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Thermospheric zonal temperature gradients observed at low latitudes

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Abstract. Fabry-Perot interferometer (FPI) measurements of thermospheric temperatures from the Doppler widths of the OI 630 nm nightglow emission line have been carried out at Cachoeira Paulista (23° S, 45° W, 16° S dip latitude), Brazil. The east-west components of the thermospheric temperatures obtained on 73 nights during the period from 1988 to 1992, primarily under quiet geomagnetic conditions, were analyzed and are presented in this paper. It was observed that on 67% of these nights, the temperatures in both the east and west sectors presented similar values and nocturnal variations. However, during 33% of the nights, the observed temperatures in the west sector were usually higher than those observed in the east sector, with zonal temperature gradients in the range of 100 K to 600 K, over about an 800 km horizontal distance. Also, in some cases, the observed temperatures in the east and west sectors show different nocturnal variations. One of the possible sources considered for the observed zonal temperature gradients is the influence of gravity wave dissipation effects due to waves that propagate from lower altitudes to thermospheric heights. The observed zonal temperature gradients could also be produced by orographic gravity waves originated away, over the Andes Cordillera in the Pacific Sector, or by dissipation of orographic gravity waves generated over the Mantiqueira Mountains in the Atlantic sector by tropospheric disturbances (fronts and/or subtropical jet streams).

Key words. Atmospheric composition and structure (airglow and aurora; thermosphere - composition and chemistry) Ionosphere (equatorial ionosphere)

1 Introduction

The OI 630 nm nightglow emission comes from the O_2^+ dissociative recombination process (O_2^+ + e → O^* + O) in the bottomside of the F-region (250–300 km). By measuring the Doppler shifts and widths of the OI 630 nm nightglow emission line, using a Fabry-Perot interferometer, it is possible to infer the thermospheric winds and temperatures, respectively, at the heights of the OI 630 nm emission layer. Thus, the Fabry-Perot interferometer has become a powerful instrument to study the thermosphere dynamics and the thermosphere/ionosphere coupling at high, mid and low latitudes (Sipler et al., 1982; Hernandez and Roble, 1984; Rees et al., 1984; Yagi and Dyson, 1985; Biondi et al., 1990; Sahai et al., 1992a, 1992b; Sastri and Ranganath, 1994; Gurubaran et al., 1995; Fagundes et al., 1995a, 1995b, 1995c, 1996a, 1996b, 1998; Bittencourt et al., 1997; Meriwether et al., 1996, 1997).

Fabry-Perot interferometer (FPI) measurements of the OI 630 nm nightglow emission line have been carried out at Cachoeira Paulista (23° S, 45° W, 16° S dip latitude), Brazil, during the period of 1988 to 1992, thereby allowing a study of several important features of the thermosphere under geomagnetically quiet or disturbed conditions (Sahai et al., 1992a, 1992b; Fagundes et al., 1995a, 1995b, 1996a, 1996b, 1998; Bittencourt et al., 1997). Sahai et al. (1992a, 1992b) presented important features of the seasonal behaviour of the thermospheric wind velocities and temperatures during the rapidly increasing phase of the solar flux (March 1988, $F_{10.7} = 113.8$ and December 1989, $F_{10.7} = 206.3$) at Cachoeira Paulista. Also, Fagundes et al. (1996a, 1998) studied the thermosphere/ionosphere coupling during quiet and disturbed geomagnetic conditions, using the observed wind and temperature gradient temporal variations to infer the plasma drift velocities.

Although optical instruments have been widely used to study the upper atmosphere for nearly half a century, the observations of thermospheric neutral winds and temperatures at low latitudes, using a FPI, are still recent and are providing interesting and novel scientific results. Fagundes et al. (1996a, 1998) observed unusually large thermospheric zonal temperature gradients at Cachoeira Paulista (23° S), Brazil, and Meriwether et al. (1996, 1997) observed both zonal temperature and wind gradients at Arequipa (16.5° S), Peru.

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Table 1. A list of observation dates, solar-geomagnetic conditions temperature gradients and mean nocturnal temperature, considered in this study

Date	$F_{10.7}$ [W/m^2 Hz]	Kp					Temperature gradients (west/east)	$\overline{T}$ (west – east)
22 March 88	117.6	1−	1−	1−	0+	1+	No	995
08 December 88	164.1	1	1+	2−	0+	0+	Yes	1416
03 May 89	190.6	2−	1+	4+	4−	2+	No	1241
26 October 89	171.7	5	4+	4+	3+	3+	Yes	1306
11 November 89	249.1	4	4−	3+	3	2+	No	1372
10 April 91	223.6	1−	1+	1	1	1	Yes	1472
07 July 91	226.1	2+	3−	2+	3−	4−	Yes	1009
09 August 91	154.6	3	3−	1+	2+	3	Yes	816
10 August 91	145.7	1+	2−	4+	4	4	Yes	841
05 September 91	166.2	3	3−	3	4+	3−	No	1183
07 September 91	177.1	3−	1+	4−	3+	2+	No	1244
28 January 92	230.6	3−	2	2+	3+	3+	Yes	1059
04 April 92	154.0	3	2−	3	2	3−	No	982
27 May 92	117.7	2+	2−	2	2−	3+	No	756

In this paper, we present a study of the occurrence and possible sources of the observed thermospheric zonal temperature gradients recorded at Cachoeira Paulista, using a series of 73 nights of observations (the nights studied had more than 3 hours of measurements) obtained during the period from 1988 to 1992, primarily under quiet geomagnetic conditions and mid-high solar activity. It should be pointed out that, to a certain extent, uniformity of temperature in the thermosphere is expected due to its high viscosity. The MSIS-90 model (Hedin, 1991) predicts very small east-west thermospheric temperature gradients for low latitudes.

2 Instrumentation

The FPI characteristics have been presented by Sahai et al. (1992a and 1992b). The parallelism adjustment of the etalon (15 cm diameter) and the wavelength scanning are performed by three optically contacted piezoelectric pads. Also, the temperature of the etalon is controlled ($\pm 0.1^{\circ}$C). A 64-channel digital analyzer is used to scan the interferometer in wavelengths and several scans are added in order to increase the signal-to-noise ratio. The number of additions depends on the ability to maximize the OI 630 intensity level without losing time resolution. The error in the inferred Doppler temperature is $\pm 40^{\circ}$C for an OI 630 nm emission intensity level of 200 R. The peak height of the OI 630 nm emission is around the 240 to 270 km altitude. Since the FPI can observe in the four cardinal points (north, south, east and west) at an elevation angle of 30°, the zonal horizontal distance between the observed points is about 800 to 900 km. It should be mentioned that we do not have measurements in the zenith position, and the zonal and meridional winds are calculated from the differences between east-west and north-south peak wavelength displacements of the observed fringe profiles (Sahai et al. 1992a).

3 Results and discussion

During the period of 1988 to 1992, mostly under quiet geomagnetic conditions and mid-high solar activity, a total of 73 nights of thermospheric temperature observations has been analyzed. One of the prominent features in the observed thermospheric temperatures at low latitudes (South American sector) is the occasional presence of strong thermospheric zonal temperature gradients. This feature has been reported by two independent research groups from observations carried out in two different locations in the South American sector. The first report was based on observations made at Cachoeira Paulista (23° S, 45° W, Atlantic side) by Fagundes et al. (1996a) and the second one was based on observations made at Arequipa (16.5° S, 71.5° W, Pacific side), Peru, by Meriwether et al. (1996, 1997). Table 1 lists the dates of the selected nights presented in this study, the mean nocturnal temperature, the observed temperature gradients and the solar-geomagnetic conditions. We consider the existence of a significant temperature gradient when there is a continuous difference that is greater than 100 K in the thermospheric temperatures between the east and west sectors (over about 800 km horizontal distance) for more than three hours.

Figure 1 presents a map of South America showing the locations of the Andes (west side) and Mantiqueira (east side) Mountains. Also, the sub-ionospheric points (~ 270 km altitude) of the FPI beams in the east-west direction are marked on the map for both the Cachoeira Paulista and Arequipa observatories.

The temperature gradients are more often and prominently observed in the zonal direction at Cachoeira Paulista, but the meridional temperature gradients were also observed on a few occasions. In this paper, we shall concentrate our analysis and discussion only on the zonal direction observations. Figures 2 and 3 show the temperatures observed in the east and west directions for a few representative nights with and

Table 2. Number of nights analyzed with/without thermospheric zonal temperature gradients for three solar flux levels

$F_{10.7}$ [W/m^2 Hz]	< 150	150–200	> 200	Total of Nights
Number of Nights	12	32	29	73 (100%)
With Gradients	4 (33%)	9 (28%)	11 (37%)	24 (33%)
Without Gradients	8 (67%)	23 (72%)	18 (63%)	49 (67%)

without temperature gradients. The nighttime temperature variations predicted by the MSIS-90 model (Hedin, 1991) are also presented in Figs. 2 and 3 for some nights and for two different longitudes (23° S, 41° W, closed square; and 23° S, 49° W, open circle) at the 270 km altitude, but at Cachoeira Paulista local time. These two locations are close to the positions at which the FPI observes the temperatures in the east and west directions, respectively, from Cachoeira Paulista. Notice that the MSIS-90 model gives, in general, a very small east-west temperature gradient ($\sim$ 25 K over a range of 800 km). Sahai et al. (1992) have reported that the observed thermospheric temperatures at Cachoeira Paulista are in good agreement with the MSIS-86 model for the winter and equinox seasons. However, the MSIS model results primarily represent average conditions and do not exhibit the day-to-day variability present in the thermospheric temperatures. Table 2 shows the details of all the nights analyzed (73 nights) with and without zonal temperature gradients as a function of solar activity.

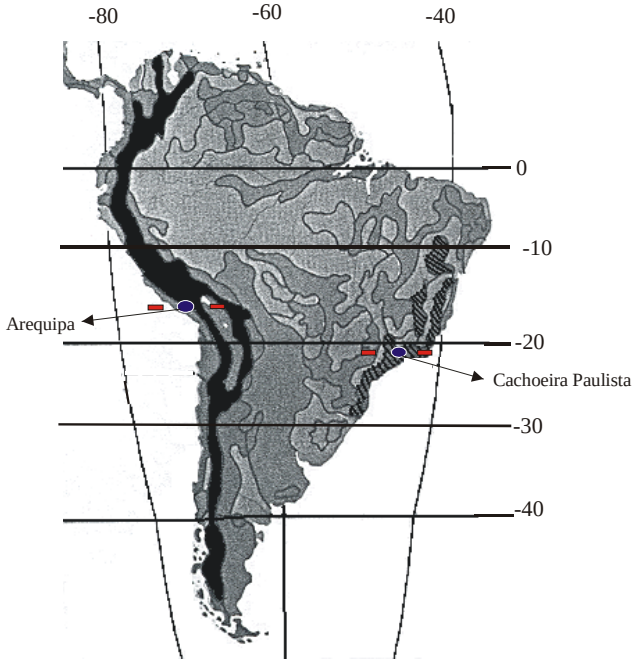

Fig. 1. Map of South America showing the location of the Andes Cordillera (left side - black) and of the Mantiqueira Mountains (right side - hatched) and the zonal sub-ionospheric points ($\sim$ 270 km) for Cachoeira Paulista and Arequipa.

3.1 Observations without temperature gradients

On most of the nights on which thermospheric temperatures were observed, during the period from 1988 to 1992, the temperature to the east and to the west directions at Cachoeira Paulista presented similar nighttime features and magnitude. Figure 2 shows the temperatures observed in the east and west directions for some representative nights without temperature gradients. On 49 (67%) out of the 73 nights of observation, the temperature behaviour was similar to that shown in Fig. 2.

It is noted that the observed temperatures in the west and east sectors presented very similar nocturnal variations during these nights. Also, this behaviour remains the same in both sectors (T_E over the sea and T_W over the continent) when the observed temperatures presented either smooth nighttime variations (e.g. 22 March 1988) or wave-like variations (e.g. 11 November 1989). On the nights when the thermospheric temperature variations showed wave-like structures, it is seen that the temperatures in both sectors presented a similar amplitude of variation (100 K to 400 K). These wave-like variations could possibly be caused by the presence of gravity waves at the thermospheric heights, in periods of a few hours.

3.2 Observations with temperature gradients

During the period studied, 24 nights (33%) showed the presence of significant zonal temperature gradients. Table 2 shows the number of nights that presented zonal temperature gradients and the number of nights that did not, for three different levels of solar activity. It is noted that the occurrence of zonal temperature gradients is somewhat higher when $F_{10.7} > 200$ [W/m^2 Hz] (37%) than when $F_{10.7}$ is between 150–200 [W/m^2 Hz] (28%). This indicates that the occurrence of zonal temperature gradients has some dependence on solar activity level and this result agrees with that previously presented by Meriwether et al. (1997). However, we find that the occurrence of zonal temperature gradients, when $F_{10.7} < 150$ [W/m^2 Hz] (33%), is similar to that when $F_{10.7} > 200$ [W/m^2 Hz] (37%), but due to the small number of nights (12) when $F_{10.7} < 150$ [W/m^2 Hz], these results must be considered with some reservation. The number of nights analyzed when $F_{10.7}$ is between 150–200 [W/m^2 Hz] and $F_{10.7} > 200$ [W/m^2 Hz] are more significant (32 and 29

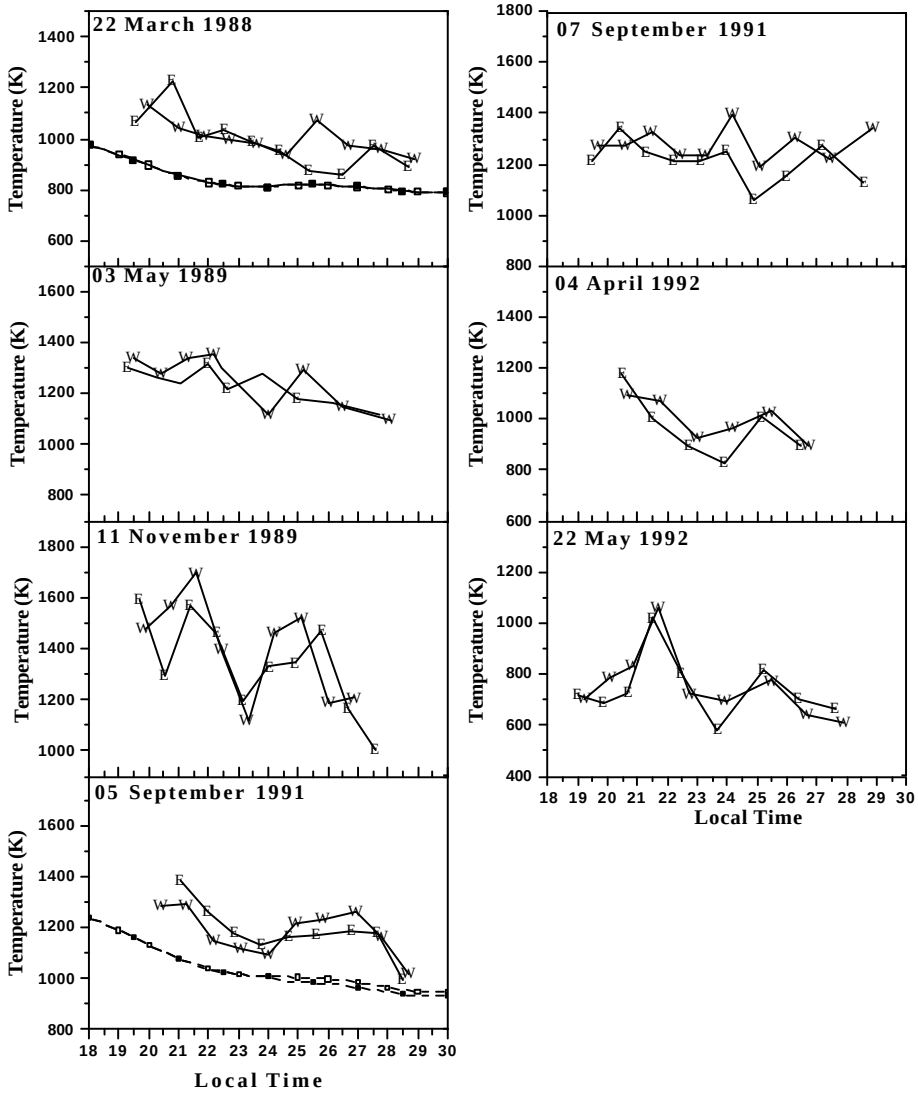

Fig. 2. Nighttime variations of the observed temperatures to the east and west, for representative nights without thermospheric zonal temperature gradients. The temperatures obtained from the MSIS-90 model are also shown for two different longitudes (23° S, 41° W, closed square) and (23° S, 49° W, open circle) at 270 km of altitude.

nights, respectively), so that these results are more representative. The dependence of the observed temperature gradients on solar activity could be associated with the increase in the F-region electron density with solar activity and possible increase in the transmission of gravity waves from the lower to the upper atmosphere (Meriwether et al., 1997). It should be mentioned that Meriwether et al. (1997) observed thermospheric temperature gradients only during the winter in the high solar activity period, whereas in the present investigations, thermospheric temperature gradients occurred in all seasons with medium to high levels of solar activity.

3.3 Possible mechanisms causing zonal temperature gradients

Meriwether et al. (1996, 1997) have suggested that the temperature gradients observed at Arequipa (16.5° S, 71.5° W) are produced by orographic gravity wave viscosity dissipation. They have suggested that low-frequency components of orographic gravity waves are generated at low-altitudes (troposphere) at the Andes Cordillera and propagate vertically to thermospheric heights, where these waves are dissipated, producing a localized region of heating. Also, Meriwether et al. (1997) proposed that the temperature gradients observed at Cachoeira Paulista (23° S, 45° W) (Fagundes et al., 1996a) are just a manifestation of the same heating source, since any perturbation in the thermosphere may extend farther to the east, away from the Andes, and then reach Cachoeira Paulista.

Since the thermospheric zonal wind flows eastward during the night for almost the whole year, neutral air which is heated at Arequipa could reach Cachoeira Paulista. However, this heated neutral air has to travel a distance of approximately 26° ($\sim$ 2600 km) and for a typical eastward wind of 100 m/s at thermospheric heights, this neutral air will reach Cachoeira Paulista about 7 hours later. There is no physical restriction for perturbations travelling from the Andes (Pacific) to Brazil (Atlantic), but there are some physical obstacles for its occurrence. The typical horizontal distance be-

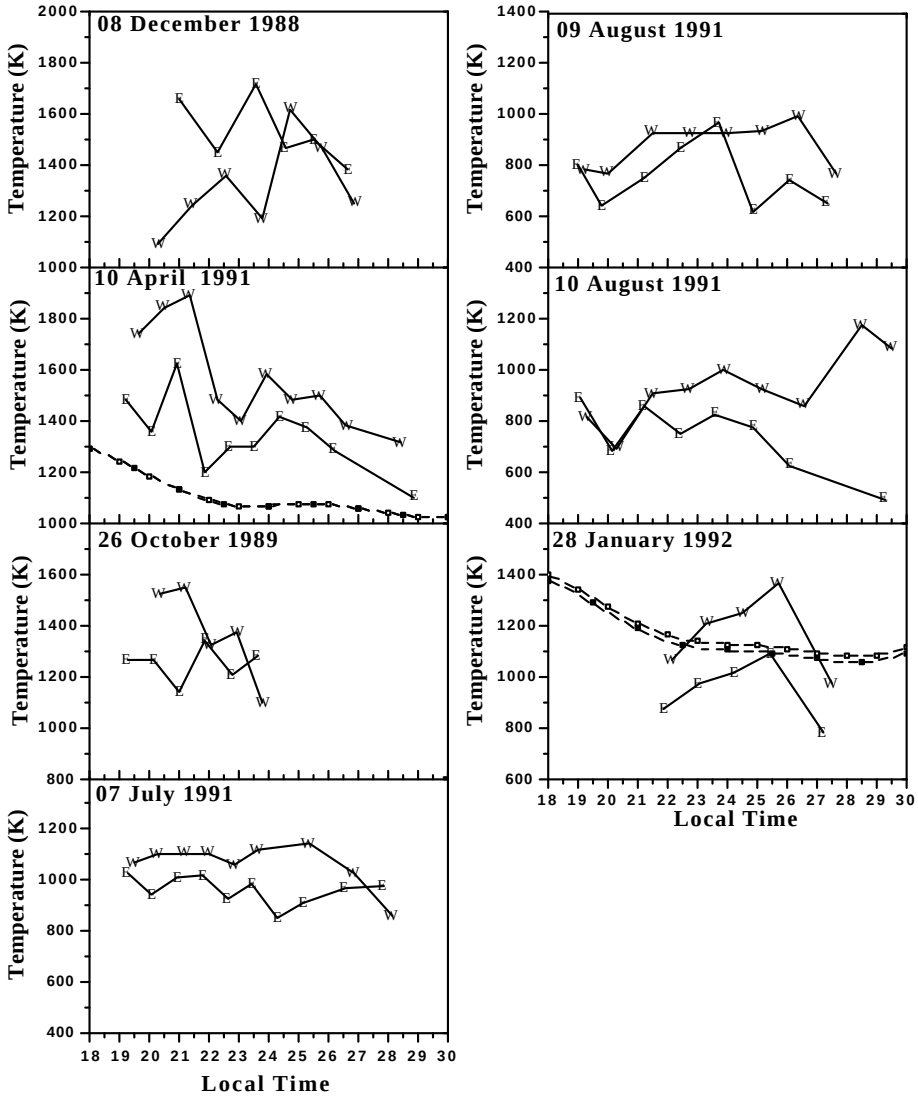

Fig. 3. Nighttime variations of the observed temperatures to the east and west, for representative nights with thermospheric zonal temperature gradients. The temperatures obtained from the MSIS-90 model are also shown for two different longitudes (230° S, 41° W, closed square) and (23° S, 49° W, open circle) at 270 km of altitude

tween the observed east-west sectors in FPI observations is about 800 km. Since we are observing temperature gradients at Cachoeira Paulista of about 100 K to 600 K (Fig. 3), the neutral air flowing eastward has to lose about 12.5 K to 75 K per each 100 km, respectively. Taking into account that the thermospheric neutral air heated at the Andes has to travel $\sim$ 2600 km to reach Cachoeira Paulista, the total temperature decrease during this long travel is estimated at 325 K to 1950 K, respectively (considering orographic heating over the Andes as a point heat source). Therefore, it is possible to explain temperature gradients of the order of 100 K at Cachoeira Paulista by taking into account the heating produced at the Andes (Pacific sector). Nevertheless, it is almost impossible to explain the temperature gradients at Cachoeira Paulista which are larger than 200 K, without taking into account other sources of localized heating. However, we have to bear in mind that the spatial structure (longitudinal/latitudinal) of orographic gravity waves generated over the Andes (which is about 300 km across) is not yet known.

It is, therefore, necessary to consider other possible sources of thermospheric heating in addition to that proposed by Meriwether et al. (1997) for the observations at Cachoeira Paulista. Ionospheric processes, such as ion-neutral coupling effects, could provide another source leading to thermospheric temperature gradients. However, within the ionosphere itself, the main longitudinal dependent factor is the geomagnetic field geometry or magnetosphere/ionosphere coupling. Since most of the observations reported here were obtained during relatively quiet geomagnetic conditions and the observation regions are fairly close in space, we could rule out the possibility of longitudinal variations contributing to the observed temperature gradients in ionospheric processes. Also, as mentioned by Meriwether et al. (1997), magnetic activity effects would not produce the form of localized heating which is observed.

Hines (1960) drew attention to the importance of atmospheric gravity waves at ionospheric heights. Sources for medium-scale gravity waves include tropospheric distur-

Table 3. Details of tropospheric disturbances in the region of observation on the nights of measurements with/without thermospheric temperature gradients (Source: Climanalise, a monthly publication by INPE)

	# of nights with observations	# of days with meteorological data available	# of days with tropospheric disturbances (passage of fronts/or sub tropical jet streams)
Nights with E-W temperatures gradients	24	23	9 (39%)
Nights without E-W temperatures gradients	49	47	6 (13%)

bances, such as the jet streams, frontal systems and penetrative convection (e.g. Bertin et al., 1978). Table 3 shows the details of the tropospheric disturbances (fronts and subtropical jet streams) present in the region close to the observation site on days with and without thermospheric temperature gradients. The Mantiqueira Mountains have several peaks as high as 2500 m in altitude. Thus, an additional source for some of the observed temperature gradients could be the interaction of the tropospheric disturbances with the Mantiqueira Mountains (which occupies an extensive region around 22° S, 44° W), thereby producing large vertical wavelength waves that propagate upward from mountains. Zonal temperature gradients in the thermosphere at low latitudes have only been identified in the last 5–10 years and their cause is still not completely understood. More simultaneous thermospheric and ionospheric observations from regions with different topography will be important to provide additional information for a better understanding of the sources of thermospheric zonal temperature gradients at low latitudes.

4 Conclusions

We have analyzed thermospheric temperature variations (on 73 nights) observed at Cachoeira Paulista (23° S, 45° W), during the period from 1988 to 1992, under primarily quiet geomagnetic conditions and mid-high solar activity. The main features associated with the occurrence of thermospheric zonal temperature gradients are summarized below:

1. Of the 73 nights studied, during the period from 1988 to 1992, 33% of the nights presented thermospheric zonal temperature gradients. Also, the occurrence of zonal temperature gradients have some dependence on the solar activity level and are observed in all seasons.

2. One of the possible sources for zonal temperature gradients greater than 100 K (over 800 km horizontal distance), at Cachoeira Paulista, is the heating produced in the Andes by orographic gravity waves, as suggested in a recent study by Meriwether et al. (1996, 1997). Nevertheless, it is not possible to explain the observed temperature gradients at Cachoeira Paulista larger than 200 K, without taking into account other localized heating sources.

3. Orographic gravity waves may be generated at the Mantiqueira Mountains and their dissipation at thermospheric heights may induce a localized heating and, consequently, produce an additional source for the observed temperature gradients.

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References

Biondi, M. A., Meriwether, J. W., Fejer, B. G., and Gonzalez, S. A., Seasonal variations in the equatorial thermospheric wind measured at Arequipa, Peru. J. Geophys. Res., 95(A8), 12, 243–250, 1990.

Bertin, F., Kersley, L., Rees, P. R., and Testud, J., Meteorological jet stream as source of medium scale gravity-waves in thermosphere - an experimental study, J. Atmos. Terr. Phys., 40(10), 1161–1183, 1978.

Bittencourt, J. A., Sahai, Y., Fagundes, P. R., and Takahashi, H., Simultaneous observations of equatorial F-region plasma depletions and thermospheric winds, J. Atmos. Terr. Phys., 59, 1049–1059, 1997.

Fagundes, P. R., Aruliah, A. L., Rees, D., and Bittencourt, J. A., Gravity wave generation and propagation during geomagnetic storms over Kiruna (67.8° N, 21.4° E), Ann. Geophysicae, 13, 358–366, 1995a.

Fagundes, P. R., Sahai, Y., Bittencourt, J. A., and Takahashi, H., Observation of thermospheric neutral winds and temperatures at Cachoeira Paulista (23° S, 45° W) during a geomagnetic storm, Advances in Space Research, 16(5), 27–30, 1995b.

Fagundes, P. R., Sahai, Y., Bittencourt, J. A., and Takahashi, H., Relationship between generation of equatorial F-region plasma bubbles and thermospheric dynamics, Advances in Space Research, 16(5), 117–120, 1995c.

Fagundes, P. R., Sahai, Y., Bittencourt, J. A., and Takahashi, H., Plasma drifts inferred from thermospheric neutral winds and temperature gradients observed at low latitudes, J. Atmos. Ter. Phys., 58(11), 1219–1228, 1996a.

Fagundes, P. R., Sahai, Y., Takahashi, H., Gobbi, D., and Bittencourt, J. A., Thermospheric and mesospheric temperatures dur-

ing geomagnetic storms at 23° S, J. Atmos. Ter. Phys., 58 (16), 1963–1972, 1996b.

Fagundes, P. R., Bittencourt, J. A., Sahai, Y., Takahashi, H., and Teixeira, N. R., Plasma drifts inferred from thermospheric neutral parameters during geomagnetic storms at 23° S, J. Atmos. Terr. Phys., 60, 1303–1311, 1998.

Gurubaran, S., Sridharan, R., Suhasini, R., and Jani, K. G., Variabilities in the thermospheric temperatures in the region of the crest of the equatorial ionization anomaly – a case study, J. Atmos. Terr. Phys., 57 (6), 695–703, 1995.

Hedin, A. E., Extension of the MSIS Thermospheric Model into the Middle and Lower Atmosphere, J. Geophys. Res., 96, 1159–1172, 1991.

Hernandez, G. and Roble, R. G., The geomagnetic quiet nighttime thermospheric wind pattern over Fritz Peak observatory during solar cycle minimum and maximum, J. Geophys. Res., 89 (A1), 327–337, 1984.

Hines, C. O., Internal atmospheric gravity waves at ionospheric heights, Can. J. Phys., 38, 1441–1481, 1960.

Meriwether, J. W., Mirick, J. L., Biondi, M. A., Herrero, F. A., and Fesen, C. G., Evidence for orographic wave heating in the equatorial thermosphere at solar maximum, Geophys. Res. Lett., 23 (16), 2177–2180, 1996.

Meriwether, J. W., Biondi, M. A., Herrero, F. A., Fesen, C. G., and Hallenback, D. C., Optical interferometic studies of the nightime equatorial thermosphere: Enhanced temperatures and zonal wind gradients, J. Geophys. Res., 102 (9), 20, 041–058, 1997.

Rees, D., Greenaway, A. H., Gordon, R., McWhirter, I., Charleton, P. J., and Åkesteen, The doppler imaging system: Initial observations of auroral thermosphere, Planet. Space Sci., 12 (3), 273–285, 1984.

Sahai, Y., Takahashi, H., Fagundes, P. R., Clemesha, B. R., Teixeira, N. R., and Bittencourt, J. A., Observations of thermospheric neutral winds at 23° S, Planet. Space Sci., 40, 767–773, 1992a.

Sahai, Y., Takahashi, H., Teixeira, N. R., Fagundes, P. R., Clemesha, B. R., and Bittencourt, J. A., Observations of thermospheric temperatures at 23° S, Planet. Space Sci., 40, 1545–1549, 1992b.

Sastri, J. H. and Ranganath, H. N. R., Optical interferometer measurements of thermospheric temperature at Kavalur (12.5° N, 78.5° E), India. J. Atmos. Terr. Physics, 56 (6), 775–782, 1994.

Sipler, D. S., Barry, B. L., and Biondi, M. A., Fabry-Perot determinations of midlatitude F-region neutral winds and temperatures, Planet. Space Sci., 20 (10), 1025–1032, 1982.

Yagi, T. and Dyson, P. L., Measurements of thermospheric temperatures at mid-latitude station, Planet. Space Sci., 33 (2), 203–206, 1985.