On the possible influence of variations in the geomagnetic field on migration paths of snow buntings

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Abstract. A hypothesis is proposed wherein changes in the Earth's magnetic field affect the migratory paths of snow buntings (plectrophenax nivalis), and in particular from wintering grounds in the Russian/Ukrainian steppes to breeding grounds on Svalbard and with a typical stopover in Finnmark in northern Norway. If one were to assume ignorance of the secular movement of the magnetic north pole approximately 1500km northwards between 1908 and 2020, the magnetoreceptor contribution to snow buntings' navigation would result in winter-to-summer migratory paths progressively further to the East. In turn, this could be a contributing factor to declining populations in Finnmark and favouring a more frequent flightpath over the Kola Peninsula. On the other hand, short-term perturbations in the magnetic field (i.e. induced by solar activity) and therefore existing for a relatively small proportion of the flight time (if at all) for the individual migrations legs seem unlikely to influence the stopover locations significantly. Even so, these space-weather induced variations cannot be disregarded, particularly for success in reaching Svalbard.

1 Introduction

It is not common knowledge in the wider scientific community that a surprisingly large number of animals are capable of sensing a magnetic field. Magnetite crystals define magnetoreceptor cells, which, for example may be found in olfactory systems of animals (e.g. Diebel et al., 2000; Walker, 2008). Thereafter, magnetoreception is thought to be employed as a supplementary navigational aid for both vertebrates (Keeton et al., 1974; Dennis et al., 2007; Vanselow et al., 2017) and invertebrates such as marine crustaceans (e.g. Cain et al., 2005). In particular, snow buntings (plectrophenax nivalis) have a well-developed magnetoreception capability as described by Sandberg and Pettersson (1996) and references therein. The reference list in Sandberg and Pettersson (1996) is, moreover, exhaustive, giving underpinning reading and illustrating the degree of existing knowledge on the geomagnetic field as a navigational aid for avian migration. More recently, Cochran (2004) Qin et al. (2016) and Friis et al. (2017) offer new insights, the last providing an exhaustive reference list. In particular, Qin et al. (2016) present alternative magnetoreception mechanism.

The snow bunting is a welcome visitor in northern Norway in transit to its summer breeding grounds, and similarly a welcome visitor to Svalbard (Snell et al., 2018; Fossøy at al., 2018), together with a number of other migratory species, signalling the onset of summer. Conceivably, snow buntings' populations are less prone to the influence of predators; the nests of the pink-footed goose, for example, are often raided by polar bears when diminishing sea ice hinders bears from hunting seal, their more natural food source. In addition, the experimental evidence reported by Sandberg and Pettersson (1996) points to a significant dependence of snow buntings on the geomagnetic field during cloudy conditions (i.e. when prevented from using solar and stellar aids). A good popularised introduction to geomagnetism is provided by Merrill (2010) and furthermore including a treatise on magnetoreception, in addition to the references provided hereafter. The geomagnetic field changes slowly due to internal processes within the Earth but is also subject to short-term and more drastic fluctuations caused by solar-terrestrial interactions. Both the long- and short-term changes are detected by magnetoreception and therefore affect the planet’s inhabitants to greater or lesser degrees; here we shall examine the potential effects of both solar disturbances and internal terrestrial processes on migration.

2 Snow bunting migration

The migration paths between winter grounds and summer breeding grounds together with stop-overs is described and illustrated by Snell et al. (2018), which is considered as the key background for this study. That such findings are only recently published is due to the use of geolocators where alternative methods (e.g. GPS transmitters) are unsuitable for use with smaller birds. Fossøy et al. (2018) have merged figures from Snell et al. (2018): Figure 1., extracted from Fossøy et al. (2018) but using figures originating from Snell et al. (2018) shows migration paths together with an inlay indicating the proportion of the year spent at the respective locations. Snell et al. (2018) define the stopover/stationary periods as being where birds remain within a 2° latitude and longitude region for 5 days or more; flight periods are defined as movements greater than 5° (latitude and/or longitude) in between the stationary periods. A description of technical aspects of geolocation, including sources of error is given by Snell et al. (2018), as well as details/sources of data underlying Figure 1. In summary, the light-level geolocators are somewhat imprecise in position (resolution of approximately 150km) but more precise in time. Relative to the autumn migration, the spring stopover is relatively confined both geographically and temporally and so the discussion in this study is restricted to this. It can be seen that, since snow buntings are not marine birds, the spring stopover region is limited by the northern coastlines of Norway (specifically Finnmark) and Russia (specifically the Kola Peninsula including the Murmansk region). As we shall examine henceforth, small deviations in longitude will result in the weight of stopover occurrences shifting between Finnmark and Kola. Furthermore it is reasonable to believe that the birds will use the last opportunity to land before launching into the flight to Svalbard over the sea (some 900-1000km), whereby the only possible resting place is the small and possibly difficult to locate Bear Island at 74.5° N, 19.1° E. The winter migration will not be addressed here (as stated above), but is further east with longer stopovers and distributed over a larger geographical area (Snell et al., 2018; Fossøy et al., 2018). Navigational discrepancies in the south-eastward winter migration are thus less critical for arriving at safe winter grounds – it is during the return migration that missing the target stopover or even breeding ground can have consequences for the summer populations and breeding success.

3. Geomagnetic field characteristics

It is well known that as the geomagnetic field changes over time (secular variation) the locations of the north and south magnetic poles change. At a given geographic location, the angle between magnetic north and geographic north, the magnetic declination, similarly exhibits a secular variation. This is illustrated in Figure 2. This and subsequent presentations of geomagnetic data are sourced from the 12th generation of the International geomagnetic reference field (Thébault et al., 2015, and referred to hereafter as IGRF-12) and available via interactive graphical user interfaces, for instance as provided by National Centers for Environmental Information ("NOAA") at https://maps.ngdc.noaa.gov/viewers/historical_declination/. As an illustration, Figure 3. shows the observed declination at the Steppes (55° N, 60° E), Finnmark (70° N, 31° E) and Novaja Zemlya (73° N, 54° E) over the period from 1988 to 2020. Finnmark (70° N, 31° E) is representative of the spring stopover, addressed here, and Novaja Zemlya (73° N, 54° E) is typical for the autumn stopover. This variation, as mentioned above, is specific to the geographic location: we can confirm this easily from the NOAA presentation of IGRF-12 and also deduce that in the Russian/Ukrainian steppes region (50-60° N, 50-60° E) (hereafter referred to as "Steppes") the declination is approximately 13° and changing by ~2° over the same period. It is therefore a non-trivial task (inappropriate for this study) to derive the changes in declination at successive locations along the postulated flightpath of snow buntings from wintering grounds in the Steppes to northern Norway/Russia and onwards to breeding on Svalbard. Furthermore, it must be remembered that progressive imprinting of navigational information through several generations (snow buntings have a typical lifetime of 6 years) is a *sine qua non* for the total cumulative deviation over timescales of the secular movement of the geomagnetic pole. Without the imprinting, a species with a 6-year lifetime would only experience a change in declination of about 0.4°.

In addition to the secular variation of the magnetic field, geomagnetic storms with origins on solar activity ("space weather") perturb the field (including the declination) over shorter timescales (e.g. Hargreaves 1992). These perturbations last typically a few hours per day and persist for several days during which the departure of declination for the mean can amount to as much as 10-15° over very short periods. Such events were postulated by Vanselow et al. (2017) as a possible cause for navigational errors by sperm whales causing them to swim into the North Sea rather than into the Atlantic. For convenience, geomagnetic activity is often characterized by the k-index, derived from fluctuations observed at one (local index) or multiple (global index) as devised by Bartels et al. (1939). The local provisional values of the k-index for selected Norwegian observatories are derived regularly by Tromsø Geophysical Observatory and in Figure 4. the average diurnal variation during 2013 (taken as an example) is shown. Together with this, variations for two particularly active days are given, these being typical of the spring migration period. It can be demonstrated that such disturbed periods (viz. 26th May and 6th June which are merely selected as examples) are largely limited to (a) late in the day – the passage of the Harang discontinuity (e.g. Hargreaves 1992), (b) the auroral regions (viz. north of ~65°N in Europe) and (c) during periods of suitable solar activity. As an example, values of k-indices around 8 can be associated with 1-hour average declinations of ~1° at Tromsø and furthermore restricted to periods of only a few hours, on relatively few days per year and usually at latitudes north of 65°. With a speed of only 30-40 $\mathrm{kmh^{-1}}$, snow buntings will typically require ~50 days to traverse the flight from the Steppes to northern Norway and/or Russia and during this time experience significant geomagnetic disturbances during a very small proportion of the flight (if any at all). Quantitatively, during a 1-hour flight (i.e. covering 40km) a 1° error in compass direction would result in a 700m error transverse to the flight direction. In extreme cases where as much as 10° perturbation has been observed, albeit over a very short period, the corresponding error would be 7km. The probability of snow buntings making such significant navigation errors are incalculably small because the condition, a rare occurrence in itself, would only be encountered during an hour or two of the conceivable total 50-day flight. A second approach is to examine the geomagnetic field disturbances directly. Instead of using the familiar k-index as a metric, Tromsø Geophysical Observatory favours calculating the average deviation of the horizontal component from its mean value over 24 hours, hereafter referred to as the "activity index". Snell et al. (2018) document specific flight data for 2014 and 2015; we have extracted daily values from the data from the observatory-class station at Tromsø (70°N, 19°E) considering these to be representative of daily geomagnetic activity in Northern Norway. We have estimated flight times of 50 and 22 days for the legs Steppes-Finnmark and Finnmark-Svalbard respectively and present, in Figure 5., activity indices for the spring migration covering these periods for 2014 and 2015. The representations are, of course a simplification, since activity index shown early in the migration is not representative for mid-latitudes, but determination of the index along a flightpath (of essentially unknown trajectory) is beyond the scope of this study. However, big excursions in the activity index as seen in Tromsø are indicative of geomagnetic storms, which also give rise to larger than usual geomagnetic disturbances at more southern latitudes. Nevertheless, we see a distinct difference between the two years, and birds approaching the auroral zone in 2015 have experienced substantially more geomagnetic disturbance than in 2014. On the other hand, the flights to Svalbard (with absence of ground-based cues) encountered magnetic disturbances during both years. Snell et al. (2018) attribute recovery of only 14% of birds in 2015 to polar day effects (as opposed to 80% in 2014) and although tempting, attributing the difference to geomagnetic activity would be pure conjecture.

A further consideration is the suggestion by Cochran et al. (2004) whereby migrating songbirds have the capability of recalibrating their compasses daily during twilight using stellar or solar cues; this applies primarily to night-time flight and is proposed as compensating for problems determining declination while traversing geomagnetic anomalies such as in North America or the geomagnetic equator region. The mechanism of Cochran et al. (2004) may be applicable to high latitude but during the spring migration period, twilight is much diminished (in fact the sun does not set at all at after mid-April on Svalbard) and furthermore declination is well defined as opposed to the geomagnetic equator region. Finally, very short period (erratic) fluctuations in the geomagnetic field, both positive and negative, may result in periods where magnetoreception is simply unusable or confusing. In the following section, we shall qualitatively examine the possible consequences of these long- and short-term variations in magnetic declination for the springtime migration of snow buntings described by Snell et al. (2018), while keeping in mind the temporal and, in particular, spatial uncertainties described in the previous section. Yet another scenario is where while large disruption in the geomagnetic field are noticed and accounted for, small deviations are not and can influence navigation more. This is addressed by Liboff (2013) but considering more than avian species; weak fields may be chronodisruptive (i.e. affecting the biological clock) such that variations ranging from the geomagnetic field's diurnal variation to space-weather effects including solar storms and thereafter affecting both navigation and, *inter alia*, sleep cycles.

4. Inferences

Let us suppose that snow buntings migrate successfully, using magnetoreceptors as a navigational aid, from the Steppes region to the northern Norway/Russia coast. Over a period of 30 years, the magnetic declination changes, varying from ~2° at the origin of the flight, to a total of approximately 6° at the stopover (a distance of approximately 2000km) before the final leg to Svalbard. Assuming no knowledge (e.g. hereditary) of the movement of the magnetic pole, the birds would then "miss" the original destination by (of the order of) 260km perpendicular to the original flightpath (i.e. N.E.). A postulated flightpath directly from the Steppes to Finnmark lies approximately parallel to the coast of the Kola Peninsula but inland. Therefore, given a deviation of 200km towards the N.E. over a 30-year period, birds would progressively encounter the northern coastline sooner, although, again, assuming imprinting of navigation information from previous generations. This would result in a diminishing population during the spring stopover in Finnmark and a corresponding increase on the Kola Peninsula. The former is in qualitative (we emphasise "qualitative") agreement with the findings of Bakken and Strann (2019), whereas evidence of population increase in the Kola region is difficult to locate. We propose a hypothesis, albeit speculative and tentative, that an explanation, presumably only as a contributing factor, for the decline in montane bird population in Finnmark may be due to a changing migration path due to movement of magnetic north. Long-term (climatic) changes in wind strength and direction, precipitation, temperature and optimal foraging are almost certainly factors, if not even dominating ones. Note, also, that snow buntings represent only part of the montane bird population's decline in in Northern Europe: Lehikoinen et al. (2014) document data specifically for snow buntings mainly for Sweden, and not Finnmark.

Addressing short-term variations in magnetic declination as a result of space weather events, we demonstrated that these are rarely large enough to cause transverse errors in navigation of more than 1 km at a time. Such events are restricted to the high-latitude (>65°N) section of the total flightpath, short periods of time (at most, a few hours per day) and for very few days during the migration timescale.

Data for this preliminary study have been obtained for Tromsø, Norway from Tromsø Geophysical Observatory, and therefore represent only one measurement point on the approximate flightpath for migrations between the Steppes and Svalbard. A deeper analysis, out of place for this preliminary work, should involve calculating cumulative navigational errors along the flightpath(s) and therefore obtaining geomagnetic data from sufficiently closely spaced observations or from a semi-empirical model. Sandberg and Pettersson (1996) suggest that snow buntings are particularly sensitive to magnetic variation but future studies could encompass other species for which good or better population and migration data exist. Furthermore, other parameters such as temperatures and winds could be included. Food abundance (such as insects) is an important factor for breeding success, in turn affected by tropospheric conditions. In particular, due to a changing climate (a debate into which we will not enter here) it should be demonstrated whether wind direction has changed secularly for the appropriate spatiotemporal window for the spring migration. Indeed, wind direction (specifically tailwind) and precipitation (including effects on foraging grounds) are important for migration success (Snell et al., 2018). Furthermore, while Cochran et al. (2004) suggest that some species have the capability of recalibrating their compass during twilight, this would need to be confirmed for high latitude where twilight barely exists in the migration window. More dramatic changes in the geomagnetic field, including reversals, are slow and infrequent relative to evolution timescales for species discussed in this study (e.g. Gubbins, 2008 and references therein) but should not be discounted if considering causes of extinction.

In conclusion: (a) one may question, although not entirely disregard, any hypothesis that snow bunting (or any migratory bird employing magnetoreception as a navigation aid) changing or redistributed populations may be to short-term space weather events; (b) secular variation in the location of the magnetic pole remains a plausible factor contributing to, although not solely responsible for, reduction of snow bunting population in Northern Norway. In particular, we have identified how both processes within the Earth and on the Sun give rise to slow and rapid changes respectively in the geomagnetic field; these changes are detectable by a variety of using magnetoreception species, including snow buntings, and therefore potentially affect migration traits, especially at high latitude in the auroral zone.

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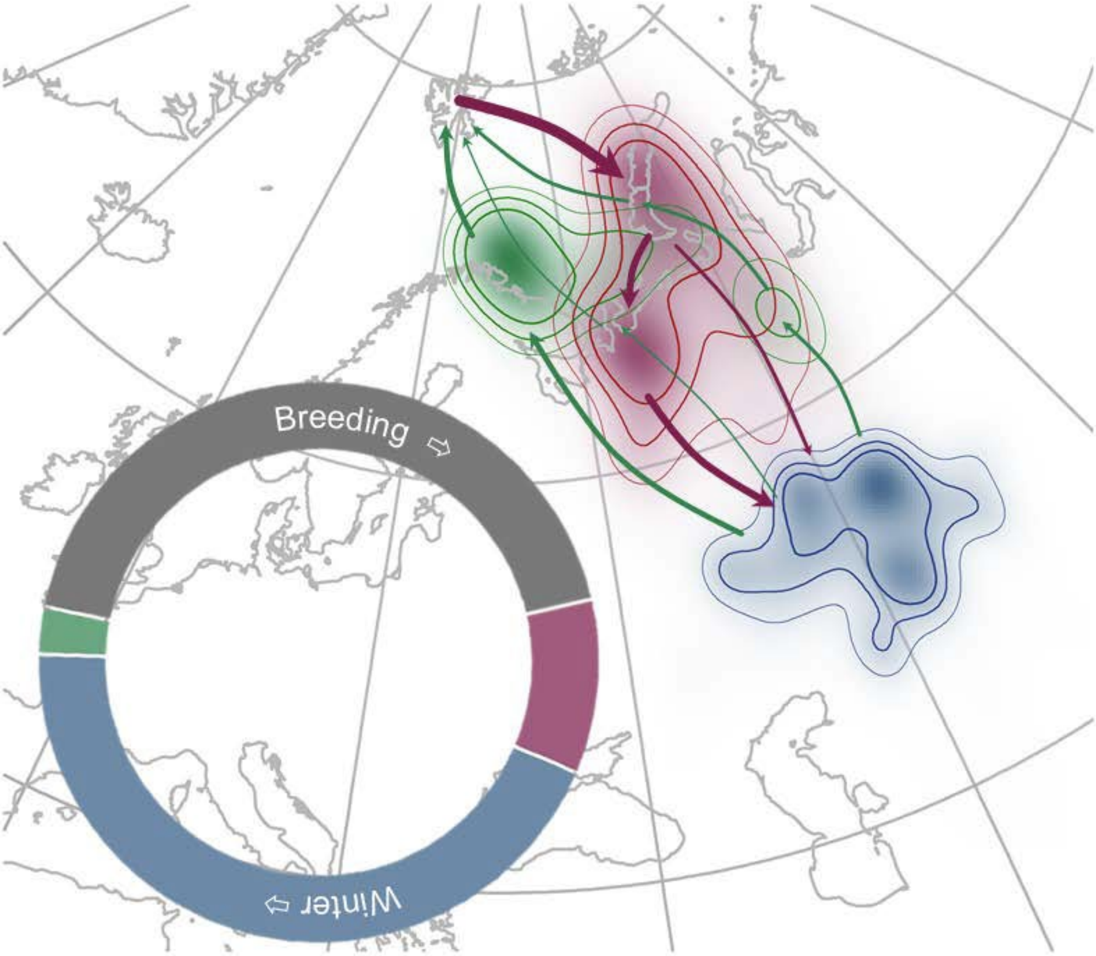

Figure 1: Migratory paths of snow buntings. Blue areas show wintering grounds; the small archipelago top-centre is the summer breeding ground (Svalbard); the green and red areas depict the spring and autumn stopover regions. The circle inlay demonstrates the time spent at each location. From Fossøy et al. (2018), using original figures from Snell et al. (2018).

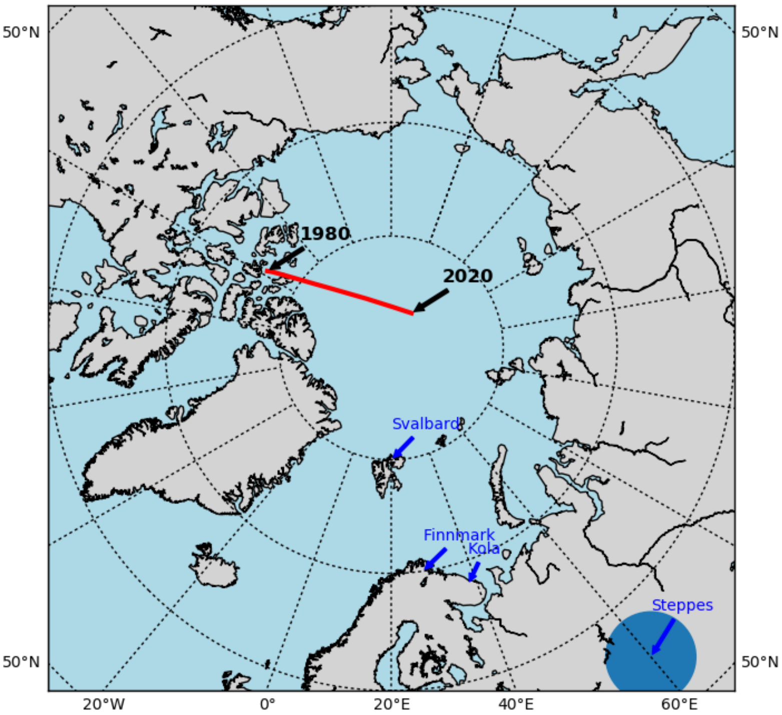

Figure 2: Movement of the magnetic north pole between 1980 and 2020 (the last two years being a prognosis) (red line). Geographic locations key to the manuscript text are indicated on the map in blue.

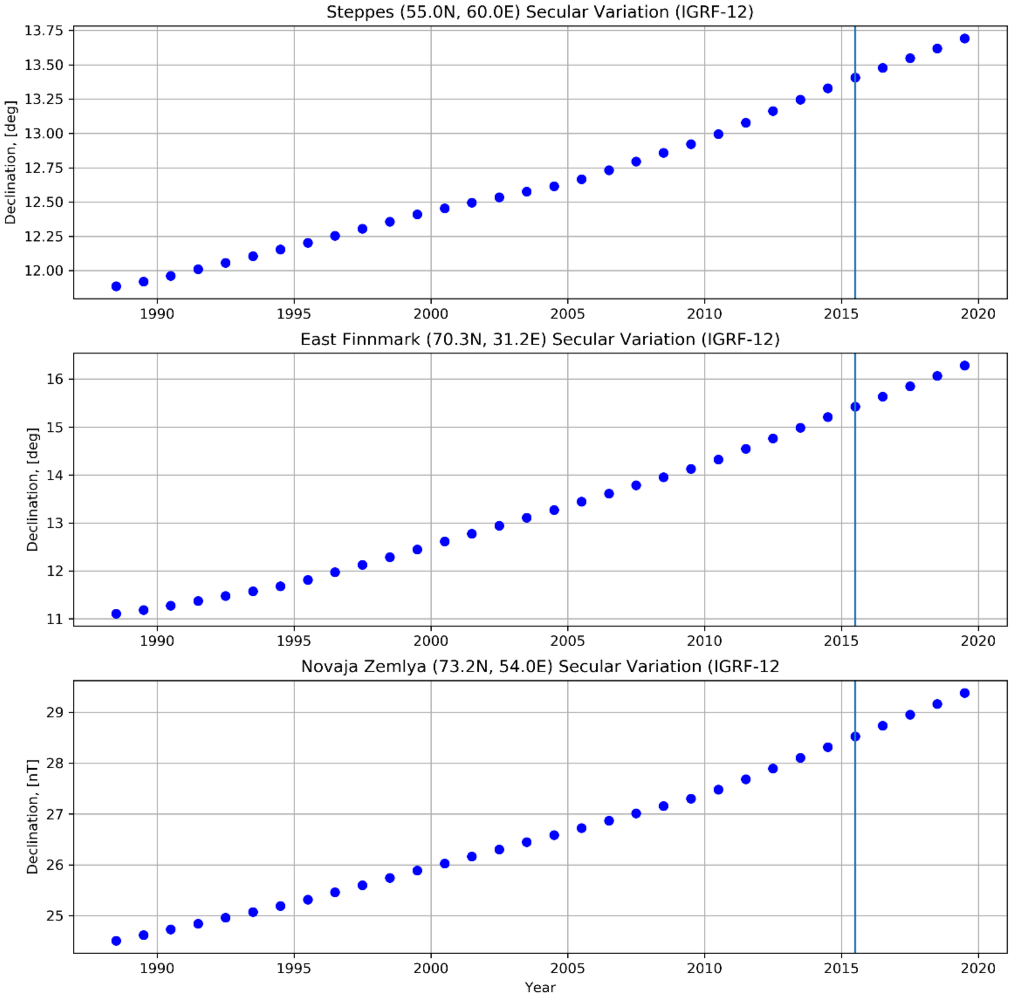

Figure 3. Change in magnetic declination (in degrees east of north) at (top) Steppes (55° N, 60° E), (centre) Finnmark (70° N, 31° E, typical stopover for spring migration) and (bottom) Novaja Zemlya (73° N, 54° E, typical stopover for autumn migration) between 1988 and 2020 (from Tromsø Geophysical Observatory / IGRF-12 semi-empirical model).

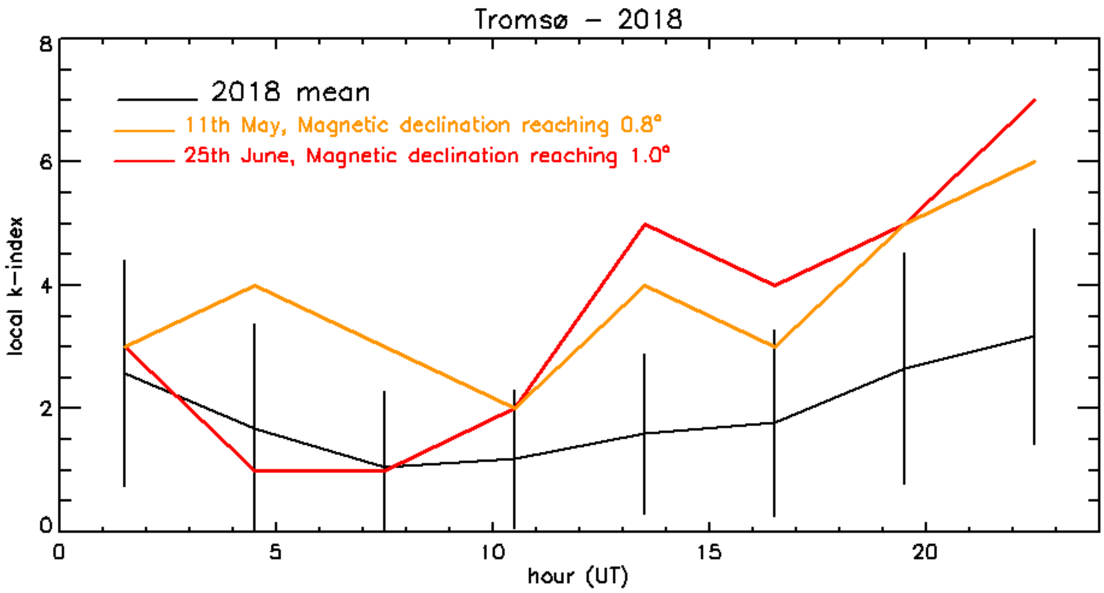

Figure 4. Time of day variation of geomagnetic activity parameterised by the local k-index at Tromsø (70° N, 19° E) during 2013 (from Tromsø Geophysical Observatory). Black: means and standard deviations (black error-bars) for 2018; Red: variation for 26th May 2013; Orange: variation for 6th June 2013. The declinations (positive east) corresponding to the highest k-values are indicated in the legend. See text for further explanation.

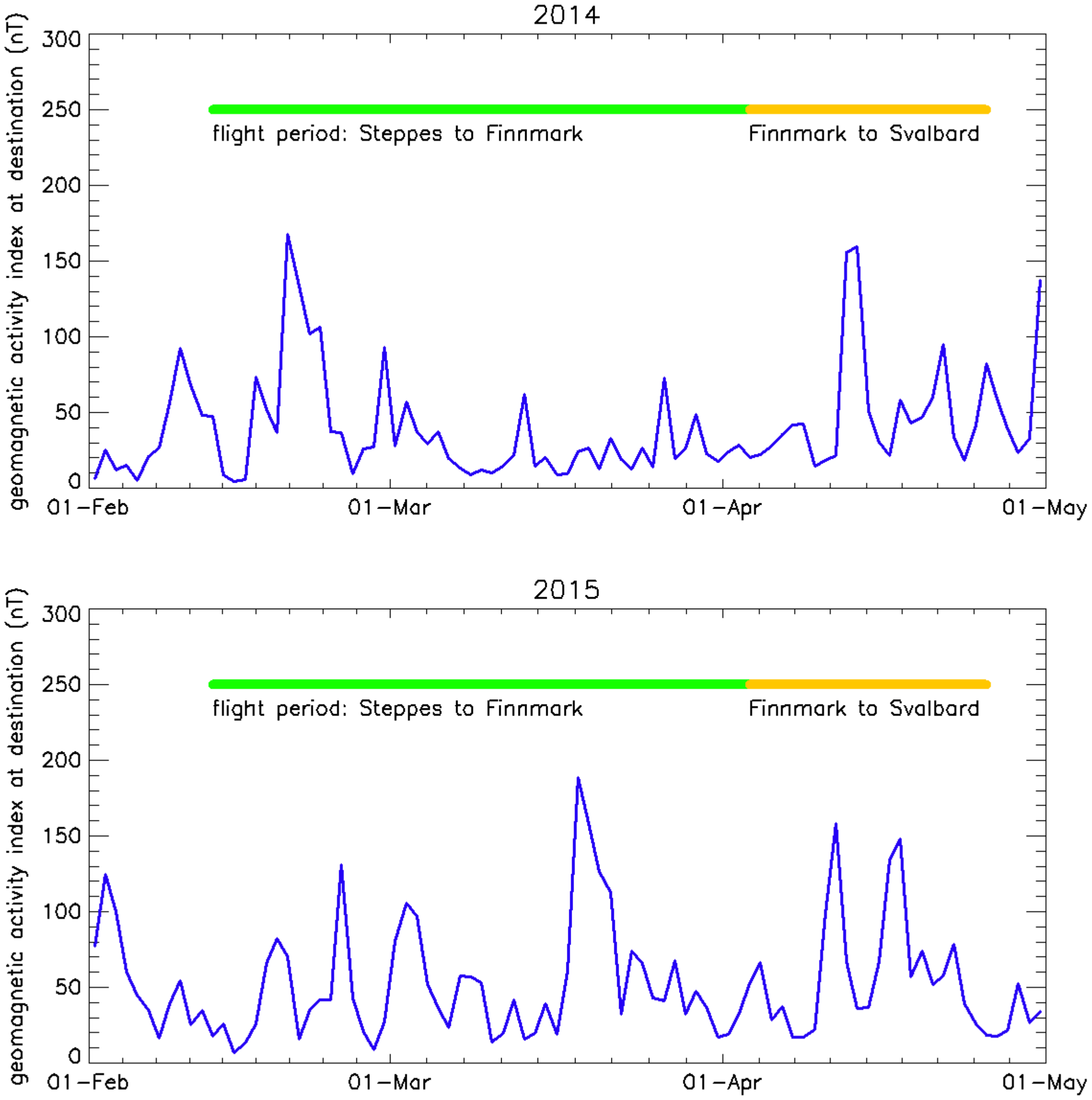

Figure 5. Daily geomagnetic activity index (daily average deviation of horizontal component from daily mean) considered representative for Northern Norway. Top: February to April inclusive, 2014; bottom: 2015. The flight periods for the spring migration are indicated, assuming a groundspeed of 40km day^{-1} and based on median values of dates given by Snell et al. (2018).