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Lower ionosphere monitoring by the South America VLF Network (SAVNET): *C* region occurrence and atmospheric temperature variability

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[1] Daily profiles of phase measurements as observed on fixed VLF paths generally show a transient phase advance, followed by a phase delay, for about 90 min after sunrise hours. This is indicative of a reflecting ionospheric *C* region developing along the terminator line at an altitude below the normal *D* region. The suggested occurrence of a *C* region is consistent with rocket measurements made in the 1960s, showing a maximum of the electron density between 64 and 68 km, and by radio sounding in the 1980s. In order to correctly describe the properties of the phase effect associated with the presence of a *C* region, it is important to understand the subionospheric propagation characteristics of the VLF paths. In this paper, we analyze the variations presented by the temporal properties of the VLF narrowband phase effect and determined a parameter associated with the appearance of the *C* region at sunrise hours observed by receivers from the South America VLF Network. Periodic patterns emerge from the parameter curves. Two distinct temporal behavior regimes can be identified: one exhibiting slow variations between March and October, and another one exhibiting faster variations between October and March. Solar illumination conditions and the geometrical configuration of the VLF paths relative to the sunrise terminator partly explain the slow variation regime. During periods of faster variations, we have observed good association with atmospheric temperature variability found in the measurements of the Thermosphere Ionosphere Mesosphere Energetics and Dynamics and Sounding of the Atmosphere using Broadband Emission Radiometry satellite instrument, which we assume to be related to the winter anomaly atmospheric phenomenon. However, when comparing the parameter time series with temperature curves, no direct one-to-one correspondence was found for transient events.

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1. Introduction

[2] Very low frequency electromagnetic waves (VLF, 3–30 kHz) may propagate with no significant attenuation over distances of thousands of kilometers through the natural waveguide with boundaries constituted by the ground and the Earth's lower ionosphere. The electric conductivity of the lower ionosphere as described by the conductivity gradient and the reference height (historically known as the Wait parameters) determine the wave propagation conditions, and any alteration of the Wait parameters will affect the measurements of the amplitude and phase on a fixed VLF path. This technique has proven to be efficient for investigating the lower ionosphere, and because the lower ionosphere is formed by the solar Lyman α spectral radiation [*Nicolet and Aikin*, 1960], it is also a useful tool for solar monitoring purposes.

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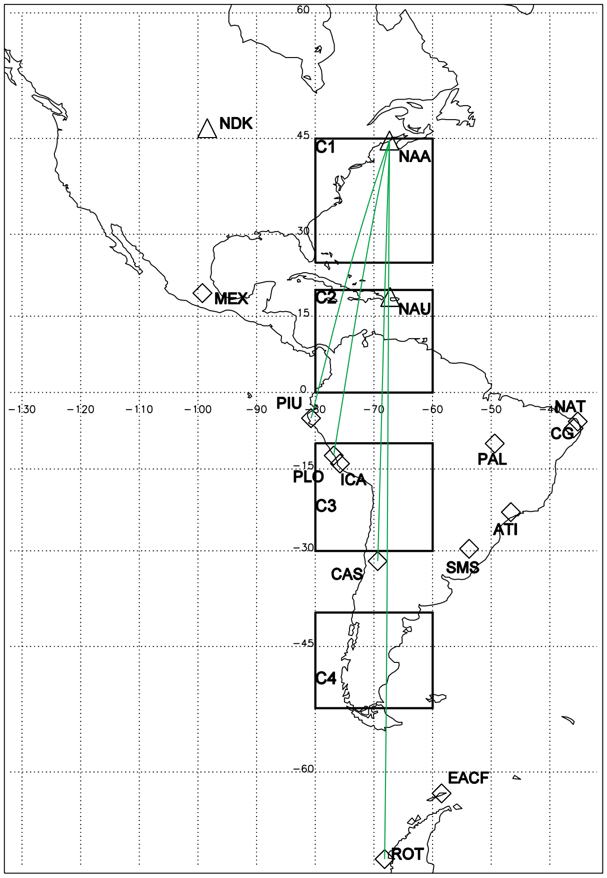

Figure 1. Map of the instrumental setup in which data were used and respective locations of the receiver stations (diamonds) and transmitters (triangles) (see the text for details).

[3] The daily profiles of phase measurements as observed on some fixed VLF paths generally show a transient phase advance followed by a phase delay for about 90 min after sunrise hours, [*Hargreaves*, 1962; *Reder and Westerlund*, 1970; *Abdu et al.*, 1973; *Comarmond*, 1977; *Kuntz et al.*, 1991]. This is indicative of a reflecting *C* region that develops along the terminator line's eastern side at an altitude below the normal *D* region. The presence of such a *C* region is supported by rocket measurements showing a maximum of the electron density between 64 and 68 km [*Mechtly et al.*, 1967; *Mechtly and Smith*, 1968] and has also been detected by radio sounding [*Rasmussen et al.*, 1980]. It reveals the presence of an electron reservoir below the normal ionospheric *D* region which forms just after sunrise and vanishes after 1 to 2 h. The importance of studying the physical properties of the ionospheric *C* region then is twofold: it informs about the local recombination coefficients and about the ratio of negative ions to electron concentrations. Furthermore, the *C* region properties can be tested as an indicator of the solar activity conditions.

[4] Earlier works suggested the cosmic ray flux as a possible ionization source forming the *C* region [*Moler*, 1960; *Abdu et al.*, 1973]. *Abdu et al.* [1973] have shown a relation between the temporal evolutions of the amplitude of the phase effect associated with the *C* region and the cosmic ray flux time variation using 1 month of VLF records. However, *Comarmond* [1977] analyzed a longer time period (few months) and was not able to conclude that the phase effect was under the control of cosmic rays. Therefore, the quantity of free electrons generated at sunrise seems to be more dependent on the content of the negative ions reservoir rather than on the cosmic ray radiation which is the nighttime main ionization source.

[5] *Turco and Sechrist* [1972] proposed a chemical model with reaction chains that involved excited species of molecular oxygen. *Comarmond* [1977] suggested, based on this model, that there is an atomic oxygen concentration increase resulting from photodissociation reactions of the molecular oxygen by the solar Lyman α radiation. The atomic oxygen first reacts with negative ions CO_4^-, CO_3^-, and NO_3^- to form O_2^- ions, which subsequently react with atomic oxygen to produce O_3 and free electrons. As a result of these reactions, a reservoir of free electrons is formed which produces the phase excess known as the *C* region, until vanishing because of electron-ion recombination.

[6] The amplitude of the phase advance characterizing the presence of a *C* layer (also called the *C* layer phase effect) depends on the geometry of the VLF propagation path configuration. For a small angle α between the propagation path and the terminator line, the amplitude of the phase effect is maximum while for $\alpha \geq 30°$, the phase effect is reduced [*Comarmond*, 1977; *Kuntz et al.*, 1991] and most of the time difficult to measure because of the presence of modal interference and conversion [*Kuntz et al.*, 1991].

[7] It is important to understand the subionospheric propagation characteristics of the VLF path in order to make correct interpretations about the properties of the phase effect associated with the presence of a *C* layer. Sometimes, another difficulty is the occurrence of perturbations due to stratospheric warmings and/or the presence of the winter anomaly. *Muraoka* [1983] and *Muraoka et al.* [1986] have shown that the winter anomaly results in perturbed (electron density) conditions in the lower ionosphere and that it is related to an intensification of mesospheric planetary waves. Also, in this case, definite conclusions were not reached because of the lack of continuous temporal coverage for both phenomena. *Comarmond* [1977] and *Kuntz et al.* [1991] also report the fact that the amplitude of the phase effect at sunrise can be totally overwhelmed by periods of strong stratospheric warming. In such cases, the use of different orientation VLF propagation paths, with different lengths, could be helpful to identify and separate all the effects present in the phase data records.

[8] *Kuntz et al.* [1991] studied the long-term evolution of the *C* layer phase effect and compared it with the solar activity cycle. Such an investigation was also performed by studying the behavior of the quiescent *D* region, using VLF propagation simulation codes [*McRae and Thomson*, 2000] and sudden phase advances at the time of 109 solar flares [*Raulin et al.*, 2006; *Pacini and Raulin*, 2006; *Raulin et al.*, 2010], both approaches leading to similar conclusions. These findings showed that the quiescent reference height H changes by about 1 km as a function of the solar activity conditions and that the solar Lyman α radiation is mainly responsible for the formation and maintenance of the daily *D* region of the ionosphere [*Nicolet and Aikin*, 1960; *Raulin et al.*, 2010]. The results found by *Kuntz et al.*, 1991 seem to indicate a *C* region phase effect dependency at least two times stronger than that expected due to variations of the solar activity cycle.

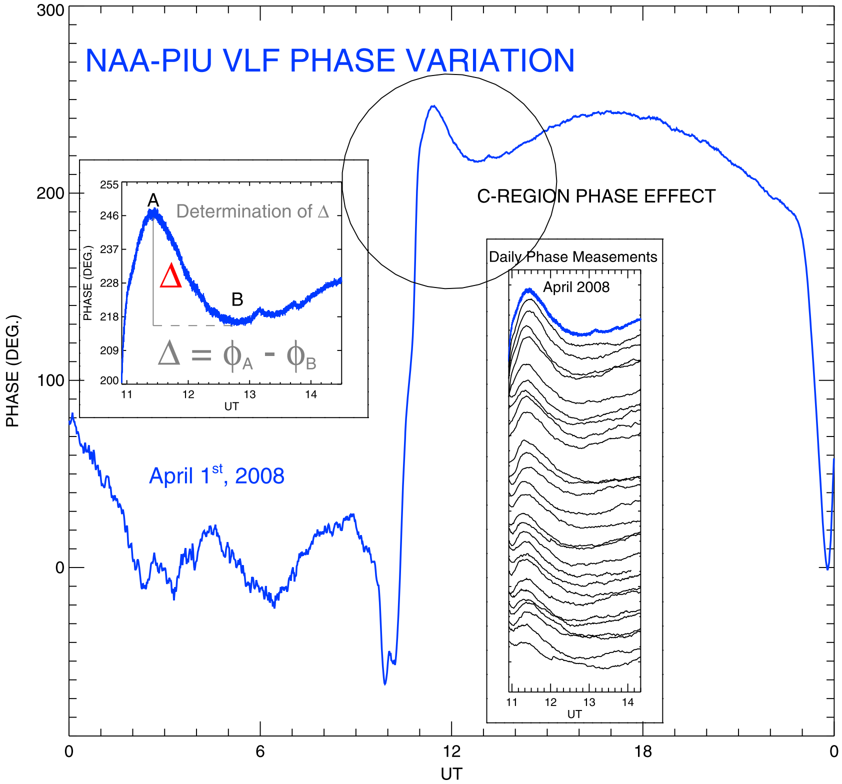

Figure 2. Typical daily phase profile as measured at the NAA-PIU VLF propagation path (blue curve). In the details it is presented: (1) graphical determination of Δ; (2) sequence of phase measurements taken during a few days of April 2008.

[9] The goal of the present work is to present the temporal properties of the phase effect associated with the appearance of the *C* region just after the sunrise hours on fixed VLF paths and to understand the responses of the lower ionosphere to the different effects generated by the geometrical characteristics of the VLF propagation paths, the occurrence of disturbed periods due to solar and geomagnetic activity, or the effects related to forcing of atmospheric origin.

2. Instrumentation

[10] The South America VLF Network (SAVNET) [*Raulin et al.*, 2009a, 2009b; *Bertoni et al.*, 2010] began operating in 2007 and is composed of receiving VLF stations at locations spread in the Latin American region. Figure 1 shows the SAVNET receiver stations spanning a latitude range between S 05 and S 60 (diamonds) and the VLF transmitters (triangles) NAA (Cutler, USA, at 24kHz), NDK (La Moure, USA, at 25 kHz) and NAU (Aguada, Puerto Rico, at 40 kHz). In this paper, we used phase measurements made at the VLF propagation paths between the transmitters NAA and NDK, and the receivers at Punta Lobos (PLO, Peru) and Piura (PIU, Peru), hereafter denominated as NAA-PLO, NDK-PLO and NAA-PIU, NDK-PIU, respectively.

[11] Each SAVNET receiver station is composed of three antennas: two square loops sensitive to the magnetic field flux variations induced by the incoming electromagnetic wave and one whip antenna that measures its electric field variations. The signals are then amplified and digitized using a commercial audio card. Precise and stable time reference measure is needed to get stable phase variations, in particular, on time scales of hours or days. In order to obtain such stability, we use a compact GPS receiver system which also provides the 1 pulse per second (pps) timing. The accurate phase measurements on long time scales are achieved by the perfect (zero drift) stability obtained by locking the analog digital sound card crystal to the 1 pps, using the Software Phase and Amplitude Logger (SoftPAL). SoftPAL is a PC-based, software-defined, scientific VLF radio receiver which uses coherent detection and optimal demodulation of minimum-shift keying (MSK) and interrupted carrier wave signals to measure and record their phase (relative to GPS time) and amplitude. SoftPAL is developed by Dr. Christopher Adams and has the capability to measure the phase of multiple-MSK signals with low noise and absolute phase, relative to GPS time. The resulting phase signal presents a precision (RMS) of about 0.05–0.07 μs, which corresponds to about less than 1° depending on the frequency of the incoming VLF wave.

[12] A typical daily (24 h) variation profile of the phase received at the SAVNET base located at Piura (Peru) from transmitter NAA (main panel) is presented in Figure 2. For about 90 min after sunrise (~10:30 UT in this example), a transient phase advance followed by a phase delay is generally observed, indicating a reflecting ionospheric *C* region below the normal *D* region. Figure 2 also shows a sequence of phase measurements taken during April 2008, with 1 min integration time that allows us to observe the day-to-day phase variability related to the *C* region occurrence effect as measured on that VLF path.

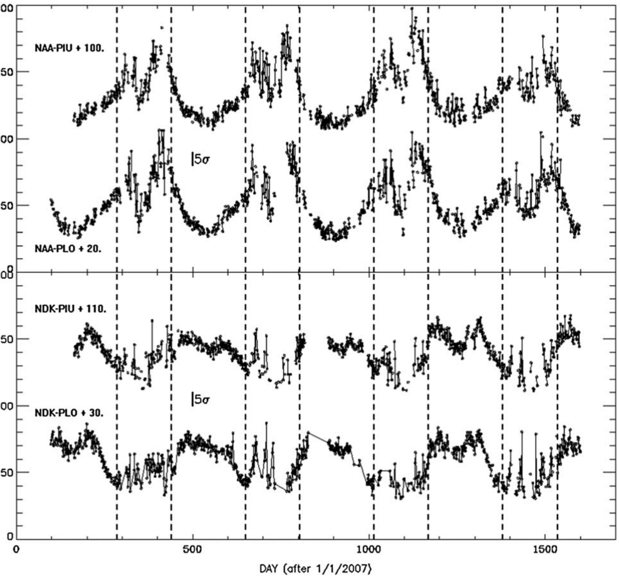

Figure 3. The Δ time series obtained for phase measurements made at the VLF paths of NAA-PIU, NAA-PLO, NDK-PIU, and NDK-PLO.

[13] We have applied the same methodology used by *Raulin et al.* [2010, 2011] and *Gavilán et al.* [2009] and performed the analysis of the *C* region phase effect parameter, Δ, defined as the difference of phase (ϕ) measured at the points A and B (as seen in the details of Figure 2):

$$\Delta = \phi_A - \phi_B (\text{degrees})$$

where ϕ_A corresponds to the daily maximum produced by the presence of the *C* region and ϕ_B corresponds to the point when the *C* region effect ends and starts to show the presence of the *D* region.

3. Results

[14] Figure 3 presents the long-term variations of Δ measurements during the period 2007–2010 as a function of the day number since 1 January 2007. Measurements are shown for four VLF propagation paths from the transmitters NAA (upper plots) and NDK (lower plots) to the receivers PIU (Piura, Peru) and PLO (Punta Lobos, Peru). Missing measurements occurred at times of transmitter or receiver maintenance, or during periods of strong local interferences or intense modal interferences. Note that in order to show all the records in the same plot, Δ time profiles have been shifted vertically. The small vertical thick bars represent the typical phase noise standard variation σ_ϕ observed on the daily time profiles; σ_ϕ generally is on the order of 1 to 3°.

[15] Clear periodic patterns are seen in all Δ time profile curves. Before 17 October 2007 (day number 290) and during the period 15 March 2008 to 17 October 2008 (day numbers 440–656), the variations of the *C* layer phase effect are rather smooth and slow, with typical temporal scale of months. Such pattern repeats itself each year between March and October (and is called period P1 hereafter). On the other hand, during the periods (called P2) from mid-October to mid-March for the years 2007, 2008, 2009, and 2010, the observed variability of Δ is much faster and more intense. It can reach values ≥50° over a few days which corresponds to phase changes greater than 25σ, where σ is the standard deviation of the Δ time series shown in Figure 3. In order to better visualize these characteristic periods, Figure 4 illustrates the temporal evolution of the phase changes due to the appearance of the *C* region year by year as measured at the NAA-PLO VLF path. The curves are shifted vertically.

[16] The overall picture given by Figures 3 and 4 is that the time variations of Δ measurements during P2 periods is disturbed and occur on typical timescales of 2–10 days. P2 periods coincide with the winter times in the Northern Hemisphere. It should be mentioned, however, that no common time variability was found for Δ, comparing records from VLF propagation paths from NAA and those recorded from the NDK transmitter.

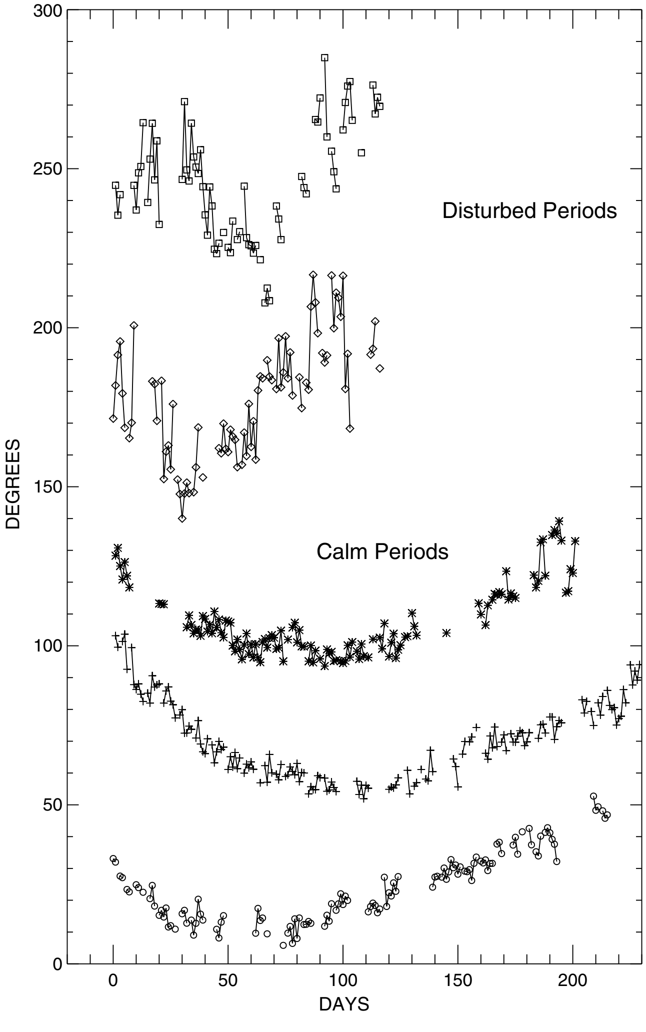

Figure 4. The Δ time series obtained for phase measurements made at the VLF path from the NAA transmitter station to the Punta Lobos (PLO) receiver station. It is clearly the contrast between the periods P1, with smooth variations, and P2, with steep variations.

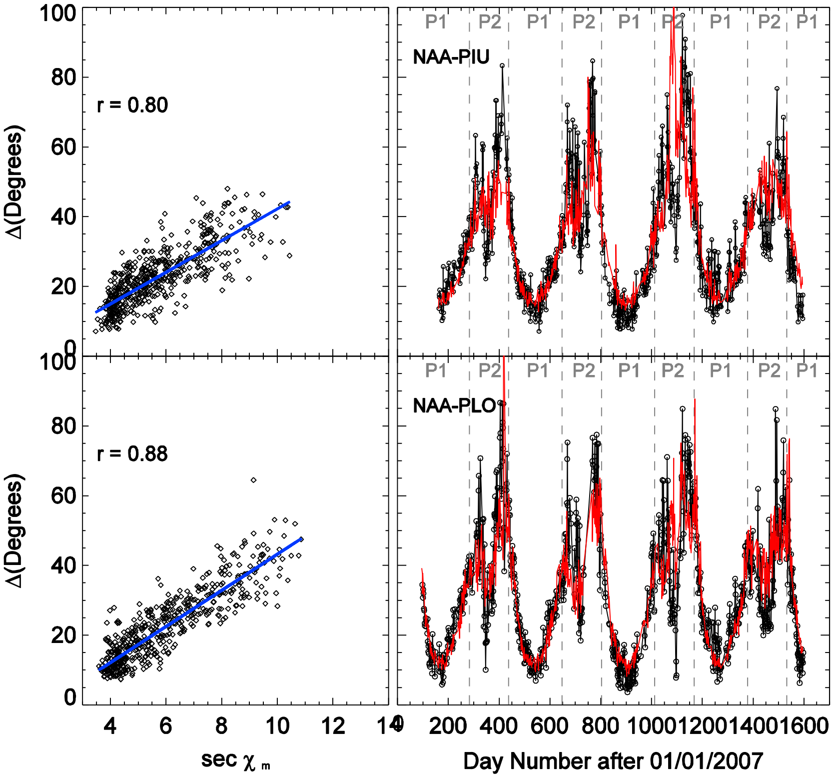

Figure 5. Correlation between mean zenith angle secant (sec χ_m, left hand panels) and Δ as measured at the NAA-PIU and NAA-PLO VLF paths (black circles, right hand panels) with sec χ_m values (in red).

4. Discussions

[17] The general pattern of the VLF narrowband phase effect associated with the appearance of the *C* region as observed by our measurements is well fitted by a function of the solar mean zenith angle (sec χ_m) daily variation for the path considered [*Raulin et al.*, 2010, 2011; *Gavilán et al.*, 2009]. χ_m is the mean zenith angle calculated by utilizing 100 discrete values of χ_i along a given VLF path at a determined time of day. Using the time when $\phi = \phi_A$ (named t_{maxC}), for the NAA-PIU and NAA-PLO VLF paths, we obtained the corresponding values of sec χ_m and calculated the correlation between sec χ_m and Δ, as shown in Figure 5 (left panels). The correlation coefficients, calculated only for P1 periods, are 0.80 and 0.88 for NAA-PIU and NAA-PLO, respectively. The Δ time series (in black) and sec χ_m (in red) show good agreement during P1 periods (right panel).

[18] On the other hand, from mid-October to mid-March for the years 2007, 2008, 2009, and 2010, the observed variability of Δ is much faster and intense, and its gross envelope can be fitted by sec χ_m but not for the faster fluctuations. Therefore, additional effects aside from the *C* region effect might be influencing the response of the lower ionosphere and subsequently producing the modulation seen in P2 periods.

[19] Important ionization loss reactions have occurrence rates that are a function of the atmospheric temperature. As a consequence of the large values of the collision frequency between electrons and neutrals, at the lower ionosphere heights, significant ionized particle density variations may occur in the *D* region plasma that might be attributed to enhancements of electron production rates and decreases of effective electron loss rate.

[20] In order to investigate possible associations of the observed time structures of 2–10 days with atmospheric temperature variations of the same scales, we have used data from the NASA's Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite mission and one of its onboard instruments named the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) [*Mlynczak*, 1997; *Russell et al.*, 1999].

[21] Although, qualitatively, the time series of the Δ parameter and the temperature measurements, seen in Figure 6, revealed good correlations between the periods of faster variations, no one-to-one correspondence has been found between temperature peaks for transient events and the respective response of the Δ parameter [*Raulin et al.*, 2010; *Gavilán*, 2009].

[22] The occurrence of perturbations due to stratospheric warmings and/or the presence of the winter anomaly may produce effects on the VLF narrowband phase measurements. *Taubenheim* [1971] has shown that seasonal variations of atmospheric temperatures and concentration of major constituents of the upper atmosphere already give rise to anomalous seasonal behavior of the lower ionosphere.

[23] *Muraoka* [1983] and *Muraoka et al.* [1986] showed that the winter anomaly leads to perturbed (electron density) conditions in the lower ionosphere and that it is related to an intensification of mesospheric planetary waves. *Taubenheim* [1983] suggested the meteorological control of the *D* region, and *Kazimirovsky* [2002] and *Laštovička* [2006] have shown that the ionospheric plasma distribution may be modulated by forcings from external origins and from tropospheric-mesospheric origins.

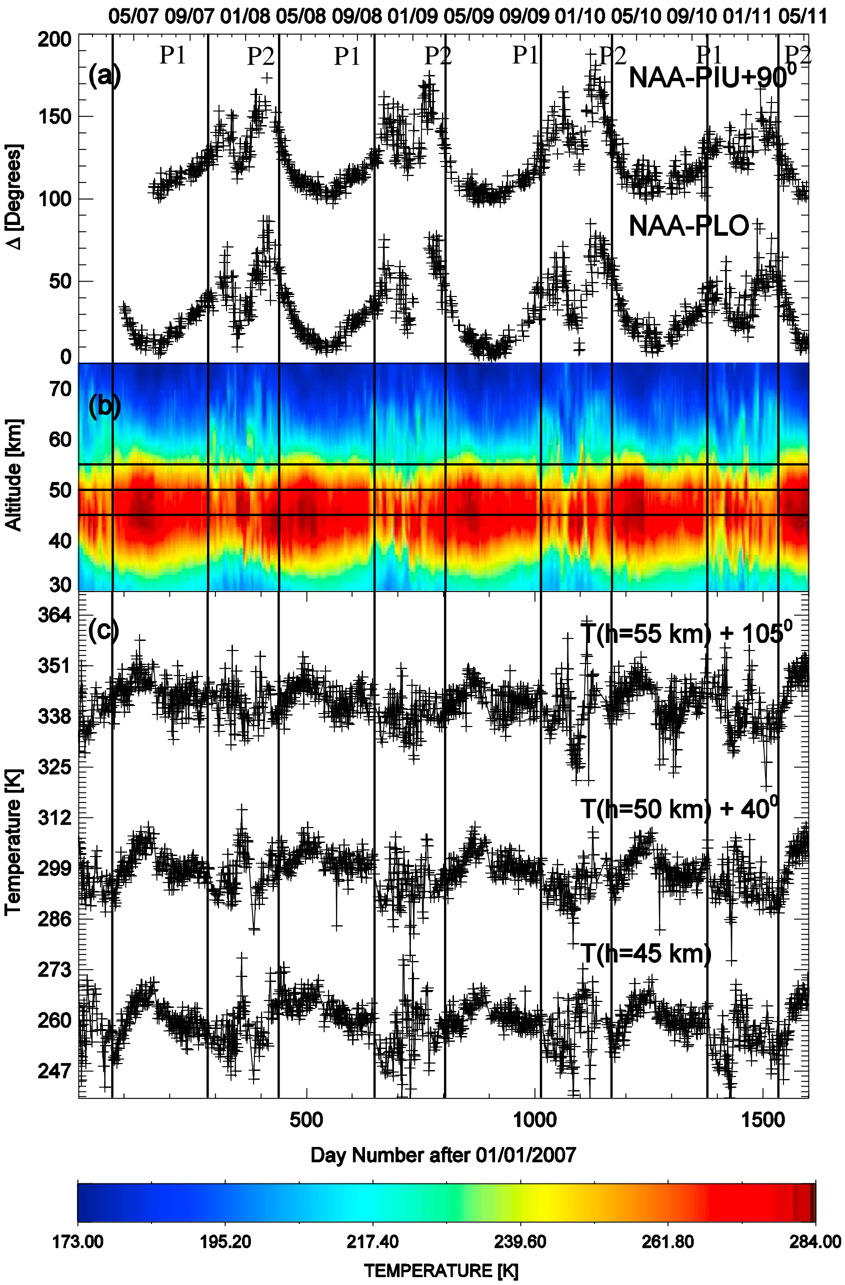

Figure 6. The Δ parameter time series obtained for phase measurements made at the (a) VLF paths from NAA-PIU and NAA-PLO, (b) TIMED-SABER atmospheric temperature contours, and (c) cuts of temperature profiles for three different heights.

[24] Figure 7 displays the latitudinal variations of the atmospheric temperature measurements between 00:00 and 09:00 UT made by TIMED-SABER satellite passages within selected boxes in the 280°E–300°E longitude range, namely, (C1) 25°N–45°N, (C2) 0°–20° N, (C3) 18°S–38° S, and (C4) 48°S–53°S (see Figure 1). Within the C1, C3, and C4 boxes, SABER measurements of atmospheric temperature exhibit faster fluctuations during the local winter period. It should be noted that the C4 region has a different sampling, because SABER observes poleward of 53° latitude only every 2 months. The measurements made within C2 (equatorial to low latitude range, close to the receiver station location) do not show any obvious fast temperature fluctuations.

[25] *Rodger et al.* [1998] have presented a simplified *D* region chemistry model in which only the ions N_2^+, O_2^+, NO^+, and O^+ are considered. The authors assumed the dissociative recombination to be the predominant type of recombination processes. Using the reaction equations and time constants presented by *Rodger et al.* [1998], we estimated that a temperature variation of 20 K, at a height of 70 km would result in 10% variation of the dissociative recombination parameters, which cannot explain some of the abrupt variations seen in the Δ parameter.

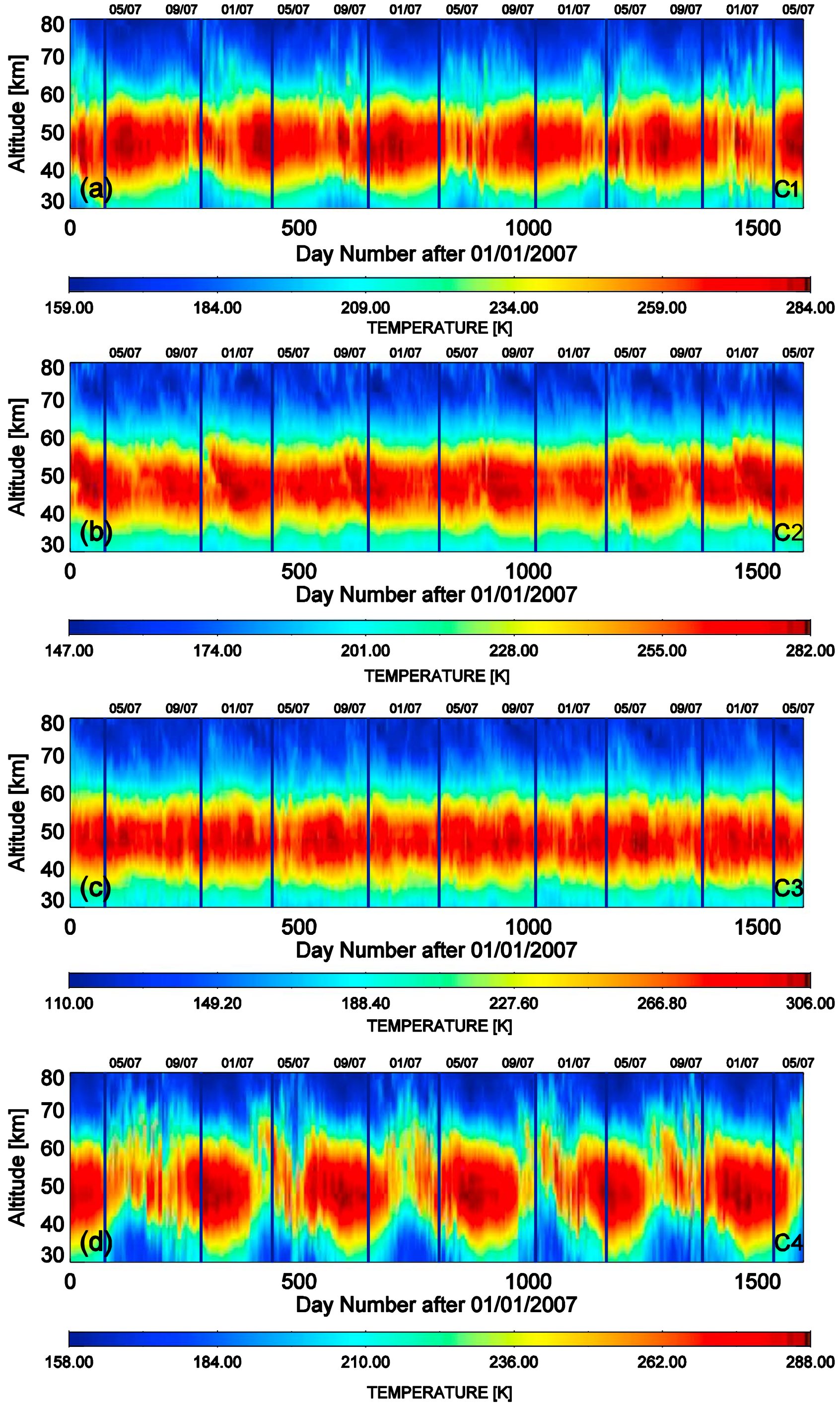

Figure 7. TIMED-SABER atmospheric temperature contours respectively measured in the four latitude-longitude boxes (C1 to C4, shown in Figure 1).

5. Conclusions

[26] In this paper, we have analyzed and presented the temporal properties of VLF narrowband measurements of a transient phase effect associated with the appearance of the *C* region at sunrise hours observed by VLF receivers from the South America VLF Network (SAVNET). SAVNET is a tool to observe the response of the lower ionosphere to distinct disturbing agents from solar to atmospheric origins. The objective is to better understand the variability of the properties of the *C* region in terms of different effects like the geometrical characteristics of the VLF propagation paths, the quiescent solar activity (Lyman α, more specifically), or the atmospheric phenomena such as stratospheric warmings and/or winter anomaly. It is important to first understand the subionospheric propagation characteristics of a VLF path in order to make correct interpretations and to describe the properties of the phase effect associated with the presence of a *C* region.

[27] The Δ time series obtained for different VLF paths, namely, NAA-PIU, NDK-PIU, NAA-PLO, and NDK-PLO have been presented. Clear periodic patterns are seen in all Δ curves. Before 17 October 2007 (day number 290) and during the period 15 March 2008 to 17 October 2008 (day numbers 440–656), the variations of the *C* region phase effect are rather smooth and slow, with temporal scale of months. Such pattern repeats itself each year between March and October. On the other hand, during the periods from October to March for the years 2007, 2008, 2009, and 2010, the observed variability of Δ is much faster and intense.

[28] Some ionization loss reactions have properties that depend on the atmospheric temperature. In order to investigate possible associations of the observed structures of 2–10 days with atmospheric temperature variations of same scales, we have used data from the NASA's TIMED-SABER satellite mission. Although, qualitatively, the time series of the Δ parameter and the temperature measurements revealed good correlations between the periods of faster variations, no one-to-one correspondence has been found between temperature peaks and the respective response of the Δ parameter. Besides, by using some of the reaction equations and time constants, we estimated that the temperature variation of 20 K at a height of 70 km would result in only 10% variation of the dissociative recombination parameters, which is not enough to explain the abrupt variations seen in the Δ parameter. Therefore, other sources of perturbations could be acting as well, and it is possible that the winter anomaly atmospheric phenomena may play an important role as a source of perturbation. This hypothesis will be further studied in a forthcoming paper.

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References

Abdu, M. A., S. Ananthakrishnan, B. A. Krishnan, and O. Massambani (1973), Cosmic ray ionization in the D region at sunrise: Evidence from VLF phase measurements, *Radio Sci.*, *8*(8–9), 733–736.

Bertoni, F. C. P., J.-P. Raulin, H. Rivero-Gavilan, W. Guevara-Day, R. Rodriguez, and G. Fernandez (2010), SAVNET: A Ground-Based Facility for Studying Ionospheric, Atmospheric, and Natural Phenomena, *Radio Sci. Bull.*, *334*, 43–48.

Comarmond, J. M. (1977), Contribution a l'étude de la basse ionosphère par des mesures de phase et d'amplitude d'ondes électromagnétiques a très basse fréquence, Thèse de doctorat d´état es sciences physiques, Université Pierre et Marie Curie.

Gavilán, H. R., J. P. Raulin, F. C. P. Bertoni, and A. Dal Lago (2009), Study of the properties of the ionospheric C-region using the South America VLF Network, In: 11th International Conference of the Brazilian Geophysical Society, 2009, Salvador de Bahia, Brazil.

Hargreaves, J. K. (1962), The behaviour of the lower ionosphere near sunrise, *J. Atmos. Terr. Phys.*, *24*(1), 1–7.

Kazimirovsky, E. S. (2002), Coupling from below as a source of ionospheric variability a review, *Ann. Geophys.*, *45*(1), 1–29.

Kuntz, V. L. R., L. R. Piazza, and P. Kaufmann (1991), C-layer dependence on solar cycle and southern latitude observed by VLF propagation, *J. Atmos. Terr. Phys.*, *53*(5), 419–423.

Laštovička, J. (2006), Forcing of the ionosphere by waves from below, *J. Atmos. Sol. Terr. Phys.*, *68*, 479–497.

McRae, W. M., and N. R. Thomson (2000), VLF phase and amplitude: Daytime ionospheric parameters, *J. Atmos. Sol. Terr. Phys.*, *62*, 609–618.

Mechtly, E. A. E., and L. G. Smith (1968), Growth of the D-region at sunrise, *J. Atmos. Sol. Terr. Phys.*, *30*, 363–369.

Mechtly, E. A. E., S. A. Bowhill, L. G. Smith, and H. W. Knoebel (1967), Lower ionosphere electron concentration and collision frequency from rocket measurements of Faraday rotation, differential absorption, and probe current, *J. Geophys. Res.*, *72*, 5239–5245.

Mlynczak, M. G. (1997), Energetics of the mesosphere and lower thermosphere and the SABER experiment, *Adv. Space Res.*, *20*(6), 1177–1183.

Moler, W. F. (1960), VLF propagation effects of a D-region layer produced by cosmic rays, *J. Geophys. Res.*, *65*(5), 1459–1468.

Muraoka, Y. (1983), Winter anomalous effects of mode conversion observed in mid-latitude VLF transmission, *J. Geophys. Res.*, *88*(A1), 311–317, doi:10.1029/JA088iA01p00311.

Muraoka, Y., K. Petzoldt, and K. Labitzke (1986), The role of atmospheric planetary-scale waves in the D region winter anomaly, *J. Geophys. Res.*, *91*(A1), 329–338, doi:10.1029/JA091iA01p00329.

Nicolet, M., and A. C. Aikin (1960), The Formation of the D Region of the Ionosphere, *J. Geophys. Res.*, *65*, 1469–1483.

Pacini, A. A., and J.-P. Raulin (2006), Solar X-ray flares and ionospheric sudden phase anomalies relationship: A solar cycle phase dependence, *J. Geophys. Res.*, *111*, doi:10.1029/2006JA011613.

Rasmussen, J. E., P. A. Kossey, and E. A. Lewis (1980), Evidence of an ionospheric reflecting layer below the classical D region, *J. Geophys. Res.*, *85*(A6), 3037–3044.

Raulin, J.-P., A. A. Pacini, P. Kaufmann, E. Correia, and G. M. M. Aparecida (2006), On the detectability of solar X-ray flares using very low frequency sudden phase anomalies, *J. Atmos. Sol. Terr. Phys.*, *68*, 1029–1035.

Raulin, J.-P., P. C. M. David, R. Hadano, A. C. V. Saraiva, E. Correia, and P. Kaufmann (2009a), The South America VLF NETwork (SAVNET), *Earth Moon Planets*, *104*, 247–261, doi:10.1007/s11038-008-9269-4.

Raulin, J.-P., P. C. M. David, R. Hadano, A. C. V. Saraiva, E. Correia, and P. Kaufmann (2009b), The South America VLF NETwork (SAVNET): Development, installation status, first results, *Geofis. Int.*, *48*(3), 253–261.

Raulin, J.-P., et al. (2010), Solar flare detection sensitivity using the South America VLF Network (SAVNET), *J. Geophys. Res.*, *115*, A07301, doi:10.1029/2009JA015154.

Raulin, J.-P., F. C. P. Bertoni, P. Kaufmann, H. R. Gavilán, E. Correia, R. Hadano, and N. Schuch (2011), Solar–terrestrial, ionospheric and natural phenomena studies using the South America VLF network, *J. Atmos. Sol. Terr. Phys.*, *73*(11–12), 1581–1586, doi:10.1016/j.jastp.2010.11.029.

Reder, F. H., and S. Westerlund (1970), VLF phase instabilities produced by propagation medium: Experimental results. In Davies, K. (Ed.), Phase and frequency instabilities in electromagnetic wave propagation, AGARD Conf. Proc. No. 33, Advisory Group for Aerospace Research and Development, North Atlantic Treaty Organisation, p. 103.

Rodger, C. J., O. A. Molchanov, and N. R. Thomson (1998), Relaxation of transient ionization in the lower ionosphere, *J. Geophys. Res.*, *103*(A4), 6969–6975, doi:10.1029/98JA00016.

Russell, J. M., III, M. G. Mlynczak, L. L. Gordley, J. Tansock, and R. Esplin (1999), An overview of the SABER experiment and preliminary calibration results. Proceedings of the SPIE, 3756, 44th Annual Meeting, Denver, Colorado, 277–288, 18–23 July.

Taubenheim, J. (1971), Some new aspects of the Winter Anomaly of ionospheric absorption, *J. Atmos. Sol. Terr. Phys.*, *33*, 1481–1485.

Taubenheim, J. (1983), Meteorological control of the D region, *Space Sci. Rev.*, *34*, 397–411.

Turco, R. P., and C. F. Sechrist Jr. (1972), An investigation of the ionospheric D region at sunrise. 3. Time variations of negative-ion and electron densities, *Radio Sci.*, *7*(7), 725–727.