Characterizing Auroral-Zone Absorption Based on Global Kp and Regional Geomagnetic Hourly Range Indices

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Abstract Increased ionization in the auroral oval leads to the absorption of high-frequency radio waves in the auroral zone, or auroral absorption. Auroral absorption is typically characterized by global geomagnetic activity indices, such as the Kp index. In this paper the hourly range of the magnetic field (HR) is examined as an alternative to the 3-hr Kp index for describing the dynamic and localized features of auroral absorption represented by the hourly range of absorption (HRA). Kp, magnetometer, and riometer data were examined for a 3-year period for stations spread across typical auroral latitudes. A general linear relationship was shown to exist between Kp and LOG10(HRA) for Kp < 4; for Kp ≥ 4 the correlation was weaker. A stronger linear correlation was demonstrated between LOG10(HRA) and LOG10(HR) for HR > 50 nT, characterized by a correlation coefficient of R = 0.63. Increased variability in the relationship between HRA and Kp was attributed to the following factors: the variability of the magnetic field within the 3-hr window characterized by the Kp index, which was better represented by a 1-hr HR; the dependence of the Kp index on subauroral magnetic data, which is not subject to the geomagnetic variations typically experienced within the auroral region; and reduced statistics for Kp > 6.

1. Introduction

Energetic electron precipitation due to magnetospheric-ionospheric coupling, occurring on a regular basis and intensified through space weather contributions originating from the Sun, leads to enhanced ionization in the ionosphere at auroral latitudes, causing both ionospheric and geomagnetic disturbances (e.g., Baker et al., 1981; Hargreaves, 1969; Liang et al., 2007; Newell et al., 2001).

At D region altitudes (75–95 km), the precipitation of high-energy (>30 keV) magnetospheric electrons causes a phenomenon known as auroral absorption which impacts the propagation of high-frequency (HF) (3–30 MHz) radiowave signals. Impacted systems include over-the-horizon radar used for long-range surveillance (Thayaparan et al., 2018) and research (e.g., Chisham et al., 2007), and HF communications systems used, for example, by the military, aviation, emergency management, coast guard, and marine transport (e.g., Agy, 1970; Cannon et al., 2013; Coyne, 1979; National Research Council, 2008; Neal et al., 2013; Pirjola et al., 2005). Recognizing the need for an operational advisory service to mitigate the impacts of ionospheric disturbances to aviation, the International Civil Aviation Organization (ICAO) initiated the development of such a service, which began operation on 8 November 2019. ICAO (2018, 2019) specifically identifies auroral absorption as a threat to international aviation.

In general, absorption is a reduction of the signal strength of a transmitted radiowave caused by interactions with ionospheric particles. Absorption is most commonly observed in the D region due to the relatively high concentration of neutral particles and, in particular, is dependent on particle collision frequency and recombination rates. Absorption is enhanced when electron density is increased due to increased ionization. There are three primary sources of D region absorption; each is attributed to a different ionization source: (1) Shortwave fade-out (SWF) is a short-lived (typically <2 hr) daytime phenomenon caused by photoionization by radiation emitted during solar X-ray flares (e.g., Frissell et al., 2014). (2) Polar cap absorption (PCA) is caused by the precipitation of energetic solar protons, usually associated with a coronal mass ejection. PCA events can be long-lived (approximately days), impacting the high-latitude region and reaching as far equatorward as ~60–65° magnetic latitude (MLAT) with primary impacts on the dayside. (e.g., Hargreaves, 2010; Kavanagh et al., 2004). (3) Auroral absorption is caused by the energetic electron precipitation at auroral latitudes. This paper focuses on auroral absorption.
Auroral absorption is a highly structured (spatially and temporally) phenomenon with an occurrence and magnitude that varies in MLAT and magnetic local time (MLT). Auroral absorption typically peaks between 64° and 68° MLAT in both the prenoon (MLT) and midnight sectors (Basler, 1963; Driatsky, 1966; Frank-Kamenetsky & Troshichev, 2012; Hargreaves, 1969; Hartz et al., 1963; Hook, 1968). Substorm activity and related electron precipitation cause the midnight peak (Hargreaves, 2010; Kavanagh et al., 2004), whereas the prenoon peak is caused by the eastward drift of substorm-injected electrons in association with keV-energy diffuse auroral electrons (Kavanagh et al., 2004; Yamagishi et al., 1998). Auroral absorption events (>0.5 dB) last on the order of 1–3 hr (Hargreaves, 2010) and are sporadic and irregular in behavior (Kavanagh et al., 2004). Due to seasonal variation of magnetospheric geometry, absorption events are more frequent and 1.5–2 times stronger in winter months than in summer months (Hargreaves, 1969; Newell et al., 2001; Yamagishi et al., 1998).

Given the impacts of radiowave absorption and reliance on affected infrastructure, it is highly desirable to develop absorption models to accurately describe absorption levels and impacted frequencies. Modeling requires an understanding of the different kinds of D region absorption, which are driven by different space weather phenomenon and have different characteristics. Absorption models do exist for modeling SWF and PCA (e.g., Fiori & Danskin, 2016; Rogers et al., 2016; Rogers & Honary, 2015; Sauer & Wilkinson, 2008). One example includes the D Region Absorption Prediction (D-RAP) model, which is operated by the Space Weather Prediction Center (SWPC) of the National Oceanic and Atmospheric Administration (NOAA) (http://www.swpc.noaa.gov/products/d-region-absorption-predictions-d-rap).

Although an established and widely accepted operational model for auroral absorption has not been incorporated into tools like D-RAP, considerable work has gone into the development of both statistical models and statistical prediction models to characterize auroral absorption parameterized using the Kp or Ap index (e.g. Foppiano & Bradley, 1983, 1984; Hargreaves, 1966, 2007; Hargreaves & Cowley, 1967; Hargreaves et al., 1987; Hartz et al., 1963; Holt et al., 1961; Kavanagh et al., 2004; Rogers et al., 2016). Additional efforts have gone into the development of statistical models to describe energetic electron precipitation using the auroral Ap and AE indices (e.g., van de Kamp et al., 2018, and references therein).

A correlation between ionospheric and ground-based magnetic data during auroral absorption is not surprising, as both are directly related to the dynamics of electrons during magnetospheric disturbances, as discussed in Hargreaves (1969) and Liang et al. (2007). Hargreaves (1966) discusses variation of auroral absorption in terms of geomagnetic activity; as magnetic activity increases, auroral absorption intensifies, and the region impacted by absorption expands and shifts equatorward, similar to the motion of the auroral oval during a geomagnetic intensification (e.g. Starkov, 1994). Enhanced auroral absorption is frequently observed during geomagnetic substorms (e.g., Kellerman & Makarevich, 2011; Sergeev et al., 2020) in association with energetic electron precipitation (Rodger et al., 2013). Additional studies examine the relationship between auroral absorption and magnetic parameters such as the polar cap (PC) index (Frank-Kamenetsky & Troshichev, 2012), solar wind parameters (Kavanagh et al., 2004; Ognomodimu, 2016), the mid-latitude positive bay index (Sergeev et al., 2020), and substorm-related phenomenon (e.g., Baker et al., 1981; Spanswick et al., 2005). Frank-Kamenetsky and Troshichev (2012) demonstrate the advantage of magnetic indices over magnetic field time series for comparing magnetic and ionospheric data. By reducing variations in the ionospheric data over 1 hour to the 1-hour maximum they were able to draw comparisons between the PC index and auroral absorption. Frank-Kamenetsky and Troshichev (2012) argue that the use of a 1-hr maximum accounts for any existing delays between the mechanisms leading to enhancements in the PC index and particle precipitation into the auroral region.

In this paper we focus on parameterization of auroral absorption derived from riometer observations by ground-based magnetic data (both global and local indices). One aspect of this paper is to investigate the accuracy of using the Kp index to describe auroral absorption. Kp is a global index, whereas auroral absorption has been shown to be a more localized phenomenon with characteristic enhancements in the prenoon and midnight sectors at auroral latitudes. Also, as Kavanagh et al. (2004) point out, Kp is a 3-hr index incapable of capturing the dynamic nature of auroral absorption. This need for a higher time resolution model to capture auroral dynamics is echoed in Sergeev et al. (2020). Finally, Kp represents the variation of the geomagnetic field at subauroral latitudes, where its contributing stations are located. However, at auroral...
latitudes, geomagnetic activity is largely driven by the precipitation of energetic electrons, which is not necessarily the dominant signal at sub-auroral stations.

Another aspect of this paper is to examine the relationship between the global Kp index and the magnetic field hourly range (HR) at individual observatories with absorption observed locally at auroral latitudes. Localization of the magnetic field variations that go into the Kp index can be achieved by examining the underlying measurements, specifically the range of the magnetic field at individual observatories. In particular, we consider the range of the horizontal components of the magnetic field determined over 1 hr and make comparisons to the range of the absorption observed over the same interval for colocated stations. Such an approach will potentially remove the limitations of a global 3-hr subauroral index to characterize a more local and dynamic auroral phenomenon.

This paper is organized as follows: Section 2 describes the instrumentation and data used in the analysis, section 3 presents the results of the study, which is followed by the discussion in section 4 and conclusions and further recommendations in section 5.

2. Data and Instrumentation

Canada provides an ideal landscape for auroral absorption studies due to the significant number of colocated riometer and magnetometer sites with instruments distributed across a wide band of latitudes spanning polar cap, auroral, and subauroral regions.

In an attempt to quantify the general relationship between absorption and geomagnetic data, 1-hr variations in both data sets are considered by comparing the hourly range of absorption (HRA) data, determined by subtracting the maximum and minimum absorption in a 1-hr period, to both Kp (general 3-hr index) and HR (local 1-hr index), as described below.

Figure 1 shows the location of the Canadian stations with colocated riometer and magnetometer instruments. The riometer station located at Fort Churchill (FCC) is operated by the University of Calgary (U of C) as a part of the Geospace Observatory Riometer Network (GO-RIO) (Rostoker et al., 1995). Riometer stations located at Cambridge Bay (CBB), Yellowknife (YKC), Baker Lake (BL), Iqaluit (IQA), Meenook (MEA), Sanikiluaq (SNK), and Ottawa (OTT) are operated by the Natural Resources Canada (NRCan) network (Danskine et al., 2008; Lam, 2011). All geomagnetic observatories are operated by NRCan. Note the high concentration of stations within the typical location of the auroral oval (yellow shading). All riometer and magnetometer data available for the BLC, CBB, IQA, MEA, SNK, and YKC stations for 2015–2017 were considered. Additionally, the FCC magnetometer (NRCan) and riometer (U of C) data were considered for the 2001–2003 (prior to the installation of the NRCan riometers) to increase the data set in an attempt to incorporate periods of higher geomagnetic activity. The FCC data were not considered during the 2015–2017 period due to excessive noise contamination of the riometer data. Magnetometer data for the OTT station are presented for discussion in Section 4. Table 1 lists the station coordinates and the data collection period considered for this study. In Table 1 geomagnetic latitude is presented in the altitude-adjusted corrected geomagnetic coordinate system (AACGM) (Shepherd, 2014).

2.1. Absorption Data

Absorption is quantified using the opacity of the ionosphere to cosmic radio noise from extraterrestrial sources as measured by a relative ionospheric opacity meter, also known as riometer. Rimeters measure a signal in volts. Deviation of the measured voltage from a quiet day value or quiet day curve (NORSTAR, 2014), expressed in decibels, gives absorption. During quiet periods, absorption is near zero at 30 MHz, which is the operating frequency of riometers used in this study, but peaks of up to 6 dB have been observed with auroral absorption (Nielsen & Honary, 2000).

Rimeters considered in this study have a dual-dipole broad-beam (wide-beam) antenna operating at 30 MHz and detect absorption over an area spanning an ~100-km diameter within the ionosphere over the riometer. Data are provided at a 1-s resolution. Due to the relative manner in which absorption is determined (i.e., deviation from a quiet day curve value), low absorption values of <0.2 dB were discarded from this study (e.g., Foppiano & Bradley, 1984).
Riometer data were filtered to remove noise contamination, environmental noise, and instrument failure. Noise contamination in the riometer data was removed first by filtering the data set for periods where the absorption was consistently <0.2 dB and then by removing periods where the HRA was <0.1 dB.

2.2. Geomagnetic Data

Magnetic data used in this study were obtained from the NRCan Canadian Magnetic Observatory System (CANMOS) (https://geomag.nrcan.gc.ca/obs/canmos-en.php). CANMOS is composed of 14 magnetic observatories distributed throughout Canada operating fluxgate magnetometers (Serson, 1957) to observe variations in the intensity of the Earth’s magnetic field, and a proton magnetometer. Data are reported in three orthogonal components ($X$, $Y$, $Z$) in a geodetic coordinate system representing the north ($B_x$), east ($B_y$), and radially inward ($B_z$) magnetic field components. Data from the fluxgate magnetometer are sampled at a frequency of 8 Hz, despiked, and resampled to 1 Hz using a 9-point rectangular filter. The 1 Hz data are

![Figure 1. Geographic location of colocated riometer and magnetometer instruments. Yellow shading indicates the approximate location of the auroral oval, bounded by 63° and 77° magnetic latitude.](image)

| Station         | Abbreviation | Geographic latitude | Geographic longitude | AACGM latitude | Data collection |
|-----------------|--------------|---------------------|----------------------|----------------|-----------------|
| Baker Lake      | BLC          | 64.3°               | 264.0°               | 72.9°          | 2015 – 2017     |
| Cambridge Bay   | CBB          | 69.1°               | 255.0°               | 76.4°          | 2015 – 2017     |
| Fort Churchill  | FCC          | 58.8°               | 265.9°               | 68.7°          | 2001 – 2003     |
| Iqaluit         | IQA          | 63.7°               | 291.5°               | 71.3°          | 2015 – 2017     |
| Meanook         | MEA          | 54.6°               | 246.7°               | 61.4°          | 2015 – 2017     |
| Sanikiliuaq     | SNK          | 56.5°               | 280.8°               | 65.5°          | 2015 – 2017     |
| Yellowknife     | YKC          | 62.5°               | 245.5°               | 68.9°          | 2015 – 2017     |
| Ottawa          | OTT          | 45.4°               | 284.8°               | 54.4°          | 2015 – 2017     |
filtered again using a 49-point Gaussian filter and resampled to a 5-s resolution to match the frequency of the proton magnetometer data. The 5-s data are filtered one more time using a 19-point Gaussian filter and resampled at a 1-min interval. The 1-min data are used in this study.

The Canadian Space Weather Forecast Center uses an additional magnetic parameter called the magnetic field HR to characterize magnetic activity (Hruska & Coles, 1987; Trichtchenko et al., 2009). To calculate the HR, the X and Y components of the horizontal magnetic field are considered. For each component, the difference between the maximum (HR_{X,MAX}, HR_{Y,MAX}) and minimum (HR_{X,MIN}, HR_{Y,MIN}) magnetic field data is determined based on 1-min magnetic field values over a period of 1 hr such that HR_{X} = HR_{X,MAX} - HR_{X,MIN} and HR_{Y} = HR_{Y,MAX} - HR_{Y,MIN}. The final HR values used in this study are the maximum of HR_{X} and HR_{Y} and represent the maximum magnetic field perturbation observed. By definition, HR is a positive value, removes the effects of long-term secular variation, and minimizes the effects of slowly varying current systems such as the solar quiet (Sq) current system (which is relatively weak at high latitudes). HR smooths rapid-scale variations in the magnetic field while maintaining large-amplitude wave structures to provide an overall characterization of magnetic field activity.

2.3. Kp Index

The Kp index characterizes global magnetic activity based on the magnetic perturbation at 13 different magnetic observatories distributed across the globe at primarily subauroral latitudes (e.g., https://www.gfz-potsdam.de/en/kp-index/; Menvielle & Berthelier, 1991). For each station, the range of the magnetic disturbance is determined for the two horizontal magnetic field components, after subtracting Sq variations, in eight 3-hr intervals. The more disturbed component is converted to a quasi-logarithmic scale ranging from 0 to 9 using a data table specific to each location to determine the local K-index for each station. The scaling is done so that the station K-index frequency distributions from all observatories are approximately the same. The K-index is a local index specifically indicative of activity at the location of the observatory. Conversion tables are used to convert the K-index to the standardized Ks index, which also varies from 0 to 9, but is broken into thirds. For example, Ks = 3−, 3o, and 3+ corresponds to 3 − 1/3, 3, and 3 + 1/3, respectively. Standardization eliminates seasonal and local time effects. The Kp index is determined as the average value of the Ks index values for the 13 stations. Kp < 3 corresponds to quiet conditions, Kp 5–6 represents moderate to strong conditions, and Kp > 8 is considered severe to extreme. All Kp data used in this study were obtained from the National Geophysical Data Centre (NGDC) (ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC_DATA/INDICES/KP_AP/).

2.4. Data Filtering

The data set was filtered to evaluate auroral absorption by removing periods contaminated by PCA and SWF. PCA event periods were identified using the solar proton event (SPE) list maintained by the NOAA SWPC (located at ftp://ftp.swpc.noaa.gov/pub/indices/SPE.txt). For each event in the SPE list, data corresponding to times between the SPE start time (rounded back to the nearest hour) and the SPE end time (rounded ahead to the nearest hour) were removed. In the 2015–2017 time period, there were only four SPE events in the list. An additional PCA event, apparently missing from the SPE list, was included for filtering: 10 September 2017 17:00 UT to 13 September 2017 20:00 UT. This was a relatively significant event with a >10 MeV solar proton flux peaking at 1071.8 pfu with observable impacts to HF radiowave propagation (Frissell et al., 2019; Redmon et al., 2018). The 2001–2003 period was a much more active time in the solar cycle, and data corresponding to 50 events were removed.

Data on solar X-ray flares were obtained from the NOAA NGDC in the form of Geostationary Orbital Environmental Satellites (GOES) X-Ray Sensor (XRS) reports, which are available by year from 1975 onward (https://www.ngdc.noaa.gov/ftp-space/weather/solar-data/solar-features/solar-flares/x-rays/goes/xrs/). All periods potentially contaminated by SWF due to “M” and “X” class flares were removed. For each solar X-ray flare, data between the flare start time (rounded back to the nearest hour) and the flare end time (rounded ahead to the nearest hour) were removed. For the joint 2001–2003 and 2015–2017 periods, data corresponding to 742 and 142 M- and X-class solar X-ray flares were removed, respectively.

Additional filtering was performed to ensure data were limited to the auroral region where auroral absorption is expected to be observed. The auroral zone was modeled using the Starkov (1994) auroral boundary
model as summarized in Sigernes et al. (2011). The Starkov (1994) model provides the poleward and equatorward boundary of the auroral oval (used in this study) as well as the equatorward boundary of the diffuse aurora (not used in this study). The MLAT and MLT for each data point were evaluated against the auroral oval boundaries calculated for the observed $Kp$ value to eliminate points expected to be outside of the auroral oval.

Figure 2 shows the poleward and equatorward boundaries of the Starkov (1994) auroral oval for $Kp = 1, 2, 3 \ldots, 9$. As the geomagnetic activity level increases, both boundaries expand to more equatorward latitudes. Overplotted are possible locations of the riometers considered in this study for a period when the Canadian sector is centered over the nightside. The CBB station is generally poleward of the auroral region, with the exception of a brief period near 12 MLT for $Kp \leq 2$. The BLC station straddles the poleward boundary of the auroral oval, drifting in and out of the auroral zone depending on geomagnetic activity level and MLT. The IQA and FCC stations are almost entirely located within the auroral zone. In the orientation illustrated in Figure 3, the SNK and MEA stations are located within the auroral zone for $Kp \geq 2$ and $Kp \geq 5$, respectively, but briefly shift equatorward of the auroral zone on the dayside into the evening sectors. The auroral location of the MEA station is interesting when considering that MEA is one of the 13 stations contributing to the $Kp$ index, a point also made by Menvielle and Berthelier (1991). The OTT station, discussed in section 4, is located entirely equatorward of the auroral region.

3. Results

Analysis of the correlation between magnetometer and riometer observations begins with the qualitative examination of specific fluctuations for a single event. The comparison is generalized to consider larger-scale fluctuations through comparison of magnetometer-derived products such as the $Kp$ index and the HR.

Riometers respond to changes in the ionospheric electron density due to increased ionization, whereas magnetometers respond to local magnetic disturbances that result from electric currents flowing through the regions of enhanced ionization. A one-to-one relationship between absorption and magnetic data is not expected. Riometers used in these studies have a limited field of view centered above the riometer location with a focus on the $D$ region phenomenon, whereas the magnetometers react to auroral electrojet currents flowing at a slightly higher altitude of ~100 km influenced by ionospheric and magnetospheric processes also acting outside of the riometer field of view. For this reason, a correlative, rather than exact, relationship between absorption and magnetic field is typically investigated through magnetic indices in contrast to direct comparisons with the magnetic field time series.

3.1. Event Study: 7 January 2015

As an example, consider Figure 3, which illustrates variations in the horizontal $X$ (north) and $Y$ (east) components of the magnetic field observed at Baker Lake on 7 January 2015. Figure 3 (bottom) shows the absorption observed by the colocated BLC riometer. Large perturbations in the $X$ and $Y$ components of the magnetic field on the nightside shortly after 9 UT correspond to large perturbations in the absorption. Both instruments observe activity having a quick onset lasting roughly 1.5 hr, but the riometer and magnetometer traces do not match exactly. This example illustrates that a general relationship is observed between
absorption and magnetic data; there is no one-to-one correspondence between the minute-by-minute small-scale fluctuations in the data.

3.2. Distribution of $K_p$, $HR$, and $HRA$

Figure 4 shows histograms of the $K_p$ index, $\log_{10}(HR)$, and $\log_{10}(HRA)$ and probability distribution functions (PDFs) of $K_p$, $HR$, and $HRA$ for the data set under consideration. Black bars and black filled circles are for the overall data set, prior to filtering out PCA and SWF events, for all MLATs and MLTs, and blue filled circles in Figures 4d–4f indicate the PDF for the filtered data set. Data with $HRA < 0.1$ dB in Figures 4c and 4f have been removed to avoid noise contamination. Note that since $K_p$ is already quasi-logarithmic by definition, the x-axis for the $K_p$ histogram and the $K_p$ PDF is not logarithmic. Red curves in Figures 4a–4c represent the best fit normal distribution.

Figures 4a and 4d show the $K_p$ distributions. The histogram plot for the overall data set is consistent with a lognormal ($K_p$ is quasi-logarithmic) distribution peaking at $K_p = 1$ and falling off rapidly as activity level increases. Observation of a lognormal distribution is consistent with the result of Mayaud (1976), who demonstrated a log-normal distribution in the $K$-index for two subauroral stations. Based on the PDF in Figure 4d, there is a minor separation between the filtered and unfiltered data sets; there is a slight reduction in low $K_p < 2$ data and high $K_p > 7$, and an increase in the distribution for $K_p = [2, 7]$.

The shift in the distribution for the filtered and unfiltered data sets can be explained through an understanding of the phenomenon and $K_p$. Filtering based on auroral oval location reduces the data set to 30% of its original size. Given the shape of the auroral oval, illustrated in Figure 2, the reduced data predominately corresponds to the nightside where geomagnetic activity level is expected to be enhanced. The only exception is for the CBB station, which, due to its high-latitude location, is only located within the auroral oval on the dayside between 10 and 15 MLT. The overall rise in the occurrence of $K_p = [2, 7]$ is not surprising. Why this effect does not expand to $K_p > 7$ can be explained by the removal of PCA events.
If filtering is limited to the removal of PCA and SWF data only, and filtering by location with respect to the auroral oval boundary is ignored, then the distributions completely overlap for $K_p \leq 6$, and the filtered distribution is slightly lower than the overall distribution for $K_p > 6$. This shift is expected as longer-duration expulsions of solar energetic particles that cause PCA are often associated with a coronal mass ejection (CME), which can cause strong geomagnetic activity, and therefore high $K_p$, once it reaches the Earth (e.g., Desai & Giacalone, 2016). Removing periods of PCA removes these intervals.

Distributions of HR are shown in Figures 4b and 4e. Similarly to that for $K_p$, the HR histogram plot is consistent with a lognormal distribution peaking at $\log_{10}(HR) = 1.65 \log_{10}(nT)$, corresponding to 44 nT, and falling off rapidly with both increasing and decreasing HR. This is also consistent with similar HR distributions presented in Danskin and Lotz (2015). Figure 4e shows that filtering the data set causes a dramatic reduction in the distribution of points for $\log_{10}(HR) < 1.6 \log_{10}(nT)$ ($HR < 40$ nT) and an enhancement of the distribution for $HR > 40$ nT. Geomagnetic activity, and therefore HR, is expected to be enhanced in the auroral region (e.g., Danskin & Lotz, 2015), resulting in the loss of data for low HR and a shift in the distribution for larger HR. The gap between distributions is largest from 2.0 to 3.0 $\log_{10}(nT)$ (100–1,000 nT). As HR increases above 1,000 nT, the overall data set is dominated by auroral data, and the distributions begin to converge. This shift in HR after filtering is strongly observed for the MEA and SNK stations and to a somewhat lesser extent for FCC and then YKC. Distributions for BLC and IQA (not shown) show very little difference between prefiltered and postfiltered data. The MEA, SNK, and FCC stations are located at the lowest latitudes and are therefore more likely than the other stations to be located in the subauroral region where HR < 100 nT are more common.
Interestingly, the highest HR are removed through filtering based on the auroral oval boundaries defined by Starkov (1994), suggesting that magnetic activity is more widespread than the defined auroral oval boundaries suggest. Some of the discrepancy can be attributed to the characterization of the auroral oval by $K_p$, which varies more slowly than geomagnetic activity and the actual auroral oval boundary.

Figures 4c and 4f show the distributions for $\text{LOG}_{10}(\text{HRA})$. Similarly to that for HR and $K_p$, the distribution for HRA is also lognormal. Note that there is a slight skew to the distribution due to the filtering of data $<0.1$ dB. The distribution peaks at $\text{LOG}_{10}(\text{HRA}) = -0.4 \text{ LOG}_{10}(\text{dB})$, or $-0.4$ dB. Unlike that for HR and $K_p$, there is very little difference between the filtered and unfiltered data set. Some $>5$-dB ($>0.7 \text{ LOG}_{10}(\text{dB})$) HRA are removed with filtering; these points are associated with PCA. However, several $>5$-dB intervals remain, which can be attributed to auroral absorption.

### 3.3. Comparison of HRA and $K_p$

Auroral absorption models typically characterize the level of absorption by $K_p$. Figure 5 shows the relationship between $\text{LOG}_{10}(\text{HRA})$ and $K_p$ for each riometer station and for the entire data set. A logarithmic relationship was evaluated due to the logarithmic nature of $K_p$ (see section 2.3). An occurrence frequency plot is used where data are binned by $1/3 K_p$ and 0.05 $\text{LOG}_{10}(\text{dB})$, and the number of points within each bin is indicated by a color corresponding to the color bar to the right of the plot. Occurrences of zero are not plotted. Due to its high-latitude location, data for the CBB station are only available for $K_p < 2$. For larger $K_p$, the auroral oval shifts to lower latitudes, excluding CBB. Conversely, data for the YKC, FCC, SNK, and MEA stations are only available for $K_p > 1$, 2, 4, and 4+, respectively, due to the lower-latitude locations of the stations. As $K_p$ drops below these thresholds the auroral oval contracts such that the equatorward edge is poleward of these stations. Only the BLC and IQA stations are entirely within the auroral boundaries.

Focusing on the BLC, IQA, YKC, FCC, and SNK stations, there is a dense distribution of data, primarily between $K_p ≥ 1$ and $K_p ≤ 4$. This distribution is elongated along a straight line. Overall correlation between $\text{LOG}_{10}(\text{HRA})$ and $K_p$ is relatively poor with $R < 0.50$ due to the spread in the data. For $K_p < 1$, the lack of correlation between $\text{LOG}_{10}(\text{HRA})$ and $K_p$ suggests that auroral absorption is not regularly observed for such low levels of geomagnetic activity, which is to be expected.

Reduced agreement for $K_p > 4$ can be largely attributed to an overall reduction in the data set for $K_p > 4$. Approximately 87% of the data are weighted to periods of $K_p ≤ 4$. The limited occurrence of $K_p > 4$ is due to the low geomagnetic activity levels associated with the 2015–2017 period considered here during which time colocated riometer and magnetometer measurements are available compared to previous solar cycles. The 2001–2003 period considered for the FCC data set helped to bolster these statistics as the interval was of higher overall geomagnetic activity. Unfortunately, many of these periods of high geomagnetic activity had to be removed from the data set as they occurred during periods of PCA and absorption could not be entirely attributed to auroral absorption. Uncontaminated $K_p > 7$ data were available over limited periods: 20 March 2001; 1–2 and 4 October 2002; 18 August 2003; 14 October 2003; 20 November 2003; 17 March 2015; 22–23 June 2015; and 7 October 2015.

Black filled circles and vertical lines indicate the average and standard deviation of $\text{LOG}_{10}(\text{HRA})$ in bins of $1/3 K_p$ (see Tables A1 and A2 in the Appendix). Correlation improves significantly for all but the CBB and MEA stations to $R > 0.85$ when considering the binned data. As with the overall distribution, these points follow a relatively straight line until $K_p > 4$, where the data appear to plateau. This plateau is visible in the BLC, IQA, YKC, FCC, and, to a lesser extent, SNK data sets. The standard deviation of data averages is greater for $K_p > 4$ than for $K_p < 4$. Figure 6 shows a comparison between binned data sets in Figure 5. Plateauing for $K_p > 4$ is very clear. The CBB, BLC, IQA, FCC, and MEA data sets closely overlap. Importantly, the FCC data, which were derived from a different riometer network, during a different solar cycle, is consistent with NRCan data for 2015–2017, closely overlapping with BLC data (the station closest in longitude) for $K_p < 4$ + before plateauing. Between $K_p = 3$ + and $K_p = 6$, FCC data are very similar to IQA (the station closest in MLAT) data. Data for the SNK and YKC stations show slightly higher values of $\text{LOG}_{10}(\text{HRA})$ than are observed at other stations. Although SNK and YKC are separated by $35^\circ$ longitude, they are located at similar MLATs in the central auroral oval, which could cause the deviation. FCC has a similar latitudinal location but is part of a different array and period of observation, explaining the
inconsistency with SNK and YKC. Both YKC and SNK have a lower overall occurrence rate than have the other stations, which could also contribute to the difference.

Although Figures 5 and 6 represent a reasonable relationship between LOG$_{10}$(HRA) and $Kp$, the spread in the data, demonstrated in Figure 5 cannot be ignored, particularly for >1 dB absorption. Based on the plot for all data, the probability of observing >1 dB absorption is roughly equivalent at $Kp = 1$ and $Kp = 6$; the likelihood of observing $A = 3$ dB is roughly the same for $Kp = 2$ to 5+.

**Figure 5.** Occurrence density of LOG$_{10}$(HRA) versus $Kp$ for the filtered data for BLC, CBB, IQA, MEA, SNK, and YKC for 2015–2017, for FCC for 2001–2003, and for the entire data set (ALL). Black filled circles and vertical lines indicate the mean and standard deviation of LOG$_{10}$(HRA) in bins of 1/3 $Kp$. Mean values are only plotted if at least 10 points were observed in the bin. Correlation coefficient ($R$) is indicated for all data in the plot and for the binned data.
The relationship between $K_p$ and HRA was further analyzed by considering conditional distributions in terms of both $K_p$ and HRA. Figure 7a shows the normalized distribution of $\log_{10}(\text{HRA})$ separately for $K_p = 0, 1, \ldots, 7$. Distributions for $K_p = 8$ and $K_p = 9$ are not included due to the lack of data. For $K_p \leq 2$, the distributions have identical peaks and very similar spreads. As $K_p$ increases above 4, there is a slight shift in the distribution peak and in the maximum boundary of the distribution, but there is still a large density of data for low HRA. Figure 7b shows the normalized distribution of $K_p$ for different levels of $\log_{10}(\text{HRA})$. In this distribution there is a clear shift in the peak of the distribution with increasing $\log_{10}(\text{HRA})$, shifting from $K_p = 1$ in the lowest distribution to $K_p = 4$ in the highest distribution. These distributions further demonstrate that larger $K_p$ values correspond to larger $\log_{10}(\text{HRA})$.

Kavanagh et al. (2004) also examine the relationship between $K_p$ and absorption and infer a quadratic empirical relationship between parameters, with an MLT dependence on the observed fit. Rather than quantifying the exact nature of the relationship, we instead compare the relationship between $K_p$ and HRA to that of HR and HRA.

### 3.4. Comparison of HRA and HR

Figure 8 shows the relationship between HRA and HR in the same format used in Figure 5. For consistency with the $K_p$ index, Figure 8 data are plotted logarithmically. Figure 8 shows occurrence density plot based on data for each station independently and for all stations together (ALL). Data in the occurrence plots are binned by $0.1 \log_{10}(\text{nT})$ in $\log_{10}(\text{HR})$ and $0.05 \log_{10}(\text{dB})$ in $\log_{10}(\text{HRA})$. For $HR < \sim 50 \text{nT} (\log_{10}(\text{HR (nT)}) \sim 1.7)$, there is no correlation between HRA and HR; HRA varies between 0.1 and 1.0 dB with no indication of a dependency. Aural absorption is not regularly observed for such periods of low geomagnetic activity, and there is very little data to support a relationship. This lack of relationship is best illustrated for CBB, which is only located within the auroral oval on the dayside and therefore does not typically observe aural absorption. As HR increases above 50 nT, a clear linear dependence between HR and HRA evolves ($R = 0.63$ for ALL for $HR > 50 \text{nT}$), which is maintained as HR reaches a maximum value of $\sim 2,300 \text{nT}$.

Relationships observed between HR and HRA are more pronounced when considering the average and standard deviation of $\log_{10}(\text{HRA})$ in bins of $\log_{10}(0.1 \text{nT})$ for $\log_{10}(\text{HR})$ (black filled circles and vertical lines in Figure 8, see Tables A3 and A4 in the Appendix). These data are overplotted in Figure 9. Data for each station follow very similar trends. Importantly, this consistency demonstrated for the FCC data set shows agreement between both the U of C instrument and the NRCan instruments and the 2001–2003 data set with the 2015–2017 data sets. FCC data most closely overlap with the BLC data set for $\log_{10}(\text{HR}) < 2.7$. As HR enhances, BLC data are no longer available, but the FCC data follow trends similar to those of SNK and YKC. As in Figure 6, data for YKC and SNK are slightly elevated compared to the overall data set, although the difference is much less pronounced. Notably, the IQA data are also elevated between $\log_{10}(\text{HR}) = [1, 2]$; IQA riometer data can be noisy and contaminated with spikes. Although efforts were taken to adequately filter the data, this could have resulted in some inconsistently high HRA values and may account for some of the discrepancy. Higher HRA at IQA was also demonstrated in Figure 5 for $K_p < 2$ where auroral activity is less likely and noise contamination would therefore stand out over auroral absorption, explaining why IQA shows better agreement with other stations for $K_p > 2$.

Based on descriptions on the Canadian Space Weather Forecast Center short-term magnetic review and forecast website (https://spaceweather.gc.ca/forecast-prevision/short-court/sfst-fr.php), HR values of $<50 \text{nT}$ correspond to “quiet” or low levels of geomagnetic activity, which is the most frequently observed geomagnetic activity level in all zones (polar cap, auroral, and subauroral) (Danskin & Lotz, 2015). The spread in absorption data is not surprising as there is little “additional” electron precipitation during quiet geomagnetic conditions. As geomagnetic activity levels increase to more active conditions, the HRA changes due to auroral absorption, explaining the change in dependency seen in Figure 8.
Importantly, the distribution illustrated in Figure 8 does not show the same spread in absorption that was observed in Figure 5: 96% of data for HRA > 1 dB correspond to periods of HR > 50 nT.

4. Discussion

This paper presents a characterization of auroral absorption based on global and local geomagnetic indices. Figures 5 and 8 demonstrate the relationships between HRA and $Kp$ and HRA and HR, respectively. Although there appears to be an overall trend of increasing HRA with increasing $Kp$ for $Kp \leq 4$, a relationship beyond $Kp = 4$ is not clear due to a plateauing in the data, possibly caused by a lack of statistics for large $Kp$. Regardless, the considerable spread in the data demonstrates that $Kp$ is not a strong parameter for characterizing auroral absorption. HR showed a more promising relationship with HRA. As geomagnetic activity reached active conditions (>50 nT) at auroral latitudes, $\log_{10}(\text{HRA})$ was shown to increase linearly with

Figure 7. (a) Conditional distribution of $\log_{10}(\text{HRA (dB)})$ for incremental values of $Kp$. (b) Conditional distribution of $Kp$ for incremental values of $\log_{10}(\text{HRA (dB)})$. 
LOG$_{10}$ (HR). Notably, the spread in the data set was considerably reduced from that found between LOG$_{10}$ (HRA) and $K_p$.

The global $K_p$ index was considered as $K_p$ is used by ICAO for defining moderate and severe levels of auroral absorption. HR was selected as a local substitute for $K_p$ due to its long time use by the Canadian Space Weather Forecast Center (also called the Geomagnetic Laboratory) since 1987 when the index was first established and due to the colocation of magnetometer stations with riometer stations over a wide range of auroral latitudes. Although the motivation of this paper was to find a more precise (i.e., auroral, local) replacement for the $K_p$ index, the $AE$ index was also examined. Despite it being a global index, $AE$ is a logical progression from $K_p$ due to the auroral zone location of its contributing stations, which includes the SNK.

Figure 8. Same as Figure 5 but for LOG$_{10}$ (HRA) and LOG$_{10}$ (HR).
station included in this study. Similar to $K_p$ and $HR$, $AE$ is also a range index representing the difference between the upper and lower envelopes of the horizontal component of magnetic variations from a collection of auroral zone stations (Davis & Sugiura, 1966).

The $AE$ index was compared to data in this study by determining the 1-hr maximum $AE$ index from values reported in the OMNI HRO 1-min data files available from the NASA Goddard Space Flight Center Coordinated Data Analysis Web (https://cdaweb.gsfc.nasa.gov/cdaweb/istp_public/). Figure 10a shows a comparison between $\text{LOG}_{10}(HR)$ and $\text{LOG}_{10}(AE)$ in the same format used in Figures 5 and 8. Excellent agreement is observed for the full range of both parameters. Correlation for the overall data set is high with $R = 0.80$ and ideal when considering the binned data ($R = 1.00$).

Given this excellent agreement, it is not surprising to see that the relationship between HRA and HR (Figure 10b) shows plateauing for small $AE$, as observed for small HR in Figure 8. There is a hint of plateauing for $\text{LOG}_{10}(AE) > 3.1$, but this could be due to the reduced data set for these activity levels. Correlation between HRA and $AE$ is slightly degraded at $R = 0.46$ (compared to $R = 0.57$ for HRA versus HR) for the overall data set.

Variation in both Figure 10a and the reduction in agreement for HRA versus $AE$ compared to HRA versus HR shown in Figure 10b is attributed to variation between local features represented by HR and the global features represented by $AE$.

Auroral absorption is a highly dynamic phenomenon associated with increased geomagnetic activity. As discussed in section 1, auroral absorption models typically characterize absorption based on global magnetic indices such as the $K_p$, $Ap$, or $PC$ indices or solar wind parameters. We argue that characterization based on a global magnetic index is limiting as auroral absorption is highly variable in time and location.

Figure 11 shows the distribution of HRA and HR in terms of MLT for data from the BLC, FCC, IQA, SNK, and YKC stations. Data in the <09 and >16 MLT sector are attributed to the BLC, FCC, IQA, SNK, and YKC stations. BLC and IQA contribute to both the 09–10 MLT and 15–16 MLT regions. BLC was the only station with observations across the entire MLT sector. CBB observations, which are not included in Figure 11, are limited to the dayside between 10 and 15 MLT and are primarily limited to only low-magnitude HR (<200 nT) and HRA (<0.5 dB). Occurrence for MEA was very low and confined to 0–1 MLT and 22–24 MLT but spanned a wide range of HR (up to ~1,000 nT) and HRA (up to ~5 dB). MLT distributions were very similar from station to station (not shown) having (1) higher occurrence across the nightside and low occurrence on the dayside and (2) a suppression of high HR and HRA on the dayside.

The occurrence of notable HRA > 1 dB (Figure 11a) is most pronounced on the nightside (<9 MLT; >20 MLT) with a notable reduction on the dayside between 10 and 18 MLT, consistent with known distributions of...
auroral absorption (Basler, 1963; Driatsky, 1966; Frank-Kamenetsky & Troshichev, 2012; Hargreaves, 1969; Hartz et al., 1963; Hook, 1968). This figure illustrates that HRA is not a globally observed phenomenon. HR is a better characterization of HRA as it varies on a more local scale. Consider Figure 11b, which plots the distribution of HR with MLT. HR is enhanced across the entire nightside, consistent with the findings of Danskin and Lotz (2015), and overlaps with both the prenoon and premidnight absorption peaks. MLT variation during periods of heightened geomagnetic activity, as represented by HR, complement the variation observed in HRA. Differences between the HR and HRA distributions indicate that some variations in HR can be caused by processes that do not lead to auroral absorption, which explains some of the spread observed in Figure 8.

It should be noted that some of the features of Figures 11a and 11b are attributed to the auroral-zone filtering used to constrain the data set to modeled regions of the auroral zone. Figures 11c and 11d repeat the distributions with the auroral-zone filtering removed. The MLT distribution for HRA is consistent with the standard picture of auroral morphology with discrete 1- to 10-keV electron precipitation in the evening and midnight sectors and harder pulsating and diffuse aurora (>30 keV) in the postmidnight and morning sectors, explaining the higher morning sector absorption observed in Figure 11a. By removing the auroral oval filtering, it is clear that large absorption can extend beyond the modeled auroral region into the dayside. In Figure 11d, the expected near-midnight peak in HR is clearly defined.

The historical choice of using $Kp$ to indicate the level of auroral absorption is not surprising given the availability and reliability of the data. As Menvielle and Berthelier (1991) point out, the $Kp$ index is often used out of “force of habit.” Unfortunately, the convenience and large-scale use of the $Kp$ index makes it very easy to
forget its purpose and meaning. Menvielle and Berthelier (1991) provide a thorough and thought-provoking description of the $Kp$ index and include a discussion on the importance of using the right index to describe a given phenomenon. The ionospheric/magnetospheric current source of magnetic perturbations varies, depending on the MLAT of the observing station. In the high-latitude polar cap, magnetic activity is dominated by reconnection and merging processes on the frontside magnetosphere and magnetotail regions, causing the transport of open magnetic field lines over the polar cap. In the auroral region focused on in this paper, magnetic activity is driven by changes in the auroral electrojets and field-aligned currents largely caused by substorm-induced energetic electron precipitation, which also drives auroral absorption. Subauroral geomagnetic variations are caused by additional contributions from the ring current, which drives geomagnetic perturbations at equatorial latitudes. Menvielle and Berthelier (1991) point out that the subauroral location of the magnetic observatories used to derive the $Kp$ index means that $Kp$ is a good global characterization of magnetic activity because this region is impacted by high-, middle-, and low-latITUDE phenomena. The most poleward $Kp$ observatory is the MEA station considered in this study (Menvielle & Berthelier, 1991), whereas the auroral oval location predicted by Starkov (1994), illustrated in Figure 2, shows a maximum equatorward extent just equatorward of the MEA station. However, this also implies that the $Kp$ index is too broad an index to use to describe a local auroral phenomenon. Substorm-associated activity does not necessarily propagate to low enough latitudes and has a duration that is often less than 3 hr. Menvielle and Berthelier (1991) repeatedly emphasize that the $Kp$ index is a midlatitude-based (typically subauroral) index intended to characterize global or subauroral phenomenon and is not limited to the effect of auroral zone dynamics.

To demonstrate the role of $Kp$ as a subauroral, opposed to auroral, descriptor, consider that in the subauroral region, there is excellent agreement between $Kp$ and HR. Figure 12a demonstrates this relationship for the OTT magnetic observatory data for 2015–2017. The OTT observatory has geographic coordinates of (45.4°, 284.4°), corresponding to 54.4° geomagnetic latitude, which is 7° equatorward of the southernmost auroral station considered in this study. Figure 2 demonstrates that the OTT station is expected to be equatorward of the expected location of the auroral oval. The occurrence distribution demonstrates a linear trend of increasing $LOG_{10}(HR)$ with increasing $Kp$. The correlation coefficient is $R = 0.74$, strongly indicating a linear fit between data sets. Correlation for the binned data is ideal at $R = 0.99$. The observed agreement is not surprising given that $Kp$ is a subauroral index to which the OTT magnetometer contributes.

As stated above, at auroral latitudes, geomagnetic activity, and therefore variations in HR, is driven by changes in the auroral electrojets, largely associated with the precipitation of energetic electrons, which also give rise to the aurora and are typically not observed at lower latitudes. Figure 12b plots the logarithm of HR and $Kp$ in the same format used in Figure 12a and includes data for all stations, similarly to Figures 5 and 8. Although correlation is still good at $R = 0.68$, a linear relationship between $LOG_{10}(HR)$ and $Kp$ is not clear;
there is a curve in the distribution that plateaus for $Kp \geq 4$. It is possible that some of the plateauing could be attributed to the reduction in data for $Kp \geq 4$ (see Figures 4a and 4d). Visually, the lower boundary of the occurrence distribution is linear, whereas the upper boundary begins to plateau for $Kp > 2$. The plateau is associated with a high degree of variation in $Kp$ for a given range of $\log_{10}(HR)$. For example, for $\log_{10}(HR)$ of ~2.5, $Kp$ varies from 1 to 8.

The degraded relationship between $Kp$ and HR in Figure 12b can be explained by the relationship between the response of HR at auroral and subauroral latitudes. Auroral magnetic measurements are sensitive to changes in the auroral electrojet, which are not always seen at subauroral latitudes, and therefore does not contribute to $Kp$. If instead the comparison performed is limited to the OTT station, which contributes

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**Figure 13.** Same as Figure 11b for the subset of points where the coefficient of variation (CV) was (a) <10% and (b) >90%.
to $Kp$, and subauroral data are considered, the agreement between $Kp$ and HR is clear, and the plateauing for $Kp > 3–4$ is eliminated.

Kavanagh et al. (2004) points out that $Kp$ is a 3-hr index not capable of capturing the dynamic variation demonstrated for auroral absorption, a statement which motivated a comparison against the more variable HR index. We investigate the variability of the HR index with respect to the $Kp$ index and the role of that variation on the agreement between the $Kp$ index and HRA or HR. To characterize the variability of HR during the 3-hr interval represented by $Kp$, the coefficient of variation (CV), or relative standard deviation, was used. CV is defined as the ratio of the standard deviation of the data divided by the mean. For each 3-hr interval in 2001–2003 (FCC) and 2015–2017 (BLC, CBB, IQA, MEA, SNK, and YKC), the CV (or relative standard deviation) in HR was determined (CV$_{HR}$). Comparisons between HR and $Kp$ (Figure 12) were evaluated for periods of low variability (CV$_{HR} \leq 10\%$) and periods of high variability (CV$_{HR} \geq 90\%$). Figures 13a and 13b show the low and high variability data for the HR-versus-$Kp$ comparison, respectively. Low-variability data shown in Figure 13b represents 4.6% of the overall data set. Data are weighted to lower-$Kp$ periods ($Kp < 4$), and the data have a high degree of correlation ($R = 0.81$). High-variability data, shown in Figure 13d, represents 5.2% of the overall data set. The correlation coefficient is much lower at $R = 0.46$, and there is significant spread in the occurrence plot. Both the low and high variability data show the same plateau for $Kp > 4$, but the data spread is considerably reduced for the low-variability subset of data.

The low-variability subset of data represent periods where geomagnetic activity is relatively stable across the 3-hr interval represented by the $Kp$ index, whereas the high-variability subset of data represent cases where geomagnetic activity significantly increases or decreases between 1-hr periods within the 3-hr interval at either the onset or end of an event or due to short bursts of active geomagnetic conditions. Agreement between HRA and $Kp$ is affected by the degree of variability represented by CV$_{HR}$, demonstrating the importance of stable conditions for representing HRA by $Kp$. Such requirements are not needed when characterizing HRA in terms of HR, further demonstrating that HR is a more dynamic representation of HRA.

5. Conclusions

The HRA measured by seven riometers located in the Canadian auroral region were compared to the $Kp$ index and to the HR observed at colocated magnetometers for 2001–2003 (FCC station) and 2015–2017 (BLC, CBB, IQA, MEA, SNK, and YKC stations). The following was observed:

1. Distributions of $Kp$ and HR are lognormal, consistent with observations cited in the literature. HRA was also shown to have a lognormal distribution.
2. There is a general linear relationship between LOG$_{10}$(HRA) and $Kp$ for $Kp = [1, 4]$. For more active geomagnetic conditions ($Kp > 4$), the relationship plateaus, and there is large variability such that a range of $Kp$ values are possible, with similar occurrence, for constant LOG$_{10}$(HRA).
3. Deterioration of the agreement between LOG$_{10}$(HRA) and $Kp$ for $Kp > 4$ is attributed to (1) the subauroral nature of the $Kp$ index compared to the auroral location of energetic electron precipitation causing auroral absorption, (2) the high degree of variability of the geomagnetic field during the 3-hr interval characterized by $Kp$, and (3) low statistics for large $Kp$.
4. There is a strong linear agreement between LOG$_{10}$(HRA) and LOG$_{10}$(HR) for HR > 50 nT characterized by $R = 0.63$. Variability is considerably reduced compared to $Kp$; 96% of data for HRA > 1 dB correspond to periods of HR > 50 nT.

The $Kp$ index is a useful parameter for characterizing global magnetic activity; it is robust and reliable, providing a continuous unbroken data set. However, due to its 3-hr resolution, subauroral dependence, and nonsensitivity to auroral disturbances, it is not ideal for characterizing a highly dynamic auroral phenomenon such as auroral absorption, which varies on a local scale at a rate that is frequently <3 hr. HR is a more dynamic characterization of geomagnetic activity varying with a 1-hr resolution based on local geomagnetic activity. As such, it is a more accurate characterization of the level of auroral absorption. Although $Kp$ and solar wind parameters are typically used for auroral absorption modeling, it is recommended that models be developed based on the HR to obtain a more accurate representation of the local auroral absorption opposed to the general global state.
Appendix A

Tables A1, A2, A3 and A4 provide the mean and standard deviation of the binned data presented in Figures 5 and 8.

### Table A1

Mean and Standard Deviation of LOG10(HRA (dB)) in Bins of 1/3 Kp for the CBB, BLC, IQA, and YKC Stations Illustrated by Black Filled Circles and Vertical Lines in Figure 5

| Kp | LOG10(HRA (dB)) | CBB  | BLC  | IQA  | YKC  |
|----|----------------|------|------|------|------|
| 0  | 0.54           |      |      |      |      |
| 1  | 0.57           |      |      |      |      |
| 2  | 0.59           |      |      |      |      |
| 3  | 0.61           |      |      |      |      |
| 4  | 0.62           |      |      |      |      |
| 5  | 0.64           |      |      |      |      |

### Table A2

Mean and Standard Deviation of LOG10(HRA (dB)) in Bins of 1/3 Kp for the FCC, SNK, MEA, and ALL Stations Illustrated by Black Filled Circles and Vertical Lines in Figure 5

| Kp | LOG10(HRA (dB)) | FCC  | SNK  | MEA  | ALL  |
|----|----------------|------|------|------|------|
| 0  | 0.54           |      |      |      |      |
| 1  | 0.57           |      |      |      |      |
| 2  | 0.59           |      |      |      |      |
| 3  | 0.61           |      |      |      |      |
| 4  | 0.62           |      |      |      |      |

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Table A2
Continued

| $K_p$ | LOG$_{10}$(HRA (dB)) | FCC | SNK | MEA | ALL |
|-------|-----------------------|-----|-----|-----|-----|
| 6+    | −0.20 0.38            | 0.22| 0.31|     |     |
| 7−    | −0.26 0.37            |     |     |     |     |
| 7o    | −0.07 0.36            |     |     |     |     |
| 7+    | −0.45 0.37            |     |     |     |     |

Table A3

Mean and Standard Deviation of LOG$_{10}$(HRA (dB)) in Bins of 0.1 LOG$_{10}$(HR (nT)) for the CBB, BLC, IQA, and YKC Stations Illustrated by Black Filled Circles and Vertical Lines in Figure 8

| LOG$_{10}$(HR (nT)) | LOG$_{10}$(HRA (dB)) |
|----------------------|-----------------------|
|                      | CBB       | BLC       | IQA       | YKC       |
| 0.65                 |           |           |           |           |
| 0.75                 |           |           |           |           |
| 0.85                 |           |           |           |           |
| 0.95                 |           |           |           |           |
| 1.05                 | −0.58 0.20| −0.72 0.21| −0.45 0.18| −0.71 0.18|
| 1.15                 | −0.58 0.17| −0.68 0.21| −0.52 0.21| −0.64 0.23|
| 1.25                 | −0.63 0.19| −0.70 0.17| −0.53 0.21| −0.78 0.19|
| 1.35                 | −0.64 0.17| −0.70 0.20| −0.49 0.19| −0.80 0.14|
| 1.45                 | −0.62 0.22| −0.67 0.19| −0.49 0.21| −0.79 0.15|
| 1.55                 | −0.62 0.17| −0.66 0.18| −0.49 0.19| −0.73 0.20|
| 1.65                 | −0.62 0.16| −0.65 0.18| −0.47 0.19| −0.71 0.18|
| 1.75                 | −0.65 0.17| −0.65 0.20| −0.45 0.20| −0.64 0.23|
| 1.85                 | −0.66 0.15| −0.64 0.22| −0.47 0.20| −0.58 0.21|
| 1.95                 | −0.64 0.15| −0.55 0.25| −0.43 0.18| −0.58 0.24|
| 2.05                 | −0.65 0.14| −0.54 0.24| −0.43 0.20| −0.47 0.26|
| 2.15                 | −0.57 0.36| −0.45 0.26| −0.39 0.18| −0.36 0.26|
| 2.25                 | −0.62 0.16| −0.37 0.26| −0.35 0.18| −0.30 0.25|
| 2.35                 | −           | −0.31 0.27| −0.33 0.18| −0.18 0.24|
| 2.45                 | −           | −0.24 0.24| −0.26 0.22| −0.06 0.24|
| 2.55                 | −           | −0.20 0.25| −0.26 0.23| 0.00 0.26|
| 2.65                 | −           | −0.11 0.22| −0.23 0.19| 0.10 0.23|
| 2.75                 | −           | −0.01 0.23| −0.78 0.19| 0.17 0.22|
| 2.85                 | −           | 0.02 0.27| −0.15 0.17| 0.42 0.25|
| 2.95                 | −           |           |           | 0.37 0.19|

Table A4

Mean and Standard Deviation of LOG$_{10}$(HRA (dB)) in Bins of 0.1 LOG$_{10}$(HR (nT)) for the FCC, SNK, MEA, and ALL Stations Illustrated by Black Filled Circles and Vertical Lines in Figure 8

| LOG$_{10}$(HR (nT)) | LOG$_{10}$(HRA (dB)) |
|----------------------|-----------------------|
|                      | FCC       | SNK       | MEA       | ALL       |
| 0.65                 |           |           |           | −0.49 0.23|
| 0.75                 |           |           |           | −0.66 0.22|
| 0.85                 |           |           |           | −0.51 0.21|
| 0.95                 |           |           |           | −0.56 0.26|
Table A4  
Continued

| $\log_{10}$ (HR (nT)) | $\log_{10}$ (HRA (dB)) | FCC | SNK | MEA | ALL |
|------------------------|-------------------------|-----|-----|-----|-----|
| 1.05                   | -0.74                   | 0.28 | -   | -   | -0.58 | 0.24 |
| 1.15                   | -0.80                   | 0.13 | -   | -   | -0.61 | 0.22 |
| 1.25                   | -0.75                   | 0.20 | -   | -   | -0.63 | 0.22 |
| 1.35                   | -0.71                   | 0.20 | -0.54| 0.17| -   | -0.62 | 0.21 |
| 1.45                   | -0.68                   | 0.24 | -0.37| 0.28| -   | -0.61 | 0.24 |
| 1.55                   | -0.70                   | 0.22 | -0.50| 0.16| -   | -0.61 | 0.21 |
| 1.65                   | -0.70                   | 0.21 | -0.41| 0.28| -   | -0.61 | 0.21 |
| 1.75                   | -0.70                   | 0.21 | -0.40| 0.23| -   | -0.60 | 0.23 |
| 1.85                   | -0.65                   | 0.21 | -0.41| 0.18| -   | -0.58 | 0.22 |
| 1.95                   | -0.61                   | 0.22 | -0.41| 0.19| -   | -0.55 | 0.23 |
| 2.05                   | -0.58                   | 0.22 | -0.34| 0.19| -   | -0.51 | 0.23 |
| 2.15                   | -0.48                   | 0.25 | -0.26| 0.21| -   | -0.42 | 0.25 |
| 2.25                   | -0.44                   | 0.26 | -0.18| 0.22| -   | -0.36 | 0.25 |
| 2.35                   | -0.34                   | 0.25 | -0.12| 0.20| -   | -0.28 | 0.25 |
| 2.45                   | -0.24                   | 0.27 | -0.01| 0.22| -   | -0.18 | 0.27 |
| 2.55                   | -0.14                   | 0.25 | 0.08 | 0.21| 0.01| 0.26 | -0.10 | 0.26 |
| 2.65                   | -0.04                   | 0.26 | 0.16 | 0.21| 0.01| 0.28 | -0.01 | 0.26 |
| 2.75                   | 0.07                    | 0.25 | 0.31 | 0.16| -   | -   | 0.08  | 0.26 |
| 2.85                   | 0.14                    | 0.28 | 0.37 | 0.21| 0.23| 0.32 | 0.19  | 0.31 |
| 2.95                   | 0.25                    | 0.20 | -   | -   | -   | -   | 0.30  | 0.22 |
| 3.05                   | —                       | —   | —   | —   | —   | —   | 0.40  | 0.21 |

Data Availability Statement

NRCan magnetic field hourly range data are available online for 2015–2017 (https://www.spaceweather.gc.ca/data-donnee/indices/si-vi-en.php?type=hourly_ranges) and from Fiori (2020a) for 2001–2003. NRCan riometer data are available from Fiori (2020b) for the BLC, CBB, IQA, MEA, SNK, and YKC stations for 2015–2017. Data for the FCC riometer for 2001–2003 can be found in the historical Churchill riometer data archive (https://www.ucalgary.ca/aurora/projects/rio), which is maintained by the University of Calgary under support from the Canadian Space Agency. Kp data used in this study were obtained from the National Geophysical Data Centre (ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC_DATA/INDICES/KP_AP/). AE index data were taken from the OMNI HRO 1-min data files available from the NASA Goddard Space Flight Center Coordinated Data Analysis Web (https://cdaweb.gsfc.nasa.gov/cdaweb/istp_public/).

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