Simulation Study of Small-scale Plasma / Neutral Dynamics from Electron Precipitation

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Abstract

Soft electron precipitation is known to initiate a range of ionospheric and thermospheric reactions, such as increased temperature, density, and upwelling. Due to the complex coupling of these reactions with the underlying plasma and neutral populations, a straightforward interpretation of the underlying physics is problematic. We investigate the small-scale dynamics associated with electron precipitation using a kilometer-scale, three-fluid, ionosphere-thermosphere numerical model which includes inertial ion and neutral terms. Simulation results are presented which detail the temporal evolution of plasma and neutral populations over a range of electron precipitation energy & energy flux inputs. The timescales of the responses vary from a few seconds (electrons) to 10s of seconds (ion upwelling) to 10s of minutes (plasma density and neutral upwelling). When viewed at these small time-scales upward moving wave-like reactions emerge which increase in amplitude with increasing altitude.

Previous work within this area is presented in the right-most section for discussion. This related work involved cycling soft electron precipitation on and off to examine the dynamics Poleward Moving Auroral Forms (PMAF's).

1. Study Overview

Sufficiently soft electron precipitation (< ~500 eV) initiates a strong upward plasma expansion above the F-region which increases with altitude. The precipitation quickly transfers energy to the ambient electron "gas" resulting in an electron temperature increase. The electron temperature increase is substantial and correlates to both decreasing electron energy and increasing electron energy flux. The electron gas subsequently undergoes a thermal (upward) expansion, establishing a vertical ambipolar field which pulls the ions upwards through the parallel electric field arising from the need for charge neutrality. Neutral upward velocity and density slowly increase as a result of ion upwelling.

Simulation results come from a two-dimensional, three-fluid model which includes inertial ion and neutral terms (Sadler et al. 2012 JASTP). Inclusion of the inertial terms allow for examination of short-term accelerations. Only one dimension (vertical) is used here.

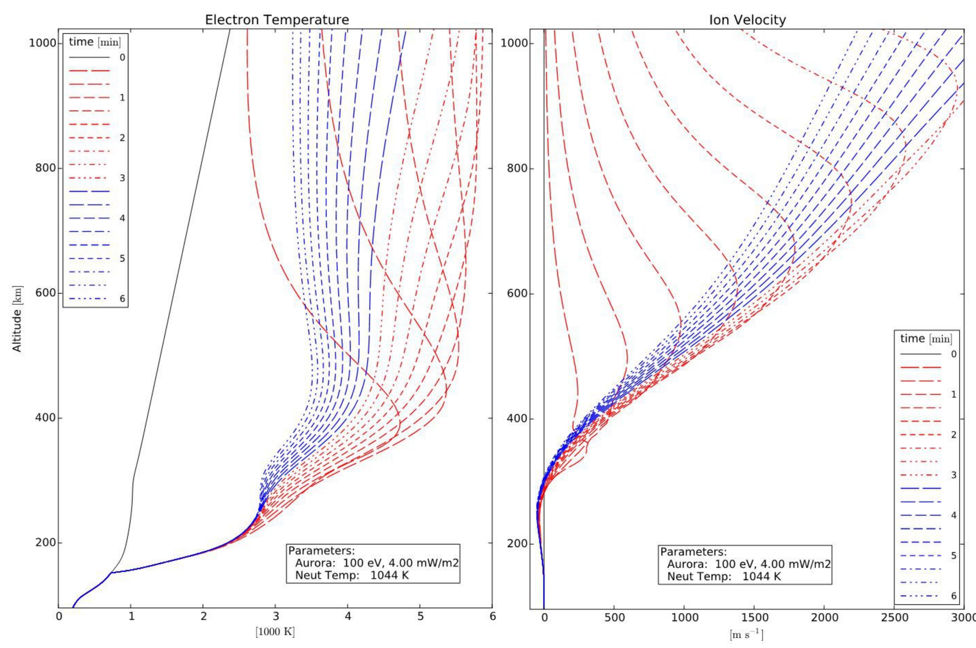
This study includes a panel of 16 separate simulations:

- Electron precipitation is continuously active for ~18 minutes for each simulation.
- Precipitation characteristic energy is varied across a range of 4 values: 100 eV, 200 eV, 500 eV, 1 keV.
- Precipitation energy flux is also varied across a range of 4 values: 1 mW/m^2, 2 mW/m^2, 4 mW/m^2, 6 mW/m^2.

Comparison of plasma number density is provided across this spectrum of input parameters.

2. Example 1: 100 eV, 4 mW/m^2

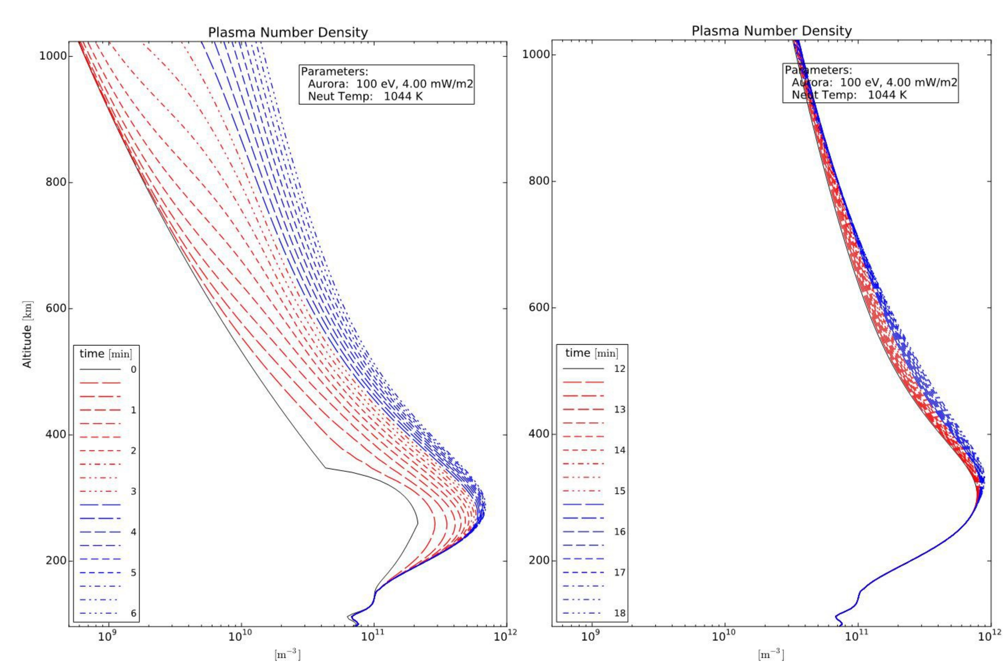
The dynamics and timescales are best illustrated with high flux, soft precipitation. Below are results for the first 6 minutes of the simulation with 100 eV characteristic energy and 4 mW/m^2 energy flux.



Several early timescales and dynamic responses are evident from electron temperature and upward ion velocity:

- Initial electron temperature "bulge" appears in seconds. Maximum value is reached over the course of a 1-2 minutes.
- Ion velocity responds within ~10 seconds and increases with altitude. Velocity wave front steepens with altitude.
- Both values decrease with time, electron density more rapidly than ion velocity. This decrease continues for remainder of simulation (not shown here).

Here, plasma number density response is shown for two time periods: the first 6 minutes and the last 6 minutes.

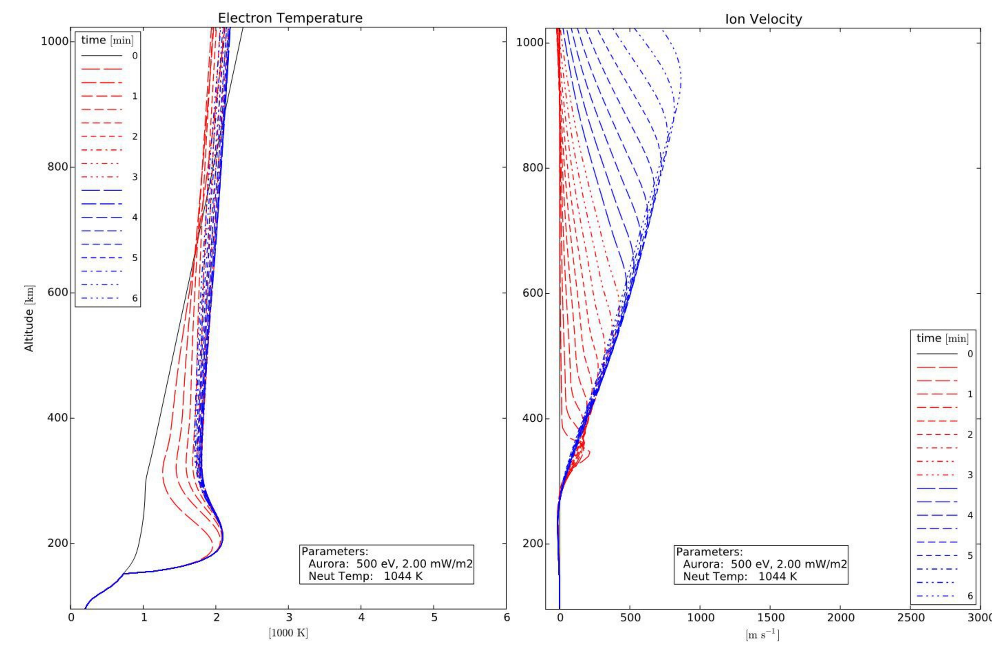


Responses in plasma number density include:

- Initial increase occurs over the course of ~10 minutes. Very little change is evident in the last few minutes.
- Density increases monotonically over the course of the simulation to a near maximum value for a given altitude.
- Very little rise occurs in latter time period.

3. Example 2: 500 eV, 2 mW/m^2

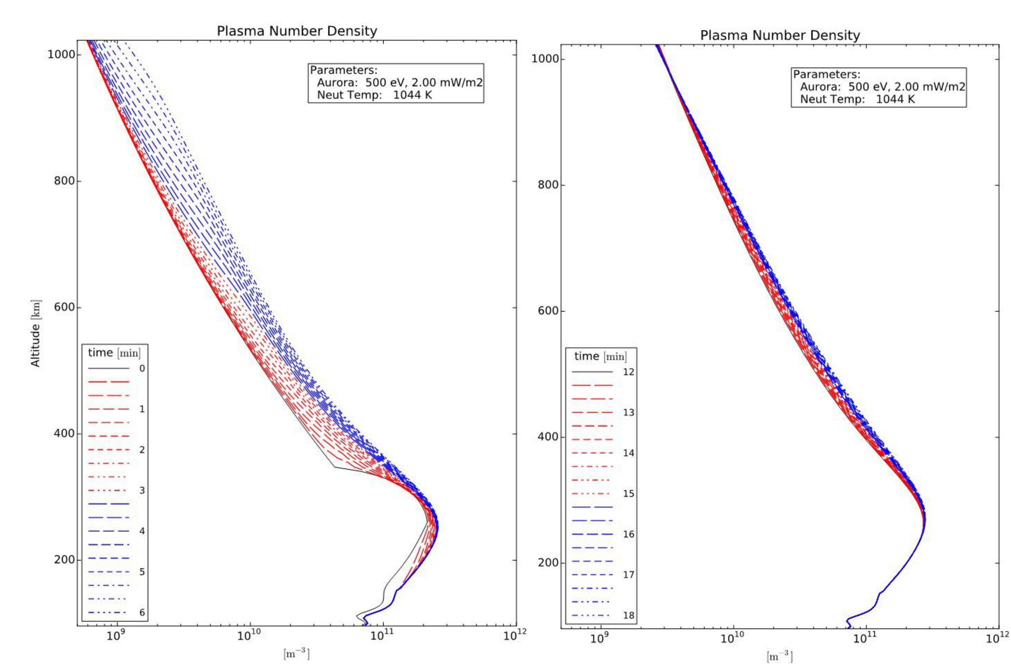
For comparison, less energetic electron precipitation shows markedly less disturbance. Below are results for the first 6 minutes of the simulation with 500 eV characteristic energy and 2 mW/m^2 energy flux.



Comparing 100 eV and 500 eV examples:

- Marked decrease in plasma response for harder electron precipitation (500 eV).
- Little, if any, temperature increase at higher altitudes
- Ion velocity peak rises in altitude approximately half as fast as 100 eV case.
- Energetic electrons travel deeper into the ionosphere where relevant process are less efficient.

Again, plasma number density response is shown for two time periods: the first 6 minutes and the last 6 minutes.



Comparing 100 eV and 500 eV examples:

- As noted above, marked decrease in plasma density response for harder electron precipitation.
- Plasma density peak migrates to lower altitude for 500 eV case (~250 km), indicative of more energetic precipitation.
- As with 100 eV, very little density rise in latter time period.

4. Results – Plasma Density

Results for plasma number density across the spectrum of simulations is tabulated below for 15 minute simulation times. The first two columns indicate the prescribed energy and energy flux for the electron precipitation. Columns 4 and 5 contain the starting and ending plasma number density at 1000 km altitude. The middle column contains the ratio of Column 4 to 5.

Energy (eV)	Flux (mW/m^2)	Relative Increase	Density 0m (cm^{-3})	Density 15m (cm^{-3})
1000	1	0.65	6.00E+008	3.90E+008
1000	2	1.12	6.00E+008	6.72E+008
1000	4	2.02	6.00E+008	1.21E+009
1000	6	3.14	6.00E+008	1.88E+009
500	1	1.58	6.00E+008	9.48E+008
500	2	3.36	6.00E+008	2.02E+009
500	4	7.76	6.00E+008	4.66E+009
500	6	11.71	6.00E+008	7.03E+009
200	1	8.54	6.00E+008	5.12E+009
200	2	16.79	6.00E+008	1.01E+010
200	4	28.20	6.00E+008	1.69E+010
200	6	35.70	6.00E+008	2.14E+010
100	1	22.74	6.00E+008	1.36E+010
100	2	38.38	6.00E+008	2.30E+010
100	4	54.20	6.00E+008	3.25E+010
100	6	58.06	6.00E+008	3.48E+010

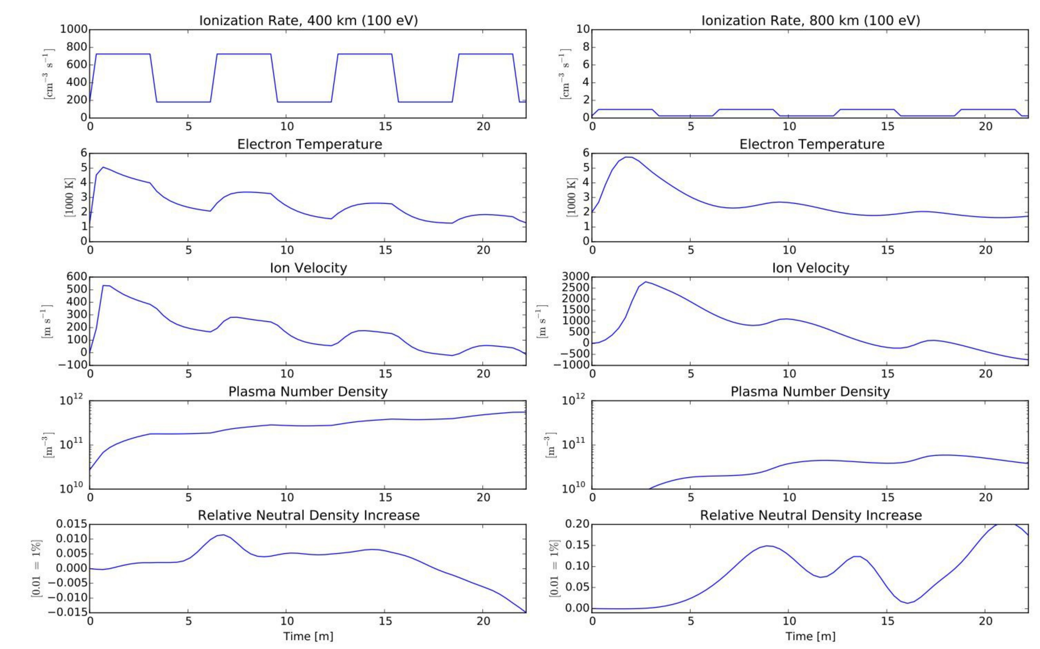
Summarizing topside density increases from above:

- For 1 keV electrons, density increases 1-3 fold.
- For 500 eV electrons, density increases ~1 order of mag.
- For 100 eV electrons, density increases ~1.5 order of mag.

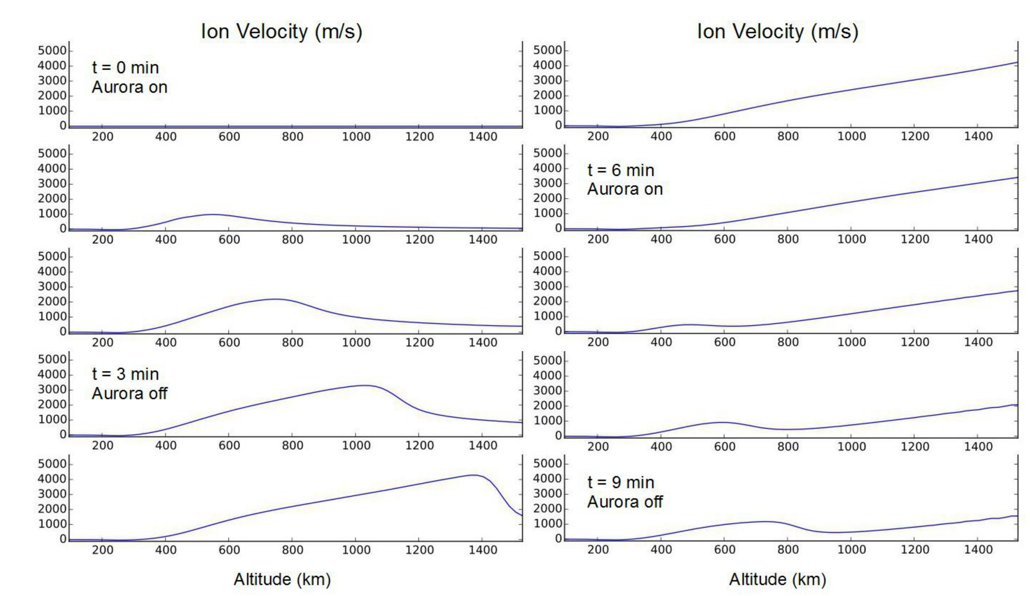
These results suggest the following trends for top-side ionospheric density with continuous soft electron precipitation:

- Both precipitation characteristic energy and energy flux play an important role. However, characteristic energy appears to be the more dominant parameter.
- Strong upward ion velocity from softer precipitation provides significant mass transport for ionospheric density.
- Additionally, softer precipitation raises the altitude of the plasma density peak. This effect, to some extent, raises the ionospheric column, increasing the topside density further.

5. Plasma / Neutral Dynamics



Plots from a previous study show response from 100 eV electron precipitation cycled between "high" and "low" energy flux values to examine dynamics associated with a series of PMAF structures. Of note is that neutral density increase is slow but steady (~10 minute scale) due to large inertia.



When electron precipitation first enters a stable unperturbed ionosphere, a shock-wave is evidently launched within the ionized gas.

- Heating from 100 eV precipitation begins in F-region causing plasma vertical plasma expansion.
- Downward waves are quickly damped due to increasing density.
- Upward waves travel more efficiently due to exponentially decreasing densities.
- Steepening velocity profile is due to compression wave traveling into a region of rarified density.
- Velocity must steepen in order to propagate carrying the same mass, momentum, and energy.
- New wave is launched due to new precipitation at 6 minutes.

Future work in this area will include a more systematic examination of the dynamics of PMAF's and two-dimensional structures such as field-aligned currents.