Testing the background solar wind modelled by EUHFORIA

Jürgen Hinterreiter\textsuperscript{1,2} · Jasmina Magdalenic\textsuperscript{3} · Manuela Temmer\textsuperscript{2} · Christine Verbeke\textsuperscript{4} · Immanuel Christopher Jeberaj\textsuperscript{3,4} · Evangelia Samara\textsuperscript{3,4} · Eleanna Asvestari\textsuperscript{2,5} · Stefaan Poedts\textsuperscript{4} · Jens Pomoell\textsuperscript{5} · Emilia Kilpua\textsuperscript{5} · Luciano Rodriguez\textsuperscript{3} · Camilla Scolini\textsuperscript{3,4} · Alexey Isavnin\textsuperscript{4}

\textsuperscript{1} Space Research Institute, Austrian Academy of Sciences, Graz, Schmiedlstraße 6, 8042 Graz, Austria
\textsuperscript{2} Institute of Physics, University of Graz, Universitätsplatz 5, 8010 Graz, Austria

\textsuperscript{3} arXiv:1907.07461v1  [astro-ph.SR]  17 Jul 2019

SOLA: Paper_Euhforia.tex; 18 July 2019; 0:35; p. 1
Abstract In order to address the growing need for the more accurate space weather predictions, a new model named EUHFORIA (EUropean Heliospheric FORecasting Information Asset) was recently developed (Pomoell and Poedts, 2018). We present the first results of the solar wind modeling with EUHFORIA and identify possible limitations of its present setup. Using the basic EUHFORIA 1.0.4. model setup with the default input parameters, we modeled background solar wind (no coronal mass ejections) and compared obtained results with ACE, in situ observations. For the need of statistical study we developed a technique of combining daily EUHFORIA runs into continuous time series. Using the combined time series we performed statistical study of the solar wind for years 2008 (low solar activity) and 2012 (high solar activity) with the focus on the in situ speed and density. We find for the low activity phase a better match between model results and observations compared to the considered high activity time interval. The quality of the modeled solar wind parameters is found to be very variable. Therefore, to better understand obtained results we also qualitatively inspected characteristics of coronal holes, sources of the studied fast streams. We discuss how different characteristics of the coronal holes and input parameters to EUHFORIA influence the modeled fast solar wind, and suggest the possibilities for the improvements of the model. SOLA_keyword_list.txt.

Keywords: Flares, Dynamics; Helicity, Magnetic; Magnetic fields, Corona

1. Introduction

The solar wind is a continuous flow of charged particles propagating radially outward from the hot corona of the Sun into interplanetary space. The speed measured at 1 AU distance range covers a range of 300 to 800 km s$^{-1}$ consisting of slow solar wind and of high speed solar wind streams. The sources of the slow solar wind are closed magnetic field regions, coronal loops, active regions, coronal hole (CH) boundaries, but also streamers and pseudostreamers (Cranmer, Gibson, and Riley, 2017). On the other hand, fast solar wind emanates from open magnetic field regions, CHs, along which ionized atoms (mainly protons and alpha-particles) and electrons may easily escape to interplanetary space. CHs are rather localized regions of low density and low temperature in the solar corona that are slowly evolving and may persist for several solar rotations (Schwenn, 2006). Compared to the hot quiet surrounding corona, CHs appear as dark features most prominently observed in the EUV wavelength channels.
Statistical study of the solar wind modeling with EUHFORIA. I. The basic setup and default input parameters (e.g., 193 Å). With the evolution of a CH over time, also associated, the in-situ measured solar wind parameters can change (Heinemann et al., 2018 e.g.). However, where exactly within the CH the high speed component of the solar wind gets accelerated is not well understood and is a subject of numerous studies. The statistical studies have shown that the equatorial parts of CHs are the main contributors to the fast solar wind streams measured at Earth (see e.g., Karachik and Pevtsov, 2011; Hofmeister et al., 2018). In general it is the morphology, area and location of CHs that play a major role in the duration of the stream and its impact level (e.g., Vršnak, Temmer, and Veronig, 2007; Garton, Murray, and Gallagher, 2018). The high speed streams interact with the slower solar wind ahead causing compression regions that can lead to geomagnetic storms. It is well acknowledged that during the maximum phase of the solar cycle space weather is affected mostly by transient events (like coronal mass ejections), however, during the declining and minimum activity phases high speed streams have significant impact (Tsurutani et al., 2006). High speed solar wind streams also strongly structure interplanetary space which is an important factor when studying and forecasting the propagation behavior of coronal mass ejections.

Models simulating the background solar wind are based on various methods, e.g., numerical algorithms such as ENLIL (Odstrcil and Pizzo, 1999) or MAS (Linker et al., 1999) using synoptic magnetic field maps as input, empirical relations between observed areas of coronal holes and measured solar wind speeds at 1 AU (Vršnak, Temmer, and Veronig, 2007; Rotter et al., 2012), or simple persistence models using in-situ measurements shifted forward by variable timespans which are depending on the spacecraft location (e.g. Opitz et al., 2009; Owens et al., 2013). The performances of all the different solar wind models in comparison to actual measurements, reveal on average root-mean-square-errors of around 100–150 km s\(^{-1}\) and time shifts in the arrival of the peak speed of about ±1 d and up to ±3 d (see e.g., Owens et al., 2008; MacNeice, 2009; Greßl et al., 2014; Reiss et al., 2016; Jian et al., 2015; Temmer, Hinterreiter, and Reiss, 2018). In general, model performances decrease for increased solar activity phases as frequent disruptions strongly disturb interplanetary space that cannot be covered by model inputs coming from solar surface observations.

In order to address the growing need for more accurate space weather predictions, a new model named EUHFORIA (EUropean Heliospheric FORecasting Information Asset) was recently developed (Pomoell and Poedts, 2018). In the following we present the first performance testing of the solar wind model identifying possible caveats related to complex solar surface situations.

2. Solar wind modeling with EUHFORIA

EUHFORIA is a physics-based simulation tool consisting of three essential parts: a coronal model, a heliospheric model and an eruption model. The main purpose of the coronal model is to provide realistic plasma conditions of the solar wind at the interface radius \(r = 0.1\) AU between the coronal and heliospheric model. The heliospheric model computes the time-dependent evolution of the plasma from the interface radius by numerically solving the MHD equations with the
boundary conditions provided by the coronal model. For simulating transient
events, coronal mass ejections are injected at the interface radius of the eruption
model. Presently EUHFORIA has a lot of similarities to another state-of-the-art
solar wind/ICME model for the inner heliosphere, i.e. WSA-ENLIL (Odstrcil,
Riley, and Zhao, 2004). However, an important new feature of EUHFORIA is
its flexibility. The three models, heliospheric, coronal and eruption one are fully
autonomous and each part of EUHFORIA can be easily substituted with other
model (more details can be found in Pomoell and Poedts, 2018; Scolini
et al., 2018). In contrast to ENLIL, which gives the background solar wind parameters
for a full Carrington rotation, EUHFORIA provides daily runs from hourly
updated standard synoptic GONG magnetograms. In this way the central part
of the magnetogram, used by EUHFORIA, is daily updated. For the purpose
of the statistical studies and easier comparison with in situ observations we
combine daily runs in order to obtain single time series (for detailed description
see Section 2.2).

In the present study we used EUHFORIA 1.0.4 version of the model, and we
focus on the coronal and heliospheric model, in order to understand how well
EUHFORIA models the background solar wind. For the testing, we considered
two phases of solar activity, one year during minimum in 2008 and another year
during maximum in 2012.

2.1. The input parameters and set up of EUHFORIA

As this is the first study of the solar wind modeling with EUHFORIA, we
employed so called default set up of EUHFORIA and default input param-
eters. For the coronal part of EUHFORIA we use synoptic magnetograms from
the Global Oscillation Network Group (GONG), and the potential field source
surface (PFSS) model (Altschuler and Newkirk, 1969) to simulate the magnetic
field up to heights of 2.6 solar radii (so called source surface height). This is
combined with the Schatten current sheet (SCS) model (Schatten, Wilcox, and
Ness, 1969) starting from the height of 2.3 solar radii. The overlap of the two
models provides a smooth transition at their boundary (see Pomoell and Poedts,
2018; McGregor et al., 2008). To characterize the solar wind plasma parameters
at its inner boundary we have used the modified empirical Wang-Sheely-Arge
model (Arge et al., 2003).

In EUHFORIA the solar wind speed depends on several parameters and its
functional form can be selected by the user. In this study we have employed
the expression (2) from Pomoell and Poedts (2018), and since the solar wind
continues to accelerate beyond the inner boundary in the MHD model, we have
additionally subtracted 50 km/s, in order to avoid an systematic overestimate
of the wind speed. Further, to compensate for the solar rotation, which is not
included in the magnetic field model, we rotate the solar wind speed map at
the inner boundary for 10 degrees. We have also limited the minimum and
the maximum solar wind speed at the inner boundary to 275 and 625 km/s,
respectively (according to McGregor et al., 2011). The maximum value, i.e.,
the fast solar wind speed of 625 km/s is considered to be in the solar wind
plasma with a magnetic field of 300 nT. The plasma number density, expression
Figure 1. Snapshot of the background solar wind radial speed modeled by EUHFORIA. The top left panel shows the MHD solution in the heliographic equatorial plane, and the right panel shows the meridional plane cut that includes the Earth (blue circle). The lower panel shows comparison of the modeled and observed solar wind by EUHFORIA and ACE, respectively.

(4) in Pomoell and Poedts (2018), is defined through the density of the fast solar wind, which was herein considered to be $300 \text{ cm}^{-3}$ (see e.g. Bougeret et al., Venzmer and Bothmer, 2018, and references therein). We note that the parameter study which is in progress indicates this value to be somewhat large and it might be related to somewhat denser regions of the corona mapped by the radio observations. Please look for reference of the lost paper! In this study we considered constant plasma thermal pressure of 3.3 nPa, at the inner boundary, that is in accordance with the fast solar wind temperature of about 0.8 MK. The angular/radial resolution of the daily runs used in this study was 4/512 degrees, respectively.

The example of the background solar wind speed modeled by EUHFORIA, for the time interval of seven days in March 2008, is presented in Figure 1. Two top panels (the heliographic equatorial and the meridional plane cuts plotted in the left and right panel, respectively) show that the Earth have entered the extended fast flow. The time of the snapshot is also marked by the black vertical line in the bottom panel which shows comparison between the in situ observations and modeled solar wind speed. We note that the modeled solar wind by EUHFORIA very well reproduces the in situ observations (bottom panel of Figure 1).
2.2. Combining individual runs and obtaining EUHFORIA time series

For the background solar wind testing we used EUHFORIA daily runs, i.e., the model outputs with default parameters, and the standard synoptic GONG magnetogram (at about 23:30 UT), for the complete years 2008 and 2012. Each daily run, based on one magnetogram input, simulates the background solar wind at the distance of 1 AU over a time span of 14 days covering $-92.4^\circ$ to $+92.4^\circ$ in longitude (see gray slice in Figure 2) with a temporal resolution of 10 minutes (this includes a solar wind relaxation time of 17 days). The central region of the Sun has the magnetic field information with the smallest projection effects, and is the most reliable part of the magnetogram. To combine the individual runs, we developed a method containing the information coming from the central region of the Sun with main focus on the proximity region around the central meridian (0 degrees) with a range of $\pm 1$ days (see schematic drawing in Figure 2a).

When combining model outputs from consecutive days the individual time series overlap. In order to obtain a smooth time series, each curve is weighted (with a Gaussian distribution) with the central part receiving the strongest weight (see Figure 2b).
Figure 3. Solar wind speed from July to August 2008. Top panel: Full EUHFORIA model output (±7 days). Middle panel: EUHFORIA model output limited to ±1 day. Bottom panel: Model output (different colors for each daily run) and resulting time series (thick red).

In Figure 3, we demonstrate how the method was applied. The top panel of Figure 3 shows the solar wind speed modeled by EUHFORIA for the full model output (±7 days). Different colors represent results for different daily runs. As can be seen, the simulated solar wind speeds for consecutive days may show significant offsets. Therefore, the results are limited to ±1 day (middle panel) and combined using the Gaussian distribution as indicated in Figure 2b. The obtained combined time series can be seen in the bottom panel of Figure 3 indicated by the thick red curve. We also tested different ranges for the individual runs, e.g. ±3 days, in order to check the quality of the method of combining the individual runs. The results show similar, but somewhat more smoothed time series compared to a time range of ±1 days.

We evaluate how the combined time series for the modeled solar wind speed are affected when shifting the central region. With this, we take into account that not the central region of the magnetogram but eastern or western regions influence more strongly the simulated solar wind. Figure 4 shows the results for shifting of the central region. We find that the shifting has more effect on the combined time series than using a longer time range, but we note that the general trend is still retained.

3. Comparison of in-situ observations and modeled solar wind

In order to test the quality of the performance of the model we chose two intervals of different solar activity levels. At first, a quiet period during 2008 is considered,
for which only three interplanetary coronal mass ejections (ICMEs), at the end of the year, were reported. This period can serve as benchmark time interval for the model performance as the solar wind has almost no sporadic fluctuations i.e. faster structures in the slow solar wind. A second considered interval covers the year 2012, a period with rather high level of solar activity during which a number of ICMEs are reported. In order to assess how well EUHFORIA models the solar wind we compare EUHFORIA combined time series with the in-situ observations provided by the Solar Wind Electron, Proton and Alpha Monitor
onboard the Advanced Composite Explorer (SWEPAM/ACE, McComas et al., 1998). The focus of this study is on the comparison of modeled and observed values of the two most important solar wind plasma parameters, i.e. bulk speed and proton density.

Figures 5 and 6 show the results for the years 2008 and 2012. The gray curves represent observed values by ACE (solar wind speed and density), while red and blue curves represent modeled values of the solar wind speed and density, respectively. The presented statistics of the background solar wind modeled with EUHFORIA shows on average significantly lower values of the modeled solar wind speed than the in-situ measured velocity. On the other hand the modeled solar wind density is strongly higher than the observed one. In the present setup of EUHFORIA these two solar wind plasma parameters are coupled, and improved modeling of the solar wind speed will also result in a better modeled solar wind density. We also noticed that the correlation between modeled and observed values is significantly better in the first half of year 2008 (Figure 5).

In the second half of year 2008, the maximum speeds for the fast solar wind speed are not well modeled by EUHFORIA, and also the minimum values are significantly different, i.e., larger than the observed ones. For the year 2012 the discrepancies between the modeled values and observations are even more pronounced. Nevertheless, the lower speed values during 2012 are rather well reproduced, which might be simply a consequence of a very low wind speed in general obtained for this year.

The in-situ solar wind speed, for both studied years, was also compared to the individual daily runs in order to assess the probability of artificially enhanced or reduced fast wind flows due to combining of the daily runs (Section 2.3). In the two studied years we found only one case of the fast solar wind which was observed in the majority of the daily runs but not in the combined time series (around 22 August 2012). The opposite cases, where the combined time series
show significant increase of the solar wind speed that was not modeled in the majority of the relevant daily runs, were not found.

As a consequence of underestimated solar wind speed modeled by EUHFORIA we noticed that the arrivals of the fast flows are systematically shifted to later times, and the amount of shift depends on the difference between the modeled and observed wind speed. For example, the fast solar wind with average speed of 600 km/s will need about 2.9 days to arrive to the Earth, while those of about 500 km/s will need about 3.5 days. In this case the induced latency of modeled solar wind will be about 14 hours. We observe the influence of this effect particularly strong in the second half of the year 2008 (Figure 5).

3.1. Evaluation of modeling results

In order to evaluate the EUHFORIA model performance we present a hit-miss statistics using two different methods for comparing measured and modeled results. We also compare the minimum and maximum phase of the results and give initial results on the effects of different input parameters for the model. In this analysis we focus only on the solar wind velocity.

3.1.1. Hit-miss statistics by automatic peak-peak matching method

To evaluate the model performance, we calculate continuous variables (e.g., RMSE) and apply an event-based approach for detecting the maxima (peak finding algorithm) in the solar wind observations. At first we used the automatic peak finding algorithm. To be defined as a peak, certain properties (min speed = 400 km/s, min gradient = 60 km/s, for further details see Reiss et al., 2016) have to be fulfilled. A hit is found, if the modeled peak appears within a time window of ±2 days around the measured peak, and a miss if the modeled peak is out of this time window. If the peak is found in the combined time series of EUHFORIA and not in observations we consider to have a false alarm.

Since the study encompasses also the year 2012 with the high level of solar activity, it was necessary to isolate intervals with possible ICMEs in the in-situ observations. The vertical pink lines in Figure 7 indicate the times of CME occurrences according to the list of Richardson and Cane (2010). We note that for 2008 only three ICMEs were reported while for 2012 there are 35 reported events.

As can be seen from Figure 7 in 2008 (top panel), 39 solar wind peaks are detected in the EUHFORIA combined time series and 43 in the in-situ data. Applying the automatic peak finding algorithm method, we obtain 18 hits, 21 false alarms and 25 misses. In 2012 (bottom panel in Figure 7), the EUHFORIA combined time series shows 21 peaks and 38 are detected in the in-situ observations. The analysis shows this corresponds to 14 hits, 7 false alarms and 24 misses. As this is a rather poor result we inspect the solar wind profiles (observed and modeled) in more detail and investigate the reason of the poor performance.

3.1.2. Hit-miss statistics by manual peak-peak matching method

The in-situ observations frequently show several subsequent local maxima of the solar wind speed associated with only one single fast flow originating from
Figure 7: EUHFORIA modeled solar wind bulk velocity (blue) in comparison to in-situ measurements (orange) for 2008 (top) and 2012 (bottom) using a peak finding algorithm. The red vertical bars indicate times of CME occurrences according to Richardson and Cane (2010).
The coronal hole is identified using EUV imagery from spacecraft while the polarity of the CH is obtained from magnetograms. b) Detection of the CH on the same day, by the CHIMERA tool (based on three wavelengths 211, 193, 171Å). Image was obtained from Solar Monitor.

Figure 8. a) Drawing of the solar surface features for 2012 May 7 provided by NOAA. The coronal hole is identified using EUV imagery from spacecraft while the polarity of the CH is obtained from magnetograms. b) Detection of the CH on the same day, by the CHIMERA tool (based on three wavelengths 211, 193, 171Å). Image was obtained from Solar Monitor.

usually large and extended, in latitude or in longitude or both, coronal hole. We derived that in such a case the automatic peak finding algorithm finds several peaks and it is not possible to make a one to one identification with the usually smooth increase of the solar wind speed modeled by EUHFORIA. In order to better understand such long lasting flows and to unambiguously relate modeled and observed velocity peaks with each other, we checked the development of the CHs on the Sun two days before and three days after the CH started its transition across the central meridian (Figure 8). For this purpose we analyzed automatic coronal hole areas detected by software CHIMERA (Garton, Gallagher, and Murray, 2018) and coronal hole drawings (see Figure 8).

The in-situ measured peaks of the solar wind speed which we could not relate to their sources observed on the Sun (mostly transients in the slow solar wind) were excluded from the statistical study. As for the automatic method, the intervals corresponding to CME arrivals, reported in a list by Richardson and Cane (2010) and observed in-situ, were excluded from the evaluation. We considered observed and modeled solar wind peaks to be associated, i.e. a hit, if the increase started more or less simultaneously and the peak was achieved within 2 days after the peak as modeled by EUHFORIA. When the modeled solar wind increase did not have the counterpart in the in-situ observations we considered to have a false alarm, and when the observed fast flow was not reproduced by EUHFORIA we consider to have a miss.
The manual identification of the CHs and associated fast flows shows 17 hits, 12 misses and 6 false alarms for 2008 and 13 hits, 18 misses and 0 false alarms for 2012. We note that these results are showing significantly smaller number of false alarms and misses in comparison to the automatic method. This indicates that the CH development and its shape has strong influence on the fast solar wind measured at 1AU.

### 3.1.3. Solar cycle dependence

In Figures 5 and 6 we show that the solar wind modeled by EUHFORIA matches much better for the interval of the minimum solar activity in 2008. This may have several reasons. During the low level of solar activity the magnetic field, the main input for the PFSS extrapolation in EUHFORIA, changes less dynamic than during the high level of solar activity, which can result in a more reliable modeling of the solar wind flow. Also, the interplanetary measurements are not disturbed by transient events which are much less frequent compared to solar maximum activity, and the solar wind flow is more persistent (Owens et al., 2013; Temmer, Hinterreiter, and Reiss, 2018).

Figure 5a shows for 2008 on average rather good model results of the minimum and maximum solar wind speed, and the majority of fast flows associated with equatorial CHs is well reproduced. However, we also found an exception where the in-situ observations show a recurrent fast flow (10 rotations) associated with a well defined equatorial CH which was modeled by EUHFORIA only at the beginning of the year 2008. We believe that modeling of the solar wind originating from this particular CH is highly influenced by the CH characteristics and development in location, size and shape.

During the high level of solar activity the magnetic field is very complex and it is known that the amount of low latitude open flux may be significantly underestimated by the PFSS model (e.g. MacNeice, Elliott, and Acebal, 2011). Underestimating the open flux leads to significantly lower solar wind speeds modeled by EUHFORIA. This effect is very strongly pronounced in 2012 (Figure 6a). We also note for 2012 the existence of large number of low latitude CHs surrounded by active regions which possibly also influences the model performance.

### 3.2. Identified limitations of the basic set up of EUHFORIA

During testing of the modeled background solar wind we identified some limitations of the present version of EUHFORIA which influences its performance. Herein we present some of the limitations of the basic set up of the EUHFORIA 1.0.4 and more detailed analysis will be presented in the follow up paper (Samara et al., in preparations).

#### 3.2.1. The default input parameters of EUHFORIA

In order to set up benchmarks for the solar wind modeling with EUHFORIA we need to understand how different input parameters influence the modeled solar wind.
Figure 9 shows the EUHFORIA model results for the time interval of several days in March 2008, using different input parameters. We vary the resolution of the heliospheric model and the input density of the fast solar wind at the inner boundary compared to the default setting (Section 2.1 herein and Section 2.1.2. in Pomoell and Poedts, 2018). We find that a decrease of the solar wind density by 50% (initial value is 300 cm$^{-3}$ at 21.5Ro) induces an increase of the modeled solar wind speed from several percent up to 15% (absolute value depends on the part of the flow which is considered). Figure 9 also shows comparison of the default, low resolution runs (angular and radial resolution of 4 degrees and 256 cells, respectively) and the intermediate resolution runs (2 degrees and 512 cells, respectively). The higher resolution runs result in the increased solar wind speed (up to about 20%) and in earlier arrival time of the high speed stream at 1AU (even for several hours). If we compare the two extreme cases, the default EUHFORIA runs i.e., low resolution and high density, and the intermediate resolution and low density runs, we find a shift of the arrival time of the fast flow of about -12 hours, and the significant increase of the solar wind speed (from about 6 to more than 40 percent, depending on which part of the fast flow is considered).

The obtained results indicate that the quality of the modeled fast solar wind varies a lot depending on the input parameters to the model. We note that when more than one parameter is modified the solar wind speed changes non-linear and that the changes strongly depend on the considered flow. This brings forward the need for a detailed ensemble parameter study which will provide a well defined benchmark for the solar wind modeling with EUHFORIA (Samara et al., in preparation).

3.2.2. Open flux and the source surface heights

The visual comparison of the CH sizes in the EUV observations, and the GONG synoptic magnetograms, shows that in average the CHs are smaller when observed in magnetograms. We believe that this characteristic induces the error in the solar wind modeling, and in particular when the fast flow originates from the narrow, small and elongated coronal holes. Since the coronal model of
EUHFORIA uses synoptic magnetograms and PFSS, the amount of the modeled open flux will be smaller than in reality, as well as the angular width and extend of the fast flow. This will result not only in the underestimated solar wind speed but also might cause modeled fast flow to completely miss the Earth (Section 3.2.3). First tests show that changing the source surface height (one of the default input parameters) significantly influence the modeled open flux (Asvestari et al., in preparation).

Figure 10. Combined EUHFORIA results in comparison to in-situ data (gray) for the same interval as in Figure 9. Earth (blue curve) represents the EUHFORIA output for the Earth location. The red curve is an average of combined EUHFORIA results for virtual spacecraft (+4, +8, +12 degree) above the Earth and the green curve shows the averaged results for virtual spacecraft (-4, -8, -12 degree) below the Earth.

3.2.3. Dependence on shape and location of CHs

While manually associating the observed and modeled solar wind flows (Section 3.1.2.), we recognized that the EUHFORIA performance is closely related also to the size, shape and location of the CHs, sources of the fast flows.

The qualitative study of the CH characteristics and the quality of the modeled fast solar wind (Section 2.1) shows that in a case of a well defined, not very elongated, compact, circular and equatorial CHs, and during the low level of solar activity, EUHFORIA models well the associated fast flows. However, the fast flows associated with narrow CHs elongated in longitude are rarely reproduced by EUHFORIA. In the case of the narrow CHs elongated in latitude, the modeled solar wind is mostly underestimated, hence, leading to a late arrival at the Earth. And when the solar wind is originating from the low/high latitude CHs (greater than ±30 deg) and/or the extensions of the polar CHs, it will be rarely reproduced correctly by EUHFORIA. We also noticed that fast flows associated with patchy CHs, irrespective of their latitudes and longitudes, are poorly reproduced or not reproduced at all by EUHFORIA.

Further on, the fast flows originating from the low latitude coronal holes might pass 'bellow' or 'above' the Earth (when the associated CHs are situated at the southern or northern solar hemisphere, respectively) and they will not be observed in the EUHFORIA time series output at the Earth. In order to check this hypothesis we have implemented virtual spacecraft around the Earth (separated by 4 degrees ranging from −12 to +12 degrees in latitude where 0 degrees indicates Earth position) and compared the modeled time series for
all these spacecraft. To amplify the effect, the values of time series at +4, +8, +12 degrees above the Earth and -4, -8, -12 degrees below the Earth were averaged and compared to in-situ data (see Figure 10). We note that the fast flow, starting on March 09, 2008 seem to be reproduced well by EUHFORIA, by all three time series, i.e. above the Earth, at the Earth and below the Earth. This gives indications on the 3D extent of the fast flow that directly impacted the Earth, which is also visible on the Figure 1 right top panel. The solar wind observed starting from March 19 (Figure 10) originates from rather large low latitude extensions of the southern polar coronal hole. EUHFORIA models at the Earth somewhat faster solar wind then observed by ACE (blue curve), and significantly faster solar wind passing below the Earth (green curve). In this case the fast flow only glanced the Earth while the main part of the fast solar wind passed below the Earth. Studies of the 3 dimensional extent of the fast flows, using the virtual spacecrafts, is among the main ongoing efforts for improving our knowledge on the solar wind and solar wind modeling with EUHFORIA (Samara et al., in preparation).

4. Summary and Conclusions

In this paper we present the first results of the solar wind modeling with new European model EUHFORIA. For the statistical study we employed so called basic set up of EUHFORIA 1.0.4. and default input parameters (Section 2.1). EUHFORIA currently provides daily modeled results using synoptic GONG magnetograms. In order to obtain a continuous time series of the background solar wind parameters, the model outputs from consecutive days have to be combined. We developed a method to derive such a continuous profile from individual runs taking only the central part of the individual curves and combining them using a Gaussian weighting (Section 2.2).

We test the quality of the performance of EUHFORIA in solar wind modeling by selecting two years of different solar activity levels, i.e. 2008 and 2012. The analysis was focused to the comparison of the modeled solar wind for the two most important solar wind plasma parameters, i.e. bulk speed and proton density, and ACE observations (Figures 5 and 6). As a general trend we notice significant underestimation of the modeled solar wind speed and overestimation of the modeled density, in comparison with in situ observations by ACE. The solar wind modeled by EUHFORIA matches better for the interval of the minimum solar activity in 2008, then for the year 2012 when the level of solar activity was high. We conclude that this results mostly from the better performance of the PFSS (main part of the EUHFORIA’s coronal model) during the low level of the solar activity.

For defining the association between modeled and observed fast flows we applied an automatic peak finding algorithm (Section 3.1.1). Using this algorithm we obtain 18 hits, 21 false alarms and 25 misses for 2008 and 14 hits, 7 false alarms and 24 misses for 2012. As a consequence of frequently underestimated solar wind speed modeled by EUHFORIA, arises also the uncertainty in the modeled arrival time of HSSs. Moreover, fast flows can show several wind speed
Statistical study of the solar wind modeling with EUHFORIA. I. The basic setup and default input parameters

maxima for just a single flow and this additionally restricts the automatic peak finding algorithm in finding the correct matching pairs. By visual inspection (Section 3.1.2) we took into account all these characteristics and assign more reliably the modeled and measured solar wind flow pairs, and obtained better statistics of 7 hits, 6 false alarms, and 12 misses for 2008 and 13 hits, 0 false alarms, and 18 misses for 2012.

Our statistical results show that the quality of the modeled fast solar wind, obtained using the basic set up of EUHFORIA and the default input parameters, can be very variable. Herein we presented some of the limitations of this set up and detailed analysis will be presented in the follow up papers (Samara et al., Asvestari et al., in preparation). In order to understand how different input parameters to EUHFORIA influence the modeled solar wind we have started the parameter studies. We found that the increase of the angular resolution from 4 to 2 degrees can result in the up to 20 percent solar wind speed increase and an earlier arrival of the fast solar wind, even up to several hours. Additionally, as expected high resolution runs show significantly more structures in the solar wind in comparison with the low resolution one. We also tested how the decrease of the fast solar wind density from $300 \text{ cm}^{-3}$ to $150 \text{ cm}^{-3}$ influences the modeled solar wind and found that in the case of the lower input density EUHFORIA will model earlier arrival and larger amplitudes of the fast solar wind (Section 3.2.1.)

The visual inspection of the CHs associated to the fast flows indicates, that the shape and the location of the CHs play an essential role in the model performance (Section 3.2.3). We found that patchy, elongated and narrow CHs are not well seen by EUHFORIA’s coronal model (i.e. PFSS does not see the open flux), which results in a poor model performance. We also found that the high latitude (> 30°) CHs, often extensions of the polar coronal holes, may be responsible that EUHFORIA models the fast flow above or bellow the Earth (in a case of CHs on the northern and southern solar hemisphere, respectively). Therefore, it is very important to have EUHFORIA set up with included virtual spacecraft for all the future studies of the solar wind modeling by EUHFORIA. This will allow us to estimate the 3D extend of the fast flows and to understand if the fast flow just missed the Earth, passing bellow or above it (Section 3.2.3).

In the herein presented studies we identified some of the limitations of the present version of EUHFORIA 1.0.4. which influences its performance, in particular during the high level of solar activity. We found that the dynamic behaviour of the CHs, together with the complex coronal magnetic field has a major role in the generation and propagation of the fast solar wind. Due to the complexity of the solar atmosphere modeling of the fast solar wind is very demanding task. Herein we presented first attempts to model background solar wind with EUHFORIA, identified some of the limitations of the present set up of the model and presented first example of the parameter studies. The presented results brings forward the need for a detailed ensemble parameter study which will provide a clear benchmark for the solar wind modeling with EUHFORIA, but which goes beyond the scope of this paper. The parameter studies, which and presently ongoing in the framework of the CCSOM project (http://www.sidc.be/ccsom/), will help us not only to improve modeling of the solar wind with EUHFORIA but also to improve EUHFORIA itself.
Acknowledgments  The authors thank ... (note the reduced point size) M.T. acknowledges the support by the FFG/ASAP Program under grant No. 859729 (SWAMI). .... To change a title use an optional parameter:
\begin{acks}\[Acknowledgements]\ldots\end{acks}

References

Altschuler, M.D., Newkirk, G.: 1969, Magnetic Fields and the Structure of the Solar Corona. I: Methods of Calculating Coronal Fields. Solar Phys. 9, 131. \DOIA [altschuler69]

Arge, C.N., Odstrcil, D., Pizzo, V.-J., Mayer, L.R.: 2003, Improved Method for Specifying Solar Wind Speed Near the Sun. In: Velli, M., Bruno, R., Malara, F., Buccı, B. (eds.) Solar Wind Ten, American Institute of Physics Conference Series 679, 190. \DOIA [arge03]

Cranmer, S.R., Gibson, S.E., Riley, P.: 2017, Origins of the Ambient Solar Wind: Implications for Space Weather. Space Sci. Rev. 212, 1345. \DOIA [cranmer17]

Garton, T.M., Gallagher, P.T., Murray, S.A.: 2018, Automated coronal hole identification via multi-thermal intensity segmentation. Journal of Space Weather and Space Climate 8(27), A02. \DOIA [garton18_1]

Garton, T.M., Murray, S.A., Gallagher, P.T.: 2018, Expansion of High-speed Solar Wind Streams from Coronal Holes through the Inner Heliosphere. Astrophys. J. Lett. 869, L12. \DOIA [garton18_2]

Gressl, C., Veronig, A.M., Temmer, M., Odstrcil, D., Linker, J.A., Mikić, Z., Riley, P.: 2014, Comparative Study of MHD Modeling of the Background Solar Wind. Solar Phys. 289, 1783. \DOIA [gressl14]

Heinemann, S.G., Temmer, M., Hofmeister, S.J., Veronig, A.M., Vennerstrom, S.: 2018, Three-phase Evolution of a Coronal Hole. I. 360° Remote Sensing and In Situ Observations. Astrophys. J. 861, 151. \DOIA [heinemann18]

Hofmeister, S.J., Veronig, A., Temmer, M., Vennerstrom, S., Heber, B., Vršnak, B.: 2018, The Dependence of the Peak Velocity of High-Speed Solar Wind Streams as Measured in the Elliptic by ACE and the STEREO satellites on the Area and Co-latitude of Their Solar Source Coronal Holes. Journal of Geophysical Research (Space Physics) 123, 1738. \DOIA [hofmeister18]

Jian, L.K., MacNeice, P.J., Taktakishvili, A., Odstrcil, D., Jackson, B., Yu, H.-S., Riley, P., Sokolov, I.V., Evans, R.M.: 2015, Validation for solar wind prediction at Earth: Comparison of coronal and heliospheric models installed at the CCMC. Space Weather 13, 316. \DOIA [jian16]

Karachik, N.V., Pevtsov, A.A.: 2011, Solar Wind and Coronal Bright Points inside Coronal Holes. Astrophys. J. 735, 47. \DOIA [karachik11]

Linker, J.A., Mikić, Z., Biesecker, D.A., Forsyth, R.J., Gibson, S.E., Lazarus, A.J., Lecinski, A., Riley, P., Szabo, A., Thompson, B.J.: 1999, Magnetohydrodynamic modeling of the solar corona during Whole Sun Month. J. Geophys. Res. 104, 9809. \DOIA [linker99]

MacNeice, P.: 2009, Validation of community models: Identifying events in space weather model timelines. Space Weather 7, S06004. \DOIA [maceface09]

MacNeice, P., Elliott, B., Acebal, A.: 2011, Validation of community models: 3. Tracing field lines in heliospheric models. Space Weather 9, S10003. \DOIA [maceface11]

McComas, D.J., Bame, S.J., Barker, P., Feldman, W.C., Phillips, J.L., Riley, P., Griffee, J.W.: 1998, Solar Wind Electron Proton Alpha Monitor (SWEPAM) for the Advanced Composition Explorer. Space Sci. Rev. 86, 563. \DOIA [mccomas98]

McGregor, S.L., Hughes, W.J., Arge, C.N., Owens, M.J.: 2008, Analysis of the magnetic field discontinuity at the potential field source surface and Schatten Current Sheet interface in the Wang–Sheeley-Arge model. Journal of Geophysical Research (Space Physics) 113. \DOIA [mcgregor08]

McGregor, S.L., Hughes, W.J., Arge, C.N., Owens, M.J., Odstrcil, D.: 2011, The distribution of solar wind speeds during solar minimum: Calibration for numerical solar wind modeling constraints on the source of the slow solar wind. Journal of Geophysical Research (Space Physics) 116, A03101. \DOIA [mcgregor11]

Odstrcil, D., Riley, P., Zhao, X.P.: 2004, Numerical simulation of the 12 May 1997 interplanetary CME event. Journal of Geophysical Research (Space Physics) 109, A02116. \DOIA [odstrcil2004]
Odstrčil, D., Pizzo, V.J.: 1999, Three-dimensional propagation of CMEs in a structured solar wind flow: 1. CME launched within the streamer belt. J. Geophys. Res. 104, 483. [DOI] ADS [odstrcil99]

Opitz, A., Karrer, R., Wurz, P., Galvin, A.B., Bochsler, P., Blush, L.M., Daoudi, H., Ellis, L., Farrugia, C.J., Giammanco, C., Kistler, L.M., Klecker, B., Kucharek, H., Lee, M.A., Möbius, E., Popecki, M., Sigrist, M., Simunac, K., Singer, K., Thompson, B., Wimmer-Schweingruber, R.F.: 2009, Temporal evolution of the solar wind bulk velocity at solar minimum by correlating the stereo a and h plastic measurements. Solar Phys. 256(1), 365. [DOI] https://doi.org/10.1007/s11207-008-9304-7. [opitz09]

Owens, M.J., Spence, H.E., McGregor, S., Hughes, W.J., Quinn, J.M., Arge, C.N., Riley, P., Linker, J., Odstrcil, D.: 2008, Metrics for solar wind prediction models: Comparison of empirical, hybrid, and physics-based schemes with 8 years of L1 observations. Space Weather 6, S08001. [DOI] ADS. [owens08]

Owens, M.J., Challen, R., Methven, J., Henley, E., Jackson, D.R.: 2013, A 27 day persistence model of near-Earth solar wind conditions: A long lead-time forecast and a benchmark for dynamical models. Space Weather 11, 225. [DOI] ADS [owens13]

Pomoell, J., Poedts, S.: 2018, EUHFORIA: European heliospheric forecasting information asset. Journal of Space Weather and Space Climate 8(27), A35. [DOI] ADS [pomoell18]

Reiss, M.A., Temmer, M., Veronig, A.M., Nikolic, L., Vennerström, S., Schöngassner, F., Hofmeister, S.J.: 2016, Verification of high-speed solar wind stream forecasts using operational solar wind models. Space Weather 14, 495. [DOI] ADS [reiss16]

Richardson, I.G., Cane, H.V.: 2010, Near-Earth Interplanetary Coronal Mass Ejections During Solar Cycle 23 (1996 - 2009): Catalog and Summary of Properties. Solar Phys. 264, 189. [DOI] ADS [richardson10]

Rotter, T., Veronig, A.M., Temmer, M., Vršnak, B.: 2012, Relation Between Coronal Hole Areas on the Sun and the Solar Wind Parameters at 1 AU. Solar Phys. 281, 793. [DOI] ADS [rotter12]

Schatten, K.H., Wilcox, J.M., Ness, N.F.: 1969, A model of interplanetary and coronal magnetic fields. Solar Phys. 6, 442. [DOI] ADS [schatten69]

Schwenn, R.: 2006, Space Weather: The Solar Perspective. Living Reviews in Solar Physics 3, 2. [DOI] ADS [schwenn06]

Scolini, C., Verbeke, C., Poedts, S., Chané, É., Pomoell, J., Zuccarello, F.P.: 2018, Effect of the Initial Shape of Coronal Mass Ejections on 3-D MHD Simulations and Geoeffectiveness Predictions. Space Weather 16, 754. [DOI] ADS [scolini18]

Temmer, M., Hinterreiter, J., Reiss, M.A.: 2018, Coronal hole evolution from multi-viewpoint data as input for a STEREO solar wind speed persistence model. Journal of Space Weather and Space Climate 8(27), A18. [DOI] ADS [temmer18]

Tsurutani, B.T., Gonzalez, W.D., Gonzalez, A.L.C., Guarnieri, F.L., Gopalswamy, N., Grande, M., Kamide, Y., Kasahara, Y., Lu, G., Mann, I., McPherron, R., Soraas, F., Vasyliunas, V.: 2006, Corotating solar wind streams and recurrent geomagnetic activity: A review. Journal of Geophysical Research (Space Physics) 111, A07S01. [DOI] ADS [tsurutani10]

Vršnak, B., Temmer, M., Veronig, A.M.: 2007, Coronal Holes and Solar Wind High-Speed Streams: I. Forecasting the Solar Wind Parameters. Solar Phys. 240, 315. [DOI] ADS [vrsnak07]