An initial study into the long-term influence of solar wind dynamic pressure on Jupiter's thermosphere

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Key Points:

- 100 days of variability in solar wind dynamic pressure leads to mean thermospheric temperatures increasing by ~7 K
- Meridional neutral winds are most strongly influenced by magnetospheric reconfigurations
- Strong equatorwards meridional winds transport heat to lower latitudes but they are short-lived

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Abstract

Jupiter's thermosphere is ∼700 K hotter than expected if it were heated only by solar Extreme Ultraviolet (EUV) radiation. Other, more effective heat sources are therefore necessary to explain the high observed temperatures ≥900 K. It has been suggested that heating resulting from the atmospheric interaction with Jupiter's dynamic magnetosphere could account for the excess heat required. However to date, no numerical models have been successful at reproducing Jupiter's hot thermosphere without invoking essentially ad-hoc heating mechanisms. Work presented in Yates et al., 2014 emphasized the importance of incorporating time-dependence in magnetosphere-ionosphere-thermosphere coupling when simulating this aspect of the Jovian system. We extend their model (for a single magnetospheric compression or expansion) to simulate the response of thermospheric heating to multiple shocks and rarefactions in the solar wind for the first time. We employ a configurable magnetosphere model coupled to an azimuthally symmetric general circulation model. We compare the response of thermospheric temperatures to these consecutive magnetospheric reconfigurations over a period of 100 Jovian rotations. We find that the thermal structure of our model thermosphere does not respond significantly to such a prolonged period of magnetospheric reconfigurations. Thermospheric mean temperatures increase by a maximum of ∼15 K throughout our simulation. The high-latitude and high-altitude thermosphere is most influenced by magnetospheric reconfigurations. While this simulation shows that magnetospheric reconfigurations can heat the thermosphere it also shows the need to consider a more realistic representation of the coupled Jovian system as well as alternate sources of heating not dependent on the magnetosphere.

1 Introduction

The upper atmospheres of Jupiter and the other gas giants are much hotter than would be expected if they were heated solely by solar Extreme UltraViolet (EUV) radiation. Jupiter's upper atmosphere is ∼700 K hotter than theoretical modelling predicts [*Strobel and Smith*, 1973; *Seiff et al.*, 1998; *Yelle and Miller*, 2004]. This is known as the gas giant 'energy crisis' and has eluded explanation for many decades. Many attempts have been made to explain Jupiter's high atmospheric temperatures; from breaking of gravity and acoustic waves [*Young et al.*, 1997; *Matcheva and Strobel*, 1999; *Hickey et al.*, 2000; *Schubert et al.*, 2003] to auroral particle precipitation [*Waite et al.*, 1983; *Grodent et al.*, 2001], Joule heating [*Waite et al.*, 1983; *Smith et al.*, 2005; *Millward et al.*, 2005] and ion drag [*Miller et al.*, 2000; *Smith et al.*, 2005; *Millward et al.*, 2005]. Atmospheric gravity waves are thought to have been observed by the Galileo probe during its descent into Jupiter's equatorial atmosphere. Work by *Young et al.* [1997] claims that the observed gravity waves are capable of accounting for Jupiter's high temperatures but later studies by *Matcheva and Strobel* [1999] and *Hickey et al.* [2000] show that the observed waves not only heat the upper atmosphere, they also cool it and the resultant net heating is too small to explain the high observed temperatures. *Schubert et al.* [2003] found that acoustic wave breaking could potentially account for Jupiter's high temperatures but they are poorly constrained by observations at Jupiter.

Auroral particle precipitation, Joule heating and ion drag result from the interaction between Jupiter's strong magnetosphere and its upper atmosphere, which consists of the neutral thermosphere and ionosphere. There has been much recent work on Jovian magnetosphere-ionosphere-thermosphere (MIT) coupling which represent the thermosphere with a general circulation model (GCM) and couple this to a magnetosphere-ionosphere (MI) model or simplified magnetospheric input[*Achilleos et al.*, 1998, 2001; *Millward et al.*, 2005; *Bougher et al.*, 2005; *Majeed et al.*, 2009, 2016; *Smith and Aylward*, 2009; *Tao et al.*, 2009, 2014; *Yates et al.*, 2012, 2014; *Ray et al.*, 2015].

Smith and Aylward [2009] coupled a simplified model of Jupiter's magnetosphere to a general circulation model (GCM) of Jupiter's thermosphere. The model was capable of self-consistently including angular momentum transfer between the magnetosphere and thermosphere. *Smith and Aylward* [2009], similarly to the study by *Smith and Aylward* [2008] for Saturn, found that meridional advection of momentum is the dominant mechanism by which angular momentum is transferred to the high-latitude thermosphere. Furthermore, the presence of the 'ion drag fridge' effect means that heat from the magnetospheric interaction is trapped at high latitudes while low latitudes remain cold [*Smith et al.*, 2007]. In order to reproduce the observed temperatures, *Smith and Aylward* [2009] included an additional component to Joule heating created by rapidly fluctuating low-latitude electric fields. Other coupled MIT models presenting steady-state conditions are those of *Tao et al.* [2009] and *Bougher et al.* [2005]; *Majeed et al.* [2009, 2016]. The *Tao et al.* [2009] study used an axisymmetric coupled model similar to the *Smith and Aylward* [2009] model, but it includes a more realistic ionosphere and equatorial heating by acoustic waves based on the works of *Schubert et al.* [2003]. The inclusion of these waves reproduces equatorial temperatures similar to those observed by the Galileo probe. The *Bougher et al.* [2005]; *Majeed et al.* [2009, 2016] models include a full three-dimensional GCM and are also able to reproduce the high observed thermospheric temperatures via Joule heating. The above models reproduce the observed temperatures by including ad-hoc low latitude heating, poorly constrained wave heating or order-of-magnitude larger Pedersen conductances . While these may one day be constrained to high degrees they are currently not supported by observational evidence and so the gas giant energy crisis remains unanswered.

Steady-state solar wind variability was investigated by *Yates et al.* [2012] by adapting the *Smith and Aylward* [2009] model. They found that Joule heating and ion drag energy increased by ~190% between compressed (45 R_J; one Jovian radius is 71492 km) and expanded (85 R_J) configurations. The power used to accelerate magnetospheric plasma increased slightly from compressed to averaged (65 R_J) configurations and subsequently decreased for an expanded magnetosphere. Most recently, *Ray et al.* [2015] were the first to investigate the de-coupling between thermospheric and magnetospheric flows by including field-aligned potentials (FAPs) in a MIT model by combing the works of *Ray et al.* [2010, 2012] with the Jovian GCM of *Smith and Aylward* [2009]. *Ray et al.* [2015] found that self-consistently including FAPs into a coupled MIT model does not significantly influence the Jovian thermospheric structure and dynamics. Temperature variations between simulations with FAPs and previous simulations without FAPs show ~1−2% changes in temperatures in high latitude regions with small changes in neutral flows. These authors show that changes in the Pedersen conductance between the simulations have a greater effect on the neutral dynamics than rotational decoupling between the ionosphere and magnetosphere.

Most gas giant MI/MIT coupling studies consider the system under equilibrium conditions when in reality planetary systems are constantly perturbed. At Jupiter, two important and time-dependent drivers of magnetospheric dynamics which effect the atmosphere are the solar wind and Io's volcanism. The amount of plasma in Jupiter's magnetosphere is dependent on the volcanic activity on Io (e.g. *Yoshikawa et al.* [2017]) and is the focus of future studies. The dynamic pressure of the solar wind often has order-of-magnitude rapid variations which act to either compress or expand the Jovian magnetosphere . *Yates et al.* [2014] investigated the influence of order-of-magnitude rapid (≤3 hours) variations in solar wind dynamic pressure on Jupiter's thermosphere. Similarly to *Cowley and Bunce* [2003a,b]; *Cowley et al.* [2007], *Yates et al.* [2014] found that magnetospheric compressions cause the super-corotation of magnetospheric plasma which reverses the flow of currents, angular momentum and energy between the atmosphere and magnetosphere. Expansions cause an increase in the degree of sub-corotation of magnetospheric plasma but do not alter the steady-state flow of energy and angular momentum (i.e. from atmosphere to magnetosphere). From a thermospheric perspective, rapid magnetospheric reconfigurations (±35 R_J) lead to an increase in high-latitude neutral temperatures (25−50 K) partly due to Joule heating. Expansions result in a factor-of-five increase in the energy dissipated by Joule heating and ion drag in the model thermosphere, and used to accelerate magnetospheric plasma. Compressions lead to an increase in Joule heating and a decrease in ion drag. Compressions also significantly increase equatorward winds capable of transporting heating from the magnetospheric interaction from higher to lower latitudes.

Another recent study focusing on the temporal variability of the Jovian thermosphere is *Tao et al.* [2014]. Here, Tao et al., investigated how Jupiter's thermosphere-ionosphere responded to variability in the solar EUV flux on both long and short timescales. *Tao et al.* [2014] found a positive correlation between long-term solar EUV flux and Jovian thermospheric temperatures and velocities. The authors propose that increases in solar EUV lead to increases in the degree of magnetospheric plasma corotation and field-aligned currents. For shorter-term (order 20 Jovian rotations) variability in solar EUV flux, *Tao et al.* [2014] find that temperatures and winds at mid-latitudes increase as the EUV flux increases and then later due to the propagation of energy from auroral latitudes where Joule heating is enhanced.

There are few remote observations of gas giant upper atmospheres and even fewer are in-situ measurements. MIT modellers use these observations to constrain and validate simulation outputs. The H_3^+ ion is the major constituent of the Jovian and Kronian ionopsheres and, due to its relatively long lifetime and bright auroral Infrared (IR) emission, it can act as a tracer of ionospheric dynamics and provide estimates for the temperature of the thermospheric neutrals (e.g. *Drossart et al.* [1989]; *Miller et al.* [1990]; *Drossart et al.* [1993]; *Lam et al.* [1997]; *Stallard et al.* [2001, 2002]; *Lystrup et al.* [2008]). UV and IR emission from H_2 can also be used to determine ionospheric and neutral thermospheric temperatures (see *Yelle et al.* [1996], *Kita et al.* [2018] and references therein). Neutral temperatures determined from remote observations are of similar order to in-situ Galileo probe measurements near Jupiter's equator [*Seiff et al.*, 1998]. *Melin et al.* [2006] analysed an auroral heating event observed by *Stallard et al.* [2001, 2002] which resulted in an ionospheric temperature increase from 940 K to 1065 K over 3 days (September 8 to 11, 1998). They found that heating from auroral particle precipitation could not account for the increase in temperature but that a combined estimate of ion drag and Joule heating rates between the 3 days (67 to $277 \mathrm{mW\,m^{-2}}$) was sufficient to explain the observations. Cooling rates by hydrocarbons and H_3^+ emission were also found to increase during this event but to a much lesser extent (~20% of the determined heating rates) suggesting that the thermosphere would be unlikely to return to its initial temperature state before the arrival of a subsequent heating event. This led *Melin et al.* [2006] to postulate that such heating events could increase equatorward winds, transporting more thermal energy from the auroral regions to lower latitudes as proposed by *Waite et al.* [1983].

In this study, we use the Jovian Axisymmetric Simulator, with Magnetosphere, Ionosphere and Neutrals (JASMIN) model [*Smith and Aylward*, 2009; *Yates et al.*, 2014] to present the first simulation investigating the influence of long-term solar wind variability on Jupiter's thermosphere. We employ almost the same model setup as in *Yates et al.* [2014] but now simulate the thermosphere's response to 100 magnetospheric reconfigurations determined from PIONEER 10/11 observations upstream of Jupiter. In section 2 we described the coupled model employed here and the changes compared to previous simulations. Our simulation results and discussion are presented in sections 3 and 4. We conclude in section 5.

2 Model description

2.1 Coupled Magnetosphere-Ionosphere-Thermosphere model

The coupled numerical model employed for this study is based on the model described by *Yates et al.* [2014]. As such, we give only a brief description here to describe the differences between the model employed here and that discussed in *Yates et al.* [2014].

The thermosphere model employed here remains unchanged from *Yates et al.* [2014]. It is a general circulation model (GCM) solving the Navier-Stokes equations of energy and momentum and the continuity equation using explicit time integration [*Müller-Wodarg et al.*, 2006]. The model solves the three-dimensional equations assuming azimuthal symmetry resulting in an essentially two-dimensional model in pressure and latitude coordinates. The latitudinal grid resolution is 0.2° and the altitude/pressure resolution is 0.4 pressure scale heights. The lower boundary is located at 0.2 μbar (300 km above the 1 bar(B) level) and its upper boundary is at 0.02 nbar. Our simplified ionosphere model is exactly the same as described in *Yates et al.* [2014] and consists of a vertical and latitudinal component. Vertical ionospheric density profiles are taken from *Grodent et al.* [2001]'s 1D model and determine how our Pedersen and Hall conductivities vary with altitude. Latitudinal variations of height-integrated Pedersen conductance Σ_P are prescribed by the user in this study and the vertical conductivity profile is scaled such that Σ_P calculated from the vertical profiles matches that prescribed by the user [*Nichols and Cowley*, 2004]. In the auroral region (60 – 74°) our model assumes a constant Σ_P of 0.5 mho. Polewards of the auroral region (latitudes >74°) Σ_P = 0.2 mho [*Isbell et al.*, 1984] while for latitudes <60° Σ_P = 0.0275 mho [*Hill*, 1980].

Our axisymmetric magnetosphere model is based on a combination of the models by *Nichols and Cowley* [2004]; *Cowley et al.* [2005, 2007] and is fully described in *Yates et al.* [2012, 2014]. Other than the equatorial magnetic field strength $B_{ze}(\rho_e)$, we calculate the ionospheric flux function $F_i(\theta_i)$ and its magnetospheric equivalent $F_e(\rho_e)$. Surfaces of constant flux function represent magnetic shells with common ionospheric co-latitudes θ_i and equatorial radial distances ρ_e. Therefore by equating the ionospheric and magnetospheric flux functions we can map radial distances in the magnetospheric equatorial plane to co-latitudes in the ionosphere. In addition, by assuming that the total magnetic flux in the system is conserved we can reconfigure the magnetosphere model to different sizes.

These models are coupled in such way that the atmospheric component solves the Navier-Stokes equations of motion and passes a thermospheric neutral angular velocity Ω_T profile (see *Smith and Aylward* [2009] for details on exactly how this is calculated) to the magnetospheric component. The magnetospheric module solves a set of equations including the Hill-Pontius equation [*Hill*, 1979; *Pontius*, 1997] in order to determine the torque balance between the outward diffusion of iogenic plasma in the magnetosphere and the $\mathbf{J} \times \mathbf{B}$ force associated with magnetosphere-ionosphere currents [*Yates et al.*, 2012]. This results in a radial plasma angular velocity Ω_M profile for the magnetosphere. Having both thermospheric neutral and magnetospheric angular velocity profiles and height-integrated Pedersen conductances allows for the determination of the magnetosphere-ionosphere coupling currents which then feed back onto the thermosphere. Specifically, the intensity of these currents determines ionospheric current density and related ion drag force / Joule heating rate. For detailed information about how this model is coupled and the equations that are solved the reader is referred to *Smith and Aylward* [2009]; *Yates et al.* [2012] and *Ray et al.* [2015].

2.2 Including long-term solar wind dynamic pressure variability

We use Pioneer 10/11 observations upstream of Jupiter to calculate the solar wind dynamic pressure (Fig. 1a) and use the model of *Joy et al.* [2002] to determine the corresponding sub-solar magnetospheric size (Fig. 1b). This gives us a time series of magnetospheric sizes which we use to drive our simulation. We begin our simulation with an initially expanded ($\mathrm{R_{MM}} = 85\mathrm{R_J}$) steady-state model.

Each Jovian rotation can be split into two portions as shown in Fig. 2: i) a dynamic portion where the magnetosphere is reconfigured and ii) a steady state portion where the magnetosphere is considered to be in or near equilibrium. For the steady-state portion, plasma angular velocity profiles are obtained by solving the Hill-Pontius equation in the

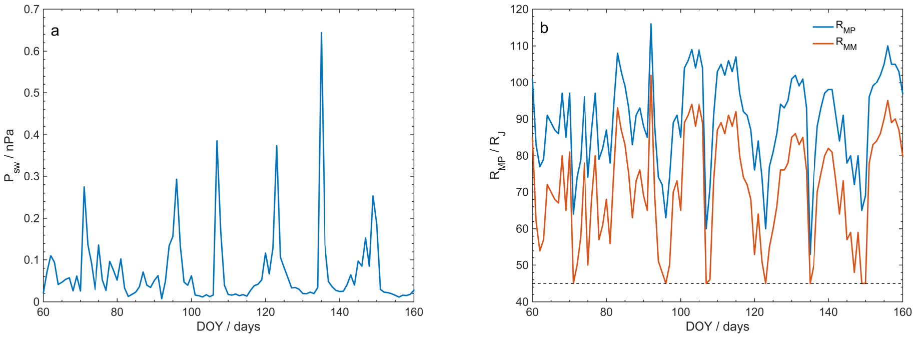

Figure 1. Shows PIONEER 10/11 derived solar wind dynamic pressures (a) and the resulting magnetopause (R_{MP}) and magnetodisc (R_{MM}) radii (b) as a function of day of year (DOY) in 1974.

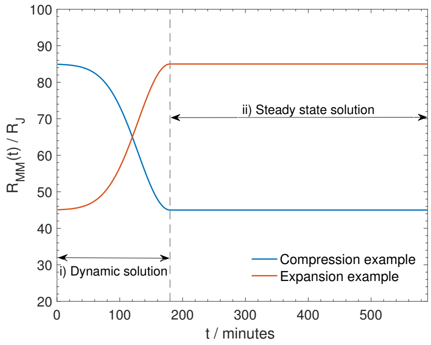

Figure 2. Magnetospheric reconfiguration example. The reconfiguration (compression or expansion) occurs during the first 180 minutes of a Jovian rotation where we solve for plasma angular velocity as in *Yates et al.* [2014]. After the reconfiguration we switch to a steady state solver as in *Yates et al.* [2012].

same manner as described in *Smith and Aylward* [2009] and *Yates et al.* [2012] but with a fixed height-integrated Pedersen conductance. During reconfigurations we employ the same assumption as *Yates et al.* [2014] where magnetospheric plasma angular momentum is conserved as long as these reconfigurations occur over small time scales (≤3 hours) [*Cowley et al.*, 2007]. Our approach differs from that of *Yates et al.* [2014] in that here the magnetosphere is reconfigured at the start of each rotation instead of the end in order to investigate the longer term response of the thermosphere. The limitations of our approach are discussed in detail in section 4.2.

3 Results

3.1 Initial steady state of the simulation

At the start of our simulation, the magnetosphere is in an expanded state with a magnetodisc radius $R_{MM} = 85R_J$. The MI coupling currents and atmospheric dynamics for this steady-state configuration have been discussed at length in *Yates et al.* [2012, 2014] and here we simply describe their general features. Fig. 3 shows the east-west (a) and north-south (b) winds, and the temperature (c) distribution of the neutral atmosphere as a function of pressure and latitude. The east-west (zonal) winds in Fig. 3a show the much discussed high-latitude sub-corotational jet (large negative velocities) and equatorward of this jet lies a low altitude super-corotational jet. There is also a second, much weaker, sub-corotational jet at high altitudes and mid-latitudes. Fig. 3b shows that there exist strong poleward winds (negative north-south velocities) at low altitudes and polewards of ~70° while at higher altitudes there exists equatorwards but weaker winds. Heating from the magnetospheric interaction (Joule heating and ion drag) is deposited at low altitudes where these strong poleward winds transport it towards the pole. At higher altitudes, the equatorwards winds transport heat towards lower latitudes but this is not efficient as these high altitude winds are weak. This results in equatorial and mid-latitudes being generally very cold in comparison to polar latitudes and observations [*Seiff et al.*, 1998; *Lam et al.*, 1997; *Lystrup et al.*, 2008]. The high-latitude thermosphere in our simulation is colder than the observed temperatures.

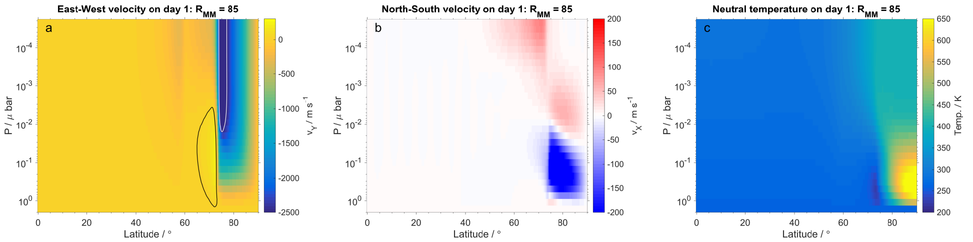

Figure 3. Pressure-latitude distributions of the east-west (a) and north-south (b) neutral winds, and the neutral temperature (c) for the initial steady-state of the simulation. Negative velocities are sub-corotational (westwards) for the east-west winds and polewards for the north-south winds. Positive velocities are therefore super-corotational and equatorwards for the east-west and north-south winds respectively. The black contour in (a) encloses regions of super-corotation greater than 25 m s^{-1} while the white contour encloses regions of sub-corotation slower than -2500 m s^{-1}.

3.2 Simulation snapshots

We now present three typical snapshots from our 100 day simulation: day 51, 76 and 100. The left column of Fig. 4 shows, from top to bottom, the east-west (a) and north-south (d) winds, and the temperature (g) distribution of the neutral atmosphere as a function of pressure and latitude for simulation day 51. Fig. 4j shows the corresponding temperature difference between day 51 and day 1 (initial state). The middle and right column of Fig. 4 show the same but for days 76 and 100 respectively.

On simulation day 51, the neutral zonal wind (Fig. 4a) structure does not change significantly. The high latitude super- and sub- corotational jets both become slightly more corotational. The mid-latitude sub-corotational jet becomes more sub-corotational while three new super-corotation regions develop (see black contours showing velocities >25m s^{-1}). In contrast, the recurring magnetospheric reconfigurations have drastically altered the north-south winds (see Fig. 4d). The strong low-altitude, high-latitude poleward flows are still present but now strong poleward flows are also present at high altitudes in the polar region. Equatorwards of ~70° there are alternating bands of strong equatorward and poleward flows. Fig. 4g shows the temperature distribution of the thermosphere. The overall structure is not very different from that seen at the beginning of our simulation - cold equatorial latitudes and hot polar latitudes. However, looking at the difference between the temperature on day 51 and on day 1 (see Fig. 4j) we can see that there are temperature variations between $-10K$ and $+80K$. The polar thermosphere is generally ~40 K warmer than in the initial state and the equatorial region has vertical warm and cold (±10 K) temperature bands which coincide with the north-south wind structures. A primary source of heating at latitudes >60° comes from recurring changes in Joule heating and ion drag. However, on simulation day 51 there is also a significant contribution from adiabatic heating. This is particularly true for the high altitude polar region where the temperature is ~80 K hotter than on day 1. Adiabatic heating and cooling is also responsible for the equatorial warm-cold vertical temperature bands where there are strong north-south and vertical (not shown) wind shears.

On simulation day 76, the magnetosphere is compressed significantly from a magnetodisc radius of 76 R_J to 45 R_J. *Yates et al.* [2014] showed that large and rapid compressions cause magnetospheric plasma to super-corotate compared to the planetary and thermospheric rotation rates. The magnetosphere essentially 'spins-up' the thermosphere and we see this in Fig. 4b where the zonal winds throughout the thermosphere show a stronger degree of corotation. Fig. 4e shows the north-south neutral winds. The low-altitude poleward winds are weaker than on day 1 and the high-altitude equatorwards winds are now much stronger. Fig. 4h and Fig. 4k show the neutral temperature and temperature difference distribution respectively. There is a significant (order 100 K or ~10% of the peak temperature) decrease in neutral temperature at low altitudes in the polar region. This is likely caused by a ~70% reduction in Joule heating and ion drag in this region combined with the large reduction in north-south winds transporting this heat polewards. At higher altitudes Joule heating and ion drag energy essentially cancel each other out and the hot regions are heated by the horizontal advection of energy while the cold regions are created by adiabatic cooling.

The simulation ends on day 100 with an expanded magnetosphere that is 2 R_J larger than the simulation's initial state. The zonal winds in Fig. 4c are very similar to those in Fig. 3a. The north-south winds are also very similar to our initial state but with an equatorward extension of equatorward flow. We also see a few small polar poleward flow regions. The temperature of the high-latitude thermosphere is ~25 K warmer than our initial state while low latitudes remain unchanged. These small temperature differences also coincide with the least drastic magnetospheric reconfiguration ($+14\,R_J$ for days 50-51, $-31\,R_J$ for days 76-75, $-3\,R_J$ for days 100-99). This small reconfiguration and the similarity with the simulation's initial state suggests that the hotter high-latitude thermosphere on day 100 is likely due to previous, more drastic magnetospheric reconfigurations and that the thermosphere is closer to an equilibrium state compared to the earlier two snapshots.

3.3 Summary of simulation output

Figs. 5a-c show the minimum, mean and maximum thermospheric temperature as a function of simulation days respectively. Fig. 5d shows how the magnetodisc radius varies with simulation time. The minimum and maximum temperatures are well correlated with the size of the magnetosphere while the mean temperature has a more complex relation with magnetospheric size. Fig. 5b suggests that significant ($>10\,R_J$) magnetospheric reconfigurations occurring in rapid succession do indeed increase the mean thermospheric temperatures.

Fig. 5e shows how the average vertical thermal structure of the thermosphere changes with latitude (colored lines - see figure legend) in our simulation. The error bars represent the temporal spread of thermospheric temperature at each pressure level. Fig. 5e shows that magnetospheric reconfigurations:

1. have essentially no effect on our model thermosphere for low altitudes and latitudes $\leq 50°$,
2. do influence high altitude temperatures at all latitudes but more so towards the pole,
3. have the largest effect on latitudes $\geq 80°$.

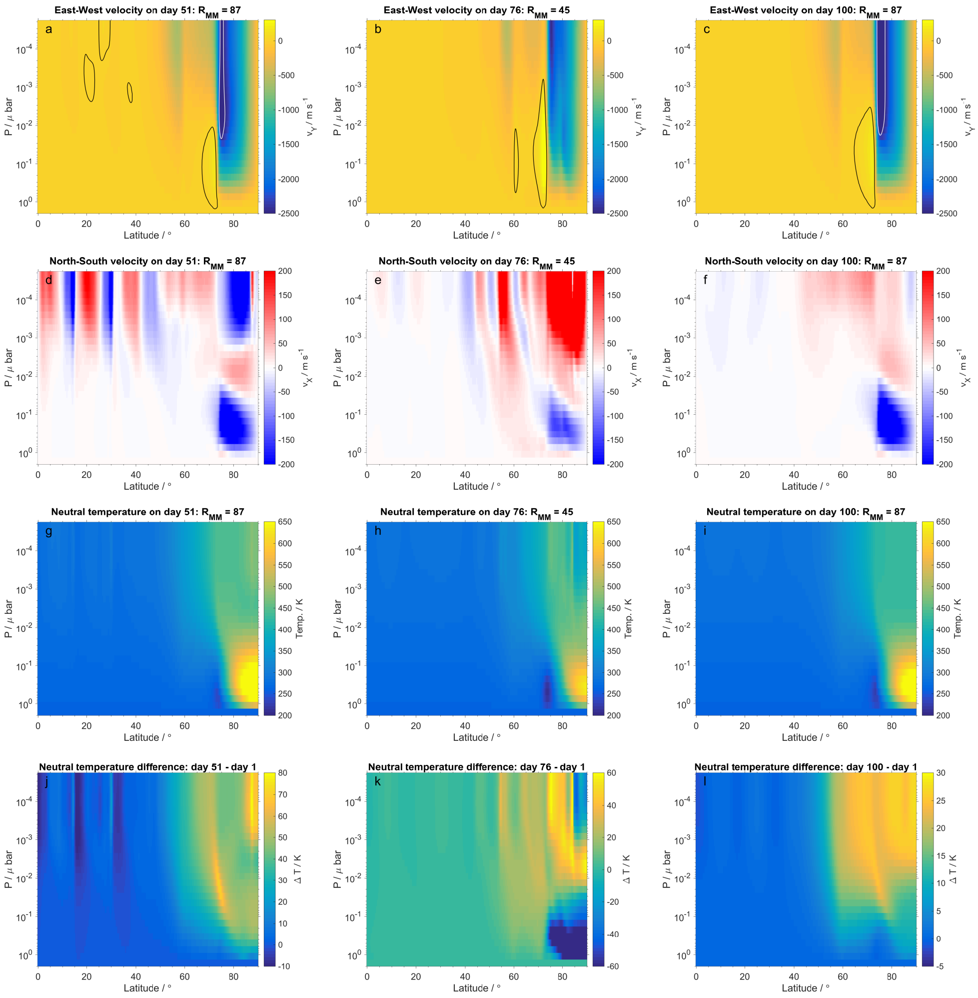

Figure 4. Pressure-latitude distributions of the east-west (a - c) and north-south (d - f) neutral winds, and the neutral temperature (g - i) for three days in our transient simulation (days 51, 76 and 100 are shown in the left, middle and right hand columns respectively). (j -l) shows the difference in temperature between days 51, 76 and 100 and the initial steady-state (day 1). Negative velocities are sub-corotational (westwards) for the east-west winds and polewards for the north-south winds. Positive velocities are therefore super-corotational and equatorwards for the east-west and north-south winds respectively. The black contour in (a-c) encloses regions of super-corotation greater than 25 $\mathrm{m\,s^{-1}}$ while the white contour encloses regions of sub-corotation slower than -2500 $\mathrm{m\,s^{-1}}$.

These summary plots imply that recurring magnetospheric reconfigurations do significantly influence the thermosphere but this response is focused at high altitudes and latitudes.

4 Discussion

4.1 Energetics of the magnetospheric interaction

This study investigates the effect of recurring magnetospheric reconfigurations on Jupiter's upper atmosphere. As such we focus our discussion on heating related to the magnetospheric interaction. We realise that other heating and cooling terms play signifi-

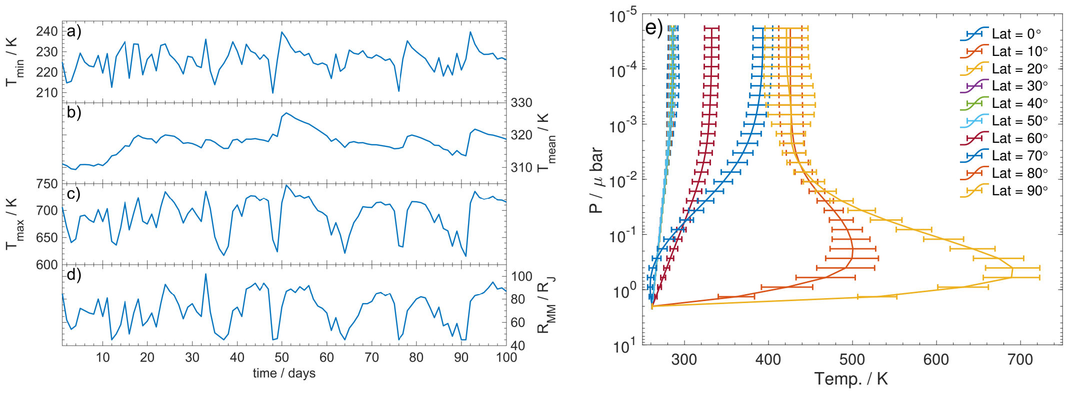

Figure 5. Shows the minimum (a), mean (b) and maximum (c) temperature as a function of simulation time in days. d) shows the magnetodisc radius R_{MM} as a function of simulation time. e) shows the mean vertical neutral temperature profiles for latitudes between 0° and 90° in 10° steps. The error bars represent the standard deviation of the temperature profile at each vertical pressure level throughout the simulation time. Note that lines representing latitudes 0−50° lie on top of each other.

cant roles in planetary atmospheres, especially once perturbed, but detailed investigation of these other terms is saved for future studies.

The strength of the magnetospheric interaction with the atmosphere can be determined by looking at the power per unit area used to accelerate magnetospheric plasma towards corotation P_M as well as the power per unit area that is dissipated in the atmosphere via Joule heating P_{JH} and ion drag P_{ID} given by:

$$P = \Omega_J \tau,$$

$$P_{JH} = (\Omega_T - \Omega_M)\tau, \tag{1}$$

$$P_{ID} = (\Omega_J - \Omega_T)\tau, \tag{2}$$

$$P_M = \Omega_M \tau, \tag{3}$$

where

$$\tau = \rho_i i_P B_i. \tag{4}$$

Here P is the total power per unit area of the ionosphere transferred from Jupiter's rotation, τ is the torque exerted by the $\mathbf{J} \times \mathbf{B}$ force per unit area of the ionosphere and $B_i = 2\,B_J$ is the assumed magnitude of the radial ionospheric magnetic field in the polar region, $B_J = 426400\,\mathrm{nT}$ is the equatorial magnetic field strength on Jupiter's surface. We can then integrate these powers over latitude to obtain the magnetospheric, Joule heating and ion drag power per hemisphere. These are shown in Fig. 6 as a function of magnetodisc radius. The solid blue dots represent integrated Joule heating (a), ion drag (b) and magnetospheric (c) powers for each day in our simulation. The solid orange dots show the equivalent integrated powers in a steady-state simulation with the same magnetodisc size. The yellow and cyan solid lines show quadratic and cubic fits to the steady-state simulation output respectively and the fit coefficients are given in Table 1. One can immediately see from Fig. 6a-c that two trends emerge for both our perturbed 100-day simulation and the steady-state simulations. The first is that Joule heating and ion drag integrated powers seem to increase with increasing magnetodisc size and the second is that the magnetospheric power increases with magnetodisc size until $R_{MM} \sim 56 R_J$ before decreasing.

These general trends were also observed in the three steady-state simulations of *Yates et al.* [2012].

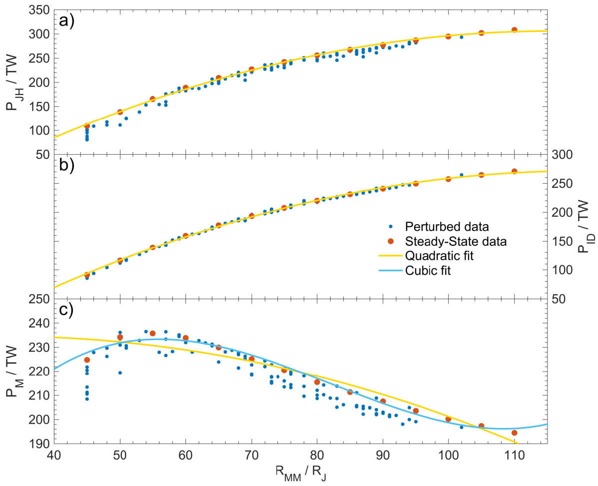

Figure 6. Integrated powers per hemisphere for Joule heating (a), ion drag (b) and magnetospheric power (c) as a function of magnetodisc size for the transient simulation are represented by the blue dots. Each blue dot represents powers at the end of each rotation in the simulation. The red dots show the same powers but for a steady-state simulation with the same magnetospheric size. Each red dot represents one steady state simulation. Quadratic and cubic fits to these powers are represented by the yellow and cyan lines respectively. Fit coefficients are given in Table 1.

We compare the integrated powers from this perturbed simulation with powers from steady-state simulations of the same magnetospheric size and discuss the implications that recurring magnetospheric reconfigurations have on the gas giant energy crisis. To aid this comparison we calculate the difference in integrated powers between the perturbed simulation and steady-state fits, and we call these 'residual' powers. These residuals are shown as a function of the change in magnetodisc radius in Fig. 7.

In Fig. 7 residual Joule heating, ion drag and magnetospheric powers are represented by blue, red and yellow dots respectively. Fig. 7 allows us to compare the difference in power between the perturbed and steady-state simulations following magnetospheric compressions or expansions. It indicates that compressive events, particularly, significant ones lead to the largest difference between perturbed and steady-state integrated powers with the latter being larger. Compressive events increase the degree of corotation of the plasma which causes a reversal in the flow of energy and angular momentum, spinning up the atmospheric neutrals and thus decreasing the shear between neutral, plasma and the planetary (deep interior) angular velocities. As such we expect most compressive events to have lower integrated power resulting from the magnetospheric interaction than in an equivalently sized steady-state system as is shown in Fig. 7.

Expansion-type reconfigurations should therefore lead to the perturbed simulation having larger integrated powers than the steady-state one but this is not evident in Fig. 7. Angular velocity profiles during expansive reconfigurations show that both the neutral and plasma profiles change less than for the compressive reconfigurations and their profiles are not dissimilar to their steady-state counterparts. This explains why the residual integrated powers are generally smaller and more evenly spread about zero compared to compressive reconfigurations. At first glance, angular velocity profiles during expansive reconfigura-

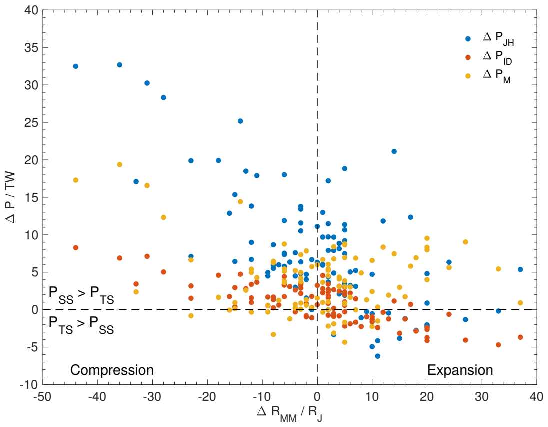

Figure 7. Shows the residual integrated powers per hemisphere as a function of the change in magnetodisc size. Joule heating, ion drag and magnetospheric powers are indicated by blue, red and yellow dots respectively. Positive (negative) residuals indicate that powers are greater (lower) in the steady state simulation compared to the time-dependent one. Positive (negative) ΔR_{MM} indicate magnetospheric expansions (compressions).

Table 1. Integrated Joule heating, ion drag and magnetospheric powers fit coefficients for the steady-state simulations. Fits are polynomial of the form $p_0 + p_1\,R_{MM} + p_2\,R_{MM}^2 + p_3\,R_{MM}^3$.

	Fit type	p_0	p_1	p_2	p_3	R^2
Joule heating	Quadratic	-209.90 ± 24.30	8.90 ± 0.66	$(-38.41 \pm 4.20) \times 10^{-3}$		0.99
Ion drag	Quadratic	-181.70 ± 16.60	7.53 ± 0.45	$(-31.30 \pm 2.90) \times 10^{-3}$		0.99
Magnetospheric	Quadratic	227.20 ± 38.60	0.46 ± 1.04	$(-7.20 \pm 6.70) \times 10^{-3}$		0.93
	Cubic	16.31 ± 78.80	9.37 ± 3.27	-0.13 ± 0.04	$(0.52 \pm 0.19) \times 10^{-3}$	0.98

tions do not behave as we would expect. However, the neutral thermosphere has significantly more mass and inertia than the magnetospheric plasma. When an expansive reconfiguration occurs and the magnetospheric plasma sub-corotates to an even greater degree this extracts energy and angular momentum from the neutrals, leading to a slight increase in sub-corotation of the thermospheric neutrals. Once the reconfiguration ends and the coupled model relaxes back towards steady-state, the neutrals are able to accelerate the magnetospheric plasma towards corotation and equilibrium. Fig. 7 essentially suggests that the model thermosphere is closer to equilibrium for expansive magnetospheric reconfigurations than for compressive ones.

4.2 Limitations of the current model setup

The model employed here is heavily based on that presented in *Yates et al.* [2014] and hence shares its limitations listed below.

1. Use of a fixed height-integrated Pedersen conductance in the auroral region (60 - 74° latitude). This does not significantly influence the thermosphere compared to

using variable Pedersen conductance when considering a perfectly coupled MIT system i.e. no field-aligned potentials. For example, with regards to Joule heating and ion drag powers there are differences of a few percent between steady-state simulations employing fixed [*Yates et al.*, 2014] and variable [*Yates et al.*, 2012] Pedersen conductances.

2. Assuming the thermosphere to be axially symmetric about the rotation axis. *Smith and Aylward* [2009] showed that this leads to modelling errors of ~20 % which is similar to, or less than, errors from other assumptions within the coupled model. Breaking the symmetry in the thermosphere and magnetosphere is the subject of ongoing work.
3. Using a fixed value for the plasma angular velocity mapping to latitudes >80° instead of one determined using solar wind dynamic pressure and the formulation of *Isbell et al.* [1984] was shown to be negligible for the range of magnetodisc sizes considered herein [*Yates et al.*, 2014].
4. Not allowing for the development of field-aligned potentials and therefore rotational decoupling. *Ray et al.* [2015] found that inclusion of FAPs did not significantly alter the thermosphere compared to not including FAPs. However, they found that the changes in the Pedersen conductance due to FAPs had a larger effect on the thermosphere.

Our approach to simulate multiple magnetospheric reconfigurations is split into two portions as described in section 2.2. Firstly, the dynamic portion where the reconfiguration occurs, and secondly, the steady state portion where the model is assumed to be in its new equilibrium configuration. In the steady-state portion we solve for the magnetospheric plasma flows using the Hill-Pontius equation and in the dynamic portion we assume that the plasma angular momentum is conserved as in *Yates et al.* [2014]. The main caveat with this simulation is that we abruptly switch between the dynamic and steady-state portions; meaning that there is no ‘transition’ phase between the dynamic and steady-state portions where magnetospheric plasma flows are allowed to relax towards a new equilibrium. Ideally we would like a single time-dependent and self-consistent way to solve for magnetospheric plasma angular velocity but this is beyond the scope of this study and the subject of future work. The impact of this abrupt change in regime is unlikely to significantly affect the neutral thermosphere considering that the Pedersen conductance is fixed and we simply allow the thermosphere to respond to changes in magnetospheric plasma flows. Fortuitously, the inertia of the thermosphere benefits our simulation as it means that the magnetospheric plasma sees, and is influenced by, a perturbed neutral atmosphere with non steady-state flows and so the new steady-state plasma angular velocity solution will differ from a true steady-state solution. Consequently, while not ideal, we believe that this perturbed simulation is able to shed light on the relatively long-term response of Jupiter's upper atmosphere to multiple magnetospheric reconfigurations.

5 Conclusions

The interaction between Jupiter's upper atmosphere and its strong magnetosphere is a plausible candidate to explain Jupiter's high thermospheric temperatures [*Yelle and Miller*, 2004]. This interaction leads to energy deposition in the auroral regions via particle precipitation, Joule heating and ion drag. Energy from these sources is transported away from the auroral regions; however in the current steady-state GCMs the majority of this ‘magnetospheric heating’ is transported to the poles by strong poleward winds. Equatorward winds are typically very weak and do not transport much heat towards the equator. We have used Pioneer 10/11 observations upstream of Jupiter to calculate solar wind dynamic pressures in order to investigate the long term influence of solar wind on the upper atmosphere of a gas giant planet. The present study covers 100 reconfigurations, one per Jovian rotation. We then investigated Jupiter's thermospheric response to such a prolonged period of magnetospheric reconfigurations.

We find that north-south thermospheric winds are significantly influenced by these long-term reconfigurations, particularly at mid and low latitudes. The east-west winds are less affected by these reconfigurations and typically maintain a similar structure to the steady-state. The overall thermal structure of our model thermosphere also remains relatively unchanged compared to previous work [*Yates et al.*, 2014]. Consecutive reconfigurations lead to slight increases in our predicted temperatures but when averaged over the entire thermosphere, only amount to 7.60 K after 100 reconfigurations with a maximum of 15.70 K throughout the simulation. Maximum and minimum temperatures are found to be well correlated with magnetospheric size. High latitudes are also more influenced by magnetospheric reconfigurations than lower latitudes as the north-south winds which re-distribute magnetospheric heating are generally too weak, or when they are strong, are not sustained for enough time to advect enough energy equatorwards. Our work suggests that thermospheric heating due to solar wind forcing of the MIT coupled system cannot account for Jupiter's high thermospheric temperatures. This somewhat null result suggests that the magnetospheric interaction is unlikely to be solely responsible for the observed high temperatures of Jupiter's upper atmosphere. Therefore other sources of heat, perhaps such as gravity and acoustic wave-breaking, should also play crucial roles in heating the Jovian thermosphere. It is worth noting that this conclusion is relevant for the axisymmetric coupled model presented herein. A full three-dimensional GCM coupled to a more realistic tilted magnetosphere model will lead to asymmetric (within and between each hemisphere) energy deposition from the magnetospheric interaction, potentially creating different thermospheric flows perhaps capable of more efficiently redistributing Joule heating and ion drag energy to lower latitudes.

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