Angeo-2019-134

Response (*in italic*) to Referee #1.

First of all, we are grateful to the Referee #1 for very useful suggestions. We have incorporated most of their suggestions and the responses are in italics following each of the questioning or suggestion.

Review report of the manuscript entitled "Diurnal mesospheric tidal winds observed simultaneously by meteor radar in Costa Rica (10°N, 86°W) and Cariri (7°S, 37°W)" by R. A. Buriti et al. The paper presents comparative features of mean winds and tides in the MLT between two low latitude sites located in the opposite hemispheres using meteor radar winds. They further compared the observations with GSWM model. The topic of the present paper is interesting to the scientific community. However, the present manuscript contains several serious issues pertained to technical and scientific aspects. In view of presentation and language/vocabulary it can be considered as a draft and requires substantial modification to improve it to a communicatory level. Anyways, I am detailing my comments/suggestions below.

Major points

The theme of the paper is not clear as the title/abstract/conclusion points out the diurnal tide characteristics, but the results start with SAO and AO of the mean winds. Authors should decide the theme and organize the manuscript accordingly.

Yes, we agree. The main idea of this work is to compare diurnal tides observed by meteor radars from two different places, Costa Rica (10°N) and Cariri (7°S). They are 5800 km apart. We decided to present the background wind because we believe it was important information in case of reader wishes to compare the winds in CR and CA. Also, the reader can use that information to compare to CIRA and/or HWM models. This is because we plotted the monthly average.

In the present comparative study the observational interval is too short (9.5 months) to present seasonal behaviour over a year which is another weak point of the paper. Derived AO features are questionable, especially at CR due to short data length. Since CA and GSWM database is longer, results can be shown for the missing months of the year.

You are right. We presented the annual oscillation results but with some restrictions. In the text we discussed about it. We changed the text to remove any information about AO in the manuscript. We have maintained the figure of the background wind and, briefly, we described the semiannual oscillation even with 10 months of observation.

Fig. 2: It seems that the authors carry out least square fit considering both SAO and AO simultaneously in the fitting function (as found in the caption of the figure). It is not clear how the authors decipher the individual SAO/AO amplitude/phase from the figure.

We decided that the importance of background wind should be secondary. So, we just presented and discussed the figure of the background wind and semiannual oscillation results briefly. Actually, in this second analysis, we fitted only 182.5 days to the original data according to each altitude gate.

Fig. 7: Here GSWM data are shown over whole latitude range of ±12°, which is not necessary. Also, authors limit to only two height bins. Instead of the present figure the authors can show four subplots using contours, estimating the difference between radar and GSWM amplitudes incorporating total MLT range of zonal/meridional for CR/CA. Deviation of amplitude can provide better clarity regarding the scientific point authors attempt to express.

The idea to present GSWM from 12°S to 12°S was to emphasize the minimum amplitude of zonal and meridional components close to the equator. We changed to contour plots. Now we present the percent variance from April to January and from 82 to 98 km height.

Language needs significant improvement to bring coherence in the results/interpretations. It hinders spread of the essence of the work to the readers. Vocabulary, tense and preposition should be corrected. It will be a good idea to check with a native English speaker.

Other points

L. 21: "In regard to phases, agreement between meridional tidal phases at the two sites was excellent". The statement is incorrect. The meridional tide phases of two sites are almost opposite (~ 12 h difference).

We changed to "Considering phases calculated by GSWM-09 between 82 and 98 km, the difference between CR and CA should be, on average, 8.7 ± 0.6 hour. The GSWM-00, an earlier version of the model that does not include non-migrating tides, shows the difference between CA and CR should be 12.0 ± 1.6 hr, on average. That result is close to the observations."

Fig. 1: Assign marks, i.e., a, b, c, d. *Done*

Fig. 2: Wind data should be shown along with the fit. *That figure was removed.*

L. 96-116: The amplitudes of SAO and AO contain temporal variability. Authors' statement of specific amplitude at a particular altitude raises confusion as it does not make any sense. Same applies to phases.

It was removed from the text.

L.25: correct "heat latent release" to "latent heat release" *Done*

L. 37: Replace "diagnostics" by "parameters" *Done*

L. 42: Correct "has shown…." to "showed…." *Done*

L. 44: Correct "have shown that…." to "showed that…." *Done*

L. 51: Delete "atmospheric" from the statement "mesospheric atmospheric dynamics…" *Done*

L. 86: Correct "variationson scalesof months…" to "variation on the time scale of month…" *Done*

L. 96: What do the authors mean by the term "A long-term yearly harmonic analysis"?

It was changed to "A semiannual harmonic analysis"

Amplitude of SAO and AO are found to be very small ~ 1-2 m/s. Information related to the uncertainty of the radar winds should be discussed in section 2.

We wrote some lines about it. I hope it can clarify the uncertainty of the radar.

"Concerning the standard deviation of amplitude and phase, it is important to note that, each hour of composite day, includes several thousands of meteor trails detected by the radar. The consequence of this is that the errors in amplitude and phase can be estimated in less than 10% and 1 hour, respectively."

Do the values shown after " ± " represent standard deviations? *Yes, it represents the standard deviation.*

L.116: "On average, the phase is close to 6 doy (January 6th)". The meaning is not clear as the range in Fig. 2 is shown within 90-390 doy.

We have removed all text concerning to annual oscillation.

L. 136: correct "maximum intensity to the south…" to "maximum magnitude towards south…". *Done.*

L. 140: correct "do not coincident…" to "do not coincide…" *Done*

L. 183: "upward propagation…". Please mention upward propagation of what.

We changed to "upward propagation of diurnal tide is clear, especially in CR where the phase decreases as the altitude increases."

L. 204: Correct "presented previously" to "mentioned ealier". *Done*

L. 206: Correct "thing that was…" to "feature…" *Done*

L. 210: Delete the statement "So the phases are close to 12 hours different." *Done*

Discussion: The first paragraph provides information related to the GSWM and it should be shifted to section 2 with some modifications.

L. 301: "Some reports have proposed that latent heat release is important to semidiurnal tides." Please provide reference. *Done*

L. 307: "So, convective activity could explain the difference of zonal component behavior between CR and CA". Since the tide is more prominent in the meridional wind such influence of convective activity should also be visible in that. Authors' claim of convective effect only on zonal component is not acceptable. Similar statement is also mentioned at the end of the abstract section.

Yes, we changed the text including meridional component because it also presented a large variation that was not observed in CA and was not predicted by the model.

The abbreviations CA and Cariri are used interchangeably throughout the manuscript. Please adhere to either CA or Cariri. Same applies to Costa Rica. *Done.*

Angeo-2019-134

Response (*in italic*) to Referee #2.

***Interactive comment on* "Diurnal mesospheric tidal winds observed simultaneously by meteor radar in Costa Rica (10° N, 86° W) and Cariri (7° S, 37° W)" *by* Ricardo A. Buriti et al.**

Anonymous Referee #2

Received and published: 1 February 2020

The paper presents some new radar wind measurements in equatorial mesosphere and discussion on the diurnal tidal modulations in zonal and meridional winds. Al- though the description is relatively clean and easy to follow, my major concern is the comparisons with GSWM. The model version utilized in the paper is GSWM00 that does not include non-migrating tide. However, in equatorial region, the some non- migrating diurnal tides, such as DE3 and DE2, are equally important compared with diurnal tidal component, as the author mentions in the paper. Some of the major discrepancies in the paper are most likely due to this issue. There are more complete GSWM versions available, such as GSWM02, GSWM09 etc. that have non-migrating tidal components included. I strongly suggest the author to include the latest model predictions in the next version of the paper, in addition to the current GSWM00 comparison, and expand the discussion based on the new comparison results. Minor comments: 1. line 24-26. I do not think the local weather can affect the tidal feature that much in mesosphere at the same location, since the tidal waves are global scale waves, propagating horizontally with very fast phase speed. The local observations in upper atmosphere reflect the tidal forcing several thousand km away, so the connection to the local tropospheric weather is not straight forward. 2. Line 43. I would add some more references on the tidal comparisons work between ground-based measurements and model. Here are a couple of them: Ward et al., 2010 and Yuan et al., 2006. 3. Line 111. "very low value" sounds strange, may be replaced with "less value". 4. Line 127. Maybe consider to add some brief discussion, from theoretical point of view, why there is such big difference between southern and northern hemisphere equatorial region. 5. Line 196-197, please consider to remove "We also have ... not included in this work" 6. Line 254, see my comment above. Unless there is some solid reference on this topic, I would hesitate to make such statement.

Interactive comment on Ann. Geophys. Discuss.,
https://doi.org/10.5194/angeo-2019-134, 2019.

First of all, we are grateful to the Referee #2 for very useful suggestions. We have incorporated most of their suggestions and the responses are in italic font.

The suggestion to use GSWM-09, the last version of the GSWM, is very good and welcome because the manuscript does a reference to non-migrating tide. Initially, we worked with version 00 because its results were available for us. The last version is not available on the internet. We thank Maura Hagan and Xiaoli Zhang for sending the result of the model to make this work. An interesting feature observed was concerning the two versions of the model: GSWM-00 is closer to the observed meridional diurnal phase difference between CR and CA than GSWM-09. We only commented on this result in the text. The idea was not comparing models.

1. line 24-26. I do not think the local weather can affect the tidal feature that much in mesosphere at the same location, since the tidal waves are global scale waves, propagating horizontally with very fast phase speed. The local observations in upper atmosphere reflect the tidal forcing several thousand km away, so the

connection to the local tropospheric weather is not straight forward.

It makes sense that the response of tides in the mesosphere does not come from local where we have observed wind. Actually the climate in a specific region is a consequence of a series of phenomena that took place in another part of the world. We decided to explore a little bit the response of ENSO to Costa Rica and Cariri.

2. Line 43. I would add some more references on the tidal comparisons work between ground-based measurements and model. Here are a couple of them: Ward et al., 2010 and Yuan et al., 2006.

You are completely right. The work of Ward et al., 201, presented comparisons between model and observations from a series of instruments installed in many places in the world and included, also, satellite data. Both references were cited in the work.

3. Line 111. "very low value" sounds strange, may be replaced with "less value".

Yes, sounds strange. We changed.

4. Line 127. Maybe consider to add some brief discussion, from theoretical point of view, why there is such big difference between southern and northern hemisphere equatorial region.

In the Introduction, we included some lines in order to explain, in general way, why the atmosphere is different according to the hemisphere. We included in the work:

"The classical theory of tides is moderately well-established because it neglect, for example, mechanical forcing and dissipation, considering the atmosphere horizontally stratified and isothermal. But many issues about interaction, excitation and temporal variability require further understanding. Those two mechanisms which drive migrating and non-migrating tides, mentioned above, are, basically, dependent on how the solar radiation heats the planet, according to seasonality and distribution of ocean and continental plates on Earth surface, which makes the global heating different to both hemispheres."

5. Line 196-197, please consider to remove "We also have ... not included in this work" *Done*

6. Line 254, see my comment above. Unless there is some solid reference on this topic, I would hesitate to make such statement.

You right. That sentence was deleted.

Diurnal mesospheric tidal winds observed simultaneously by meteor radar in Costa Rica (10°N, 86°W) and Cariri (7°S, 37°W)

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Abstract. This paper presents a study of diurnal tidal winds observed simultaneously by two meteor radars ~~sited either~~located on each side of the equator in the equatorial region. The radars are located ~~in~~at Santa Cruz (10.3°N, 85.6° W), Costa Rica (hereafter CR) and ~~in~~at São João do Cariri (7.4°S, 36.5° W), Brazil (hereafter CA). The distance between the sites is ~~5800km~~5800 km. Harmonic analysis ~~was~~has been used to obtain amplitudes and phases (hour of peak amplitude) for diurnal, semidiurnal and terdiurnal tides between 82 and 98 km altitude, but in this ~~paper~~work we concentrate on the diurnal component. The period of observation was from April 2005 to January 2006. The results were compared to the GSWM-09 model. In general, seasonal agreement between observation and the model diurnal tide was qualitatively satisfactory for CA zonal amplitude. However, magnitudes of zonal and meridional amplitudes from November to January for CR were quite different to the predictions of the GSWM-09. Peak zonal amplitudes (~25 m/s) in CR were observed in September and December between 90 and 94km. ~~In regard~~Concerning to phases, the agreement between model and radar meridional tidal phases ~~to~~on each site was good, and a vertical wavelength of 24 km for the diurnal tide was observed practically every month, although ~~at times~~in some occasions determination of the vertical wavelength was difficult~~ mainly to~~, especially for the zonal component due to non-linear phase variations with height. ~~In regard~~Concerning to the diurnal zonal amplitude, there ~~are~~were notable differences between the two sites. This is probably because while the sites are ~~somewhat complementary~~at similar latitudes, although at different hemispheres, the responses to variability of water vapor heating and latent heat release during the weak positive phase of Southern Oscillation Index (ISO), or La Niña, at the two sites are quite different~~ and it could explain such difference~~.

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Keywords: MLT dynamics, meteor wind, diurnal tide.

1 Introduction

Atmospheric tides are driven principally by solar heating which results in significant day-night differential heating~~, and~~; they are dynamically very dominant at mesospheric heights. Thermal excitation due to absorption of solar radiation by water vapor (at infrared wavelengths) and ozone (at ultraviolet wavelengths), coupled with latent heat release due to deep convection at low altitudes , results in expansion and contraction of atmospheric pressure/density fields, creating modes of oscillation with very well-defined characteristics. Such oscillations are particularly easy to observe in the lower thermosphere through their impact on wind fields, temperature, airglow and ionospheric parameters (Taylor et al., 1999; Buriti et al., 2005; Forbes et al., 2008). Because of this, tides are very important to the ionosphere-thermosphere system, and linear and non-linear interactions between solar atmospheric tides, gravity waves, and planetary waves have been studied ~~in order to~~aiming a better ~~describe~~description of the dynamics of the atmosphere from low to high altitudes (e.g., Garcia and Solomon, 1985; Teitelbaum et al., 1989; Meyer, 1999, Thayaparan e al., 1995). The classical theory of tides is moderately well-established ~~because~~but it ~~neglect~~neglects, for example, mechanical forcing and dissipation, ~~considering~~and considers the atmosphere horizontally stratified and isothermal. ~~But many~~Many issues about interaction, excitation and temporal variability require further understanding. Those two mechanisms which were mentioned above drive migrating and non-migrating tides, ~~mentioned above,~~ are, basically, dependent on how ~~the~~ solar radiation heats the planet, ~~according to~~ which in turn is dependent on seasonality and the distribution of the ocean and continental plates on the Earth´s surface~~, which~~. This makes the global heating different ~~to both~~for the two hemispheres. ~~It~~A complete description of the forcing is very complex because many others parameters and mechanisms must be included to describe realistically the ~~dynamic~~dynamics of atmosphere. ~~The presence of~~In some cases, tides in the wind fields observed by various methods (including meteor radar), ~~showed~~show good agreement with the Global Scale ~~Waves~~Wave Model (GSWM) ~~in some cases~~ (Hagan~~, et al.,~~ and Forbes, 2002, 2003; Yuan et al., 2006; Ward et al., 2010; Chang, et al., 2012,). Previous studies ~~about~~of tides in the equatorial region ~~showed~~have shown that, in the altitude-range between 82 km and 98 km, the diurnal (24-hr period) amplitude is generally more significant than the semidiurnal mode for both zonal and meridional components (Buriti, et al., 2008; Davis et al., 2013). Tides also have a dependence on altitude and season. That behavior is in accordance with tidal theory for the propagation of the (1,1) Hough mode (Chapman and Lindzen, 1970; Forbes, 1982). Frequently, the meridional diurnal mode presents a ~~better~~well-defined behavior as a function of altitude and season than the zonal component, which makes the calculation of the meridional vertical wavelength more accurate relative to the zonal component. ~~The~~ Perhaps it is because the non-migrating tides have important participation on zonal wind field at low latitudes. As noted, the semidiurnal mode (period of 12 ~~hours~~hour) is generally weaker than the diurnal mode in the low latitudes and equatorial regions. The terdiurnal and ~~quadiurnal~~quarterdiurnal tides are also present but with even smaller amplitudes, but nonetheless ~~do~~they play some role in ~~mesopheric~~mesospheric dynamics (~~e.g.~~ Tokumoto et al., 2007; Guharay et al., 2018).

This paper concentrates on diurnal tides observed simultaneously with meteor radars installed in Santa Cruz, Costa Rica (hereafter CR) and São João do Cariri (CA), Brazil, with our focus being on the period from April 2005 to January 2006 (inclusive). Both radars, separated by 5800 km, are very similar, and they are located in opposite hemispheres but very close to the equator. Their latitudes are ~~almost complementary~~very similar. The paper first presents a brief overview of the background wind at both sites, and then proceeds to a comparison between diurnal ~~tides~~tidal characteristics. Amplitudes are discussed first, followed by phases. A discussion then follows.

Interesting results include a peak in amplitude observed in the diurnal zonal amplitude at the Costa Rican site in December which is not predicted by the model, and a clear anti-phase between CR and CA in regard to the diurnal meridional component.

2 Instruments and Observation

The meteor radars used are called SKiYMet radars. These are All-Sky Interferometric meteor radars which consist of a transmitter antenna in the form of a 3-element Yagi, and a set of 5 receiver antenna comprising 2-element Yagis. The radars are installed in different locations, namely in São João do Cariri, PB, Brazil (7.4°S, 36.5°W) and Santa Cruz, Costa Rica (10.3°N, 85.6°W). The distance between the sites is about 5800 km, and they are at similar latitudes either side of the equator (10°N and 7°S). The first uses a frequency of 35.24 MHz and the second one operates at 35.65 MHz. The radars run 24 ~~hours~~hour per day without interruption, and provide meridional and zonal wind data at altitudes between 80 and 100 km. Weather conditions do not interfere with observations. Basically, the wind is measured when an ionized meteor trail, formed when a meteoroid collides with the atmosphere, reflects the radio-wave emitted by the transmitter antenna. The echo is detected by 5 receiver antennas. The phase-shift between each pair of antennas gives information about the direction in which the meteor trail was observed, the time delays of the transmitted pulses give the range to the target, and the Doppler shift of the received signal gives the radial velocity. ~~Typically several thousand meteor trails are detected per day. Radial velocities observed by the radar present a standard deviation between 1 and 2% (Clemesha et al., 2009).~~ This combination of data allows generation of a wind-field as a function of height and time (Hocking et al., 2001). Concerning the standard deviation of amplitude and phase, it is important to note that, each hour of composite day, includes several thousands of meteor trails detected by the radar. The consequence of this is that the errors in amplitude and phase can be estimated in less than 10% and 1 hour, respectively. The temperature of the mesosphere at the height of peak meteor detection (~90 -92 km) can also can be determined by meteor radar (Hocking, 1999), but we will concentrate on the wind field. In our case, we determine information of winds every 2 ~~hours~~hour centered at altitudes of 82, 85, 88, 91, 94 and 98 km, in order to make optimum use of the data, which are non-uniformly distributed in height.

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In the present work, we will use CR data corresponding to the period from 14th April 2005 to 29th January 2006, with a gap of data from 17th November to 13th December. Data from CA for the same period will be presented for comparison. A study of one year of background mean winds, as well as diurnal and semidiurnal tides observed in both the zonal and meridional components above CA during 2004-2005 has previously been reported by Buriti et al., (2008).

The Global Scale Waves Model (GSWM-09) used in this work includes migrating and non-migrating tides with zonal ~~wavenumber~~wavenumbers from eastward 6 to westward 6~~ results~~. Briefly, this software is a 2-dimensional model that solves the linearized and extended Navier-Stokes equations for a particular period and wavenumber *s* as function of latitude (from 87°S to 87°N), altitude (from 0 to 124 km) and month (from January to December). It incorporates fields of mean wind (zonal), pressure, temperature and other important physical parameters from empirical models, such as MSISE-90 (Hedin, 1991). Depending on the altitude range, information on wind comes from different models and satellite observation. For example, between the stratosphere and the mesopause, winds are provided by the High Resolution Doppler Interferometer - HRDI - on board the UARS satellite. Details about the GSWM can be obtained on HAO's homepage and a vast number of papers, such as Hagan et al, 1997; 2002; 2003; Manson et al., 2002;Pancheva et al., 2001). Information about tidal parameters determined by GSWM0-09 are presented at specific altitudes that are not exactly coincident ~~to~~with the radar heights (e.g. see Fig. ~~4~~5 and ~~5~~6), but they~~ are~~ close.

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2.1 Background winds

In order to set up the background conditions for the tides, we will here present wind variations on the time scale of months, and present the background wind observed in CR and CA. Fig. 1 shows the monthly averages of zonal (left) and meridional (right) winds in CR and CA. Data ~~of~~from February and March are missing for CR. Comparing monthly mean winds at the two sites, some interesting results are evident. In general, both sites seem to present a clear semiannual behavior, particularly in regard to the zonal wind. At heights of 82-91 km, the maximum eastward mean wind at CA is observed in June, while the maximum in CR is present in December. This is almost a 6 month delay, as might be expected due to the fact that the radars are in different hemispheres. The meridional winds are quite different at the two sites, although strong southward flows above CA in June-July and strong northward flows in December over CR are evident.

A semiannual harmonic analysis - not presented in detail in this text - was carried out in ~~regard to ~~these data. Briefly, the semiannual zonal amplitude decreased between 82 and 94 km from ~15 m/s to 6.3 m/s in CR with maximum values ~~in~~on day ~160 of the year ~~~160 ~~(June 9th). The amplitude at CA also decreased similarly to CR, and presented ~~the ~~maximum values close to doy (day of year) 160. The meridional component, on the other hand, is predominately northward in CR and southward at CA in the range between 82 and 98 km. Meridional amplitude values in CR and CA are practically the same, except ~~to~~at 98 km where the value of CA is ~~double if compared to~~twice of that at CR. In general, the semiannual meridional amplitudes did not ~~presented~~present values above 5 m/s ~~to each~~at any specific altitude in the range studied in this work.

~~Differently of~~In contrast to the zonal component, the meridional phase in CR between 82 and 85 km was ~~in~~on day 66 (or ~ doy 248), while CA was ~~in~~on doy 165.

3 Diurnal tide

We now turn to tidal analyses. The analysis of CR and CA winds, in order to determine information about the diurnal tides, was similar to the procedure described in Hocking (2001) and Buriti et al. (2008). First of all, a superposed epoch averaging of winds at two-hour steps was made, producing monthly means at 0100, 0300, ..., 2300 ~~hour~~hr (local time). After that, a standard least~~-~~ mean squares fitting technique was used to obtain amplitude, phase and DC values for each month. It is known that diurnal oscillation of meridional wind in regions close to the equator present good regularity in amplitude and phase according to altitude, and our results confirmed this. ~~Because of this~~Consequently, a precise vertical wavelength is easier to calculate for the meridional wind than for zonal wind. A very interesting observation can be made regarding the diurnal phase of the meridional wind at the two sites. They are completely out of phase. In other words, if the wind has maximum magnitude towards the south at CA, then at the same local time in CR, the meridional wind has maximum magnitude towards the north.

In ~~Figs.~~Figures from 2~~, 3, 4, and~~ to 5, information about amplitudes and phases of the GSWM-09 and radars installed in CR and CA are presented for 6 different altitudes. The altitudes used for the GSWM-09 do not coincide exactly with the specific altitudes of the radars, but nonetheless the comparisons between radar data and the GSWM-09 are still easy to make. We now turn to more detailed discussions, beginning with the zonal diurnal tide.

3.1 Zonal diurnal amplitude

A general view of the observational diurnal tidal amplitudes in CR and CA, as well as the GWSM-09 at both sites, can be seen in Fig. 2. In CR and CA the mean amplitudes, considering all months and altitudes, were close to 10 ± 5.7 m/s, but there is a clear difference between them. While CR values were above the average for November-January at all altitudes, CA values were largely below the average for altitudes between 82 and 91 km height for practically the whole period of observation. Also, amplitudes in CR were small between 82 and 98 km for May-July. CA presented similar results in October-January, but with a 6 ~~months of~~month difference ~~if~~ compared to CA observation. Comparing to the model, CA is closer to the model only in November and December in the range between 82 and 98 km height. A good agreement between model and observation is specifically observed in September at CA. Both ~~increase the~~show increasing amplitude from 91 to 98 km. The presence of large amplitudes in September seems to be a common feature between the sites; in CR the amplitude increased to values of ~24 m/s at an altitude of ~94 km in September and December. On the other hand, CA presented values above 18 m/s between 91 and 98 km (32 m/s) in September. But, the small amplitude predicted by the GSWM-09 in October-December between 82 and 91 km height is not observed over CR. On average, considering the dependence of amplitude with altitude, the amplitude in CR increased from 82 (7.8 m/s) to 91 km (15 m/s), then decreased to 98 km (6.6 m/s). CA presented a minimum at 85 km altitude (5.8 m/s), and increased almost linearly to 15.6 m/s at 98 km. ~~Comparing visually~~Visually comparing the figures, GWSM-09 seems to ~~represent~~ qualitatively represent the CR and CA observation fairly well.

3.2 Meridional diurnal amplitude

Figure 3 shows the meridional diurnal tides observed in CR and CA ~~and~~, as well as those predicted by the GSWM-09. Both sites show, according to the model, amplitudes above 20m/s in July-September and January-April at altitudes between 82 and 98 km, and minimum amplitudes in May-June and November. Observationally, CR presents larger amplitudes compared to CA, mainly in December. Comparing CR with CA, it is clear that they are similar to each other in this regard. The amplitudes in CR increase in July after presenting a minimum in May-June. On average, considering data from April to January in the range of 82 to 98 km of altitude, diurnal amplitudes in CR and CA were 23.3 ± 11.4 m/s and 22.6 ± 9.2 m/s, respectively. ~~Differently~~Differing from CA, in December CR presented ~~in December~~ a pronounced maximum, with values above 50 m/s at 94 km which is not predicted by GSWM-09 model. Details about ~~difference~~differences between model and radar will be show in Figure 4.

Comparisons ~~in~~are shown Fig. 4 for both zonal and meridional diurnal amplitudes between GSWM-09 and radar in the range of 82 to 98 km from April 2005 to January 2006 ~~are shown in Fig. 4.~~. In order to match the altitude gates of model and radar, we calculated the mean of observed ~~amplitude~~amplitudes from 85 to 88 km heights, which ~~supposed to be~~is applicable at a new altitude (86.5 km). The result was compared to the specific altitude of 86.3 km of the model. Fig. ~~Figure~~ 4 represents the percent variance of zonal and meridional amplitude from model and radar ~~to~~for each altitude and month, ~~in~~for both CR and CA. It is important to ~~inform~~note that ~~the color scale is not symmetrical concerning the~~positive values~~. Positive values~~ in the graphs mean that the value of model is bigger than that observed by radar. In regard to zonal amplitude, the ~~big~~large blue area in ~~Figure 6a is~~Fig. 4a occurs because the observed amplitude in December at 86-94 km height was quite higher, ~~and it~~which is not predicted by the model. Months from April to October present a smallest difference between model and radar. At CA, on the other hand, considering altitudes above 86 km, the amplitude observed by the radar seems to approach to the model, except in October when this difference ~~increase~~increased to ~70%. The meridional component in CR, similarly to the zonal one, also presented in November-January a huge blue area which indicates that observed ~~amplitude~~amplitudes are more than 100% of the model. This is because meridional diurnal ~~amplitude~~amplitudes observed by the radar also increased significantly in December above 91 km height. An interesting feature observed at CA was two big blue areas in meridional amplitude separated by reddish area with values below 60%. Comparing zonal and meridional components observed in CR and CA, we can say that of the two, the meridional amplitude seems to be more ~~conveniently~~accurately described by the GSWM-09.

3.3 Zonal diurnal phase

Figure 5 shows the observed and model zonal ~~phase~~phases at different altitudes ~~in~~at CR and CA as a function of month of the year ~~to~~for each interval of altitude. The zonal phase (in Local Time) presented interesting results. These included a clear uniform phase difference in altitude in CR, except for January 2006; a large variation of phase at CA for altitudes of 82-91 km from July to January; and May-July and November presented only small variations of phase according to altitude, suggesting, perhaps, a dominant evanescent mode or non-migrating tide. The phase in CR, in contrast to CA, shows a clear linear dependence on altitude in most months, which makes it possible to determine the wavelengths of the tidal propagation assuming a quasi-monochromatic wave. A decrease of the phase between May and January is generally evident. Also, an upward propagation of diurnal tide is clear, especially in CR where the phase decreases as the altitude increases. The vertical wavelength was obtained considering the altitude as an independent variable, but some additional criteria were considered in order to extract reliable vertical wavelength. In particular, a linear regression of at least 4 altitudes in sequence was required, and the fit was only accepted if the R-squared value was above 0.9. The results for CR and CA, on average, were 25.4 ± 4.0 km and 22.7 ± 7.3 km respectively. Because the zonal diurnal phase at CA showed evidence of modal superposition between the altitudes, only 4 months were available to determine the vertical wavelength using the above criteria. According to the GSWM-09, the vertical wavelength in CR and CA should be about 27.4 ± 2.1 km and 29.3 ± 4.8 km, respectively. It is almost 8% and 30% higher (respectively) than ~~that one~~the ones observed in CR and CA. We discarded very long vertical wavelengths in our analysis simply because of the criteria discussed above. Large vertical wavelength could be indicative of evanescent structure or a presence of other mode of oscillation; in addition, gravity wave breaking can act to increase the vertical wavelength (Ortland and Alexander, 2006). Nevertheless, it seems that the GSWM-09 does overestimate the vertical wavelengths.

The zonal diurnal phase, according to the GSWM-09, has difference in values in CR and CA. Comparing the same ~~altitude to~~altitudes at CR and CA, the difference of phase between ~~CR and CA~~them, from April to March, ~~in~~on average, is 3.1 ± 0.2 hr. ~~With regard~~Concerning to observational ~~and~~versus model results, ~~it is clear~~ the irregularity of phase shift from CA ~~according to months which~~ as a function of month makes the observational comparison, ~~depend~~which depends on the altitude and month, practically impossible. On the other hand, the difference between CR and model, even presenting some discrepancies at a specific altitude and month, is 0.2 ± 4 hr, in average.

3.4 Meridional diurnal phase

The meridional phase (in Local Time) presents a behavior quite different to that of the zonal component. ~~Figure~~Fig. 6 presents meridional phase observed by radar and by GSWM-09 in CR and CA. It is clear that ~~a~~an observed downward phase propagation is evident at both sites, and a small decrease of phase from June to January occurs. The regularity of phase with altitude permitted us to estimate the vertical wavelength, using the criteria ealier mentioned~~ ealier~~, for all months with data.

The results were vertical wavelengths of 25.1 ± 5.3 m/s and 25.6 ± 4.6 m/s in CR and CA, respectively. According to GSWM-09, the vertical wavelengths in CR and CA should be 24.5 ± 0.8 km and 24.2 ± 1.0 km. An interesting feature observed was the difference of phase, in Local Time, between CR and CA. At the same altitude and month, the difference in the time of maximum at ~~CA~~CR compared to ~~CR~~CA was 13.3 ± 2.3 hour, on average, if we consider that CR is ahead of CA. ~~If we concentrate on altitudes between 85 and 94 km, then that value, on average, goes to 12.2 ± 1.6 hour from May to October.~~ Considering phases calculated by GSWM-09 between 82 and 98 km, the difference between ~~CA~~CR and CA should be, on average, 8.7 ± 0.6 ~~hours.~~ hour. The GSWM-00, an earlier version of the model that ~~do~~does not include non-migrating tides~~-~~, shows the difference between CA and CR ~~is~~should be 12.0 ± 1.6 ~~hours~~hr, on average. That result is close to the observations.

4 Discussion

The observational results were compared ~~to~~with the Global-Scale Wave Model (GSWM), version 2009, the newest one. In general, the GSWM-09 predicts the meridional component more satisfactory than the zonal one. However, just as for the zonal amplitude, the meridional component also showed large quantitative differences between model and observed results in most months. When comparisons are made between the sites, June and July present similar results for zonal and meridional amplitude, respectively. In August and October, the zonal winds at 82 km in CR and CA are similar in magnitude but they are different in November-December. The increase of the zonal and meridional diurnal amplitude in CR in December was not observed in CA and it is not predicted by the model.

Davis et al., (2013~~,~~), reported a study of the diurnal amplitude of meteor wind observed at Ascension Island (8°S, 14°W) from 2002 to 2011. They show in Figure~~Fig.~~ 6 of their work a composite-year monthly wind of zonal and meridional diurnal amplitudes which present a good agreement to CA and good agreement to the GSWM-09 model. The availability of 9 years of data may have smoothed out irregularities that arise in any one year; this is not our case. In that work, they also have compared their observation with the Canadian Middle Atmosphere Model (eCMAM) and the Whole Atmosphere Community Climate Model (WACCM) (Fomichev et al., 2002; Du et al., 2007).

The zonal diurnal ~~amplitude~~amplitudes calculated by GSWM-09 ~~to~~ in the range between 82 and 98 km altitude for CR and ~~CR~~CA are, in general, ~~very~~ similar, ~~as well as~~in behavior, to the meridional component. ~~The difference, basically, is~~ Both components present a decrease in amplitude during summer and winter solstices. However the magnitude of the meridional ~~component~~diurnal amplitude is ~~double~~twice that of the zonal one ~~because atmospheric tides are more important to~~ during the whole year. Concerning the diurnal phase, the model presents a regular phase variation in time and altitude for both components. That regular variation was not observed in zonal diurnal phase, in contrast to the meridional one. The reason is possibly related to the influence of non-migrating modes, especially at CA, which are in turn dependent on the zonal background wind ~~at low latitudes. An~~field (Hagan and Forbes, 2002, 2003). Also, an increase in zonal and meridional amplitude at 88-98 km height in CR was observed in December which is not predicted by the model.

Geographic conditions in CR and CA are quite dissimilar. ~~It~~For example, it would be reasonable to expect different behavior of the tides at the two sites because of~~, e.g.,~~ their different levels of response to water vapor absorption and tropospheric latent heat release by large-scale deep convection. Lieberman et al., (2007~~,~~), modeled how the variations of diurnal tropospheric heating due to water vapor and latent heat could effects could affect the amplitude of the meridional tidal winds in the mesosphere. This work concentrated ~~in~~on 1997-1988, when the ENSO was very strong. Because water vapor heating presents a migrating component, it is to be expected that it ~~rules~~helps define the migrating tide in the mesosphere wind~~; on~~. On the other hand, the non-migrating component is ~~forcing~~forced by the latent heat~~. In~~ effects. The 2005-2006 ~~was a~~ period was one of weak positive Southern Oscillation Index (SOI). ~~It~~This means that the water of the eastern and central tropical Pacific Ocean was cooler, or La Niña was occurring. Thermal excitation due to absorption of solar radiation by water vapor ~~decrease~~would have decreased at that time, and the effect in the mesosphere could decrease too~~, on~~. On the other hand, during a La Niña period~~ exists,~~, a tendency exists to be wetter than normal in CR and CA, which increase the latent heat effects due to deep convection in the troposphere.

Specifically, the climate is desert-like at CA but very tropical in CR which is a country of width ~120 km from southwest to northeast, surrounded by the Atlantic (east) and Pacific (west) Ocean. São João do Cariri, on the other hand, is a city in the country of the Northeast of Brazil, having the Atlantic Ocean 190 km to the east and 250 km to the north. The Pacific Ocean is 4800 km to the west. CA is located in the driest region in Brazil. Some reports have proposed that latent heat release is important to semidiurnal tides (Hagan and Forbes, 2003, Zhang et al., 2010). Lindzen (1978) originally considered that latent heat release is not important to the diurnal tide. Since then, however, many reports about the possibility of diurnal tides, including migrating and non-migrating, in the MLT being affected by ground-level sources in the tropical region have been published (Hamilton, 1981; Hagan, 1996; Forbes et al., 1997). Hagan et al., (1997) showed the importance of the seasonality of convective activity in the Troposphere to the diurnal amplitude of the meridional wind at 21°N; it is strong in January and weak in July. This clear dependence is due to the diurnal amplitude of the effective rainfall rate that varies with months. So, convective activity could explain the difference ~~of zonal component~~in behavior ~~between~~of the zonal and meridional components at CR and CA. Ascension Island, which is located practically in the middle of the Atlantic Ocean, has a desert climate with total precipitation of only 200 mm per year. This is almost half that of CA, and ten times less than CR. As we have presented above, CA (and Ascension) ~~tends~~tend to be closer to the model predictions than CR. It is likely that others modes of oscillation (including non-migrating tides), which are more sensitive to latent heat release, are present in the CR winds.

5 Conclusions

Ten months of simultaneous observation of mesospheric winds by meteor radar installed in CR and CA have been analyzed in order to compare tidal winds, with emphasis here on the amplitudes and phases of zonal and meridional diurnal tides. A comparison of these observed parameters ~~have~~has been made ~~to~~with those predicted by ~~GSWM00~~the GSWM-09 model. Background winds were, briefly, presented in the work. The monthly zonal winds at CA presented a semiannual oscillation similar to CR, with values of amplitude close to 15 m/s at 82 km, decreasing to ~6 m/s at 94-98 km height. The meridional winds, on the other hand, were small relative to the zonal ones, at least for altitudes above 85 km at both locations. The zonal and meridional diurnal tidal parameters showed interesting results. CR presented a peak in diurnal zonal amplitude in September at 94 km, in general agreement with the GSWM-09 model. December also presented a peak at 91 km but, in contrast to the September case, this was not predicted by the model. With regard to the meridional winds, observations in CR presented a peak at 94 km height in December, while the model predicted a peak earlier, in October. CA showed no strong activity at all in the meridional tides in the September to December time-frame. In a general way, diurnal meridional parameters measured over CA compared better to the GSWM. Vertical wavelengths measured at the site were often in broad agreement with the GSWM, being in the range 25-30 km, with the observational data showing slightly shorter vertical wavelengths. Detailed comparisons (summarized in Fig. ~~6~~4) showed periods of good agreement and periods of poor agreement with the GSWM. The case has been made that the very different climates at the two sites (with CA being desert-like and CR being very tropical, which ~~can~~may well be a consequence of large scale tropospheric phenomena that ~~take care~~are initiated far away from the sites) may be producing significant non-migrating tides, especially over CR. A longer-term study over many years may help clarify this possibility.

***Data availability**:* All meteor radar data can be requested from INPE and UWO. Contact Dr. Paulo Batista (paulo.batista@inpe.br) and Prof. Wayne Hocking (whocking@uwo.ca)

~~Authors~~Author contributions: Ricardo Buriti is responsible for the operation of the radar at CA and has written the manuscript and made the analyses of data using software provided by Wayne Hocking. The same software is used ~~-~~on the CR meteor radar, which was also built ~~and~~ by W. Hocking using grants from NSERC in Canada~~.~~. Paulo Batista and B. Clemesha (in memoriam)~~-~~ is responsible for the data and for the meteor radar of CA. I. Paulino, A. Paulino and A. Medeiros have contributed to the discussion of the manuscript. M. Garbanzo-Salas is a collaborator of W. Hocking and responsible for operation of the CR meteor radar.

Competing interests: The authors declare they do not have any competing interests.

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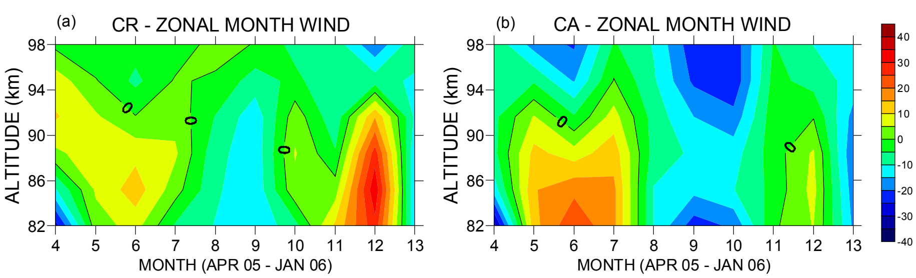
Figures



(a)
CR - ZONAL MONTH WIND
ALTITUDE (km)
MONTH (APR 05 - JAN 06)
(b)
CA - ZONAL MONTH WIND
ALTITUDE (km)
MONTH (APR 05 - JAN 06)

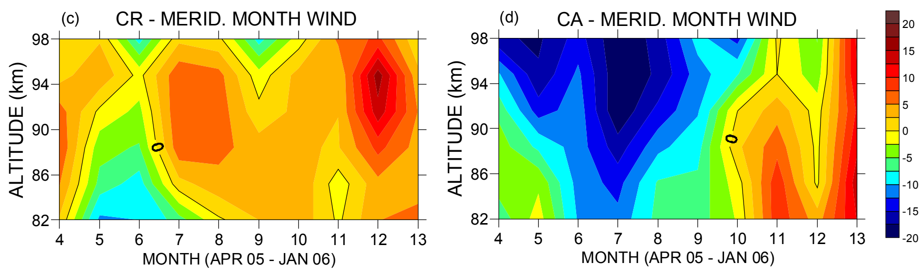


Figure. 1: Monthly averages of zonal (top) and meridional winds in CR (*a* and *c*) and CA (*b* and *d*) from April 2005 to January 2006. The color scales used for the zonal and meridional winds in the graphs are different.

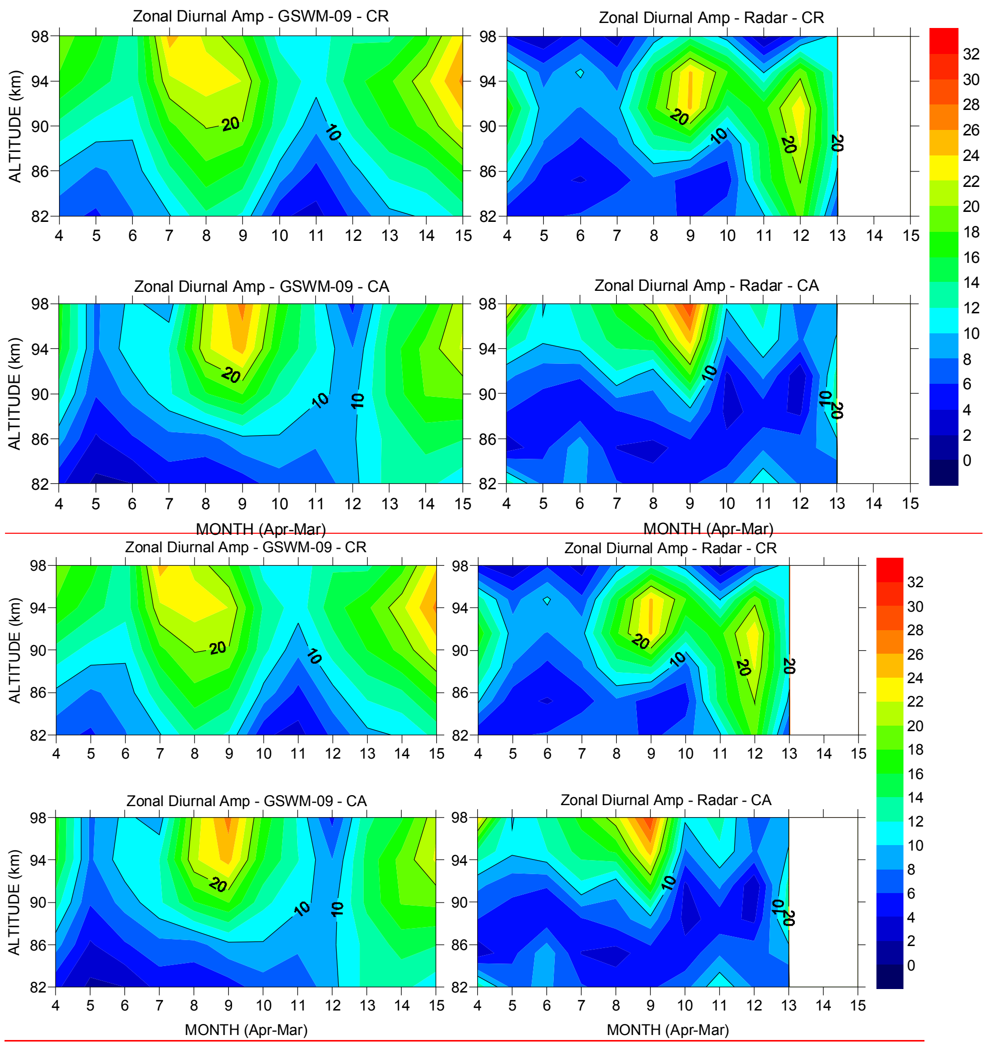


Figure. 2: The left-hand panels show diurnal zonal amplitudes as predicted by the GWSM-09 model in the range between 82 and 102 km height from April to March in CR and CA. The right-hand panels show diurnal zonal amplitudes observed by radar in CR and CA in the same range from April 2005 to January 2006. The color scale represents the amplitude in m/s.

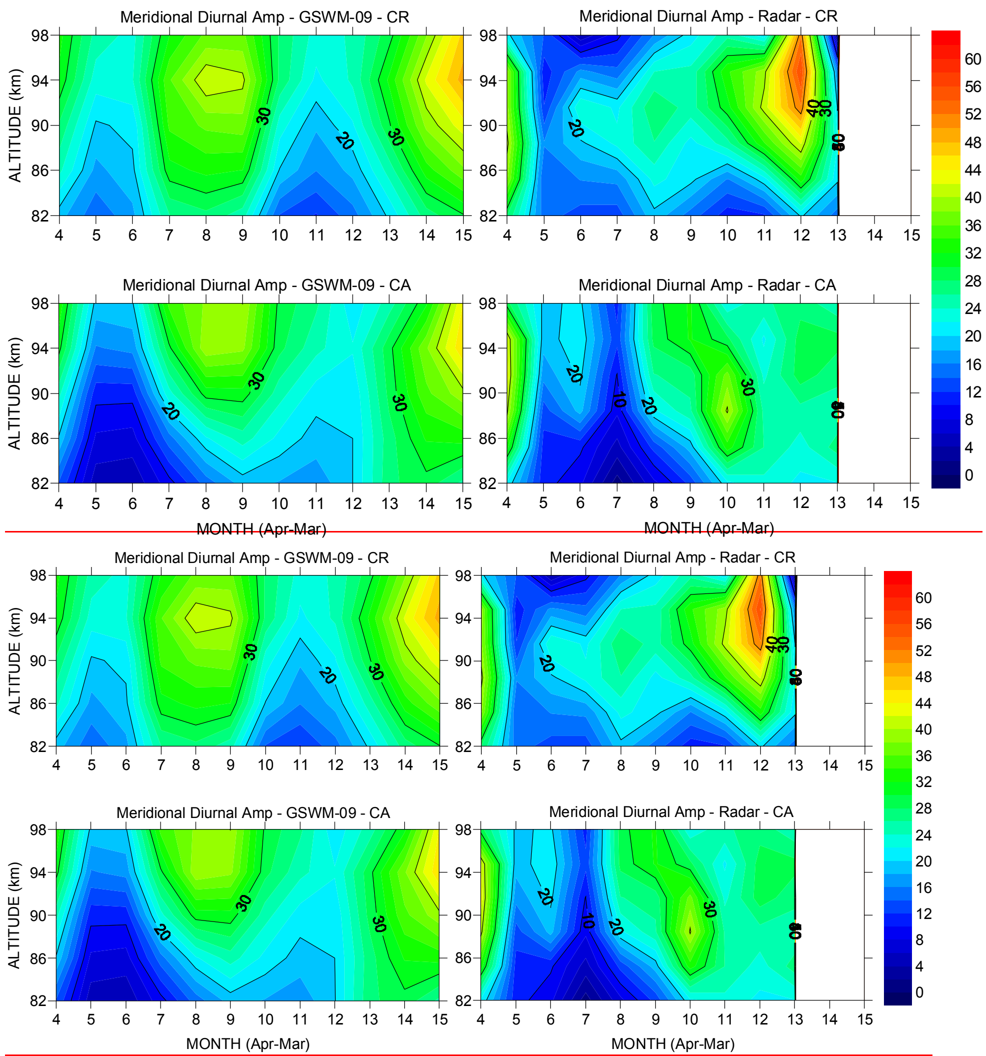


Figure. 3: Same as Fig. 2, but for meridional amplitude. The color scale is the double of the Fig. 2.

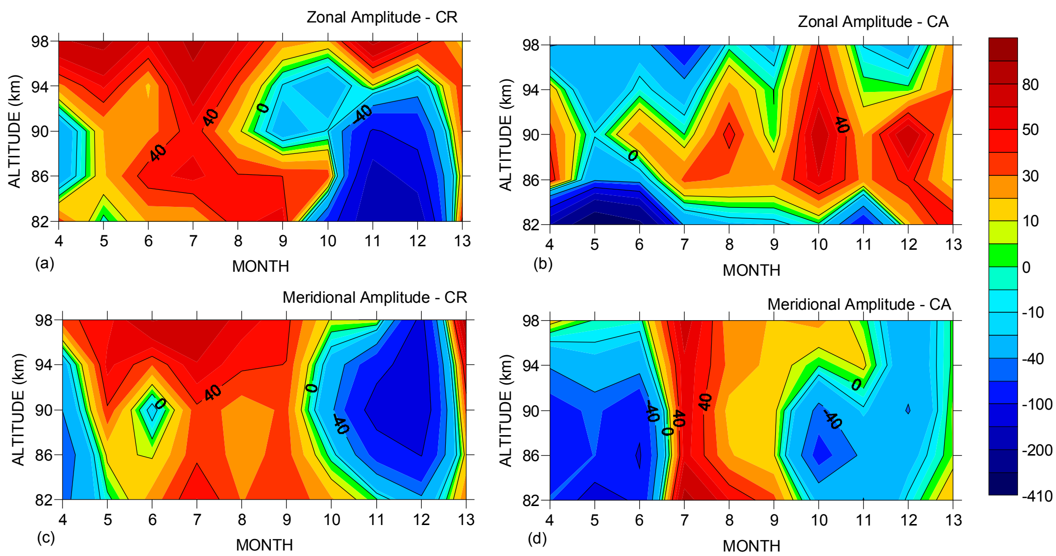


Figure. 4: Percent variance ((model – radar)*100/model) between GSWM-09 and radar diurnal amplitude ~~to~~for zonal (a and b) and meridional (a and d) components ~~to~~at CR and CA from April 2005 and January 2006.

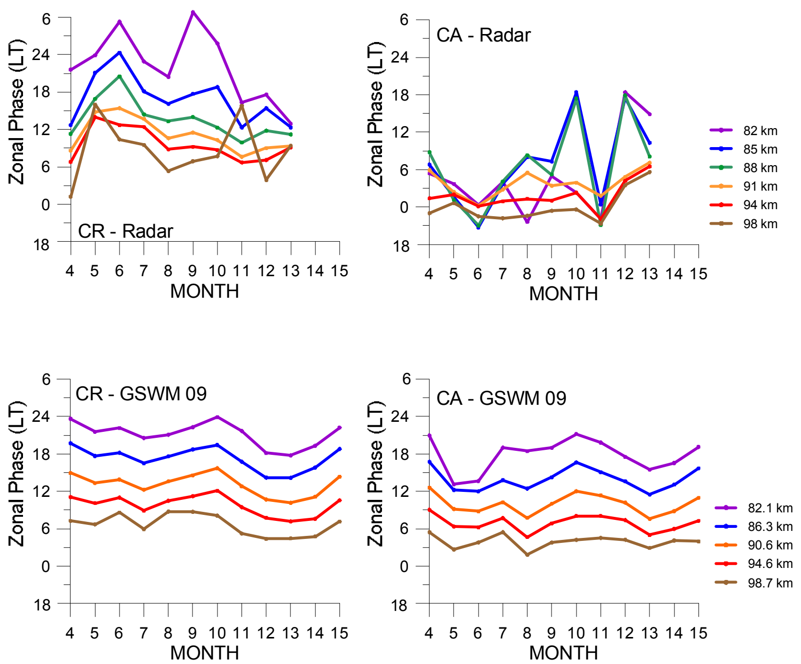


Figure. 5: Zonal diurnal phase in LT for CR (upper left), and CA (upper right) from April 2005 to January 2006, and GSWM-09 ~~(below~~for CR (lower left) and CA (lower right) from April to March. The height gates for the radar data and the GSWM-09 data are not quite the same, but close enough for visual comparisons.

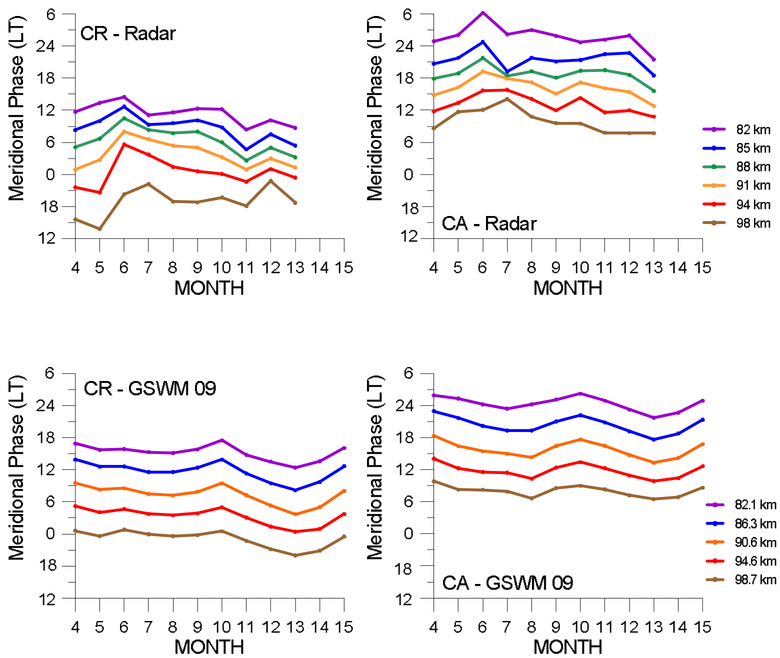


Figure. 6: Meridional diurnal phase in LT for CR (upper left), and CA (upper right) from April 2005 to January 2006, and GSWM-09 ~~(below~~for CR (lower left), and CA (lower right)) from April to March. The height gates for the radar data and the GSWM-09 data are not quite the same, but close enough for visual comparisons.