Space physics in Svalbard: A study of the energy input in the polar ionosphere using SuperDARN

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1. Introduction

At approximately 08:00–12:00 local time each day, Svalbard passes through a narrow, funnel-shaped region of the Earth's magnetic field known as the "cusp". This region channels charged particles from the Sun into the Earth's upper atmosphere, producing auroral displays which can be observed from Svalbard during the polar night. The long polar night and the availability of supporting infrastructure make Svalbard the only place on Earth where it is both possible and practical to study the cusp from the ground. It is also an ideal location for observing a wide range of other high-latitude magnetospheric and upper atmospheric processes driven by solar activity. Svalbard has therefore been the focus of major investments in space physics research infrastructure, both from Norway and abroad, over several decades.

The major Norwegian investments in space physics research infrastructure in Svalbard are as follows:

- The Kjell Henriksen Observatory (KHO), the world's largest optical observatory for auroral and middle atmospheric studies, with 34 instruments, located on Breinosa about 12 km southeast of Longyearbyen;
- Svalrak, a rocket range owned by the Andøya Space Centre, located in Ny-Ålesund;
- The European Incoherent Scatter (EISCAT) Svalbard Radar, located on Breinosa. This radar provides measurements of temperatures, densities and velocities of particles in the upper and middle atmosphere over and around Svalbard.

A recent addition to Svalbard's space physics research infrastructure is the Svalbard SuperDARN Radar, located on Breinosa near the KHO and EISCAT facilities. SuperDARN (Super Dual Auroral Radar Network) is an international network of more than 30 high frequency (HF) radars designed for studying high-latitude plasma convection driven by interactions between the magnetic fields of the Sun and the Earth (Greenwald et al. 1995; Chisham et al. 2007; Nishitani et al. 2019). The Svalbard SuperDARN radar fills an important gap in the spatial coverage of SuperDARN and complements the local optical and radio observations from KHO and EISCAT. SuperDARN is operated by researchers from 10 countries and is often cited as a prime example of successful international scientific collaboration (Greenwald 2017). Collectively, the SuperDARN radars provide coordinated observations of global-scale plasma structures and dynamics, whilst individually providing observations of mesoscale (100–500 km) processes and turbulence.

1.1. Energy transfer from space to the upper polar atmosphere

The vast majority of near-Earth space physics phenomena derive their energy from the Sun through a wide range of coupling mechanisms. In addition to light, the Sun emits a stream of ionised energetic particles called the solar wind, which also carries with it the solar or interplanetary magnetic field (IMF). The Earth is protected from the solar wind and the IMF by its own magnetic field; thus, most of the solar wind is deflected around the Earth. At the dayside magnetopause, the IMF and the Earth's magnetic field can connect (through a process called magnetic reconnection), forming a gateway between the two systems which channels particles and energy directly into the Earth's upper atmosphere. This process is illustrated in Figure 1. The IMF connects with the Earth's magnetic field at the magnetopause, forming an 'open' field line configuration over the polar regions. One visible consequence of this process is the dayside aurora, which occurs when the solar wind particles collide with atmospheric nitrogen and oxygen in the cusp. The polar cusp in each hemisphere forms at the point where the field lines first become 'open' to the IMF, and it is the footprint of this region where the 'dayside' aurora can be observed (Figure 1, inset).

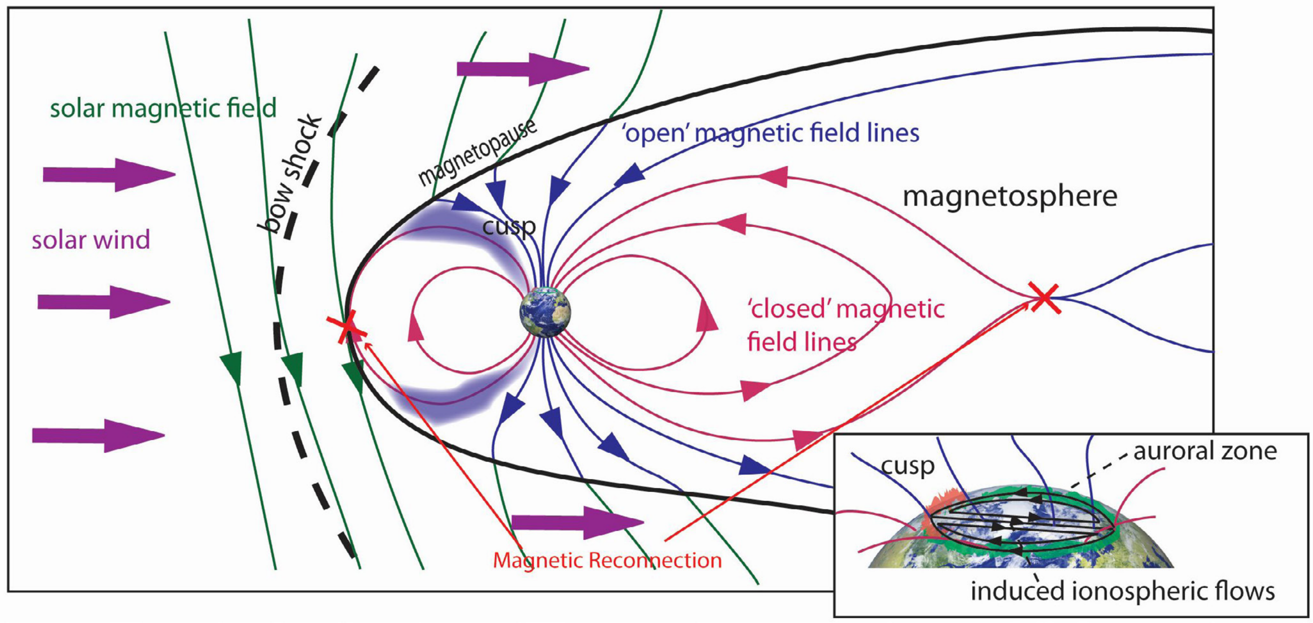

Figure 1: Interaction between the solar magnetic field and the Earth's magnetic field, which drives the ionospheric convection measured by SuperDARN radars.

In addition to providing this gateway for particles, the solar wind flow drags the open magnetic field lines across the polar regions, from the dayside to the nightside. Once on the nightside, these field lines sink into the magnetosphere where they reconnect, forming closed loops between the two hemispheres. The act of closing these field lines transfers energy and momentum from the solar wind into the magnetosphere, which drives auroral activity on the night side of the Earth (Figure 1, inset). Once closed, the field lines convect around the flanks of the magnetosphere to the dayside and the process repeats. This process of opening, convecting and closing of field lines, known as the Dungey cycle (Dungey 1961), sets up large-scale horizontal velocity flows up to 2 km/s over the polar regions, which can be measured by SuperDARN radars at around 250 km altitude (F region ionosphere). The direction, speed and turbulent nature of these ionospheric flows are controlled by the interaction with the IMF. These processes also induce large horizontal current systems in the 90–120km altitude range (E region ionosphere), dissipating energy into the neutral atmosphere through Joule heating or frictional heating processes (Brekke 2013). Collisional heating and turbulence associated with various auroral processes also serve to dissipate energy into the system (e.g. Frey et al. 2019; Hosokawa et al. 2019). Joule heating and particle precipitation account for 22% of the total global upper atmospheric energy budget, and in cases of extreme solar wind driving, the energy contribution from Joule heating can exceed the energy input from solar UV (Knipp et al. 2005). The coupled solar wind-magnetosphere-ionosphere system thus acts to direct energy into the high latitude atmosphere through a wide variety of processes and over a range of temporal and spatial scales. The term 'space weather' is often used to describe disturbances in this system that may impact technology and infrastructure.

1.2. Space physics research infrastructure on Svalbard

Due to its vast size, it is not possible to monitor the entirety of the Earth's magnetosphere in-situ. However, the outer magnetosphere maps into a relatively small region of the ionosphere at polar and auroral latitudes along the geomagnetic field lines. Magnetospheric processes can therefore be studied by monitoring their footprints in the ionosphere. The signatures of the ionospheric energy deposition assume many different forms; hence, the vast majority of studies must combine data from many types of instrumentation. Moreover, radio instruments such as radars can sometimes be used in place of traditional optical instrumentation during periods of daylight or cloud cover to construct a continuous dataset. Svalbard's extensive research infrastructure and unique location under the cusp make it a world-class location for ground-based remote sensing of the cusp and polar atmosphere using this multi-instrument complementary approach.

In addition to the Kjell Henriksen Observatory and the EISCAT facilities at Breinosa, Norwegian research institutes operate a wide variety of space physics instruments elsewhere in Svalbard. These include cameras, photometers, ground magnetometers and GNSS receiver stations in Ny Ålesund and Hornsund; an ionosonde, meteor radar and mesospheric radar (SOUSY) in Adventdalen and a riometer in Ny Ålesund. A full list of the current Norway-owned instrumentation and the instrumentation that Norwegian researchers have direct access to through ongoing collaborations is provided in Table 1. A more detailed list of the international instrumentation at the KHO is available on the KHO webpage[1].

Other countries with relevant research infrastructure in Svalbard (either individually or through collaboration) include China, Japan, UK, Sweden, Finland, Denmark, the USA, South Korea, France, Russia, Italy, Ukraine and Poland. Five of these countries (China, Japan, the UK, Italy and the USA) also operate SuperDARN radars. Many of these countries collaborate through data sharing or focused experimental campaigns.

To obtain a detailed understanding of the system and, more importantly, to be able to model and predict the atmospheric responses to external forcing over the long term, consistent, complementary datasets are required. Datasets from Svalbard represent some of the longest time series of measurements of ionospheric processes in the world. These include mesospheric temperature measurements (1980–present), auroral camera observations (1978–present) and EISCAT radar observations (1997–present). The recent addition of the Svalbard SuperDARN radar marks a new era of complementary, long-term and continuous monitoring of the polar atmosphere and cusp by an HF system, joining the global database of SuperDARN observations that stretches over 25 years.

1 http://kho.unis.no/nordlysstasjon_instr.htm

Table 1: Norwegian owned instrument or instruments to which Norway has direct access (e.g. EISCAT)

Instrument	Parameters	Period	Location	Metadata/Data access	Data provider	Category
Svalbard SuperDARN radar	F-region convection velocity and dynamics, HF absorption, mesoscale processes and turbulence	Nov 2016–Oct 2018, early 2021 -	Breinosa	RiS: 11568 https://www.bas.ac.uk/project/superdarn/#data.	UNIS	Radars
HF Doppler transmitter/receiver	Horizontal ionospheric velocity	Aug 2020–present	Hornsund/Breinosa	RiS: 11522	UNIS	Radars
Dynasonde	Electron density profile	May 2020–present	Breinosa	http://kho.unis.no/Ionosonde/index.html	UNIS/UiT	Radars
SOUSY radar	Middle atmosphere structure and turbulence	2001–present	Adventdalen	RiS: 3729 http://radars.uit.no/	UiT	Radars
Riometer	Cosmic noise absorption	2013–present, Dec 2020 - present	Ny Ålesund Adventdalen	RiS: 6696, http://radars.uit.no/	UiT/TGO TGO/UNIS	Radars
Meteor radar	Mesospheric velocity	April 2019–present	Adventdalen	RiS: 3729 http://radars.uit.no/	UiT/TGO	Radars
EISCAT radar	Ionospheric density, temperatures and velocities (E and F region)	1997–present	Breinosa	http://portal.eiscat.se/madrigal/	EISCAT	Radars
7 all-sky cameras	Auroral and airglow: morphology, emission intensity, mesospheric studies	Variable depending on instrument (~5 years to 20 years, winter season)	KHO	http://kho.unis.no/Keograms/keograms.php	UNIS	Optical
3 all-sky cameras	Emission intensity, auroral morphology	Ny Ålesund: 1997–present, Hornsund: 2019–present, KHO: 1996–present	Ny Ålesund, Hornsund, KHO	RiS: 10977 http://tid.uio.no/plasma/aurora/	UiO	Optical

4 spectrometers	Spectral emission intensities, mesospheric temperatures, particle precipitation energies	Variable depending on instrument (~5 years to 40 years, winter season)	KHO	http://kho.unis.no/Keograms/keograms.php	UNIS / U of Alaska / UiT	Optical
2 photometers	Open-closed boundary, particle boundaries, auroral morphology	Variable depending on instrument (~5 years to 20 years, winter season)	KHO	http://kho.unis.no/Keograms/keograms.php	UNIS / U of Alaska	Optical
4 fluxgate magnetometers	Magnetic field motion, waves	KHO: 1993–present, Ny Ålesund: 1980–present, Hopen: 1988–present, Bjornøya: 1997–present	Ny Ålesund, KHO, Hopen, Bjornøya	RiS: 6083 https://flux.phys.uit.no/geomag.html	UiT / TGO	Others
GNSS scintillation receivers	Total electron content, scintillation of GNSS signals	Ny Ålesund: 2009–present, Hornsund: 2018–present	Ny Ålesund, Hornsund	RiS: 10977 http://tid.uio.no/plasma/gps/	UiO	Others
GNSS scintillation receivers	Total electron content, scintillation of GNSS signals	2013–present	Ny Ålesund, KHO, Bjornøya, Hopen	https://site.uit.no/spaceweather/data-and-products/ionospheric-conditions/ionospheric-scintillation/	UiB	Others
SvalRAK	Rocket, in-situ ionospheric measurements	1997–present	Ny Ålesund	RiS: 10620	Andøya Space Centre	Others

2. Ionospheric and upper atmospheric research using SuperDARN HF radars

SuperDARN radars have provided invaluable knowledge about the large-scale structure and dynamics of the ionospheric convection, energy transfer processes and mesoscale structures over several decades. In the polar cap and auroral zones, including over Svalbard, significant attention has been accorded to determining the location of the boundary between open and closed magnetic field lines using SuperDARN and comparing the results to the optical signature of this boundary (e.g. Chisham et al. 2004; Imber et al. 2013; Chen et al. 2015). The radars have also been used for performing high spatial resolution observations of small-scale velocity features within the large-scale convection pattern (e.g. Herlingshaw et al. 2019; Baddeley et al. 2007), patches of enhanced electron density (polar cap patches) that are transported through the polar caps within the background convection flow (Oksavik et al. 2006; Zhang et al. 2013; Fæhn Follestad et al. 2019) and estimations of Joule heating rates (Billet et al. 2020; Kiene et al. 2018).

In addition to the above applications, focused primarily on the F-region ionosphere, SuperDARN data have also been used in studies focused on E-region structures, such as nightside auroral arcs (e.g. Hosokawa et al. 2010) and large-scale atmospheric tidal motions at 100 km altitude (e.g van Caspel et al. 2020). Some recent studies have also used SuperDARN data to validate atmospheric and climate modelling results (Hibbins et al. 2019) or develop improved inputs for these models (Bland et al. 2019, 2020). The SuperDARN radars are therefore highly versatile research tools which can be used to address a wide range of topics in upper and middle atmospheric physics.

2.1. The Svalbard SuperDARN radar (2016–2018)

The Svalbard SuperDARN radar is part of a global network of more than 30 HF radars used for studying the structure and dynamics of the Earth's ionosphere. The SuperDARN network began over 25 years ago. The Svalbard radar was added to the network in 2016 to fill a spatial coverage gap in the cusp and polar cap ionosphere. The field of view of the Svalbard radar is shown in Figure 2 (red shading), along with the fields of view of the other SuperDARN radars in each hemisphere. Each field of view covers an azimuthal sector of at least 52° and extends to over 3500 km in range. Two radars located in Finland and Iceland provide coverage over Svalbard (grey shading), and the data from these radars have been used extensively in studies of cusp and auroral phenomena together with KHO, EISCAT and sounding rocket instrumentation (e.g. Lorentzen et al. 2010; Moen et al. 2012; Oksavik et al. 2012; Chen et al. 2015). These two radars, however, were decommissioned in 2018 and 2019 after more than 20 years of operation. The research groups who are responsible for these radars have obtained funding to refit both radar systems, and it is hoped that they will resume operations in 2022.

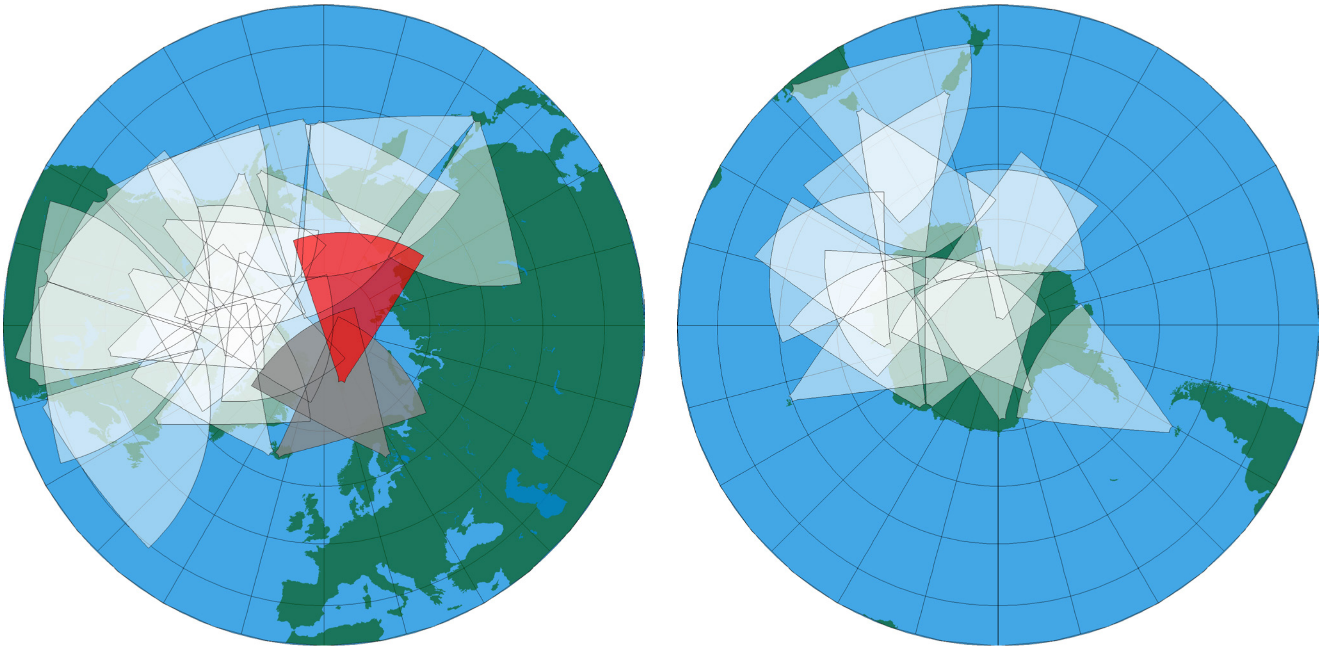

Figure 2: Fields of view of the SuperDARN radars in the northern hemisphere (left) and southern hemisphere (right). The Svalbard SuperDARN radar field of view is shaded red. The two radars in Finland and Iceland that provide coverage over Svalbard are shaded grey.

Funding for the Svalbard SuperDARN radar was obtained by the research group at the University Centre in Svalbard (UNIS) in 2012 through the ConocoPhillips/Lundin High North Research Program.[2] This radar is located on Breinosa alongside the EISCAT Svalbard Radar and the KHO and is Norway's first SuperDARN radar. Working with an externally employed company, MultiConsult, planning permission was granted on 13 May 2014. Two research groups were brought onboard for the construction phase of the project: the Radio and Space Plasma Physics Group at the University of Leicester (UoL), UK, and the Institute for Space and Atmospheric Studies at the University of Saskatchewan (UoS), Canada. The UoL group designed and built the radar electronics and transmitter elements. They have also built several other SuperDARN radars and operated two of the radars in Iceland and Finland. The UoS group designed and built the radar antenna units and masts. This group has designed several such structures and operates five SuperDARN radars across Northern Canada.

Due to the sensitive nature of the Arctic tundra, all elements of the radar had to be mounted on top of wooden posts driven into the tundra. This ensured minimal environmental impact since no elements would lie directly on the tundra. To limit environmental impact during the construction phase, the antenna masts were erected by hand by a crew of 10 people from UNIS, UoL and UoS during the summer of 2015. The radar consists of the following 3 elements: a main transmitter array of 18 antenna masts, an interferometer array of six antenna masts placed 100 m behind the main array and a 20 ft shipping container which houses the transmitters and other electronics. After an initial commissioning and testing phase, the radar officially became part of the SuperDARN network in October 2016.

The radar operated continuously until October 2018, when an unusual storm caused heavy icing on both antenna arrays. The storm brought sustained periods of strong winds, snow and supercooled rain. The icing created a total mass loading on the system of 1.6 kg/m, resulting in over 10 tonnes of additional weight on the antenna masts, which caused significant irreparable damage. Following this incident, a climate load report was commissioned from Kjeller Vindteknikk, which outlined the ice and wind loads during the incident and provided recommendations for a new mast design that would be able to withstand a 'once in 50 years' storm with a mass loading up to 6 kg/m.

2 http://static.conocophillips.com/files/resources/arctic_approach.pdf

Norconsult was then commissioned to design new masts for the Svalbard SuperDARN radar, given the recommended climate loads. The new masts have been constructed from a durable, corrosion-resistant aluminium alloy and include top plates, custom-made foundation base plates, guy rope brackets and other accessories. The masts have been delivered to Svalbard and the new Svalbard SuperDARN radar will be operational from 2021.

2.2. SuperDARN: A global network

Collectively, SuperDARN performs coordinated observations of the large-scale plasma convection driven by the Dungey cycle. Although there are minor differences in hardware across the network, the radars produce identical data products which can be readily combined into maps of global convection. The radars have no moving parts, allowing them to operate continuously and autonomously with relatively little maintenance. The SuperDARN radars typically have 16 beams (pointing directions), which are scanned sequentially to sample the entire field of view. The temporal resolution of a complete scan is either 1 or 2 minutes in a standard operating mode, and the standard range (radial) resolution is 45 km. Once transmitted, the radiowaves are modified and refracted by the ionosphere towards the horizontal, where the amount of refraction is determined by the ionospheric electron density along the ray path. The transmitted radiowaves are reflected from decametre electron density irregularity structures in the ionosphere, as illustrated in Figure 3. They then return to the radar where they are analysed. These irregularities are created through a range of instability and turbulent processes in the ionosphere and move at the background convection velocity. If the electron density is sufficiently high, in addition to the ionospheric scatter close to the radar (0.5 hop propagation mode), the radiowaves may be refracted back to the ground (1-hop propagation mode). They can then also be forward-scattered up from the ground and can be scattered from the ionosphere at a much greater distance from the radar (1.5 hop propagation mode).

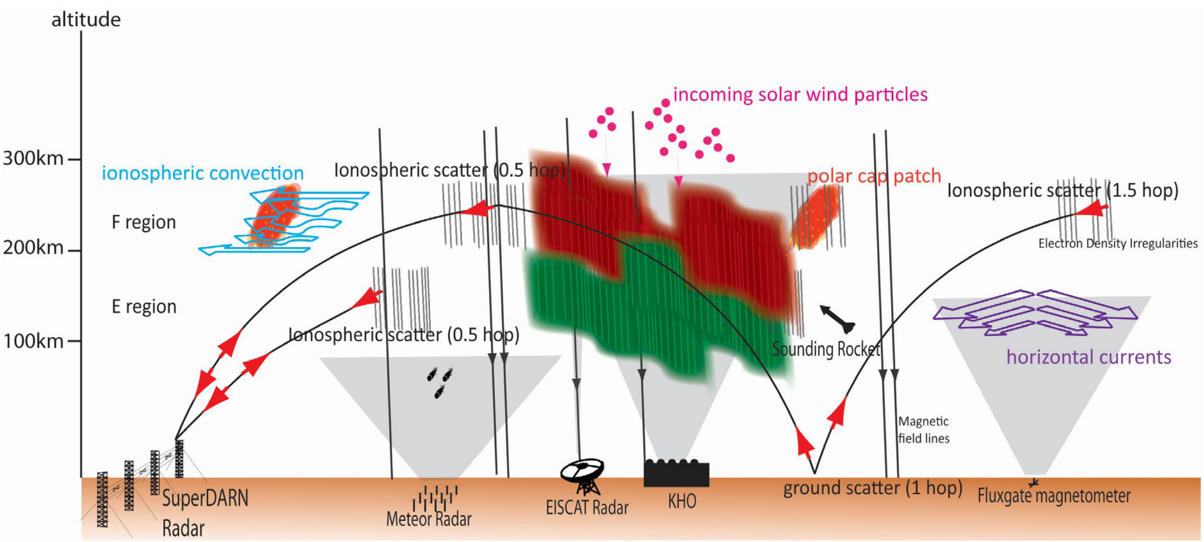

Figure 3: Illustration of space physics phenomena and the instrumentation used to study them from Svalbard.

The primary data products from the radars are the following: backscattered power, line-of-sight Doppler velocity and spectral width. The spectral width parameter is often used as an indicator of turbulence occurring within the scattering volume. Since a single radar can only measure the velocity component parallel to the beam direction, the network is designed with overlapping fields of view so that the full horizontal velocity vector can be estimated by merging data from radars observing the same geographical area (Hanuise et al.1993; Cerisier and Senior 1994). Data from all radars are combined into a central database, using a grid of nearly equal-area grid cells measuring 1° in geomagnetic latitude, to produce global maps of the ionospheric F-region convection in each hemisphere (Ruohoniemi and Baker 1995) at a spatial resolution of 1° latitude. Figure 4 shows the typical two-cell convection pattern driven by the Dungey cycle. The radar data are shown as coloured vectors, with the colour and length of the line relating to the magnitude of the flow according to the colour bar. The flow direction is clockwise in the dusk (left) convection cell and anticlockwise in the dawn (right) convection cell. In places where there are no data (i.e. inside the black circled area), the modelled large-scale convection flow is denoted by black lines. The field of view of the Svalbard SuperDARN radar is also overlaid for reference with the red circle indicating data provided by the radar in an area to the north of Svalbard. In this example, the velocity vectors over Svalbard (LYR) are provided by the (currently non-operational) SuperDARN radar in Hankasalmi, Finland, with the Svalbard SuperDARN radar providing velocity measurements in an area northeast of Svalbard.

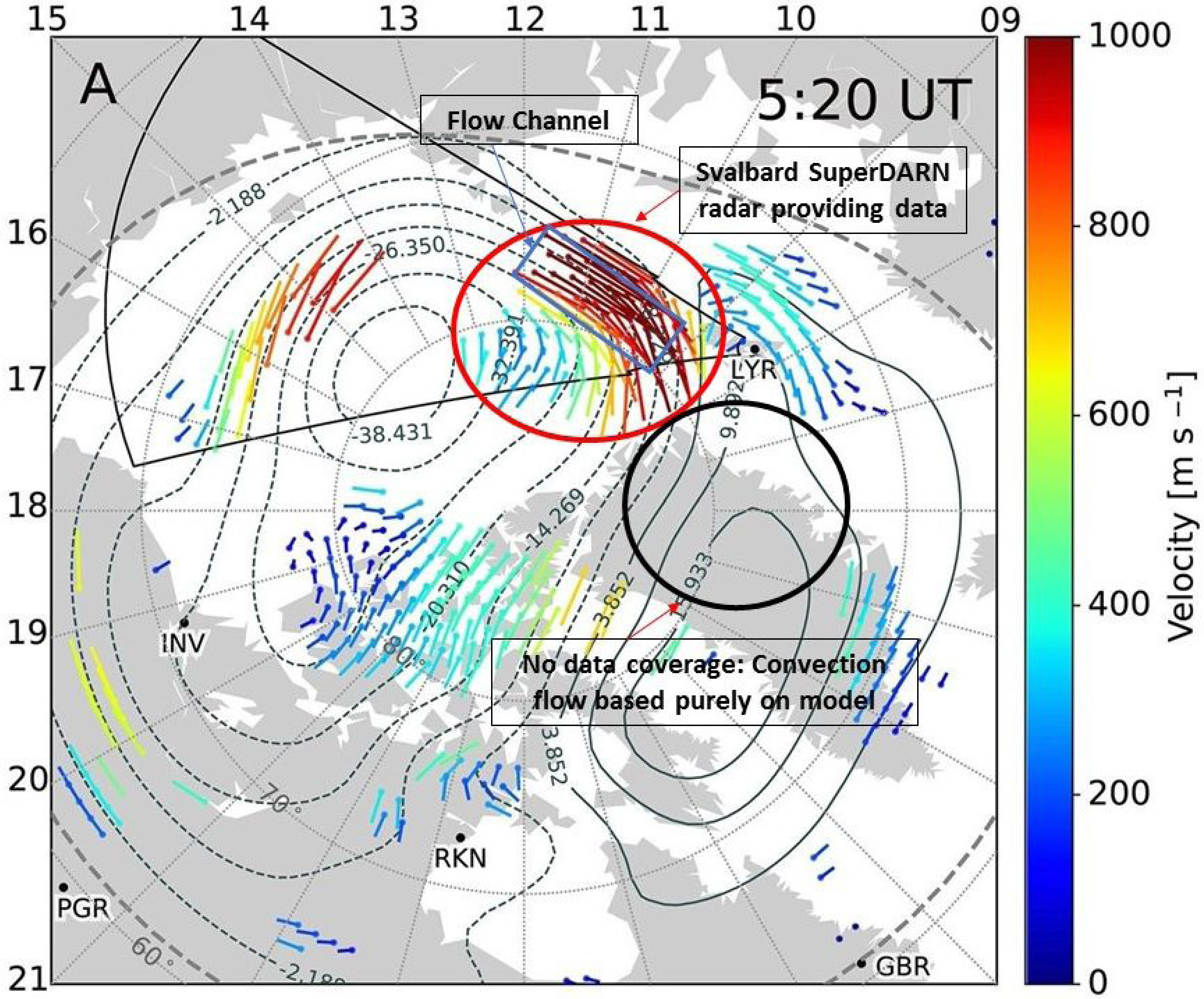

Figure 4: Ionospheric convection map produced from combined observations from the northern hemisphere SuperDARN radars. The Svalbard radar field of view (triangular region, also indicated in red in Figure 2) is shown for reference. The red circle indicates data provided by the Svalbard SuperDARN radar, to the north of Svalbard, and the blue box within that shows a plasma flow channel with velocities up to 1 km/s [Adapted from Herlingshaw et al. (2019)].

These global maps are used extensively across the space and ionospheric physics communities and are unrivalled in their ability to observe large-scale flows. However, there are some caveats. The available propagation modes limit the locations from which ionospheric backscatter can be detected; thus, most of the data used to determine the convection are line-of-sight velocities from single radars, rather than merged velocity measurements from overlapping fields of view. In areas without any data coverage, the convection pattern is based purely on a model, which introduces a significant source of error in the large-scale convection. Moreover, the spatial resolution of convection patterns determined using the standard method is unsuitable for studying mesoscale flows and turbulence, which are often under-represented in models of energy dissipation. Bristow et al. (2016) proposed an alternative method that enables the convection to be determined at the native spatial resolution of the radar (typically 45 km), providing a more detailed representation of the mesoscale ionospheric flow. Expanding the network's spatial coverage by building new radars in strategically-chosen locations would provide a more accurate picture of the large-scale ionospheric convection and also offer new opportunities to study mesoscale structures in combination with other ground-based instrumentation.

3. Scientific highlights

Some examples are given below highlighting some applications of the Svalbard SuperDARN radar, both as a standalone instrument (providing detailed measurements of the cusp and mesoscale ionospheric structures) and as part of the global network of radars (providing observations of the polar cap and cusp for the convection maps in addition to allowing comparative studies with other radars in the network).

3.1. Daily and long-term observations

Figure 5 shows 24 hours of observations from the Svalbard SuperDARN radar, colour-coded according to the power of the returned signals and the Doppler velocity. Positive velocity values indicate plasma flow towards the radar, and negative velocities are directed away from the radar. The slant range (vertical axis) is the distance along the radiowave path to the ionospheric scattering target. Backscatter is detected almost continuously and covers 500–1000 km of range at any given time. The high-power and high-velocity backscatter observed at around 09:00 UT is indicative of the dayside cusp region, where the highly structured irregularities scatter the radiowaves very efficiently.

A summary of the long-term observations from the radar is shown in Figure 6. These results cover the October 2016–October 2018 period and are divided according to season. In the F region ionosphere (top panel), the greatest amount of ionospheric backscatter was detected in the morning hours (~06:00UT/07:00 local time). This peak is higher in winter compared to summer. This result could be due to the highly structured irregularities in the wintertime cusp acting as efficient scattering targets for the radiowaves. A smaller secondary peak occurs at around 19:00 UT, which might be associated with auroral substorm activity. These findings are similar to those for other polar cap SuperDARN radars (Koustov et al. 2019). In the E region ionosphere (bottom panel), a morning sector peak is also present at around 06:00 UT, with a greater number of detections in the summer months. This may be attributed to the continuous ionisation by solar radiation during summer. Overall, the number of detections during each season is lower in the E region, which reflects its smaller vertical extent.

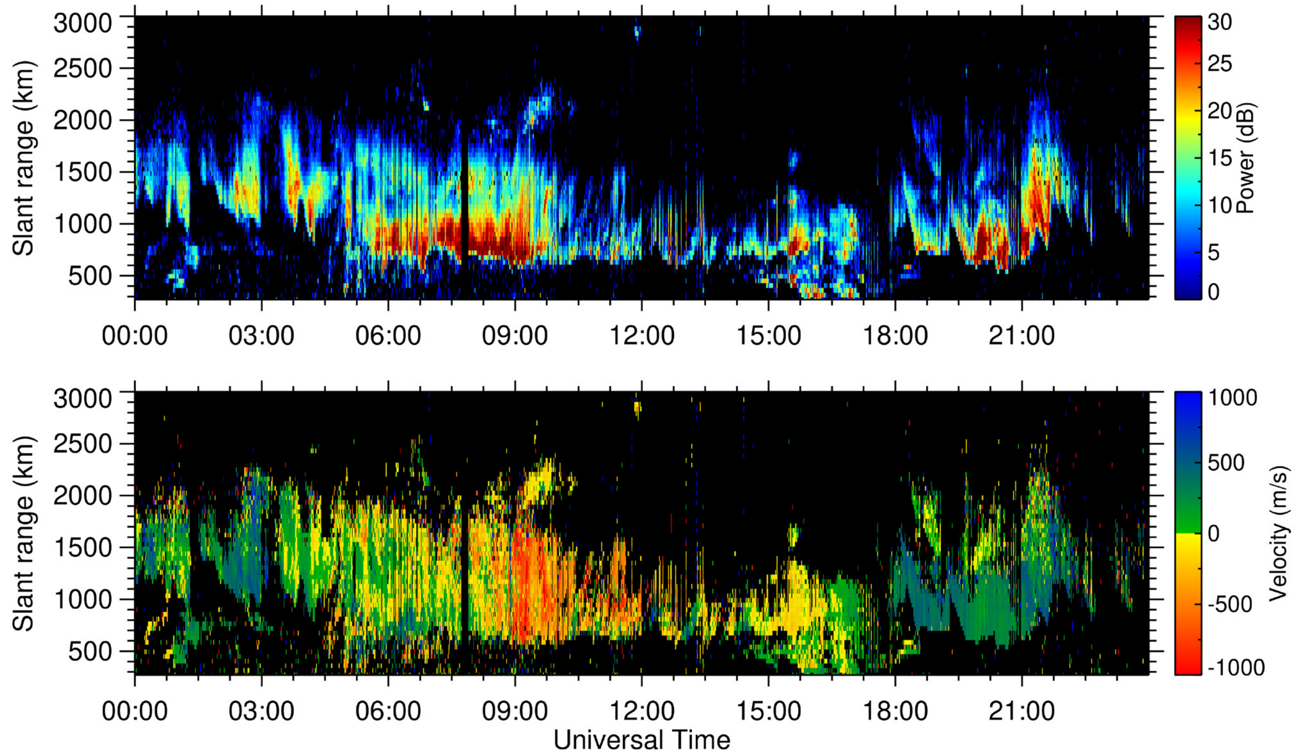

Figure 5: 24-hour summary plot from the Svalbard SuperDARN radar, showing the power of the received backscatter and the line-of-sight velocity measurements.

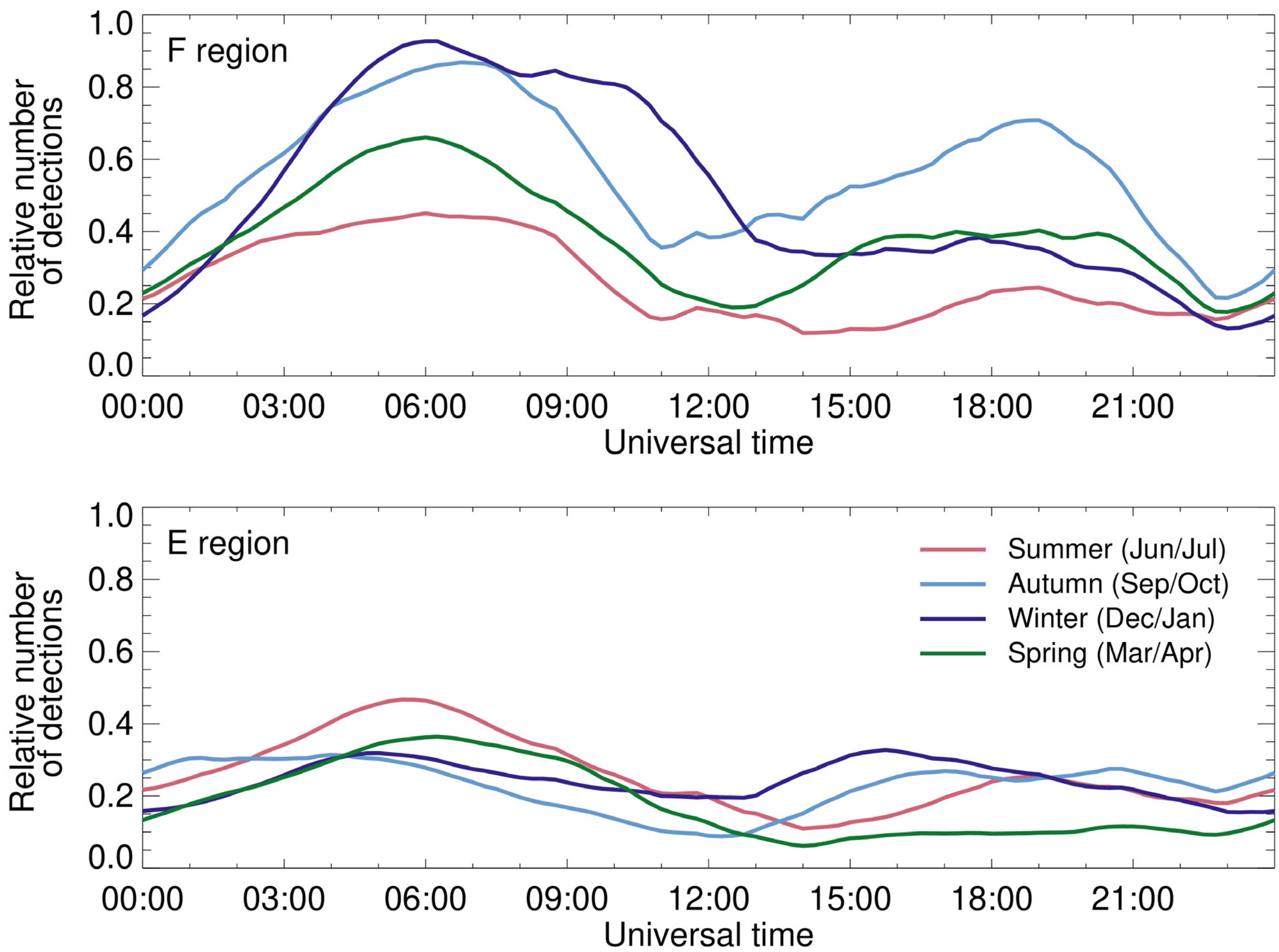

Figure 6: Seasonal and diurnal variations in E region and F region backscatter occurrence for the Svalbard SuperDARN radar, from October 2016 to October 2018.

3.2. Polar cap flow channels

As seen in Figure 5 (bottom panel), the flows in the polar cap ionosphere are highly dynamic both in magnitude and structure. Flow channels are defined as high-speed (>1 km/s) ionospheric flows embedded within the slower moving large-scale background convection and can be identified in SuperDARN radar data as narrow regions of enhanced plasma velocities within the field of view. A new algorithm has been developed to automatically detect these fast flows using the Svalbard SuperDARN radar. An example of a large flow channel identified by the algorithm in the Svalbard radar field of view is marked in a blue box in Figure 4. The flow region extends over 45 degrees in longitude, from Svalbard, across the Arctic Ocean. The proof of concept study (Herlingshaw 2019) indicated that even relatively small (400 km in width) short-lived (13 min) channels can provide a significant fraction (60%) of the total amount of open flux transported across the entire polar cap region by the Dungey cycle. The algorithm was used to perform a quantitative statistical analysis of over 1000 channels and investigate their relationship to the IMF orientation and solar wind conditions (Herlingshaw et al. 2020). This study showed that ~50% of detected flow channels are quite short-lived phenomena, lasting only 3 minutes or less and ranging from about 70 km to 650 km in width (often of a similar magnitude as the resolution of the large-scale convection maps). This work has highlighted the need for increased radar coverage of the polar regions if an accurate representation of the F-region ionosphere is to be obtained.

3.3. Polar cap patch formation and impact on GNSS

Ionospheric plasma irregularities, which SuperDARN radars rely on, impact also the propagation of trans-ionospheric radiowaves, such as Global Navigation Satellite System (GNSS) signals. In the polar cap, irregularities are mostly associated with polar cap patches which get highly structured by plasma instabilities when following the convection pattern and, in particular, when they enter the nightside aurora (Jin et al. 2014). Mitigation of their effects on GNSS signals can be achieved through a forecast of polar cap patch formation, propagation and modelling of the associated GNSS signal disturbance. Fæhn Follestad et al. (2019) presented a new method to forecast space weather disturbances on GNSS at high latitudes, in which they describe the formation and propagation of polar cap patches and predict their arrival at the nightside aurora. The space weather prediction model incorporates an ionospheric convection model and total electron content (TEC) observations from the Global Positioning System (GPS) network. Fæhn Follestad et al. validated their new forecast by comparing its results to GPS global TEC observations from MIT's Madrigal database, ionospheric convection data from SuperDARN and scintillation data from instruments in Ny Ålesund. They were able to show that the model describes the polar cap patch motion effectively and can be used to predict scintillations of GPS signals at high latitudes. The dynamics of signal scintillations, which are the measure of trans-ionospheric radiowave perturbation, often agree with the plasma velocities deduced from the SuperDARN measurements. Thus, the radar data can be incorporated into both global and local models for the space weather effects on the GNSS signals and hence contribute to precise positioning services in the polar regions.

3.4. Space weather impact on radio communications

Energetic particles and solar X-ray flares cause increased ionisation of the lower ionosphere, leading to strong attenuation of HF radiowaves. This can impact the critical industries that rely on HF radio communications, including aviation, maritime, emergency services and defence (Redmon et al. 2018). Space weather events in September 2017 highlighted the capability of SuperDARN radars for monitoring these impacts in real-time. In the polar regions, energetic proton precipitation resulted in strong radiowave absorption which was detected by multiple SuperDARN radars over a period of 10 days (Bland et al. 2018). At the same time, the mid-latitude SuperDARN radars detected several shortwave fadeout events caused by ionisation by solar X-ray flares (Chakraborty et al. 2018). The absorption response measured by SuperDARN near the peak of this space weather event is shown in Figure 7. Other recent work has shown that SuperDARN radars are sensitive enough to detect radiowave absorption caused by energetic electron precipitation (EEP) in the auroral zones, providing a new method for determining statistical occurrence rates and spatial coverage of EEP events (Bland et al. 2019, 2020). This information is being used to improve the energetic particle forcing used in climate models.

These results demonstrate that SuperDARN has the potential to support routine space weather monitoring efforts through the provision of real-time observations. In addition to monitoring HF radio absorption, coordinated real-time SuperDARN observations could be used to track space weather disturbances across the polar cap between the Norwegian and Canadian sectors, which would provide advanced notice of approaching disturbances.

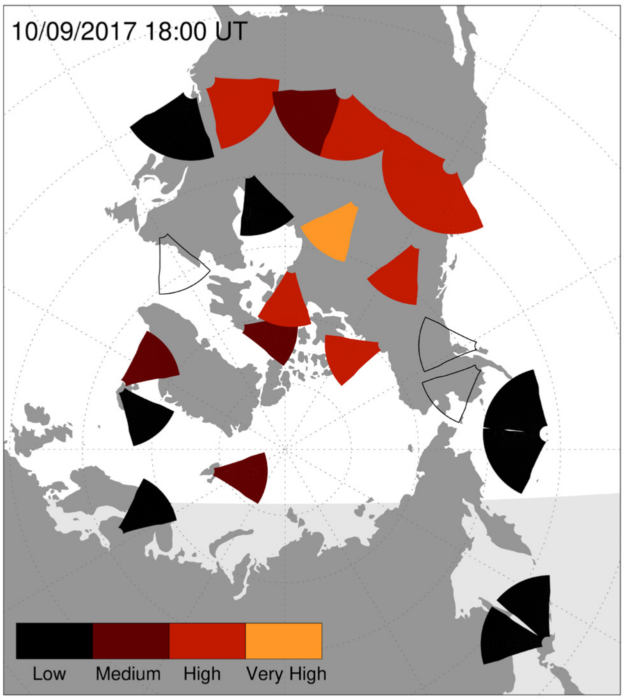

Figure 7: The amount of high frequency radio absorption, rated from 'Low' to 'Very High', observed by the northern hemisphere SuperDARN radars during space weather events in September 2017. Radio blackouts lasting several hours occurred at mid-latitudes, and 10 days of absorption due to energetic proton precipitation was detected in the polar cap.

4. Connections and synergies with other SESS report chapters

Space physics research through the use of rockets has been highlighted in two previous SESS reports. This chapter complements these two previous report chapters by providing a focus on the ground-based instrumentation in Svalbard. Specific points of relevance are as follows:

- Moen et al. (2020) recommended that key parameters from radar instruments should be given status as SIOS core data. As discussed in Section 7 of this report, the Svalbard SuperDARN radar is available online (with full metadata and software tools) in near real-time and has a > 5 years collecting commitment, which makes it suitable to be included as SIOS core data.
- Moen et al. (2019) identifies the critical ground-based observations provided by the instrumentation on Svalbard in regards to rocket campaigns. The Svalbard SuperDARN radar adds to this support network.

5. Unanswered questions

The underlying challenge is to understand, predict and model the response of the atmospheric column as a whole (from the ionosphere, down through the mesosphere and into the stratosphere) to energy input from the Sun and solar wind. Coupling between the neutral and ionised parts of the upper atmosphere is particularly important in the polar regions. Here, the dynamical processes are highly variable in their response to the solar activity levels, with nonlinear processes, instabilities and turbulence in the ionosphere facilitating the energy transfer to the neutral atmosphere. The instrumentation in Svalbard can provide the necessary datasets to assist scientists in several of these aspects.

Specific questions with applications for the Svalbard SuperDARN radar are given below.

- What processes govern the dynamics and structuring of the polar cap patches as they travel across the polar cap ionosphere?
- What are the characteristics of the ionospheric flow channels and how much energy is deposited into the ionosphere through frictional heating both inside and at the edges of flow channels?
- How is the energy originating from ionospheric processes (flow channels, auroral particle precipitation, waves, etc.) redistributed in latitude and altitude?
- What is the average impact area of energetic electron precipitation into the mesosphere/lower thermosphere region?
- How are the irregularities related to other specific large-scale ionospheric features and what is the physics behind the formation of smaller, deca (< 10 m) and hectometre (< 100 m), irregularities?
- How can the large-scale convection pattern be incorporated into local space weather prediction models related to the positioning accuracy in the European Arctic sector, in particular north and southwest of Svalbard, over the Arctic ocean and towards Greenland?

All these questions address the major open issues in space and upper atmospheric sciences within the context of the energy transfer from space down to the Earth's atmosphere. They are concerned with the upper atmosphere dynamics, its heating, instabilities and turbulence, and addressing them will contribute to the modelling and forecasting of space weather effects. This will increase the resilience of human-based infrastructure to adverse space weather events, thus ensuring safety and continuity of human operations in the polar regions.

6. Recommendations for the future

1. Rebuild the Svalbard SuperDARN radar and secure ongoing funding for maintenance and operational costs.
2. Designate the area on Breinosa (which currently includes EISCAT, the KHO and SuperDARN) as a research infrastructure zone with limited land rental costs. Such costs unnecessarily decimate research budgets diverting funding away from core research.
3. Construct a second SuperDARN radar on the same site as the current radar, with a field of view covering the region southwest of Svalbard. This would cover the flight path of sounding rockets from Ny Ålesund as well as providing a complementary field of view to existing all-sky cameras and any newly developed SuperDARN radars on Iceland.
4. Develop a collaboration between Norway and North America to build the real-time space weather monitoring capability of SuperDARN, including tracking of space weather disturbances across the polar cap and monitoring HF radio absorption.

5. Support an extension to the Longyearbyen meteor radar to allow 2-D measurements of the atmospheric velocities and temperatures in the mesosphere. This would provide a complementary dataset to the higher altitude SuperDARN dataset.

7. Data availability

SuperDARN radar data are used throughout the international space physics community. The data are archived in two open-access repositories, where a username and password are required to access the system:

- Globus (https://www.globus.org/)
- British Antarctic Survey (https://www.bas.ac.uk/project/superdarn/#data)

The SuperDARN community maintains two software packages to support scientific research:

- Radar Software Toolkit (RST), the primary SuperDARN data analysis software
- pyDARN, a python library for SuperDARN data visualisation

These open-source packages are maintained and distributed by an international team of scientists, engineers and software developers. In addition, a web-based interface for visualising the radar data is available from Virginia Tech.[3] The Svalbard SuperDARN radar also had (and will have) an online real-time data feed.

Data from the other instrumentation mentioned in this report are available through online databases, some of which are already compatible with the SIOS data access portal (e.g through the already established National Infrastructure for Research Data, NIRD). Table 1 lists the Norway-owned instruments and instrumentation to which Norwegian researchers have direct access through ongoing collaborations.

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3 http://vt.superdarn.org/tiki-index.php

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