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Forecasting geomagnetic activity at monthly and annual horizons: Time series models

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ABSTRACT

Most of the existing work on forecasting geomagnetic activity has been over short intervals, on the order of hours or days. However, it is also of interest to predict over longer horizons, ranging from months to years. Forecasting tests are run for the Aa index, which begins in 1868 and provides the longest continuous records of geomagnetic activity. This series is challenging to forecast. While it exhibits cycles at 11–22 years, the amplitude and period of the cycles varies over time. There is also evidence of discontinuous trending: the slope and direction of the trend change repeatedly. Further, at the monthly resolution, the data exhibits nonlinear variability, with intermittent large outliers. Several types of models are tested: regressions, neural networks, a frequency domain algorithm, and combined models. Forecasting tests are run at horizons of 1–11 years using the annual data, and 1–12 months using the monthly data. At the 1-year horizon, the mean errors are in the range of 13–17 percent while the median errors are in the range of 10–14 percent. The accuracy of the models deteriorates at longer horizons. At 5 years, the mean errors lie in the range of 21–23 percent, and at 11 years, 23–25 percent. At the 1 year horizon, the most accurate forecast is achieved by a combined model, but over longer horizons (2–11 years), the neural net dominates. At the monthly resolution, the mean errors are in the range of 17–19 percent at 1 month, while the median errors lie in a range of 14–17 percent. The mean error increases to 23–24 percent at 5 months, and 25 percent at 12 months. A model combining frequency and time domain methods is marginally better than regressions and neural networks alone, up to 11 months. The main conclusion is that geomagnetic activity can only be predicted to within a limited threshold of accuracy, over a given range of horizons. This is consistent with the finding of irregular trends and cycles in the annual data and nonlinear variability in the monthly series.

1. Introduction

Most of the existing work on forecasting geomagnetic activity has been over short horizons, on the order of a few hours to a few days. However, it is also of interest to be able to predict over longer horizons, ranging from months to years. Geomagnetic activity is challenging to forecast. While it exhibits cycles at 11 and 22 years, corresponding to reversals in the sun's magnetic field, the amplitude and period of the cycles varies over time. There is also evidence of discontinuous trending: magnetic activity is observed to rise, sometimes for as long as several decades, and then decline. The length of the intervals of trending can vary considerably, while the transition points between increases and decreases do not occur at fixed intervals. Further, at the monthly resolution, the data also exhibits a great deal of nonlinear variability, with large outliers at irregular intervals.

This study runs forecasting tests for the Aa index, the longest continuous record of geomagnetic activity, at horizons of 1–11 years and 1–12 months. The methodology includes regressions, neural networks, frequency domain methods, and combined models. The data and its properties are summarized in Sections 2–4. The forecasting models are set out in Section 5. Section 6 reports the findings for forecasting experiments with the annual data, while Section 7 reports the findings for the monthly data. Section 8 concludes.

2. Measures of geomagnetic activity

Some of the variation in geomagnetism can be attributed to solar activity. The 11–22 year solar cycles, as well as the rise in solar activity during the early 20th century are both reflected in the geomagnetic data. However, over longer horizons, the electric currents generated by rotation of the earth's liquid outer core have

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a major impact in driving geomagnetic activity. Secondary factors include interactions between the magnetosphere and the ionosphere, and local currents in the magnetosphere itself.

In selecting measures of geomagnetism, the investigator faces a tradeoff between the length of time spanned by the index and breadth of coverage. The Aa index, which begins in 1868, is based on the magnetic activity measured at two antipodal stations, Canberra, Australia, and Hartland, England (Mayaud, 1972) on the basis of *K* indices. The index is the average of the northern and southern values of magnetic activity, weighted to account for differences in the latitudes of the two stations and local induction effects.

The *K* index is a 3-hour range index. It is a measure of activity relative to an estimated quiet day. It was introduced at the beginning of the 1940s (Mayaud, 1980; Menvielle and Berthelier, 1991), and extrapolated backwards at some magnetic observatories. It is sensitive to irregular and short-term magnetic activity, and not to secular variation. Several broader measures are based on the *K* indices. The Ap index, beginning in 1932, uses 13 observatories, 11 in the northern and 2 in the southern hemisphere. The Am index, beginning in 1959, spans 23 locations, 13 northern and 10 southern subauroral stations arranged in groups representing longitude sectors (Menvielle and Berthelier, 1991; McPherron, 1995; Mayaud, 1980).

Although the Am index is the most complete measure, the Aa index has the advantage that it spans a much longer interval, incorporating 13 complete 11-year cycles. Forecasting experiments over extended horizons typically require long training sets. If the Ap or Am indexes were used, the forecasting experiments would have to be limited to recent history. In this respect, prior studies have determined that the ability to identify lower-frequency signals in time series and forecast over longer horizons is dependent both on the resolution of the data and the length of time spanned. If the forecast horizon is limited to a few months, monthly data can be used. If the forecast horizon is several years in the future, annual data is preferable (Schiller and Perron, 1985; Perron, 1988; Perron and Phillips, 1988). This argues for using the data at lower resolutions, and over the longest possible period, i.e., the Aa index. The values for 1868–2010 were downloaded from the National Geophysical Data Center (2014).

3. The annual data

Fig. 1 shows the Aa index at an annual resolution. Several features stand out. First, the trend is observed to change over time. The index exhibited no visible trend from the late 19th century until about 1900. From 1900 until the late 1960s, there was a sustained increase. In the early 1960s, magnetic activity fell off abruptly but then recovered. From the early 1970s until 1990s, there was a very gradual rise. The next decade was marked by turbulence, with a steep trough in 1996 followed by an unusually high peak in 2003. Thereafter, magnetic activity fell off sharply, decreasing to levels not seen since the early 20th century. In effect, the trend is stochastic, a concept that it familiar from other fields, primarily econometrics (Watson, 1986; Clark, 1987; Cochrane, 1988; Stock and Watson, 1988).

Second, both the amplitude of the cycle and the period are observed to vary over time. Particularly at the peaks, there are irregular sharp spikes, and in several cases double or even triple peaks. Some of this variation is related to solar activity, but there is also evidence of periodicities which are unique to the earth's magnetic field, and apparently uncorrelated to the solar cycle (Rangarajan and Iyemori, 1997). In effect, the cycle is also stochastic (Harvey, 1989).

In the last decade, substantial progress has been made in developing physics-based models for space weather (Gombosi et al., 2001; Toth et al., 2005) and the solar cycle (Tobiska et al., 2000; Dikpati and Gilman, 2006). However, neither retrospective simulations nor forecasts are currently available. In the absence of a complete physics model, it may be possible to model geomagnetic activity statistically. A natural model for the Aa index is a regression on lags with time-varying coefficients. Regressions are often thought of as linear, but when the coefficients are stochastic, they can capture a great deal of nonlinearity (Granger, 2008). Let Y_t be the Aa index, let ln denote natural logs, let the subscript t denote time variation, and let ε_t denote the residual. The model is of the form.

$$\ln Y_t = \omega_{0t} + \omega_{1t} \ln Y_{t-1} + \omega_{2t} \ln Y_{t-11} + \omega_{3t} \ln Y_{t-22} + \varepsilon_t; \quad \varepsilon_t \sim P\left(0, \sigma_t^2\right) \tag{1}$$

where P is the probability distribution and σ_t^2 is the residual variance. The lags at 11 and 22 years capture the cycles, while the stochastic coefficients can pick up changes in amplitude. Additional lags can be used as needed. However, the widely-used Akaike (1973) information criterion favored this specification.

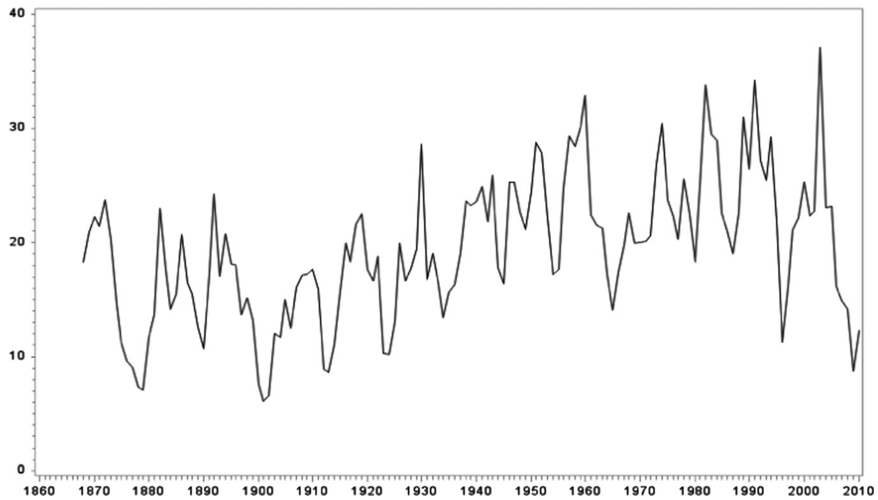

Fig. 1. The Aa Index, annual frequency. The left scale is the index values. The series runs from 1868 through 2010. Notable features include the 11–22 years cycles, and the upward trend in the early 20th century. From 1960 onward, the series becomes markedly more volatile.