Comparison of meteor radar and TIDI winds in the Brazilian equatorial region

Ana Roberta Paulino[1], Delis Otildes Rodrigues[1], Igo Paulino[2], Lourivaldo Mota Lima[1], Ricardo Arlen Buriti[2], Paulo Prado Batista[3], Aaron Ridley[4], and Chen Wu[4]

[1]Departamento de Física, Universidade Estadual da Paraíba. Rua Baraúnas, 351. Campina Grande, PB, Brazil.
[2]Unidade Acadêmica de Física, Universidade Federal de Campina Grande. Rua Aprígio Veloso, 882. Campina Grande, PB, Brazil.
[3]Division of Heliophysics, Planetary Science and Aeronomy, National Institute for Space Research. Avenida dos Astronautas, 1.758. São José dos Campos, SP, Brazil.
[4]University of Michigan, 1416 Space Research Building Ann Arbor, MI 48109-2143, USA.

Correspondence: A. R. Paulino (arspaulino@gmail.com)

Abstract. Using data collected from a meteor radar deployed at São João do Cariri (7.4^{o}S, 36.5^{0}S^{o}W) and the TIMED Doppler Interferometer (TIDI) on board of the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) satellite for 2006, comparisons of the horizontal winds (meridional and zonal components) were made in order to evaluate these techniques for scientific investigation investigations and pointed out advantages of each instrument. A grid of ± 5 degrees of latitude and longitude centered at São João do Cariri was used to calculate the mean winds from the TIDI, which have a resolution of 2.5 km, starting from 82.5 km up to 102.5 km altitude. Otherwise, the meteor radar computes the winds winds was computed for 7 layers of 4 km overlapping 0.5 km above and below, which produces layers spaced by 3 km from 81 to 99 km altitude. When almost simultaneous measurements were compared, substantial discrepancies were observed in the vertical wind profiles. It happened because the meteor radar uses one hour bin size to estimate the wind from the echoes detected in the whole sky. While TIDI measures quasi instantaneous winds from the airglow emissions of a small region. In contrast, when the longer period of observation was taken into account, the time temporal meteor radar wind variations along the day, averaged within the months, were smoothed and showed more clearly the characteristics of the propagation of tides. The responses of the horizontal wind to the intraseasonal, semiannual and annual oscillations were satisfactory for both techniques.

1 Introduction

The mesosphere and lower thermosphere (MLT) is rich in dynamical processes. A large spectrum of mechanical oscillations can be observed in this region, it includes gravity waves, atmospheric tides, planetary waves, seasonal oscillations, quasi-biennial oscillations and so on. Those phenomena are important to understanding the general circulation of the atmosphere because the propagation of the waves can transfer energy and momentum among different levels (Smith, 2012).

Wind measurements in the MLT are important to investigate the interaction between the background atmosphere and waves (e.g., Hindley et al., 2022). The main instruments that have been used to estimate the wind in this region are: meteor radar (e.g., Jones et al., 1998; Buriti et al., 2008); mesosphere-stratosphere-troposphere radar (e.g., Balsley et al., 1980; Qiao et al., 2020);

middle and upper atmosphere radar (e.g., Fukao et al., 1985); laser imaging, detection, and ranging (LIDAR) (e.g., Clemesha et al., 1981); medium frequency radar (e.g., Igarashi et al., 1996) and Fabry-Perot interferometer (e.g., Fujii et al., 2004). In the last decades, satellite measurements of the wind have contributed to ~~know~~ the knowledge of global responses of planetary, tidal and gravity and others using wind measurements (e.g., Killeen et al., 2006; Niciejewski et al., 2006).

The meteor radar is a relatively moderate cost instrument used in the studies of the MLT dynamics. Generally, the meteor radar can estimate hourly horizontal wind from 80 to 100 km altitude (e.g., Hocking and Thayaparan, 1997; Paulino et al., 2015). This time sample is very good to investigate long period oscillations like tidal and longer period waves (e.g., Lima et al., 2006). Nevertheless, those kind of measurements have been used to investigate the background atmospheric conditions for the propagation of short period gravity waves (e.g., Fechine et al., 2009; Bageston et al., 2011; Carvalho et al., 2017, and references therein).

On the other hand, satellite measurements can provide ~~instantaneous winds~~quasi instantaneous winds, because it is necessary by about 2 min of integration. The TIMED Doppler Interferometer instrument (TIDI) on board of the Thermosphere-Ionosphere-Mesosphere Energetic Dynamics (TIMED) satellite can provide horizontal winds with 2.5 km vertical resolution from 82.5 km up to 102.5 km (Killeen et al., 2006; Niciejewski et al., 2006). Besides, the high resolution sample of the TIDI measurements is useful to investigate short period gravity waves (e.g., Baumgarten et al., 2018).

In the tentative of better understanding the potential of the satellite wind measurements, some questions appear: (i) how does TIDI winds compare with meteor radar measurements? (2) what are the advantages and disadvantages of each technique? Some works have been published elsewhere trying to answer such questions (e.g, Xu et al., 2009; John et al., 2011; Su et al., 2014). The present work aims to advances in this topic comparing measurements of a meteor radar deployed at São João do Cariri (7.4^{o}S, 36.5^{o}W) to the TIDI measurements for a grid of ~~$10^o \times 10^o$~~ $5^o \times 5^o$ (latitude × longitude) centered at São João do Cariri during 2006. Salient aspect of instantaneous and long period ~~observation~~ observations will be presented and discussed.

2 Instrumentation and Observations

The meteor radar is an instrument consisting of ~~a~~ an interferometric receiver set of yagi antennas of two elements, a transmitter yagi antenna of three elements, a receiver and a transmitter modulus. It operates at 35.24 MHz emitting 2144 pulses per second. The meteor radar uses the ablation of the meteoroids that penetrate in the MLT region. The ionized trails serve to reflect the transmitted radio waves back to the ground as meteor echoes. Operating with a low power of 12 kW, the ~~low power~~ meteor radar can detect between 1,000 and 3,000 echoes per day (e.g., Hocking et al., 2001). Depending on the position of the Earth in its orbit, the planet can find more or less particles, which introduce large variability of the detected echoes. During the day there is a strong variability as well, the radar detects more meteors in the early morning than the evening, it is explained by the motion in the orbit as well. For meteor radars deployed at middle and high latitude there is also a strong seasonal variation in the detection of echoes.

The traveling time of the radio waves from the transmitter antenna, reflecting in the trail and coming back to the receiver antennas allows to calculate the distance of the detected meteor. The set of receive antennas in an asymmetric cross configuration is used to estimate the location of the meteor in the sky. Lastly, the Doppler shift of the signal gives the information of the wind that is pushing the meteor trails (e.g., Hocking, 2005).

Using the parameters described above, the next step is estimate the mean wind components. It is necessary to define vertical and temporal bin sizes to estimate the northward and eastward winds. In the present work, seven layers of 4 km thickness overlapping 0.5 km above and below were used in the vertical profiles, while the temporal resolution was one hour (Clemesha et al., 2001; Paulino et al., 2012).

Basically, the TIMED Doppler Interferometer (TIDI) is a Fabry-Perot interferometer on board the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) satellite. The TIDI is equipped with a charged coupled device (CCD) and has four identical telescopes, besides the modulus of control and operation (Killeen et al., 2006).

The TIDI was designed to measure wind and temperature in the MLT region from 70 to 120 km altitude using the airglow emissions as tracer. The interferometer measures the radiation from the OI5577 and rotational line of O_2(0,0) airglow emission. It has a vertical resolution of 2.5 km and an accuracy of $\sim$3 m/s for the estimated wind (Skinner et al., 2003; Niciejewski et al., 2006).

Thus, in the MLT region there are overlapping measurements from the meteor radar and TIDI that can be used to comparisons and, consequently, it can be used to identify advantages of each instrument for different kind of scientific investigations. The present work aims to contribute on this topic by comparing data collected during 2006 by a meteor radar deployed at São João do Cariri (7.4^{o}S, 36.5^{o}W) with the measurements by the TIDI, considering a geographical grid of $\pm$ 5 degree of latitude and longitude, centered at São João do Cariri. The size of this window approximately coincides to the field-of-view of the meteor radar. This meteor radar started to operate is 2005 and during the year of 2006 it had an excellent data acquisition with high quality data, that is the reason for choosing 2006 to make the comparisons, which has an adequate temporal window to reach the objetives of this work.

3 Data analysis and Discussion

Figure 1 shows vertical profiles for meridional (blue) and zonal (red) winds. Solid lines represents the meteor radar measurements at 14:00 universal time (UT) on 15 March 2006, while the dashed (14:13 UT), dot-dashed (14:15 UT) and dotted (14:17 UT) lines represent the TIDI measurements on the same day. One can observe that there are large discrepancies between two measurements, even within a short time interval. Although these discrepancies are well known by the community, in this paper, we have returned this discussion with the objective to show which technique is more advantageous to do investigation using MLT wind with a short time interval.

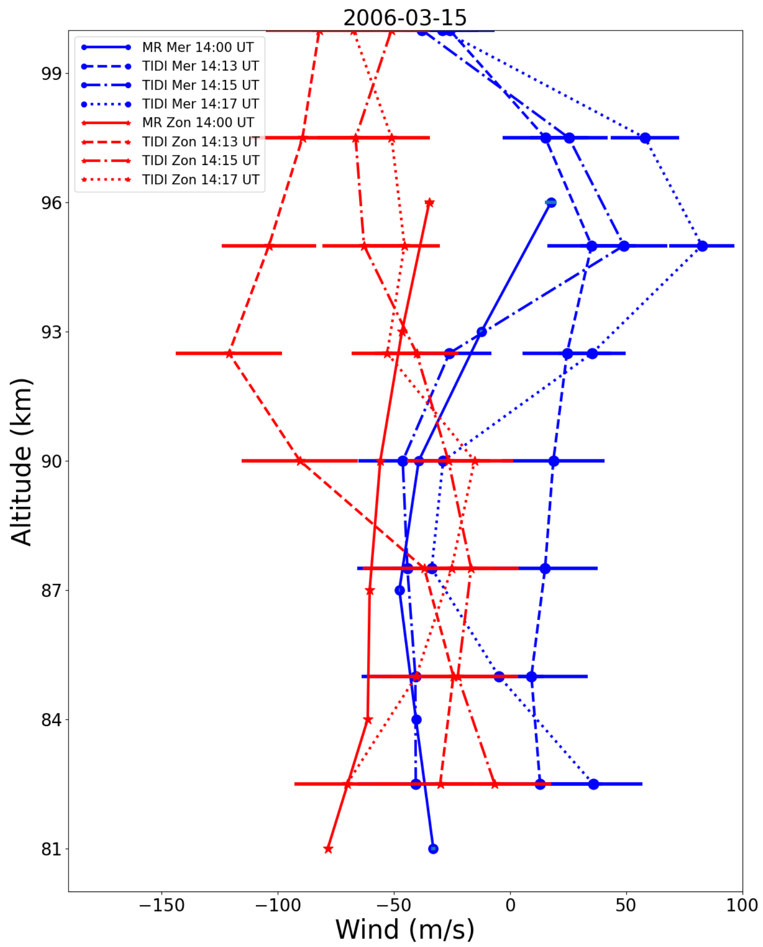

Figure 1. Vertical profiles of the meridional (blue) and zonal (red) winds measured by the meteor radar (solid lines) and TIDI (dashed, dot-dashed and dotted lines) over São João do Cariri. The meteor radar profiles were calculated at 14:00 UT on 15 March 2006. The TIDI measurements were retrieved at 14:13 UT (dashed lines), 14:15 UT (dot-dashed lines) and 14:17 UT (dotted lines).

On the one hand, the calculation of the mean winds from the meteor radar uses the bin size of one hour, centered in half hour, computing all meteors within its field of view. On the other hand, TIDI estimate the wind from the airglow within 2.5^o horizontally during a single sounding (Killeen et al., 2006). Therefore, the wind profiles from the two instruments could be largely different each other.

Another thing that call the attention is that the TIDI measurements are quite different, even within a time interval of 2 minutes. However, as shown by John et al. (2011), if a long time interval is used to do climatological mean wind profiles using the two instruments, the profiles will get close enough.

Figure 2 shows the horizontal distribution of the meteor echoes used to compute the mean wind profile showed in Figure 1. Additionally the geographical position of the TIDI's soundings are showed as blue stars. In fact, there is a long distance between two soundings, which could be separated by the same distance of the field of view of the meteor radar. Even the TIDI sounding that is very close São João do Cariri (at 14:15 UT) revealed wind profiles which have significative differences when compared to the meteor radar ones.

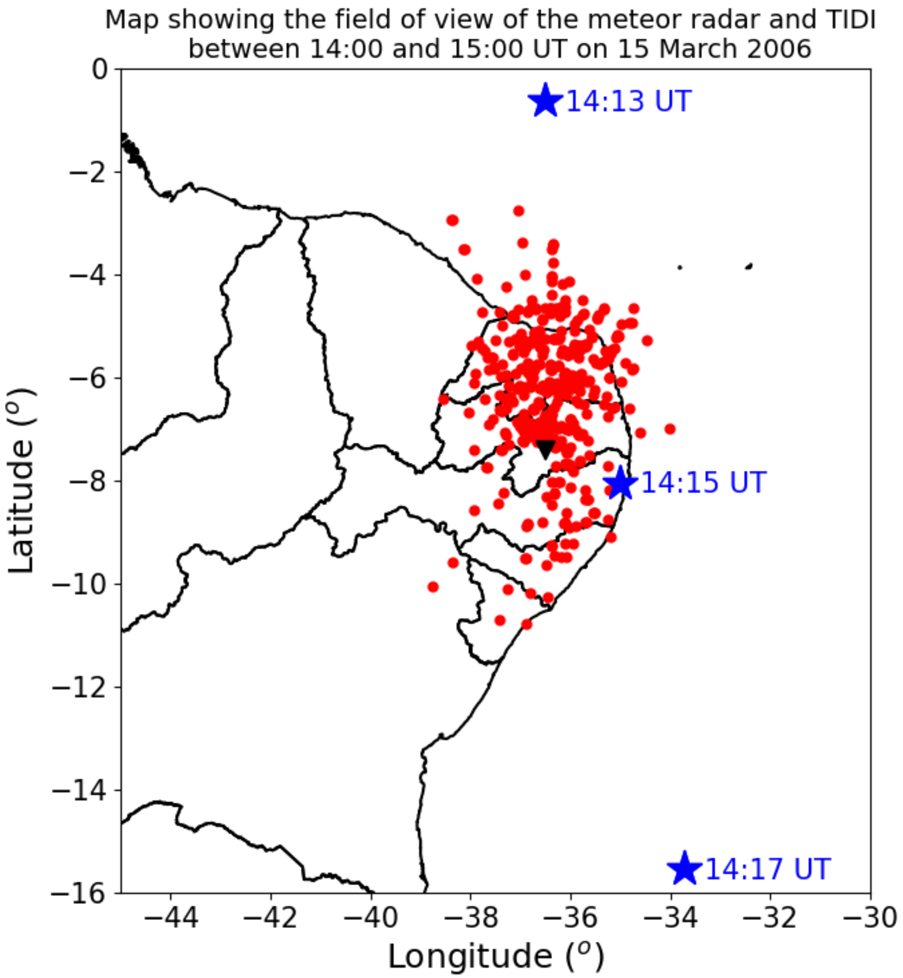

Figure 2. Horizontal distribution of the meteor echoes (red dots) detected on 15 March 2006 between 14:00 UT and 15:00 UT over São João do Cariri (black triangle), which were used to compute the winds showed in Figure 1. These meteor echoes were detected from ∼78 up to 102 km altitude. The blue stars show the position of the vertical soundings showed in Figure 1.

It is well known that the wind in the MLT can change quickly (e.g., Clemesha et al., 1981; Kishore Kumar et al., 2018), primarily, as response for the passage of gravity waves in this region (Baumgarten et al., 2018). However, in this case, the time interval between to sounding is very short (∼2 min) and the likely explanation for the discrepancies between the consecutive profiles could be the large horizontal separation.

Satellite measurements are more reliable to investigate the propagation of gravity waves and their interaction with the background atmosphere. For instance, winds measured by radars have been used to evaluate the background condition of the atmosphere in the creation of Doppler ducts in the MLT (Fechine et al., 2009; Bageston et al., 2011; Carvalho et al., 2017, e.g.,), that are necessary conditions for the propagation of ducted waves in the atmosphere (Dewan and Picard, 1998). Indeed, the usage of the TIDI winds for case studies of mesosphere fronts could produce more confident results, if the the sounding is within the field of view where the front is observed.

Another important contribution for the studies of ducted gravity waves is their interaction with the background atmosphere that can produce either convective or dynamic instabilities (Fritts and Rastogi, 1985). The most common parameter used for classify the instability as convective or dynamic is the Richardson number, which is the ratio between the buoyancy and wind shear. Thereby, TIDI is indeed advantageous for coincident measurements.

A disadvantage of investigating gravity waves combining TIDI and background measurements is to have coincident soundings of the satellite crossing the field of view of the instrument deployed in the ground.

How are the long term ~~averagedl~~ averaged winds from the TIDI reliable, since they have strong short time variations? In order to try to answer this question, a variation of the mean wind along the day was calculated for each month of 2006 using the meteor radar (Figures 3, 5) and TIDI (Figures 4, 6). In the analysis of both measurements, winds faster than 150 m/s were treated as missed points.

Figure 3 ~~show~~ shows that the time variation of averaged meridional wind calculated using the all days within the months as function of the altitude. One can observe that the meridional winds range approximately between -120 to 100 m/s, where the large values were observed in the summer months. It is clear the presence of diurnal oscillation propagating with the decrease of the altitude in most of the months. For some months, primarily in the autumn and winter, the semidiurnal oscillations appear dominant in the upper levels. This annual variability of the diurnal and semidiurnal tides is well ~~know~~ known in the equatorial region (e.g., Lima et al., 2007). As the wind calculated by the meteor radar data is averaged in time bin size of one hour, none short time (< 2 h) oscillations were observed clearly.

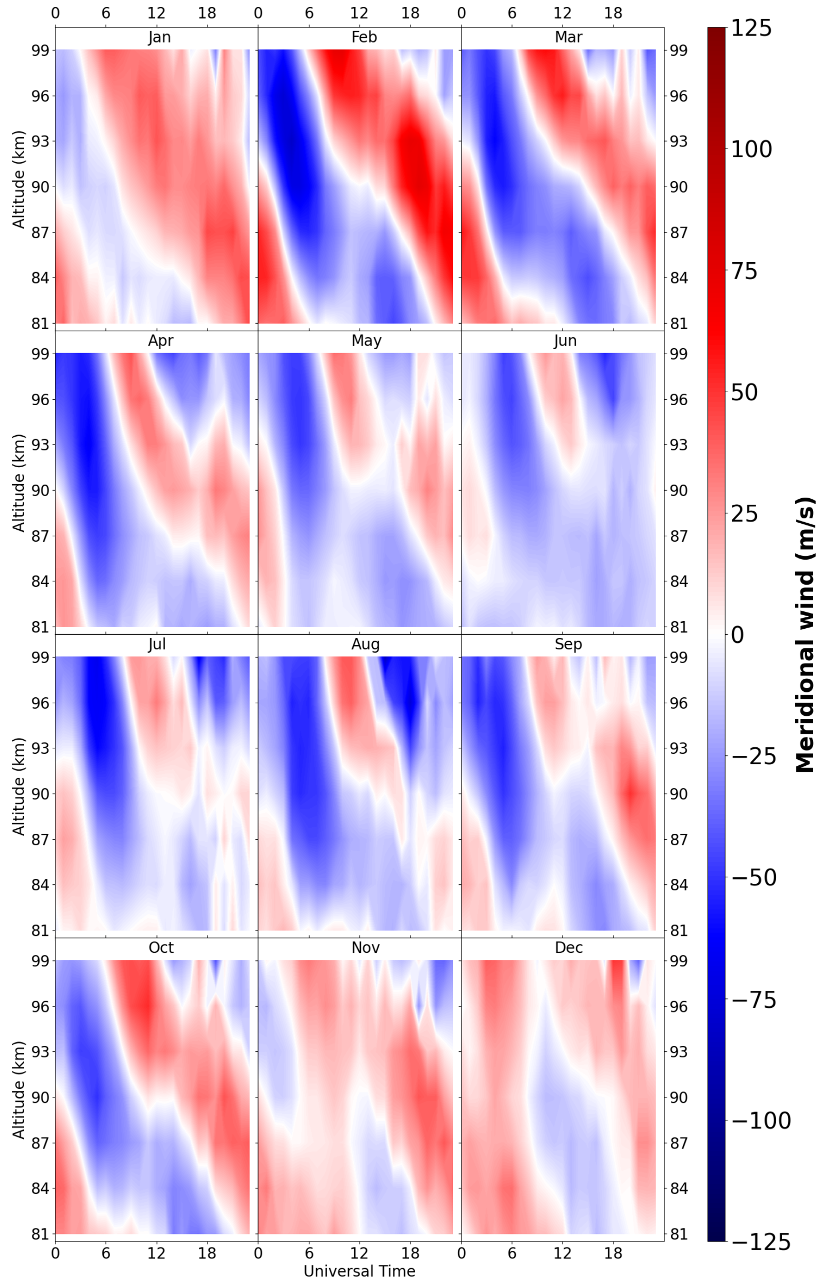

Figure 3. Monthly time variation of averaged meridional wind calculated used the meteor radar for 2006.

Figure 4 is similar to Figure 3, but for TIDI meridional winds. It has been produced using the data retrieved from the TIDI within a grid of $\pm$ 5^o (latitude $\times$ longitude) centered at São João do Cariri within 60 days centered in each month of 2006.

The color bar is in the same scale of Figure 3, thereby, the amplitudes of the wind and the seasonal changes are quite similar comparing the two kind of measurements. This good qualitative comparison was concluded by Xu et al. (2009) as well.

Furthermore, even using a temporal window of 60 days, some gaps have appeared in Figure 4 due to the small number of sounding soundings for a given hour. If the window size is enlarged to 30 $\times$ 30 degrees (figure not shown here), these gaps substantially disappear and the behaviours of the composite day meridional wind is quite similar to what can been meridional wind composite day trends to approach to what can be see in Figure 4.

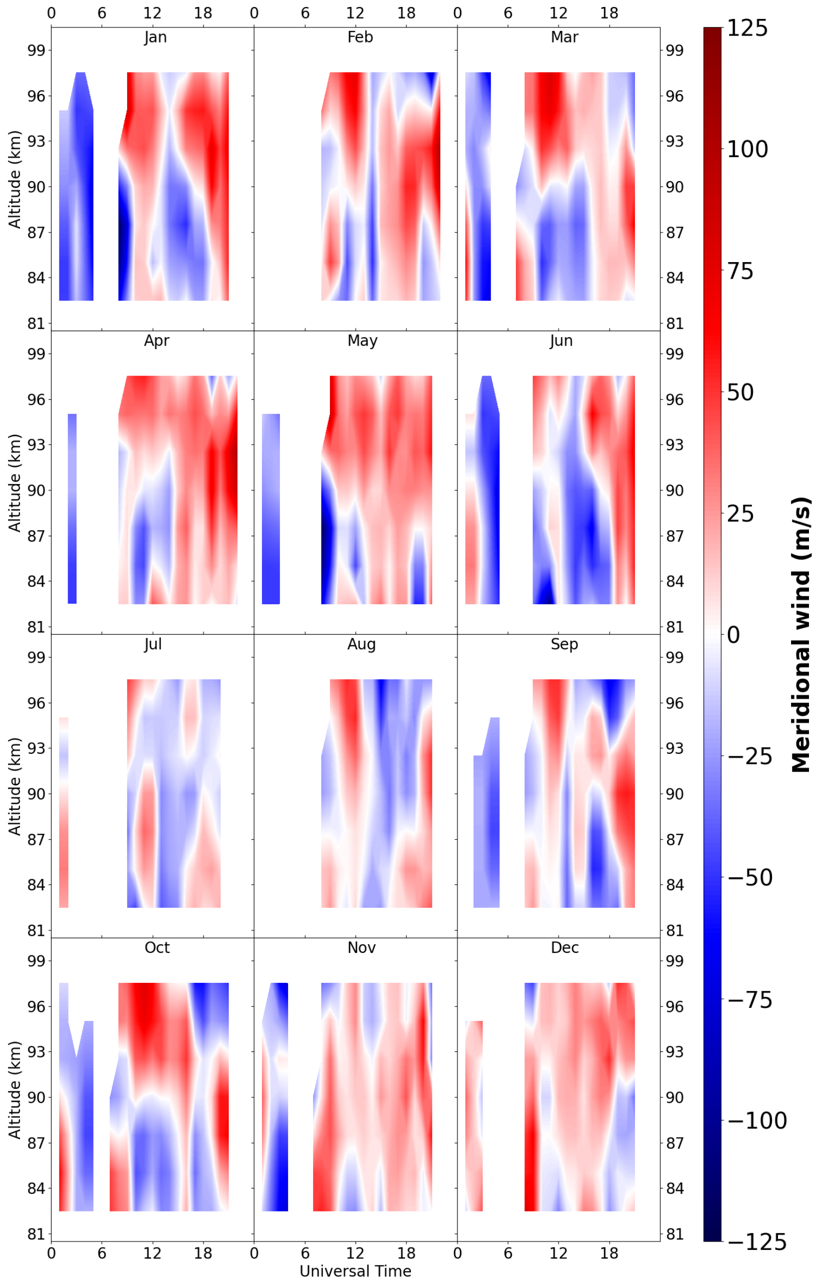

Figure 4. Same of Figure 3, but for the TIDI measurements.

In addition, most of the months presented well-defined diurnal oscillations, however, short period structures are more evident for the TIDI meridional winds. Maybe the presence of ~~the small oscillations oscillations~~ atmospheric oscillations during some days could modulate the observed diurnal tide phase. Furthermore, the small number of soundings by the satellite within the chosen window may not be enough to nullify the effects of short period variations. John et al. (2011) compared the wind within temporal wind of three months and reached quite good agreements over Thumba (8.5^o N, 77^o E), which is the equatorial region as well.

Figure 5 is the same of Figure 3, but for the zonal component. It is in the same scale of Figures 3 and 4. Thus, one can observe that the zonal winds have smaller amplitudes than the meridional ones. Similarly, the diurnal oscillation is stronger during the summer, while the semidiurnal one appear sporadically for some altitudes.

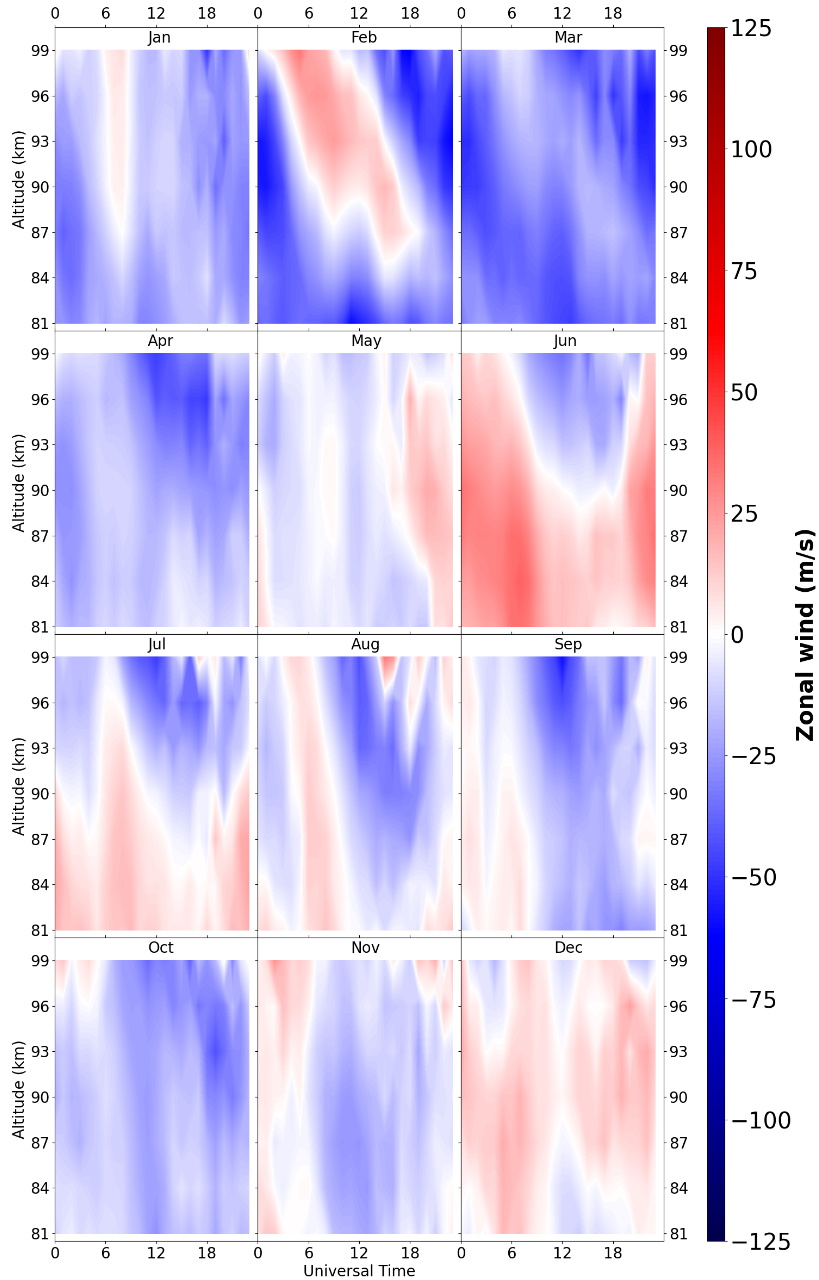

Figure 5. Monthly time variation of averaged zonal wind calculated used the meteor radar for 2006.

Figure 6 presents the same kind of chart as Figure 4, but for the zonal component. For almost all months, the amplitudes of the zonal winds are larger than the meteor radar ones. Diurnal structures can be observed but shorter period structures appear as well for practically the whole year. Although, the mean zonal wind calculated from TIDI compares favorably to meteor radar measurements, there are several short structures that could be associated with short period oscillation in the MLT, for instance. The same discussion about the gaps of Figure 4 can be applied to Figure ~~??~~ 6.

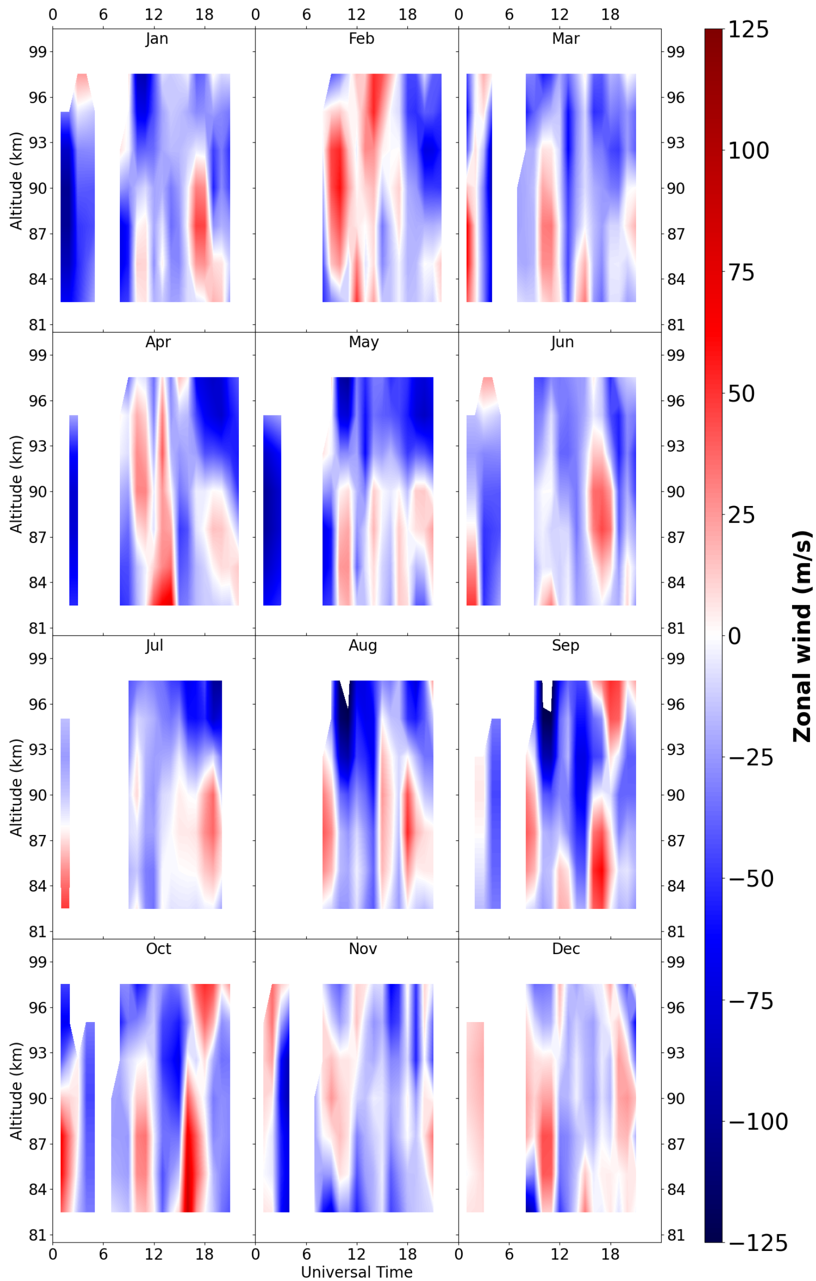

Figure 6. Same of Figure 5, but for the TIDI measurements.

Su et al. (2014) made a comparison of these two kind of measurements during the Leonids meteor shower in 2012 and observed reasonable agreement, but short time structures were presented in the TIDI as well.

The last question to be discussed within the scope of these comparisons is how do the TIDI wind measurements respond to the seasonal, semiannual and annual variations? Features like quasi-biennial oscillation (QBO), semiannual oscillation (SAO) and annual oscillation (AO) have been pointed as responsible for the long term variability of the migrating diurnal tide (e.g., Xu et al., 2009).

Figure 7 shows the meridional wind measured by the two instruments along 2006 for ~~90 km altitude~~averaged for all available altitudes. The meteor radar and TIDI wind points, within the window centered over São João do Cariri, were daily averaged.

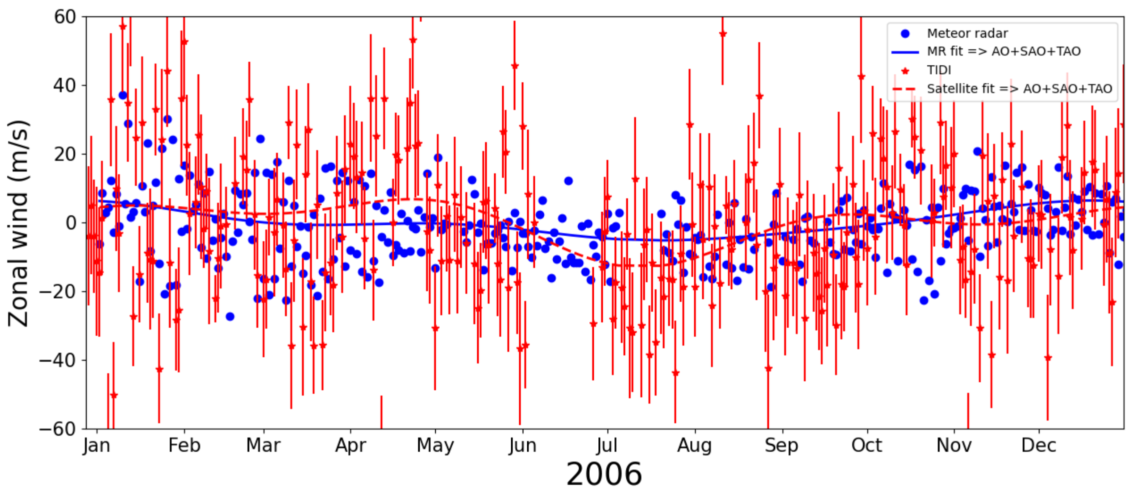

Figure 7. Temporal evolution of the meridional wind calculated ~~at 90 km altitude~~ for all available altitudes for the meteor radar (blue) and TIDI (red) during 2006. Solid blue line (meteor radar) and dashed red line (TIDI) represent the least square fits for AO, SAO and triannual oscillations (TAOs).

The meteor radar meridional wind presents a predominant annual oscillation with maximum during the summer and other small period structures. Even though the zonal wind from TIDI presenting spread points during 2006, the points approach the general behaviour of the radar measurements, which can be seen comparing the solid and dashed lines.

Figure 8 is the same of Figure 7, but for the zonal component, which has a semiannual oscillation more pronounced and other short oscillations along the year. Again, the TIDI winds follows the meteor radar winds. Additionally, the least square fits were close in phase for the SAO, which is the dominant oscillation in the rada data. Otherwise, there is the presence of a triannual oscillation in the TIDI winds, which is not strong in the radar winds.

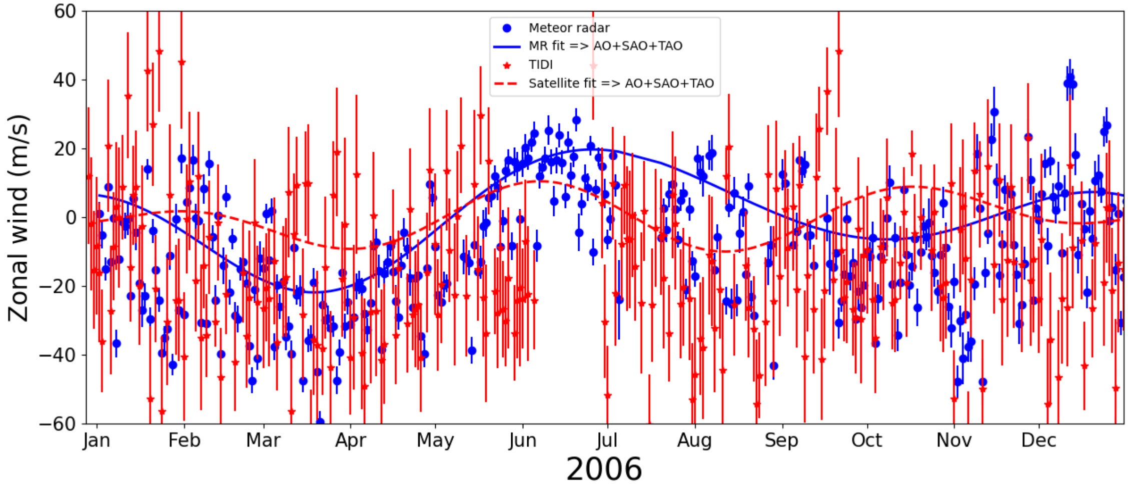

Figure 8. Same of Figure 7, but for the zonal component.

The ~~date~~ data shown in Figure 7 and 8 obey a statistical Gaussian distribution, which is not shown here, but the parameters, i.e., the averages and standard deviation (SD) for the TIDI and meteor radar (MR) measurements are presented in Table 1. Note that the parameters of the Gaussian distribution for the total data are close each other, except for the standard ~~deviations that are~~ deviation of the meridional component, which is greater for the TIDI measurements. Thereby, it suggests that, in addition to being close, the values of the two measurements, ~~c ould~~ could obey the same statistical distribution. Additionally, the averages for each season are close to each other, except in Fall and in Winter for zonal component. It can be the result of the reduced number of the points and the seasonal effects, which can be seen in Figures 7 and 8.

Table 1. Statistical parameters for a Gaussian distribution for the zonal and meridional winds measure by the TIDI and meteor radar.

	~~Zonal average~~	~~Zonal SD~~ Zonal average	~~Meridional average~~ Zonal SD	~~Meridional SD~~ Meridional averag
Total	**MR (m/s)**	~~-9.6~~ -8.9	~~23.1~~ 18.6	-1.0
	TIDI (m/s)	-14.3	23.0	-0.4
Summer	**MR (m/s)**	-17.7	18.0	1.0
	TIDI (m/s)	-13.0	24.0	2.2
Fall	**MR (m/s)**	-7.3	18.9	-2.5
	TIDI (m/s)	~~-10.7~~ -16.8	~~36.6~~ 18.5	~~8.1~~ 4.1
Winter	**MR (m/s)**	-2.7	14.8	-5.6
	TIDI (m/s)	-16.3	27.3	-9.7
Springer	**MR (m/s)**	-6.8	18.5	1.7
	TIDI (m/s)	-11.9	20.7	2.3

Xu et al. (2009) compared the amplitude of the migrating diurnal tide calculated from wind retrieved by these two technique and the results showed good agreement as well. It suggests that for studies of long period observation, these measurements converges.

4 Summary

The present work compared the horizontal wind measured by the TIMED Doppler Interferometer and a meteor radar over São João do Cariri in 2006. Three aspects were analysed and discussed: (i) quasi instantaneous measurements; (ii) time variation of the average wind for every month and (iii) the responses of the two techniques to the intraseasonal, semiannual and annual oscillations in the wind. The objective was figure out advantages and disadvantages of each technique. So, the main results are:

- A case study for 15 March 2006 showed that almost simultaneous measurements of the zonal and meridional wind vertical profiles were substantially different comparing TIDI and meteor radar measurements. It happens because the TIDI measure an quasi instantaneous wind in the MLT region, while the meteor radar uses a bin size of one hour to average the wind over the whole sky. Thus, a single TIDI profile is more reliable to conduct studies involving short period waves (gravity waves) in the MLT. However, the disadvantage of using the TIDI to study gravity waves, for instance, is the difficult of matching simultaneous measurements from different instruments;
- Looking at the time variation of the averaged of the zonal and meridional winds calculated using the TIDI measurements for every month of 2006, there are ~~qualitative~~ poor agreements with the meteor wind calculations. ~~However,~~ The main discrepancy is that the meteor radar calculations for each month is smoother compared to the TIDI ones. For this reason, the meteor radar shows clearly the contribution of the tides (diurnal and semidirunal) to the dynamics of the MLT. It was discussed that extending the temporal window for integrating the daily wind from the TIDI measurements, the behaviours approaches each other;
- Both measurements respond satisfactorily to the long period (seasonal, semiannual and annual) oscillations. Thus, they could be comparable to studies of long term dynamics in the MLT, although the large spread of the TIDI averaged wind could introduce some discrepancies.

Data availability. The meteor radar data can be requested to P.P. Batista (paulo.batista@inpe.br). TIDI data is available on line at https://cdaweb.gsfc.nasa.gov/pub/data/timed/tidi/vector/. The version 11 (D011), level 3 of the TIDI data was used in this work.

Author contributions. ARP - Conceptualization of this study, Methodology and Analysis; DOR and IP - Conceptualization, analysis and revision; LML - Conceptualization and revision; RAB, PPB, AR and CW - Experiment and revision

Competing interests. I. Paulino is a member of the editorial board of Annales Geophysicae.

Acknowledgements. The present work has been supported by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (#404971/2021-0, #309981/2023-9) and Fundação de Amparo à Pesquisa do Estado da Paraíba (Edital PRONEX - grant no. 002/2019 and Edital Universal 09/2021).

References

Bageston, J. V., Wrasse, C. M., Batista, P. P., Hibbins, R. E., C Fritts, D., Gobbi, D., and Andrioli, V. F.: Observation of a mesospheric front in a thermal-doppler duct over King George Island, Antarctica, Atmospheric Chemistry and Physics, 11, 12 137–12 147, https://doi.org/10.5194/acp-11-12137-2011, 2011.

Balsley, B. B., Ecklund, W. L., Carter, D. A., and Johnston, P. E.: The MST radar at Poker Flat, Alaska, Radio Science, 15, 213–223, https://doi.org/https://doi.org/10.1029/RS015i002p00213, 1980.

Baumgarten, K., Gerding, M., Baumgarten, G., and Lübken, F.-J.: Temporal variability of tidal and gravity waves during a record long 10-day continuous lidar sounding, Atmospheric Chemistry and Physics, 18, 371–384, https://doi.org/10.5194/acp-18-371-2018, 2018.

Buriti, R. A., Hocking, W. K., Batista, P. P., Medeiros, A. F., and Clemesha, B. R.: Observations of equatorial mesospheric winds over Cariri (7.4^o; S) by a meteor radar and comparison with existing models, Annales Geophysicae, 26, 485–497, https://doi.org/10.5194/angeo-26-485-2008, 2008.

Carvalho, A., Paulino, I., Medeiros, A., Lima, L., Buriti, R., Paulino, A., Wrasse, C., and Takahashi, H.: Case study of convective instability observed in airglow images over the Northeast of Brazil, Journal of Atmospheric and Solar-Terrestrial Physics, 154, 33 – 42, https://doi.org/http://dx.doi.org/10.1016/j.jastp.2016.12.003, 2017.

Clemesha, B., Batista, P., and Simonich, D.: Simultaneous measurements of meteor winds and sporadic sodium layers in the 80 – 110 km region, Advances in Space Research, 27, 1679–1684, https://doi.org/https://doi.org/10.1016/S0273-1177(01)00238-1, 2001.

Clemesha, B. R., Kirchhoff, V. W. J. H., Simonich, D. M., and Batista, P. P.: Mesospheric winds from lidar observations of atmospheric sodium, Journal of Geophysical Research: Space Physics, 86, 868–870, https://doi.org/https://doi.org/10.1029/JA086iA02p00868, 1981.

Dewan, E. M. and Picard, R. H.: Mesospheric bores, Journal of Geophysical Research: Atmospheres, 103, 6295–6305, https://doi.org/https://doi.org/10.1029/97JD02498, 1998.

Fechine, J., Wrasse, C. M., Takahashi, H., Medeiros, A. F., Batista, P. P., Clemesha, B. R., Lima, L. M., Fritts, D., Laughman, B., Taylor, M. J., Pautet, P. D., Mlynczak, M. G., and Russell, J. M.: First observation of an undular mesospheric bore in a Doppler duct, Annales Geophysicae, 27, 1399–1406, https://doi.org/10.5194/angeo-27-1399-2009, 2009.

Fritts, D. C. and Rastogi, P. K.: Convective and dynamical instabilities due to gravity wave motions in the lower and middle atmosphere: Theory and observations, Radio Science, 20, 1247–1277, https://doi.org/10.1029/RS020i006p01247, 1985.

Fujii, J., Nakamura, T., Tsuda, T., and Shiokawa, K.: Comparison of winds measured by MU radar and Fabry-Perot interferometer and effect of OI5577 airglow height variations, Journal of Atmospheric and Solar-Terrestrial Physics, 66, 573–583, https://doi.org/https://doi.org/10.1016/j.jastp.2004.01.010, 2004.

Fukao, S., Sato, T., Tsuda, T., Kato, S., Wakasugi, K., and Makihira, T.: The MU radar with an active phased array system: 1. Antenna and power amplifiers, Radio Science, 20, 1155–1168, https://doi.org/https://doi.org/10.1029/RS020i006p01155, 1985.

Hindley, N. P., Mitchell, N. J., Cobbett, N., Smith, A. K., Fritts, D. C., Janches, D., Wright, C. J., and Moffat-Griffin, T.: Radar observations of winds, waves and tides in the mesosphere and lower thermosphere over South Georgia island (54° S, 36° W) and comparison with WACCM simulations, Atmospheric Chemistry and Physics, 22, 9435–9459, https://doi.org/10.5194/acp-22-9435-2022, 2022.

Hocking, W., Fuller, B., and Vandepeer, B.: Real-time determination of meteor-related parameters utilizing modern digital technology, Journal of Atmospheric and Solar-Terrestrial Physics, 63, 155–169, https://doi.org/https://doi.org/10.1016/S1364-6826(00)00138-3, radar applications for atmosphere and ionosphere research - PIERS 1999, 2001.

Hocking, W. K.: A new approach to momentum flux determinations using SKiYMET meteor radars, Annales Geophysicae, 23, 2433–2439, https://doi.org/10.5194/angeo-23-2433-2005, 2005.

Hocking, W. K. and Thayaparan, T.: Simultaneous and colocated observation of winds and tides by MF and meteor radars over London, Canada (43 °N, 81 °W), during 1994–1996, Radio Science, 32, 833–865, https://doi.org/https://doi.org/10.1029/96RS03467, 1997.

Igarashi, K., Nishimuta, I., Murayama, Y., Tsuda, T., Nakamura, T., and Tsutsumi, M.: Comparison of wind measurements between Yamagawa MF Radar and the MU Radar, Geophysical Research Letters, 23, 3341–3344, https://doi.org/https://doi.org/10.1029/96GL03241, 1996.

John, S. R., Kumar, K. K., Subrahmanyam, K. V., Manju, G., and Wu, Q.: Meteor radar measurements of MLT winds near the equatorial electro jet region over Thumba (8.5° N, 77° E): comparison with TIDI observations, Annales Geophysicae, 29, 1209–1214, https://doi.org/10.5194/angeo-29-1209-2011, 2011.

Jones, J., Webster, A. R., and Hocking, W. K.: An improved interferometer design for use with meteor radars, Radio Science, 33, 55–65, https://doi.org/https://doi.org/10.1029/97RS03050, 1998.

Killeen, T. L., Wu, Q., Solomon, S. C., Ortland, D. A., Skinner, W. R., Niciejewski, R. J., and Gell, D. A.: TIMED Doppler Interferometer: Overview and recent results, Journal of Geophysical Research: Space Physics, 111, https://doi.org/https://doi.org/10.1029/2005JA011484, 2006.

Kishore Kumar, G., Nesse Tyssøy, H., and Williams, B. P.: A preliminary comparison of Na lidar and meteor radar zonal winds during geomagnetic quiet and disturbed conditions, Journal of Atmospheric and Solar-Terrestrial Physics, 168, 70–79, https://doi.org/https://doi.org/10.1016/j.jastp.2018.01.010, 2018.

Lima, L. M., Batista, P. P., Clemesha, B. R., and Takahashi, H.: 16-day wave observed in the meteor winds at low latitudes in the southern hemisphere, Advances in Space Research, 38, 2615–2620, https://doi.org/https://doi.org/10.1016/j.asr.2006.03.033, 2006.

Lima, L. M., Paulino, A. R. S., Medeiros, A. F., Buriti, R. A., Batista, P. P., Clemesha, B. R., and Takahashi, H.: First observation of the diurnal and semidiurnal ocillation in the mesospheric winds over São João do Cariri-PB, Brazil, Revista Brasileira de Geofísica, 25, 35–41, https://doi.org/10.1590/S0102-261X2007000600005, 2007.

Niciejewski, R., Wu, Q., Skinner, W., Gell, D., Cooper, M., Marshall, A., Killeen, T., Solomon, S., and Ortland, D.: TIMED Doppler Interferometer on the Thermosphere Ionosphere Mesosphere Energetics and Dynamics satellite: Data product overview, Journal of Geophysical Research: Space Physics, 111, https://doi.org/https://doi.org/10.1029/2005JA011513, 2006.

Paulino, A., Batista, P., and Clemesha, R.: Lunar tides in the mesosphere and lower thermosphere over Cachoeira Paulista (22.7 °S; 45.0 °W), Journal of Atmospheric and Solar-Terrestrial Physics, 78-79, 31–36, https://doi.org/https://doi.org/10.1016/j.jastp.2011.04.018, structure and Dynamics of Mesosphere and Lower Thermosphere, 2012.

Paulino, A., Batista, P., Lima, L., Clemesha, B., Buriti, R., and Schuch, N.: The lunar tides in the mesosphere and lower thermosphere over Brazilian sector, Journal of Atmospheric and Solar-Terrestrial Physics, 133, 129–138, https://doi.org/https://doi.org/10.1016/j.jastp.2015.08.011, 2015.

Qiao, L., Chen, G., Zhang, S., Yao, Q., Gong, W., Su, M., Chen, F., Liu, E., Zhang, W., Zeng, H., Cai, X., Song, H., Zhang, H., and Zhang, L.: Wuhan MST radar: technical features and validation of wind observations, Atmospheric Measurement Techniques, 13, 5697–5713, https://doi.org/10.5194/amt-13-5697-2020, 2020.

Skinner, W. R., Niciejewski, R. J., Killeen, T. L., Solomon, S. C., Gablehouse, D., Wu, Q., Ortland, D., Gell, D. A., Marshall, A. R., Jr., E. W., Cooper, M., and Kafkalidis, J. F.: Operational performance of the TIMED Doppler Interferometer (TIDI), in: Optical Spectroscopic

Techniques and Instrumentation for Atmospheric and Space Research V, edited by Larar, A. M., Shaw, J. A., and Sun, Z., vol. 5157, pp. 47 – 57, International Society for Optics and Photonics, SPIE, https://doi.org/https://doi.org/10.1117/12.503727, 2003.

Smith, A. K.: Global Dynamics of the MLT, Surveys in Geophysics, 33, 1177–1230, https://doi.org/10.1007/s10712-012-9196-9, 2012.

Su, C. L., Chen, H. C., Chu, Y. H., Chung, M. Z., Kuong, R. M., Lin, T. H., Tzeng, K. J., Wang, C. Y., Wu, K. H., and Yang, K. F.: Meteor radar wind over Chung-Li (24.9 $^{\circ}$N, 121 $^{\circ}$E), Taiwan, for the period 10–25 November 2012 which includes Leonid meteor shower: Comparison with empirical model and satellite measurements, Radio Science, 49, 597–615, https://doi.org/https://doi.org/10.1002/2013RS005273, 2014.

Xu, J., Smith, A. K., Liu, H.-L., Yuan, W., Wu, Q., Jiang, G., Mlynczak, M. G., Russell III, J. M., and Franke, S. J.: Seasonal and quasi-biennial variations in the migrating diurnal tide observed by Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED), Journal of Geophysical Research: Atmospheres, 114, https://doi.org/https://doi.org/10.1029/2008JD011298, 2009.