Ion-neutral coupling in the geomagnetically disturbed mid-latitude ionosphere as observed by SuperDARN HF radars and NATION Fabry-Perot Interferometers

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ABSTRACT

The earth’s ionosphere-thermosphere region is a coupled environment which is governed by interactions between the overlapping neutral constituents and ionospheric plasma. The mid-latitude thermosphere-ionosphere system is very complex owing to its sensitivity to both the polar and equatorial processes. The mid-latitudes is also a relatively unexplored and less understood region primarily due to the paucity of observing instruments that have traditionally been available. However, the past 9 years of mid-latitude expansion of the Super Dual Auroral Radar Network (SuperDARN) has provided new access to continuous large-scale observations of the sub-auroral ionosphere. On the other hand, the past 3 years of mid-latitude expansion of the North American Thermosphere Ionosphere Observation Network (NATION) Fabry-Perot interferometer array, has created a critical resource for measuring the thermospheric neutral winds. The overlap of these two observing networks in the mid-east North American sector has resulted in a strong ground-based large-scale platform for co-located study of mid-latitude thermosphere-ionosphere dynamics for the first time. The coupling between ions and neutrals is a very important process for controlling the thermospheric dynamics. Ion-neutral coupling at high latitudes has been studied in many previous papers, but there have been very few studies focused on the mid-latitude region. Hence, in this work we have studied the ion-neutral coupling mechanisms and timescales at mid-latitudes during disturbed geomagnetic conditions by using the co-located observations from the SuperDARN-NATION array. The study has focused on the main phase as well as the late recovery phase of a geomagnetic storm which occurred on October 2-3, 2013. Ion drag is known to drive the neutral circulation during the main phase of storm at auroral latitudes,
while the neutral wind disturbance dynamo mechanism is known to generate ionospheric electric fields and currents during the recovery phase. By using the methods of ion-neutral momentum exchange theory and time lagged correlation analysis, we analyzed the timescales at which the ion-neutral coupling operates. The ions are observed to drive the neutral winds on a timescale of $\sim 84$ minutes in the storm main phase which is significantly faster than expected from the driving due to local ion-drag alone ($\sim 124$ minutes). This suggests that along with ion-drag, other local and non-local storm-time influences like Joule heating are also playing an important part in driving the neutral winds. On the other hand, in the late recovery phase, the neutral winds are found to be strongly coupled with the ions and maintain the ion convection without any significant time delay which is consistent with effect of the ‘disturbance dynamo’ or ‘neutral-flywheel’ persisting well into the late recovery phase. The timescales and underlying physics understood through this work serve as an important contribution to our knowledge of ion-neutral coupling processes at the middle latitudes. Looking forward, the expansion of co-located SuperDARN-NATION coverage at mid-latitudes, and developments in the tools of large-scale visualization through FPI wind field mapping and SuperDARN convection maps, has created a very strong basis for using the results and analysis tools developed in this work for large-scale ion-neutral coupling characterization in future.
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Chapter 3: Observations of storm-time mid-latitude ion-neutral coupling using SuperDARN radars and NATION Fabry-Perot interferometers

Dr. J. B. H. Baker and Dr. J. M. Ruohoniemi are the heads of the ‘SuperDARN’ group in Virginia Tech. They have been the primary advisors on this research and served as the primary co-authors on this work. They have made a major contribution in the problem definition, research approach and analysis, and writing of the journal paper.

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Chapter 1

Introduction

1.1 The Ionosphere and $\mathbf{E} \times \mathbf{B}$ Plasma Drift

The ionosphere is a charged region of the upper atmosphere, starting at about 85 km (53 mi) altitude and tapering off above 500 km (310 mi). It is a region of plasma created primarily due to ionization by UV radiation from the sun. The ionosphere is divided into 3 layers. The D layer is the innermost layer extending from 60 km (37 mi) to 90 km (56 mi) above the surface of the Earth. Ionization here is predominantly due to Lyman alpha hydrogen radiation at a wavelength of 121.5 nm ionizing nitric oxide (NO). The E layer is the middle layer stretching from 90 km (56 mi) to 120 km (75 mi) above the surface of the Earth. It is formed primarily due to soft X-ray (1-10 nm) and far ultraviolet (UV) solar radiation ionization of molecular oxygen ($O_2$). The F layer, also known as the Appleton layer, extends from about 120 km (75 mi) to more than 500 km (310 mi) above the surface of Earth. It is the densest point of the ionosphere where extreme ultraviolet (UV, 10-100 nm) solar radiation ionizes atomic oxygen. The right hand panel of Figure 1.1 shows the plasma density vs altitude distribution of these ionospheric layers along with identification of these primary ionization processes. The earth’s geomagnetic field lines control the influence of internal and external ionospheric factors at different latitudes, structuring the ionosphere into equatorial (low-latitude), sub-auroral (mid-latitude) and polar (high-latitude) regions. At auroral latitudes, a second important process is produced by the precipitation of energetic charged
particles which are carried along the magnetic field lines connecting the magnetosphere to the ionosphere. At equatorial latitudes solar photoionization dominates. The mid-latitude ionosphere acts as a buffer between these two regions and is a more complex region due to combined effects arising from the physical processes at both the auroral and equatorial latitudes.

Ionospheric irregularities form when irregular electron density structures in the ionosphere are amplified relative to the background level by a plasma instability [Fejer and Kelley, 1980; Tsunoda, 1988]. The spatial scale of these plasma irregularities can range from few centimeters to hundreds of kilometers depending on the seeding ionospheric processes. In the F-region of ionosphere, the horizontal drift of these plasma irregularities ($\vec{V}$) is governed primarily by the background plasma motion, which is related to the electric and magnetic fields as,

$$\vec{V} = \frac{\vec{E} \times \vec{B}}{B^2}$$

where, $\vec{E}$ is the ionospheric electric field and $\vec{B}$ is the geomagnetic field. This plasma drift velocity ($\vec{V}$) is a very important measurable that represents the dominant large-scale plasma motion in the ionosphere.

1.2 Thermospheric Neutral winds

The thermosphere is the uppermost region of the earth’s atmosphere, from about 90 km (55 mi) to 600 km (370 mi), and is characterized by an increasing temperature profile with respect to the altitude. The left panel in Figure 1.2 shows the temperature altitude distribution of the earth’s atmospheric layers. Comparing the left and right panels it can be seen that the bulk of the ionosphere is collocated with the thermosphere. It is thus common
Figure 1.1: Vertical profiles and regions of the ionosphere and neutral atmosphere. The left panel represents the variation of neutral temperature with altitude generated using the Mass Spectrometer and Incoherent Scatter Radar (MSIS) model. The right panel shows the variation of plasma density with altitude generated using the International Reference Ionosphere (IRI) model and the dominant types of ionizing solar radiation. The red and blue curves represent typical day and night ionospheres, respectively.
to refer to this region as the thermosphere-ionosphere because the interactions and collisions between ions and neutrals couple the thermosphere and ionosphere together. The major constituents of the F-region Thermo-ionosphere are O+, NO+, O2+ ions and the neutral atoms of NO, O2, N2, Ar, He. Figure 1.2 shows the variation in composition and density of the neutrals (dashed lines) and ions (solid lines) with respect to the atmospheric altitude [Luhmann, 1995]. It can be seen that the Oxygen and Nitrogen ions and neutral atoms form the major constituents of the F-region ionosphere around the density peak region at altitudes of 250-350 km. This is a noteworthy feature as it is the region of focus for the research presented in this thesis.

Thermospheric neutral winds are driven by four major sources: A) Daily absorption of solar UV radiation which creates diurnally varying temperature and pressure gradients that accelerate and decelerate winds as earth rotates; B) Upward propagation of atmospheric tides generated by diurnally varying heating in the troposphere and stratosphere [Kato, 1981]; C) Acceleration by rapidly drifting ions at high latitudes (ion-drag) [Axford and Hines, 1961]; and D) Pressure gradients produced by high latitude Joule heating [Mayr and Volland, 1974]. The interplay and dominance of these mechanisms for defining thermospheric wind circulation varies with the geomagnetic conditions as well as with latitude. During geomagnetic storms the high latitude forcing results in increased equatorial winds above 120 km at mid-latitudes. The angular momentum transported by these winds creates westward thermospheric motion with respect to the earth via the Coriolis force. Equatorial Pedersen currents created by these westward winds result in accumulation of charge towards the equator which produces a poleward electric field, an eastward current, and westward E x B drift. This mechanism called the ‘Disturbance Dynamo’ [Blanc and Richmond, 1980], is known to be a dominant process through which the disturbed neutral winds drive the ionospheric convection after the end of storm growth phase. Popular thermospheric models like
Figure 1.2: Altitude variation of electron number density and composition of the ionosphere (solid line) and neutral atmosphere (dashed line) measured by mass spectrometer [Luhmann, J. (1995), Ionospheres, Introduction to space physics, pp. 183-202, used under fair use, 2015. The oxygen ions and atoms are the dominant constituents at F-region altitudes].

the CMIT model [Wang et al., 2008], TIEGCM model [Deng et al., 1993], TIME-GCM model [Garner et al., 2013] have been able to capture the small-scale and large-scale thermospheric dynamics. However, they are more efficient in modeling the thermospheric circulation at polar latitudes due to inputs from the dense network of high-latitude ground instruments. Mid-latitude dynamics of the thermosphere is a relatively less understood domain mainly due to the absence of adequate observations arising from instrumentation gaps. Hence, it is the primary focus of the research presented in this thesis.
Figure 1.3: Magnetic reconnection mechanism. Successive configurations of magnetic field line in the process of reconnection are denoted by the number field lines. The mapping of the footprint of the numbered field lines in high latitude convection pattern is represented by the inset [Hughes, W. (1995), The magnetopause, magnetotail, and magnetic reconnection, Introduction to Space Physics, pp. 227-287. Used under fair use, 2015].
1.3 The Magnetosphere

Earth’s magnetosphere is the region of plasma extending beyond earth’s ionosphere into space and consists of various plasma regions and current systems which serve to maintain its distinctive comet-like magnetic topology. The solar wind is a stream of high energy charged particles from the sun and carries the ‘frozen-in’ solar magnetic field with it, which is also termed as Interplanetary Magnetic Field (IMF). Conditions and processes in the high-latitude and mid-latitude ionosphere are largely governed and affected by the interactions of the solar wind with earth’s magnetosphere. The magnetopause is the boundary between the planet’s magnetic field and the solar wind and its location is determined by the balance between the pressure of the dynamic planetary magnetic field and the dynamic pressure of the solar wind. When a southward IMF encounters a closed magnetic field line in the earth’s magnetosphere it results in magnetic reconnection as seen in field lines 1 and 1’ in Figure 1.3. These solar-terrestrial field lines have an orientation such that one end is connected to earth’s pole and the other end extends far out in the interplanetary space. Due to the high conductivity of these magnetic field lines, this configuration allows the plasma particles of solar origin to flow freely into the ionosphere along these magnetic field lines. As the solar wind continues its flow through the magnetosphere, these field lines extend into the geomagnetic tail propagating through the successive locations in Figure 1.3 until they snap back and reconnect at locations 6 and 6’ depositing high energy solar plasma in the ionosphere. The inset in Figure 1.3 shows how the ionospheric footpoints of these numbered field lines progress through their antisunward flow across the polar cap in the high-latitude ionosphere and return back at lower latitudes on the dayside [Hughes, 1995]. The intensity of interaction between the earth’s geomagnetic field and the Interplanetary magnetic field (IMF) is measured through the perturbations in the geomagnetic field by
1.4 Magnetic Indices and Geomagnetic Storms

The AE index is an auroral electrojet index obtained from magnetometer stations distributed in longitude in the latitude region that is typical of the northern hemisphere auroral zone [Sugiura and Davis, 1966]. For each of the stations the north-south magnetic perturbation $H$ is recorded as a function of universal time and provides a measure of the strength of the overhead ionospheric current. After superposition of the data from all stations the difference between maximum and minimum values (AU-AL) gives AE index which represents the maximum strength of the ionosphere closure current associated with the aurora. Excursions in the AE index from a nominal daily baseline are called magnetospheric substorms and may have durations of tens of minutes to several hours.

The planetary $K_p$ index [Bartels and Johnston, 1939] is obtained from magnetometer stations at mid-latitudes. The mid-latitude stations are rarely directly under an intense horizontal current system and thus magnetic perturbations can be dominant in either the $H$ or $D$ component. The $K_p$ index utilizes both these perturbations by taking the logarithm of the largest excursion in $H$ or $D$ over a 3-h period and placing it on a scale from 0 to 9. If $K_p$ rises to 5 or higher the magnetosphere is considered to be in a state of disturbance called a ”geomagnetic storm”, which occurs during periods of elevated solar wind and/ or IMF magnitude.

A more precise measure of the geomagnetic storm activity is provided by the Dst and Sym-H indices. The hourly Dst index [Sugiura and Poros, 1971] is obtained from magnetometer stations near the equator. At such latitudes the $H$ (northward) component of the magnetic perturbation is dominated by the intensity of the magnetospheric ring current

various geomagnetic indices ($K_p$, Sym-$H$, AE).
which becomes enhanced during geomagnetic storms. Dst index is a direct measure of the hourly average of this perturbation. Large negative perturbations are indicative of an increase in the intensity of the ring current and typically appear on time scales of about an hour. The decrease in intensity typically takes longer, on the order of several days. The entire period is called a geomagnetic storm. Following the convention introduced by Fagundes et al. [1996], storms are classified in regards to the peak Dst value seen during the storm activity as intense geomagnetic storms ($-150nT \leq Dst < -100nT$), moderate geomagnetic storms ($-100nT \leq Dst < -50nT$), and weak geomagnetic storms ($-50nT \leq Dst < -30nT$). Finally, the Sym-H index is a one minute version of the Dst which uses more than 4 magnetometers.

1.5 Thesis Objectives and Organization

The timescales and coupling mechanisms between the ionospheric plasma and the neutral winds in the mid-latitude thermo-ionosphere is a very important component which has had controversial observations and theories from modeling studies and measurements from satellite and Incoherent Scatter Radars (ISRs). Recent expansion of the co-located coverage of the North American Thermosphere Ionosphere Observing Network (NATION) [Makela et al., 2012] and the Super Dual Auroral Radar Network (SuperDARN) [Chisham et al., 2007] at mid-latitudes has resulted in new opportunities to study mid-latitude ionosphere-thermosphere dynamics in the North American sector. In addition, the SuperDARN convection maps provide a large-scale visualization of the wider context of ionospheric convection which can aid the interpretation of localized neutral measurements. Hence, in this thesis, we use the co-located SuperDARN - NATION measurements to examine the physics and time-scales of midlatitude ion-neutral coupling during disturbed geomagnetic conditions.

Chapter 1 has presented the discussion along with the review of relevant literature on
ionosphere, thermospheric neutral winds and earth’s magnetosphere and geomagnetic storms. Chapter 2 will follow the discussion with detailed description of the principles, operations and data products of SuperDARN radars and NATION Fabry-Perot Interferometers which are used to measure the ions and thermospheric neutral winds. Chapter 3 will give a comprehensive description of a specific application of storm-time ion-neutral coupling using the SuperDARN and NATION instruments. Chapter 4, will outline the summary, conclusions and discuss the possible future developments based on the research presented in this work.
Chapter 2

Observation Principles and Instruments

2.1 SuperDARN

The Super Dual Auroral Radar Network (SuperDARN) is composed of more than 35 high frequency (HF, from 8-20 MHz) doppler radars that cover mid-latitude (sub-auroral) and high-latitude (auroral) ionosphere across both the northern and southern hemispheres [Chisham et al., 2007]. Figure 2.1 shows the geometry and field-of-view of SuperDARN radars in both the northern and southern hemispheres. The mid-latitude radars represented in orange are of prime focus in the work of this thesis. SuperDARN radars are low power (kW) radars that operate continuously to observe large-scale motion of the ionosphere, and hence are very useful for study of ionospheric processes over large spatial and temporal scales in both hemispheres. SuperDARN radars use the dispersive properties of ionosphere to get an orthogonal incidence with respect to magnetic field lines and backscatter from the field-aligned decameter scale ionospheric irregularities. The variable electron density in ionosphere results in refraction of HF waves, where the refractive index is expressed by the Appleton formula [Davies, 1990].
2.1.1 SuperDARN Measurement Principle

SuperDARN radars obtain backscatter from decameter-scale field-aligned ionospheric irregularities. In order to reflect from the ionospheric irregularity, any incident radio wave signal has to satisfy Bragg’s scattering condition of \( \vec{k} \) equal to \( \vec{k}_r \), where \( \vec{k}_r \) is the “wave vector” or “wave number” of the radio wave signal and \( \vec{k} \) is the wave vector of the irregularity. As the irregularities are field-aligned their wavevector lies perpendicular to the geomagnetic field line, i.e \( (\vec{k} \perp \vec{B}) \). Hence, to obtain a backscatter from the irregularities, the wavevector of the incident radio wave \( (\vec{k}_r) \) should lie in the plane perpendicular to the geomagnetic field line. Very high frequency (VHF) and ultra high frequency (UHF) radio signals are capable of getting orthogonal propagation and backscatter only up to E-region altitudes. On the other hand, High frequency (HF) signals are more efficient in getting backscatter from E and F region altitudes because of their ability to use ionospheric refraction to obtain orthogonal incidence [Greenwald et al., 1995].

2.1.2 Operation and Data Products

Refractive propagation of the SuperDARN HF rays provide two types of backscatter:

1) Ground Scatter: Some HF signals refract in ionosphere to a point where they turn back towards ground and get backscatter depending on the geometry and composition of the terrain [Ponomarenko et al., 2010].

2) Ionospheric scatter: Variable size irregularities develop in the ionosphere due to plasma instabilities [Tsunoda, 1988]. The orthogonal incidence of HF rays to these field-aligned irregularities result in ionospheric backscatter. In this thesis we are only interested in ionospheric scatter.

Figure 2.2 shows the propagation of the HF radio waves through the ionosphere as
Figure 2.1: Geometry and field-of-view of the SuperDARN radar array in the northern and southern hemisphere. The polar, high-latitude and mid-latitude radars are denoted by the green, blue and orange colors respectively. Observations by the mid-latitude SuperDARN radars (orange) are the focus of this research work.

Figure 2.2: Typical HF radio wave propagation and SuperDARN backscatter regions. The white curves represent the geomagnetic field lines and the grey lines are the transmitted rays. Black shaded features represent the ionospheric and ground backscatter regions. The background consists of electron densities plotted using (IRI-2012) model [De Larquier, S. (2013), The mid-latitude ionosphere under quiet geomagnetic conditions: Propagation analysis of superdarn radar observations for large ionospheric perturbations, Ph.D. thesis, VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY. Used under fair use, 2015].
seen using a ray tracing model. The regions where we get ionospheric backscatter from the refracted HF rays are shaded in black. The ground scatter points are indicated by the black parts where the rays are reflected from the ground. As can be seen by the ray paths, ionospheric backscatter is obtained by 0.5 hop and 1.5 hops, whereas ground scatter is obtained primarily through 1 hop or 2 hop propagation.

The primary data products measured by SuperDARN consist of the ion drift velocities and doppler widths and the backscatter power for every 2 minute radar scan. The data products generated by all the SuperDARN radars are uniformly processed and stored in a single multi-radar dataset. The line-of-sight (LOS) measurements from all the radars are then combined using a spherical harmonic fitting procedure along with statistical model constraints to create global ionospheric convection maps [Ruohoniemi and Baker, 1998]. Figure 2.3 shows an example of SuperDARN convection map for a 2 minute scan period during the growth phase of geomagnetic storm on June 1, 2013. The past 9 years of mid-latitude SuperDARN expansion has made it possible to continuously observe and study the sub-auroral ionospheric physics on a large spatio-temporal scale under all geomagnetic conditions.

2.2 NATION

2.2.1 Measurement Principle

The North American Thermosphere Ionosphere Observing Network (NATION) is a network of Fabry-Perot interferometers (FPIs) to study the earth’s upper atmosphere and ionosphere [Makela et al., 2012]. As of July 2015, the North American Thermosphere Ionosphere Observing Network (NATION) is comprised of five Fabry-Perot Interferometers located at Michigan (ANN), Illinois (UAO), Virginia (VTI), eastern Kentucky (Eiku) and North Car-
Figure 2.3: Ionospheric convection map for a 2 minute scan period of 0230 - 0232 UT on June 1, 2013 derived from SuperDARN radar observations.
olina (PAR) as shown in Figure 2.4. The NATION Fabry-Perot interferometers measure the thermospheric neutral wind velocities and temperatures by observation of nighttime Doppler shift of the 630nm oxygen emission line which is assumed to occur in F-region of ionosphere at $\sim 250$ km altitude. The major constituents of the F-region thermosphere are O+, NO+, $O_2+$ ions and the neutral atoms of NO, $O_2$, $N_2$, Ar, He. The 630 nm emission is created by the excited state of oxygen O*. In the F-region ionosphere this O* is generated because of the dissociative recombination of molecular ions of oxygen and nitric oxide, (that is, $O_2+ + e = O + O^*$ and $NO+ + e = N + O^*$) which follows the production of these ions by charge exchange between O+ and N+ with $O_2$ and N, respectively. The imaging FPI instrument observes the spectral line shape of the 630 nm OI emission with a typical spectral resolution of $\frac{\lambda}{\delta \lambda} \sim 310,000$ using the highly sensitive quality back-thinned CCD technology. A cloud sensor which measures infrared radiation from the sky between 8-14 $\mu$m using a thermopile is integrated with every FPI site to deduce the sky temperature and hence the cloud cover conditions for uncertainty estimates of the measurements.

2.2.2 Modes of Operation

NATION FPIs generally operate in 3 distinct modes to make multi-look measurements of thermospheric neutral winds depending on availability of favorable atmospheric conditions and experimental needs. The most common mode of operation consists of imaging sequentially in the cardinal look directions of east, west, north, south and zenith at an elevation of 45°. This measurement geometry is seen in Figure 2.5, in terms of the separation distances between the zonal and meridional cardinal look directions, which generally account for about 4°–6° of spatial variation in both the latitude and longitude. To constrain the uncertainties in the measurements within a fixed lower range, the integration times in each of these look directions is variable between 1 min to 6 mins. This results in a measurement
Figure 2.4: The NATION FPI array of 5 North American sites along with representation of the operation modes. The red arrows represent the cardinal mode of operation whereas the blue, purple and green arrows denote the common volume (CV) mode of operation at the respective pair of FPI sites [Makela, J. J., J. W. Meriwether, A. J. Ridley, M. Ciocca, and M. W. Castellez (2012), Large- scale measurements of thermospheric dynamics with a multisite fabry-perot interferometer network: Overview of plans and results from midlatitude measurements, International Journal of Geophysics, 2012, doi:10.1155/2012/872140. Used under fair use, 2015].
Figure 2.5: Geometry of FPI operation and spatial separation between the FPI cardinal look directions. The left panel (a) shows the FPI operation with 45° elevation angle at an altitude of 250 km, the right panel (b) shows the spatial separation of 174 km between the FPI cardinal look directions pairs of east-west and north-south, respectively.
cadence that ranges between 5-30 mins in every look direction, and it might vary from scan to scan because of the variable intensity of 630 nm emission line and changing atmospheric conditions. Under favorable conditions, the FPI also operates in the common volume (CV) mode to determine two dimensional wind vectors over the seven common volume locations associated with the FPI site pairs of UAO-ANN, UAO-PAR, PAR-EKU, UAO-EKU, VTI-EKU, VTI-UAO and ANN-EKU. As per the need, the FPIs also have the functionality to operate using the dedicated inline mode at individual FPI sites to measure vertical winds and tristatic mode over the common volume of any three sites to measure the three dimensional wind profile. Recently [Makela, 2014], have developed a new method in which they directly estimate the apparent wind field over the region encompassing the NATION FPI array from the raw line-of-sight measurements from all the instruments, by assuming that a low-order polynomial in longitude and latitude can approximate the three dimensional wind field, \((u, v, w)\). This approach to wind field calculation incorporates a linear approximation which efficiently captures the large-scale features in the data, but does not represent the spatial features on small scales.

With this understanding of the measurement principles and instrumentation, the next chapter will present a comprehensive discussion of the application of SuperDARN-NATION array to study ion-neutral coupling at mid-latitudes under disturbed geomagnetic conditions.
Chapter 3

Observations of storm-time mid-latitude ion-neutral coupling using SuperDARN radars and NATION Fabry-Perot interferometers

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Abstract

Ion drag is known to play an important role in driving neutral thermosphere circulation at auroral latitudes, especially during the main phase of geomagnetic storms. During the recovery phase, the neutrals are known to drive the ions and generate ionospheric electric fields and currents via the disturbance dynamo mechanism. At mid-latitudes, the precise interplay between ions and neutrals is less understood largely because of the paucity of measurements that have been available. In this work, we investigate ion-neutral coupling at middle latitudes using co-located ion drift velocity measurements obtained from SuperDARN radars and neutral wind velocity and temperature measurements obtained from the NATION Fabry-Perot interferometers. We examine one recent storm period on October 2-3, 2013 during both the main phase and late recovery phase. By using ion-neutral momentum exchange theory and a time-lagged correlation analysis, we analyze the coupling timescales and dominant driving mechanisms. We observe that during the main phase the neutrals respond to the ion convection on a timescale of \(~ 84\) minutes which is significantly faster than what would be expected from local ion-drag momentum forcing alone. This suggests other storm time influences are important for driving the neutrals during the main phase, such as Joule heating. During the late recovery phase, the neutrals are observed to drive the ion convection without any significant time delay, consistent with the so-called “neutral fly wheel effect” or disturbance dynamo persisting well into the late recovery phase.
3.1 Introduction

Coupling between the ionosphere and thermosphere at mid-latitudes is primarily driven by electric fields originating from the dynamo action of thermosphere winds and those originating from the solar wind and inner magnetosphere. At high latitudes, a large-scale convection electric field of magnetospheric origin drives a two-celled ionospheric plasma convection with typical ion velocities of several hundreds of meters per second [Banks et al., 1973]. This plasma convection expands to midlatitudes during intense geomagnetic storms which typically have very large southward IMF values (-10 nT or less) sustained for several hours [Foster, 2013; Heelis, 2013; Tsurutani et al., 2013]. During the main phase of such intense geomagnetic storms these convecting ions transfer energy and momentum to the thermospheric neutrals resulting in neutral temperature enhancements and increased equatorward flow of neutral winds out of the nightside auroral zone. In the F-region, thermal pressure and ion-drag form the primary balance of forces on neutrals [Killeen et al., 1984, 1988; Thayer et al., 1995]. Effectiveness of the ion drag momentum source in driving zonal winds during the main phase of intense storms has been verified by theoretical and modeling studies [Fedder and Banks, 1972; Hays et al., 1979; Killeen and Roble, 1988; Deng and Ridley, 2006] as well as satellite observations [Killeen et al., 1985, 1988, 1991]. On the other hand, Buonsanto [1999] proposed that during the main phase, the Joule heating-induced hot equatorial winds are redistributed westwards by the Coriolis force. Furthermore, Thayer et al. [1995] and later Meriwether [2013] suggested that ion-drag forcing cannot solely determine the thermospheric response, even during geomagnetic storms.

During the recovery phase, when the magnetospheric driver declines, the neutrals drive the ions via the so-called disturbance dynamo mechanism [Blanc and Richmond, 1980]. Observations of disturbance dynamo winds at midlatitudes have demonstrated the potential
for global thermospheric circulation to generate and modify ionospheric ion drifts [Testud et al., 1975; Roper and Baxter, 1978; Lu et al., 1995, 2008; Meriwether, 2013; Shiokawa et al., 2013]; however, the scarcity of colocated ion and neutral measurements has made it difficult to quantify the timescales of mid-latitude ion-neutral coupling. Many dynamical thermospheric features have been captured by modeling studies using the CMIT model [Wang et al., 2008], TIEGCM model [Deng et al., 1993], TIME-GCM model [Garner et al., 2013] and numerical results presented by Fuller-Rowell et al. [2013a], but the reliability of the thermosphere dynamo response and recovery timescales generated by the models has not been adequately verified, on account of insufficient mid-latitude measurements. Thus, it is that on both observational and modeling grounds, there is still uncertainty regarding the relative importance of the various driving mechanisms for ion-neutral coupling.

A related source of controversy is the timescale on which ion-neutral coupling operates. During both the main phase and recovery phase of geomagnetic storms, a wide range of timescales have been observed in previous studies by satellites, Fabry-Perot interferometers, and incoherent scatter radars. During the main phase, the time-scale measured at high-latitude by the Dynamics Explorer 2 satellite ranged from 0.5 to 3.5 hours [Killeen et al., 1984, 1988] while those from ISR experiments and momentum exchange theory ranged from 0.63-0.9 hours [Baron and Wand, 1983; Heelis et al., 2002]. In the recovery phase, modeling studies using the NCAR-TIGCM model have found that the neutrals are capable of driving the westward $\vec{E} \times \vec{B}$ ionospheric drifts for 5-6 hours after the magnetospheric convection declines [Deng et al., 1991; Lyons et al., 1985]. On the observational side, Oyama et al. [2000] used ISR and FPI observations at high-latitudes to determine that neutrals drive field aligned ion oscillations on a timescale of $\sim$ 40 minutes. Most of these previous works relied heavily on thermospheric models and/or co-located coverage of ISR and FPI instruments at high latitudes. The ion-neutral coupling timescales at middle latitudes thus remains
an outstanding issue largely because of the paucity of available colocated ion and neutral measurements.

Recent expansion of the North American Thermosphere Ionosphere Observing Network (NATION) [Makela et al., 2012] and the Super Dual Auroral Radar Network (SuperDARN) [Chisham et al., 2007] to mid-latitudes provides new opportunities to study mid-latitude ionosphere-thermosphere dynamics in the North American sector. In addition, the SuperDARN convection maps provide a large-scale visualization of the wider context of ionospheric convection which can aid the interpretation of localized neutral measurements. In this study, we use colocated SuperDARN - NATION measurements to examine the time-scale of mid-latitude ion-neutral coupling during the main phase and late recovery phase of a geomagnetic storm that occurred on October 2-3, 2013. We use two methods to calculate the coupling time-scales from the SuperDARN-NATION measurements: 1) empirical relations of the ion-neutrual momentum exchange theory, and 2) time-lagged correlation analysis. Comparing the two time-scales provides a basis for evaluating the applicability of the momentum exchange theory during this particular storm.

This paper is organized as follows: Sections 2, 3 and 4 describe the instrumentation, observations and analysis of this event, respectively, followed by Section 5 which provides a summary and conclusion.

### 3.2 Instrumentation

In this section, we describe the details of the SuperDARN and NATION instrumentation that are used in this study to acquire observations of ion drift velocity and neutral velocity and temperatures.
3.2.1 SuperDARN

The Super Dual Auroral Radar Network (SuperDARN) is an international network of HF radars that study the Earth’s upper atmosphere and ionosphere from middle to polar latitudes [Chisham et al., 2007; Lester, 2013]. A standard SuperDARN radar operates at 8-20 MHz and scans over a field of view comprised of 16-24 beams each divided into 70-100 range gates of 45-km range resolution. The time taken to complete one azimuth scan is typically 1-2 minutes. SuperDARN radars make line-of-sight (LOS) measurements of the $\vec{E} \times \vec{B}$ drift velocity of F-region field-aligned decameter-scale ionospheric irregularities. Two-dimensional patterns of the electrostatic potential and fitted ion velocity vectors can then be calculated by applying a spherical harmonic fitting technique on the measured LOS drift velocities [Ruohoniemi and Baker, 1998]. Statistical models are used to constrain the spherical harmonic solution in regions of poor data coverage. Figure 3.1 shows the geographical distribution and field of view (FOV) of the mid-latitude SuperDARN radars used in this study, namely, Blackstone (BKS), Wallops (WAL), Christmas Valley East and West (CVE and CVW), Fort Hays East and West (FHE and FHW) and Adak East and West (ADE and ADW).

3.2.2 NATION

The North American Thermosphere Ionosphere Observing Network (NATION) is a network of five Fabry-Perot interferometers (FPIs) located in the mid-west and eastern United States which make coordinated measurements of neutral winds and neutral temperature in the Earth’s thermosphere [Makela et al., 2012]. In the cardinal mode of operation, the FPIs use an elevation angle of 45° from the ground and azimuthally scan in the cardinal directions (east, west, north, south, zenith), measuring the Doppler shift of the 630-nm OI emission line assumed to peak at an altitude of 250-km. The nominal measurement locations for
Figure 3.1: Collective Fields of View (FOV) of the North-American mid-latitude Super-DARN radar chain comprised of radars at Blackstone (BKS), Wallops (WAL), Christmas Valley East and West (CVE and CVW), Fort Hays East and West (FHE and FHW), and Adak East and West (ADE and ADW).
Figure 3.2: Detailed view of the overlapped coverage of BKS and FHE midlatitude Super-DARN radars with the Illinois (UAO) and Michigan (ANN) NATION FPI sites. The 5 red circles around UAO and ANN FPI sites represent the Zenith (Z), East (E), West (W), North (N) and South (S) nominal measurement locations for the cardinal mode of operation.
the Illinois (UAO) and Michigan (ANN) FPI sites are identified by red circles in Figure 3.2, which indicates that these two FPIs share a common field of view with the BKS and FHE SuperDARN radars. The line of sight components of zonal and meridional neutral wind velocities and temperatures are typically calculated at each location with a temporal resolution between 5-30 minutes, depending on the brightness of the 630-nm emission. For the event presented in this study, the FPIs made cardinal mode measurements, allowing estimates of the thermospheric zonal, meridional, and vertical winds. However, it should be noted that in a previous study of the NATION FPI observations from this storm period, Makela et al. [2014] concluded that observations made to the zenith by each NATION FPI indicated the presence of an anomalously large and persistent downward Doppler shift of the thermospheric redline emission resulting in downward apparent vertical winds of the order of 100-140 m/s. That study hypothesized that this was evidence for a contamination of this emission due to downward moving hot O atoms, and therefore the inferred velocities are not completely indicative of the background thermospheric motion. If the Makela et al. [2014] hypothesis is correct, then the analysis applied to infer the horizontal neutral winds during the storm main phase used in the present study would result in somewhat erroneous velocity estimates, as it is assumed the emission arises from a thermalized population. One way to check this possibility is to examine the zenith measurements in addition to the cardinal look directions.
Figure 3.3: Overview of the geomagnetic storm which occurred on October 2-3, 2013. Panels a-f represent (from top): IMF Bz, Solar wind dynamic pressure (Dp), Sym-H index, AE index, Kp index. The grey shaded intervals (i-ii) and (iii-iv) identify two periods of detailed study during the main and late recovery phase corresponding to the availability of collocated measurements from FPIs and SuperDARN radars.
3.3 Observations: Geomagnetic Storm of October 2-3, 2013

3.3.1 Event Overview

An intense geomagnetic storm began with a sudden commencement on October 2, 2013, and was well into its recovery phase by October 3, 2013. Figure 3.3 shows an overview of the geomagnetic activity and interplanetary conditions during the entire storm period. Panels from top to bottom show the time series of: a) IMF Bz, b) solar wind dynamic pressure (Dp), c) Sym-H index, d) AE index, and e) Kp index, respectively. Close examination of Sym-H (panel c) shows the storm commenced on October 2 at around 0200 UT, with a main phase which lasted for about five and half hours until \( \sim 0730 \) UT, followed by a recovery phase which extended over at least 2 days. The grey shaded intervals (i-ii) and (iii-iv) identify two periods during the main and late recovery phase when collocated measurements from the NATION FPIs and SuperDARN radars were available. Examining the timescales of ion-neutral coupling during these two intervals is the focus of this study. Close examination shows that the main phase period (i-ii) corresponded to strong solar wind forcing (IMF Bz and Dp), sustained auroral substorm activity (AE index), increasingly enhanced ring current (Sym-H index) and intense geomagnetic field and auroral activity (Kp). By contrast, the recovery phase period (iii-iv) corresponded to weak solar wind forcing (IMF Bz and Dp) and weak auroral substorm activity (AE index) along with a gradual decrease in strength of the ring current (Sym-H index). In the following subsections we examine each of these intervals in separate detail.
Figure 3.4: SuperDARN ionospheric convection maps during the main phase of a geomagnetic storm on October 2, 2013, with fitted vectors in locations where measurements were obtained (color coded according to the scale at right) and superposed neutral wind velocity (black vector) measured at the Illinois (UAO) and Michigan (ANN) FPI site. Panels a to d represent four separate 10-minute time intervals during the night. Locations of the midlatitude SuperDARN radars operational at this time are identified. The direction of the wind at both Illinois and Ann Arbor is seen to reverse from eastward to westward and follows the dynamic behavior of the ions as the high latitude ion convection steadily expands equatorward to encompass the two FPI sites (see text for details).
Figure 3.5: Comparison of the eastward (upper panel) and northward (lower panel) line-of-sight neutral wind velocities obtained in the four look directions at the UAO FPI site during the main phase of the storm on October 2, 2013. In the upper (lower) panel yellow represents eastward (northward) look direction while blue represents westward (southward) look direction.
Figure 3.6: Time series of geomagnetic conditions and co-located ion and neutral parameters at the UAO FPI site [40.91°N, 89.43°W] FPI during the main phase of a geomagnetic storm on October 2, 2013 between 0030 UT - 0830 UT, (from top): (a) IMF Bz, (b) AE index, (c) SYM-H index, (d) Line of sight ion drift velocity in east and north look directions (\(V_{e,LOS}^{LOS}\), \(V_{n,LOS}^{LOS}\)), (e) Line of sight neutral velocity in east look direction (\(U_{e,LOS}^{LOS}\)), (f) Line of sight neutral velocity in north and zenith look directions (\(U_{n,LOS}^{LOS}\), \(U_{z,LOS}^{LOS}\)), and (g) neutral temperature (T). The solid yellow trace in panels (d-g) represents measured storm time velocities and temperatures. The dashed blue trace in panels e,f represents the HWM14 model wind velocities and the long and short dashed red trace in panel 6e,f,g represents the monthly averaged values. All velocities are positive eastward and northward. Vertical lines labelled (i), (ii) and (iii) represent the times of peak of ion drift velocity, zonal wind velocity and meridional wind velocity respectively.
3.3.2 Main phase of geomagnetic storm on October 2, 2013

During the night of October 1-2, 2013, the SuperDARN mid-latitude radars operated in a standard 2-minute azimuth scan mode measuring F-region ion drift velocities. The NATION FPI at Illinois (UAO) and Michigan (ANN) sites operated in cardinal mode measuring neutral velocities and temperatures in the thermosphere with a time resolution between 5 and 30 mins in every cardinal look direction. Figure 3.4 shows a sequence of four SuperDARN ion drift convection maps with overlain neutral velocity vectors (black arrows) obtained by the UAO and ANN FPIs. The neutral velocity vector components have been obtained by averaging the FPI measurements at each site in the east/west (zonal) and north/south (meridional) look directions, respectively. To ease NATION-SuperDARN comparison the SuperDARN ion drift convection patterns have been calculated assimilating data typically over 10-minute time interval. Collectively, the four panels in Figure 3.4 show how the hemispheric pattern of ion convection and localized neutral winds at UAO and ANN varied during the main phase of the storm between 0100 UT and 0900 UT. Close examination of the panels shows that as the pattern of ion convection expanded equatorward to mid-latitudes driving higher westward ion drift velocities, the neutrals gradually turned westward from their initial quiet-time eastward flow. These observations are thus qualitatively consistent with ion drag being a dominant driving influence for the neutral circulation during the main phase of this storm.

A more detailed understanding of ion-neutral coupling can be obtained by analyzing the time series of the neutral winds estimated from the FPI measurements. This is done in Figure 3.5 and 3.6 for the UAO site which provided slightly better data quality than ANN during this particular interval due to better observing conditions. Figure 3.5 compares the eastward and northward line-of-sight components of the wind field at UAO across the four FPI look directions, while Figure 3.6 compares the UAO FPI measurements to the
SuperDARN measurements and several measures of geomagnetic activity. Figure 3.5 shows significant variations in the wind measurements across the four UAO look directions, particularly in the meridional component (lower panel), such that the equatorward wind northward of UAO (yellow) becomes significantly enhanced compared to the southern measurement location (blue), starting around 0310 UT. This is consistent with a prominent north-south gradient in the wind field developing at this time, as expected during a storm. However, some of this divergent behavior is also attributed to red-line contamination from hot oxygen atoms [Makela et al., 2014].

For the purpose of comparing the UAO FPI measurements with SuperDARN, the east and north look measurement locations provide the best overlap with the radar fields-of-view so these are the FPI measurements shown in Figure 3.6. Panels from top to bottom are: (a) IMF $B_z$, (b) AE index, (c) SYM-H index, (d) Line of sight ion drift velocity in east and north look directions ($V_{LOS}^e$, $V_{LOS}^n$), (e) Line of sight neutral velocity in east look direction ($U_{LOS}^e$), (f) Line of sight neutral velocity in north look direction ($U_{LOS}^n$), and (f) neutral temperature (T). The four lower panels (d-g) all correspond to the UAO site with the lower three (e-g) derived from the FPI measurements and panel (d) derived from the SuperDARN convection maps. Error bars on the ion drift measurements (panel d) represent the standard deviation in SuperDARN fitted vectors during the 10-minute FPI measurement cycle. We highlight the following observations: (A) From 0240 UT (i) onwards, the ion drift velocities become increasingly westward with the line of sight component exceeding 500 m/s at 0330 UT; (B) in response to fluctuations in the overall level of geomagnetic activity the ions exhibit an eastward excursion followed by steadily increasing westward flow (ii); (C) after 0300 UT the eastward flow of neutrals switches and becomes increasingly westward with the line of sight component peaking to 90 m/s at 0520 UT and several dynamic excursions mirroring dynamics of the ion flow (iii); (D) Starting at around 0300 UT, the meridional winds become
increasingly equatorward (negative) with the line of sight component reaching a maximum magnitude near 450 m/s at 0630 UT (iv). Comparing these observations with the HWM14 model [Drob et al., 2015] [dashed blue trace in panel f] and monthly average [long and short dashed red trace in panels e,f] indicates the neutral wind has an anomalously high southwest component during this period. This is consistent with the equatorward expansion of the ion convection producing subsequent turning of the neutral wind as was seen in Figure 3.4. Also noteworthy is the bump in apparent vertical wind at around 0430 UT (panel f) which occurs during the period of hot O contamination and corresponds to a spike in temperature (panel g) as well as the passage of a stable auroral red (SAR) arc over the observatory [Makela et al., 2014].

Examination of Figure 3.6 indicates a time lag estimate of about 85-95 minutes corresponding to the approximate time difference between the westward peaks of the ion and neutral velocities. Also noteworthy, is the temperature enhancement of neutrals starting at ~ 0330 UT following the storm onset [Figure 3.6g], which is highly suggestive of ion-drag driven frictional heating of the neutrals. Finally, the enhancement in meridional wind around 0630 UT is perhaps indicative of a burst of equatorward wind produced by Joule heating in the auroral zone poleward of UAO. In the next section, we carry out a similar analysis during the recovery phase of this same storm.

3.3.3 Recovery phase of geomagnetic storm on October 3, 2013

Figure 3.7 shows SuperDARN ionospheric convection maps and overlaid UAO and ANN FPI data during the recovery phase of the storm on the night of October 2-3, 2013 (same format as Figure 3.4). Again, we show four separate 10-min time intervals which collectively demonstrate the good coverage of SuperDARN measurements and the general sense of time variation of ion and neutral velocities. During this period, the ion convection pattern is
Figure 3.7: SuperDARN ionospheric convection maps and overlaid UAO and ANN FPI neutral wind velocity during the recovery phase of a geomagnetic storm on October 3, 2013 (same format as Figure 3.4). Qualitatively, the ions and neutrals are both seen to maintain weak westward velocities after the hemispheric pattern of ion convection retreats poleward when primary magnetospheric driver has declined.
Figure 3.8: Comparison of the line-of-sight neutral wind velocities obtained in the four look directions at the ANN FPI site during the late recovery phase of the storm on October 3, 2013 (same format as Figure 3.5).
Figure 3.9: Time series of geomagnetic conditions and co-located ion and neutral parameters at the ANN FPI site [42.28°N, 83.75°W] during the recovery phase of the geomagnetic storm on October 3, 2013 between 0100 UT - 0700 UT, (from top): (a) IMF B\textsubscript{z}, (b) AE index, (c) SYM-H index, (d) Line of sight ion drift velocity in east and north look directions (V\textsubscript{LOS}\textsubscript{e}, V\textsubscript{LOS}\textsubscript{n}), (e) Line of sight neutral velocity in east look direction (U\textsubscript{LOS}\textsubscript{e}), (f) Line of sight neutral velocity in north and zenith look directions (U\textsubscript{LOS}\textsubscript{n}, U\textsubscript{LOS}\textsubscript{z}), and (g) neutral temperature (T) (same format as Figure 3.6).
observed to be much weaker than Figure 3.4 and the strongest auroral zone velocities steadily retreat to latitudes significantly north of the FPI sites, consistent with expectations during the recovery phase. Initially the westward ion convection is seen to be relatively strong, but rapidly declines in strength as the recovery phase of the storm progresses. The FPI wind measurements are relatively steady in the southwest direction throughout with small variations in magnitude. Qualitatively, these observations suggest that the main phase driven westward circulation of neutrals is perhaps maintaining weak westward ion convection after the primary magnetospheric driver has declined consistent with the “neutral fly-wheel effect” or disturbance dynamo.

As was done in Figure 3.5 and 3.6, we further investigate the detailed recovery phase ion-neutral dynamics and geomagnetic context in a more quantitative fashion using time series plots. The results are presented in Figure 3.8 and 3.9 for the ANN site which provided slightly better data quality than UAO during this particular interval because of better observing conditions. Figure 3.8 shows ANN FPI measurements in the east-west (panel a) and north-south (panel b) look directions are weaker and much more consistent during the recovery phase compared to the main phase (Figure 3.5). This suggests spatial gradients between the measurement locations and hot oxygen contamination were less of an issue. The vertical winds during this period [panel f] are negligible showing minimal signs of the hypothesized contamination. The north and east locations are better overlapped with SuperDARN and so these FPI measurements are further analyzed in Figure 3.9. Consistent with Figure 3.7, the zonal neutral winds show weak westward velocities (negative $U_{eLOS}$) with line of sight component averaging about 20 m/s, while the meridional winds ($U_{nLOS}$) exhibit a weak equatorward flow with average line of sight component of about 35 m/s. Also noteworthy is the fact that the ions and neutral winds exhibit very correlated variation in directions as well as magnitude of flow suggesting a strong coupled nature between the ions and neutrals.
Further, the neutral wind was larger in the southwest direction relative to the HWM14 model winds [dashed blue trace in panels e,f] and the monthly averaged FPI winds [long and short dashed red trace in panels e,f]. Even after the magnetospheric driver declined [panel a-c] and the auroral zone convection had retreated poleward, the ions maintained a weak westward flow with an average line of sight component of about 20 m/s over a period of several hours. This behavior is consistent with the storm-enhanced neutral wind circulation continuing to drive the subauroral ionospheric convection well into the recovery phase, long after the decline in the magnetospheric driver, as was hinted in Figure 3.7.

3.4 Calculation of Ion-Neutral Coupling Timescales

In the previous section, we presented time series observations which suggest the ions were driving the neutrals during the main phase with a time delay of about 85-95 minutes but during the recovery phase the inertia of the neutrals served to maintain weak westward ion convection long after the auroral convection had retreated poleward. Now, we investigate the ion-neutral coupling timescales in more quantitative detail using two broad quantitative approaches. First, we use simplified ion-neutral coupling relations from theory to calculate the coupling timescales using the zonal measurements of ion drift and neutral velocities. Second, we use a time-lagged correlation analysis of the ion and neutral velocities directly as an independent test of the theoretical results.

Method 1: Momentum Exchange Theory

The first approach for calculating ion neutral coupling time is to use the theoretical relations of momentum exchange. For simplicity, we assume ion-drag is the only force driving the neutrals during the storm main phase, in which case, the ion-neutral momentum exchange equation is given by Baron and Wand [1983] as,
\[
\frac{\partial \vec{U}}{\partial t} = \frac{n_i}{n_n} \nu_{in} \left( \vec{V} - \vec{U} \right) \left[ m/s^2 \right]
\] (3.1)

where \( \vec{V} \) denotes the ion drift velocity, \( \vec{U} \) is the neutral wind velocity, and \( n_i, n_n \) and \( \nu_{in} \) represent the ion density, neutral density and ion-neutral collision frequency, respectively. We can also define the e-folding ion-drag coupling time as,

\[
\tau_{inc} = \frac{\left( \vec{V} - \vec{U} \right)}{\partial \vec{U} / \partial t} = \frac{n_n}{n_i} \frac{1}{\nu_{in}} \left[ sec \right]
\] (3.2)

where \( \tau_{inc} \) is the 1/e time required for the neutrals to accelerate from one steady state to another state in response to a step change in ion drag forcing.

It is worth noting that previous studies have tended to use the right hand side of equations 2 to calculate \( \tau_{inc} \) which requires estimates of \( n_n \) and \( \nu_{in} \) which are inherently uncertain. Furthermore, Baron and Wand [1983] suggest the uncertainty in \( \nu_{in} \) estimate is primarily dependent on variation of ion density, whereas other studies [Lockwood et al., 1993; Davis et al., 1995; Kosch et al., 2001] suggest it is most dependent on variations in the ionospheric temperature and composition. In this study, we use the more direct observables of co-located ion drift velocity \( \langle \vec{V} \rangle \) and neutral velocity \( \langle \vec{U} \rangle \) from SuperDARN and NATION to calculate the ion-drag coupling time \( \tau_{inc} \) using the middle term of equation 2.

**Method 2 : Time-lagged Correlation Analysis**

The second approach for calculating the ion-neutral coupling time is to carry out a simple-minded time-lagged correlation analysis using the time series of ion and neutral velocities in the zonal direction. The peak value of the correlation coefficient and its corresponding time lag give an empirical measure of the strength of the coupling and the timescale required for the ion or neutral activity to drive each other. However, it should be noted that this
peak correlation time lag incorporates all of the influences playing a role in the ion-neutral driving (e.g., different mechanisms, local vs non-local effects, etc.) and hence is not entirely equivalent to the momentum exchange e-folding times described above. However, the degree to which the two methods agree with each other provides a basis for assessing whether or not ion-drag might be the dominant influence during a period of interest. For this particular event the SuperDARN radars measure the ion drift velocities predominantly in the zonal direction. As seen from the time series in Figure 3.6 and Figure 3.9, the SuperDARN ion drift measurements in the meridional direction \( V_{n}^{LOS} \) are much weaker and hence the comparison in the meridional directions do not provide any reliable basis to study ion-neutral coupling timescales or mechanisms. This study thus focuses on ion-neutral timescale analysis in the zonal direction. In the next section, we apply both of these techniques to calculate the coupling timescales during the main phase and recovery phase of the geomagnetic storm which progressed over the successive nights of October 2-3, 2013.

### 3.4.1 Ion-neutral coupling time analysis during the main phase (October 2, 2013)

We first apply the analysis during the main phase of the storm on October 2, 2013 using the time series observations presented in Figure 3.6. Figure 3.10a shows the results of applying time-lagged cross-correlation analysis to the line of sight (LOS) zonal ion and neutral wind velocities shown in Figure 3.6d,e, while Figure 3.10b represents the minute-by-minute coupling timescale calculated using momentum exchange theory (i.e., middle term of equation 2). In Figure 3.10a, positive time lag corresponds to ions driving the neutrals, whereas negative time lag represents neutrals driving the ions. In this case, during the main phase, the correlation analysis produces a maximum correlation at a positive time lag of \( \sim 84 \) minutes. This suggests the ions are driving the neutrals, so it is appropriate to use equation 2 to calculate the minute by minute e-folding ion-drag coupling time, which is shown in Figure
Figure 3.10: Ion-neutral coupling timescale analysis during geomagnetic storm main phase (October 2, 2013) for collocated measurements at the UAO FPI site. Panel a shows the variation of correlation coefficient versus time-lag between the zonal components of the ion and neutral velocities. Panel b shows the temporal variation of the e-folding coupling time calculated using equation 2 (refer text for details). The horizontal and vertical blue dashed lines in panel a indicate the peak correlation coefficient and the corresponding optimal time lag. The horizontal blue color dashed line in panel b represents the average value of e-folding time. Positive time lag corresponds to ions driving the neutrals. The maximum correlation (0.525) corresponds to ions driving the neutrals on a timescale of $\sim 84$ minutes.
The average e-folding time from momentum exchange theory is calculated to be \( \sim 125 \) minutes [Figure 3.10b], which is considerably longer than the observed coupling time of \( \sim 84 \) minutes obtained using the time-lagged cross-correlation analysis [Figure 3.10a]. However, as noted previously, the e-folding time from momentum exchange theory is a measure of ion drag forcing alone, whereas the coupling time obtained from the time-lagged correlation analysis is a cumulative measure of all influences playing a role in the ion-neutral coupling. Hence, the fact that the observed timescale is smaller compared to the e-folding time suggests that ion-drag is an important influence during the main phase but other storm-time factors are also contributing [e.g., Joule heating and associated transport]. As a result, the neutrals are driven faster than what can be expected from the local ion drag forcing acting alone. Indeed, referring back to Figure 3.6 we can see several prominent features in the ion-neutral time series which seem to be correlated on timescales much shorter than 84 minutes. For example, at 0300 UT \((V_\text{LOS}^e), (U_\text{LOS}^e)\) and \((U_\text{LOS}^n)\) began to increase almost at the same time, whereas \((V_\text{LOS}^n)\) was relatively stable and \((U_\text{LOS}^n)\) was larger than \((V_\text{LOS}^e)\) most of the time between (i) and (iii). This latter observation suggests high-latitude Joule heating may also have been important for collectively driving enhanced neutral winds and ion drifts equatorward towards mid-latitudes. The enhancement in neutral winds was thus a cumulative effect of both the local ion-drag and the non-local effects of the high latitude joule heating to reduce the difference between \(\vec{V}\) and \(\vec{U}\). The timescale of \(\sim 84\) minutes observed from the correlation analysis should thus be considered an average (or effective) ion-neutral coupling timescale, which includes the response to other non-local driving factors [e.g., Joule heating].

In summary, during the main phase of this particular storm ion-drag momentum forcing is identified as a dominant influence for driving mid-latitude thermosphere winds but it is combined with other significant thermospheric influences (e.g., non-local effects from high-latitude Joule heating) such that the overall timescale for ion-neutral coupling is reduced
Figure 3.11: Ion-neutral coupling timescale analysis during geomagnetic storm recovery phase (October 3, 2013) for collocated measurements at the ANN FPI site (same format as Figure 3.10). The maximum correlation (0.584) corresponding to \( \sim 0 \) minutes suggests strong coupling between neutrals and ions in the late recovery phase of the storm.

from 125 minutes (theory) to 84 minutes (observations). This falls within a narrow range of previous estimates obtained by satellites \( [Killeen et al., 1984, 1988] \) and ISR\( [Baron and Wand, 1983; Cierpka et al., 2000; Kosch et al., 2001; Heelis et al., 2002] \) at high-latitudes.

3.4.2 Ion-neutral coupling time analysis during the recovery phase (October 3, 2013)

We now repeat the ion-neutral coupling timescale analysis for the recovery phase of the storm on October 3, 2013 and the observations shown in Figure 3.9. The results are shown in Figure 3.11. In this case, during the recovery phase, the maximum correlation (0.584) corresponds to a time lag of \( \sim 0 \) minutes. This suggests that the neutrals and ions are strongly coupled with no significant time delay during this period. Because the ions and neutrals have reached a relatively steady and coupled state there is no basis for applying the empirical relations of momentum exchange theory for comparative evaluation, as was
done in the analysis of main phase [Figure 3.10b]. This zero time lag result is consistent with our preliminary conclusion from section 3.3; namely that in the absence of high latitude and sub-auroral forcing during the late recovery phase of the storm, the enhanced westward neutral circulation initiated during the main phase is strongly coupled with the ions during the recovery phase and causes the ions to convect westward as seen in Figure 3.7 and Figure 3.9. Such a result is consistent with observations from other studies which have suggested neutrals can drive westward ion drifts in the sub auroral ionosphere during the storm recovery phase via the disturbance dynamo effect [Blanc and Richmond, 1980; Lu et al., 1995; Wang et al., 2008; Fuller-Rowell et al., 2013b].

3.5 Summary and Conclusion

In this paper, we have presented colocated mid-latitude F-region observations of upper thermospheric ion-neutral coupling using SuperDARN radars and NATION Fabry-Perot interferometers. The ion-neutral coupling timescales were examined on two successive nights representing the main phase and recovery phase of an intense geomagnetic storm which occurred during October 2-3, 2013. During the main phase, the neutrals responded to the ions on a time-scale of ~ 84 minutes, much faster than what would be expected from ion drag momentum forcing alone. This suggests that other storm-time influences are also important (e.g., Joule heating). During the late recovery phase, when the primary magnetospheric driver had declined and the auroral zone convection had retreated poleward, the neutrals and ions were found to be strongly coupled such that the neutrals were driving the ions weakly in a westward direction without any significant time delay. This latter result is consistent with the so-called ”neutral-flywheel effect”, or disturbance dynamo persisting well into the late recovery phase.
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Chapter 4

Summary and Suggestions for Future Work

The motivation for this research was to acquire a good understanding of the F-region ion and neutral interactions that constitute a major component of the coupled ionosphere-thermosphere system. This work achieved this goal by capitalizing on the recent developments in co-located coverage of the SuperDARN-NATION instrument array. Chapter 1 provided a discussion of the ionosphere-thermosphere-magnetosphere system as a part of the broader sun-earth geomagnetic environment. This chapter provided background information to understand the primary atmospheric regions and processes which were analyzed in this research. Chapter 2 gave a detailed discussion of the SuperDARN and NATION instruments with respect to their observation principles, design, operation, and data products. It outlined the strengths and possibilities arising out of these recent advancements in facilities and thus laid a foundation of the approach and measurements that were used to define and address the research objective in this thesis. Chapter 3 presented a comprehensive study of storm-time ion-neutral coupling at mid-latitudes and focus the center piece of the thesis. A detailed analysis of ion-neutral coupling during the main phase and late recovery phase of the storm period on October 2-3, 2013 over the co-located SuperDARN-NATION sites of Illinois (UAO) and Michigan (ANN) was presented. The primary objectives were to study the timescales and primary interaction mechanisms governing the coupling between ions and
neutrals in the main phase and late recovery phase of the storm. It was determined that in the main phase, local ion-drag along with other non-local influences like Joule heating were observed to be the dominant mechanisms driving the neutrals on a timescale of $\sim 84$ minutes. In the late recovery phase, after the magnetospheric convection had retreated polewards, the main phase driven neutral winds were found to be strongly coupled with the ions and maintained the sub-auroral ion convection, consistent with the effects of so-called ‘disturbance dynamo’ extending far into the late recovery phase. These results are an important and timely contribution to our understanding of mid-latitude thermosphere, and present a strong base for carrying out additional large-scale characterization studies as the co-located SuperDARN-NATION coverage expands in future. However there are some outstanding questions raised through this study which could be subject of future research expanding on this work.

In particular, [Baron and Wand, 1983] suggest that variation in the timescale of ion-neutral coupling depends primarily on the variation of ion density (ionization). Whereas, [Kosch et al., 2001; Davis et al., 1995; Lockwood et al., 1993] proposed that the variation in ion-neutral coupling time has more to do with sensitivity of the ion-neutral collision frequency to the temperature and composition variations in the ionosphere. This presents a ripe challenge for additional ion-neutral coupling analysis but it would require accurate data for ion and neutral densities and collision frequency. Another outstanding question relates to the ion-neutral coupling time constants in the afternoon and evening sector and their comparison to the night-time observations during storm periods. This would require instruments which can continuously monitor and measure the neutral winds on the dayside unlike the constraint of night-time operation of NATION FPIs. Finally there is also a need to study the effect of other important factors such as thermal pressure, advection and Coriolis force and their significance on ion-neutral coupling under different geomagnetic conditions.
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