State Space Reconstruction for Sunspot Area Time Series

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Abstract.

We analyzed the sunspot area time series by means of state space reconstruction for the time period between 1875 and 2015. Two different local neighborhood models, namely Simplex Projection and S-Map are employed to project state space reconstructions. Various classification schemes in the literature are then tested in these models to compare the predictive ability of multivariate and univariate time series. According to our results, multivariate time series represent the true dynamics of sunspot areas better than univariate time series, which implies more accurate predictions, can be obtained if proper classification schemes of sunspot area time series are employed and each class is predicted separately.

Introduction

Studies on understanding and forecasting solar activity comprises sunspot recognition, classification and analysis. Sunspot observations have a long temporal expansion (~400 years) and since the beginning of their recognition on the solar disk, various attempts have been performed to investigate their dynamics, distribution and periodicities. The earliest results demonstrated a statistical causality of powerful solar eruptions with the large and complex sunspots (Giovanelli R.G., 1939). This discovery led the earlier studies on classifying sunspots to be more systematically and detailed. After several modifications on the earlier classification schemes, the most widely used system up to now, "McIntosh Classification" which is also known as "Modified Zurich Classification" (McIntosh P.S., 1990) is introduced.

On the other hand, it has been long known that, sunspots display different temporal variations on different solar hemispheres. This phenomenon is known as "Hemispheric Asymmetry" or "North-South Asymmetry". Also some other studies regarding sunspot classification is performed by various authors based on the sizes or complexities of sunspot groups (e.g. Kilcik A. et al., 2011; Javaraiah J., 2016; Gao P.X. et al. 2017). Here, we performed multivariate prediction methods on four different classification schemes and calculated their prediction performance to compare with each other.

Classification Schemes

i) Empirical Classification

Sunspot observations in the Debrecen and Greenwich photoheliographic data are empirically classified from the last (complexity) parameter of Zurich Classification Scheme (c, o, i and x parameters). Each groups average areas are taken from the NOAA Space Weather Prediction Center (SWPC) and upper/lower bounds for each empirical group are calculated by means of these averages. Determined ranges are extrapolated to the historical measurements.

ii) Ratio Classification

This classification scheme is introduced by Gao P.X. et al. (2017) as the ratio of the total sunspot area to its umbra. The authors stated that if this ratio is less or equal to 4.5, corresponding sunspot group is simple. They call a sunspot complex, if the ratio is greater than 6.2. The frequencies of simple and complex sunspots after the Solar Cycle 12 can be seen in Figure 1. It should be noted that these authors did not take into account the values between 4.5 and 6.2, showed with black bar in Figure 1. Both possibilities are tested in this

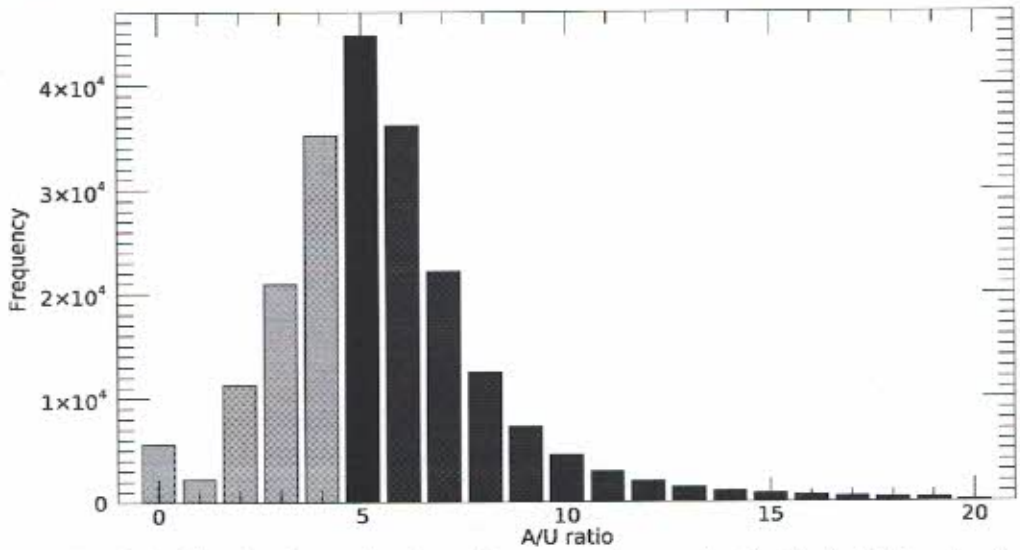


Figure 1 – Simple (yellow) and complex (green) sunspots frequencies for the last 13 cycles based on the ratio of total area and umbral area. (Adapted from Gao P.X. et al. 2017).

study by first considering only simple and complex sunspots, and also considering simple, middle and complex sunspots.

iii) Small & Large Classification

This classification scheme is introduced by Kilcik A. et al. (2011) as using the first parameter of modified Zurich classification. A sunspot group is called as small if their Zurich class is A, B, C, H, or J classes and called as large if their Zurich class is D, E, F, or G classes. Here, NOAA SWPC data are used as reference again to extrapolate this classification to the historical measurements of Debrecen and Greenwich photoheliographic data. Averages of the reference data for both classes and their mean ranges used for extrapolating can be seen in Table 1.

Table 1 – Mean values of small & large sunspots for the last 2 cycles and their extrapolated ranges for the last 13 cycles. Adapted from Kilcik et al. (2011).

	Large	**Small**
Means from reference [MSH]	233.28	51.72
Range for Extrapolation	large ≥142.5	142.5>small

iv) North-South Hemispheric Classification

It has been long known that, sunspots display different temporal variations on different solar hemispheres and there is a so called "Hemispheric Asymmetry" of sunspots (Roy J.R. 1977). This classification scheme is both used as a distinct separation and also combined with other three classification schemes that are mentioned above

Methods

All components of each classification scheme are taken into account as a separate dimension of the target time series which is the total sunspot area in a method called Multiview Embedding. The main idea of that method is that multidimensional time series can be used to reconstruct target time series from multiple viewpoints, and these viewpoints can be combined into a single model (Ye H. and Sugihara G. 2016). Although this method is proposed in the field of ecosystems, it is also possible to apply on various complex systems. Multiple state spaces from components of the time series which are classes of each scheme

are reconstructed and a single nearest neighbor is selected from each of them to produce final predictions. These reconstructions are then tested according to their prediction performance by comparing and calculating their correlation coefficient with the observed values. Combining information from multiple state space reconstructions is expected to improve the performance with increasing dimensionality

Results

As a first step of our analysis, we calculated the prediction performance of total sunspot areas without any components, which can be seen in Figure 2. Here, the optimal embedding dimension is found as 4 and the decay of prediction performance, which is an indicator of chaotic dynamics, can also be seen. We selected 12-month prediction performance, which has a correlation coefficient of 0.67 with the observed values to compare with other classification schemes.

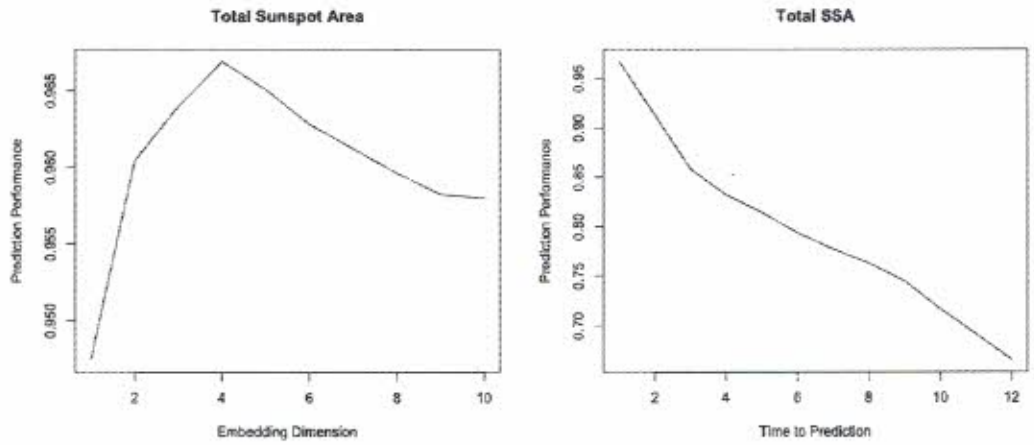


Figure 2 – Optimal embedding dimension and reference prediction performance for total SSA

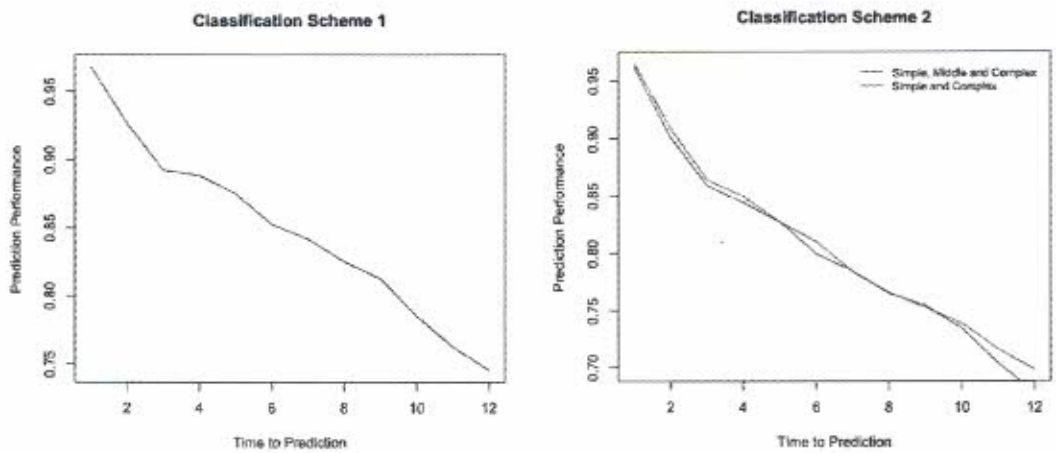


Figure 3 – Multiview Embedding prediction performance of Empirical and Ratio Classificaiton Schemes

Then we applied the Multiview Embedding with the same parameters to the first two classification schemes. They both slightly improved the 12-month prediction performance as can be seen in Figure 3. It should be noted that, in the second classification scheme (ratio classification), Gao P.X. et al. (2017) did not consider the middle group. Here we performed the analysis in both ways and show that taking the middle group into account, has improved the performance of the predictions after 10 months.

We also analyzed remaining two classification schemes (Small & Large and North & South) but they both decreased the prediction performance (Figure 4). In order to overcome this problem, these two classification schemes are combined as Small-North, Small-South, Large-North, and Large-South. This combination is greatly increased the Multiview Embedding prediction performance as can be seen at Figure 4.

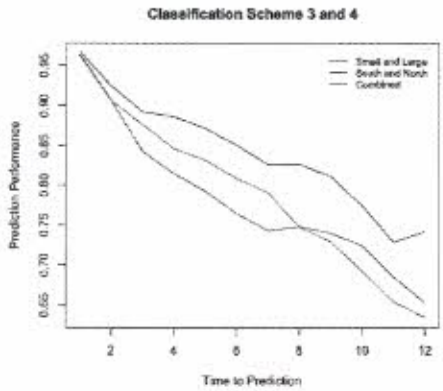


Figure 4 – Multiview Embedding prediction performance of Small & Large (red curve) and North & South (blue curve) classificaiton schemes and their combinations (black curve).

Conclusions

1. Empirical Classification (complexity parameter of Zurich class) gives the highest increase in prediction performance (Table 2).
2. North – South Classification can be combined with other classification schemes.
3. Separating SSA time series to constituents increases the prediction performance

Table 2 – Results of Multiview embedding prediction performances of each classification scheme (first row) and combining them with the North & South asymmetry (last row)

Empirical	A/U ratio	Small & Large	C North & South
0.75	0.70	0.64	0.65
0.79	0.78	0.74	<- Combined

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