# Magnetosphere-Atmosphere Coupling at Saturn: 1. Response of Thermosphere and Ionosphere to Steady State Polar Forcing

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**Abstract**

We present comprehensive calculations of the steady state response of Saturn's coupled thermosphere–ionosphere to forcing by solar radiation, magnetospheric energetic electron precipitation and high latitude electric fields caused by sub–corotation of magnetospheric plasma. Significant additions to the physical processes calculated in our Saturn Thermosphere Ionosphere General Circulation Model (STIM-GCM) include the comprehensive and self–consistent treatment of neutral–ion dynamical coupling and the use of self–consistently calculated rates of plasma production from incident energetic electrons. We find thermospheric dynamics to play a crucial role in redistributing energy and neutral mass in the upper atmosphere, highlighting the importance of including dynamics in any energy balance studies. Our calculations successfully reproduce the observed high latitude temperatures as well as the latitudinal variations of ionospheric peak electron densities that have been observed by the Cassini Radio Science Subsystem experiment (RSS). Our calculations suggest the major ion at equatorial latitudes to be $H_3^+$, being replaced as principal ion at mid and high latitudes by $H^+$. By exploring the parameter space of possible high latitude electric field strengths and incident energetic electron fluxes, we determine the response of thermospheric polar temperatures to a range of magnetospheric forcing parameters. We thereby define a range of combinations of electric field strength and electron energy flux which are consistent with observed thermospheric polar temperatures. Our calculations highlight the importance of considering thermospheric temperatures as one of the constraints when examining the state of Saturn's magnetosphere and its coupling to the upper atmosphere.

*Keywords:*
Aeronomy, Saturn, Atmospheres, Dynamics, Ionospheres, Magnetospheres

## 1. Introduction

For the Gas Giants in our solar system the coupling between magnetospheres and atmospheres is likely to play a key role for the energy and momentum balance of their thermospheres and ionospheres. While the same can be said to be the case at polar latitudes on Earth, its global energy balance due to closer proximity to the Sun is most of the time dominated by solar heating. Magnetospheric forcing on Earth is controlled by the interaction between the solar wind and magnetosphere via the Dungey cycle, while on Jupiter the planet's rotation represents the primary generator of electric fields and driver of magnetospheric currents which ultimately lead to auroral emissions and ionospheric Pedersen and Hall currents. On Saturn evidence from auroral observations indicates that planetary rotation and solar wind both play a role, though their exact relative importance is still subject of debate.

As first described by Hill (1979), corotation of magnetospheric plasma with the planet is ultimately ensured by transfer of angular momentum from the upper atmosphere to the magnetosphere via a system of field-aligned Birkeland currents. In the magnetosphere the Birkeland current system is closed via radial currents in the equatorial plane which via **E**×**B** accelerations drive the plasma towards corotation. In the ionosphere the Birkeland currents close via field-perpendicular Pedersen and Hall currents which exert westward (against the sense of planetary rotation) acceleration on the ionospheric plasma and, via ion-neutral collisions, onto thermospheric neutrals. The upper atmosphere at auroral latitudes where this coupling occurs will thus corotate to a lesser extent with the planet which, in the rotating frame of the planet, is manifested via westward wind velocities in the thermosphere. Furthermore, the Pedersen and Hall currents due to the ionosphere's resistivity cause thermal heating, often referred to as Joule heating.

Using a radial profile of magnetospheric plasma velocities inferred from Voyager plasma observations and assuming fixed ionospheric conductances of 1 mho, Cowley et al. (2004) calculated the associated field aligned currents and resulting ionospheric Joule heating rates of around 2.5 TW per hemisphere, considerably larger than energy from the direct precipitation of electrons ($\leq$0.06 TW) and solar EUV heating (0.15–0.27 TW) (Müller-Wodarg et al., 2006). Using simultaneous observations of fields and plasmas in Saturn's magnetosphere from Cassini and UV images from the Hubble Space Telescope (HST), Cowley et al. (2008) confirmed their earlier general results but revised the assumed conductances in the southern (summer-) hemisphere up from 1 to 4 mho.

A visual manifestation of Magnetosphere-Atmosphere coupling are the auroral emissions that have been studied on Saturn in the EUV and FUV (emitted by H, $H_2$) and in the IR (emitted by $H_3^+$) (Kurth et al., 2009; Galand et al., 2011). The EUV/FUV emissions are associated primarily with energetic electron precipitation at energies ranging from 5–30 keV (Sandel et al., 1982; Gérard et al., 2004; Gustin et al., 2009; Lamy et al, 2010). Galand et al. (2011) studied the response of Saturn's ionosphere to precipitation of hard (10 keV) and soft (500 eV) electrons using their particle transport code to self-consistently calculate the ionisation rates as input to the ionospheric model of Moore et al. (2010) to infer the resulting profiles of ion and electron densities. Galand et al. (2011) calculated Pedersen and Hall conductances as a function of precipitating particle energy and energy flux, deriving a square-root dependency of the conductances to energy flux for hard electrons. They also found the soft electrons to have a minor influence only upon the conductances.

The following study will investigate Magnetosphere-Atmosphere coupling, specifically its effects on Saturn's polar thermosphere and ionosphere. Our goal is to present a comprehensive investigation of the effects of magnetospheric currents on temperatures, dynamics and composition. Using a global model of Saturn's coupled thermosphere and ionosphere (Moore et al., 2004; Müller-Wodarg et al., 2006; Galand et al., 2009; Moore et al., 2010; Galand et al., 2011), we calculate for the first time the response of the coupled thermosphere-ionosphere system to a range of values for energetic particle precipitation flux and high latitude electric fields. Through comparisons of our calculations with observed thermospheric temperatures and ionospheric drifts, we define the ranges of magnetospheric parameters that are consistent with atmospheric observations, thereby presenting a framework for using the atmosphere as an additional constraint in quantitatively describing Saturn's coupled magnetosphere/atmosphere system. Our study extends the work of Galand et al. (2011) in that it calculates the response of the neutral atmosphere to changing conductances, while their calculations had assumed a constant background neutral atmosphere. Our calculations show that thermospheric dynamics are crucial in determining the thermal structure in the polar atmosphere, highlighting the limitation of any 1–D thermal balance calculations which cannot include dynamics.

In Section 2 we introduce the model and provide an overview of the simulations which are presented in more detail in Section 3 and validated with observations. We provide a broader discussion of our findings including any limitations of our approach in Section 4.

## 2. The STIM Model

The main tool in this study is the Saturn Thermosphere Ionosphere Model (STIM), a General Circulation Model (GCM) that treats the global response of Saturn's upper atmosphere to solar and magnetospheric forcing. Key parameters calculated by the code include global neutral temperatures, global densities of key neutral and ion constituents, as well as neutral and ion dynamics. In the following section, we describe components of STIM in more detail and list the range of simulations presented in this study.

### *2.1. Thermosphere-Ionosphere GCM*

Our simulations originate from two codes developed side-by-side but separately, namely, the Saturn Thermosphere GCM (Müller-Wodarg et al., 2006) and Saturn 1-D Ionosphere Model (Moore et al., 2004) which were subsequently fully coupled to form the Saturn Thermosphere Ionosphere Model (STIM). The thermosphere component globally solves the non-linear Navier-Stokes equations of momentum, continuity and energy on a spherical pressure level grid. The momentum equation includes terms such as pressure gradients, viscous drag, Coriolis acceleration, curvature accelerations and advection. The energy equation includes all processes of internal energy redistribution, including advection, adiabatic heating and cooling as well as molecular and turbulent conduction. Solar EUV heating is calculated through explicit line-of-sight integration of solar irradiance attenuation (the Lambert-Beer Law), assuming solar spectra derived from the Thermosphere Ionosphere

Mesosphere Energetics and Dynamics (TIMED) / Solar EUV Experiment (SEE) (Woods et al., 2005; Woods, 2008). While including direct solar EUV heating in our calculations, it has a negligible influence on the energy balance of Saturn's thermosphere, as shown earlier by Müller-Wodarg et al. (2006). We will show that the main importance of solar EUV radiation lies in its ionising role that leads to conductivities and ion drag. These in turn affect the neutral energy balance at high latitudes where magnetospheric electric fields drive currents in the ionosphere, which dissipate heat in the thermosphere (see Section 2.3). Ion drag affects the neutral momentum balance considerably, and thereby the neutral dynamics.

A new addition to the thermospheric energy equation is inclusion of $H_3^+$ cooling, a process known to be important on Jupiter (Miller et al., 2006, 2010). At thermospheric temperatures typically found on Saturn (320–500 K (Nagy et al., 2009)), we do not expect $H_3^+$ cooling to play an important role, but we included the process to be able to assess its importance for cases where polar magnetospheric heating raises temperatures above ~500 K. We implemented $H_3^+$ cooling rates of Miller et al. (2010) in the form of a parameterised table of cooling rates as a function of thermospheric temperature, from which the code calculates the local cooling rate at each grid point at minimal expense to the overall computing time.

The STIM GCM calculates the transport by winds and molecular and turbulent diffusion of key neutral species (H, $H_2$, He, $CH_4$, $H_2O$), following the procedures outlined by Müller-Wodarg et al. (2006). The global spherical grid has flexible resolution. For simulations in this study we assumed spacing in latitude and longitude of 2° and 10°, respectively, and a vertical resolution of 0.4 scale heights. Our time integration step was 5 sec and we ran the code for 500 Saturn rotations to reach steady state.

Fully coupled chemically and dynamically to the thermosphere is a global ionosphere model based largely on the 1-D model of Moore et al. (2004). Neutral species undergo primary ionisation by solar EUV photons, assuming the solar spectra specified above. We include secondary ionisation by suprathermal photoelectrons using the parameterisation of Moore et al. (2009). The ions ($H^+$, $H_2^+$, $H_3^+$, $He^+$, $CH_3^+$, $CH_4^+$, $CH_5^+$, $H_2O^+$, $H_3O^+$) undergo reactions of charge exchange and recombination with neutral species, following the chemical scheme of Moore et al. (2004), assuming $T_e = T_i = T_n$, with additional reactions for hydrocarbon ions $CH_3^+$, $CH_4^+$ and $CH_5^+$, as given by Moses and Bass (2000). We calculate ion velocities resulting from accelerations by magnetospheric electric fields, collisions with neutral gas particles and field-aligned diffusion (Moore et al., 2004).

The ion continuity equation is solved considering photo-and particle ionisation, chemical sources and sinks as well as transport by winds and diffusion. As shown by Moore et al. (2004), the ionosphere throughout the region studied here (near the main ionospheric peak) is largely in photochemical equilibrium, so dynamics have little influence on the ion distribution. This was predicted from comparison of transport and chemical life times by Moore et al. (2004), but with the fully coupled model used here we confirm their finding. In particular, neutral winds are of little importance to the ion distribution. This is different from what is found in other atmospheres including those of Earth, Venus and Titan.

### *2.2. Water and vibrationally excited $H_2$*

Two important components of the ionospheric photochemistry in STIM are the ion charge exchange reactions with ambient neutral water molecules and with vibrationally excited $H_2$. As shown by Moses and Bass (2000) and Moore et al. (2004), the dominant ion produced in Saturn's ionosphere is $H_2^+$ which results from photo-ionisation of the dominant neutral species near the main ionospheric peak, $H_2$, primarily by the solar 30.38 nm HeII emission line. The produced $H_2^+$ is rapidly lost through charge exchange reaction with $H_2$, forming $H_3^+$, a shorter lived ion (relative to $H^+$)whose presence in the auroral regions of Saturn has been confirmed by ground based observations (Stallard et al., 1999) .

Another primary ion produced on Saturn is $H^+$ which as an atom recombines very slowly only with free electrons, making it potentially much more long-lived than $H_3^+$. As a result, $H^+$ becomes a key ion alongside $H_3^+$ despite the $H^+$ production rate near the ionospheric peak being lower by about an order of magnitude than that of $H_2^+$. In the absence of any further chemical sink, $H^+$ becomes the dominant ion on Saturn and due to its long lifetime barely varies with local time. A pattern of no appreciable diurnal behaviour is in contradiction to Saturn Electrostatic Discharge (SED) measurements (Kaiser et al., 1984; Fischer et al., 2011) and the dawn/dusk asymmetries observed by the Cassini Radio Science Subsystem (RSS) (Nagy et al., 2006; Kliore et al., 2009). This dawn-dusk asymmetry suggests ionospheric recombination timescales of the dominant ion on Saturn's nightside to be of the order of a few hours, giving ions enough time to recombine on the nightside and their densities to be reduced in the dawn sector.

Two chemical processes have been investigated over the past decades which could effectively destroy $H^+$ ions, thereby reducing its (and the ionosphere's) chemical lifetime, generating local time variations in Saturn's ionosphere. These are the charge exchange reactions of $H^+$ with water,

$$H^+ + H_2O \rightarrow H_2O^+ + H \quad (1)$$

and with vibrationally excited $H_2$,

$$H^+ + H_2(\nu \geq 4) \rightarrow H_2^+ + H \quad (2)$$

The reaction rate of (1) assumed in STIM is given by $k_{H2O} = 8.2 \times 10^{-9}$ cm$^3$s$^{-1}$ (Anicich, 1993). Moore et al. (2006) presented a comparison of calculated ionospheric densities with low latitude Cassini RSS observations (Nagy et al., 2006) and concluded that the observed dawn–dusk asymmetry in the ionosphere at low latitudes was best reproduced by the model when imposing an external influx of neutral water molecules into the low– to mid–latitude upper atmosphere at a rate of $(0.5 - 1.0) \times 10^7$ cm$^{-2}$ sec$^{-1}$. In their more extensive recent study, Moore et al. (2010) obtained a best fit between latitudinal profiles of Total Electron Content (TEC) in model and data when imposing the water flux as a Gaussian profile centered on the equator with a peak value of $0.5\times10^7$ cm$^{-2}$ sec$^{-1}$ and full width half maximum (FWHM) of 23.5° latitude.

Figure 1 shows the influx of water that we assume as upper boundary condition in the present study, as specified in Moore et al. (2010). Our model calculates the global transport of water molecules by diffusion and advection, and thereby their horizontal and vertical redistribution in the thermosphere. In imposing a peak water influx at equatorial latitudes, rather than a latitudinally more uniform distribution, we follow the notion that the bulk of gaseous water in the Saturnian system would originate from the plumes of Enceladus and impact Saturn's upper atmosphere as a neutral constituent, thereby being unaffected by the magnetosphere and concentrated in the equatorial plane (Moore et al., 2006, 2010).

For reaction (2) above, as discussed by Moore et al. (2010) and Galand et al. (2011), the basic reaction rate of $H^+$ with vibrationally excited $H_2$ has recently been updated to a value of $(0.6 - 1.3) \times 10^{-9}$ cm$^3$ sec$^{-1}$ (Huestis, 2008). Yet, a large uncertainty remains in the fractional abundance of $H_2(\nu \geq 4)$ required for the reaction to proceed. Moore et al. (2010) defined an "effective" reaction rate ($k_1^*$), the product of the rate $k_1$ for reaction (2) and the volume mixing ratio, $\chi$, of $H_2(\nu \geq 4)$ relative to $H_2$: $k_1^* = k_1 \cdot \chi(H_2(\nu \geq 4))$ [cm$^3$ s$^{-1}$]. Thus the uncertainty in population of vibrationally excited $H_2$ manifests itself in the reaction rate $k_1^*$ of reaction (2).

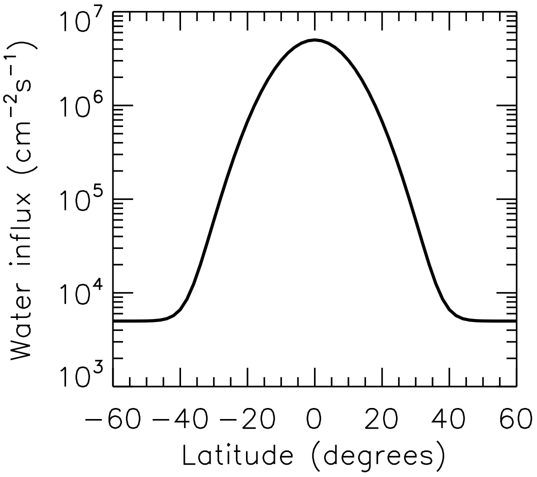


Figure 1: Water influx imposed at the upper boundary of STIM in all simulations presented in this study. For numerical stability a minimum base level influx is assumed poleward of ~40° in both hemispheres, but ignored in the ionospheric photochemistry calculations at those latitudes.

Moore et al. (2010), in the light of additional Cassini RSS observations, revisited their $k_1^*$ rate and concluded that best fit between model and observations was obtained when multiplying the original reaction rate of Moses and Bass (2000) by a factor of 0.125 which, with a revised average base reaction rate (from $k_1=2\times10^{-9}$ to $k_1=1\times10^{-9}$cm$^3$sec$^{-1}$) (Huestis, 2008), corresponds effectively to a reduction of the assumed volume mixing ratio of $H_2(\nu \geq 4)$ by a factor of 4 with respect to that assumed by Moses and Bass (2000). For a more detailed discussion of this see Moore et al. (2010) and Galand et al. (2011).

The auroral region, which is the focus of the present study, is subject to energetic electron precipitation from Saturn's magnetosphere. We expect this precipitation to enhance the population of vibrationally excited $H_2$. As a result, we have for this study assumed a $H_2(\nu \geq 4)$ abundance of twice the value assumed by Moses and Bass (2000), thus effectively obtaining a $k_1^*$ rate identical to theirs. This approach was equally followed by Galand et al. (2011).

### 2.3. *Ion drag and Joule heating*

Key new additions to the thermospheric component of STIM with respect to that of Müller-Wodarg et al.

(2006) are the inclusion of dynamical (momentum) coupling between the thermospheric neutrals and ionospheric ions and self-consistent calculations of Joule heating. The momentum coupling arises physically since ions, in the absence of an external electric field, are constrained in their motion by the magnetic field. The neutral gases have collisional interactions with ions leading to a viscous–type force damping the motion of the neutral gases relative to that of the ions. When an external electric field is present, the ions are accelerated and the same collisional interaction leads to an acceleration of the neutral gases in the direction of ion motion. This latter interaction becomes important at auroral latitudes. The ion drag term can, in general, be expressed as

$$\mathbf{a}_{ni} = -\nu_{ni}\ (\mathbf{u} - \mathbf{v}) \tag{3}$$

where $\mathbf{a}_{ni}$ denotes the acceleration due to neutral–ion collisions in the atmosphere, $\nu_{ni}$ is the neutral–ion collision frequency and $\mathbf{u}$, $\mathbf{v}$ are the neutral and ion velocities, respectively. In our model we implement the ion drag term in a different form, following the procedure used by Fuller-Rowell and Rees (1981), whereby the ion drag term is instead expressed as a function of the current density $\mathbf{J}$ in the ionosphere:

$$\mathbf{a}_{ni} = -\nu_{ni}\ (\mathbf{u} - \mathbf{v}) = \frac{1}{\rho}\ \mathbf{J} \times \mathbf{B} \tag{4}$$

where $\mathbf{B}$ denotes the ambient magnetic field in Saturn's ionosphere (Davis and Smith, 1990), and $\rho$ is the mass density. In the simulations presented here we enforced hemispheric symmetry in the magnetic field.

We calculate the current density $\mathbf{J}$ by using a generalisation of Ohm's law

$$\mathbf{J} = \underline{\sigma} \cdot (\mathbf{E} + \mathbf{u} \times \mathbf{B}) \tag{5}$$

where $\underline{\sigma}$ denotes the $3 \times 3$ conductivity tensor, $\mathbf{E}$ is an externally applied electric field (or internal polarisation field) and $\mathbf{u} \times \mathbf{B}$ represents the dynamo field. Following Rishbeth and Garriott (1969), we assume the concept of layer conductivities, whereby the conducting layer is assumed to have a limited vertical extent and may thus instead be expressed as a $2 \times 2$ tensor in the horizontal, given by

$$\underline{\sigma} = \begin{vmatrix} \sigma_P/sin^2(I) & \sigma_H/sin(I) \\ -\sigma_H/sin(I) & \sigma_P \end{vmatrix} \tag{6}$$

Here, $\sigma_P$ and $\sigma_H$ denote the Pedersen and Hall conductivities, respectively, and $I$ is the dip angle of the magnetic field $\mathbf{B}$. Combining the 2-D version of (5) with (6) yields expressions for the latitudinal ($j_\theta$) and longitudinal ($j_\phi$) components of the current density as

$$j_\theta = \frac{\sigma_P}{sin^2(I)}\left(E_\theta + u_\phi B_r\right) - \frac{\sigma_H}{sin(I)}\left(-E_\phi + u_\theta B_r\right) \tag{7}$$

and

$$j_\phi = \sigma_P\left(E_\phi - u_\theta B_r\right) - \frac{\sigma_H}{sin(I)}\left(E_\theta + u_\phi B_r\right) \tag{8}$$

where $E_\theta$ and $E_\phi$ denote meridional and zonal components of the electric convection or polarisation field, $u_\theta$ and $u_\phi$ are the meridional and zonal neutral wind components and $B_r$ is the radial magnetic field. With equation (4) we obtain for the meridional and zonal ion drag acceleration terms the expressions

$$a_{ni,\theta} = \frac{1}{\rho}\ j_\phi \cdot B_r \tag{9}$$

and

$$a_{ni,\phi} = -\frac{1}{\rho}\ j_\theta \cdot B_r \tag{10}$$

which are added to the neutral wind momentum equation of Müller-Wodarg et al. (2006). The above implementation is consistent with that commonly used by General Circulation Models for Earth, such as the Coupled Thermosphere Ionosphere Model (CTIM) by Fuller-Rowell et al. (1996). While the above treatment assumes the layer conductivity concept, which neglects vertical currents, we have in a test version of STIM also implemented the ion drag term in its more generalised form using the full $3 \times 3$ conductivity tensor and found almost identical results. In the interest of simplicity and computing speed we have thus retained the $2 \times 2$ treatment in our model.

When currents flow in the ionosphere, an environment which is not perfectly conducting, resistive heating occurs, a process often referred to as Joule heating. Following the treatment of Fuller-Rowell and Rees (1981), we express the rate of Joule heating per unit mass using the relation

$$q_{Joule} = \frac{1}{\rho}\ (\mathbf{J} \cdot \mathbf{E}) = \frac{1}{\rho}\left(j_\theta E_\theta + j_\phi E_\phi\right). \tag{11}$$

Note that the electrical current $\mathbf{J}$ in the Joule heating term (Eq. 5) includes the effect of neutral winds. Physically this means that the above expression for Joule heating consists of two components, the thermal heating of the atmosphere by electrical currents and the change of kinetic energy of the atmospheric gases which results from the momentum change due to ion drag (Equs. 9, 10). Sometimes this latter component of heating is referred to as ”ion drag heating”. While the thermal heating by currents can only be a positive quantity, the ion drag heating can also attain negative values, implying loss of kinetic energy of the neutral atmosphere (Vasyliũnas and Song, 2005).

The Joule heating expression (Eq.11) is added to the neutral gas energy equation of Müller-Wodarg et al. (2006). The ion drag and Joule heating terms are thus calculated self-consistently in STIM, assuming a given external electric field **E**. This electric field originates from the departure of regions in Saturn's magnetosphere from corotation due to plasma production from internal sources. Thus **E** represents in our calculations a key parameter determining the coupling between magnetosphere and ionosphere. In a fully two–way coupled ionosphere–magnetosphere model, the value of **E** would change in response to atmospheric conditions, but we currently do not include this feedback in our model and define a fixed value of **E** based on calculations of Cowley et al. (2004).

### 2.4. *Auroral electron precipitation*

At polar latitudes, Saturn is known to possess auroral ovals which have been observed in the UV (Judge et al., 1980; Clarke et al., 1981), IR (Geballe et al., 1993; Stallard et al., 1999) and at visible wavelengths, as reviewed by Kurth et al. (2009). They are signatures of magnetosphere-ionosphere-thermosphere coupling processes, such as precipitation of energetic electrons and ions into the upper atmosphere, yielding ionisation, excitation, dissociation and heating. Particle ionisation processes exceed solar primary and secondary ionisation in the auroral regions during local winter and at equinox. Ionisation at auroral latitudes due to precipitating suprathermal electrons thus plays a key role not only locally, but more globally due to the currents that can then flow, which in turn substantially affect the global energy balance.

To account for auroral particle ionisation processes, we calculate primary and secondary ionisation rates from suprathermal magnetospheric electrons using the model of Galand et al. (2011). They presented ionisation rates for two suprathermal energy populations in STIM, one consisting of hard electrons with a mean energy of $E_m = 10$ keV and one consisting of soft electrons with $E_m = 500$ eV. Both populations have been identified at Saturn in Voyager/UVS, Hubble Space Telescope (HST), Cassini/CAPS and Cassini/UVIS observations (Sandel et al., 1982; Gérard et al., 2004; Grodent et al., 2010). In STIM we have the option of specifying the incident energy fluxes of suprathermal electrons independently for 3 populations (10 keV, 3 keV, 500 eV) and assume ion production rates to be proportional to the energy flux. Additionally, we can independently specify their latitudinal distribution as well as any local time variations. In our present study we apply 10 keV electron particle precipitation alone.

| Run code | Peak electric field strength | Incident electron energy flux (local time averaged) | Season |
|---|---|---|---|
| R1 | 95 mV/m | 0.07 mW/m$^2$ | Equinox |
| R2 | 85 mV/m | 0.07 mW/m$^2$ | Equinox |
| R3 | 75 mV/m | 0.07 mW/m$^2$ | Equinox |
| R4 | 95 mV/m | 0.12 mW/m$^2$ | Equinox |
| R5 | 85 mV/m | 0.12 mW/m$^2$ | Equinox |
| R6 | 75 mV/m | 0.12 mW/m$^2$ | Equinox |
| R7 | 95 mV/m | 0.17 mW/m$^2$ | Equinox |
| R8 | 85 mV/m | 0.17 mW/m$^2$ | Equinox |
| R9 | 75 mV/m | 0.17 mW/m$^2$ | Equinox |
| R10 | 95 mV/m | 0.22 mW/m$^2$ | Equinox |
| R11 | 85 mV/m | 0.22 mW/m$^2$ | Equinox |
| R12 | 75 mV/m | 0.22 mW/m$^2$ | Equinox |
| R13 | 95 mV/m | 0.62 mW/m$^2$ | Equinox |
| R14 | 85 mV/m | 0.62 mW/m$^2$ | Equinox |
| R15 | 75 mV/m | 0.62 mW/m$^2$ | Equinox |
| R16 | 95 mV/m | 1.24 mW/m$^2$ | Equinox |
| R17 | 85 mV/m | 1.24 mW/m$^2$ | Equinox |
| R18 | 75 mV/m | 1.24 mW/m$^2$ | Equinox |
| R19 | 75 mV/m | 0.62 mW/m$^2$ | Solstice |

Table 1: Summary of STIM GCM simulations discussed in this study. The auroral electron energy flux is for 10 keV electrons incident at 78° latitude. While all simulations assume this flux to vary with local time, as shown in Figure 3 (black line), the table gives diurnally averaged values. Peak electron fluxes near 08:00 local time are roughly a factor of 2 times the values given above. The listed electric field strengths are peak field strengths, attained near 78° latitude (see Figure 2). Simulation R19 is the same as R15 in terms of auroral forcing, but assumes southern hemisphere summer solstice conditions. All simulations were run to steady state for 500 Saturn rotations.

### 2.5. *Simulation settings*

In simulating the response of Saturn's coupled thermosphere-ionosphere system to magnetospheric forcing, we varied two key parameters in the model, namely, the energy flux of precipitating auroral 10 keV electrons and the auroral electric field strength. Table 1 provides a summary of all simulations, which will hereafter be referred to by their run codes (R1–R19).

We have run all simulations for solar minimum conditions (May 15, 2008), identical to the fluxes used by Galand et al. (2009, 2011). Simulations R1–R18 assume equinox conditions, while R19 is identical to R15 but for southern hemisphere summer conditions. We find however the seasonal variations in Saturn's upper atmosphere to be of secondary importance only. All simulations were run to steady state for 500 Saturn rotations. While the ionosphere reaches steady state conditions considerably earlier, the thermosphere is characterised by long thermal time scales, thus requiring long run times before a steady state is reached. Yet, we note that no evidence is available to determine whether or not Saturn's upper atmosphere is in thermal equilibrium.

Figure 2 shows the azimuthal (equatorward) electric field strength that we applied in all simulations. The (co–)latitude variations are consistent with calculations by Cowley et al. (2004) but we chose to vary the peak electric field strength from a maximum value consistent with that of Cowley et al. (2004) (E≤95 mV/m, solid line) to scalings of 0.9 and 0.8 times their value (E≤85 mV/m (dotted) and E≤75 mV/m (dashed), respectively). The field is applied symmetrically in both hemispheres (pointing southward in the northern hemisphere and northward in the southern hemisphere) and assumed independent of local time and longitude. The black box in Figure 2 indicates the location of maximum precipitating energetic electron flux assumed in this study. It coincides with the location of sudden change in the degree of corotation. This shear is may contribute towards the acceleration of the particles into the atmosphere (Cowley et al., 2004). The electric field strength mapped into the polar upper atmosphere is effectively a measure of the degree of corotation of plasma in Saturn's magnetosphere. A lower electric field strength implies stronger corotation for any given value of conductance. While not a free parameter *per se*, enough uncertainties in the observed degree of plasma corotation in Saturn's magnetosphere (and in the modelling of associated electric fields) justify investigating the atmosphere response to variations of **E** within ≈20 %. In reality the electric field will be more complex, including a zonal field component as well as longitude, latitude and temporal variations, but this is a reasonable first attempt.

The ionospheric plasma densities, and thereby Pedersen and Hall conductivities in the auroral region, are primarily controlled by the second parameter we vary, the incident electron energy flux. We assume a single population of electrons (10 keV), though in practice other energies are also present. We assume 5 different levels of electron energy flux which we allow to vary with local time. Local time averages of the fluxes we assumed are listed in Table 1 as 0.07, 0.12, 0.17, 0.22, 0.62 and 1.24 mW/m$^2$.

The black line in Figure 3 shows the local time variation of incident electron energy flux that we assume

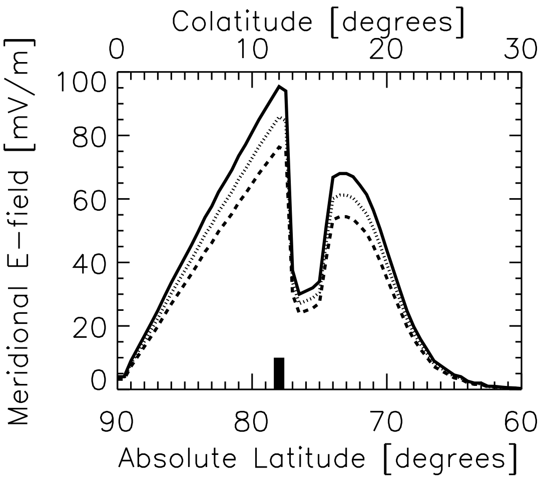


Figure 2: Azimuthal (equatorward) electric field strength applied in simulations of this study. The solid line represents 1.0 times the field strength of Cowley et al. (2004), the dotted and dashed lines represent cases where the field strength of Cowley et al. (2004) was multiplied by 0.9 and 0.8, respectively. The field is applied symmetrically in both hemispheres (pointing southward in the northern hemisphere and northward in the southern hemisphere) and assumed independent of local time and longitude. The black box indicates the location of maximum precipitating energetic electron flux assumed in this study. It coincides with the location of sudden change in the degree of corotation. This shear is may contribute towards the acceleration of the particles into the atmosphere (Cowley et al., 2004).

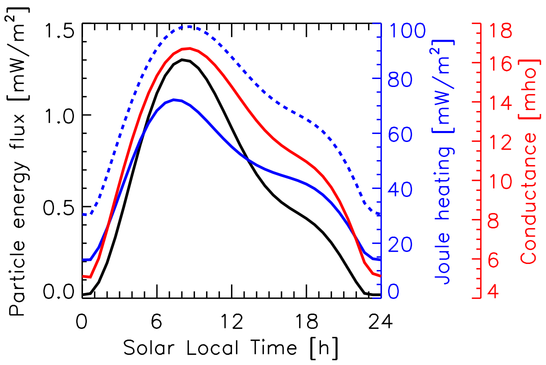


Figure 3: Key auroral parameters in simulation R15 (see Table 1). The black line denotes energy flux of incident 10 keV electrons at 78° latitude, with a local time averaged value of 0.62 mW/m$^2$. The assumed local time variations are consistent with those inferred from auroral observations by Lamy et al. (2009). The incident electrons ionise Saturn's thermosphere at the rates calculated by Galand et al. (2011), leading to Pedersen conductances shown here as red line which range from 5–17 mho, with a local time average of 11.5 mho. Applying an external equatorward electric field with peak strength of 75 mV/m (dashed line in Figure 2) leads to Joule heating shown as blue lines. The dashed blue line represents thermal Joule heating, while the solid blue line represents the sum of thermal Joule heating terms and kinetic energy transfer to the thermosphere and thus the actual rate of heating of the neutrals. The discrepancy of both lines highlights the need of considering neutral winds when calculating auroral energy deposition rates. For details, please see Section 2.3.

for the representative case of simulation R15 (see Table 1) at the latitude of maximum incident flux (78° in both hemispheres, see also black marker in Figure 2 ). Fluxes in Figure 3 vary from 0.03 mW/m$^2$ at midnight to 1.3 mW/m$^2$ at 08:00 h Solar Local Time (SLT). These local time variations are consistent with those inferred from Hubble Space Telescope (HST) auroral observations in the UV analysed by Lamy et al. (2009), scaled to our assumed average incident flux of 0.62 mW/m$^2$ in R15 and to different averages for other simulations, as listed in Table 1. The local time dependent incident electron flux is applied in the model with a latitudinal Gaussian weighting function centered around 78° latitude, assuming a FWHM of 1.4°.

In response to particle precipitation and associated ion production rates of Galand et al. (2011), ionospheric plasma densities are locally enhanced, generating an increase in Pedersen and Hall conductances as well as thermal Joule heating. The red curve of Figure 3 shows the resulting Pedersen conductances which range from 5 mho at 00:40 h SLT to 16.7 mho at 08:40 h SLT, with an average of 11.5 mho. Conductances at Saturn are considerably larger than those at Jupiter due to the weaker magnetic field at Saturn. Note the 40 minute SLT (corresponding to ~17 min real time) delay in local time between the maximum in precipitation and that in conductances. This delay, identified also by Galand et al. (2011) at similar magnitude, is associated with photochemical lifetimes in the ionosphere.

The purely thermal component of Joule heating (dashed blue line in Figure 3) responds simultaneously to changes in conductance, with a similar delay to the precipitation flux. However, as discussed in Section 2.3 the actual heating rate in the atmosphere due to Pedersen and Hall currents needs to take into account the neutral wind velocities as well and is shown in Figure 3 as solid blue line. Values range from 13.9 mW/m$^2$ at 00:00 h SLT to 72 mW/m$^2$ at 07:20 h SLT. As a result of westward neutral winds (discussed later) the maximum in Joule heating thus interestingly occurs before the maximum in electron precipitation. This highlights the importance of considering neutral winds when calculating auroral energy deposition rates.

## 3. Simulation results

The simulations R15 and R19 serve as representative cases for average levels of magnetospheric forcing under equinox and solstice conditions, respectively. Comparisons with ionosphere and thermosphere observations are used to validate these simulations. In Section 3.5 we will explore the sensitivity of Saturn's upper atmosphere to changes in magnetosphere forcing.

### *3.1. Ionosphere*

Vertical profiles of noontime ionospheric plasma densities are shown in Figure 4 for the case of R15. The left panel shows profiles in the region of maximum electron precipitation (78°) while the right panel shows densities at the sub-solar point (latitude 0°). Black lines denote the total electron density, blue lines are $H^+$ and red lines $H_3^+$ densities. Not shown individually are profiles of other ions calculated in the model, namely $H_2^+$, $CH_3^+$, $CH_4^+$, $CH_5^+$, $H_20^+$ and $H_30^+$. The hydrocarbon densities populate the bottomside ionosphere, accounting for most of the electron density below around 1000 km altitude.

Calculated electron densities are around a factor of 10 larger in the auroral region than at the equator. Furthermore, the principal ion at the equator is $H_3^+$ while in the auroral region it is $H^+$. This difference is primarily

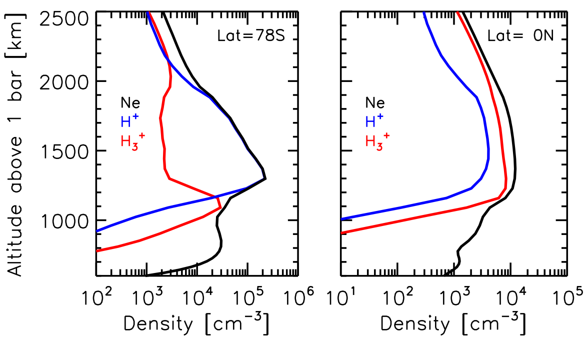


Figure 4: Vertical profiles of plasma densities at noon in Saturn's ionosphere as calculated in simulation R15 (see Table 1) for the auroral region (78° latitude, left panel) and equatorial region (0° latitude, right panel). Black lines denote the total ion (and thereby electron-) densities, blue lines are $H^+$ and red lines $H_3^+$ densities. To eliminate any effects of differing thermal structures at low and high latitude we applied the same (auroral) pressure level to altitude mapping also for the equatorial profiles. In the auroral region which is dominated by electron precipitation, $H^+$ ions constitute the main ionospheric peak, while at low latitudes the additional influx of water (see Figure 1) leads to $H_3^+$ being the dominant ion. The bottomside ionosphere is dominated by hydrocarbon ions ($CH_3^+$, $CH_4^+$, $CH_5^+$, $H_20^+$, $H_30^+$), not shown here individually but only in terms of their total density (black line).

due to differences in neutral composition, specifically the presence of water at equatorial latitudes. As shown in Figure 1, we assume a water influx over the equator and ignore water chemistry poleward of around 20° latitude. $H_2O$ is particularly effective in removing $H^+$ from the ionosphere via the charge-exchange reaction given in Equation 1 which generates an ionosphere richer in molecular ions and depleted in $H^+$. At high latitudes (left panel) the solar zenith angle is too large for solar EUV incidence to produce a substantial ionosphere, and most ion production is due to particle precipitation. Ionisation rates for 10 keV electrons peak in the lower ionosphere near 800 km above the 1 bar level (Galand et al., 2011), explaining the bottomside secondary maximum in electron densities in the left panel. The main ion peak at 78° latitude is despite the large zenith angles a result of solar ionisation. With $H^+$ being the principal ion, chemical loss is sufficiently small for large ion densities to build up despite low production rates (Galand et al., 2011).

Figure 5 shows the peak electron densities in Saturn's ionosphere as a function of latitude. The "plus" and "star" symbols are values observed by the Cassini RSS experiment for dusk and dawn conditions, respectively (Nagy et al., 2006; Kliore et al., 2009). Blue and red lines are calculated peak electron densities from simulations R15 and R19, respectively, for dusk (solid lines) and dusk (dashed) conditions. The RSS observations were made between 2005 and 2008 when Saturn was transitioning from southern hemisphere summer to vernal equinox conditions.

Our calculated values for equinox (blue) and solstice (red) capture the range of observed values, thus validating our simulations and furthermore indicating that the observed trends between 2005 and 2008 can be accounted for by changes in solar ionisation. At low latitudes our calculations reproduce well the observed differences between dusk and dawn densities. This validates our calculated equatorial ion composition shown in Figure 4 (right panel) as the dominance of $H_3^+$ there generates sufficiently short ion recombination times to produce the observed dawn-dusk asymmetry. The general trend of electron densities increasing away from the equator is well captured by our calculations.

To-date radio occultations have not knowingly observed the auroral regions. For clarity, auroral electron density values are not fully captured with the chosen axis range in Figure 5. Calculated peak densities at latitude 78° at dusk/dawn are $2.2\times10^5$ cm$^{-3}$/$2.0\times10^5$ cm$^{-3}$ for the equinox simulation (R15, blue) and for solstice (R19, red) they are $2.4\times10^5$ cm$^{-3}$/$2.2\times10^5$ cm$^{-3}$ in the summer hemisphere

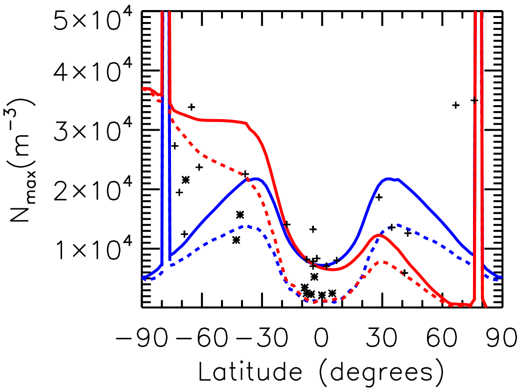


Figure 5: Latitudinal variation of peak electron densities in Saturn's ionosphere, as observed by the Cassini RSS experiment for dusk (plus symbols) and dawn (star symbols) conditions (Nagy et al., 2006; Kliore et al., 2009). Super-imposed are peak electron densities from simulations R15 (blue) and R19 (red) for dusk (solid lines) and dusk (dashed). The red and blue lines at low and mid latitudes encompass the range of peak densities produced by solar EUV radiation at different seasons. Calculated values are consistent with observations which were taken between 2005 and 2008 when Saturn was transitioning from southern hemisphere summer to vernal equinox conditions, indicating that most of the observed trends can be accounted for by solar ionisation. Our calculations reproduce well the observed differences between dusk and dawn densities which are particularly prevalent in the low and mid latitude regions where $H_3^+$ as relatively short-lived ion dominates. To-date no radio occultation observation has knowingly sampled the auroral regions. The dominance of chemical processes over dynamics imply that dynamics are ineffective in redistributing plasma densities outside of the regions of particle precipitation, generating the seen sharp boundaries.

(78°S) and 2.2×10$^5$ cm$^{-3}$/2.0×10$^5$ cm$^{-3}$ in the winter hemisphere (78°N). Thus, seasonal differences in solar ionisation in the auroral region near the terminator amount to no more than around 10% of the local plasma density. This is a direct consequence of the $H^+$ dominance in our calculations at high latitude and the resulting long ion lifetimes.

Despite the longer chemical lifetimes of $H^+$ relative to $H_3^+$, chemistry still dominates over dynamics. As calculated by Moore et al. (2004), the overall chemical lifetime of an ionosphere dominated by $H^+$ is $\tau_C \leq 10^{-2}$ sec. Meridional wind speeds in the auroral region (discussed in Section 3.3) are below 200 m/s, giving an approximate transport time scale of $\tau_u \approx 10^3$ sec, considerably longer than $\tau_C$, implying that the ionosphere of Saturn near the peak is approximately in photochemical equilibrium. Furthermore, the large inclination angles of the **B** field at high latitudes imply primarily vertical redistribution of plasma by horizontal neutral winds. The implication of this is that horizontal thermospheric winds are ineffective in redistributing plasma densities to regions outside of the regions of particle precipitation, giving rise to the sharp boundaries between auroral and non-auroral regions seen in Figure 5.

### *3.2. Thermosphere temperatures*

Diurnally averaged thermospheric temperatures, as calculated in simulation R15, are presented in Figure 6 for the southern hemisphere (with those in the northern hemisphere being identical). We find daily variations of polar temperatures to be less than 5 K and thus virtually negligible, despite the strong diurnal variation of Joule heating (Figure 3). The reasons for this are the long thermal time scales in Saturn's upper atmosphere combined with the fast planetary rotation rate. This justifies discussing diurnally averaged quantities in the following.

Temperatures poleward of 75° latitude above $10^{-5}$ mbar reach between 350–500 K, well within the range of observed high latitude temperatures on Saturn of 400–460 K(Melin et al., 2007; Vervack and Moses, 2012). Thermospheric temperatures poleward of 80° decrease slightly (≤50 K) when moving to higher levels in the atmosphere above $10^{-5}$ mbar. This decrease, as will be shown later, is associated with adiabatic cooling due to atmospheric expansion there. Thus we find the thermosphere to be approximately isothermal above $10^{-5}$ mbar to within ∼50 K, implying that observed of $H_3^+$ temperatures (Stallard et al., 1999; Melin et al., 2007) are almost the same as exospheric temperatures in polar regions on Saturn. This is also confirmed by the similarity of exospheric temperatures inferred from Voyager UVS observations at 82°S of 418±54 K (Vervack and Moses, 2012) to temperatures inferred from ground-based observations of $H_3^+$ IR emissions of 400±50 K (Melin et al., 2007). Our calculated polar temperatures in R15 are thus well in agreement with observations.

At lower latitudes our calculations do not capture observed values well. Figure 6 shows that exospheric temperatures decrease from around 450 K near the pole to around 180 K near the equator. Voyager 2 UVS occultations of $\delta$–Sco suggested an exospheric temperature of 420±30 K near 29.5°N (Smith et al., 1983), while a recent reanalysis of Voyager UVS data inferred a value of 488±14 K (Vervack and Moses, 2012). These and other observations suggest low and mid–latitude exospheric temperatures on Saturn to be of the order of 450 K, roughly twice the value shown in Figure 6 . Our model is presently unable to reproduce observed low and mid–latitude exospheric temperatures on Saturn. This illustrates that magnetospheric energy is not being transported from the polar to the equatorial regions. This is related to Saturn's fast rotation rate and the sub–corotation of the auroral thermosphere, which ultimately generates a meridional wind transporting energy from equator to pole in the deep atmosphere, thus cooling down the equatorial regions (Smith et al., 2007). However, since this study is concerned with polar temperatures only we will defer discussion of the equatorial temperature problem to future investigations.

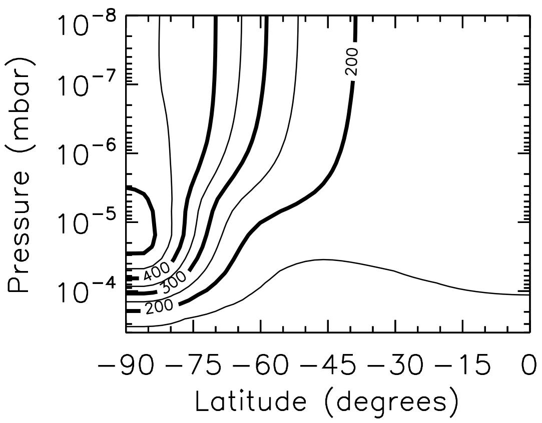


Figure 6: Local time averaged temperatures in Saturn's upper atmosphere, as calculated by the STIM GCM in simulation R15 (see Table 1). Diurnal temperature variations at all latitudes and pressures are below ~6 K and hence negligible. Whilst auroral temperatures are in good agreement with observations, the low and mid latitude temperatures are considerably colder, highlighting our current lack of understanding of the energy balance in Saturn's thermosphere at low and mid latitudes, commonly referred to as the "Energy crisis", which is similarly prevalent for Jupiter.

### *3.3. Dynamics and composition*

As previously discussed, auroral forcing not only controls polar thermospheric temperatures but via ion drag and pressure gradients also has a profound influence on thermospheric winds which we will discuss in the following. Figure 7 shows vertical profiles of diurnally averaged meridional (left panel), zonal (middle panel) and vertical winds (right panel). Local time variations in all wind components above the $10^{-5}$ mbar level are below 1%, making the display of diurnally averaged quantities there plausible. In the deeper atmosphere at and below $10^-5$ mbar however the ion-neutral momentum coupling is more efficient and causes considerable local time variations in neutral wind velocities. There the displayed diurnal averages do not fully capture the wind behaviour, which we will discuss separately below.

Figure 7 displays wind velocities for a near–auroral latitude of 82° (solid line), high mid–latitude (dashed) and low mid latitude (dotted). Velocities are defined as positive southward, eastward and upward. In the region poleward of the auroral oval (solid line) meridional

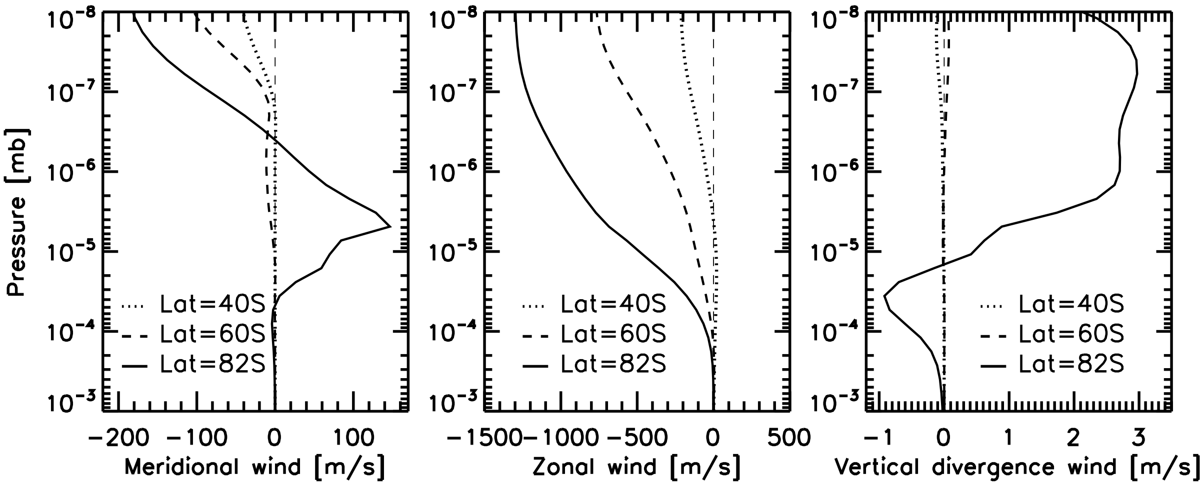


Figure 7: Vertical profiles of meridional (left panel), zonal (middle panel) and vertical (right panel) thermosphere winds as calculated in simulation R15. Values are shown for near–auroral latitude of 82° (solid line), high mid–latitude (dashed) and low mid latitude (dotted). Velocities are defined as positive southward, eastward and upward. The polar forcing in our simulations generates strong westward (sub-corotating) winds and considerable upwelling above the ionospheric peak (near $10^{-5}$ mbar and downwelling below. The forcing generates southward (poleward) winds near the ionospheric peak which result from Coriolis accelerations of the strong westward jets. At higher altitudes the pressure gradients drive meridional winds northward (equatorward). Polar forcing causes the entire atmosphere to sub-corotate, though at a decreasing rate towards the equator. At 60°S (dashed line, middle panel) the thermosphere near the ionospheric peak co-rotates with the planet at ~98%.

winds near $10^{-5}$ mbar are directed poleward, away from the region of Joule heating. At levels above $4{\times}10^{-5}$ mbar they reverse direction and blow away from the pole, towards the equator. Equatorward winds in the upper thermosphere persist towards mid–latitudes as well (dashed and dotted lines), but decreasing from around 200 m/s near the pole to around 40 m/s at mid–latitudes and zero at the equator (not shown). The wind pattern is symmetric in both hemispheres and thus indicates a global meridional circulation cell driven at polar latitudes and consisting of a large pole–to–equator circulation in the upper thermosphere followed by a return flow at lower levels.

The polar forcing via ion drag generates strong westward (sub-corotating) winds at peak velocities of around 1300 m/s near 82° latitude and ~1600 m/s near 78° (not shown). In order to relate zonal wind velocities near the ionospheric peak to the degree of corotation of the upper atmosphere, Figure 8 shows latitudinal profiles of the atmospheric angular velocity relative to Saturn's rotational velocity, $\omega/\Omega_S$. The solid black line displays the magnetospheric plasma angular velocity of Cowley et al. (2004) from which the electric field used in our simulations (Figure 2) was derived. The solid blue line is the atmosphere's diurnally averaged angular velocity near the ionospheric peak.

We see from the solid blue line in Figure 8 that the magnetospheric sub–corotation via electric fields mapped into the upper atmosphere is related to sub–corotation of the upper atmosphere with $\omega/\Omega_S \approx 0.45$ near 78° latitude in simulation R15 (high precipitation). The magnitude of $\omega/\Omega_S$ is affected by the conductivity of the ionosphere. In simulation R6 (low precipitation, dashed line), the peak incident electron flux is around 20% the value of R15, resulting in maximum Pedersen conductances of 1.4 mho in R6 (versus 11.2 mho in R15) and $\omega/\Omega_S \approx 0.60$ in R6. Thus, the lower conductances in R6 lead to a lesser degree of sub–corotation in the atmosphere. At reduced conductances angular momentum is less efficiently transferred from the upper atmosphere to the magnetosphere.

The right panel of Figure 7 shows vertical divergence winds in Saturn's upper atmosphere. These are wind velocities generates by the divergence of horizontal winds and represent the motion of atmospheric gases relative to levels of fixed pressure (rather than simple expansion/contraction of the atmosphere) (Rishbeth and Müller-Wodarg, 1999). In our simulation upwelling occurs above the ionospheric peak (near $10^{-5}$ mbar) and downwelling below.

Vertical divergence generate composition changes in the atmosphere relative to pressure levels, which are

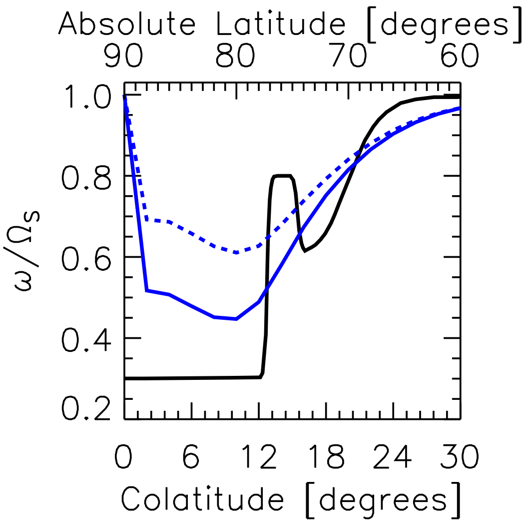


Figure 8: Angular velocity of plasma in Saturn's magnetosphere (black line), as assumed by Cowley et al. (2004) and mapped into the polar atmosphere. Using a magnetospheric current model, Cowley et al. (2004) inferred from this profile the current densities and electric field that is mapped into the ionosphere and used as polar forcing in our simulations (shown as solid line in Figure 2). Blue lines denote the thermospheric response to this polar forcing, showing the thermosphere's angular velocity near the peak ionospheric density in simulations R6 and R15 (dashed and solid lines, respectively). The stronger sub-corotation in R15 (solid line) is due to the higher conductances (11.2 mho (R15) versus 1.4 mho (R6)) which are caused by the enhanced particle flux (0.62 mW/m$^2$ (R15) versus 0.12 mW/m$^2$ (R6)). The more conducting ionosphere in R15 can more efficiently transfer angular momentum to the magnetosphere.

presented in Figure 9 for simulation R15. Solid lines represent mole fractions of neutral gases at 78° and dashed curves are mole fractions over the equator. The high latitude upwelling identified in Figure 7 enhances mole fractions of heavier gases (He, blue) at a given pressure level and reduces those of lighter gases (H, black). We see wind-induced composition changes only above the $10^{-5}$ mbar pressure level and not below since eddy mixing is the dominant process transporting gases below the homopause (near $10^{-4}$ mbar in our model) and vertical gradients of mixing ratios are small there. Hence the auroral $CH_4$ profile (green) is identical to that at the equator. We note that $H_2O$ is present only over the equator since we specified a topside influx of water which peaked over the equator (Figure 1), so densities at auroral latitudes are negligible. Not shown in Figure 9 is the dominant gas ($H_2$) which is given by $(1 - \sum_i X_i)$, $X_i$ being the mole fractions of the gases shown in the figure. $H_2$ mole fractions are close to 1 and, being the principal gas throughout the domain examined, are little affected by vertical motion in the atmosphere.

One important aspect of thermospheric dynamics is the overall transport of gases which they induce. To examine this, Figure 10 displays the neutral gas mass flux in Saturn's upper atmosphere which results from neutral wind transport of gases in simulation R15. The figure displays height– and longitude–integrated mass fluxes from meridional winds (solid line), zonal winds (dotted) and vertical divergence winds (dashed). Mass fluxes particularly emphasise the importance of dynamics in the lower thermosphere (below the $10^{-5}$ mbar pressure level) where wind velocities are smaller (see Fig. 7) but mass densities considerably larger than in the upper thermosphere.

We see from the solid line in Figure 10 that considerable meridional transport occurs in the auroral region, transporting material away from the sub-auroral thermosphere (76–78°) primarily into the polar cap region (poleward of 78°) and to a smaller extent equatorward as well. Vertical transport ensures continuity throughout, supplying mass from the deeper atmosphere into the 76–78° latitude region and transporting material downward in the polar cap area. Note that the downward wind velocities seen in the right panel of Figure 7 are the dominant cause of this mass flux in the polar cap despite, by far offsetting the upwelling that is seen at higher levels where the atmospheric densities are considerably lower. Similarly, the meridional wind velocities in Figure 7 (left panel) near the ionospheric peak are responsible for the bulk of meridional mass transport, rather than the high–altitude winds. Zonal mass fluxes (dotted line in Figure 10) are negligible (despite the larger zonal

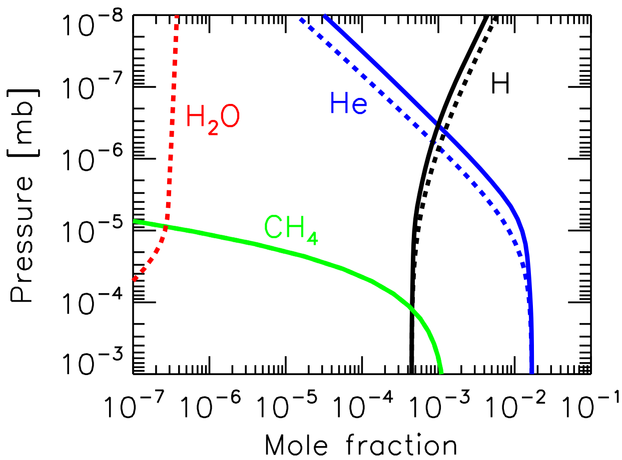


Figure 9: Vertical profile of neutral gas mole fractions in simulation R15. Solid lines denote mixing ratios at auroral latitude (78°) and dashed lines are for equatorial latitude (0°). Not shown is the principal gas, $H_2$, which has a mole fraction close to 1. No $H_2O$ is present at auroral latitudes since we specify a low latitude topside influx of $H_2O$ only. Mole fractions of $CH_4$ are almost identical at both latitudes. Upwelling over the auroral region causes the heavier main gas in the upper thermosphere (He) to be enhanced and the lighter gas (H) to be depleted.

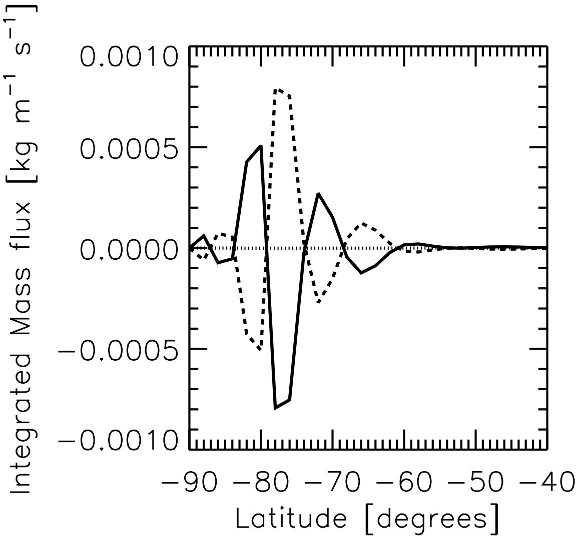


Figure 10: Neutral gas mass flux in Saturn's upper atmosphere which results from neutral wind transport of gases. The plotted quantities are height– and longitude–integrated mass fluxes due to meridional transport (solid line), zonal transport (dotted) and vertical transport (dashed) in simulation R15.

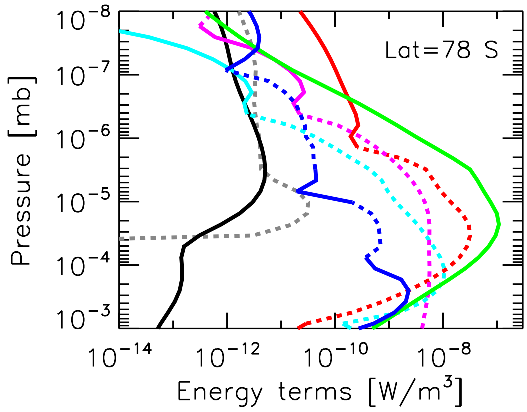


Figure 11: Diurnally averaged energy terms in the auroral region (78°) as calculated in simulation R15. Solid lines denote energy sources and dashed lines are energy sinks. Dominant energy source is Joule heating (green), as given by Equation 11. Solar EUV heating (black) plays a minor role only. Vertical molecular conduction (blue) acts mostly as an energy sink in the upper thermosphere and energy conducted away from there is deposited in the lower thermosphere below around $10^{-4}$ mbar where it acts as a key energy source. Horizontal advection (red) provides the main energy sink in the region of peak heating, primarily driven by meridional winds transporting the energy equatorward. In the upper thermosphere energy is transported from the hotter polar region towards the equator, so advection acts as an energy source near 78°. Vertical upward winds provide a further key energy sink in the region via adiabatic cooling (magenta) and vertical advection (cyan). Cooling by $H_3^+$ IR emissions (grey) plays a minor role only on Saturn, unlike Jupiter. The figure illustrates the importance of thermospheric dynamics in determining the auroral energy balance.

wind velocities) since zonal mass density gradients are negligible.

### *3.4. Energy balance*

We now examine the thermospheric energy balance in the auroral region. Figure 11 shows diurnally averaged energy terms at (78°) from simulation R15. Solid lines denote energy sources and dashed lines are energy sinks. The dominant energy source is total Joule heating (green) which includes the contribution from thermospheric neutral winds according to equation 11. As expected for Saturn, and polar regions in particular, solar EUV heating (black) plays only a minor role. Vertical molecular conduction (blue) acts mostly as an energy sink in the upper thermosphere, conducting the energy down into the lower thermosphere (below around $10^{-4}$ mbar) where it is deposited and represents a key energy source. Horizontal advection (red) provides the main energy sink in the region of peak heating, due to meridional winds transporting the energy equatorward. In the upper thermosphere energy is transported from the hotter polar region towards the equator, so advection acts as an energy source near 78°. Vertical upward winds provide a further key energy sink in the region via adiabatic cooling (magenta) and vertical advection (cyan). Cooling by $H_3^+$ IR emissions (grey) plays a minor role only on Saturn, unlike what is found on Jupiter (Miller et al., 2010; Bougher et al., 2005; Achilleos et al., 1998).

Our calculations illustrate that dynamics play a key role in controlling the energy balance on Saturn, particularly in the auroral region. The mass flux of Figure 10 can be regarded as representing the bulk energy flow in the atmosphere and thus ultimately also helps understand the thermal structure (Fig. 6), including the cold equatorial temperatures. As can be inferred from Figure 10, auroral (magnetospheric) energy is transported by meridional winds primarily into the polar cap region, explaining the temperature maximum there (Figure 6). Equatorward energy transport is negligible despite the upper thermosphere pole–to–equator winds (left panel of Fig. 7) since those occur in a region where the atmospheric density is considerably lower and hence energetically insignificant.

### 3.5. Sensitivity to magnetospheric forcing parameters

Having focused so far on simulations for specific high latitude magnetospheric forcing conditions, we will in the following explore the parameter space of possible electric field and particle precipitation fluxes to examine the atmospheric sensitivity to magnetospheric forcing. Diurnally averaged temperatures at the peak ionospheric density level ($10^{-5}$ mbar) and latitude 78° from simulations R1–R18 (Table 1) are shown in Figure 12 as a function of 10 keV electron energy flux and peak electric field strength. As previously discussed (and shown for R15 in Figure 6) the temperatures may be regarded as representing to within ±40 K exospheric and $H_3^+$ temperatures. While the values are based on equinox simulations, we found seasonal differences to be insignificant, generating temperature changes of ≤10 K. High latitude temperatures in Saturn's upper atmosphere published to–date have values below ~460 K (Melin et al., 2007; Vervack and Moses, 2012), but recent unpublished observations of polar temperatures by the Cassini Visual Imaging Spectrometer (VIMS) instrument have inferred $H_3^+$ temperatures reaching ~540 K (T. Stallard, *pers. comm.*, 2012). The yellow line in Figure 12 shows the 540 K contour line and thus roughly separates values of polar temperatures that have been observed on Saturn (T≤540 K) from those that as yet have not been observed (T>540 K).

The general trend we find in our simulations is that polar temperatures increase with electric field strength and electron energy flux. At a given energy flux of 1.2 mW/m$^2$ the temperatures increase from 450 K to 850 K (by a factor of ~1.9) when increasing the electric field strength from 80 mV/m to 100 mV/m. At the lower energy flux of 0.2 mW/m$^2$ the temperature changes from 450 to 550 K, or by a factor of ~1.2. Thus, temperatures are less responsive to electric field variations when ionospheric conductivities (at lower energy fluxes) are smaller. A wider implication of this finding is that Saturn's thermosphere responds less efficiently to magnetospheric input bursts when it is less ionised and more efficiently when in a more ionised state, either due to enhanced electron energy fluxes or due to enhanced solar EUV ionisation (at solar maximum). For the case of magnetic storms, thus, Saturn's upper atmosphere responds stronger to variations in magnetic field if they were preceded by enhancements in precipitating electron fluxes.

For a fixed value of electric field strength the temperature changes with electron energy flux depend on the electric field strength. For a moderate field strength of

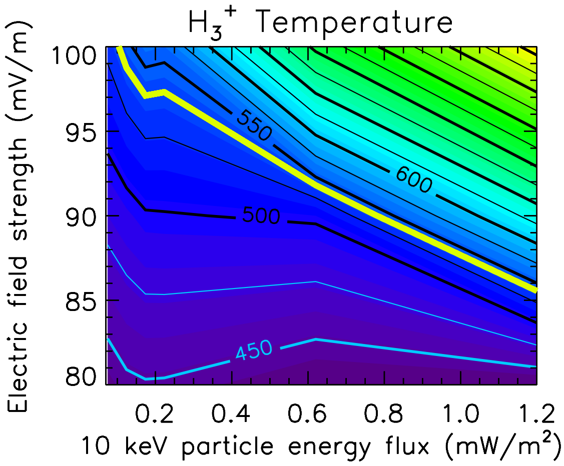


Figure 12: Diurnally averaged thermosphere temperatures (in units of Kelvin) in the auroral region (78°) as a function of magnetospheric forcing parameters, as obtained from simulations R1–R18 (see Table 1). Temperatures are from near the ionospheric peak (~$10^{-5}$ mbar), but are almost identical (within ±40 K) to exospheric temperatures, as can be seen also from Figure 6 for the particular case of R15. Diurnal temperature variations are below 5 K. While the values in the figure were obtained for equinox conditions, the effect of season is around 10 K only and thus negligible. The yellow line shows the 540 K contour and approximately separates regions of polar temperatures that have been observed on Saturn (T≤540 K) from those that as yet have not been observed (T>540 K). Thus the figure illustrates not only the sensitivity of polar temperatures to magnetospheric forcing, but limits the parameter space of possible combinations of electric field strength and 10 keV electron energy flux. A magnetospheric electric field of ~100 mV/m mapped into the ionosphere would in combination with a 10 keV electron flux of 1.0 mW/m$^2$ would generate thermosphere temperatures of ~800 K, well in excess of observed values, and thus cannot occur for extended periods.

80 mV/m the temperature is virtually constant when increasing the energy flux from 0.2 to 1.2 mW/m$^2$, while at E=100 mV/m they increase from ~550 to 850 K. So, we can make the more general statement that Saturn's thermospheric temperatures are more responsive to changes in electric field strength than incident energetic electron flux.

A further finding from Figure 12 relates to the limitations on combinations of electric field strength and 10 keV electron energy flux that it implies. The bottom left half of the figure (below the yellow line) represents a range of observed temperatures on Saturn and thus of "allowed" combinations of electric field strength and particle flux. In contrast, combinations of these two magnetospheric forcing parameters that result in temperatures in the top right part of the figure (above the yellow line) need to be treated with caution as they produce temperatures in excess of observations. A magnetospheric electric field of ~100 mV/m mapped into the ionosphere would in combination with at 10 keV electron flux of 1 mW/m$^2$ generate thermosphere temperatures of ~800 K, well in excess of observed values. This combination of values cannot thus occur for extended periods on Saturn.

Most observational constraints available for Saturn's polar temperatures derive from $H_3^+$ emissions, which in turn result from a combination of two parameters that cannot unambiguously be determined from the emission flux alone, namely the temperature and $H_3^+$ column density. Figure 13 shows diurnally averaged $H_3^+$ column densities in the auroral region (78°) as a function of the same parameters and from the same simulations as Figure 12. We find, as expected, that column densities vary primarily as a function of the assumed 10 keV electron energy flux which directly causes the ionisation. At E=80 mV/m column densities increase from 2.0–3.6×10$^{15}$ m$^{-2}$, illustrating that the column densities vary relatively weakly with 10 keV electron flux. The stronger increase of column density for larger electric fields (at 100 mV/m from 2.0 to 5.0×10$^{15}$ m$^{-2}$) is less related to enhanced ion production than to a rise in thermospheric temperature (see Figure 12). We integrate a column between pressure levels 4×10$^{-3}$ to 3×10$^{-9}$ mbar which range from 500 to ~2500 km for an exospheric temperature of $T_{exo}$=450 K and from 500 to ~4000 km for an exospheric temperature of $T_{exo}$=850 K. As a result, the column densities as a result of thermal expansion alone increase by around 1.6 at E=100 mV/m. Thermal expansion also causes the increase in column density with electric field strength for any given value of electron flux. Combining Figures 12 and 13 allows calculating $H_3^+$ emissivities and thus a more direct com-

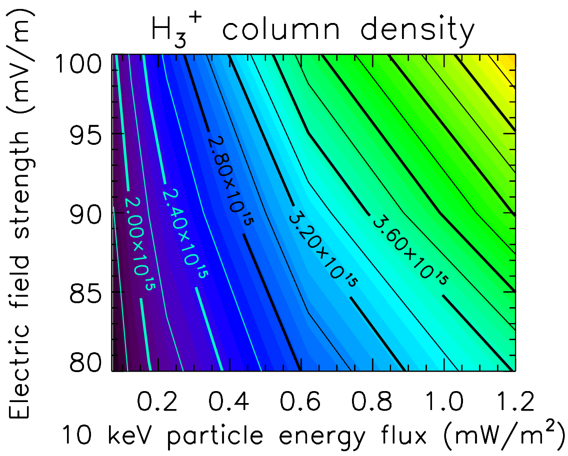


Figure 13: Diurnally averaged $H_3^+$ column densities (in units of m$^{-2}$) in the auroral region (78°) as a function of magnetospheric forcing parameters, as obtained from simulations R1–R18 (see Table 1). The column densities vary primarily as a function of the assumed 10 keV electron energy flux. The increases in column density with electric field strength at a fixed electron energy flux is caused by the temperature increase (Figure 12) and associated expansion of the atmosphere, which increases the column height within a given range of pressures.

parison with $H_3^+$ observations which may affect the exact shape of the yellow separation line in Figure 12.

## 4. Discussion and Conclusions

Our simulations over a range of magnetospheric forcing parameters and seasons successfully reproduce observed ionospheric densities and high latitude temperatures. Analysis of the simulations gives a basic understanding of the processes that control the dynamics and energy balance in Saturn's high latitude coupled thermosphere and ionosphere. We have seen that magnetospheric forcing is responsible for the bulk of energy and mass transport in the atmosphere, driving bulk atmospheric internal mass, momentum and energy redistribution. Thermospheric winds driven by ion drag and Joule–heating induced pressure gradients play a crucial role in determining the high latitude energy balance and, more far–reaching, in controlling the global distribution – or lack thereof – of magnetospheric energy deposited at high latitudes. Under the range of conditions examined in this study the general pattern was consistently that of polar energy being "trapped" at high latitudes and not propagating equatorward. This behaviour results from poleward energy transport in the lower thermosphere, a response previously reported by Smith et al. (2007) with same conclusions.

We find the sub–corotation of the high latitude thermosphere which results from magnetospheric plasma sub–corotation and associated electric fields to be a relatively localised phenomenon which does not extend equatorward of around 65° latitude, beyond which the upper atmosphere is in near co–rotation with the planet. However, our results are a direct consequence of the assumed magnetospheric plasma velocity profile (and high latitude electric field), so any future revisions of our assumed profile (Figure 8, black line) in the context of Cassini plasma observations in Saturn's magnetosphere will similarly affect our results in terms of wind velocities, degree atmospheric co-rotation and thermal structure.

Our simulations demonstrate that dynamical coupling to Saturn's ionosphere via ion drag (Equation 3) critically controls the pattern of thermospheric winds at high latitudes. Radio Science observations of Saturn's ionosphere over the past decades (Atreya et al., 1984; Nagy et al., 2006; Kliore et al., 2009) have revealed a high degree of variability. Our simulations successfully reproduce the overall latitudinal trend of peak electron densities (Figure 5), suggesting that the overall neutral–ion collisional coupling calculations are likely to be realistic in our model as well, but in looking at a steady state situation we have not considered the effects of a variable ionosphere. These may have an influence on thermospheric dynamics as well, particularly near the ionospheric peak where we found horizontal winds to vary greatly with local time, responding directly to auroral forcing. Forthcoming studies will examine variability in Saturn's thermosphere-ionosphere system.

In our calculations the dominant ion at the ionospheric peak varies with latitude. At mid and high latitudes including the auroral region $H^+$ is the principal ion, while at low latitudes it is $H_3^+$ – a consequence of our assumed influx of $H_2O$ there. The shorter chemical lifetimes of $H_3^+$ give rise to dawn–dusk asymmetries which have been observed near the equator and are captured remarkably well in our calculations, supporting the notion of an influx of $H_2O$, most likely from Enceladus. As a result of the dominance of $H^+$ away from the equator (outside of the region of $H_2O$ influx), chemical lifetimes there increase, thus reducing the chemical sinks and leading to a build–up of ionisation, despite the higher zenith angles at mid latitudes and reduced solar photo–ionisation. The increase of peak ion density away from the equator is entirely consistent with observations by Cassini RSS (Nagy et al., 2006; Kliore et al., 2009; Moore et al., 2010). At auroral latitudes the main ion production is due to particle ionisation from incident electrons. Despite strong thermospheric winds at high latitudes we find photochemical equilibrium to hold remarkably well throughout, reducing any role of thermospheric horizontal winds in redistributing ionisation and giving rise to sharp boundaries in ion densities between the auroral and non–auroral regions. Such sharp boundaries may in practice affect the propagation of radio waves through the atmosphere, which may be of relevance during radio occultation measurements at auroral latitudes. To–date no Radio Science observations have knowingly the vertical structure of the auroral ionosphere, so our simulations can only be validated there using available $H_3^+$ IR observations.

Our calculations assumed fixed electrical fields at high latitudes and we did not change these in response to changing conditions in the atmosphere. In principle, enhanced conductivity would lead to more efficient transport of angular momentum from atmosphere to magnetosphere, thus reducing the departure from co–rotation there and the generated electric field which maps into the upper atmosphere. By keeping the electric field constant we assume a continuous supply of material into Saturn's magnetosphere which will generate a continuos lag from co–rotation. This aspect of coupling from atmosphere to magnetosphere is not considered in our model. Smith et al. (2008) developed a simple model of Saturn's coupled thermosphere–ionosphere–magnetosphere which considered the feedback from atmosphere to magnetosphere, but assumed a constant ionosphere which did not change in response to thermospheric and magnetospheric conditions. The effects of the feedback to the magnetosphere did however have little influence on the atmosphere behaviour, which is the focus of our study here. Future developments, though should ideally focus on an upper atmosphere model such as STIM considering the full feedback to the magnetosphere as well, as addressed by Smith et al. (2008), thereby providing the possibility of using additional observational constraints from the magnetosphere to validate the calculations.

According to the simulations of our study magnetospheric energy cannot explain the observed thermospheric temperatures at low and mid latitudes. While the "energy crisis" is not focus of this study, this result emphasises the need to consider thermospheric winds when examining the energy balance, rendering problematic the use of 1–D models which by nature cannot account for winds.

In exploring the parameter space of two magnetospheric forcing parameters, electric field strength and incident particle flux, we have demonstrated that the thermosphere observations (in particular, $H_3^+$ IR emissions) need to be considered when examining Saturn's magnetosphere. Sub–corotation of plasma there will have a direct effect on atmospheric temperatures and dynamics, and a multi–instrument analysis is necessary to ensure that any magnetospheric observations are consistent with those of the atmosphere. In applying STIM to an examination of this coupling we have shown that multi-dimensional time–dependent models of the coupled thermosphere–ionosphere–magnetosphere are a powerful and important tool in understanding the exchange of energy and momentum between the regions and in ultimately understanding the global energy balance of Gas Giants within and beyond our solar system.

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