

**OBSERVATIONS AND MODELLING OF THERMOSPHERIC
DYNAMICS AT HIGH LATITUDES**

CHRISTIAN WILDER BARRETO SCHULER

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Abstract

A strong westward wind pattern in the lower middle thermosphere at high latitudes over both hemispheres, known as a “wind wall”, is investigated. Since scarce information is available about this region of the atmosphere, model simulations by the WACCM-X model are employed. Model simulations, along with WINDII observations, allowed describing in a great detail most of the wind wall features, as well as its impact on other altitudes and regions. One of the main goals of this study was the determination of the atmospheric circulation pattern linked to the wind wall. Our results indicate that the wind wall is linked to the high latitude convection system. This atmospheric circulation is particularly stronger during active geomagnetic conditions, which results in the origin of the wind wall. The study reveals, the impacts of the wind wall on the dynamics and structure of the lower middle thermosphere, which are mainly a response to the complex high latitude convection system and its time variation.

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Chapter 1

1. Introduction

1.1. The Thermosphere

Based on the vertical structure of the temperature profile, the atmosphere can be categorized in five regions: troposphere, stratosphere, mesosphere, thermosphere, and exosphere (Solomon & Roble 2015). The thermosphere is the layer of the atmosphere that extends from a height of ~ 90 km to about 500 km above the Earth's surface (Forbes, 2007). The temperature of the thermosphere varies greatly with solar activity (and the ~ 11 years solar cycle), ranging from about 2000 K at the time of solar maximum conditions to 500 K at the time of solar minimum conditions at 500 km altitude (Saha, 2008; Basavaiah, 2011; Solomon & Roble, 2015).

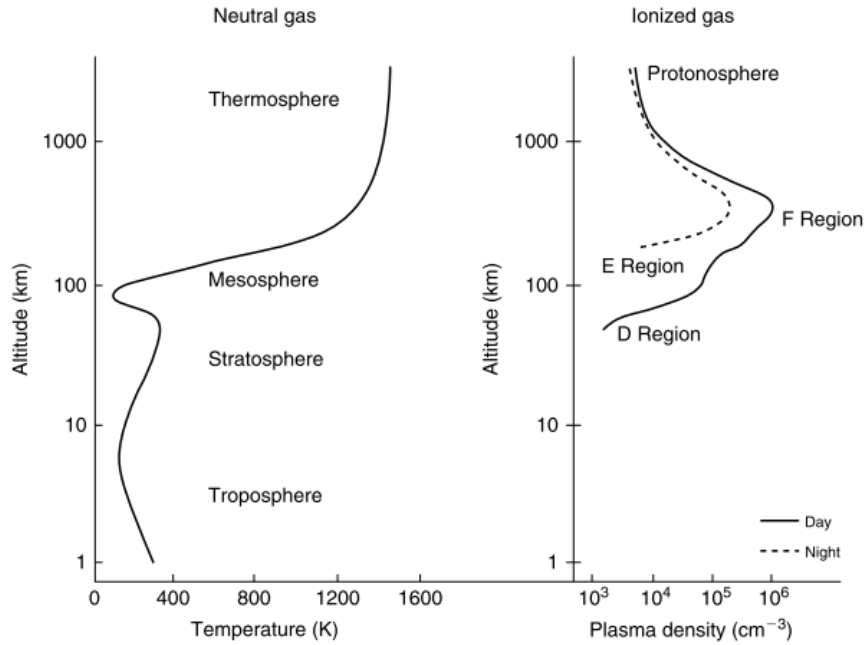


Figure 1.1. Typical profiles of neutral atmospheric temperature and ionospheric plasma with the various layers designated. From Kelley (2009).

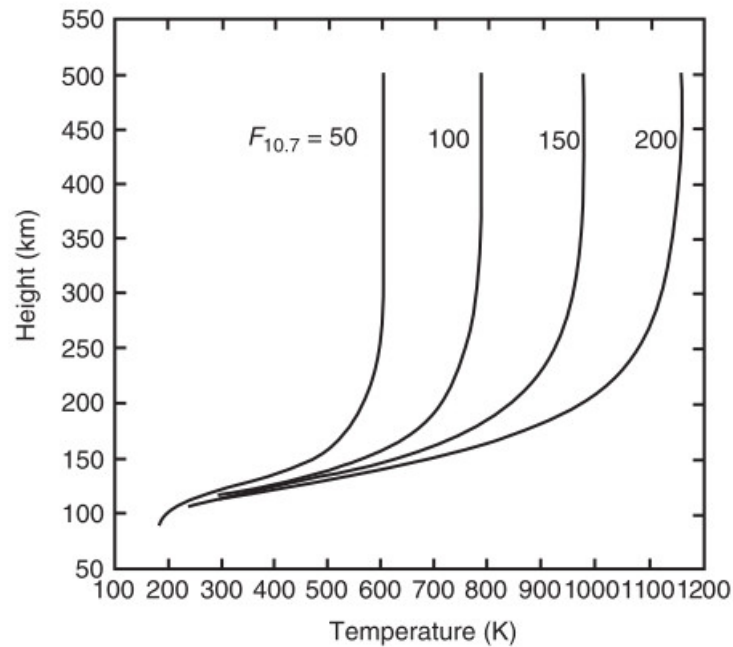


Figure 1.2. Global mean neutral gas temperature vertical profiles as a function of the solar decimeter radio emission at 10.7 cm wavelength ($F_{10.7}$). The solar decimeter radio emission $F_{10.7}$ (in units of $10^{-22} \text{ Wm}^{-2} \text{ Hz}^{-1}$) is an indicator of the solar EUV radiative output. From Solomon & Roble (2015).

The major species of the thermosphere are molecular oxygen, molecular nitrogen, and atomic oxygen. These components can be ionized and dissociated due to the absorption of shortwave radiation, mainly solar ultraviolet (UV) and extreme ultraviolet (EUV) radiation (wavelengths shorter than 103nm), as well as energetic particles. Therefore, as was specified by Solomon & Roble (2015), embedded within the thermosphere is the ionosphere, which is a weakly ionized plasma that has strong dynamic and electrodynamic interactions with the neutral gases in the thermosphere. Further, as seen in Figure 1.1, the ionosphere is organized according to the plasma number density. As described by Kelley (2009), the altitude range 150-500 km is termed the F region (which is often separated into F1 and F2 during daytime due to the role of molecular ions), the altitude range 90-150 km is called the E region, and the ionization below 90 km is termed the D region.

The energy and momentum inputs into the ionosphere and thermosphere are governed by the interaction of the highly variable solar wind (the continuous outward flow of solar particles, mainly electrons and protons, and magnetic fields from the sun) with the Earth's geomagnetic field. Momentum variability is also depending on waves from lower layers of the atmosphere, such as gravity waves, tides, and planetary waves. These waves are capable of propagating to higher altitudes where they undergo dissipation and deposit heat and momentum into the mean flow (Forbes, 2007).

The solar wind forcing contribution into the upper atmosphere is more significant during geomagnetic storm times, where energy and momentum are transferred into the thermosphere. This latter can respond almost immediately to sudden increases in solar wind dynamic pressure at very high latitude regions (Oliveira et al., 2017). Fuller-Rowell et al. (1994) reported that during geomagnetic storms, through ion-neutral momentum transfer and through

thermospheric heating, winds at all thermospheric altitudes strengthen. Therefore, the thermosphere is very sensitive to the varying solar and magnetospheric inputs, and can vary significantly on time scales ranging from minutes to a solar cycle (H. L. Liu et al., 2010).

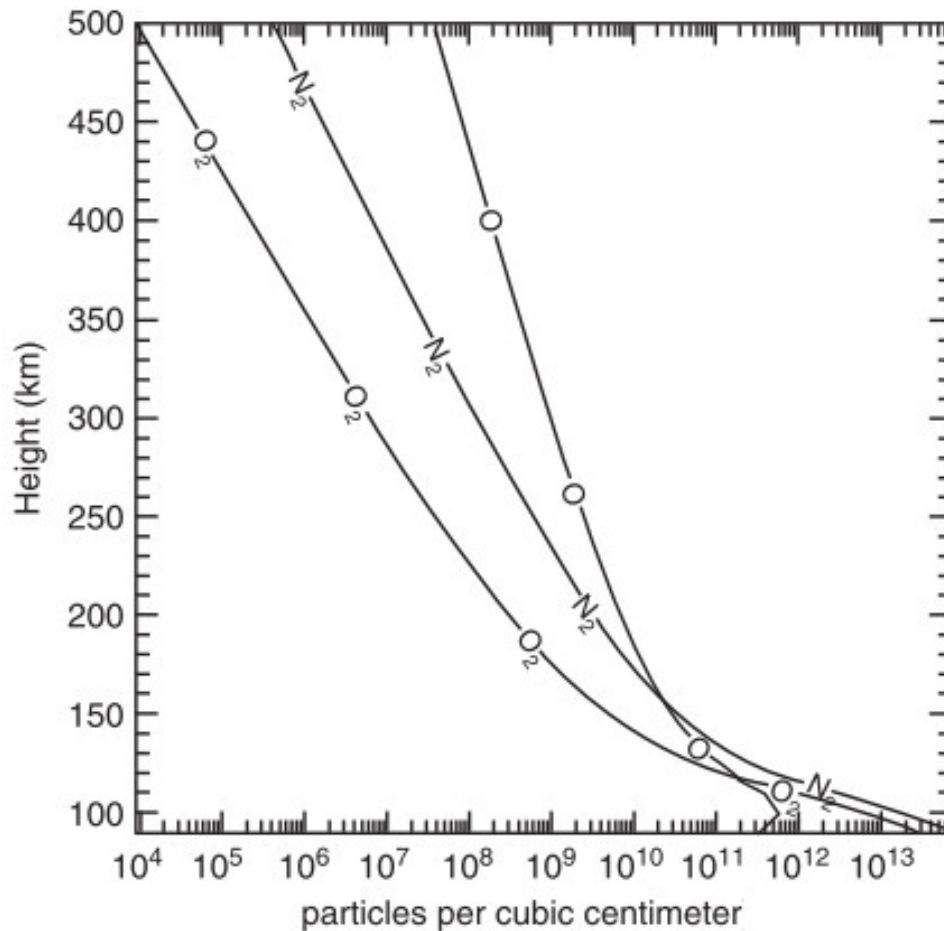


Figure 1.3. Vertical distribution of the major thermospheric species O, O₂, and N₂. From Solomon & Roble (2015).

1.1.1. High Latitude Thermosphere

As was mentioned, the thermosphere has a strong variability, which is especially true at high latitudes. In addition to the solar EUV and UV radiation, magnetosphere electric fields, particle precipitation, field-aligned currents (FAC), heat flows, and ion and neutral escape fluxes also affect the ionosphere-thermosphere system at high latitudes (Schunk & Zhu, 2008).

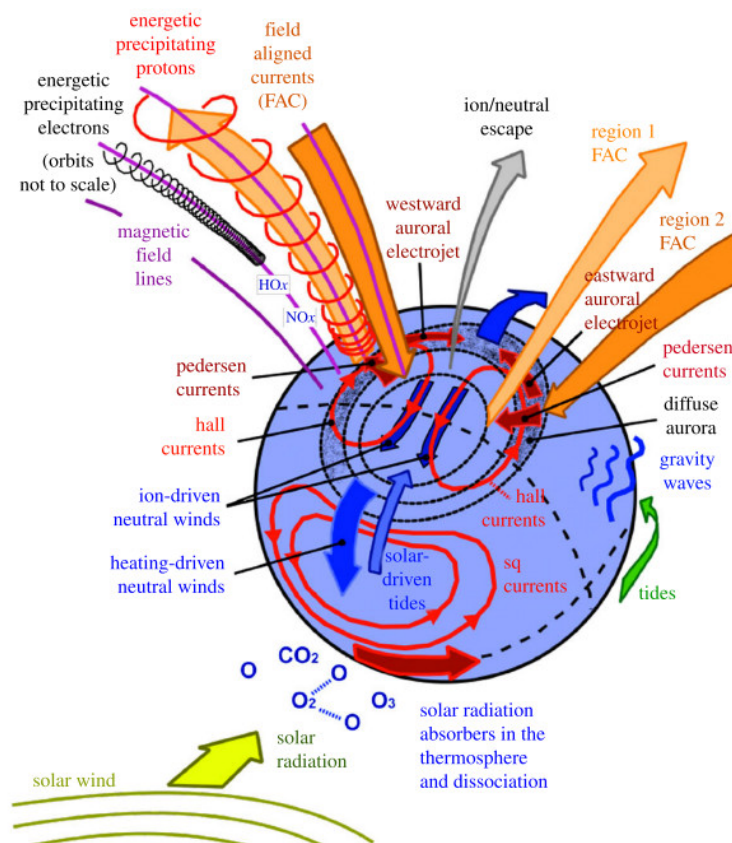


Figure 1.4. Overview of the Ionosphere-Thermosphere processes and their interaction with the magnetosphere and the solar wind. From Sarris (2019).

One of the more important results from the continuous complex interaction of the earth's magnetosphere and the solar wind, which carries the frozen-in interplanetary magnetic field (IMF, solar magnetic field stretched out away from the sun by the solar wind (Wilcox, 1968)), is the large-scale ionospheric convection at high latitudes. The ionospheric convection system can be defined as a two-dimensional (horizontal) structure, which consist of a two-cell convection pattern, with the anti-sunward convection across the polar cap (over the geomagnetic pole), and with a sunward return flow in the auroral ovals (Dungey, 1961; Lu et al., 2002; Papitashvili & Rich, 2002; Grocott et al., 2010). The two main drivers for this configuration is the viscous effect and the reconnection process, as the latter is currently believed to be the main driving force of the convection (Tanaka et al., 2019). Dungey (1961) gave an early explanation for the ionospheric convection pattern, normally described during southward IMF, and known as the Dungey convection cycle. However, the convection also exists during northward IMF, but it is weaker, and its configuration is more complicated (Tanaka et al., 2019). It is essential to mention that the ionospheric convection pattern is seen in both hemispheres, and that the strength and form of the effect of all processes indicated in Figure 1.4 is determined to a large degree by the solar wind dynamic pressure and the orientation of the IMF (Schunk & Zhu, 2008).

Since the ionosphere is embedded in the thermosphere, continuous interactions between ion and neutral flows occur at this region of the atmosphere. As mentioned by Deng and Ridley (2006), the thermosphere and ionosphere are tightly coupled in many ways, including chemistry, momentum transfer, and heating due to velocity differences. At high latitudes thermospheric winds are strongly influenced by collisions with ions that are rapidly drifting in the electric and magnetic fields (Richmond et al., 2003). Then, because of the momentum transfer between ions and the neutrals, the neutrals move in a similar way to the movement of the ions

(Liu et al., 2020). In other words, the large-scale horizontal convection system with its two-cell convection pattern (over the dawn and dusk side) is also seen in the neutral upper thermospheric winds (above 200 km) at high latitudes, especially over the dusk sector, where they form a strong anticyclonic vortex; on the other hand, in the dawn sector the ion convection often fails to produce a significant cyclonic wind vortex (Richmond et al., 2003).

Another phenomenon that is important to mention with regard to the high latitude thermosphere is the aurora. It has long been known that energetic electrons and protons penetrating the polar atmosphere from above are the ultimate cause of auroral emission, which is the result of the ionization of the neutral gas, dissociation of molecular species, and the excitation of various atomic and molecular energy levels. There is also a current system of about a million amperes associated with the aurora; the Joule dissipation of these currents strongly heats the thermosphere and can also accelerate the gases in the thermospheric polar regions (Brekke, 2013; Solomon & Roble, 2015). Further, the aurora is also affected by the different kind of configurations of the IMF and the solar activity.

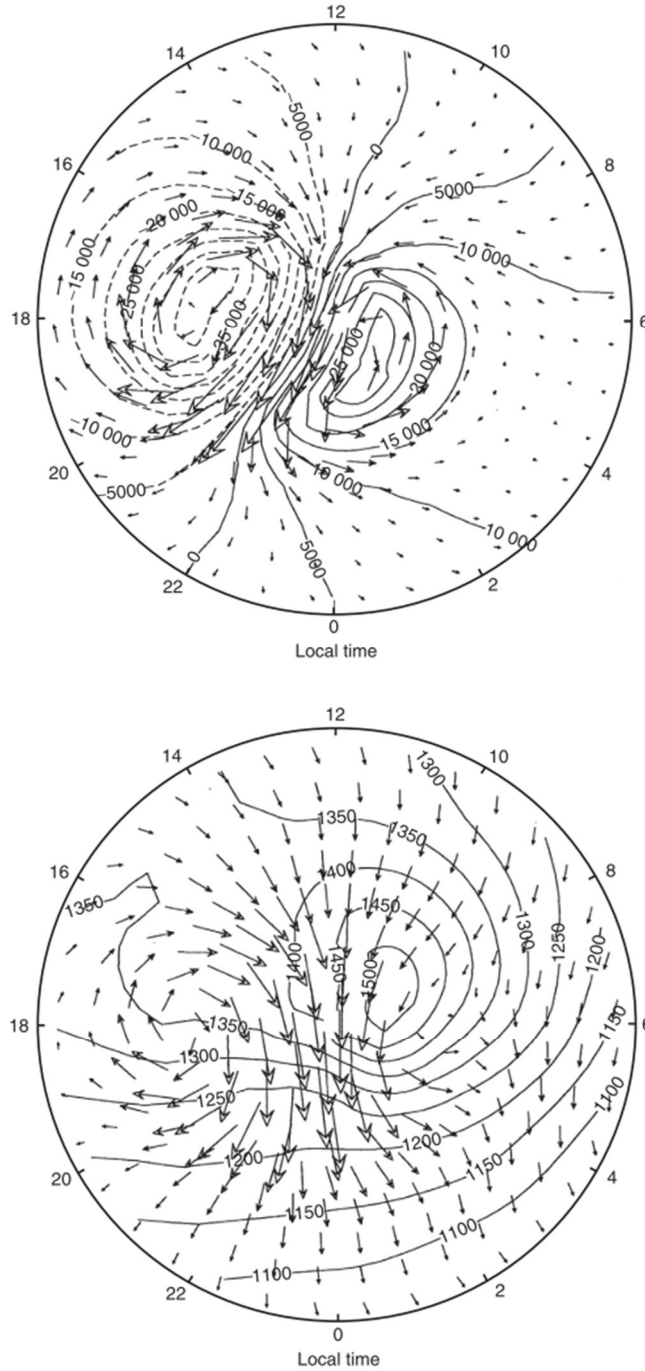


Figure 1.5. The top image shows a calculation of the ionospheric electric potential in volts over the Northern Hemisphere polar cap. The vectors show the $E \times B$ ion drift for moderate levels of auroral activity, the length of the largest arrow represents a drift speed of 650 m s^{-1} . The bottom image shows a calculation of temperature in degrees Kelvin, (contours) and wind vectors (arrows) in the upper thermosphere near 300 km altitude responding to the ion drag forcing shown at the top. The length of the maximum wind vector represents 600 m s^{-1} . From Solomon & Roble (2015).

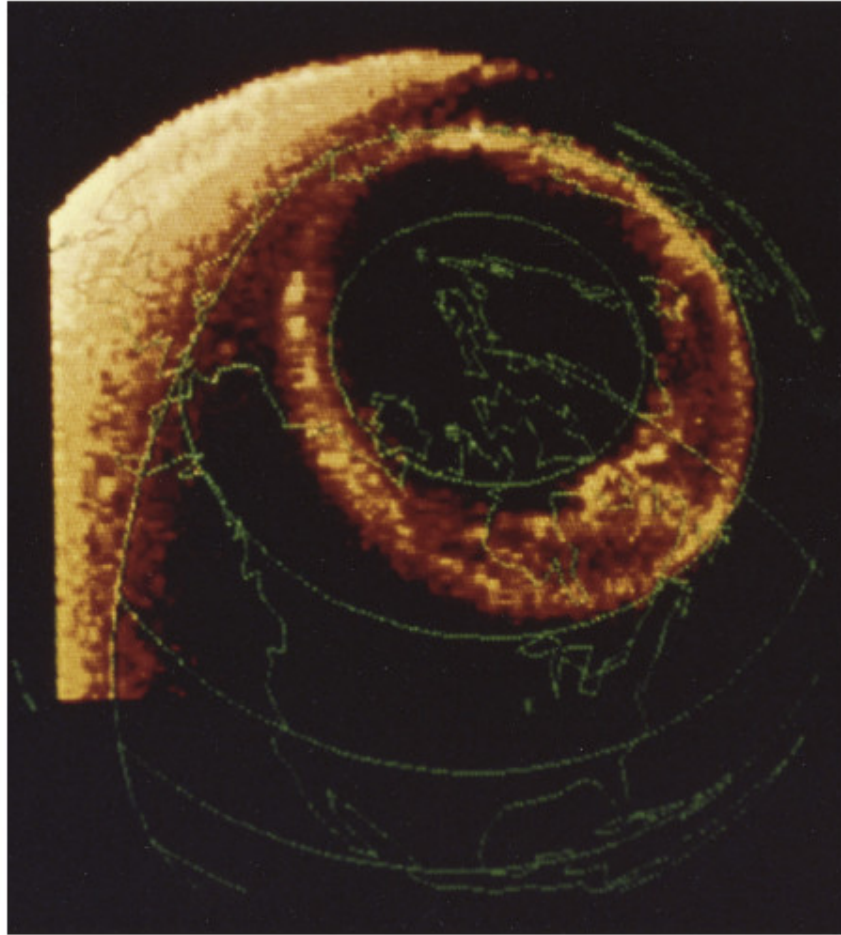


Figure 1.6. Auroral image during the later stage of a magnetic storm, displayed as a geographic polar projection covering latitudes greater than 40°N . From Solomon & Roble (2015).

1.1.2. Thermospheric winds

At this point, it is important to mention the main components of the horizontal momentum equation for the thermosphere, which are viscosity, the Coriolis force, ion drag, momentum advection and the pressure gradient force (Wang et al., 2008). Fuller-Rowell (1995) indicates that the equation of motion in the thermosphere describing the balance of forces acting on a parcel of neutral gas and the resultant time rate of change of velocity is given by:

$$\frac{D}{Dt} U = -\frac{1}{\rho} \nabla P - 2\Omega \times U - v_{ni}(U - V) + \frac{1}{\rho} \nabla(\mu \nabla U) \quad (1.1)$$

Where U is the neutral wind velocity, P the gas pressure, Ω the angular rotation rate of the Earth, V the ion drift velocity, v_{ni} the neutral-ion collision frequency, ρ gas density, and μ the sum of the molecular and turbulent viscosity coefficient. The first term on the right side of the Equation 1.1 represents the pressure gradient force, the second term the Coriolis force, the third term the ion drag force, and the last term the viscosity. The above equation shows the forces in a Lagrangian frame of reference. However, atmospheric models typically solve the equations in an Eulerian coordinate system (where latitude and longitude are independent variables). Thus, as a result of the expansion of the left term in Equation 1.1 (the total derivative term), the momentum advection term is considered in the momentum equation in an Eulerian frame of reference (not shown).

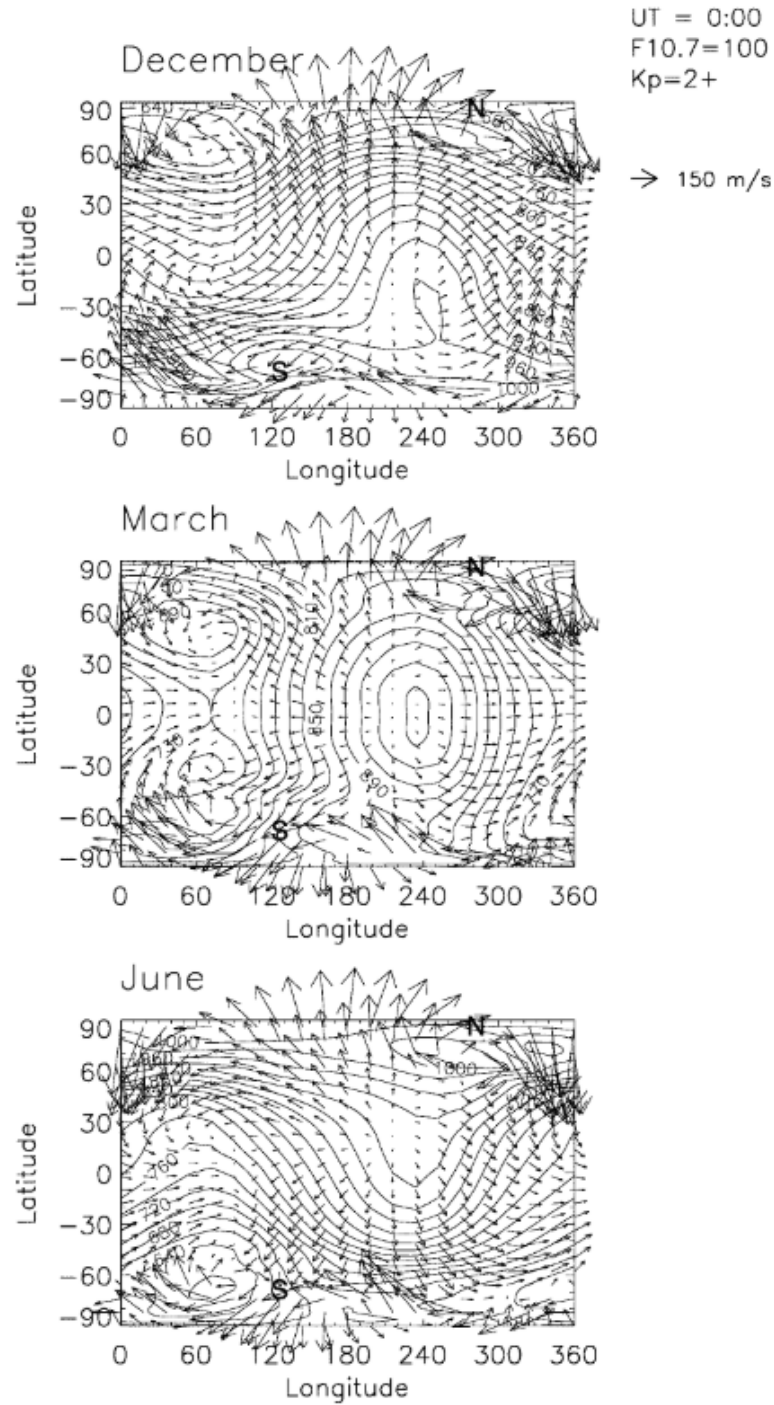


Figure 1.7. Horizontal wind (m/s) and temperature fields (K) as a function of latitude and longitude at 00 UT near 300 km, corresponding to moderate solar activity and quiet geomagnetic conditions for December, March and June, respectively. From Rishbeth et al. (2000).

At high latitudes, the flow is influenced by momentum transfer from the convecting ions to the neutrals, and winds attain amplitudes up to $\sim 500 \text{ m s}^{-1}$. At middle and low latitudes, the flow is less intense ($\sim 50\text{--}150 \text{ m s}^{-1}$) and notably tends to be across the isobars, or equivalently, isotherms. This latter is mainly because of the balance between the pressure gradient and ion-neutral collision terms (Forbes, 2007).

In addition, Dickinson and Geiser (1968) have shown (see also Forbes (2007)), that vertical winds play an important role in determining the amplitude and phase of the temperature response with respect to EUV heating, as well as, that the total vertical wind (ω) may be expressed in terms of two components, the barometric wind (ω_B) and the divergence wind (ω_D). The former is due to thermal expansion/contraction of the atmosphere, and the latter is caused by diverging horizontal winds and the conservation of mass:

$$\omega = \omega_B + \omega_D = \left(\frac{\delta h}{\delta t}\right)_P + \frac{1}{\rho} \nabla \cdot \int_{h_{P0}}^{\infty} \rho \vec{U} dz \quad (1.2)$$

where h is the height of a given pressure surface, P is the air pressure, ρ is the total mass density, z is the altitude, and $\vec{U}$ is the horizontal wind vector.

Finally, Dickinson and Geiser (1968) also demonstrated that the temperature variation equation can be written with the inclusion of the parameter ω_D :

$$\frac{dT}{Dt} \approx \frac{\partial T}{\partial t} + \omega_D \frac{\partial \bar{T}}{\partial z} \rightarrow \frac{\partial T}{\partial t} = \frac{J}{c_p} - \omega_D \Gamma \quad (1.3)$$

Where J is the net heating from all sources, including conduction, T is the temperature, C_p is the specific heat at constant pressure, and Γ is the mean atmospheric stability. As indicated by Forbes (2007), the adiabatic cooling term $-\omega_D \Gamma$ in (1.3) serves as an additional “heat source” that is as important as the EUV heating, and accounts for much of the observed time shift of the thermospheric temperature maximum to late afternoon with respect to the noontime maximum in EUV heating.

1.1.2.1. The wind wall

Shepherd and Shepherd (2018) reported a wind pattern called “wind wall”, this after an analysis of wind observations at hours close to the noon local time in the middle-lower thermosphere from the Wind Imaging Interferometer (WINDII) data at high latitudes. The wind wall was defined as a narrow region of strong westward (negative) zonal winds from an altitude of 140 to 250 km at latitudes around $\sim 65^\circ$ in a longitude range of 100°E to 200°E in the southern hemisphere, and from 200°E to 300°E in the northern hemisphere. Liu et al (2019), extended this study by using the WACCM-X (Whole atmosphere community climate with thermosphere and ionosphere extension) model experiments. They found that these very strong westward (negative) zonal winds (associated with the wind wall) have a substantial dependence on the solar activity and the geomagnetic conditions.

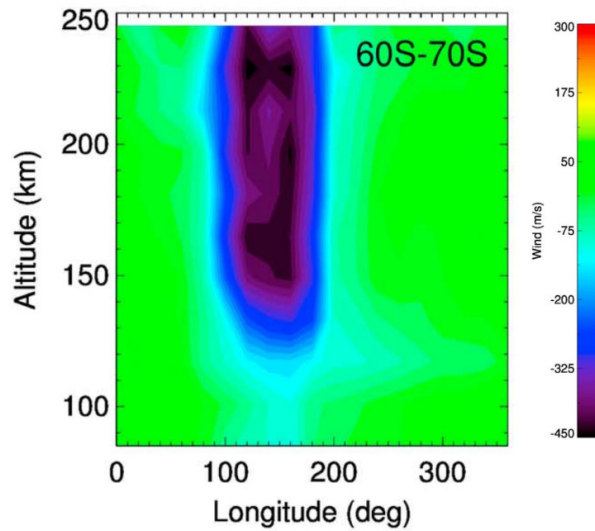


Figure 1.8. Vertical cross section of the zonal wind at noon local time in an average latitude range of 60° - 70°S for March 13th, 1996. Blue to purple colors indicates westward (negative) zonal winds greater than 200 m/s. Similarly, green colors express the eastward (positive) zonal wind values (from westward to eastward) with magnitudes not greater than 75 m/s. The wind wall pattern is defined as the region where winds are very strong ($> \sim 200$ m/s). From Shepherd & Shepherd (2018).

1.2. The Airglow and the O(¹S) Green line emission

The terrestrial upper atmosphere emits light at discrete wavelengths throughout the spectrum, known collectively as airglow, but often referred to as dayglow, nightglow, and aurora, for different locations and excitation mechanisms (Solomon, 2017). As described by He et al. (2020), the emission confined to the northern and southern polar regions is termed the aurora, and the faint luminescence of the global upper atmosphere is called the airglow. In addition, it is important to mention that the aurora is primarily generated through impact excitation, while chemical/photochemical processes mainly induce the airglow (von Savigny, 2017; He et al., 2020).

Airglow is a phenomenon occurring in the Earth's upper atmosphere; in the mesosphere it occurs at altitudes between about 50 km and about 100 km, and in the thermosphere at altitudes above about 100 km (von Savigny, 2017). The airglow, which persists during the daytime, at twilight and at night, is recognized as the consequence of non-thermal processes, such as the ionization by the solar ultraviolet radiation, as well as numerous photochemical, fluorescent and scattering processes (He et al., 2020).

Depending on solar elevation one distinguishes between dayglow, twilight glow and nightglow. However, airglow is commonly not visible to the unaided eye due to its weak emission intensity or a strong sky background (von Savigny, 2017; He et al., 2020). In general, dayglow emissions are the brightest airglow emissions. During nighttime direct solar illumination does not occur, but this nightglow is due to exothermic chemical reactions, a process also known as chemiluminescence (von Savigny, 2017). Then it can be understood that (in general) fewer processes are involved in the production of the nightglow in comparison with the dayglow.

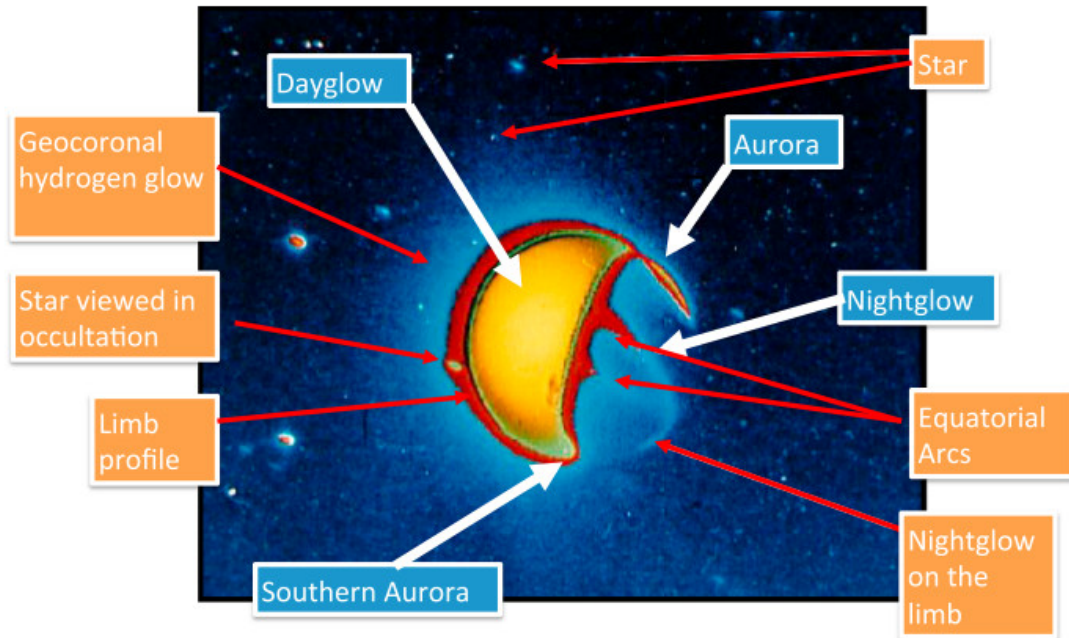


Figure 1.9. The Earth observed from the Moon in the far ultraviolet from above the sunset meridian. The major emission features are indicated. From Paxton et al. (2017).

Furthermore, airglow is a globally occurring, continuous and generally homogeneous phenomenon, while the aurora occurs intermittently, is typically highly structured and generally limited to the area known as the auroral oval (von Savigny, 2017). A general description of the aurora has been given in the section 1.1.1, while the main intention for what follows is to provide a brief description of the airglow, and more specifically about the $O(^1S)$ green line emission.

The airglow has been used in remote sensing of the upper atmosphere and ionosphere, providing an accurate description of their production and loss mechanisms. In fact, a significant part of our scientific understanding of middle and upper atmospheric chemistry is based on airglow observations (von Savigny, 2017; Solomon, 2017). This light source has been also used for estimation/detection of wind fields, temperatures, etc.

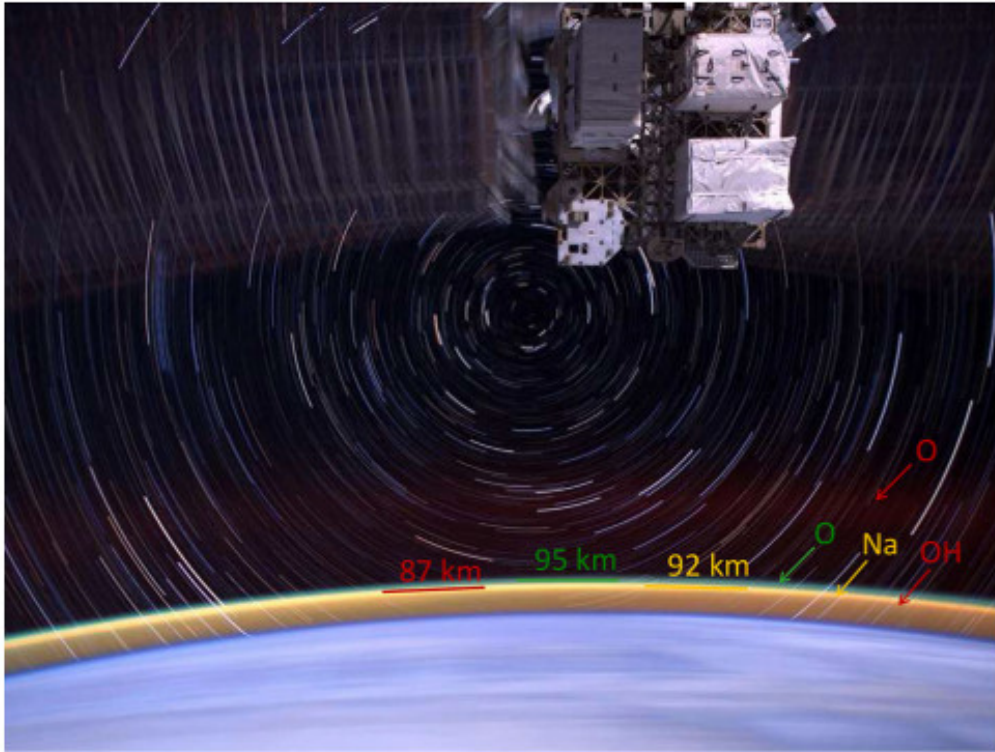


Figure 1.10. Photograph of terrestrial nightglow emissions taken from the International Space Station (ISS). The atoms/molecules associated with their corresponding emission and altitude are indicated. The high altitude red emission corresponds to the oxygen red lines ($O(^1D \rightarrow ^3P)$) near 630 nm, which peak occurs at about 250 km . From von Savigny (2017).

As pointed out by Tang et al. (2011), between the most important spectral lines of the airglow are the atomic oxygen green line $O(^1S)$ 557nm, the oxygen red line $O(^1D)$ 630nm, and the $O^+(^2P)$ 732nm in the visible range. In the next paragraphs a more detailed description of the oxygen green line emission will be provided as it is strongly related to the observations used in this study. It is worth mentioning that the wind wall pattern was recognized thanks to $O(^1S)$ green line observations at daytime and the horizontal wind information derived from this variable.

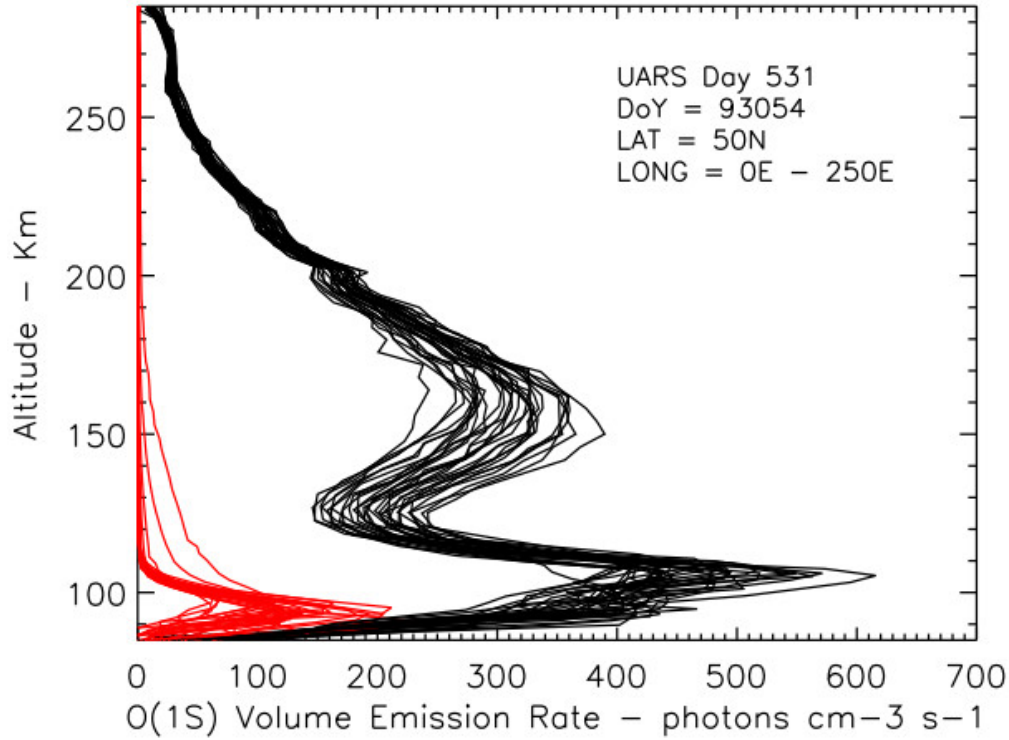


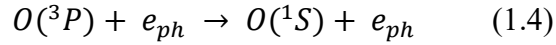
Figure 1.11. The WINDII O(¹S) volume emission profiles observed on Day 47, February 16, 1993 at 45°N–55°N, and for longitudes from 0° to 250°E. The O(¹S) dayglow volume emission rate profiles (SZA ≤ 77°) are shown in black, while the O(¹S) nightglow profiles are given in red. From Shepherd & Shepherd (2011).

The transition O(¹S–¹D) results in the formation of green line dayglow emission at 557.7 nm. This emission has two altitudinal peaks during the daytime, one in the mesosphere (98–102 km) and the other in thermosphere (150–175 km). On the other hand, during nighttime it presents only one peak, which (as shown in Figure 1.11) occurs at ~95 km (von Savigny, 2017; Singh & Upadhyaya, 2004; Thirupathaiah et al., 2013). It is relevant to mention that the O(¹S) green line emission is not only a proxy of the atomic oxygen (which plays an important role in the energy balance of the upper mesosphere and lower thermosphere), but also an indicator of the

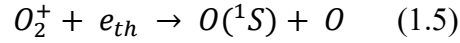
neutral dynamics of the upper atmosphere (Gao et al., 2012; S. P. Zhang & Shepherd, 2002; Zhu & Kaufmann, 2019).

As mentioned before, more processes are involved in the origin of the dayglow, and therefore also in the $O(^1S)$ green line emission during daytime. The main mechanisms for the production of green line dayglow emission are as follows (Tyagi & Singh, 1998):

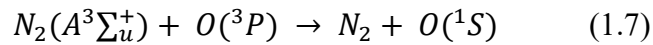
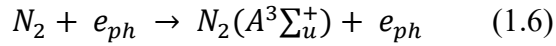
- 1) Photoelectron impact excitation of atomic oxygen



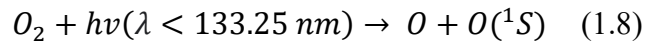
- 2) Dissociative recombination of O_2^+



- 3) Energy transfer to atomic oxygen from $N_2(A^3\Sigma_u^+)$

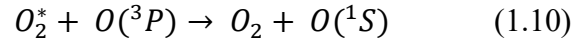


- 4) Photodissociation of molecular oxygen by solar EUV photons



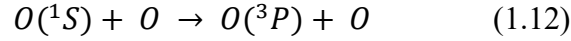
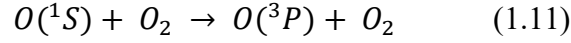
- 5) Three body recombination of atomic oxygen (also known as the Barth mechanism).

This mechanism is also responsible for the green line emission during nighttime. In this equation O_2^* is an excited state of O_2 and M is a third body species (mostly O_2 or N_2).

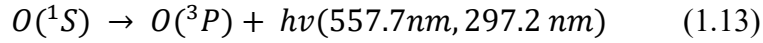


The thermospheric green line dayglow peak region (150–175 km) is due to three important processes: dissociative recombination, energy transfer from $N_2(A^3\Sigma_u^+)$ to atomic oxygen, and the photoelectron excitation of atomic oxygen (Singh & Upadhayaya, 2004). On the other hand, the mesospheric peak is mainly generated by the three body recombination process of atomic oxygen. Below 140 km the photodissociation of O_2 also contributes toward the production of atomic oxygen and $O(^1S)$. It is important to mention that changes in the atomic oxygen concentration in the upper mesosphere lower thermosphere would directly affect the emission rate of 557.7 nm emission (Tyagi & Singh, 1998; Singh & Upadhayaya, 2004).

Finally, as stated by Zhang & Shepherd (2005), the main loss processes of the $O(^1S)$ include quenching by O_2 , N_2 , or O and spontaneous emission, which can be expressed as:



and



Regarding the $O(^1S)$ production mechanisms, it is important to highlight that the green line emission from these processes is normally quantified in terms of volume emission rate (VER), which is defined as the number of photons emitted per second in all directions from a unit volume of one m^3 , so that the formal units are $\text{photon s}^{-1} m^{-3}$ (but typically expressed in $\text{photon s}^{-1} cm^{-3}$) (Shepherd, 2002). In the recent past, several model calculations have been carried out to obtain accurate estimated values of volume emission rates (Singh & Upadhyaya, 2004), either from the $O(^1S)$ or other components. A good example of this, is the GLOW model, which is described in section 2.3.

1.3. Solar activity and the F10.7 index

The Sun is a gaseous globe with an effective temperature of about 5800 K surrounded by a hot and fairly irregular cloud of plasma with a temperature of a few million degrees, the solar corona (Low, 1996). According to Liu et al. (2011), the solar activity can be described into two main components, which have a close relationship as well as distinct differences. The first refers to the level of solar activity indicating the intensity of solar electromagnetic radiation (such as X-rays and EUV). The second refers to solar activity events, for instance: coronal mass ejection and solar proton events. It is important to mention that these features are driven by the solar dynamo and its variable magnetic field (de Jager, 2008). In general, it has been seen that the variability of the solar activity initiates huge variations in the neutral density and temperature, ion and electron densities and temperatures, neutral winds, and electric fields in the thermosphere-ionosphere. Furthermore, many studies have also been focused on the direct impact of the solar activity not only on the lower layers of the atmosphere (troposphere, stratosphere), but also on the climate system.

EUV fluctuates regularly and irregularly over timescales from minutes (flares) and roughly 27 days (solar rotation) to decades (the well-known 11-year solar cycle), with amplitudes varying up to more than 1000 times (Gorney, 1990; Liu et al., 2011). Other long-time variations in the solar activity have been also reported, with an overall waxing and waning over the centuries. For instance, the solar activity was particularly weak during the last half of the 17th century, the so-called Maunder Minimum (1645–1715) (Parker, 2001; de Jager, 2008).

Direct measurements of the solar EUV spectrum and its variability are not available for most times. In the absence of direct EUV observations, we rely on solar proxies to indicate the intensity of solar activity (Liu et al., 2011). Among the many solar indices some of the most used are the sunspot number (SSN), the solar radio flux at 10.7cm wavelength (F10.7), the Mg II, Flare index, etc. (Pap et al., 1990).

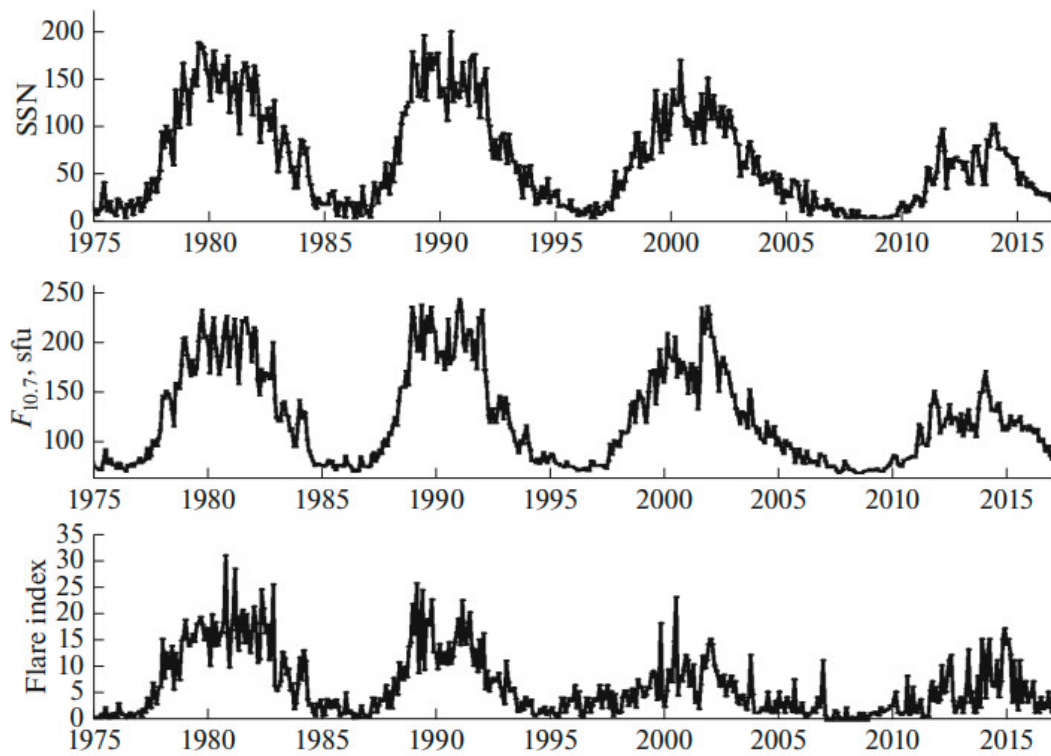


Figure 1.12. Time series of solar activity indices – monthly average values of SSN, F10.7 and Flare Index (FI). From Bruevich et al. (2017).

Between the indices mentioned above, the F10.7 index has been widely used in many scientific studies, since it has a good correlation with the number of sunspots and with the solar extreme ultra-violet radiation (Tapping, 2013). More precisely, the F10.7 index is the measurement of the strength of solar radio emission in a 100 MHz-wide band centered on 2800 MHz (a wavelength of 10.7 cm), averaged over an hour, and expressed in solar flux units (sfu), where $1 \text{ sfu} = 10^{-22} \text{ Wm}^{-2} \text{ Hz}^{-1}$ (Tapping, 2013). This measure of solar activity has advantages over sunspot numbers and areas in that it is completely objective and can be made under virtually all-weather conditions. Measurements of this flux have been taken daily by the Canadian Solar Radio Monitoring Programme since 1946 (Hathaway, 2015). Other indices related to the F10.7 are: F10.7a, which is the F10.7 average of the previous 81 days; and F10.7p, calculated as the mean of the daily F10.7 of the day of interest and its corresponding F10.7a value.

There is no universal categorization of the F10.7 index. Many studies have analyzed the response of the atmosphere to different solar activity based on their own empirical thresholds (e.g., Kim et al., 2011; Pietrella & Perrone, 2008). Similar to Liu et al. (2019) and Kim et al. (2011) we have used the following simple categorization for the solar activity:

Table 1.1. Solar activity Categorization based on the F10.7 index

F10.7	Category
$F10.7 \leq 100$	Low Solar Activity (Low SA)
$F10.7 > 100$	High Solar Activity (High SA)

1.4. Geomagnetic disturbances and the Ap index

As stated by Fraser-Smith (1972), the sun provides the driving force for nearly all geomagnetic and ionospheric fluctuations. However, the manner in which it does this varies widely. Fraser-Smith (1972) also indicates that some geomagnetic and ionospheric fluctuations result from variations in the intrinsic state of the sun (solar-flare effects and geomagnetic storms are two well-known examples). Several studies have also demonstrated the good correlation between solar activity and disturbances in the Earth's magnetosphere, although it is important to point out that the geomagnetic activity maximum lags behind the solar activity maximum with about two to three years (Obridko et al., 2013; Gavrilieva & Ammosov, 2018). Obridko et al. (2013) mentions that the geomagnetic disturbances have two main sources. One of the sources, Coronal mass ejections, agrees well with the solar cycle variations since it is related to strong closed local fields characterized by the sunspot number. The second source is high-speed solar wind streams (HSS). However, even in solar minimum conditions, geomagnetic disturbances can occur, because of changes in the background solar wind (BSW) and in the internal properties of HSS (mainly over its structure's pressure) (Kirov et al., 2015). As we can see the geomagnetic activity is also an important geophysical factor that affects the thermosphere-ionosphere system.

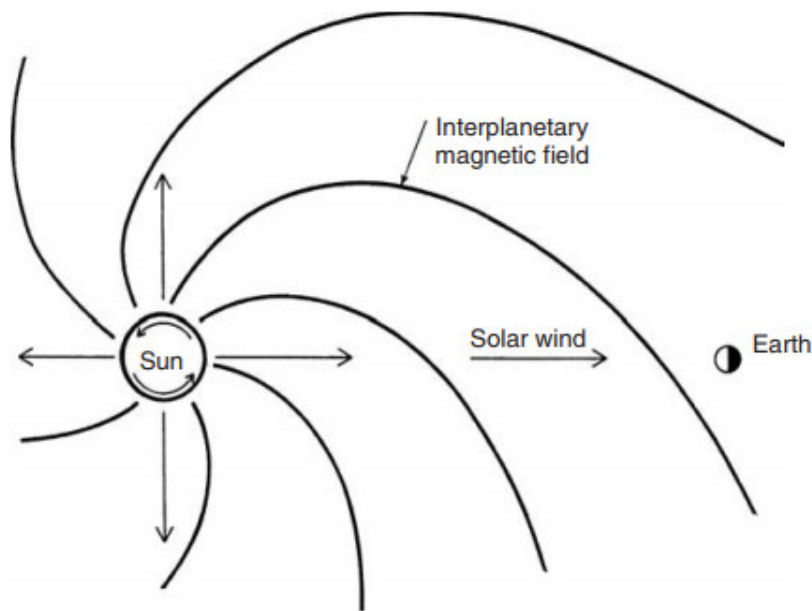


Figure 1.13. Schematic diagram of the Sun–Earth system in the Sun’s ecliptic plane. The solar wind is in the radial direction away from the Sun and the magnetic field lines bend into spirals as the Sun slowly rotates. From Schunk & Nagy (2009).

A geomagnetic disturbance can be defined as the result of the interaction between Earth’s magnetosphere with the solar magnetic field carried by the solar wind (the interplanetary magnetic field), the result of this interaction is a considerable transfer of energy into Earth’s magnetosphere (Zaourar et al., 2013). Indicators of the geomagnetic activity can be identified as magnetospheric storms, substorms, and aurora. Where magnetic storms are driven directly by solar drivers (e.g., coronal mass ejections); substorms instead, are ultimately caused by the solar wind (Lakhina et al., 2006). The intensity of a geomagnetic disturbance depends on the orientation of the magnetic field of the solar driver. For instance, geomagnetic storms depend on the orientation of the magnetic field in coronal mass ejections; the stronger the southward polarity field orientation of the IMF, the more the depression in geomagnetic disturbance storm time is generally expected (Rathore et al., 2014). Strong geomagnetic disturbances can cause considerable (significantly over

high-latitudes) global deviations of the upper atmosphere from its normal state, either in its dynamics, composition, and thermal states (Chen et al., 2014; Gavrilieva & Ammosov, 2018). Finally, in terms of geomagnetic disturbance's duration, the weakest storms had a median duration of 6 hours and the most intense storms last on average to 30 hours, noting that the duration of the most intense storms ranged from 12 to 93 hours (Haines et al., 2019).

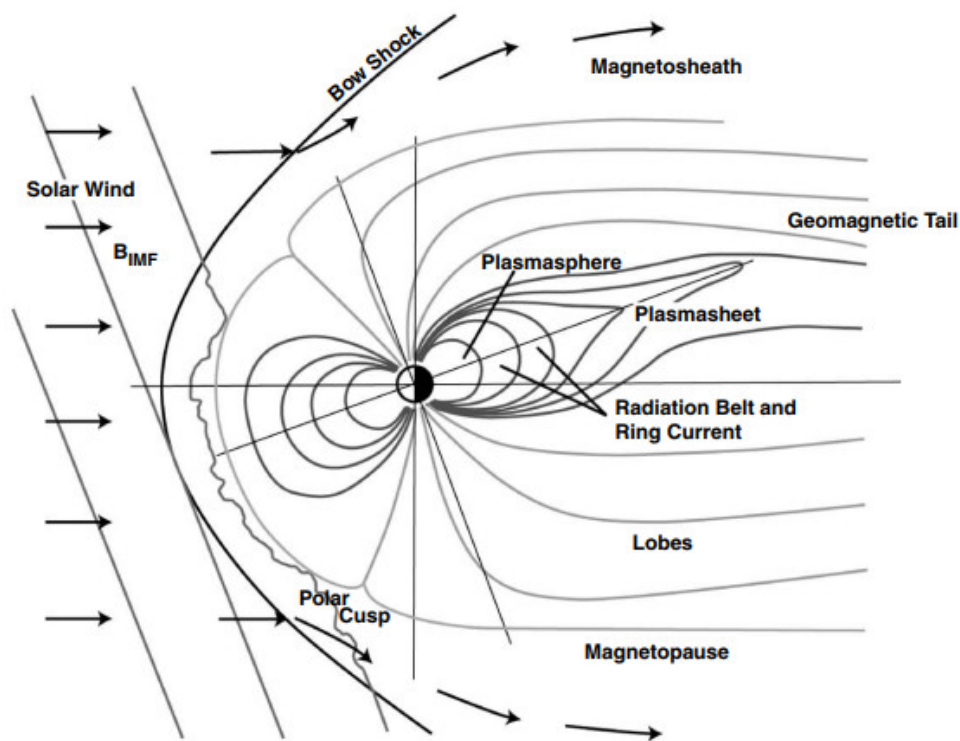


Figure 1.14. A noon–midnight cross section of Earth’s magnetosphere. Note the dipole shape of the inner magnetosphere. The Sun (hence noon) is to the left and north is up. From Moldwin (2008).

Many indices have been developed for quantifying the disturbances of the Earth's magnetic field. The most familiar magnetic indices are K, Kp Ap, AE and Dst (Abunina et al., 2013; Du et al., 2010). In this section, the Kp and Ap indices are described, since they have been widely used not only for exploring the causes and consequences of geomagnetic activity, but also as an input in several thermosphere-ionosphere models. As described by Du et al. (2010), the K index was introduced by Bartels et al. (1939) to provide an objective monitoring of the irregular variations observed at a given station. It is based on the amplitude of the variations of the observed horizontal components after removing the solar regular variations. Du et al. (2010) also details that the K index is computed once every 3 h, beginning at 0 UTC (Universal Time Coordinated) time. He also mentions that its determination is a pure code to characterize the geomagnetic activity level from 0 to 9 (0 being the least active field and 9 the most active field). Each observatory has its own table for converting the amplitude to the K index, and the conversion table depends on the geomagnetic latitude of the observatory. The K-derived planetary index Kp, is the mean standardized K index from 13 reference observatories, which is designed to measure the global geomagnetic activity. It contains contributions from at least two major sources, the auroral electrojet and the ring current (Echer et al., 2006). Furthermore, a conversion scale transforms the quasi-logarithmic Kp to a linear index named ap (Echer et al., 2006). The daily average of ap index is named as Ap. Again, more details about the Ap index is given by Bartels et al. (1939).

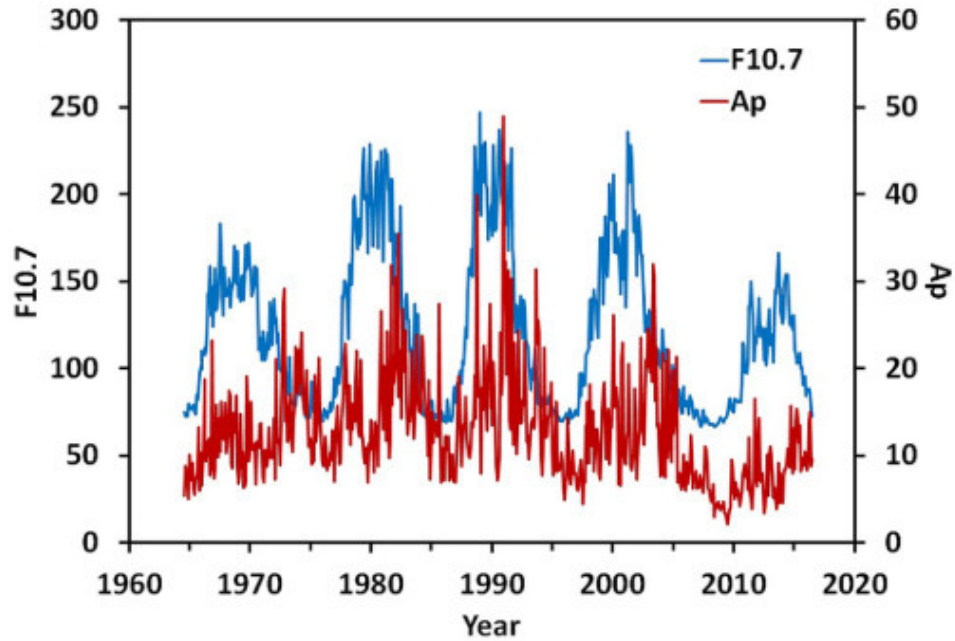


Figure 1.15. Monthly mean F10.7 and Ap for 1965–2016. From Gavril'yeva & Ammosov (2018).

Similar to the F10.7, there is no unique classification of the Ap index. For this study, similar to Gavril'yeva & Ammosov (2018), Liu et al. (2019), and Kim et al. (2011), the impact of the geomagnetic conditions has been analyzed by following the next Ap categorization:

Table 1.2. Geomagnetic disturbance categorization based on the Ap index

Ap	Category
$Ap < 7$	Quiet Geomagnetic Conditions (Quiet GC)
$Ap \geq 7$	Active Geomagnetic Conditions (Active GC)

1.5. Thesis objectives

As previously described, the thermosphere is a region of the atmosphere with scarce information (either in temporal or spatial resolution). However, the thermosphere behaves in a complex way, especially during geomagnetic disturbances and at high latitudes. The wind wall pattern, characterized as a region of strong westward zonal winds at high latitudes in both hemispheres, is one of the recent results from the study of the available data on the thermosphere. Currently, it is possible to get a better understanding of the thermospheric dynamics by using Global Circulation Models (GCM). One of the recently GCMs available to the scientific community is the Whole Atmosphere Community Climate Model with thermosphere and ionosphere extension (WACCM-X). Therefore, by using simulated and observed data, the main goal of this research is to “Understand the origin of the wind wall and its impact on the lower and middle thermosphere”. For this purpose, two main objectives were followed:

- 1) Analysis of the wind wall behavior under different solar and geomagnetic conditions.
- 2) Description of the wind wall morphology, and the atmospheric circulation associated with this pattern.

The Following Chapter 2 will provide details about the models employed in this study (WACCM-X and GLOW), as well as the characteristics of the observed data. In Chapter 3 discussions about our results are presented. Chapters 4 and 5 provide the main conclusions of this study and bibliographic references, respectively. Finally, supplementary figures are attached in the appendices section, Chapter 6.

Chapter 2

2. Data and Methodology

2.1. The WINDII instrument

The Wind Imaging Interferometer (WINDII) instrument is a limb scanning Michelson interferometer, which was launched on NASA's Upper Atmosphere Research Satellite (UARS) on 12 September 1991 and operated until 2003. The UARS mission was dedicated to the measurement of energy input, abundances of minor species, temperature, and winds in the stratosphere and mesosphere in order to study their mutual relationship and to build and validate atmospheric models (Shepherd et al., 1993). However, as stated by Shepherd et al. (2012), despite the emphasis of the UARS goals was on the mesosphere and lower thermosphere, it has been recognized that middle thermosphere data and analysis is relevant for a better understanding of the whole atmospheric system.

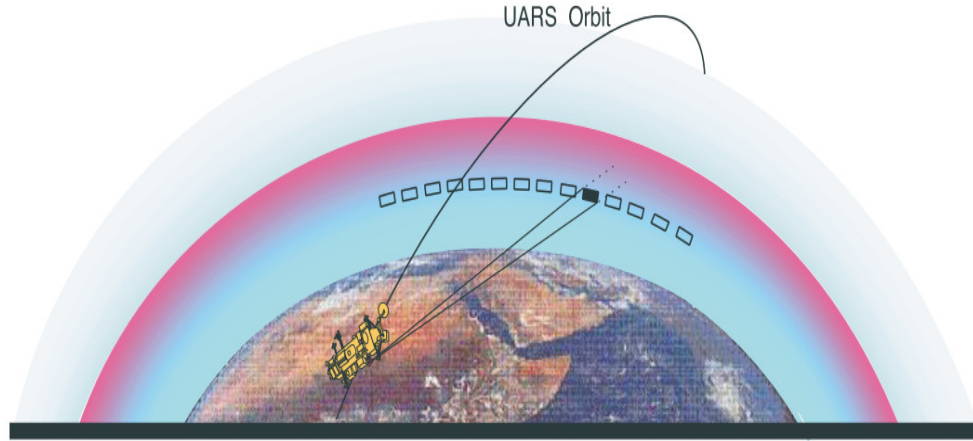


Figure 2.1. General scheme of the UARS orbit and the airglow measurement process. From Hays et al. (2003).

By measuring Doppler shifts of the airglow in an altitude range of 80 to 300 km, WINDII was able to provide horizontal vector winds over all these altitudes (Shepherd et al., 2012). WINDII also produced Doppler temperatures and airglow emission rates over the same range of altitudes (Liu et al., 2019). The species (with their corresponding emissions lines) from which winds and temperatures were estimated are: OH, in the upper mesosphere; O₂ and O(¹S), in the lower thermosphere; and O(¹S), O(¹D), and O⁺(²P), in the middle thermosphere (Shepherd et al., 1993). More details about the instrument itself and the measurement processes are described by Shepherd et al. (1993, 2012). It is worth mentioning that most of the wind data analyzed in this study comes from the O(¹S) green line emission in the lower and middle thermosphere.

WINDII had two fields of view and acquired two images side by side on a CCD (Charge-Coupled Device) detector; one viewing at 45° to the UARS velocity vector and the other at 135°. The two fields of view sampled the same atmospheric volume within about 8 min of each other (Shepherd et al., 1993, 2012). The UARS orbit had an orbit inclination of 57°, an orbital

period of 96 min, precession rate was 5° per day, and after 36 days the spacecraft was reversed in its flight direction so that the Sun was kept on the “Sun side” of the spacecraft. This latter maneuver is called a “yaw,” and the 36 days is called a “yaw period” (Shepherd et al., 2012; Shepherd et al., 1993, Liu et al, 2019). Then, due to this flight behavior, for 36 days WINDII (which was looking away from the sun) took measurements from 42° latitude in one hemisphere to 72° latitude in the other hemisphere, and after the “yaw” the WINDII views reversed. Therefore, measurements over the latitude range of 42°N to 42°S were always covered. Measurements at latitudes greater than 42° in a given hemisphere were taken only in alternate months.

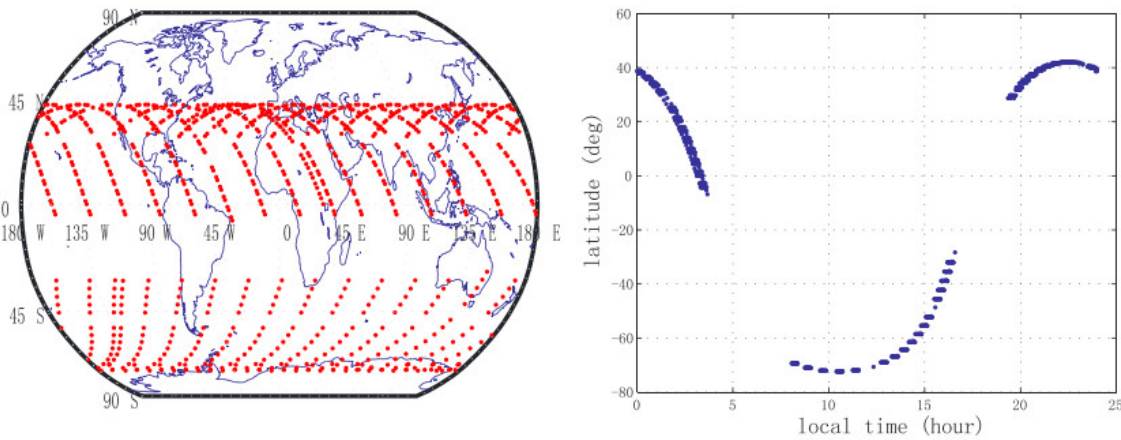


Figure 2.2. Global coverage of the WINDII observations on February 3rd, 1992, in longitude and latitude (left) and local time and latitude (right). From Liu et al. (2019).

As part of our study, a composite analysis was performed. The composite study along with a dynamical analysis inside of each of the groups detailed in Table 2.1 aimed to get a better knowledge of the wind wall behavior and its origin, as well as its impact on the lower middle thermosphere (100 – 250 km). Four groups were selected according to the solar activity and the geomagnetic conditions, which were based on the F10.7 and Ap index, correspondingly. Days with

high (low) solar activity are defined where F10.7 is greater than (less than or equal) to 100. Similarly, active (quiet) geomagnetic conditions are denominated when Ap is greater than or equal (less than) to 7. The thresholds for F10.7 and Ap were based on previous research done by Gavrilieva and Ammosov (2018), Du et al. (2010), and Murphy et al. (2011). Zonal and meridional winds, along with O(¹S) green line emissions were mainly studied by vertical cross section around ~65° for each hemisphere at local times (LT) near noon (11-14 LT).

Table 2.1. Categories for the composite analysis

Indices	Category	Nomenclature	Group number
$F10.7 \leq 100 \text{ \& } Ap < 7$	Low Solar Activity & Quiet Geomagnetic Conditions	Low SA – Quiet GC	1
$F10.7 > 100 \text{ \& } Ap < 7$	High Solar Activity & Quiet Geomagnetic Conditions	High SA – Quiet GC	2
$F10.7 \leq 100 \text{ \& } Ap \geq 7$	Low Solar Activity & Active Geomagnetic Conditions	Low SA – Active GC	3
$F10.7 > 100 \text{ \& } Ap \geq 7$	High Solar Activity & Active Geomagnetic Conditions	High SA – Active GC	4

The WINDII observations employed in this study correspond to two specific years, 1992 and 1996. The first one is a general solar maximum year, and the second one is a general solar minimum year. As described before, even high solar activity or active geomagnetic conditions can be found in a solar minimum year, mainly due to short-lived solar events. The overall amount of WINDII information used in this study is 178 days, where 88 days of high-latitude data (data at latitudes greater than 42°) correspond to the northern hemisphere, and 90 days to the southern hemisphere.

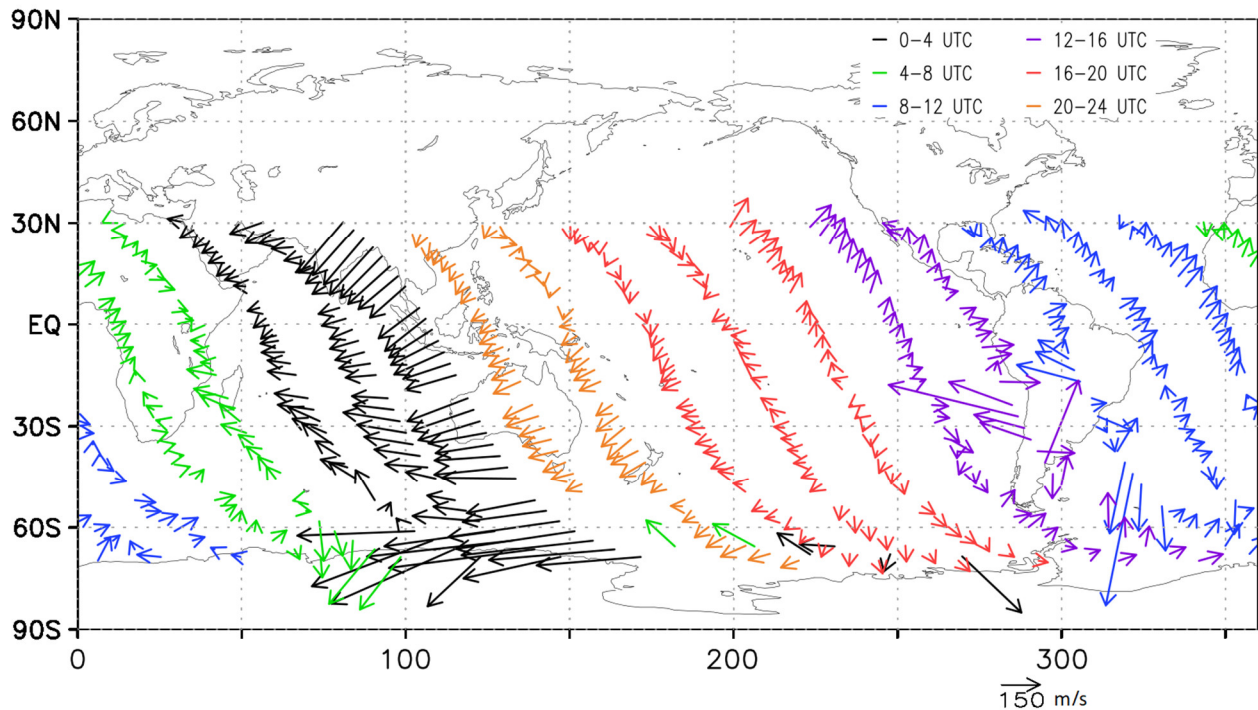


Figure 2.3. Wind pattern at an altitude of 200 km from WINDII for March 13th, 1996. This day corresponds to an event with active geomagnetic conditions and low solar activity. The colors indicate the range of UTC times at which the measurement was taken. The length of the maximum wind vector corresponds to 150 m s^{-1} .

2.2. The WACCM-X model

WACCM-X is a global general circulation model, which is also a configuration of the NCAR Community Earth System Model (CESM) (Hurrell et al., 2013). WACCM-X is based on the Community Atmosphere Model (CAM) component of CESM and its configuration allows to simulate the necessary processes from troposphere to the thermosphere. It is worth mentioning that up to the lower thermosphere (~ 130 km) the model is based on the WACCM model version 4; while above this altitude, ionospheric processes, including the transport of O^+ , self-consistent electrodynamics, and energetics are based on the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM) (Liu et al., 2018; Pedatella et al., 2019). The model provides information at different levels, assuming hydrostatic equilibrium and employs a log-pressure coordinate system (the top boundary is set at 4.0×10^{-10} hPa), which extends from 0 to around ~ 500 - 700 km in altitude (depending on solar activity) (Solomon et al., 2018; Liu et al., 2018). The vertical resolution in the mesosphere and thermosphere (above ~ 0.96 hPa) is a quarter of a scale-height, and the horizontal resolution is $1.9^\circ \times 2.5^\circ$ in latitude and longitude, respectively (Liu et al., 2018). The simulations include realistic solar and geomagnetic forcing, which are parameterized by the F10.7 cm solar flux and Kp indices, respectively (Pancheva et al., 2020). A more detailed explanation of WACCM-X is given by Liu et al. (2018).

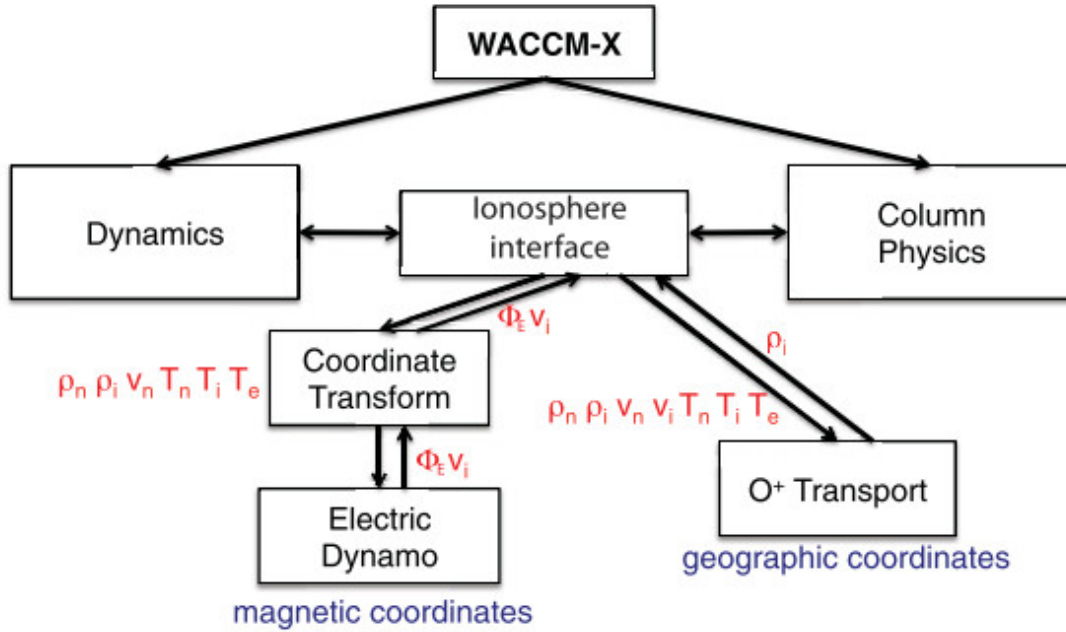


Figure 2.4. Schematic diagram describing the coupling of the ionospheric modules with other model components through the ionosphere-interface module. ρ , v , and T are the density, the velocity, and the temperature, respectively, with subscript n , i , and e denoting neutral, ion, and electron, respectively. Φ is the electric potential. From Liu et al. (2018).

WACCM-X has the option to constrain the tropospheric and stratospheric dynamics by reanalysis, namely, the “specified-dynamics” or SD version of the model (SD-WACCM-X) (Liu et al, 2018). In this configuration, dynamical fields (temperature, zonal and meridional winds, and surface pressure) are specified in the troposphere and stratosphere (up to ~50 km) from the Modern Era Retrospective Analysis for Research and Applications (MERRA-2) (Malhotra et al., 2020). As stated by Pancheva et al. (2020), it is worth noting that the meteorological fields in SD-WACCM-X are assimilated only in the troposphere and stratosphere (up to ~50 km). Therefore, the mesosphere lower-thermosphere (MLT) response is entirely due to vertical connections in internal dynamics of the model. Pancheva et al. (2020) also point out that tides are primarily excited in the

troposphere and stratosphere, and hence a more realistic lower atmospheric state would lead to a more realistic MLT tidal state particularly in terms of climatology.

Current simulations are based on WACCM-X version 2.1, which slightly differs from the version 2.0 described by Liu et al. (2018). The main difference between versions 2.0 and 2.1 is in the implementation of a ramp-down of the eddy diffusion coefficient above the turbopause¹ (Pancheva et al., 2020). In addition, a minor change have been done over the electron temperature solver, and extra options for the D-region ion chemistry and the magnetospheric inputs have also been added.

The thermosphere is a region with scarce observational data. Therefore, WACCM-X provides valuable information for a more detailed study either in time or space. Furthermore, as described in section 2.1, a composite analysis was performed to examine the wind wall response to different solar activity and geomagnetic conditions (see Table 2.1). Within this latter process, a validation of the WACCM-X data is also evaluated. For these comparison purposes (between WINDII and WACCM-X), the number of events was selected according to the WINDII observations availability. Thus, the observations studied come from the years 1992 and 1996, as detailed in section 2.1. The modelling information for the composite analysis corresponds to the 3 hourly data of the SD-WACCM-X configuration (version 2.1), and was downloaded in a netCDF format from <https://doi.org/10.26024/5b58-nc53>.

¹Turbopause is defined as the surface (usually at a height of about 100 km) that separates the homosphere and the heterosphere (this latter is the region above the turbopause in which constituents adopt their individual distributions with height as the result of molecular diffusion).

A climatological analysis of the wind wall was also performed by extending the composite analysis for a 30-year period, 1981-2010. In both composite analyses, zonal, meridional, and vertical winds were studied at noon local time.

Finally, in order to determine the impact of the wind wall in the lower middle thermosphere, we performed four specific simulations. The representative four days (where SD-WACCM-X data from the website had a good correlation with WINDII, $r \geq 0.8$) correspond to events with High SA Active GC and Low SA Quiet GC over both hemispheres. The solar and geomagnetic conditions for the specific cases are detailed in Table 2.2. For these specific SD-WACCM-X (version 2.1) simulations, the model was run on the Niagara supercomputer of SciNet (<https://www.scinethpc.ca/niagara/>), and initiated 42 days before each specific target day.

Table 2.2. Specific cases under different Solar and Geomagnetic conditions

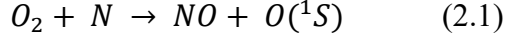
Region	Day	Ap	F10.7	Category
Northern Hemisphere	22 nd May, 1992	50	148.4	High SA Active GC
Northern Hemisphere	01 st March, 1996	5	70.6	Low SA Quiet GC
Southern Hemisphere	25 th March, 1992	16	185.1	High SA Active GC
Southern Hemisphere	31 st March, 1996	5	70	Low SA Quiet GC

2.3. The GLOW model

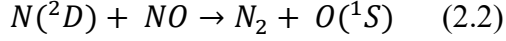
The Global Airglow (GLOW) model is a comprehensive set of numerical routines in a FORTRAN language that calculate energetic electron fluxes in the atmosphere and use them to derive profiles for a variety of atmospheric observables (Bailey et al., 2002). More specifically, the GLOW model computes ionization, dissociation, and excitation rates; performs energetic electron transport calculations; applies ion-neutral chemistry; and outputs ionized/excited species densities and airglow emission rates (Solomon, 2017). The GLOW model allows to get these emissions, including the O(¹S) green line emission, at different altitudes (from 80 km to 600 km) for a single column and time, however, horizontal gradients and transport are neglected. Then, for building up a global map or a range of time, the model needs to be run repeatedly. It is important to mention that the volume emission rates are calculated separately from each of their respective mechanisms, after that, the individual contributions are summed to obtain the total volume emission rates. More details about the GLOW model is described by Solomon (2017).

For the O(¹S) green line emission, GLOW considers only four of the five mechanisms described in section 1.2: 1) photoelectron impact excitation of atomic oxygen, 2) dissociative recombination of O_2^+ , 3) energy transfer to atomic oxygen from $N_2(A^3\Sigma_u^+)$, and 4) photodissociation of molecular oxygen by solar EUV photons. The three-body recombination of atomic oxygen mechanism that is important in the upper mesosphere and also for the nightglow is not included in the routines yet. However, two extra mechanisms are added for the green line emission:

Atom-ion interchange



and chemiluminescence



Therefore, as pointed out by Solomon (2017), currently the GLOW model region of validity does not extend below ~ 100 km, which is especially true for the $O(^1S)$ green line emission.

The GLOW model is intended to be used in this research for comparisons and validation of the wind wall effects in the lower middle thermosphere for the cases listed in Table 2.2.

The GLOW model requires a set of minimum inputs (e.g., neutral atoms and molecules and ions), as well as information on the solar and geomagnetic conditions (F10.7, F10.7a, F10.7p, and ap). Other optional inputs may be used, such as those related with auroral electron precipitation. Most of the neutral and ion inputs, as well as other variables (electron concentration, ion temperature, etc.) required for the GLOW model were obtained from our SD-WACCM-X simulations. Table 2.3 details the inputs employed for the GLOW model. The F10.7, F10.7a, F10.7 and ap indices were extracted from the following website: <http://www.celestrak.com/SpaceData/>. WACCM-X also uses this source as part of its solar and geomagnetic configuration. Some neutrals and ions were obtained from the default empirical models inside GLOW (e.g., NRLMSISE-00).

Table 2.3. Required Inputs for the GLOW model

Variable	Source
O	SD-WACCM-X
O ₂	SD-WACCM-X
N ₂	NRLMSISE-00
NO	SD-WACCM-X
N(⁴ S)	NRLMSISE-00
Neutral temperature	SD-WACCM-X
Ion temperature	SD-WACCM-X
Electron temperature	SD-WACCM-X
Electron concentration	SD-WACCM-X
O ⁺	SD-WACCM-X
O ₂ ⁺	SD-WACCM-X
NO ⁺	SD-WACCM-X

Finally, the GLOW model has 4 different configurations for the chemical calculations (inside the file named gchem.f90). The configuration kchem = 2 has been used in this research, which is set in the file glowbasic.f90. This option allows the calculation of supplementary excited molecules and atoms at all altitudes, such as O⁺(²P), N⁺, N₂⁺, etc.

Chapter 3

3. Results and Discussions

3.1. The wind wall behavior under different solar and geomagnetic conditions

Four main groups were considered for the composite analysis, which were based on the solar activity and geomagnetic conditions (Table 2.1). These groups are: 1) High Solar Activity and Active Geomagnetic Conditions (High SA-Active GC), 2) Low Solar Activity and Active Geomagnetic Conditions (Low SA-Active GC), 3) High Solar Activity-Quiet Geomagnetic Conditions (High SA-Quiet GC, and 4) Low Solar Activity-Quiet Geomagnetic Conditions (Low SA-Quiet GC). The number of events for each hemisphere and case employed for the composites are detailed in Table 3.1.

Table 3.1. Number of events for each group based on the Ap and F10.7 index in the northern hemisphere (NH) and southern hemisphere (SH).

	High SA Active GC	Low SA Active GC	High SA Quiet GC	Low SA Quiet GC
SH	42	25	9	14
NH	36	29	13	10
TOTAL	78	54	22	24

It is worth mentioning that, since the time frequency of the modelling data employed at this section is three hours, after the selection process of information at 12 LT, the longitudinal resolution is reduced to 45° . This latter turns on a source of disagreement between SD-WACCM-X and WINDII observations. However, as it is possible to see in Figures 3.2 - 3.5, there is a general good agreement between modelling data and observations.

According to the modeling and observations (Figure 3.2 and Figure 3.3), westward zonal winds are a permanent behavior over the wind wall region (in both hemispheres), with zonal wind velocity of $\sim 75\text{-}100$ m/s for Low SA – Quiet GC over the region of the wind wall. This permanent behavior suggests that the westward pattern is associated with the general circulation of the thermosphere at high latitudes. Figure 3.1 shows the SD-WACCM-X average (1981-2010) wind circulation at 200 km for the month of March, which is comparable to what was shown by Rishbeth et al. (2000) in Figure 1.7. Therefore, at this point it is possible to suggest that the wind wall pattern is associated with the climatological clockwise (counterclockwise) system localized at longitudes in the northern hemisphere (southern hemisphere). Both of these circulations that show strong westward winds at a latitude of about 65° at around $\sim 150^\circ\text{E}$ and $\sim 250^\circ\text{E}$ in the southern and northern hemisphere, respectively, are associated with the impact of the ion convection over the neutral winds at high latitudes.

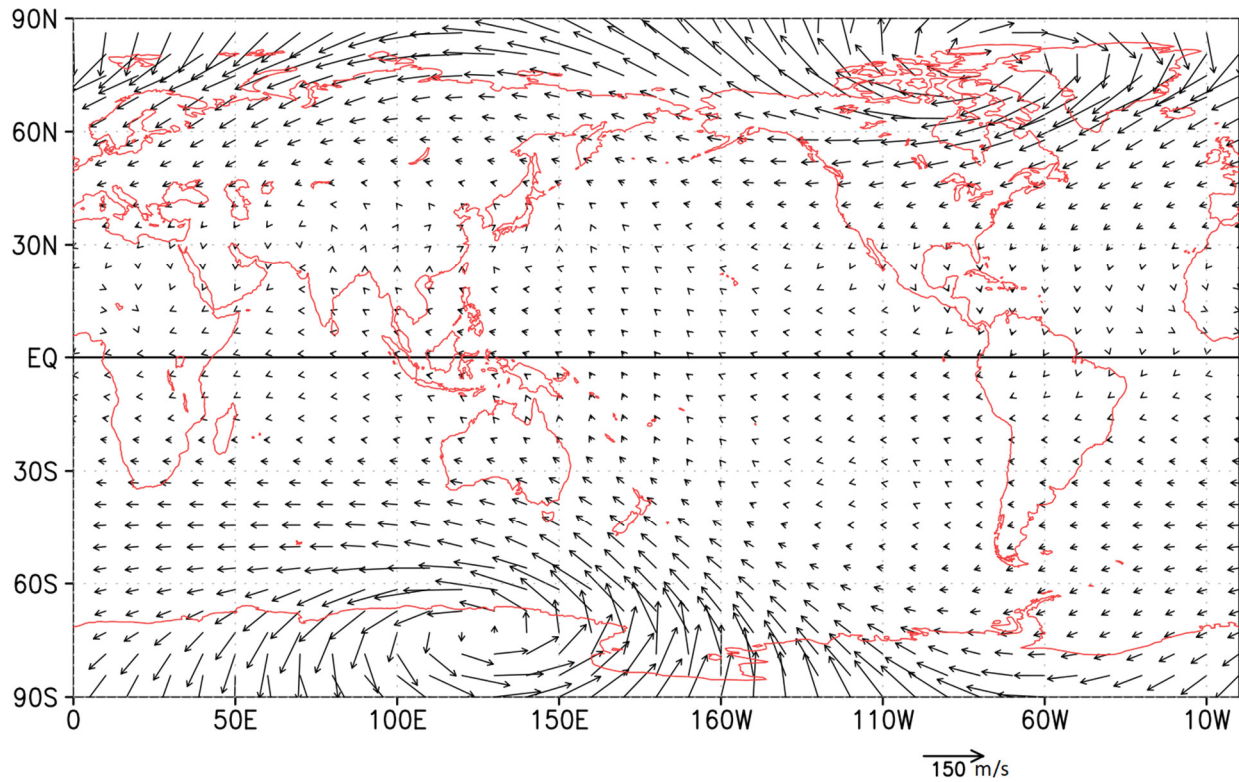


Figure 3.1. Climatological (1981-2010) wind circulation at 250 km for March at 0UTC, from SD-WACCM-X data.

Vertical cross sections of the zonal wind at a latitude of $\sim 65^\circ$ in the northern hemisphere for each of the four groups described above are presented in Figures 3.2 and 3.3. Either WINDII or SD-WACCM-X composites show that the wind wall pattern (with wind velocities greater than 200 m/s) is more evident during active geomagnetic conditions, independently of the solar activity conditions. In general, these very strong westward winds appear at longitudes between 200° and 340° in the northern hemisphere. The composite analysis permits the extension of the longitudinal region of interest over the northern hemisphere, where Shepherd & Shepherd (2018) reported it to be from 200°E to 300°E . In the southern hemisphere this pattern occurs in a longitude range between 100°E and 200°E (Figures 3.4 and 3.5). It is important to point out that in the southern hemisphere the wind background outside the wind wall region has predominantly an eastward

direction, which is stronger in the WINDII observations. The northern hemisphere has a westward wind background outside the wind wall area. For the zonal wind, there is a better spatial (altitude and longitude) agreement between SD-WACCMX-X and WINDII in the northern hemisphere.

Figures 3.2 – 3.5 also allow the analysis of the meridional wind patterns at noon local times. Northward/positive (southward/negative) values of meridional wind predominate over the northern (southern) hemisphere. However, during Active GC meridional winds also show an enhancement, which has a special behavior. At Active GC, the northern (southern) hemisphere, strong northward (southward) meridional winds at the west side of the wind wall, and southward (northward) winds over its east side, are apparent. On the other hand, at Quiet GC, both hemispheres still present the special meridional circulation described before, but with less intensity (which is harder to distinguish at the northern hemisphere, especially during Low SA). The meridional wind circulation description together with the zonal wind analysis, may suggest that an atmospheric circulation of larger spatial scale is located over the northern hemisphere.

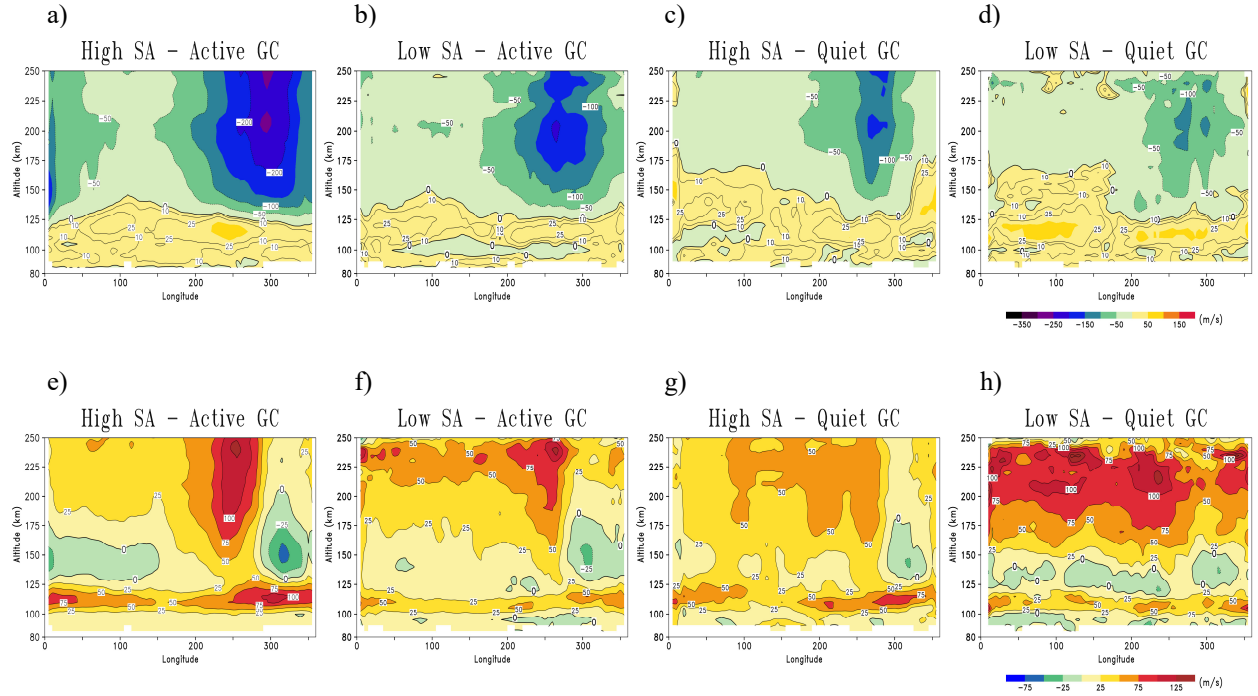


Figure 3.2. (a-d) Vertical cross section of the zonal wind around noon local time (11-14 LT) at $\sim 65^\circ\text{N}$ from WINDII observations for each of composite groups. (e-h) The same as in (a-d) but for the meridional wind.

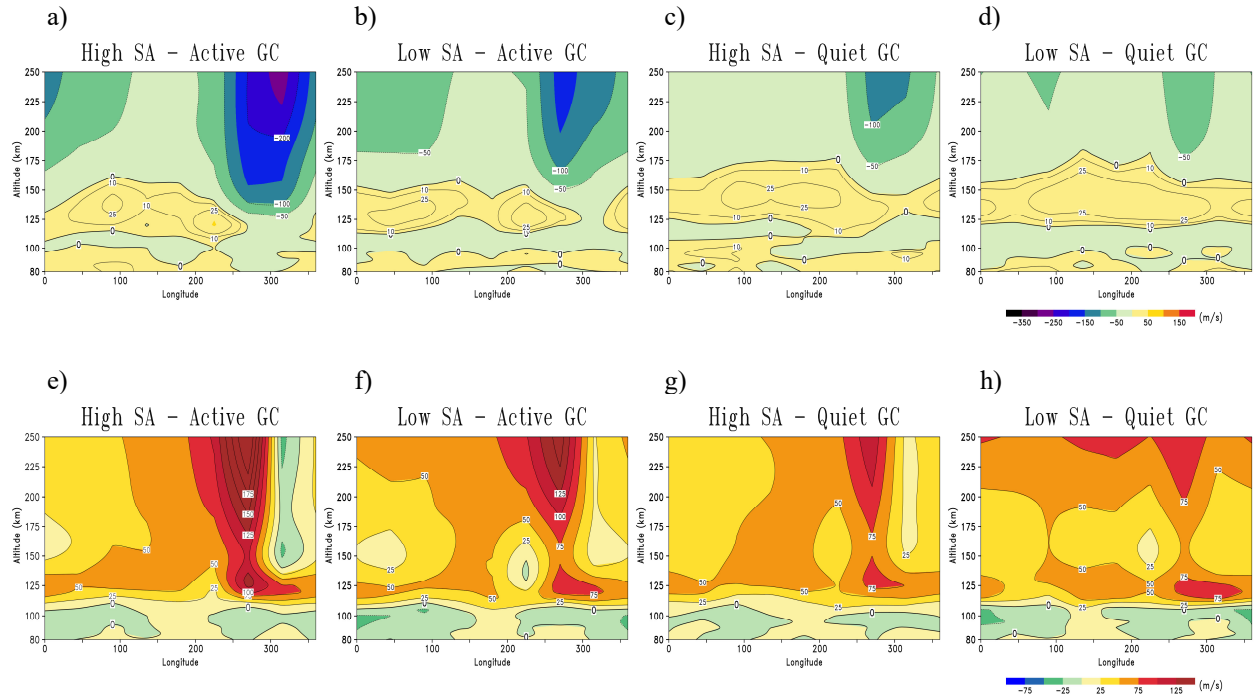


Figure 3.3. (a-d) Vertical cross section of the zonal wind at noon local time (12 LT) at 65°N from SD-WACCM-X for each of composite groups. (e-h) The same as in (a-d) but for the meridional wind.

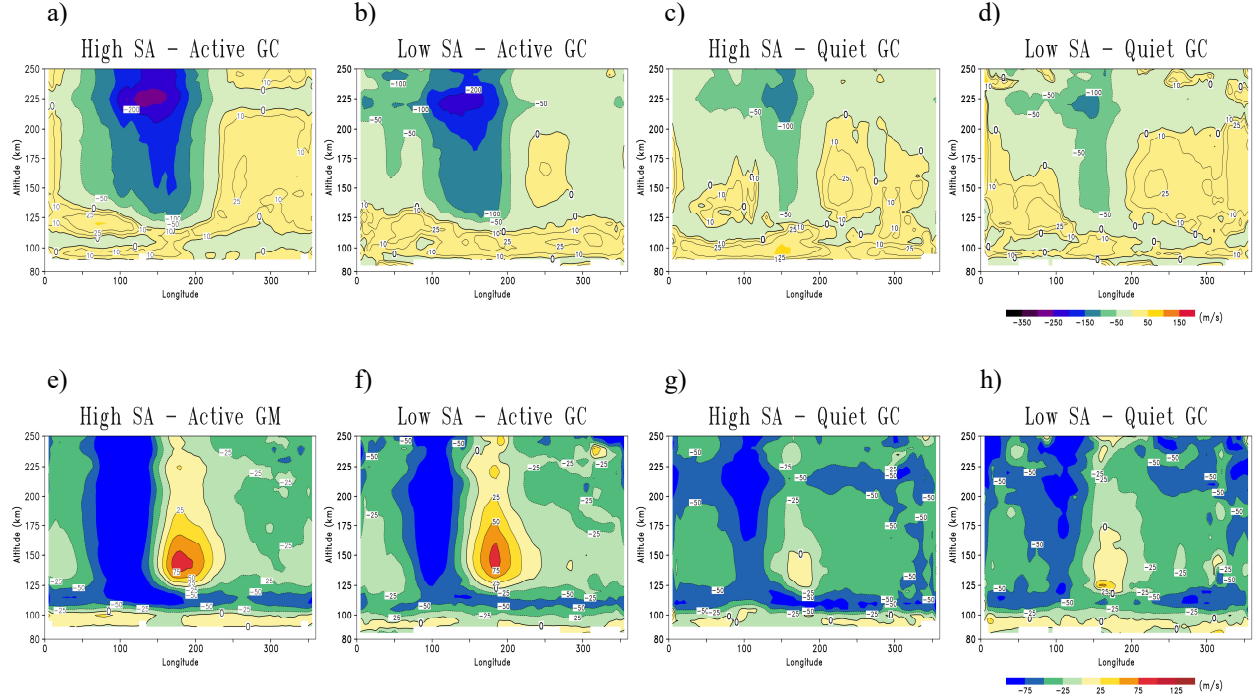


Figure 3.4. (a-d) Vertical cross section of the zonal wind at around noon local time (11-14 LT) at $\sim 65^\circ\text{S}$ from WINDII observations for each of composite groups. (e-h) The same as in (a-d) but for meridional wind.

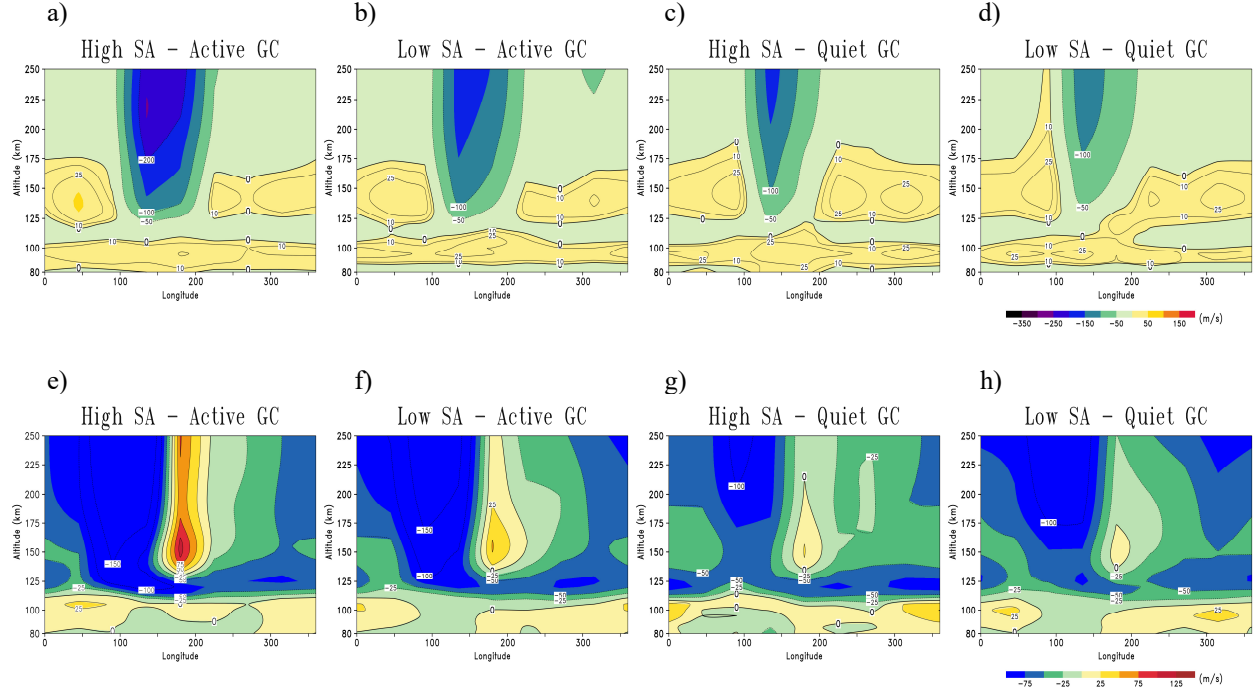


Figure 3.5. (a-d) Vertical cross section of the zonal wind at noon local time (12LT) at 65°S from SD-WACCM-X for each of composite groups. (e-h) The same as in (a-d) but for the meridional wind.

Figure 3.6 indicates the average zonal and meridional wind values over the wind wall core region, which is determined as the region from 200°E-340°E (100°E-200°E) in longitude and 150 to 250 km in the northern (southern) hemisphere. A gradual increase (either in modelling data or observations) of the westward winds is noticeable from Low SA-Quiet GC (group 1) to High SA-Active GC (group 4), with the latter especially pronounced in the northern hemisphere. This, in agreement with Figure 3.2 and 3.3, shows that high solar activity also leads to an increase of the westward zonal winds within the wind wall region, but its effect is still less than that of the geomagnetic disturbances. On the other hand, WINDII observations in the southern hemisphere, allow us to confirm that geomagnetic activity is a dominant factor for the appearance of strong westward zonal winds. For the southern hemisphere, the gradual increase of the strong westward winds from group 1 to 4 is not as evident as in the northern hemisphere.

In addition to the zonal wind analysis, Figure 3.6 also helps to determine that northward (southward) winds are predominant in the northern (southern) hemisphere over the region of the wind wall. A geomagnetic disturbance impact on the meridional circulation is not clear, when the wind velocities in both hemispheres (in average) are not greater than 100 m/s. Thus, meridional winds contribution to the resultant velocity vector over the wind wall region is less than that of the zonal wind. Further, according to the BIAS (SD-WACCM-X values minus WINDII) shown in Figure 3.6, zonal wind magnitude observations are greater than those from SD-WACCM-X, especially during active geomagnetic conditions and in the northern hemisphere. An opposite situation occurs for the meridional wind magnitudes, where the SD-WACCM-X overestimates these values by about ~ 40 m/s during active geomagnetic conditions.

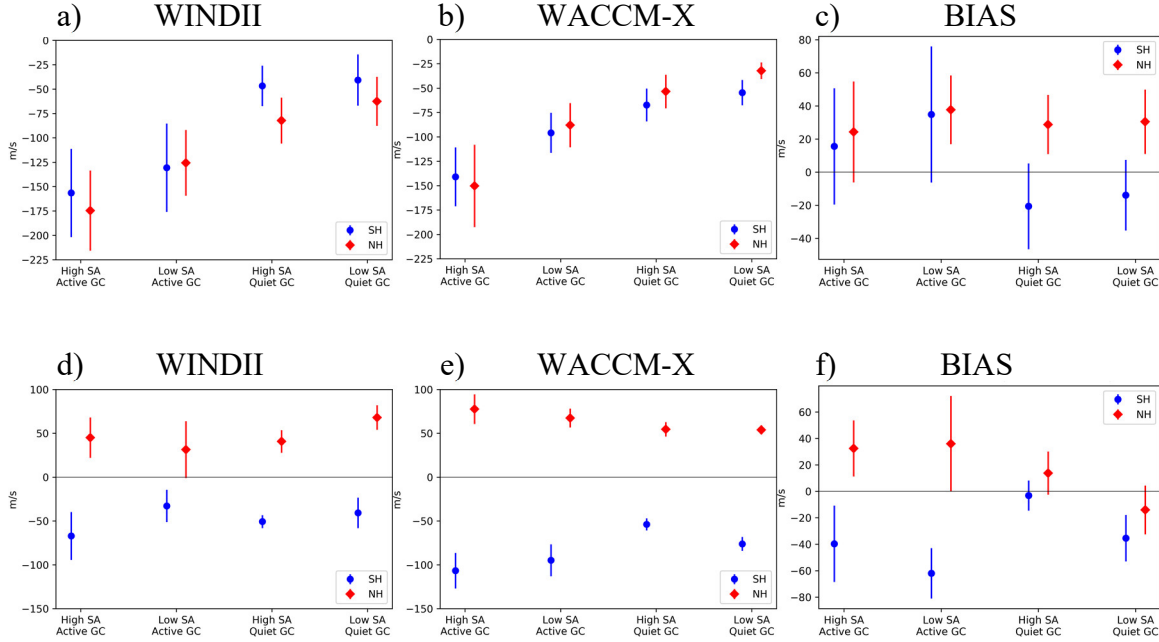


Figure 3.6. a) Average variability of the zonal wind over the wind wall core region for each of the four groups of analysis from (a) the WINDII observations; (b) The same as in (a) but for WACCM-X, and (c) zonal wind BIAS (SD-WACCM-X minus WINDII) over the wind wall region. The error bars are computed as half of the standard deviation from the data inside each group. (d-f) Similar to (a-c) but for the meridional wind.

Figures 3.7 and 3.8 indicates the SD-WACCM-X vertical wind difference between Active and Quiet GC during High and Low SA for both hemispheres at the referenced latitude (65°). The vertical winds described henceforth were computed by using the omega values from SD-WACCM-X and the hydrostatic approximation. As predicted by Shepherd & Shepherd (2018), in both hemispheres a downward movement (negative vertical wind values) dominates the west side of the wind wall over altitudes from 100 to ~ 150 km. In addition, upward winds (positive vertical wind values) are also noticeable over the east side of the wind wall, and this behavior is especially stronger above 150 km. Southern hemisphere results show that these upward winds can go down to about ~ 125 km during Active GC and High SA. A more detailed analysis of the vertical winds is performed for the four specific cases in Section 3.2.

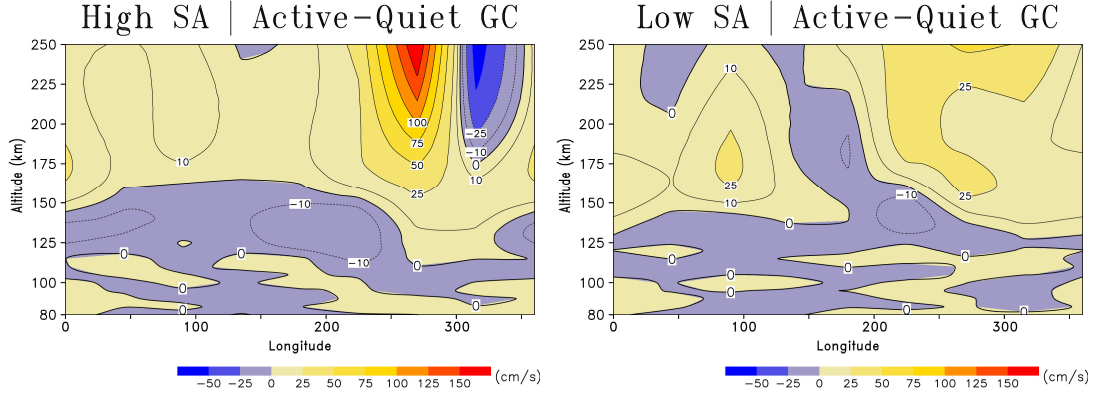


Figure 3.7. The left (right) panel shows a vertical cross section of the vertical wind difference as predicted by SD-WACCM-X between Active and Quiet Geomagnetic conditions during High (Low) Solar Activity at a latitude of 65° in the northern hemisphere.

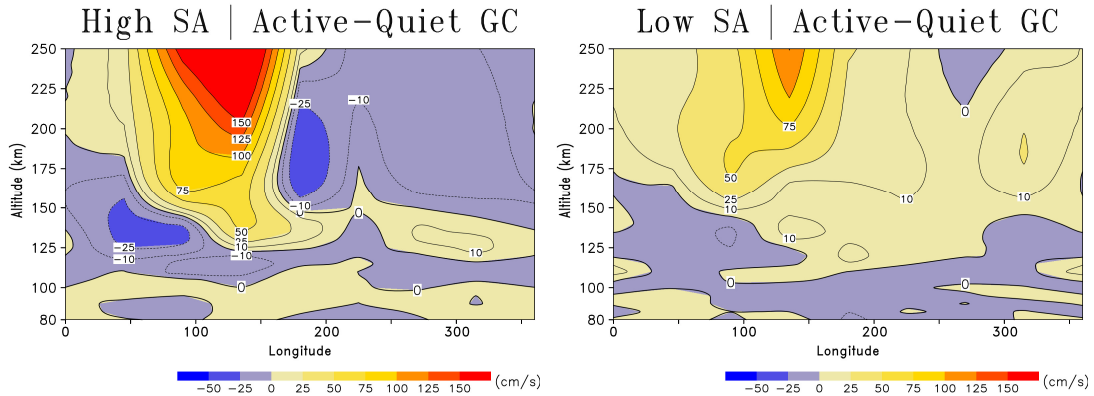


Figure 3.8. The left (right) panel shows a vertical cross section of the vertical wind difference as predicted by SD-WACCM-X between Active and Quiet Geomagnetic conditions during High (Low) Solar Activity at a latitude of 65° in the southern hemisphere.

3.1.1. The wind wall climatology

WINDII data provide unique information for the lower and middle thermosphere. However, due to the limited lifetime of the UARS satellite mission they do not provide enough information for representative means over long climatological periods, such as for example, 1981-2010. As shown in the previous section, the SD-WACCM-X has a very good agreement with WINDII, especially above 125 km. Therefore, further analysis was carried out employing the SD-WACCM-X to determine if the wind wall pattern changes over the different seasons of the year.

Figures 3.9 and 3.10 indicate the vertical cross sections of zonal wind averages for representative months of the four seasons of the year at 12LT over 65°N and 65°S, respectively. One of the first noteworthy characteristics from these figures is the stronger impact of Active GC, where westward zonal winds, independently of the season of the year, have larger values over the wind wall region in comparison with Quiet GC. Furthermore, it is possible also to determine that High SA can enhance the westward (negative) zonal wind values in the northern hemisphere, an observation that is not easy to differentiate in the southern hemisphere.

Another feature shown in Figures 3.9 and 3.10, is that over the wind wall core region, during any of the four composite groups, a slightly lower westward zonal wind magnitude is reached during the month of July. Stronger zonal winds are seen in the months of January and October. This characteristic might be related (as pointed out by other studies) to the relative oscillations in the position and angle between the Earth and the Sun.

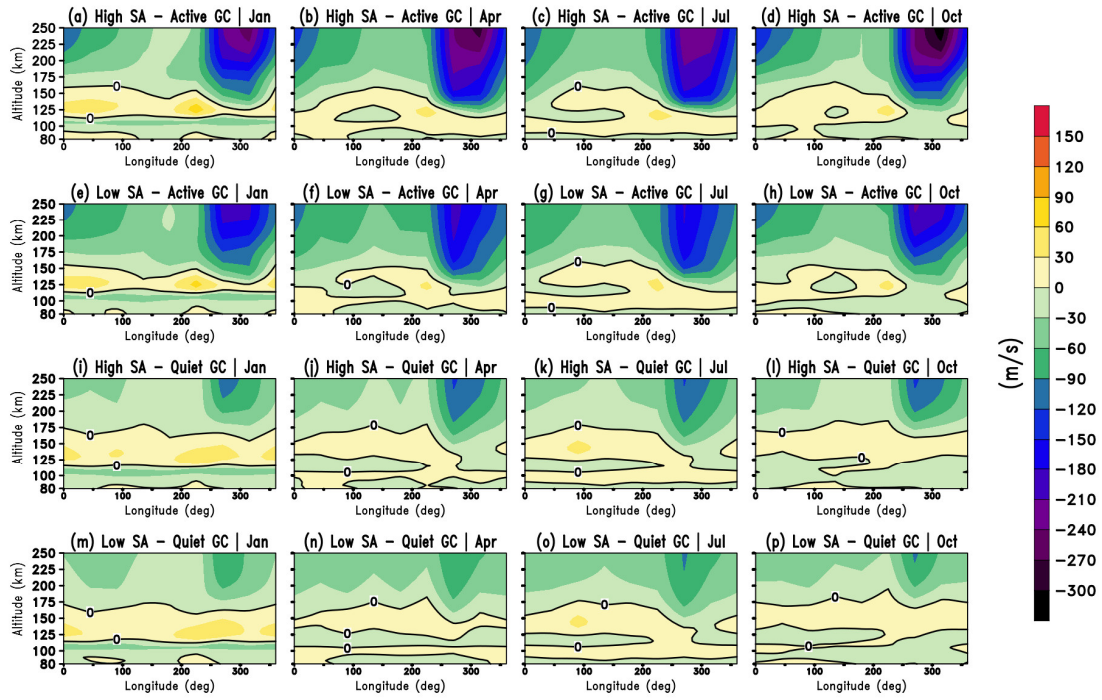


Figure 3.9. Climatological (1981-2010) vertical cross section of the zonal wind at 65°N for the months of January, April, July, and October and each of the different 4 composite groups.

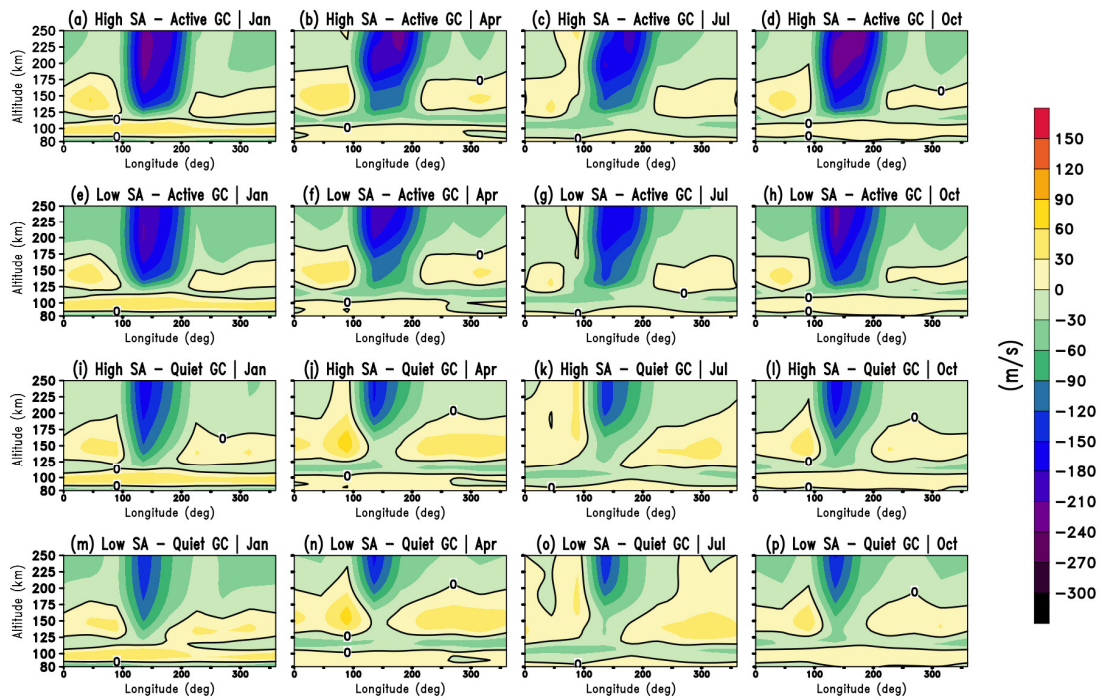


Figure 3.10. Similar to Figure 3.9 but at 65°S.

Finally, the wind wall depth, which is determined as the manifestation of westward zonal winds at lower altitudes over the longitudinal region of the wind wall, has a seasonal variation. Over the northern hemisphere it is possible to recognize that the maximum depth (close to 125 km) occurs during summer (July in Figure 3.9), while the minimum happens during winter (January in Figure 3.9). This behavior can also be seen in the southern hemisphere (Figure 3.10), but again, the maximum and minimum depths occur over its respective summer and winter months.

3.2. The wind wall morphology and its impact on the lower and middle thermosphere

At this point it is important to indicate that, as a result of the previous analysis and in agreement with Liu et al. (2019)'s study, the wind wall pattern is the result of Active GC. In line with this, most of the results discussed in this section correspond to two High SA and Active GC specific cases, where it is possible to compare with the WINDII observations for both hemispheres. The first results are intended to explain the main characteristics of the wind wall, especially its dynamics and its influence on the $O(^1S)$ green line emission. The second analysis is focused on the main features of the atmospheric circulation associated with the wind wall. Finally, the impact of this circulation on the atomic oxygen is detailed, which is compared also with Low SA and Quiet GC events.

Figure 3.11 shows the vertical distribution of horizontal winds at 14 LT from WINDII and SD-WACCM-X at 65°S, its corresponding figure for 65°N is shown in Figure A.3. Similar to what was described at the beginning of section 3.1, it is important to mention that since the time frequency of our simulations is one hour, after the selection process of information at 14 LT, the longitudinal resolution was reduced from 2.5° to 15°. Despite this horizontal resolution change, a good agreement between both kinds of data is possible to appreciate, especially above 150 km. The bottom picture in Figure 3.11 also shows the vertical velocity behavior from the SD-WACCM-X simulation, where upward and downward motion (positive and negative values of vertical velocity, respectively) are seen at the east and west boundary of the wind wall, respectively, between altitudes of 100 and 125 km. The approximate east (west) boundary of the wind wall is pointed out with a red (blue) line in Figures 3.11 and 3.12, which correspond with the longitude of 180° (60°).

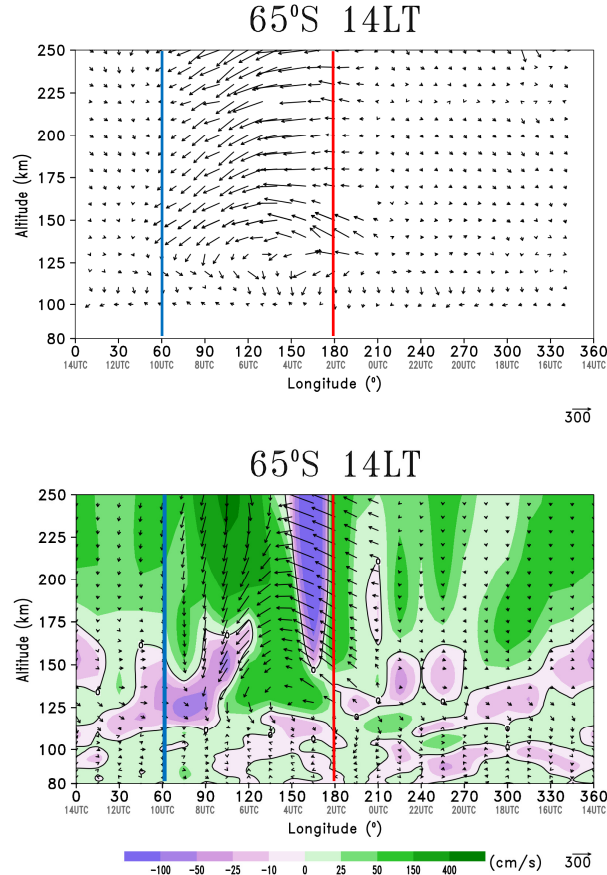


Figure 3.11. Vertical cross section of the horizontal winds (vectors) from WINDII (top) and SD-WACCMX (bottom). Vertical velocity (colors) is also shown in the bottom image. Both images correspond to a latitude of 65°S and 14LT on March 25th, 1992. The red (blue) line points out the longitude of 180° (60°), which is the at the east (west) side of the wind wall. UTC hours are specified below each longitude.

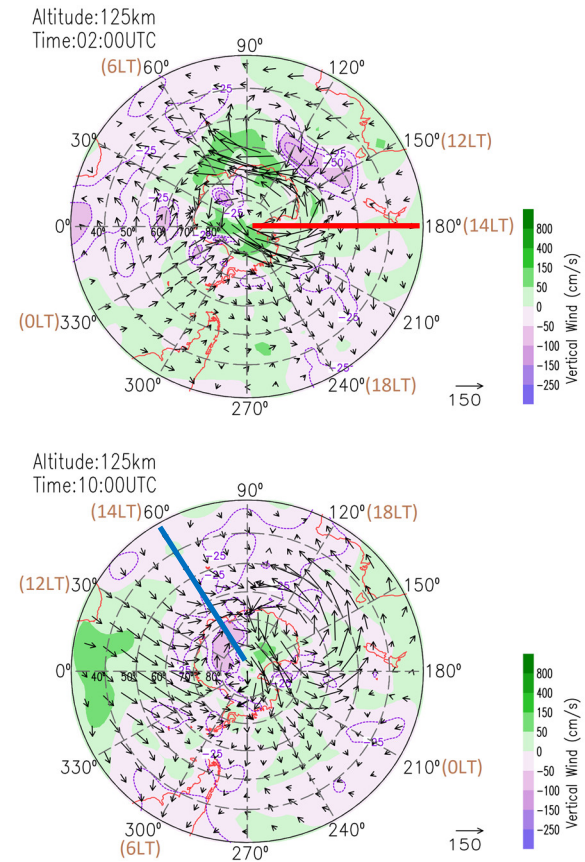


Figure 3.12. The top (bottom) image shows the horizontal wind distribution in vectors and the vertical velocity in colors at 125 km and at 02 (10) UTC in the southern hemisphere. Both images come from SD-WACCM-X simulations on March 25th, 1992. The outer circle indicates a geographic latitude of 30° and goes up to the pole every 10°. The red (blue) line points out the longitude of 180° (60°), for comparison against Figure 3.11. Local Times (LT) are pointed out at specific longitudes.

Figure 3.12 illustrates the behavior of the horizontal and vertical winds at 125 km for the 02 and 10 UTC. From this latter, it is seen that the upward velocities seen over the east side of the wind wall (red line, at the point of 180° longitude and 65° latitude) are linked to positive/upward vertical wind values at the entrance of the anti-sunward convection line at high latitudes close to the counterclockwise dusk circulation. On the other hand, the downward motion over the west side of the wind wall (blue line, at the point of 60° longitude and 65° latitude) is associated with negative vertical velocities in the dawn side of the anti-sunward convection pattern, more specifically with the clockwise circulation cell over this region. A similar behavior is seen for the northern hemisphere in Figures A.3 and A.4. This description allows us to confirm that, as predicted previously, the wind wall pattern relates to the neutral convection system at high latitudes, more specifically to the strong counterclockwise (clockwise) circulation over the dusk side on the southern (northern) hemisphere.

As another point of view from this section, the impact of the wind wall over the $O(^1S)$ green line is also discussed. Figures 3.13a and 3.13b indicate a good agreement for the green line mission between the GLOW/SD-WACCM-X results and WINDII, which is better over the east side of the wind wall in both hemispheres. However, it is important to highlight that in general the modelled green line emissions are lower than observations, possibly due to lower concentrations of atomic oxygen in the SD-WACCM-X, as well as the omission of the three body recombination mechanism for the $O(^1S)$ production, which is especially observed at altitudes around 100 km.

Figure 3.13c shows the vertical distribution of the horizontal and vertical winds from SD-WACCM-X, similar as the bottom picture in Figure 3.11, but for 16LT. Furthermore, Figure 3.13d displays the vertical distribution of the atomic oxygen, where it is possible to see that its greater concentrations are found between 80 and 125 km. Figure 3.13d also shows the vertical distribution of the electron density concentration under the same local time and latitudinal location. Finally, Figure 3.13e presents the vertical distribution of the zonal deviation of the atomic oxygen in a longitudinal range of 30° and 210° . These last three pictures (Figure 3.13c, d, e) permit to determine that the WINDII and GLOW/SD-WACCM-X extension to upper altitudes of the $O(^1S)$ green line emission over the east side of the wind wall, are not only due to the upward winds in the lower thermosphere (which contributes to the transport of atomic oxygen to upper levels, as is observed at the same vertical axis in Figure 3.13e), but also to the greater concentration of electrons at this region. It is worth mentioning that the greater concentrations of electrons at both sides of the wind wall are associated with the position of the auroral oval (see Figures A.6 and A.7).

In contrast with the good agreement of the $O(^1S)$ green line emission at the eastside of the wind wall, the west side shows less concordance for both hemispheres. For the specific case analyzed here at the southern hemisphere, there is a remarkable difference in the location of the west side peak of the green line emission, which occurs at around 30° longitude in WINDII observations, and around 60° longitude in the simulation. Despite this discordance, we can estimate that the lower values of green line emission over the west side peak section are due to downward velocities (and transport of atomic oxygen) and to smaller concentration of electrons. The latter, together with the difference in the location of the west side peak, suggests that the real auroral oval (associated with the electron concentration at both peaks, see Figure 3.15) for this case has a larger spatial scale than the simulation. Finally, the disagreement on the west side green

line emission intensity and its altitude, may also suggest that the vertical velocity negative values over this section are greater than those indicated by the SD-WACCM-X.

The main second point of this section is the description of the circulation linked to the wind wall, which is the high-latitude atmospheric convection pattern. As described in Section 1.1.1, this convection pattern is the result of the ion drag impact over the neutral flow, which is especially stronger during Active GC. It is worth mentioning that the main impact on the zonal wind (together with its much more evident zonal position) of the thermospheric convection pattern occurs at 0 (12) UTC hour in the southern (northern) hemisphere. Thus, these hours were chosen for the description of the specific features of this complex flow for both hemispheres. The altitude of the analysis corresponds to 200 km, enabling a better description of the characteristics of the high latitude convection system.

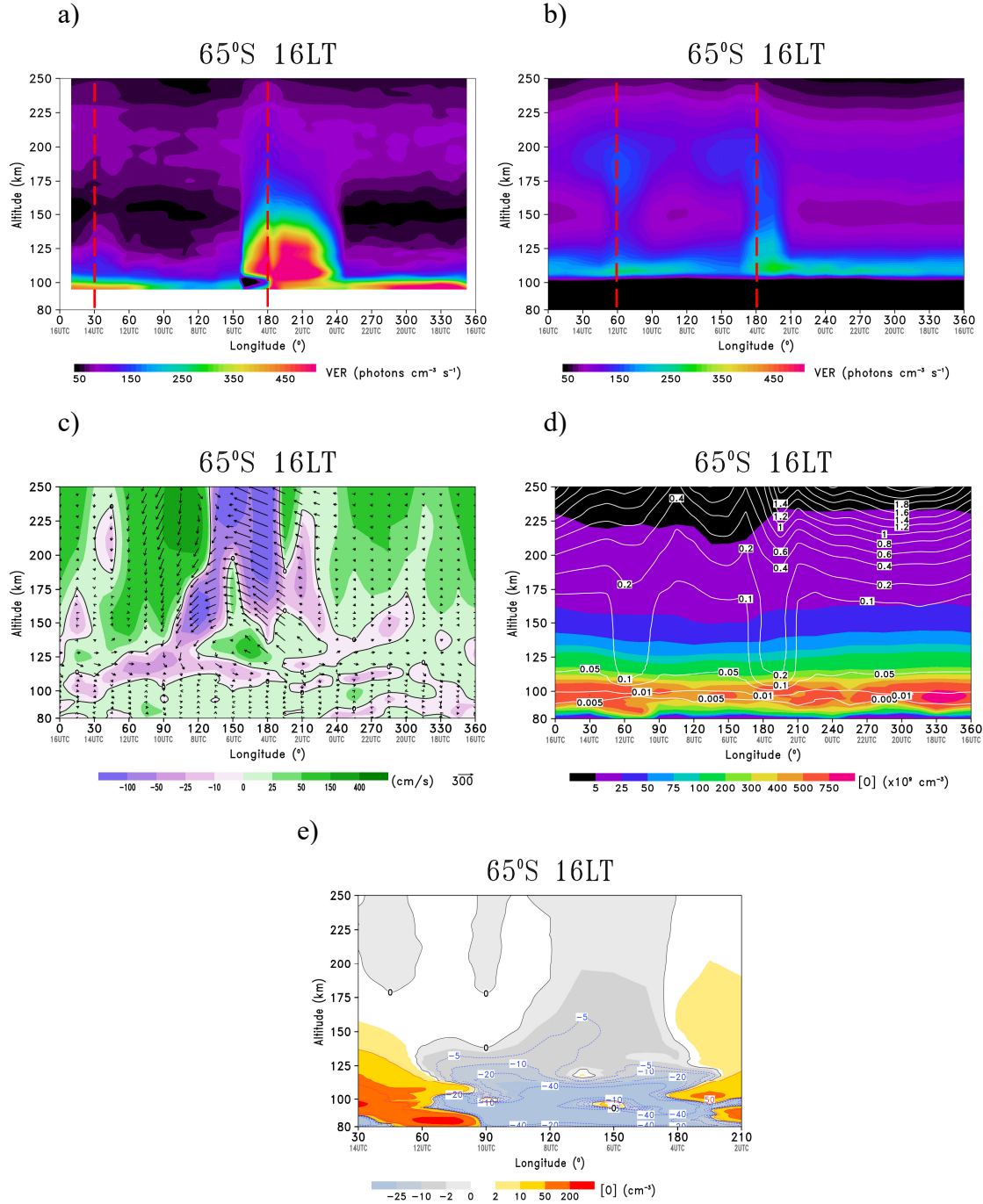
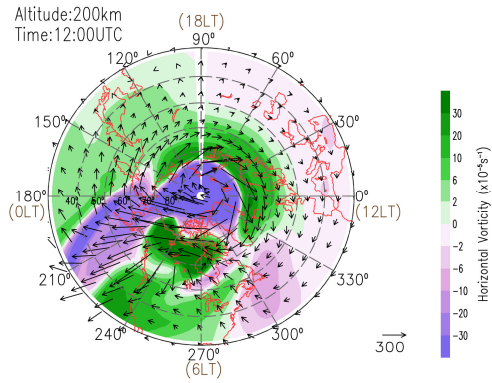


Figure 3.13. a) Vertical cross section of the O(¹S) green line emission from WINDII. b) Similar to a), but from the GLOW/SD-WACCM-X. c) Vertical cross section of the horizontal wind (vectors) and vertical velocity (colors). d) Vertical cross section of the atomic oxygen (colors) and the electron density (x10⁶, contours) concentration. e) Vertical cross section of the [O] zonal deviation. All plots in this figure are at 16 LT and 65°S, on March 25th, 1992. Red dashed lines in a) and b) indicate the green line emission peaks at both sides of the wind wall.

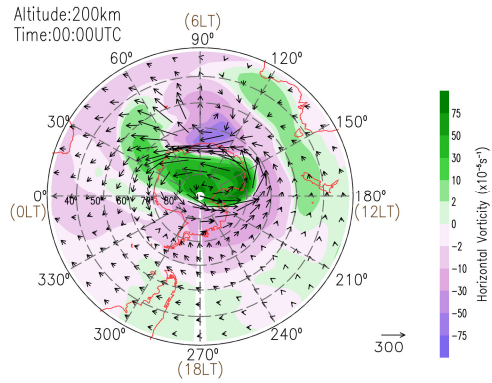
In the northern hemisphere, a cyclonic (anticyclonic) circulation can be identified in regions with positive (negative) values of relative horizontal vorticity. However, for the southern hemisphere, a cyclonic (anticyclonic) circulation corresponds to negative (positive) values of relative horizontal vorticity. In Figures 3.14a and 3.14d, positive values of horizontal vorticity are shown in green colors, and negative values in purple colors. Thus, both figures allow us to point out the two main features (for both hemispheres) associated with the convection pattern, the cyclonic and anticyclonic circulation over the dawn and dusk side, respectively. It has been quite well described by many studies that the anticyclonic circulation is more intense and well-defined than its cyclonic counterpart (e.g., Schoendorf et al., 1996; Forbes, 2007; Kwak & Richmond, 2007).

In addition, negative (positive) values of vertical velocity dominate over the cyclonic (anticyclonic) region; however, negative values over the anticyclonic flow can appear, which is part of the conservation mass as a result of the stronger winds over this region (only possible during Active GM). This effect in the anticyclonic region has been referred to as an “anomalous anti-baric flow” (Forbes, 2007). In addition, in both hemispheres is seen that the vertical wind has more complex behavior along the anti-sunward convection flow, characterized by a kind of wave pattern in the vertical velocity, where upward and downward motions are interspersed, upwelling (downwelling) flows are found at the entrance of the anti-sunward motion. The behavior of the vertical winds agrees with the divergence pattern at this altitude (200 km), where convergence (divergence) regions correspond to negative (positive) values of the vertical velocity. Finally, it is important to mention that these vertical velocities can reach values of more than 800 cm/s.

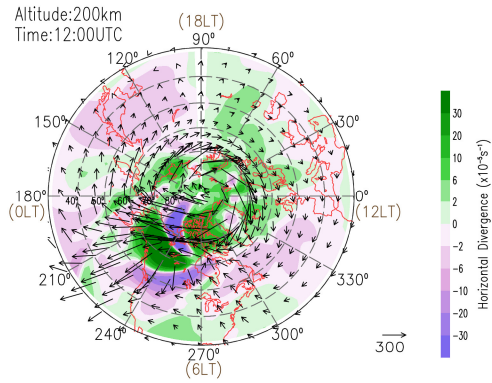
a) Relative Vorticity at NH



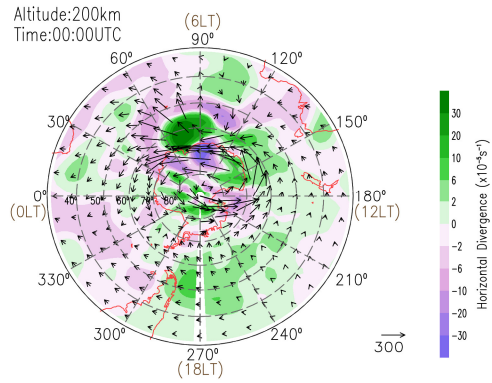
d) Relative Vorticity at SH



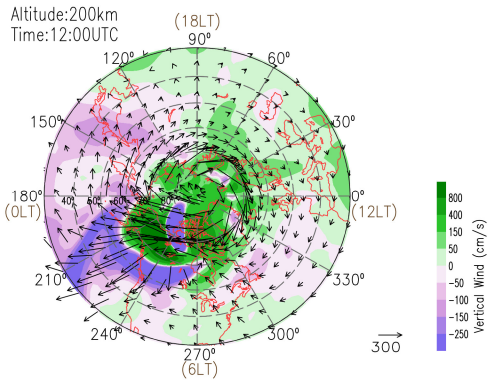
b) Divergence at NH



e) Divergence at SH



c) Vertical velocity at NH



f) Vertical velocity at SH

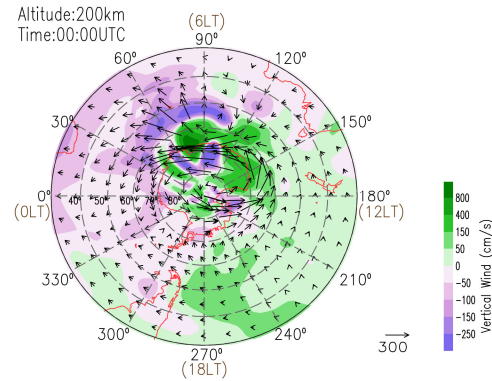


Figure 3.14. a), b), and c) indicate the horizontal relative vorticity, horizontal divergence, and vertical velocity at 200 km, 12UTC, in the northern hemisphere, respectively, on May 22nd, 1992. d-f) Similar to a-c) but at 00UTC in the southern hemisphere, on March 25th, 1992. The outer latitude boundary corresponds to 30°. Local times (LT) are specified at 0°, 90°, 180°, and 270° longitude.

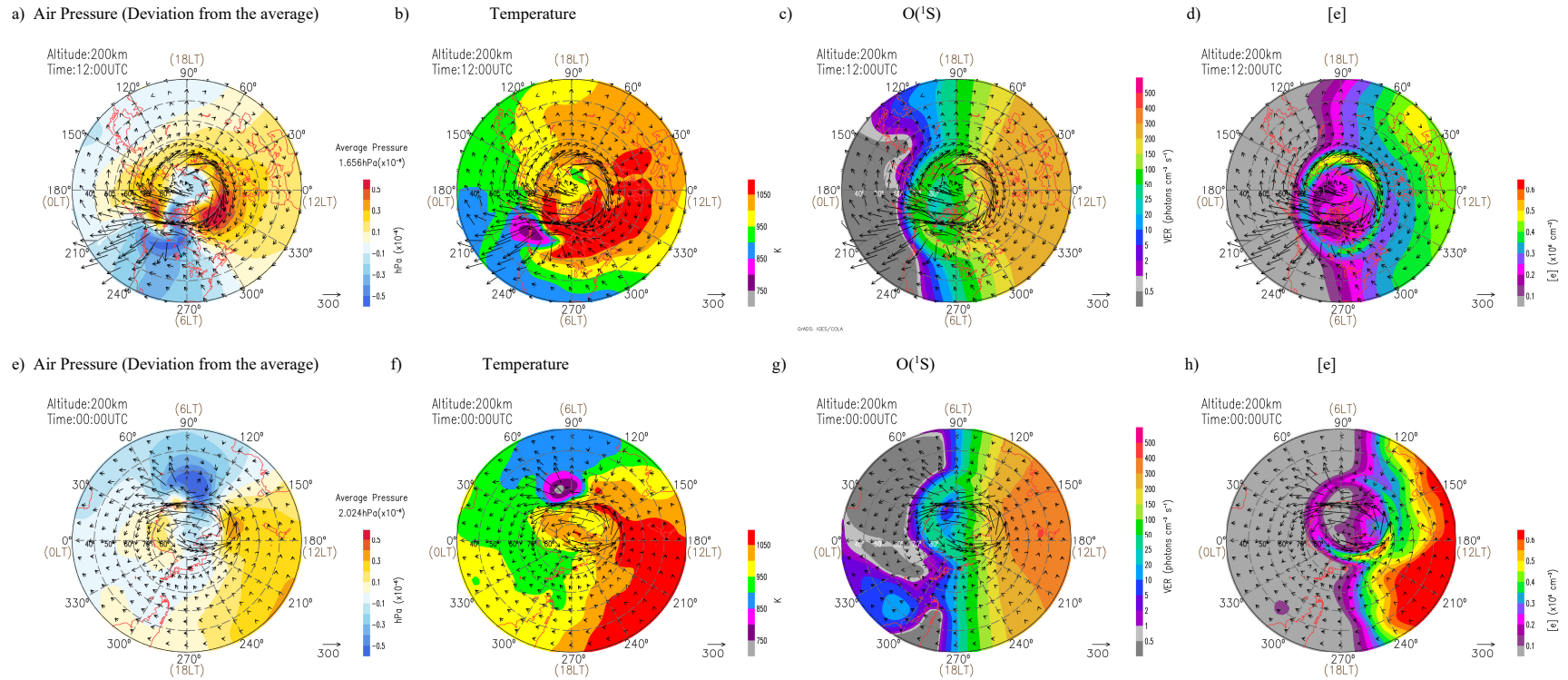


Figure 3.15. a), b), c), and d) indicates the deviation from the average of the air pressure, temperature, the $O(^1S)$ green line emission from GLOW/SD-WACCM-X, and the electron concentration ($[e]$) at 200 km and 12UTC, for the northern hemisphere, respectively, on May 22nd, 1992. e-h) Similar to a-d) but at 00UTC in the southern hemisphere, on March 25th, 1992. The outer latitude boundary corresponds to 30°. Local times (LT) are specified at 0°, 90°, 180°, and 270° longitude.

Figure 3.15 shows a low-pressure region over the cyclonic circulation, which agrees with a classical meteorological behavior. However, relative low-pressure values are also localized in the center of the anti-cyclonic circulation, that is also explained as a result of mass conservation due to the very strong winds around this vortex. An anticyclonic flow with a pressure low inside the circulation cell is called an “anomalous or antibaric low” (Shoendorf et al., 1996; Forbes, 2007). On the other hand, relative high-pressure areas are recognized at the entrance and departure region of the anti-sunward line of convection, these high-pressure areas are placed nearer to the dusk section. The strong contrast in air pressure over these high latitude thermospheric regions are also an important source of strong winds.

In addition to the pressure variations over the high latitude convection system, Figure 3.15 also shows relatively low temperatures confined around the cyclonic vortex, which resembles the well-known cold-core lows that occur in the upper troposphere. Furthermore, greater temperature values are also found over the dayside, especially in hours close to the noon UTC time.

On the other hand, no significant spatial variation of the $O(^1S)$ green line emission is seen at 200 km. In general, the $O(^1S)$ pattern follows the distribution of the electron density concentration, which is mainly higher over the dayside and around the aurora oval. For the southern hemisphere event an increment of the green line emission is observed over the night side around 300° longitude and 30° - 40° latitude. The latter might be related to higher values of temperature over this area. Further, our simulations indicate that the neutral wind does not have a significant impact over the electron and $O(^1S)$ spatial distributions. Instead, both variables might have closer relationship with the field-aligned currents and the ion wind.

3.2.1. The wind wall impact on the atomic oxygen distribution

Since the convection system rotates throughout the day together with the sun, the patterns and variables behavior described before also changes accordingly. This means that for different UTC times, different regions over high latitude areas will show the features detailed above. This is also seen in Figure 3.16, where the spatial distribution of the atomic oxygen at 200 km is shown at different UTC times. The intention of this section is to provide a general description of the impact of the atmospheric circulation associated with the wind wall over the atomic oxygen concentration ($[O]$), which is a complementary objective of this study. The reason why it is important to study the $[O]$, is because the neutral atomic oxygen can stay for longer periods (from hours to days) in the lower-middle thermosphere, and therefore is a good proxy of the dynamical processes of this region.

Figure 3.16 shows that a general $[O]$ depletion is taking place over the whole high latitude convection system, which (as mentioned before) rotates along the day over this region of the globe. Over the departure area of the anti-sunward convection line, greater $[O]$ occurs. This greater concentration has an extension over the surrounding regions of the cyclonic and anticyclonic vortices. A second important feature is the localized atomic oxygen depletion at the core of the cyclonic vortex. A relative $[O]$ depletion can also appear over the anticyclonic vortex, but its intensity is less in comparison with what is noticed on the cyclonic core. On the other hand, the lower values of $[O]$ for the case in the northern hemisphere can be explained because this event is for May 22nd, which is close to the summer in this hemisphere. Fuller-Rowell (1998) suggests that during the summer more heating sources are found in the thermospheric polar cap, which enhances the meridional circulation (equatorward), transporting more oxygen from polar regions to lower latitudes.

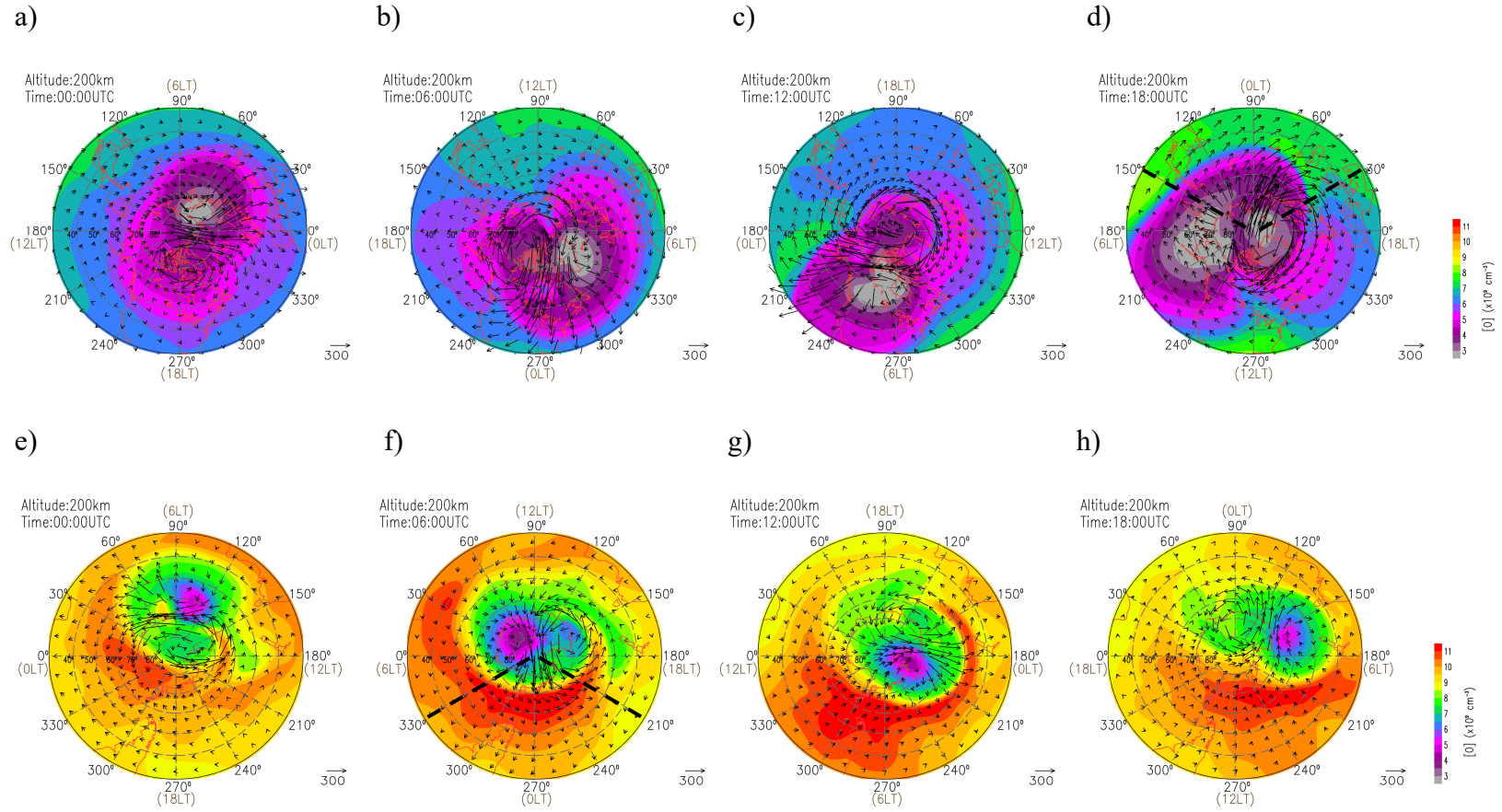


Figure 3.16. a), b), c) and d) illustrate the spatial distribution of the atomic oxygen concentration at 0, 6, 12 and 18 UTC, respectively at an altitude of 200 km in the northern hemisphere, on May 22nd, 1992. e-h) Similar to in a-d) but for the southern hemisphere, on March 25th, 1992. Local times (LT) are specified at 0°, 90°, 180°, and 270° longitude. Black dashed lines indicate the longitudes corresponding to the vertical cross sections in Figure 3.17.

Figure 3.17 shows the vertical cross section of the vertical movement along the 150°E (330°E) and 30°E (210°E) longitude at 18 (6) UTC time in the northern (southern) hemisphere. The 150°E (330°E) and 30°E (210°E) longitude sections are shown at the west and east side of each of the four plots in this figure, respectively. The spatial behavior of the atomic oxygen concentration is also shown in the background of this plot.

The general [O] depletion over the convection circulation has been recognized in other studies (Volland, 1979; Lühr et al., 2004; Schunk & Zhu, 2008). Our results in Figures 3.16 and 3.17, in agreement with previous investigations, indicate that the general atomic oxygen depletion is related to a general upwelling pattern along the line of convection (especially over the departure area) at the lower and middle thermosphere (Figure 3.17), mainly above 120 km. This upwelling circulation is linked to the equatorward transport of [O], which is stronger (weaker) at the departure (entrance) side of the horizontal high-latitude anti-sunward convection line, while less equatorward transport is noticed at the surroundings.

Finally, the low atomic oxygen concentration together with the smaller density values at the core of the cyclonic circulation (Figure 3.16 and 3.15) are associated with the downward motion over this region. This special feature has recently been also recognized by Guo et al. (2019). As described before, this behavior can also appear over the anticyclonic vortex especially during strong Active GC.

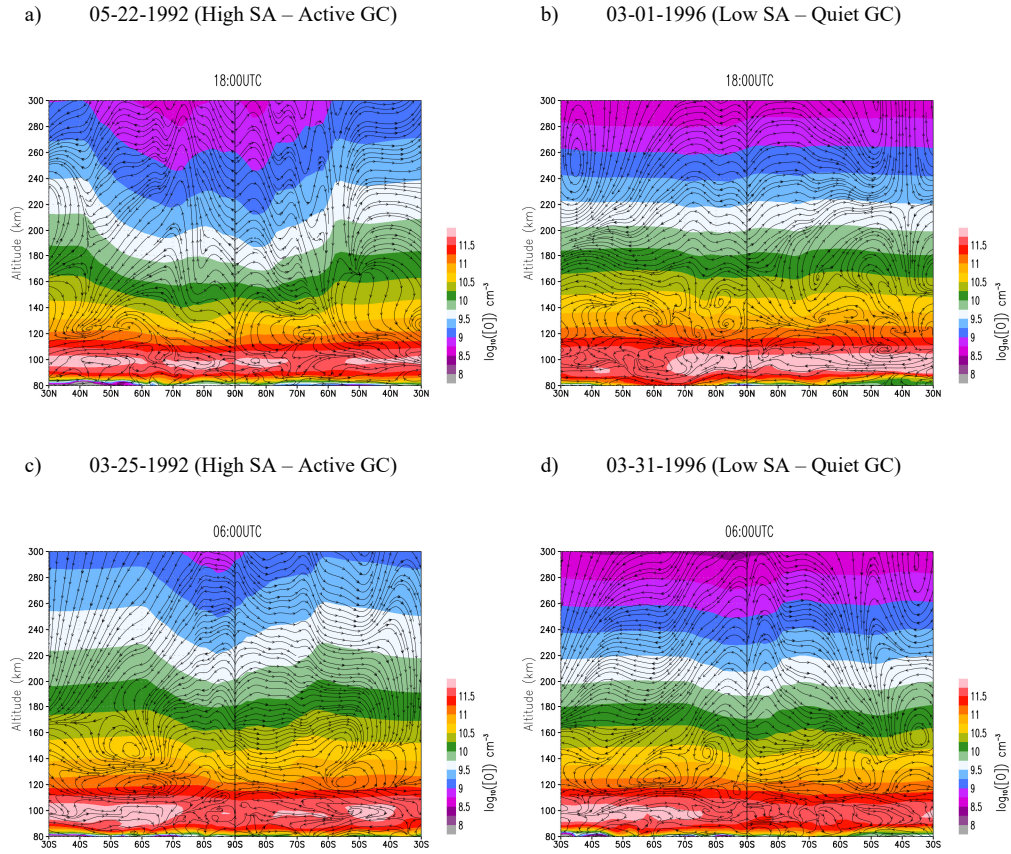


Figure 3.17. a) Vertical cross section of the atomic oxygen concentration and the vertical motion (vertical and meridional velocity values are in cm/s and m/s, respectively) for a latitude range of 30°N-90°N over a longitude of 150° (on the left side) and 30° (on the right side), on May 22nd, 1992, at 18UTC. b) Similar to a) but on March 1st, 1996. c) Similar to a) but for a latitude range of 30°S-90°S over a longitude of 330°E (on the left side) and 210°E (on the right side), on March 25th, 1992, at 6UTC. d) Similar to c) but on March 31st, 1996.

Chapter 4

4. Conclusions

An extensive analysis of the wind wall pattern has been performed. Its impact on the lower and middle thermosphere together with the atmospheric circulation associated with it has also been determined. This work has not only demonstrated the overall good temporal and spatial agreement between the SD-WACCM-X model with WINDII observations, but also revisited and detailed the different variables associated with the neutral circulation at high latitudes. The main conclusions of this study are:

1. The wind wall pattern has an origin in the active geomagnetic conditions.
2. The wind wall is associated with the continuously high latitude convection pattern for both hemispheres, which extends to lower latitudes and gets stronger during geomagnetic disturbances. High solar activity does not have a significant impact on the neutral winds, as it does during active geomagnetic conditions.
3. Stronger winds associated with the wind wall can reach lower altitudes of the thermosphere during summer months. Slightly less zonal wind values were observed during the month of July for both hemispheres.

4. As predicted by Shepherd & Shepherd (2018), the extension of O(¹S) green line emission to upper altitudes at the eastside of the wind wall is associated with upward winds. On the other hand, over the west side green line peak, modelling information permits us to conclude that its lower values are related to downward motion over this section, which transports atomic oxygen to lower altitudes. Lower values of electron density are also observed in this region. The areas of upward and downward velocities respond to the variable and complex influence of the different regions of the high latitude convection system.
5. The general atomic oxygen depletion over the high latitude convection system is the result of the upwelling pattern along the anti-sunward convection line and its respective equatorward transport, especially over its departure side.
6. Finally, the core of smaller values of atomic oxygen at the cyclonic vortex is related to the low-density cell at this region, which is due to downward velocities over its center. On the other hand, the core of smaller values of atomic oxygen at the anticyclonic circulation is also related to the low-density cell, but this latter occurs because of the strong winds around this vortex during active geomagnetic conditions.

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Appendix

This appendix is intended to present additional information for a better comprehension of the wind wall pattern at both hemispheres. For instance, Figures A.1 and A.2 show the behavior at different UTC hours of the horizontal wind (vectors) and the zonal wind (colors) during High SA and Active GC at 200 km for the northern and southern hemisphere, respectively. From these figures it is possible to appreciate that the westward zonal winds dominate over the whole high latitude region on the northern (southern) hemisphere at 12 (0) UTC. In addition, in terms of the spatial distribution of the zonal wind and the horizontal wind patterns, a 12-hours lag it is appreciated between both hemispheres.

Furthermore, Figures A.3, A.4 and A.5 present the result of the wind wall analysis for a specific case (May 22nd of 1992) on the northern hemisphere. These figures show similar characteristics to those described at the beginning of Section 3.2 for the specific case in the southern hemisphere (see Figures 3.11, 3.12, and 3.13). The green line peak at the east side of the wind wall it is well represented by the GLOW/SD-WACCM-X model, showing an extension to upper altitudes, which occurs because of the upward winds around 125 km (which transport atomic oxygen to higher altitudes) and the greater concentrations of electrons around the longitude of $\sim 330^\circ$. On the other hand, over the west side of the wind wall, this specific case does not show a second peak in the observations, which may suggest that the negative values of vertical velocity (linked to the downward transport of atomic oxygen) at this longitude ($\sim 240^\circ$) are greater than those showing by SD-WACCM-X.

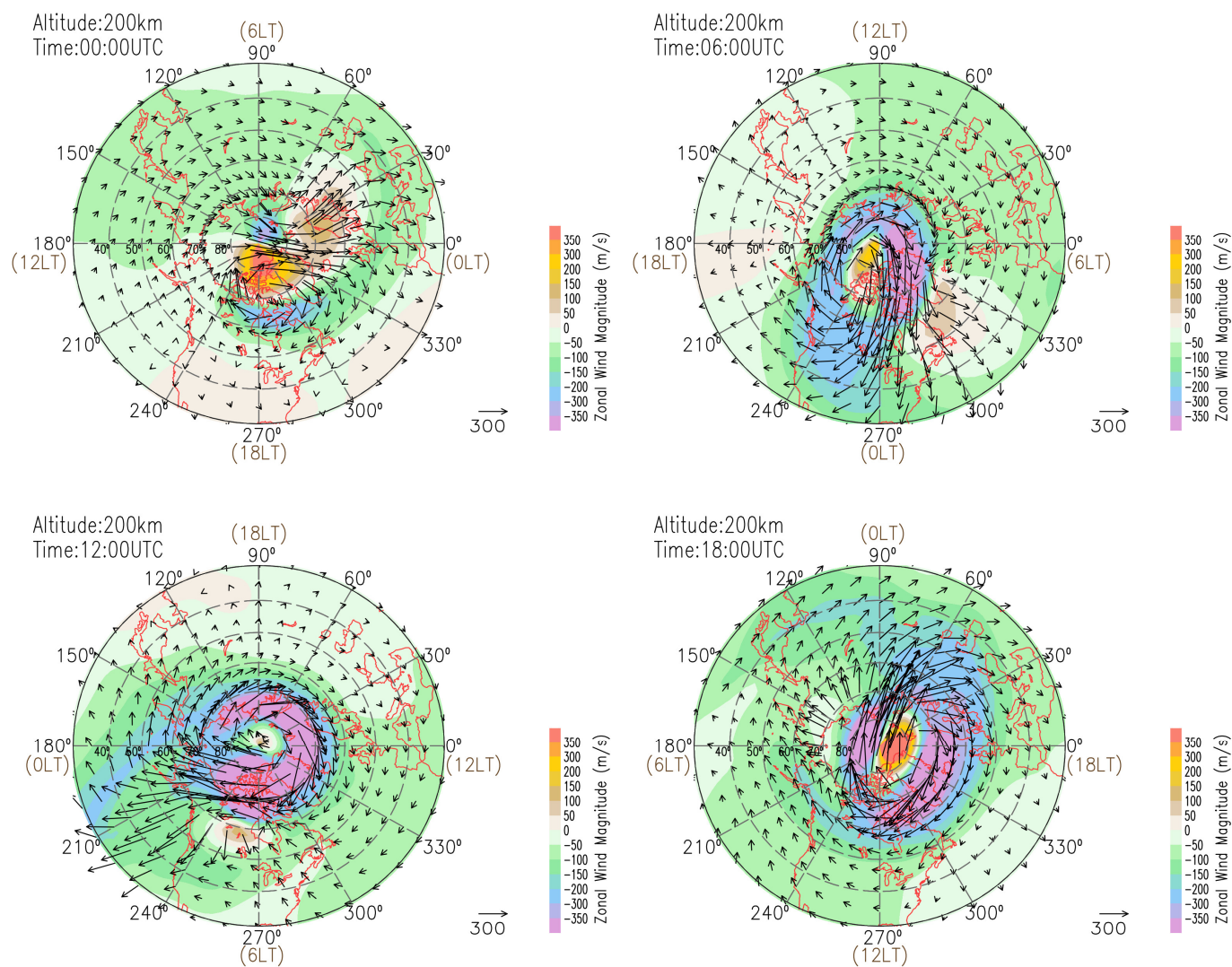


Figure A.1. Zonal wind (colors) and horizontal wind (vectors) in the northern hemisphere at 200 km, from 0 to 18 UTC on May 22nd, 1992. Local times (LT) are specified at 0°, 90°, 180°, and 270° longitude.

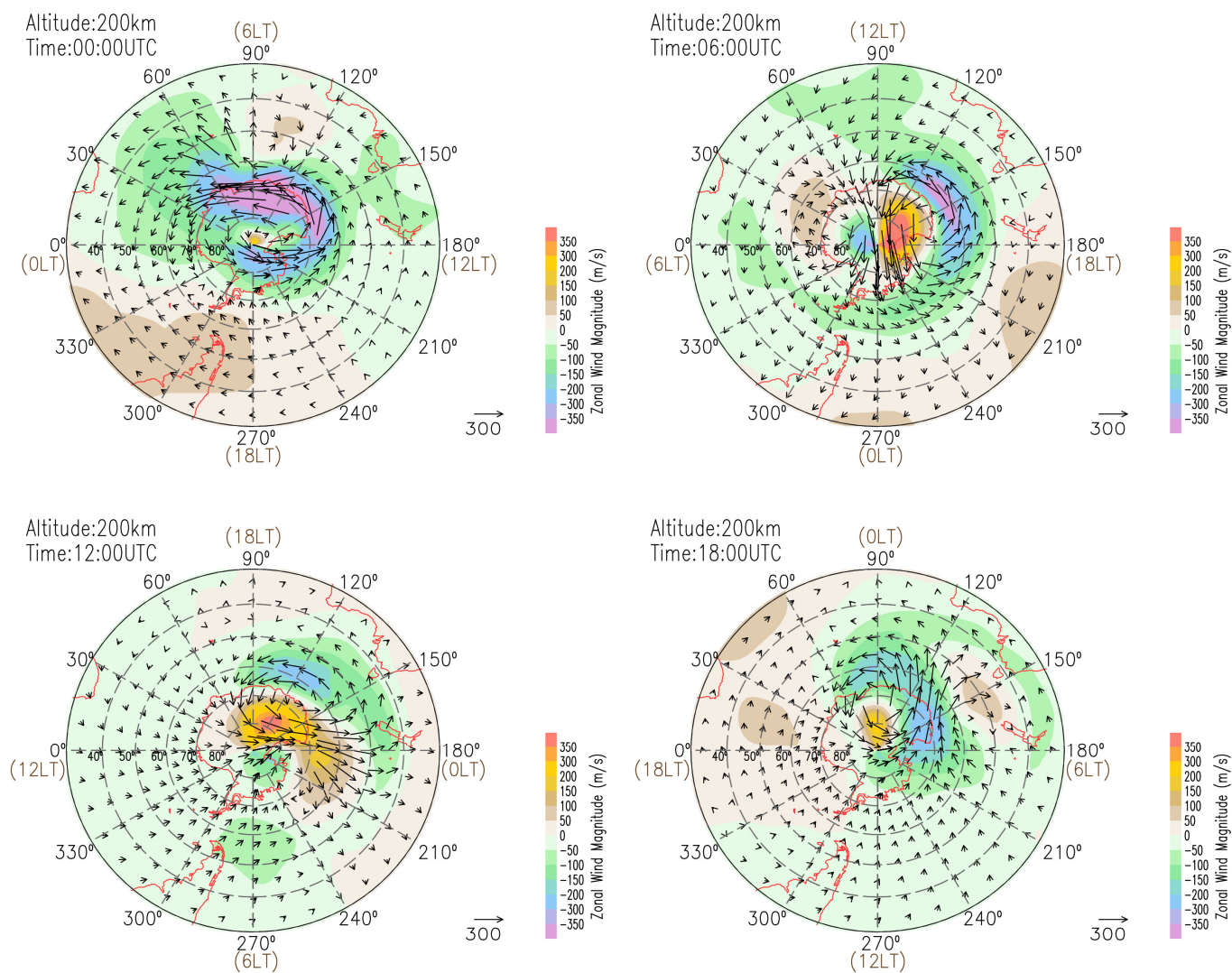


Figure A.2. Similar to Figure A.1 but in the southern hemisphere on March 25th, 1992.

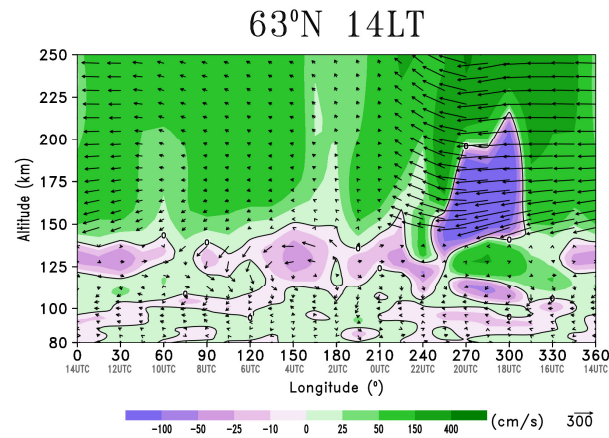
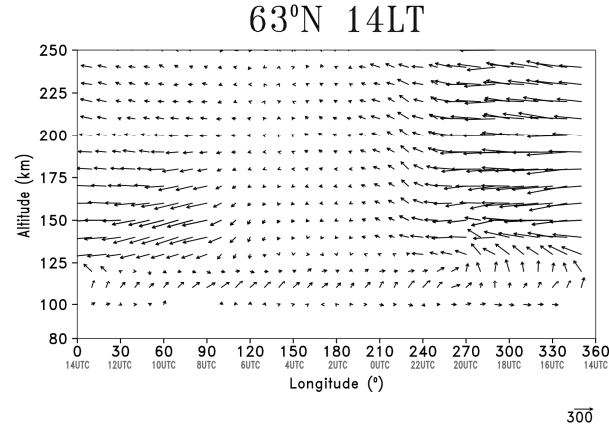


Figure A.3. Vertical cross section of the horizontal winds (vectors) from WINDII (top) and SD-WACCMX (bottom). Vertical velocity (colors) is also shown in the bottom image. Both images correspond to a latitude of 63°N and 14LT on May 22nd of 1992.

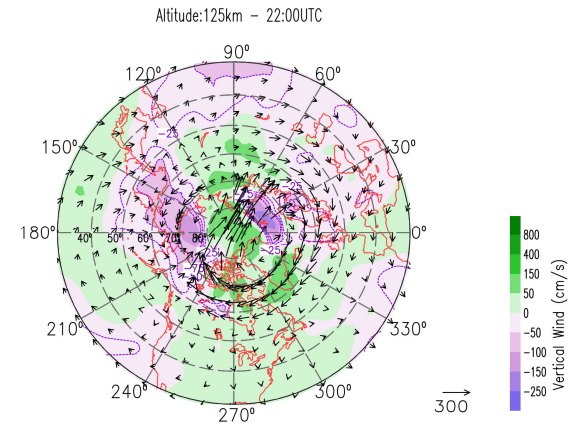
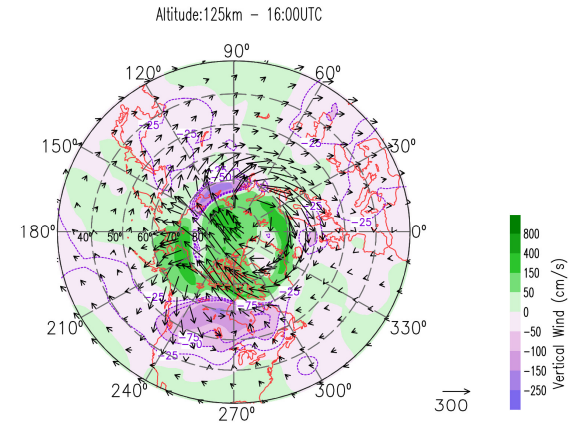


Figure A.4. The top (bottom) image shows the horizontal wind distribution (vectors) and vertical velocity (colors) at 125 km and 02 (10) UTC in the northern hemisphere. Both images come from SD-WACCM-X simulations of May 22nd of 1992.

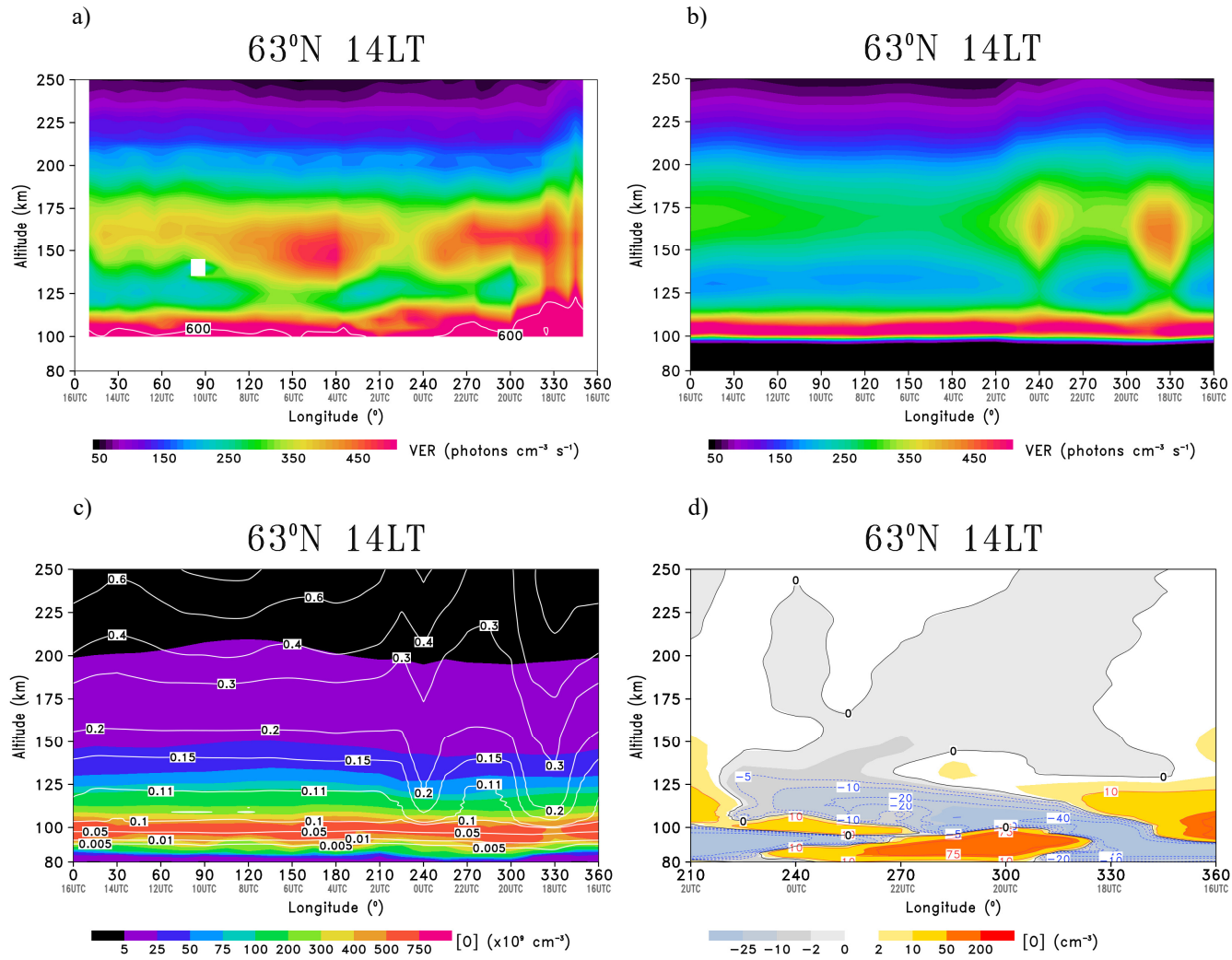


Figure A.5. a) Vertical cross section of the O(¹S) green line emission from WINDII. b) Similar to a), but from the GLOW/SD-WACCM-X. c) Vertical cross section of the atomic oxygen (colors) and electron density (x10⁶, contours) concentration. e) Vertical cross section of the [O] zonal deviation. All the plots in this figure are at 14 LT and 63°N, on May 22nd, 1992.

The wind wall and its relationship with the green line emission for the specific case in the southern and northern hemisphere has been shown in Figure 3.13 and A.5, respectively. Figure 3.13 allowed to identify that the peaks at both sides of the wind wall, localized at $65^{\circ}\text{S}\sim 180^{\circ}\text{E}$ at 4UTC (east side) and $65^{\circ}\text{S}\sim 60^{\circ}\text{E}$ at 12UTC (west side), were also associated with greater values of electron density concentration. However, Figure A.6, which shows the horizontal distribution of the electron density (colors) and the horizontal wind (vectors) at 125 km and specific UTC times, permits to determine that these both peaks of greater concentrations of electron are also associated with the relative position of the auroral oval, see the white start marks at Figure A.6a and A.6b. In addition, Figure A.6c is presented in order to point out that at a longitude inside the wind wall pattern ($65^{\circ}\text{S}\sim 120^{\circ}\text{E}$ at 8UTC) no greater values of electron density can be found since for this position and UTC time this point is localized inside the auroral oval, where smaller values of atomic oxygen can be also expected, as seen in Figure 3.13e. For the specific case in the northern hemisphere, in Figure A.7, a similar behavior is seen, but the green line peaks occur at $65^{\circ}\text{N}\sim 330^{\circ}\text{E}$ at 18UTC (east side) and $65^{\circ}\text{N}\sim 240^{\circ}\text{E}$ at 0UTC (west side). The middle location pointed out in Figure A.7 is $65^{\circ}\text{S}\sim 270^{\circ}\text{E}$ at 22UTC.

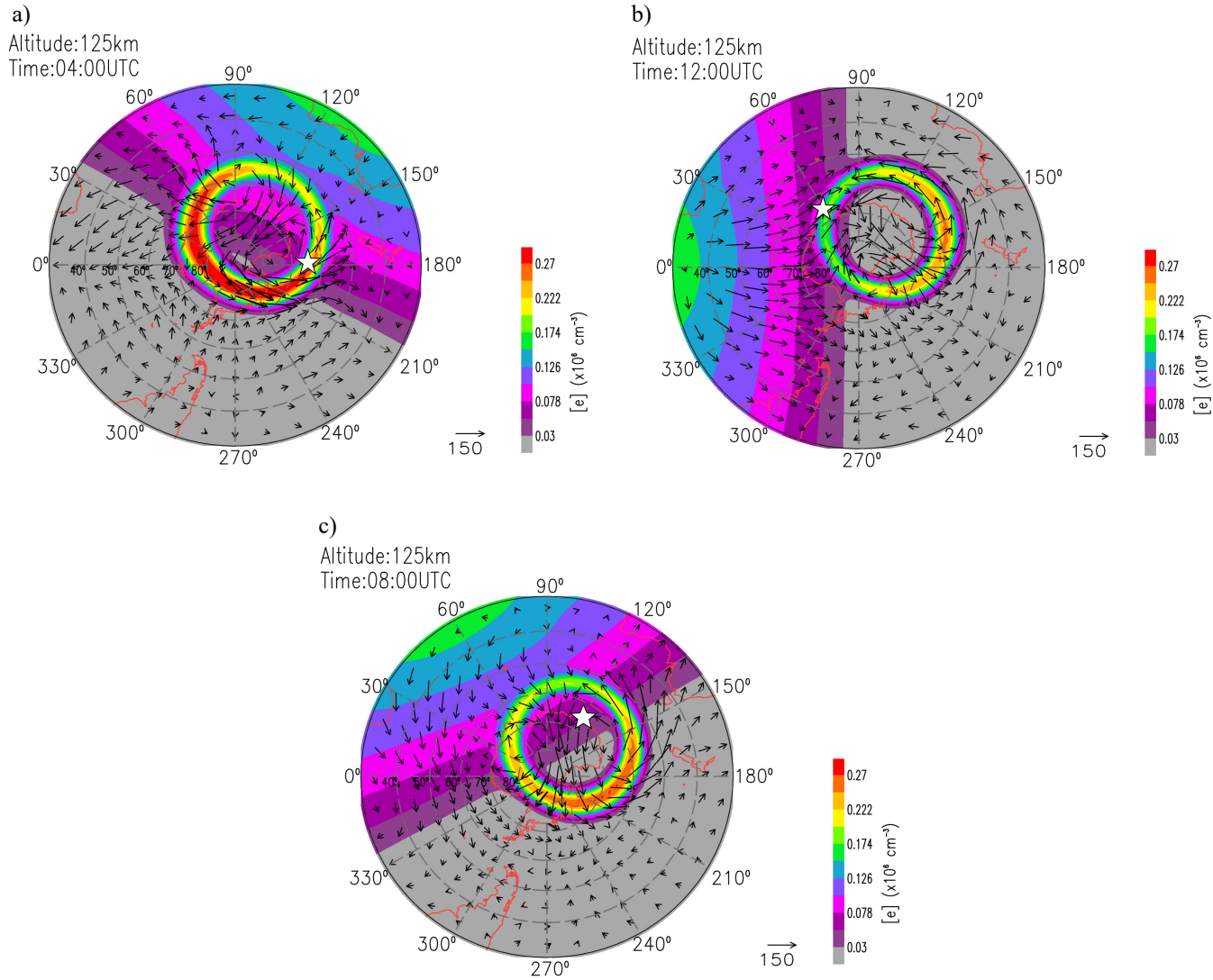


Figure A.6. Horizontal wind (vectors) and electron density concentration (colors) are shown for 4, 12, and 8 UTC hours at 125 km in the southern hemisphere on March 25th, 1992. The white stars in a) and b) indicate the locations at the east and west side of the wind wall, where the green line peaks occur. The white star in c) corresponds to a location inside the wind wall pattern.

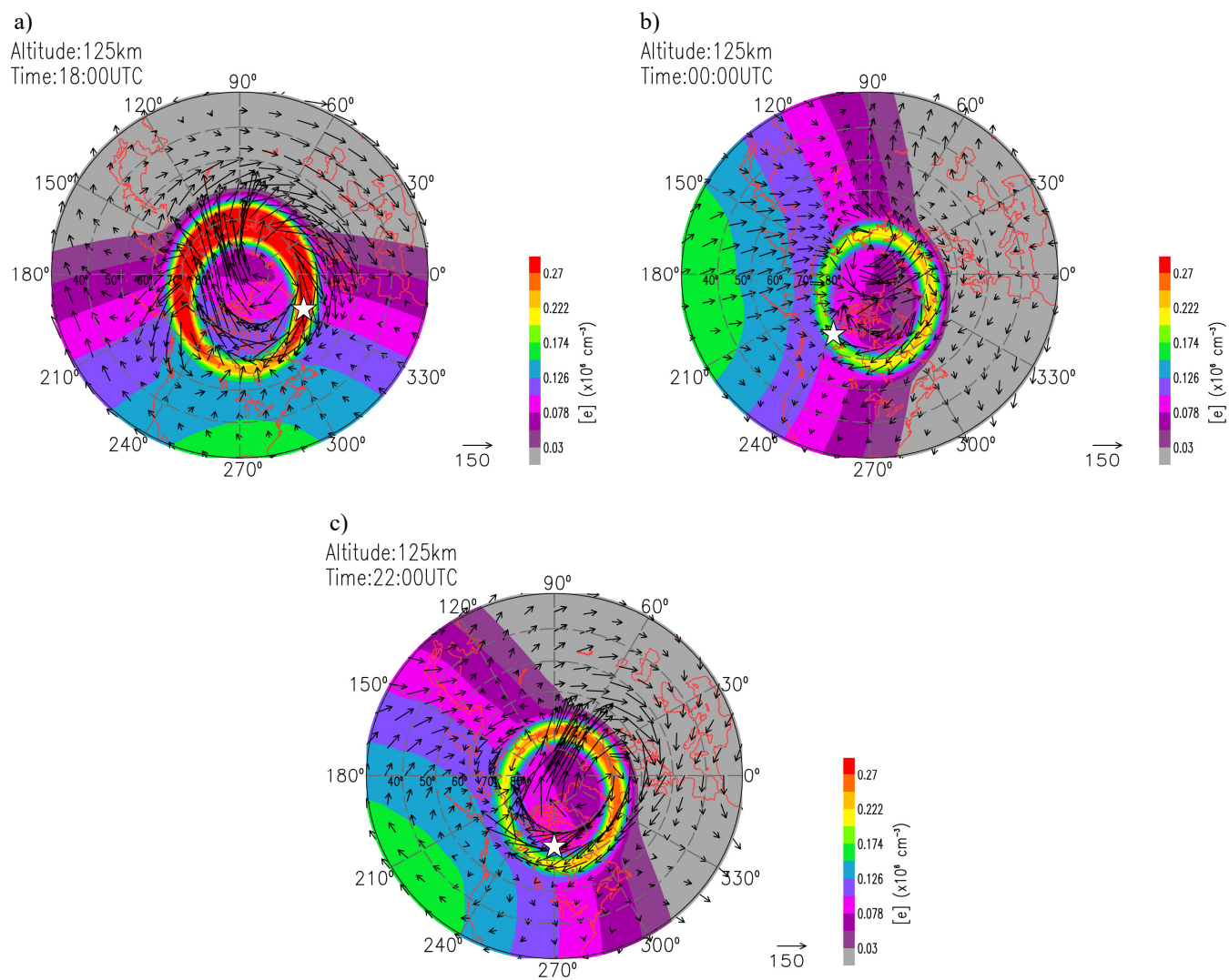


Figure A.7. Similar to Figure A.6, but for the northern hemisphere on May 22nd, 1992.