Relationship between lunar tidal enhancements in the equatorial electrojet and stratospheric wind anomalies during stratospheric sudden warmings

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Abstract

A number of studies in recent years have reported about the lunar tidal enhancements in the equatorial electrojet (EEJ) from ground- and space-based magnetometer measurements during stratospheric sudden warming (SSW) events. In this study, we make use of the ground magnetometer recordings at Huancayo observatory in Peru for the years 1978 – 2013 to derive a relationship between the lunar tidal enhancements in the EEJ and tropospheric eddy heat fluxes at 100 hPa during the SSW events. Tropospheric eddy heat fluxes are used to quantify the amount of wave activity entering the stratosphere. Anomalously large upward wave activity is known to precede the polar vortex breakdown during SSWs. We make use of the superposed epoch analysis method to determine the temporal relations between lunar tidal enhancements and eddy heat flux anomalies during SSWs, in order to demonstrate the causal relationship between these two phenomena. We also compare the lunar tidal enhancements and eddy heat flux anomalies for vortex split and for vortex displaced SSWs. It is found that larger lunar tidal enhancements are recorded for vortex split events, as compared to vortex displaced events. This confirms earlier observation; larger heat flux anomalies are recorded during vortex split SSW events than the heat flux anomalies during vortex displaced SSW events. Further, the temporal relations of lunar tidal enhancements in the EEJ have been compared separately for both the QBO phases and with the phases of the moon with respect to the central epoch of SSWs by means of the superposed epoch analysis approach. The EEJ lunar tidal enhancements in the east phase of QBO are found to be larger than the lunar tidal enhancements in the west phase of QBO. The phase of moon relative to the central SSW epoch also affects the lunar tidal enhancement in the EEJ. It is found that the lunar tidal enhancements are significantly larger when the day of new or full moon lies near the central SSW epoch, as compared to cases when new or full moon occur further away from the central SSW epoch.

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Introduction

Stratospheric Sudden Warmings

- Stratospheric Sudden Warmings (SSWs) are large-scale meteorological events usually occurring during the northern hemisphere winters. SSW was first observed by Richard Scherhag at the Free University of Berlin in 1952.

- SSWs are characterized by a weakening or sometimes even a reversal of the westerly winds in the northern stratosphere that leads to a sudden rise in polar stratospheric temperature by several tens of degrees.

- The underlying mechanism behind SSWs is understood to be the nonlinear interaction of the vertically propagating planetary waves with the zonal mean flow (**Matsuno, 1971**).
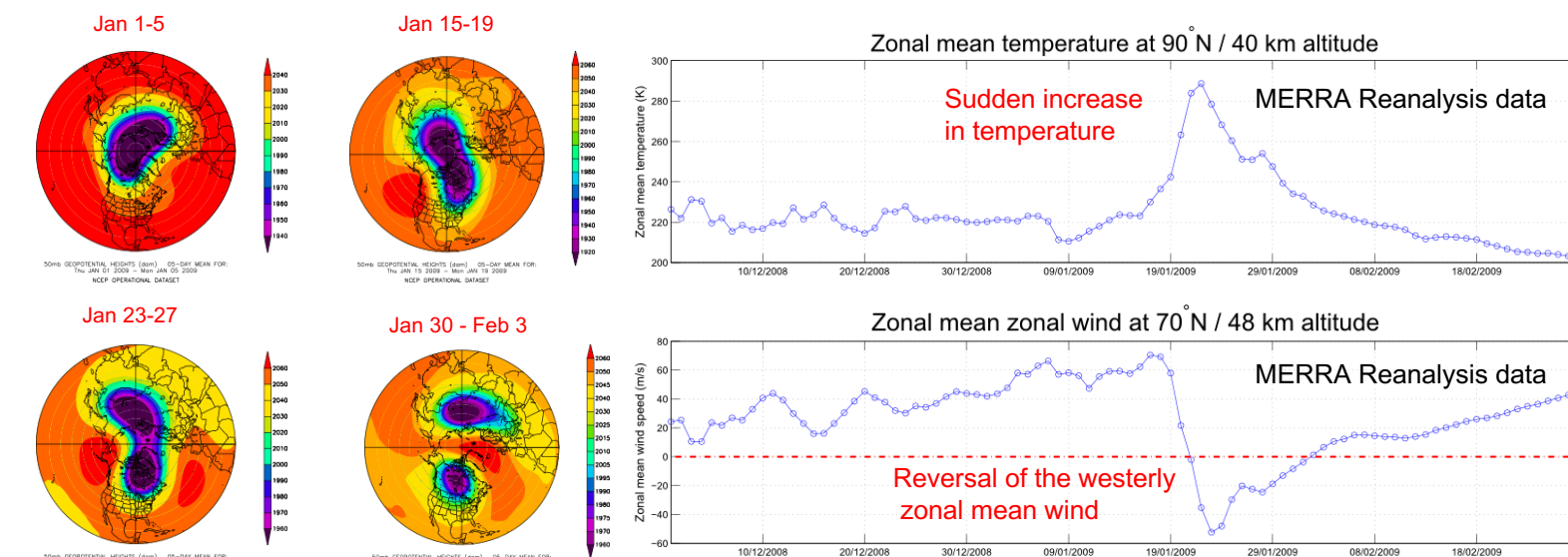
The 2009 SSW event

Figure (left) presents the composite of 50 mb geopotential heights (dam) for the above-mentioned dates and shows the splitting of the polar vortex during the 2009 SSW event. The plots are downloaded from https://www.esrl.noaa.gov. Figure (right) shows the temperature at North Pole at 40 km altitude and the zonal mean zonal wind at 70° N and 48 km altitude during Dec 2008 – Feb 2009 from the MERRA reanalysis data set.

SSW related impacts in the atmosphere
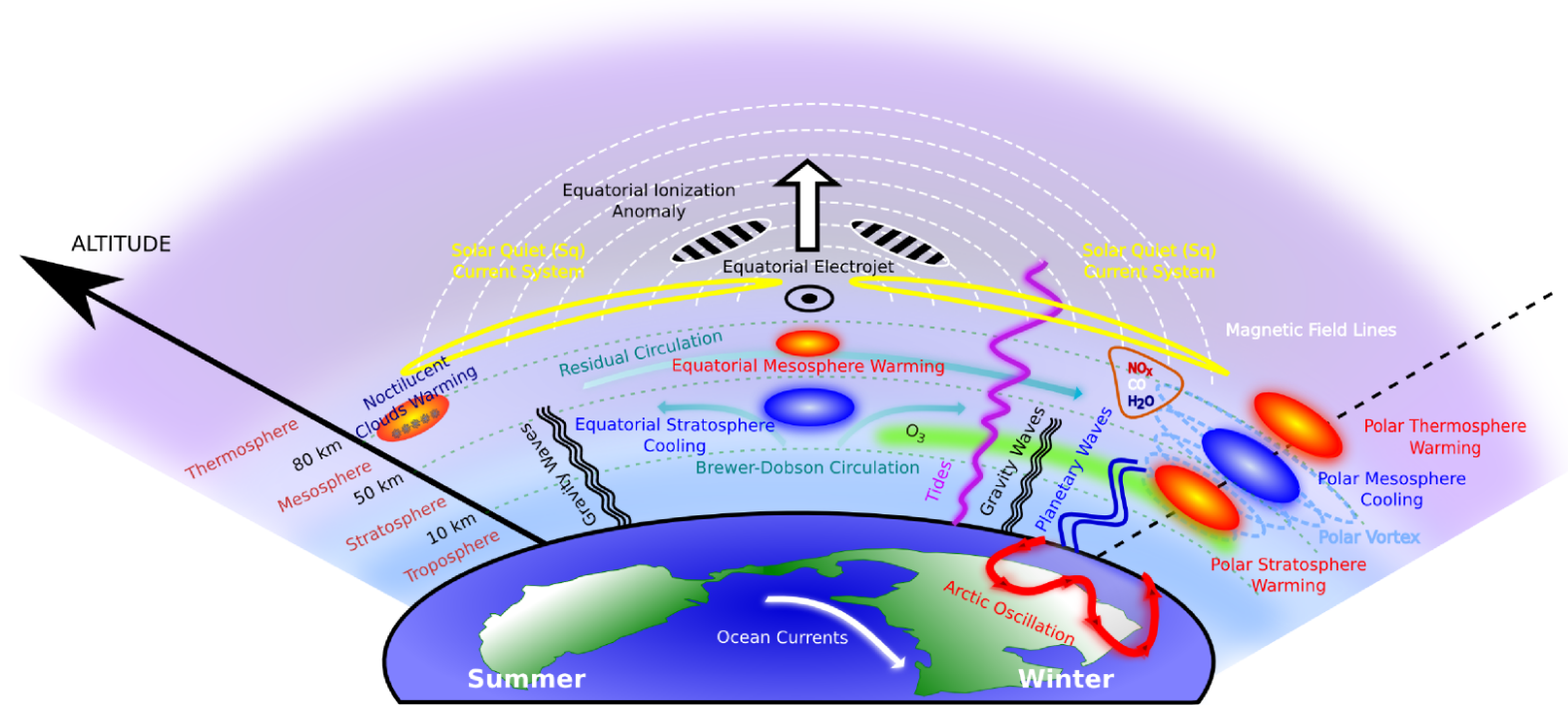
The schematic shows the known impacts of SSW in the atmosphere (Figure adapted from **Pedatella et al., 2017** - accepted in Eos).

Equatorial Electrojet

- The equatorial electrojet (EEJ) is a narrow band of an intense electric current confined to a latitude band of about ±3° and flowing above the magnetic dip equator at an altitude of around 110 km in the daytime E-region of the ionosphere.

- The primary reasons for the high current densities at these latitudes can be attributed to the horizontal geometry of geomagnetic field lines and the Cowling effect that leads to regions of enhanced conductivities over the dip equator.
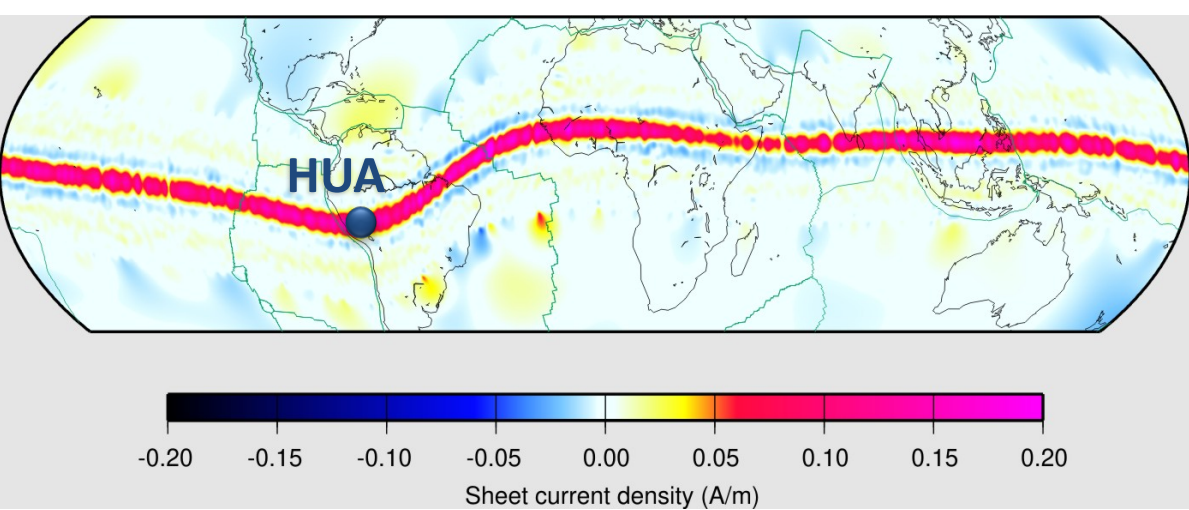

Electrojet current densities inferred from 2600 passes of the CHAMP satellite over the magnetic equator between 11:00 and 13:00 local time (Figure is from http://geomag.org/info/equatorial_electrojet.html). The Huancayo observatory location is marked with a dot.

Atmospheric lunar tide

- The atmospheric lunar tide is a global-scale oscillation of the atmosphere due to the gravitational attraction of the moon (**Lindzen and Chapman, 1969**). It is generated mostly near the Earth's surface and then it propagates to higher altitude. The amplitude of the lunar tide increases with altitude due to the decreasing atmospheric density.

- The lunar tide on reaching the ionospheric dynamo region (90-150 km) heights modulates the solar quiet (Sq) current system and the EEJ.

- Recent observational and simulation studies (e.g., **Chau et al., 2012** and references therein) have focused on the role of lunar tide in the equatorial ionosphere during SSWs. It is suggested that the lunar tide gets noticeably enhanced and plays an important role in producing equatorial ionospheric perturbations during SSWs.

Background & Motivation

- Lunar tidal enhancements in EEJ during SSWs from ground-magnetometer recordings has been widely studied in recent years (e.g., **Fejer et al., 2010; Yamazaki et al., 2012; Siddiqui et al., 2015**). Figure (a) on the right side shows the EEJ lunar tidal power between 1998-2013 from the HUA magnetometer recordings. The strong lunar tidal amplification during 1998, 2003, 2004, 2006, 2008, 2009, 2010 and 2013 SSW events can be clearly seen in this figure.

- Figure (b) presents the correlation between the day of peak lunar tidal power and day of polar vortex weakening (based on **Zhang and Forbes, 2014**) during SSWs. The strong correlation suggests a close relationship between the EEJ lunar tidal enhancements and polar stratospheric wind conditions.

- The magnetometer recordings at HUA started in 1922 but a long data gap existed at World Data Centre particularly between mid- 1960s and mid-1980s for this observatory. With the recent digitization of handwritten HUA magnetometer recordings (**Matzka et al., 2017**), barring the years between 1991-1996 as seen in Figure (c), almost 100 years of hourly magnetometer recordings at HUA is now available.

- The HUA magnetometer recordings between 1958-2013 is used in this work to study the composite EEJ lunar tidal response to vortex split and displaced SSWs. We also investigate the composite lunar tidal response for SSWs recorded during the Quasi-Biennial oscillation (QBO) East and West phases and different solar flux conditions.
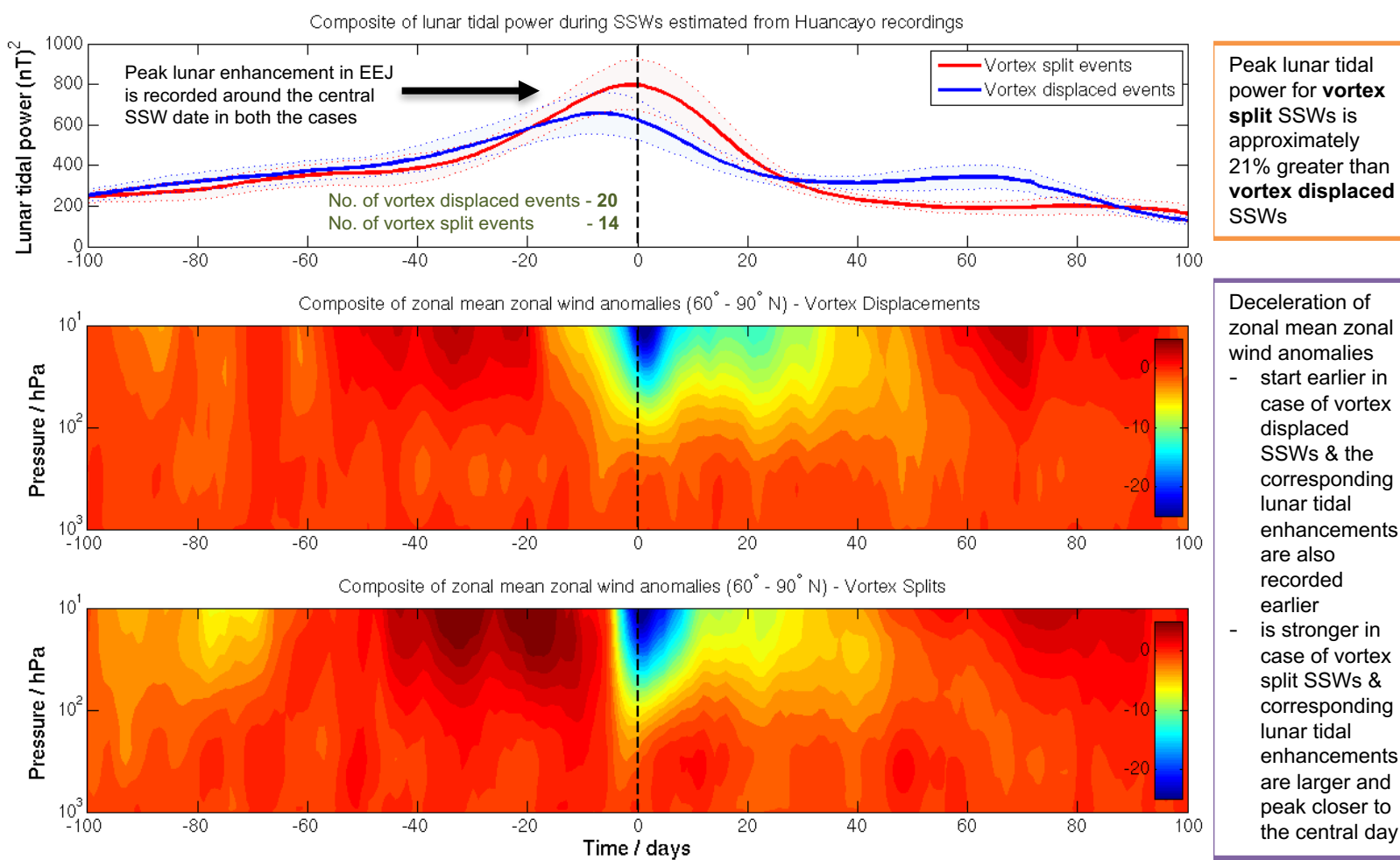

Siddiqui et al., 2015

Digitization of handwritten HUA magnetometer recordings between 1965 -1984 from handwritten tables (Matzka et al., 2017)
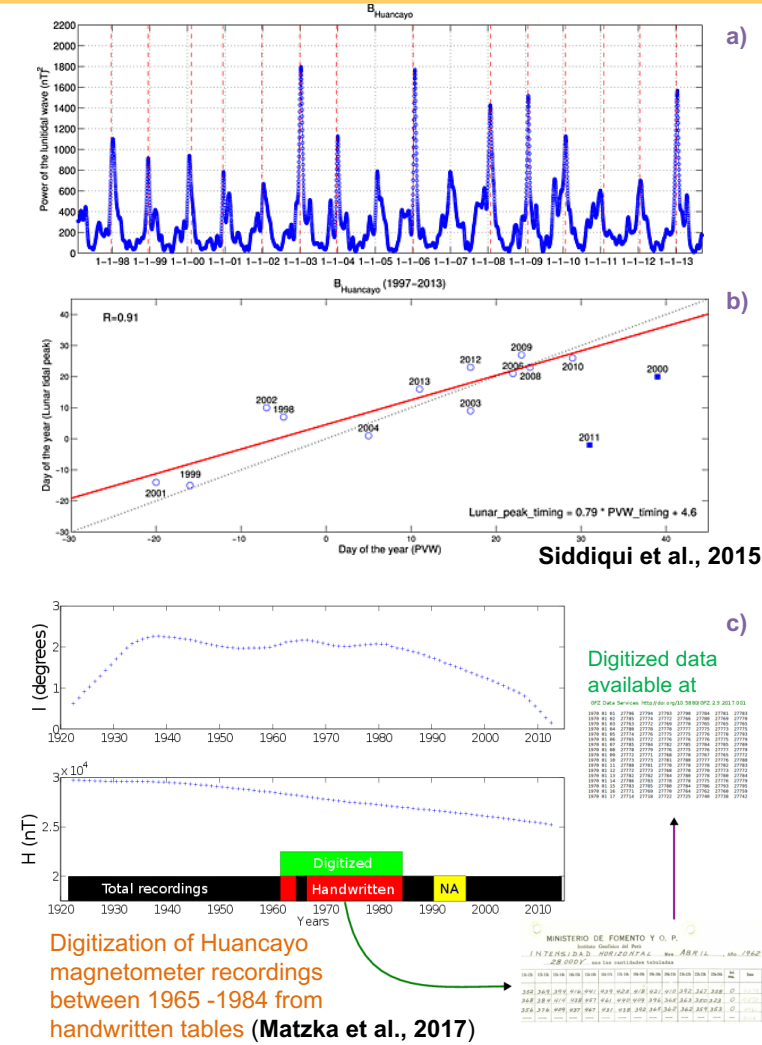
List of SSW events recorded between 1958-2013

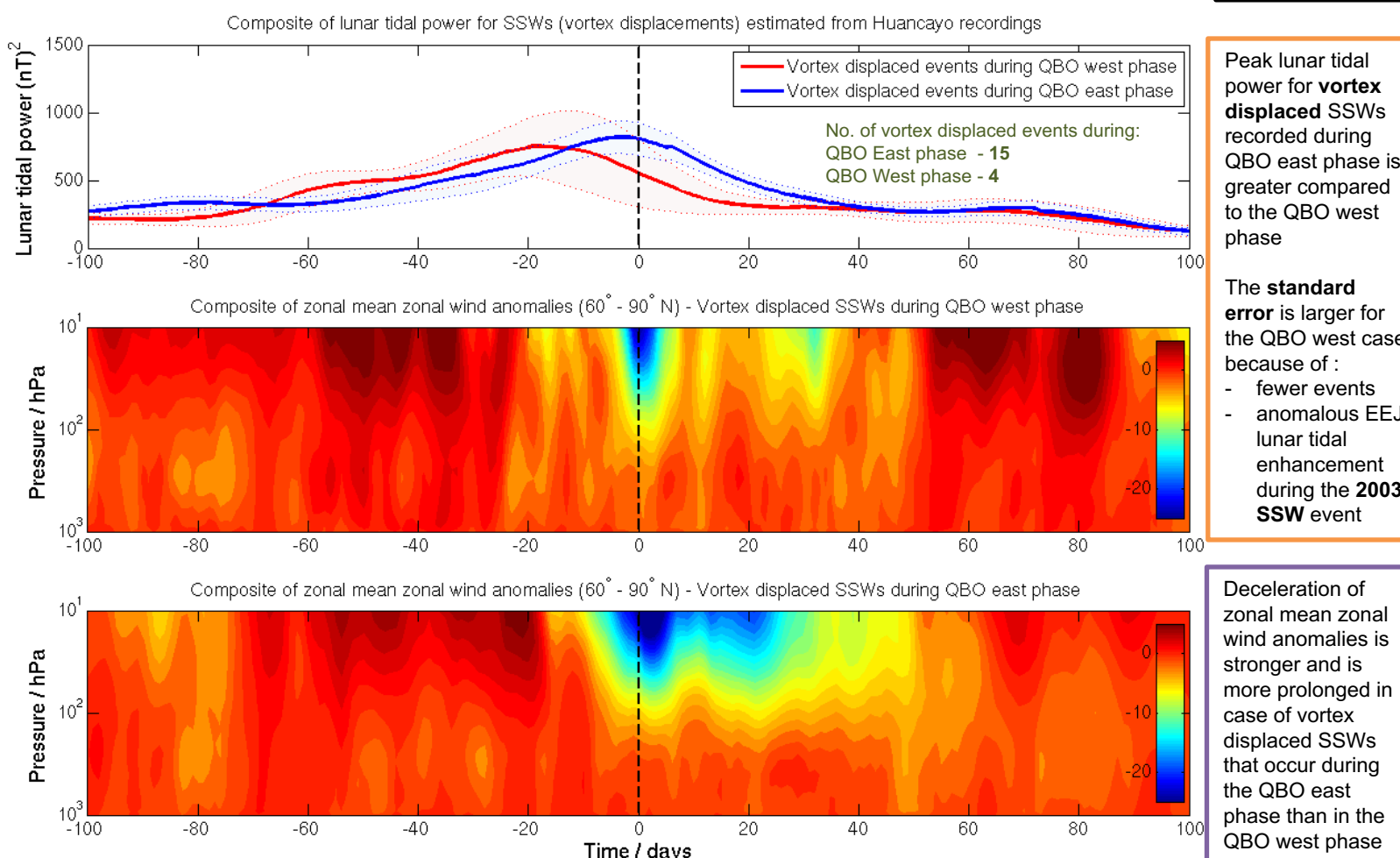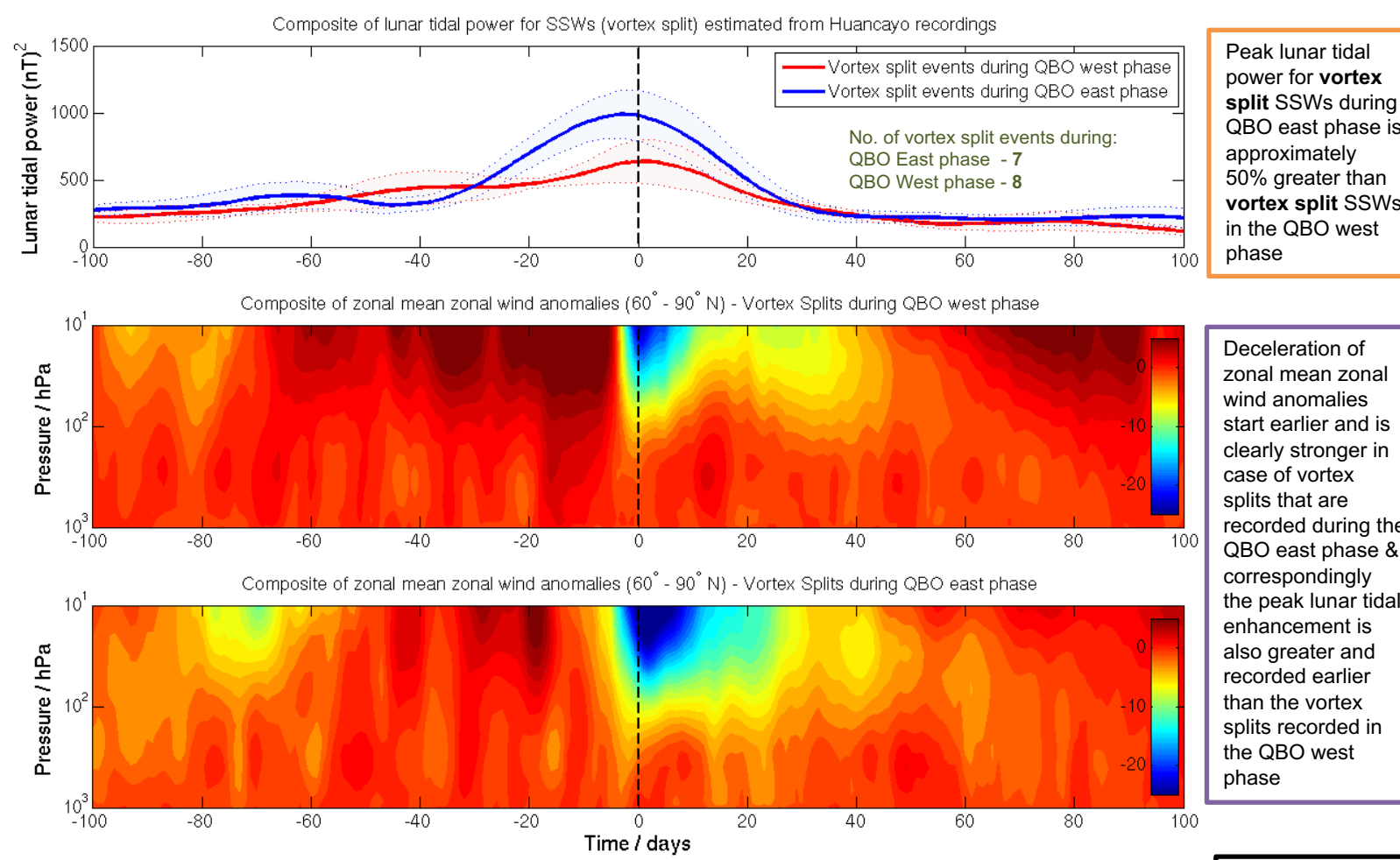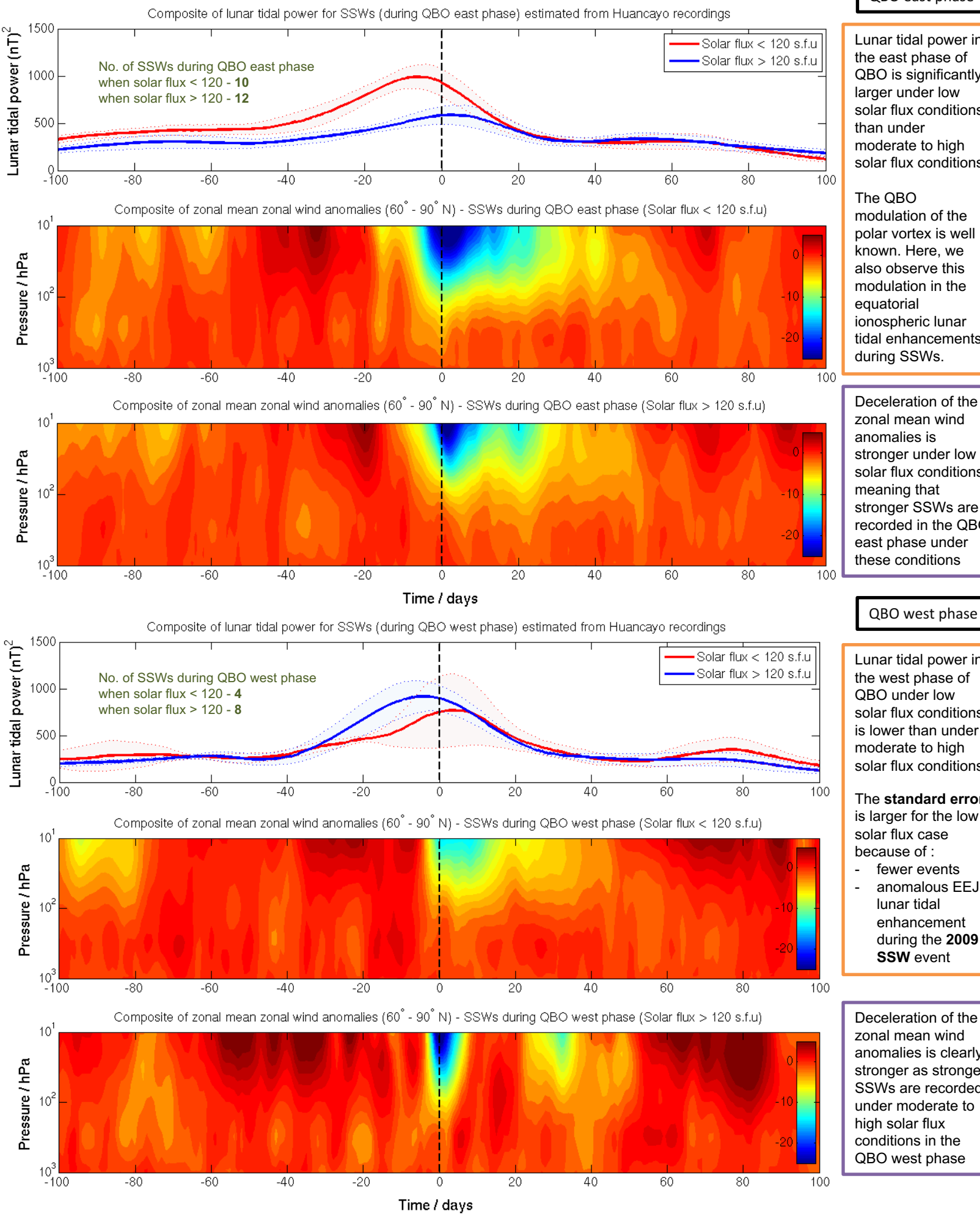| No.	Central date (CD)	Vortex type	QBO phase	Monthly mean F10.7 (s.f.u)
1	30 Jan 1958	S	W	243.45
2	30 Nov 1958	D	W	204.58
3	16 Jan 1960	D	W	195.20
4	23 Mar 1965	S	W	73.01
5	8 Dec 1965	D	E	74.06
6	24 Feb 1966	S	E	82.15
7	8 Jan 1968	S	W	183.06
8	27 Nov 1968	S	E	135.51
9	13 Mar 1969	D	E	170.62
10	2 Jan 1970	D	W	153.48
11	17 Jan 1971	D	E	157.38
12	20 Mar 1971	D	E	110.79
13	2 Feb 1973	S	E	96.25
14	22 Feb 1979	S	W	199.11
15	29 Feb 1980	D	E	195.06
16	4 Dec 1981	D	E	201.36
17	24 Feb 1984	D	E	137.17
18	2 Jan 1985	D	E	72.08
19	23 Jan 1987	D	E	70.18
20	8 Dec 1987	S	W	91.45
21	14 Mar 1988	S	W	113.83
22	22 Feb 1989	D	W	216.95
23	15 Dec 1998	D	E	145.46
24	25 Feb 1999	S	E	138.59
25	20 Mar 2000	D	W	206.11
26	11 Feb 2001	D	E	143.10
27	2 Jan 2002	D	E	220.05
28	18 Jan 2003	D	W	139.53
29	7 Jan 2004	D	E	109.86
30	21 Jan 2006	D	E	80.46
31	22 Feb 2008	D	E	69.38
32	24 Jan 2009	S	W	67.62
33	9 Feb 2010	D	E	82.77
34	7 Jan 2013	S	E	122.62
	CD based on Charlton and Polvani (2007)	S - splits D - displacements	QBO phase based on Labitzke et al., (2006)	

Results

Composite of lunar tidal power from EEJ for vortex split and displaced SSWs

Peak lunar enhancement in EEJ is recorded around the central SSW date in both the cases

No. of vortex displaced events - 20
No. of vortex split events - 14

Peak lunar tidal power for **vortex split** SSWs is approximately 21% greater than **vortex displaced** SSWs.

Deceleration of zonal mean zonal wind anomalies
- start earlier in case of vortex displaced SSWs & the corresponding lunar tidal enhancements are also recorded earlier
- is stronger in case of vortex split SSWs & corresponding lunar tidal enhancements are larger and peak closer to the central day

Composite of lunar tidal power from EEJ for vortex split and displaced SSWs during different phases of QBO

No. of vortex split events during:
QBO East phase - 7
QBO West phase - 8

Peak lunar tidal power for **vortex split** SSWs during QBO east phase is approximately 50% greater than **vortex split** SSWs in the QBO west phase

Deceleration of zonal mean zonal wind anomalies start earlier and is clearly stronger in case of vortex splits that are recorded during the QBO east phase & correspondingly the peak lunar tidal enhancement is also recorded earlier than the vortex splits recorded in the QBO west phase

No. of vortex displaced events during:
QBO East phase - 15
QBO West phase - 4

Peak lunar tidal power for **vortex displaced** SSWs recorded during QBO east phase is greater compared to the QBO west phase

The **standard error** is larger for the QBO west case because of :
- fewer events
- anomalous EEJ lunar tidal enhancement during the **2003 SSW event**

Deceleration of zonal mean zonal wind anomalies is stronger and is more prolonged in case of vortex displaced SSWs that occur during the QBO east phase than in the QBO west phase

Composite of lunar tidal power from EEJ during different QBO phases and solar flux conditions

QBO east phase

No. of SSWs during QBO east phase
when solar flux < 120 – 10
when solar flux > 120 – 12

Lunar tidal power in the east phase of QBO is significantly larger under low solar flux conditions from moderate to high solar flux conditions

The QBO modulation of the polar vortex is well known. Here, we also observe this modulation in the equatorial ionospheric lunar tidal enhancements during SSWs.

QBO west phase

No. of SSWs during QBO west phase
when solar flux < 120 – 4
when solar flux > 120 – 8

Lunar tidal power in the west phase of QBO under low solar flux conditions is lower than under moderate to high solar flux conditions

The **standard error** is larger for the low solar flux case because of :
- fewer events
- anomalous EEJ lunar tidal enhancement during the **2009 SSW event**

Deceleration of the zonal mean wind anomalies is clearly stronger as stronger SSWs are recorded under moderate to high solar flux conditions in the QBO west phase

Summary and Conclusions

- From the composite analysis it is clear that the equatorial ionospheric lunar tidal response, on an average, is greater for vortex split SSWs than vortex displaced SSWs.

- The equatorial lunar tidal amplitude in each of the vortex split and displaced cases is greater during the east phase of QBO than in the QBO west phase.

- The influence of the solar cycle and QBO on the stratospheric polar vortex is empirically known from the results of **Labitzke et al., 2006**. The Arctic polar vortex is comparably weaker and more suitable for SSWs under high solar flux conditions in the west phase of QBO and under low solar flux conditions in the QBO east phase than during other times. In our results, we also see this influence extending to the equatorial ionospheric lunar tidal enhancements.

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