Magnetosphere-Ionosphere-Thermosphere coupling at Jupiter using a three-dimensional atmospheric general circulation model

J. N. Yates[1,2], L. C. Ray[3], N. Achilleos[4,5], O. Witasse[6], and N. Altobelli[1]

[1]European Space Agency, ESAC, Spain
[2]Imperial College London, UK
[3]Lancaster University, UK
[4]University College London, UK
[5]Centre for Planetary Science, UCL-Birkbeck, UK
[6]European Space Agency, ESTEC, Netherlands

Key Points:

- A new model of Jupiter's magnetosphere-ionosphere-thermosphere coupling is presented.
- This new 3D model demonstrates the importance of including zonal terms in the momentum and energy equations.
- The high-latitude temperatures are comparable to the lower range of observed temperatures.

Corresponding author: J.N. Yates, `japheth.yates@esa.int`

Abstract

Jupiter's upper atmosphere is ∼700 K hotter than predicted based on solar extreme ultraviolet heating alone. The reason for this still remains a mystery and is known as the 'energy crisis'. It is thought that the interaction between Jupiter and its dynamic magnetosphere plays a vital role in heating its atmosphere to the observed temperatures. Here, we present a new model of Jupiter's MIT coupled system where we couple a three-dimensional atmospheric general circulation model to an axisymmetric magnetosphere model. We find that the model temperatures are on average ∼60 K, with a maximum of ∼200 K, hotter than the model's two-dimensional predecessor making our high-latitude temperatures comparable to the lower limit of observations. Stronger meridional winds now transport more heat from the auroral region to the equator increasing the equatorial temperatures. However, despite this increase, the modelled equatorial temperatures are still 100s of Kelvin colder than observed. We use this model as an intermediate step towards a three-dimensional atmospheric model coupled to a realistic magnetosphere model with zonal and radial variation.

1 Introduction

The solar system's giant planets all have very hot upper atmospheres. Their atmospheres are much hotter than would be expected if they were heated primarily by solar extreme ultraviolet radiation (EUV) like the terrestrial upper atmosphere. Jupiter's thermosphere is ∼700 K (∼4.5×) hotter than predicted [e.g *Strobel and Smith*, 1973; *Seiff et al.*, 1998; *Yelle and Miller*, 2004]. The other giant planets Saturn, Uranus, and Neptune are respectively ∼2.5×, ∼5.8×, and ∼4.5× hotter than predicted. This is known as the giant planet energy crisis. To date, we still cannot explain the source of these high temperatures despite many attempts. The high thermospheric temperatures at Jupiter are thought to be caused by i) the interaction between its upper atmosphere and magnetosphere via Joule heating [*Waite et al.*, 1983; *Millward et al.*, 2005; *Smith et al.*, 2005], ion drag [*Miller et al.*, 2000; *Millward et al.*, 2005; *Smith et al.*, 2005] and particle precipitation – be it auroral [*Waite et al.*, 1983; *Grodent et al.*, 2001] or mid- and low-latitude [*Yelle and Miller*, 2004]; ii) the breaking of acoustic and/or gravity waves in the upper atmosphere [*Young et al.*, 1997; *Matcheva and Strobel*, 1999; *Hickey et al.*, 2000; *Schubert et al.*, 2003]; or iii) by some combination of both. The Galileo probe's descent into Jupiter's atmosphere remains the only potential in situ evidence of Jovian atmospheric waves [*Young et al.*, 1997]. Combined with the fact that such waves are difficult to detect remotely it is complicated to quantify and confirm the plethora of waves and wave modes that can be sustained within Jupiter's atmosphere. Recently, *Müller-Wodarg et al.* [2019] discovered atmospheric waves present in Saturn's thermosphere. The authors found that these waves may be damped and as such could enhance the eddy friction resulting in an increase in atmospheric temperature. Due to the similarity between Jupiter and Saturn such damped waves could also be present in the Jovian system and should be considered in future studies. In this study, we therefore focus solely on the magnetospheric interaction.

The interaction between a planet's upper atmosphere, consisting of an ionosphere embedded in a neutral thermosphere, and magnetosphere is known as magnetosphere-ionosphere-thermosphere (MIT) coupling. This coupled system is investigated using numerical models, where the neutral atmosphere is represented by a general circulation model (GCM) which is coupled to either a simplified model representing the currents in the magnetosphere-ionosphere (MI) system [*Smith and Aylward*, 2009; *Tao et al.*, 2009, 2010, 2014; *Ray et al.*, 2015; *Yates et al.*, 2012, 2014; *Yates et al.*, 2018] or by imposing electric fields directly into the thermospheric GCM [*Achilleos et al.*, 1998, 2001; *Bougher et al.*, 2005; *Majeed et al.*, 2005, 2009, 2016; *Millward et al.*, 2002, 2005]. The Jovian Ionosphere Model (JIM) (*Achilleos* and *Millward*) and the Jupiter Thermospheric GCM (JT-GCM) (*Bougher* and *Majeed*) are models which investigated the 3D dynamics and chemistry of Jupiter's upper atmosphere and its MIT coupling. The JIM model was the first Jovian 3D MIT coupling model employing an offset tilted dipole magnetic field model and an Earth-like parameterization of Jupiter's ionospheric electric field. JIM investigated the creation of Jupiter's ionosphere within the auroral region and how ionospheric ion motion influenced the thermospheric neutrals. JTGCM simulates MIT coupling by using terrestrial parameterizations of ion drag and Joule heating and ion drifts generated using a convection electric field model based on Voyager measurements. Joule heating is then scaled down until the model reproduces the observed temperatures. Both JIM and JTGCM model how the neutral winds are modified by their coupling with Jupiter's ionospheric ions and the resulting re-distribution of heat from the auroral regions to lower latitudes. The resulting neutral flows amount to a sub-corotational (westward) zonal jet at high-latitudes, equatorward high-altitude flows and poleward flows in the high-latitude and low-altitude thermosphere. JTGCM's flows are, however, very asymmetric in coverage and speeds due to their use of the VIP4 [*Connerney et al.*, 1998] magnetic field model instead of a simple tilted-dipole field, and some may argue that this is more realistic.

The 3D models presented above impose magnetospheric forcing in the polar regions but do not self-consistently couple the magnetosphere to the upper atmosphere. Self-consistently coupling the magnetosphere and ionosphere-thermosphere allows the field-aligned currents to affect the magnetospheric convection electric field and magnetospheric plasma. A series of models were subsequently developed to self-consistently include such coupling. Due to the complexity of such coupling the models were designed to initially be axisymmetric. The *Smith and Aylward* [2009]; *Tao et al.* [2009]; *Ray et al.* [2015] and *Yates et al.* [2014] models all consist of a one-dimensional (1D) magnetosphere model self-consistently coupled to a two-dimensional (2D) atmospheric GCM. Of all the 2D coupled MIT models, only the *Tao et al.,* models could reproduce atmospheric temperatures comparable to those observed at all latitudes by including heating terms due to acoustic waves as parameterized by *Schubert et al.* [2003]. The other 2D models did not include heating due to acoustic wave breaking for reasons given above. This means that their temperatures, particularly at equatorial latitudes, were modelled to be much lower (~300 K) than observed (~900 K). It is worth noting that the *Smith et al.,* model can reproduce the observed temperatures if the authors include an extra, low-latitude, Joule heating term due to fluctuating electric fields. Regarding neutral dynamics, the suite of 2D models found similar flow cells to those found using the 3D models albeit with generally lower meridional velocities. Most MIT coupling studies assume that the system is in quasi-equilibrium (or steady state). The works of *Yates et al.* [2014]; *Tao et al.* [2014]; *Yates et al.* [2018] were the first to include time-dependence outside of the thermospheric GCM by either having a time-dependent magnetospheric size [*Yates et al.*, 2014; *Yates et al.*, 2018] or solar EUV flux [*Tao et al.*, 2014]. Including variable solar EUV fluxes (factors of one to three) results in moderate thermospheric temperature (~10 K) and neutral velocity (~20%) increases while large changes in magnetospheric size (~40 R_J ; Jovian radii with 1 R_J = 71492 km) lead to temperature variations of a few tens of Kelvin. Moreover, varying the size of the magnetosphere leads to an increase in equatorward transport of heat which is typically prohibited in the steady-state simulations pertaining to Jupiter and Saturn [e.g. *Smith and Aylward*, 2008, 2009]. If we exclude the effect of wave heating, the time-dependent additions discussed above have been unable to reproduce the observed temperatures despite adding considerable complexity to the MIT coupling models.

This study presents results from a newly developed Jovian 3D thermospheric GCM self-consistently coupled to a 1D magnetosphere model. We describe our coupled model including its limitations in section 2 and present our simulation results while comparing them to its 2D progenitor model [*Yates et al.*, 2014] in section 3. In section 4 we discuss how the new model compares to available observations and previous Jovian 3D models . We summarize and conclude in section 5.

2 Model description

The coupled magnetosphere-ionosphere-thermosphere steady-state model presented here is largely based on that presented in numerous studies [e.g. *Smith and Aylward*, 2009; *Yates et al.*, 2014; *Ray et al.*, 2015] and as such we will briefly summarize the model below and introduce the new components that have been added for this study.

2.1 Thermosphere model

The thermosphere model here is a GCM solving the full time-dependent non-linear three-dimensional (3D) Navier-Stokes equations of energy, momentum and continuity, using explicit time integration [*Müller-Wodarg et al.*, 2006] and a time-step of 3s. The model has been developed from the 2.5D (2.5D because zonal gradients in the Navier-Stokes equations are not included) azimuthally symmetric GCM of *Smith and Aylward* [2009] to fully include the third dimension. Our new model solves the Navier-Stokes equations in a spherical-pressure coordinate system, providing time dependent distributions of thermospheric wind, temperature and energy. The horizontal (zonal and meridional) momentum, energy and continuity equations which we solve can be found in *Achilleos et al.* [1998] or *Müller-Wodarg et al.* [2006]. We assume hydrostatic equilibrium in our model so the full vertical momentum equation is not solved. Our model is resolved on a 0.2° latitude, 10° longitude and 0.4 pressure scale height grid, with a lower boundary at $2\mu bar$ (300 km above the 1 bar (B) level) and an upper boundary at 0.02 nbar.

2.2 Ionosphere model

The ionosphere model we employ is the same as that described in *Yates et al.* [2014] and *Yates et al.* [2018]. The model is separated into two parts: i) a vertical part describing the relative change of conductivity with altitude [*Grodent et al.*, 2001]; and ii) a horizontal part, that scales the vertical conductivity profiles such that the height-integrated Pedersen conductance Σ_P is equal to the fixed values which we prescribe. The only difference between this ionospheric model and that in *Yates et al.* [2018] is that here we have day-night variation in Σ_P. In this 3D model we have four fixed conductance regions:

1. polar regions ($|\theta| > 74°$) with $\Sigma_P = 0.2$ mho [*Isbell et al.*, 1984];
2. auroral region ($|\theta| = 60 - 74°$) with $\Sigma_P = 0.5$ mho [*Nichols*, 2011; *Yates et al.*, 2014];
3. day-side low latitude region ($-60° \leq \theta \leq 60°$) with $\Sigma_P = 0.0275$ mho [*Hill*, 1980];
4. night-side low latitude region ($-60° \leq \theta \leq 60°$) with $\Sigma_P = 0.0$ mho.

The conductance in the night-side low latitude (region 4 above) region is set to zero. The conductivity model employed in this study basically consists of conductances due to solar EUV radiation (region 3) and enhancements due to particle precipitation in the high-latitude regions (regions 1 and 2). Solar EUV does not reach the night-side ionosphere and so the conductance at low-latitudes depends on the lifetime of the ionospheric species and whether low-latitude particle precipitation is present. For simplicity, we assume that there is no low-latitude particle precipitation and that the lifetime of ionospheric species is small enough so that there is zero conductance on the night-side. This assumption does not influence the atmosphere as such as is investigated in this study. A future study will incorporate a more realistic night-side ionospheric conductance.

2.3 Magnetosphere model

We use the same magnetosphere model described in *Smith and Aylward* [2009]; *Yates et al.* [2012, 2014]; *Yates et al.* [2018] which is based on the works of *Nichols and Cowley* [2004]; *Cowley et al.* [2005] and *Cowley et al.* [2007]. The model is axisymmetric, aligned with Jupiter's rotation axis and solves for the magnetospheric plasma angular velocity. Additionally, it allows for the magnetic mappping between the magnetosphere and ionosphere. This mapping is achieved by assuming that surfaces of constant flux function form shells of magnetic field lines with common magnetospheric equatorial radial distances ρ_e and ionospheric co-latitude θ_i. As such, one can equate the ionospheric flux function $F_i(\theta_i)$ with its magnetospheric equivalent $F_e(\rho_e)$ (magnetic flux integrated between a given ρ_e and infinity) giving

$$F_i(\theta_i) = B_J R_i^2 sin^2\theta_i = F_e(\rho_e). \tag{1}$$

Where $B_J = 426\,400\,\mathrm{nT}$ [*Connerney et al.*, 1998] and is the equatorial magnetic field strength at the planet's surface. R_i is the ionospheric radius which for this study we set to R_J. $F_e(\rho_e)$ (and the corresponding equatorial magnetic field) are taken from *Nichols and Cowley* [2004].

2.4 Coupled Magnetosphere-Ionosphere-Thermosphere model

Our three model components are coupled as shown in Fig. 1a. The atmospheric module solves the time-dependent Navier-Stokes equations before passing an "effective" thermospheric angular velocity Ω_T to the magnetosphere module. Ω_T is the weighted average of all the horizontal winds and is the thermospheric neutral velocity that the magnetosphere sees (see *Smith and Aylward* [2008, 2009] for details on how this is calculated). The magnetosphere module solves for the steady-state magnetospheric plasma angular velocity Ω_M using the Hill-Pontius equation [*Hill*, 1979; *Pontius and Hill*, 1982; *Pontius*, 1997] which balances the torque 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]. These two angular velocities combined with the height-integrated Pedersen conductance from the ionosphere module enable us to self-consistently determine the MI coupling currents and the resultant heating of the atmosphere due to the magnetospheric interaction. The full details on how these modules are coupled together can be found in *Smith and Aylward* [2009]; *Yates et al.* [2012, 2014] and *Ray et al.* [2015]. In this new 3D model the northern and southern magnetospheric hemispheres are solved separately and then combined in the thermosphere module. We also only couple the noon local time / longitude gridpoints of the thermosphere to our magnetosphere model and then impose the resulting magnetospheric currents to the other longitudes of the thermosphere. The noon local time coupling is schematically shown in Fig. 1b. The limitations of our current approach are discussed below.

2.5 Limitations of the current model

Given that this model is built on the previous models of *Smith and Aylward* [e.g. 2009]; *Yates et al.* [e.g. 2014] it also shares some of their limitations. We begin by briefly describing some of the common limitations before discussing limitations which are particular to the current model.

1. Using fixed Pedersen conductances in the auroral region ($\pm 60-74°$ latitude). Works by *Yates et al.* [2012, 2014] have shown that using a fixed Pedersen conductance, instead of a variable one, in this region does not significantly alter the local thermospheric dynamics and heating if we consider perfect coupling between the ionosphere and magnetosphere i.e. there are no field-aligned potential (FAP) drops. We also employ a fixed, albeit smaller, Pedersen conductance polewards of the auroral region. The ionosphere and precipitating particles in this region are only recently being investigated by Jupiter's polar orbiting Juno spacecraft which will undoubtedly shed light on the conditions in this relatively unexplored region of Jupiter's

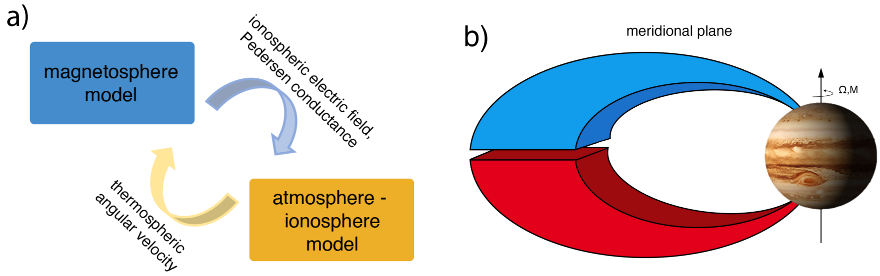

Figure 1. a) Diagram representing our coupled magnetosphere-ionosphere-thermosphere model. b) Schematic showing the separate magnetosphere models for each magnetic hemisphere which couple to the thermosphere model.

upper atmosphere and high-latitude magnetosphere. The day- and night-side equatorial regions have little, if any, MI coupling there so having a fixed conductivity in these regions will not influence the coupled model.

2. Using a fixed magnetospheric plasma angular velocity profile mapping to Jupiter's outer magnetosphere ($\pm 74 - 80^\circ$ latitude) and polar cap ($> \pm 80^\circ$ latitude). We employ fixed estimates of Jupiter's magnetospheric plasma flow (based on works by *Isbell et al.* [1984] and *Cowley et al.* [2005]) in these regions due to the limited amount of measurements taken in Jupiter's distant magnetosphere. Recent work by *Johnson et al.* [2017] has shown that there is a strongly sub-corotating ($\sim < 20\%$) ion flow region possibly mapping to the distant magnetosphere. Therefore, we continue to use these fixed flow assumptions to allow comparison with older models and until further observations are available.
3. No field-aligned potential (FAP) development. In this work we do not allow for the development of FAP drops resulting in the decoupling between the ionospheric and magnetospheric flows - we assume perfect MI coupling. Work by *Ray et al.* [2015] was the first to include FAPs in a MIT coupling model and found that neutral temperatures and flows were changed by a few percent when compared to the same MIT model without FAPs. The variation in the Pedersen conductance due to its self-consistent formulation was found to have a greater influence on the thermosphere.

Our model uses a full 3D thermospheric GCM and ideally this would be coupled to a full 3D magnetohydrodynamic (MHD) magnetosphere model but this is currently too computationally expensive to carry out any feasible studies. Simplifications of the MIT system therefore need to be made to allow for reasonable computation times. As discussed in section 2.4, our approach is to couple our axisymmetric magnetosphere model [based on *Yates et al.*, 2014] to the noon local time (LT) slice of the thermosphere assuming that the magnetosphere is aligned with Jupiter's rotation axis. We solve for the northern and southern magnetosphere separately before combining the results in the thermosphere. We then project and impose the magnetospheric output at all other LT/longitudes. The result is a 3D GCM coupled to a magnetosphere with no zonal variation. This is not physically realistic as Jupiter's magnetosphere shows much local time variation [e.g. *Khurana*, 2001; *Ray et al.*, 2014; *Connerney et al.*, 2018]. However, we do believe this model to be a suitable intermediate step-towards a more comprehensive and self-consistent 3D MIT coupled model. It allows us to investigate the influence of gradually increasing the complexity of the coupled system.

2.6 Angular velocity profiles

In this study we present two simulations, one using a two-dimensional atmosphere model [*Yates et al.*, 2014] and the other using the new three-dimensional atmospheric GCM described above. Both simulations employ a magnetodisc size of 65 R_J with all parameters kept equal. The simulations have been run for 500 rotations and have achieved steady-state.

The normalized thermospheric and magnetospheric angular velocities discussed above are plotted as a function of atmospheric latitude in Fig. 2. Solid lines show the new 3D output and dashed lines show 2D output from *Yates et al.* [2014] for comparison. Thermospheric angular velocities are shown in blue and purple lines while magnetospheric angular velocities are shown in red and yellow lines. Magnetospheric angular velocities essentially remain unchanged between the 2D and 3D models due to the similarities in the magnetosphere model. The thermospheric angular velocities however differ, particularly for latitudes polewards of 75°. These polar regions sub-corotate to a larger degree in the 3D simulation compared to the 2D one until ~86° where 3D velocities increase to ~70% of corotation. This highlights the difference between using an axisymmetric atmospheric GCM and a full 3D one which will be discussed in more detail below.

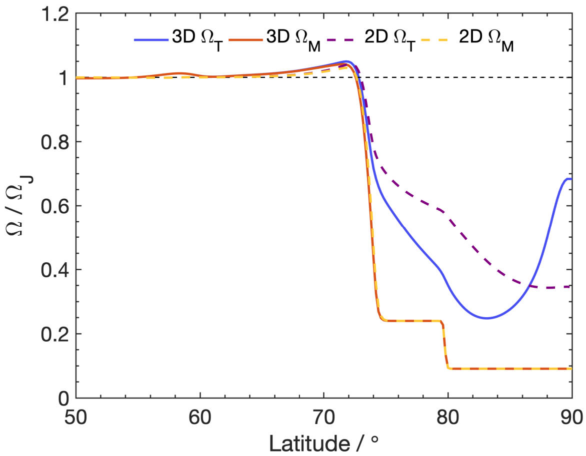

Figure 2. 3D (solid lines) and 2D (dashed lines) thermospheric (blue and purple lines) and magnetospheric (red and yellow lines) angular velocity profiles as a function of latitude.

3 Simulation results: 3D and 2D comparison

3.1 Atmospheric dynamics

Fig. 3 compares neutral wind velocities between our new 3D (Figs. 3d-f) simulation and an equivalent 2D northern hemisphere (Figs. 3a-c) steady-state simulation [*Yates et al.*, 2014]. Figs. 3 a, d show the zonal (east-west) winds in the corotation frame as a function of pressure and latitude. Figs. 3 b, e show meridional (north-south) winds and Figs. 3 c, f show vertical (up-down) winds respectively as a function of pressure and latitude. The structure of the neutral winds remains almost unchanged between our 2D and 3D simulations. The 3D zonal winds show strong sub-corotating (blue colors) jets in the polar regions (latitudes >75°) and also weaker sub-corotating jets at mid-latitudes. Super-corotating (black contour) jets are also seen at low altitudes in each simulation. In our 2D simulation the winds are more corotational (sub-corotating and super-corotating to a lesser degree). The meridional winds consist of strong poleward flows (blue) at high latitudes and low altitudes. At high altitudes most of the flows are equatorward. The main differences between our 2D and 3D simulations is that the mid-altitude, high-latitude equatorward 3D flow is much stronger (~2×) than the 2D model meaning that mid-altitude winds can transport heat equatorwards. Vertical winds are very similar in both simulations but the upward winds in the poles are much stronger (~2.75×) in the 3D simulation. The faster 3D winds lead to the averaged thermospheric angular velocity profiles shown in Fig. 2. In particular, the angular velocity profile polewards of ~85° shows that neutral winds are significantly faster than in the 2D simulation and approach ~$0.7\Omega_J$ at the poles. In the 3D simulation, eastwards (corotational) fictitious (Coriolis and curvature) forces are unopposed at low altitudes beyond 75°, this accelerates the neutrals towards corotation and given that this low altitude region has a stronger weighting in the Ω_T calculations due to its higher ionospheric conductances [see *Smith and Aylward*, 2009] compared to altitudes above, the integrated average Ω_T profile shows much faster winds near the poles. The large flow shears near the poles require faster vertical winds in order to maintain hydrostatic equilibrium.

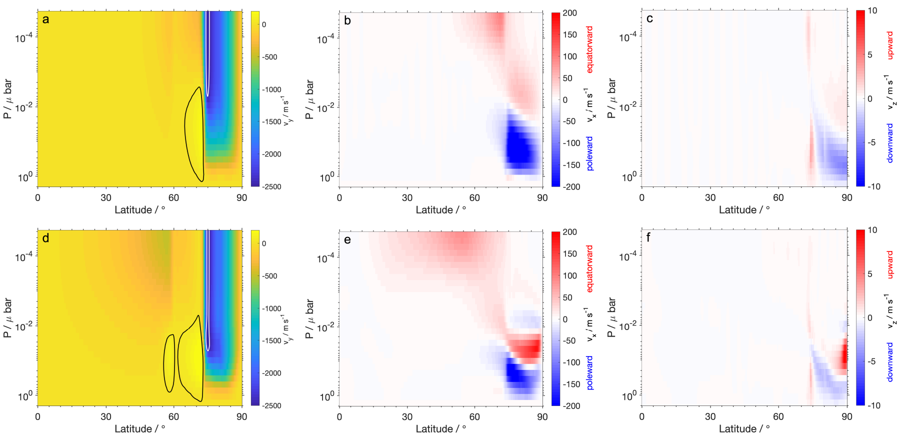

Figure 3. 2D (top row) and 3D (bottom row) neutral winds as a function of pressure and latitude. a) and d) show azimuthal (east-west) velocities in the corotating frame. Black contours enclose regions of super-corotation greater than 25 m s^{-1} and white contours enclose regions of sub-corotation slower than -2500 m s^{-1}. b) and e) show meridional (north-south) velocities where equatorward (poleward) flows are positive (negative). c) and f) show vertical velocities with upwards (downwards) flows being positive (negative).

Figs. 4a, c show neutral temperature as a function of pressure and latitude for the 2D and 3D simulation respectively. Fig. 4b shows the 3D temperature as a function of latitude and local time (LT) at the top pressure level of the model (0.02 nbar). The arrows indicate the direction of the horizontal winds. In addition, Fig. 4d shows the vertical thermal structure for our 2D (dashed colored lines) and 3D (solid colored lines) simulations at various latitudes (see figure legend) compared with the Galileo probe measurements shown in black line.

From Figs. 4a and c we see that the latitudinal and vertical structure remains relatively unchanged between our 2D and 3D models i.e. hot polar regions with a cold equator. The polar hotspots arise from the advection of Joule heating and ion drag energy near the model auroral zone (~74°) towards the poles by strong meridional winds [e.g. *Smith and Aylward*, 2008, 2009; *Tao et al.*, 2009; *Yates et al.*, 2012; *Ray et al.*, 2015]. These rapid poleward winds also lead to up-welling of neutrals just equatoward of the auroral zone which are cooled adiabatically creating a relatively cold spot. Adiabatic heating from down-welling at the poles and vertical advection also contribute to the polar hotspots. The cold equatorial regions result from the lack of low-latitude heat sources (in the current model setup) and the 'ion drag fridge' effect discussed by *Smith et al.* [2007]; *Smith and Aylward* [2008] which gives rise to the strong low-altitude poleward flows discussed above. This effect confines heat from the magnetospheric interaction into the polar regions while essentially cooling the mid-to-low latitudes. Fig. 4b shows the hot pole and cold equator . In particular, it shows the minimal effect, compared to other heat sources, of solar radiation in heating the Jovian upper thermosphere.

The only difference between the two simulations is that the 3D atmosphere is hotter than the 2D one, at mid and high latitudes. In fact, the maximum temperature in the 3D simulation is ~200 K hotter than the 2D one (see also Fig. 4d). The increase in temperature is due to a number of factors including, but not limited to, the faster wind speeds being able to redistribute more heat (including to mid and low latitudes), the increased heating rates (compared to 2D) at polar mid-altitudes and auroral latitudes, and additional zonal advection terms – albeit this is local time dependent.

In Fig. 4d we see the improvement achieved with this new 3D simulation (compared to the 2D one) in increasing the temperature of Jupiter's upper atmosphere. Despite this, there is still a large discrepancy at equatorial latitudes. This suggests that the current assumptions employed here and in much of the recent literature are still inadequate and that these need to be removed and/or amended to explain the observations.

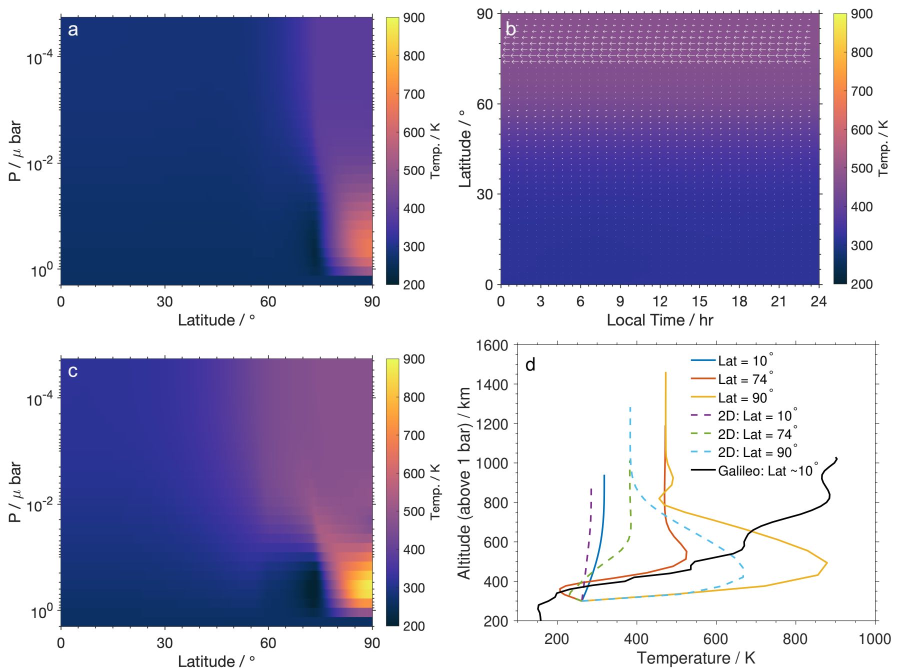

Figure 4. 2D (a) and 3D (c) neutral temperature as a function of pressure and latitude. b) shows the 3D temperature distribution as a function of local time (LT) and latitude. The arrows show the horizontal winds with arrow length representing their speed. d) shows the vertical thermal structure for the 2D (dashed colored lines) and 3D (solid colored lines) simulation at latitudes of 10°, 74°, 90° and that measured with the Galileo probe (black line) [*Seiff et al.*, 1998].

3.2 Coupling currents and auroral emission

The currents responsible for coupling Jupiter's atmosphere and magnetosphere can be approximated to a three-current circuit: i) the Pedersen current in the ionosphere, ii) the radial current in the magnetosphere, and iii) the field-aligned current (FAC) completing the circuit. The Pedersen current is directed equatorwards and Eq. 2 gives the azimuthally-integrated Pedersen current $I_P(\theta_i)$ [e.g *Cowley et al.*, 2007; *Smith and Aylward*, 2009] representing the total current in each hemisphere.

$$I_P(\theta_i) \quad = \quad 2\pi\rho_i\Sigma_P E_\theta, \tag{2}$$

where ρ_i is the perpendicular distance to the planet's magnetic/rotation axis, and $E_\theta = B_i\rho_i(\Omega_T - \Omega_M)$ is the meridional electric field in the rest frame of the neutrals. B_i (= $2B_J$) is the magnitude of the radial ionospheric magnetic field . Radial currents are directed radially outwards in the magnetodiscand FACs connect the ionosphere to magnetosphere. FACs are responsible for angular momentum and energy transfer between the ionosphere and magnetosphere. The FAC density at the ionosphere is given by

$$j_{||i}(\theta_i) \quad = \quad -\frac{1}{2\pi R_i^2 \sin\theta_i}\frac{dI_P}{d\theta_i}. \tag{3}$$

Fig. 5a compares the FAC density profiles in the 3D simulation (blue line) with the 2D simulation (orange line). Fig. 5b shows the corresponding brightness of the UV auroral emission associated with these FACs. Auroral emissions are calculated from the precipitating electron energy flux assuming that 1 $mW\,m^{-2}$ = 10 kR as described by *Yates et al.* [2014] [based on the works of *Knight*, 1973; *Lundin and Sandahl*, 1978; *Cowley et al.*, 2007] in order to allow for comparison. However, it is worth noting that recent Juno observations [*Ebert et al.*, 2019] have found that the above relationship between downward energy flux and auroral emission is not always true across the auroral region, or would require a deeper understanding of Jupiter electron acceleration region

The FAC density profiles show regions of strong upward FACs maximizing at 74°. Upward FACs mean downward propagating electrons which collide with atmospheric neutrals and result in UV emission. These upward FACs therefore correspond to the large peaks in auroral emission shown in Fig. 5b which represent the main auroral oval in our coupled MIT model. The regions of upward FAC are immediately followed by strong downward FACs indicating the return current. With the present model, no emission is expected in this region. Even further poleward, our model has another region of upward FACs and corresponding UV emission but with much smaller magnitude than that of the main oval. This region corresponds to the boundary between our model's outer magnetosphere (or cushion region) and the polar cap (open field region). The magnetospheric flows in this region are not well constrained by observations so the currents and emissions are susceptible to the values we prescribe for plasma flow and ionospheric conductances here. The maximum upward FAC in the 3D simulation is ~90 % that of the 2D simulation. This difference is caused by the shear between the neutral and plasma angular velocities being larger around ~74° latitude in the 2D simulation than in the 3D one because of the 3D neutral winds sub-corotating to a larger degree in this region (see Fig. 2). The corresponding maximum auroral emissions amount to UV brightnesses of ~270 kR for our 3D simulation and ~340 kR for the 2D one with total integrated powers of ~2 TW and ~2.5 TW respectively. These emissions are of similar order-of-magnitude to observations and the integrated powers are comparable to recent observations taken using the Hubble Space Telescope (HST) [e.g. 1-3 TW in *Grodent et al.*, 2018] , the Hisaki space telescope [e.g. ~1.3 TW up to ~11 TW *Tao et al.*, 2018], and the UVS instrument [*Gladstone et al.*, 2017a] onboard the Juno spacecraft [e.g. 2-3 TW in *Gladstone et al.*, 2017b].

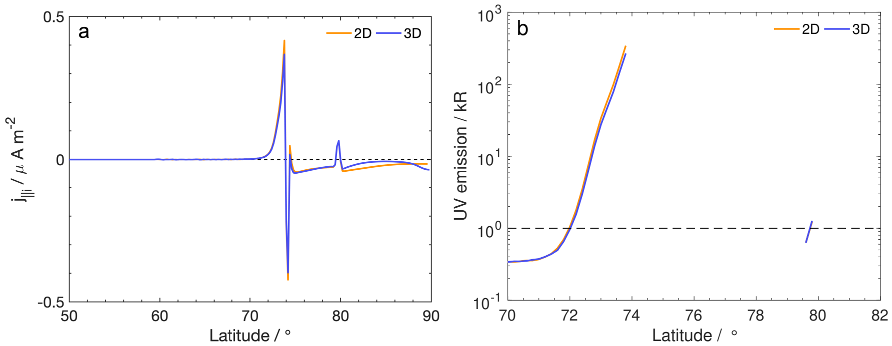

Figure 5. Ionospheric field-aligned current density (a) and auroral ultraviolet (UV) emission (b) is shown as a function of latitude. 2D and 3D current/emission are represented by the orange and blue lines respectively. . The dashed line in (b) shows the limit of detectability of the Hubble Space Telescope (HST).

3.3 Atmospheric energetics

We also examine the energy transferred from Jupiter's deep rotation to its upper atmosphere and magnetosphere. The power per unit area available due to Jupiter's rotation is given by P, this can be subdivided into the power used to accelerate sub-corotating plasma within Jupiter's magnetosphere P_{M} and the power dissipated within Jupiter's upper atmosphere consisting of Joule heating P_{JH} and ion drag P_{ID}.

$$
\begin{aligned}
P &= \Omega_J \tau, \\
P_{JH} &= (\Omega_T - \Omega_M)\tau, && (4) \\
P_{ID} &= (\Omega_J - \Omega_T)\tau, && (5) \\
P_M &= \Omega_M \tau, && (6)
\end{aligned}
$$

where $\tau = \rho_i i_P B_i$ is the torque exerted by the $\mathbf{J} \times \mathbf{B}$ force per unit area of the ionosphere. $i_P = I_P/(2\pi\rho_i)$ and is the Pedersen current density.

Fig. 6a shows the integrated ion drag (light blue), Joule heating (light green), magnetospheric (orange) and total (gold) power per hemisphere for the 2D simulation (northern hemisphere) along with the northern hemisphere in the 3D simulation. Immediately obvious is that the powers in the 2D simulation are larger than each 3D hemisphere. Ion drag, Joule heating and magnetospheric powers are respectively ~1.06×, ~1.8× and ~1.2× larger in the 2D simulation than the 3D. The differences between the 3D and 2D simulations are primarily due to the difference in neutral angular velocity between the two. As shown in Figs. 2, 3a and 3d, the neutral winds between 73−86° latitude sub-corotate to a much larger degree in the 3D simulation leading to smaller Pedersen currents (and torques) in the ionosphere. This large region of sub-cororating neutral flow maps to regions of the magnetosphere whose flows are prescribed in our model (for details see section 2.5 or *Yates et al.* [2012]) suggesting that these changes are purely due to atmospheric effects and the added momentum and energy terms in the 3D simulation. Fig. 6b shows the fraction of power in atmospheric regions mapping to the magnetodisc (55.4 - 74.2° latitude shown in blue), outer magnetosphere (74.2 -79.8° latitude shown in gold) and polar cap (79.8 - 90° latitude shown in red). The fraction of power used in the outer magnetosphere is similar for both 2D and 3D simulations. The differences lie in the power used in the magnetodisc and polar cap regions where the 3D simulation uses ~7% more power in the magnetodisc and ~5% less power in the polar cap. From Fig. 6b we see that

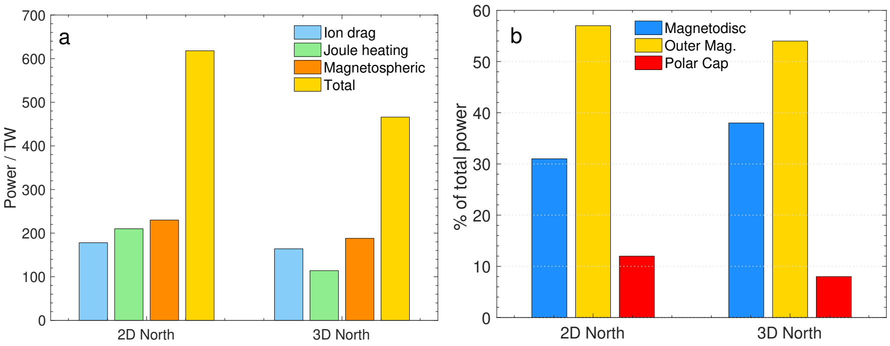

Figure 6. a) shows integrated ion drag (light blue), Joule heating (light green), magnetospheric (orange) and total (gold) power per hemisphere for the 2D model and the northern hemisphere of the 3D model. b) shows the fraction of total integrated power mapping to the magnetodisc (55.4 - 74.2° latitude shown in blue), outer magnetosphere (74.2 -79.8° latitude shown in gold) and polar cap (79.8 - 90° latitude shown in red) regions of the magnetosphere.

approximately 60 − 70% of power extracted from Jupiter's rotation is consumed within atmospheric regions where we prescribe the plasma flows. In order to understand how Jupiter's atmosphere is heated we must gain better understanding of the plasma flows in the high-latitude ionosphere which map to the distant magnetosphere.

4 Discussion

4.1 Comparison with observations

4.1.1 Neutral temperatures

There are many in situ observations of Jupiter's magnetosphere. On the other hand, Jupiter's atmosphere has only one set of in situ observations by NASA's Galileo Probe (see black line in Fig. 4d and/or *Seiff et al.* [1998]). All other observations of Jupiter's atmosphere are remote (space- or Earth-based telescopes). Temperatures of Jupiter's upper atmosphere can be inferred remotely from auroral observations at infrared (IR) and ultraviolet (UV) wavelengths [e.g. *Yelle et al.*, 1996; *Lam et al.*, 1997; *Stallard et al.*, 2002; *Raynaud et al.*, 2004; *Lystrup et al.*, 2008; *Adriani et al.*, 2017; *Moore et al.*, 2017; *Johnson et al.*, 2018; *Kita et al.*, 2018; *Migliorini et al.*, 2019]. Using IR emission from the ionospheric H_3^+ ion, Jupiter's thermospheric temperature is observed to range from ~400 K at 300 km (above the 1 bar level) and increasing to between ~900 K and ~1400 K at altitudes ≥700 km, with larger temperatures located at higher latitudes [e.g. *Moore et al.*, 2017; *Johnson et al.*, 2018; *Migliorini et al.*, 2019].

Comparison of our model neutral temperatures to those observed can be split into two regions:

1. The polar thermosphere (≥74°): Here, our model achieved its maximum temperature of 878 K at low polar altitudes (~500 km). Our model temperatures then decrease with increasing altitude to ~450 K. This is contrary to expectations and available observations. This temperature inversion is likely caused by the lack of (or weak) energy sources at high altitudes within our model. The heat in this region is transported towards the equator by the high altitude equatorward winds. The higher model temperatures in this polar region are comparable to the lower limit of

the observed high-latitude temperatures but at higher altitudes our model temperatures are at most 50% of those observed.

2. The mid-to-low latitude thermosphere (<74°): The high-altitude temperature maximums vary from ~320 K at the equator to ~480 K at 70°. These maximums are approximately a factor-of-two times smaller than the mid-to-low latitude temperatures derived by *O'Donoghue et al.* [2016] at altitudes between 600 *km* and 1000 *km*. At low altitudes these temperatures have an average of ~290 K with a base of 260 K at the lower boundary (equivalent to 300 km above the 1 bar level). These temperatures are ~100 – 200 K smaller than those determined at 300 km by *Migliorini et al.* [2019]. Compared to the Galileo Probe measurements, our equatorial model temperatures are similar only at altitudes lower than 400 km; at higher altitudes our equatorial temperatures are ~100 – 600 K smaller than measured.

The differences between the model temperatures and observations act to highlight that there is still much work to be done in being able to reproduce the observations. Other sources of heat, such as wave heating [*Tao et al.*, 2009; *Müller-Wodarg et al.*, 2019], need to be included the model as well as a better understanding of the distant magnetospheric plasma flows.

4.1.2 Neutral winds

In addition to estimating thermospheric neutral temperatures, Jupiter's auroral IR emission can be used to determine the line-of-sight velocity of H_3^+ ions (Jupiter's main ionospheric constituent) using the Doppler shift technique [e.g. *Stallard et al.*, 2001; *Chaufray et al.*, 2011; *Johnson et al.*, 2017]. The works of *Stallard* and *Johnson* find regions where the ionosphere is super-corotating between ~0.5 – 1 km s^{-1} and regions where it is sub-corotating between ~1 – 2 km s^{-1}. *Chaufray et al.* [2011] however only found ionospheric winds sub-corotating at ~3 km s^{-1}. Additionally, *Chaufray et al.,* estimated neutral wind velocities in Jupiter's thermosphere using IR emissions from H_2; these were found to be of order ~1 km s^{-1} suggesting that the neutral thermosphere rotates faster than the ionosphere. The authors do note that more simultaneous neutral and ion wind measurements are needed to fully understand the system.

Our new 3D model obtains both super- and sub-corotating neutral winds and ion/plasma angular velocities. The neutral zonal winds achieve velocities between ~0.25 km s^{-1} (super-corotating) and ~−2.7 km s^{-1} (sub-corotating). We do not calculate ionospheric ion winds using the ion momentum equation but instead calculate the plasma angular velocity (using the Hill-Pontius equation described in section 2.4) within the magnetosphere and assume that the ionospheric plasma angular velocity is the same. In order to use this method, the magnetosphere interacts with an 'effective' neutral thermosphere and therefore an 'effective' neutral angular velocity Ω_T which is dependent on both the zonal and meridional neutral winds. The plasma angular velocity up to the auroral region ~74° tracks Ω_T very well albeit being a little smaller. Our model neutral and plasma velocities are comparable to those in the above observational studies up to the auroral oval region. Poleward of this region, our plasma flows are prescribed to rotate at a small fraction of Jupiter's rotation velocity as is shown in Fig. 2. The polar region neutral flows are strongly influenced by these prescribed flows and should be interpreted with a degree of scepticism. However, we note that the line-of-sight velocity of H_3^+ ions observed by *Johnson et al.* [2017] in their UV-dark region shows flows which are near stationary (<20% of Ω_J). If we assume that the UV-dark region applies to a "polar cap" type region then these observations add credence to our use of small plasma velocities. Nevertheless, more observations of Jupiter's polar ionosphere and outer magnetosphere are needed to further constrain the ionospheric flows and NASA's Juno [*Bolton et al.*, 2017] can shed some light on this poorly understood region.

4.2 Comparison with other Jovian 3D models

There are a few 3D Jovian upper atmospheric models which investigate Jupiter's MIT coupling (JIM and JTGCM). These models do not self-consistently couple the upper atmosphere to the magnetosphere but instead impose electric and magnetic fields, and MI coupling parameterizations onto the atmospheric model. They do however include detailed atmospheric chemistry and therefore include a somewhat realistic ionosphere. In contrast, the new model described in section 2 includes MIT coupling self-consistently in addition to solving the atmospheric neutral momentum and energy equations. It however, includes only a simplified conductivity parameterization representing Jupiter's ionosphere. The differences in the ionospheric components of these models result in different values of Pedersen conductances which is important in MIT coupling [e.g. *Ray et al.*, 2015]. The JIM [*Millward et al.*, 2002] model conductances are comparable ($1-3\times$) to those used in this study but conductances in JTGCM [*Bougher et al.*, 2005] are $\sim10\times$ higher than those employed here. Furthermore, we assume that our magnetic field model is rotationally-aligned and axisymmetric, contrary to the magnetic field models employed in JIM (offset tilted dipole [*Acuna et al.*, 1983]) and JTGCM (VIP4 [*Connerney et al.*, 1998]). We therefore perform only simple comparisons between this new model and previous Jovian 3D MIT models. We note that this new model, as described herein, is midway in its development to include self-consistent 3D MIT coupling.

With regards to neutral temperature, our model is generally colder than both JIM and JTGCM with the exception being in the low-altitude polar regions where our models have comparable temperatures. JIM's atmospheric temperature increases from 400 K at the models lower boundary to 1200 K at its upper boundary and is heated primarily by Joule heating and auroral particle precipitation. It is worth noting that while the JIM model did reach a quasi-dynamical equilibrium state it did not achieve thermal equilibrium during its model runs. JTGCM includes ion drag, particle precipitation and Joule heating but their Joule heating parameterization requires being down-scaled to 15% in order to reproduce equatorial temperature profiles comparable to those observed by the Galileo Probe. JTGCM's high-latitude temperatures reach ~1100 K in the southern polar region and ~900 K in the northern due to asymmetries in the VIP4 magnetic field model.

Zonal thermospheric neutral velocities were found to be of order ~0.5 km s^{-1} in the JIM model [e.g. *Millward et al.*, 2005] compared to ~1.6 km s^{-1} and ~0.6 km s^{-1} respectively in JTGCMs southern and northern auroral ovals [e.g. *Majeed et al.*, 2016]. These result from ion winds of ~1 km s^{-1} in JIM and ~3.5 km s^{-1} in JTGCM (note that ion winds are imposed in JTGCM). The zonal winds in our new model are typically stronger (more subcorotating) than both JIM and JTGCM, reaching sub-corotating values of ~2.7 km s^{-1}. Our model also includes a region equatorward of the auroral oval where the neutral atmosphere super-corotates with speeds up to ~0.25 km s^{-1} resulting from the Coriolis force and the strong ($\sim0.2-0.3$ km s^{-1}) low altitude poleward winds. Above the peak conducting region, our meridional flows switch to being equatoward and with similar speed. These equatorward flows slow down to only a few m s^{-1} at the equator. The meridional winds in JTGCM and JIM are stronger than in the model presented herein and reach poleward speeds up to ~0.6 km s^{-1} and equatoward speeds of ~0.25 km s^{-1}. As discussed above, JTGCM employs the VIP4 magnetic field model which causes considerable asymmetry in heating and neutral flows. As such, JTGCM also obtains strong ($\sim0.1-0.2$ km s^{-1}) equatorward flows even at low southern latitudes which allows for the redistribution of heat from the auroral region.

5 Summary and conclusions

Jupiter's upper atmosphere is ~700 K hotter than predicted based on solar EUV heating alone. The interaction with Jupiter's strong and dynamic magnetosphere is thought to play a vital role in heating its upper atmosphere to its observed temperatures. However, to date no coupled magnetosphere-ionosphere-thermosphere model has been able to self-consistently reproduce Jupiter's thermospheric temperatures without imposing particular plasma flows, large Pedersen conductances inconsistent with modelling/predictions, and/or including a low-latitude heat source such as acoustic wave breaking or small-scale Joule heating generated by fluctuating electric fields. We present a new model of Jupiter's MIT coupled system that couples a three-dimensional atmospheric general circulation model to an axisymmetric magnetosphere model. This new model is an intermediate step towards the development of a self-consistently coupled 3D atmosphere-magnetosphere model. We compare this new model to its two-dimensional predecessor, available observations and other 3D Jovian upper atmosphere models.

Compared to the 2D simulations of *Yates et al.* [2014], the new model has a mean temperature that is ~60 K hotter, with a maximum temperature that is ~200 K hotter in the polar regions. Zonal and poleward neutral winds were found to be comparable in both simulations while the equatorward winds are twice as strong (~190 m s^{-1}) in the new 3D simulation resulting in more energy transport from high to low latitudes. 3D vertical winds were also found to be 2-3× stronger in the upward direction and half as strong in the downward direction. The velocity shear between the neutrals and plasma is larger in the 2D simulation between 74 – 86° leading to larger MI coupling currents, powers, and UV emission. Our 3D model is still in development and is not yet fully comparable to the other 3D Jovian thermosphere models available. However, our model is converging towards the results found in the JIM and JTGCM models and unlike these models it also includes self-consistent coupling between the ionosphere and magnetosphere. Our model also compares reasonably well with some ionospheric wind observations and its predicted total UV power is of the same order of magnitude as those determined from HST observations. The neutral temperatures in the auroral and polar regions are comparable to the lower range of observed temperatures while the models equatorial temperatures are still a few 100 K colder than observed.

The axisymmetric rotationally-aligned magnetosphere model that we employ in this study results in a small (few degrees latitude) circular region of interaction between Jupiter's magnetosphere and atmosphere centred on 74° latitude. In actuality, Jupiter's magnetic field is tilted with respect to its rotation axis and has very complex structure [e.g. *Connerney et al.*, 2018]. Furthermore, observations of Jupiter's auroral emission - a 'visible' manifestation of the MI interaction - show that this interaction region is anything but small and circular; in fact, it is highly asymmetric within and between each hemisphere [e.g. *Connerney et al.*, 2017]. Such a complex asymmetric interaction region would lead to different neutral flow and heating structures which cannot be simulated with the current model setup. The JIM and JTGCM models, while not self-consistently coupling the atmosphere and magnetosphere, do employ more realistic magnetic field models at the planet which is one of the main reasons that their findings are different from those presented above. The next step in the development of the presented model is to include a more realistic magnetic field model [e.g. *Connerney et al.*, 2018] including realistic mapping from the magnetosphere to the ionosphere and local time variation, a more detailed ionosphere model [e.g. *Blelly et al.*, 2019], and parameterizations allowing for the incorporation of atmospheric waves [e.g. *Tao et al.*, 2009; *Müller-Wodarg et al.*, 2019]. This model will be the most realistic three-dimensional representation of Jupiter's coupled magnetosphere-atmosphere system.

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