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Brief communication “Monitoring ionospheric variations before earthquakes using the vertical and oblique sounding network over China”

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Abstract. The problem of earthquake prediction has stimulated the research for correlation between seismic activity and ionospheric anomaly. Many observations have shown the existence of anomaly of critical frequency of ionospheric F-region, *fo*F2, before earthquake onset. Ionospheric sounding has been conducted routinely for more than 60 years in China by the China Research Institute of Radiowave Propagation (CRIRP), and deveoloped a very powerful ability to observe the ionosphere. In this paper, we briefly describe the anomalous variation of the *fo*F2 before M_S8.0 Wenchuan earthquake (occurred on 12 May 2008 at 14:28 LT; 31.00° N, 103.40° E), which is a sign of the great interest arising in the seismo-ionospheric investigation of Chinese researchers. Furthermore, we introduce the routine work on seismo-ionospheric anomaly by the ground based high-resolution ionospheric observation (GBHIO) network comprising 5 vertical and 20 oblique sounding stations.

1 Introduction

The ionosphere is known to be influenced by solar and geomagnetic activities. The perturbations of ionosphere under the quiet helio-geomagnetic conditions may be considered due to some other sources, such as severe thunderstorms, radioactive pollution, seismic activity, etc. (Pulinets and Liu, 2004). Since the phenomenon related to ionospheric perturbation caused by the earthquake in Alaska in 1964 was firstly reported (Barnes and Leonard, 1965), there has been a growing interest in precursor ionospheric anomalies related to earthquakes (Liperovksy et al., 2008; Pulinets and Ouzounov, 2010).

At the present time, there are huge amount of data which can be used for seismo-ionospheric research obtained from different measurements, from satellites and ground based soundings. The search for ionospheric precursors has been performed within the scope of the special-purpose project of natural disaster space monitoring: COMPASS-1, COMPASS-2, Sich-1M, QuakeSat, and DEMETER (Namgaladze et al., 2009). Satellite data have advantages including worldwide coverage, mobility and a range of sampling heights. Meaningful results have been reported based on data from satellites, particularly the DEMETER satellite (Parrot et al., 2006; Sarka et al., 2007; Rozhnoi et al., 2009; Akhoondzadeh et al., 2010). However, as presented by Rishbeth (2006), the sampling of localized events is very intermittent, if not chancy and repeat observations are shifted in longitude and occur only at intervals set by the orbital period. The ground-based monitoring instruments, such as ionosondes, have a powerful ability for monitoring ionospheric variations before earthquakes because of their frequent, regular and sustained in-situ observations at fixed locations. Many results have shown that anomalous variations of critical frequency of ionospheric F-region, *fo*F2 have been observed by ionosondes before earthquake onset (Chen et al., 2004; Rios et al., 2004; Dabas et al., 2007; Depueva et al., 2007; Liperovskaya et al., 2008, 2009; Sharma et al., 2008; Tsolis and Xenos, 2010).

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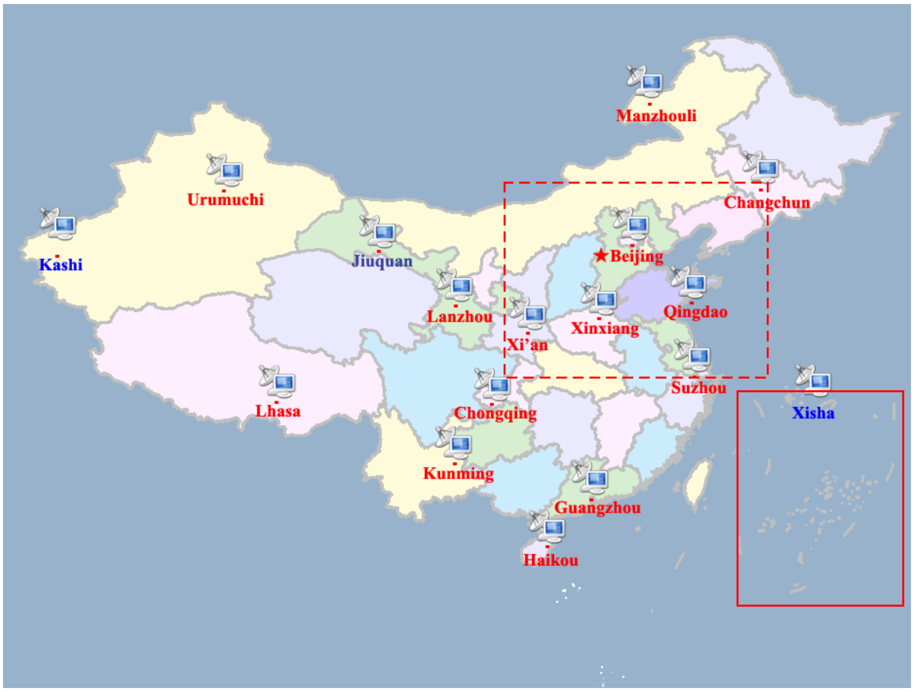

Fig. 1. The vertical sounding network over China. The established ionosondes are indicated in read, and the being established ionosondes are in blue.

In China, the ionospheric sounding started in the early 1940s (Liu et al., 2005), and a complete network of ground-based sounding sites covers the Chinese subcontinent including vertical and oblique sounding, GPS TEC ionopsheric measurements combined with VLF observations (Wu et al., 2000) provide good support for seismo-ionopsheric research. However, Chinese scientists have not paid much attention to ionospheric precursors over the last several decades.

On 12 May 2008 at 14:28 LT, a destructive earthquake (M8.0) occurred in Wenchuan (31.00° N, 103.40° E), China, and killed about 100 000 people. From this great earthquake arose intense interest in seismo-ionospheric research, especially of Chinese researchers and caused much attention of Chinese related governmental departments. In this paper, we briefly present the observations of the giant perturbations in the ionosphere *fo*F2 prior to the Wenchuan earthquake, and introduce the network of ground-based high-resolution ionospheric observation (GBHIO), using vertical and oblique ionosondes for monitoring seismo-ionospheric anomaly.

2 The vertical sounding network over China

In the 1940s, the first vertical ionosonde was established in Chongqing, China. After 1960, more and more ionosondes were established. There are 14 sites spread from lower (20.00° N) to middle latitudes (49.60° N), as shown in Fig. 1, conducted routinely by China Research Institute of Radiowave Propagation (CRIRP) and 3 sites are in the process of being built. CRIRP is responsible for collecting, processing and exchanging ionospheric data. At present, observed ionospheric data has been collected during several solar cycles. CRIRP is the only institute in China focussing on radiowaves from VLF to EHF ranges. This institution provides and covers different ionospheric research fields: mapping, forecast, artificial modification and data service (Zhen and Feng, 2009). After the catastrophic Wenchuan earthquake, seismo-ionospheric precursors and coupling has become a very important research field of CRIRP.

3 Anomalous ionospheric variations before Wenchuan earthquake

Our group has researched intensively into the variations of the ionosphere before the Wenchuan earthquake onset (e.g., Hu et al., 2010; Xu et al., 2010a, b, 2011). Moreover, there are other relevant papers which have provided more details about the ionospheric anomalies prior to this earthquake (Zhao et al., 2008; Liu et al., 2009). Hence, at the present time, the ionospheric anomalous variations before the Wenchuan earthquake onset are well recognized: the unusual large enhancement of ionospheric electron density limited around the epicenter on 9 May 2008, 3-days prior to the earthquake occurrence under quiet heliogeomagnetic conditions ($\mathrm{Dst_{min}} > -10\,\mathrm{nT}$). Variations of other parameters obtained by ionosondes measurements, e.g. h'F2, *fo*F1 and *fo*Es were found to be unobvious.

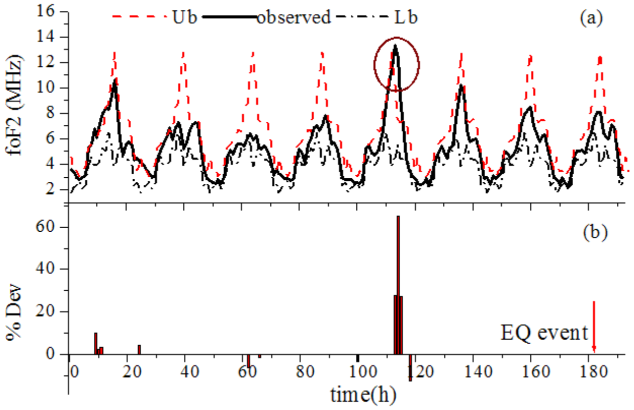

Fig. 2. *fo*F2 ionospheric variation from 5 to 12 May, 2008 over Chongqing station. The observed *fo*F2 variation and the corresponding upper- and lower-bounds are indicated, respectively, by full, dashed-point and dashed lines. The ellipse and the arrowhead indicate the obvious deviations time and the earthquake time occurrence.

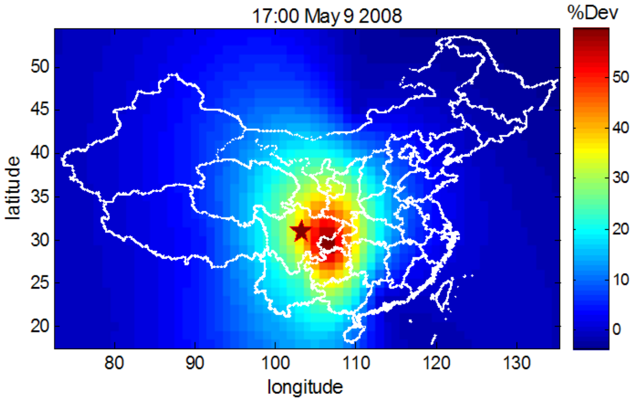

Fig. 3. Two-dimensional map of %Dev at 17:00 LT where and the red star denotes the epicenter (Xu et al., 2010a).

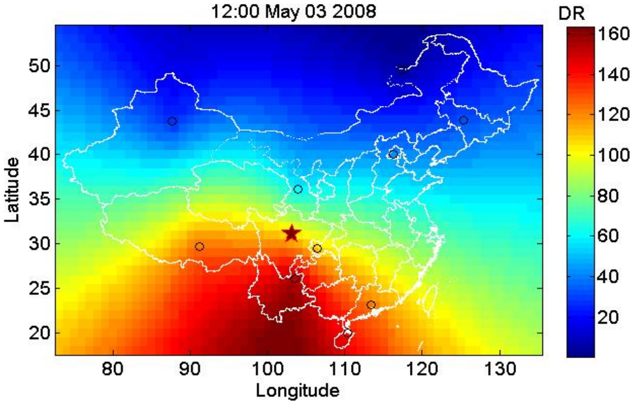

Fig. 4. Two-dimensional map for ionospheric *fo*F2 disturbance trigged by a moderate magnetic storm at 12:00 LT, on 3 May, 2008 (Xu et al., 2010b). The geomagnetic activity remained at a considerable level (the maximum of ap reached up to 39 nT). Supposing that *fo*F2 has a second-degree relationship with the effective sunspot number defined by Xu et al. (2010b), the effective sunspot number can be derived from the second-degree relationship with the observed *fo*F2. DR is the deviation of the effective sunspot number from the observed sunspot number. Hence, DR corresponds to the disturbed magnitude of *fo*F2.

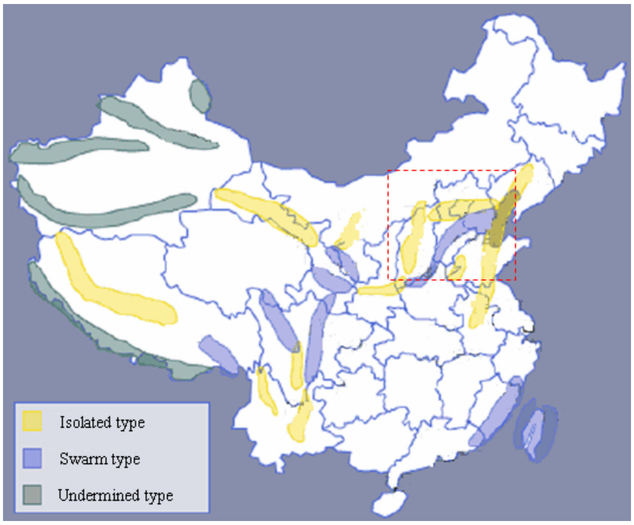

Fig. 5. The distribution of seismic belts in China.

Figure 2 displays the variation of *fo*F2 ionospheric parameter over Chongqing station, about 300 km east of the epicenter, before the earthquake occurrence. Using the method proposed by Liu et al. (2004), the interquartile range (IQR) is calculated to construct the upper bound (UB) X+IQR and lower bound (LB) X-IQR for the data estimation. Here, X is the median of the data. To assess the percentage of *fo*F2 ionospheric measurements from the normal variation, relative deviations are estimated using the following relation: %Dev = 100×(*fo*F2 – UB or LB)/UB or LB. If *fo*F2 parameter varies between LB and UB, then the deviation percentage (i.e. %Dev) is equal to zero. The result is shown in Fig. 2. One can see that the *fo*F2 ionospheric parameters were disturbed significantly and positively on 9 May. At 17:00 LT, the relative deviation (%Dev) was up to 65% and the anomalous disturbances lasted 3 h. With the data of the 13 vertical sounding stations (excluding Xi'an station, because they were built recently and the data was collected only from September 2010), a more illustrative form of %Dev is presented, in a two-dimensional map in Fig. 3. As shown in this figure, a giant positive perturbation of *fo*F2 with limited rounded shape is observed on the right side of the epicenter (i.e. localization). This is an important feature different from the disturbances trigged by geomagnetic storm, as shown in Fig. 4. Moreover, Pulinets et al. (2000) demonstrated that sometimes, before an earthquake occurs, horizontal distribution of the ionospheric plasma concentration is characterized by two sharp foci of positive and negative perturbations over

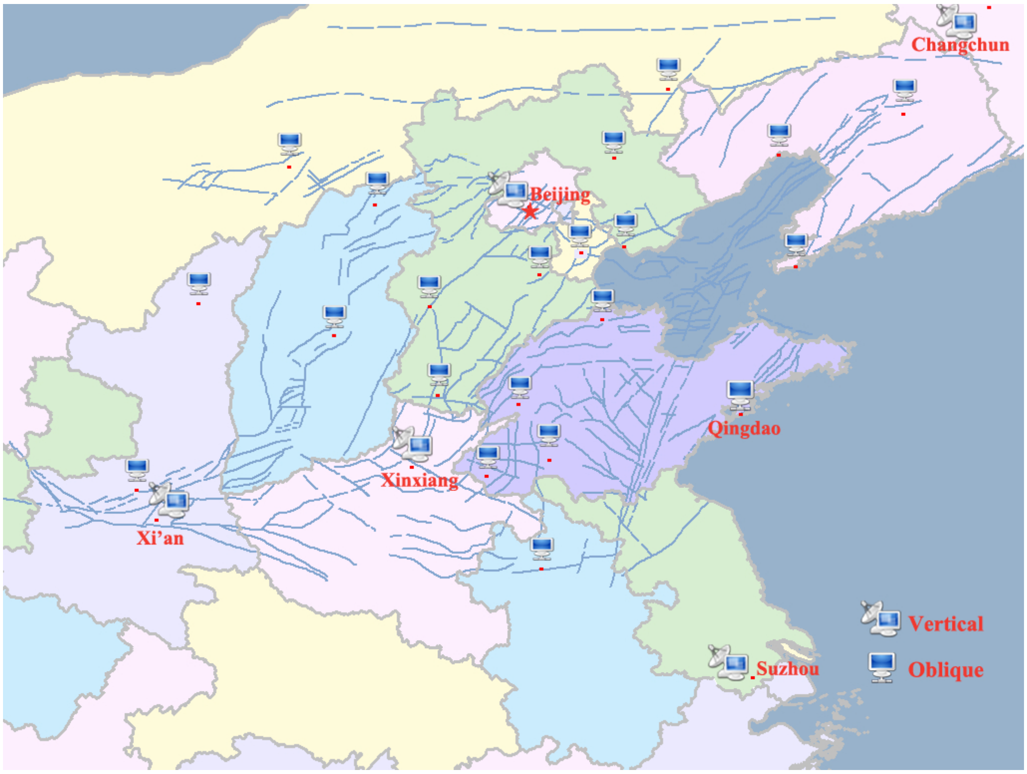

Fig. 6. The distribution of the ground-based high-resolution ionospheric observation (GBHIO) network.

the epicenter. There was no obvious negative perturbation on the opposite side, which may be due to sparse ionospheric vertical sounding stations in the West of the epicentre, and inadequate data of *fo*F2 parameter that can be analysed (Xu et al., 2010a).

4 The network of ground based high-resolution ionospheric observation

The ionospheric disturbed range is almost limited over the earthquake preparation zone, a conception introduced by Dobovolsky et al. (1979), depending on magnitude of the earthquake ($R = 10^{0.43M}$, where R is the radius of the earthquake preparation zone and M is the earthquake magnitude). This localization is one of the most meaningful characteristics different from ionospheric disturbances due to magnetic storms. For the Wenchuan earthquake, the radius of the earthquake preparation zone is more than 2000 km, but there was unapparent perturbation in *fo*F2 over Lhasa station, ~1200 km away from the epicenter, and the most remarkable anomaly that can be easily distinguished is located near the epicenter, as shown in Fig. 3. In addition, the bifocal structure (focus of positive and negative) of ionospheric disturbance is another important characteristic trigged by seismic activity. But with inadequate distribution of sounding stations, this feature is difficult to obtain, as discussed above.

Hence, for better seismo-ionospheric monitoring, more ionospheric sounding stations should be built in suitable distribution on/near seismic belts. However, the establishment of vertical sounding station has a high cost and rigorous requirements for electromagnetic circumstance and location. The use of oblique soundings, receiving the radio wave from the vertical ionopsheric stations, is feasible. Figure 5 shows the distribution of seismic belts in China where the North China seismic belt is denoted by the red dashed square. The catastrophic earthquake, Tangshan earthquake (1976, $M7.8$, killed more than 300 000 people) occurred in this area. In June 2009, the ground-based high-resolution ionospheric observation (GBHIO) network was established, shown in Fig. 6. This network consists of 5 vertical sounding stations and 20 oblique receivers, forming more than 100 channels of radio wave transmission through the ionosphere and more than 100 maximum observable frequencies (MOFs, f_{O}) at different paths can be obtained, with which we can achieve the information of the reflected points of the ionosphere with the relationship $f_{\mathrm{O}} = f o\mathrm{F2} k \sec\varphi$, where k is the Earth sphericity coefficient and φ is the incidence angle. About 40 radio paths are chosen, whose ground distances $D \leq 600$ km, which makes up ~10% of the path length and does not significantly affect the accuracy of *fo*F2 calculations (Kotovich et al., 2006). With this network, ionospheric variation of a high resolution at a size of ~100 km can be observed, as illustrated in Fig. 7.

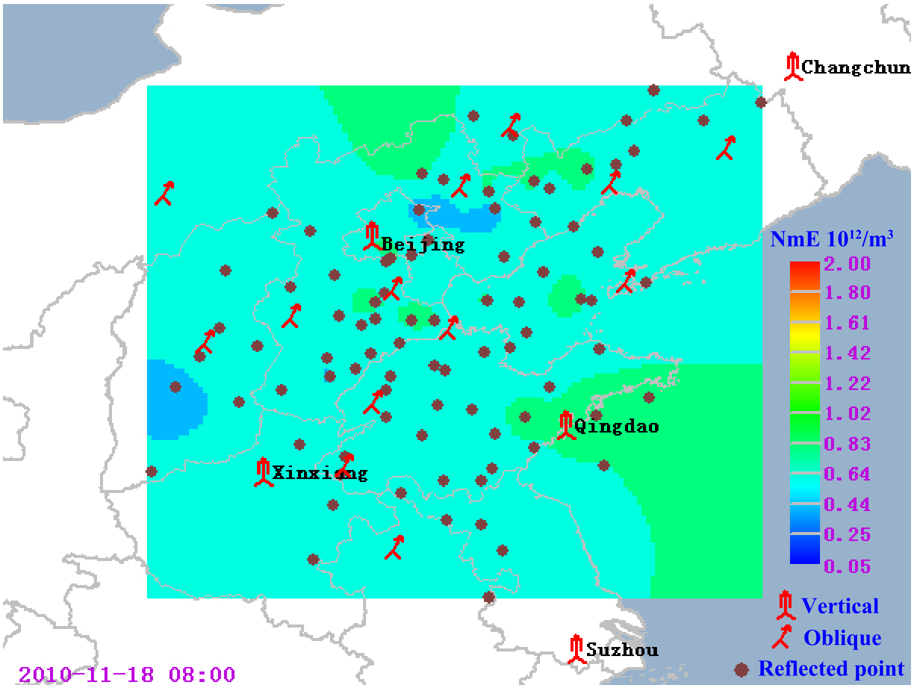

Fig. 7. Two-dimensional map of NmF2 ($1.24 \times 10^4 (foF2)^2$) based on the GBHIO network.

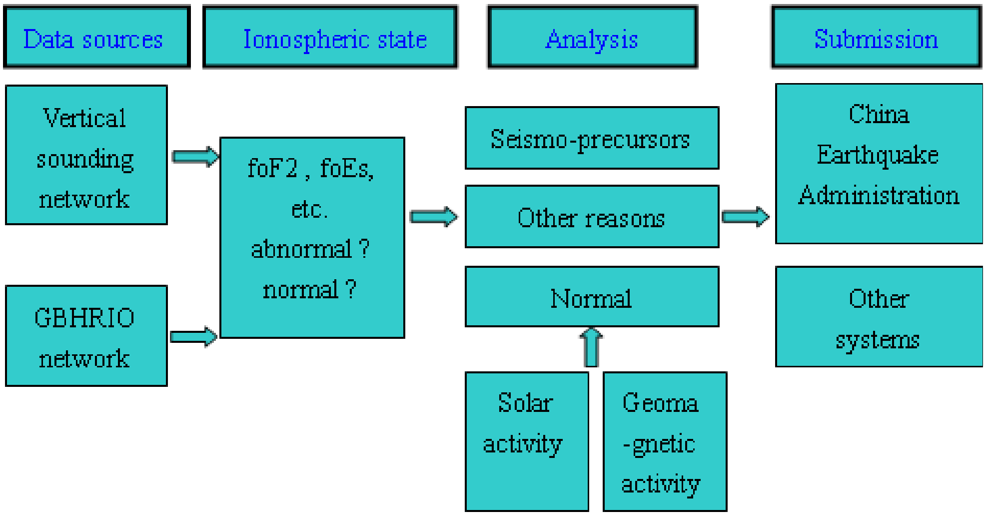

Fig. 8. The flow process of monitoring anomalous ionospheric variation related to seismic activity in the GBHIO.

On 13 June 2009, the GBHIO data center was established in CRIRP, Qingdao, China. The vertical and oblique sounding data are proceeded by manual scale and software developed by CRIRP. Until now, the GBHIO data center consisted of more than 20 people involved in seismo-ionospheric research, data scale and software maintenance, and is being completed gradually. The flow process of monitoring the anomalous variation of ionosphere phenomena related to seismic activity in the GBHIO is to:

1. Obtain the *fo*F2 data timely using the network.
2. Analyze data.
3. Submit the results to related departments (e.g., China Earthquake Administration).

The detail of the flow process is illustrated in Fig. 8. A high variability of the ionosphere and the influence of solar and geomagnetic activities are the main arguments against the existence of seismo-ionospheric precursors. Hence, when analyzing the data of the vertical and oblique sounding, the solar and geomagnetic activities are considered. Additionally, other sources, e.g. typhoon (Sorokin et al., 2005), which can cause similar ionospheric disturbances, should be carefully analyzed and then excluded.

5 Summary

Ground based ionospheric sounding can continuously monitor on disturbances before earthquakes. In this paper, the *fo*F2 anomaly before Wenchuan earthquake is briefly presented, from which much interest of Chinese researchers has arisen. As a result, the ground- based high-resolution ionospheric observation (GBHIO) network in north China comprising 5 vertical sounding stations and 20 oblique sounding stations was established in 2009, with which the small scale ($\sim$100 km) of ionospheric variations can be monitored. Moreover, the plan of the Chinese seismo-electromagnetic satellite and another GBHIO network are in the process of being authorized. The new network consists of 3 to 5 vertical and 50 to 200 oblique sounding stations covering the main belts in the Southwest of China where the great Wenchuan earthquake occurred. Combining this with ground based measurements (such as TEC, *fo*F2, subionospheric VLF signal) and satellite detection (e.g. electric field E, ion/electron temperature T_{i}) could be a powerful tool for the development of earthquake monitoring and forecasting methods.

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