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Nighttime morphology of vertical plasma drifts over Vietnam during different seasons and phases of sunspot cycles

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Abstract:

This study is the first which gives the nighttime morphology of vertical plasma drifts over Vietnam at the equatorial trough and the northern tropical crest of ionization anomaly in the Asian sector. We use the h'F data in Vietnam from Bac Lieu observatory (9.28°N, 105.73°E, dip: 1.73°N) during the 2006-2019 period and Phu Thuy observatory (21.03°N, 105.96°E, dip: 14.49°N) for the 1964-2011 period, to calculate the vertical plasma drift velocity (Vd), and analyze the annual, seasonal, sunspot cycle, and sunspot cycle (SC) phase evolutions. For Bac Lieu, the PRE and minimum reversal peaks evolve according to the sunspot cycle. The seasonal average of drift pattern shows that the PRE peak appears earlier one hour in summer (1800 LT) than in equinoxes and winter (1900 LT) and the minimum reversal peak occurred about 2100-2200 LT, except in summer, in which this peak identifies around 0100 LT. This drift pattern exhibits a semiannual asymmetry during PRE/minimum reversal periods with peaks in March and September/October. The evening-time PRE at Bac Lieu is dependent on the phase of sunspot cycle. For Phu Thuy, the mean annual peak magnitudes of Vd during the PRE and minimum reversal periods exhibits poorly correlated with the sunspot number (Rz). For the SC seasonal variation, the lowest PRE peak magnitude in autumn appeared one hour later compared with winter, one hour earlier than summer, and same time as spring while the minimum reversal peak is larger in summer for SCs 20-23 and in autumn for SCs 20, 23, and 24 at around 0200-0300 LT than other season at about 2000, 2200, and 2300 LT. The morphology of the seasonal average variations of Vd is rather similar for the all SCs except the SC 24 at Phu Thuy. The PRE peak during the high solar activity years (2000 LT) appears earlier about 4 hours than the low solar years (at 2300 LT/0000 LT). The monthly average of plasma drift also exhibits semiannual asymmetry during PRE event for cycles 22, 24 and minimum reversal period for cycle 24 with peaks in March and September, in addition, it shows an annual variation for remaining cycles during PRE/minimum reversal periods with peaks in summer months. The pre-sunrise enhancement characteristic (0500 LT) was observed during all seasons and phases (ascending, descending, minimum) at Bac Lieu, summer for all SCs, equinoxes for SC 24, the ascending and minimum phases for the SC 24, and the descending phase for the SC 23 at Phu Thuy.

Keywords: Zonal plasma drift, h'F, equatorial ionosphere, solar activity, pre-sunrise drift enhancement.

1. Introduction

The low latitudes ionosphere is characterized by different phenomena related to the geometry of the Earth's magnetic field. There is the existence of an equatorial ionization anomaly, EIA (Namba and Maeda, 1939; Appleton, 1946), the existence of an enhanced ionospheric electric current flowing along the magnetic equator, the equatorial electrojet (EEJ) (Chapman, 1951) and the existence of equatorial irregularities of plasma (Basu and Basu, 1981). These plasma irregularities (bubbles) disrupt radio signals. They are at the origin of the spread F for HF waves, plume for VHF waves and scintillations for GPS signals.

During the day the eastward electric field and the northward geomagnetic field produce in the E region of the ionosphere a vertical **E X B** drift (Vd) which lifts up the plasma. At higher altitudes in F region, the plasma diffuses downward along the geomagnetic field lines into both hemispheres under the influence of gravity and pressure gradients, this produces the EIA which is characterized by an electron density trough at the magnetic equator, and two crests of enhanced electron density at about ±15° magnetic. At night, the westward zonal electric field interacts with the meridian magnetic field causing a Vd downward directed plasma drift. Around the sunset before reversing to the west the plasma drift Vd increases sharply, this phenomenon is called the PRE (Pre-Reversal Enhancement). The vertical drift velocity is prominent in the equatorial region and gradually decreases at low latitudes.

During the quiet magnetic periods, the variations of Vd are explained by the coupling processes arising from upward propagating tides, planetary waves and gravity waves (Abdu et al., 2006a; Fejer et al., 2008a). During the disturbed magnetic periods, Vd is affected by different physical processes related to solar wind magnetosphere dynamo which are 1) the short-lived prompt penetration electric PPEF (Vasyliunas, 1970) and 2) electric field from ionospheric dynamo disturbance DDEF (Blanc and Richmond, 1980) due to enhanced energy and momentum deposition into the high latitude (Rabiu et al., 2007; Fejer et al., 2008b; Abdu et al., 2009; Santos et al., 2012; Adekoya and Adebesin, 2015).

The sources of vertical drift variability during quiet and disturbed periods are related to the solar EUV flux and F10.7 index variations (Abdu et al., 2010; Santos et al., 2013). The nighttime vertical drift investigation during the quiet and disturbed conditionsexplain the large F2 layer uplift and the evening time resurgence of the EIA. The nighttime vertical drift also serves as an indicator/seeding mechanism for the commencement of equatorial spread F or/and scintillation, and the rate of inhibition of the likely appearance of scintillation effect (Adebesin et al., 2013a; Adeniyi et al., 2014a; Adebesin et al., 2015b). The longitudinal variations in equatorial plasma drifts exist at different local times and seasons (Abdu et al., 1981b; Walker, 1981; Batista et al., 1986; Deminov et al., 1988; Sastri, 1996; Su et al., 1996; Doumouya et al., 2003; Hartman and Heelis, 2007), these variations may be related to longitudinal variations of geomagnetic field strength along the equator. The seasonal and solar activity variations of the post sunset equatorial F-region zonal plasma drift are attributed to the corresponding variations in the neutral winds (Aswathy and Manju, 2020).

In this paper we present the results concerning the vertical drift of the ionospheric plasma during the night estimated from the data of two ionosondes in Vietnam, Bac Lieu observatory (9.28°N, 105.73°E, dip: 1.73°N) located near the equatorial trough of the EIA and Phu Thuy observatory (21.03°N, 105.96°E, dip: 14.49°N) located near the Northern crest of the EIA. Therefore, the study of the ionospheric vertical drift variability at Bac Lieu and Phu Thuy can provide the interesting characteristics of plasma dynamics in the ionosphere in Vietnam low-latitude region, contributes important information for building regional and global ionospheric models.

Bac Lieu and Phu Thuy observatories have been operated since 2006 and since 1962, respectively. It is the first time in Vietnam that we use the ionosphere observation data at two stations to carry out researching on plasma drift velocity. This paper is organized in four sections. The first section presents the plasma drift and its various variations. Section 2 introduces the data and methodology employed. Section 3 is devoted to the annual, seasonal, sunspot cycle evolution, and sunspot cycle (SC) phase for the sunspot cycle 24 at Bac Lieu and the entire sunspot cycles 20-24 at Phu Thuy. Then we discuss our results and recommendations conclude in section 4.

2. Data analysis

In many studies, drift observations are inferred using ground-based measurements obtained either from the height of the peak electron density of the F2 layer, hmF2 as (Liu et al., 2004; Adebesin et al., 2013b), the virtual height of the F layer, h'F (Sreeja et al., 2009; Adebesin et al., 2015a, 2015b), or by employing the real height at some fixed frequencies and using the means at such selected frequencies (Abdu et al., 2004). The use of inferred drift from ground-based height measurements as near accurate in the absence of direct measurements had validated by Bittencourt and Abdu (1981) and Bertoni et al. (2006). In this work, h'F data obtained from Bac Lieu and Phu Thuy were used to infer the drift, Vd. The drift observations are limited to the evening/nighttime periods (1600-0600 LT) because of some physical limitations associated with the accuracy of inferred vertical plasma drifts during the daytime using h'F (Adeniyi et al., 2014a; Adebesin et al., 2015a).

The virtual heights of the ionospheric layer F, h'F recorded by the ionosondes of Bac Lieu-Vietnam during the period from 2006 to 2019 (complete solar cycle 24 and three last years of the 23 one) and Phu Thuy-Vietnam during the period from 1964 to 2011 (complete solar cycles 20, 21, 22 and incomplete ones 23, 24). The positions of the ionospheric observatories Bac Lieu and Phu Thuy have been presented in the Table 1 and Fig. 1. A Digital SKI02098-Japanese ionospheric vertical sounder continuously recorded the ionosonde data at Bac Lieu (2006-2019). The ionosonde data at Phu Thuy were obtained by the four different ionospheric vertical sounders: the IRX-Hungarian (1962-1966), the AIC-Russian (1967-1994), the IPS71-Australian (1994-2002) and the Digital SKI02098-Japanese (2006-2011). The data of two Digital SKI02098-Japanese are available on the website http://seg-web.nict.go.jp/sealion/.

The hourly monthly mean of h'F for each nighttime hour (1600-0600 LT) were computed from the daily values. From these monthly hourly mean values, vertical plasma drift velocities were determined by measuring the time rate of change of h'F:

$$Vd = d(h'F)/dt \qquad (1)$$

The daily hourly values h'F are used, so the vertical drift at the i^{th} hour is calculated as following:

$$V_d(i) = \frac{h'(i+1) - h'(i-1)}{2} \qquad (2)$$

where h'(F) in km, Vd in m/s.

Monthly mean hourly value is the arithmetic mean daily hourly value for a month.

Annual mean hourly value is the arithmetic mean monthly hourly value for a year.

Seasonal mean value is the arithmetic mean monthly hourly value of the months constituting a particular season in a year.

Sunspot cycle seasonal mean value is the seasonal mean value for the years that made up the sunspot cycle.

The cycle monthly mean PRE/minimum reversal peak value is the arithmetic mean of the monthly PRE/minimum reversal peak values for the all years during a sunspot cycle. For instance, for the month of January during SC 20, the mean is the monthly mean values of all data sets during the PRE/minimum reversal periods in 1964-1975; same for February, March, and so on.

The sunspot cycle phase mean value is the arithmetic mean hourly values of the years that constitute a particular cycle phase (as listed in Table 2).

The minimum reversal peak magnitude is the maximum negative value of the plasma drift.

The seasonal variation is grouped into 4 seasons: Spring (March, April), summer (May, June, July, August), autumn (September, October), and winter (November, December, January and February).

The different sunspot cycles phases listed in Table 2 are distinguished four parts: the minimum phase, years with Rz<20, the increasing phase, years with $20 \leq R_Z \leq 100$, the maximum phase, years with Rz >100 and the decreasing phase, years with $100 \geq R_Z \geq 20$. Rz is the Zurich sunspot number.

3. Results and Discussion

3.1. Ionosphere Height Profile at Bac Lieu and Phu Thuy

Fig. 2 illustrated the nighttime annual profiles of h'F at Bac Lieu (panels a) during the 2006-2019 period and Phu Thuy (panels b) for the years from 1964 to 2011.

Fig. 2a, for Bac Lieu, during the SCs 23-24, the maximum amplitude of h'F occurs around 1900-2000 LT and the minimum one about 0200 LT, except in 2008, 2009, and 2019 (minimum solar activity), these maxima observed at 0000 LT. During nighttime observations in 2013 and 2014, Fig. 2a also show that the F layer height attains a maximum with above the 300 km threshold value, these results are similar to the findings of (Adebesin et al., 2013a; Adebesin et al., 2015b). For considered years (2007, 2008, 2009, 2010, 2016, and 2019) at Bac Lieu, the pre-sunrise enhancement characteristic observed about 0400-0500 LT.

Fig. 2b, for Phu Thuy, shows the average of h'F altitudes are relatively high during SC 21 compared to SCs 22, 23, and 24. For the high solar activity years (1967-1970 for cycle 20, 1978-1982 for cycle 21, 1988-1992 for cycle 22, 1998-2002 for cycle 23), height enhancement was observed during the post sunset period attaining maximum about 2000 LT or 2100 LT.

Particularly, the high solar activity years (1979 and 1980) of the SC 21, the increasing of the F layer height was observed above the 300 km threshold value (Adebesin et al., 2013a) during the evening time observations. For the low solar activity conditions (1964-1965, 1973-1977, 1983-1987, 1993-1997, and 2007-2011 for the solar cycles 20-24), the maximum amplitudes of the altitudes of the h'F profile are about midnight, three hours later than the ones during the high solar activity year. A interesting feature is found in 2007 and 2008 of SC 23 and the low solar activity years (2009-2011) of SC 24 that the pre-sunrise enhancement characteristic presents a small magnitude compared to the PRE observation with the time enhancement also starts at about 0500 LT as observed at Bac Lieu (2007, 2008, 2009, 2010, 2016, and 2019). In addition, each h'F curve of the considered five SCs presents an additional minimum around 0300-0400 LT.

Bac Lieu is located near the magnetic equator; the altitude of the h'F post-sunset peaks is due to the pre-reversal enhancement (PRE) of the eastward electric field which causes a large upward ExB drift (Farley et al., 1986). The post-sunset h'F peaks during maximum solar activity are higher than those during minimum solar activity. This is explained by the fact that the PRE eastward electric field is larger for high solar activity than for low solar activity (Fejer et al., 1999). The same result was obtained by Adebesin et al., (2015b).

At Phu Thuy, the h'F peaks appear at post-sunset during maximum solar activity year is also due to the effect of PRE, while these peaks appear around midnight during minimum solar activity year. This was caused by the meridional winds and diffusion, which could also play roles in raising or suppressing the height of F layer at low latitude (Abdu, 1997).

Furthermore, Maruyama et al. (2008, 2009) used ionospheric height data, h'F, obtained during nighttime at a pair of magnetic conjugate points at low latitudes and the third was near the magnetic equator along the magnetic meridian in Southeast Asia to derive thermospheric winds in the magnetic meridional plane for transequatorial and convergent/divergent components (with respect to the magnetic equator). They demonstrated that ionospheric height differences between the conjugate points can be used for inferring thermospheric meridional winds within limits. That is, when the height difference changes rapidly, say with a period as short as 6 hours, the wind variation may precede the height variation by several tens of minutes, and the size of the shift depends on the rate of variation in the wind. When the wind direction varies gradually and the cumulative height descent become large, the response of the height change may saturate. Thus, the different height variations of the h'F post-sunset at Bac Lieu and Phu Thuy could associated with meridional winds. Future work will need to build numerical models to clarify explain the height variations of nighttime F-layer at these stations.

3.2. Annual Nighttime Drift Pattern at Bac Lieu and Phu Thuy

Fig. 3 illustrates the hourly annual nighttime variation of the inferred plasma drift velocities (Vd) observed at Bac Lieu during the entire years (2006-2011, 2013-2016, 2019) for the different phases of the sunspot cycle 24 and last three years (2006-2008) of SC 23. PRE peak magnitudes at around 1800-1900 LT and minimum reversal peak magnitudes at from 2100-2200 LT were observed during all the years of the sunspot cycle 24. These peak magnitudes are greatest during the maximum solar activity years and minimum during the minimum solar activity years. This shows that the vertical drift is solar cycle dependent. This figure was shown also the pre-sunrise enhancement at around 0400-0500 LT.

Fig. 4 shows the hourly annual nighttime variation of the inferred plasma drift velocities (Vd) at Phu Thuy during the period from 1964 to 2011 (sunspot cycles 20 (1964-1975), 21 (1976-1985), 22 (1986-1995), 23 (1996-2008), 24 (2009-2011)). During the high solar activity years of the SCs 20-23, Vd has the maxima PRE peaks around 2000 LT and the minima reversal peaks between 2200 and 2300 LT for all cycles, where the magnitude peaks in cycle 20 are lower than in other cycles. In Fig. 4 also appears simultaneously reversal peak amplitude about 0300 LT for the high solar activities years. For the low solar activity years, Vd shows the peak magnitudes from 2200-0000 LT and the minimum reversal magnitudes around 0300 LT. In addition, the pre-sunrise enhancement (around 0500 LT) was clearly shown for SC 24, but absent during SC 20, 21, 22 and 23.

The pre-sunrise enhancement characteristic of plasma drift in the morning local time at Phu Thuy and Bac Lieu was observed similar to the one at Trivandrum (8.33°N, 77°E, and dip 0.4°N) in the Indian sector (Nayar et al., 2009) and at Ouagadougou (12.4°N, 358.6°E) in the African Equatorial Ionization Anomaly trough (Adebesin et al., 2015b). Nayar et al. (2009) explained that this characteristic related to the zonal electric field at the equatorial F-region produced by the electric polarization field developed from the activities of thermosphere wind and sharp conductivity gradients in the E region. The F-region electric field builds first for a short period causing the increasing of the E-region conductivity around the sunrise resulting in the added effect of E- and F-regions near the morning sunrise terminator, this added effect creates vertical velocity pattern similar anomalous feature in drift pattern (Rishbeth, 1971). Recently, Zang et al. (2016) indicated the sunrise enhancement drift can lift the equatorial ionosphere to higher heights and distort the equatorial electron density profiles; their simulations display an F3 layer in the equatorial F region during the sunrise enhancement, and a new F2 layer develops at lower altitudes under jointed control of the usual photochemical and dynamical processes.

In order to have a clearer view of the nocturnal morphology of Vd at Bac Lieu and Phu Thuy, Fig.5 illustrates the nighttime mean monthly variation of vertical drift velocity at Bac Lieu (Fig. 5a) and Phu Thuy (Fig. 5b) for the different solar activity years: ascending (left bottom panel), maximum (left upper panel), descending (right upper panel), and minimum (right bottom panel). In 2014 there is no enough twelve months of data, and so we use the data of 2015 (high solar activity year) for analysis in Fig. 5a.

In Fig. 5a for Bac Lieu, in general, the vertical plasma Vd is characterized first by an upward enhancement around 1700-1900 LT have peak velocity in the range 3.4-14.4 m/s for all seasons, then by a downward reversal give a minimum mean peak of 0.2-13.9 m/s around 1900-2200 LT. But in July 2015 and in May and June 2006, the minimum mean peak is at about 0100 LT. During all the phases, we clearly observe the semi-annual variation of Vd with highest values at equinoxes and minima at solstices. The first maximum arises generally in March; the second maximum appears in October/November. This shows that the vertical drift is season dependent

Fig. 5b for Phu Thuy, during the maximum solar activity year of 1991, the enhancement which occurred around between 1800-2100 LT has peak velocity in the range 2.05-12.47 m/s for all seasons, giving a mean evening reversal peak of 2.75-8.62 m/s around 2200-2300 LT in equinoxes and winter and at 0200 LT in summer. The highest seasonal variations for PRE and minimum reversal peak were recorded in spring (12.42 m/s and -9.92 m/s) followed by summer (7.81 m/s and -5.67 m/s), and autumn (5.25 m/s and -5.15 m/s), and the least in winter (3.60 m/s and -4.56 m/s), respectively. This also shows that the vertical drift is season dependent. In addition, the observations in 1991 show that the pre-reversal enhancement time starts about 2000-2100 LT from January-October, around 1800 LT between November-December, two hour or three hours earlier than other months. During the minimum solar activity year of 1996, the early minimum appeared around 1900-2100 LT, followed by the main maximum at about 2100-

2400 LT, and the second minimum appeared from 0200-0400 LT. But from January to July, a maximum is smaller at 1800-1900 LT. In summer and equinoxes, the first minimum and main maximum appear two hours later than other seasons, on the contrary, the second minimum occurs earlier than two hours. The monthly mean PRE peak magnitudes of Vd (about 2100-2400 LT) are largest (6.4-12.3 m/s) for autumn and smallest (~5.5-6.5 m/s) for winter, with a medium value of 7.4-9.5 m/s and 6.3-7.5 m/s for summer and spring, respectively. The reversal peak (around 2300-0400 LT) presents a semi-annual with maxima in April and September. For the ascending (2010) and descending (1974) solar activity years, the Vd exhibits a semi-annual variation with two maxima in spring/autumn and summer months, respectively. During the descending and minimum solar activity years, the Vd has a morphology and the pre-reversal enhancement time, which present rather similar variations. In general, Fig. 5b shows that Vd variation presents a semi-annual behavior.

The pre-reversal enhancement time of the vertical drift at Phu Thuy and Bac Lieu are different, which can be explained in section 3.1 by the different time of occurrence of h'F peak at these two stations.

3.3. Seasonal Nighttime Drift Pattern at Bac Lieu and Phu Thuy

Fig. 6 depicts the average seasonal observations of plasma drift velocity for each solar cycle with the average response shown by the black line for each season of all SCs at Bac Lieu (Fig. 6a) and Phu Thuy (Fig. 6b) for spring (left top panel), autumn (left bottom panel), summer (right top panel) and winter (right bottom panel). On each panel, the colored curves correspond to the different solar cycles.

In Fig. 6a at Bac Lieu, during the SC 24, we observe that the PRE peak during the equinoxes and winter solstice (at 1900 LT) occurred one hour after comparison to the summer solstice (at 1800 LT). The reversal peak reaches a minimum value at about 2100-2200 LT for all seasons except in summer, there is a positive small minimum peak (0.1 m/s amplitute) at 2200 LT, and then Vd downward drifts and attaints a negative large peak at 0100 LT. We clearly observe the PRE peak and minimum reversal peak magnitudes with highest values at equinoxes and smallest in summer season in comparisons with other seasons. Aswathy and Manju (2020) observed that the time of F-region zonal wind reversal, from westward to eastward direction, is delayed. This is explained that longer day time and shorter nights in summer season lead to the heating up of the eastern side persists for longer time relative to the west, before it reverses thereby setting up a reversed pressure gradient while cooling persists for a shorter duration in summer night leading to the relatively smaller magnitudes of wind in the night time. As result as, the weak zonal drifts in summer from the reduced zonal wind interacts with Earth's magnetic field.

The pre-reversal enhancement times of the nighttime average seasonal observations at Bac Lieu and at Ouagadougou in the African Equatorial Ionization Anomaly trough (Adebesin et al., 2015b) are different in summer and in equinoxes, in which this PRE period at Bac Lieu appears one hour before in summer and one hour after in equinoxes.

In Fig. 6b, the largest seasonal variation of the PRE peak mean value is found in summer (3.47 m/s), spring (2.94 m/s), winter (2.37 m/s), and the lowest value is found in autumn (1.56 m/s) during the solar cycles 20-24. The PRE peak magnitude in spring for SC 24 (1800LT) and summer for all SCs (1800-1900 LT) occurred one hour/two hours/three hours earlier comparison to other season (2000-2100 LT) for all SC activities.

The minimum reversal peak appears at 2200-2300 LT in spring and winter for all SCs except in spring of SC 24, in which this peak occurs at 2000 LT. During summer and autumn, the minimum peak occurs at around 0200-0300 LT for all SCs except during summer for SC 24 and autumn for SCs 21-22, there is a minimum peak at around 2000 LT and 2200 LT, respectively. After the PRE period, the velocity drift upwards creating another peak around the midnight, then downward and reaching the second minimum value from 0100 to 0400 LT in all seasons for all solar cycles except in autumn for SCs 20 and 24, in which the second minimum peak coincident with the first minimum. The second minimum peak magnitudes are larger than the first ones. In general, the morphology of the average seasonal variations of plasma drift velocity is rather similar for the all SCs except the SC 24 at Phu Thuy. In addition, pre-sunrise enhancement at 0500 LT was observed in summer for all SCs and in equinoxes for SC 24.

Fig.7 presents the average monthly of vertical plasma drift for SC 24 at Bac Lieu (Fig. 7a) and for SCs 20-24 at Phu Thuy (Fig. 7b) during peak PRE (left panel) and minimum reversal peak (right panel) periods.

Fig. 7a for Bac Lieu, the PRE peak and minimum reversal peak amplitudes show clearly a semiannual variation with the first maximum in March, the second maximum in September/October and two minima in solstices. Fig. 7a also presents an equinoctial asymmetry with the PRE peak and minimum reversal peak amplitudes are larger in March than in

September/October. The major causes of the equinoctial asymmetry as suggested by Rishbeth et al. (2000, and the reference therein) are the neutral air composition changes evolving from the large scale thermospheric dynamics, changes in atmospheric turbulence, inputs from atmospheric waves, and variations in geomagnetic activities.

In Fig. 7b, the maximum PRE exhibits an annual variation with highest values in summer and minima in winter during SCs 20, 21, and 23, while in SCs 22 and 24 the semiannual asymmetry variation was observed with highest values at equinox and minima at solstices: the autumnal maximum is smaller than the spring one. We observe that the monthly variation of the drift for five sunspot cycle events during the PRE period is in general summer higher than winter. For the minimum reversal peak magnitude, right panel shows the annual variation with highest values in summer and minima in winter for all sunspot cycles except during SC 24, its magnitude exhibits semiannual pattern with two maxima in March and September and two minima in solstices.

3.4. Solar cycle variations at Bac Lieu and Phu Thuy

Fig. 8 illustrates the solar cycle variation of PRE peak (top left panel) and minimum reversal peak (bottom left panel) periods, during SC 24 at Bac Lieu (Fig.8a), during sunspot cycles 20, 21, 22, 23, 24 at Phu Thuy (Fig. 8b), is superimposed the yearly mean value of the sunspot number. On the each panel on the right side corresponds respectively to the figures of the linear equation and correlation coefficients between observed parameters.

In Fig. 8a for Bac Lieu, the annual average peak PRE and minimum reversal peak magnitudes of the plasma drift exhibit a good correlation with sunspot number Rz. The correlation coefficients between the annual mean PRE peak and the minimum reversal peak periods with Rz are approximately 0.984, 0.982, respectively, shown in Table 3. This correlation shows that the pre-reversal enhancement process at Bac Lieu is sunspot cycle dependent. The linear equations are shown on the right Fig. 8a which shows the slopes for relationship between the minimum reversal peak and Rz and the PRE peak and Rz are nearly equal (0.062 and 0.056, respectively). The results are similar to the ones for Ouagadougou observatory in the African Equatorial Ionization Anomaly trough (Adebesin et al., 2015b).

Fig. 8b for Phu Thuy shows poorly correlated between the PRE peak and minimum reversal peak and the sunspot cycle. The correlation coefficients of the annual mean PRE peak and the inverse peak for five SCs are 0.363 and -0.098 (on the right of Fig. 8b) and the slops of linear regression lines are 0.009 and -0.002, respectively. The correlation coefficients for each SC presented in Table 3. The correlation coefficient of PRE peak during SCs 20, 24 is negative, while during SCs 21, 22, 23, this correlation coefficient is positive. The relationship between the PRE peak with the sunspot cycle is better during SCs 21, 22, 24 than during other cycle. The correlation of the reversal peak with the Rz index is equivalent during SCs 20, 23, medium during SC 22, the smallest during SC 21, the largest during SC 24. In general, the correlation of the PRE peak with sunspot number is larger than the reversal peak.

3.5. Drift Observation During Difference Phases of SCs 20-24 at Bac Lieu and Phu Thuy

Fig. 9 presents the night time hourly average values of Vd according to the four sunspot phases (ascending (left bottom panel), maximum (left upper panel), descending (right upper panel), and minimum (right bottom panel)) during different solar cycles at Bac Lieu (Fig. 9a) and Phu Thuy (Fig. 9b). These entire sunspot phases corresponding with years listed in Table 2.

Fig. 9a for Bac Lieu, the PRE peak amplitude from 1800-1900 LT and the minimum reversal peak amplitude at 2200 LT is the largest during the maximum phase compared to others. The peak amplitudes during the ascending and descending phases are almost the same, the oscillation amplitude of Vd during the minimum phase is the smallest, a result of the corresponding reduction in the equatorial zonal wind and conductivity gradient (Adebesin et al., 2013a) and lead to the decrease of F region heights. Observations in Fig. 9a are the agreement with the height profile, where altitude is lower than 300 km height level during the low sunspot activity years of the SC 24. Therefore, these observations show that sunspot cycle phases are a factor to be considered in characterizing the magnitude of the PRE and minimum reversal peaks. The higher the sunspot cycle phase is, the higher the peak magnitude of the plasma drifts is and vice versa. Fejer et al. (1999) had indicated that the PRE eastward electric field is higher in high solar activity years in comparison with low solar activity years by using the incoherent scatter radar observation from Jicamarca. Observations of the evening-time PRE at Bac Lieu is sunspot cycle phase dependent. The observed results at Bac Lieu are consistent with the previous study by (Adebesin et al., 2015b). In Fig. 9a also shows a striking feature of the enhancement of the plasma drift at local time (0500 LT), as explained earlier in section 3.2, and its magnitude changes with the phase of the sunspot cycle and disappears during the maximum phase.

In Fig. 9b, during the maximum phase, the PRE and minimum reversal peaks peaked at around 1900 LT, between 2200 and 2300 LT, respectively, its magnitude is higher SCs 21 and

22 than SCs 20 and 23. The morphology drift during the ascending and descending phases is general similar with the PRE peak at around 1800-1900 LT, the second peak at 0000LT, and the minimum reversal peak at around 0300 LT. During the ascending phase, PRE magnitude recorded higher SC 21 than SCs 20, 22, 23, and 24. For all SCs during the minimum phase and SCs 20, 23 during the descending phase, the PRE peak almost occurred later four hours relative to other phases. The night time hourly average variations of Vd at Phu Thuy exhibit the same morphology for each sunspot phase. Fig. 9b also observes a depletion in the variation around the pre-sunrise (0500 LT) period during the ascending and minimum phases for the SC 24 and the descending phase for the SC 23.

4. Conclusion

In this paper, we estimated the night time vertical drift of the ionospheric plasma Vd for two Vietnam stations located in the Equatorial Ionization Anomaly. One of them Bac Lieu is located in the trough of the EIA and the other Phu Thuy is located on the northern crest of the EIA. We have studied the seasonal and annual variations of Vd according to the different phases of the solar cycle. For the Bac Lieu station, the study period extended over solar cycle 24 (2006-2019) and for the Phu Thuy station over cycles 21, 22 and 23 (1964-2011). In equatorial region the vertical drift of plasma directed upwards increases around sunset before turning downwards. This is the PRE. Our study therefore allows us to characterize the PRE. We found the following results (see also Table 4):

1) At Bac Lieu (through of EIA) the PRE magnitudes during SC 24 vary with the phase of solar cycle, it is highest at the maximum of sunspot cycle, 9;87m/s, and minimum at the minimum phase 4,63m/s. During the ascending and descending phases, the amplitudes of the PRE are respectively 6,84m/s and 7,06 m/s.
2) At Bac Lieu, the PRE peak time is 1900 LT for maximum, ascending, and descending phases but for the minimum phase the peak of PRE occurs at 1800 LT.
3) At Bac Lieu, the seasonal variations of the PRE and reversal peak magnitudes were highest/lowest during the equinoctial/solstice periods.
4) At Phu Thuy, located at the northern crest of EIA, the magnitude of PRE during the sunspot cycle minimum is higher than for all the other sunspot cycle phases. Similar Vd patterns were observed during the ascending and descending phases.

5) At Phu Thuy, the PRE peak time shows strong phase changes from minimum (2300 LT) to maximum (2000 LT), ascending (1900 LT), and descending (1800 LT), respectively.
6) At Phu Thuy, seasonal variations of PRE peak magnitude are larger in summer than in other seasons.

To conclude the characteristics observed at Bac Lieu: larger PRE during the maximum solar flux and larger PRE at the equinox than at solstice were found both in the American (Fejer et al., 2008a) and African (Abedesin et al., 2015b) longitude sectors. Concerning Phu Thuy we have no point of comparison because Vd has never been studied on the crest of the EIA.

The result study of the ionospheric vertical drift variability at Bac Lieu and Phu Thuy can provide the interesting characteristics of ionospheric plasma dynamics in Vietnam at equatorial and low latitude, contributes important information for building regional and global ionospheric drift models.

Acknowledgements

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Table 2. Years of the different solar cycle phases at Bac Lieu and Phu Thuy.

Table 3. Correlation coefficients between the plasma drift observations and the sunspot number Rz.

Table 4. Peak Magnitudes of Plasma Drift for Different Activities and Conditions.

Figure captions

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Figure 7. Average monthly variation of vertical plasma drift at Bac Lieu for SC 24 and Phu Thuy for SCs 20–24 during maximum PRE and minimum reversal peak periods.

Figure 8. Nighttime yearly average variation of solar sunspot number Rz (black line) with vertical drift pattern at Bac Lieu (a) and Phu Thuy (b) and during peak PRE (red line, right) and minimum peak reversal (pink line, right) periods. The linear equations and correlation coefficients are shown on the pane of each figure on the right-hand side.

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Table 1. Geographic coordinates and dip latitude of the ionospheric observatories in Vietnam.

Observatory	Geographic		Dip latitude (ºN)
	Latitude (ºE)	Longitude (ºN)	
Bac Lieu	9.28	105.73	1.73
Phu Thuy	21.03	105.96	14.49

Table 2. Years of the different solar cycle phases at Bac Lieu and Phu Thuy.

Stations	Cycles	Minimum Phase	Increasing phase	Maximum phase	Decreasing phase
Bac Lieu	**23**	2008			2006, 2007
	24	2009, 2019	2010-2011	2013-2014	2015, 2016
Phu Thuy	**20**	1964	1965-1966	1968-1970	1971-1975
	21	1976	1977-1978	1979-1980	1982-1985
	22	1986	1987-1988	1989-1991	1992-1995
	23	1996, 2008	1997-1999	2000-2002	2007
	24	2009	2010-2011		

Table 3. Correlation coefficients between the plasma drift observations and the sunspot number Rz.

Stations	Sunspot cycles	Correlation coefficients	
		Rz and PRE peak	Rz and Reversal peak
Bac Lieu	**24**	0.984	0.982
Phu Thuy	**20**	-0.293	-0.330
	21	0.735	-0.106
	22	0.651	0.184
	23	0.087	-0.293
	24	-0.999	0.520
	All	0.363	-0.098

Table 4. Peak Magnitudes of Plasma Drift for Different Activities and Conditions.

Station	Activity/Condition				Plasma Drift (m/s)		
			Peak PRE	Local Time (Peak PRE)	Minimum Reversal Peak	Local Time (Minimum Reversal Peak)	Maximum Presunrise
Bac Lieu	**Sunspot Cycle**	**SC 24**	6.52	1900	-3.70	2200	2.21
	Solar Activity Phase	**Minimum**	4.63	1800	-0.15	2100	1.76
		Ascending	6.84	1900	-3.98	2200	3.05
		Maximum	9.87	1900	-6.22	2200	
		Descending	7.06	1900	-4.68	2200	3.17
	Seasonal Activity	**Spring**	8.15	1900	-6.67	2200	2.67
		Summer	5.19	1800	-2.54	0100	-0.21
		Autumn	6.98	1900	-5.33	2100	2.85
		Winter	5.96	1900	-4.21	2200	
Phu Thuy	**Sunspot Cycle**	**SC 20**	3.11	0000	-3.82	0300	
		SC 21	2.44	2000	-3.97	0300	
		SC 22	2.51	1900	-3.17	0300	
		SC 23	1.58	1800	-3.27	0300	
	Solar Activity Phase	**Minimum**	5.08	2300	-4.13	0300	
		Ascending	2.03	1900	-3.97	0300	
		Maximum	4.86	2000	-2.04	2300	
		Descending	1.88	1800	-.388	0300	
	Seasonal Activity	**Spring**	2.94	2000	-1.02	2200	
		Summer	3.47	1900	-5.18	0200	1.79
		Autumn	1.56	2000	-4.41	0300	
		Winter	2.37	2100	-1.23	2300	

Figure captions

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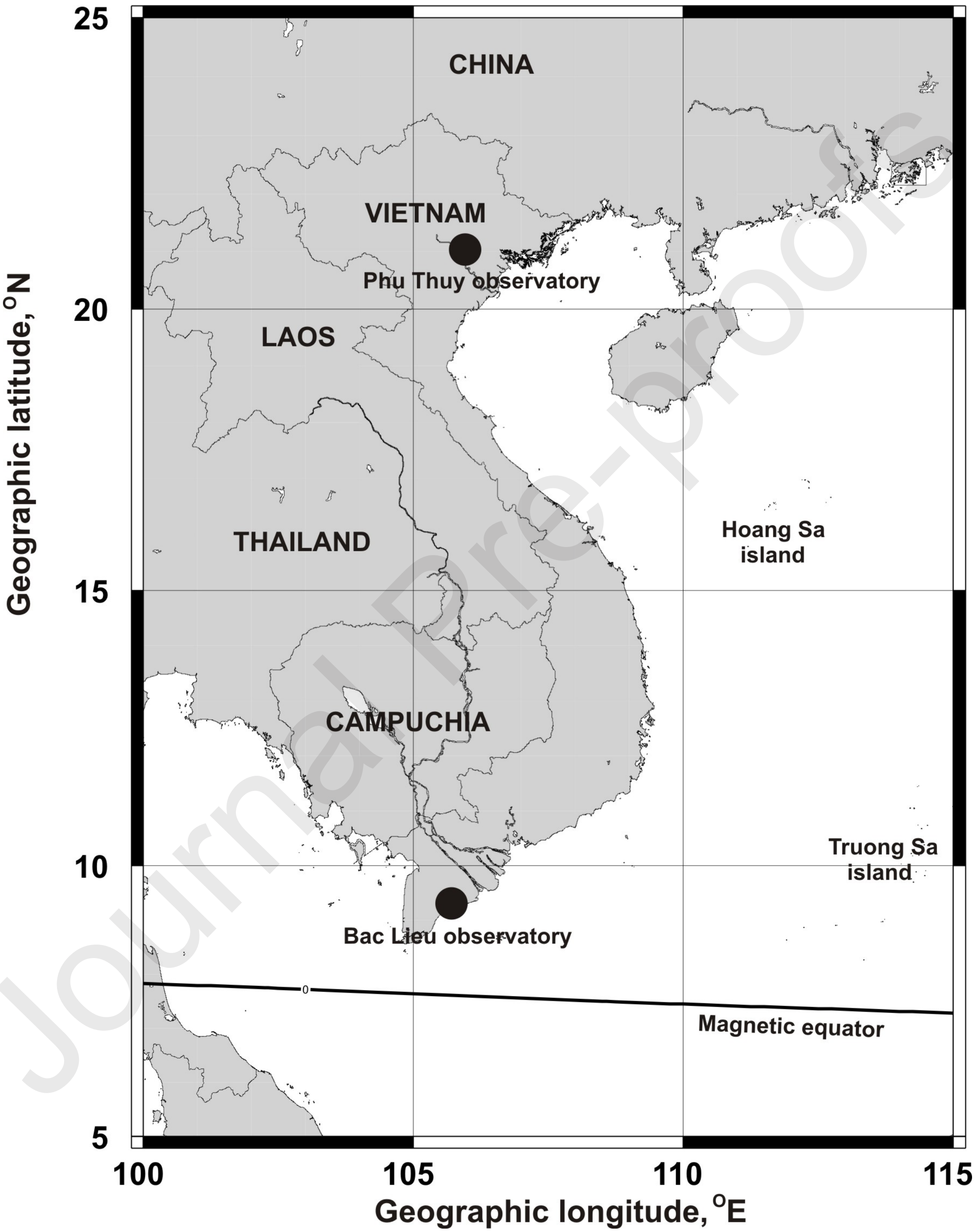

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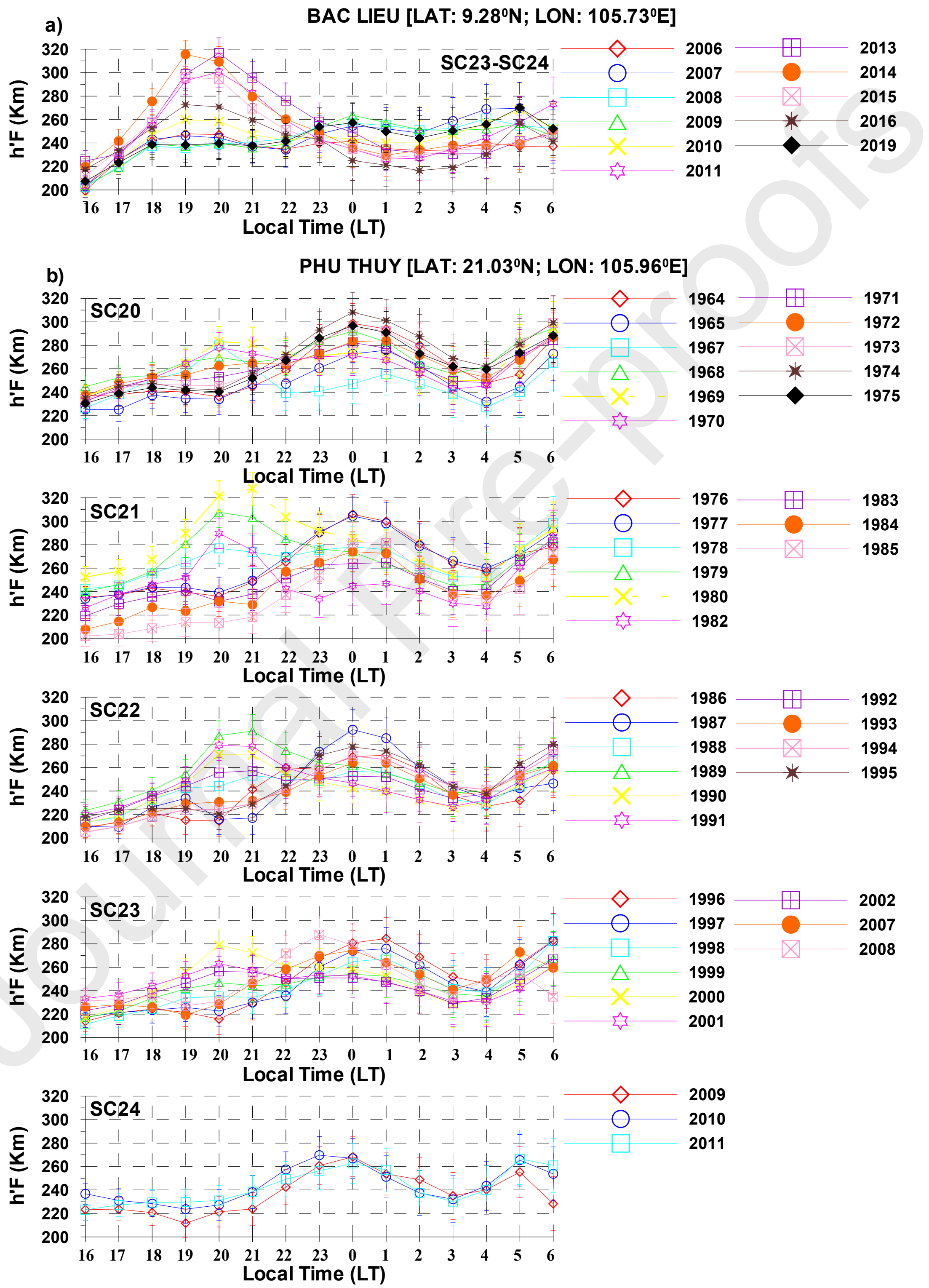

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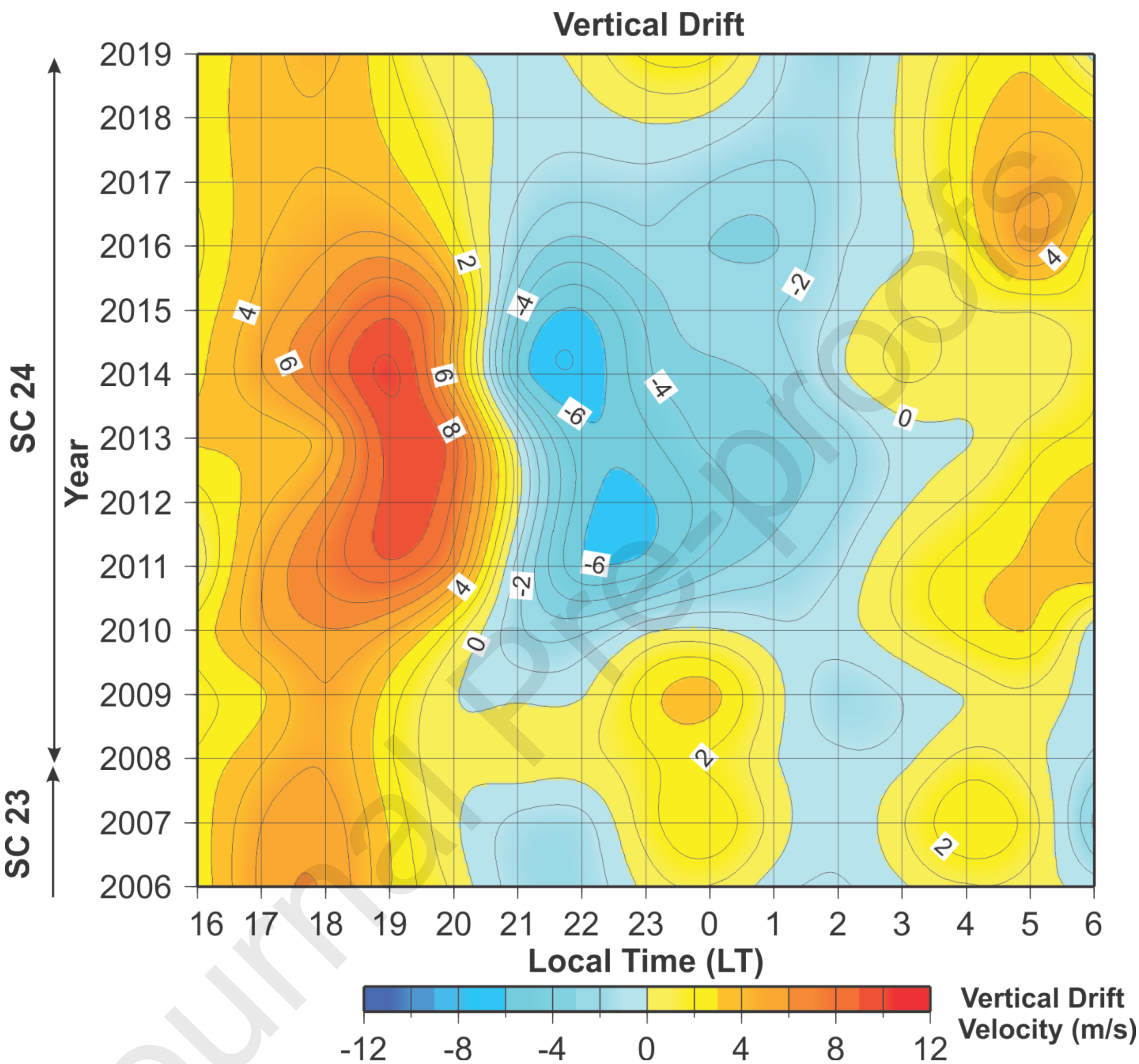

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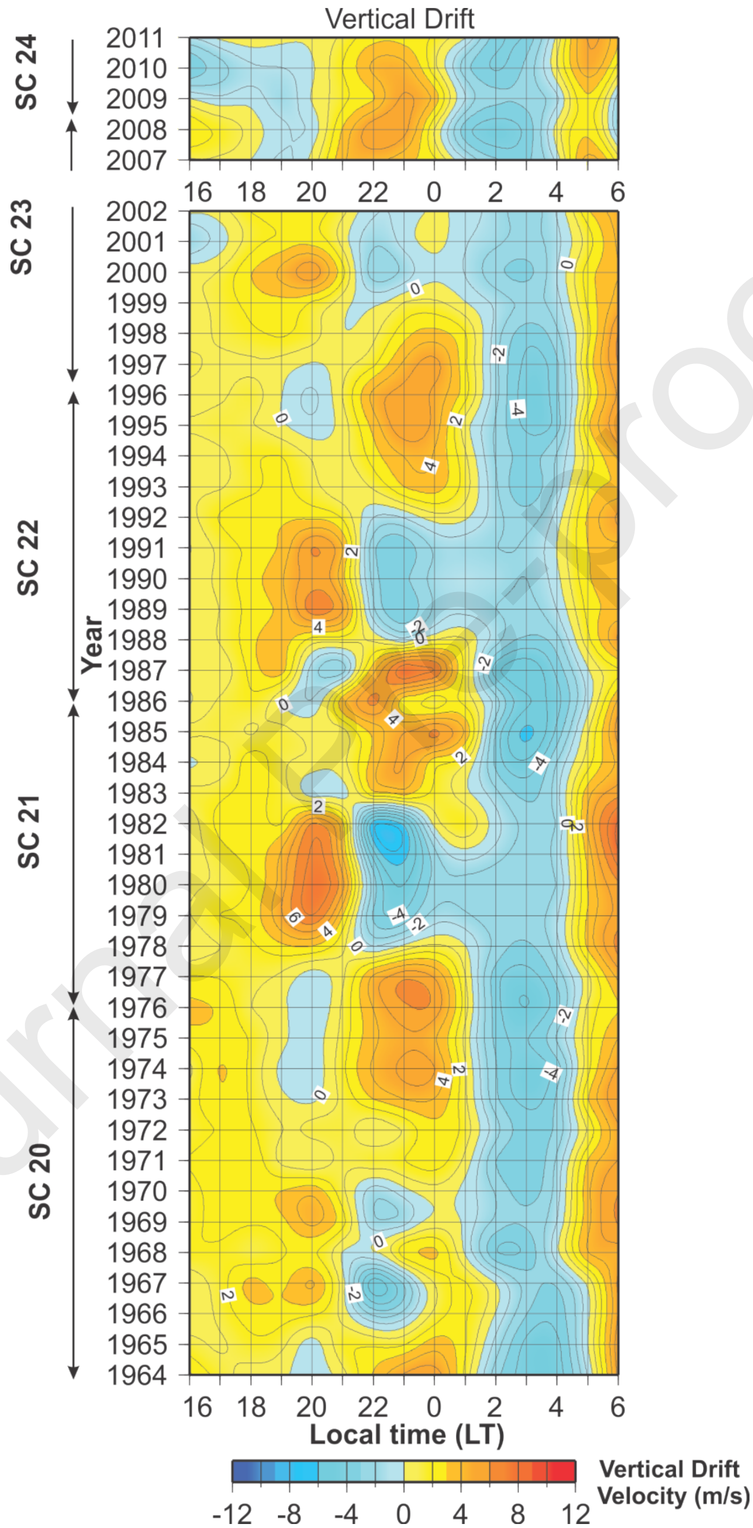

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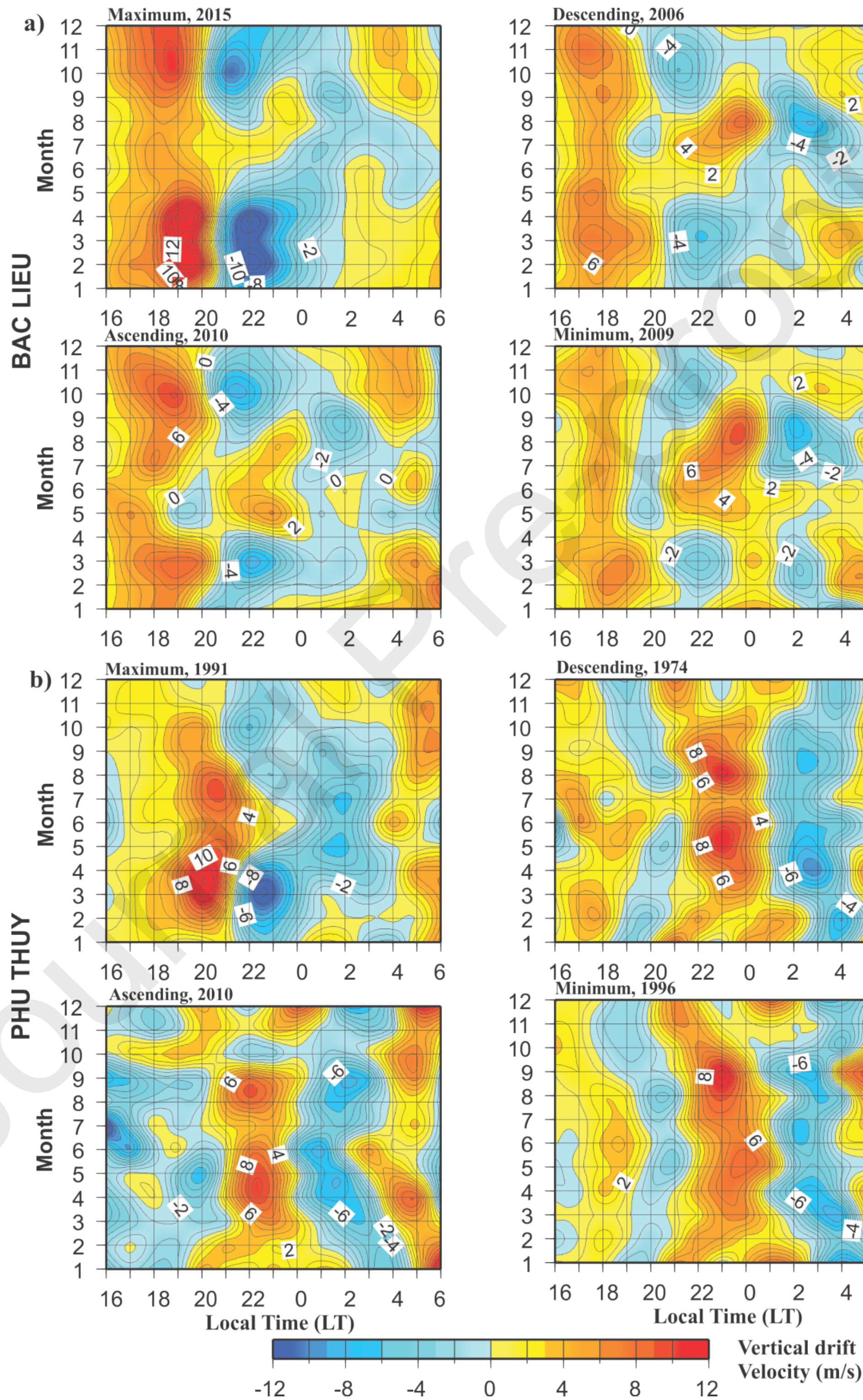

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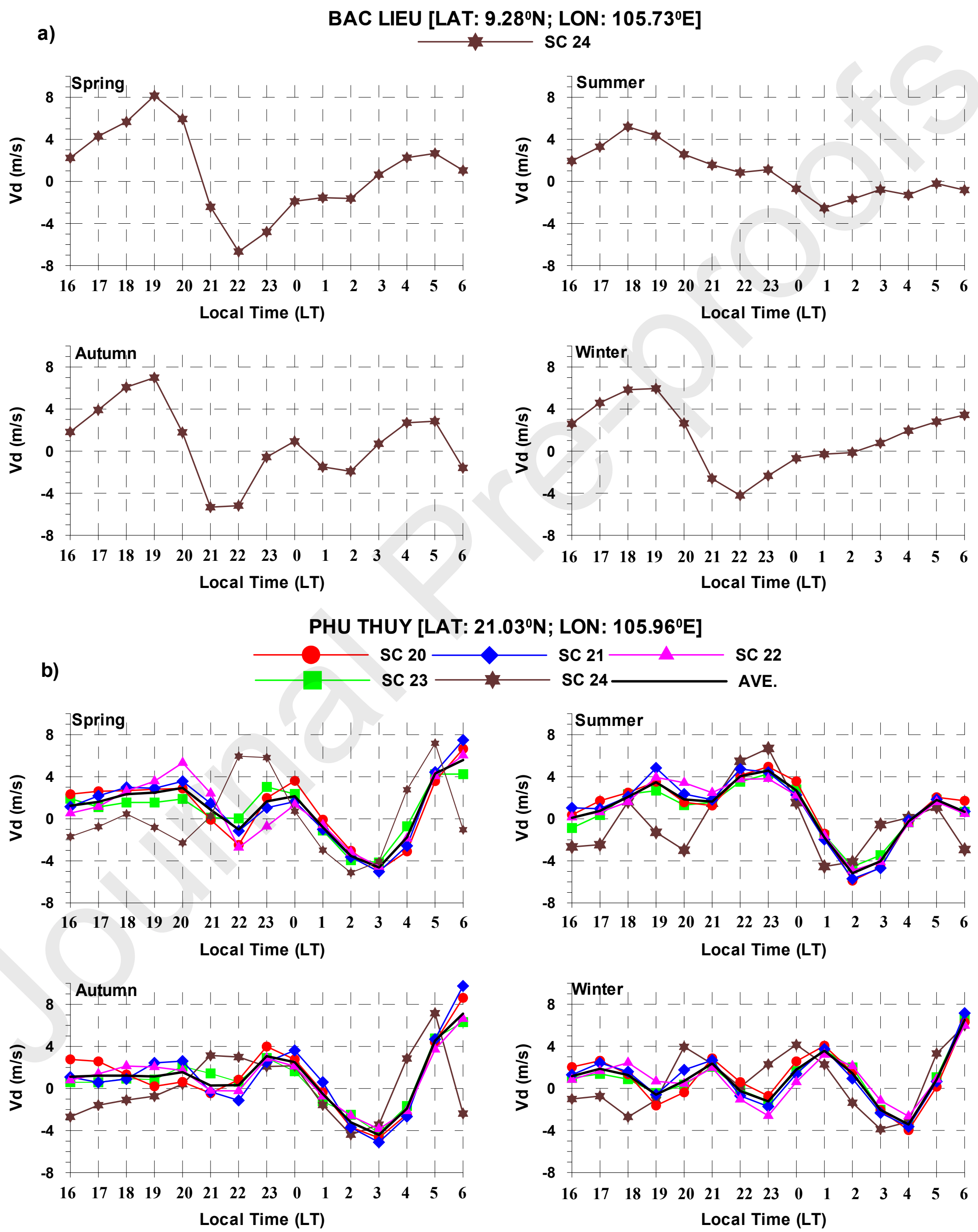

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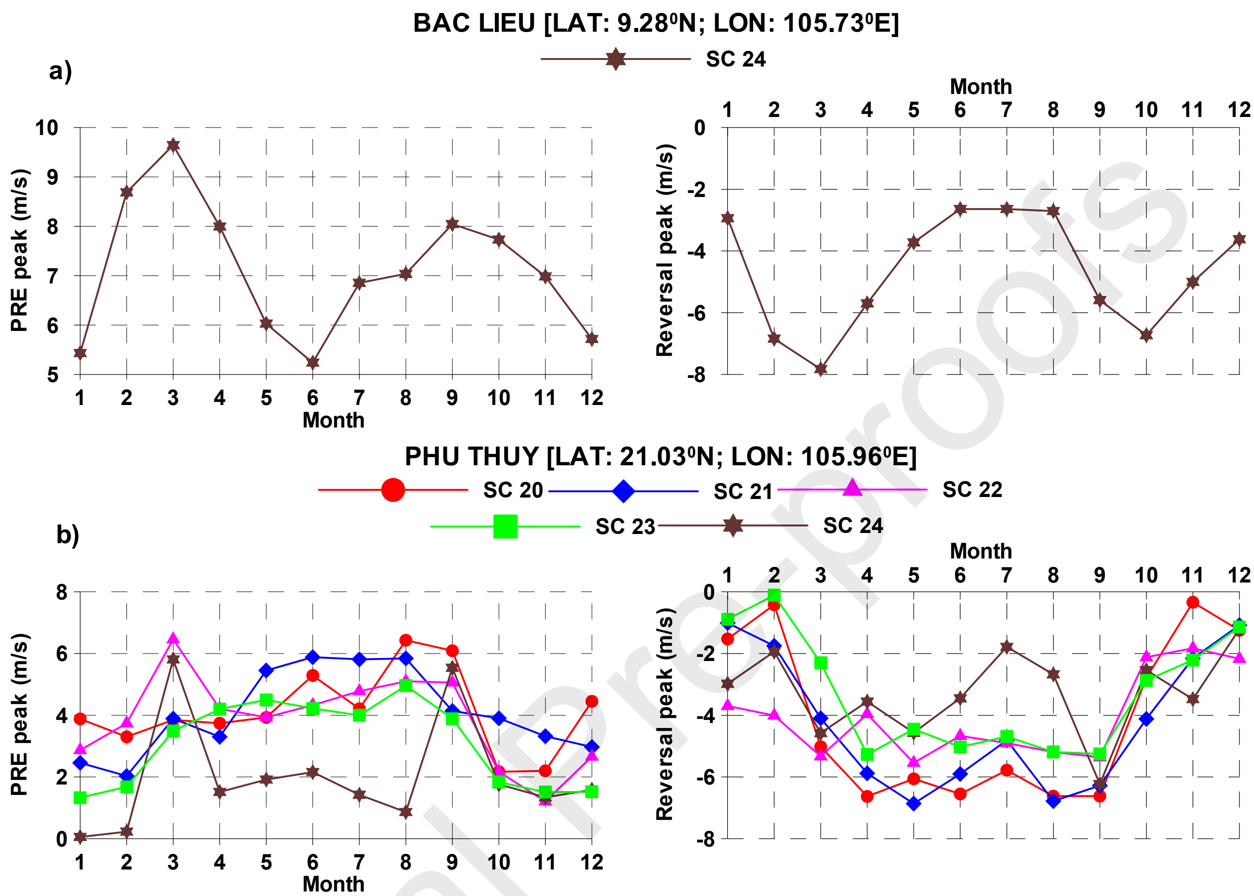

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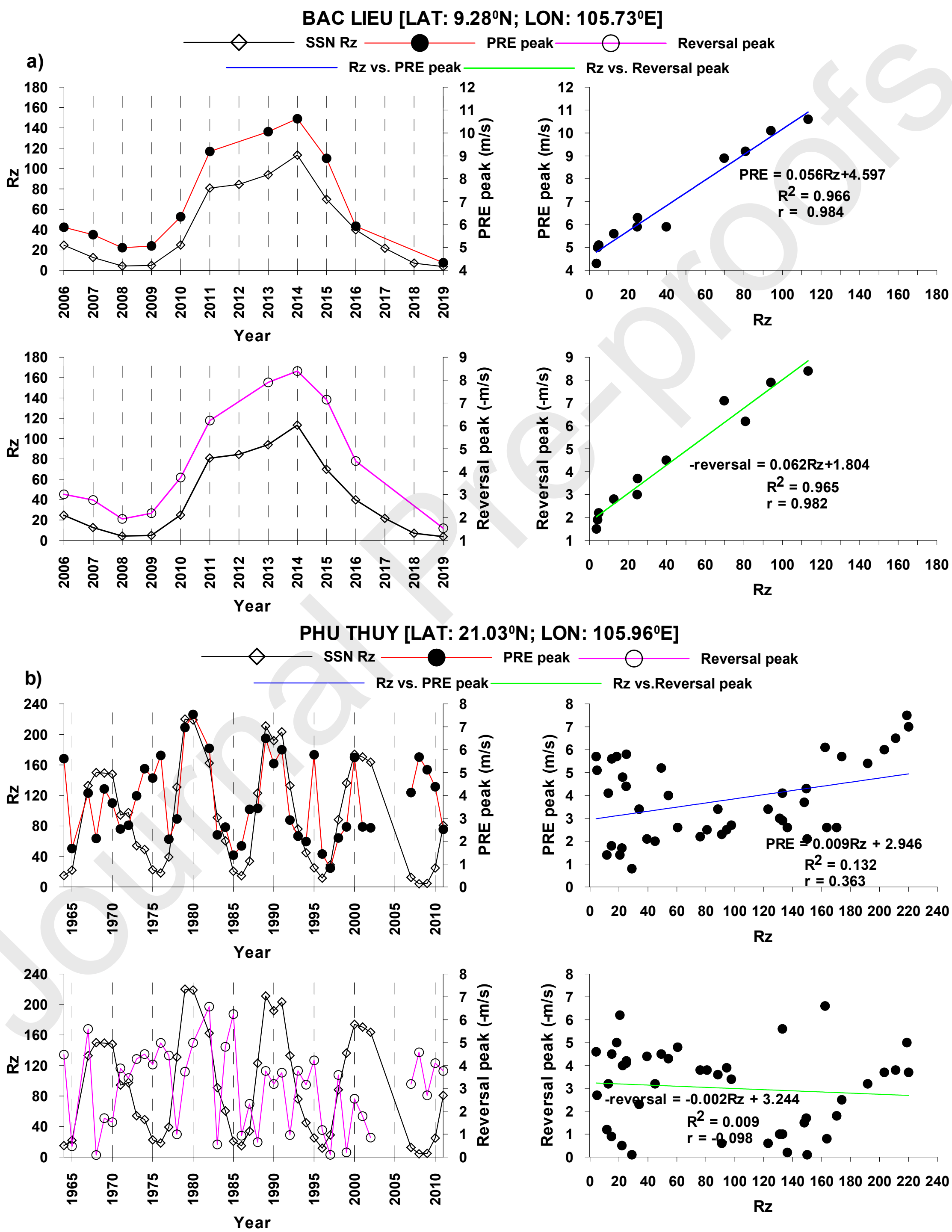

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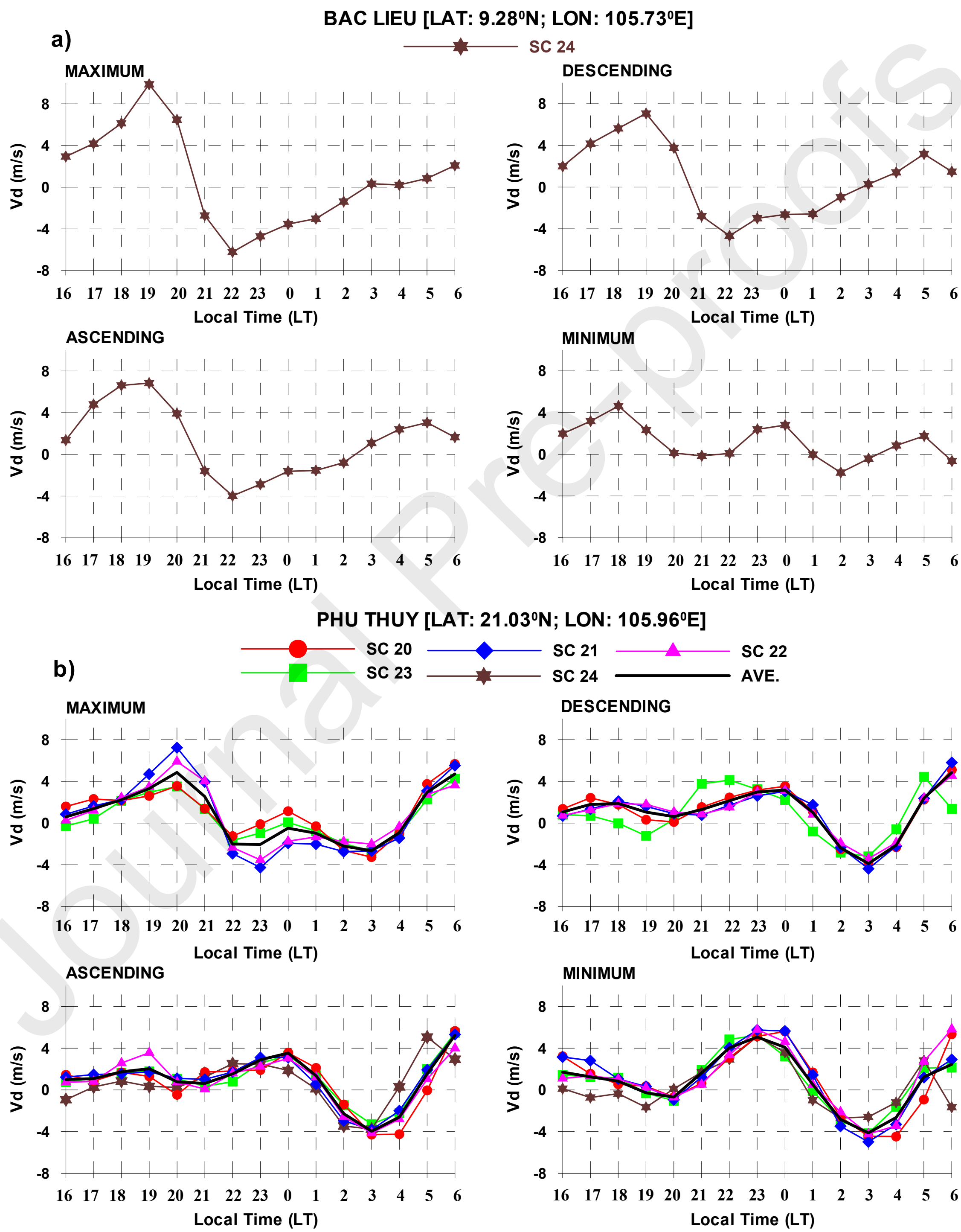

Declaration of interests

☐The authors declare that they have no known competing financial intercessor personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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