Influence of Solar Activity Cycles on Earth's Climate

Task 2 – Identification of Relevant Data

WP202 – Possible Interactions and Modifications

N. Marsh, H. Svensmark, and F. Christiansen
Danish National Space Center

June 14, 2005

Contents

INTRODUCTION 3

DATA SETS – DESCRIPTIONS 6

MAGNETOSPHERE/IONOSPHERE 6

OZONE 8

GALACTIC COSMIC RAYS 9

TEMPERATURES 11

EARTH RADIATION BUDGET 13

REANALYSIS DATA 14

BERLIN STRATOSPHERIC DATA SERIES 15

CLOUD DATA 16

AEROSOLS 18

WATER VAPOR 20

CONCLUSIONS 22

REFERENCES 23

DATA SETS – TABLES OF SOURCES AND AVAILABILITY 25

Introduction

In the literature survey in Task 1 of the ISAC study a number of different mechanisms were identified through which solar activity can influence climate on Earth. In this report we describe various observations that may help to identify the ways solar activity interacts with, and modifies, Earth's climate. Solar activity affects various parameters that have the potential to influence Earth's environment. Total Solar Irradiance and its spectral components, galactic cosmic rays, Magnetosphere and Ionosphere responses to the solar wind all need to be considered. The response of the lower denser layers of the atmosphere to these inputs may determine the climate we feel at the surface. To explore this possibility it is necessary to compare these solar dependent input parameters with the response, if any, from various atmospheric processes. This includes constituents such as ozone and aerosols that exist in relatively small amounts but play potentially important roles in the general dynamics of the atmosphere, together with quantities that are both an integral part of Earth's climate and play a central role in modifying it, such as clouds and water vapour.

The data sets under consideration need to fulfil some objectives concerning both spatial and temporal coverage. Since the climate response may vary between different geographic zones, high latitude vs. low latitude, oceans vs. land, it is important that the data have a reasonable geographic resolution. Satellite data meet this criterion perfectly, typically covering the globe uniformly, whereas ground based measurements are often unevenly spread. However, the availability of satellite data only covers a relatively short time span and there can be difficulties with the inter-calibration between satellites to generate spatially and temporally homogeneous dataset. Going back more than 2 solar cycles will in most cases mean being restricted to ground based measurements. The many different time scales in the Sun's activity also means that the temporal resolution of the data is important. For some parts of this study monthly or even yearly averages will suffice, whereas for other parts hourly measurements may be important.

When performing a correlation study between solar activity, possible modes of interaction from different kinds of solar output (e.g. solar irradiance, parts of the solar spectrum, or the solar wind) and various climate parameters, it is important to consider the mechanisms thought to be responsible for the interaction. Accidental correlations between the observations under investigation are bound to occur, where correlations have stemmed from a common cause, i.e., solar activity cycles, but in themselves are not related through cause and effect. For some of the quantities under investigation, the energy input into the Earth's climate system is far too small to have a direct effect. In the table below we give some numbers for the energy input directly into Earth's environment, including the total solar irradiance, the solar wind, galactic cosmic rays, and precipitating energetic particles within the magnetosphere. Variations in these quantities are even smaller over a solar cycle. Compared to the irradiance from the Sun, the other quantities are miniscule. In addition variations in the direct heating from solar irradiance over a solar cycle, e.g., 0.1% for total solar irradiance, is believed to be too small to have had a significant impact on climate. Therefore, for these quantities to play a role in climate change, some mechanism for magnifying their effect must be in place. The UV component of solar irradiance can amplify the direct solar heating effect through its interaction with stratospheric ozone and the resulting dynamical response of the atmospheric layers below. For galactic

cosmic rays, a plausible mechanism has been suggested involving aerosols and clouds, which have a strong impact on the radiation budget of the Earth. However, no such amplifying mechanisms currently exist for the direct input of the solar wind or precipitating energetic particles. A correlation study involving these latter components is much more difficult to pursue, since it is less obvious which of the many possible correlations should be chosen for closer examination. Close attention should therefore be paid to the characteristics of the quantities studied that make them different from other possible influences. For example, precipitating particles have a clear signature both geographically, concentrating mainly at auroral latitudes, and temporally, varying by orders of magnitude between geomagnetic quiet times and magnetic storms/substorms.

Parameter	No. Density (cm^{-3})	Energy/Particle (eV)	Energy Density ($eVcm^{-3}$)	Velocity (ms^{-1})	Energy Flux (Wm^{-2})
Solar Irradiance	-	-	2.8×10^{7}	3×10^{8}	1360
Solar Wind	6	10^{3}	6×10^{3}	4.5×10^{5}	4.4×10^{-4}
Galactic Cosmic Rays	5×10^{-10}	10^{8}	0.5	3×10^{8}	2.4×10^{-5}
Precipitating particles		10^{4}			6×10^{-5}

Table 1: Energy input directly from the solar irradiance and different types of energetic particles impinging on the Earth. The solar irradiance, solar wind and galactic cosmic ray quantities are estimates at the top of the atmosphere outside the magnetosphere. The precipitating particles are those measured within the magnetosphere and have been estimated from the Total Hemispheric Power Input. The energy input from cosmic rays is nearly isotropic, whereas the solar irradiance impinges only on the dayside. The solar wind impinges on the much larger area of the magnetosphere, compared to the surface of the Earth, but only in the region of open field lines (the cusp) can the solar wind penetrate directly down to the uppermost layers of the atmosphere.

In the next section we describe the data sets that we propose to include in the remaining tasks of the ISAC study. The subject of this work package is Possible Interactions and Modifications, i.e., the link between the direct solar output and the actual observations of the Earth's climate. Some of these links, clouds for instance are themselves part of the climate. Some overlap with WP203 – Earth's Climate – is therefore unavoidable. Here we give a short introduction to the various data sets and the reasons for including them.

- External to the Earth we have the galactic cosmic rays. These are clearly modified by solar activity through the interplanetary magnetic fields and have been suggested to play an important part in the process of cloud creation through ionisation of the atmosphere. The cosmic rays are observed through a world wide net of neutron monitors that has delivered neutron counts since the International Geophysical Year (IGY) 1957/1958. Also included in our data sets are muon counts from a single station in Adelaide; the muons are particularly important for the ionisation in the lower parts of the atmosphere. Finally, a model based data set of ionisation throughout the whole atmosphere below 35km is included.
- Closer to the Earth, but normally not considered to be part of the climate system, lies the magnetosphere. The magnetosphere is strongly driven by the solar wind and thus very susceptible to solar activity cycles. The dynamics of

the magnetosphere is not as easily observable as many of the processes closer to the Earth's surface. Observations of the constituent plasma are normally only possible through in-situ measurements, i.e., by spacecraft such as the DMSP satellites. We have included ion drift measurements from these satellites as well as the total hemispheric power input from precipitating particles.

- On the boundary between the magnetosphere and the denser parts of the atmosphere lies the ionosphere. The physics of the ionosphere is mainly observed by ionosondes from a world wide net of stations producing regular data also since the IGY 1957/58.
- For climate studies the most obvious quantity to investigate is the temperature of the atmosphere. The very subject of climate change is to some extent equal to the study of temperature change as this parameter reflects the response of the Earth system to a whole host of complex processes. We have included temperature data sets from satellite, radiosondes and surface measurements.
- Observations of meteorological parameters have been collected from an extensive network of stations for a number of years. These have been integrated into a physical model (similar to a weather prediction model) to give a good indication of the general state of the dense layers of the atmosphere, i.e., troposphere and stratosphere. This data, which is referred to as re-analysis data, will also be used as it includes many atmospheric parameters that are relevant for the study.
- There are many parts of the Earth's climate that may be considered not just as integral components of the climate, but also as direct modifiers of the climate itself. A prime example is clouds, which are clear manifestations of the Earth system but also, through their influence on the radiation budget, are active players in modifying the climate. Several data sets of satellite observations of clouds have been included.
- The Earth's radiation budget is of utmost importance when considering climate change. The balance between the incoming radiation from the Sun and the outgoing thermal and reflected radiation is what ultimately determines the temperature on Earth. Data from the Earth Radiation Budget Experiment (ERBE) have been included.
- There are also constituents of the atmosphere that play a more important role in the amplification of a solar signal than might be expected given their relatively small abundance. We have included two data sets of ozone measurements and two sets of aerosol observations.
- Finally, we have included some data on water vapour and a meteorological data set specifically describing the state of the stratosphere.

The subject of possible interactions and modifications opens up the field for a vast number of observations. The study of climate change is a relatively young field and as such many questions are still open and under investigation. We have included the data sets that we have found to be most fundamental according to the literature survey presented in Task 1 of the ISAC study. The data sets presented here will be used in the following Tasks, but are not necessarily exhaustive. As the study evolves additional data may be considered useful and if so will be included accordingly.

Data Sets – Descriptions

Magnetosphere/Ionosphere

The dynamics of the magnetosphere is driven by the solar wind, and thus is strongly correlated with solar activity. The physical state of the ionosphere is determined predominantly by solar illumination and precipitating particles, so it too reflects variations in solar activity, but it is also sensitive to changes in the atmosphere below. For there to be a significant effect on the climate of the lower atmosphere a strong amplifying mechanism is required which couples the Solar wind-magnetosphere-ionosphere-lower atmosphere. This coupling could take various forms, e.g., through precipitating particles or through magnetospheric current systems closing in the ionosphere thereby depositing Joule heating to the upper layers of the atmosphere. While precipitating particles fluctuate by several orders of magnitude between quiet times and magnetic storms/substorms, magnetospheric current systems are more persistent existing even during very quiet periods. However, the energies involved are extremely small, thus a currently unknown amplifying mechanism is required if the Magnetosphere – Ionosphere system is to have a significant impact on the climate of the lower atmosphere. To explore the possibility for such a mechanism, data obtained from a number of magnetosphere/ionosphere satellite based instruments will be used, most notably those onboard the Defense Meteorological Satellite Program (DMSP) for which data are available from 1983. Below is a description of the relevant parameters that will be used in this study.

DMSP/SSIES

The SSIES (Special Sensor - Ions, Electrons, and Scintillation) package on the DMSP satellites consists of four instruments: a Retarding Potential Analyzer, a Drift Meter, a Langmuir probe, and a Scintillation Meter. Together these four instruments provide an in-situ measurement of the plasma velocity, temperature, atomic composition, electrostatic potential, and density at an altitude of 800 km. The data are available continuously from 1995 to the present for single orbits with output every 4 seconds from http://cindispace.utdallas.edu/DMSP/. Offline data is available back to 1987. Figure 1 shows an example of the measurement available from a single orbit of the satellite DMSP-F12 in July 2000.

Total Power Input (TPI)

The total hemispheric power input estimates the energy deposited by precipitating particles over an entire hemisphere, but mainly concentrated at auroral latitudes. This parameter is derived from NOAA/TIROS and DMSP satellite measurements of high latitude precipitating energy flux. This energy flux is carried by ions and electrons that are observed in the energy range 300 eV-20 keV on the NOAA/TIROS platform, and 460 eV-30 keV on the DMSP platform. The energy flux observations made during a single pass over the polar regions (above about 45 degrees of magnetic latitude) are used to estimate the total precipitating power input to a single hemisphere at that time. The TPI during the year 2000 is shown in Figure 2. Notice the large spikes that coincide with periods of high solar activity. Total Power Input is available during the period 1983-2001 as a single hemispheric pass for each satellite, i.e., with intervals of about 50 minutes. The data can be obtained from http://spidr.ngdc.noaa.gov/spidr/dataset.do. A description of the derivation of this parameter can be found in Foster et al. (1986) and Fuller-Rowell and Evans (1987).

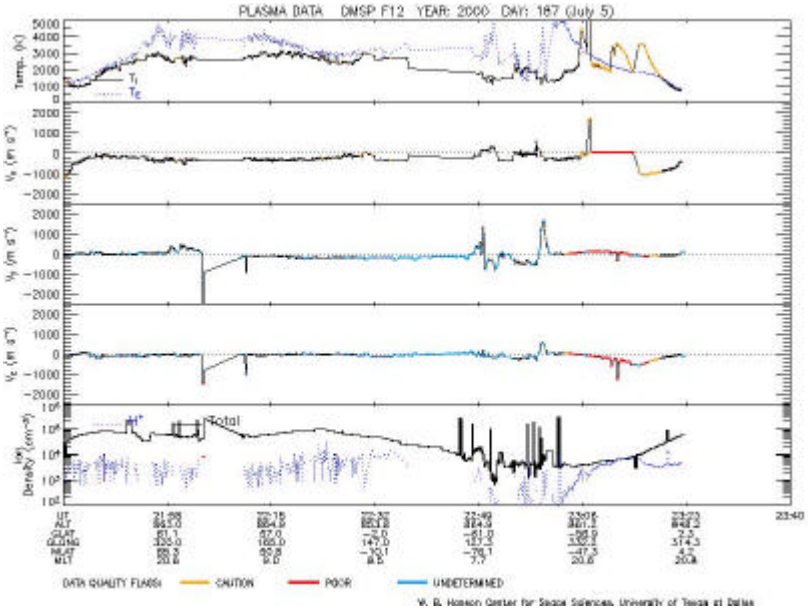

Figure 1: Plasma data from the SSIES package on DMSP F12 for a single orbit July 5, 2000. From http://cindispace.utdallas.edu/DMSP/.

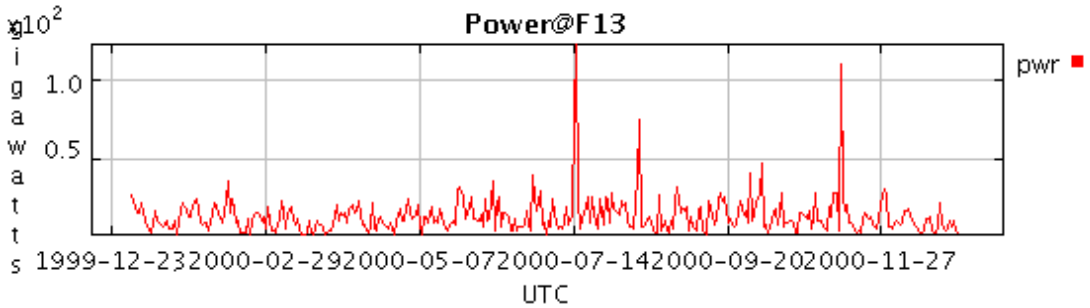

Figure 2: Total hemispheric power index from DMSP-F13 for 2000. From http://spidr.ngdc.noaa.gov/spidr/dataset.do.

Ionograms

The dynamics of the ionosphere is most easily observed from ground with ionosondes producing ionograms. Ionograms are recorded tracings of reflected high frequency radio pulses. A unique relationship exists between the sounding frequency and the ionisation densities of the reflecting medium. The resulting echoes form characteristic patterns that comprise the ionogram. Characteristic values of virtual heights (designated h'E, h'F, and h'F2, etc.) and critical frequencies (designated foE, foF1, and foF2, etc.) of each layer are scaled from these ionograms. A world wide network of more than 200 ionosonde stations exists with measurements available from 1942-present and output every 15 minutes or 1 hour. Only a few stations were operational in the early years, but global coverage was possible following the IGY in 1957/58. The data are available from http://spidr.ngdc.noaa.gov/spidr/dataset.do. Observations of ionospheric layer heights from Sondrestrom for 2000 are shown in Figure 3.

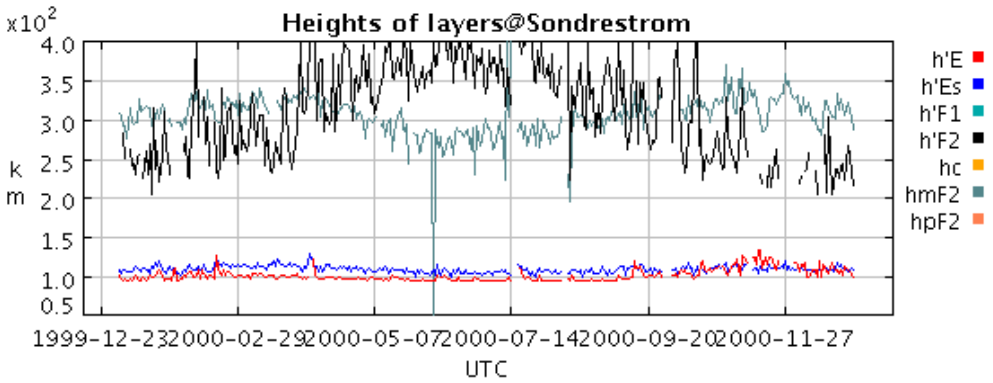

Figure 3: Ionospheric layer heights from Sondrestrom for 2000. From http://spidr.ngdc.noaa.gov/spidr/dataset.do

Ozone

Ozone plays a leading role in the UV-radiation budget of the Earth. Model simulations have suggested that one route by which solar activity can influence Earth's climate is via changes in UV irradiance and the resulting response in photolysis reactions in the stratosphere, e.g., ozone. While Total Solar Irradiance varies by only 0.1% over a solar cycle, UV irradiance at wavelengths absorbed in the stratosphere can vary by as much as 8%. Increased UV irradiance during solar maximum conditions leads to an additional ozone production of up to 3% in the upper stratosphere, which enhances heating rates in the stratosphere and above. By modifying the meridional temperature gradient this heating can alter the propagation of planetary and smaller scale waves driving global circulation. This not only has the effect of amplifying a relatively weak solar irradiance signal, but also provides a mechanism for coupling energy exchanges in the stratosphere with the large-scale dynamics of the troposphere. To further explore this possibility a comprehensive data set describing the distribution of ozone throughout the atmosphere is required.

There are a number of ozone data providers. Here we include NASA/GSFC's Total Ozone Mapping Spectrometer (TOMS) and ESA's Global Ozone Monitoring Experiment, both providing daily global ozone levels in Dobson units. TOMS provide global ozone levels from 3 satellites, Earth Probe, Meteor 3, and Nimbus 7, giving a data time span from November 1978 to the present (with a gap between December 1994 – July 1996). GOME started operating in 1995, and currently data are available up to 2003. Both data sets are daily and gridded at 1.25 x 1 degree - also available are monthly means as well as zonal averages. Furthermore, GOME also delivers information on other atmospheric trace gases. Figure 4 shows an example of the two data sets from Jan 1, 2003. The data are available from http://toms.gsfc.nasa.gov/ozone/ozone_v8.html and http://www-iup.physik.uni-bremen.de/gome/wfdoas/. The GOME data set is available at DNSC. A comparison between the TOMS and GOME measurements and ground observations is given in Bramstedt et al. (2003).

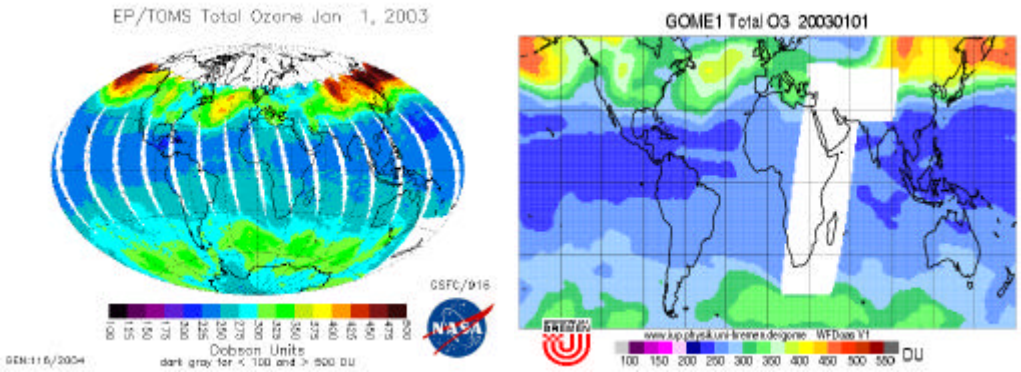

Figure 4: The ozone levels from TOMS and GOME for Jan 1, 2003. From http://toms.gsfc.nasa.gov/ozone/ozone_v8.html and http://www-iup.physik.uni-bremen.de/gome/wfdoas/.

Galactic Cosmic Rays

It is well established that cosmic rays are strongly modulated by the magnetic shielding of the solar wind, and therefore reflect past solar activity levels. However, they are also the dominant source of ionisation in the atmosphere below 35 km. Observations suggest that cosmic rays are correlated with cloud properties, and that low cloud amount varies by 1.5-2% over a solar cycle. Clouds contribute a net cooling of ~28 W/m^2 so even a small change in cloud properties could have a potentially large impact on the Earth's radiation budget. A mechanism linking cosmic rays and clouds is thought to involve the role of atmospheric ionisation in the nucleation and subsequent growth of aerosols that ultimately act as cloud condensation nuclei. The possible role of cosmic ray induced ionisation, as a modulator of Earth's climate, is currently an active research topic. Data describing cosmic ray ionisation of the atmosphere will be required to explore this potential link with climate, and to enable a comparison with other solar related mechanisms that have been proposed.

Neutron monitors

There exists a world wide net of cosmic ray stations, mostly neutron monitors. A comprehensive data set is available at the WDC-C2 at www.env.sci.ibaraki.ac.jp/ftp/pub/WDCCR/. These data sets span the period 1953-2004. Only a few stations were in operation during the early years, but this increased rapidly with more than 40 stations in operation by the time of the IGY 1957/58. The data are generally reported as hourly neutron counts. A full description of the data set and coverage can be found at the WDC-C2 homepage.

An example of a cosmic ray station delivering real time data is the Moscow Neutron Monitor. The monthly cosmic ray count from 1958 to present is shown in Figure 5. The solar cycle modulation is evident.

Muon monitors

Cosmic ray-generated muons play a key role in the ionisation of the atmosphere, particularly in the lower troposphere below ~6km. A muon detector is operated at the Adelaide University: http://www.physics.adelaide.edu.au/astrophysics/index.html. Hourly muon counts from this detector are available at DNSC for the period 1998-

2001. 15-minute data for the period June 2003-present are available from Adelaide University: http://www.physics.adelaide.edu.au/astrophysics/muon/data/. An example of muon counts for a 30-day period is shown in Figure 6. Notice the dip around May 15; this was a period of intense solar activity with a Coronal Mass Ejection (CME) passing close to the Earth, the resulting response seen in the cosmic rays is known as a Forbush decrease.

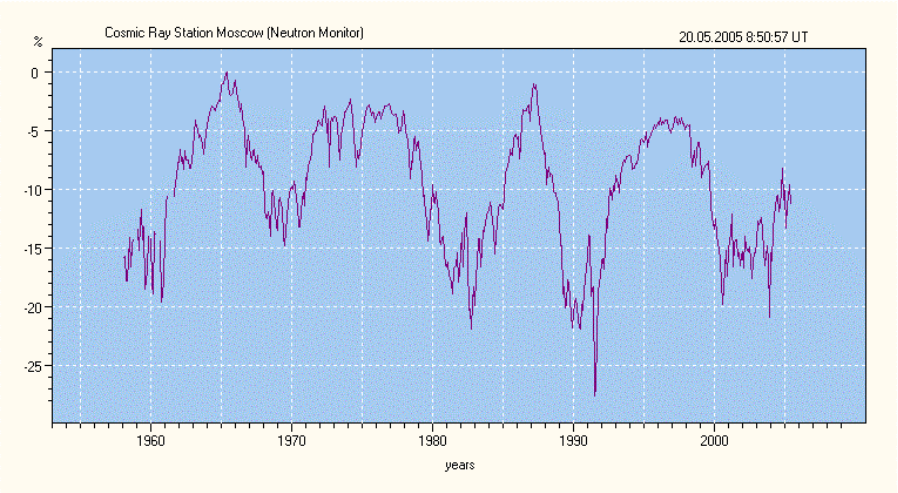

Figure 5: Monthly neutron counts at the Moscow Cosmic Ray station 1958-present. Figure generated at http://helios.izmiran.rssi.ru/cosray/months.htm.

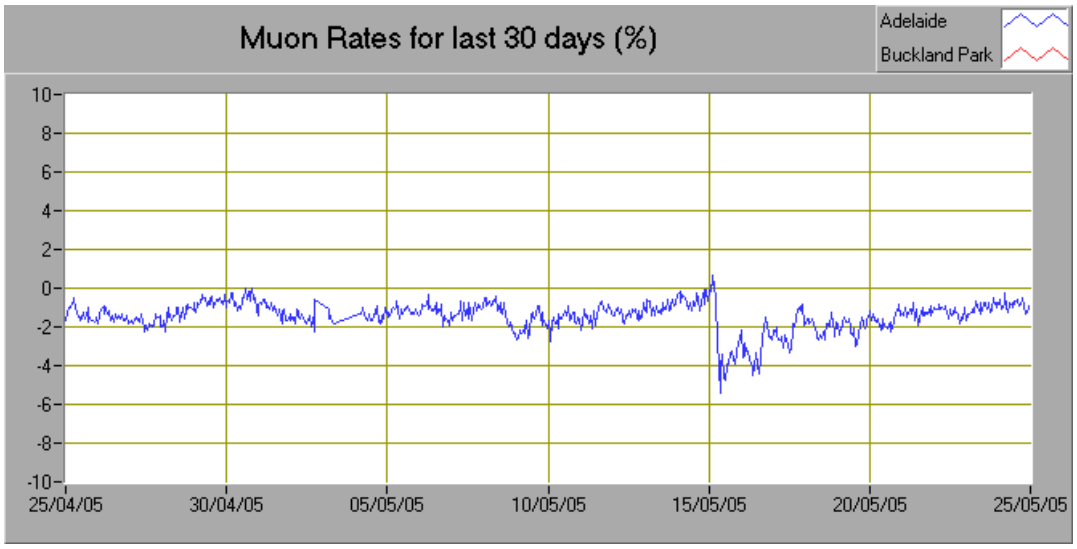

Figure 6: 15 minute Muon counts from the muon detector at Adelaide University. Figure generated at http://www.physics.adelaide.edu.au/astrophysics/muon/Plot.png.

Global ionisation

To achieve a detailed picture of the potential climate response from cosmic rays it is useful to know the ionisation rate on a 3D grid. Usoskin et al. (2004) have made detailed calculations of the time-variable spatial distribution of cosmic ray-induced ionisation of the lower atmosphere using a physical model and incorporating the data from the neutron monitor network. The result is a 3D set of equilibrium ion

concentrations in the lower atmosphere for the period 1951-2000. This data set is available at DNSC. In Figures 7 and 8 examples are shown of the spatial and temporal variation of cosmic-ray induced ionisation generated by this semi-empirical model

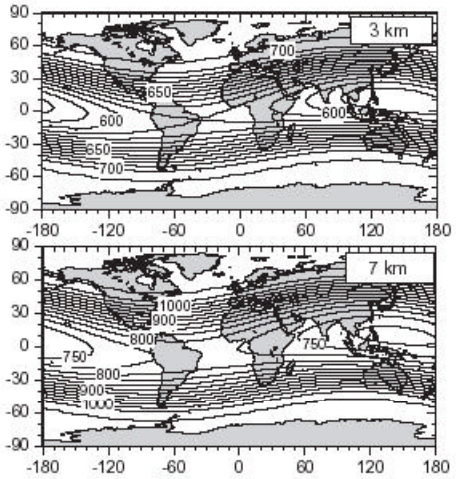

Figure 7: Calculated cosmic ray induced ionisation for altitudes of about 3 km (upper panel) and 7 km (lower panel) for the year 2000. From Usoskin et al. (2004).

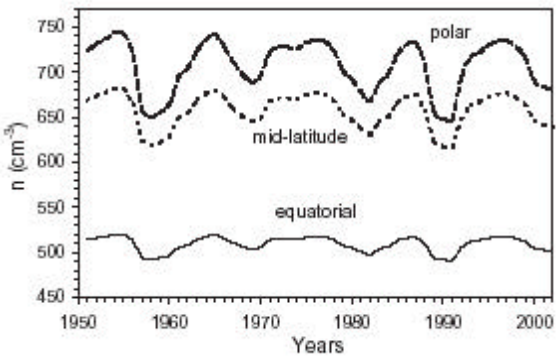

Figure 8: Calculated time profiles of the annual cosmic ray induced ionisation at the altitude of 3 km for polar, mid-latitude and equatorial regions. From Usoskin et al. (2004)

Temperatures

A number of data sets describing the global distribution of atmospheric temperatures exist. Most reliable of these are satellite measurements since they provide global coverage at much higher densities than in-situ observations. Also local biases are avoided with satellite observations. However, ground based measurements from surface stations or by radiosonde have the advantage of spanning a longer period. Both types of observations therefore have a role to play in a climate study.

Microwave Sounding Units

Satellite measurements of the Earth's microwave emissions are a crucial element in the development of an accurate system for long-term monitoring of atmospheric temperature. The prime source for satellite temperature profiles is the Microwave Sounding Units (MSU) that have been on board the NOAA polar-orbiting satellites for more than 25 years. The MSUs operate in four channels measuring atmospheric temperature in four thick vertical layers spanning the surface through the stratosphere. Since 1998 the Advanced Microwave Sounding Units (AMSUs) have been in operation. This makes use of a larger number of channels, thus sampling the vertical temperature profile of the atmosphere with a much higher resolution. The MSU and AMSU instruments are not strictly intended for climate research, but rather for weather forecasting. However, NOAA produces a long-term data set that can be used for climate studies through inter-calibrating the measurements from nine different satellites. For a description of the technique of generating and validating temperature anomalies from MSU measurements, see Spencer and Christy (1992a and 1992b)

The temperature profiles for the lower troposphere and the lower stratosphere for the period 1979-2001 are available at DNSC, present day updates are continuously available from the Global Hydrology and Climate Center http://www.nsstc.uah.edu/data/msu/. Examples of the data available can be seen in Figures 9 and 10.

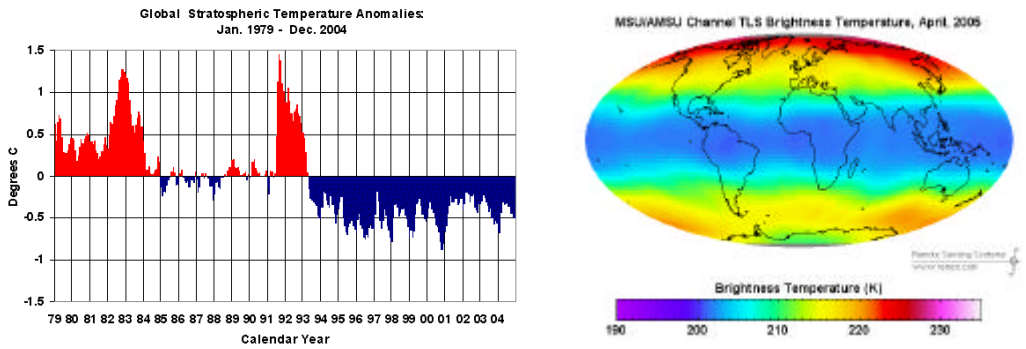

Figure 9: Global temperature average for 1979-present and a global view of the temperature of the lower stratosphere for April 2005. The global average is given as a deviation from a seasonally adjusted average. From http://www.ghcc.msfc.nasa.gov/MSU/msusci.html.

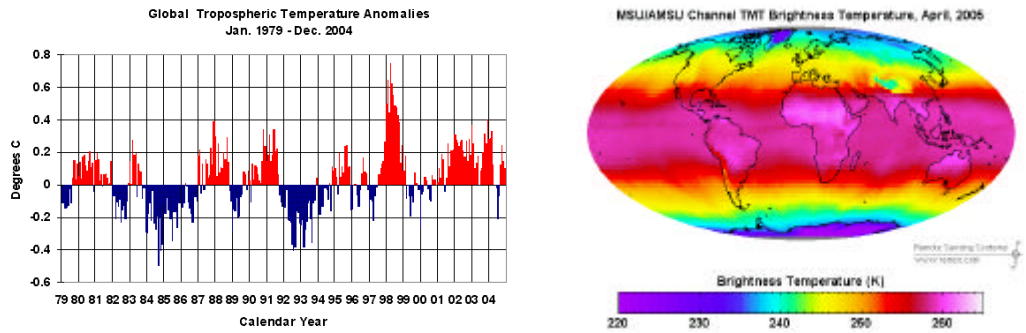

Figure 10: As Figure 9, but for the lower troposphere.

Surface stations

Surface measurements suffer greatly from inhomogeneous geographic distribution, however, their advantage is the relatively long time span for which surface temperature measurements exist. At the Climate Research Unit, University of East Anglia (http://www.cru.uea.ac.uk/cru/data/) a 5 degree by 5 degree gridded data set is available for 1851-present. The coverage is extremely sparse in the early years, however, hemisperic averages are also available from 1856-present. A slightly older version of the data set is available at DNSC. A number of references for the use of this data set can be found at http://www.cru.uea.ac.uk/cru/data/temperature/#sciref, see for eample Jones and Moberg (2003) for a description of the derivation of the gridded data set, and Folland et al. (2001) for the global long time span data series. Figure 11 shows the hemispheric and global averages for 1856-present.

Radiosonde measurements

Radiosonde measurements have been recomputed into a gridded data set spanning 1958 to present by the British Atmospheric Data Centre. The data are represented as monthly or seasonal temperature anomalies with respect to 1971-1990 and are available at 9 levels (850, 700, 500, 300, 200, 150, 100, 50, 30hPa) on a 5-degree

latitude by 10-degree longitude grid. The data for 1958-present are available at DNSC while updates can be applied for at http://badc.nerc.ac.uk/data/hadrt/. The data set is described in Parker et al. (1997).

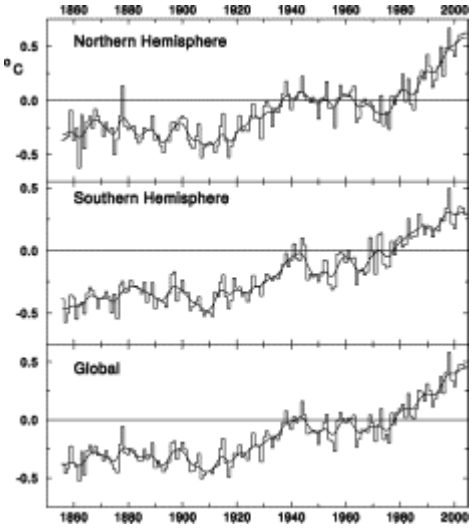

Figure 11: Hemispheric and global averages of the surface temperature for 1856-present. From http://www.cru.uea.ac.uk/cru/data/temperature/.

Earth Radiation Budget

Earth's energy balance is defined at the top of the atmosphere as the balance between the incoming energy from the Sun and the outgoing thermal (longwave) and reflected (shortwave) energy from the Earth. The climate system contains considerable inertia as a result of the oceans, thus in the presence of an increasing climate forcing an imbalance will be observed between the energy absorbed and that emitted by the planet. This imbalance reflects the extent of a net climate forcing, which can have originated either internally or externally to the Earth system. Such information is a vital part of this study as it will give an indication of the overall response in the climate system to changes in solar activity.

NASA's Earth Radiation Budget Experiment (ERBE) is a multi-satellite system designed to measure the Earth's radiation budget, and has been in operation since 1984. Each satellite carries both a scanner and a non-scanner instrument package. The scanner has an effective field of view of 3 degrees and detects at three wavebands: shortwave (0.2 to 5 microns), longwave (5 to 50 microns) and total (0.2 to 50 microns). The non-scanner instrument detects at only two wavebands (shortwave and total) with two spatial resolutions: Wide Field of View (WFOV) covering the whole Earth, and a Medium Field of View (MFOV) limited to ~1000km in diameter.

These instruments provide a range of radiation products including longwave, shortwave, net radiance fluxes, albedo, and solar incidence at top of the atmosphere. Spatial resolutions are provided from 2.5 degrees up to the size of the Earth, with temporal output including hourly, daily, monthly and annual observations. A detailed description of the ERBE data products can be found in Barkstrom et al. (1985), while the data can be obtained from

http://eosweb.larc.nasa.gov/PRODOCS/erbe/table_erbe.html. Figure 12 shows an example of the outgoing longwave radiation averaged over April 1985.

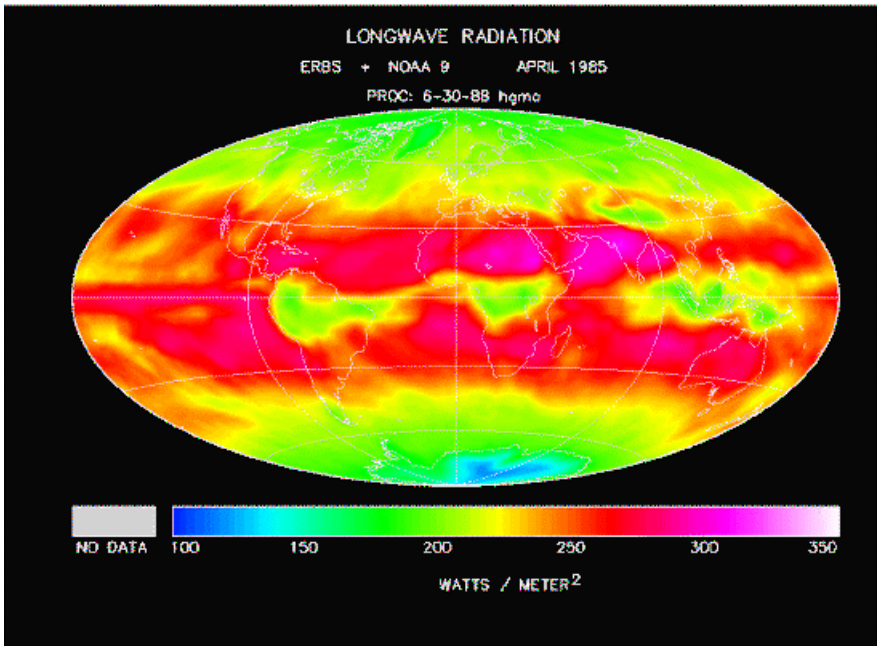

Figure 12: The outgoing longwave radiation from Earth for April 1985. From http://asd-www.larc.nasa.gov/erbe/ASDerbe.html.

Reanalysis Data

The aim of a reanalysis project is to assimilate comprehensive sets of historical meteorological data into full physical models of the atmosphere. The models take into account parameterizations of all major physical processes, such as convection, large-scale precipitation, shallow convection, gravity wave drag, etc. Data from two major reanalysis projects are available, the NCEP/NCAR project at the NOAA Climate Diagnostics Center and the ERA-40 project at the European Centre for Medium-Range Weather Forecasts.

NCEP/NCAR

The NCEP/NCAR model uses a horizontal resolution of approximately 200 km and vertical resolution at 28 levels from the surface to about 3 hPa. The model assimilates past data from 1948 to the present. Output is 4 times daily and a variety of output data is available, for example Temperatures, Geopotential Heights, Humidity, Precipitation, etc. Available at DNSC are monthly Air Temperatures and Geopotential Heights on a 2.5-degree grid at 17 vertical levels. The full data sets can be obtained from http://www.cdc.noaa.gov/cdc/reanalysis/.

ECMWF

The reanalysis project ERA-40 covers the period from mid-1957 to 2001. The reanalysis involves comprehensive use of satellite data, starting from the early Vertical Temperature Profile Radiometer data in 1972. The output is similar to the NCEP/NCAR model with output 4 times daily and a variety of output parameters. The ERA-40 project is described in a series of project reports that maybe found at

http://www.ecmwf.int/publications/library/do/references/list/192. Of particular interest is Simmons et al. (2004) that presents a comparison between ERA-40, NCEP/NCAR and CRU surface air temperatures. Figure 13 shows an example of the output from the ERA-40 project: winds at 10 and 850 hPa averaged over August 2002. The ERA-40 data products are available from http://www.ecmwf.int/products/data/index.html.

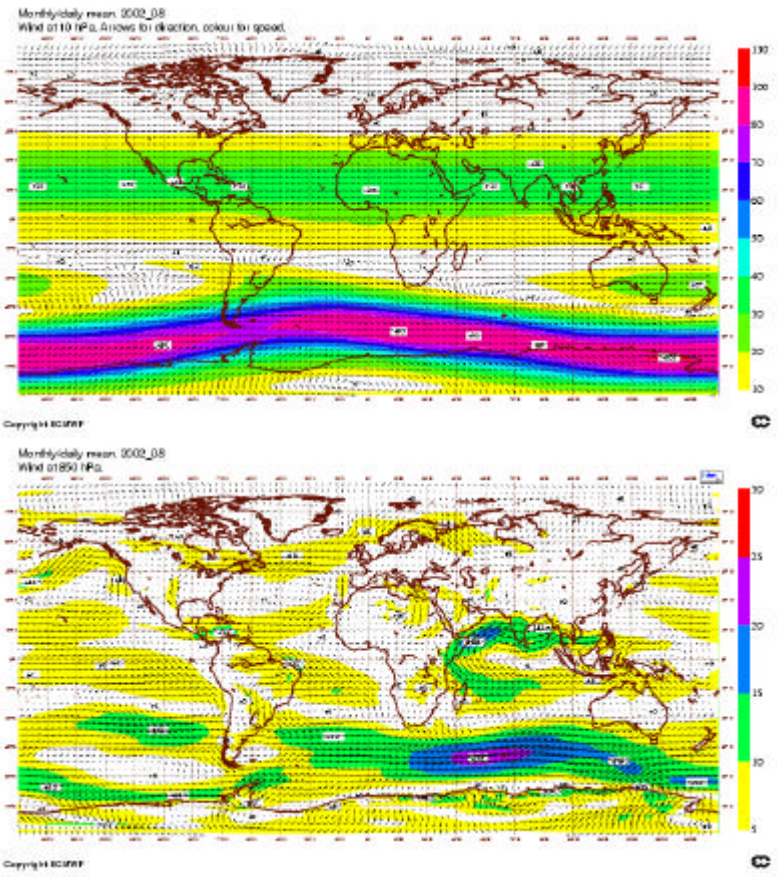

Figure 13: Average winds at 10 and 850 hPa in August 2002. From http://www.ecmwf.int/products/data/index.html.

Berlin Stratospheric Data Series

The Berlin dataset consists of more than 30 years (Nov 1964-Jun 2001) of daily (every two days in summer) geopotential height and temperature fields at 50, 30 and 10hPa in the northern hemisphere. The full data set is available at DNSC and may also be found at http://strat-www.met.fu-berlin.de/products/#database. A description of the data may be found at http://strat27.met.fu-berlin.de/products/cdrom/html/main.html

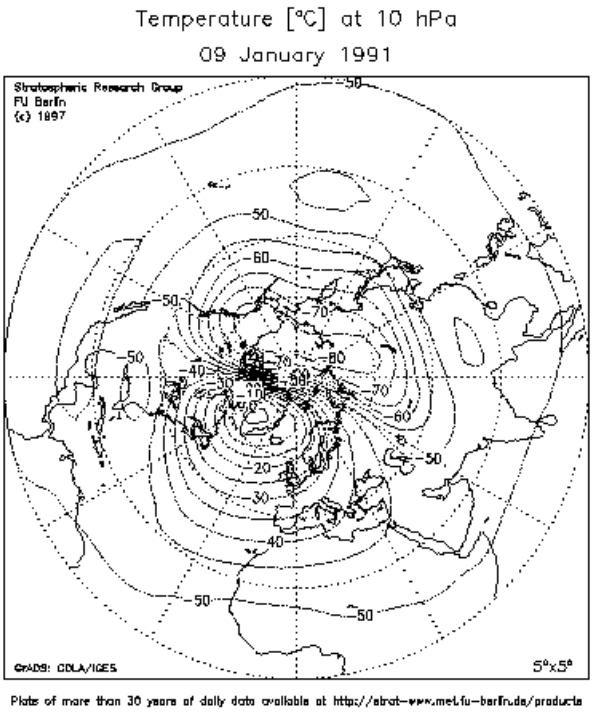

Figure 14: an example of the Berlin data set showing the temperature at 19 hPa on January 9, 1991. From http://strat-www.met.fu-berlin.de/products/#database.

Cloud data

Certainly, one of the most complex areas in a solar-climate study is the relationship between solar activity, cloud cover on Earth, and climate change. The varying effects on the radiative balance of different types of clouds demands a high quality cloud dataset to be used in the analysis. Particularly, the possible role of cosmic ray-induced ionisation of the atmosphere in seeding clouds is interesting since it introduces a causal link between solar activity and climate change.

ISCCP – The International Satellite Cloud Climatology Project

The ISCCP cloud data sets provide a systematic view of global cloud behaviour over the period July 1983 – September 2001. ISCCP collects weather satellite radiance measurements in order to infer the global distribution of clouds, their properties, and their diurnal, seasonal and interannual variations. Figure 15 shows an example of monthly total cloud cover. ISCCP divides clouds into three types based on altitude, low, middle, or high, using either infrared or a combination of infrared and visual observations. The most important parameters are gridded on a 280 km equal area resolution. Descriptions and derivations of the various data sets may be found at http://isccp.giss.nasa.gov/research.html, see for example Rossow et al. (1996) for the latest description of the ISCCP-D2 data set.

The various data sets at ISCCP include parameters such as Cloud Amount, Cloud Type, Cloud Top Temperature/Pressure, Cloud Optical Thickness, Surface Temperature, Surface Reflectance, Surface Total Albedo, and many others. The ISCCP-D2 monthly data set is available at DNSC, as are parts of the ISCCP-D1 3 hourly data set. The full spectrum of ISCCP data sets is available from http://isccp.giss.nasa.gov/ISCCP.html.

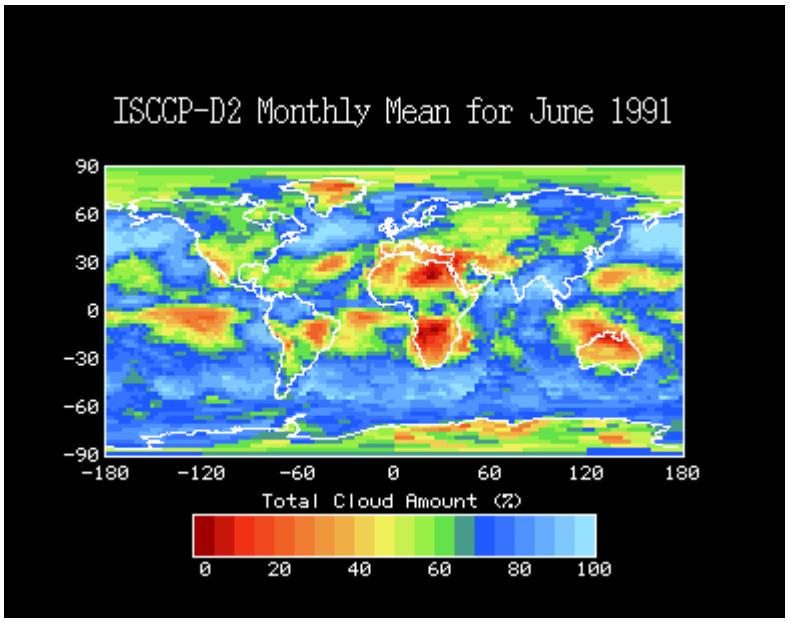

Figure 15: Total cloud cover for June 1991. From http://isccp.giss.nasa.gov/ISCCP.html.

NIMBUS-7 Cloud Matrix Data

The NIMBUS-7 global multilevel cloud-climatology data archive spans the interval April 1979 through March 1985 and has been created from Nimbus-7 THIR and TOMS measurements. UV and IR reflectivities are combined to give a composite estimate of the cloud cover. The NIMBUS-7 data set differs from ISCCP in some respects. Only local noon and midnight data are computed and also the altitude resolution of low, middle, and high clouds is somewhat different. The data are monthly averages at 4.5^{o} resolution. The NIMBUS-7 Total Cloud Cover data set is available at DNSC. Other data sets, such as Cloud Type Cover can be obtained from http://www.cgd.ucar.edu/cas/catalog/satellite/cmatrix/ and a description of the data can be found from Stowe et al. (1988) and Yeh et al (1989).

HIRS

Another cloud data set complementary to ISCCP is the Wisconsin HIRS 6.5 Year Cloud Climatology data spanning the period 1989-1994. The data are monthly averages of cloud probabilities accumulated from the top the atmosphere and downwards. The HIRS measurements provide a better means of detecting semi-transparent cloud than other cloud analyses. A description of the technique can be found in Wylie et al. (1994). In Figure 16 an example is shown of the HIRS data. A 2x3 degree gridded version of the HIRS data set is available at DNSC. The full data set can be obtained from http://www.ssec.wisc.edu/~donw/PAGE/CLIMATE.HTM.

SSM/I – the Special Sensor Microwave/Imager

The SSM/I operated by the Defense Meteorological Satellite Program (DMSP) offers a variety of data spanning the period July 1987 – present. Cloud and Atmospheric products are derived from observations from four channels at microwave wavelengths. This technique is particularly adept at detecting liquid water in the atmosphere and so provides a comprehensive coverage of properties in the lower

troposphere. Monthly average products are produced for precipitation, cloud liquid water, total precipitable water, snow cover, sea-ice cover, and oceanic surface wind speed. The cloud liquid water data set is available at DNSC. The technique for retrieving cloud liquid water from SSM/I is discussed in Weng and Grody (1994). The full data set may be obtained from
http://www.ncdc.noaa.gov/oa/satellite/ssmi/ssmiclw.html.

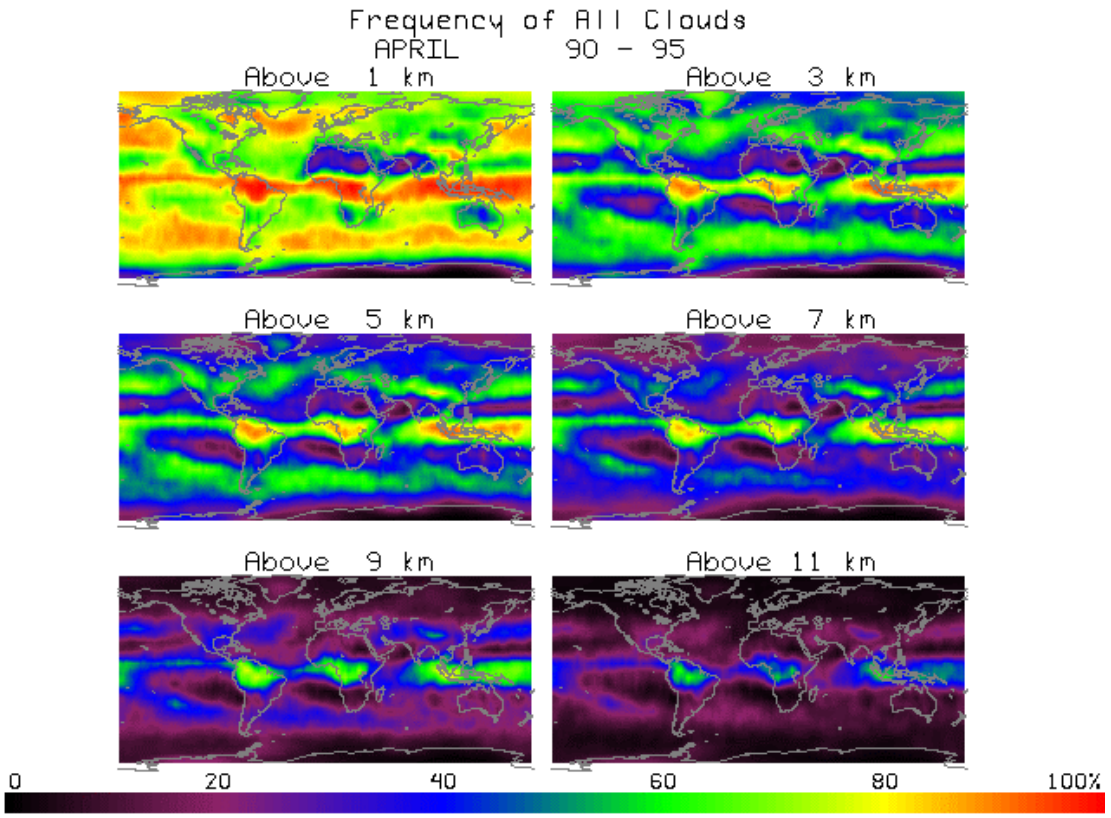

Figure 16: HIRS accumulated cloud probability for 6 altitude levels. From http://www.ssec.wisc.edu/~donw/PAGE/CLIMATE.HTM.

Aerosols

The effect of aerosols on climate is a highly complex subject. The various forcing mechanism associated with anthropogenic aerosols are mostly cooling, but with different spatio-temporal patterns. Most importantly, the magnitude of the collected cooling effect of aerosols is highly uncertain. Anderson et al. (2003) summarizes a number of studies on the effects of aerosols, dividing them into forward methods, based on aerosol physics and chemistry, and inverse methods where the influence of aerosol driving of the climate is inferred from the premise that the observed warming is caused by a positive total forcing over the industrial era. The forward methods puts aerosol forcing at –1.5 Wm^{-2} with uncertainties that extend beyond –3 Wm^{-2} whereas the inverse methods constrain the aerosol forcing to around –1 Wm^{-2}. This uncertainty has a strong effect on climate models considering that these numbers are comparable to the magnitude of the (positive) non-aerosol forcings over the industrial era (2.7 Wm^{-2}). A better understanding of the role of aerosols is therefore paramount in

climate studies, and a link to solar variability via cosmic ray induced ionisation could have potentially important implications.

A number of sites deliver aerosol data of different types: aerosol optical thickness or aerosol index. We include two data sets based on satellite measurements.

TOMS Aerosol Index

NASA/GSFC's Total Ozone Mapping Spectrometer (TOMS) delivers an aerosol index based on the difference in measured UV backscattering compared to the UV backscattering from a pure molecular atmosphere. A description of the technique may be found in Torres et al. (1998). The Aerosol Index spans November 1978 – present with a gap from June 1993 to July 1996. The data give global coverage – both over oceans and land and are available as daily outputs. The derivation of the aerosol data is described in Torres et al. (1998). Figure 17 shows an example from May 12, 2005. TOMS also delivers monthly means of Aerosol Optical Thickness. The TOMS aerosol data may be downloaded from
http://toms.gsfc.nasa.gov/aerosols/aerosols_v8.html.

Aerosol Optical Thickness

NOAA produces Aerosol Optical Thickness data from the Advanced Very High Resolution Radiometer data sets. The outputs are daily, weekly, and monthly global 1-degree maps of Aerosol Optical Thickness over the oceans. AOT is a dimensionless quantity that indicates the amount of depletion that a beam of radiation undergoes as it passes through a layer of the atmosphere. The method for deriving AOT from AVHRR observations is described in Holben et al. (1992). Figure 18 shows the AOT for the same day as Figure 17. The data span the period November 1998 to the present and are available from http://www.osdpd.noaa.gov/PSB/EPS/Aerosol/Aerosol.html. Weekly data are available at DNSC.

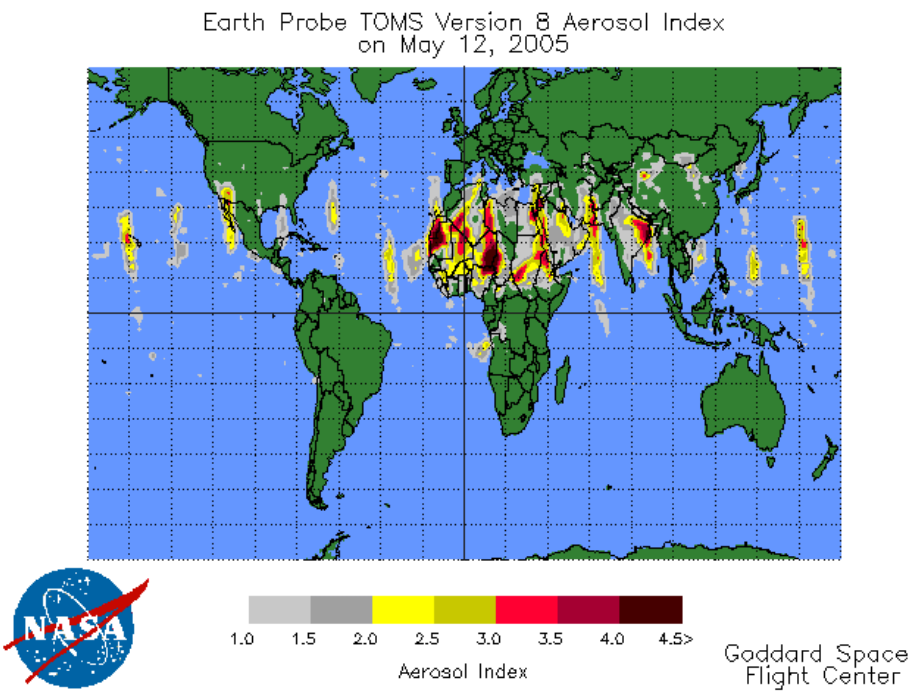

Figure 17: Aerosol Index for June 1, 2005. From toms.gsfc.nasa.gov/aerosols/aerosols_v8.html.

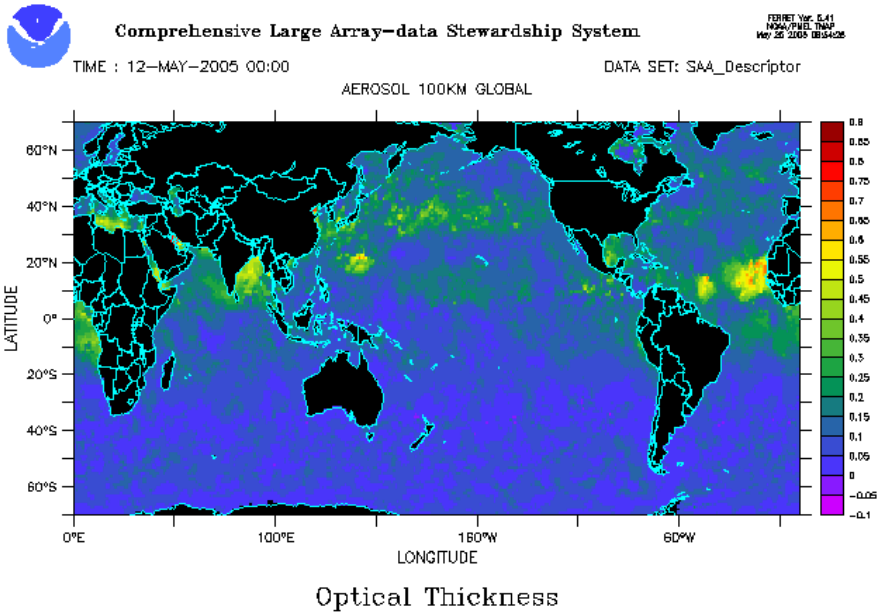

Figure 18: Aerosol Optical Thickness over the oceans on May 12, 2005. From www.osdpd.noaa.gov/PSB/EPS/Aerosol/Aerosol.html.

Water vapor

NASA's Water Vapor Project has produced a global water vapour data set spanning the period 1988-2001. The NVAP project combines a number of data sources to produce the output of daily averages with 4 vertical layers and a 1-degree horizontal resolution. The technique is described in Randel et al. (1996). The role of water vapor in the daily weather as well as for climate dynamics can hardly be overstated. Figure 19 compares the global average of total water vapor over the oceans together with sea surface and lower tropospheric temperatures. The correlation is evident. The NVAP data are available for the period 1988-1997 at DNSC. The full data set can be obtained from
http://www.cira.colostate.edu/climate/NVAP/climate_wvsci.html.

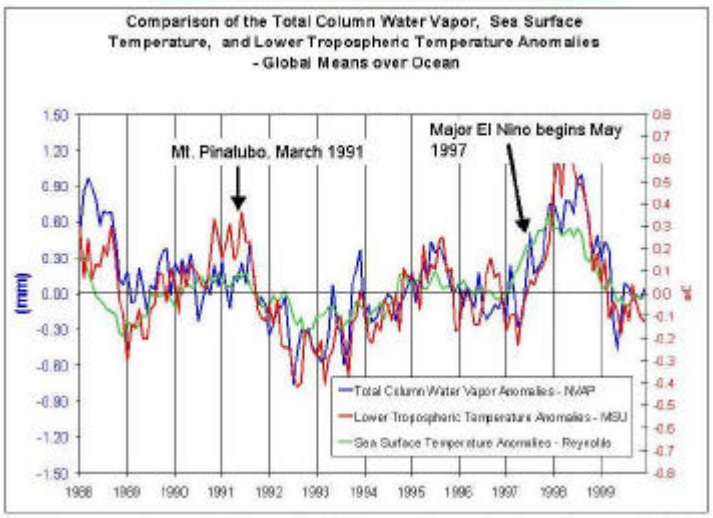

Figure 19: Correlation between Total Column Water Vapor and Sea Surface and Lower Tropospheric Temperatures. From http://www.cira.colostate.edu/climate/NVAP/climate_wvsci.html.

Conclusions

In this report we have described the data sets selected for the remaining Tasks of the ISAC study. The selection is based on the Literature Survey of Task 1 (WP100), where a number of possible mechanisms relating solar variability to climate change were identified. The selection of data is in no sense unique – other data sets could have been chosen since the field is vast. Nor is the selection necessarily final – if the need for further data input arises in the remaining parts of this study the current data selection will be augmented.

The subject of this report is "Possible Interactions and Modifications", i.e., the link between "Solar Output", described in WP201, and "Earth's Climate" in WP203. Some of the parameters involved in this link, galactic cosmic rays and the magnetosphere, can be viewed as distinct from Earth's climate, but other quantities such as clouds are very much integral to the climate system and a large overlap with the "Earth Climate" report is therefore to be expected.

We have in our choice of data sets placed an emphasis on physical parameters more or less directly obtainable from measurements. We have also weighed in favour of satellite data wherever possible since these give by far the best geographical coverage. This choice, however, means that the data sets span a fairly limited time interval, since the majority of satellite observations only cover 2, or at best 3, solar cycles. This will place obvious constraints on the extent of the correlation studies that can be performed with these data.

Some of the data are already available at DNSC as described in the tables of coverage and availability at the end of this report. During Task 3 the relevant data will be acquired and stored in a database at DNSC – to the extent that it is practicable – else comprehensive links to the relevant internet based data archives will be included in the DNSC database and made available online.

References

Barkstrom, B., E. Harrison, G. Smith, R. Green, and J. Kibler, Earth Radiation Budget Experiment (ERBE) Archival and April 1985 Results *Bulletin of the American Meteorological Society, 70*, 1254–1262, 1989.

Bramstedt, K., J. Gleason, D. Loyola, W. Thomas, A. Bracher, M. Weber, and J. P. Burrows, Comparison of total ozone from the satellite instruments GOME and TOMS with measurements from the Dobson network 1996-2000, *Atmospheric Chemistry and Physics 3*, 1409-1419, 2003.

Folland, C.K., Rayner, N.A., Brown, S.J., Smith, T.M., Shen, S.S.P., Parker, D.E., Macadam, I., Jones, P.D., Jones, R.N., Nicholls, N. and Sexton, D.M.H., Global temperature change and its uncertainties since 1861. *Geophysical Research Letters 28*, 2621-2624, 2001

Foster, J. C., J. M. Holt, R. G. Musgrove and D. S. Evans, Ionospheric Convection Associated with Discrete Levels of Particle Precipitation, *Geophysical Research Letters, 13*, 656-659, 1986.

Fuller-Rowell, T., and D. S. Evans, Height-Integrated Pedersen and Hall Conductivity Patterns Inferred from the TIROS-NOAA Satellite Data, *Journal of Geophysical Research, 92*, 7606-7618, 1987.

Holben, B., E. Vermot, Y. J. Kaufman, D. Tanre, and V.Kalb, Aerosol Retrieval over Land from AVHRR Data-Application for Atmospheric Correction. *IEEE Transactions on Geoscience and Remote Sensing, 30*, 212-222, 1992.

Jones, P.D. and Moberg, A., Hemispheric and large-scale surface air temperature variations: An extensive revision and an update to 2001, *Journal of Climate 16*, 206-223, 2003.

Managing Office for WDC C2, Cosmic Ray Data Set – READ.ME file, *www.env.sci.ibaraki.ac.jp/ftp/pub/WDCCR/READ.ME*, 2001

Parker, D.E., Gordon, M., Cullum, D.P.N, Sexton, D.M.H, Folland, C.K., and Rayner, N., A New Gridded Radiosonde Temperature Data Base and Recent Temperature Trends, *Geophysical Research Letters, 24*, 1499-1502, 1997.

Randel, D. L., T. H. Vonder Haar, M. A. Ringerud, G. L. Stephens, T. J. Greenwald, and C. L. Combs, A New Global Water Vapor Dataset, *Bulletin of the AMS, 77*, 1233-1246, 1996.

Rossow, W. B., A. W. Walker, D. E. Beuschel and M. D. Roiter, International Satellite Cloud Climatology Project(ISCCP) : documentation of new cloud datasets, p. -115, World Meteorological Organization, Geneva, 1996.

Simmons, A.J., P.D. Jones, V. da Costa Bechtold, A.C.M. Beljaars, P.W. Kållberg, S. Saarinen, S.M. Uppala, P. Viterbo and N. Wedi, Comparison of trends and variability in CRU, ERA-40 and NCEP/NCAR analyses of monthly-mean surface air temperature, *ERA-40 Project Report Series No. 18*, 2004.

Spencer, R.W. and J.R. Christy, Precision and radiosonde validation of satellite gridpoint temperature anomalies, Part I: MSU channel 2, *Journal of Climate, 5,* 847-857, 1992a.

Spencer, R.W. and J.R. Christy, Precision and radiosonde validation of satellite gridpoint temperature anomalies, Part II: A tropospheric retrieval and trends 1979-90, *Journal of Climate, 5,* 858-866, 1992b.

Stowe, L.L, C.G. Wellemeyer, T.F. Eck, H.Y.M. Yeh, and the Nimbus-7 Cloud Data Processing Team, Nimbus-7 global cloud climatology, Part I: Algorithms and validation, *Journal of Climate, 1,* 445-470, 1988.

Torres O., P.K. Bhartia, J.R. Herman and Z. Ahmad, Derivation of aerosol properties from satellite measurements of backscattered ultraviolet radiation. Theoretical Basis, *Journal of Geophysical Research, 103,* 17099-17110, 1998.

Usoskin, I. G., O. G. Gladysheva, and G. A. Kovaltsov, Cosmic ray-induced ionization of the atmosphere: spatial and temporal changes, *Journal of Atmospheric and Solar-Terrestrial Physics, 66,* 1791-1796, 2004.

Weng, F. and N.C. Grody, Retrieval of cloud liquid water using the special sensor microwave imager (SSM/I), *Journal of Geophysical Research, 99,* 25535-25551, 1994.

Wylie, D.P., W. P. Menzel, H. M. Woolf, K. I. Strabala, Four Years of Global Cirrus Cloud Statistics Using HIRS, *Journal of Climate, 7,* 1972-1986, 1994

Yeh, H.Y.M., T.F. Eck, C.G. Wellemeyer, H.L.Kyle, and the Nimbus-7 Cloud Data Processing Team, Nimbus-7 cloud climatology, Part II. *Journal of Climate, 2,* 671-709, 1989

Data Sets – Tables of Sources and Availability

Below we summarize the data sets, their geographical and temporal coverage, the sources where they may be obtained, and the current availability at DNSC. During Task 3 the data will be acquired by DNSC to the extent that it is practically doable. Clearly, in some cases, for example the reanalysis data, the entire data set will not be downloaded, but rather parts of the data set will be acquired on case by case criteria.

	Observation	Geographic coverage	Temporal coverage
Cosmic Rays			
	Neutron counts	World wide network 30-60 stations (1953-1956: 2-5 stations)	1953-2004 Hourly data
	Source: www.env.sci.ibaraki.ac.jp/ ftp/pub/WDCCR/ Available at DNSC: none		
	Muon counts	Single station Adelaide	1998-present 15 minute data
	Source: http://www.physics.adelaide.edu.au/astrophysics/index.html Available at DNSC: 1998-2001		
	Cosmic ray-induced ionisation	Global 5x5 degrees grid 16 vertical levels	1951-2000 Monthly data
	Source: I. G. Usoskin, Oulu, Finland Available at DNSC: full data set		

	Observation	Geographic coverage	Temporal coverage
Magneto-/ ionosphere			
	DMSP/SSIES: Ion drift, composition, temperatures	Global (satellites in Sun-synchronous orbit)	(1987)1995-present 4 second data (at satellite position)
	Source: cindispace.utdallas.edu/DMSP/ Available at DNSC: none		
	Total Power Input	Hemispheric average	1983-2001 app. 50 minute
	Source: spidr.ngdc.noaa.gov/spidr/dataset.do Available at DNSC: none		
	Ionograms	World wide network > 200 stations	1942-present 15 minute data
	Source: spidr.ngdc.noaa.gov/spidr/dataset.do Available at DNSC: full data set		

	Observation	Geographic coverage	Temporal coverage
Temperatures			
	Microwave Sounding Units: temperature anomalies	Global Hemispheric, zonal or gridded (2.5 degree) 3 vertical layers	1979-present Daily or monthly data (gridded data only monthly)
	Source: http://www.nsstc.uah.edu/data/msu/ Available at DNSC: monthly hemispheric data 1979-2001		
	Surface stations: temperature anomalies	Global Hemispheric or gridded (5 degree)	1856-present Monthly data (gridded data only from 1960)
	Source: http://www.cru.uea.ac.uk/cru/data/temperature/ Available at DNSC: full data set		
	Radiosonde: temperature anomalies	Global Gridded (5x10 degrees) 9 vertical levels	1958-present Monthly data
	Source: http://badc.nerc.ac.uk/data/hadrt/ Available at DNSC: 1958-1999, updates need to be applied for		

	Observation	Geographic coverage	Temporal coverage
Clouds			
	ISCCP data: type, amount, top temperature, top pressure, optical thickness and many others	Global Gridded (280 km) (Pixel level data at 30 km) 3 vertical levels (cloud types)	1983-2001 3 hour, daily, monthly
	Source: http://isccp.giss.nasa.gov/index.html Available at DNSC: full monthly data set, parts of 3 hr data set		
	Nimbus-7: type, amount, radiance	Global Gridded (4.5 degree) 3 vertical levels (cloud types)	1979-1985 Monthly (twice daily)
	Source: http://www.cgd.ucar.edu/cas/catalog/satellite/cmatrix/ Available at DNSC: total cloud cover data set		
	HIRS: cloudiness	Global Gridded (2x3 degrees) 16 vertical levels	1989-1994 Monthly data (averages over the data period)
	Source: http://www.ssec.wisc.edu/~donw/PAGE/CLIMATE.HTM Also available: 22 year data set Available at DNSC: full 6.5 year data set		

	SSM/I: Cloud liquid water, precipitation, total precipitable water and others	Global Gridded (1 and 2.5 degree)	1987-present Monthly data
	Source: http://www.ncdc.noaa.gov/oa/satellite/ssmi/ssmiproducts Available at DNSC: cloud liquid water data set		

	Observation	Geographic coverage	Temporal coverage
Reanalysis			
	NCEP/NCAR: Meteorological variables	Global Gridded (200 km) 28 vertical layers	1948-present 4 times daily Monthly means
	Source: http://www.cdc.noaa.gov/cdc/reanalysis/ Available at DNSC: air temperatures and geopotential heights – monthly means		
	ECMWF: Meteorological variables	Global Gridded (40 km) 60 vertical levels	1957-2002 4 times daily Monthly means
	Source: http://www.ecmwf.int/research/era/ Available at DNSC: none		

	Observation	Geographic coverage	Temporal coverage
Radiation Budget			
	Albedo, radiation flux, solar incidence	Global, zonal and regional averages (5 or 10 degrees)	1984-present Monthly means of hourly or daily values or actual hourly data
	Source: eosweb.larc.nasa.gov/PRODOCS/erbe/table_erbe.html Available at DNSC: none		

	Observation	Geographic coverage	Temporal coverage
Aerosols			
	Aerosol index	Global Gridded (1.25 x 1 degree)	Nov 1978-present (gap June 1993 – July 1996) Daily
	Source: http://toms.gsfc.nasa.gov/aerosols/aerosols_v8.html Available at DNSC: none		
	Aerosols Optical Thickness	Global (over oceans) Gridded (1 degree)	1998-present Daily

	Source: http://www.osdpd.noaa.gov/PSB/EPS/Aerosol/Aerosol.html Available at DNSC: weekly data

	Observation	Geographic coverage	Temporal coverage
Ozone			
	TOMS Total ozone	Global Gridded (1.25 x 1 degree)	Nov 1978-present (gap June 1993 – July 1996) Daily
	Source: http://toms.gsfc.nasa.gov/ozone/ozone_v8.html Available at DNSC: none		
	GOME Total ozone	Global Gridded (1.25 x 1 degree)	1995-2003 Daily
	Source: http://www-iup.physik.uni-bremen.de/gome/wfdoas/ Available at DNSC: full data set		

	Observation	Geographic coverage	Temporal coverage
Other data			
	NVAP: Water vapor	Global Gridded (1 degree) 4 vertical layers (from 2000 0.5 degree and 5 layers)	1988-2001 Daily (from 2000 twice daily)
	Source: http://www.cira.colostate.edu/climate/NVAP/climate_wvsci.html Available at DNSC: 1988-1997		
	Berlin data: Geopot. height, temperature	Northern hemisphere Gridded (5 degrees) 3 vertical layers	Nov 1964-Jun 2001 Daily data (twice daily in Summer)
	Source: http://strat27.met.fu-berlin.de/products/ Available at DNSC: full data set		