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Ion upflow and downflow at the topside ionosphere observed by the EISCAT VHF radar

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Abstract. We have determined the MLT distribution and \( K_p \) dependence of the ion upflow and downflow of the thermal bulk oxygen ion population based on a data analysis using the EISCAT VHF radar CP-7 data obtained at Tromsø during the period between 1990 and 1996: (1) both ion upflow and downflow events can be observed at any local time (MLT), irrespective of dayside and nightside, and under any magnetic disturbance level, irrespective of quiet and disturbed levels; (2) these upflow and downflow events are more frequently observed in the nightside than in the dayside; (3) the upflow events are more frequently observed than the downflow events at any local time except midnight and at any \( K_p \) level and the difference of the occurrence frequencies between the upflow and downflow events is smaller around midnight; and (4) the occurrence frequencies of both the ion upflow and downflow events appear to increase with increasing \( K_p \) level, while the occurrence frequency of the downflow appears to stop increasing at some \( K_p \) level.

Key words: Ionosphere (particle acceleration; plasma waves and instabilities) – Space plasma physics (transport processes)

1 Introduction

The polar wind is a field-aligned ion flow from the polar ionosphere to the magnetosphere (Axford, 1968). Deslaur and Michel (1996), Bauer (1966), and Nishida (1966) suggested that a "continuous" escape of thermal light ions such as \( H^+ \) and \( He^+ \) should occur due to ambipolar diffusion along the geomagnetic open field line.

A number of models of the polar wind have been proposed; hydrodynamic models (Banks and Holzer, 1968, 1969a, b; Marubashi, 1970; Raitt et al., 1975, 1977; Schunk et al., 1978), kinetic models (Lemaire and Scherer, 1970, 1973), models solving the generalized transport equations (Schunk and Watkins, 1981, 1982; Demars and Schunk, 1987; Ganguli et al., 1987) and time-dependent models (Gombosi and Nagy, 1989; Schunk and Sojka, 1989). Polar wind observations are dated from the early years of the 1970s with the Explorer 31, OGO 2, and ISIS 2 satellites (Hoffman, 1970; Taylor and Walsh, 1972; Hoffman et al., 1974) and in the 1980s case studies of the polar wind were carried out based on data obtained from the Dynamic Explorer (DE) 1 satellite (Shelley et al., 1982; Nagai et al., 1984; Chandler et al., 1991).

Recent observations with satellites such as Akebono (EXOS-D) and GEOTAIL have shown that thermal ions, including not only light ions \( H^+ \) and \( He^+ \) but also heavy ions \( O^+ \) and \( NO^+ \) flow out of the polar ionosphere and they are found in the lower magnetosphere (Watanabe et al., 1992; Abe et al., 1993a, b; Yau et al., 1991, 1993, 1995) and in the lobe magnetosphere (Mukai et al., 1994; Hirahara et al., 1996; Seki et al., 1996, 1998). A very comprehensive review of the terrestrial plasma source obtained from the DE mission was given by Chappell (1988).

The "classical" polar wind theory can only be applicable, however, to the upward flow of thermal light ions such as \( H^+ \) and \( He^+ \) in the polar cap region. The heavy ions escaping from the ionosphere to the magnetosphere require additional energy source. In other words, some other physical processes rather than ambipolar diffusion must be involved in accelerating heavy ions from the polar ionosphere since the heavy ions driven only by ambipolar diffusion are not able to overcome the Earth’s gravity and furthermore they are likely to be lost by a charge exchange reaction \( O^+ + H \leftrightarrow H^+ + O \) in the topside ionosphere and
O + O$^+$ → O$^+$ + O in the F region (Moore, 1984). Simulations have concentrated on the effects of ion frictional heating in the presence of large electric fields (Loranc and St.-Maurice, 1994; Wilson, 1994). Outflow could be reproduced during conditions of very strong heating. Satellite observations and theory of ion outflow were recently reviewed by Yau and André (1997), André and Yau (1997), and Horwitz and Moore (1997).

Although extensive satellite observations at altitudes of more than 1000 km have been made, what seems to be lacking is observations below 1000 km where the light and heavy ions are likely to be heated and/or accelerated and start to flow. Generally, it is difficult to observe altitude profiles of several parameters in the F region by means of satellites. On the other hand, radar observations in the polar region, such as EISCAT radar, are ideal for ion upflow studies in the F region.

A number of authors studied ion upflow events based on data obtained from the EISCAT radar in Scandinavia (Blelly et al., 1992a, b; Wu et al., 1992; Wahlund et al., 1992). They found that ion upflow can occur above Tromsø located at 66 invariant latitude, which is presumed to be on and inside the polar cap boundary only occasionally. This may suggest that the ion upflow can occur in the closed field line region. Wahlund et al. (1992) also disclosed that the ion upflow event is often associated with the enhancement of the electron and/or ion temperatures. The previous studies concentrated on case studies, while there have been few studies on statistical characteristics of the ion upflow with EISCAT.

The present study aims at determining the statistical characteristics of ion upflow and downflow based on an analysis using Common Program 7 (CP 7) data obtained from the EISCAT VHF radar. As we show in later sections, the ion upflow and downflow events we have considered do not have continuous features but have intermittent features with only a few minutes to a few tens of minutes from appearance to disappearance, which may consist of bursts with shorter time duration (Wahlund et al., 1993). We therefore think that the upflow ions we consider are upgoing ions heated up and accelerated in the topside ionosphere rather than classical polar wind ions. We will focus particularly on the magnetic local time (MLT) distribution of the occurrence frequency of these ion upflow and downflow events, and their dependence on magnetic disturbances, for which we will use the $K_p$ index.

### 2 Observations

The EISCAT VHF radar (224 MHz), located at Ramfjord near Tromsø (69.6N, 19.2E), Norway, is a monostatic system using a 120 × 40 m parabolic cylinder antenna, divided into four sectors. These sectors can be individually steered in the meridian plane from 30° south to 60° north of the zenith (EISCAT Scientific Association, 1991). The Common Programme 7 (CP 7) is one of the seven EISCAT CPs and one of the three CPs using VHF radars. A 900 μs pulse is used to sample 21 signal gates at about 65 km increments in range, with the first gate at 285 km range and the last gate at 1654 km range. Vertical antenna pointing is used.

We have used 22 sets of the EISCAT CP7 data that cover all CP 7 data during the period between 1990 and 1996, for about 820 h altogether. The data used in this study are listed in Table 1. The data integration is 5 min, but for some datasets (marked a) it is 2.5 min and for some others (marked b) it is 2 min.

The standard EISCAT program was used for the analysis of the raw data. This assumes 100% O$^+$ throughout the upper F region, no H$^+$ or He$^+$. So far substantial fractions of light ions have rarely been observed with the VHF radar even at altitudes up to about 1600 km. Furthermore, in this study only the fitted velocities are used, which should not suffer from significant errors, even if the assumed ion composition is biased. It has been reported that associated with ion upflow frequently naturally enhanced ion-acoustic lines occur (Rietveld et al., 1991; Wahlund et al., 1992, 1993). These are not normal IS spectra, but show asymmetrical features. In the present study we have excluded only the strongest of these abnormal spectra that lead to a digital overflow in the EISCAT correlator. The typical duration of an event with naturally enhanced ion-acoustic lines is about 1 min (Rietveld et al., 1991). Since our integration time is mostly 5 min, the effect of the weaker abnormal spectra on the fitted velocity should be relatively small. Recently Forme and Fontaine (1999) studied the Doppler velocity during naturally enhanced ion lines with a new technique. They found that in all the events studied the ion flow speed was upward before the enhancement, and the spectra became even more Doppler shifted during the event. The velocities used in this study might therefore be occasionally somewhat

### Table 1. Data used in this study

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deviates from this concentration. Positive deviations
< 400 m/s at 1400 km. The ion velocity for other data
< 100 m/s at 300 km, < 200 m/s at 800 km, and
concentrated in a certain velocity range around zero;
The ion velocity for the majority of the data is
where we have over-plotted all the data points for 69 h
transient phenomenon, as for the ion upflow in Fig. 1a.
Fig. 1a shows a typical example of the ion upflow
event observed between 1745 and 1830 UT on May 13,
1991, where we show 9 time sequential height profiles
of the vertical ion velocity. The abscissa shows the vertical
ion velocity where a positive (negative) value means ions
moving upward (downward). The ordinate is the height
from 200 km to 1700 km. Each circle denotes the ion
velocity at a corresponding altitude with a horizontal
bar showing one-sigma error. The quality of the data
vary (see figure caption).
Between 1745 and 1800 UT there are no significant
enhancements of the ion velocity at any height. At 1800–
1805 UT the ion velocity becomes positive, implying
that ions start to move upward, above say 900 km with the
largest velocity of about 500 m/s around 1300 km. During
the next five minutes between 1805 and 1810 UT, lower altitude ions also start to move, with the
lowest altitude of the ion upflow of 600 km and the
largest velocity of 800 m/s around 1200 km. Five
minutes later, the maximum velocity becomes larger,
1300 m/s with the altitude of the maximum velocity
becoming higher, up to around 1500 km. The ion
upflow then fades away and returns to the previous
(quiet) level at 1745–1750 UT. Generally, as shown
here, the ion upflow appears to be a transient phenomenon on a time scale of minutes.

Figure 1b shows an example of the ion downflow
event observed between 1940 and 2025 UT on September
26, 1990, where we show again 9 sequential height profiles of the ion velocity. The format is same as for
Fig. 1a. Ion downflow is seen between 1945 and
2010 UT, although the data quality is not good above 1300 km. The ion downflow appears to be also a transient phenomenon, as for the ion upflow in Fig. 1a.

Figure 2 shows a height profile of the ion velocity,
where we have over-plotted all the data points for 69 h
from 1000 UT of May 12 to 0645 UT of May 15, 1990.
The ion velocity for the majority of the data is concentrated in a certain velocity range around zero;
this range changes depending on the altitude, that is,
± 100 m/s at 300 km, ± 200 m/s at 800 km, and
± 400 m/s at 1400 km. The ion velocity for other data deviates from this concentration. Positive deviations

Figure 3 shows a height profile of the ion velocity,
where we have used the following quantitative definition for
the ion upflow (or downflow) and

\[ \frac{\Delta v}{\Delta z} > A_1 \] for the ion upflow and
\[ \frac{\Delta v}{\Delta z} < A_2 \] for the ion downflow

where \( A_1 \) and \( A_2 \) are the threshold values for the ion upflow and downflow, respectively.

3 Statistical analysis
We have used the following quantitative definition for selecting the ion upflow and downflow events from the
CP 7 database. We have set two conditions which the ion upflow and downflow must satisfy. The first
condition is that the altitude of the maximum velocity
is more than a certain value \( A_1 \) for \( N \) consecutive heights. \( N \) is 3 for an example obtained at
0740–0745 UT on May 14, 1991, shown in Fig. 3. The second condition is that the maximum velocity \( V_{\text{max}} \) is more than \( A_2 \). Furthermore, the lowest altitude of the
ion upflow and downflow is defined to be an altitude
where, for the first time, the absolute value of the
altitudinal gradient \( \frac{\Delta v}{\Delta z} \) of the ion velocity exceeds a
certain value \( A_3 \). We have set three threshold criteria for
these conditions from less severe to severe, as tabulated in Table 2, in order to check whether the choice of the
threshold criteria of the conditions affects the statistical characteristics of the ion upflow and downflow.

Figure 4 shows the magnetic local time (MLT) distributions of the occurrence frequency of the ion
upflow (on the left-hand side) and the downflow (on the
right-hand side) for case 1 through case 3. For both ion
upflow and downflow, only data under \( K_P < 4 \) are
selected. We have used, throughout the present work,
the occurrence frequency of the ion upflow and downflow,
which is defined as \( B/A \), where \( B \) is the number of
the ion upflow (or downflow) and \( A \) is the total number of
samples during a certain period. For Fig. 4 the
abscissa is MLT (from 0000 to 2400 MLT) with each
bin of 5 min. The horizontal line is the occurrence frequency averaged over the 24 MLT hours.

With increasing the threshold criterion, the occurrence
frequency decreases, because the occurrence of the
ion upflow (or downflow) decreases while the total
number of samples does not change. (This is also
evident from the average occurrence frequencies.)
It should be noted, however, that the MLT dependence,
that is, relative increase/decrease of the occurrence
frequency for both ion upflow and downflow by MLT,
is retained regardless of the threshold criterion. For the
ion upflow, for example, several maxima around 05, 10, 17, 20–01 MLT and minima around 08 and
19 MLT are commonly recognised for all threshold
criteria. For the downflow, maxima around 01, 06, 11,
23 MLT and some minima are also commonly seen
for all threshold criteria. Since the choice of the threshold
criteria does not change the characteristics of the MLT
dependence and \( K_P \) dependence (not shown here),
hereinafter we will show results only for the threshold
criterion 2.
Figure 5 shows the distributions of the upflow and downflow for four magnetic local time regions: 21 ≤ MLT < 3, 3 ≤ MLT < 9, 9 ≤ MLT < 15, and 15 ≤ MLT < 21, under two geomagnetic disturbance levels: $K_p < 4$ for quiet conditions and $K_p ≥ 4$ for disturbed conditions. More quantitative $K_p$ dependence will be shown later. The occurrence frequencies of the upflow and downflow are denoted by thick and thin vertical bars and those averaged over 24 MLT hours are shown by solid and dotted horizontal lines, respectively.

Figure 1. a) Typical examples of the ion upflow observed at 1745–1830 UT on May 13, 1991 and b) ion downflow observed between 1940 and 2025 UT on September 26, 1990. Each figure contains 9 time sequential height profiles of the vertical ion velocity. The abscissa shows the vertical ion velocity where a positive (negative) value means ions moving upward (downward). The circles represent good quality data and the dots represent not very good quality data judging from the degree to which well-observed EISCAT spectrum is fitted to a theoretical spectrum.
and downflow are smaller in the midday and becomes larger in the nightside region. The occurrence frequency of the upflow is generally larger than that of the downflow except for midnight and midday periods under the lower $K_p$ level where these two occurrence frequencies are nearly the same or the occurrence frequency of the downflow slightly dominates over that of the upflow. When the $K_p$ level becomes higher, the occurrence frequency of the upflow generally becomes greater, while that of the downflow does not change so much for $21 \leq \text{MLT} < 3$ and $9 \leq \text{MLT} < 15$. This tendency is also clearly seen in the large increase of the average occurrence frequency of the upflow but a smaller increase of the downflow, with increasing $K_p$ level.

The middle and bottom panels show the duration and the maximum velocity of the upflow and downflow. The ion upflow and downflow have a duration of the order of and possibly shorter than the integration period used. The MLT distribution of the maximum velocities...
shows small differences between the two $K_p$ levels and furthermore the difference of the occurrence frequency between the upflow and downflow becomes larger with the higher $K_p$ level except the midday region.

The $K_p$ dependence of the ion upflow and downflow for all MLTs is shown in Fig. 6. The abscissa is the $K_p$ level from 0 to 8. The ordinate is the occurrence frequency for the lines with circles and the number of samples for each $K_p$ bin. A $K_p$ bin ‘$N$’ includes actually three $K_p$ levels; $N^-$, $N$, and $N^+$. The numbers of sampling for bins from 0 to 6 are respectively more than 500 with relative uncertainties of less than 5%, but those for bins of 0 and of 7 and 8 are respectively less than 250 where the occurrence frequency may contain larger uncertainties of more than 10%. The occurrence frequency of the ion upflow increases rather monotonically with the increasing $K_p$ values: about 0.15 at $K_p = 1$, 0.2 at $K_p = 2$, 0.27 at $K_p = 3$ and 0.35 at $K_p = 5$. The occurrence frequency of the downflow also increases unless the $K_p$ value is more than 3: about 0.1 at $K_p = 1$, 0.2 at $K_p = 2$ and 0.23 at $K_p = 3$. The difference between the upflow and
downflow at each $K_p$ level is smaller than 0.5, implying that there is no significant net flow in terms of the occurrence frequency. When the $K_p$ values become larger than 3, the occurrence frequency of the downflow appears not to increase but to remain at a particular value. The $K_p$ dependence mentioned here again suggests that the net flow in terms of the occurrence frequency be small at the lower $K_p$ range but become significant at the higher $K_p$ range.

Figure 7 shows the $K_p$ dependence of the ion upflow and downflow in the four MLT regions, as those in Fig. 5; dawn, midday, dusk and midnight regions. The abscissa is again the $K_p$ levels and the ordinate is the occurrence frequency and the number of samples for each $K_p$ bin. Due to too small numbers of samples, we will see the occurrence frequency at $K_p = 0 \sim 5$.

In the midnight region ($21 \leq MLT < 3$), with the increasing $K_p$ values, the occurrence frequencies of both upflow and downflow increase at lower $K_p$ values (1 and 2) but appear to stop increasing at higher $K_p$ values (more than 2). The difference between the two occurrence frequencies is markedly small throughout all the $K_p$ values less than 6, which is consistent with the occurrence frequencies at $21 \sim 03$ MLT in Fig. 4.

In the dawn ($3 \leq MLT < 9$) and dusk ($15 \leq MLT < 21$), the occurrence frequencies of both the ion upflow and downflow increase monotonically with the increasing $K_p$ values. The occurrence frequency of the upflow is significantly greater than that of the downflow for all $K_p$ values.

In the midday ($9 \leq MLT < 15$), with the increasing $K_p$, the occurrence frequencies of both the upflow and downflow increases at lower $K_p$ values ($1 \sim 3$) without a significant difference between them. At higher $K_p$ values (more than 3), with the increasing $K_p$, the occurrence frequency of the upflow appears to increase slightly or remains at a particular value, while that of the downflow decreases.

### 4 Discussion and conclusions

The ion upflow has been considered to be a phenomenon that ionospheric ions flow out along the magnetic field line of forces. The CP 7 mode experiment, data from which we have used in this study, provides physical parameters, however, not in the magnetic field-aligned direction but in the vertical direction from 285 to 1654 km high. This offset of the beam direction from the field-aligned direction by 12.5° obviously implies that a measured vertical ion motion is a combination of ion motions parallel to and perpendicular to the local magnetic field, as shown in Fig. 8. Only the geomagnetic northward component of the ion motion perpendicular to the magnetic field produces the vertical component of the ion motion while the eastward component does not.

Let us estimate the contamination of the perpendicular plasma motion in the north-south directions to the vertical motion. The vertical velocity $V$ is a sum of the projections from the velocities perpendicular and parallel to the magnetic field to the vertical line.

$$V = \pm V \parallel \cos 12.5° \pm V \perp \sin 12.5° = \pm 0.98 V \parallel \pm 0.22 V \perp$$

The contribution of the perpendicular plasma velocity to the vertical component is 22% of its velocity, that is, $V = 220$ m/s for $V \perp = 1000$ m/s (equivalently about 50 mV/m electric field at 285 km).

We will next estimate the change of the plasma velocity with altitudes. We assume the electric equipotentiality along a magnetic field line, a uniform plasma motion (equivalently a uniform electric field) in the region we consider, and a dipole magnetic field. Since the magnitude of the magnetic field is proportional to $(r/r_0)^{-3}$, where $r_0$ and $r$ are in each case the distance from the Earth’s centre to 285 km altitude and to an altitude where the distance between two specific magnetic field lines aligned in the north-south direction is proportional to $(r/r_0)^2$. Hence, the southward and eastward components of the ion velocity perpendicular to the magnetic field, which is supposed to be $E \times B$ drift velocity, are
Fig. 4. The magnetic local time (MLT) distribution of the occurrence frequency of the ion upflow (left) and the downflow (right) for the threshold criterion 1 (case 1) through the threshold criterion 3 (case 3). For both ion upflow and downflow, data only under \( K_P < 4 \) are selected.

Fig. 5. The distributions of the upflow and downflow for four magnetic local time regions: \( 21 \leq \text{MLT} < 3, 3 \leq \text{MLT} < 9, 9 \leq \text{MLT} < 15, \) and \( 15 \leq \text{MLT} < 21, \) under two geomagnetic disturbance levels: \( K_P < 4 \) for quite conditions and \( K_P \geq 4 \) for disturbed conditions.
proportional to \((r/r_0)^2\) and \((r/r_0)\), respectively. The northward and eastward velocities \(V_{\perp}\) perpendicular to the magnetic field at 1654 km are about 1.45 and 1.21 times larger than those at 285 km, respectively.

Although the plasma velocity perpendicular to the magnetic field thus produces a certain amount of vertical velocity, the ion upflow and downflow events, e.g. shown in Fig. 1a, b, may not so much suffer such a contamination from the perpendicular component. There are two reasons for this. First, this vertical velocity may rarely exceed 200 m/s, since the perpendicular plasma velocity seldom becomes larger than the corresponding velocity 1000 m/s (see e.g., Fig. 3a of Fujii et al., 1999). Hence the threshold criterion 2 for the maximum velocity 200 m/s is reasonable. Second, as is obvious from the discussion, the contamination must be a relatively constant value along the vertical line, only slowly varying in magnitude. The height distribution of the ion upflow/downflow shown in Fig. 1a, b does not match this feature.

The ion upflow is characterised not only by the enhancement of the field-aligned ion velocity but also by the increases of the ion and/or electron temperatures (Wahlund et al., 1992). It is thus considered to be driven either by frictional heating or by ion heating through plasma instabilities that are excited by free energy from particle precipitation. Hence, the ion upflow is mainly located in the regions where an intense electric field and/
or precipitation is observed. Those regions are the polar cusp, the polar cap boundary, and the auroral zone. An ion outflow study with DE 1 satellite observations (Kondo et al., 1990) has indeed shown the enhancements of the ion outflow in these regions, in particular, around the polar cusp region.

Tromsø is located at 66° invariant latitude (INV), and is thus most frequently in the sub-auroral zone in the midday time, in the auroral zone in the dawn and dusk, and in the auroral zone and sometimes in the polar cap through the polar cap boundary in the midnight region (Feldstein and Strakov, 1967). A reason why we see a smaller occurrence frequency of the ion upflow in the midday region than in other regions may be that the 66° INV ionosphere overhead Tromsø at midday is relatively distant from the region where ion heating effectively takes place.

The driving force for the downflow ions appears to be the Earth’s gravity by which the ions fall down after they are lifted up by the mechanisms mentioned. Unless upflowing ions have enough energy of motion to escape the Earth’s gravity, they will come back to the ionosphere. Naturally this motion energy can become larger with increasing geomagnetic disturbances, since both particle precipitation and the electric field are enhanced accordingly. This is why the occurrence frequency of the ion upflow is rather monotonically increased with the increased of the \( K_p \) index in all MLT regions.

The occurrence frequency of the ion upflow is nearly the same as that of the downflow for lower \( K_p \) values, since enough energy is not given to ions to escape from the Earth’s gravity. On the other hand, the occurrence frequency of the upflow becomes greater than that of the downflow with increasing \( K_p \) index, since the ions tend to gain enough energy to escape from the Earth’s gravity.

The difference of the occurrence frequencies between the ion upflow and downflow has also an MLT dependence. The difference is small in the midnight region, suggesting little net ion flow there, but larger differences between the two occurrence frequencies both in the dawn and dusk regions. Although we do not fully understand what causes this MLT dependence, one possible explanation is as follows. Statistically, the electric field strength, the electromagnetic energy input from the magnetosphere to the ionosphere and the Joule heating rate become largest in the dawn and dusk regions (Fujii et al., 1999), rather than in the midnight region. This MLT dependence may suggest that ions in the dawn and dusk regions more frequently obtain greater energy than those in the midnight region. On the other hand, in the midnight region we expect intense particle precipitation in terms of energy and flux particularly associated with substorms and storms. These precipitating plasmas with rather high energies ionise most efficiently neutral atmosphere in the lower \( E \) region but probably not so efficiently at higher altitudes where ions are heated up.

We have not discussed the fluxes of the ion upflow and downflow, which are highly dependent on the threshold criteria. These will be covered in future works together with the evaluation of these fluxes, their seasonal variations, spatial confinement and movement of the upflow/downflow.

5 Summary

We have determined the MLT distribution and \( K_p \) dependence of ion upflow and downflow events based on a data analysis using the EISCAT VHF radar CP-7 data obtained at Tromsø.

1. Both ion upflow and downflow events can be observed at any local time (MLT), irrespective of dayside and nightside, and under any magnetic disturbance level, irrespective of quiet and disturbed levels.
2. These upflow and downflow events are more frequently observed in the nightside than in the dayside regions.
3. The upflow events are more frequently observed than the downflow events at any local time except midnight and at any \( K_p \) level and the difference of the occurrence frequencies between the upflow and downflow events is smaller around midnight.
4. The occurrence frequencies of both the ion upflow and downflow events appear to increase with increasing \( K_p \) level, while the occurrence frequency of the downflow appears to stop increasing at some \( K_p \) level.

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