anorthositic layered complexes[6] and lesser incidence of Banded Iron Formation. The difference in magnetic signature of the Eastern and Western blocks can be explained either in terms of the difference in environment of deposition and/or the difference in grades of metamorphism. This difference can be due to either or a combination of the following: (a) The Western Dharwar has a larger sedimentary component, while the Eastern is dominantly volcanic in origin. (b) Metamorphism affects the nature of iron compounds in rocks and thus affects susceptibility. The magnetic field of the Eastern Dharwar is consistent with a higher grade of metamorphism compared to the Western Dharwar. (c) The Eastern Dharwar craton might have been uplifted with respect to the Western Dharwar craton, with the characteristics of the deeper crustal layers now exposed by erosion.

Any theory of the evolution of the Dharwar craton should incorporate the difference between the Eastern and the Western Dharwar, as evidenced from different data sets: magnetic, geology, gravity, heat flow, radiometric dating, seismic, magneto-telluric, etc.

1. Pichamuthu, C. S., *J. Geol. Soc. India*, 1962, **3**, 106–118.
2. Harikumar, P., Rajaram, M. and Balakrishnan, T. S., *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, 2000, **109**, 381–391.
3. Project Vasundhara, Special Publication AMSE Wing, Geological Survey of India, Bangalore, 1994.
4. Swami Nath, J., Ramakrishnan, M. and Viswanatha, M. N., *Rec. Geol. Surv. India*, 1976, **107**, 149–175.
5. Subrahmanyam, C. and Verma, R. K., *Tectonophysics*, 1982, **84**, 225–245.
6. Radhakrishna, B. P. and Vaidyanadhan, R., Text Book Series, No. 6, Geol. Soc. India, 1997, p. 354.
7. Geological Survey of India, *Seismotectonic Atlas of India and its Environs*, 2000.
8. Geological Survey of India, *Catalogue of Aerogeophysical Maps*, Airborne Mineral Surveys and Exploration Wing, Bangalore, India, 1995.
9. Johnson, A., Cheeseman, S. and Ferris, J., *Ann. Geofis.*, 1999, **42**, 249–259.
10. Nayak, S. S., Kasiviswanatham, C. V., Reddy, T. A. K. and Nagaraja Rao, B. K., *J. Geol. Soc. India*, 1989, **31**, 343–346.
11. MacLeod, I. N., Jones, K. and Dai, T. T., *Explor. Geophs.*, 1993, **24**, 679–687.
12. Roset, W. E., Verhoef, J. and Pilkington, M., *Geophysics*, 1992, **57**, 116–125.

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Thermospheric temperature and magnetic field measurements from Mt Abu during a geomagnetically disturbed period – a case study

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During the recovery phase of a 'moderate' geomagnetic storm, spectroscopically measured night-time thermospheric temperatures from Mt Abu (24.6°N, 73.7°E, dip 19.09°) are found to deviate considerably (~ 200–600 K) from the MSIS-90 model temperatures on many occasions, implying the model's limitations as applied to low-latitude thermosphere. The measured temperatures exhibit oscillatory features as opposed to the flat, featureless temperature profiles rendered by the MSIS-90 model. The temperature variabilities are found to succeed the variations in the time rate of change of the total magnetic field measured by a standard Proton Precession Magnetometer by ~ 12.5 h, revealing the 'response time' of the low-latitude thermosphere to the disturbances over higher latitudes.

HIGH-resolution spectroscopic measurements of the thermospheric temperatures from the broadening of the OI 630.0 nm atomic oxygen line (O^1D–O^3P) are widely used to decipher the kinetic temperature of the neutral thermosphere. It is known that a Fabry–Perot (FP) spectrometer is an ideal device for such measurements owing to its large light-gathering power at high spectral resolution[1]. Most of the earlier measurements were concentrated on mid and high latitudes and measurements from low-equatorial latitudes are rather sparse[2–4]. However, with the advent of multi-instrumented, coordinated investigations using space as well as ground-based platforms, it is now understood that the neutral thermosphere and the ionized ionosphere do not act in isolation, and they are coupled by various electrodynamical and neutral dynamical processes. Thermospheric temperature data from a low-latitude station can be very useful to understand the various coupling (energetic as well as dynamic) aspects of the high and low latitude thermosphere–ionosphere system (TIS) during varying geophysical conditions.

During geomagnetic storms, large amount of energy gets injected in the high-latitude region primarily in the form of energetic particle precipitation. This excess energy then gets redistributed through meridional wind circulation (owing to the pressure difference between the

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poles and the equator), and alters the heat budget of the low-equatorial latitude thermosphere[5], the manifestation of which is seen in the form of temperature enhancements of ~ 100–600 K in the low-latitude regions[6]. During such disturbed geophysical conditions, it has been noted that the measured temperatures deviate[6,7] significantly from the temperatures rendered by MSIS (86/90), a semi-empirical model[8] which predicts thermospheric temperatures on the basis of indices related to solar UV and high-latitude precipitating particle fluxes, e.g. $F_{10.7}$, K_P or A_P, etc. On the other hand, the magnitude and spatial configurations of the currents flowing in the auroral ionosphere change substantially in response to the ionospheric perturbations[9,10] brought forth by the geomagnetic storms (e.g. through an electric field) and, as a consequence, the global upper atmospheric current systems get modulated. As an example, one can notice that the strength of the magnetospheric ring current (symbolized by D_{st}) which flows over the low-equatorial latitudes, increases during geomagnetic storms. Apart from these, the energy injection at high latitude triggers a broad spectrum of gravity waves which, dissipate their energy by heat conduction, viscosity and ion drag during their propagation[11]. In a nutshell, the manifestations of geomagnetic storms in low-latitude TIS depend on the prevalent coupling processes between the high and low latitude TIS. A comprehensive understanding of these coupling aspects is still due.

Although the magnitude of the storm effects is smaller and mostly indirect at low-latitude thermosphere, the effects do persist for a significantly longer period even after the storm subsides[12]. The time-delayed response of the low-latitude thermosphere to geomagnetic forcing has been shown using satellite data[13]. On the basis of a case study using ground-based high-resolution spectrometer data, Pant and Sridharan[6] clearly established that the low-latitude thermosphere ~ 20° dip latitude (Mt Abu) takes about 14–16 h to respond to the forcings during a magnetic storm. To arrive at the above conclusion, time-delayed cross correlation analysis was performed between the deviations of observed F-region temperatures (ΔT_n) from the MSIS-90 model and the time rate of change of the ring current index D_{st}. It was shown that the D_{st} variations act as a precursor to the variabilities in the neutral temperatures. Recently, it has been shown by the same investigators using the *in situ* measured neutral temperatures by the DE-2 satellite and the ring current index D_{st}, that the low-latitude thermosphere has a seasonally varying time-delayed response to any energy input over the polar regions[14].

Although the current systems and the neutral thermosphere throughout the globe respond to the geomagnetic disturbances, the 'response times' are different. Thermospheric responses are known to be 'sluggish' in comparison to the ionospheric and magnetospheric responses. Thus, over low latitudes, it can be expected that the upper atmospheric current systems would respond to the magnetic storm at an earlier instant of time than the neutral thermosphere. However, to find out a time delay between the signatures of the magnetic and the thermospheric perturbations, one needs to have reasonably identifiable features, if any, in the magnetic and temperature variations. It is in this context that the present investigation has been carried out to explore the possibility of correlation, if any, between the time rate of change of the total magnetic field (B) measured by a standard Proton Precession Magnetometer (PPM) (Geometrics, model G856) stationed at Mt Abu, and the thermospheric temperature (T) variabilities recorded by the high-resolution FP spectrometer at the same location during a moderate geomagnetic storm. Details regarding the experimental set-up of FP spectrometer and the data reduction technique are available in the literature[15].

Figure 1 illustrates the variations in the ring current index D_{st} from 7 to 18 March 1999. It is evident from Figure 1 that the period is marked by the recovery phase of a geomagnetic storm (A_p was 34 on 10 March). The mean D_{st} variation remained negative mostly throughout the period, with three major depressions around 7–8 March, 9–11 March and 15–17 March. Simultaneous nocturnal thermospheric temperature and magnetic field data were available for 8, 9, 11 and 17 March. Temperature data were available every night for ~ 3–3.5 h with a datum point in ~ 22 min. Since PPM was set to record the magnetic field fluctuations every 2 min, the magnetic field values recorded by the PPM were first subjected to a running average of 11 points and a time-averaged representative of dB/dt was taken. It is found that the variations in dB/dt with a time delay of ~ 12.5 h match well

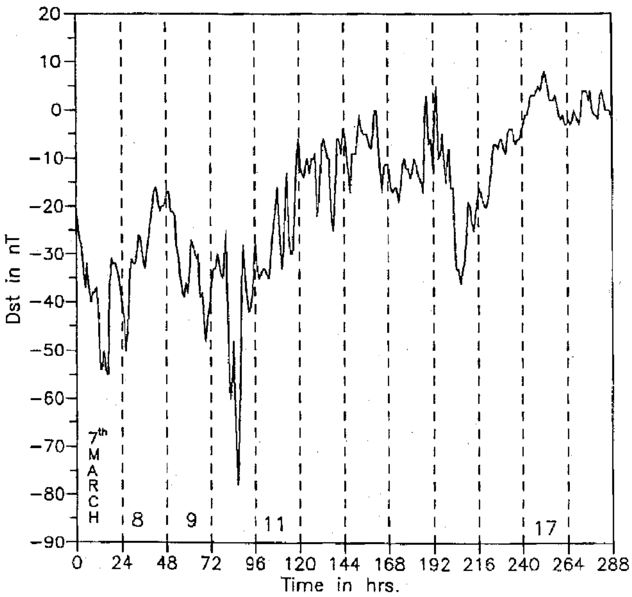

Figure 1. Variations of the D_{st} index during 7–18 March 1999.

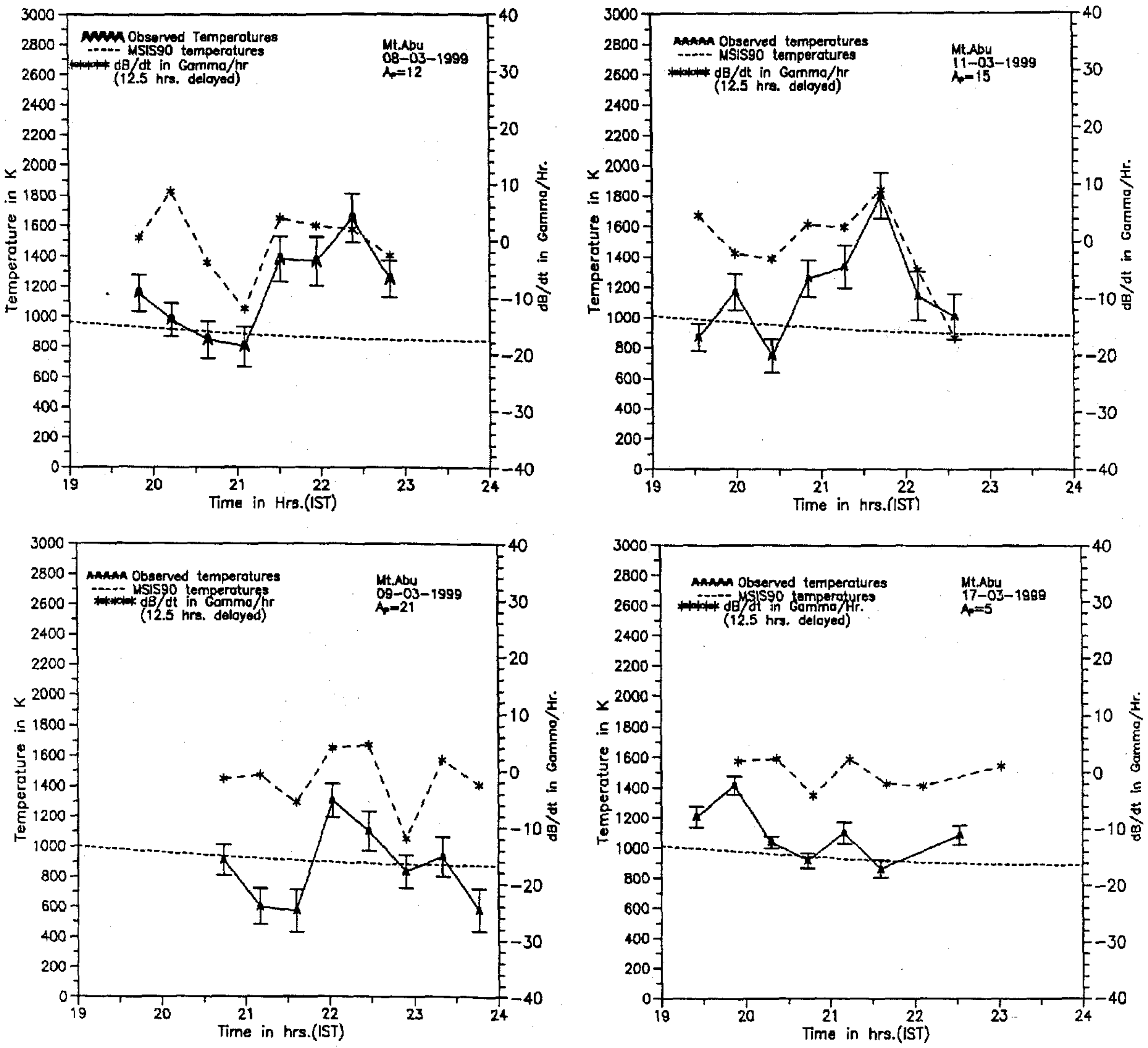

Figure 2. Nocturnal variations of the observed thermospheric temperatures (along with error bars) are plotted with the time delayed d*B*/d*t*. MSIS-90 model predicted temperatures are also shown.

with the variations in the measured temperatures for all the four nights under investigation (Figure 2). MSIS-90 model predicted temperatures are also plotted in Figure 2. It is noticed that the model does not reproduce the variabilities in the experimentally measured temperatures and on all the nights provides flat and featureless temperature profiles. On certain occasions, especially on 8 and 11, one notices large deviations in temperatures (~ 200–600 K) compared to those from the MSIS-90 model values within ~ 1–1.5 h. It is also seen that, among all the nights, the measured temperatures on 17 March closely follow the model-predicted values.

The similarities between the time delayed d*B*/d*t* and *T* indicate that during disturbed geophysical conditions, the electrodynamical perturbations on the upper atmospheric current systems (of which *B* is due) precede the neutral dynamical forcings and the time delay is representative of the 'response time' of the thermosphere over low latitudes. This is possible since the electrodynamical forcing is often instantaneous in nature and is manifested in the form of modifications in the electric field and current systems throughout the globe, almost simultaneously. Neutral dynamical forcings, on the other hand, take certain time to affect the thermal budget of the low-latitude thermosphere and this is found to be ~ 12.5 h in the present investigation. The time delay varies with season, solar epoch, etc. and is in close agreement with the time delay found by Pant and Sridharan[14] for March. The similarities between the time delayed d*B*/d*t* and *T* open up another possibility to appropriately modify the MSIS model in order to make it more realistic for low latitudes, by incorporating the total magnetic field (measured locally) in place of the ring current index D_{st} (which is a global index) in the empirical relation suggested by Pant and Sridharan[14]. The deviations from the model values (and also the oscillatory features) which are indicative of the arrival of the excess energy from the high latitudes by equatorward meridional wind circulation and gravity waves, can then be deciphered using the relationship and can be added with the MSIS model temperatures to estimate the observed temperatures. Interestingly, one notices that on 17 March, when the ring current almost recovered the pre-storm values, the measured temperatures closely follow the model-predicted values, substantiating the fact that on that day the low-latitude thermosphere experiences little 'non-local' energetical influence. It is to be noted that PPM does not discriminate between the magnetic fields generated by the ionospheric and magnetospheric current sources and as a result, variabilities in the magnetic field recorded by a PPM are due to the superposition of the variations of both ionospheric and magnetospheric components. Thus, it is difficult to address the detailed physical mechanisms responsible for the features noticed in the magnetic field variations. However, this does not alter the propositions made in the present investigation to explain the delayed thermospheric response over low latitudes to geomagnetic forcing. More coordinated and multi-instrumented investigations are needed to understand such aspects of the magnetosphere–ionosphere–thermosphere coupling.

1. Hernandez, G. and Killeen, T. L., *Adv. Space Res.*, 1988, **3**, 149–213.
2. Biondi, M. A. and Meriwether, J. W., *Geophys. Res. Lett.*, 1985, **12**, 267–270.
3. Sahai, Y. *et al.*, *Planet. Space Sci.*, 1992, **40**, 1545–1549.
4. Sastri, J. H. and Ranganathrao, H. N., *J. Atmos. Terr. Phys.*, 1994, **56**, 775–782.
5. Prolls, G. W., *J. Geophys. Res.*, 1982, **87**, 5260–5266.
6. Pant, T. K. and Sridharan, R., *Ann. Geophys.*, 1998, **16**, 1513–1518.
7. Gurubaran, S., Sridharan, R., Suhasini, R. and Jani, K. G., *J. Atmos. Terr. Phys.*, 1995, **57**, 695–703.
8. Hedin, A. E., *J. Geophys. Res.*, 1991, **96**, 1159–1264.
9. Foster, J. C., Holt, J. M., Musgrove, R. G. and Evans, D. S., *Geophys. Res. Lett.*, 1986, **13**, 656–659.
10. Knipp, D. J. *et al.*, *J. Geophys. Res.*, 1989, **94**, 16913–16923.
11. Richmond, A. D., *ibid*, 1979, **84**, 1880–1890.
12. Fuller Rowell, T. J. and Rees, D., *J. Atmos. Terr. Phys.*, 1981, **43**, 701–721.
13. Burns, A. G. and Killeen, T., *Geophys. Res. Lett.*, 1992, **10**, 977–980.
14. Pant, T. K. and Sridharan, R., *J. Atmos. Sol. Terr. Phys.*, 2001, **63**, 987–992.
15. Gurubaran, S. and Sridharan, R., *J. Geophys. Res.*, 1993, **98**, 11629–11635.

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