Dynamic High-latitude Ionospheric Convection: Drivers and Effects

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June 23, 2016
Outline

Drivers:
- Solar Wind and IMF drivers
- Modification of convection due to magnetospheric internal processes

Effects:
- Neutral dynamics effects
- Uplifting/downshifting effects
- Structuring the polar cap ionosphere
- Ion-neutral coupling within SAPS/SAID
The Geospace System

- The solar wind and IMF shape and structure the Earth magnetosphere
- Dayside magnetopause compressed
- Nightside magnetotail elongated
Magnetospheric and Ionospheric Convection: Fluid Description

- Reconnection model proposed by J. Dungey [1961]
- Major energy and momentum coupling mechanism between the solar wind and magnetosphere

Modified from G. Lu 2005 GEM Tutorial
Magnetospheric and Ionospheric Convection: Fluid Description

Noon-Midnight Meridional Plane

Ionosphere

Plasma Sheet

Cross Tail Current

Auroral Oval

V_{SW} Solar Wind

60°
Viscous Interaction

- Proposed by W. I. Axford, [1964]
- Viscous interaction moves closed field lines anti-sunward in the low-latitude boundary layer and sunward in the plasma sheet.
- Believed to play a major role under northward IMF condition and a minor role compared to dayside reconnection under southward IMF condition
High-latitude Reconnection under Northward IMF

- Solar wind-magnetosheath plasma enters the magnetosphere through high-latitude reconnection.
- Result in complex convection pattern
In the F region, plasma drifts in the ExB direction, and no horizontal currents flow.

In the lower E region, electrons drift in the ExB direction. Ions drift roughly in the direction of the electric field.

As altitude increases from lower E region, the ion drift velocity rotates toward the ExB direction because the ion–neutral collision frequencies decrease with altitude.

Horizontal currents flow in the E region.

Heelis, 2004
IMF Dependence of Convection Pattern

- Without corotation
- 2-cell convection pattern during southward IMF
- 3 or 4-cell convection pattern during northward IMF
- Cusp flow direction depends on the sign of IMF By
The total electric field is the sum of uniform convection electric field and the corotation electric field.

The separatrix is the boundary between closed and open drift trajectories.
Energetic particles are subject to gradient and curvature drift.

- Positively charged particles gradient and curvature drift towards the dusk side.
- Negatively charged particles gradient and curvature drift towards the dawn side.

\[ \phi_{\text{eff}}^{\text{hot}} = -E_0 r \sin \varphi + \frac{\mu B_0 R_E^2}{qr^3} \]

Kivelson and Russell, 1995
a) An equilibrium configuration with no convection electric field
b) Convection E field increases and moves the inner edge of the plasma-sheet sunward. Ions drift to the duskside and electrons drift to the dawnside. The shielding E field, in effect, reduces the imposed convection E field in the inner magnetosphere.
c) Shielding electric field is stronger than the convection E field.
Aspects of the shielding process:

- Partial westward ring current forms across the night side.
- Field-aligned Region-2 currents, flow up/down from dawnside/duskside ionosphere near the plasma sheet inner edge.
- Convection features, including the Harang reversal and SAPS, form during this process.
  - Overlap between the upward and downward Region-2 FACs necessary for the Harang reversal formation [Gkioulidou et al. 2009, 2011].

Gkioulidou et al. 2011
Effects Part 1: Neutral Dynamics Effects
Ion-neutral coupling

- Convecting ionosphere can be a significant source of momentum and energy for the thermosphere via ion–neutral collisions.

- Resulting interactions act to modify the thermospheric circulation, temperature, and composition, which, in turn, affects the ionosphere.

- Extent of the coupling depends on plasma density. For plasma densities of $10^3$ to $10^6$ cm$^{-3}$, the characteristic time constant for accelerating the thermospheric particles ranges from 200 hours (several days) to 10 minutes.

\[
\frac{\partial}{\partial t} T_i = v_{in} \left(-T_i + T_n + \frac{M_n}{3k} (\bar{v} - \bar{u})^2 \right)
\]

Temporal change of ion temperature:

Time scale for ions to respond to frictional heating:

\[
\tau \propto \frac{1}{\gamma_{in}}
\]

A few seconds to a few tens of seconds

Time scale for neutrals to respond to frictional heating:

\[
\tau \propto \frac{1}{\gamma_{ni}} = \frac{n_i m_i}{n_n m_n \gamma_{in}} \gg \frac{1}{\gamma_{in}}
\]

Because the neutral density is much higher than the ion density, the time scale for neutrals is much longer than that of ions.
Evidence of Ion-Neutral Coupling at High Latitudes

- High-latitude thermospheric wind pattern mimics the plasma convection pattern.
- The wind speed is typically smaller than plasma convection speed but much greater than expected if solar heating was the only process driving the flow.

Schunk and Nagy, 2009
High-latitude winds on average play a secondary role in the magnetosphere-ionosphere electrodynamic coupling.

However, they can play a more important role immediately following a period of high magnetic activity.

Neutral winds tend to maintain the ion convection pattern after the external sources are cut-off.
Effects Part 2: Uplifting/downshifting Effects
Decompose ExB Drift to Horizontal and Vertical Drifts

- ExB drift has both horizontal and vertical components when the magnetic field line is not purely vertical.
- During southward IMF, the vertical drift is upward on the day side and downward on the night side.

Schunk and Nagy, 2009
Induced Vertical Plasma Drift

Total vertical plasma drift speed:

$u_{iz} = \frac{E}{B} \cos I + u_n \sin I \cos I - \sin^2 ID_a \left( \frac{1}{n_i} \frac{\partial n_i}{\partial z} + \frac{1}{T_p} \frac{\partial T_p}{\partial z} + \frac{1}{H_p} \right)$

Vertical plasma drift is determined by the interplay between convection electric field, thermospheric wind, and ambipolar diffusion.

Schunk and Nagy, 2009
Major Chemical Reactions in the F-region

\[ O^+ + N_2 \overset{K1}{\rightarrow} NO^+ + N \quad (1) \]
\[ O^+ + O_2 \overset{K2}{\rightarrow} O_2^+ + O \quad (2) \]
\[ O^+ + NO \overset{K3}{\rightarrow} NO^+ + O \quad (3) \]
\[ NO^+ + e^- \overset{K4}{\rightarrow} O + N \quad (4) \]
\[ O_2^+ + e^- \overset{K5}{\rightarrow} O + O \quad (5) \]
\[ O^+ + e^- \overset{K6}{\rightarrow} O \quad (6) \]

- O\(^+\) is the dominant ion in the F region.
- Major chemical reactions in the F-region are charge exchanges (1-3) and dissociative recombinations (4-5).
- Radiative recombination (6) is very slow compared to other reactions.
- Moving F-layer plasma up or down by the induced vertical plasma drift can affect the lifetime of plasma by moving away or towards regions of denser neutrals.
Density Variability within Storm-Enhanced Density (SED)

- Result of magnetosphere-ionosphere-thermosphere coupling processes;
- Important mechanism for transporting solar produced high density plasma into low density polar cap and nightside auroral region;
Both convection flow and field-aligned drift contribute to the upward vertical drift.

In this case, convection flow plays a major role.

Zou et al. 2013

Vertical Plasma Drift within SED

2011 Oct. 24-25 storm IMF southward turning
Upward vertical flows are due to penetration electric field after sudden southward turning of the IMF.

Zou et al. 2014
Field-aligned downward flows largely increased, overturned the lifting due to convection flow and resulted in net downward vertical flows.

These net downward vertical flows push plasma to lower altitudes, where higher recombination rates lead to plasma density decrease.

Both poleward thermospheric wind and enhanced downward diffusion contribute to the field-aligned downward flows.
Not Every Plume Can Make To The Polar Cap!

Zou et al. 2014
Plasma in the same simulation column are traced backwards in time to study the origin and major loss and source mechanisms.

F-region plasma density sensitively responds to the strength of the convection electric field.
Because of non-vertical magnetic field, poleward/equatorward convection leads to ionospheric density increase/decrease.

Heelis et al. 2009
TIMEGCM Simulation of SED

Vertical drift due to electric field

Vertical drift due to meridional wind

Total vertical drift

Lu et al. 2012

- Quantified the contributions from convection electric field and meridional wind to vertical plasma drift.
- Convection electric field is more important in the subauroral region.
- Meridional wind plays an important role at mid latitudes.
Coupled SAMI3-RCM Simulation of SED

- Minimum $D_{st}$ during March 31, 2001 storm reached -387 nT.
- Plasma from the expanded Appleton anomaly contributes to the formation of SED plume.

Huba and Sazykin, 2014
Summary Part 1

- Given non-vertical magnetic field, poleward convection flows can lift the plasma to higher altitudes where the recombination rate is lower.
- Given continuous production on the dayside, the ionospheric plasma density can increase significantly.
- Convection electric field pattern influences the thermospheric wind pattern through ion-neutral collisions.
- Interplay between the convection electric field and the thermospheric wind determines the ionospheric density variability, such as that within SED.
- Quantifying the roles of different formation mechanisms at different locations during geomagnetic active periods is a very active research topic.
Effects Part 3: Structuring the Polar Cap Ionosphere
Polar Cap Patches

Plasma patches are regions of enhanced plasma density (at least a factor of 2 greater than background densities) at polar latitudes.

Zou et al., 2014

Hosokawa et al., 2010
Various formation mechanisms of patches have been proposed [Carlson, 2012 and references therein]:

- Time dependent reconnection and pulsating soft electron precipitation
- Sudden expansion and contraction of the convection pattern
- IMF By direction changes
- Enhanced recombination within high speed convection flows creating low density regions

There is evidence for each mechanism. But which one is responsible for the majority of the patches?

Moen et al., 2013
Seasonal and UT Dependence of Patches

- Patches preferentially occur during winter and during 12-24 UT [Coley and Heelis, 1998; David et al. 2016].

Sojka et al. 1994

David et al. 2016
A one-to-one spatial correspondence between the SuperDARN power and ASI airglow for the optical patches.

The motion of the optical patches has been shown to be consistent with the background plasma convection.

Patches can be used as tracers of polar cap convection.
Optical emission from patches has been used as tracers of convection flows to study the day-night coupling [Nishimura et al., 2014], and evolution of meso-scale fast flow channels [Zou Y. et al., 2015].
Boundary and auroral blobs are regions of enhanced plasma density that are located either inside of or on the equatorward edge of the auroral oval.

Boundary blobs are not created locally. They are polar cap patches that have convected through the nightside auroral oval and subsequently moved around towards dusk.
Polar Cap Patch Circulation

Zhang et al., 2013
Convection electric field in the dayside cusp region is crucial for the formation of polar cap patches.

After formation, patches drift anti-sunward at convection speed and can be used as tracers of convection flows.

Patches are important plasma sources for the polar cap and nightside ionosphere.

Open Question:
- What is the major formation mechanism for polar cap patches?
- How do polar cap patches exit the nightside polar cap?
Effects Part 4: Ion-Neutral Coupling within SAPS/SAID
SubAuroral Polarization Stream (SAPS) and SubAuroral Ion Drift (SAID)

- SAPS: Enhanced convection flows equatorward of duskside electron precipitation.
- SAID is a narrower region within SAPS where the flow speed is higher.

Foster and Burke, 2002
Formation Mechanisms of SAPS and SAID

- Southwood and Wolf [1978] suggested that large SAPS electric fields arise as a result of the closure of downward Region-2 FACs in the low conductance ionosphere. In this scenario, ionosphere plays a passive role.

- Banks and Yasuhara [1978] suggested that poleward transport due to large poleward electric field in the subauroral E region can decrease the density and conductance.

- Schunk et al. [1976] suggested that frictional heating increases ion temperature and then increase the recombination rate and reduce the density and conductance.

- The latter two scenarios emphasize the role of positive feedback between the ionosphere and magnetosphere.
- Large electric field leads to fast conversion from $O^+$ to $NO^+$.
- Dissociative recombination of $NO^+$ is much faster than radiative recombination of $O^+$. 
- The electron density decreases rapidly.

Schunk et al., 1975
Creation of Plasma Density Troughs

- Large horizontal ion drift near the equatorward boundary of precipitating electrons
- Ion temperature >10000K
- O\(^+\) converted to NO\(^+\)
- Total ion density decreases

Courtesy: Rod Heelis
SAPS forms during the growth phase of substorm as part of the Harang reversal [Zou et al. 2009, 2012; Bristow and Jensen, 2007].
SAPS Response to Substorm Westward Traveling Surge (WTS)

- SAPS increases when WTS moves into the same MLT but at higher latitude [Zou et al., 2009].

- Highly varying SAPS responses to the fine structures within WTS observed [Lyons et al., 2015].
Fine Structure of Ring Current

Complex structure of the ring current and Region-2 FACs seen in RCM [Yang et al., 2008] and CRCM [Buzulukova et al., 2008, 2010] simulations.
Proton precipitation within SAPS can increase conductance and suppress the SAPS electric field.

- Topside ionosphere shows a density trough but not a local dip in the E region.
- Be cautious about the altitude of the trough associated with SAPS.
- Proton precipitation should be included in the SAPS modeling.

Nilsson et al., 2005
Summary Part 4

- SAPS/SAID are unique convection flow structures reflecting the feedbacks between the magnetosphere-ionosphere-thermosphere coupling.
- Observationally, latitudinal profile of conductivity within SAPS is needed to identify the formation mechanism.
- Successfully modeling the formation and evolution of SAPS/SAID requires to include 2-way coupling between magnetosphere-ionosphere-thermosphere.
  - Self-consistent conductance, including both electrons and protons
  - Particle injection in the inner magnetosphere and the formation of structured partial ring current
  - Plasma temperature dependent chemical reactions
Summary

Drivers:
- High-latitude ionospheric convection dynamically responds to solar wind and IMF drivers.
  - Reconnection
  - Viscous Interaction
- Hot plasma in the magnetosphere modifies the convection pattern through the closure of field-aligned currents in the ionosphere.
  - Region-2 FACs
  - Harang reversal and SAPS

Effects:
- Neutral dynamics effects
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- Structuring the polar cap ionosphere
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References part 1:


