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The ineffectiveness of Joule heating in the stratosphere

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ABSTRACT

Several papers have recently invoked Joule heating in the stratosphere, generated from electric currents induced by solar wind interactions with Earth, as possibly playing a significant role in warming the polar stratosphere. This commentary assesses the accuracy of that contention and demonstrates that in situ Joule heating can take no significant part in warming the stratosphere, and thus cannot be used to suggest a link between stratospheric temperatures and solar activity.

1. Introduction

When charged particles, their motion driven by an electric field, pass through a conducting medium in the form of an electric current, it produces heat. This frictional or Joule heating is generated by the energy given up by these charged particles when they are in collision with the constituent particles of the medium. In the case of a partly ionised atmosphere, the electrons and ions move in different directions under the action of the electric field and collisions with the particles of the neutral atmosphere dissipate energy and thus heat the atmosphere. At thermospheric altitudes in the polar regions, Joule heating is an important and effective source of energy and can heat the thermosphere by more than 400 K during an intense geomagnetic storm (Dobbin et al., 2006). During a period of geomagnetic activity, the maximum height-integrated energy production rate from Joule heating in the polar thermosphere can typically be $40\times10^{-3}\,\mathrm{J\,m^{-2}\,s^{-1}}$ (Ahn and Akasofu 1983). If we assume that most of this occurs between 90 and 130 km altitude (Ahn and Akasofu, 1983) then the mean Joule heating power input is approximately $1\times10^{-6}\,\mathrm{J\,m^{-3}\,s^{-1}}$.

Makarova et al. (2004), Zubov et al. (2005, 2006) have published results suggesting that Joule heating can also be effective in directly warming the stratosphere, that this can explain discrepancies in polar stratospheric temperatures within chemistry climate models, and that the warming may change the structure of the polar vortex, which would contribute to changes in global climate and weather systems. Makarova et al. (2004) calculated the power produced by Joule heating in the polar stratosphere to be typically $180\times10^{-6}\,\mathrm{J\,m^{-3}\,s^{-1}}$. That rate of stratospheric Joule heating energy generation is therefore two orders of magnitude greater than the Joule heating power input into the thermosphere. The stratosphere mass density is about six orders of magnitude greater than that of the thermosphere (MSISE00 model of Picone et al., 2002), and thus the actual temperature change that would be caused by the same Joule heating energy input will be $\sim10^6$ times less in the stratosphere than in the much more tenuous thermosphere. Nevertheless, Makarova et al. (2004) demonstrated that their calculated Joule heating rate of $180\times10^{-6}\,\mathrm{J\,m^{-3}\,s^{-1}}$ in the stratosphere would still lead to a heating rate of 1.2 K/day.

However, there appears to be no experimental evidence for such stratospheric heating during geomagnetic activity even though such a heating rate might be readily detectable as a consequence of a period of intense geomagnetic activity. Lu et al. (2007) used Hadley Centre HadAT2 data, which is based on radiosonde data (Thorne et al., 2005) over four solar cycles (1958–2004) to examine the effect of geomagnetic activity, defined by the Ap index, on stratospheric temperatures. Taking composites of high Ap conditions relative to low Ap conditions they found temperature increases reaching $\sim$0.5 K in the Arctic stratosphere (and elsewhere) from $\sim$100 hPa (approx. 18 km) to 30 hPa (approx. 25 km), which was the upper altitude limit of the analysis, poleward of $\sim50^{\circ}$N. However, this Ap effect is only present if a 2-month lag is imposed between the Ap data and the stratospheric data, implying that the temperature change is driven indirectly through dynamical processes and not, as would be the case for Joule heating, by a quasi-instantaneous effect. If the same analysis is undertaken with no lag between Ap and stratospheric temperature, then the high Ap relative to low Ap signature in the polar stratosphere tends to be negative, rather than positive, and is statistically insignificant (Lu: private communication). One process advocated for the possible presence

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of a lag between Ap and stratospheric temperature changes is the slow descent of NO_x generated by auroral precipitation (e.g. Clilverd et al., 2006).

The purpose of this commentary is to show that the Joule heating estimates in Makarova et al. (2004) are very significantly over-estimated and that the conclusions of Zubov et al. (2005, 2006) are consequently unrealistic. It re-calculates the Joule heating in the stratosphere to show that it is insignificant as a source of warming. It also aims to halt the spread of the consequent misconception, both within the scientific and wider communities, that there can be a link between solar activity and stratospheric temperature change through direct heating via electric currents.

2. Calculation of stratospheric Joule heating

Makarova et al. (2004) (from hereon referred to as "Mak04") calculated the Joule heating produced by electric current in the middle stratosphere at ~20–30 km altitude. Firstly they derived expressions for current density and conductance based on the equations of Alfven and Falthammar (1963) such that the conductivity $\sigma = \sum n_k e_k b_k$ where n_k is the number density of charged particles of type k which have charge e_k, and where b_k is a constant. This is a simplified equation, which can be applicable to basic calculations in the relatively collisionless environment of the thermosphere; however, it is less applicable to the collision-dominated environment of the stratosphere. Following the method of Mak04 and nevertheless applying this simplified approach to the stratosphere, there appears to be an oversight in Mak04 when converting to the Joule heating rate. The assertion in Section 2 of Mak04 that 'the ionic component is the main part in the expression of resistance' would appear to be unsubstantiated. This can be demonstrated, using two simple approaches, as follows.

Firstly, the resistance (if indeed this terminology can be applied to a plasma) as used in Mak04 is the inverse of the conductance and it is clear from combining Eqs. (3) and (6) from Mak04 that the conductance is proportional to $\sum (n_k e_k^2 / m_k v_k)$, where charged particles of type k have mass m_k, and collision frequency with the neutrals v_k. In this summation, the conductance will thus primarily be defined by the electrons because they have a mass at least four orders of magnitude smaller than that of any of the ions, but they have similar number density, charge and collision frequency.

Another way to assertain whether the simplified derivation of Mak04 is physically sound, is to consider what would happen if the ions were infinitely heavy. If this was the case, then the Joule heating should be entirely dependent upon the electrons because the ions would not move. However, in the Mak04 derivation of Joule heating (Mak04 Eq. (10)), ions with infinite mass would result in infinite Joule heating, which is clearly unrealistic.

However, as noted above these assertions are based on the simplified current equation used by Mak04. To more rigorously quantify the Joule heating in the stratosphere, the average drift velocity, u_k, used in Eqs. (1) and (2) of Mak04 should be replaced by the vector difference between the average ion velocity $\boldsymbol{V_i}$ and the average electron velocity $\boldsymbol{V_e}$ following a similar method to that used in Thayer and Semeter (2004). Then, assuming charge neutrality, we have

$$\boldsymbol{J} = n_e e (V_i - V_e) \tag{1}$$

$$\boldsymbol{V}_i = \boldsymbol{U}_n + [(k_i/B)\boldsymbol{E}' + (k_i/B)^2 \boldsymbol{E} x \boldsymbol{B} + (k_i/B)^3 (\boldsymbol{E} \cdot \boldsymbol{B}) B]/(1 + k_i^2) \tag{2}$$

$$\boldsymbol{V}_e = \boldsymbol{U}_n + [(k_e/B)\boldsymbol{E}' + (k_e/B)^2 \boldsymbol{E} x \boldsymbol{B} + (k_{ie}/B)^3 (\boldsymbol{E} \cdot \boldsymbol{B}) B]/(1 + k_e^2) \tag{3}$$

where $\boldsymbol{U}_n$ is the neutral wind velocity, E' indicates the electric field in the reference frame of the neutral bulk motion and k_i is ω_i / v_{in}, and k_e is ω_e / v_{en}.

It can be easily shown, by substitution for $k = \omega / v$, that the three terms, in square brackets, of Eqs. (2) and (3) when paired together into Eq. (1) relate to the three basic conductivities used in magnetohydrodynamics of the thermosphere. Thus the combined first terms are the Pedersen conductivity:

$$\sigma_1 = (n_e e / B)(\omega_{ci} v_{in} / (v_{in}^2 + \omega_{ci}^2) - \omega_{ce} v_{en} / (v_{en}^2 + \omega_{ce}^2)) \tag{4}$$

where ω_{ci} the ion gyrofrequency, ω_{ce} the electron gyrofrequency, and v_{in} and v_{en} are, respectively, the ion and electron collision frequencies with the neutral air.

The combined second terms are the Hall conductivity

$$\sigma_2 = (n_e e / B)(\omega_{ci}^2 / (v_{in}^2 + \omega_{ci}^2) - \omega_{ce}^2 / (v_{en}^2 + \omega_{ce}^2)) \tag{5}$$

and the combined third terms, σ_3, are σ_2^2 / σ_1 such that the first and third terms together give the Cowling conductivity as $\sigma_1 + \sigma_2^2 / \sigma_1$ (Parks, 1991, p284).

Note that the ion-neutral and electron-neutral collision frequencies can be very different, but in the stratosphere they are approximately equal. A rigorous calculation is very complicated because of the need to account for the distribution of velocities within the particle populations, but, as described by Rishbeth and Garriott (1969), it was shown by Chapman (1956) that they can be approximately represented by the equations $v_{in} \approx 2.6 \times 10^{-15} M^{-0.5} N$ and $v_{en} \approx 5.4 \times 10^{-16} T^{0.5} N$ where N is the neutral gas concentration, M the mean molecular mass of the air and T its temperature. If we take $M = 29$, $T = 220$ K and $N = 0.27 \times 10^{18}$ m^{-3}, then these equations give $v_{in} \approx 1.5 \times 10^9$ Hz and $v_{en} \approx 2.2 \times 10^9$ Hz. Thus, the ion-neutral and electron-neutral collision frequencies in the stratosphere are very similar and consequently for simplicity in the calculations below we use a single collision frequency $v = 1.5 \times 10^9$ Hz (the value used by Mak04). This is much greater than the electron gyrofrequency (typically ~1.5×10^6 Hz) or ion gyrofrequency (~50 Hz for O^+ for instance) and thus the conductivity terms reduce to

$$\sigma_1 = (ne/B)(\omega_{ci}/v - \omega_{ce}/v) \tag{6}$$

$$\sigma_2 = (ne/B)(\omega_{ci}^2/v^2 - \omega_{ce}^2/v^2) \tag{7}$$

$$\sigma_3 = (ne/B)(\omega_{ci}^3/v^3 - \omega_{ce}^3/v^3) \tag{8}$$

Substituting in the fact that the gyrofrequency $\omega = eB/m$, where B is the local geomagnetic field strength, and taking into account that the ions are at least 10^4 times the mass of an electron

$$\sigma_1 = n_i e^2 / m_i v - n_e e^2 / m_e v \approx -n_e e^2 / m_e v \tag{9}$$

$$\sigma_2 = n_i e^3 B / m_i^2 v^2 - n_e e^3 B / m_e^2 v^2 \approx -n_e e^3 B / m_e^2 v^2 \tag{10}$$

$$\sigma_3 = -n_e e^4 B^2 / m_e^3 v^3 \tag{11}$$

Taking values of $m_e = 9.1 \times 10^{-31}$ kg, $v = 1.5 \times 10^9$ s^{-1}, $e = 1.6 \times 10^{-19}$ C, $B = 30 \times 10^{-6}$ T, and $n_e = 4 \times 10^8$ m^{-3}, the magnitudes of the conductivity components therefore become

$$\sigma_1 = 7.5 \times 10^{-9}\,\mathrm{Sm^{-1}}$$

$$\sigma 2 = 26 \times 10^{-12}\,\mathrm{Sm^{-1}}$$

$$\sigma_3 = 93 \times 10^{-15}\,\mathrm{Sm^{-1}}$$

This demonstrates that in the highly collisional environment of the stratosphere the Pedersen conductivity, σ_1, dominates the other terms by over two orders of magnitude. At stratospheric altitudes, the movement of the electrons and ions is not primarily controlled by the electric field, as it is in the thermosphere, but is totally dominated by the motion of the neutral gas through