Over 20-Year Global Magnetohydrodynamic Simulation of Earth's Magnetosphere

Ilja Honkonen, Max van de Kamp, Theresa Hoppe, and Kirsti Kauristie

1Finnish Meteorological Institute, Helsinki, Finland

Abstract

We present our approach to modeling over 20 years of the solar wind-magnetosphere-ionosphere system using version 5 of the Grand Unified Magnetosphere-Ionosphere Coupling Simulation (GUMICS-5). As input we use 16-s resolution magnetic field and 1-min plasma measurements by Advanced Composition Explorer satellite from 1998 to 2020. The modeled interval is divided into 28 hr simulations including 4 hr overlap. We use maximum magnetospheric resolution of 0.5 Earth radii ($R_E$) up to about 15 $R_E$ from Earth and decreasing resolution further away. In the ionosphere we use a maximum resolution of approximately 100 km poleward of ±58° magnetic latitude and decreasing resolution toward equator. With respect to previous version GUMICS-4, we have parallelized the magnetosphere of GUMICS-5 using the Message Passing Interface and have made several improvements which have for example, decreased its numerical diffusion. In total we have performed over 8,000 simulations which have produced over 10,000,000 ionospheric files and 2,000,000 magnetospheric files requiring over 100 TB of disk space. We compare these results to several empirical models and geomagnetic indices derived from ground magnetic field measurements. GUMICS-5 reproduces observed solar cycle trends in magnetopause stand-off distance and magnetospheric lobe field strength but consistency in plasma sheet pressure and ionospheric cross-polar cap potential is lower. Comparisons with geomagnetic indices show better results for $K_p$ index than for auroral electrojet index. Our extensive results can serve, for example, as a foundation for combined physics-based and black-box approach to real-time prediction of near-Earth space, or as input to other physics-based models of the inner magnetosphere, upper and middle atmosphere, etc.

Plain Language Summary

We present our approach to modeling over 20 years of interaction between the solar wind, Earth’s magnetosphere and ionosphere using version 5 of the Grand Unified Magnetosphere-Ionosphere Coupling Simulation (GUMICS-5). In total we have performed over 8,000 simulations which have produced over 10,000,000 ionospheric files and 2,000,000 magnetospheric files requiring over 100 TB of disk space. We compare the simulation results to several empirical models and geomagnetic indices derived from ground magnetic field measurements. GUMICS-5 reproduces observed solar cycle trends in Earth’s outer magnetosphere but inner magnetosphere and ionosphere are not reproduced as well. Our extensive results can serve as a foundation for a combined physics-based and black-box approach to real-time prediction of near-Earth space, or as input to other physics-based models of the inner magnetosphere, upper and middle atmosphere, etc.

1. Introduction

Global magnetohydrodynamic (GMHD) simulations have been used for studying the interaction between solar wind, magnetosphere and ionosphere since the late 70s and early 80s (e.g., Brecht et al., 1981; Leboeuf et al., 1981; Wu et al., 1981, and references therein) and have become an especially important tool for understanding strong and/or dynamic events for which for example, empirical models are either not suitable or lack observations. Models based on first principles, such as GMHD, might also help understand space climate—the long-term effects of the Sun on the Earth’s magnetosphere, ionosphere and thermosphere—but currently the ability and accuracy of GMHD models in reproducing space weather over time scales of one or more solar cycles is unknown.

So far GMHD models have been mostly used and validated for individual events and output parameters or synthetic solar wind inputs. Continuous simulations of more than 1 week are rare and in many cases the simulation outputs are not available publicly. Table 1 lists the longest published GMHD simulations to date which use real solar wind as input and the domain(s) or parameter(s) that were studied. In most cases long runs have...
be used in statistical validation of GMHD performance. Studies listed in Table 1 report on GMHD models’ ability to forecast geomagnetic activity (Camporeale et al., 2020; Haiducek et al., 2017; Liemohn et al., 2018), to map between magnetosphere and ionosphere along magnetic field lines (Facskó et al., 2016), and to reproduce observed magnetospheric (Guld et al., 2008a, 2008b) or ionospheric properties (Wiltberger et al., 2017; Zhang et al., 2011). Juusola et al. (2014) compare seasonal variability in the observed modified $A_p$ index with that of a 1-year run produced by GUMICS-4.

We present the first results from GMHD simulations that span several solar cycles—from 1998 to 2020. Our main objective is to determine whether GUMICS-5 can reproduce the time evolution of magnetosphere and ionosphere over such time scales. Section 2 describes our model and input parameters. In Section 3 we compare the results to empirical models of the ionosphere and magnetosphere, and to measured indices of the Earth’s geomagnetic field. We discuss the results in Section 4 and draw our conclusions in Section 5.

2. Modeling and Post-Processing Setup

2.1. GUMICS-5

We use the fifth major version of Grand Unified Magnetosphere-Ionosphere Coupling Simulation (GUMICS-5), which is a parallelized version of GUMICS-4 described extensively by Janhunen et al. (2012). In the magnetosphere GUMICS-4 and 5 solve the ideal MHD equations using a first-order conservative finite volume method. The MHD equations are solved primarily using Roe’s approximate Riemann solver (Roe, 1981) and in rare cases when that solution fails a more robust and numerically diffusive solver is used for that particular calculation. The Earth’s intrinsic field is modeled as an Earth-centered dipole. Similarly to GUMICS-4 and Tanaka (1994), the magnetic field is split into a static background dipole ($B_0$) and a perturbed part ($B_1$) which is modified by the MHD solver(s). The ionosphere is modeled as a spherical surface with radially integrated current continuity, from which the electric potential is solved using a dipole-field-aligned electric current and a radially integrated conductivity tensor. Ionospheric conductivity is controlled by the magnetospheric temperature and mass density and by a parameter characterizing the loss cone filling rate. The ionosphere—thermosphere interaction processes impacting conductivities are based on the MSIS model (Hedin, 1991).

On a high level the ionospheric and magnetospheric grids of GUMICS-5 are identical to GUMICS-4: The magnetosphere is discretized as a cell-by-cell run-time adaptive octogrid and in GUMICS-5 it is built on a custom version of DCCRG (Honkonen et al., 2013) with the solution calculated in parallel using the Message Passing Interface. The ionosphere is modeled as a spherical surface and is discretized as a static cell-by-cell adaptive triangular grid. In GUMICS-4 the ionospheric grid had a maximum resolution of approximately 100 km only in the auroral oval region, while in GUMICS-5 the maximum resolution has been extended to everywhere poleward of ±58° magnetic latitude.

The initial objective for developing GUMICS-5 was to obtain identical results compared to GUMICS-4 with significantly faster time to solution. During subsequent development several features of the model were improved, for example, removal of divergence of perturbed magnetic field and mapping between ionosphere and magnetosphere along dipole field lines, and the code was updated to a more recent C++ standard used by current compilers. Perhaps most importantly, a rotating background dipole field was added that was not available in GUMICS-4. With these modifications, results between GUMICS-4 and -5 are very similar overall but not identical.

2.2. Simulation Parameters

The interval 1998–2020 is divided into simulations of 1 UTC day with an additional 4 hr overlap with the previous day’s simulation. A 4 hr overlap was considered as a safe value, since Facskó et al. (2016) showed that, along the orbit(s) of Cluster spacecraft, switching from one simulation to another after 1 hr of overlap produced on average a discontinuity smaller than the natural variation of the results. As shown in Section 3.1 a 4 hr overlap is indeed sufficient for emulating one long simulation using several independent shorter simulations.

As input we use solar wind data measured by Advanced Composition Explorer (ACE) consisting of 1-min resolution plasma data and 16-s magnetic field data, available under https://cdaweb.gsfc.nasa.gov/pub/data/ace. Missing and invalid data are interpolated linearly from the nearest existing data regardless of gap length, except for gaps that spanned a change in calendar year. Because of this, approximately 20 days of simulations were not
performed due to missing solar wind data, often during the last few days of December on several years. Figure 1 shows monthly 20, 50, and 80 percentiles of solar wind velocity magnitude on top, with the median marked by a solid line and vertical bars showing the range of 20 and 80 percentiles, and the difference to corresponding percentiles of solar wind modeled by GUMICS-5 below.

The simulation extends to $\pm 248 R_E$ in X dimension in geocentric solar ecliptic (GSE) coordinates, where $R_E = 6,371$ km is the radius of Earth. In GSE Y and Z dimensions the simulation extends to $\pm 64 R_E$. We use a maximum magnetospheric resolution of 0.5 Earth radii ($R_E$) up to about 15 $R_E$ from Earth and a decreasing resolution further away down to a minimum resolution of 8 $R_E$. The boundary of the simulation on the Sun-ward side is set every minute to the position of ACE although it rarely changes from one layer of grid cells to another during one simulation. With the correct location for the source of solar wind to within approximately 4 $R_E$, the simulation should give realistic timings for modeled phenomena within limitations of the solved MHD and electrostatic equations.

The background dipole field direction is updated every minute, the divergence of the perturbed magnetic field is removed every 20 s and the ionospheric potential solution is updated every 4 s. We save snapshots of the

### Table 1

| Interval (days) | Model | Subjects | Reference(s) |
|----------------|-------|----------|--------------|
| 2015-04-19/2017-07-17 (821) | SWMF | Dst, ground dB/dt | Liemohn et al. (2018), Camporeale et al. (2020) |
| 2002-01-30/2003-02-02 (369) | GUMICS-4 | Ionosphere, $\vec{B}$ mapping, plasma sheet | Juusola et al. (2014), Kallio and Facskó (2015), and Facskó et al. (2016) |
| 1996-02-23/1996-04-26 (64) | LFM | Ionosphere, plasma sheet | Zhang et al. (2011), Guild et al. (2008a, 2008b) |
| 2005-01-01/2005-01-31 (31) | SWMF | $K_p$, SYM-H, AL, CPCP | Haiducek et al. (2017) |
| 2008-03-20/2008-04-16 (28) | LFM | FAC, CPCP | Wiltberger et al. (2017) |
| 1998-02-06/2020-12-31 (≈8,300) | GUMICS-5 | Magnetopause, magnetosphere, plasma sheet, ionosphere, geomagnetic indices | This work |

Figure 1. Monthly 20, 50, and 80 percentiles of solar wind velocity magnitude on top and the difference to corresponding percentiles of solar wind modeled by version 5 of the Grand Unified Magnetosphere-Ionosphere Coupling Simulation below. Median is marked by solid line and vertical bars show the range of 20 and 80 percentiles.
3. Results

We compare GUMICS-5 results to empirical models of the magnetosphere and ionosphere, similarly to Gordeev et al. (2013), Gordeev et al. (2015), as well as geomagnetic indices. Gordeev et al. (2013) compared 162 GUMICS-4 simulations with stationary solar wind input to empirical models of magnetopause, tail lobe magnetic field, plasma sheet pressure and cross-polar cap potential (CPCP). These parameters were selected because they characterize the global state of magnetosphere and have empirical solar wind driven models published in literature. Gordeev et al. (2015) extended this study to other GMHD models, quasi-stationary solar wind input and a wider selection of simulated key parameters, such as global convection and total field-aligned currents. In both studies solar wind inputs were selected to be consistent with the average statistical distribution of observed solar wind parameters used in the empirical models. Using empirical models avoids many of the challenges related to interpreting data from a diverse collection of space instruments located in different parts of the magnetosphere at different stages of the solar cycle or even different solar cycles. These challenges have been addressed adequately by the developers of said empirical models, making them suitable for comparison with the results of GUMICS-5 presented here. The use of over 20 years of real solar wind data as input comprises a significant difference between our comparison and that of for example, Gordeev et al. (2015), where approximately 200 hr of simulations were run with quasi-stationary solar wind data.

As solar wind input for empirical models, we use the output of GUMICS-5 taken at $X = 12 \, R_E$, $Y = 44 \, R_E$, $Z = 44 \, R_E$ in GSE coordinates. This is well outside of the modeled magnetosphere regardless of the location of the bowshock and represents the undisturbed solar wind impacting the magnetosphere. As demonstrated by Claudepierre et al. (2010), GMHD models act as a low-pass filter for solar wind, with the cutoff frequency determined mainly by magnetospheric resolution and the solar wind speed. Using the solar wind modeled by GUMICS thus avoids the highest-frequency variations from appearing in empirical results which would consist for example, of unrealistically fast signal propagation through the magnetosphere and ionosphere. On a monthly scale the solar wind as modeled by GUMICS-5 is nearly identical to observations in Figure 1.

In the heatmaps below, color coding indicates the number of data points in each bin. The total number of data points is approximately 100,000 for magnetospheric results and 500,000 for ionospheric results, per year. We present an overview of our results for the years 1998–2020 and show details for the maximum of solar cycle 23 in 2001 and for the subsequent minimum in 2009.

3.1. Convergence of Overlapping Simulations

In order to test the convergence of GUMICS-5 results, Figure 2 shows the Pearson product-moment correlation coefficients (CC) between ionospheric potentials of overlapping simulations for years 2001 and 2009. For each point in time that was modeled by two simulations, the CC is calculated between electric potentials of all ionospheric cells of both simulations. Thus for each minute between 20:00 and 23:59 we obtain up to 364 CCs each calendar year. The 10th, 50th, and 90th percentiles of CCs are shown as functions of the number of minutes since beginning of the overlaps. The convergence results for other years are very similar to those shown in Figure 2.

The ionospheric results converge after about 3 hr of overlap. Even after 2 hr of overlap, using separate simulations instead of one continuous simulation most likely results in smaller errors than from other sources discussed in Section 4.2. As shown by Facskó et al. (2016), the dayside magnetosphere converges sufficiently even in 1 hr and we assume that the magnetosphere converges faster than the ionosphere, hence the 4 hr overlap used here should guarantee that the error from switching from one simulation to the next is insignificant compared to other sources. After about 1 hr of overlap, convergence in the ionosphere appears to be very similar regardless of the phase of solar cycle.
3.2. Comparison to Higher Resolution GUMICS-4 One Year Run

In order to assess the differences to previous version of GUMICS, we compare our results to those presented by Juusola et al. (2014) which were obtained with the previous single-core version GUMICS-4, using a twice higher maximum spatial resolution of 0.25 \( R_E \) in the magnetosphere (Facskó et al., 2016).

3.2.1. Modified \( A_L \) and \( A_U \) Indices

Figure 3 shows the daily median modified \( A_L \) and \( A_U \) indices produced with GUMICS-5, in the same format as Figure 4a of Juusola et al. (2014). The \( A_L \) and \( A_U \) indices are described by Davis and Sugiura (1966) and characterize time variations in the intensity of westward and eastward auroral electrojet currents. Instead of the standard derivation of \( A_U \) and \( A_L \) indices, we use the procedure from Juusola et al. (2014): The modified indices...
are computed as minimum and maximum of the northward components of external ground magnetic field at all \( A_E \) stations.

An exact one-to-one match between GUMICS-4 and 5 cannot be expected due to additional features and improvements of GUMICS-5 but the overall behavior of daily median modified \( A_L \) and \( A_U \) indices are very similar. The GUMICS-based indices have a seasonal dependence that does not exist in observations. Both versions of the code underestimate the absolute values of modified \( A_L \) and \( A_U \) compared to observations. Underestimation of \( A_L \) is particularly strong in the summer and of \( A_U \) in winter.

Comparison of Figure 3 with Figure 4a by Juusola et al. (2014) reveals that the extreme values of \( A_U \) and \( A_L \) of GUMICS-5 are systematically smaller than those of GUMICS-4. This discrepancy is mainly the result of different magnetospheric resolutions used in the two simulations: Figure 4 shows daily median modified \( A_L \) and \( A_U \) indices produced with GUMICS-5 on 12 selected days using highest magnetospheric resolutions of 0.5, 0.375, and 0.25 \( R_E \), and GUMICS-4 using highest magnetospheric resolution of 0.25 \( R_E \). The absolute values of daily median \( A_L \) and \( A_U \) increase systematically with magnetospheric resolution used in the simulation. When using a resolution of 0.25 \( R_E \), the magnitudes of \( A_L \) and \( A_U \) are consistent between both GUMICS-5 and 4. For example, both versions yield a daily median modified \( A_L \) of approximately \( -70 \) nT on 24 October 2002 and \( A_U \) of approximately 30 nT on 23 May 2002.

Overall the daily median modified \( A_L \) index produced by GUMICS-5 is similar to that of GUMICS-4. For example, the peaks in the beginning and end of March 2002, as well as the peaks in October 2002, are local maxima in both versions with similar relative amplitudes. The \( A_L \) index produced by GUMICS-5 is very similar to that of GUMICS-4, for example, from October 2002 until the end of the modeled interval. A few notable differences are for example, a missing negative peak in 1 November 2002 in GUMICS-5, and that the peak of 21 November 2002 is smaller than the peak of 7 December 2002 in GUMICS-5 (\( -20 \) vs. \( -22 \) nT), while being larger in GUMICS-4 (\( -70 \) vs. \( -50 \) nT). Together Figures 3 and 4 strongly suggest that in this work GUMICS-5 can be safely used in place of GUMICS-4.

### 3.2.2. Cross-Polar Cap Potential in Northern Hemisphere

Figure 5 shows the daily median CPCP in the northern hemisphere from GUMICS-5 in the same format as Figure 1a of Juusola et al. (2014) from GUMICS-4. The overall behavior and many details of GUMICS-5 solution are same as in GUMICS-4 but there are also more differences between the models than with modified \( A_L \) and \( A_U \) indices. During the northern summer months, the GUMICS-5 daily median CPCP is somewhat smaller than in GUMICS-4, but during winter the difference is approximately a factor of two, similarly to \( A_L \) and \( A_U \) indices.

Figure 6 shows north CPCP produced with GUMICS-5 on select days using highest magnetospheric resolutions of 0.5, 0.375, and 0.25 \( R_E \). The effect of increasing magnetospheric resolution is not as straightforward in CPCP as in \( A_L \) and \( A_U \). For example, on 1 October 2002, CPCP increases from 30 kV at 0.5 \( R_E \) to over 60 kV at 0.25
While on 23 October 2002 CPCP increases only from 25 to 35 kV. The artificial seasonal variation of CPCP seems weaker in GUMICS-5 than in GUMICS-4 but this might be due to lower magnetospheric resolution. Improvements in dipole field-aligned mapping between ionosphere and magnetosphere can also contribute to changes in minimum/maximum values of electric potential solution in ionosphere thus affecting CPCP.

Based on comparisons of modified $A_E$ and CPCP we conclude that GUMICS-5 can be used in place of GUMICS-4 at least on solar cycle time scales. It should be noted that, although in general using higher magnetospheric resolution should improve consistency between simulations and observations, this is not always the case. Ridley et al. (2010) showed that even using the highest feasible resolution in one short simulation may not guarantee that the results converge to any particular value.

Figure 5. Daily median cross-polar cap potential in northern hemisphere in same format as Figure 1a of Juusola et al. (2014) but produced using version 5 of the Grand Unified Magnetosphere-Ionosphere Coupling Simulation (GUMICS-5) and highest magnetospheric resolution of 0.5 $R_E$ instead of GUMICS-4 and highest resolution of 0.25 $R_E$.

$R_E$ while on 23 October 2002 CPCP increases only from 25 to 35 kV. The artificial seasonal variation of CPCP seems weaker in GUMICS-5 than in GUMICS-4 but this might be due to lower magnetospheric resolution. Improvements in dipole field-aligned mapping between ionosphere and magnetosphere can also contribute to changes in minimum/maximum values of electric potential solution in ionosphere thus affecting CPCP.

Based on comparisons of modified $A_E$ and CPCP we conclude that GUMICS-5 can be used in place of GUMICS-4 at least on solar cycle time scales. It should be noted that, although in general using higher magnetospheric resolution should improve consistency between simulations and observations, this is not always the case. Ridley et al. (2010) showed that even using the highest feasible resolution in one short simulation may not guarantee that the results converge to any particular value.

Figure 6. Comparison of daily median cross-polar cap potential in northern hemisphere from version 5 of the Grand Unified Magnetosphere-Ionosphere Coupling Simulation (GUMICS-5) using highest magnetospheric resolution of 0.5, 0.375, and 0.25 $R_E$ and from GUMICS-4 (Juusola et al., 2014) using highest magnetospheric resolution of 0.25 $R_E$. Note that a small horizontal offset has been applied for clarity and that GUMICS-4 values are approximate.
3.3. Magnetospheric Lobe Field Strength

Figures 7 and 8 compare the magnetic field strength in magnetospheric lobe(s) to the empirical model of Fairfield and Jones (1996). From GUMICS-5 we select the maximum magnetic field strength along $Z$ direction at, from left to right, $-15$, $-20$, and $-25$ R$_E$ GSE X in Earth's magnetotail. Figure 9 shows the 20th, 50th, and 80th percentiles of GUMICS-5 and empirical magnetospheric lobe field strength for each calendar year between 1998 and 2020 at $-20$ R$_E$ GSE X in Earth's magnetotail.

GUMICS-5 reproduces the solar cycle time variations of lobe field well when compared to Fairfield and Jones (1996). In particular, both approaches show the exceptionally strong lobe fields in 2003 and 2012. GUMICS-5 underestimates the median field intensity by approximately 10 nT but the underestimation seems to decrease further from Earth.

The empirical model produces values in a much larger range for the solar maximum in 2001 than for the minimum in 2009. In 2001 the empirical model produces values as low as 0 nT at all studied positions, while GUMICS-5 yields rather fixed minimum values: approximately 15 nT at $-15$ R$_E$, 8 nT at $-20$ R$_E$ and 6 nT at $-25$ R$_E$. This is not the case in 2009, when both the empirical model and GUMICS-5 yield values above approximately 10 nT. In Gordeev et al. (2015), lobe field strength was underestimated by GUMICS-4, BATS-R-US, LFM, and for large fields by OGGCM as well.

3.4. Magnetopause Standoff Distance

Figure 10 compares the magnetopause standoff distance on the Sun-Earth line to the empirical model of Lin et al. (2010). From GUMICS-5 we select the position on the GSE X-axis between 5 and 30 R$_E$ from Earth with maximum $J_y = \nabla \times B_1 \mid_{y}$, where $B_1$ is the perturbed magnetic field solved by GUMICS-5. This magnetopause current is a simple and reliable way of detecting the location of the magnetopause along the Sun-Earth line in GUMICS. Figure 11 shows the 20th, 50th, and 80th percentiles of GUMICS-5 and empirical magnetopause standoff distance for each calendar year between 1998 and 2020.
GUMICS-5 reproduces the solar cycle time variations in magnetopause standoff distance quite well when compared to Lin et al. (2010). For example, the years 2003 and 2012 associated with strong lobe fields (Figure 9) are local minima in stand-off distance in both GUMICS-5 and the empirical model. GUMICS-5 underestimates the standoff distance on average by about 0.5 $R_E$, that is, by one grid cell, but the two median curves are within their error bars as characterized by the 20th and 80th percentiles.

In 2001 and to some extent in 2009 in Figure 10, the results consist of two distinct populations mostly separated by the sign and magnitude of the solar wind electric field ($E_y$, not shown). In the larger population IMF $B_z$ is

---

**Figure 9.** Statistics of magnetospheric lobe field strength from version 5 of the Grand Unified Magnetosphere-Ionosphere Coupling Simulation (GUMICS-5) and Fairfield and Jones (1996) at $20 R_E$ geocentric solar eclipse X in Earth's magnetotail. Solid lines denote yearly medians while tops and bottoms of vertical lines denote 80 and 20 percentiles respectively. The total number of data points every year is approximately $10^5$.

**Figure 10.** Magnetopause standoff distance on Sun-Earth line in 2001 during the maximum of solar cycle 23 and in 2009 during the subsequent minimum. The red line indicates 1:1 correspondence.
mostly negative and the standoff distance is underestimated by about 0.5 \textit{R}_E. In the smaller population IMF $B_z$ is positive and, when $E_y$ is larger than about 3 mV/m, GUMICS-5 overestimates the standoff distance by several \textit{R}_E. The larger population is close to the results of GUMICS-4 in the lower panel of Figure 4 of Janhunen et al. (2012), while in Gordeev et al. (2015) the standoff distance was also underestimated by OGGCM and LFM and slightly underestimated by GUMICS-4.

### 3.5. Plasma Sheet Pressure

Figure 12 compares plasma sheet pressure to the empirical model of Tsyganenko and Mukai (2003). From GUMICS-5 we select the maximum thermal pressure within $\pm 10 \textit{R}_E$ in $Y$ and $Z$ dimensions, at three distances from Earth along the GSE $X$ axis. We only show the results at $-20 \textit{R}_E$ GSE $X$ as at other distances the results

Figure 11. Yearly percentiles of magnetopause standoff distance from version 5 of the Grand Unified Magnetosphere-Ionosphere Coupling Simulation and Lin et al. (2010) in same format as Figure 9.

Figure 12. Plasma sheet pressure at $-20 \textit{R}_E$ geocentric solar eclipse $X$ in the Earth’s magnetotail in 2001 during the maximum of solar cycle 23 and in 2009 during the subsequent minimum. The red line indicates 1:1 correspondence.
are essentially the same except for a smaller range of values further from Earth and larger range closer to Earth. Figure 13 shows the 20th, 50th, and 80th percentiles of GUMICS-5 and empirical plasma sheet pressure at −20 \( R_E \) each calendar year between 1998 and 2020.

The modeled and empirically estimated plasma sheet pressures do not appear to be correlated. This is visible also in the solar cycle time variations, which are less consistent with each other than in the cases of lobe magnetic field and magnetopause standoff distance. The correlation also does not seem to improve by grouping results based on time of year, \( K_p \), hourly average of solar wind \( B_z \) nor \( V_x \) (not shown). The behavior of GUMICS-5 is similar to that of GUMICS-4 in Gordeev et al. (2015), except that here the spread of input and output values is much wider and correlation is significantly smaller. This is likely due to the stark contrast in coverage of simulation inputs between approximately 200 hr of synthetic versus over 20 years of real solar wind.

### 3.6. Cross-Polar Cap Potential

Figure 14 shows the 20th, 50th, and 80th percentiles of CPCP from GUMICS-5 and the empirical models of Boyle et al. (1997), Ridley (2005) on each calendar year between 1998 and 2020. Using the Alfvén Mach number and magnetopause size corrections of Ridley (2005) seems to minimize the difference between GUMICS-5 and the empirical model, although their effect is small. Similarly to plasma sheet pressure, there is not much correlation in 5 min values, nor longer averages, of CPCP between GUMICS-5 and Ridley (2005) (not shown).

There does not seem to be much correlation between yearly GUMICS-5 and empirical CPCP at any percentile, although both show a decreasing linear trend from 1998 to 2020. In GUMICS-5 the behaviors of minimums and maximums of both hemispheres' CPCP resemble each other closely.

### 3.7. \( K_p \) and GUMICS-5-Specific \( K_p \) Indices

We convert horizontal ionospheric currents from GUMICS-5 to variations of external ground magnetic field (\( dB \)) using the method of Vanhamäki and Juusola (2020), after which we convert \( dB \) to \( K_p \) using the same procedure used for real \( K_p \). We convert \( dB \) to a local \( K \) index using the FMI method described for example, by Sucksdorff
et al. (1991), Menvielle et al. (1995) and software available at https://space.fmi.fi/image/software. We then transform this $K$ index to the standardized index $K_s$ and finally obtain $K_p$ as described by Matzka et al. (2021), using the same stations that were used for the real $K_p$.

The left panel of Figure 15 compares the $K_p$ index obtained from GUMICS-5 to the measured one. Due to the significantly smaller amplitude of GUMICS-5-derived ground $dB$ compared to measurements, GUMICS-5 severely underestimates $K_p$. Hence, we derive GUMICS-5-specific $K$ indices for all stations used in $K_p$ by adjusting the station-specific $K9$ threshold such that the frequency of $K \geq 5$ is approximately 5% (Matzka et al., 2021, and references therein). After deriving the GUMICS-5-specific $K$ index, the same procedure as above is used to compute the GUMICS-5-specific $K_p$ index. This brings the dynamic range of the GUMICS-5-specific $K_p$ to the same level as the observed one and is compared to real $K_p$ in middle and right panels of Figure 15.

In Figure 15 the minimum value of GUMICS-5-specific $K_p$ seems to be mostly between 1 and 2, contrary to measurements, especially during solar minimum in 2009 when real $K_p < 1$ is seen most often. During solar maximum in 2001, real $K_p$ values are divided somewhat evenly in the range from 0 to 2, while a value of 2 is most often seen in GUMICS-5-specific $K_p$. Figure 16 shows the yearly averages of real $K_p$, real $K_p$ calculated from GUMICS-5 and GUMICS-5-specific $K_p$ while Figure 17 shows the 20th, 50th, and 80th percentiles of real and GUMICS-5-specific $K_p$ each calendar year between 1998 and 2020.

In Honkonen et al. (2018), horizontal ionospheric currents accounted for approximately 90% of modeled ground $dB$. However the effects of ring current and radiation belts on ground $dB$ were not studied, hence their contribution...
Figure 16. Yearly averages of real $K_p$ (Obs), version 5 of the Grand Unified Magnetosphere-Ionosphere Coupling Simulation (GUMICS-5)-specific $K_p$ (G5*) and real $K_p$ derived from GUMICS-5 scaled up by a factor of 30 (G5 x30).

Figure 17. Yearly percentiles of real and version 5 of the Grand Unified Magnetosphere-Ionosphere Coupling Simulation-specific $K_p$ indices in same format as Figure 9, except that the number of data points is approximately 2,900 per year.
to \( dB \) produced by GMHD models is less well known. As the ring current and radiation belts are neglected also here, our \( Kp \) estimates are more dependent on high-latitude activity than the observed \( Kp \) is.

### 3.8. Auroral Electrojet Index

Figure 18 compares the auroral electrojet index \( (A_E) \) obtained from GUMICS-5 to the real one and Figure 19 shows their 20th, 50th, and 80th percentiles each calendar year between 1998 and 2018 when observed \( A_E \) is available. The method for deriving \( A_E \) is described by Davis and Sugiura (1966). Determining \( A_E \) involves removal of the quiet-day baseline, which is defined as the average of the horizontal magnetic field component over the 5 international quietest days of every month. Quiet-day determination is based on the \( Kp \) index and we find

Figure 18. Auroral electrojet index in 2001 during the maximum of solar cycle 23 and in 2009 during the subsequent minimum. The red line indicates 1:1 correspondence.

Figure 19. Yearly percentiles of real and version 5 of the Grand Unified Magnetosphere-Ionosphere Coupling Simulation (GUMICS-5)-derived auroral electrojet \( (A_E) \) index in same format as Figure 9. Note that GUMICS-5 results have been scaled up by a factor of 15. The measured \( A_E \) index is available only up to 28 February 2018.
relatively small differences in $A_E$ and $A_U$ indices produced by GUMICS-5 (not shown) whether we use observed quiet days or quiet days determined from GUMICS-5-specific $Kp$. The $A_E = A_U - A_L$ index is not affected by the determined baseline.

There are some similarities in the yearly percentiles of $A_E$ between measurements and GUMICS-5 but their correlation is not very good. The worse correlation of GUMICS-5 versus $A_E$ compared to $Kp$ is likely due to the fact that $A_E$ reflects more the effects of for example, substorms, whose formation is less directly driven by solar wind and hence is more difficult to capture using GMHD models. The higher time resolution of $A_E$ likely also contributes to worse correlation with GUMICS-5 compared to $Kp$, a conclusion also reached by Haiducek et al. (2017).

4. Discussion

Previous comparisons of GUMICS results with empirical models have shown that the simulation underestimates the intensity of magnetospheric and ionospheric activity (Gordeev et al., 2013; Juusola et al., 2014). However, as shown by Palmroth et al. (2005), the time evolution of substorm activity as described by the simulation is in reasonable agreement with observations. In this study our main objective is to determine whether GUMICS-5 can reproduce the time evolution of the magnetosphere and ionosphere over one or more solar cycles. When considering the yearly statistic this is indeed the case for the magnetospheric lobe magnetic field strength, the magnetopause standoff distance and the $Kp$ index, although GUMICS-5 requires a constant offset or scaling factor for best fit to observations and empirical models. The auroral electrojet index and plasma sheet pressure are not reproduced as well and GUMICS-5 does not seem to be able to reproduce the solar cycle effects of cross-polar cap potential observed in empirical models.

4.1. Comparison to GUMICS-4 and Other GMHD Models

The strength of magnetospheric lobe field is modeled similarly by both GUMICS-5, GUMICS-4 and other GMHD models. In Gordeev et al. (2015) lobe field was underestimated by GUMICS-4, BATS-R-US and LFM, and for large fields by OGGCM as well.

The behavior of GUMICS-5 w.r.t. plasma sheet pressure is also similar to GUMICS-4 in Gordeev et al. (2015), except that here the spread of input solar wind and output pressure values is much wider and correlation is significantly smaller. This is likely due to the fact that we have simulated an approximately three orders or magnitude longer time interval than was simulated by Gordeev et al. (2015).

The magnetopause standoff distance is modeled similarly by GUMICS-5 and GUMICS-4, when comparing to the lower panel of Figure 4 of Janhunen et al. (2012). More specifically the behavior of both models seems similar at least when IMF $B_z$ is mostly southward, although this could due to the much shorter amount of simulations performed with GUMICS-4. In Gordeev et al. (2015) magnetopause standoff distance was also underestimated by OGGCM and LFM and slightly underestimated by GUMICS-4.

4.2. Sources of Modeling Error

4.2.1. Low Magnetospheric Resolution

Due to limitations in computational and storage capacity we changed the highest magnetospheric resolution from $0.25 \ R_E$ used mostly with GUMICS-4, to $0.5 \ R_E$ which had been used in early GUMICS-4 simulations. In future studies, with larger computational and storage resources available and with further optimization of GUMICS-5, we hope to use the standard for GUMICS value of $0.25 \ R_E$.

The effects of low magnetospheric resolution on results of GMHD models are well understood on daily or shorter time scales. Lower resolution increases numerical diffusion which leads to for example, smaller gradients in plasma parameters and thus smaller energy transfer through the magnetopause (Palmroth et al., 2010), thicker current sheet and smaller $j \times B$ forces as well as slower plasma sheet flows (Guild et al., 2008b), etc. Ideal MHD equations do not admit magnetic reconnection but numerical diffusion acts as a nonphysical resistive term that does lead to resolution-dependent reconnection. Using very high resolution for example, on dayside can reduce reconnection enough to cause magnetic flux build-up and periodic flux transfer events (Ridley et al., 2010).
At Earth higher magnetospheric resolution leads to, for example, better predictions of geomagnetic indices (Haiducek et al., 2017) and it increases CPCP by up to a factor of 5 in both GUMICS-4 (Lakka et al., 2018) and BATSRUS (Ridley et al., 2010). Ionospheric field-aligned currents (FAC) are also strongly affected by magnetospheric resolution. Using too low a magnetospheric resolution causes region 2 field-aligned currents to be missing or to be significantly smaller than region 1 currents (Ridley et al., 2010; Wilberger et al., 2017). Region 1 FAC are also affected by magnetospheric resolution and for example, in GUMICS-4 lower resolution decreases FAC which leads to smaller CPCP (Gordeev et al., 2015; Lakka et al., 2018). Furthermore, due to underestimation of region 2 currents, relatively large amount of FAC close through the polar cap (Lakka et al., 2018) which can lead to further underestimation of CPCP. The GUMICS ionospheric conductance model consists solely of solar ultra-violet radiation and electron precipitation based on MHD parameters (Janhunen et al., 2012), and errors in the polar cap conductivity can also cause errors in CPCP (Nagatsuma, 2004). For example, Mukhopadhyay et al. (2020) showed that enhancing ionospheric conductance within SWMF during strong FAC improved the prediction of ionospheric currents and thereby also of $\frac{dB}{dt}$. The larger ionospheric conductance also leads to smaller CPCP since the strength of FAC is not affected, in agreement with Mukhopadhyay et al. (2021), who showed that GMHD models tend to overpredict CPCP under general conditions. Dimmock et al. (2021) additionally found that increasing magnetospheric resolution produced more realistic amplitudes and timings for geomagnetically induced currents and increased regional variations of ground magnetic field perturbations.

4.2.2. Lack of Inner Magnetosphere Model

GUMICS-5 lacks an inner magnetosphere model for higher-energy particles of the ring current and radiation belts that ideal single-fluid MHD cannot describe. Incorporating such a model into GUMICS would require a large effort and likely would be done in the context of overall modernization of GUMICS’ solvers. The effects of an inner magnetosphere model, either two-way or one-way coupled to a GMHD model, are reasonably understood on timescales shorter than the solar cycle. As reported by for example, De Zeeuw et al. (2004), Zaharia et al. (2010), and Pembroke et al. (2012), an inner magnetosphere model significantly increases plasma pressure within approximately 15 RE of Earth as well as region 2 field-aligned currents in ionosphere. These currents partially shield the inner magnetosphere from the convection electric field (De Zeeuw et al., 2004; Pembroke et al., 2012). Geomagnetic indices are also improved substantially by an inner magnetosphere model (e.g., Gloer et al., 2013; Haiducek et al., 2017; Liemohn et al., 2018; Zaharia et al., 2010). A GMHD model without an inner magnetosphere model reaches steady state significantly faster than one with an inner magnetosphere model (e.g., De Zeeuw et al., 2004) which might require even 10 hr or longer overlap between runs to emulate one continuous simulation. In such a case overlaps could potentially be shortened if they occur during low geomagnetic activity.

4.2.3. Other Sources

The poor agreement of plasma sheet pressure with the empirical model might be explained by the lack of an ionospheric outflow model in GUMICS-5. Adding solar activity-dependent outflow might improve plasma sheet pressure results considerably over solar cycle time scales, while adding ionospheric activity-dependent outflow could improve the results over hourly and/or daily time scales.

We have set $B_x = 0$ in the solar wind, in order to have a divergence-free magnetic field at the solar wind boundary. In the future, a straightforward solution could be to introduce a slow, for example, 1 mHz at most, global variation in the background $B_x$ within the simulated volume, in order to better take into account a changing IMF $B_x$ while maintaining a divergence-free field. This could perhaps be calculated automatically from the solar wind magnetic field already given as input to GUMICS-5.

Similarly to most simulations carried out with GUMICS-4 (Janhunen et al., 2012), we use a constant solar EUV flux that is parametrized by solar radio F10.7 cm flux. We expect the effect of changing F10.7 flux to be small based on Gordeev et al. (2013).

We have not omitted simulations with gaps in solar wind data even though sufficiently long gaps could cause GUMICS-5 to miss certain short-term effects in magnetosphere or ionosphere. Most likely this does not impact results presented here but it should be kept in mind when analyzing for example, individual storms.

The relatively low magnetospheric resolution in GUMICS-5 used here, as well as the first-order MHD solvers, likely also contribute to the low correlation between GUMICS-5 and $A_p$ compared to the correlation with $K_p$. We also neglect the effect of ground conductivity when deriving geomagnetic indices. Its effect on the largest
horizontal ground magnetic fields can be a few tens of percent (Juusola et al., 2020) but such a relatively small error will likely not change our results significantly.

5. Conclusions

We present our approach to modeling over 20 years of the solar wind-magnetosphere-ionosphere system using version 5 of the Grand Unified Magnetosphere-Ionosphere Coupling Simulation (GUMICS-5). We run over 8,000 1-day simulations, save the magnetospheric results every 5 min and ionospheric results every minute, producing over 2 and 10 million files respectively that required over 100 TB of disk space.

We compare the simulation results to several empirical models of the magnetosphere and ionosphere, and to geomagnetic indices derived from ground magnetic field measurements. GUMICS-5 reproduces observed solar cycle trends in magnetopause stand-off distance and magnetospheric lobe field strength, while consistency in plasma sheet pressure and ionospheric cross-polar cap potential is lower. Comparisons with geomagnetic indices show better results for Kp index than for A-index.

Our extensive results can serve for example, as a foundation for a combined physics-based and black-box approach to real-time prediction of near-Earth space, or as input to other physics-based models of the inner magnetosphere, upper and middle atmosphere, etc.

Data Availability Statement

The simulation results are available at https://doi.org/10.23729/ca1da110-2d4e-45c4-8876-57210fbb0b0d under CC BY 4.0, consisting of full ionospheric files and size-optimized magnetospheric files as well as Python programs for converting them to ASCII format. The data used for Figures is available at https://doi.org/10.5281/zenodo.6641258 under CC BY 4.0. Solar wind data used as input is freely available at https://cdaweb.gsfc.nasa.gov/pub/data/ace. IMAGE software used for processing ground magnetic field data is freely available as C source code at https://space.fmi.fi/image/software.

Acknowledgments

We thank Ari Viljanen for insightful discussions and the Finnish Center for Scientific Computing for providing help with and managing the Puhti supercomputer, Atlas object storage system and Fairdata service. We are grateful to NASA National Space Science Data Center, the Space Physics Data Facility, and the ACE Principal Investigator, Edward C. Stone of the California Institute of Technology for providing access to ACE data. We are also grateful to GFZ German Research Centre for Geosciences for Kp and quiet days data, and to Kyoto World Data Center for Geomagnetism for A-index data (Nose et al., 2015). This work was supported by the Academy of Finland projects 314670, 339329 and by the European Space Agency project 4000118383/16/I-EF.

References

Boyle, C. B., Reiff, P. H., & Hairston, M. R. (1997). Empirical polar cap potentials. Journal of Geophysical Research, 102(A1), 111–125. https://doi.org/10.1029/96JA01742

Breth, S. H., Lyon, J., Fedder, J. A., & Hain, K. (1981). A simulation study of east-west IMF effects on the magnetosphere. Geophysical Research Letters, 8(4), 397–400. https://doi.org/10.1029/GL008i004p00397

Camporeale, E., Cash, M. D., Singer, H. J., Balch, C. C., Huang, Z., & Töth, G. (2020). A gray-box model for a probabilistic estimate of regional ground magnetic perturbations: Enhancing the NOAA operational Geospace model with machine learning. Journal of Geophysical Research: Space Physics, 125(11), e2019JA027684. https://doi.org/10.1029/2019JA027684

Claudepierre, S. G., Hudson, M. K., Lotko, W., Lyon, J. G., & Denton, R. E. (2010). Solar wind driving of magnetospheric ULF waves: Field line resonances driven by dynamic pressure fluctuations. Journal of Geophysical Research, 115(A11). https://doi.org/10.1029/2010JA015399

Davis, T. N., & Suguri, M. (1996). Auroral electrojet activity index AE and its universal time variations. Journal of Geophysical Research (1896–1977), 71(3), 785–801. https://doi.org/10.1029/92JH03p00785

De Zeeuw, D. L., Suzykin, S., Wolf, R. A., Gombosi, T. I., Ridley, A. J., & Töth, G. (2004). Coupling of a global MHD code and an inner magnetospheric model: Initial results. Journal of Geophysical Research, 109(A12), A12219. https://doi.org/10.1029/2003JA010366

Dimmock, A. P., Welling, D. T., Rosenqvist, L., Forsyth, C., Freeman, M. P., Rae, I. J., et al. (2021). Modeling the geomagnetic response to the September 2017 space weather event over Fennoscandia using the Space Weather Modeling Framework: Studying the impacts of spatial resolution. Space Weather, 19(5), e2020SW002683. https://doi.org/10.1029/2020SW002683

Facskó, G., Honkonen, I., Živković, T., Palin, L., Kallio, E., Ågren, K., et al. (2016). One year in the Earth's magnetosphere: A global MHD simulation and spacecraft measurements. Space Weather, 14(5), 351–367. https://doi.org/10.1002/2015SW001355

Fairfield, D. H., & Jones, I. (1996). Variability of the tail lobe field strength. Journal of Geophysical Research, 101(A4), 7785–7791. https://doi.org/10.1029/95JA03713

Glocer, A., Fok, M., Meng, X., Töth, G., Buzulukova, N., Chen, S., & Lin, K. (2013). CRCM + BATs—R-US two-way coupling. Journal of Geophysical Research: Space Physics, 118(4), 1635–1650. https://doi.org/10.1002/jgra.50221

Gordeev, E., Facskó, G., Sergeev, V., Honkonen, I., Palmroth, M., Janhunen, P., & Milan, S. (2013). Verification of the GUMICS-4 global MHD code using empirical relationships. Journal of Geophysical Research: Space Physics, 118(6), 3138–3146. https://doi.org/10.1002/jgra.50359

Gordeev, E., Sergeev, V., Honkonen, I., Kuznetsova, M., Rastätter, L., Palmroth, M., et al. (2015). Assessing the performance of community-available global MHD models using key system parameters and empirical relationships. Space Weather, 13(12), 868–884. https://doi.org/10.1002/2015SW001307

Guild, T. B., Spence, H. E., Kepko, E. L., Merkin, V., Lyon, J. G., Wilberger, M., & Goodrich, C. C. (2008a). Geotail and LFM comparisons of plasma sheet climatology: 1. Average values. Journal of Geophysical Research, 113(A4). https://doi.org/10.1029/2007JA012611

Guild, T. B., Spence, H. E., Kepko, E. L., Merkin, V., Lyon, J. G., Wilberger, M., & Goodrich, C. C. (2008b). Geotail and LFM comparisons of plasma sheet climatology: 2. Flow variability. Journal of Geophysical Research, 113(A4). https://doi.org/10.1029/2007JA012613
