Investigation of Sunspot Area Dynamics in Different Categories

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Abstract.

In this study, sunspot areas are divided into four empirical categories according to their corrected areas on the solar disk in order to analyze their temporal variations and non-linear dynamics. Complexity parameter (last parameter) of the modified Zurich classification scheme for the last two solar cycles (Solar Cycle 23 and 24) is used as reference to determine the upper and lower bounds for distinct sunspot areas of each empirical group. Simplex Projection and S-Map algorithms are used to determine the embedding dimension and nonlinearity parameter of each category, respectively. Cross-Correlation (CC) and Convergence Cross Mapping (CCM) methods are also applied to determine unidirectional and bidirectional relationships of these classes. Obtained results have shown that smoothing process drastically affects the embedding dimension and nonlinearity of each category. The empirical groups are also found consistent with each other as well as total sunspot number and sunspot area. Thus, we may conclude that the proposed empirical classification can be used for further studies.

Introduction

McIntosh sunspot Classification scheme is formed by three parameters. The first parameter is related to the structure and distribution of penumbra as well as the polarity (unipolar or bipolar) and length of the sunspot group. Second parameter focuses on the largest spot in the group and related to the type and size of its penumbra, and also symmetry of umbra and surrounding penumbra. Final parameter is related to the compactness of the sunspot groups. In other words, combination of this third parameter shows how a sunspot group is distributed on the solar disk (McIntosh P.S., 1990).

There are various studies in the literature that show sunspot related time series display different temporal variations in different groups (Kilcik A. et al., 2011 and references therein). However, there are very good data for the McIntosh Classification and all group information together for the last two solar cycles (Solar Cycle 23 and 24). On the other hand, there exists sunspot photoheliographic data after the year 1872. Therefore, the main motivation of this study is to confirm the possibility of extrapolating classification schemes to the historical measurements by using empirical groups and also investigating possible relationships and/or interactions between the dynamics of these extrapolated groups.

Data

Zurich Classifications and corrected areas for each observed sunspot for the time period between 1996 and 2018 are taken from "NOAA Space Weather Prediction Center". These data are used as reference values for extrapolating the classification to the historical measurements of corrected sunspot areas observed from 1874 to 2018. Historical measurements are taken from "Revised version of Greenwich Photoheliographic Results (GPR) sunspot catalogue" (1874-1974) and "Debrecen Photoheliographic Data" (1974-2018). The new sunspot number data (Clette and Lefèvre, 2016) are also used to compare the separated time series and analyze their coherency.

Methods

The reference data is separated according to each sunspot's complexity parameter of the Modified Zurich Classification scheme, namely x, o, i, and c. Therefore 4 empirical groups

are introduced by calculating the mean values of each parameters corrected sunspot are on the solar disk. Upper and lower bounds for empirical groups are determined from the middle values of each consecutive mean area of reference data. These separations can be summarized as in Table 1.

Table 1 – Empirical Classification Scheme

Complexity Parameter	**x**	**i**	**o**	**c**
Means of reference data [MSH]	51.49	87.24	272.12	561.78
Range for Empirical Classification [MSH]	69.36> **x** ≥0	179.68> **i** ≥69.36	416.95> **o** ≥179.68	**c** ≥416.95
Empirical Groups	**Group 1**	**Group 2**	**Group 3**	**Group 4**

In order to determine the embedding dimension parameter of these empirical groups, Simplex Projection (Sugihara and May, 1990) method is used. This method is based on the state space reconstruction of time series data and these reconstructions are assumed to map one-to-one to the original attractor of the comprising dynamic system (Takens, 1981). Thus, we can use prediction skill to identify the optimal embedding dimension.

An approximation of the nonlinearity of these empirical groups is calculated by using S-map (Sugihara, 1994) approach. In addition to the standard parameters of Simplex Projection, S-maps also contain a nonlinearity parameter (θ) that determines the degree to which points are weighted when fitting the model. If θ parameter is equal to zero, the model will be the same for each place in the reconstruction and so it will be identical to an autoregressive model. When values of θ are greater than 0, closer points in the reconstruction will get more weights, and so the local model can vary in state-space to accommodate nonlinear behavior.

A generic property of the reconstructions is that the states of each time series maps one-to-one onto to the states in the original attractor. So, if two variables are dynamically coupled, then local neighborhoods on their reconstructions will map to each other since they are essentially alternative observations of the common original attractor. Thus, we used Convergent Cross Mapping (CCM) method which analyses how well local neighborhoods of two time series correspond to each other (Sugihara et al. 2012) to see the interactions of empirical group

Results

Monthly temporal variations of each empirical group and their comparison with total sunspot number and sunspot area can be seen in Figure 1. It is clear that these empirical groups behave differently especially during the maximum and declining phases of solar activity, although the main peaks are generally determined by the SSA Group 4. Both original versions of these groups and their smoothed versions are tested in the Simplex Projection algorithm (Figure 2). The original time series' embedding dimensions are failed to converge a low dimension, possibly because of their intrinsic noise levels. On the other hand, a small smoothing, 3-month running average, fixed the optimal embedding dimension to 4 for all empirical groups. The same pattern is also revealed in terms of nonlinearity parameter during the S-map analysis.

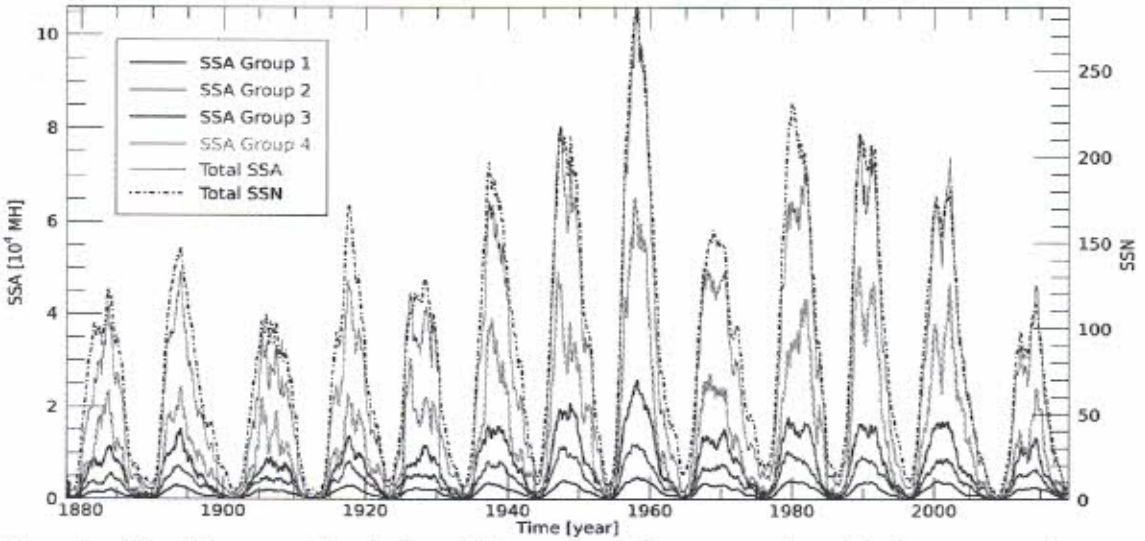


Figure 1 – Monthly temporal variations of 3-month running averaged empirical groups, total sunspot numbers and total sunspot areas.

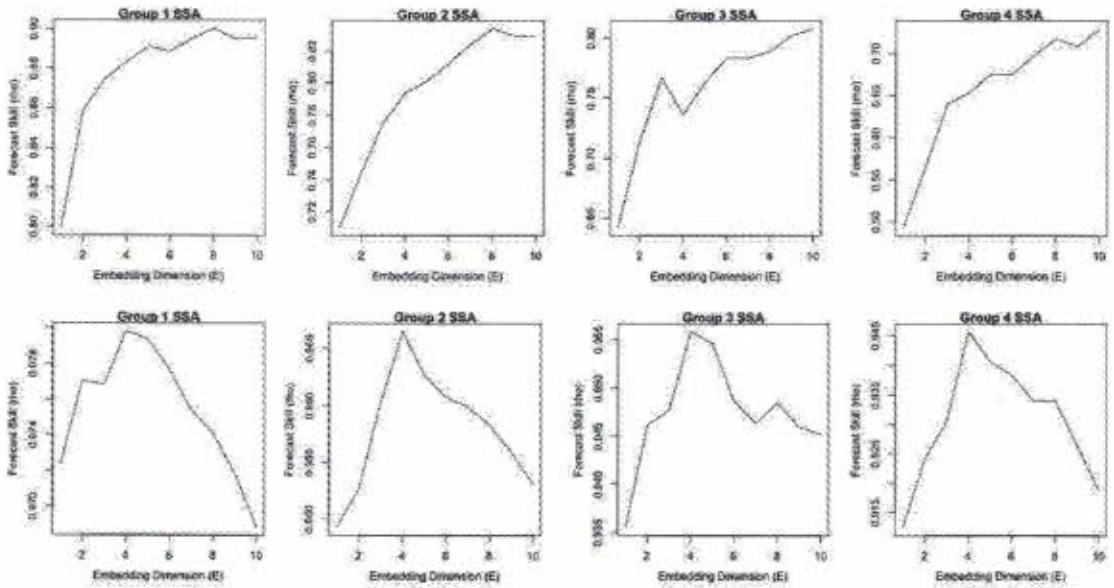


Figure 2 – Forecast skills of each empirical group for varying embedding dimension from 1 to 10. First row represent the original time series while second row represent the smoothed versions of the same time series.

We also calculated the correlation coefficients between the empirical groups and their temporal delays. These results are presented in Table-2. Finally, we analyzed the interaction of these groups with the SSN and SSA time series. The CCM results of this analysis can be seen in in Figure 4.

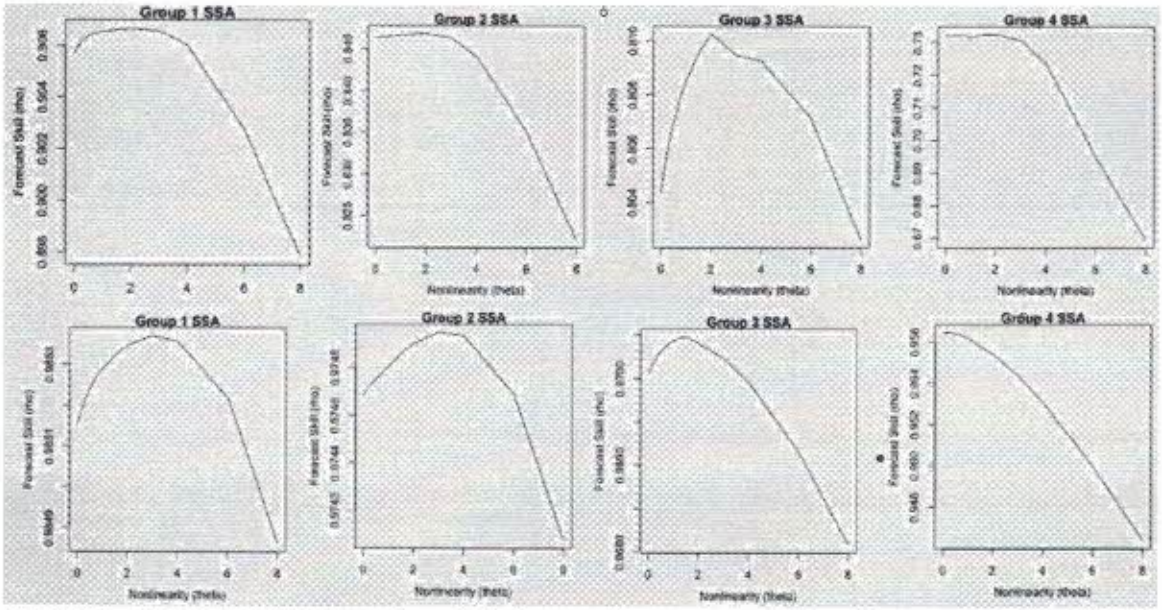


Figure 3 – Forecast skills of each empirical group for varying nonlinearity parameter from 1 to 8. First row represent the original time series while second row represent the smoothed versions of the same time series.

Table 2 – Correlation Coefficients between empirical groups and SSN, SSA time series. The correlation values which marked with bold corresponds to the one month temporal delay.

Group 1	1.00					
Group 2	0.87	1.00				
Group 3	0.81	0.83	1.00			
Group 4	**0.71**	**0.70**	**0.72**	1.00		
Total SSA	**0.83**	0.82	0.85	0.96	1.00	
Total SSN	0.92	0.91	0.90	0.83	0.95	1.00
	Group 1	Group 2	Group 3	Group 4	Total SSA	Total SSN

Conclusions

1. This empirical classification scheme introduced four consistent sunspot series, that is based on the last parameter of modified Zurich Class and can be used for future studies.
2. All groups have identical embedding dimensions and similar nonlinearity parameters that can be used to reconstruct their state space models.
3. Total SSA has the highest correlation with Group 4, while Total SSN has the lowest correlation and one month temporal delay with this group. Thus we conclude that, there are asymmetrical relationships between these two time series.
4. Each time series used in this study perform a higher CCM score than correlation coefficient values except mapping to Group 4 from Total SSA library. This indicated the uni-directional relation from Group 4 to Total SSA. In other words, Total SSA dynamics are sensitive to the variations in Group 4, but the opposite is not true.

Acknowledgment

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