Geomagnetic Impact on Upper Atmospheric Nitric Oxide

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Student: Max Lindberg Stoltz
Assistant: Koen Hendrickx & Linda Megner
Abstract

Nitric oxide (NO), in the mesosphere-lower thermosphere, is produced at high latitudes by energetic particle precipitation (EPP). At times of higher geomagnetic activity, a stronger EPP occurs, and more NO is produced. NO can descend, inside the polar vortex in the winter polar area, to the stratosphere where it participates in ozone depletion processes which leads to a thinning of the ozone layers. Ozone absorbs UV-radiation, which makes it important to the heat budget in the stratosphere. Changes in the ozone volume alter the heat budget which in turn affects the dynamics in the middle atmosphere.

In the end of 2014 the sub-millimetre radiometer (SMR), on board the satellite Odin, measured the NO volume mixing ratio during two short periods with the objective to observe how NO density changes with enhanced geomagnetic activity. In this project, the retrieved SMR data is analyzed to investigate the NO response due to geomagnetic activity. The first observed period had quiet geomagnetic conditions, while the second period started with active conditions. The NO densities in these periods were compared, and the second period showed larger densities, compared to the first, especially at high latitudes in the Northern hemisphere. Enhanced densities were also found in the auroral region in the Southern hemisphere during the second period. The difference between morning and evening densities was investigated. Larger morning densities were found at high altitudes in the northern auroral region, while in the equatorial, and southern mid-latitudes, larger evening densities were found, at the same altitudes. To investigate the direct response of NO due to geomagnetic activity a correlation and regression analysis was made between the NO density and two geomagnetic indices, the AE- and Kp index, for different lags of the indices, and for different regions. This analysis showed a significant correlation for the southern auroral region during the second period, for a lag time of 14 hours. The AE index showed larger correlations compared to the Kp index and the regression analysis showed better results for a linear relation.
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1 Introduction

Nitric oxide (NO) is an important constituent in the mesosphere and lower thermosphere (MLT) region and takes part in several physical processes. It is formed in the upper atmosphere by incoming energetic particles, transported within the plasma from coronal mass ejections (CMEs), or other solar particle events. Incoming CMEs increase the geomagnetic activity in the Earth's magnetosphere and thus an enhanced geomagnetic activity leads to larger NO densities in the upper atmosphere. NO is a two-atomic heteronuclear molecule which, unlike two-atomic homonuclear molecules such as oxygen and nitrogen, makes it able to emit IR-radiation. The long wave radiation from NO leads to a cooling of the lower thermosphere. Consequently, NO is a major participant in the thermospheric energy balance. NO is also an important participant in the ionosphere, because of the lower requirement of energy needed to ionize the NO-molecule, compared to most homonuclear molecules. Due to the formation process of NO, it is effectively an indicator of solar energy input into the MLT-region. The density of NO fluctuates strongly as the energy output of the Sun changes (Barth, 1995). The Sun is not only a source of NO in the MLT-region, it is also a sink. During sunlit conditions, NO is photo-dissociated, leading to a density decrease. Thus, the lifetime of NO varies depending on the time of year and latitude. The lifetime of NO is up to a few days in those areas that receive incoming sunlight, while in the polar night area, the lifetime is substantially longer, up to several weeks. This prolonged lifetime enables a further transport of NO, both downwards and meridionally. The meridional transport of NO can be used as an indicator of motions in the atmosphere, for example to detect gravity waves (Barth, 1995). The transport downward, especially in the polar night region (inside the polar vortex) can increase the NO2 (NO and NO2) density in the stratosphere and, via catalytic reactions, destroy ozone (Pérot et al., 2014). As is commonly known, a thinning of the ozone layer has an impact on humans as stronger UV-radiation reaches the troposphere, which is harmful for living organisms. Ozone in the stratosphere also have a large influence on the heat budget in the middle atmosphere and changes in the ozone concentration affect the dynamical properties in the middle atmosphere. Knowledge of NO formation and transport is therefore important to understand both the ozone destruction in the stratosphere, and to determine if the production and loss mechanisms in models are correct.

In this study, the amount of NO in the upper atmosphere during two periods in the end of 2014 is investigated, by examining two small periods of data. These two periods represent both high and low geomagnetic activity, where the second period has the highest. By comparing the density of NO with geomagnetic indices, the response in NO due to arriving CMEs and higher geomagnetic activity is analyzed. The NO was measured by the sub-millimetre radiometer- (SMR) instrument on board the research satellite Odin. The data is a set of specific runs to study NO with high temporal resolution, and it is observed by SMR in a special mode to study the effects on NO due to a CME arrival. Other satellites measuring NO often have lower temporal resolution.

One aim of the project is to investigate the meridional impact of NO. The two poles, the winter pole and the summer pole, are both analyzed and a comparison between the two is made. The geomagnetic activity is analyzed by using geomagnetic indices, mainly the AE- and the Kp-index. Also, the daytime and nighttime NO density is examined, mainly at low latitudes, around the equator. A correlation and regression analysis is also performed to see if a direct relationship exists between values in the indices and the density of NO in the MLT-region, and if this relationship is linear. The aim of the project can be summed up into three general questions:

- What is the visible response on NO density in the MLT-region during, or after, a geomagnetic storm, and how much does the response differ depending on latitude and season?

It is important to investigate this to gain deeper understanding of how different meridional regions are affected by enhanced geomagnetic activity. Other studies have been made on this subject, but not with high temporal resolution data. The data used in this project includes NO measurements at altitudes between 80 km to 115 km only, and extends further than a single day.

- Is there a difference in NO density between the morning and the evening and if so, how much?
Uncertainties exist regarding how fast the NO formation, due to enhanced geomagnetic activity, occurs. To investigate the morning and evening NO densities, comparisons with models can be made to see how the models represent the NO formation and destruction in the upper atmosphere.

- What is the lag between NO density increase and AE or Kp indices, and is the relationship between them linear?

Models only represent linear relationships between NO densities and the AE index. By using the high temporal resolution data, the linearity of the relationship and the lag time between incoming CME and NO formation is analyzed. In previous research, lag times have been examined with lower temporal resolution. By using higher temporal resolution, the results can show more detailed lag times.

This project will seek to answer the three questions above, and to do that a theoretical background is necessary.

1.1 Background

There are many different molecules in Earth’s atmosphere, which participate in different processes depending on their position and altitude. Even though a particular type of molecule has its own specific structure, its formation process is different at different altitudes. One example of such a molecule is NO. Near the surface, in the troposphere, NO is formed by lightning and combustion engines, while in the MLT-region, the main source of NO is the Sun. The Sun emits electromagnetic waves, in all wave lengths, from X-ray to radio waves. Incoming X-rays from the Sun contribute to the formation of NO at low- and mid-latitudes (Barth et al., 2002). However, not only radiation from the Sun reaches Earth, but charged particles as well. These charged particles originate from large solar events, as for example CMEs. The charged particles precipitate down into the atmosphere and produce NO from a combination of ionization, dissociation and recombination. This process is called energetic particle precipitation (EPP) and contributes to the formation of NO at high latitudes (>45°) (Clilverd et al., 2016). In this section, a brief review of previous research and the theory behind the formation of NO in the MLT-region will be presented. Information about what a geomagnetic storm is, and what causes it, will also be included, together with an explanation of the geomagnetic indices.

1.1.1 Previous research

Knowledge about NO formation due to incoming CMEs and energetic particle precipitation has existed for several years. Rusch and Barth (1975) showed that more NO existed at high latitudes, compared to low latitudes. Based on this finding they suggested that an auroral source of NO must exist. Years later, Siskind et al. (1989) studied satellite data of NO, after an auroral storm, and found a higher NO increase at mid-latitudes compared to the equatorial region, due to Joule heating. Barth (1995) found that variations in the output of the Sun lead to a highly variable NO density in the lower thermosphere, at low latitudes. At high latitudes, NO density change is largely due to geomagnetic activity, created by changes in the solar wind. Siskind et al. (1998) compiled a climatology of NO in the MLT-region from observations done by two different satellites in the 1980's and 1990's, the solar mesosphere Explorer and the UARS satellite. This showed a NO density decrease during the decline of the solar cycle, and an increase of mesospheric NO at high latitudes in the winter hemisphere, due to downward transport from the thermosphere. The climatology was presented as a reference model of NO. Barth et al. (2002) analyzed global measurements of thermospheric NO during a period between 1998 and 2000. These observations concluded that two major NO sources exist in the thermosphere, solar X-rays and auroral electrons from the magnetosphere. Research about the vertical transport of NO has also been made, for example by Funke et al. (2005), which showed on a strong descent of NO within the polar vortex. This knowledge was later supplemented by Pérot et al. (2014) who found an enhanced descent of NO after a sudden stratospheric warming, that broke up the Arctic polar vortex in the early winter of 2013. The enhanced descent of NO was enabled by a strong downward transportation of air by the reformation of a strong polar vortex in the upper stratosphere. Hendrickx et al. (2015) observed the production and
descent of NO during a 27-day solar cycle, and studied the relationship between the production of NO and different geomagnetic indices.

1.1.2 Coronal Mass Ejections and Geomagnetic storms

The highest part of the solar atmosphere is called the convection zone, where the energy is transmitted by convection. This zone consists of convection cells, which are comprised magnetic fields, that move around the Sun. The central part of the Sun also creates magnetic fields, and the magnetic fields in the convection zones interact with the magnetic field of the Sun, giving rise to a complex magnetic field system in constant variation. The complexity of the Sun’s magnetic field is demonstrated by sunspots and active regions. Due to the convection in the solar atmosphere, the corona, a part of the Sun’s outer atmosphere containing plasma, is expanding. This expansion releases energy in the form of solar wind. Sometimes, the top of the convection zone forms a local, stable formation in the magnetic field, which prevents the corona from expanding, and the energy is accumulated instead of being released. When the energy has been built up in such amounts that the magnetic field configuration cannot hold it in any longer, it is released in the form of a CME. The kinetic energy released in a CME varies, but can be over $10^{39}$ J, which is $1.3 \times 10^{22}$ times the energy released by the nuclear bomb that detonated over Hiroshima during the second world war. Solar flares, even though they release large amounts of stored energy from the Sun, only carry up to 10% of the energy the typical CME carries (Howard, 2014).

When large amounts of energetic particles from space burst into the magnetosphere the magnetic field of Earth becomes disrupted. This is known as a geomagnetic storm. These particles originate both from outside our solar system, in the form as galactic cosmic rays, and from solar particle events. The two largest solar particle events are solar flares and CMEs. Even though solar flares occur more frequently, the CMEs cause most of the geomagnetic storms on Earth. Solar flares eject large amounts of energetic particle into space resulting in a distortion of the ionosphere. The CMEs, on the other hand, eject large masses of magnetized plasma, and transports magnetic fields from the Sun, which can interact with the Earth’s magnetic field and funnel energetic particles into the atmosphere. The typical mass of a CME is about $10^{11} - 10^{12}$ kg, but it can in special cases contain mass over $10^{13}$ kg (Howard, 2014). Because of the size of the CME and the scattering of the plasma, normally only a small part of this mass hits the Earth. The speed of a CME is between 300 and 1000 km/s, but it can in some cases be over 1000 km/s (Hundhausen et al., 1994). The Sun follows a 11-year cycle in activity. During solar maximum, there are more sunspots on the Sun compared to during solar minimum. This also affects the CMEs. During the solar minimum, on average one CME erupts a day, while during the solar maximum, about five CMEs erupt per day, but only a few hit Earth (Yashiro et al., 2004).

Figure 1: Coronal mass ejection that occurred 2000-02-27. Picture taken from SOHO (ESA & NASA).
Howard (2014) compares the structure of a CME with a light bulb. The “core” of the CME is the filament (a in figure 1), outside this filament there is a cavity (b in figure 1) and outermost there is the leading edge (c in figure 1). The CME, until early eruption, consists of magnetic field and magnetic flux. The cavity is the central magnetic field (Howard et al., 2012) and it is surrounded by coronal fields. The coronal fields could either be open, when located at the Sun, with one end going in the solar wind or closed. The filament is brighter than the rest of the CME and is believed to consist of mass originating from a lower part of the solar atmosphere. The leading edge consists of mass pushed out in front of the CME central field, both coronal and solar wind mass. After some time, when the CME has moved a vast distance from the Sun, the structure has changed. In the central parts of the CME one finds an area that is usually of lower density. This area is known as the magnetic cloud. The sheath region, in front of the magnetic cloud, is the leading edge with more turbulence. The leading part of the CME is the forward shock, which is characterized by an acute increase of solar wind density and magnetic field strength (Howard, 2014).

![Figure 2](image)

**Figure 2**: Overview of the magnetosphere surrounding Earth. Picture taken from NASA (2017).

The magnetic field, figure 2, around Earth is generated by the rotating molten interior of the planet. This magnetic field is constantly bombarded with magnetized plasma from the solar wind. Magnetized plasma from the Sun carries magnetic fields through the interplanetary space. Away from the Sun, it is called the Interplanetary Magnetic Field (IMF). Some of this plasma is led by Earth’s magnetic field around the planet and some of it gets caught. This combination of magnetic field and trapped plasma from the solar wind is what is called the magnetosphere (Parker, 1959). The solar wind creates a bow shock, left in figure 2, which compresses the day side of the magnetic field. The magnetic field lines on the night side extend far from Earth, also because of the solar wind, right of Earth in figure 2. Just behind Earth, seen from the Sun, there is a plasma sheet, which contains trapped magnetized plasma. The plasma is trapped because the magnetic field of Earth cannot interact with IMF to open up the magnetic field lines. The dynamics whereby two different magnetic fields interact is called magnetic reconnection. Two different fields can merge and create a new magnetic configuration. This occurs when bodies of magnetized plasma from separate origins containing anti-parallel components approach each other. As mentioned, magnetic reconnection does not occur on the night side of Earth, but it does on the day side. A CME with an anti-parallel component could magnetically reconnect with the day side of Earth’s magnetic field. The magnetic poles on Earth are reversed compared to the geographic poles, and magnetic field lines go from the magnetic north to the magnetic south, which means the magnetic field lines go from the geographic South pole to the geographic North pole. The magnetic field of a CME must thus be directed southward (in the opposite direction to the magnetic field lines of Earth) to be able to reconnect with the magnetic field of Earth. When this happens, the magnetic field of Earth connects with the magnetic field lines of the CME, which opens up the protecting field around the planet. This
enables energetic particles and energy from the CME to be inserted into the magnetosphere, resulting in a large disturbance of the magnetosphere, which in other words is called a geomagnetic storm (Howard, 2014). A consequence of a geomagnetic storm is that energetic particles can precipitate down into the thermosphere, or even reaching lower altitudes.

1.1.3 NO in the upper atmosphere, formation and transportation

As already mentioned, the formation of NO in the upper atmosphere is mainly caused by two physical processes, EPP and X-ray radiation. EPP forms NO at high latitudes and X-ray radiation at low latitudes, around the equator. This report will concentrate principally on the direct effect of the EPP. EPP-direct effect relates to the in-situ formation of NO. First, the direct effect, the formation, will be explained and then theory about the transportation of NO will be presented.

Formation

As explained earlier, the EPP direct effect is the process where NO is formed due to incoming energetic particles originating from solar flares, CMEs and other types of solar wind and cosmic events. The incoming particles, mostly protons and electrons, precipitate down into the atmosphere following the magnetic field lines, which make most of the particles enter the atmosphere at high latitudes (Smith-Johnsen et al., 2017). The particles penetrate more or less deeply into the atmosphere depending on their energy.

Figure 3: Ionization rate for different types of incoming radiation and particles. Picture taken from Mironova et al. (2015).

Figure 3 shows different types of particles and radiation as a function of altitude and ionization rate for each kind. Figure 3 includes not only particles that originate from the Sun, but solar radiation and particles that originate from outside the Solar system as well (galactic cosmic rays). As can be seen, solar Extreme Ultra Violet (EUV) and X-rays, and auroral electrons (energies of 1-10 keV, (Sinnhuber et al., 2012)), deposit their energy at the highest altitude. Auroral electrons lead to a higher ionization rate compared to solar EUV and X-rays and deposit their energy at higher geomagnetic latitudes (GML), around 65°. The radiation belt electrons peak in ionization rate further down, because of their higher energy (from tens of keV up to a few MeV (Sinnhuber et al., 2012)). The solar protons can penetrate deep into the atmosphere and ionize particles at low altitudes. The peak in ionization rate is at an altitude of 50 km. The most energetic particles take the form of galactic cosmic rays, and can penetrate the atmosphere to low altitudes. The peak in ionization occurs at about 10 km (Mironova et al., 2015). In this project, the particles in focus are auroral electrons and radiation belt electrons, and to some extent solar EUV and X-rays, mainly because of the altitudes represented in the satellite data used in this project and that these altitudes also are the most important for NO production.
The incoming energetic particles enable the formation of NO by a combination of dissociation, ionization and excitation, by colliding with abundant species in the MLT-region. These species are for example the homonuclear molecules O$_2$ and N$_2$, or the oxygen radical O (Sinnhuber et al., 2012). The main primary reactions are:

\[ M_2 + p \rightarrow M + M + p \]  
\[ M_2 + p \rightarrow M_2^+ + p + e^- \]  
\[ N_2 + p \rightarrow N^+ + N + p + e^- \]  
\[ O + p \rightarrow O^+ + p + e^- \] 

where M is either N or O and p is the incident particle (secondary electron or primary electron, ion, or proton). The secondary electron is a result of the ionization and interacts with the surrounding species in similar processes as for the primary particles, until the secondary electron reaches the same mean kinetic energy as the constituents in the surrounding air (Sinnhuber et al., 2012). In each of the reactions, 1 to 4, reactants in the excited state can also be formed (Jones et al., 1973). In the MLT-region, the main source of NO is the reaction between an excited nitrogen atom and oxygen,

\[ N(2^D) + O_2 \rightarrow NO + O \]  

where \( N(2^D) \) is atomic nitrogen in the excited state. Another reaction which is a large source of NO, that occurs at a higher altitude, above the MLT-region, is:

\[ N(4S) + O_2 \rightarrow NO + O \] 

where \( N(4S) \) is the ground state nitrogen. Reaction 6 is however less important in this project, compared to reaction 5, due to the altitudes observed by Odin/SMR.

Different sinks for NO exist. The major sink is the reaction between NO and a nitrogen atom in the ground state, reaction 7. Other sinks are the photochemical reaction of NO and a photon, corresponding to a wave length of 190.8 nm, coming with the UV-radiation from the Sun, reaction 8, and the reaction between NO and ionized oxygen, reaction 9 (Barth, 1995).

\[ NO + N(4S) \rightarrow N_2 + O \]  
\[ NO + h\nu \rightarrow N(4S) + O \]  
\[ NO + O_2^+ \rightarrow NO^+ + O_2 \]
Transportation

To understand the transport of NO in the middle and upper atmosphere, large-scale circulation cannot be disregarded. Due to the spherical shape of Earth, the rotation and the orbit around the Sun, most of the heating occurs in the equatorial region. This radiative change in temperature gives rise to different meridional circulation cells, which even out the temperature differences between low and high latitudes. These cells are called the Hadley and the Ferrel cell. The Hadley cell is thermally driven and consists of ascending air at the equator and descending air at \( \sim 30^\circ \) latitude. The Ferrel cell is driven by eddies and consists of rising air at \( \sim 60^\circ \) latitude and sinking air at \( \sim 30^\circ \) latitude. These two cells give rise to the meridional transport in the troposphere. Unlike the situation in the lower atmosphere, in the middle and upper atmosphere, a larger circulation cell exists, consisting of upward motions at the summer pole and downward motions at the winter pole. The upward moving air at the summer pole is cooled adiabatically, which leads to lower temperatures at the mesopause, compared to the adiabatically heated air, by the downward motion, at the winter pole. This pole to pole meridional flow is caused by gravity waves, which can propagate vertically if the phase speed have the opposite sign compared to the zonal wind. When they propagate vertically, the decreasing density leads to an increase of amplitude of the gravity waves, due to conservation of energy. The waves become unstable when they have grown large enough which leads to breaking. When the waves break, energy and momentum is released. This will change the zonal flow, as well as the thermal wind balance which the atmosphere adjusts with adiabatic cooling and heating. The adjustment give rise to a meridional flow. The flow in the summer hemisphere is equatorward, and in the winter hemisphere the flow is towards the pole. These two flows lead to a summer to winter meridional flow in the mesosphere (Karlsson, 2008). The temperature gradient from the winter pole down to mid-latitudes, due to the lack of incoming solar radiation at high latitudes, creates a low pressure over the poles which in turn gives rise to a large circulating cell in the upper troposphere and up to the mesosphere. The exact height of this rotating cell, called the polar vortex, is not known.

As mentioned under section 1.1.3, NO is photo-dissociated during sunlight conditions, reaction 8. However, when the Sun is absent, at the winter pole, the lifetime of NO is extended and further transport is enabled. Transportation is especially important in the, more dynamical variable, Northern Hemisphere (NH). Within the polar vortex there is downwelling, which transports NO from high altitudes, the MLT-region, to lower altitudes, the stratosphere. In the stratosphere NO\(_x\) contributes to the depletion of ozone (Smith-Johnsen et al., 2017). In the Southern Hemisphere (SH), the polar vortex is normally stable, because of the topography, or lack of it, around the pole. However, the polar vortex in the NH is more variable. Sometimes planetary waves propagate from the troposphere up into the stratosphere and brake. The release of energy into the stratosphere disturbs the polar vortex and may lead to its break-up. This phenomenon is called a Sudden Stratospheric Warming (SSW) and leads to a strong increase of temperature. In the weeks following after a SSW, the polar vortex builds up again at higher altitudes, which enables a stronger descent of mesospheric air into the stratosphere (Pérot et al., 2014). Although this breakup of the polar vortex, and the following stronger descent of air, does not happen every year in the NH, Orsolini et al. (2010) showed that for three out of eight years, the Arctic region experienced a stronger descent of air from the mesosphere into the stratosphere, after a SSW during winter time.

The air inside the polar vortex is isolated and little mixing occurs with the air outside the vortex. This leads to an accumulation of NO inside the polar vortex, which increases the density of NO at high latitudes during winter time. The summer pole, on the other hand, does not have a strong polar vortex with downwelling and that isolates air. This results in a shorter lifetime of NO, due to the incoming solar radiation, and a larger mixing of air, which decreases the density, compared to the winter pole. However, due to the summer to winter circulation in the mesosphere, NO can also be transported to lower latitudes in the summer hemisphere, especially during night time.

1.1.4 Geomagnetic indices

There are several solar- and geomagnetic indices that show the current, and historical, status of Earth’s magnetic field and how the solar wind and incoming CMEs affect it - in short, measures of geomagnetic activity: the Auroral Electrojet (AE) index, the Disturbance storm time (Dst) index, the planetary K
The Auroral Electrojet (AE) index is used for studies in aeronomy, Sun-Earth physics and geomagnetism. It was first presented in 1966 as a measure of electrojet activity in the auroral zone by Davis and Sugiura (1966). The auroral electrojets, one at each magnetic pole, are electric currents containing electrons at an altitude between 100 and 150 km. There are 12 observatories located in the NH (between latitude 61° - 74°) within the auroral zone. These observatories measure variations in the horizontal component of the geomagnetic field, where H being the horizontal, along the geomagnetic north direction, geomagnetic field component. The AE index is then derived from the variations in component H. The AE index is defined as the difference between the AU and AL index, $AE = AU - AL$. The AU index represents the maximum intensity of the current in the eastward electrojet and is the largest value of H deviation, whilst AL represents the maximum intensity of the current in the westward electrojet and is the smallest H deviation value. The difference of these two currents is the general activity in the auroral electrojet. The auroral electrojet is usually located around the auroral oval, but under times with a larger geomagnetic activity, the auroral electrojet both moves in location and in intensity. When CMEs reconnect with Earth’s magnetic field, and give rise to an enhanced EPP, the electrojet becomes disturbed and the AE index increases - i.e. the higher the AE index, the higher the geomagnetic activity (Menouville et al., 2011).

The Disturbance storm time (Dst) index is derived from the hourly average values of the H component. It is based on measurements from four different observatories (on latitudes -34.43°, 18.11°, 21.32° and 36.23°). The full definition of the Dst index is found in Menouville et al. (2011), and it is dependent on time, the disturbance variation of H and geomagnetic latitudes at all four observatories. There is a global electrical current at the equator, called the equatorial electrojet (or the ring current) at an altitude between 90 km to 150 km. This current is nearly always flowing in a westward direction. During geomagnetic storms and EPP, energy is injected into the equatorial electrojet. This increase of energy depresses H. The perturbation of H is measured by the observatories and from these measurements, the Dst index is derived. The disturbance field in H, generated by a geomagnetic storm, is directed southward, which means that the Dst index gets more negative the more intense the storm is. So, for higher geomagnetic activity, the Dst index becomes smaller (Menouville et al., 2011).

The planetary K (Kp) index and the planetary A (Ap) index are related to each other. The Kp index is derived from the K index and the Ap index is a linear version of the Kp index. The K index is a quasi-logarithmic index on the scale 0-9 and is used for measuring the geomagnetic activity at subauroral latitudes (latitudes between 45° and 55°). It measures the fluctuations of the horizontal components in the magnetic field at different specific locations. Higher fluctuations are needed at higher latitudes to achieve a higher K index value. The Kp index, as mentioned before, is derived from the K index by taking the average of fluctuations for the horizontal components. The measurements for the K index come from eleven different observatories, the majority of which are in the northern hemisphere. The Kp index follows the same scale as the K index, ranging from 0 to 9. Since the Kp index is quasi-logarithmic, the need for a linear relation between an index and geomagnetic activity resulted in the creation of the Ap index. The values of the Ap index are acquired by using a table for conversion. The scale of the Ap index goes from 0 to 400, where a Kp value of 0 corresponds to an Ap value of 0, and a Kp value of 9 corresponds to an Ap value of 400 (Menouville et al., 2011).
2 Method

The purpose of this section is to go through the methodology of the project. As mentioned in section 1, the aim of the project is to investigate the response of NO due to geomagnetic activity by analyzing data from the SMR-instrument on board the satellite Odin. The data itself, both from Odin and the geomagnetic indices, will be discussed here, together with general information about the satellite and the setup of the project.

2.1 The Odin satellite

Odin, which has a total weight of 250 kg and dimensions of $2 \times 3.8 \times 3.8$ m, is a satellite created in collaboration between Sweden, Finland, Canada and France. It was launched from Svobodny, Russia on 20 February 2001. From the beginning Odin was used for both astronomy and aeronomy studies, but since 2007 the mission is, with a few exceptions, focused on aeronomy studies. The satellite project had several initial goals before the launch. The goals were split up into four different categories: stratospheric ozone science, mesospheric ozone science, summer mesosphere science and coupling of atmospheric regions.

Odin orbits Earth at an altitude of 620 km. The orbit is sun-synchronous, meaning it passes every point at the same local time, and it follows the border between night and day. It passes near the poles, so it follows the local time of 18:00 at one side of the Earth, and on the other side, it follows the local time of 06:00, except when it is traveling over the poles. This type of orbit positions Odin so it always is in the sunlight Murtagh et al. (2002). Initially, the lifetime of Odin was estimated to be around two years, but it is still active, making 15 orbits each day collecting data with a vertical velocity of 750 km/s.

![Figure 4: The different parts of Odin. Picture taken from Murtagh et al. (2002).](image-url)

There are two different instruments on board Odin, the sub-millimetre radiometer (SMR) and the Optical Spectrograph and Infrared Imager (OSIRIS), figure 4. These two instruments are aligned together and point at the limb of the atmosphere. Then, the whole satellite tilts up and down to take measurements on different tangent heights, which enables determination of altitude distributions. The movement of the satellite is controlled by an altitude control system, which uses star trackers as its main sensors. The satellite also has magnetometers, Sun-sensors and gyros to help with the movement control. On top of Odin, there is a Gregorian telescope, measuring 1.1 m in diameter, used in the astronomy studies. The satellite includes a protecting plate with solar-panels, which powers the electronics. An antenna is mounted on the plate and is used to send information and data down to ground station control, located at Esrange in northern Sweden. Data is usually sent to the control station 10 times a day. This depends on the orbit of Odin and the distance from Esrange (Murtagh et al., 2002).

The data used in this project are measurements done by the sub-millimetre radiometer instrument on board Odin. The instrument observes the emission lines of several molecules: NO, ozone, chlorine monoxide and nitrous oxide. The instrument consists of four sub-millimetre channels, within 486.1 - 580.4
GHz, and one millimetre channel at 119 GHz. It has the possibility to scan the limb of the atmosphere at tangent heights of 10 - 120 km. More information about the instrument, the retrieval procedure, and errors of the measurements are found in the articles by Murtagh et al. (2002) and Baron et al. (2002).

2.2 Data

The satellite data came in netCDF-format and included values for different variables, such as temperature, time of measurement, date, pressure, latitude/longitude and volume mixing ratio of NO. The data included measurements for 20 different heights, for each measurement in time. The datasets covered two different periods in time. The first period stretched from 2014-11-29 to 2014-12-04, but in this dataset data from 2014-12-02 is missing. The second period was smaller than the first and stretched from 2014-12-22 to 2014-12-23, with missing data in the middle of the period.

Since the data of NO came in the units of volume mixing ratio it was converted into number density, and only the number density of NO was then used.

The relation between number density (nd) and volume mixing ratio (vmr) is:

\[ NO_{\text{nd}} = n_a \cdot NO_{\text{vmr}} \]  \hspace{1cm} (10)

where \( NO_{\text{nd}} \) is the number density of NO, \( n_a \) is the density of air and \( NO_{\text{vmr}} \) is the volume mixing ratio of NO. The density of air, \( n_a \), is defined as:

\[ n_a = \frac{A_v \cdot N}{V} \]  \hspace{1cm} (11)

where \( A_v \) is Avogadro's constant \((6.022 \cdot 10^{23} \text{ mol}^{-1})\), \( N \) is moles of air and \( V \) is volume. The ideal gas law is:

\[ PV = NRT \]  \hspace{1cm} (12)

where \( P \) is pressure, \( V \) is volume, \( N \) is the number of moles, \( R \) is the gas constant \((8.3145 \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1})\) and \( T \) is temperature. Combining equation 10, 11 and 12, the conversion equation is obtained:

\[ NO_{\text{nd}} = \frac{A_v P}{RT} \cdot NO_{\text{vmr}} \]  \hspace{1cm} (13)

Equation 13 shows that number density is dependent on both pressure and temperature. During the conversion, measurements of both temperature and pressure from Odin were used. Number density was chosen over volume mixing ratio because of the large differences in temperature in the MLT-region on a global scale. Temperature affects pressure, and thus the number of particles. Number density includes both temperature and pressure, which simplifies the comparison between regions with different values of these parameters.

Every measurement was unique in respect to altitude; the values of NO are interpolated onto a fixed altitude grid, ranging from 80 km - 120 km, with a resolution of 2 km. Before the interpolation, the altitude profile of NO was controlled in an altitude spacing check, where the maximum space between two consecutive data points of NO was set to 4 km. This showed that the data was not reliable above 116 km and therefore only data below 116 km is used.

Meridional means were used for different latitude intervals. These were computed by choosing every data point that included the chosen latitudes (for example 70° - 90° for the north pole). Then the
mean values of NO were computed for each region at each altitude level. This could however lead to variabilities in the data between points within the same region. The means were used nevertheless to be able to examine how the different regions differ with respect to NO density. Meridional profiles were also computed, for each latitude. For example, the mean of NO number density for every data point at latitudes 60 to 61 was computed. In the data, a value of latitude at every altitude was given, because Odin moves during each scan. The satellite moved approximately 3° between each scan. The middle position latitude for the whole height distribution was used instead and was also used in the conversion into geomagnetic latitudes. Geomagnetic latitudes are defined relative to the geomagnetic poles, instead of the geographic poles, as the tangent latitudes. Most of the results are shown in geomagnetic latitudes, except results involving the equator. Geomagnetic coordinates are important because the geomagnetic pole is not located at the same location as the geographical pole. The energetic particles precipitate down around the geomagnetic pole. To identify if NO is formed due to EPP, geomagnetic latitudes are used.

The time of each data point given was in Universal Time Coordinated (UTC) format. UTC is the same as Greenwich mean time, except from that it excludes daylight saving time. To be able to differentiate between morning data and evening data, the time in UTC was converted into local time (also excluding daylight saving time). The longitude related to UTC-times is 0°. For every 15° east of this location, the local time moves forward one hour. To compute the local time, first the difference in latitude is determined, then this difference is divided by 15 to establish the difference in time. To get the final local time, the difference in time is added to the UTC time. However, this is only valid for the 180° east of Greenwich. To the west, the difference in time is instead subtracted from the UTC-times. The conversion to local time was made to divide the data into morning and evening. The morning and evening densities were used to see how sunlit and dark periods affect NO density. Some regions were however either constant dark or constant sunlit, which one must have in mind during the analysis.

The data of the AE-, AP- and Dst indices comes from WDCG, Kyoto (2017), while the Kp index data comes from SPIDR (2015). The AE- and Dst indices are one hour means and Kp- and Ap are three hourly means. During the correlation analysis, only the AE index is used, while for the regression analysis both the AE and Kp indices are used. The Dst index is excluded because earlier research, for example by Hendrickx et al. (2015), shows that the AE index gives reliable results in a correlation analysis.

Figure 5 shows all local times, as a function of latitude, for all measurements. The times are either around 06:00 or 18:00 at sub-polar latitudes. Local time varies quickly when Odin passes the pole. This is due to the orbit; Odin does not pass directly over the poles, which changes the local times compared to sub-polar latitude, when Odin is located on the terminator. This figure also shows that Odin follows the sun-synchronous orbit, and that the measurements can be divided into morning and evening data.

The data of the AE-, AP- and Dst indices comes from WDCG, Kyoto (2017), while the Kp index data comes from SPIDR (2015). The AE- and Dst indices are one hour means and Kp- and Ap are three hourly means. During the correlation analysis, only the AE index is used, while for the regression analysis both the AE and Kp indices are used. The Dst index is excluded because earlier research, for example by Hendrickx et al. (2015), shows that the AE index gives reliable results in a correlation analysis.

Figure 5: The local time, and latitude, converted from each data point obtained from Odin.
2.2.1 Correlation and regression

In this study, the correlation coefficient is computed between values of NO density and two geomagnetic indices (AE and Kp). The correlation coefficient is an indicator of how well data points from two variables fit a straight line. The correlation coefficient examined in this study is Pearson correlation coefficient, which is defined as:

\[
\rho(x, y) = \frac{1}{1 - N} \sum_{i=1}^{N} \frac{(x_i - \bar{x})(y_i - \bar{y})}{\sigma_x \sigma_y}
\] (14)

where \(\rho(x, y)\) is the correlation coefficient between variables \(x\) and \(y\), \(\bar{x}\) is the mean and \(\rho_x\) is the standard deviation for variable \(x\) (and analogously for variable \(y\)). The correlation coefficient ranges between -1 and 1, where 1 indicates perfect linear relationship, -1 indicates anti-correlation and 0 indicates that there is no linear relationship between the two variables. A perfect linear relationship means that the data points from the two variables lie on a straight line in a scatter plot. Two variables are more correlated the closer the correlation coefficient is to 1. The correlation coefficient is a reliable statistical tool to examine linear relationships between two variables. However, data sets with a finite number of data points can show large correlation by chance. To remove the chance that uncorrelated variables show correlation a significance test is made (Taylor, 1997).

Significance tests are performed to examine if the results are statistically significant. The purpose of significance tests is to distinguish if the null hypothesis is true or not. The null hypothesis is a default statement that there is no relationship between two variables. In this study, the null hypothesis is that higher geomagnetic activity does not have any impact on NO density. If the null hypothesis is rejected, an alternate hypothesis could be assumed, which is that there exists a relationship between geomagnetic activity and NO density. To test the null hypothesis different methods can be used, and in this study the probability value (p-value) is applied to the correlation coefficients. The p-value is the probability of a sample to show the measured values as for a true null hypothesis. If the p-value is lower than a chosen significance level - which, in this study is 5%, the null hypothesis is rejected, and the correlation coefficients are significant. The p-value method was chosen because it is widely used in many scientific fields, and is a reliable significant test if used correctly (Taylor, 1997). The p-value shows if a correlation is significant, or if the null hypothesis is true, but it does not support the probability of the alternate hypothesis. However, this can be tested further with a regression analysis.

Linear regression analysis is used, in a similar manner to correlation, to examine the strength of a relationship between two variables, by constructing a linear model. The linear model is used to predict the behavior of a dependent variable \(y\) (NO density) based on an independent variable \(x\) (AE and Kp indices). The distance between the data points and the linear model determines the relationship strength between the two variables. To examine how well the data points fit the linear model, the coefficient of determination (\(R^2\)) is computed. This coefficient indicates how much of the observed variance in the data set can be explained by the model. The values of \(R^2\) range between 0-1, where 1 means that the dependent variable can be predicted perfectly from the independent variable (Noone and Vong, 2011).

The correlation coefficient and \(R^2\) do indicate the strength of the relationship between the two variables, especially when the reasoning is based on the two together. However, large values of these two do not necessarily show the exact truth. Other processes could be involved, affecting the results. It is known that NO is formed by energetic particles. The time scale of the formation is, on the contrary, not certain. This is the reason different correlation and regression coefficients are computed for different lag times. However, the reactions involved in the formation of NO are dependent on other variables, such as temperature. These processes are disregarded in this study, and only the direct relationship between the geomagnetic indices, primarily the AE index, and NO density is in focus in the analysis, due to the main objective of the project: the geomagnetic impact on NO and how this is seen in the Odin/SMR data.
2.2.2 Data limitations

The data used comes from satellite observations and contains inherent limitations. Satellites can not scan the whole globe at the same time; instead they scan small strips, where each observation is at a certain time and a certain location. What happens outside the possible observation area is thus not known. It takes approximately 1 hour and 40 minutes for Odin to orbit the Earth. As a result, when analyzing one special meridional region, measurements have small temporal gaps. However, these gaps are shorter compared to many other satellites, and the formation time of NO after an enhanced geomagnetic activity is longer than the orbit time. Due to the fact that the data is a time line of NO density, this could have an impact on the results when computing meridional means. Different fast processes, such as dynamics or earlier fluctuations in the geomagnetic activity, can affect the NO formation and distribution, resulting in variabilities inside the meridional region affecting the NO densities. Since NO observations are not Odin’s primary objective, the satellite needs to be reconfigured before measurements of this molecule can begin. For this reason, the data sets cover a relative short time. This also makes it more difficult to match an incoming CME with NO observations. These relatively short data sets are also sensitive to observation interruptions, especially when a certain meridional region is examined.

![Figure 6: The time evolution of NO density in the Northern hemisphere auroral region (60° - 70° geomagnetic latitude) as a function of altitude. The AE index is also shown, with values on the right y-axis.](image)

Figure 6 shows the time series of the NO density, and all the gaps in the data, as an example. When using a small area such as the auroral region, much data is missed due to the satellite orbit. However the major problem with this data is the missing part in the middle of the data set. A whole day of observation is missing, which makes it difficult to connect NO density with the geomagnetic indices. Longer data sets, including both high and low geomagnetic activity, would be very beneficial. To be able to analyze the winter polar areas, data from before the start of increased geomagnetic activity is most useful so that the accumulated NO could be removed and only the newly formed NO could be seen. Hendrickx et al. (2015) (and references within) stated that the largest correlation between NO production and the AE index is found after 1 day. Figure 6 shows that data is missing 1 day after the AE index peak. However, this data set has a higher temporal resolution, compared to the one Hendrickx et al. (2015) used, which would make it interesting to see whether the 1 day lag still gives the best results. The most interesting data for the lag analysis is missing based on that. There is also a large gap in observations of the first period, that covers a day. Sheese et al. (2011) concluded that, through a correlation analysis, the descent rate in the Southern hemisphere during night time is 3.8 km/day in the MLT-region. Even though the dynamics between the North and South pole differ during polar winter, mainly because of differences in topography, that kind of descent rate could be assumed in the North pole. This is not something that could be analyzed with the current Odin/SMR data due to the gaps in the time series.

The variability in the data is investigated by computing the standard deviation (STD) of the computed mean values. The ratio between these two shows how varied the data is. For high values of the ratio, large fluctuations exist in the data, and vice versa for low ratio values. This ratio is called the coefficient...
of variation ($c_v$) which is defined as:

$$c_v = \frac{\sigma_x}{\bar{x}}$$

(15)

where $\sigma_x$ is the standard deviation and $\bar{x}$ is the mean for a variable $x$. There are differences between the examined regions in terms of incoming sunlight and NO formation which have an impact on NO densities. To be able to compare the regions in terms of variability between the data points within each region, the coefficient of variation is computed, which shows the relative standard deviation.

### 2.3 Project setup

The setup of the project is based on the three questions in section 1. The data was collected during two periods, the second period being more geomagnetically active than the first period.

![Figure 7: AE index, in November and December 2014. First period is shown within the black lines and the second period within the red lines.](image)

Figure 7 shows the AE index for the two last months of 2014. One can see that the first period starts geomagnetically quiet, but has some activity in the middle of the period. The second period, on the other hand, shows strong activity in the beginning, but with a strong decrease in activity towards the middle. Then, at the end of the period, the activity increases again. Even though the AE index shows less activity in the middle of the second period, the strong activity in the beginning of the second period makes it more geomagnetically active than the first period, and especially interesting for the studies of the time-lag of NO formation.
Figure 8: Kp index, in November and December 2014. First period is shown within the black lines and the second period within the red lines.

Figure 8 also shows the same time period for the Kp index, and also indicates that there is enhanced geomagnetic activity at the beginning of the second period.

Table 1: The auroral activity for different values in Kp index and where the auroras can be seen. Data taken from Parsec vzw (2017)

<table>
<thead>
<tr>
<th>Kp</th>
<th>Geomagnetic latitude</th>
<th>Auroral activity</th>
<th>Auroras visible from (and locations on similar geomagnetic latitudes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>66.5° or higher</td>
<td>Quiet</td>
<td>Reykjavik (Iceland)</td>
</tr>
<tr>
<td>1</td>
<td>64.5°</td>
<td>Quiet</td>
<td>Jokkmokk (Sweden)</td>
</tr>
<tr>
<td>2</td>
<td>62.4°</td>
<td>Quiet</td>
<td>Umeå (Sweden)</td>
</tr>
<tr>
<td>3</td>
<td>60.4°</td>
<td>Unsettled</td>
<td>Sundsvall (Sweden)</td>
</tr>
<tr>
<td>4</td>
<td>58.3°</td>
<td>Active</td>
<td>Stockholm (Sweden)</td>
</tr>
<tr>
<td>5</td>
<td>56.3°</td>
<td>Minor storm</td>
<td>Gothenburg (Sweden)</td>
</tr>
<tr>
<td>6</td>
<td>54.2°</td>
<td>Moderate storm</td>
<td>Dublin (Ireland)</td>
</tr>
<tr>
<td>7</td>
<td>52.2°</td>
<td>Strong storm</td>
<td>London (England)</td>
</tr>
<tr>
<td>8</td>
<td>50.1°</td>
<td>Severe storm</td>
<td>Paris (France)</td>
</tr>
<tr>
<td>9</td>
<td>48.1° or lower</td>
<td>Extreme storm</td>
<td>Madrid (Spain)</td>
</tr>
</tbody>
</table>

Table 1 shows the intensity of geomagnetic activity based on different values of the Kp index, and where auroras could be seen for these values. Figure 8 and table 1 show that during the first period, the Kp index did not exceed 4, and the auroral activity was unsettled, while during the start of the second period there was a minor storm and the end of the second period was active. Auroras could be seen down to latitudes corresponding to Gothenburg. The Dst index (not shown) shows mostly positive values during the first period, while in the beginning of the second period, the Dst index shows values of -50. As mentioned in section 1.1.4, the Dst index becomes more negative for more intense storms, and this also confirms that the second period was more geomagnetically active.

Execution of the project

The data within the periods was divided into different meridional areas, the North/South pole (± 60° - 90°), the equator (−15° - 15°), mid-latitudes (± 30° - 60°) and the whole Northern or Southern hemisphere. When the measurements were taken, in late 2014, the South pole experienced summer and the North pole experienced winter. The summer and winter poles are compared with respect to NO density to investigate the response to increased geomagnetic activity. Due to the low geomagnetic
activity during the first period, this could be seen as a reference case. The variability of the values in the computed means was also controlled by examining the ratio between standard deviation and meridional mean.

The data was also divided into morning and evening, see figure 5. The morning data is every data point before 12:00, and the evening data is every data point after 12:00. As described earlier the local times of most of the data points are either 06:00 or 18:00. To simplify the analysis, the percentage difference between morning and evening was computed, both for the equator area and for both hemispheres. Both the difference and the ratio between morning and evening densities were computed and these two methods showed the same locations for either larger morning or evening densities. However, the use of percentage difference makes it clearer which regions have higher NO densities compared to the other two methods. To examine the variability in the data, the ratio between the standard deviation and meridional mean was computed.

The correlation analysis was done by computing the correlation coefficient between data points on NO density and the AE index, for different meridional areas. Different lags in the AE index were introduced, and the lags were applied by choosing values of AE from 1, 2, 3, etc hours before the time series of NO density began. The correlation coefficient between the lagged time series of the AE index values and the time series of NO density was then computed, so that one value of NO density at a certain time was matched to an AE index value at the same, or a lagged, time. The correlation coefficients were computed for both a one hour mean and a three hour mean of the AE index and NO density. Only the significant correlations, with a p-value below 0.05, were used. The regression analysis was done in a similar way, but instead of computing the correlation coefficient, the coefficient of determination ($R^2$) was computed by making a linear fit between the AE and Kp indices (with different lags) and NO density. To investigate if the linear relations that are used in today’s models are accurate, the regression analysis is carried out with both linear and logarithmic values of NO density.
3 Results and discussion

In this section, figures of NO density will be shown and discussed. First, the difference between the first and second period for different areas are analyzed, followed by a discussion of the differences between morning and evening. Lastly, the correlation and regression analysis is presented.

3.1 NO densities, comparison between the first and second period

A comparison between the two periods with respect to NO density in the MLT-region is shown in this section. This comparison is made for different meridional regions over the globe. As mentioned in section 2.3, the first period experienced calmer geomagnetic conditions compared to the second period and should, based on the theory, show a lower number density. The two periods will also be compared to earlier measurements, done by Barth et al. (2002).

The measurements were made in late 2014, i.e. it was winter in the Northern hemisphere and summer in the Southern hemisphere. This will influence the NO distribution in the MLT-region.

![Figure 9: Meridional mean of NO number density, with corresponding standard deviation, for different areas and altitudes. First period is shown in figure 9a and second period in 9b. The polar areas are chosen between 60° and 90° (for both NH and SH), the mid-latitudes are between 30° and 60° (for both NH and SH) and the equator is between -15° to 15°](image-url)
Figure 9 shows the altitude profile of the meridional mean of NO for both periods and different areas, with corresponding standard deviation. One can easily see that the North pole has the highest NO density mean of all areas, and the second period at the North pole has the maximum NO. The percentage difference between the first and second period for the North pole is \( \sim 50 \% \). The second period has the highest NO density for all areas. The percentage difference between the North pole and South pole, for the second period, is \( \sim 97.5 \% \). The difference between the areas for both periods respectively is small, North pole excluded. Except for the North pole, the second period South pole has the highest number density, followed by the mid-latitudes. The equator has the lowest.

The error for the North Pole is large in each period. However, the NO number density in this area still exceed the others, at each area altitude of peak number density, even if one uses the lowest possible values of North polar NO. The largest mean value for the second period is larger than one standard deviation for the first period. Even though the error fields overlap for the North pole between the periods, the second period has twice the NO density mean which is a strong indicator that there was more NO in the MLT-region during the second period. When investigating the other areas, excluding the North pole, the error fields overlap. This make it hard to draw conclusions about which area having a larger number density than the others. These areas have equal large errors except for the norther mid-latitudes and the reason of this is discussed further down, under “uncertainties”.

Barth et al. (2002) presented altitude profiles of NO densities for both the auroral region and the equator, measured from the Student Nitric Oxide Explorer (SNOE) between 1998-03-11 to 2000-11-30. The 11-year solar cycle was on the rise during this time (solar maximum was reached in 2001). For the equatorial region, the NO densities observed by SNOE were larger than the SMR mean NO densities, however for the auroral region the SMR data showed larger mean values of NO compared to the SNOE data. The maximum mean, observed by SNOE, for times with high geomagnetic activity, was \( 1.3 \cdot 10^{8} \text{ cm}^{-3} \) for the equatorial region and \( 3.8 \cdot 10^{8} \text{ cm}^{-3} \) for the auroral regions. These maxima were measured at an altitude of 110 km. The maximum mean value for the auroral region from the SMR data, figure 9, measured during the second period at the North pole, was \( 4.5 \cdot 10^{8} \text{ cm}^{-3} \) and around \( 1.0 \cdot 10^{8} \text{ cm}^{-3} \) for the equatorial region. The region around the equator does not experience a high seasonal variability in incoming solar radiation, temperature or dynamics. The equatorial SMR data of NO density is therefore directly comparable to the data Barth et al. (2002) presented, except for the difference in solar cycle (solar maximum was reached in early 2014). NO formation at the equator regions is dependent on X-rays, instead of EPP. The equatorial data from SNOE was divided into three categories, low, mid and high solar activity. The definition of high solar activity by Barth et al. (2002) was a 10.7 cm radio flux over 165 “solar flux units” \( (1 \text{ sfu} = 10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}) \). During the second period in the SMR data the 10.7 radio flux went from 173.4 sfu to 160.5 sfu, i.e. mid to high according to the Barth et al. (2002) classification. The reason for the lower NO densities in the SMR data is likely due to lower 10.7 radio flux values in parts of the second period compared to the SNOE measurements. The auroral region densities from Barth et al. (2002) were measured around the equinox periods, which makes it hard to directly compare this data to the SMR data, because of seasonal differences. However, this gives an indication that the winter densities are higher than the equinox densities. The auroral region data from SNOE was divided into three categories: low, mid and high geomagnetic activity. The definition of low activity was set to an Ap value less than 6, the mid activity was an Ap value between 6 and 12 and high activity was set to 12 or greater. An Ap value of 12 corresponds to a Kp value slightly less than 3 (Parsec vzw, 2017), which in table 1 corresponds to quiet conditions. This means that some of SNOE’s data did not represent high geomagnetic activity, and this may have lowered the mean of NO density. The NO densities chosen from periods with high geomagnetic activity, from the Barth et al. (2002) classification, were in fact observed during period of quiet geomagnetic conditions, and thus lower. The different time of measurement and the definition of high geomagnetic activity therefore explain the difference of SNOE NO density and Odin/SMR NO density in the auroral region.

The altitude profiles, for the different areas, figure 9, have a similar structure, but with different locations and magnitudes of the maxima. The one that stands out is the mid-latitude Northern hemisphere profile. It consists of a sub-peak in density at around 92 km, and then the density decreases slightly until it starts increasing again up to the real peak at around 106 km. Except for the North pole, every area has its NO maximum at around 106 km. The North pole, on the other hand, has its NO maximum further down, compared to the other areas, at around 92 km. There are small differences in density at the top of the profile at all areas between the periods except for the equator. This will be discussed in the end of this
section. The altitude profiles are further examined by investigating the zonal mean of NO density.

Figure 10: The logarithm of zonal mean NO density for the first period plotted against altitude and geomagnetic latitude. The Southern hemisphere is found in the left half of the figure and the Northern hemisphere is found to the right in the figure. The red line represents the altitude for which every latitude has the highest density.

Figure 11: The logarithm of zonal mean NO density for the second period plotted against altitude and geomagnetic latitude. The Southern hemisphere is found in the left half of the figure and the Northern hemisphere is found to the right. The red line represents the altitude for which every latitude has the highest density.

Figure 10 and 11 show the logarithm of the zonal mean NO number density for both hemispheres as a function of geomagnetic latitudes, for each period respectively. Both figures show an enhanced density at latitude 60° and towards the pole in the Northern hemisphere, but the second period has higher values. The red line also shows that the maximum density descends northward of 50° from ~106 km to ~94 km. In the Southern hemisphere, the maximum density is rather constant in altitude, with small fluctuations in altitude the second period, but with no strong descent towards the poles as in the Northern hemisphere. In the second period, at -60°, enhanced densities are seen, compared to the same latitude during the first period. It can be seen in figure 3 that the auroral electrons typically account
for the most of the ionization at an altitude of 110 km. At around 100 km, the auroral electrons and the radiation belt electrons are equally active. The maximum Southern hemisphere NO density is at an altitude of 106 km in both periods, but the enhanced densities in the second period may depend on the enhanced EPP of auroral electrons. Sinnhuber et al. (2012) showed that electrons precipitate at ±65°. The maximum meridional mean of NO at the South pole (60° - 90°) was 1.65 · 10^8 cm^-3, in the second period. However, the maximum meridional mean of NO in the auroral region (60° - 70° geomagnetic latitude) was 1.87 · 10^8 cm^-3, during the same period. Figures 9, 10 and 11 show that the second, more geomagnetic active period have higher NO densities in the MLT-region, in general, but especially in the auroral region in the Southern hemisphere and in the whole polar region in the Northern hemisphere. The enhanced densities at the North pole reach further down the atmosphere. Even though the formation of NO occurs at ~ 65° geomagnetic latitude, the NO density increase is the most prominent at higher latitudes due to the polar vortex, where an accumulation of NO occurs. Sheese et al. (2011) found that the peak in EPP-NO was found at altitude of 95 km near the winter solstice in the Southern hemisphere. The NO was however formed at higher altitudes and was transported down to lower altitudes. This seems also to be the case in the Northern high latitudes. However, it is not only the polar vortex that contributes to the enhanced NO densities at the North pole, it is also the lack of sunlight, via reaction 8. UV-radiation from the Sun is a sink for middle atmospheric NO. High latitudes in the Southern hemisphere experience more UV-radiation than in the Northern hemisphere. NO in the Southern hemisphere is destroyed quite fast while in the Northern hemisphere it accumulates to higher densities. The combination of the polar vortex and the lack of UV-radiation leads to greater densities at lower altitudes at the North pole, compared to the South pole.

Figures 9, 10 and 11 show larger mean densities of NO at the Southern mid-latitudes compared to the Northern mid-latitudes. This is most likely due to the large global circulation from summer pole to winter pole which transports the formed NO at the Southern auroral region to lower latitudes. The equator is not shown in figures 10 and 11 because of the use of geomagnetic latitudes. However, figure 9 shows that the equatorial MLT-region mean NO number density was slightly larger during the second period, compared to the first period.

Uncertainties

The data used to compute the meridional mean of NO number density was measured at certain times and locations, which implies that the atmosphere within a meridional region experienced different properties and dynamical conditions. The winter hemisphere experienced the largest variability which affected the NO number density. Standard deviations (STD) are used to examine how the different values within each region vary.

![Coefficient of variation](image.png)

**Figure 12:** The coefficient of variation (c_v) for each region in percent, for different altitudes.
Figure 12 shows the coefficient of variation, computed with the mean values shown in figure 9, for the different regions, as a function of altitude. The southern hemispheric regions and the equator, show a relatively small $c_v$, compared to the same region in the northern hemisphere. The largest $c_v$ is found in the northern mid-latitudes at the lowest observed altitudes and at the north pole. The other regions show similar profiles where the $c_v$ differs slightly between each region. Although these regions show smaller $c_v$ values, the variability in the data is high. The standard deviation for the northern mid-latitudes is almost twice the size of the mean at the low altitudes. The observed NO densities are varied and the reason for this is found in figures 11 and 10. The chosen northern limit for the mid-latitudes is set to $60^\circ$, which is often inside the polar vortex, where large NO densities are found, while lower latitudes within the same region show small amounts of NO. This leads to large differences between the NO density values within the chosen mid-latitude region. However, due to the low mean of NO density, the value of the STD is approximately $0.5 \cdot 10^8\, \text{cm}^{-3}$ at an altitude of 82 km, where the largest STD is found. The same principle goes for the northern polar region, where larger data variability is found at lower latitudes, which increases the STD. Lower mean values are more sensitive to fluctuations between the data points, which implies that when the STD is high for a high mean, the fluctuations between the data points are large, as in the North pole region.

To summarize, the second period had higher NO densities. The two poles showed different NO density profiles, where the NO accumulated into large values at the North pole (winter), while at the South pole (summer) NO was destroyed faster and no accumulation took place, leading to less NO in the MLT-region. The highest NO density observed by Odin/SMR was found at the North pole during the second period. This value was higher than previous observations made by Barth et al. (2002). This may be explained by the time of the observations; Barth et al. (2002) used observations from the equinox, while in this project the observations were from the time of winter solstice. The other areas had similar values in NO density with overlapping error fields, figure 9. No direct comparison between these areas are possible, except for concluding that the NO number density mean were higher during the second period in general.

3.2 Morning and evening

In this section, the difference between morning and evening with respect to NO density for different meridional regions will be investigated. This can be used to analyse whether the production and loss mechanisms in the models are correct. As previously mentioned, the time scale of NO formation and destruction is not fully known. To develop a deeper understanding of this, high temporal resolution data is used to examine how the morning and evening densities differ.

As explained earlier, the lifetime of NO is dependent on sunlight, or the lack of it. In sunlit conditions the lifetime decreases drastically, compared to dark conditions, due to reaction 8. Because of the importance of sunlight, there should be a difference between morning and evening with higher NO densities in the morning.
Figures 13 and 14 show the difference in percentage between the morning and evening in NO density for the two periods respectively. The equatorial region has no seasonal variability, which means that the Sun sets and rises at approximately the same time all year round. This makes the equatorial region a good location to analyze the differences in NO between day and night. With the exception of the equinoxes, it is difficult to analyze this at high latitudes because of the seasonality and in respect of incoming sunlight. The North pole experiences no incoming solar radiation, while the South pole experiences incoming solar radiation all the time, during the time of the measurements. Therefore, there should not be any difference between the morning and the evening due to sunlight.
Figure 15 shows the largest difference between morning and evening mean NO number density for the first period is found at \(\sim 97\) km and was \(33.1\%\). For the second period, the largest difference is found at \(\sim 96\) km, due to the fact that the atmosphere had shifted from darkness into light, when these measurements were made. The photo-dissociation, reaction 8, had not had enough time to destroy NO, compared with the evening values. This is what is expected because in the equatorial region, it is the solar X-rays that contribute to the formation of NO. This means that both formation and destruction of NO occur during the day, and only accumulation occurs during the night. According to Barth et al. (2002) the solar X-ray in the 2 - 5 nm wavelength region is most effective in NO formation at an altitude of 113 km. This explains the larger evening densities at altitudes above \(\sim 108\) km, for both periods, in figure 15. During the night no formation or destruction of NO occurs. NO densities are then increased due to the diffusion of molecules from the formation altitudes and an accumulation at lower altitudes is seen in the morning densities.

There is however hard to conclude which time and period that has the highest number density due to the overlapping standard deviation in figure 15. On the other hand, at the altitude where the difference is largest, the morning number densities are approximately slightly larger than one standard deviation compared to the evening densities. This indicates that the morning number densities in reality are larger than the evening ones.

In summary figures 13 and 14 show the following characteristics.

1. Higher morning densities at altitudes below \(\sim 105\) km in the equatorial region.
2. Higher evening densities at altitudes above \(\sim 105\) km in the equatorial region and the Southern mid-latitudes.
3. Enhanced morning densities above \(\sim 100\) km in the latitudinal interval between 45° and 75°.

The equatorial densities (1 and 2 in the list) are explained above. The Southern hemisphere mid-latitude (2 in the list) also depends on the X-ray NO formation, like the equatorial region. To explain the high Northern morning densities (3 in the list) geomagnetic latitudes (GML) are used.
Figure 16 shows the difference between morning and evening, for the second period, in geomagnetic latitudes (unlike figure 14 that shows the same in geographic latitudes). The first period is not shown since the only difference between the first and second period is that the second period shows larger percentage differences. The distribution of larger morning or evening differences are at the same location and altitudes. The larger morning densities are located at and around a latitude of ~ 60°. As mentioned before, NO formation due to energetic particles occurs at ~ 65° geomagnetic latitude, in the auroral region. This region experiences some sunlight during the winter season. However, the hypothesis is that the higher morning densities are due to geomagnetic activity. Even though the magnetic pole is located on the dark side of the Earth during the night, magnetic field lines go from the North magnetic pole (at the geographic South) to the South magnetic pole (at the geographic North) on the day side of Earth. As mentioned in section 1.1.2, magnetic reconnection between the IMF and Earth’s magnetic field, enabling EPP, occurs on the day side. Although high Northern latitudes experience night, incoming particles affect the atmosphere above this region. NO formation due to energetic particles leads to an accumulation of NO in the auroral region, which leads to enhanced densities in the morning. The evening densities are lower due to destruction of NO by solar radiation.

Uncertainties

When the data was split into morning and evening densities, the number of data points for the two (morning data and evening data) were reduced. The number of NO observations is approximately 4 for each latitude in the second period, for the morning and evening densities respectively. The fewer the data points are, the more sensitive the mean becomes. Similar to the results in section 3.1, the NO densities are also in this comparison influenced by more than enhanced geomagnetic activity. The data variability is investigated by examining the coefficient of variation, computed with the STD and the latitudinal averages, which were used to compute the percentage difference between morning and evening.
Figure 17 shows the coefficient of variation, as a function of altitude and latitude, for the morning densities in the second period. The other period and times are not presented as figures in the report, but the large \( c_v \) values are found at similar locations as in figure 17. The largest \( c_v \) is found in the transition area for the polar vortex, at the lower altitudes, which depends on a dynamic influence on the NO density. The northern hemisphere shows a larger variability between the data points compared to the southern hemisphere. The smallest values of \( c_v \) are found where the difference between morning and evening is smallest, as seen in figures 13 and 14, at an altitude level of \( \sim 80 \text{ km} \) and \( \sim 105 \text{ km} \).

The values of NO density seem to be most uniform at these altitudes, excluding the north polar region. There are enhanced values of \( c_v \) at both sides of the 105 km region, indicating that the NO density fluctuates mostly there. This could be because of dynamic conditions, the small data set, geomagnetic activity, or other processes. The morning and evening values are sensitive to large gaps in the data. Much can happen between two consecutive mornings, but if there is a large gap that coverts a whole day, the connection between the mornings is lost. There is also a lot of noise in the figure, which indicates that long and consistent data observation runs are needed. In general, the \( c_v \) profile shows that the standard deviation are high, compared to the mean, indicating a natural variability in the data. There are also high variations between the observed NO densities at the same latitude, suggesting that the computed differences are uncertain, due to the fact that the standard deviation in some places are as large or larger than the mean values of NO number density. To improve the analysis, other processes could also be considered, such as wind patterns, time of sunlight etc.

In summary, the North pole experienced darkness during the second period, while the South pole experienced constant sunlight. With this in mind the local difference between the morning and evening should not be substantial at high latitudes. Nevertheless, differences were found. Three interesting areas were found where differences between morning and evening were large. These areas were the north auroral region high altitudes, the equator, and southern mid-latitudes. In the equatorial region, NO is formed by X-rays at high altitudes, and is accumulated during the night, which leads to higher evening densities at higher altitudes and higher morning densities below. In the north auroral region, EPP is the most important factor for the NO formation, which can take place both during the day and night. Higher morning densities are seen at high altitudes due to accumulation of NO during the night. There is however a large variation of NO number density in the data set within each region and time of day. This is seen in the coefficient of variation and could be avoided with a longer and more consistent data set.
3.3 Correlation and regression analyses

A comparison was made in section 3.1 between NO densities in the MLT-region for the geomagnetically quiet first period and the geomagnetically active second period. That comparison showed that the NO densities were larger during the second period in general. In this section, the direct relation between NO densities and geomagnetic activity is studied. The correlation coefficient between the AE index and NO are analyzed for different lags on the AE index. A regression analysis is also made between NO densities and both the AE- and Kp indices. The correlation coefficient and $R^2$ are computed for two different areas, the auroral oval region ($60^\circ$ - $70^\circ$ geomagnetic latitude) and the polar region ($70^\circ$ - $90^\circ$ geomagnetic latitude) for both periods, but $R^2$ is computed with an altitudinal mean between 96 km and 116 km, where the highest correlations are found, except for one figure, where the altitudinal mean between 80 km and 96 km is used due to higher correlation at a lower altitude. Both regions in the Northern hemisphere for both periods will be presented, as these regions showed enhanced NO density during the time of measurements, but for the Southern hemisphere, only the second period is presented with figures. The first period in the Southern hemisphere showed few significant results.
3.3.1 Northern hemisphere

![Figure 18](image)

**Figure 18:** a) The altitude profile of the correlation coefficient in the Northern hemisphere auroral region (60° - 70° geomagnetic latitude), for different lags of the AE index and the first period. b) The coefficient of determination ($R^2$) based on a linear and logarithmic regression, respectively, for the Northern hemisphere auroral region and different lags. The regression is computed for the AE index and the altitudinal mean between 96 km and 116 km of NO density.

Figure 18 shows the correlation coefficient as a function of altitude for different lags, and the coefficient of determination as a function of lags, in the auroral region during the first period. Figure 18a shows that the highest correlation in the Northern hemisphere auroral region, during the first period, occurs with a lag of 21 and 24 hours at an altitude of ~113 km, and the correlation coefficient is below 0.5 for every introduced lag. All showed results are significant and the largest correlations are located above 100 km. None of the introduced lags show higher correlation than 0.5. The correlations are relatively weak in general and do not indicate a strong direct linear relationship between the AE index and NO density in this region and at this time.

Figure 18b shows the $R^2$ value for different lags of the AE index and NO density, in the same meridional region as figure 18a, but for an altitudinal mean of NO density between 96 km and 116 km. The largest $R^2$ value is found with the lag of 13 hours. The $R^2$ values are low in general, and for the maximum value only ~15% of the variability could be explained with a linear regression. Together with the correlations (figure 18), this indicates that there is no direct relationship between the AE index and NO densities in
this region during the first period. The auroral region in the Northern hemisphere is the transition area for the polar vortex, as can be seen in figure 10. The NO density goes from having a maximum at high altitudes, to lower altitudes within the polar vortex. The density also increases within the polar vortex, due to an accumulation of NO. Due to the orbit of Odin, measurements from both outside the polar vortex and within are included in this region, which complicates the correlation and regression analysis. The difference between the linear and logarithmic regressions is small.

Figure 19 shows the same as figure 18 but for the polar region during the first period. Figure 19a shows higher correlations above 100 km compared to figure 18a. Most of the correlation profiles follow the same trend, with an increasing correlation coefficient up to \(\sim 85 \text{ km} \), then a small decrease up to \(\sim 100 \text{ km} \), where they start to increase again up to the top of the profile. The highest correlation is found at an altitude of 115 km with 21 and 24 hours’ lag, similar to figure 18a, but with a larger correlation of 0.65. The three-hour mean (not shown) has a slightly larger correlation for the 24-hour lag, with a correlation coefficient of 0.67. The maximum NO density is located at lower altitudes in this area but the correlation could indicate that some NO production could have occurred at higher altitudes during the first period. Figure 19b shows on the other hand that \(R^2\) is quite low. However, it is still the 21 and 24-hour lags that
show the highest $R^2$ value, like the correlation. In this region, the logarithmic regression gives slightly larger values on the coefficient of determination, demonstrating a weak direct relation between the AE index and NO density in this region during the time of measurement as only up to 30% of the variability is explained by the regression. The first period was geomagnetically quiet, so one should not expect to see a strong correlation as NO formation needs energetic particles. Therefore the more geomagnetically active period in the Northern hemisphere will be studied.

(a) Correlation coefficient

(b) Coefficient of determination

**Figure 20:** a) The altitude profile of the correlation coefficient in the Northern hemisphere auroral region ($60^\circ - 70^\circ$ geomagnetic latitude), for different lags of the AE index and the second period. b) The coefficient of determination ($R^2$) based on a linear and logarithmic regression, respectively, for the Northern hemisphere auroral region and different lags. The regression is computed for the AE index and the altitudinal mean between 96 km and 116 km of NO density.

Figure 20 shows the same as previous figure but for the auroral region during the second period. Figure 20a shows a correlation coefficient between 0.5 and 0.7 at altitudes above 107 km. The highest correlation is found when the AE index is shifted 4 hours. Below 107 km, the correlation coefficient becomes negative. The lag times that showed the largest correlation in the first period, now show anti-correlation. During the second period, the NO densities were higher at high Northern latitudes, but the transition area for the polar vortex is still in the auroral region. Even though the correlations are quite high for some lags, $R^2$ is low also in the auroral region during the second period, figure 20b, which indicates that there is a weak direct relationship between the AE index and NO density. The reason for the negative correlations is unclear, but one explanation could be that some of the NO was transported away from the auroral region to higher latitudes, or lower altitudes, within the polar vortex.
Figure 21: a) The altitude profile of the correlation coefficient in the North magnetic pole region (70° - 90° geomagnetic latitude), for different lags of the AE index and the second period. b) The coefficient of determination ($R^2$) based on a linear and logarithmic regression, respectively, for the Northern magnetic pole region and different lags. The regression is computed for the AE index and the altitudinal mean between 80 km and 96 km of NO density.

Figure 21 shows the same as previous figures but for the Northern hemisphere polar region during the second period. Figure 21a shows a relatively high correlation at lower altitudes compared to figure 19a, and an anti-correlation at higher altitudes. Compared to figure 19a, it is reversed. Nearly all the different lag times show high correlation at altitudes below 96 km. This is because of the accumulated NO trapped inside the polar vortex, matching the high AE index at the beginning of the second period. The negative correlation coefficients above 105 km depend on the relative difference in density between the beginning of the time series (lower) and the end (higher). Figure 21b shows the $R^2$ values for different lag times computed from the altitudinal mean of NO density between 80 km and 96 km. This altitude interval differs from the other plots and is chosen because the largest correlations are found there, figure 21a. The $R^2$ values are the largest for the Northern hemisphere, with the largest value of 0.45 for a lag time of 8 hours. Other lag times of 7, 9, 17 and 18 hours also have $R^2$ values of roughly the same size. Even though these values are larger compared to the first period and the auroral region, the result shows that the AE index and NO density have an intermediate relationship, with 45% percent of the NO densities that is explained by higher AE index values.

The correlation and regression analysis shows that there is a relationship between the AE index and NO density at high geomagnetic latitudes in the Northern hemisphere, but only around half of the data point
shows this relationship. However, figures 10 and 11 show that the more geomagnetically active second period has enhanced NO densities compared to the first period. As mentioned in section 3.1 Sheese et al. (2011) concluded that the peak density occurs around the winter solstice at high latitudes and an altitude of $\sim 95$ km. The enhanced NO densities seen during the second period are an accumulation of NO during the whole winter, where NO has been formed by geomagnetic activity several times, and certainly from the incoming CME seen at the beginning of the second period. But the dynamics in this area make it difficult to see the direct relationship between the AE index and the NO densities. There are also periods in the time series with missing data.

### 3.3.2 Southern hemisphere

The geomagnetically quiet first period was analyzed with figures for the Northern hemisphere. No figures for the first period will be shown for the Southern hemisphere. The computation of correlation for the first period shows that there are low correlations between the AE index and NO density in the Southern auroral region, with the largest correlation coefficient on 0.45 at an altitude of 90 km with AE shifted 8 hours. The different lag then shows correlations between 0.25 and 0.4 at every altitude. The coefficient of determination is low for all lag times, with the maximum value on $R^2$ at 0.19, when AE is lagged 20 hours. For the Southern geomagnetic pole, the correlation is higher, with the largest value at $\sim 0.7$ with 20 hours’ lag at 105 km altitude. The regression also showed higher $R^2$ values, with the largest at 0.45 for a 21-hour lag. The correlation and regression analysis in the Northern hemisphere did not show any strong relation between the geomagnetic activity and NO density, mainly because of the dynamics and the gaps in data. In the summer hemisphere, however, no polar vortex exists. This does not lead to an accumulation of NO, and the lifetime is substantially shorter. As a result, formation of NO due to EPP should be easily visible in the analysis.
Eureka, shouted Archimedes when he came to think of what today is called Archimedes’ principle. Although this isn’t a eureka moment, the correlation and regression analysis shows a relation between the AE index and NO density. Figure 22 shows the correlation coefficient as a function of altitude for different lags, and the coefficient of determination as a function of lags, in the auroral region during the second period. The largest correlation in figure 22a is 0.8 and is found at altitudes above 100 km for lag times of 7, 8 and 14 hours. The corresponding $R^2$ values are 0.65, 0.64 and 0.7, respectively for the linear regression. The logarithmic regression is slightly smaller. All lag times in the interval 7 to 17 have $R^2$ values above 0.5. Here it is shown that what Barth et al. (2002) mentioned, the formation of NO due to EPP occur in the auroral region, at around 65° geomagnetic latitude, and the altitude at which the NO is formed imply that the auroral electrons participate in the formation, figure 3. However, the lag time does not match what Hendrickx et al. (2015) (and references within) showed: that the best correlation is after 1 day. This could result from the temporal gaps in the observations. The correlation coefficient for 24-hour lag is not significant, and the $R^2$ value is small, below 0.1. The difference in results can also depend on the fact that higher temporal resolution shows shorter lag times, something low temporal resolution can not.

As for the polar region (not shown), only one lag configuration had a significant correlation, at only one
altitude. This was the 24-hour lag which had a correlation coefficient of 0.5, at an altitude of 105 km, but the corresponding $R^2$ value is low, below 0.15. The largest $R^2$ value computed with the Kp index and three-hour mean of NO density is 0.5, at a lag time of 6 hours, for the auroral region. The analysis using the AE index shows larger correlation and better regression, compared to the Kp index, which Hendrickx et al. (2015) also concludes.

**Uncertainties**

The only region that shows large correlation together with large values of the coefficient of determination is the southern hemisphere auroral region, during the second period, which implies that the results have a strong relation between NO and AE. The other regions and period showed both high and low values of the correlation coefficient, but the regression indicated that the variance in only a small part of the variability could be explained by the linear model. Since the $R^2$ values were low in these cases, the results are uncertain.

As for the southern region, the correlation and regression analysis shows statistically significant results that there exists a relationship between the AE index and NO density, especially for the 14 hour lag. To investigate this further, the coefficient of variation, computed with the STD and the vertical mean of NO, on which the linear model created in the regression was based, is used. This is made for every point in time and the whole time line included 20 points. The largest value of $c_v$, in percent, is 43% and the majority of the points have a ratio of $\sim 25\%$. This is quite low compared to the ratios computed in sections 3.1 and 3.2. However, the ratios show some variability between the observation values. The lag time of 14 hours is not definite, based on this, and some uncertainty still exists.

The regression analyses was done by computing the mean NO number density over the altitudes which had the highest correlation. This was done to further examine the lag times without any internal variations in the data. All correlations showed in this report is significant. The significance test used is mentioned in section . With this in mind the results in this section should be seen as trustworthy. However, due to the short data sets and the gaps in the time line further research is needed to improve the knowledge about formation times of NO due to enhanced geomagnetic activity, especially with new and longer data sets.

To summarize, no strong significant correlation was found between the AE index and NO density for any of the meridional areas or periods, except for one. The largest correlation was found during the second period in the southern auroral region, for lag times of 7, 8 and 14 hours. This does not match earlier research done by Hendrickx et al. (2015), which concluded that the lag time with the largest correlation is 24 hours. However, this conclusion was based on lower temporal resolution. No direct comparison between that data and the current SMR data is possible because of the missing observations in the SMR data set. Better data sets are needed without large gaps in the data. For the second period, NO data 24 hours after the peak in AE index is missing. Perhaps this would show higher correlation.
4 Conclusions

Nitric oxide, one of the important background constituents in the upper atmosphere, is formed by energetic particles that precipitate down during increased geomagnetic activity. Increased geomagnetic activity depends on incoming CME’s that interact with Earth’s geomagnetic field. NO, formed by energetic particles, can be transported down from the upper atmosphere to the stratosphere and there contribute to the destruction of ozone in catalytic reactions. A change in the ozone concentration affects the heat budget in the stratosphere, which in turn affects the winds and circulation in the atmosphere. This makes it important to understand the influence geomagnetic activity has on NO density. NO also changes the radiation balance in the upper atmosphere, due to its ability to emit thermal radiation. A change in temperature in the MLT-region could also change the dynamics.

In this project, a small dataset with observations from the SMR-instrument aboard the satellite Odin from the end of 2014 was studied. These were specific runs to study the NO impact due to incoming CME with high temporal resolution. The dataset was divided into two parts which represented two different periods, where the first period was geomagnetically quiet and the second period was geomagnetically active. These two periods of observations were used to answer three questions.

- What is the visible response on NO density in the MLT-region during, or after, a geomagnetic storm, and how much does the response differ depending on latitude and season?

There was a clear difference in NO density at high latitudes between the two periods. The geomagnetically more active second period had larger NO densities in the auroral regions, and around the equator. The largest NO densities were found at the North pole. The profiles of NO differed also depending on season, where the winter pole had higher NO densities compared to the summer pole, due to an accumulation of NO inside the polar vortex, and the lack of solar radiation that destroys NO. There were also enhanced NO densities in the summer polar region during the second period, an increase of $\sim 0.65 \times 10^8 \text{cm}^{-3}$, which indicates that NO formation had taken place due to the geomagnetic activity, since the second period was more geomagnetically active and the lifetime of NO in the Southern hemisphere was short during this time, about a day. The direct response of NO at the North pole was hard to see. Even though the second period showed a higher NO density, it is hard to separate the newly formed NO created by EPP from the accumulated NO from earlier events. Longer observations are needed for that, ranging from before the incoming CME to a couple of days after. The data showed large variability within each region, especially in the Northern Hemisphere, as seen in the large STD values. Further research is needed to get more certain results.

- Is there a difference in NO density between the morning and the evening and if so, how much?

The results indicates that this is the case, and that the difference depends on latitude and season. In the equatorial region, evening densities were higher at around 113 km, with a percentage difference of 20% for the second period and 10% for the first period. Below this, morning densities had largest values, with percentage differences between 30% to 40% depending on the period. NO is formed during the day by X-rays in the lower thermosphere, then it diffuses down during the night. In the North auroral region, morning densities were larger at high altitudes, with percentage differences ranging between 40% to 100%, due to production during the night by EPP, especially during geomagnetically active periods. The mid-latitudes, like the equator, had larger evening densities at high altitudes and then larger morning densities below that, with a percentage difference of 40%. The results are however uncertain, due to large standard deviation values, and further research is needed, with longer and more consistent time series of NO number density.

- What is the lag between NO density increase and AE or Kp indices, and is the relationship between them linear?

In the southern auroral region a strong correlation was found during the second period, with the AE index lagged 14 hours. The AE index correlated better than the Kp index and the linear regression gave
better results than the logarithmic. Lower correlations were found in the northern hemisphere, largely as a result of the short time series and the dynamics, which lead to an accumulation of NO. The one hour mean time series of NO density for the Southern auroral region in the second period only consisted of 20 data points, which in a statistical analysis is quite few, even though the analysis showed good results. This nevertheless indicates that data from Odin/SMR can show NO formation due to enhanced geomagnetic activity, and further research is possible with longer measurement periods with more data points. The linear regression showed better results in nearly all the cases with larger $R^2$ values, compared to the logarithmic regression, which implies that the models should keep the linear configuration. The AE index shows better correlation and regression results, compared to the Kp index. The AE index also has one hour observations, compared to the three hourly observations of the Kp index, meaning that a more temporal detailed analysis can be conducted.

The data sets contained gaps, which obstructed the correlation and regression analysis. Odin/SMR gives good measurements on NO, but longer times series are needed. Further analysis of the winter polar density response to incoming CME requires longer periods observations, from both before the incoming CME and after. The morning and evening density analysis should be based on observations around the equinoxes. High temporal regression and correlation analyses require continuous time series, without any gaps. Fortunately, longer runs of SMR observations are planned at a later time, based on this study.
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