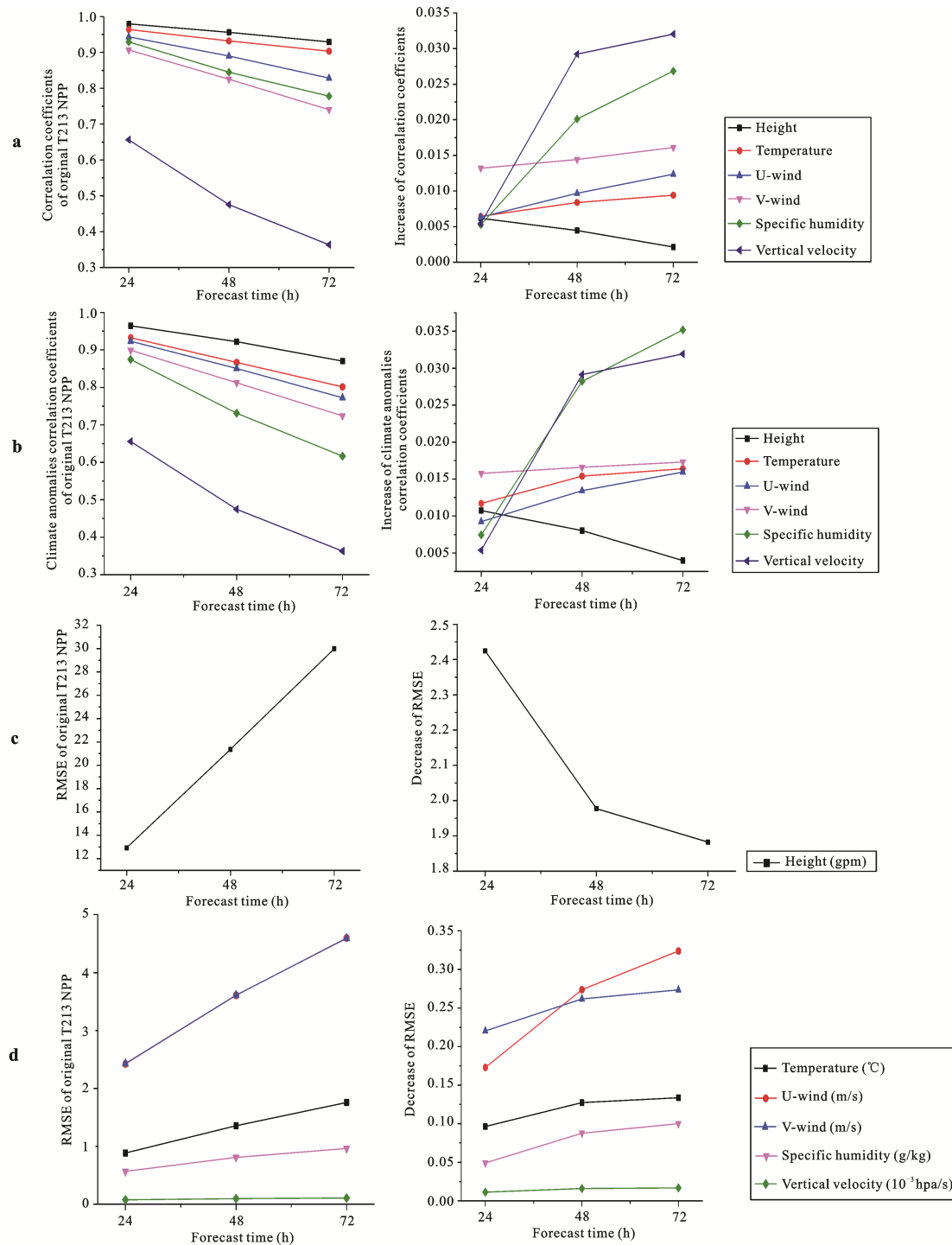
Fig. 2 Three indices after correction through ensemble equations in validation period (mean values of all the points on all the isobaric surfaces for each forecast variable). a, correlation coefficients of original T213 NPP and increase of correlation coefficients after correction; b, climate anomalies correlation coefficients of original T213 NPP and increase of climate anomalies correlation coefficients after correction; c, RMSE of original T213 NPP and its decrease after correction of height field; d, RMSE of original T213 NPP and its decrease after correction of other fields

Using the output from the instant correction system applied to the T213 NPP, the graphical display module draws contour lines. The main functions are as follows:

(1) Spatial information platform. It displays the base layers with zoom in, zoom out, and pan functions. The base layers include a national boundary layer, a provin-
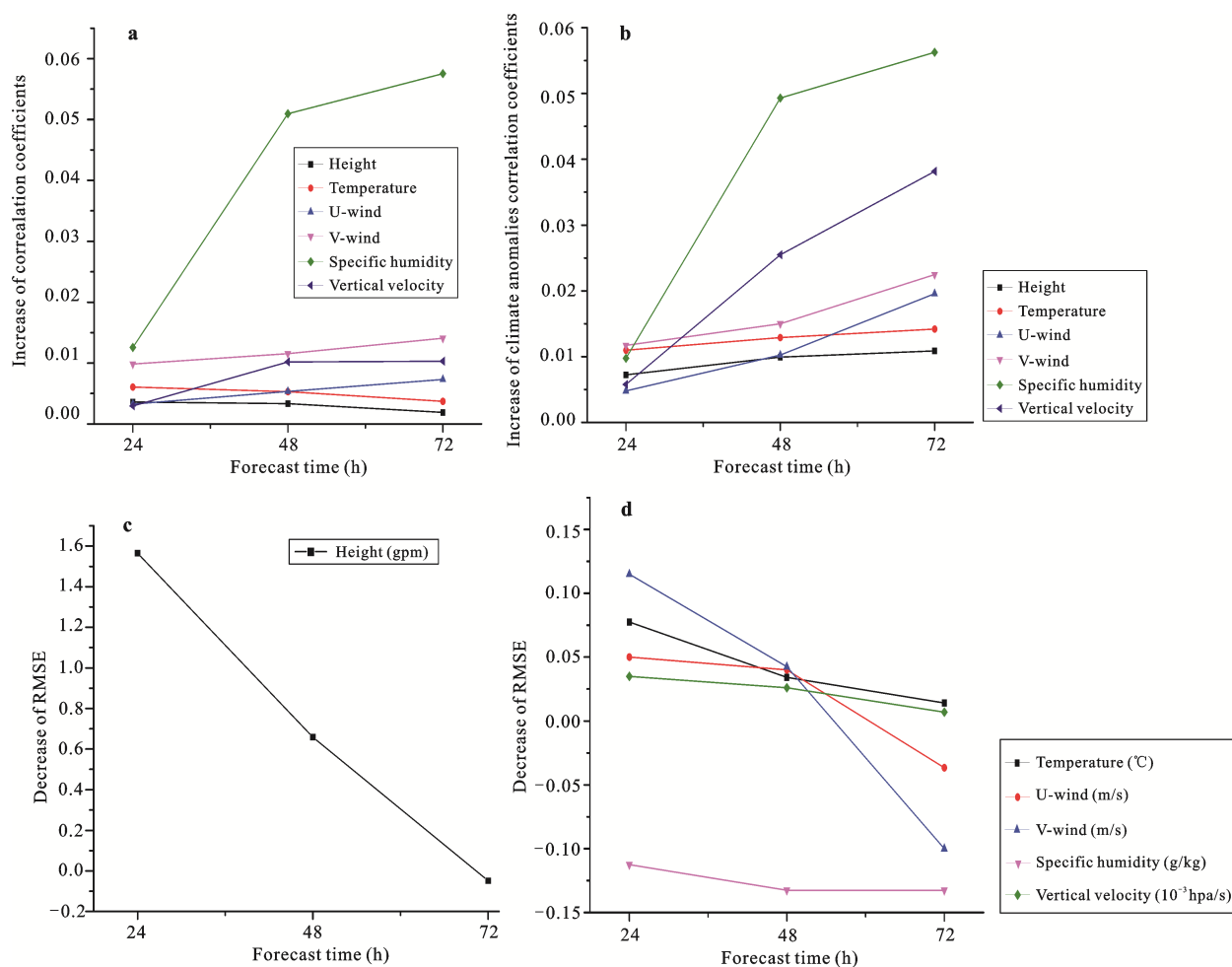
Fig. 3   Mean increase of three indices of ICM T213 NPP comparing with SCM T213 NPP of all grids on all isobaric surfaces for each forecast variable in training period. a, increase of correlation coefficients; b, increase of climate anomalies correlation coefficients; c, RMSE decrease of height field; d, RMSE decrease of other fields

cial boundaries layer, a rivers layer, and a cities layer.

(2) Correction result display. It draws contour lines and displays them according to the needs of the user. First, the user selects forecast variables, a standard isobaric surface, and a forecast time. Then the module draws contour lines for the selected variables, and displays them by overlapping the base map. Error warnings are given if the correction is not finished.

The interface of the graphical display module is shown in Fig. 7.

3.3   Key technologies of NPPCDS

The key technologies of the NPPCDS include processing, extracting, and displaying the spatial information and the T213 NPP based on SharpMap, an open source software. The specific technologies are briefly described below.

3.3.1   SharpMap overview

SharpMap is a piece of open source software which provides basic geographical information system (GIS) functions. It can render GIS data in many formats including Environmental Systems Research Institute (ESRI) Shape and PostGIS. It is developed with C sharp on *.NET* Compact Framework. It can be applied to both desktop and internet platforms. SharpMap can generate electronic maps with different functions such as zoom in, zoom out and pan. It can also manage geospatial data in ESRI Shape and PostGIS formats, as well as meteorological data. Compared to other GIS software systems, SharpMap has the following advantages (Li *et al.*, 2011; Zhang and Zhou, 2011): 1) SharpMap is open source software. Therefore, it is cheap and convenient, and its code can be easily modified. 2) SharpMap uses less storage and computation resources
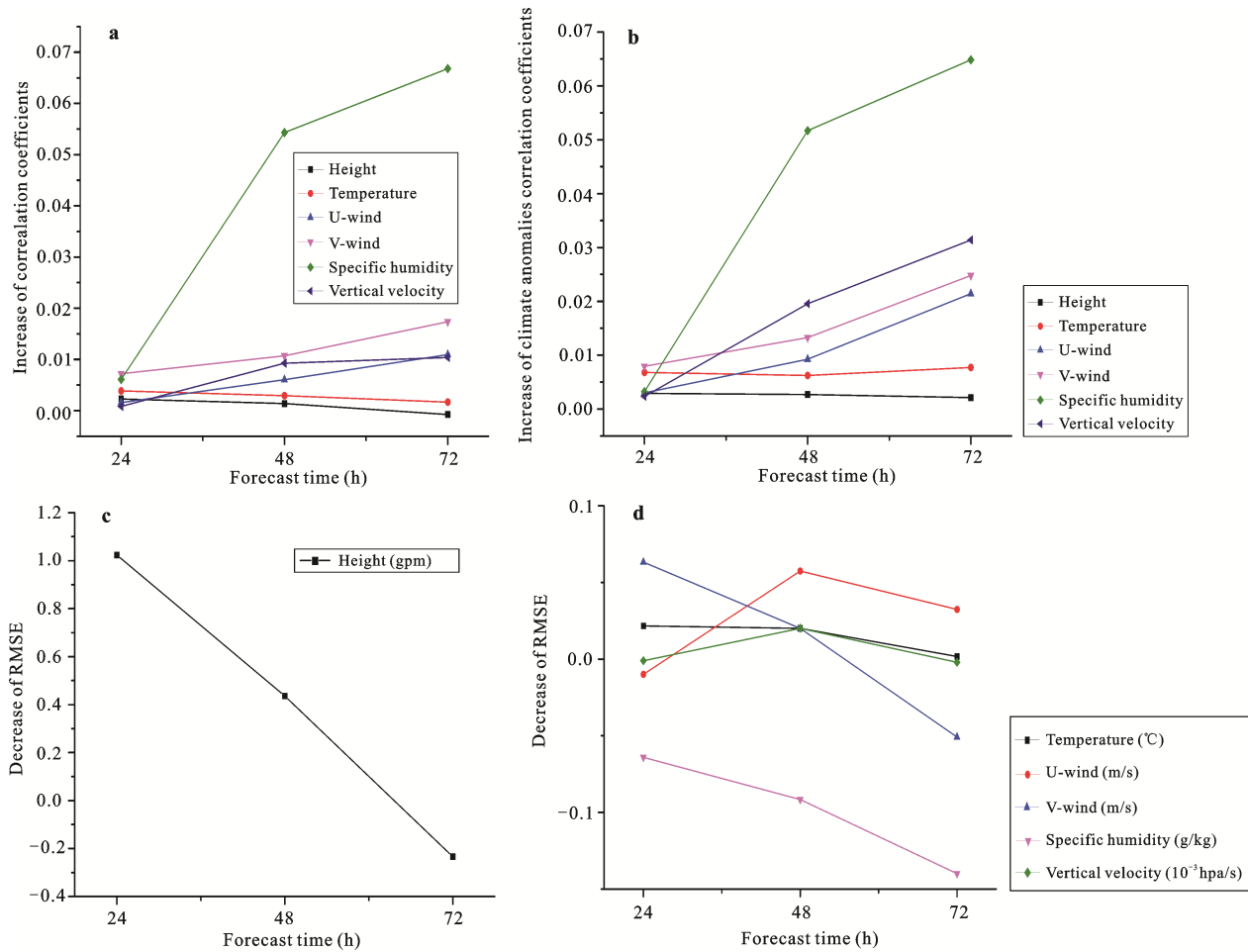
Fig. 4 Mean increase of three indices of ICM T213 NPP comparing with SCM T213 NPP of all grids on all isobaric surfaces for each forecast variable in validation period. a, increase of correlation coefficients; b, increase of climate anomalies correlation coefficients; c, RMSE decrease of height field; d, RMSE decrease of other fields
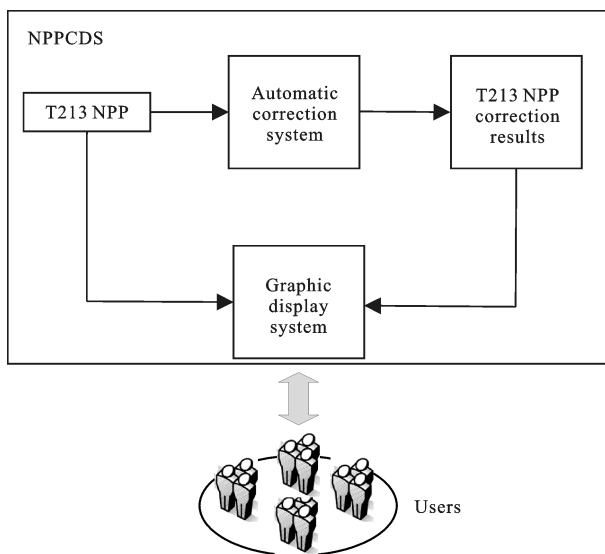
Fig. 5 Structure of numerical prediction products correction and display system (NPPCDS). NPP, numerical prediction product

than other GIS software (e.g., ESRI ArcGIS), shortening its response time. 3) Both SharpMap and the NPPCDS are developed on *.NET* Compact Framework, therefore, SharpMap is compatible with the NPPCDS. Thus, SharpMap is used to construct a spatial information platform for the NPPCDS in this study.

3.3.2 Spatial information platform

As SharpMap only provides the classes, we have developed a spatial information platform, as part of the NPPCDS to provide basic GIS functions.

(1) Base layers display

MapHandler class is developed in this study to generate the base map. First, the *MapHandler* class sets up the parameters of all the layers through the *SharpMap. Layers* class (which is provided by SharpMap). Then it loads all the layers of the base map by function *Sharp-Map. Layers.Add()* and sets up map attributes such as
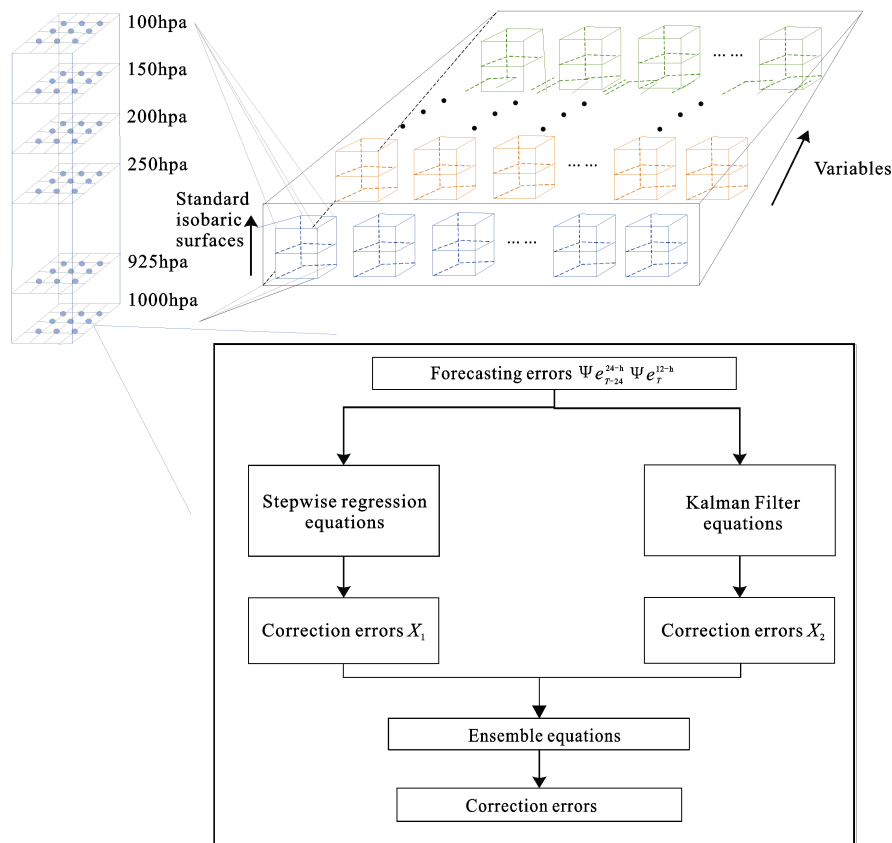
Fig. 6   Flowchart of automatic correction module

scale, center and background color. Finally, it displays the base map by sentence *picturebox.Image = map. GetMap()*.

(2) Zoom in, zoom out and pan

The zoom in and zoom out functions are realized by modifying the *zoom* attribute of *map*. Zoom in: *map. zoom = map.zoom/*magnification; zoom out: *map.zoom = map. zoom* × reduction rate. The *pan* function is associated with mouse action. It is realized by setting the map center.

3.3.3   Contour lines

The T213 NPP and its correction results are displayed as contour lines on the base map. As this function is not provided by SharpMap, the contour line generating function was developed through C sharp and the results displaying function was developed based on SharpMap in this study.

(1) Principle

First, a temporary file is generated according to the query constraints. The file includes information such as longitude, latitude and inquiry results. Second, a contour line file in *shapefile* format is generated by using *ContourOCX.dll*. Finally, the contour line file is displayed on base map by calling *MapHandler* class.

ContourOCX.dll is a dynamic link library characterized by microkernel, short response time and little computing resource (Li *et al.*, 2011). The contour lines generated by *ContourOCX.dll* are smooth and accurate, and are stored in *shapefile* format.

(2) Contour lines generation

Contour lines are generated by the function *DZX()* developed in this study. Function *DZX()* has 5 parameters: 1) *sourcefile* represents a temporary file including information such as longitude, latitude, and query results; 2) *lineN* represents the insert line count; 3) *dotN* represents the near point count; 4) *sp* represents the contour lines step; and 5) *shpfile* represents the storage path of the contour lines file.

Function *DZX()* reads a temporary file, sets related parameters and generates a contour line file. The return value is an integer. While the return value is 1, the contour line file is generated successfully. If the return value is 2, there is an error.

Function *DZX()* interpolates through the Kriging method, which is provided by *ContourOCX.dll*. The method has been used widely in meteorological research (Krige, 1951).
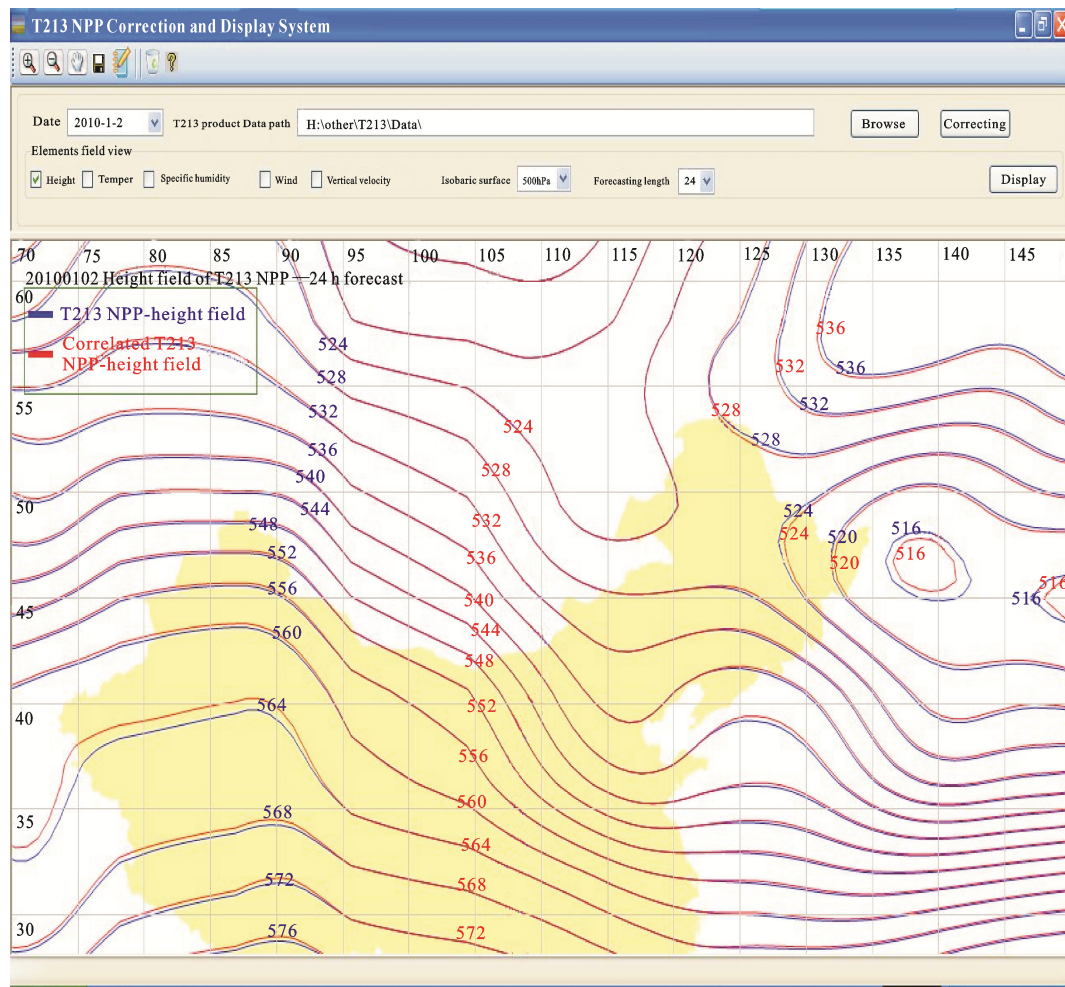
Fig. 7   Interface of graphical display module

(3) Contour lines display

Contour lines are displayed by calling the *MapHandler* class which was developed in this study. The contour line file is superimposed on the base map as a layer. First, *MapHandler* class initializes layers and sets map attributes. Then the contour lines layer is loaded by function *map.Layers.Add()*. Finally, the new map is displayed using the command *picturebox.Image = map.GetMap()*.

3.4   Application of NPPCDS

The NPPCDS can be used in all the forecast units which make forecasts based on the T213 NPP around China. The system has been used by forecasters of Huludao Meteorological Bureau in China for the past three years. It is robust and stable. Meanwhile, it is simple and easy to use, and end users can use it without any training.

The NPPCDS requires low computational resources and can run on any computer using the Windows oper-

ating system. On a computer with a Penium 4.0 processor and 2GB of memory, the system takes about 2 minutes to correct the T213 NPP and 30 seconds to display the results. Without the system, forecasters have to correct the T213 NPP one grid by one grid manually themselves for all the equations of the instant correction method, taking at least 20 hours. And they also have to convert the format of correction results to match MICAPS 3.0. It is a tedious and lengthy process. With the NPPCDS, however, the correction and display of the T213 NPP is robust, user friendly, and efficient.

4   Conclusions

The instant correction method (ICM) was developed by making use of the continuity of the forecast errors to improve the accuracy of the NPP. It utilizes the forecast errors that have been obtained up to the current time to correct the subsequent forecast errors after the raw NPP

are created. The method provides the meteorological variables on grids. The application of the method at Huludao Meteorological Bureau in Liaoning Province of China shows that the instant correction method is stable, reliable, and effective, especially in short range (the forecast time within 72 hours).

To facilitate the application of the instant correction method, the NPPCDS, a NPP correction and display system has been developed in this study. It not only corrects the T213 NPP automatically, but also simultaneously displays the T213 NPP and its correction results. The system has been running stably at Huludao Meteorological Bureau in China for the past three years. It is simple and easy to use, and end users can use it without any training. Compared with MICAPS 3.0, the system has more functions and uses less storage and computational resources. Thus, it can instantaneously correct and display the T213 NPP.

The NPPCDS helps forecasters avoid post-processing details and extract the most relevant information quickly. Such a system is useful to improve the accuracy of short-range weather forecasting in China. As the study area is East Asia, the system can be directly applied in the forecast units in China without any alteration. Meanwhile, because of its low computational costs, it is particularly useful for forecasting offices that lack advanced computing capacity, but still need to make short-range weather forecasts.

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