

Observations of the Tongue of Ionization with GPS TEC and SuperDARN

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ABSTRACT

Tongue of ionization (TOI) events in both the northern and southern hemisphere have been identified with polar maps of total electron content (TEC) derived from the global network of GPS receivers. The TOI, as observed by GPS, extends through the dayside cusp, across the polar cap to the nightside, in both hemispheres. The TOI is a source of ionospheric irregularities. Its distribution across the high latitude ionosphere is believed to be controlled by plasma convection. The GPS maps show the development of TOI from mid-latitude plumes of ionization known as storm enhanced density (SED) [1]. The SED feature is observed to be magnetically conjugate, although data coverage is considerably more sparse in the southern hemisphere. In this paper, SuperDARN HF radar observations of the high-latitude convection pattern have been overlaid onto the GPS TEC polar plots for multiple TOI events. It is observed quantitatively that the GPS TEC observations of the TOI match the SuperDARN estimates of the convection pattern. Using SuperDARN observations of the evolving convection pattern, we study the evolution of the TOI and the associated redistribution of plasma structure. The locations and conditions under which HF backscatter occurs in the vicinity of the TOI plumes are examined. We explore the similarities between TOI events observed simultaneously in the two hemispheres and look especially for the impact of convection-induced asymmetries. Gradients, irregularities, and velocities are examined between the two hemispheres. Spatial and temporal estimates of the TEC at individual locations along the SED plume and the TOI are studied in an attempt to quantify the percentage of the TEC that enters into the trans-polar convection pattern.

1.0 INTRODUCTION

One of the prominent features observed in the mid-latitudes during geomagnetic storms is storm enhanced density (SED). SED manifests as an extended region of enhanced plasma density which flows from a region of enhanced plasma in the lower mid-latitudes, across the mid-latitudes, and then into the sub-auroral and polar regions. The enhanced plasma distribution in the lower mid-latitudes is likely to be the extension of the equatorial anomaly region [2]. Plasma from this enhanced plasma region is driven northward and westward under the influence of the sub-auroral polarization stream (SAPS) [3], [4]. The term SAPS describes the underlying poleward directed electric field that is present at subauroral latitudes during storm time conditions in the nightside magnetosphere-ionosphere system. This poleward field cannot extend into the dayside due to high conductivity. The plume of plasma flows in a narrow channel along the dusk terminator where the enhanced plasma is overlapped by the SAPS electric field. SED plumes have been shown to map into the plasmaspheric drainage plumes associated with the stormtime erosion of the plasmaspheric boundary layer

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(PBL) [5]. Once the high density plasma associated with SED reaches the auroral latitudes, at least in some instances, the SED plasma is entrained in the local convection pattern and is convected over the poles, producing what is known as the polar tongue of ionization or TOI.

The polar tongue of ionization (TOI) is a continuous stream of dense ionization following the global convection pattern. Related to TOIs are patches of ionization – both of which can be defined as limited regions of increased plasma density in the polar cap region [6],[7],[8]. TOIs were suggested by [9] and were investigated by [10], who looked at the effects of rapid anti-sunward convection on the polar F layer plasma as it convected through the cusp, over the polar cap, and into the nightside auroral latitudes. Foster [11] reviewed radar observations which characterized plasma streaming from low-latitudes as the source of the polar TOI. The source of TOIs and polar cap patches has been investigated for many years. Foster [1] was the first to report observations showing that the SED is at least one of the sources for the TOI plasma.

This paper examines specific cases of what happens once the high density SED plasma reaches the auroral latitudes, and more specifically, examines the relationship of storm enhanced density (SED) to the polar tongue of ionization (TOI). Using a combination of GPS global maps of the total electron content (TEC) and SuperDARN data, we will try to answer the following questions concerning the relationship between SED and TOIs: 1) Under what conditions does the plasma from the SED enter the dayside cusp and follow the convection pattern? 2) What is the relationship between irregularities that produce HF backscatter and SED/TOI plasma? 3) What can additional SuperDARN observations in Antarctica contribute to SED/TOI studies as there are so few GPS observations in that region?

In this paper, we will first describe the GPS and SuperDARN observations, and then examine each of the different questions posed above.

2.0 FACILITIES AND DATA

2.1 GPS TEC

The GPS TEC data was processed using the MIT Automated Processing of GPS (MAPGPS) software described in [12]]. The GPS TEC data has been incorporated into the Madrigal database, which is an open source, web-based, distributed database system developed at MIT Haystack Observatory. The data can be accessed through the website <http://www.haystack.mit.edu/madrigal>. Approximately 250 days have been processed at this time. The data is provided as estimates of TEC in 1 degree by 1 degree bins every 5 minutes distributed over locations where GPS data is available. TEC maps representing an integration of TEC data every 20 minutes throughout the day are provided.

2.2 SuperDARN

The Super Dual Auroral Radar Network (SuperDARN) is an international collaboration involving scientists and funding agencies of over a dozen countries that operates chains of HF radars in both the northern and southern hemispheres. Currently, SuperDARN consists of ten Northern hemisphere and seven Southern hemisphere coherent-scatter HF radar systems located at sub-auroral and auroral latitudes. Tables 1 and 2 list the individual radars, their geographic locations, and affiliations. Greenwald [13] has described the concept of the collaboration and its utility for making large-scale, continuous observations in the high-latitude ionosphere. Software developed mainly by the Johns Hopkins University Applied Physics Laboratory (JHU/APL) is used to operate the radars and to generate data in common formats. Each radar transmits a

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series of pulses in the HF band and samples the returned echoes. The autocorrelation function of the returned echoes is used to calculate the back-scattered power, spectral width, and velocity of ionospheric plasma irregularities. Data from the SuperDARN facilities can be accessed at <http://superdarn.jhuapl.edu/>.

Usually the radars sweep through scans in azimuth every 1 or 2 minutes. Except for outages due to equipment malfunction or repair work, the radars operate continuously under computer control. They detect backscatter from decameter-scale ionization irregularities in the ionosphere that have been amplified far above thermal fluctuation levels by plasma instability processes. At F region altitudes the predominant motion of the irregularities is due to \mathbf{ExB} drift of the ambient plasma [14], [15]. Among other measurements, the Doppler velocity imparted to backscattered HF signal is recorded as a function of time, direction, and range. The SuperDARN radar thus detects the occurrence of small-scale irregularities in the ionosphere and provides snapshots of the line-of-sight component of the plasma convection velocity.

The rate at which backscatter occurs is variable [16]. Successful operation at F region altitudes requires a measure of refraction in the ionosphere to satisfy the condition that the radar signal propagate orthogonally to the geomagnetic field where it encounters irregularities. To cope with the changing condition of the ionosphere, the operating frequency of a radar can be varied between 8 and 20 MHz. During highly disturbed periods, increased absorption in the D and lower E regions may extinguish any returned HF signal.

The combination of measurements from all the radars in each hemisphere allows for the mapping of plasma convection over polar regions [17]. Comparison between SuperDARN plasma irregularities measurements and plasma convection maps and total electron content (TEC) maps may provide useful information regarding TEC structure observed within the tongue of ionization associated with storm enhanced density (SED).

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Table 1 Northern Hemisphere SuperDARN Radar Network

RADAR	Geographic Location	Affiliation
King Salmon	58.68°N 156.65°W	Communications Research Lab, Japan
Kodiak	57.6°N 152.2°W	Geophysical Institute, UAF, United States
Prince George	53.98°N 122.59°W	University of Saskatchewan, Canada
Saskatoon	52.16°N 106.53°W	University of Saskatchewan, Canada
Kapuskasing	49.39°N 82.32°W	JHU/APL, United States
Wallops Island	37.93°N 75.47°W	JHU/APL, United States
Goose Bay	53.32°N 60.46°W	JHU/APL, United States
Hankasalmi	62.32°N 26.61°W	University of Leicester, United Kingdom
Stokkseyri	63.86°N 22.02°W	CNRS/LPCE, France
Pykkvyaer	63.86°N 19.20°W	University of Leicester, United Kingdom

Table 2 Southern Hemisphere SuperDARN Radar Network

RADAR	Geographic Location	Affiliation
Halley	75.52°S 26.63°W	British Antarctic Survey, UK
SANAE	71.68°S 2.85°W	University of KwaZulu-Natal, Hermanus Magnetic Observatory, South Africa
Syowa South	69.0°S 39.58°E	National Institute of Polar Research, Japan
Syowa East	69.01°S 39.61°E	National Institute of Polar Research, Japan
Kerguelen	49.35°S 70.26°E	CNRS/LPCE, France
TIGER	43.38°S 147.23°E	LaTrobe University, Australia
TIGER Unwin	46.51°S 168.38°E	LaTrobe University, Australia

3.0 OBSERVATIONS

3.1 SED TOI events and SuperDARN Convection patterns

The first reported analysis of an SED TOI event mapping into a SuperDARN convection pattern was in Foster et al., 2004 for the 20 Nov 2003 super storm ($K_p = 9$). The two cases shown here are for the 1-2 October 2001 storms which were only moderately disturbed days ($K=6$ and $K_p=5$ respectively). These storm periods are described in detail by [18]. The data in Figure 1 show the 1 October 2001 SED mapping into the TOI at 7:00 UT. The SED/TOI plasma is indicated by the gray scale, and it clearly follows the contours of the convection pattern determined with SuperDARN data over the pole. In this case, the SED plasma is observed entering the daytime cusp from the European section and exiting over Canada. The data in Figure 2 show the 2 October 2001 SED plasma mapping into the TOI at 20:00:00 UT. The SED/TOI plasma once again can be seen following the contours of the convection pattern over the pole. In this case, we are seeing plasma entering the daytime cusp from the Canadian sector and exiting over Europe.

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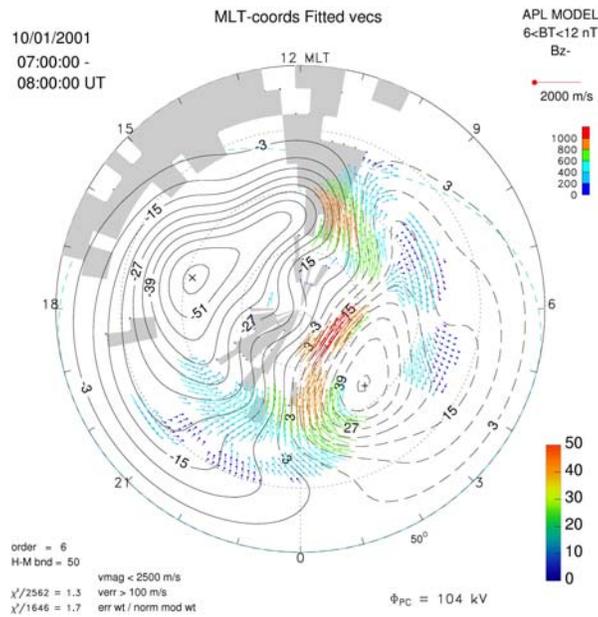


Fig. 1 Oct 1, 2001 TOI mapping into SuperDARN convection pattern.

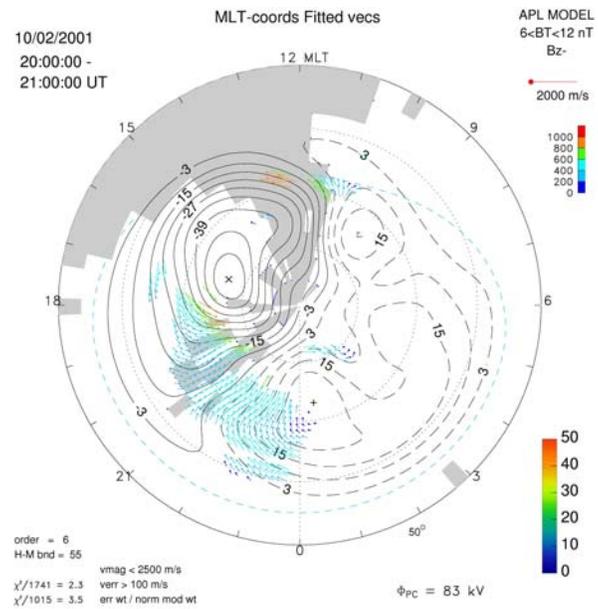


Fig. 2. Oct. 2, 2001 TOI mapping into SuperDARN convection pattern.

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What is not understood are the conditions that allow some (or all) of the SED plasma to enter the dayside cusp. The 15 July 2000 storm, the 11 April 2001 storm, and the 31 March 2001 storm all produced SED structures. The storms are illustrated in Fig 3a-c. None of these storms show the SED plasma converting to a TOI as the SED plasma reaches the dayside cusp region. Possible explanations may involve the strength of the interplanetary magnetic field (IMF) or the value of B_z , as the strongest coupling occurs when the B_z component is oriented southward.

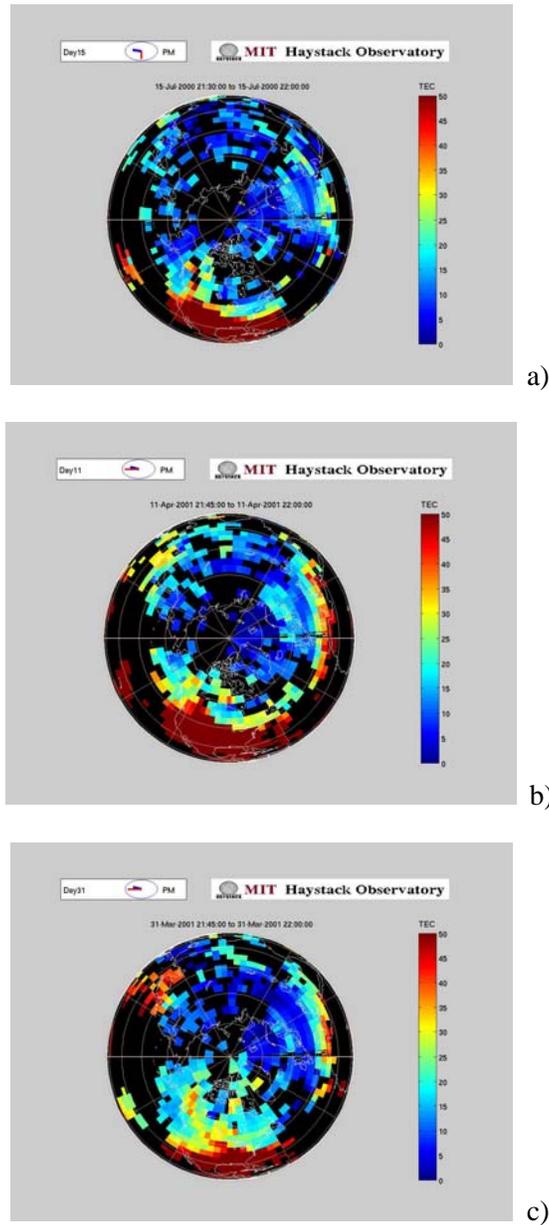


Fig. 3a,b,c Observations of the Plume of Ionization that does not appear to convect over the pole.
 a) 15 Jul 2000 21:30-22:00 UT b) 11 Apr 2001 21:45-23:00 UT c) 31 Mar 2001 21:45-22:00 UT

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3.2 Observations of SuperDARN Backscatter and the TOI

In this section we will discuss the observations of SuperDARN backscatter at a time when the tongue of ionization was evident in both hemispheres, 30 Oct 2003 at 21:40-22:00 UT. The TOI in the northern hemisphere is clearly evident in Fig. 4 where enhanced TEC (indicated in red) is shown to leave Canada, flow over Greenland and Iceland, and enter Northern Europe. On this day, several of the SuperDARN radars were blanked out due to HF absorption. However the radar at Prince George which looks up into Alaska saw backscatter at 22:00 UT immediately after they switched frequencies. The observed Prince George backscatter indicates that the SED plasma shown in Fig. 4 shifted towards the west and at 22:00 UT was reaching up into Alaska (in reality, the SED plasma is fixed in space and the earth is rotating under it). The primary observations in this section however concern the timing of the observed backscatter at the Stokkeyri SuperDARN in South Iceland (Fig. 5) and the Hankasalmi SuperDARN in Finland (Fig. 6).

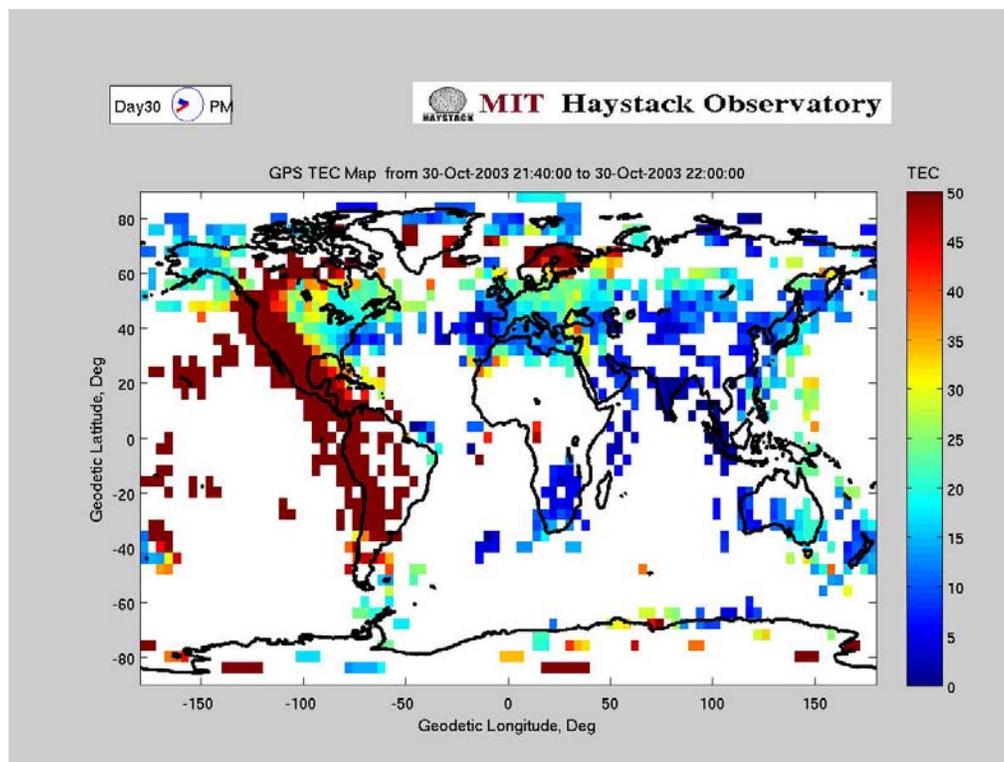


Fig. 4. Observation of the TOI on 30 Oct 2003 at 21:40-22:00 UT.

The Stokkeyri SuperDARN in South Iceland observes HF backscatter during the entire interval from 19:40 to 22:20 UT on the October 2003 (see Fig. 5). From the data shown in Fig. 4, it is apparent that the TOI was clearly established at 21:40 UT, and from other analysis, it is also known that there is an indication of a weak TOI over Iceland as early as 19:40 UT. A strong TOI over Iceland is not observed until 20:20 UT, which is also the first time period that strong HF backscatter is observed at Stokkseyri.

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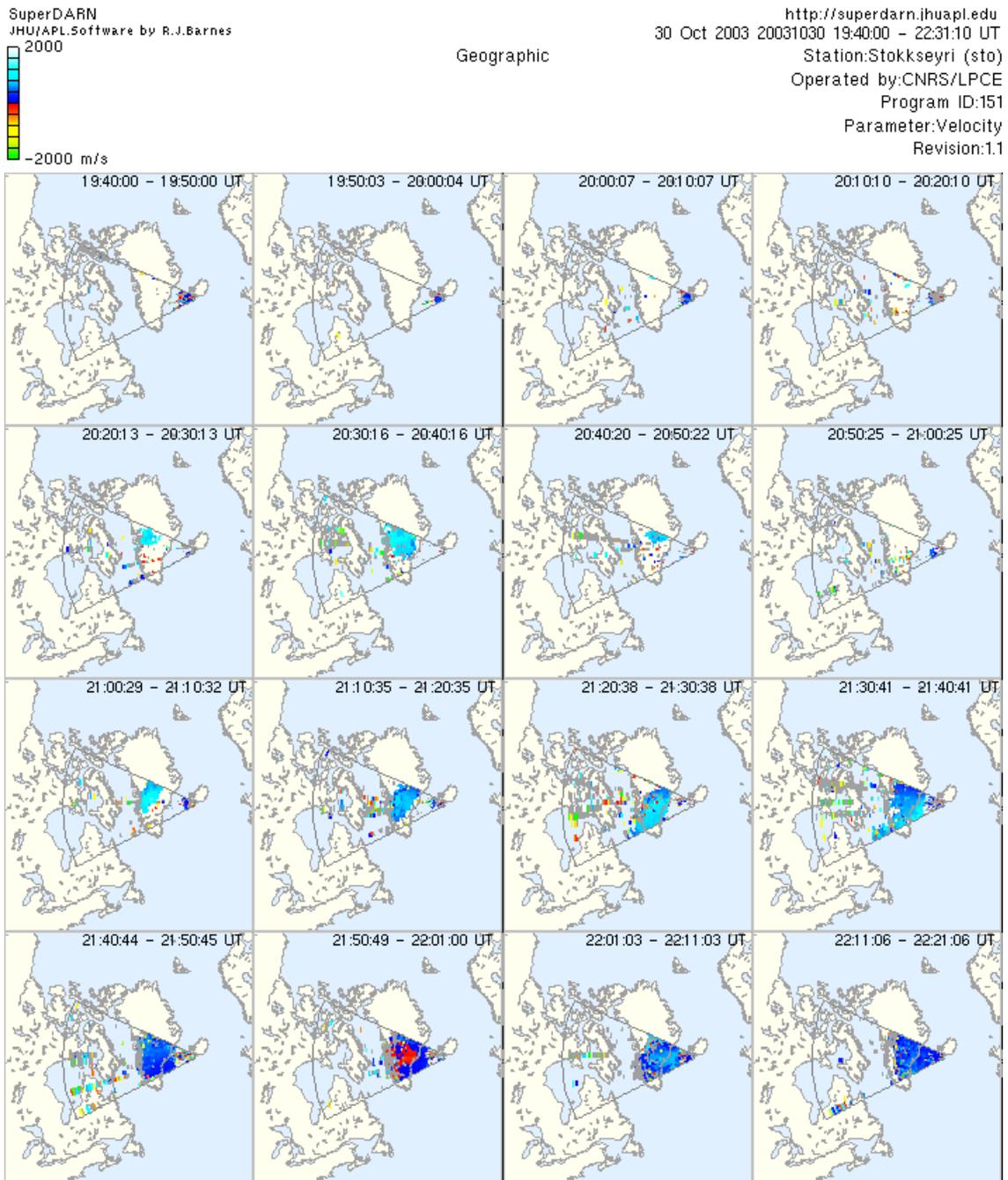


Fig. 5 Observations of HF backscatter by the Stokkeyri SuperDARN in South Iceland

The Hankasalmi SuperDARN station in Finland did not observe strong backscatter until 21:40 UT, which corresponds to the time period shown in Fig. 6.

Observations of the Tongue of Ionization with GPS TEC and SuperDARN

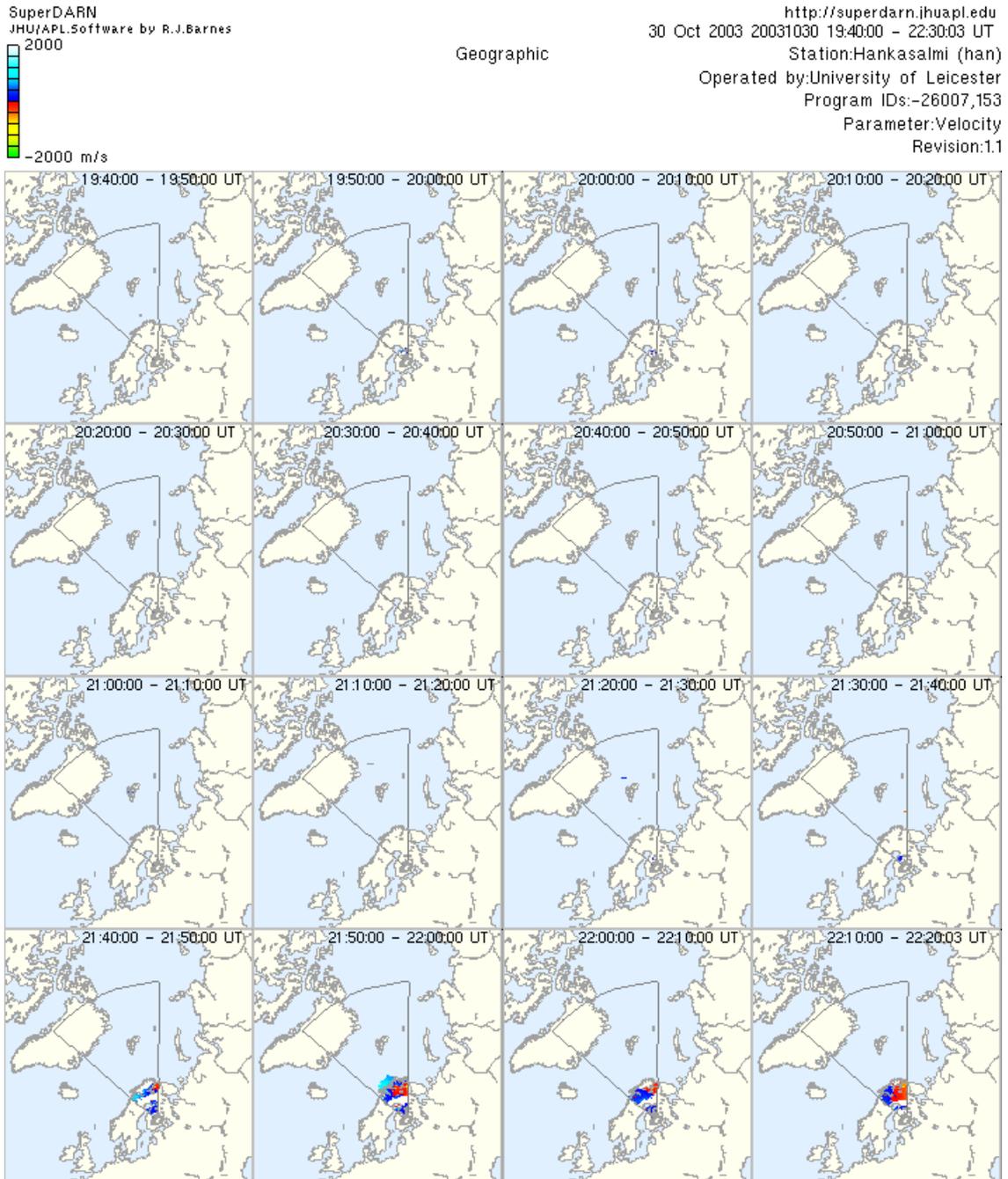


Fig. 6 Observations of HF backscatter at the Hankasalmi SuperDARN station in Finland.

3.3 Observations of the TOI and HF backscatter at the South Pole

The last observation examines the similarities between TOI events observed simultaneously in the two hemispheres. Fig. 7 a,b shows the TOI observed in both hemispheres. Clearly the North Pole has better GPS coverage than the South Pole. In fact, in all of the storms we have examined so far, if the SED and TOI are observed in the Northern hemisphere, they are strongly hinted at in the Southern hemisphere.

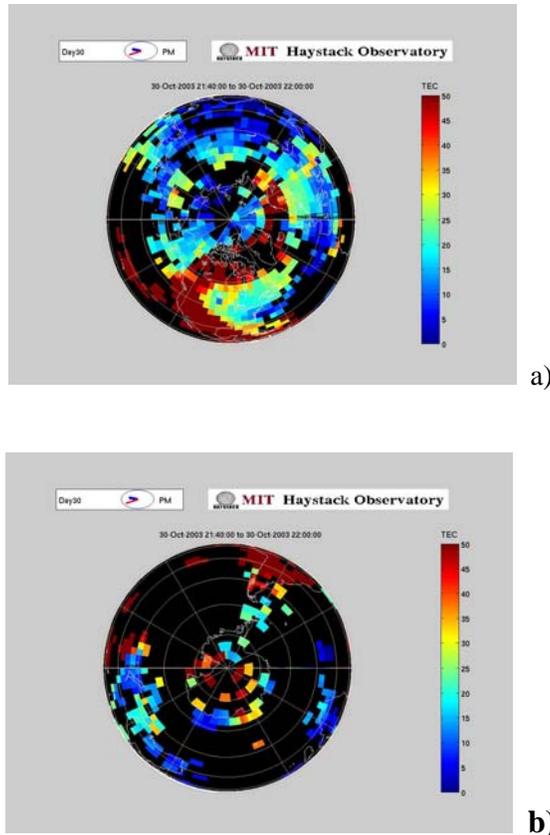


Fig. 7 a,b. SED feeding a TOI over both the North (top) and South pole (bottom). This 30 October 2003 SED is observed over the North and South Poles at 21:40 UT.

a) North Pole b) South Pole

For this time period, we examine the backscatter observed by the Syowa East HF radar which is located in Antarctica (69.00 deg S, 39.58 deg E) and looks over a section of ionosphere poleward of 70 deg S that includes the east Antarctica ice cap and the southern ocean. HF backscatter can be first observed at 21:20 UT. At 21:40 UT, this station and the Hankasalmi station in Finland and the Stokkeyri station in South Iceland are all observing HF backscatter.

Observations of the Tongue of Ionization with GPS TEC and SuperDARN

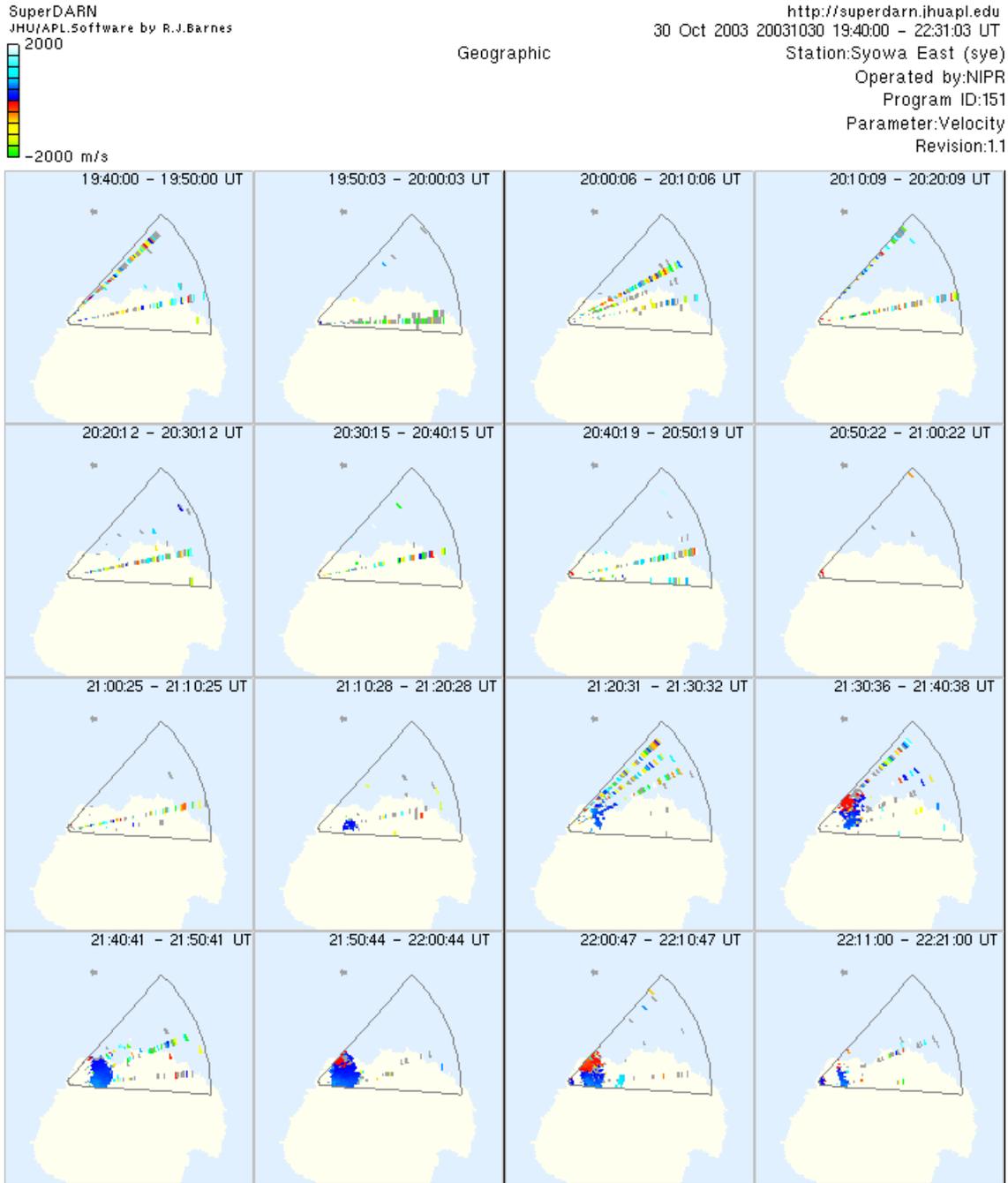


Fig. 8 Observations of HF backscatter at the Syowa East SuperDARN

4.0 SUMMARY

The combination of SuperDARN data with the GPS TEC maps allows for a detailed study of the transport of the SED plasma into the polar cap. We have discussed a few of the unresolved issues of this transport, such as the question of why the TOI is not always observed. From our studies, it appears that the SED feature and the associated TOI form simultaneously in both hemispheres. The SuperDARN observed HF backscatter appears to correlate well with regions of enhanced plasma associated with the TOI, and that these irregularities are being carried in the TOI to the different locations. As we continue this work, we hope to shed light on many of the unknown factors affecting SED and TOI.

5.0 ACKNOWLEDGEMENTS

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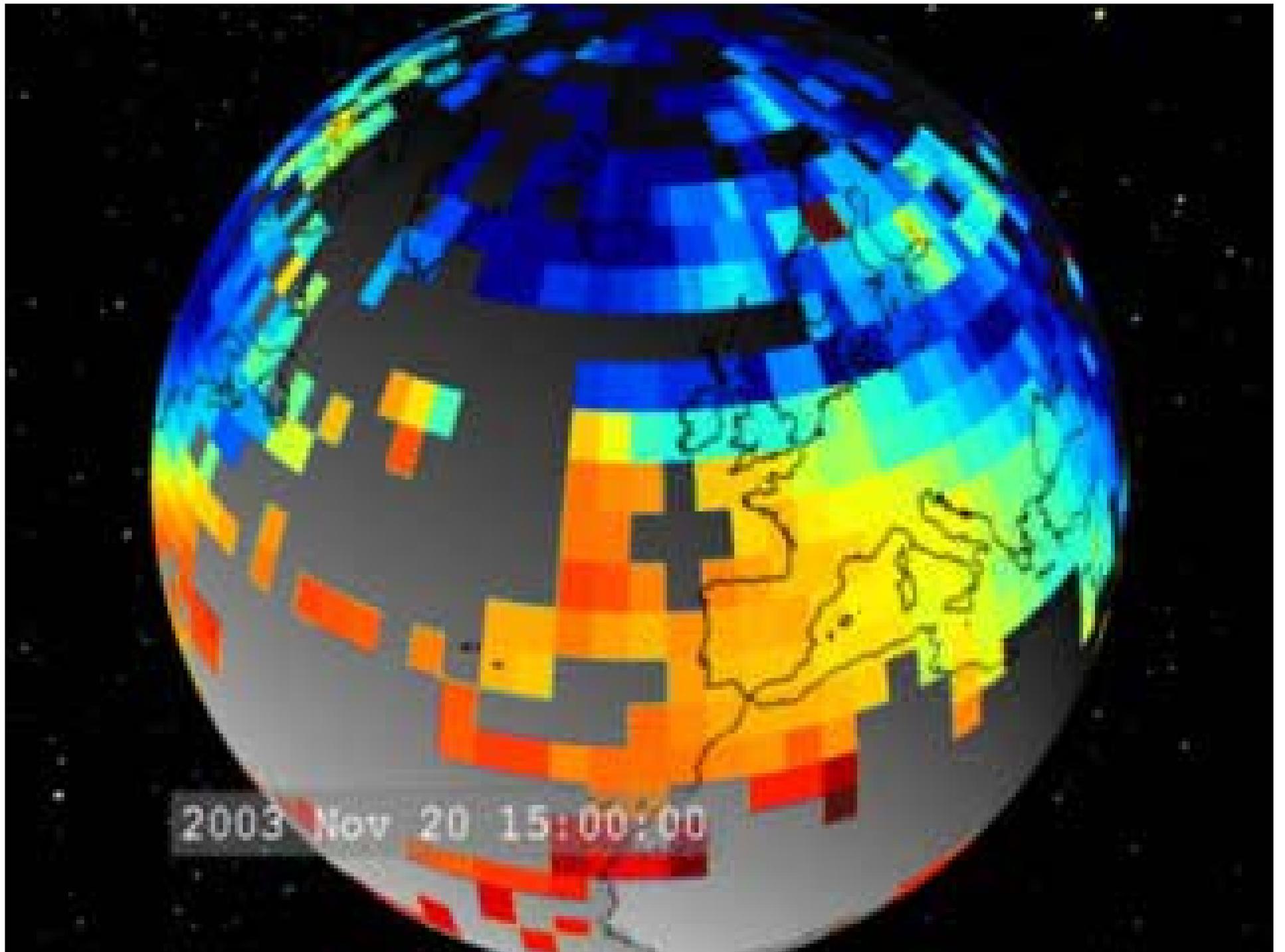
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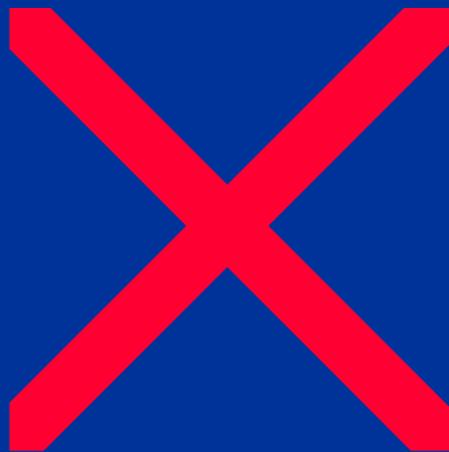
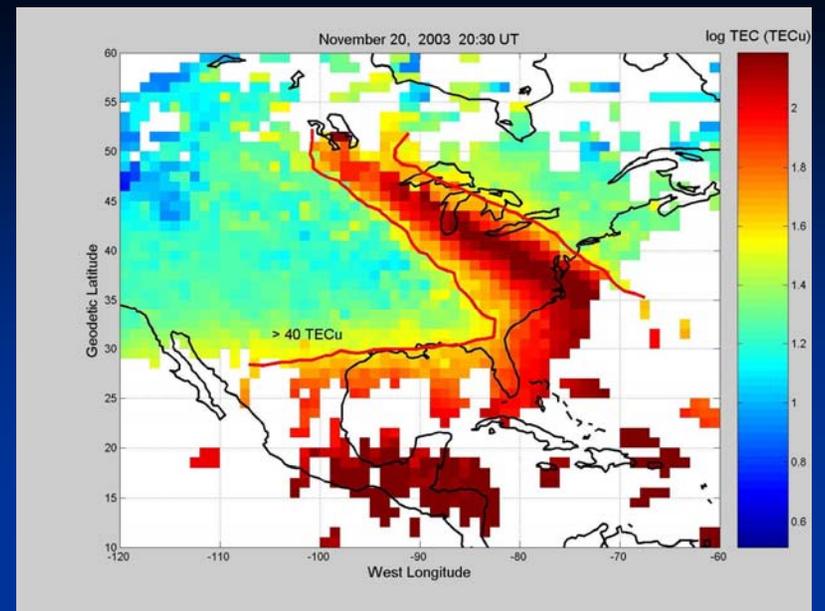
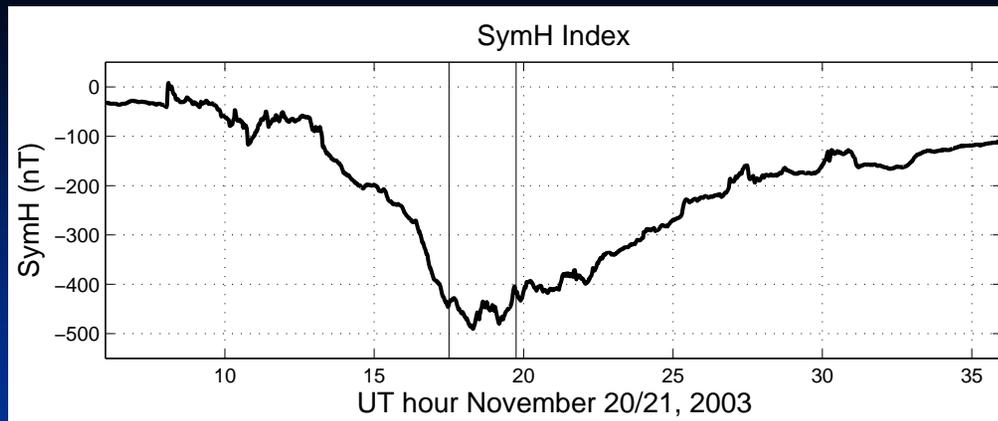
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Applied Physics Laboratory



2003 Nov 20 15:00:00



**Mid-Latitude
Enhancements
extend to Polar
Latitudes**

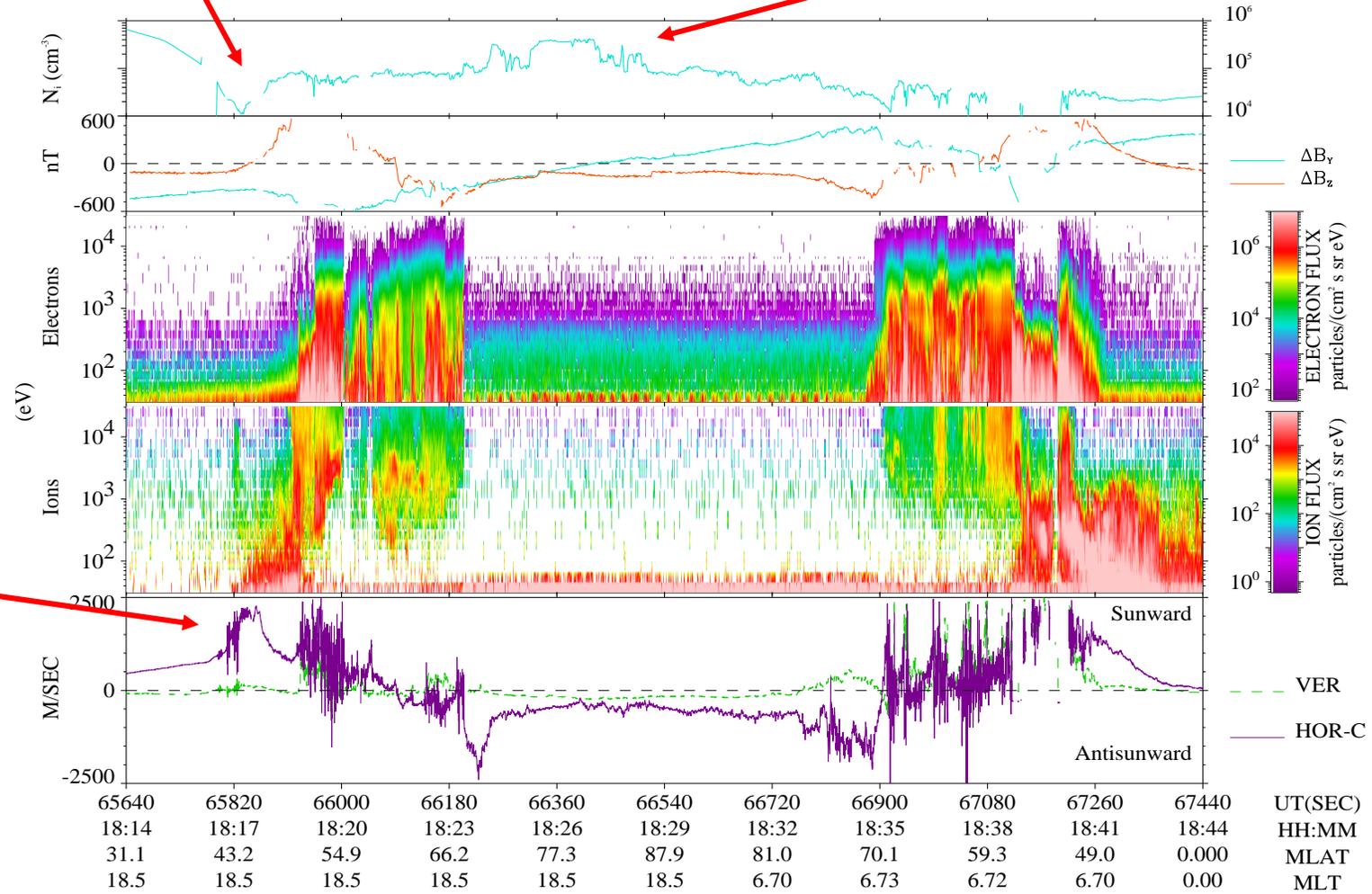
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Trough

Polar TOI

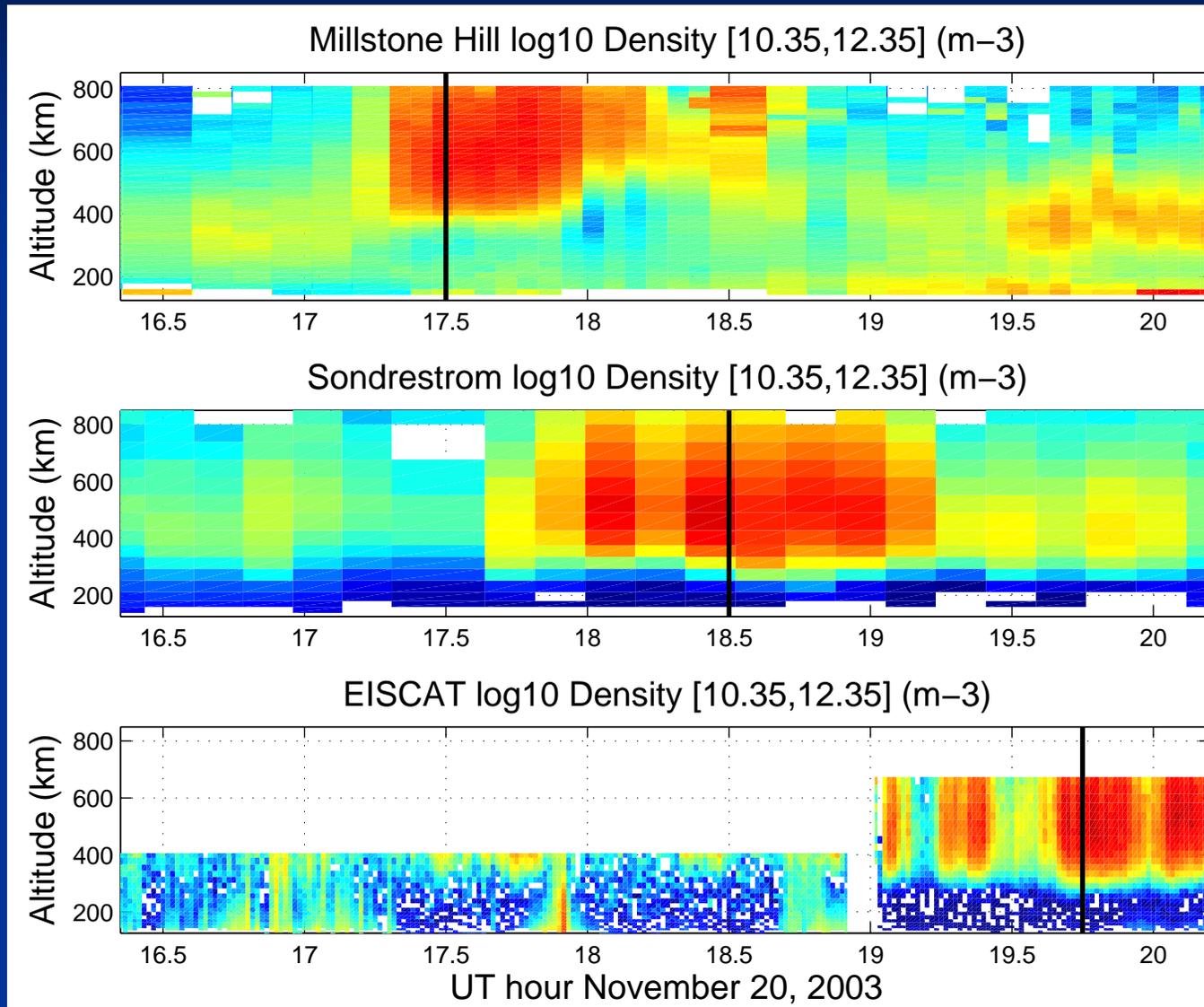
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20 Nov 2003



SAPS

High-Latitude Incoherent Scatter Radars Probe the Nov 20, 2003 SED/TOI Plume



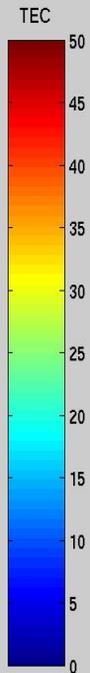
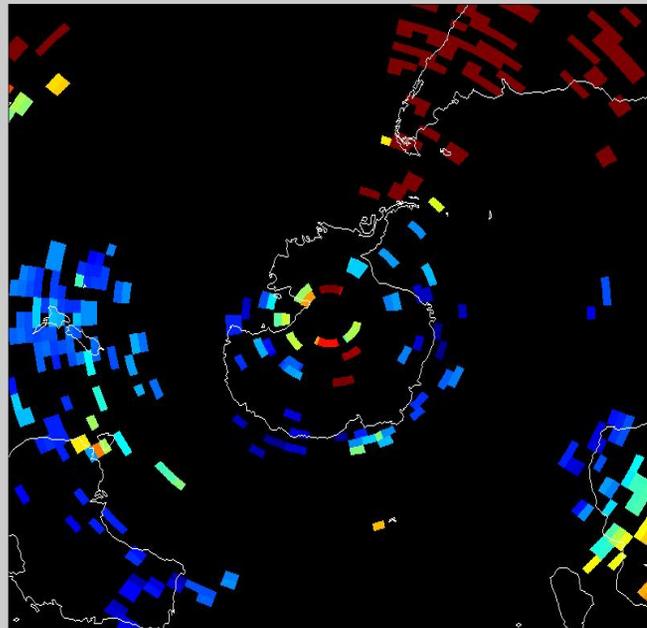
20 Nov 2003 18:20 UT

Day324  PM

 **MIT Haystack Observatory**

Geodetic GPS TEC Map

from 20-Nov-2003 18:10:00 to 20-Nov-2003 18:20:00

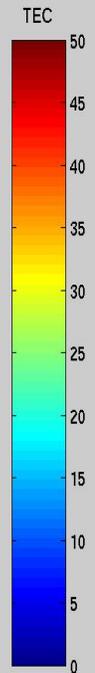
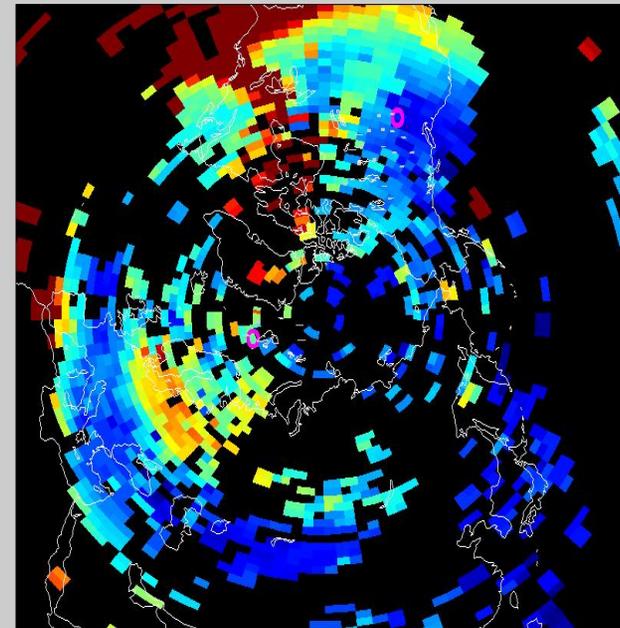


Day324  PM

 **MIT Haystack Observatory**

Geodetic GPS TEC Map

from 20-Nov-2003 18:10:00 to 20-Nov-2003 18:20:00

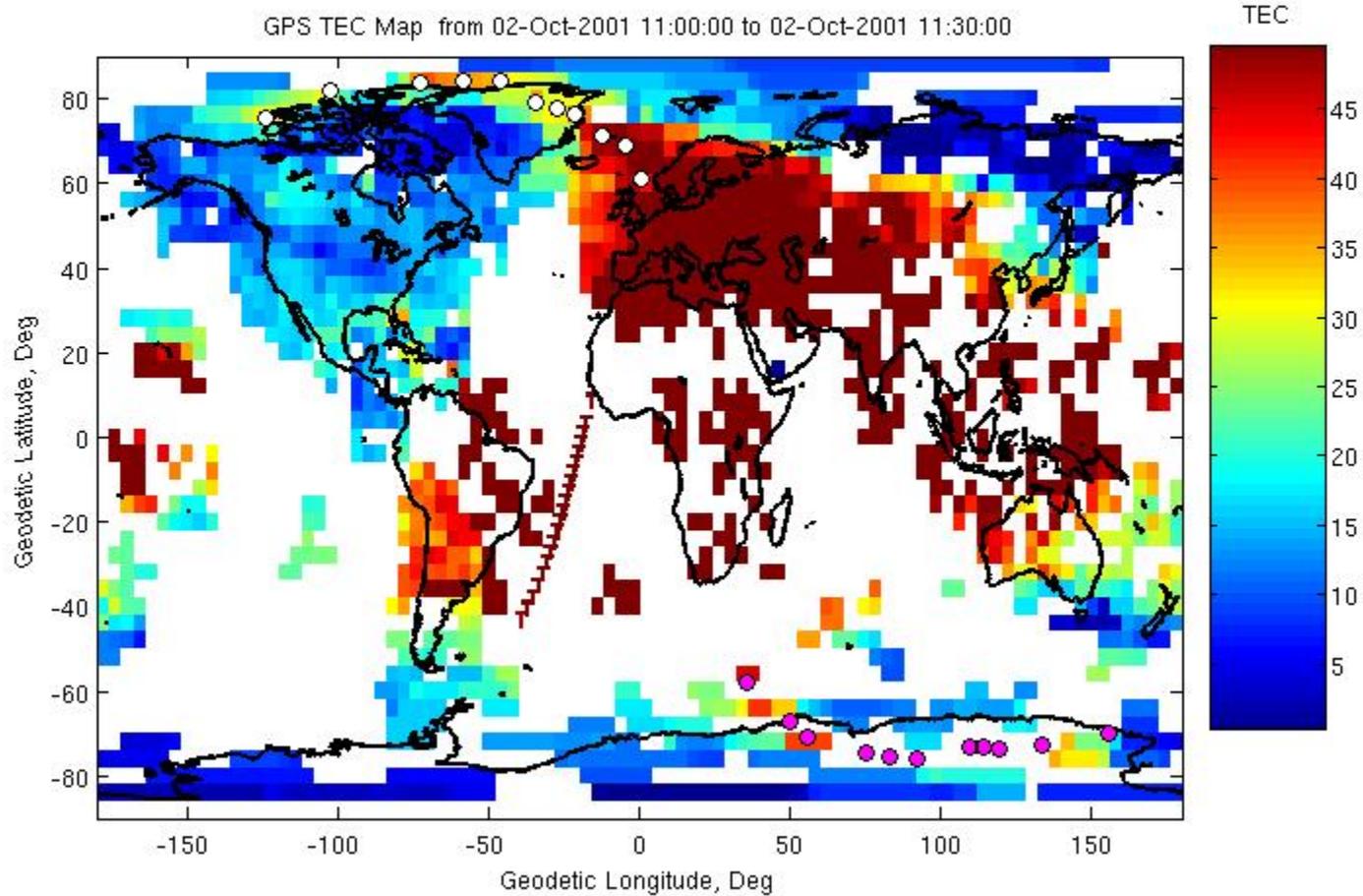


Conjugacy Examples

Day275  AM



MIT Haystack Observatory



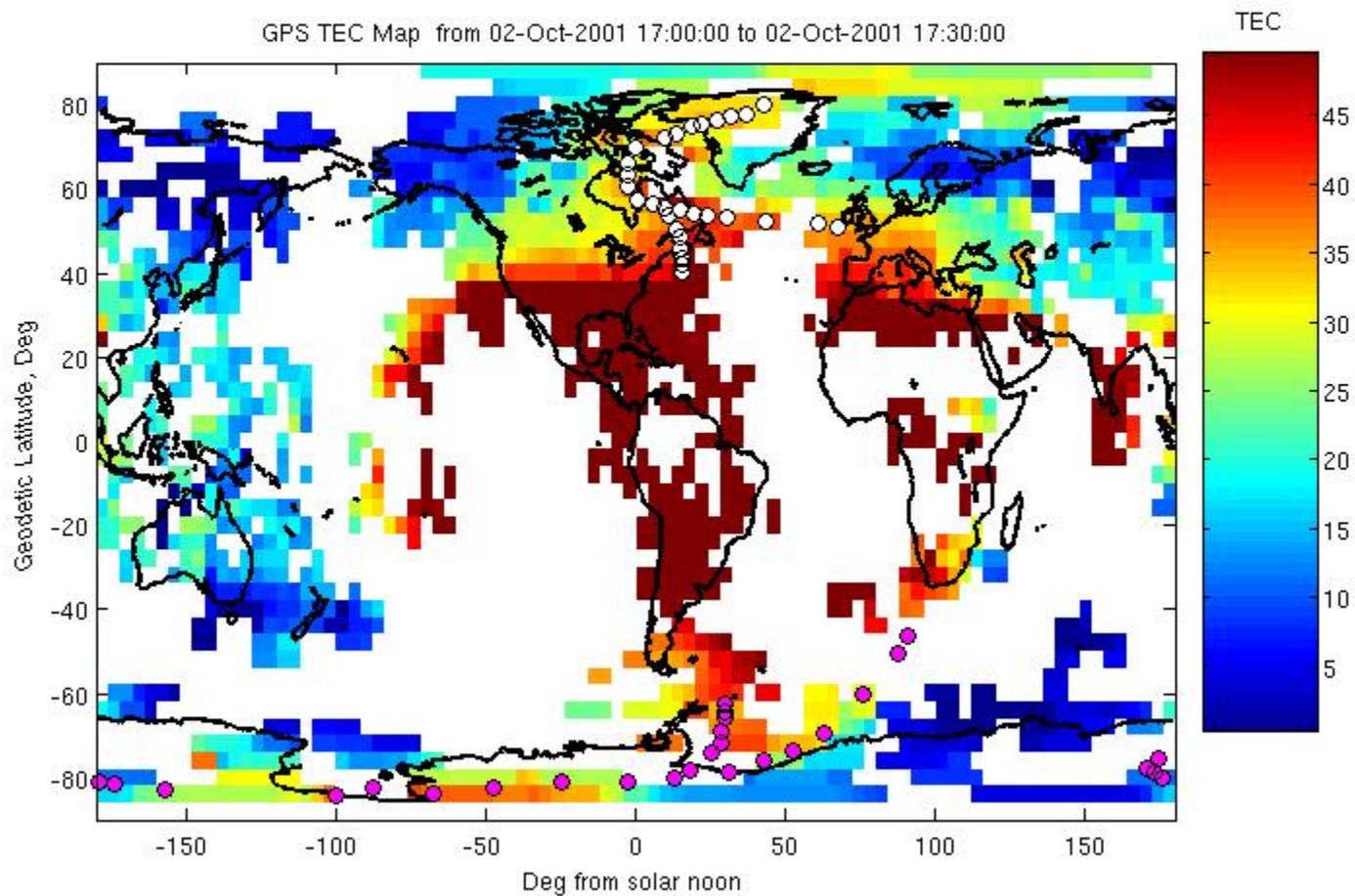
Conjugacy Examples

Day275  PM



MIT Haystack Observatory

GPS TEC Map from 02-Oct-2001 17:00:00 to 02-Oct-2001 17:30:00



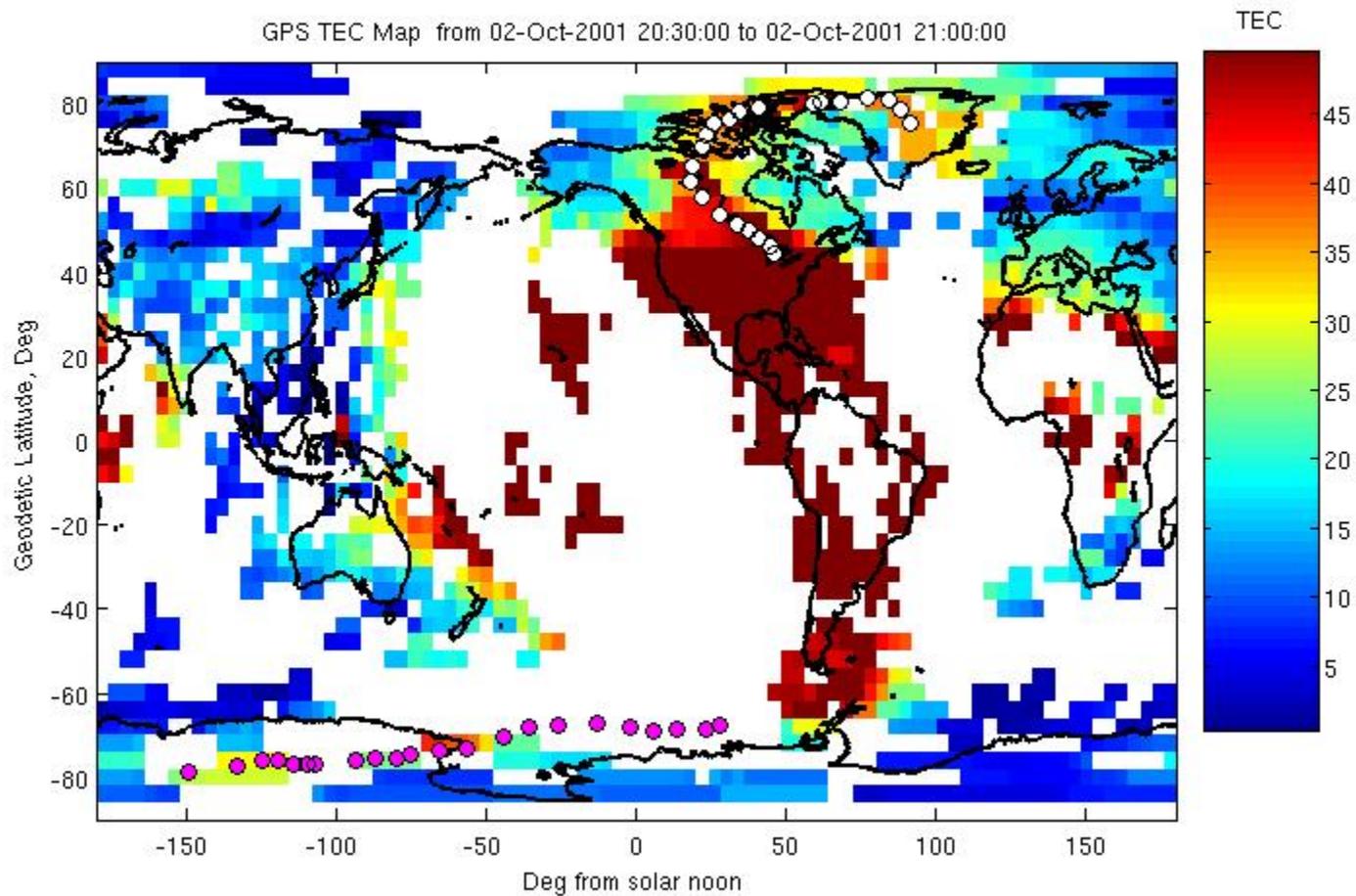
Conjugacy Examples

Day275  PM



MIT Haystack Observatory

GPS TEC Map from 02-Oct-2001 20:30:00 to 02-Oct-2001 21:00:00



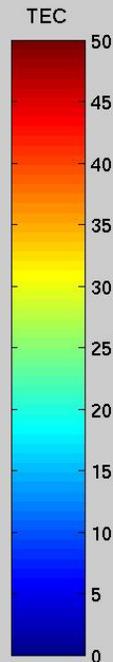
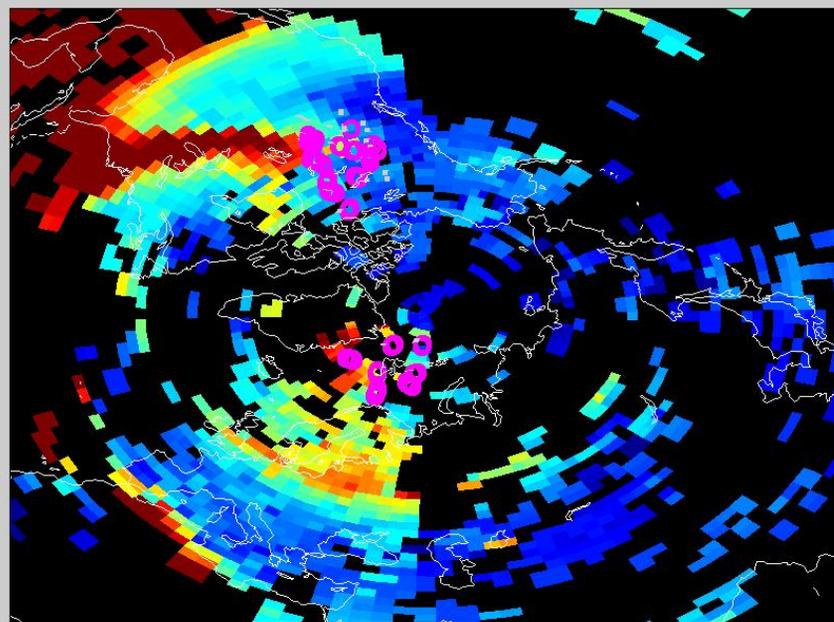
Observed L-Band Phase Scintillation

20 Nov 2003 21:00:00 UT

Day324  PM

 **MIT Haystack Observatory**

Geodetic GPS TEC Map
from 20-Nov-2003 20:45:00 to 20-Nov-2003 21:00:00



Storm-time Electric Fields

- Cross-tail electric fields energize and inject particles into the inner magnetosphere forming the disturbance Ring Current
- Strong penetration eastward electric field **uplifts equatorial ionosphere**
 - **Equatorial anomaly enhanced**
- Radial/Poleward Polarization Jet Electric Fields form (Sub Auroral Polarization Stream). As the Polarization Stream overlaps the outer plasmasphere
 - **Storm-Enhanced Density (SED)**
 - **Detached plasmas/plasma tails**

Sub-Auroral Polarization Stream

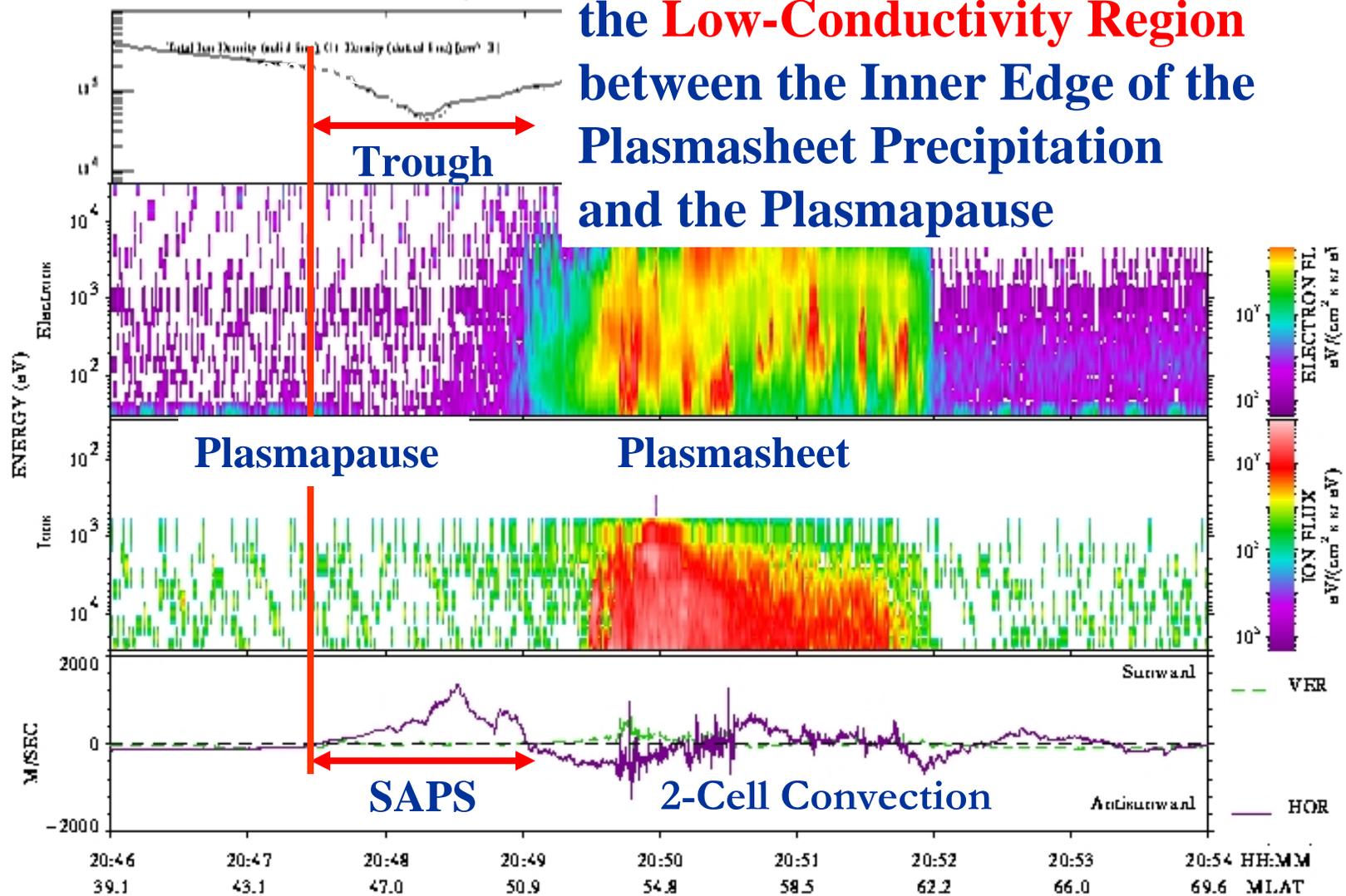
DMSF F15

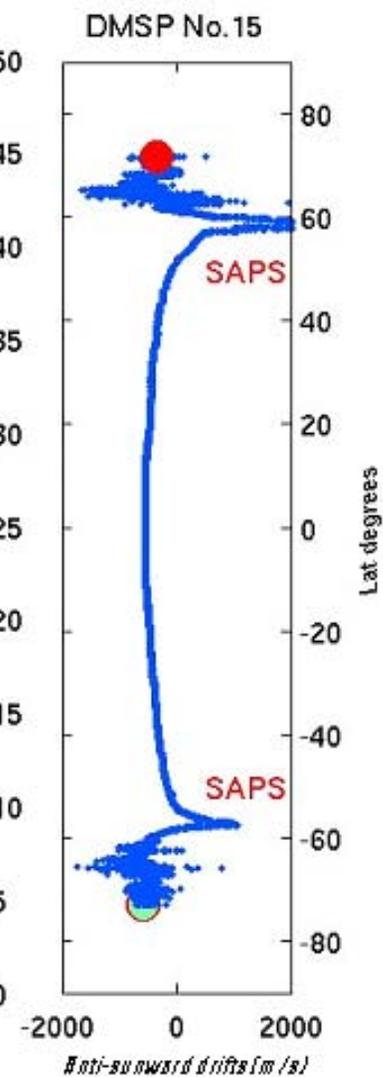
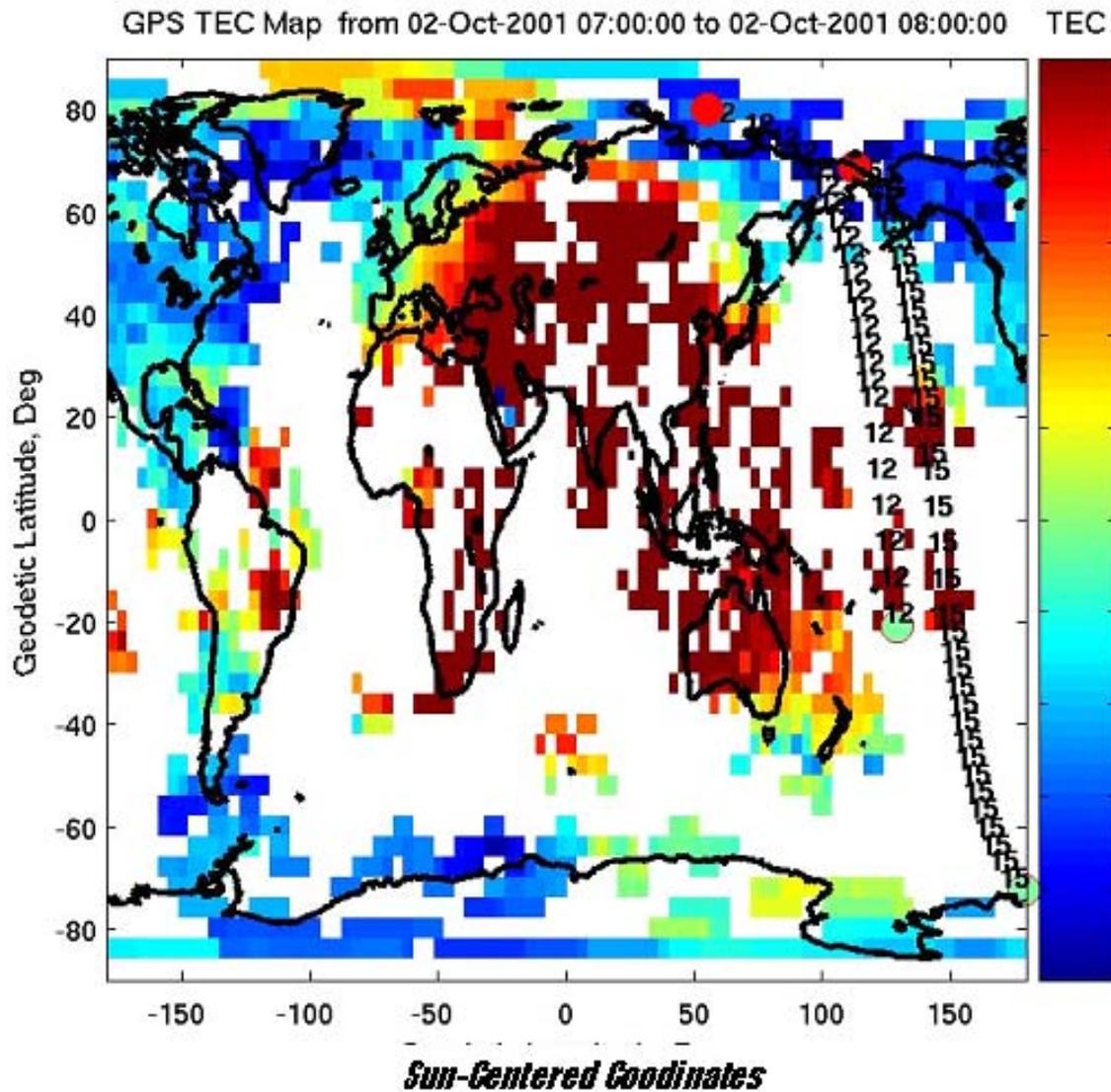
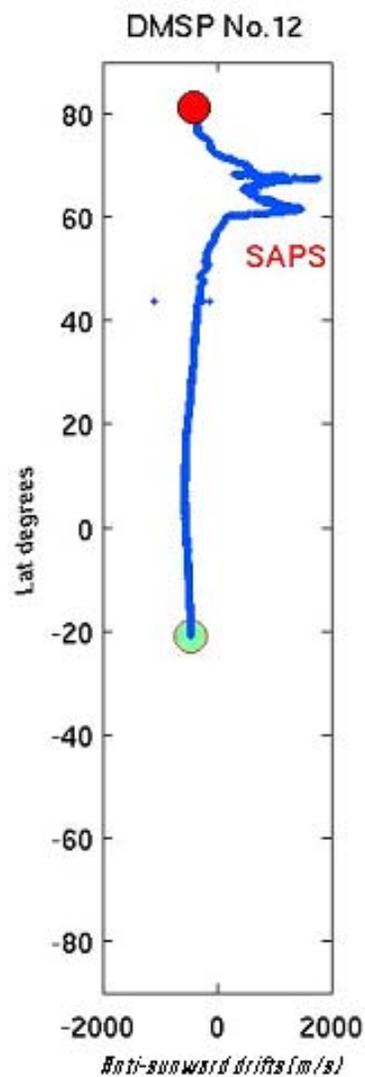
6 April 2000

21 MLT

F15

A Strong Electric Field forms in the **Low-Conductivity Region** between the Inner Edge of the Plasmasheet Precipitation and the Plasmapause



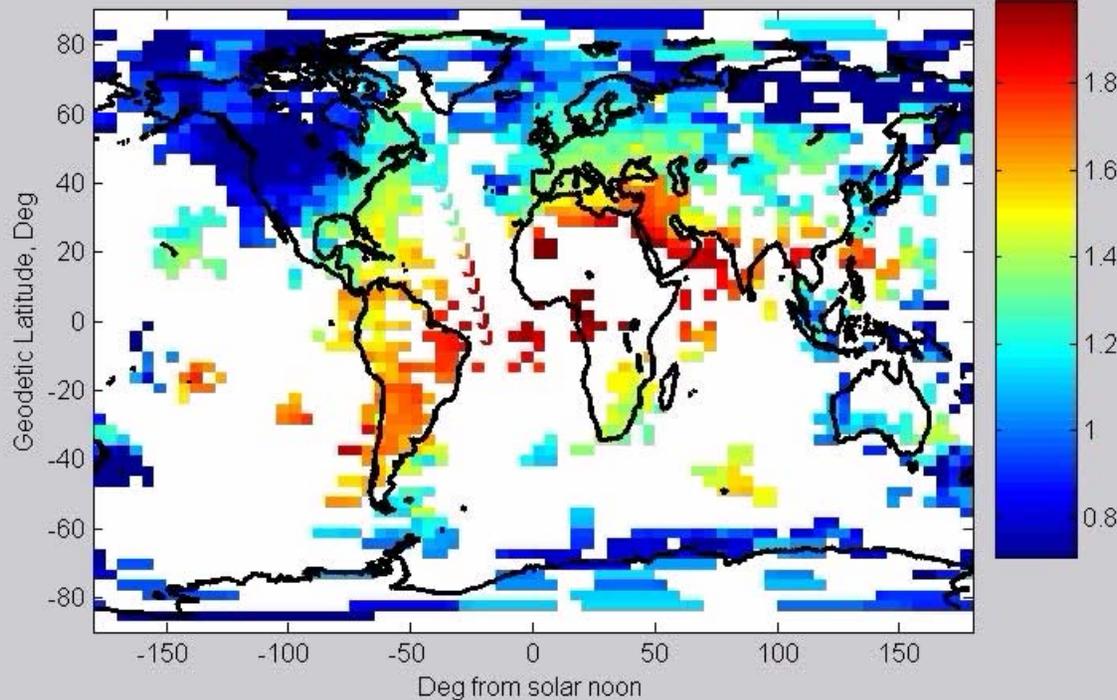


Global TEC (Noon in center)

Day303 PM

MIT Haystack Observatory

GPS TEC Map from 30-Oct-2003 12:30:00 to 30-Oct-2003 12:40:00 Log10(TEC)



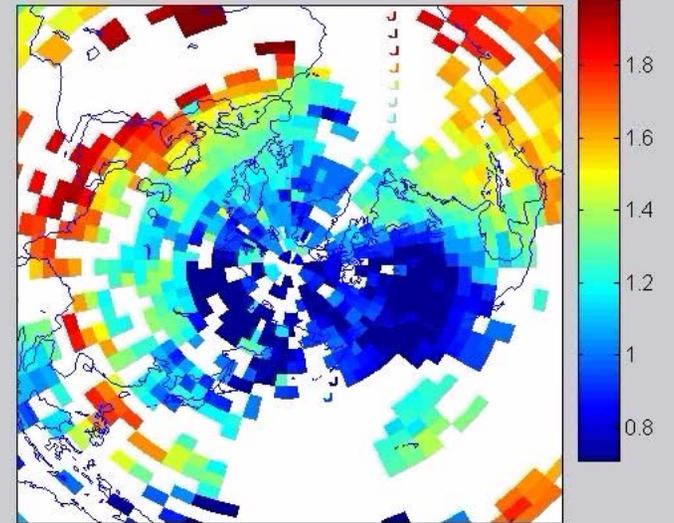
**October 29/30, 2003 Storm
Global Thermal Plasma
Redistribution.**

Northern Hemisphere

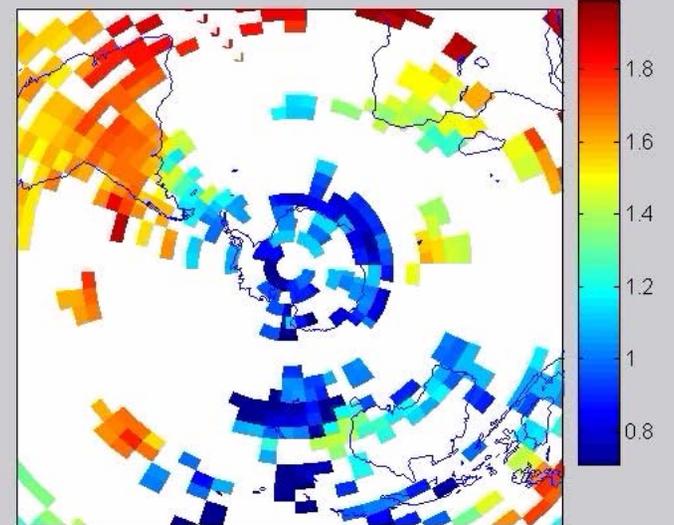
Day303 PM

MIT Haystack Observatory

Geodetic GPS TEC Map from 30-Oct-2003 12:30:00 to 30-Oct-2003 12:40:00 Log10(TEC)

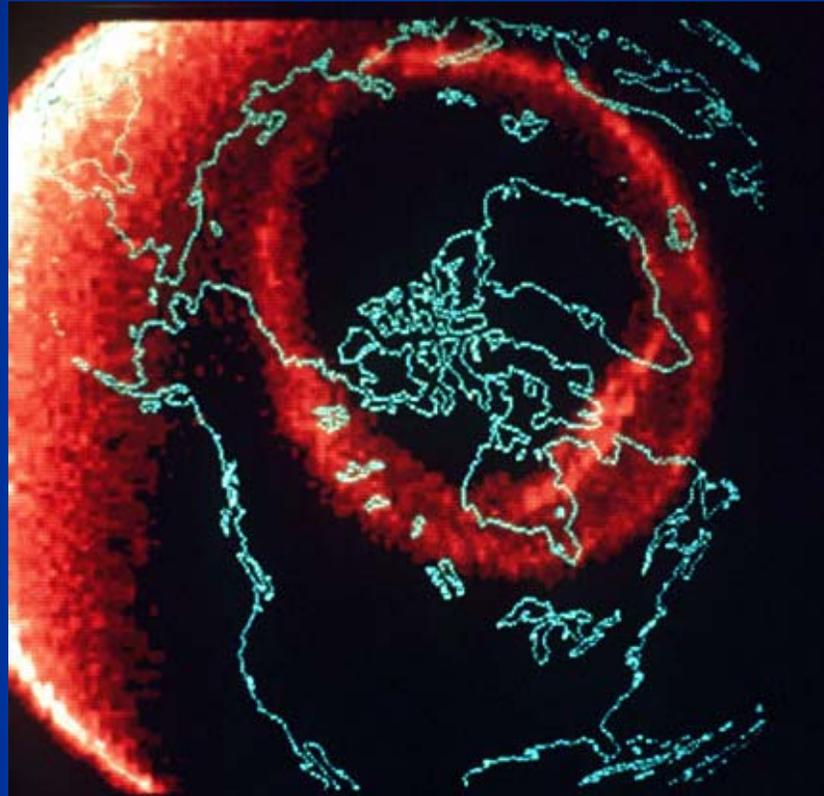


from 30-Oct-2003 12:30:00 to 30-Oct-2003 12:40:00 Log10(TEC)



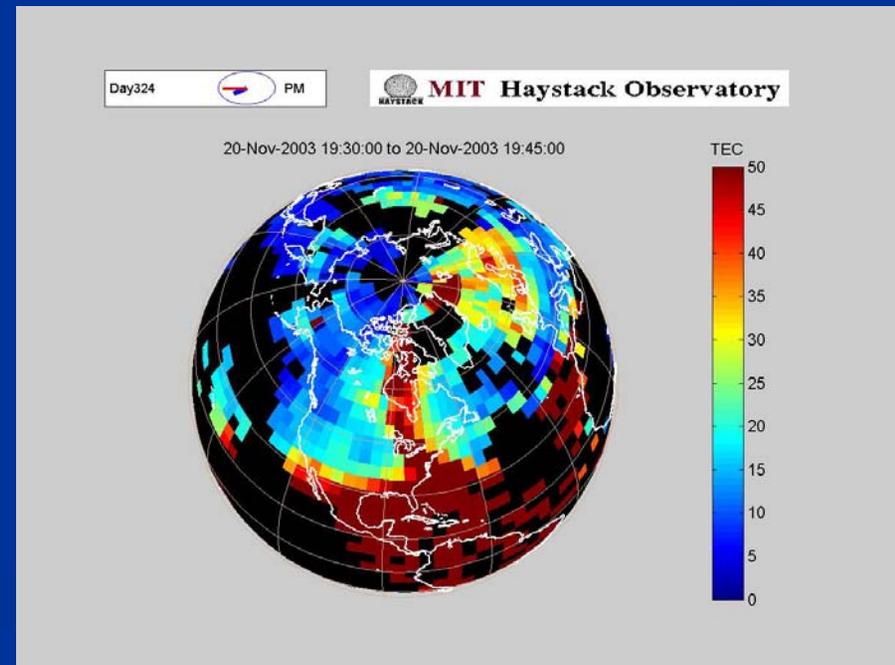
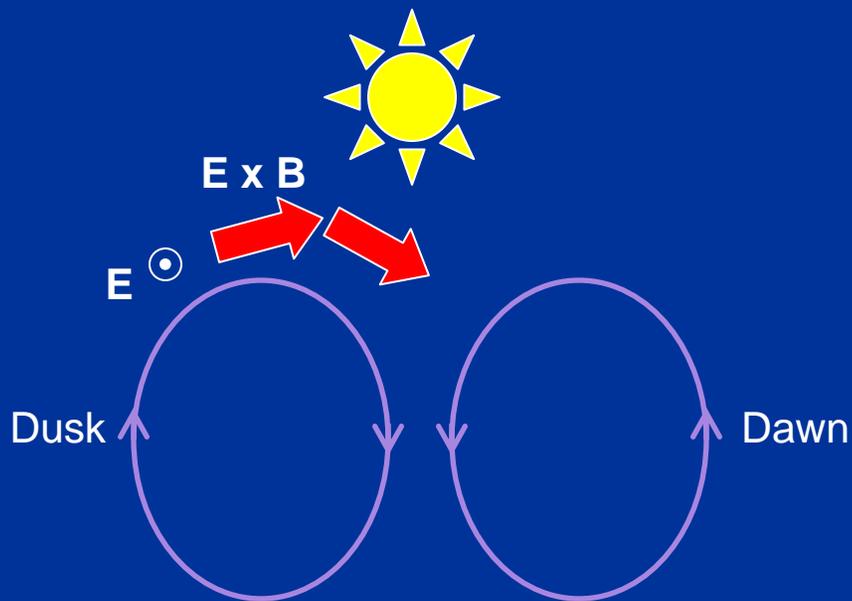
Southern Hemisphere

Auroral Region



Polar Convection

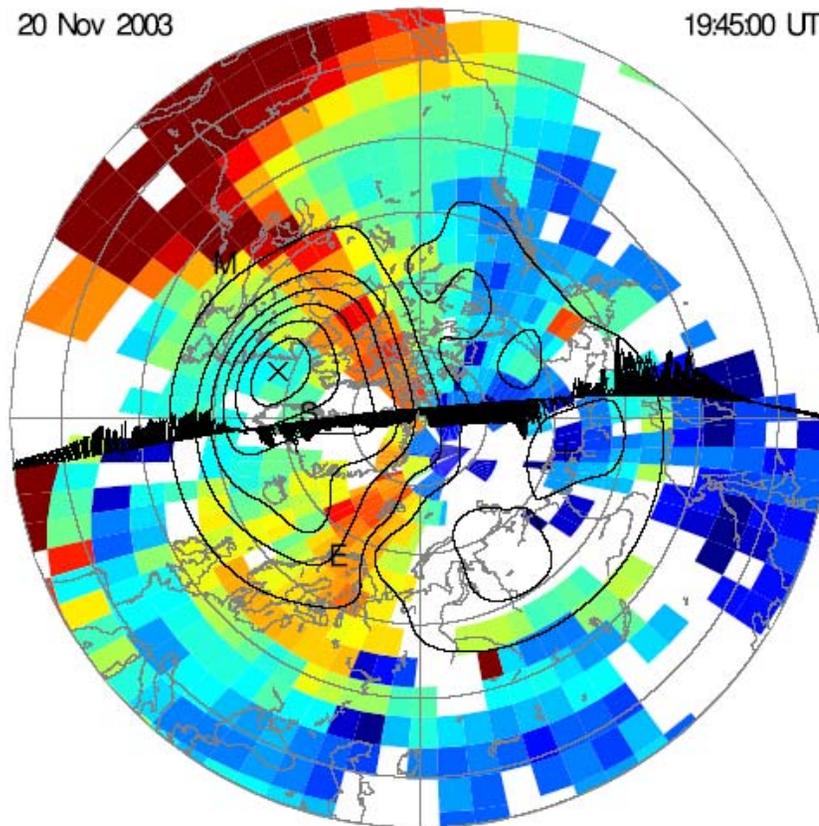
- The SAPS electric field produces a westward plasma flow at subauroral latitudes
- Some plasma travels through dayside cusp into polar regions where it becomes entrained in the polar convection and carried over the pole



SuperDARN HF Radars

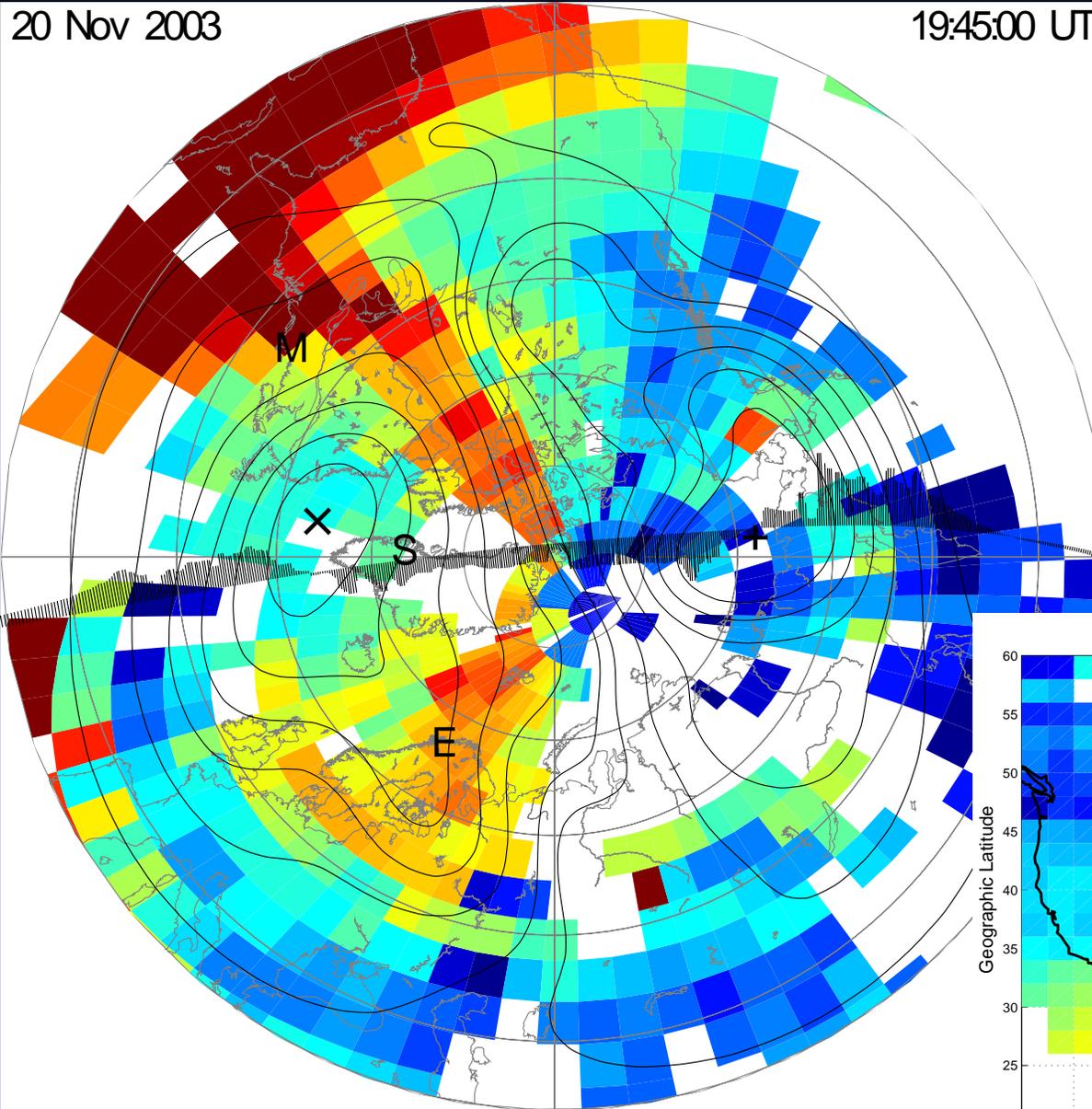


20 Nov 2003 - GPS TEC, DMSP, SuperDarn Convection Patterns, and ISR Radar Measurements



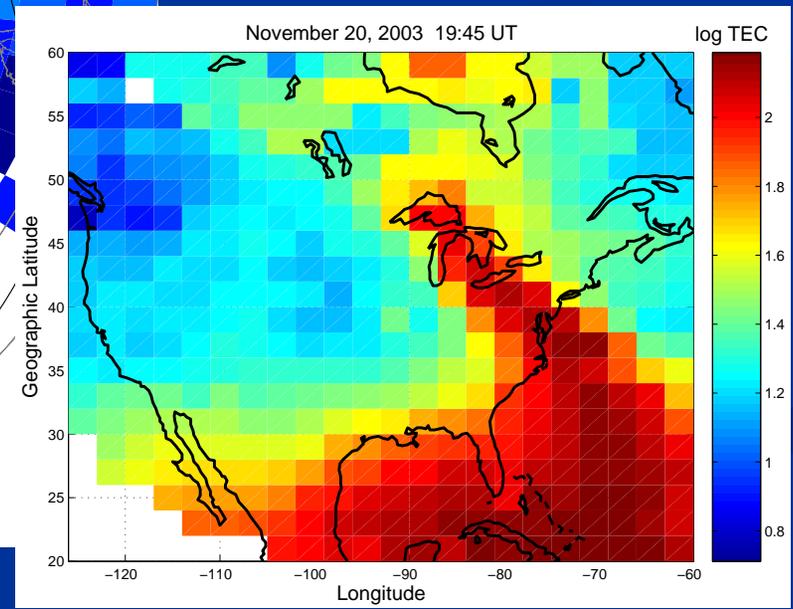
20 Nov 2003

19:45:00 UT



SED Plume forms Polar Tongue of Ionization

GPS TEC Map

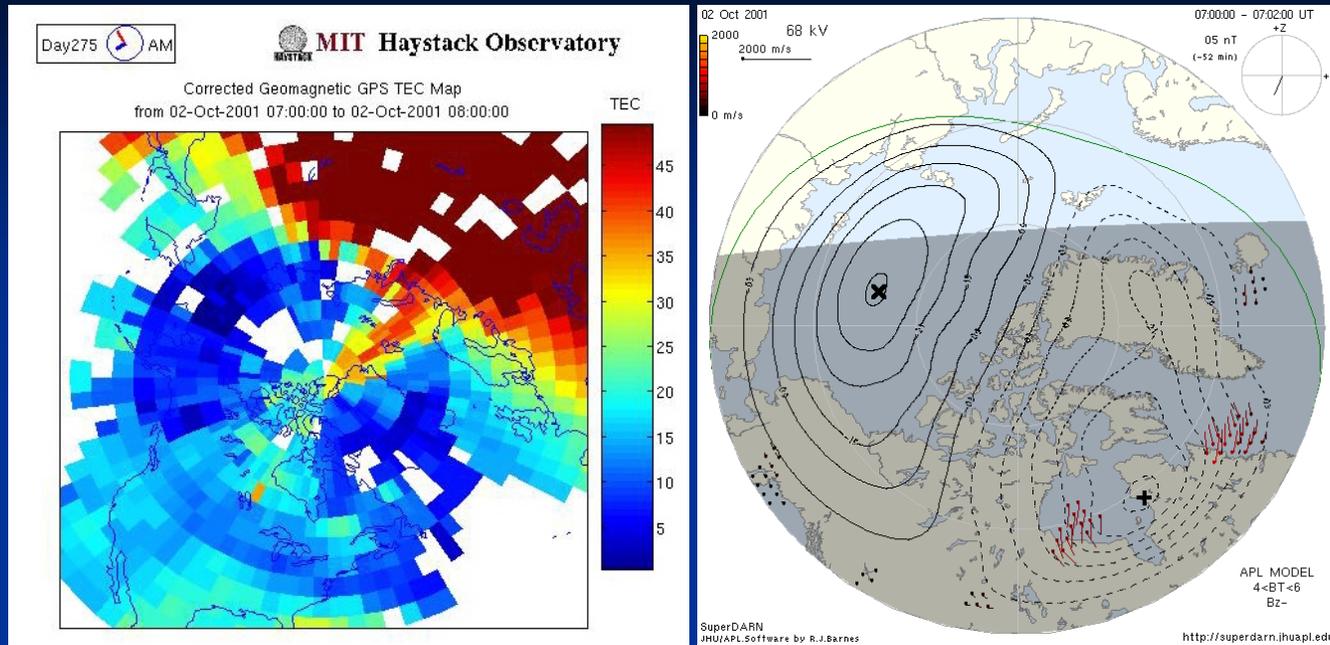


Merged SuperDARN/DMSPP Convection

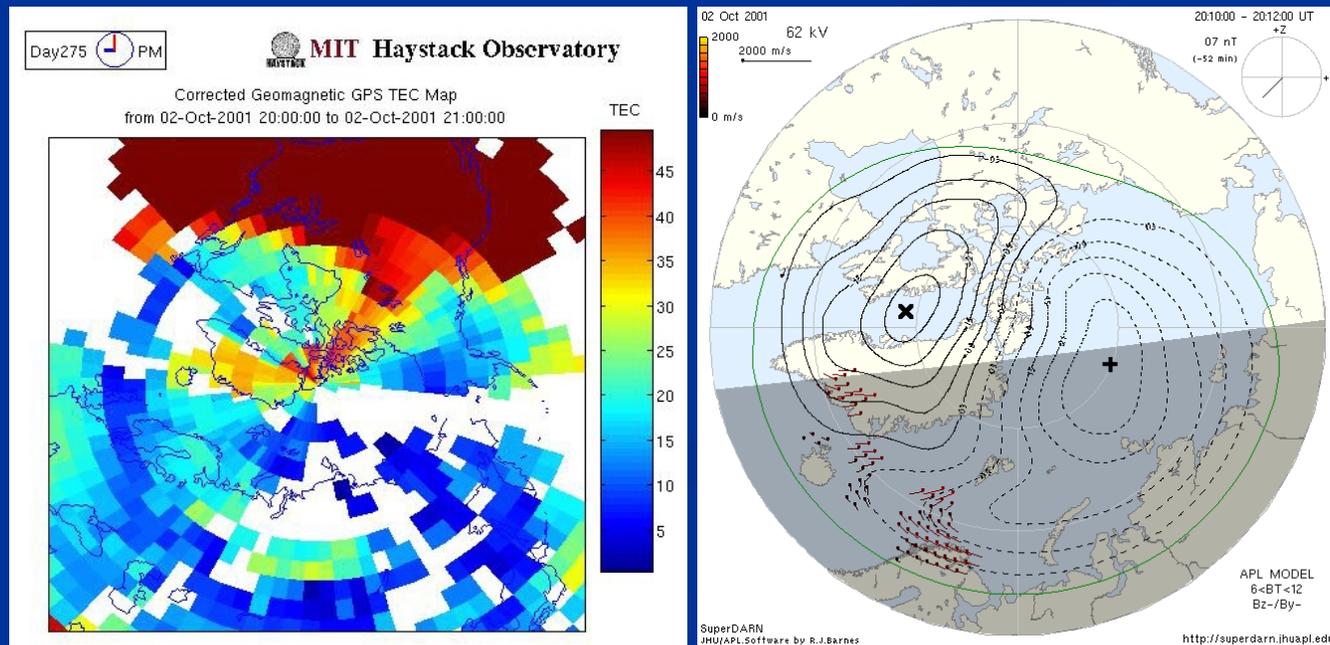
[Foster et al., JGR 2005]

Northern Europe and American Sector SED Plumes

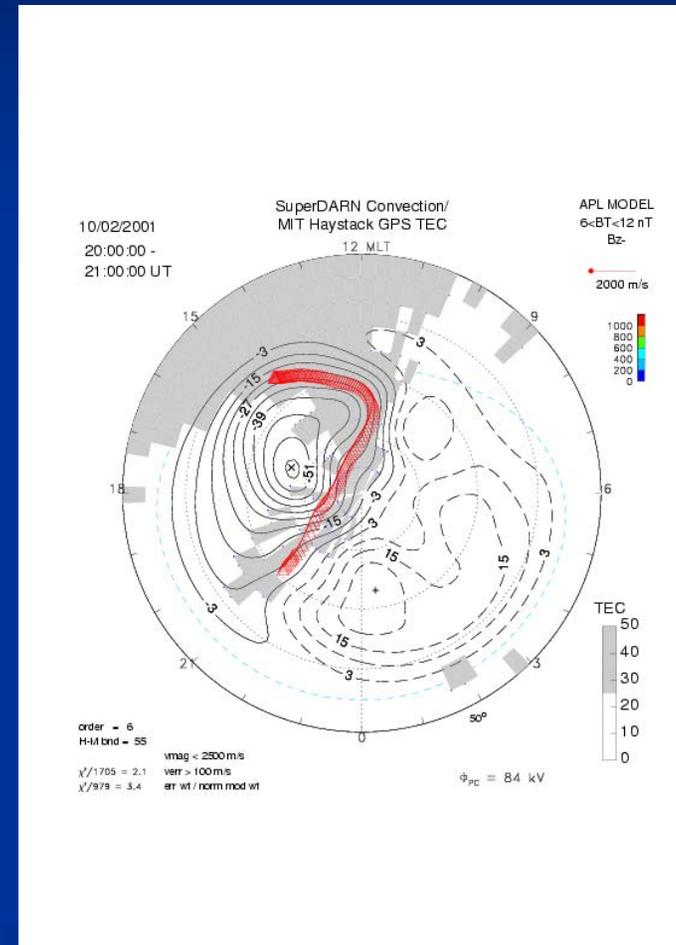
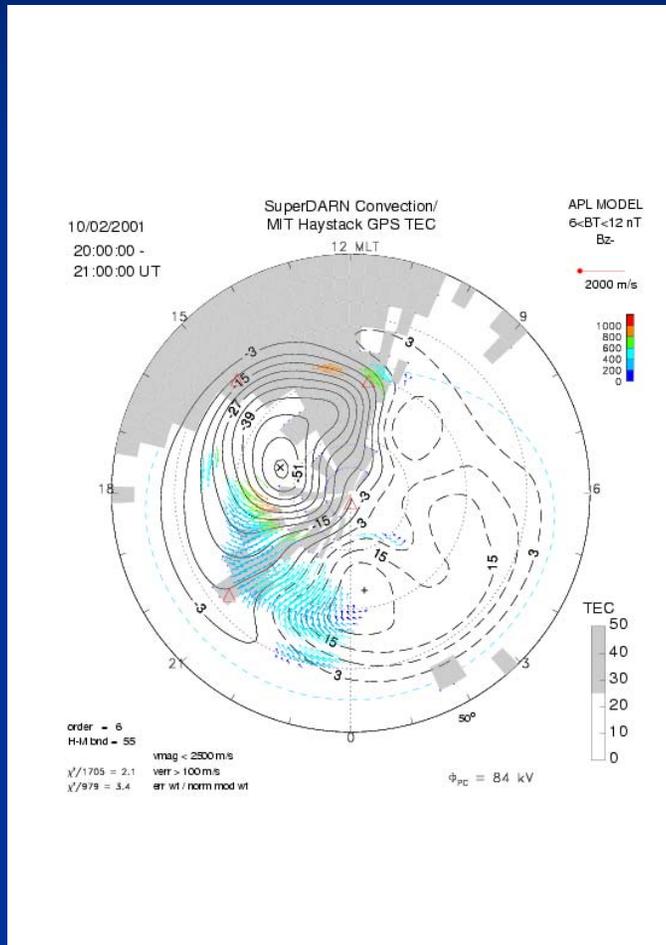
Northern Europe



American Sector



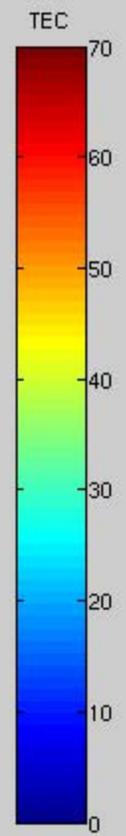
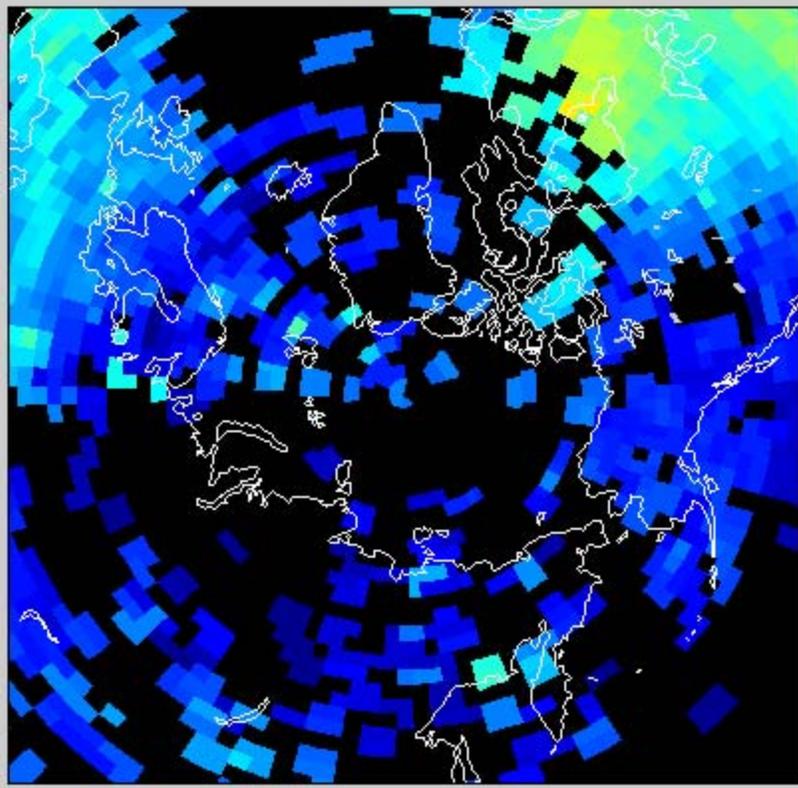
The trajectory of a parcel of plasma

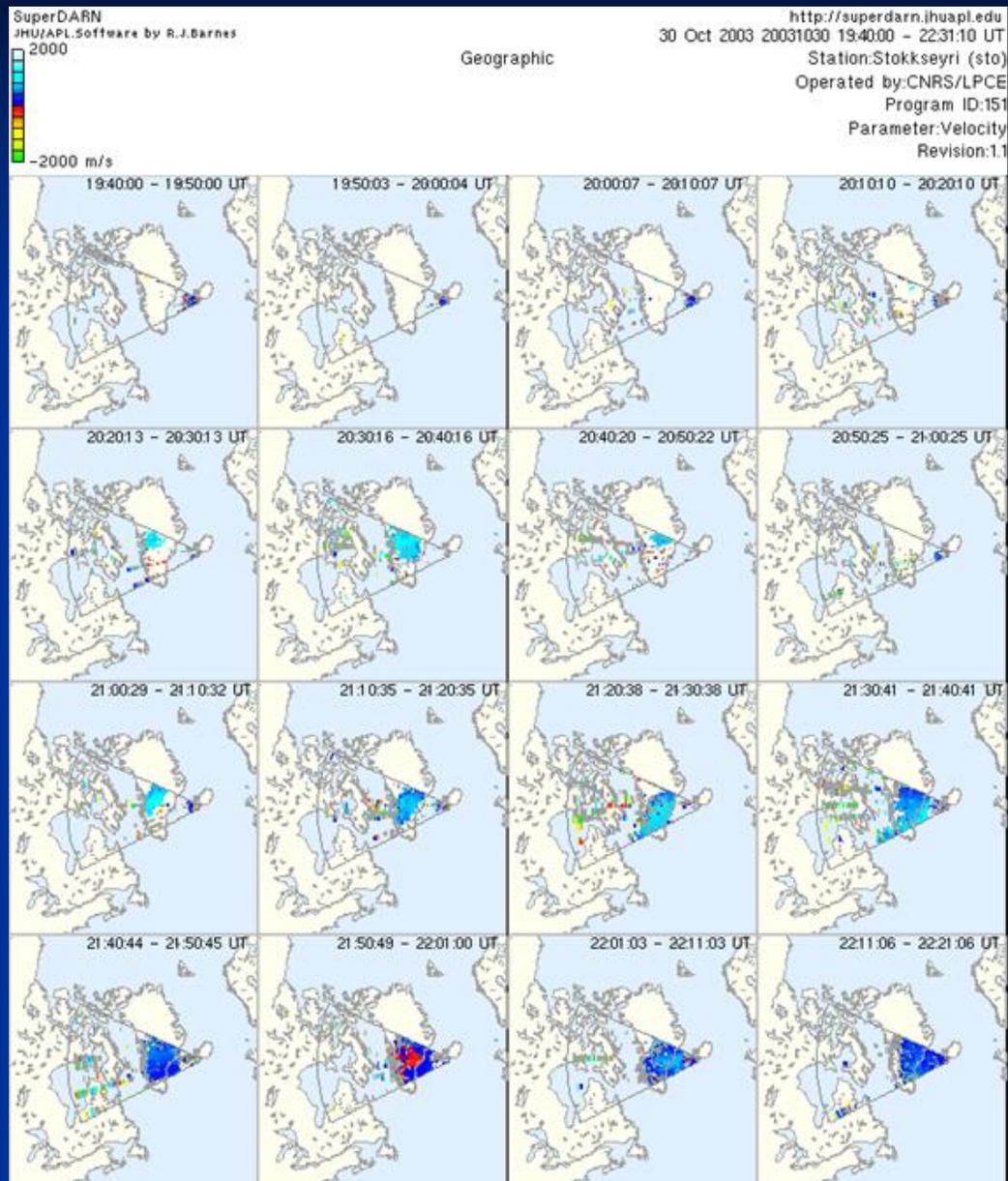


Day303  PM

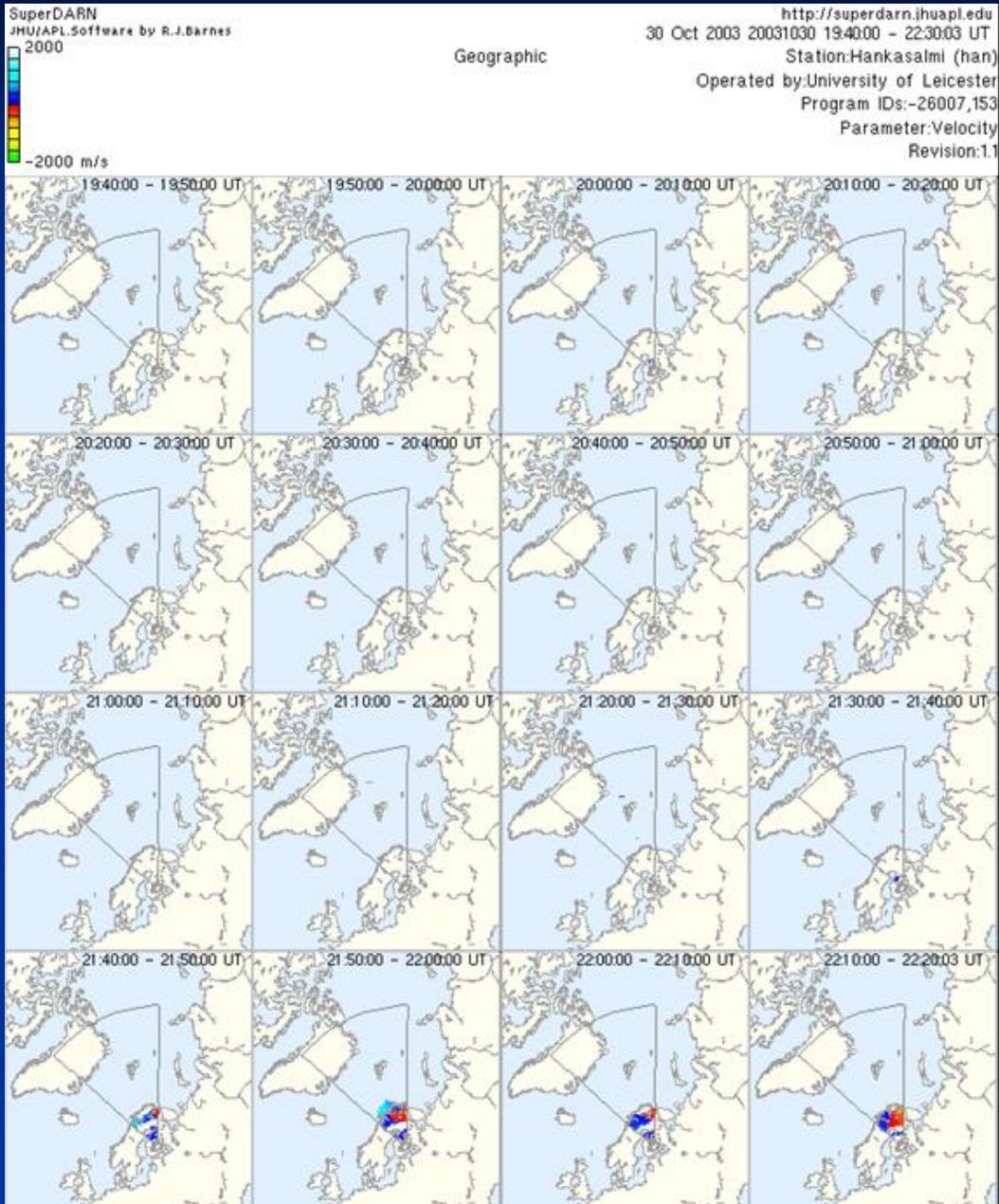
 **MIT Haystack Observatory**

Geodetic GPS TEC Map
from 30-Oct-2003 15:00:00 to 30-Oct-2003 15:15:00



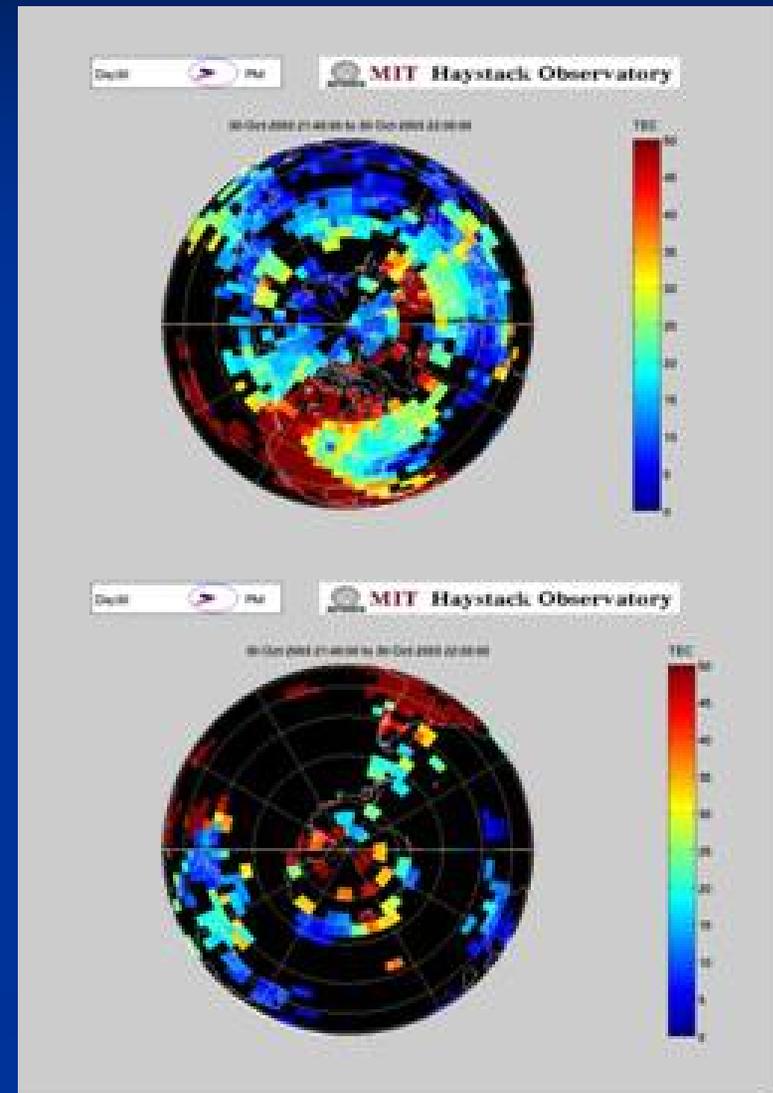
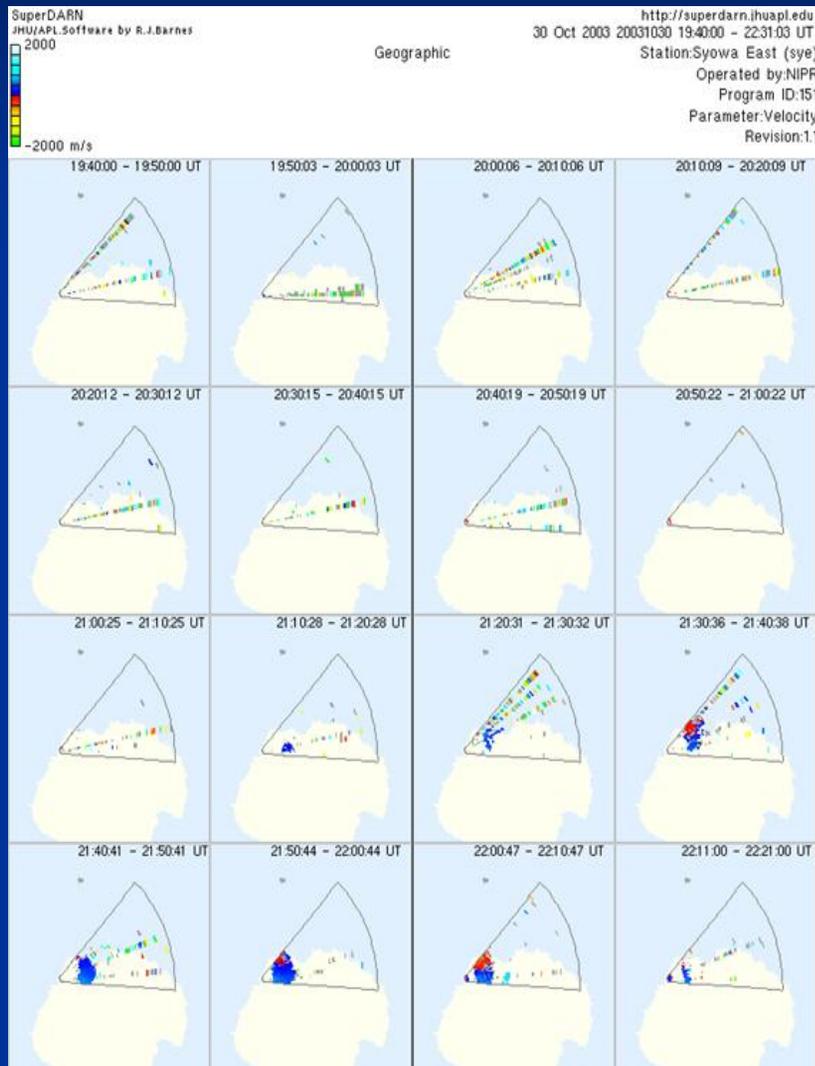


The Stokkeyri SuperDARN in South Iceland observes HF backscatter from 19:40 to 22:20 UT on the 30 October 2003. A strong TOI over Iceland is not observed until 20:20 UT, which is also the first time period that strong HF backscatter is observed at Stokkseyri

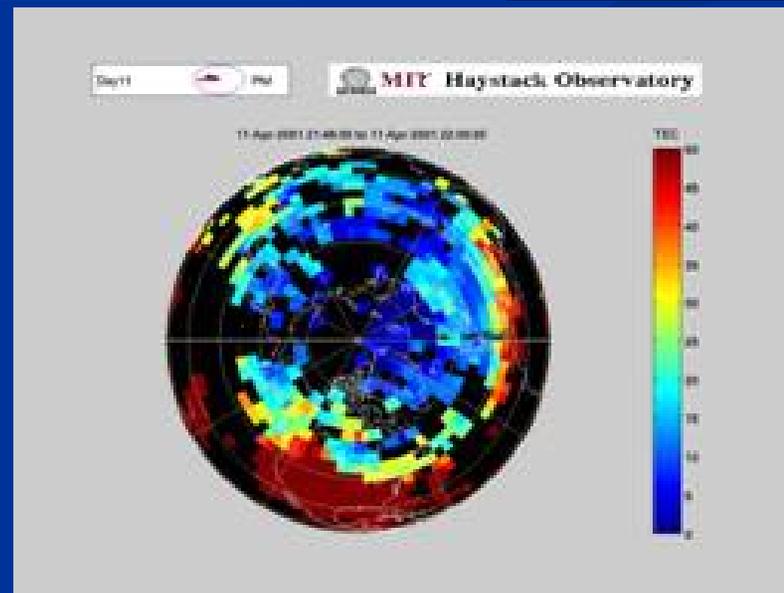
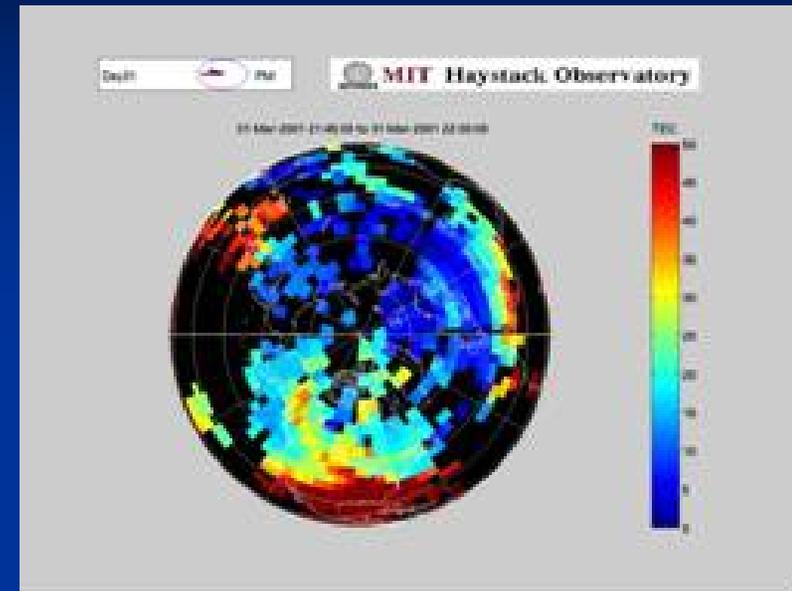
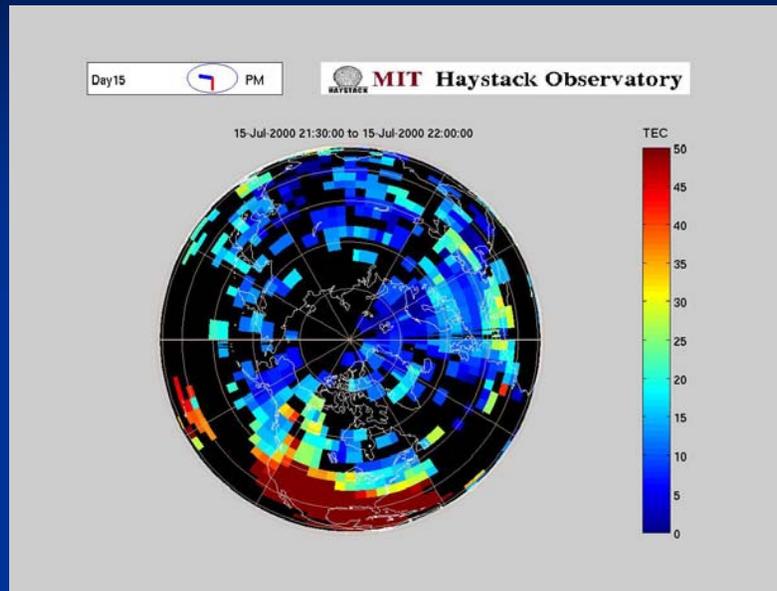


**The Hankasalmi
SuperDARN station
in Finland did not
observe strong
backscatter until
21:40 UT.**

HF backscatter can be first observed at the Syowa East at 21:20 UT

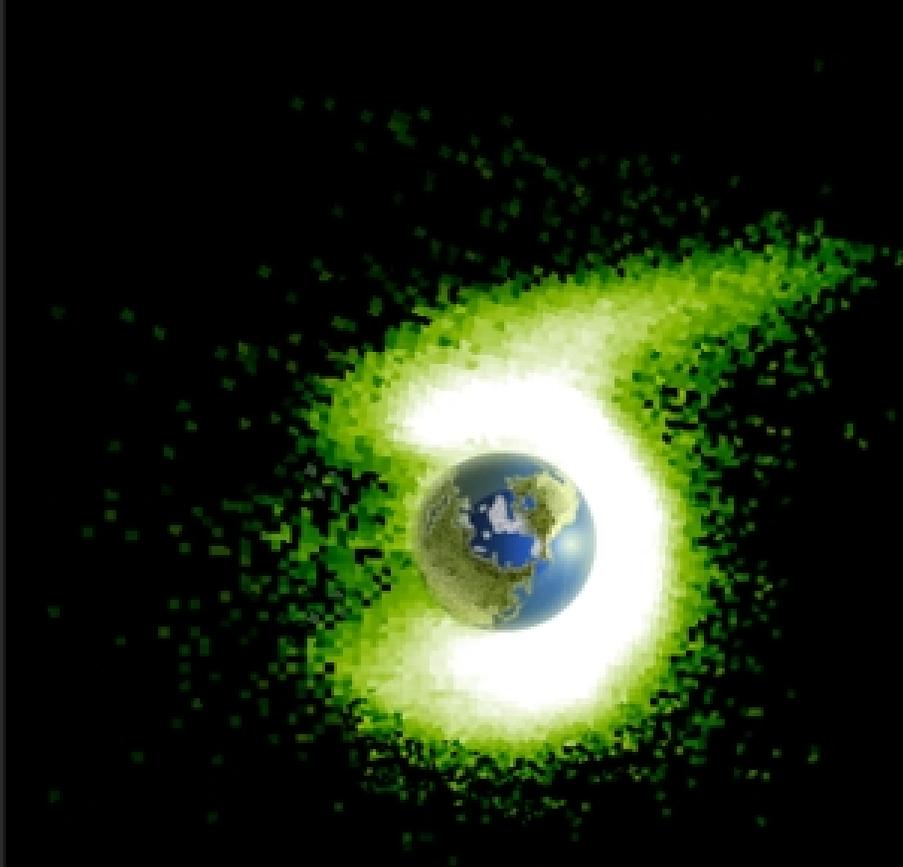
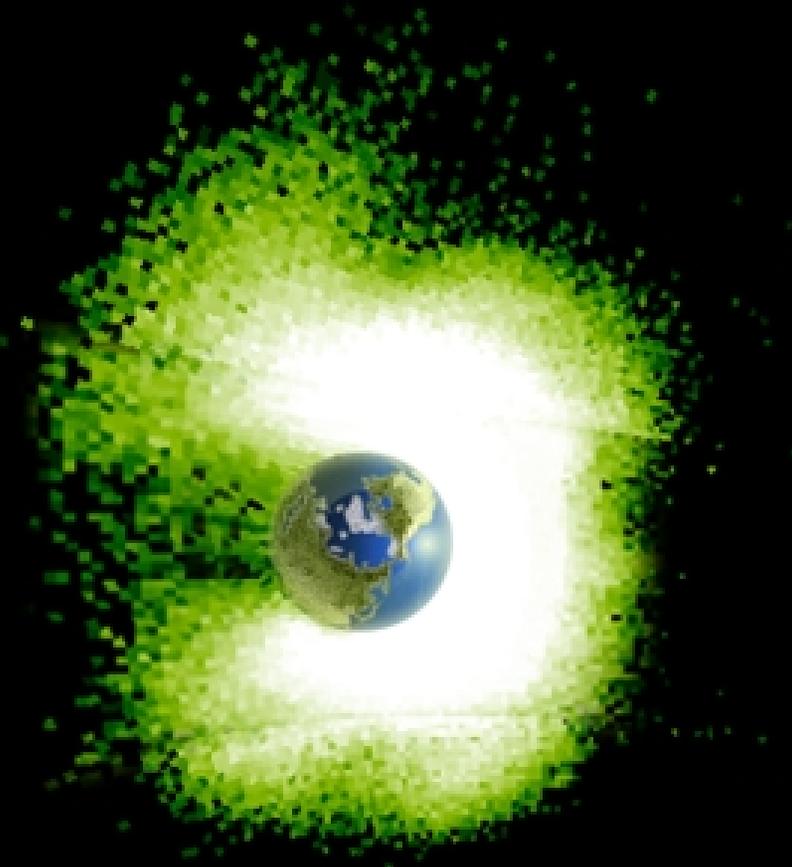


Cases where the SED did not produce a TOI: 11 April 2001, 31 March 2001, and 15 July 2000



Before Storm

After Storm

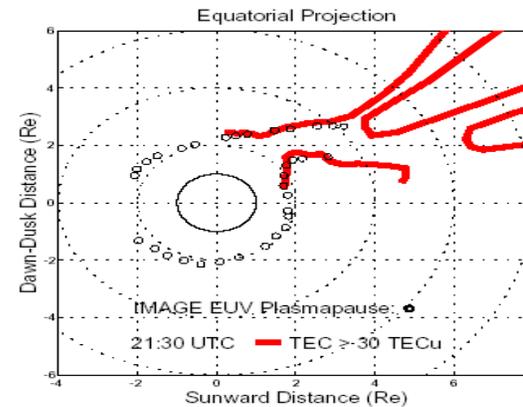
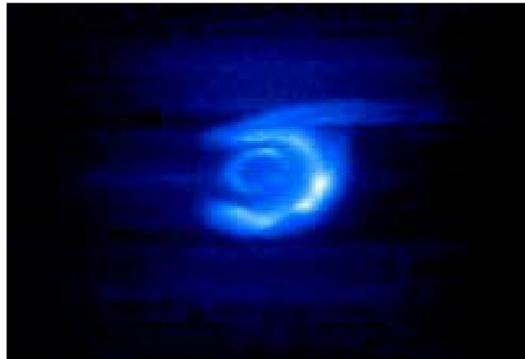


2001 Apr 11 00:24

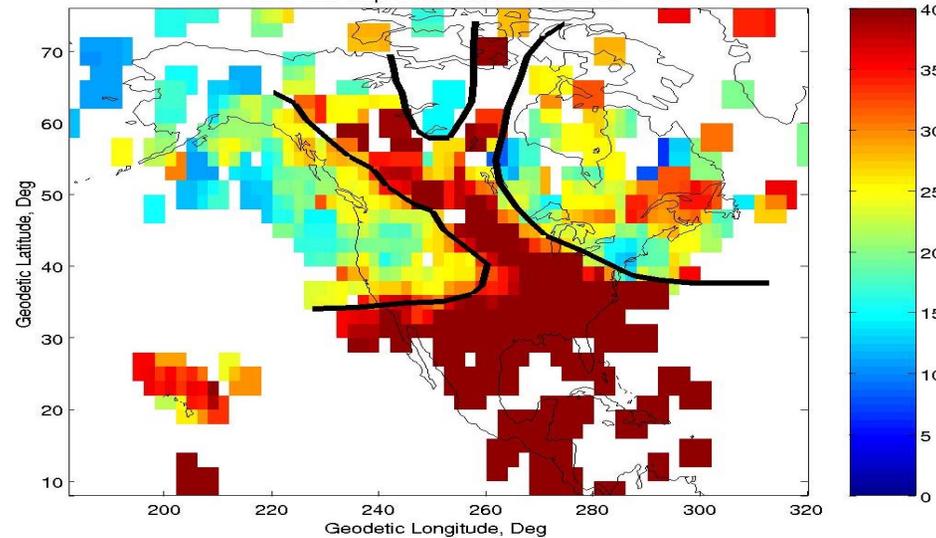
2001 Apr 12 02:25

Plasmaspheric Tails and Storm Enhanced Density

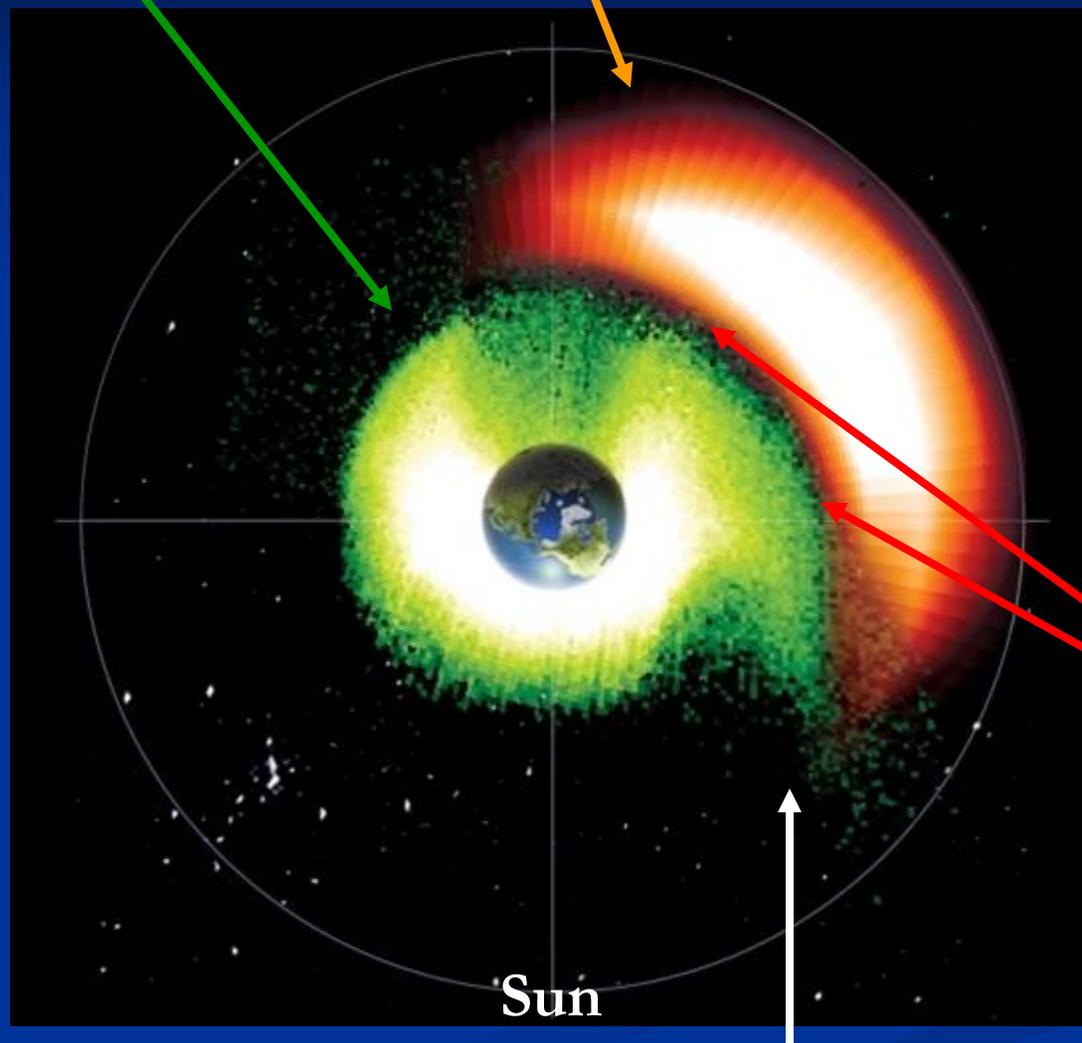
IMAGE EUV 21:21 UTC



GPS TEC Map 31 March 2001 21:20 UT



Plasmasphere / Ring Current Interactions



April 17, 2002
NASA IMAGE

SAPS Channel

Sun

Plasmasphere Erosion Plume

(Merged image courtesy J. Goldstein)

