The hourly and half-hourly, open-ended, Kp-like planetary geomagnetic Hpo index family

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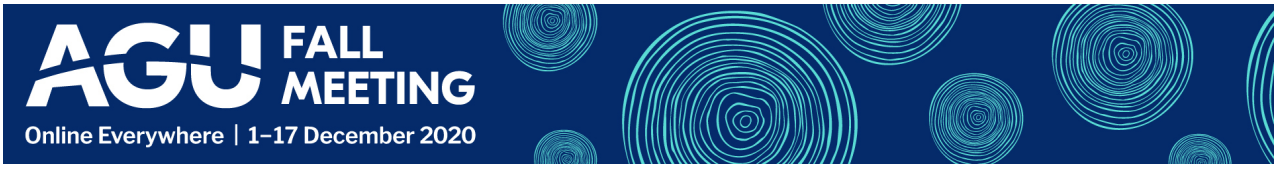

INTRODUCING THE HPO INDEX FAMILY (HP60, AP60, HP30, AP30)

The new Hpo indices and where to download them

We have developed a new group of *Kp*- and ap-like geomagnetic indices, the **Hpo** indices, where **H** stands for hourly respectively half-hourly, **p** for planetary, and **o** for open-ended.

These are the **hourly Hp60** and its linear **ap60** index and the **half-hourly Hp30** and its linear **ap30** index. Collectively, they can be referred to as **Hpo** or **Hpo and apo** indices.

The three-hourly Kp and ap were introduced by Bartels in 1949 (e.g. Bartels, 1957) and have been widely used indices in geomagnetism, space physics and space weather research and operations. The aim of the Hpo indices is to provide similar information but with higher time resolution.

In this box, we present the design criteria for the new indices, provide links for downloading the index, and illustrate the new indices by the example of the geomagnetic storm on Sept. 7 and 8, 2017.

In the following boxes, we compare the Hpo indices to other geomagnetic indices and solar wind parameters, we demonstrate the open-endedness of the Hpo indices, and we finally investigate their behavior during substorms and storms.

The Hpo indices were developed as part of the Space Weather Atmosphere Models and Indices project SWAMI (http://swami-h2020.eu/).

The design criteria for our Hpo indices were:

1. to keep as much as possible of the original methodology for the derivation *Kp* (Hpo indices are based on the same 13 geomagnetic observatories and use the same standardization tables as *Kp*)
2. to result the same frequency distribution of index values as the *Kp* index
3. to extend the scale of Kp, which goes in thirds from 0 to 9, beyond 9, to provide a more nuanced description of the events with strongest geomagnetic disturbance (Hpo = 9, 9+, 10-, 11-, ...)

Download the Hpo and *Kp* indices from:

New data formats for Hpo and *Kp*

New formats for downloading Hpo (since 1995) and *Kp* (since 1932) including nowcast values:

Hpo download via FTP: ftp://ftp.gfz-potsdam.de/pub/home/obs/Hpo

The Hpo FTP server is also linked from the Hpo-website (https://www.gfz-potsdam.de/en/section/geomagnetism/data-products-services/hpo-index/)

Kp download via FTP: ftp://ftp.gfz-potsdam.de/pub/home/obs/Kp_ap_Ap_SN_F107

The Kp FTP server is also linked from the official *Kp*-website (https://www.gfz-potsdam.de/en/kp-index/)

Nowcast graphical display of Hpo

Nowcast Hp30 and Hp60 (https://isdc.gfz-potsdam.de/index.php?id=152)

Our traditional download for *Kp*

via FTP: ftp://ftp.gfz-potsdam.de/pub/home/obs/kp-ap/

The official *Kp*-website

https://www.gfz-potsdam.de/en/kp-index/ (https://www.gfz-potsdam.de/en/kp-index/)

Illustrative example: geomagnetic storm Sept. 7 and 8, 2017

In the following, we compare actual geomagnetic disturbance measured at the observatories that contribute to Kp, Hp60 and Hp30 with the indices for the geomagnetic storm on September 7 and 8, 2017.

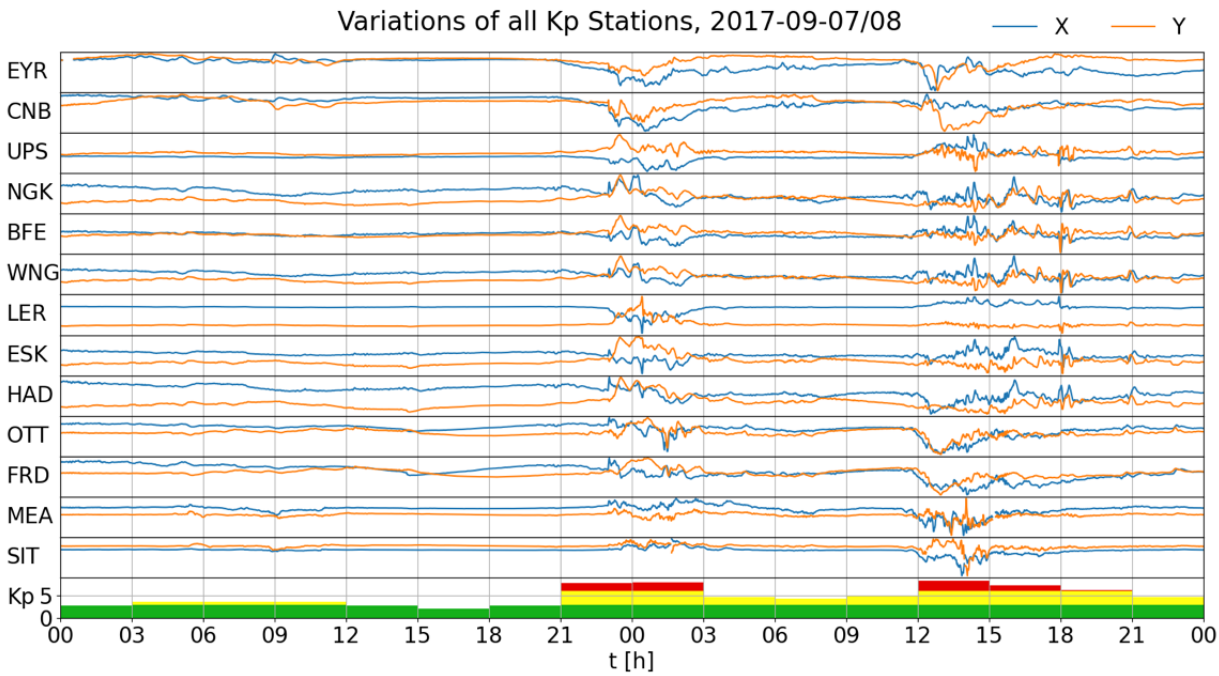

Fig. 1: Shown are the horizontal geomagnetic components X (blue) and Y (orange) for the *Kp*-observatories (EYR to SIT) and *Kp* (green, yellow, red) September 7 and 8, 2017. Extreme geomagnetic disturbance starts around 23 UT on September 7 and ends around 03 UT on September 8. However, since the Kp index is defined on three-hourly UT intervals, Kp shows already an increase starting at 21 UT. On September 8, extreme geomagnetic activity lasts from about 12 UT to 15 UT, thus coincidentally agreeing with the thee-hourly UT interval, for which *Kp* is defined.

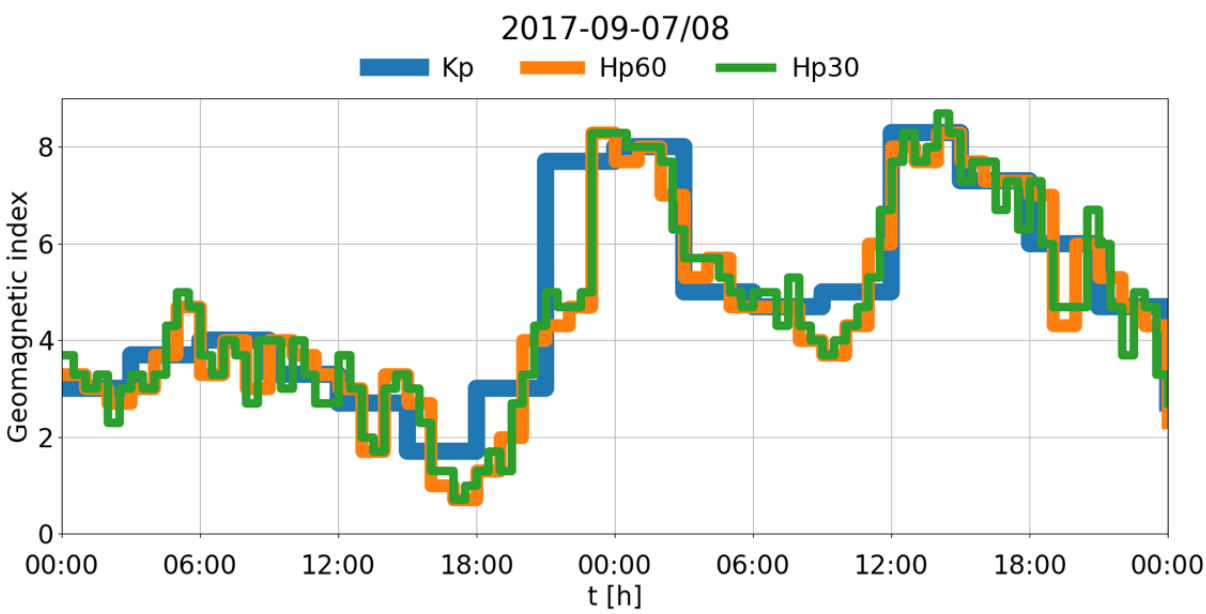

Fig. 2: Shown are *Kp* (blue), Hp60 (orange) and Hp30 (green) for September 7 and 8, 2017. Hp60 and Hp30 correctly identify the starting time of extreme geomagnetic disturbance at 23 UT on September 7, while Kp wrongly shows a starting time at 21 UT. For the other times, *Kp* and the Hpo indices show good agreement. This demonstrates on the one hand the usefulness of an index with higher time resolution than the three-hourly *Kp* index, and on the other hand it demonstrates that the Hpo indices behave indeed *Kp*-like.

Note: We will use the same example for the calculation of hemispheric power, see 'Application 3: Hpo and storm time hemispheric power for ionospheric modeling'.

COMPARISON OF KP AND HPO WITH OTHER GEOMAGNETIC INDICES AND SOLAR WIND PARAMETERS

We compare Kp and Hp30 (our Hpo with the highest time resolution) to the following indices and parameters:

- auroral electrojet index AE (1995 to 2017)
- total current of field-aligned currents measured by the AMPERE satellites (2010 to 2017)
- composite polar cap index PCC (1995 to 2017)
- Newell coupling function dΦ/dt (1995 to 2017)

We cap the open-ended Hp30 at 9 to make it comparable to *Kp*, as *Kp* is only defined for $0 \leq Kp \leq 9$. The correlation coefficient is given for all panels:

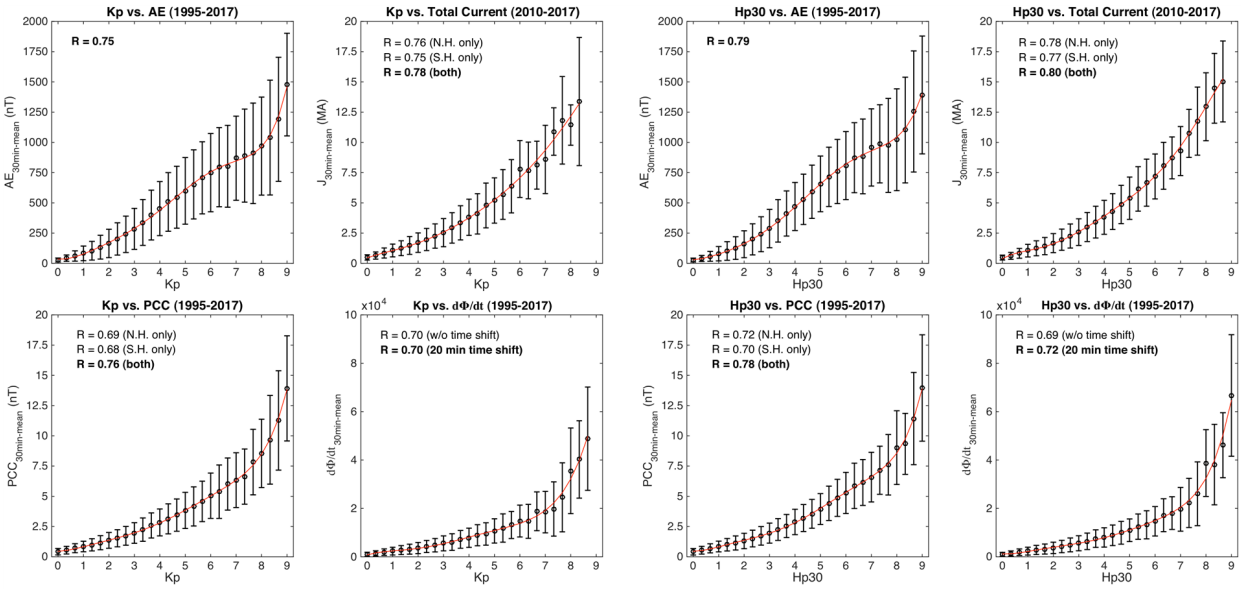

Fig. 3: Four panels on the left side: *s*hown are AE, total current, PCC and dΦ/dt versus *Kp.* Four panels on the right side: *s*hown are AE, total current, PCC and dΦ/dt versus Hp30.

The relationship between AE, total current, PCC and dΦ/dt and *Kp* on the one side and Hp30 on the other side are very similar. This is evidence that Hp30 is indeed a *Kp*-like index. To all four quantities, Hp30 is even slightly better correlated than *Kp* is.

OPEN-ENDEDNESS OF THE INDICES

The concept

To allow for a more nuanced description of the strongest geomagnetic disturbance events, the Hpo indices are open-ended and divide the events with *Kp* = 9 into finer-scaled classes Hp30 or Hp60 = 9, 9+, 10-, 10, 10+, ... The relationship between observed geomagnetic activity and Hpo values ≥ 9 to was determined in a 'trial and error' process and aided by the comparison with other open-ended space weather indicators (see below). Since 1995, the highest observed value for Hp30 and Hp60 was 11.7 during the Halloween storm.

The relationship of Hpo ≥ 9 to geomagnetic activity can be demonstrated by comparing the indices ap30 and ap60, which are linear equivalent amplitudes corresponding to Hp30 and Hp60. For comparison, we also show the ap index, which is the linear equivalent amplitude of *Kp* (multiplying ap by 2 nT gives the average geomagnetic disturbance range at 50° geomagnetic latitude):

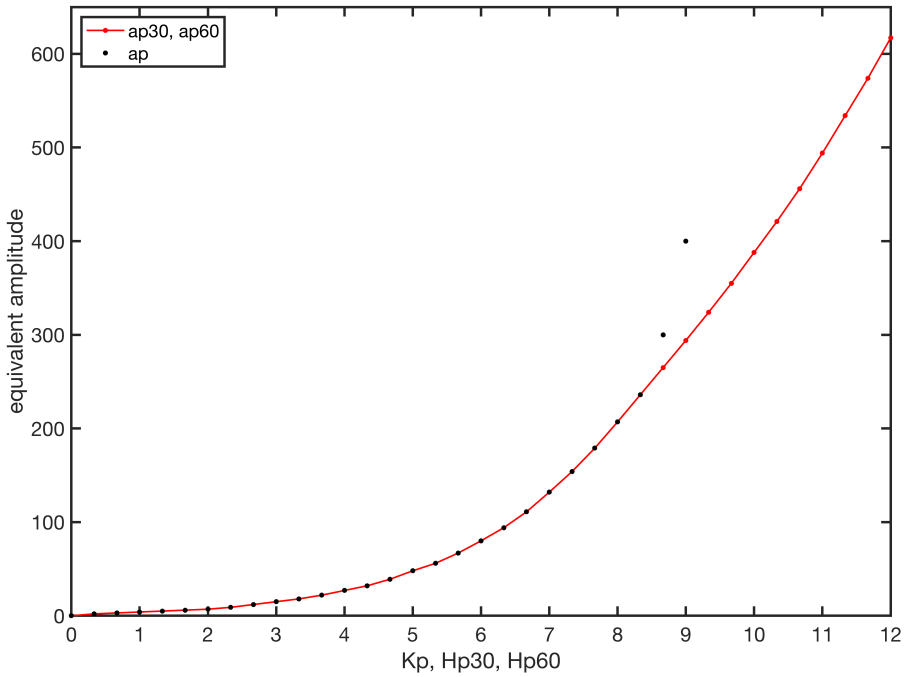

Fig. 4: The relationship ap30 (ap60) versus Hp30 (Hp60) is shown as red line for Hpo up to 12. The ap30 (ap60) is linearly related to the average geomagnetic disturbance range for the given Hp30 (Hp60). The ap index versus *Kp* is shown as black dots: for Kp ≤ 8+, it is identical to ap versus *Kp*.

Comparison with other open-ended space weather indicators

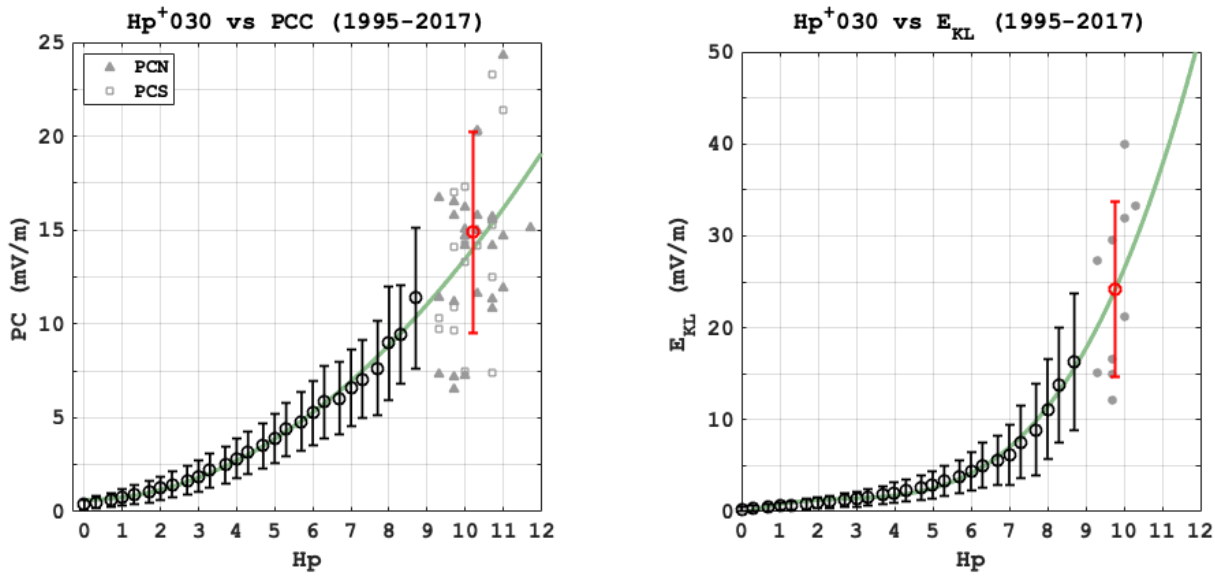

Fig. 5: In order to test, how well our open-ended index is relating to other open-ended indices, we have compared our final version (i.e. the final result from the 'trial and error' process) Hp30 to the polar cap composite index PCC and the merging electric E_{KL} field after Kan and Lee (1979). Solar wind data was time shifted by 20 minutes to account for the propagation from the magnetosphere bow-shock nose to the ionosphere. PCC and E_{KL} are averaged over 30 minutes and the relationship between PCC and E_{KL} with Hp30 is evaluated for Hp < 9 and expressed as third order polynomial (green line). For Hp > 9, the prediction of this third-order polynomial is also plotted, together with data points (grey) of PCN versus Hp30 (left panel) and E_{KL} versus Hp30 (right panel) and their mean (red). The good correspondence of the mean of the data (red) and the prediction (green) indicates, that our relationship between index values and geomagnetic activity that is implicit in our open-ended Hpo indices is reasonable.

APPLICATIONS: HPO AND SUBSTORMS, HPO AND GEOMAGNETIC STORMS, HPO AND STORM TIME HEMISPHERIC POWER FOR IONOSPHERIC MODELING

Application 1: Hpo and substorms

Data

- ap (traditional three-hour index), ap60 and ap30
- SuperMAG substorm list (http://supermag.jhuapl.edu/substorms/)

Method

- Superposed epoch analysis
- Zero-epoch is defined to be the beginning of the time bin that contains the substorm onset given by the SuperMAG list
- Substorms with other substorm onsets in the preceding 6h and following 12h are excluded
- 1846 isolated substorms are found during 1995−2017

Results

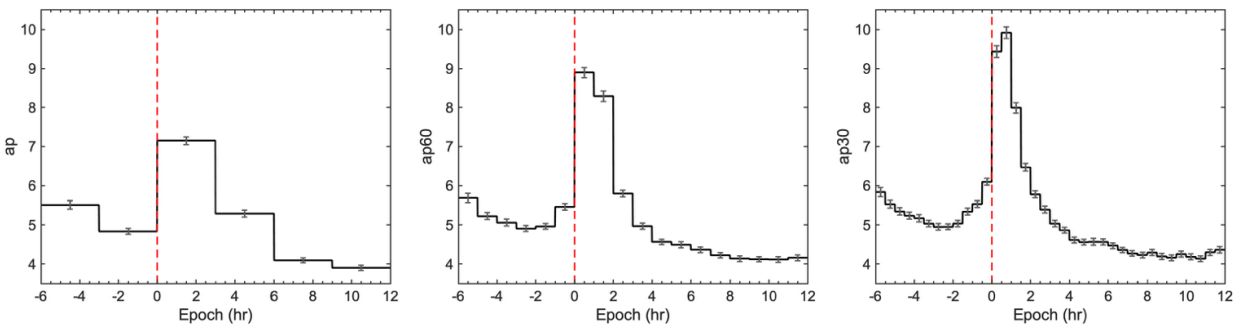

Fig. 6: ap30 (right panel) shows the substorms starting at epoch = 0 more pronounced than ap (left panel) and ap60 (center panel) and reflects best the expected temporal evolution of magnetic disturbances for a substorm at subauroral latitude: the substorm is expressed by a positive bay in H (e.g. McPherron and Chu, 2017) that last for an hour or two.

Thus, ap30 might better be suited than *Kp* to specify forcing by convection electric field, Joule heating and particle precipitation during substorms for atmospheric models like TIE-GCM (Qian et al., 2014). The background level (for -6 to -3 hours and for 6 to 10 hours) is very similar for all three indices, as expected for the *ap*-like ap60 and ap30.

Application 2: Hpo and geomagnetic storms

Data

- *Kp*, Hp90 (a 90 minute index, now discontinued, derived in the same way as Hp60 and Hp30), Hp60, Hp30
- For the five strongest storms in the period 1995 to 2019
- For 7 days around the storm, with day 3 corresponding to storm main phase

Method

- Calculate and compare the occurrence frequencies Kp, Hp90, Hp60, Hp30 for each storm and the storms' composite

- Calculate the three-hourly mean of Hp90, Hp60, Hp30 and their correlation with *Kp* for each storm and the storms' composite

Result

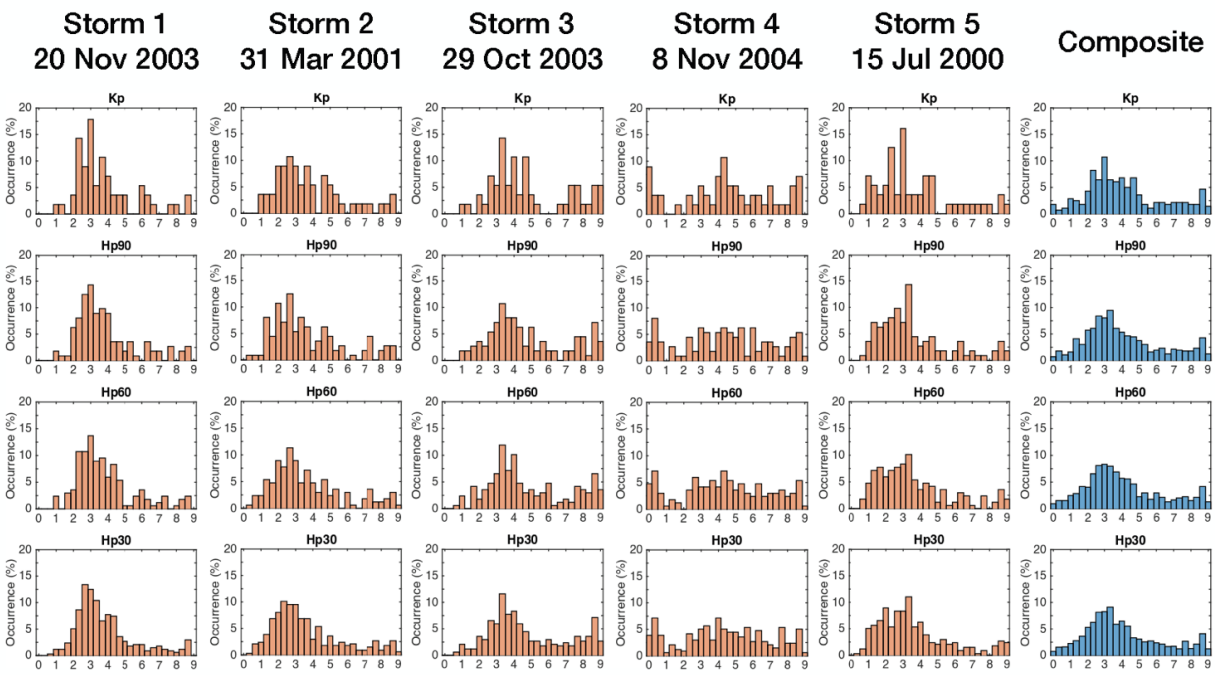

Fig. 7: The frequency distribution of *Kp*, Hp60, Hp30 (and Hp90) is similar for each individual storm and their composite. This is evidence that Hp60 and Hp30 describe geomagnetic storms in a similar way as *Kp*.

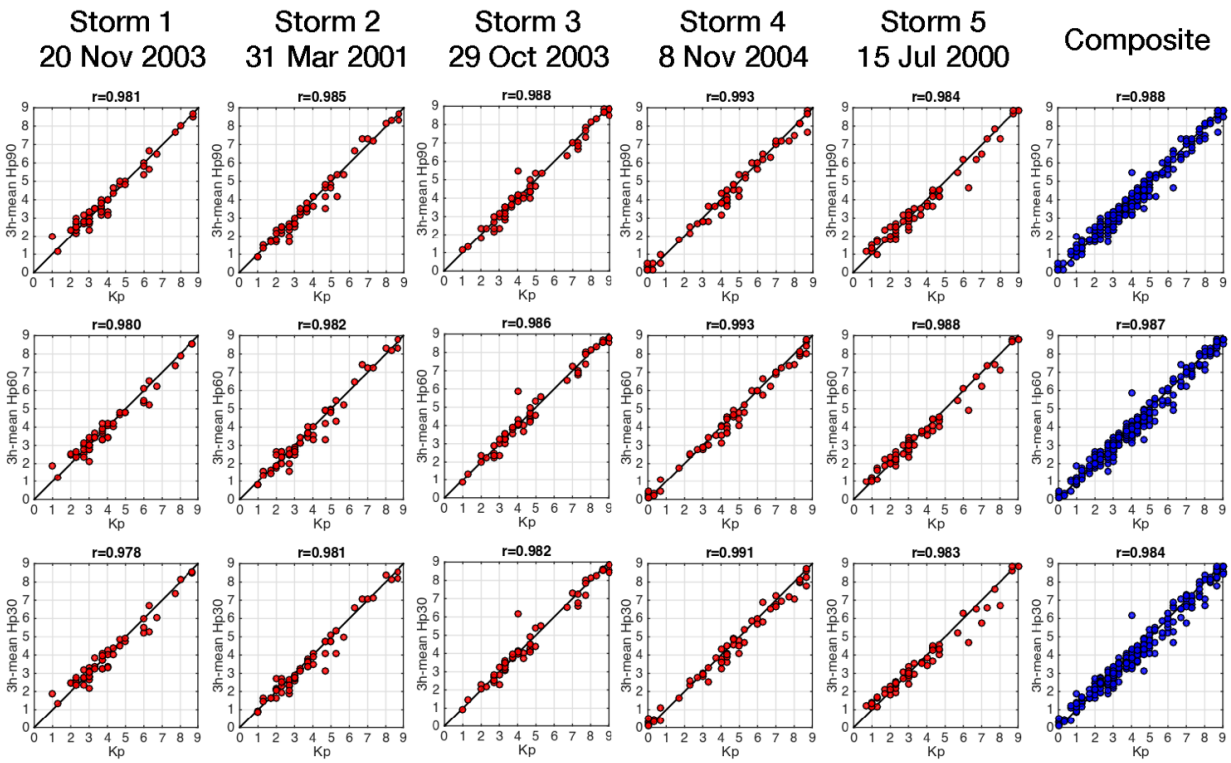

Fig. 8: The three-hourly mean of Hp60 and Hp30 (and Hp90) correlate well with Kp for each individual storm and their composite. This again is evidence that Hp60 and Hp30 describe geomagnetic storms in a similar way as *Kp*.

Application 3: Hpo and storm time hemispheric power for ionospheric

modeling

Data

- *Kp*, Hp90 (a 90 minute index, now discontinued, derived in the same way as Hp60 and Hp30), Hp60, Hp30
- For the two UT-days of geomagnetic storm on September 7 and 8, 2017
- Note: these indices and the geomagnetic observatory data they are based on are shown in the box 'Introducing the Hpo index family (Hp60, ap60, Hp30, ap30'

Method

- Hemispheric power hp (Zhang and Paxton, 2008) is calculated in the same manner as in the TIE-GCM (Quian et al., 2014): the indices *Kp*, Hp90, Hp60, Hp30 are linearly interpolated to the model time step (30 sec) and then the interpolated indices are used with the empirical equation that relates hemispheric power hp and *Kp (from Zhang and Paxton, 2008):*

$$\begin{aligned} &\text{if} \quad Kp \leq 7 \\ &\quad hp = 16.82 \cdot e^{(0.32kp)} - 4.86 \\ &\text{if} \quad Kp > 7 \\ &\quad hp = 153.13 + \frac{kp-7}{9-7}(300 - 153.13) \end{aligned}$$

Result

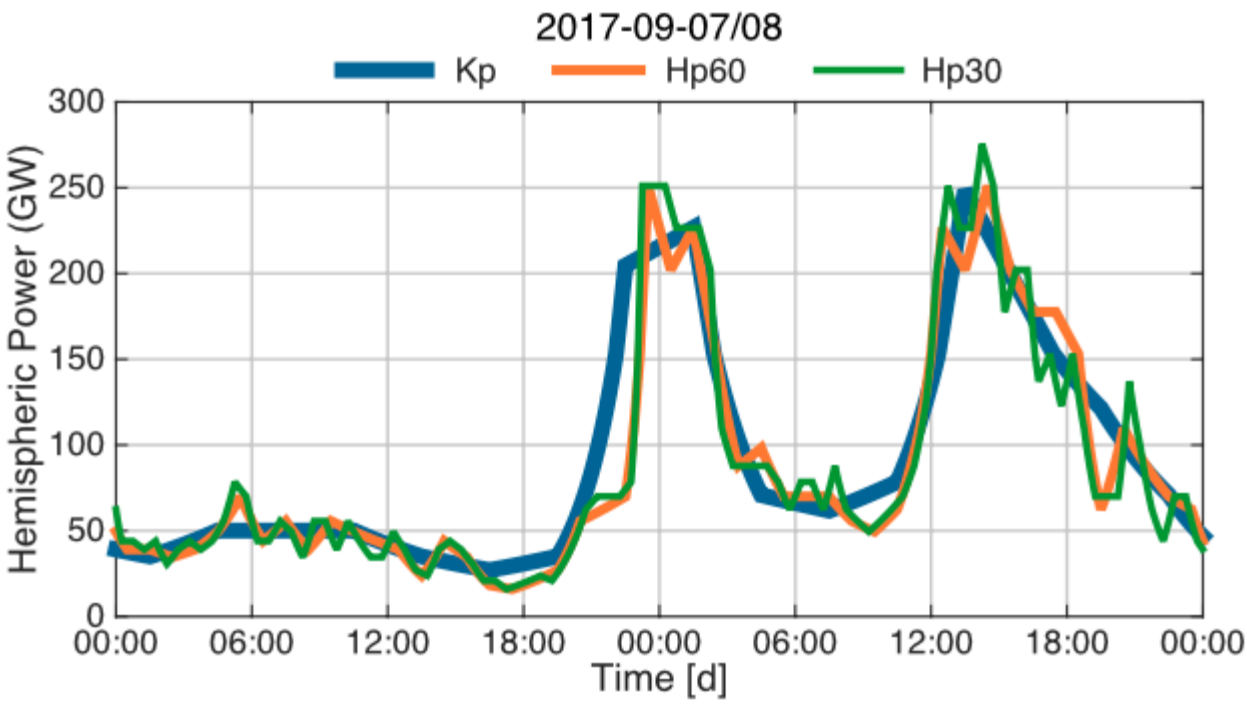

Fig. 9: Shown is hemispheric power calculated from *Kp* and the Hpo indices. As demonstrated in 'Introducing the Hpo index family(Hp60, ap60, Hp30, ap)', extreme geomagnetic disturbance only starts at 23 UT on September 7 and in the time interval 21 UT to 23 UT of that day the Hpo indices give a more realistic picture of geomagnetic disturbance than *Kp* does. Consequently, we can expect that hemispheric power calculated from the Hpo indices is more realistic than hemispheric power calculated form *Kp*. For the other times shown, hemispheric power hp calculated from *Kp* and the Hpo indices agrees well. The time-integrated hemispheric power (i.e. total energy input) for this event from Hp60 (Hp30) is slightly smaller by 4.6% (4.0%) than total energy input calculated from *Kp* and we know that *Kp* is overestimating geomagnetic disturbance and thus hemispheric power in the interval 21 to 23 UT on September 7, 2017. This example again suggests that the *Kp*-like Hpo indices might be a useful input for empirical models of hemispheric power, which are important for forcing of atmospheric models liek TIE-GCM (Quian et al., 2014).

ABSTRACT

We present the new geomagnetic Hpo indices that resembles the widely used three-hourly Kp index, as it is based on the same 13 geomagnetic observatories and has a frequency distribution similar to that of Kp. A notable difference is the increased temporal resolution of one hour for the Hp60 version and half an hour for the Hp30 version of the Hpo. Hpo is open-ended and divides the events with Kp = 9o into a number of index values 9o, 9+, 10-, 10o, etc. Like Kp, which for some purposes is mapped to the linear ap index, our Hpo is accompanied by the linear apo (ap60 and ap30 indices). To assess and validate the new index, we compared it to other geomagnetic indices and solar wind parameters and investigate the index behavior during geomagnetic storms and substorms. We also tested Hpo instead of Kp to determine hemispheric power, which is an important parameter for high latitude forcing to atmospheric models. The index was developed within the H2020 project Space Weather Atmosphere Models and Indices (SWAMI) project.

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