Joule heating due to vertical ion currents in the lower thermosphere over the dip equator

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The theory of equatorial electrojet predicts the presence of vertical ion currents (Pedersen currents) as a part of the electrojet current system. The vertical ion current density profile over the dip equator, that forms a part of the meridional current system is derived from an electrojet model. The joule heating due to these currents flowing upward during daytime for a local time for 1100 hrs has been estimated. The primary east-west current density of the model is kept at the same value as that measured by means of rocket-borne magnetometer on one occasion. The electrical power dissipated as heat in the narrow belt in the height region of 100–180 km is estimated and found to be significant. The height of maximum power dissipation coincides with the altitude of maximum ion velocity i.e. 122 km. By solving the heat conduction equation we obtain a maximum temperature increase of 8°K around 135 km. The importance of this localized heating in the lower thermosphere around $\pm 2^\circ$ of the dip equator is discussed.

1. Introduction

Global scale dynamo action in the E-region caused by the neutral winds, viz. ion-neutral colllisions results in currents being set up between 90–160 km, being carried mostly by ions. As this current is in general divergent, polarization electric fields ($\boldsymbol{E}$) build up instantaneously to force a non divergent current flow. These electric fields are height independent and drive Hall and Pedersen currents known as *Sq* currents.

The electric field E_x generated at the magnetic equator as part of the dynamo action (not by in situ winds) is eastward during the day and gives rise to a downward Hall current. However, as the upper and lower boundaries are non conducting, an upward vertical polarization field (E_r) is quickly set up opposing the downward Hall current. This field in turn drives the eastward (as there are no boundaries in the east-west direction) Hall current known as the "equatorial electrojet". Forbes (1981) has exhaustively reviewed the theory of equatorial electrojet and compared the theoretical predictions in the experimental observations.

Untiedt (1967) first visualized the inconsistency of arguments in having a single current system for the electrojet as the integrated layer conductivities viz. Pedersen and Hall conductivities vary with latitude even in the narrow latitude region of the electrojet. He then showed that meridional currents must exist, in addition to the primary east-west currents if the theory is to be self consistent and the currents must be divergence free. The meridional currents would essentially consist of two current cells on either side of the dip equator (clockwise in the southern and anti clockwise in the northern side, as seen from west) both of them adding and flowing upward over the dip equator during the day in a narrow latitude zone of $\pm 2^\circ$. It should be noted from basic physical considerations that the currents would be constituted of ions in the direction perpendicular to the magnetic field and would be of electrons parallel to the same. These vertical ion currents have successfully been invoked in the explanation of the generation of a deep valley in the plasma density profiles and the enhancement of plasma density around 100 km in the night-time equatorial E-region by Raghavarao *et al.* (1984).

The potential difference that is developed across the vertical currents adds to the already developed vertical polarization field and enhance the eastward current in the jet for a given eastward electric field (E_ϕ). At the equator the vertical electric field (E_r) could be written as

$$E_r = \left[\frac{\sigma_{\mathrm{H}}}{\sigma_{\mathrm{P}}} E_\phi + \frac{J_r}{\sigma_{\mathrm{P}}} \right]. \tag{1}$$

The present paper deals with the joule heating due to the daytime vertical ion currents, when the electrojet reaches its maximum intensity and shows that it is significant in the 100–160 km height region. Attempts have been made by the earlier workers (Kato, 1963; Sampath *et al.*, 1974) to explain the prevailing thermal imbalance between the constituents of the equatorial E-region, namely, electrons, ions and neutrals, by estimating the joule heating due to the horizontal electron currents, which preferentially heat up only the electrons leaving the neutrals unaffected. The vertical Pedersen current, unlike the horizontal electron Hall current, is constituted of ions and therefore the heating due to these currents will be imparted to the neutrals directly. We estimate the amplitude of the excess neutral temperature by the Joule heating and show that it is significant in the 100–160 km height region.

2. Method of Estimation of the Net Temperature Increase

The theoretical estimate of the net increase in the neutral temperature T_{n} due to the vertical ion current (J_r) is carried

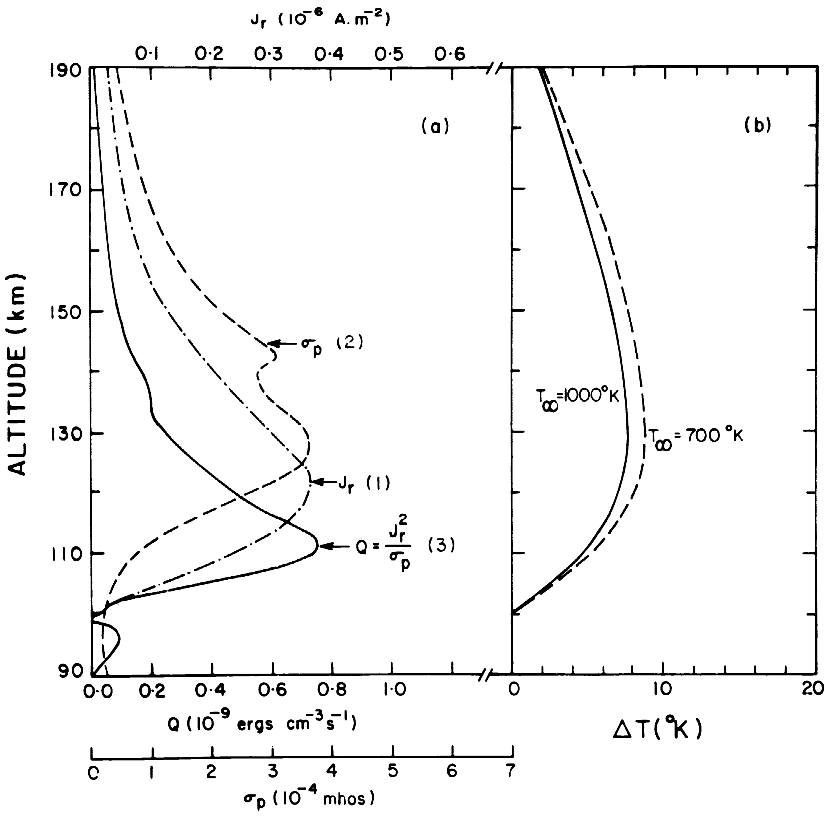

Fig. 1. (a): Altitude profile of (1) the vertical ion currents (J_r), (2) the Pedersen conductivity σ_P and (3) the dissipated power due to Joule heating (Q) over the dip equator for maximum east-west current density (J_ϕ) of 10.4 Amp/km^2 at a local time of 1100 hrs. (b): The profile of the increase in neutral temperature due to Joule heating for two exospheric temperatures.

out over the dip equator for noon time conditions. The vertical profile of the eastward current density (J_ϕ) measured at 1100 LT by Sampath *et al.* (1974) from TERLS (Thumba, India) is used to identify the strength of the primary eastward electric field. Sampath *et al.* (1974), had measured a maximum current density of 10.4 Amp/km^2 at 106 km. According to the electrojet model of Anandarao (1976) and Anandarao and Raghavarao (1979) the primary eastward electric field strength should then be 0.71 mV/m for a J_ϕ of 10.4 Amp/km^2 for a typical electron density profile (Rees *et al.*, 1976) for 1100 LT. The electron densities increased from 7×10^4 cm^{-3} at 90 km to 2.1×10^6 cm^{-3} at 140 km. The altitude profile of collision frequencies were estimated following Gagnepain *et al.* (1977) and incorporated in the model. We have considered a case without ambient neutral winds in making this estimate. The corresponding vertical ion currents are obtained from the model. These values could very well be taken as representative of the typical noontime conditions over the dip equator. Figure 1(a) depicts the model and computed values of the altitude profiles of the vertical ion currents, the Pedersen conductivity and the power dissipated due to the Joule heating. Curve (1) represents the J_r values over the dip equator at 1100 LT. The current density maximum is seen to occur at an altitude of 122 km. The Pedersen conductivity profile (curve (2)) shows a prominent maximum around 128 km and a smaller secondary maximum around 142 km. Above 100 km the conductivity is essentially due to the ion density and not due to that of electrons. Because of the finite conductivity and the flow of ion Pedersen currents a net power is dissipated as Joule heat $\boldsymbol{Q}$ which is equal to J_r^2/σ. The variation of $\boldsymbol{Q}$ with altitude estimated using J_r and σ_P profiles is shown by curve (3). The power dissipation is seen to maximize around 112 km altitude and is zero at 100 km where J_r is zero. The downward current below 100 km is constituted of electrons and therefore the dissipated power is not considered in the heating of the neutrals. This aspect is discussed later.

The calculated power dissipation $\boldsymbol{Q}$ is substituted in the thermal conduction equation to obtain the net neutral temperature increase.

The thermal conduction equation could be written as:

$$\lambda = \frac{d^2(\Delta T)}{dz^2} = -\boldsymbol{Q} \tag{2}$$

where λ (erg cm^{-3}K^{-1}s^{-1}) is the thermal conductivity and ΔT is the difference in temperature with and without Joule heating effects. The thermal conductivity parameter 'λ' and its altitude variation was determined for an atmospheric mixture following the expression.

$$\lambda = AT^{0.69} + BT + C \tag{3}$$

where A, B and C are coefficients given as 38.2, 1.90 and 51.4 corresponding to nitrogen rich atmosphere (Banks and

Kockarts, 1973) and are dependent on the neutral composition. The composition values are taken from the Jacchia-77 (1977) static models for typical exospheric temperature viz. 700°K and 1000°K and are made use of in the estimation of the conductivity parameter 'λ'. These estimates are only representative and usage of any other more recent model like the MSIS does not alter the main conclusion of the paper.

The integration of the thermal conduction equation is carried out numerically to obtain 'ΔT' with the boundary conditions viz. $\Delta T = 0$ at 90 km and at 200 km. The assumption for such boundary conditions is justified later.

Thus obtained 'ΔT' i.e. the increase in neutral temperature and its variation with altitude are plotted in Fig. 1(b) for both the exospheric temperatures i.e. 700°K and 1000°K. As seen, the 'ΔT' profiles have a broad maximum centered around 130 km, and the amplitude of increase being from 8–9°K. This increase in temperature at such low altitudes is significant and further, as the source of this heat is highly localized, has important consequences as would be discussed later.

3. Discussion

Joule heating arising from electric currents in the ionosphere is regarded as an important source of energy. Cole (1962, 1971) was the first to point out its importance in the dynamic and thermal structure of the thermosphere over auroral latitudes. It was Kato (1963) who first suggested the possibility of this mechanism being important at the equatorial latitudes. However, in the calculations, Kato (1963) had been dealing only with the east-west electron currents. Though the power dissipation due to these electron currents is significant and larger than the power dissipated by the ion currents, the transfer of energy to the neutrals is insignificant due to their large difference in masses. It is established that the energy exchange between different constituents of the ionosphere is essentially through inelastic collisions i.e. by the excitation of internal energy states (rotation, vibration, electronic) of the dominant neutral constituents viz. N_2 and O_2 (Banks and Kockarts, 1973). This is efficient because it permits the direct transfer of kinetic energy to the colliding particles without the intervening mass factor. However, in the case of thermal electrons, with energies <1.5 eV the inelastic collisions become virtually ineffective due to the non-availability of excited states in the colliding neutral species. Only elastic collisions transfer energy to the neutrals with an energy decrement of $2\, m_e/m_n$ where 'm_e' is the electron mass and 'm_n' is the neutral mass. Therefore one could conclude that though the power dissipation due to the electron currents is large, all the power is virtually shared only among electrons thus enhancing only the electron temperature 'T_e'.

Ions which quickly dissipate their energy and attain thermal equilibrium with neutrals, in contrast, can have an energy decrement of upto one-half as $2\, m_1 m_2/(m_1 + m_2) \simeq 1/2$ for elastic collisions in a gas composed of particles of nearly the same mass. Hence it will be the ion currents that will be able to alter the neutral temperature and not the electron currents. In fact the neutral temperatures inferred by means of composition measurements (Shirke *et al.*, 1977) over the dip equator during local noon also reveal considerably larger temperatures as compared to the corresponding model values which is indicative of at least one more source of heat apart from the solar UV radiation. In the evaluation of the net temperature increase 'ΔT' we have assumed that ΔT at 90 km is zero and it can be justified as the ion currents are nil in these altitudes and the currents are mainly constituted of electrons. The net power dissipation is zero and therefore no increase in neutral temperature is envisaged. Similar arguments apply to altitudes above 200 km.

Further, in the estimation of the excess neutral temperatures, we have made use of the electrojet model currents without ambient winds which happens to be a special case. Detailed modelling efforts by Anandarao and Raghavarao (1987) incorporating the measured winds have revealed that the vertical ion currents are altered considerably which will then get reflected in the estimated neutral temperature increase. Inclusion of actual winds and estimation of the Joule heating due to the wind modified currents and inturn the winds due to the localized heating altering the currents, is rather complex and much beyond the scope of the present paper. These aspects are extremely important when the thermal balance of the lower thermosphere is studied wherein one normally expects $T_e = T_i = T_n$ where T_e, T_i and T_n represent the electron, ion and neutral temperatures and on several occasions it had been noticed that there are some unexplained differences with T_e turning out to be larger than $T_i \sim T_n$ (Sampath *et al.*, 1974). So far all the emphasis had been in trying to account for the differences only through T_e. In the present exercise it is demonstrated that there does exit a possibility of the neutral temperatures going up thus being able to account for the difference much better.

The most interesting aspect of the Joule heating mechanism discussed in this paper is that, it is highly localized. The intensity of the vertical currents taper off sharply as one goes away from the dip equator on either side. Figure 2(a) depicts the altitude profiles of J_r at 0°, 2°, 4° and 6° dip latitude, while the estimated power dissipation at 130 km where the heating effects are maximum with latitude is depicted in Fig. 2(b). The dissipated power decreased steeply as one goes away from the dip equator and is close to zero around 4°. There is a slight tendancy to increase especially in the altitude region of 130–150 km. This means that the Joule heating effects and the excess neutral temperature will be correspondingly changed, essentially resulting in gradients in the neutral temperature. This infinitesimal increase might be due to the imposed boundaries to the model and could well be an artefact. The emphasis in the present paper is, to a latitude zone of $\pm 4°$ centered around the dip equator where the heating effects are maximum. The exact consequences of such gradients could possibly be worked out only in a detailed two dimensional modelling. However, there is a distinct possibility of local circulation cells getting set up. This may result in significant vertical winds. Earlier vapour release experiments have revealed (Anandarao *et al.*, 1978) the presence of vertical winds and these had been shown to have important repercussions like the generation of counter electrojet etc. (Raghavarao and Anandarao, 1980). At present the effects of the localized heating is only a conjecture calling for detailed, well planned experiments to verify the same.

Further, when the intensity of the primary electric field

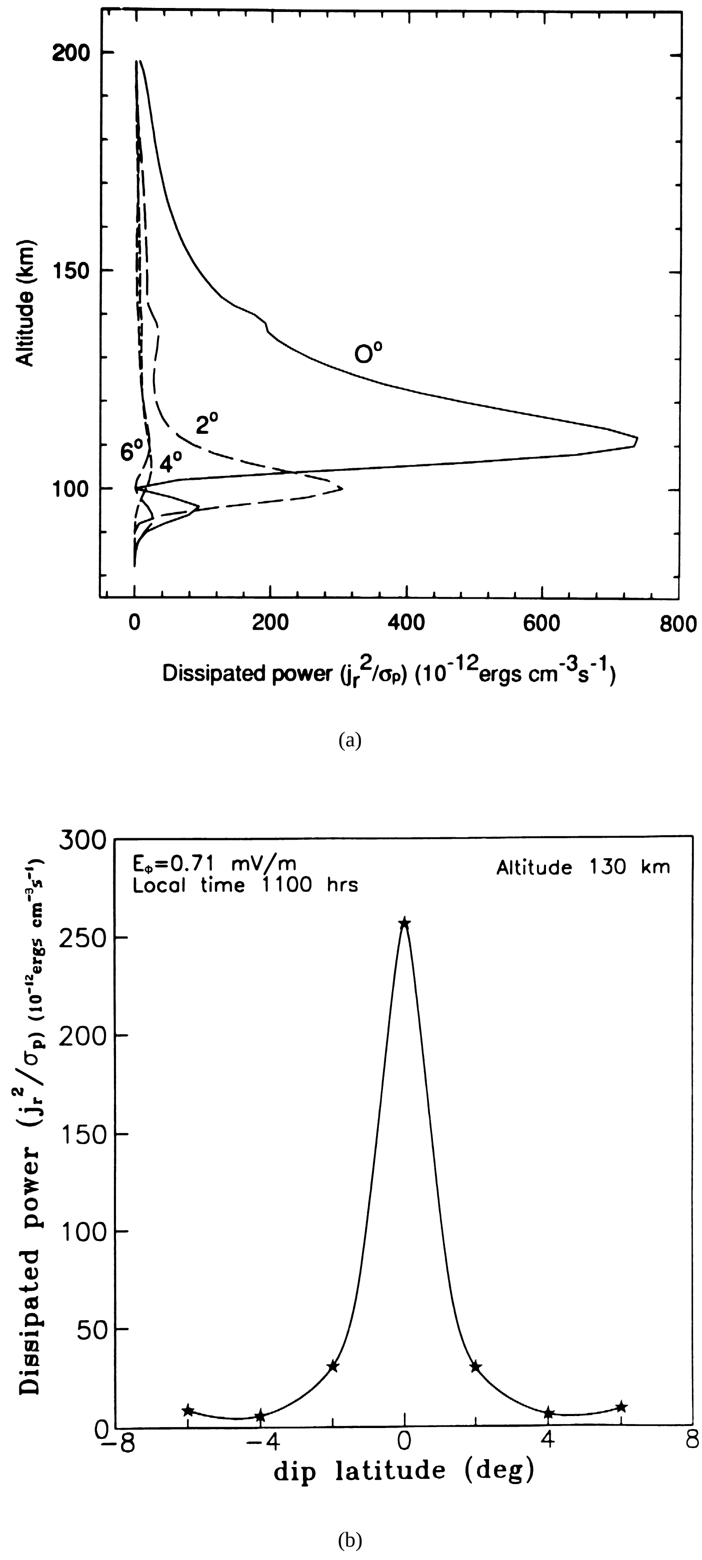

Fig. 2. (a): Altitude profile of the dissipated power at different latitudes for typical noon time conditions. (b): The dissipated power due to vertical ion currents with latitude at 130 km where the joule dissipation maximizes.

varies there will be a corresponding variation in the vertical currents and in the resultant joule heating. Such fluctuations could possibly result in the generation of waves. Detailed studies have revealed strong vertical shears in the horizontal winds and also presence of significant vertical winds which were earlier ascribed to internal atmospheric gravity waves (Anandarao and Raghavarao, 1979). The localized deposition of power due to Joule heating and its fluctuations could be source for these waves. The presence of this localized source of heat over the equator may possibly alter the equatorial circulation pattern in general and thus is considered to be an important aspect.

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References

Anandarao, B. G., Effects of gravity wave winds and wind shears on the equatorial electrojet, *Geophys. Res. Lett.*, **3**, 545–548, 1976.

Anandarao, B. G. and R. Raghavarao, Effects of vertical shears in the zonal winds on the electrojet, *Space. Res.*, **XIX**, 283–286, 1979.

Anandarao, B. G. and R. Raghavarao, Effects of vertical shears in the currents and fields of the equatorial due to zonal and meridional winds, *J. Geophys. Res.*, **92**, 2514–2526, 1987.

Anandarao, B. G., R. Raghavarao, J. N. Desai, and G. Haerendel, Vertical winds and turbulence over Thumba, *J. Atmos. Terr. Phys.*, **40**, 157–163, 1978.

Banks, P. M. and G. Kockarts, *Aeronomy Part B*, Academic Press, N.Y., 1973.

Cole, K. D., Joule heating of the upper atmosphere, *Aust. J. Phys.*, **15**, 223–235, 1962.

Cole, K. D., Electrodynamic heating and movement of the thermosphere, *Planet. Space Sci.*, **19**, 59–75, 1971.

Forbes, J. M., The equatorial electrojet, *Rev. Geophys. Space Phys.*, **19**, 469–504, 1981.

Gagnepain, J., M. Crochet, and A. D. Richmond, Comparison of equatorial electrojet models, *J. Atmos. Terr. Phys.*, **39**, 1119–1124, 1977.

Jacchia, L. G., Smithsonian. Astrophys. Obs. Special Rep., No. 375, 1977.

Kato, S., Joule heating at the magnetic equator, *Planet. Space Sci.*, **11**, 1297–1302, 1963.

Raghavarao, R. and B. G. Anandarao, Vertical winds as a plausible cause for equatorial counter-electrojet, *Geophys. Res. Lett.*, **7**, 357–360, 1980.

Raghavarao, R., R. Sridharan, and R. Suhasini, The importance of vertical ion currents in the nighttime ionization in the equatorial electrojet, *J. Geophys. Res.*, **89**, 11033–11037, 1984.

Rees, D., P. D. Bhavsar, J. N. Desai, S. P. Gupta, A. D. Farmer, and P. Rounce, Preliminary report on commonwealth collaborative rocket programme from Thumba equatorial rocket launching station for the investigation of atmospheric and ionospheric processes, *Space. Res.*, **XVI**, 407–412, 1976.

Sampath, S., T. S. G. Sastry, K. Oyama, and K. Hirao, Joule heating due to the equatorial electrojet as observed by rocket-borne probes, *Space. Res.*, **XIV**, 253–258, 1974.

Shirke, J. S., R. Sridharan, S. R. Das, A. D. Danilov, A. A. Pokhunkov, and V. A. Semenov, Simultaneous measurements of ionospheric parameters at the dip equator, *Space. Res.*, **XVII**, 403–407, 1977.

Untiedt, J., A model of the equatorial electrojet involving meridional currents, *J. Geophys. Res.*, **72**, 5799–5810, 1967.

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