Space Weather Activities at Danish Meteorological Institute

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ABSTRACT

We present space weather activities at Danish Meteorological Institute (DMI). The Solar-Terrestrial Physics Division of DMI conducts observations in the auroral and polar regions of magnetic disturbances and precipitation of high-energy radiation: (1) The Greenland chain of ground-based magnetometer measurements of ionospheric currents; and (2) Riometer measurements of energetic particle precipitation. These provide unique space weather observations at high latitudes and serve as a valuable database for space weather studies. The Division also plays an important role in several planned and proposed satellite missions relevant for space weather studies: (a) Ørsted; (b) SAC-C; and (c) AXO (Atmospheric X-Ray Observatory). These satellites will further enhance DMI's capability in space weather observations and studies. The space weather research program which has been developed at DMI is presented here. Studies of how space weather may influence atmospheric weather/climate which are, in particular, of great interest for the Division are proposed.

1. WHAT DOES SPACE WEATHER MEAN TO US?

Space weather refers to conditions in the space environment that can affect technological systems in space and on the ground and can endanger human life or health. Large space weather programs have now been funded in the United States, and plans to do likewise in Europe are emerging.

Space weather research has two aspects. When space weather studies focus on the spatiotemporal evolution of conditions from the Sun down to the Earth, they are science-oriented. When focusing on the effects of space weather on technological system, they are application-oriented. Therefore, we can say space weather research is within the field of solar-terrestrial physics but can be more application-oriented.

The Sun is the most important source for space weather and the solar wind is the primary means by which the Sun imposes its impact on the near-Earth space environment. Magnetic storms and substorms, with brilliant auroras in the polar regions, are some of the manifestations of space weather. The two primary agents of space weather in the magnetosphere-ionosphere-atmosphere which are modulated - or directly driven - by the solar wind are:

- Energetic particles
  - cosmic rays: Their flux is modulated by the state of the heliosphere, i.e. the interplanetary magnetic field embedded in the solar wind. Their entry into the magnetosphere is affected by the geomagnetic field, for instance by allowing access for lower energies at higher magnetic latitudes.
  - solar energetic protons: They may directly enter the magnetosphere at high latitudes and migrate further into the magnetosphere. They are a serious concern for spacecraft and cause high latitude absorption events, which affect communication in polar regions.
  - energetic electrons originating within the magnetosphere: The particles are energized by the solar wind-magnetosphere interactions. They are a serious concern for spacecraft systems.
  - energetic electrons originating in the atmosphere: This source of energetic particles has only recently been discovered. It is thought to originate from acceleration regions above severe thunderstorm systems. The particles may populate the inner radiation belts.
- Electric fields and currents
  - Large fields and currents in the ionosphere: They cause sudden heating of the upper atmosphere giving increased air drag on satellites, in this way reducing their lifetime
  - Large fields and currents induced in ground systems: These may for instance cause power networks to fail.

The "Space Weather" term generally refers to a description of conditions in space extending from the Sun down to the terrestrial thermosphere. However, it is clear from the list above that space weather conditions in addition may have effects on the Earth's climate and weather, because energetic particles can penetrate to low altitudes. Thus, the study of the external forcing of the Earth's atmospheric weather and climate may be considered as a part of space weather research.

2. EXAMPLES OF SPACE WEATHER EFFECTS

Space weather affects the near-Earth space environment on time scales ranging from minutes to days and months. During a geomagnetic storm, the fluxes of energetic particles trapped in the radiation belts are greatly enhanced, thereby increasing the radiation levels in space. This poses a hazardous space environment to technological systems in space and may lead to operational anomalies (e.g. due to single event effects, deep dielectric discharging or gaseous arc discharging, etc). Furthermore, the increased plasma density and irregularities in the ionosphere can adversely influence ground and satellite communication and various applications of global positioning satellite systems (GPS).

2.1. Loss of AT&T Telstar 401

One very recent event showing how space weather affects technological systems in space occurred in January 1997. On 6 January, 1997, a halo coronal mass ejection (CME) occurred on the Sun. The CME-produced magnetic cloud engulfed the magnetosphere on 10 January 1997 and triggered a moderate magnetic storm. With the WIND input data the major storm would have been accurately predicted [*Wu et al.*, 1998a]. The day after, on January 11 1997, the AT&T Telstar 401 satellite was lost during the recovery phase of the storm. The price tag: $200 million. Many other satellites have been lost in the past due to adverse space weather. Some of these could have been saved if the satellites had been put in a "safe mode" in advance.

2.2. Power Distribution Network Failure

Space weather can also affect technological systems on the ground. During a geomagnetic storm, the extra burst of energy extracted from the solar wind drives currents of millions of amps in the upper atmosphere at heights around 100 km. These ionospheric currents induce secondary electric fields and currents, geomagnetically induced currents (GIC), at ground level. In high-voltage power lines the GIC may cause failure in line protection relays and damage to transformers resulting in power outages over large regions. In arctic pipelines the GIC are causing corrosive effects.

A well-known event of space weather effects on ground-based and space-born technological systems occurred on 13 March 1989. A major magnetic storm caused 1/3 of Canada (in Quebec) and part of upstate New York to lose electric power due to geomagnetically induced failures in the high voltage power system. The main phase of power outage lasted for up to 9 hours. The time from the onset of problems to the system collapse was about 90 seconds. In addition, high-frequency radio frequencies were virtually unusable worldwide. A Japanese communication satellite lost half of its dual redundant command circuitry. A NASA satellite dropped 3 miles in its orbit due to increased atmospheric drag. Several other satellites experienced various types of upsets. Damages ran into hundreds of millions of dollars.

2.3. The Sirius Patrol Suddenly Without Communication

The Sirius patrol in north-eastern Greenland may occasionally without warning lose shortwave radio communication from the base station to the patrol units. This happens because energetic particles, emanating from the Sun and precipitating in the polar upper atmosphere, cause ionospheric disturbances that hinder communication for days. This is the so-called polar cap absorption event [e.g., *Stauning*, 1982; *Ranta et al.*, 1993; *Stauning*, 1996].

2.4. The Future

Mankind relies more than ever on satellite-based systems. Think of GPS-driven systems for airline navigation, cars with computers containing street maps and connected with GPS receivers for location and route determination, telecommunications between remote areas or in so-called third world contries, etc. The effect of this evolution is the society being increasingly vulnerable to adverse space weather.

In addition, research of space weather is challenging due to the chain of coupling processes involved, and therefore stimulates fundamental research in solar-terrestrial physics. With the available knowledge base in the Solar-Terrestrial Physics Division of DMI, serious studies of space weather-induced effects on Earth's weather and climate can be undertaken.

3. DMI SPACE WEATHER RESEARCH

3.1. Space Weather Observations

There are a wealth of long-history space weather observations ranging from solar, solar wind, energetic particle data (including cosmic rays) to terrestrial data. These observations serve as an extensive database for space weather modeling and forecasting.

The Solar-Terrestrial Physics Division of DMI conducts observations in the auroral and polar regions of magnetic disturbances and precipitation of high-energy radiation, as shown in Figure 1:

- The Greenland chain of ground-based magnetometer measurements of ionospheric currents
- Riometer measurements of energetic particle precipitation

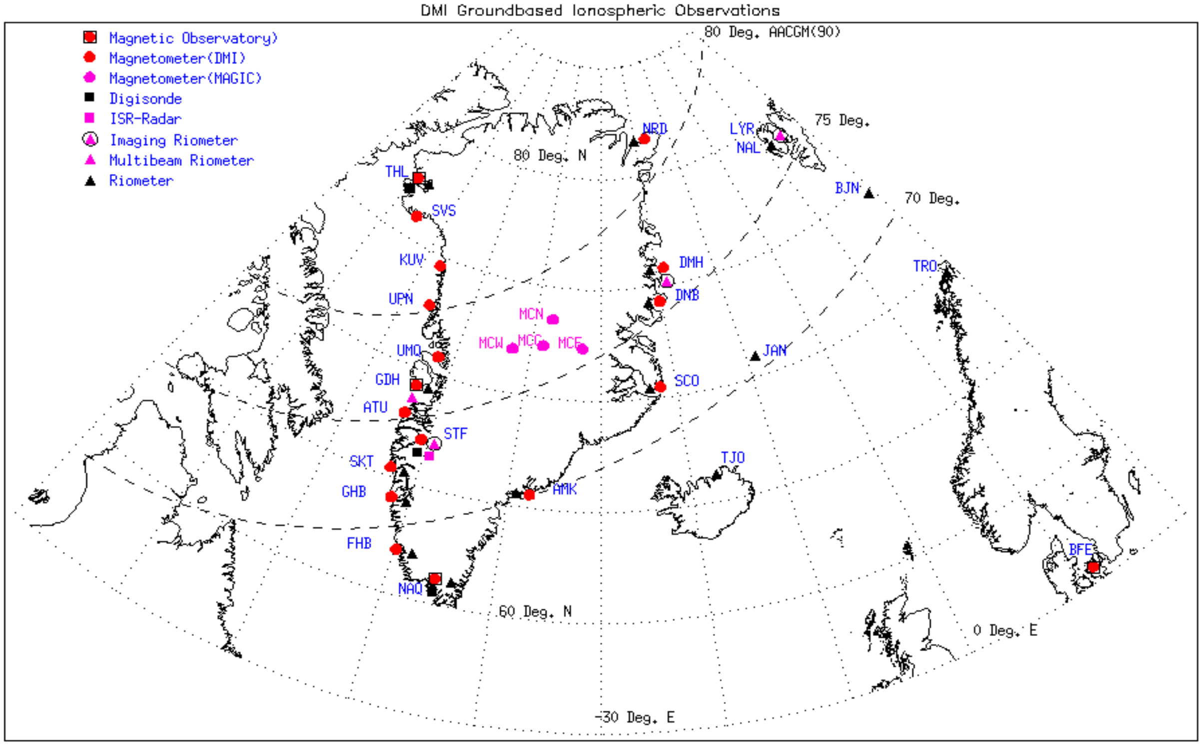

Figure 1. DMI space weather observations.

These observations are used for monitoring actual space weather conditions and for space weather studies. The division also plays an important role in several planned and proposed satellite missions relevant for space weather studies:

- Ørsted (launch in January 1999)
- SAC-C (planed launch in 1999)
- AXO (Atmospheric X-Ray Observatory, proposed new mission)

These satellites will further enhance DMI's capability to study how space weather influences atmospheric processes.

3.2. Proposed Space Weather Activities

To make full use of the observations available at DMI and to fully exploit the expertise available at the Division, the following research programs are established:

1. Study relationships between conditions on the Sun and the solar wind and effects observed by DMI geomagnetic stations
2. Study relationships between high latitude events observed by DMI stations and energetic particle conditions in the inner magnetosphere
3. Make selected ground-based magnetometer measurements available to the community over the web in real-time
4. Provide real-time estimates of geomagnetic indices from DMI ground-based magnetometer measurements using linear and nonlinear methods (e.g. neural networks)
5. Construct an index quantifying ionospheric disturbances from riometer measurements and make it available in real-time
6. Develop and implement data-driven dynamic neural network models for forecasting of selected space weather parameters
7. Study space weather effects on atmospheric weather and climate using, e.g., neural network methods

Studies of the relations between solar wind conditions and polar magnetic disturbances have a long and strong tradition at DMI [e.g., *Svalgaard*, 1968, 1972; *Friis-Christensen et al.*, 1972, 1985; *Wilhjelm et al.*, 1978; *Stauning et al.*, 1994; *Stauning*, 1994]. Investigations of the relations between high-latitude ionospheric disturbances and the solar and magnetospheric high-energy particle radiation is also one of the strong research fields at DMI [e.g., *Stauning, 1982, 1996, 1998a,b*; *Baker et al., 1981, 1982*; *Ranta et al.*, 1983, 1993]. The continuation of these research fields will constitute a basic element of DMI Space Weather investigations.

Neural networks (NNs) have been extensively exploited in solar-terrestrial physics [e.g., *Lundstedt*, 1992; *Freeman et al.*, 1993; *Hernandez et al.*, 1993; *Lundstedt and Wintoft*, 1994; *Lundstedt et al.*, 1994, 1995, 1996; *Wu*, 1997; *Wu and Lundstedt*, 1996a, 1996b, 1997a, 1997b; *Gleisner and Lundstedt*, 1997; *Wintoft and Lundstedt*, 1997; *Wu et al.*, 1997, 1998a] and in studies of space weather effects on spacecraft [e.g., *López and Hilgers*, 1997; *Hilgers et al.*, 1998; *Wu et al.*, 1998b, 1998c, 1998d].

NNs will be one of the main tools in space weather research at DMI, in combination with physics-based models and statistical analysis methods. NNs are well suited for studies at DMI on the basis of the excellent computer facilities and expertise available at DMI.

Item 7 above has special interest for the division and is further expanded in the following section.

3.3. Space Weather Effects on Atmospheric Weather and Climate

It has been shown that conditions in the near-Earth space environment may affect the atmospheric weather and climate [e.g., *Friis-Christensen and Lassen*, 1991; *Tinsley*, 1994; *Lassen and Friis-Christensen*, 1995; *Svensmark and Friis-Christensen*, 1997; *Arnold and Robinson*, 1998; *Cliver et al.*, 1998], although the physical mechanisms as yet are not known. However, it is likely that solar activity affects the weather and climate through a chain of interactions involving solar wind-magnetosphere-ionosphere-atmosphere coupling processes.

Solar electromagnetic radiation is the major natural external driving force of the terrestrial atmospheric weather/climate system. The magnitude of the effect of solar variability on climate change is therefore an important issue for climate studies. Knowledge of the effect are also essential for understanding the climate response to other influences including increasing greenhouse gas concentrations.

However, changes in solar radiation seem too small to account for significant changes in climate according to model calculations, unless, for instance, processes involving EUV radiation are shown to be important. This is the reason that space weather effects are thought important in external forcing of weather and climate.

Energetic particles in the radiation belts are controlled by solar activity. This can be seen from their periodic enhancements of 27 days solar rotation and solar activity cycle [*Baker et al.*, 1986]. These relativistic particles deposit their energy down to 40-60 km altitude, and their impact on atmospheric processes may dominate over that of solar EUV and cosmic rays.

However, the response in the middle and upper atmosphere (lower thermosphere and upper mesosphere) to severe space weather event is not well understood. Such studies will open a new area in the space weather-atmospheric weather/climate link.

Only cosmic rays and extremely energetic solar protons can penetrate down to the lower atmosphere and affect processes in the lower atmosphere directly. Therefore, cosmic rays and large proton events will be very important for studies of the atmospheric response at lower altitude.

If the electric charge density of the neutral atmosphere is an important parameter, as studies of cosmic ray correlations with cloud cover indicate [*Svensmark and Friis-Christensen*, 1996], then the whole atmospheric fair-weather electric circuit is important. This means that the charge levels achieved by global thunderstorms may play a role (they power the circuit), and that level, in turn, is affected by cosmic ray showers or energetic solar proton events which act as discharge triggers.

Internal atmospheric oscillations are also important for atmospheric weather patterns on various time scales. It is absolutely mandatory to have a firm grasp of these oscillations before correlations with for instance the solar cycle is claimed, in particular if the internal oscillation bears a physically significant relationship to solar activity frequencies.

Thus when studying the solar-climate link, the following research topics are proposed:

1. Study the lower atmospheric response (e.g., cloud parameters) to cosmic ray and proton events;
2. Study atmospheric electrodynamics and chemistry (e.g., thunderstorm, sprites) and their dependances on energetic electrons and cosmic rays;
3. Study solar wind-geomagnetic activity-weather/climate (e.g., global surface temperature or precipitation) links.

4. SUMMARY

Space weather actvities at DMI consist of space weather observations and space weather studies. The Greenland chain of ground-based magnetometer measurements of ionospheric currents and riometer measurements of energetic particle precipitation offer unique space weather observations at high latitudes. In addition, the planned and proposed satellite missions (Ørsted, SAC-C, AXO) will further provide powerful platforms for monitoring space weather, and a valuable space environment database. On the basis of the space weather observations available and to be available at DMI, the space weather research program has been developed. In particular, studies of how space weather may influence atmospheric weather/climate are proposed.

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