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# Applying artificial neural network to derive long-term foF2 trends in the Asia/Pacific sector from ionosonde observations

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[1] An artificial neural network (ANN) method is first used for deriving long-term trends of the F2-layer critical frequency (foF2) at 19 ionospheric stations in the Asia/Pacific sector. It is found that the ANN method can eliminate the geomagnetic activity effect on foF2 more effectively than usual regression methods. Of the selected 19 stations, there are significant long-term trends corresponding to a confidence level ≥90% at 14 stations and 12 of these stations present negative trends. An average trend of −0.05% per year in the selected area can be obtained if the 12 stations with significant negative long-term trends be considered. No pronounced diurnal and latitudinal effects in trends and no uniform pattern of seasonal variation in most stations are detected. The long-term trends for low latitude and equatorial stations differ from other stations suggest that some special dynamical processes may take effects in the equatorial anomaly region. Many factors which can influence ionosphere, such as the greenhouse effect, solar and geomagnetic activity, and neutral background gas, might contribute to the trend.

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## 1. Introduction

[2] Huge efforts have been made to search for the greenhouse effects in the ionosphere since *Roble and Dickinson* [1989] showed that the upper atmosphere would be expected to cool significantly as a result of increasing greenhouse gas concentrations [*Keating et al.*, 2000]. *Rishbeth* [1990] and *Rishbeth and Roble* [1992] predicted the changes in the ionosphere by a model and found that the peak heights and electron density of the F2 layer would decrease by doubling the atmospheric greenhouse $CO_2$. These results greatly stimulated the interest in the ionospheric long-term trend analysis. Recently, many investigations have been performed on the long-term trends of ionospheric parameters by using long time series of ionospheric observations [*Alfonsi et al.*, 2001, 2002; *Bremer*, 1998, 2001; *Bremer et al.*, 2004; *Danilov*, 1998, 2001, 2002a, 2002b, 2003, 2005; *Danilov and Mikhailov*, 1999, 2001; *Foppiano et al.*, 1999; *Jarvis et al.*, 1998; *Laštovička*, 1997, 2001, 2005b; *Marin et al.*, 2001; *Mikhailov*, 2002; *Mikhailov and de la Morena*, 2003; *Mikhailov and Marin*, 2000, 2001; *Mikhailov et al.*, 2002; *Ulich and Turunen*, 1997; *Upadhyay and Mahajan*, 1998].

[3] Main efforts have been directed towards the analysis of the F2 region parameter long-term trends since the F2-layer observations are most abundant and high-frequency (HF) wave propagation is mainly influenced by the behavior of the F2 region. The most suitable parameter for the trend analysis of the F2-layer is the critical frequency, foF2. However, the trends of foF2 from different stations are far from consistent and sometimes show interruptions or reversals [*Bremer*, 1998, 2001; *Upadhyay and Mahajan*, 1998]. A brief critical review of problems with the trend determination in the F2 region was given by *Ulich et al.* [2003]. The credibility of the derived trends depends strongly on the method used because the useful signal is very small comparing with the background [*Mikhailov et al.*, 2002]. The method most frequently used is linear or nonlinear regression between ionospheric parameters and solar and geomagnetic activity indices [*Bremer*, 1998, 2001; *Hall and Cannon*, 2002; *Jarvis et al.*, 1998; *Sharma et al.*, 1999; *Ulich and Turunen*, 1997; *Upadhyay and Mahajan*, 1998; *Xu et al.*, 2004]. *Danilov and Mikhailov* [1999] and *Mikhailov and Marin* [2000, 2001] used a revised method to derive the long-term trends of foF2. Using their method, *Danilov and Mikhailov* [1999] found a pronounced dependence of foF2 trends on geomagnetic latitude by analyzing foF2 data at a set of ionospheric stations with a wide latitudinal and longitudinal coverage; *Mikhailov* [2002] and *Mikhailov and Marin* [2000, 2001] showed periods of negative and positive foF2 trends correspond to the periods of increasing and decreasing geomagnetic activity, and they put forward a geomagnetic control concept to explain the revealed latitudinal and diurnal variations of the foF2 trends; *Danilov and Mikhailov* [2001] presented negative foF2 trends at two southern hemispheric stations and proposed that the long-term changes of geomagnetic activities may be an important cause of all the trends of foF2 derived by several groups of authors. Recently, significant work was done by *Danilov* [2002b] who developed a

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**Table 1.** List of the Ionosonde Stations Used for foF2 Trends Analysis and the Corresponding Long-Term Trends[a]

| Station Name | MLat, deg | GLat, deg | GLong, deg | Years Coverage | Yearly Trends ($10^{-5}$) |
|---|---|---|---|---|---|
| Hobart | −51.4 | −42.9 | 147.2 | 1950–2005 | −78.54[90] |
| Canberra | −43.7 | −35.3 | 149.0 | 1950–2004 | −45.84[90] |
| Mundaring | −43.2 | −32.0 | 116.3 | 1959–2005 | −16.86[90] |
| Brisbane | −35.4 | −27.5 | 152.9 | 1950–2005 | −24.61[90] |
| Norfolk | −34.5 | −29.0 | 168.0 | 1964–2005 | −3.72 |
| Townsville | −28.5 | −19.3 | 146.7 | 1951–2004 | 36.66[90] |
| Vanimo | −12.3 | −2.7 | 141.3 | 1964–2004 | 35.70[90] |
| Manila | 3.6 | 14.6 | 121.1 | 1964–1999 | 10.83 |
| Taipei | 13.8 | 25.0 | 121.5 | 1959–2000 | −127.1[90] |
| Okinawa | 15.5 | 26.3 | 127.8 | 1957–2005 | −36.68[90] |
| Wuhan | 19.3 | 30.6 | 114.4 | 1957–2004 | −53.82[90] |
| Yamagawa | 20.6 | 31.2 | 130.6 | 1957–2005 | −42.68[90] |
| Kokubunji | 25.7 | 35.7 | 139.5 | 1957–2005 | −63.72[90] |
| Akita | 29.8 | 39.7 | 140.1 | 1957–1989 | −21.51 |
| Wakkanai | 35.5 | 45.4 | 141.7 | 1948–2005 | −12.86[90] |
| Khabarovsk | 38.1 | 48.5 | 135.1 | 1959–2001 | −7.20 |
| Irkutsk | 41.2 | 52.5 | 104.0 | 1957–2000 | −56.63[90] |
| Magadan | 50.9 | 60.0 | 151.0 | 1968–2002 | −49.85[90] |
| Yakutsk | 51.2 | 62.0 | 129.6 | 1957–1993 | −25.89 |

[a]Yearly trends in the table are obtained by making regression between the yearly average of $\delta foF2$ and the year number. Significant yearly trends at a confidence level of 90% are denoted by a superscript "90."

special method to separate the "non-geomagnetic" trend component and obtained a decrease rate −0.012MHz/year in foF2 by averaging foF2 trends at global 23 ionosonde stations [*Danilov*, 2003]. Another attempt to eliminate the geomagnetic influence on the foF2 trends is carried out by *Mikhailov et al.* [2002]. They obtained foF2 trends nearly independent of latitude and the phase of long-term changes of geomagnetic activity, and most trends are negative and not significant.

[4] On the basis of different methods and trend values, many authors interpreted the trends as a consequence of greenhouse cooling [*Bencze*, 2005; *Bremer*, 1998, 2001; *Jarvis et al.*, 1998; *Ulich and Turunen*, 1997; *Upadhyay and Mahajan*, 1998], or being controlled by geomagnetic activity [*Mikhailov*, 2002; *Mikhailov and Marin*, 2000, 2001; *Danilov and Mikhailov*, 2001], or under the influence of sun [*Laštovička*, 2005b], or as a result of a long-term decrease of the O concentration in the thermosphere [*Danilov*, 2005]. Detailed description about methods and interpretations of ionospheric long-term trends are given by *Rishbeth* [1997], *Bremer* [2001], *Bremer et al.* [2004], and *Danilov* [1998, 2002a, 2005].

[5] In this paper we introduce artificial neural network (ANN) to derive long-term trends of foF2 in the Asia/Pacific sector. Data are measured at 19 ionosonde stations which have a geographic latitudinal coverage from 42.9°S to 62.0°N. The data length for every station exceeds three solar cycles. Despite of many investigations in the long-term trends of foF2 as described above, results remain to be contradictive among various authors who use different methods and interpret the observed trends in different ways. So it is still of great importance for us to continue the investigation of long-term trends with regard to certain unresolved questions and is especially worthwhile over certain regional areas and stations for several reasons as follows. (1) In the past decade, many studies have been carried out to verify the long-term changes of ionosphere. The main reason of the trend investigations became so popular may be that such trends could be caused by anthropogenic activities and it is an apparent evidence of long-term changes of upper atmosphere [*Keating et al.*, 2000]. Such investigations will enrich our knowledge of the dependence of ionosphere on solar and geomagnetic activities and the relationship between ionosphere and thermosphere [*Clilverd et al.*, 2003; *Danilov*, 2005]. Furthermore, this work will lead to a better understanding of atmospheric greenhouse effect. (2) Although trend analysis have been carried out for only one or a few stations [*Adler et al.*, 2002; *Chandra et al.*, 1997; *Danilov and Mikhailov*, 2001; *Foppiano et al.*, 1999; *Givishvili et al.*, 1995; *Hall and Cannon*, 2002; *Jarvis et al.*, 1998; *Laštovička*, 1997; *Sharma et al.*, 1999; *Ulich and Turunen*, 1997; *Xu et al.*, 2004], or for a set of regional stations [*Bremer*, 1998; *Danilov*, 2003; *Danilov and Mikhailov*, 1999; *Marin et al.*, 2001], or for global stations [*Bremer*, 2001; *Ulich and Turunen*, 1997; *Upadhyay and Mahajan*, 1998], the trends in Asia/Pacific sector have not been systematically investigated except for one individual analysis [*Xu et al.*, 2004]. Many results have shown that the ionospheric long-term changes have distinct regional characteristics [*Bremer*, 1998; *Bremer et al.*, 2004; *Foppiano et al.*, 1999; *Upadhyay and Mahajan*, 1998]. So it is valuable to derive the long-term changes of the ionosphere in the Asia/Pacific sector, which covers many ionosonde stations in the equatorial anomaly region. It may be a good complement for a generation of a global morphology of the ionospheric long-term trends. Another important reason for us to select this region is that most of ionosonde stations in this sector are low-latitude stations (13 of the selected stations have a geographic latitude less than 40°) which have been rarely investigated systemically before. (3) Because the F-region ionosphere is mainly controlled by solar activity and also influenced by geomagnetic activity, *Mikhailov and Marin* [2001] stressed that the success of the long-term trends analysis strongly depends on the method used to eliminate solar and geomagnetic activity. *Clilverd et al.* [2003] also revealed that the validity of removing solar cycle is one of the most significant factors affecting the trend estimate.

[6] Artificial neural network, which is an effective tool in pattern recognition, nonlinear function approximation and prediction, has been widely used recently in ionospheric

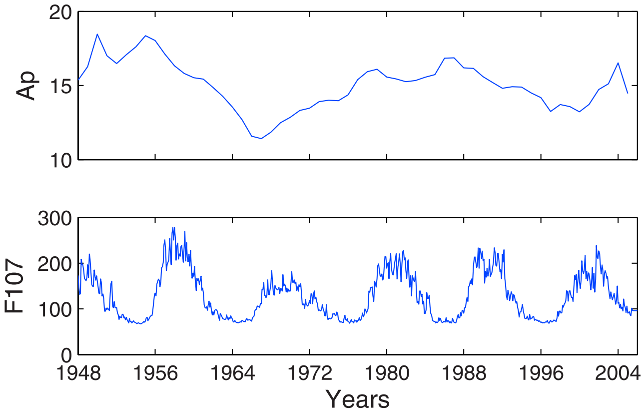


**Figure 1.** The 11-year running mean values of Ap and monthly mean F107 during the interval of 1948–2005.

researches such as developing empirical models or prediction models and very encouraging results were obtained [*Poole and McKinnell*, 2000; *Altmay et al.*, 1997; *Francis et al.*, 2000; *Jankovičová et al.*, 2002; *Weigel et al.*, 1999; *Wintoft and Cander*, 2000; *Zeng et al.*, 2002]. The success of artificial neural network in ionospheric modeling propels us to try to use it for elimination of the strong and nonlinear dependence of ionospheric foF2 on solar and geomagnetic activity. In a word, there is still controversy and inconsistency on the interpretation of the observed foF2 trends [*Danilov*, 2003; *Laštovička*, 2005b; *Ulich et al.*, 2003]. So it is necessary for us to continue investigating ionospheric trends for methodical and scientific reasons.

[7] The aim of this paper is to derive the long-term trends of ionospheric foF2 in Asia/Pacific sector systemically by applying artificial neural network and give some constructive discussions on the interpretation of the trends. We describe the method and data source in section 2. Trend results and discussions are given in sections 3 and 4 separately. Finally, we conclude in section 5.

## 2. Data Source and Method

[8] The foF2 data over Wuhan was obtained from Wuhan ionospheric observatory. For the residual 18 ionosonde stations in Asia/Pacific sector as listed in Table 1, foF2 were obtained from the database of U.S. National Geophysical Data Center (NGDC-NOAA) and the World Data Center (WDC) for Ionosphere, Tokyo. The selected stations have a geographic latitudinal coverage from 42.9°S to 62.0°N near geographic longitude 130°E. At all stations there are more than three solar-cycle observations which is the basic requirement to obtain steady trends.

[9] In order to eliminate the short-term geomagnetic effects, we only consider the quiet days when calculating monthly medians of foF2 as *Mikhailov et al.* [2002] have done. However, we define a day to be quiet if daily Ap < 12 regardless whether the previous days are quiet or not. The month is not considered if there is less than 6 quiet days.

[10] The 12-month running-mean hourly foF2 values are used in our investigation. This treatment can strongly decrease the scatter in the observation [*Marin et al.*, 2001]. For example, the standard deviation (STD) of model deviations from observations for local noon time in Kokubunji is larger by using no smooth foF2 (0.11) than 12-month running mean foF2 (0.09). Obvious scatters of the deviations are also removed by using 12-month running mean values of foF2 and the trend results are not changed (figure not shown).

[11] We use solar 10.7 cm radio flux (F107) as solar activity index. A comparison between trends by using different indices has been done by *Danilov* [2003]. He found that there is no apparent morphological difference except for some difference of statistical significance by selecting different indices. It should be stressed that we use 11-year running mean Ap rather than monthly median values as has been done by *Mikhailov et al.* [2002]. We have made a comparison and found that the dependence of foF2 on geomagnetic activity can be eliminated more effectively by using 11-year running mean Ap than using just monthly Ap. Therefore the 11-year running mean Ap are used afterward. The 11-year running mean Ap and monthly median F107 during the interval of 1948–2005 are plotted in Figure 1. An obvious 11-year cycle of F107 and long-term variation of Ap can be found.

[12] We eliminate the solar and geomagnetic activity by applying artificial neural network (ANN). Detailed descriptions of the method are displayed as follows: As we know, the ionospheric parameters such as foF2 strongly depend on the solar and geomagnetic activities [*Liu et al.*, 2004; *Richards*, 2001]. If long-term trends are derived from ionosonde observations, the influence of solar and geomagnetic activity should be eliminated effectively. Different regression models have been tried so far as follows:

$$X = A + B \times S \quad (1)$$

$$X = A + B \times S + C \times S^2 \quad (2)$$

$$X = A + B \times S + C \times S^2 + D \times S^3 \quad (3)$$

$$X = A + B \times S + C \times G \quad (4)$$

$$X = A + B \times S + C \times S^2 + D \times G \quad (5)$$

where X represents ionospheric characteristic parameter foF2, S represents solar activity index such as solar 10.7 cm radio flux (F107) or solar sunspot number or new EUV proxy E107 [*Tobiska*, 2001], and G represents geomagnetic activity index such as daily Ap. Detailed comparisons between the above regression models have been done by *Bremer* [2001]. It should be noted that the geomagnetic activity can not be eliminated successfully by using above models. So several authors tried to find trends independent of geomagnetic activity called "nongeomagnetic" trends by developing different methods and very encouraging results were obtained [*Danilov*, 2002b, 2003; *Mikhailov et al.*, 2002]. However, ANN as an effective tool in pattern recognition, function approximation and prediction has not been noticed by trends analyzers. So we would like to explore, for the first time, the possibility of eliminating solar and geomagnetic activity effectively from foF2 by using ANN.

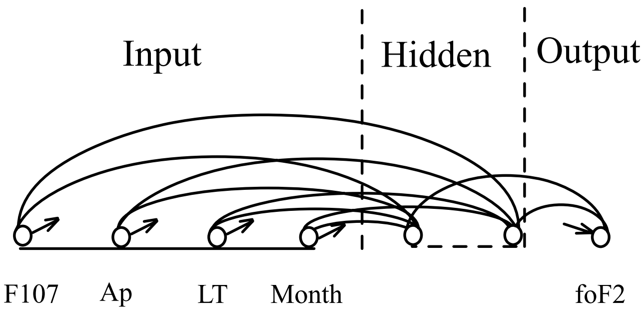


**Figure 2.** The sketch map of the ANN system used in this investigation.

[13] An ANN is a system of interconnected computational elements operating in parallel, arranged in patterns similar to biological neural nets and modeled after the human brain. It can acquire, store, and utilize experiential knowledge. A neural network consists of many connected, nonlinear and simple processing units, or named neurons. Neurons can be thought of as variables that take on certain values, and can be classified into three distinct types: (1) input neurons, for example, previous known values of a time series, (2) output units which are the end results of a network's processing, for example, predictions, and (3) hidden units which are only involved in the processing, whose values usually have no interpretable meaning. The values of hidden and output neurons are determined by both the values of the neurons that they are connected to and also the strength of the connections (or "weights"). For the network to be able to perform a given task, it is necessary to find appropriate values for the connections. This process is known as training and involves compiling a training set of examples of input-output pairs and iteratively presenting them to the network, altering the connection values a little each time, according to how the network's outputs differ from the desired outputs [*Conway et al.*, 1998; *Gureney*, 1996; *Hu and Hwang*, 2002]. Briefly, an ANN is a computer program that is trained to identify the relationship between the input vectors and the known output.

[14] To find the best network we have to choose a criterion with which to measure the modeling accuracy. Most authors chose the root-mean-square error (RMSE) as a suitable measure. The RMSE is defined in our investigation:

$$RMSE = \sqrt{\frac{1}{n}\sum \left(foF_{2,obs} - foF_{2,\mathrm{mod}}\right)^2} \qquad (6)$$

where n is the number of training samples and $foF_{2,obs}$ and $foF_{2,mod}$ are the observed and modeled $foF_2$ respectively. The optimal artificial neural network is defined as the network that gives the smallest RMSE on the validation set.

[15] ANN training is an iterative process that starts with randomly chosen weights in the ANN model. Sometimes the choice of initial weights leads to a network that does not converge and thus does not perform very well. In our investigation, the networks are initialized with small random weights. The input vectors are ordered randomly, and then each is presented in turn to the network. In each case, an output is produced, and compared with the measured output. An algorithm is then applied to update the weights in such a way as to minimize the difference. This process is repeated until the RMSE is stabilized.

[16] Among different types of neural network, the feed forward neural network is most frequently used to solve many geophysical problems, including the forecast of solar cycle, magnetic storm, and foF2 [*Conway et al.*, 1998; *Francis et al.*, 2000; *Jankovičová et al.*, 2002]. The ANN used in this paper is also a static feed forward network and the back propagation algorithm is adopted for training the ANN to minimize the RMSE. The number of the hidden layers depends on the complexity in the relationship between the input data and the desired output [*Gureney*, 1996]. According to the Kolmogorov continuous function denoted theorem, a three layer ANN can approximate any continuous functions in any accuracy if the number of the hidden layers is appropriate [*Gureney*, 1996]. In the hidden layers there should be sufficient neurons to represent the underlying complexity of the time series. 18 neurons in the hidden layers are adequate in our investigation. There is also an essential requirement for training an ANN, that is a large database of data describing the history of the relationship between the input and output parameters. This database of data usually takes the form of a number of input vectors, each with a corresponding output. In our investigation, all the selected stations have more than three solar-cycle observations which are enough to identify the relationship between $foF_2$ and solar and geomagnetic activity.

[17] We chose F107, Ap, local time (LT) and month as input neurons to represent solar, geomagnetic, daily and seasonal variations, respectively. 12-month running means of Quite-medians of foF2 are used as output neuron. The training process will stop if the RMSE becomes smaller than the designed value or the maximum training epochs is reached. Figure 2 illustrates the structure of the ANN system used in this paper. We train the network to identify the complicated relationship between foF2 and the four input variables for every station separately. Then foF2 values are calculated for the same four input vectors by the trained network and taken as $foF2_{mod}$. The deviations of model values from observations will contain information about long-term changes.

[18] To avoid errors resulting from different background values when we make average value during a day or a year for model deviations from observations of foF2, relative deviations are considered in this paper:

$$\delta foF2 = \left(foF2_{obs} - foF2_{\mathrm{mod}}\right)/foF2_{\mathrm{mod}} \qquad (7)$$

A linear trend can be derived through a linear regression fitting:

$$\delta foF2 = a + k \times year \qquad (8)$$

On the basis of equation (8), a relative trend of foF2, *k*, can be derived for each hour and each month separately.

[19] The test of significance of the linear trend is made with the Fisher's F criterion [*Pollard*, 1977].

$$F = r^2(N-2)/\left(1-r^2\right) \qquad (9)$$

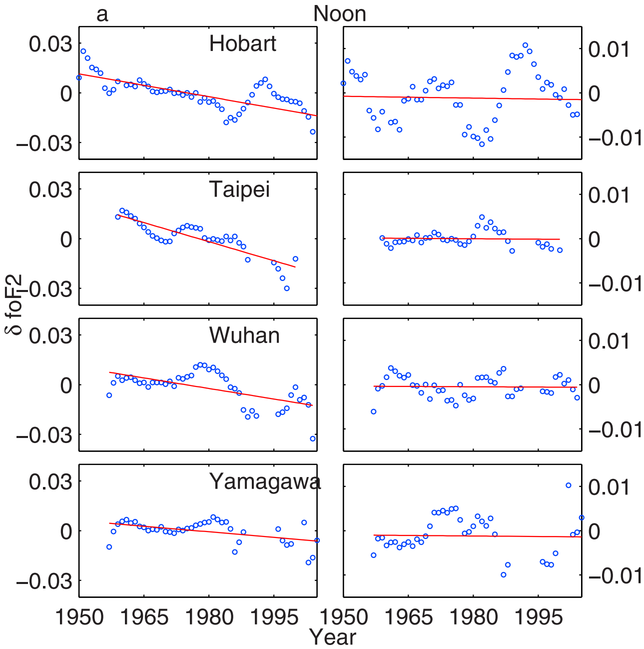


**Figure 3a.** Yearly $\delta foF2$ (open circles) and their linear regressions (lines) versus years for noon time. In the right panels, year is used as an input in ANN modeling, while in the left panels not. Panels from top to bottom are for stations of Hobart, Taipei, Wuhan, and Yamagawa, respectively.

where r is the correlation coefficient between variables $\delta foF2$ and year in equation (8); N is the number of variable pairs considered.

## 3. Results

### 3.1. Validation of the Method

[20] It is necessary for us to test the validity of ANN in analyzing long-term trends of ionosphere. There should be apparent difference in $\delta foF2$ whether year is taken as an input in the ANN system or not, if long-term trend exists. Here we chose four ionosonde stations (Hobart, Taipei, Wuhan, and Yamagawa) to make a comparison. The calculation for each selected station will be carried out for two times. During first calculation year is not taken as an input in the ANN method when the network is trained while in the second calculation year is taken. The yearly $\delta foF2$ variations are illustrated in Figure 3a and 3b for two situations. There are evident negative long-term trends in $\delta foF2$ when year is not taken as an input in the ANN modeling, while the residuals show no apparent long-term changes when year is an input in the ANN modeling. The significance of the linear trend derived when year in not used as input is tested with F-test and results show that four selected stations' trends have a confidence level of 99%. This indicates that ionosonde foF2 indeed vary against years and the dependence can be distinguished by using ANN method.

[21] As described above, the success of the long-term trend analysis strongly depends on the method used to eliminate solar and geomagnetic activity. It is difficult for the usual method to eliminate geomagnetic activity effectively. To verify the ability of ANN method in eliminating geomagnetic activity, we plot diurnal variations of correlation coefficients between $\delta foF2$ and Ap in Figure 4 for six selected stations. As shown in Figure 4, the amplitudes of correlation coefficients derived by ANN method are smaller than those of regression method. Mean amplitude of derived correlation coefficients by ANN (regression) method is 0.28 (0.64), 0.12 (0.39), 0.08 (0.3), 0.21 (0.49), 0.07 (0.37), 0.15 (0.6) at Akita, Magadan, Kokubunji, Taipei, Wuhan, and Yakutsk separately. Obviously ANN method is better than the regression method in eliminating geomagnetic activity.

[22] According to the results of *Mikhailov and Marin* [2000, 2001] and *Mikhailov* [2002], periods with negative and positive foF2 trends correspond to the periods of increasing and decreasing geomagnetic activity if the dependence of foF2 on geomagnetic activity is not eliminated effectively. So we can test the ability of a method in eliminating geomagnetic activity by looking over whether the derived long-term trends are sensitive to the phase of geomagnetic activity. Here we select three typical intervals of Ap index and calculate the corresponding long-term trends of foF2. In Figure 5a, the top panel corresponds to the interval 1950–1974 when Ap has an overall decreasing trend. The middle panel corresponds to the interval 1958–1980 when Ap has insignificant systematic change, and the bottom corresponds to 1967–2001 when Ap has an increasing trend. Figure 5b shows long-term trends in the same three intervals for Wuhan and Brisbane. Both stations have steady negative long-term trends of foF2 during all the three intervals, no matter how Ap varies. This indicates that the ANN method can eliminate geomagnetic activity effectively and the derived long-term trends are insensitive to the phase of geomagnetic activity.

### 3.2. Diurnal and Latitudinal Variations

[23] The analyzed results of the long-term trends for 19 stations are shown in Table 1. The yearly trend is obtained by making regression between the yearly average of $\delta foF2$ and the year number. Significant yearly trends at a confidence

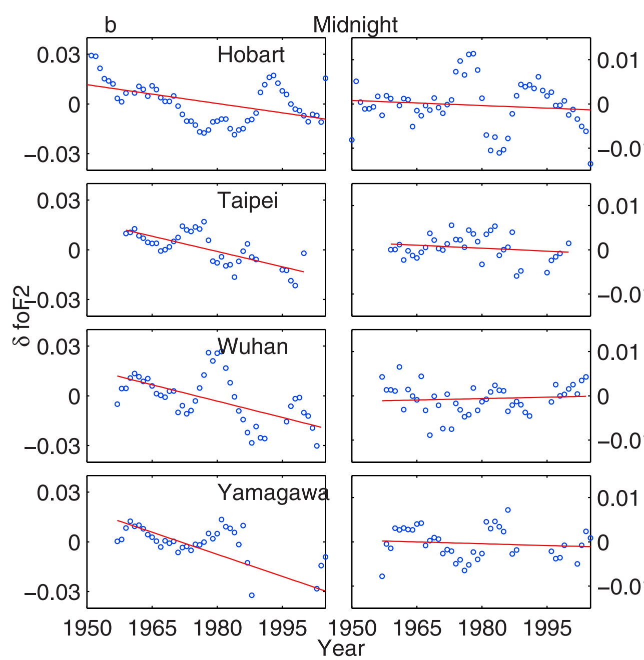


**Figure 3b.** The same as Figure 3a, but for midnight.

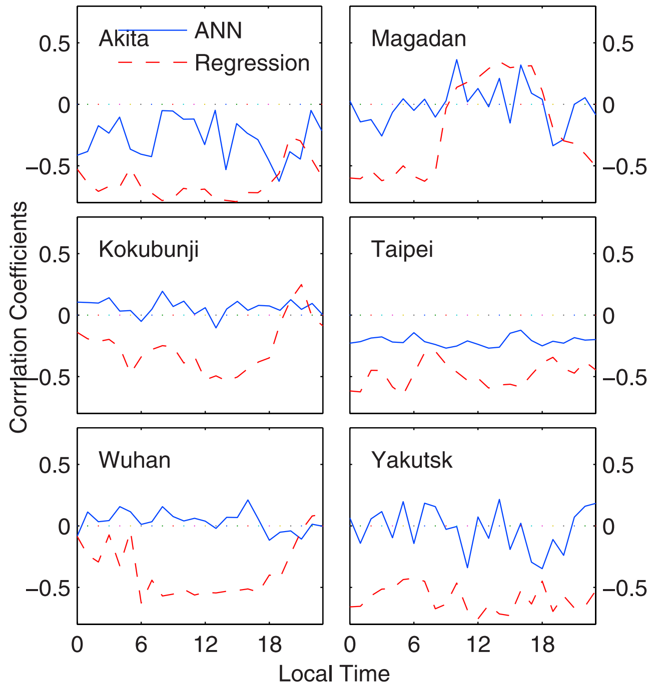


**Figure 4.** Diurnal variations of correlation coefficients between $\delta foF2$ and Ap index. Solid and broken lines are for ANN method and nonlinear regression method respectively.

level of 90% are denoted by a superscript "90." According to Table 1, most stations (except for Norfolk, Manila, Akita, Khabarovsk, and Yakutsk) have significant yearly trends (confidence level is more than 90%). We will exclude these stations whose confidence level is less than 90% in further analysis. For the residual 14 stations, most stations (except Townsville and Vanimo) have negative trends.

[24] To verify whether there is pronounced diurnal variation in the trend, diurnal variations of the trends derived by ANN method are plotted in Figure 6 for 14 stations whose trends are thought to be credible. Diurnal variations of $k$ obtained by regression method are also plotted for comparisons. It is obvious that the values of the trends derived by ANN vary more smoothly than those derived by regression method. Furthermore, there are no pronounced diurnal variations for trends derived by ANN method at most stations (except Townsville and Irkutsk), and trends by regression method display evident diurnal variations for most stations. No pronounced diurnal variations of the long-term trends were also obtained by *Mikhailov et al.* [2002] and *Danilov* [2003].

[25] There is also no pronounced latitudinal dependence of the trends derived by ANN method, as shown in Figure 7. If the trends at different stations are assumed to vary with the latitude in a linear manner as has been found by *Mikhailov and Marin* [2000] and *Danilov and Mikhailov* [1999], then, the Fisher's F criterion test shows that the significant levels are less than 90% for the six situations.

[26] Pronounced diurnal and latitudinal variations of foF2 long-term trends have been found by using usual regression method [*Danilov and Mikhailov*, 1999, 2001; *Foppiano et al.*, 1999; *Mikhailov and Marin*, 2000, 2001; *Sharma et al.*, 1999; *Xu et al.*, 2004]. *Mikhailov and Marin* [2001] and *Danilov and Mikhailov* [2001] put forward a geomagnetic control concept to interpret this phenomenon in accordance with contemporary F2-region storm mechanisms. However, common regression methods can not eliminate geomagnetic activity effectively. *Mikhailov et al.* [2002] and *Danilov* [2002b, 2003] tried two different methods to eliminate geomagnetic activity efficiently and obtained very encouraging results. Both *Mikhailov et al.* [2002] and *Danilov* [2003] obtained a negative long-term trend of foF2 by averaging trends from a set of stations and no pronounced diurnal and latitudinal variations of foF2 long-term trends are detected. These results agree with ours. This consistency also indicates that ANN method can remove geomagnetic activity efficiently (Figure 4).

### 3.3. Seasonal Variations

[27] Prominent seasonal variations of trends of foF2 have been investigated by *Danilov and Mikhailov* [1999] and *Foppiano et al.* [1999] and *Sharma et al.* [1999]. However, all these results are obtained by regression method. To investigate the seasonal dependence of the trends derived by ANN method, the trends have been studied for each month. Seasonal variations of trends at 14 stations are shown in Figure 8. There is no uniform pattern of seasonal variations at middle and low latitude stations and at midday and midnight times. Take several northern stations as examples, the midday trends have larger negative values during autumn and spring at Irkutsk and Magadan and during summer in Wuhan and Okinawa. Even in the same station, seasonal variation is different for midday and midnight. This phenomenon is most obviously at Irkutsk and Townsville. For

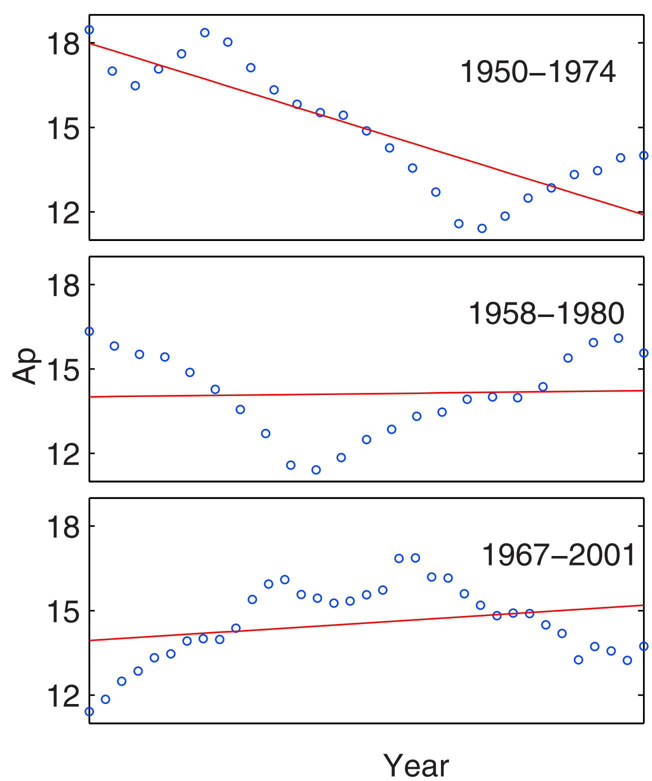


**Figure 5a.** Ap index varies versus years during three different time intervals corresponding to negative trend (1950–1974), no significant trend (1958–1980), and positive trend (1967–2001).

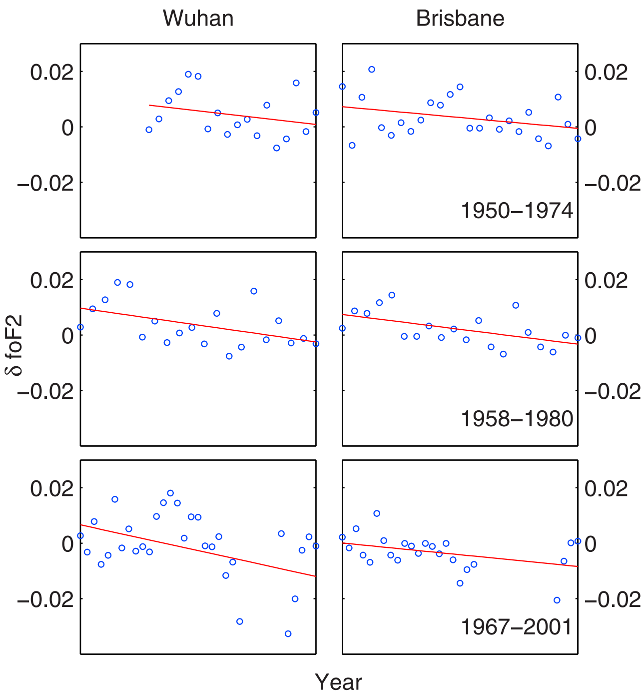


**Figure 5b.** Yearly $\delta foF2$ (circles) and its linear regressions (lines) versus years are plotted for Wuhan (left) and Brisbane (right) respectively. The panels from top to the bottom are for the interval of 1950–1974, 1958–1980, and 1967–2001, respectively.

Irkutsk, the midday trends have largest negative values in September while midnight trends have largest positive values in October. The marked difference between midday and midnight trends for Townsville is occurred in summer. Furthermore, it is notable that seasonal variations for northern stations are more evident than those for southern hemispheric stations. It also shows that seasonal variations for middle latitude stations are more obvious than low latitude stations in the northern hemisphere. The variation from summer to autumn or spring is more marked in Magadan and Irkutsk than in Tapei and Okinawa. Some different dynamical processes between middle and low latitude zone are thought to be the main influencing factors.

### 3.4. Mean Trend in the Asia/Pacific Area

[28] Table 1 shows that of the 14 stations with significant trends most stations except Townsville and Vanimo have negative trends and the values of trends lie within −12.86 ($10^{-5}$) to −127.1 ($10^{-5}$) per year. Since Townsville and Vanimo are located in the equatorial anomaly, the positive trends of these two stations may be originated from some special dynamical processes which can not be represented by solar or geomagnetic activity index. So, we average the trend values for the residual 12 stations and obtain the value of mean trend −0.0005 per year with the standard deviation 0.0003. It shows that from 1950 to 2005 when most data concentrate in during our investigation, the value of foF2 has been systemically decreased by 0.05% per year in Asia/Pacific area. The above relative trend means an relative decrease of foF2 by 0.0005 per year. This reveals that the value of foF2 decreases 0.0275 during the interval of 1950–2005 in the selected area, which is consistent with those of *Danilov* [2003] and *Mikhailov et al.* [2002]. The only difference is that our mean trend is greater than −0.0012 of Danilov and smaller than −0.00022 of Mikhailov et al. This difference may be due to the disparities in method and data source. Our stations are selected from middle and low latitudes while theirs are mainly from high and middle latitudes.

## 4. Discussion

### 4.1. Hysteresis Effect

[29] The hysteresis effect in the ionospheric F2 region is presented in detail by *Ostrow and PoKempner* [1952]. According to their opinion, foF2 varies differently with solar activity during the rising and the falling parts of the solar cycles. Since the useful signal is very small comparing with the background in the trend analysis, it is important for us to examine whether we should consider the hysteresis effect in the ANN method. To avoid the influences of the hysteresis effect on the derived trends, *Danilov and Mikhailov* [1999] and *Mikhailov and Marin* [2000] selected only 3 years' foF2 around solar maxima and minima (M3+m3) or only around minima for analysis. *Bremer* [2001] showed that the

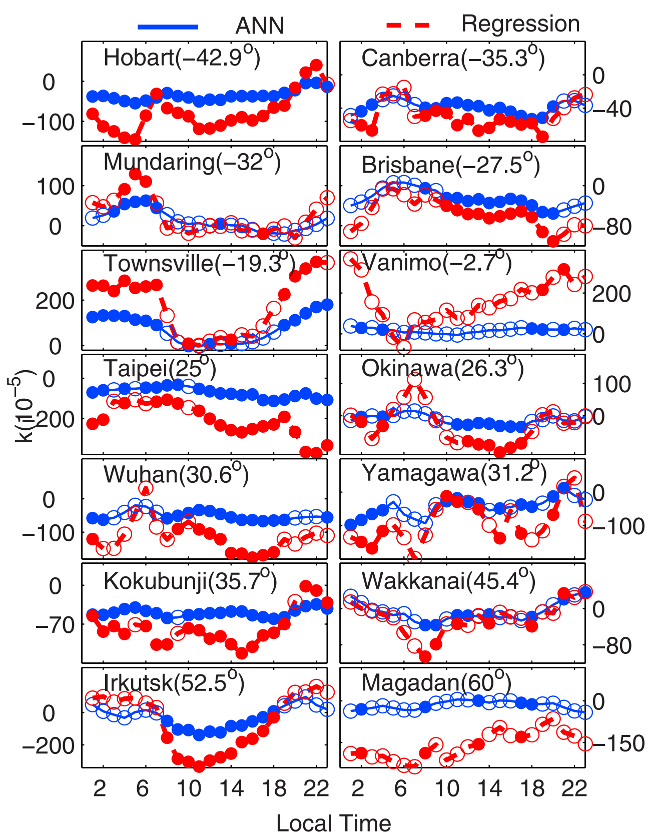


**Figure 6.** Diurnal variations of relative long-term trends of foF2 k (in $10^{-5}$ per year) derived by ANN method (solid lines) and regression method (dotted lines) are illustrated for 14 stations (which have no less than 5 hours that correspond to 90% confidence level). Solid circles represent the hours corresponding to 90% confidence level while open circles mean not significant k. The number in the bracket after each station name is the corresponding geographic latitude.

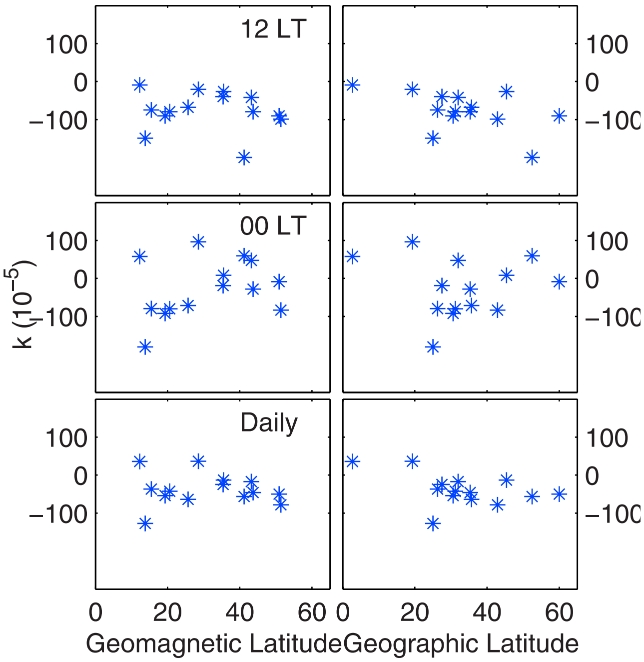


**Figure 7.** Geomagnetic (left) and geographic (rights) latitudinal variations of long-term trends (in $10^{-5}$ per year) of foF2 are plotted versus modulus of latitudes for 1200 LT (top), 0000 LT (middle), and all local times (bottom), respectively.

influence of the hysteric's effect is small by comparing the trend of foF2 for rising and falling parts of the solar cycles. Comparisons of foF2 trends derived by ANN method for all the years (solid lines) and M3+m3 (dotted lines), illustrated in Figure 9 for 14 stations, show that seasonal variation has no systematic change between two choices in each station. The same inconsistency of seasonal variations of foF2 trends between northern and southern hemispheres and between middle and low latitude stations in northern hemisphere also can be found for both data selections. Note that the number of months which correspond to a confidence level of 90% in the regression decreases when M3+m3 is chosen. This maybe result from the reduction of the data sample because the training effect of ANN is correlated with the amount of the training sample [*Gureney*, 1996]. So we chose data of all years to make training more adequately and improve the confidence level. It is reasonable for us to ignore the hysteric's effect as it will not alter the final conclusions.

### 4.2. Differences Between Trends at Middle and Low Latitude Stations

[30] As mentioned above, seasonal variations for middle latitude stations are more obvious than for low latitude stations in the northern hemisphere. In addition, if we consider yearly trends in Table 1, the three positive trends (Townsville, −19.3°; Vanimo, −2.7°; Manila, 14.6°) and the largest negative trend (Taipei, 25.0°) are all from low latitude and equatorial stations (geographic latitude <26°). These phenomena exhibit some differences in long-term trends between middle and low latitude stations. *Torr and Torr* [1973] showed that, due to different controlling factors at different latitudes, annual variation of foF2 was also more prominent in middle and high latitude than in low latitude. According to the results of *Rishbeth* [1998], seasonal variations of foF2 maybe caused by composition changes due to large scale dynamical effects in the thermosphere or from changes in atmospheric turbulence or from several other factors. If these factors have different long-term variations, the seasonal variations of trends in foF2 probably have differences between middle and low latitude zone. *Danilov and Mikhailov* [1999] and *Mikhailov and Marin* [2001] showed that the foF2 trends are negative at high and middle latitudes with a tendency to be small or positive at lower latitudes. *Mikhailov and Marin* [2001] interpreted positive foF2 trend at lower latitudes as an increase in the equatorward thermosphere wind and in atomic oxygen concentration. In conclusion, the trends finally derived for Townsville, Vanimo, Manila, and Taipei differ very much from other stations, may be due to different long-term changes of controlling factors such as large-scale dynamical effects in the thermosphere or atmospheric turbulence or the equatorward thermosphere wind or atomic oxygen concentration. The marked difference in trend results between Taipei and the

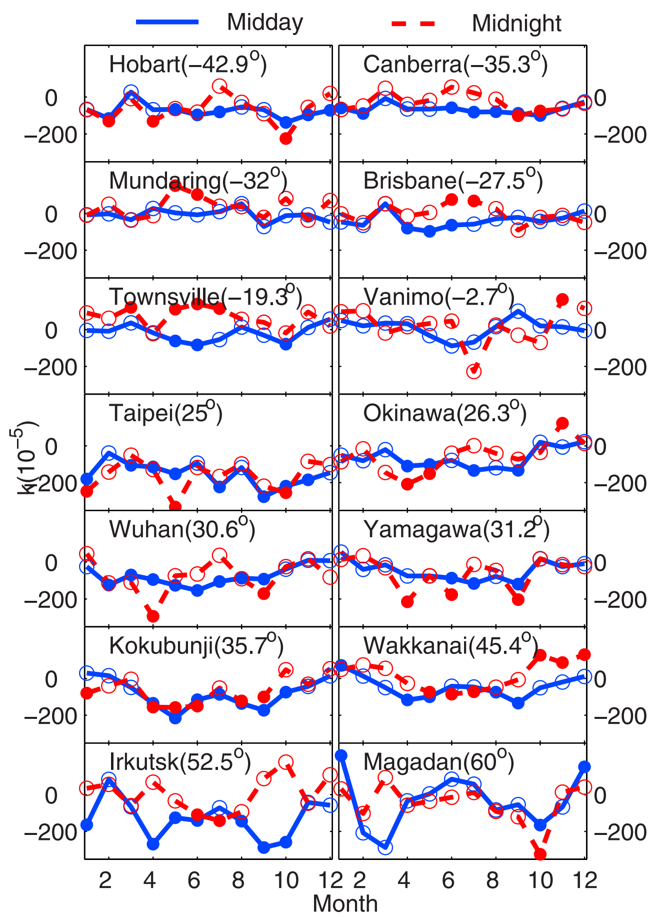


**Figure 8.** Seasonal variations of relative long-term trends of foF2 k (in $10^{-5}$ per year) for midday (solid lines) and midnight (dashed lines) are illustrated for 14 stations. Solid circles represent the months corresponding to 90% confidence level while open circles mean not significant k. The number in the bracket after each station name is the corresponding geographic latitude. Midday and midnight here mean a 5-hour period around local noon and night.

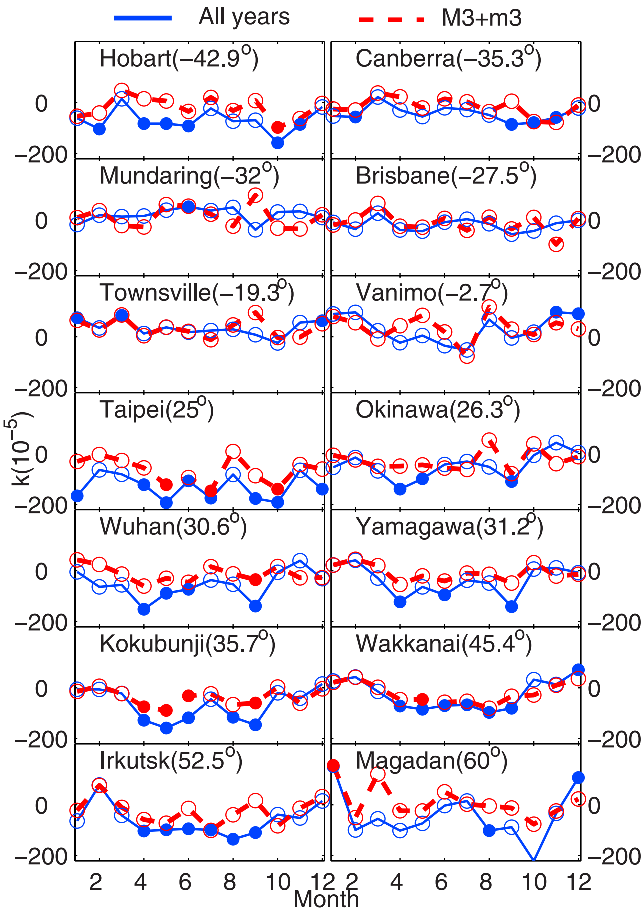


**Figure 9.** Seasonal variations of relative long-term trends of foF2 k (in $10^{-5}$ per year) derived by ANN method for foF2 of all the years (solid lines) and M3+m3 (dotted lines) are illustrated for 14 stations. Solid circles represent the months corresponding to 90% confidence level while open circles mean not significant k. The number in the bracket after each station name is the corresponding geomagnetic latitude.

remaining three stations (Townsville, Vanimo, and Manila) may be due to the special dynamical processes in equatorial anomalistic area. However, the influence of the movement and the changes in instrumentation and scaling practices of the Taipei station on long-term trends can also not be excluded.

### 4.3. Origin of the Trends

[31] There is a lot of arguments about the interpretation of observed trends in foF2, and even in their values and signs obtained by different methods [*Bremer*, 1998, 2001; *Bremer et al.*, 2004; *Danilov*, 2002a, 2003; *Danilov and Mikhailov*, 1999; *Mikhailov and Marin*, 2000, 2001]. On the basis of different method and trend values, many authors interpreted the trends as a consequence of greenhouse cooling [*Bencze*, 2005; *Bremer*, 1998, 2001; *Jarvis et al.*, 1998; *Ulich and Turunen*, 1997; *Upadhyay and Mahajan*, 1998], or as been controlled by geomagnetic activity [*Danilov and Mikhailov*, 2001; *Mikhailov*, 2002; *Mikhailov and Marin*, 2000, 2001], or influenced by contribution of Sun's origin [*Laštovička*, 2005b], or as a result of a decrease of the O concentration in the thermosphere [*Danilov*, 2005].

[32] The most popular viewpoint is anthropogenic pollution (e. g. $CO_2$, $CH_4$, $O_3$). *Rishbeth* [1990] and *Rishbeth and Roble* [1992] had predicted a decrease of foF2 with 0.2–0.5 MHz by doubling the atmospheric greenhouse $CO_2$. On the other hand, there is indeed a negative trend of foF2 at most stations if geomagnetic activity has been eliminated effectively [*Danilov*, 2003; *Mikhailov et al.*, 2002]. The mean value of foF2's decrease (−0.275 MHz) in Asia/Pacific area agrees with the prediction by *Rishbeth and Roble* [1992]. However, during the past 55 years (1950–2005) when most data concentrate in our trend analysis, the doubling has not yet happened. So we should look for other origins of the trends except greenhouse effect. *Danilov* [2003] also obtained a mean trend which can not be interpreted only by greenhouse effect.

[33] Although the ANN method can eliminate solar and geomagnetic activities effectively, it can not remove the very long-term changes of solar and geomagnetic activity that longer than the length of the data series if these very long-term changes really exist. *Stamper et al.* [1999] and *Clilverd et al.* [2002] indicated the very long-term changes of solar activity in terms of sunspot numbers and geomagnetic activity in terms of aa index very clearly. Long-term trends in solar and geomagnetic activity and their influences in long-term trends in ionospheric system have been comprehensively reviewed by *Laštovička* [2005b]. The aa-index was increasing throughout the 20th century and appeared to stabilize near its end [*Stamper et al.*, 1999]. According to the geomagnetic control concept by *Mikhailov and Marin* [2000, 2001] and *Mikhailov* [2002] and *Danilov and Mikhailov* [2001], this positive trend in geomagnetic activity should result in negative trend in foF2 as has been obtained in our investigation. The sunspot number was increasing throughout the first half of the 20th century until the peak in 1958–1959, then dropped a little until the end of the century [*Laštovička*, 2005b]. Since most data concentrate in second half of the 20th century for our trend analysis, the feeble negative trend of solar activity in this interval may also result in a negative trend of foF2. However, as the length of the data of most ionosonde stations is shorter than 60 years in this investigation, we can not quantitate or eliminate the influence of the very long-term changes of geomagnetic activity and solar activity on foF2.

[34] Except solar and geomagnetic activity, ionosphere is also influenced by many other factors, such as neutral gas concentration, neutral temperature and neutral wind. So the long-term changes in these factors may also result in long-term changes in ionosphere. *Laštovička* [2005a] have summarized the results of the long-term trends with focus on the mesosphere, ionosphere and thermosphere. Key parameters, such as thermosphere gas density [*Emmert et al.*, 2004; *Keating et al.*, 2000], neutral wind field [*Jacobi et al.*, 2001; *Jacobi*, 2004] and mesopause temperatures [*Beig*, 2002; *Beig et al.*, 2003], have long-term trends indeed. So it is valuable for us to look for the origin of the trend of foF2 from these parameters. *Danilov* [2005] had given a self-consistent interpretation of the long-term trends of foF2 and hmF2 based on a hypothesis that there is a negative trend of the O concentration in the thermosphere.

[35] In conclusion, the long-term trends of foF2 obtained in our investigation can be interpreted as a consequence of natural origin such as very long-term changes of solar and geomagnetic activity and an anthropogenic origin such as greenhouse effect ($CO_2$ increase and long-term cooling in stratosphere and mesosphere) or other anthropogenic pollution in the thermosphere.

## 5. Conclusions

[36] In this paper, artificial neural network (ANN) method is used for deriving long-term trends of foF2 at 19 ionosonde stations in Asia/Pacific sector around geographic longitude 130°E. The ANN method used here is a static feed-forward network and the back-propagation algorithm is adopted for training the ANN to minimize the RMS error. F107, Ap, local time (LT), and month are chosen as input neurons which represents solar, geomagnetic, daily and seasonal variation respectively. We chose 18 neurons in the hidden layers and 12-month running means of Quite-medians of foF2 as output neuron. The results can be concluded as follows:

[37] 1. Compared with linear or nonlinear regression method, ANN method has a better performance on reducing the influences of geomagnetic activity on foF2. The influences of the hysteretic effect on the results of the long-term trends can be ignored in ANN method.

[38] 2. Of the selected 19 stations, 14 stations have significant long-term trends, and 12 of them are negative with the values lie within $-12.86$ ($10^{-5}$) to $-127.1$ ($10^{-5}$) per year. The averaged trend for the residual 12 stations is about $-0.0005$ per year. It shows that the value of foF2 in Asia/Pacific area has been systematically decreasing by 0.05% per year during the past 5 decades.

[39] 3. Long-term trends of foF2 in Asia/Pacific sector derived by ANN method show no pronounced diurnal and geomagnetic or geographic latitudinal variations. For most stations there is a pronounced seasonal effect in the trends, but there is no uniform pattern of seasonal variation between middle and low latitude stations and between midday and midnight times. Generally, seasonal variations for northern hemispheric stations are more evident than those for southern hemispheric stations. We also show that seasonal variations for middle latitude stations are more obvious than for low latitude stations in the northern hemisphere. These differences may be interpreted as certain asymmetry between southern and northern hemispheres and some different dynamical processes between middle and low latitude zone separately. The three positive trends (Townsville, $-19.3°$; Vanimo, $-2.7°$; Manila, 14.6°) and the largest negative trend (Taipei, 25.0°) are all from low latitude and equatorial stations (geographic latitude <26°). This may be due to some special dynamical processes in the equatorial anomaly area.

[40] 4. The trend of foF2 obtained in our investigation can not be interpreted only by the greenhouse effect, but it may also be resulted from the very long-term changes in solar and geomagnetic activity. Variations in some other factors which can influence ionosphere, such as neutral gas concentration, neutral temperature and neutral wind, might partly contribute to the trend.

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