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Comparison of the dynamics of coronal holes identified by two detection methods in solar activity cycles 24-25

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Abstract. In this study, we analyze for the first time the long-term variations of coronal holes (CHs) identified by two different automatic detection schemes: Spatial Possibilistic Clustering Algorithm (SPoCA) and Convolutional Neural Network (CNN193). The source material was the observational data acquired by the Atmospheric Imaging Assembly instrument onboard the Solar Dynamics Observatory (AIA/SDO) in the Fe XII 19.3 nm line in the period from June 16, 2010, to May 13, 2021. An initial analysis comparing the long-term variations of the CH areas extracted by the SPoCA method and used by us in earlier works to study their evolution at different stages of the 24th and at the beginning of the 25th cycles showed fairly good agreement with the trend of the CH areas identified by the CNN193 algorithm for the same period. Both schemes reveal hemispheric asymmetry in the generation of CHs both in time and in amplitude.

Keywords: methods: data analysis; techniques: image processing; Sun: corona

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1 Introduction

Coronal holes, regions where magnetic field lines are open to outer space and appear darker in extreme ultraviolet (EUV) and soft X-ray (SXR) images, have lower solar coronal density and temperature due to the special configuration of the magnetic field. CHs are usually associated with high-velocity solar wind (SW) streams and allow us to estimate the SW parameters and the corresponding geomagnetic effects. CHs are of interest both for short-term space weather forecasting and for forecasting on longer time scales. Methods for identifying CHs are diverse and range from fully manual procedures to fully automatic ones using observations at different wavelengths. Currently, automatic detection schemes are the standard approach for detecting CHs in EUV images acquired by AIA/SDO (Lemen et al. 2012). One reason for this is the huge amount of archival data transmitted daily. However, factors such as the noisy nature of solar images, instrumental effects, and others make it difficult to identify CHs using these automated schemes. The astronomical community has put a lot of effort into finding the optimal algorithm for extracting CHs. In a recent work, Reiss et al. (2024) analyzed CHs detections in 29 SDO solar images by 14 of the best known automatic schemes. The authors showed that the choice of automatic detection scheme can have a significant impact on the size and shape of CH regions, their physical properties, and hence the interpretation of the results.

2 Data and methods for detecting coronal holes

Historically, in our previous work to investigate coronal holes from observations of the AIA/SDO instrument in the Fe XII 19.3 nm line, we used the Heliophysical Events Knowledge (HEK) base (Hurlburt et al. 2012). The tool used to extract the area information was the SPoCA-suite of procedures (Verbeeck et al. 2014). SPoCA uses fuzzy clustering and allows us to distinguish CHs, active regions and quiet Sun in a solar image. In Andreeva (2023), we obtained a series of cyclic variations of the CH areas of the entire visible surface of the solar disk, separately in the N and S hemispheres, and identified the contribution of polar and non-polar CHs to the overall dynamics of solar activity of the 24th and the ascending phase of the 25th cycles. With these results, we would like to compare how it relates to variations in the CH areas extracted by other algorithms.

For comparison, the development of CNN193 by Russian colleagues (Illarionov & Tlatov 2018) was chosen, which uses a neural network to detect CHs at the widely used wavelength of 19.3 nm. The neural network is trained on segmentation maps of CHs monitored by solar scientists and then tested on a new set of images. The detection of CHs is performed on both solar disk images and synoptic maps of the

Sun, which are a compilation of successive disk images over the Sun's rotation period. Guided by the idea that the concept of CHs should be the same in both cases, the authors investigated universal models that can learn the CH segmentation from disk images and reproduce the same segmentation from synoptic maps. The simulation showed quite good results (Illarionov et al. 2020), which interested us. The author of this model, E. Illarionov, kindly provided us with data on the magnetic fluxes and areas of CHs segmented with CNN193. Next, the behavior of long-term CH variations extracted from solar disk images using the SPoCA algorithm will be compared with CH variations segmented on synoptic maps using the CNN193 convolutional neural network model.

It should be noted here that in our works we considered two types of CHs: polar and non-polar. Polar CHs are located at the solar poles, sometimes descending to middle and low latitudes and even passing to the opposite hemisphere. Non-polar CHs are mainly confined to low, middle, sometimes high latitudes, but not associated with polar CHs. For the authors of the CNN193 model, the boundary separating polar and low-latitude zones is $\Theta = \pm 50°$. We admit that such a separation could affect the result of the comparison.

3 Dynamics of coronal holes detected by SPoCA and CNN193 methods

Comparison of methods of CH segmentation on separate images has been performed repeatedly. However, we are not yet aware of any work on analyzing the long-term variations of CHs segmented by different automated methods. In this study, we compared the behavior of CHs identified by SPoCA and CNN193 methods from June 16, 2010 to May 13, 2021. Figure 1 shows the behavior of polar CHs in hemispheres during the period. Figure 2 shows the behavior of polar and non-polar CHs on the entire visible surface of the Sun's disk over the same period. The top and middle panels of Fig. 1 and Fig. 2 represent the variations of magnetic fluxes and CH areas extracted by the CNN193 method. The lower panel is the areas of the CHs extracted by the SPoCA method.

Figure 1 shows that the variations of magnetic fluxes of polar CHs extracted by CNN193 in hemispheres almost repeat the variations of CH areas. Similar dynamics is observed for the CHs extracted by the SPoCA method. Both methods show that during the 24th cycle and the early phase of the 25th cycle, the solar dynamo operated differently in the hemispheres in terms of CH generation. You can see the pronounced peaks in the hemispheric dominance of CH areas. During the ascending phase in 2011–2012 and in 2015, the Southern Hemisphere led in terms of maximum polar

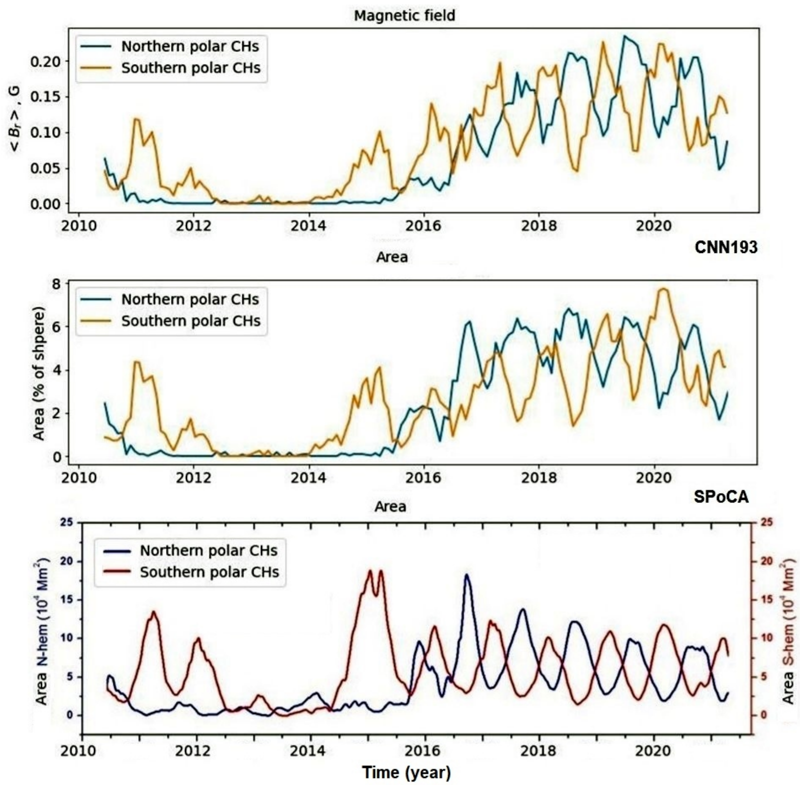

Fig. 1. Dynamics of polar CHs in the N and S hemispheres in the period from June 16, 2010, to May 13, 2021. The variations of magnetic fluxes (top panel) and CH areas (middle panel) identified by the CNN193 method. The bottom panel is the areas of the CHs identified by the SPoCA method.

CH areas. Overall, a marked increase in polar CHs extracted by CNN193 in both hemispheres during the decline phase and at the 24/25 solar minimum is seen. A similar pattern is observed for the polar CHs identified by SPoCA, but the increase is less pronounced.

All panels of Fig. 2 show two maxima of magnetic flux and regions of polar CHs observed in 2011–2012 and 2015 – the phases of solar activity ascending and descending. After the decline phase and at the minimum of 24/25 cycles, the total areas of polar CHs approach the average level of values. The maxima of non-polar areas in 2013–2014 are consistent with the second maximum of cycle 24 determined from sunspots by us earlier. The total areas of non-polar CHs (SPoCA) have low values at the beginning of the study period, and in the decline phase of the 24th cycle and in the minimum of the 24/25 cycles, these CHs practically disappear. The low-latitude CHs segmented by the CNN193 increase in the decline phase and the

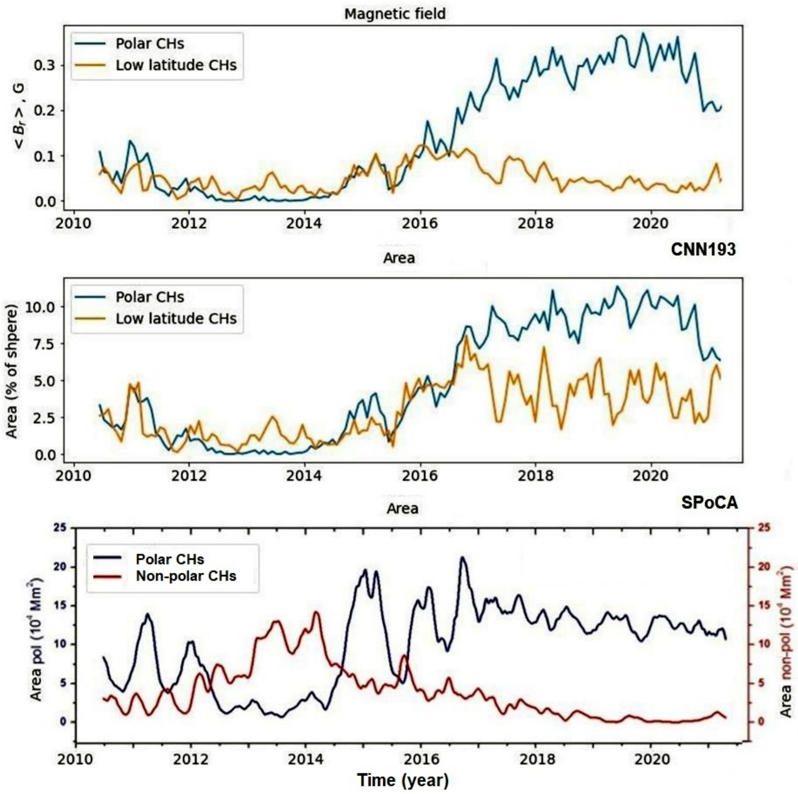

Fig. 2. Dynamics of polar and non-polar CHs on the visible solar surface in the period from June 16, 2010, to May 13, 2021. The variations of magnetic fluxes (top panel) and CH areas (middle panel) identified by the CNN193 method. The bottom panel is the areas of the CHs identified by the SPoCA method.

minimum of cycles 24/25 in the same way as the polar CHs, but with much smaller amplitude. The magnetic flux (CNN193) of low-latitude CHs drops markedly.

4 Conclusions

In this study, the dynamics of coronal holes, identified by two different automatic methods, on the scales of the solar cycle was analyzed for the first time. An initial comparison of the dynamics of the CH areas identified by the SPoCA method and used in our previous studies to investigate their evolution at different stages of the 24th and early 25th cycles showed fairly good agreement with the trend of the CH regions identified by the CNN193 over the same period. An initial analysis comparing the dynamics of the CH areas extracted by the SPoCA method and used in our previous works to investigate their evolution at different stages of the 24th and early 25th cycles, has shown fairly good agreement with the dynamics of the CH areas defined by CNN193 over the same period. Both schemes reveal hemispheric asymmetry in the generation of CHs both in time and amplitude.

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