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The impact of coronal hole characteristics and solar cycle activity in reconstructing coronal holes with EUHFORIA

E Asvestari^{1,2}, S G Heinemann¹, M Temmer¹, J Pomoell², E Kilpua², J Magdalenic³ and S Poedts⁴

¹IGAM/Institute of Physics, University of Graz, Universitätsplatz 5/II, A-8010 Graz, Austria

²Department of Physics, University of Helsinki, P.O. Box 64, FI-00014 Helsinki, Finland

³Solar-Terrestrial Centre of Excellence—SIDC, Royal Observatory of Belgium, 1180 Brussels, Belgium

⁴Centre for mathematical Plasma Astrophysics (CmPA), KU Leuven, 3001 Leuven, Belgium

E-mail: eleanna.asvestari@helsinki.fi

Abstract. Modelling with high accuracy the open magnetic field and the fast solar wind in the heliosphere is essential for space weather forecasting purposes. Primary sources of open magnetic field flux are Coronal Holes (CH), uni-polar regions that appear as dark patches in the solar corona when observed in X-ray and extreme-ultraviolet (EUV) images due to having significantly lower density and temperature to their surroundings. Therefore, when assessing how well the open magnetic field and the fast solar wind are modelled one can look at how well the model performs on one of its fundamental functions, that of reconstructing coronal hole areas. In this study we investigate how the CH morphology (i.e. latitudinal position of the centre of mass, area, intensity, elongation) and the solar variability, from high to low activity periods, can affect the results. We also investigated the possibility that the model is reconstructing CHs that are systematically shifted with respect to their observed position. The study is applied on 15 CHs exhibiting different latitudinal position and geometry. We compare the modelled CH areas with boundaries obtained by remote sensing EUV observations using the CATCH tool (Collection of Analysis Tools for Coronal Holes). We found no apparent effect of the CH characteristics on the modelling capabilities. In addition, solar cycle activity seems not to have any effect either. However, we emphasize that our sample is small and this outcome highlights the need for an extended research.

1. Introduction

Space weather can have a strong socioeconomic impact and accurate predictions of solar transient phenomena, such as Coronal Mass Ejections (CME) and solar energetic particles, that can impact Earth and human activity in space and on ground, have become essential. This has led to the development of physics-based forecasting tools such as ENLIL [1] and EUHFORIA (EUropean Heliospheric FORecasting Information Asset) [2]. However, these tools have limitations both in accurately modelling the background interplanetary conditions (i.e. solar wind and interplanetary magnetic field), as well as, CME transients. Some identified limitations include the accuracy of predicting CME arrival times [3], high-speed solar wind stream arrival times and speeds [4] based on Coronal Hole (CH) area reconstructions [5].



Forecasting tools often divide the Sun-to-Earth space in two domains: the coronal domain, which extends from the solar surface up to $21.5R_{\odot}$, and the heliosphere domain, from $21.5R_{\odot}$ to Earth and beyond. To reconstruct the solar wind plasma conditions and the magnetic field configuration in the corona the most commonly employed model is the Wang - Sheeley - Arge (WSA) [6, 7, 8]. The magnetic field configuration employed by the WSA model consists of the coupled Potential Field Source Surface (PFSS) [9, 10] and the Schatten Current Sheet (SCS) [11] models, that model the inner and outer corona respectively. In these models there are two important free parameters that can have an impact on the modelled results. These are the height R_{ss} of the outer boundary of the PFSS model, which is called the source surface, and the height R_i of the inner boundary of the SCS model. The boundary conditions at R_i are provided by the PFSS solution there. Although, in the traditional WSA $R_{ss} = R_i$, [12] showed that this leads to unrealistic results due to the magnetic field solution of PFSS being purely radial at R_{ss} whereas the SCS model is not. To deal with this discrepancy they placed R_i below R_{ss} . The default values of $[R_i, R_{ss}]$ are taken to be $[2.3, 2.6]R_{\odot}$ [12]. This improved WSA version is also adopted in EUHFORIA model [2].

A study carried out recently [5] showed that the WSA model, using the default pair of model boundary heights, strongly underestimates CH areas, while lowering the heights showed improvement of the result. CHs are regions of relatively low density and temperature on the Sun. They are considered to be sources of high speed solar wind and open field lines, which are stretched outwards forming the interplanetary magnetic field. Discrepancies in modelling CHs will lead to poor predictions of high-speed solar wind streams. Therefore, it is important to understand the causes of the model discrepancies and explore possible ideas that can improve the results.

In this work we run EUHFORIA for 15 CHs (same sample used in [5]) using the default values for the heights, and we compare the reconstructed CH areas to those extracted using CATCH (Collection of Analysis Tools for Coronal Holes) [13]. We divide our CH sample in sub-groups based on their apparent characteristics (area, latitudinal location, elongation, and intensity) and we search for trends between the model efficiency and the CH characteristics. In addition, the impact of the solar activity on the model's robustness is investigated. Lastly, we assess the possibility of model reconstructed CH areas being systematically shifted with respect to their expected position on the solar surface as indicated by EUV observations. The methodologies followed are given in Sec. 2, while, the results are analysed in Sec. 3.

2. Data and methodologies

We employed the same set of 15 CHs as in [5]. The sample consists of CHs lying within the central meridional zone of the Sun as seen from Earth covering both low and mid latitudes. High latitude CHs, i.e. polar CHs, were not considered due to strong line-of-sight effects and also the problem of having only the part of the CH that faces Earth being visible in EUV images at a certain time. Despite that, one CH that extends over a wide latitudinal range and is connected to a polar CH is included in the sample. CHs of different morphological features such as area, elongation, and orientation have been considered. The selected CHs were observed throughout the years 2012 - 2017 covering the extended solar maximum of the solar cycle 24 and its descending phase all the way to the current minimum in 2017. Thus the sample covers a range of high, average, and low activity of the Sun. The variety in the sample provides grounds for assessing the impact of the CH morphology and of the solar activity in the robustness of the model.

To run EUHFORIA we need to select as input a magnetogram, which provides the radial component of the magnetic field on the solar surface. We used synchronic magnetograms provided by the Global Oscillation Network Group (GONG) and used as input in the Air Force Data Assimilative Photospheric flux Transport (ADAPT) model

(ftp://gong.nso.edu/adapt/maps/gong/) [14, 15]. Magnetograms are selected for the specific date-times when each CH lies within the central meridional zone. With that magnetogram as input we run EUHFORIA with the default setup, where the pair of modelling boundary heights is $[2.3, 2.6]R_{\odot}$. The model output represents the magnetic field configuration throughout the solar corona. To define CH areas in the modelled results we segregate the solar surface with a mesh having resolution of 2×2 degrees per pixel. A field line is traced for each such pixel on the solar surface upwards towards the source surface. For those field lines that pierce through and stretch beyond the source surface, and are thus open, the pixel is assigned as an open field pixel. Areas of concentrated open field pixels define modelled reconstructed CH areas. An example of a EUHFORIA generated map of open-closed field areas is given in Fig. 1.

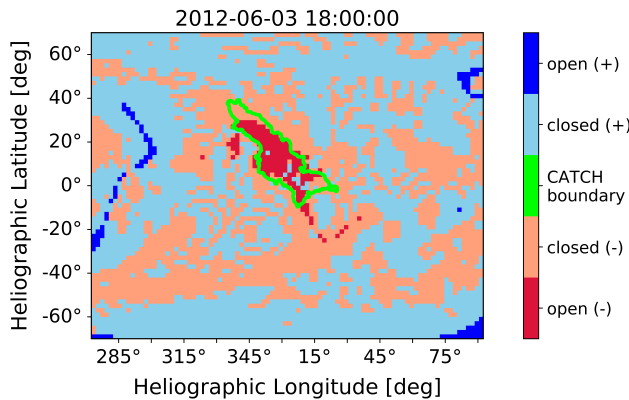


Figure 1. An example of a EUHFORIA generated open-closed field map. Dark colours indicate open flux of positive (blue) and negative (red) magnetic polarity, while light colours mark closed coronal magnetic structures of positive (light blue) and negative (pale orange) polarity. On top of the map the boundaries of the CHs obtained from the EUV images with CATCH are overplotted (green).

The location and area of the modelled CHs were compared with remote sensing observations. For that purpose we employed CATCH to extract boundaries of observed CHs from EUV images at a wavelength of 193 \AA obtained with the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamic Observatory (SDO) [13, and references there in]. These full disc images are available from the Joint Science Operation Center (JSOC). In addition, using CATCH we calculated the latitudinal position of the centre of mass of each CH, as well as, their area in 10^{10} km^2 , and their intensity in counts [DN]. An example of a CH boundary extracted with CATCH is given in Fig. 1 in lime colour, where the boundary is over-plotted on top the EUHFORIA generated map.

Using the CH boundaries extracted from observations we assessed how well the model reconstructs the geometry and location of CHs. That was done by considering the total number of pixels of the EUHFORIA generated map which are enclosed by the CH EUV boundaries, N_{tep} , and the number of enclosed pixels that are correctly modelled as open field ones, N_{ofp} . We define this way the coverage which is given by:

$$coverage = \frac{N_{ofp}}{N_{tep}} * 100[\%] \quad (1)$$

High coverage percentage indicates a good correspondence between the modelled open field area and the CH determined from EUV observations with CATCH, while low coverage suggests a poor match between the modelled and observed CH.

3. Results

Model runs based on the default pair of heights $[R_i, R_{ss}]$ resulted in underestimated CH areas. This is characterised by a coverage value below 60% for the vast majority of the CHs which can be seen in Fig. 2. Although, the coverage value is low the result is better for some CHs comparing to others. This suggests that CHs characteristics might have an effect on the modelled

results. In Fig. 2, the sample is divided into subgroups depending on the latitudinal position of the centre of mass of the CHs. Low-latitude CHs have a centre of mass located within $[-30, 0]$ south and $[0, 30]$ degrees north of the solar equator. Mid-latitude CHs include those whose centre of mass lies within $[-60, -30]$ degrees south and $(30, 60]$ degrees north. Low-latitude CHs are represented with blue/magenta circles, while mid-latitude ones are represented with green/pink diamonds for southern/northern hemisphere CHs. No high-latitude (polar) CHs were considered to reduce problems generated from line-of-sight observations. As can be seen in the figure the scattering of points indicate that the latitudinal position does not affect the model robustness.

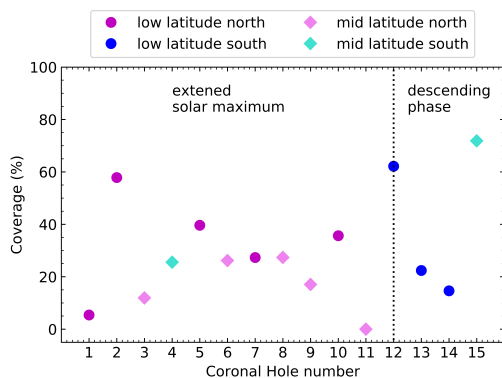


Figure 2. Coverage value obtained for each CH. The x-axis is the nominal number of the CH. The results are divided into subgroups based on the latitudinal position of the CH centre of mass as indicated in the legend.

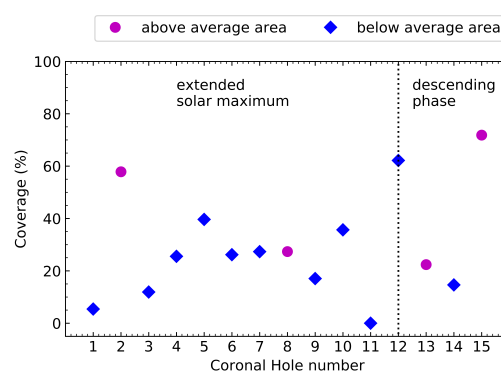


Figure 3. Coverage value obtained for each CH. In this case the results are divided into subgroups based on the area of the CH with respect to the average area of the sample as indicated in the legend.

The second CH characteristic that we consider is the CH area. To assess whether the CH size has an effect in the modelling capability we considered the average area of the sample and grouped the CHs to those that have areas above average and below average (magenta circles and blue diamonds respectively in Fig. 3). It is clear from Fig. 3 that the area does not show any correlation to the coverage. Thus, it can be concluded that the model does not show preference in modelling CHs of a particular size. The possibility of two CH characteristics having a coupled effect on the CH modelling was also assessed, but no such correlation could be determined for the considered set of CHs. Similar results can be inferred when the elongation and the intensity of the CHs were considered.

In order to determine whether the overall activity of the Sun, which is imprinted in the magnetograms used for running the code, could affect how well the model will reconstruct CH areas we divided the CHs into groups based on whether they existed during the ascending, maximum or descending phase of the activity cycle of the Sun. Our sample covers only the maximum and descending phase of solar cycle 24, periods marked by high, gradually declining and very low activity. In the same Fig. 2 - 3, one can see the plots are divided into two zones, the one on the left is related to the extended solar maximum of solar cycle 24, and the one on the right to its descending phase. The coverage is not consistently better during one period comparing to the other which suggests that the result is not modulated by the solar cycle.

For some CHs, visual inspection of the EUHFORIA output of open-closed field maps indicated that the modelled CH areas might be shifted with respect to the areas extracted from EUV observations. One such example is given in Fig. 4, where the modelled CH area appears to be shifted towards the south-west of the solar surface. To assess the possibility of systematically

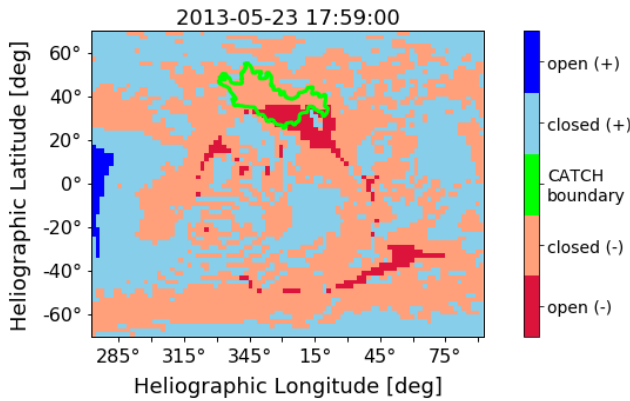


Figure 4. An example of a EUHFORIA generated open-closed magnetic field map based on the default values for the heights where the CH appears shifted as compared to the EUV extracted boundaries. The colour scheme is the same as in Fig. 1.

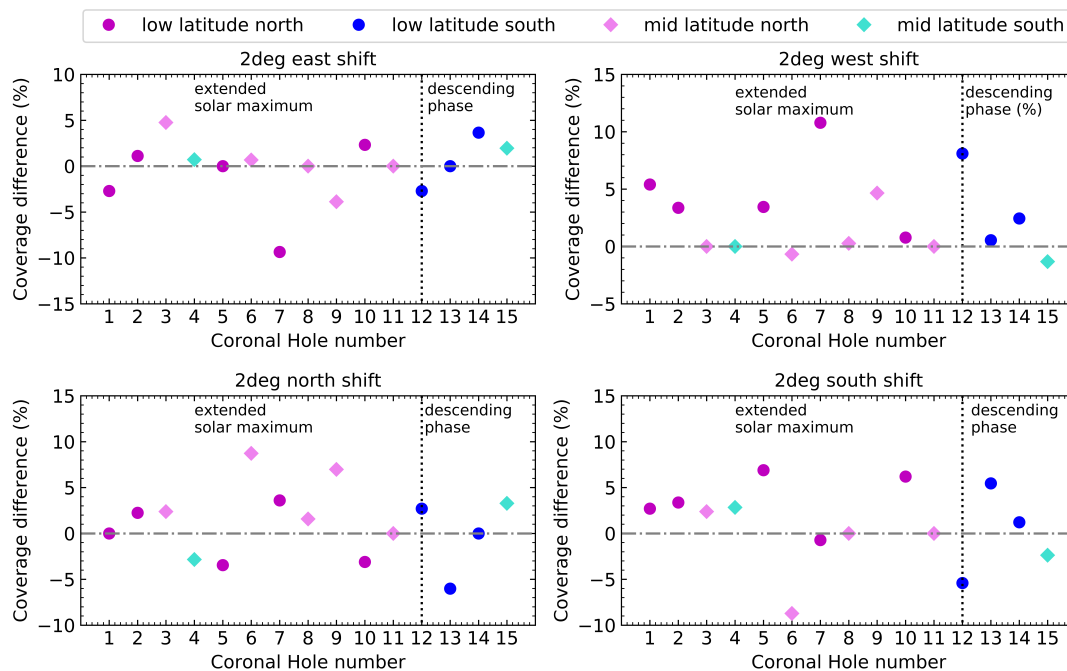


Figure 5. Coverage difference between the expected and the possibly shifted position in order to asses for the possibility of a systematically shifted reconstructed CH with respect to the latitudinal position of the centre of mass of the CH.

shifted modelled CHs we examined whether the coverage is improved for a 2 degrees shift to all four orientations independently (eastward, westward, northward, and southward). Instead of shifting the modelled map, which is a more complicated task, we applied the shifting to the boundaries extracted from EUV observations and recalculated the coverage. If the difference between the coverage obtained for the true position and the new shifted position is positive, we conclude that the modelled reconstructed the CH shifted to that direction, while if it is negative then no shifting to that direction is expected. The results are given in Fig. 5 which presents the coverage difference between the one calculated for the originally modelled position and for the shifted position. If there was a systematic offset of the modelled output towards one direction it is expected that the coverage difference would systematically be positive. However, there is no such trend which concludes that the model does not systematically shift CHs in a particular direction. We tried to divide the CHs based on their characteristics (i.e., latitudinal position

of the centre of mass, area, intensity and elongation) and see whether there is a systematic shifting for a particular group of CHs. In Fig. 5 the CHs are grouped based on the latitudinal position of their centre of mass, however, grouping CHs based on the other characteristics was also considered. We can conclude that the model results do not show any systematic shifting for CHs bearing specific characteristics either.

4. Conclusions

In this study we focused on investigating whether CH characteristics, and the solar cycle variability can have an effect on the modelling capabilities of the adopted WSA model by EUHFORIA when used for reconstructing CH areas. We focused on the model output obtained based on the default values for the model input parameters. This means that the height of the inner boundary of the SCS model and the source surface height are $[2.3, 2.6]R_{\odot}$ respectively. To assess the model output we compared the areas of open field, that are expected to represent the particular CH under study, with the boundaries of the CH extracted with CATCH using EUV imaging observations. We found that the performance of the model is low, with coverage below 60%, however, it is unrelated to the CH characteristics and the solar activity cycle. We also eliminate the possibility that the model systematically reconstructs shifted CHs with respect to their observed position. It is important, however, to stress that our sample consists only of 15 CHs and extends only over the second half of solar cycle 24. This minimises the statistical significance of the results, and highlights the importance of repeating such investigation with a larger sample that extends over at least the whole solar cycle 24.

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