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Analysis software for upper atmospheric data developed by the IUGONET project and its application to polar science

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Abstract To comprehensively understand the Arctic and Antarctic upper atmosphere, it is often crucial to analyze various data that are obtained from many regions. Infrastructure that promotes such interdisciplinary studies on the upper atmosphere has been developed by a Japanese inter-university project called the Inter-university Upper atmosphere Global Observation Network (IUGONET). The objective of this paper is to describe the infrastructure and tools developed by IUGONET. We focus on the data analysis software. It is written in Interactive Data Language (IDL) and is a plug-in for the THEMIS Data Analysis Software suite (TDAS), which is a set of IDL libraries used to visualize and analyze satellite- and ground-based data. We present plots of upper atmospheric data provided by IUGONET as examples of applications, and verify the usefulness of the software in the study of polar science. We discuss IUGONET's new and unique developments, i.e., an executable file of TDAS that can run on the IDL Virtual Machine, IDL routines to retrieve metadata from the IUGONET database, and an archive of 3-D simulation data that uses the Common Data Format so that it can easily be used with TDAS.

Keywords **data analysis software, metadata database, upper atmosphere, ground-based observation, polar science, interdisciplinary study, IUGONET**

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1 Introduction

Recent major environmental problems, such as the warming of the Earth's atmosphere, are essentially global phenomena that occur in the Earth's complex system. For example, in contrast to the warming of the troposphere, an increase of greenhouse gasses is predicted to cool the stratosphere, mesosphere, and thermosphere[1]. Furthermore, phenomena observed in the Arctic or Antarctic atmosphere are often related to phenomena observed in the middle and low latitudes, as well as in the ionosphere and magnetosphere, through latitudinal and vertical couplings. Previous papers have reported the influences of stratospheric sudden warming on the low to middle latitudes[2-5], and of energetic par-

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ticle precipitation from the magnetosphere on the lower atmosphere in the polar region[6-8]. To comprehensively understand such global and complex phenomena, it is necessary to conduct an interdisciplinary study that uses various types of data from multiple regions (e.g., tropospheric and stratospheric meteorological data, neutral parameters of the mesosphere and thermosphere, plasma parameters of the ionosphere and plasmasphere, solar wind parameters of interplanetary regions, solar images, etc.). Thus, it is important to have appropriate research infrastructures to search, retrieve, visualize, and analyze such data.

The Inter-university Upper atmosphere Global Observation Network (IUGONET) is a collaborative project that comprises five Japanese institutes and universities (Tohoku University, Nagoya University, Kyoto University, Kyushu University, and the National Institute of Polar Research) that have been developing a network of worldwide ground-based observations of the upper atmosphere, Sun and planets[9]. This project's aim is the development of infrastructure and tools to promote interdisciplinary studies of the upper atmosphere. Two tools have already been developed. One is a metadata database for searching and obtaining various upper atmospheric data that are distributed across many different universities and institutes. The other is a data analysis software tool for visualizing and analyzing data.

The purpose of this paper is to describe the two products developed by IUGONET. We focus on the data analysis software and provide examples of its application to the study of polar science research. We give a brief outline of the data analysis software in Section 2. Section 3 describes some of IUGONET's unique developments that are included in the analysis software. In Section 4, we provide visualization examples using upper atmospheric data from the Arctic and Antarctic regions. Section 5 summarizes and concludes this paper.

2 Data analysis software developed by IUGONET

Our analysis software is called the iUgonet Data Analysis Software (UDAS). It is written in Interactive Data Language (IDL; http://www.exelisvis.com/ProductsServices/IDL.aspx), which is a widely used programming language within the solar-terrestrial physics community. The software is based on the Time History of Events and Macroscale Interactions during Substorms (THEMIS) Data Analysis Software suite (TDAS), which is a set of IDL libraries that provides an integrated analysis platform for visualizing and analyzing satellite- and ground-based data obtained during the THEMIS mission[10]. Detailed information about TDAS can be found on the web page (http://themis.ssl.berkeley.edu/software.shtml, http://themis.ssl.berkeley.edu/software_docs.shtml). Figure 1 illustrates the relationships between UDAS, TDAS, and IDL. UDAS is provided as plug-in software for TDAS; therefore, TDAS and IDL are prerequisites for UDAS.

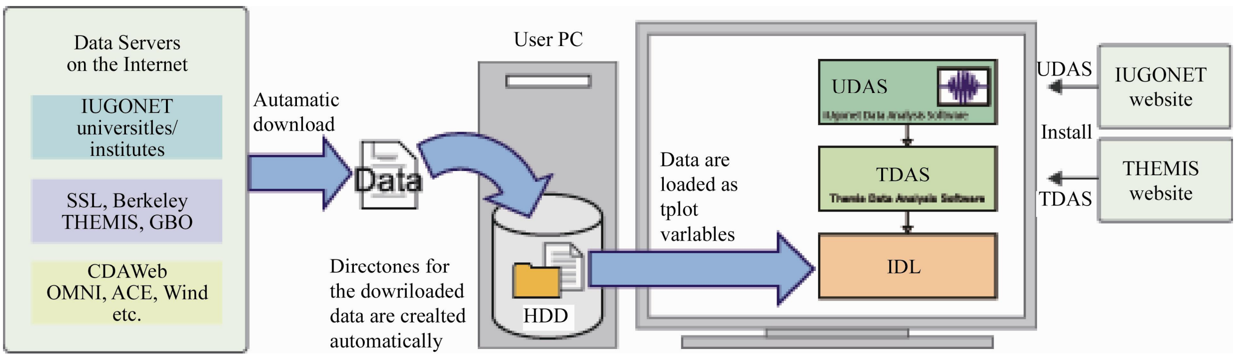

Figure 1 Relationship between UDAS, TDAS, and IDL, and the flow of the data loading.

TDAS has some useful features: (1) It can download data files from remote web servers via the internet, regardless of the location and format of the files (Figure 1). (2) TDAS can easily plot the time series data using the metadata that is often included in the data files for visualization. (3) Many useful routine procedures for time series analysis are available (such as digital filters, the Fourier transform, and wavelet transforms). (4) TDAS is open source software, so it can be freely modified by users. (5) A graphical user interface (GUI) is available to those new to IDL and TDAS.

In addition to THEMIS satellite data, TDAS can handle data obtained from other satellite missions such as the Advanced Composition Explorer (ACE), the Geostationary Operational Environmental Satellites (GOES), and the Radiation Belt Storm Probes (RBSP). Furthermore, TDAS is the primary data analysis platform of the Japanese satellite mission Energization and Radiation in Geospace (ERG), which will explore the dynamics of the radiation belts in the Earth's inner magnetosphere when it is launched in 2015[11]. Therefore, TDAS is an important tool for comparing space- and ground-based data.

Table 1 shows the data that is available in the latest version of UDAS (v3.00.2 as of 26 August, 2013), and their load routines. The package includes many routines to load data obtained by solar telescopes, solar/planetary radio telescopes, atmospheric and ionospheric radars, magnetometers, etc. There are some helpful tutorials that use example screenshots, example routines, and movies to demonstrate UDAS routines. These tutorials can be found on the IUGONET website (http://www.iugonet.org/en/software/loadprocedures.html). It should be noted that our databases are distributed across the members of IUGONET and each of the data file formats are different, although TDAS includes many useful routines to handle Common Data Format (CDF; http://cdf.gsfc.nasa.gov/), which is a self-describing data file format developed by the National Aeronautics and Space Administration/Goddard Space Flight Center (NASA/GSFC). The files are not converted to any specified format but can be read by load routines that are individually developed for each data set. We have developed these routines in collaboration with the ERG Science Center.

Table 1 Data and load routines when using UDAS v3.00.2, the latest version of UDAS as of 26 August 2013

No.	Data	Load routines
1	Solar images obtained by the SMART telescope	iug_load_smart
2	Solar HF radio spectrum	iug_load_iprt
3	Jupiter's/solar wide band spectral data in HF-band	iug_load_hf_tohokuu
4	Surface meteorology data taken by the automatic weather station	iug_load_aws_rish
5	Boundary layer radar data	iug_load_blr_rish
6	L-band Lower Troposphere data	iug_load_ltr_rish
7	Equatorial Atmosphere Radar (EAR) data	iug_load_ear
8	Middle Upper atmosphere radar (MU radar) data	iug_load_mu
9	Meteor radar data	iug_load_meteor_rish
10	Medium Frequency (MF) radar data	iug_load_mf_rish
11	Wind Profiler radar data	iug_load_wpr_rish
12	Ionosonde data	iug_load_ionosonde_rish
13	Radiosonde data	iug_load_radiosonde_rish
14	SuperDARN radar data	iug_load_sdfit
15	EISCAT radar data	iug_load_eiscat
16	EISCAT radar data (ion velocity and electric field vectors)	iug_load_eiscat_vief
17	Imaging Riometer data	iug_load_irio_nipr
18	Low Frequency Radio Transmitter Observation data	iug_load_lfrto
19	Geomagnetic indices (AE, Dst, ASY/SYM) and Geomagnetic field data at the WDC Observatories	iug_load_gmag_wdc
20	Geomagnetic field data at Syowa and Iceland stations	iug_load_gmag_nipr
21	210° Magnetic Meridian magnetometer data	iug_load_gmag_mm210
22	MAGDAS magnetometer data	iug_load_gmag_serc
23	Induction magnetometer data from STEL	iug_load_gmag_stel_induction
24	Induction magnetometer data from NIPR	iug_load_gmag_nipr_induction
25	Kyushu GCM simulation data	iug_load_kyushugcm

UDAS also includes a statistical analysis package, which was not included in the original TDAS library[12]. We require functions that objectively judge the analysis results (for example, time-series data trends and cross-correlation between two different datasets) to investigate long-term variations in the upper atmosphere using various kinds of data. The statistical analysis package contains functions that calculate the slope of a linear regression, the cross-correlation coefficient (and non-correlation test), the coherence and phase for each frequency component, the difference in the mean values of two data distributions, the spectral density and dominant frequency for transient phenomena using the S (Stockwell) transform, etc. The data is linearly interpolated before any statistical analysis, to handle missing data and non-constant sampling intervals.

This software may also be useful for researchers who do not typically use IDL for data analysis, because it allows users to download data files via the internet without any information of the file location, and, if necessary, convert them to a general format such as ASCII. Non-IDL users can therefore use this software to download and convert data files, and then analyze the data using their preferred applications. We have developed TDAS to be executable on an IDL Virtual Machine (IDL-VM) to accommodate users who do not own an IDL license (explained in detail in Section 3).

We will now briefly describe the IUGONET Metadata Database (IUGONET-MDB). The IUGONET-MDB enables cross-searching of observational data distributed across the members of IUGONET. The search results allow users to access the required data. Figure 2 shows a snapshot of the IUGONET-MDB search page (http://search.iugonet.org/iugonet/). It is possible for users to search data by specifying keywords, the date and time, or location in geographic coordinates (or heliographic coordinates for solar data). The metadata format used for the IUGONET-MDB is based on the Space Physics Archive Search and Extract (SPASE) data model/metadata format, which we have slightly modified for the IUGONET's upper atmospheric data[13-14]. We have used DSpace (http://www.dspace.org/) as the IUGONET-MDB platform. DSpace is an open-source repository software used mainly for academic information repositories.

Figure 2 Snapshot of the IUGONET-MDB search page (http://search.iugonet.org/iugonet/).

3 New and unique developments by IUGONET

The new and unique developments of the IUGONET project are: (i) TDAS was successfully developed to run on an IDL-VM; (ii) IDL routines were developed to make metadata from the IUGONET-MDB accessible; and (iii) three-dimensional (3-D) data calculated using numerical simulations were converted and stored for better availability.

Item (i) was necessary because a commercial license is needed to use all the required functions of the IDL software. To allow users who have no IDL license to use TDAS, we collaborated with the THEMIS Science Support Team to compile an executable file that can run on an IDL-VM. The IDL-VM is a freely-distributed cross-platform utility for running complied IDL code. The command line interface is not available on the IDL-VM, but the GUI of TDAS is. This executable file is available as a free download on the THEMIS Software website (http://themis.ssl.berkeley.edu/software.shtml). It should be noted that users may first need to download and install the full version of IDL (which includes the IDL-VM) from the Exelis web site (http://www.exelisvis.com). Then, the executable file can be run on the IDL-VM without a paid IDL license.

The routines in item (ii) are used to extract data information from the metadata database. The IUGONET-MDB supports the OpenSearch interface (http://www.opensearch.org/Home), which allows users to search the database via the internet. The UDAS routines can query the MDB, receive the search results as an Extensible Markup Language (XML) file, parse the XML file, and extract the required information. This function is implemented in a few UDAS load routines to dynamically obtain location information for data files (i.e., URL), and is hard-coded in the original load routines of TDAS. This is efficient, because the metadata in the MDB can be updated without any modifications to the load routines.

Item (iii) was required because it is important to compare observed and simulated data when studying the upper atmosphere. In particular, global 3-D simulations are essential tools for investigating the mechanisms of global phenomena such as global warming. We calculated the 3-D simulation data using the General Circulation Model developed by Kyushu University (Kyushu GCM)[15]. We have archived the data as CDF files, so that they can be loaded and displayed using TDAS. To avoid long download times and out of memory errors, each physical parameter such as temperature, pressure, and the zonal, meridional, and vertical components of wind velocity, has been stored in an individual file. This results in an approximate total file size of 100 MB for a one day period. We discuss an example of the GCM simulation data in Section 4.

4 Examples of upper atmospheric data displayed by TDAS using the UDAS plug-in

As an example, Figure 3 shows five time series plots of aurora and satellite data. The figure contains a plot of solar wind dynamic pressure (Figure 3a), and a plot of the north-south component of an interplanetary magnetic field (IMF-Bz) in a GSM coordinate system (Figure 3b). Both sets of data were obtained from satellites. Also displayed are the ionospheric electron density (Figure 3c) and temperature (Figure 3d) from the European Incoherent SCATter Svalbard radar (EISCAT Svalbard radar: ESR)[16] at Longyearbyen, Norway (78.2°N, 16.0°E), and a keogram (Figure 3e) of the north-south geomagnetic meridian from an all-sky image with a green color filter at Longyearbyen, Norway[17] during the period 0600–0800 UT (about 09 and 11 magnetic local time) on 24 January, 2012. The solar wind parameters were provided by the OMNI database at NASA/GSFC's Space Physics Data Facility[18]. Remarkably, such data can be easily plotted with just a few basic commands in the command line interface of TDAS using the UDAS plug-in. For example, “timespan” sets the time interval, “iug_load_xxx” (where xxx indicates a dataset name such as iug_load_eiscat, as shown in Table 1) loads data, and “tplot” plots the loaded time series data.

A sharp increase in the solar wind dynamic pressure, which corresponds to an interplanetary shock, can be seen at 0620 UT (Figure 3a). At almost the same time, the ionospheric electron density at an altitude of 200–300 km, the ionospheric temperature above 200 km, and the auroral luminosity show responses to the dynamic pressure increase. We can deduce from this figure that the interplanetary shock caused the Earth’s magnetosphere to compress, which caused energetic electrons to precipitate from space and enter the dayside polar ionosphere. An auroral emission was thus generated by the electron precipitation. In this manner, TDAS can plot various kinds of upper atmospheric data (including satellite data) on identical time axes, which is useful when examining correlations and causal relationships.

Figure 4 compares upper atmospheric data at the auroral latitudes with data from the equator. Figures 4a and b show the auroral electrojet (AE) and longitudinally symmetric (SYM-H) geomagnetic indices from the World Data Center (WDC) for Geomagnetism, Kyoto[19-20]. These correspond to the activities of an aurora and geomagnetic storm. The SYM-H index decreased to about −100 nT on the 18 February 2005, and then gradually increased and recovered on 23 February. A common geomagnetic storm is considered to have occurred during this period. Substorm events occurred intermittently with the AE index sometimes greater than 1 000 nT, indicating a lot of auroral activity. Figures 4c and 4d display zonal and meridional winds in the lower thermosphere and mesosphere, estimated from MF radar observations at the Syowa Station (69.0°S, 39.6°E; 66.6°S geomagnetic latitude), Antarctica[21]. When the recovery phase of the geomagnetic storm began, these winds clearly changed above 84 km. The zonal wind changed from eastward to westward, and the westward wind was maintained for 3 d (Figure 4c). The meridional wind plot shows a positive variation with an amplitude of 20–30 $m \cdot s^{-1}$, which persisted for 1 d. As shown in Figure 4e, the diurnal tide in the zonal component (estimated from the meteor wind radar at Koto Tabang (0.2°S, 100.3°E), Indonesia[22]) was enhanced above 88 km, which corresponds to the wind variation at the auroral latitude. Moreover, the semi-diurnal tide in the meridional component was also enhanced above 84 km during this period (Figure 4f). The enhancement of the westward zonal wind observed at Syowa Station during the recovery phase is consistent with a previous numerical simulation study, in which the equatorward wind driven by auroral heating was directed westward at the mid-latitudes due to angular momentum[23-24].

Figure 5 shows temperature and wind variations between 0–105 km (calculated by the Kyushu GCM) and wind variations between 70–105 km (observed with the Nippon/Norway Tromsø Meteor Radar (NTMR) at Tromsø (69.6°N, 19.2°E), Norway[25]) during a major stratospheric sudden warming (SSW) in January 2009. For comparison, we have displayed the daily average of the simulated data at the 69.6°N, 19.2°E grid point, and the observed NTMR data over a day. Because the SSW in January 2009 was the strongest and most prolonged on record[26], some studies have been conducted on the influence of this event on the upper atmosphere[26-27]. A major SSW is characterized by a rapid increase in temperature and a reversal of winds from westerly to easterly at 10 hPa (~30 km) at 60°N. The criteria for a major SSW were fulfilled on 24 January. The GCM data show typical features of SSW, namely a rapid increase in temperature and a reversal of zonal winds in the stratosphere from an eastward to a westward direction (at 20–50 km in Figures 5a and 5b). The zonal wind reversal in the mesosphere (at 50–90 km) seems to precede that in the stratosphere by a few days (Figure 5b). This is clearly seen at 80–100 km in the NTMR data (Figure 5c), as reported by Kurihara et al.[27]. The downward propagation of the zonal wind reversal observed in the mesosphere and stratosphere gives important clues for understanding the generation mechanism of the major SSW.

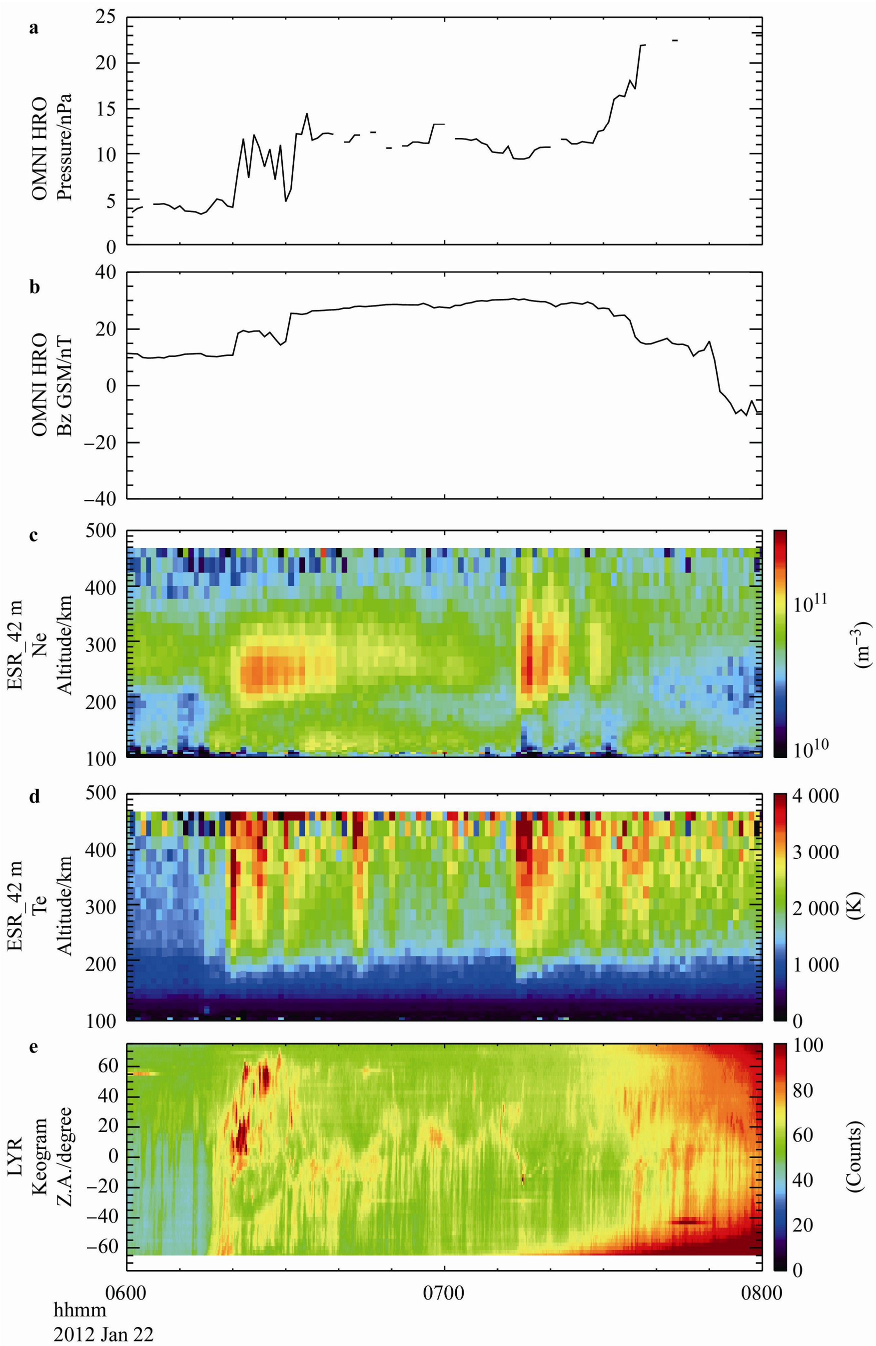

Figure 3 Examples of time series plots using TDAS with the UDAS plug-in. Solar wind dynamic pressure (**a**) and IMF-Bz in the GSM coordinate system from the OMNI database (**b**), ionospheric electron density (**c**) and electron temperature from the EISCAT Svalbard radar (**d**), and N-S keogram of auroral luminosity from an all-sky imager with a green color filter (**e**) at Longyearbyen, Norway between 0600 and 0800 UT on 22 January, 2012.

Figure 6 shows screenshots of the GUI windows of TDAS using UDAS. A new tab labeled "IUGONET Data" appears in the Load Data window, in addition to the original TDAS tabs. In the IUGONET Data tab, various types of instruments can be selected from a drop-down list labeled “Instrument Type”, as shown in Figure 6a. Users can easily load and plot data by using the mouse to select the time interval, site name, and a few other parameters. When loading IUGONET data, the data use policy for each of the instrument data sets is displayed in a pop-up window. This is a new function added to TDAS by IUGONET. The data use policy varies with each instrument and location. Figure 6b shows an example of the data use policy of the EISCAT radar data. The pop-up requires the users to read and acknowledge the policy, and click the “OK” button before they can load the data. Once the users have agreed to the data use policy of a certain instrument, the policy of that instrument is not displayed again.

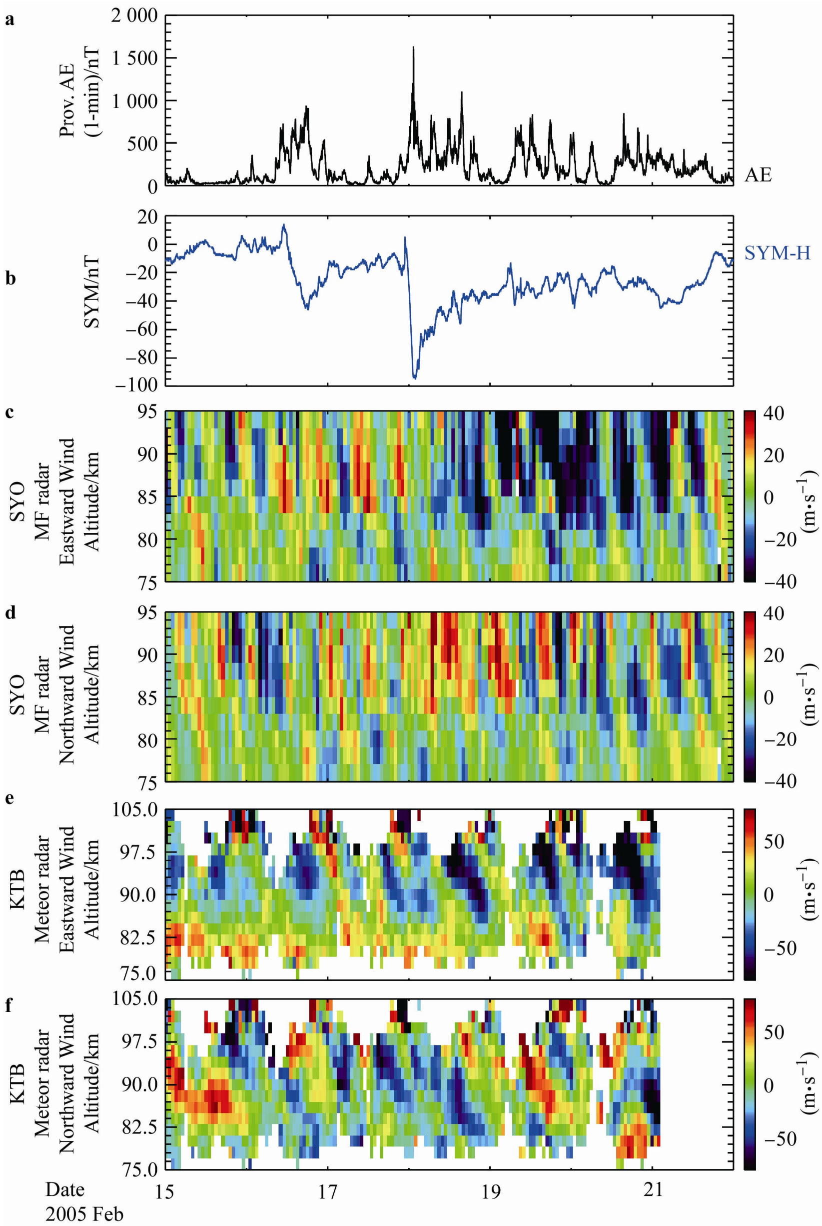

Figure 4 Provisional AE (**a**) and SYM-H indices from the WDC for Geomagnetism, Kyoto (**b**), zonal (**c**) and meridional (**d**) wind from the MF radar at Syowa Station, Antarctica, and zonal (**e**) and meridional (**f**) wind from the meteor radar at Kototaban, Indonesia, from RISH, Kyoto, 13–24 February 2005.

5 Summary and conclusions

IUGONET has developed a metadata database system (IUGONET-MDB) and data analysis software (UDAS) to search, retrieve, visualize, and analyze ground-based observational data of the upper atmosphere that are distributed across the members of IUGONET. This system and software can play an important role in the promotion of interdisciplinary studies, which can lead to a more comprehensive understanding of the Arctic and Antarctic upper atmospheres. The primary focus of this paper is UDAS, a plug-in for TDAS, which was developed to visualize and analyze satellite- and ground-based data. We have demonstrated that when UDAS is integrated into TDAS, we can easily load and plot the ground-based observational data provided by members of IUGONET, as well as satellite and simulation data. Furthermore, we have developed TDAS to run and operate on an IDL-VM, which enables users without an IDL license to use TDAS. Therefore, this analysis software has the potential to be accepted as a common tool by the solar-terrestrial physics community.

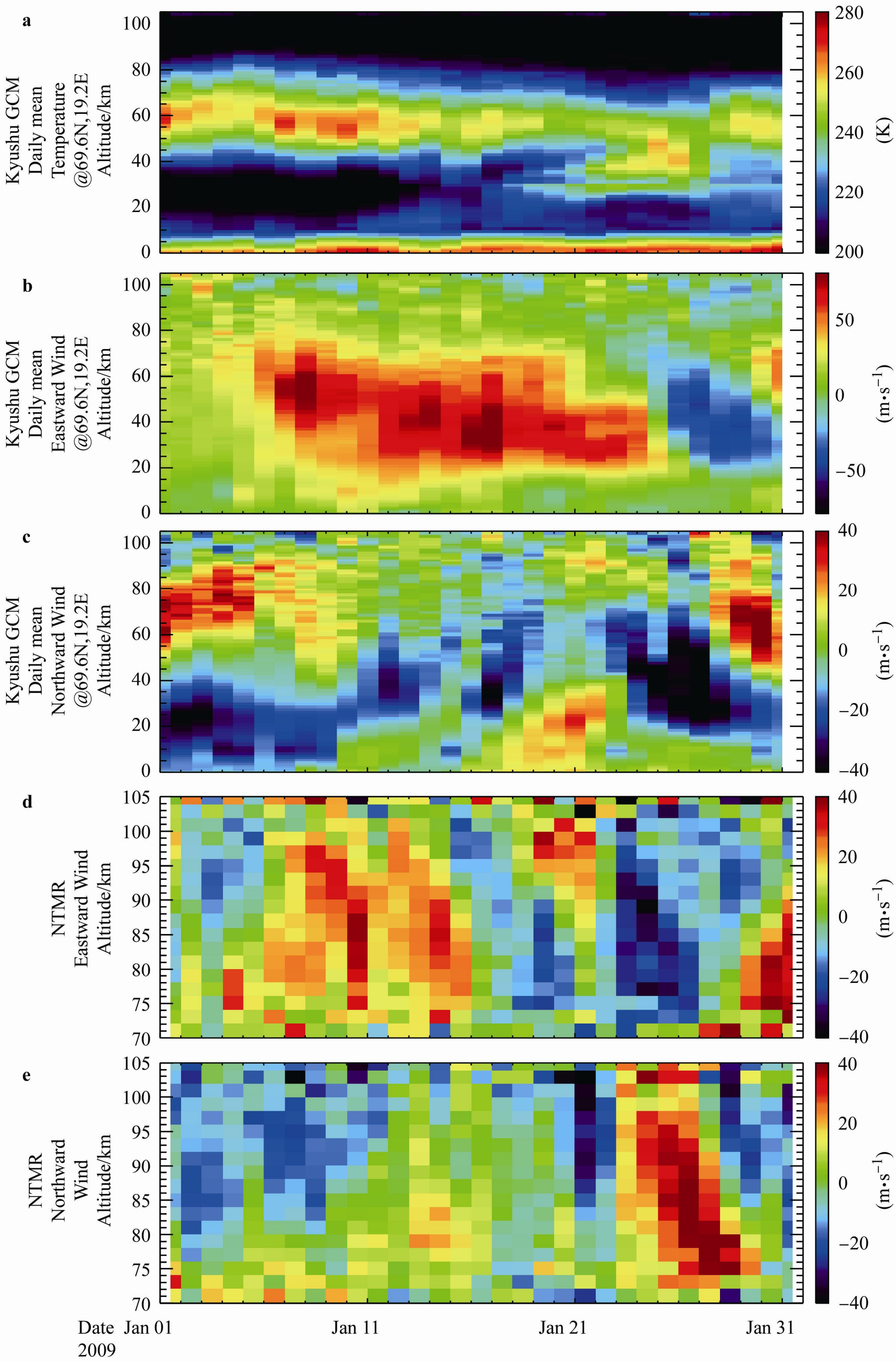

Figure 5 Examples of comparisons between simulations and observation data. Temperature (**a**), zonal wind (**b**), and meridional wind (**c**) at 69.6°N, 19.2°E, as simulated by the Kyushu GCM, and zonal (**d**) and meridional wind (**e**) as observed by the NTMR at Tromsø (69.6°N, 19.2°E, Norway, in January 2009.

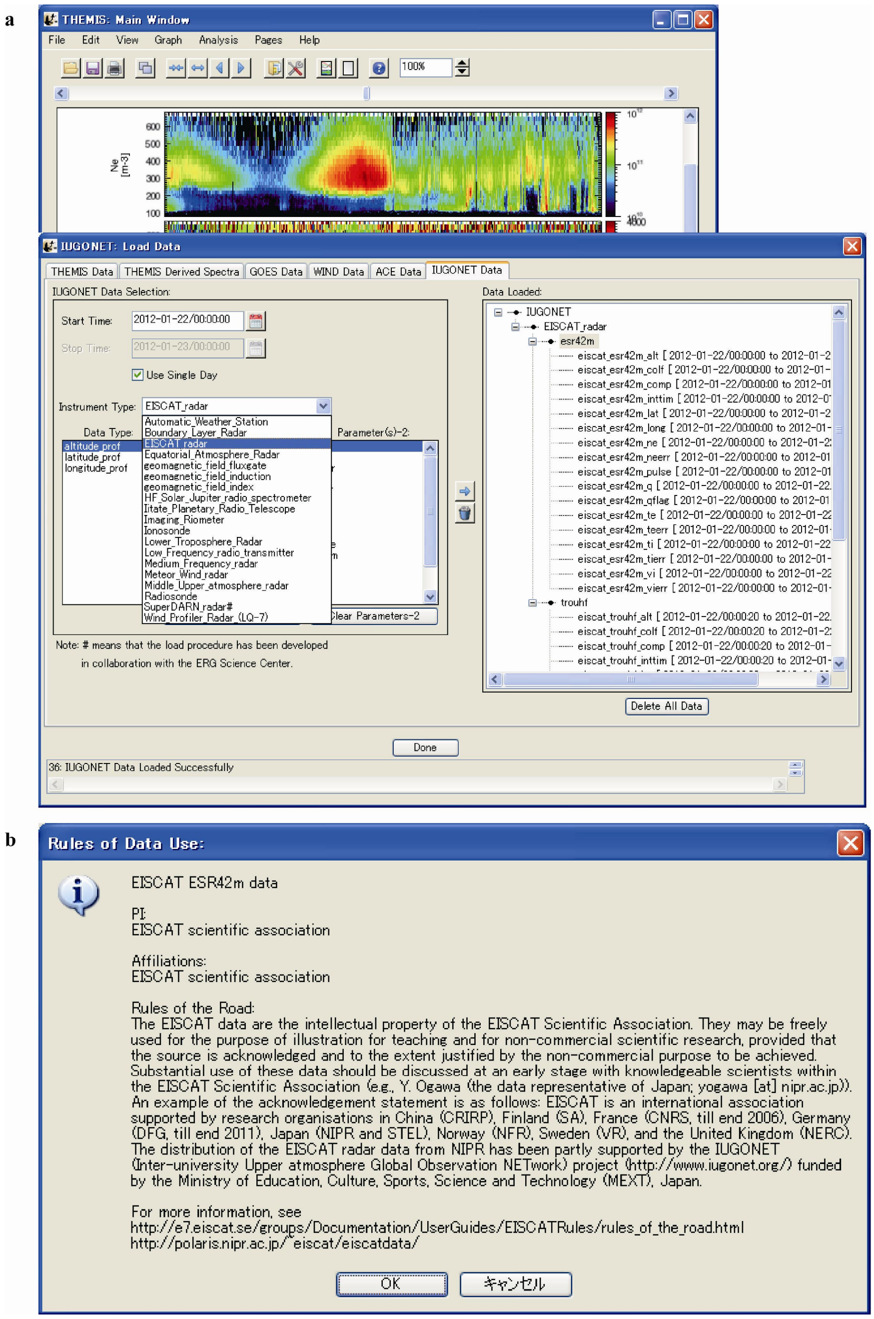

Figure 6 Screenshot of the TDAS GUI when using the UDAS plug-in (**a**). The display of the data use policy for the EISCAT radar data (**b**).

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