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

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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

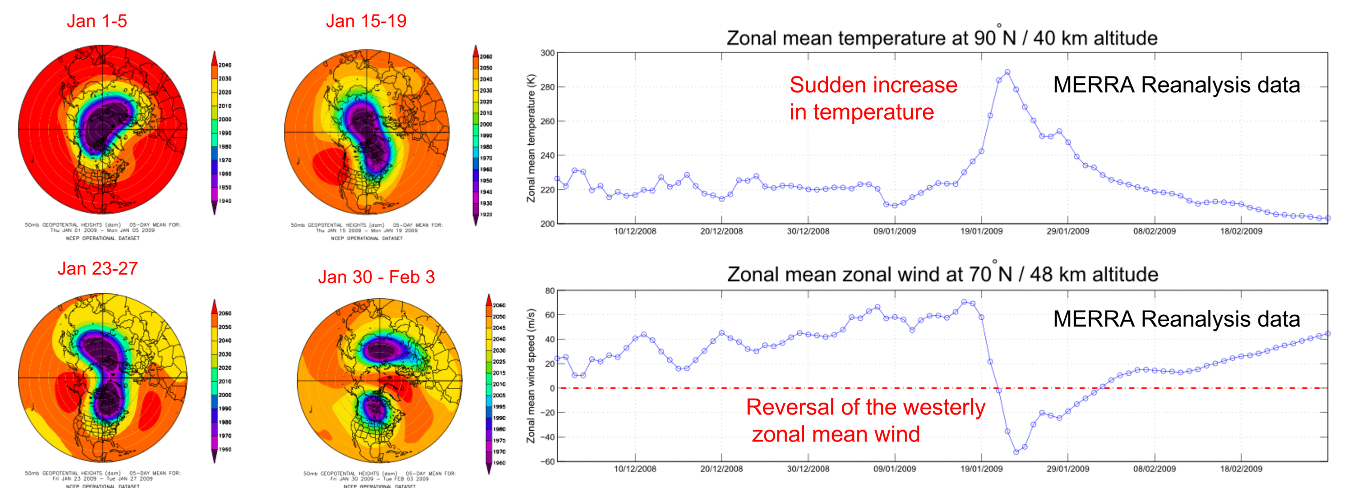
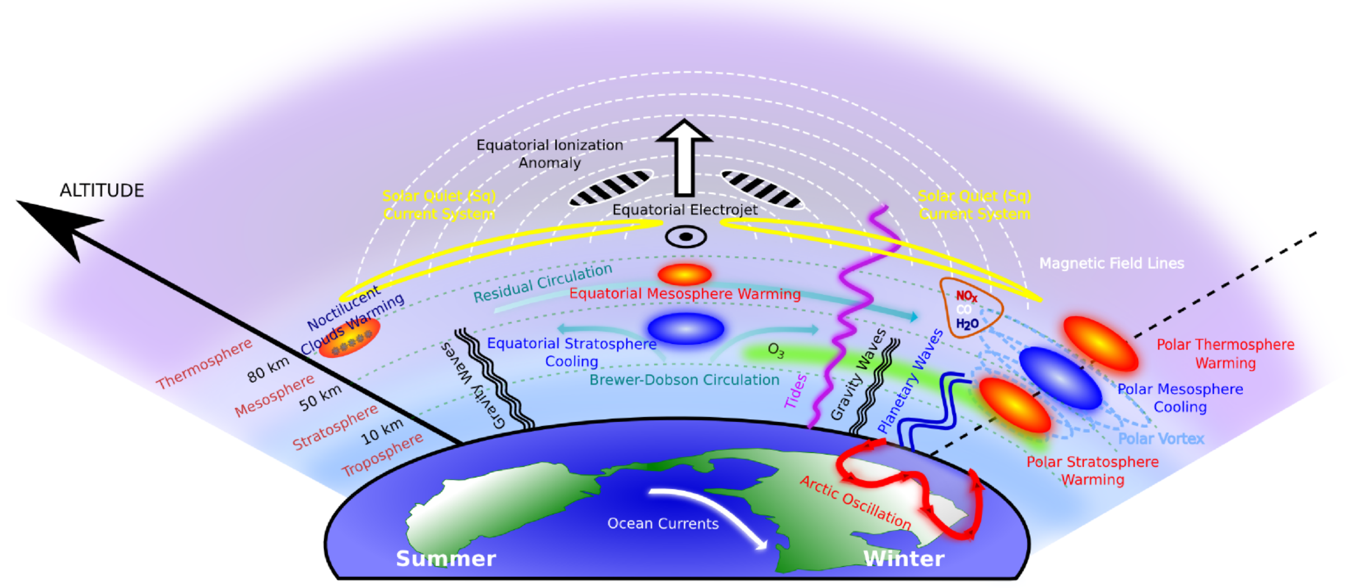


Figure (left) presents the composite of 50 mb geopotential heights (dam) for the above-mentioned dates and shows the splitting of the polar vortex during the 2009 SSW event. The plots are downloaded from https://www.esrl.noaa.gov. Figure (right) shows the temperature at North Pole at 40 km altitude and 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

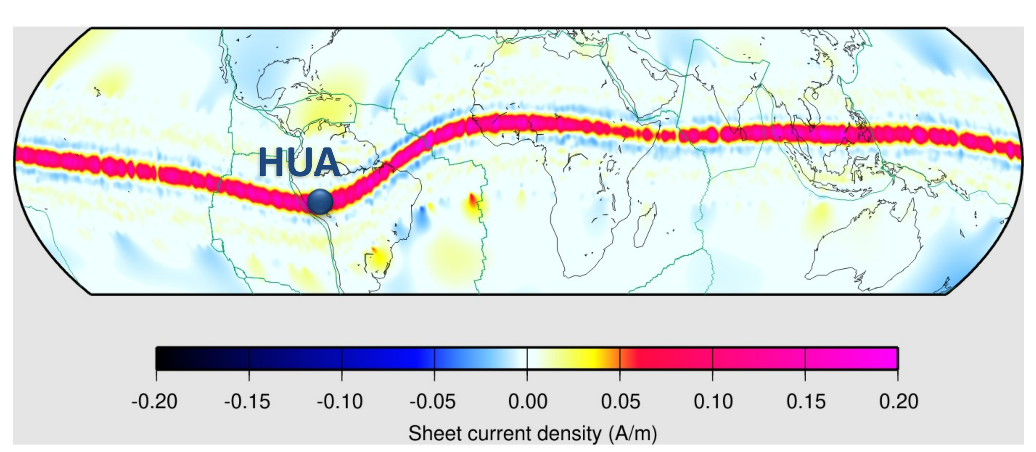


IMPACTS OF SSW

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 $\pm 3^{\circ}$ 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.



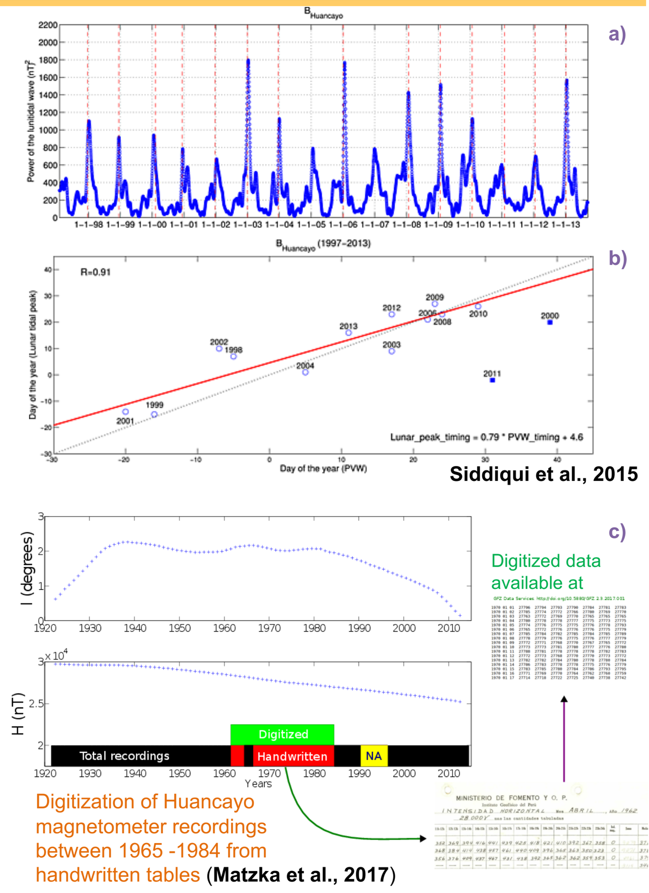
Electrojet current densities inferred from 2600 passes of the CHAMP satellite over the magnetic equator between 11:00 and 13:00 local time (Figure is from http://geomag.org/info/equatorial_electrojet.html). The Huancayo observatory location is marked with a dot.

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.

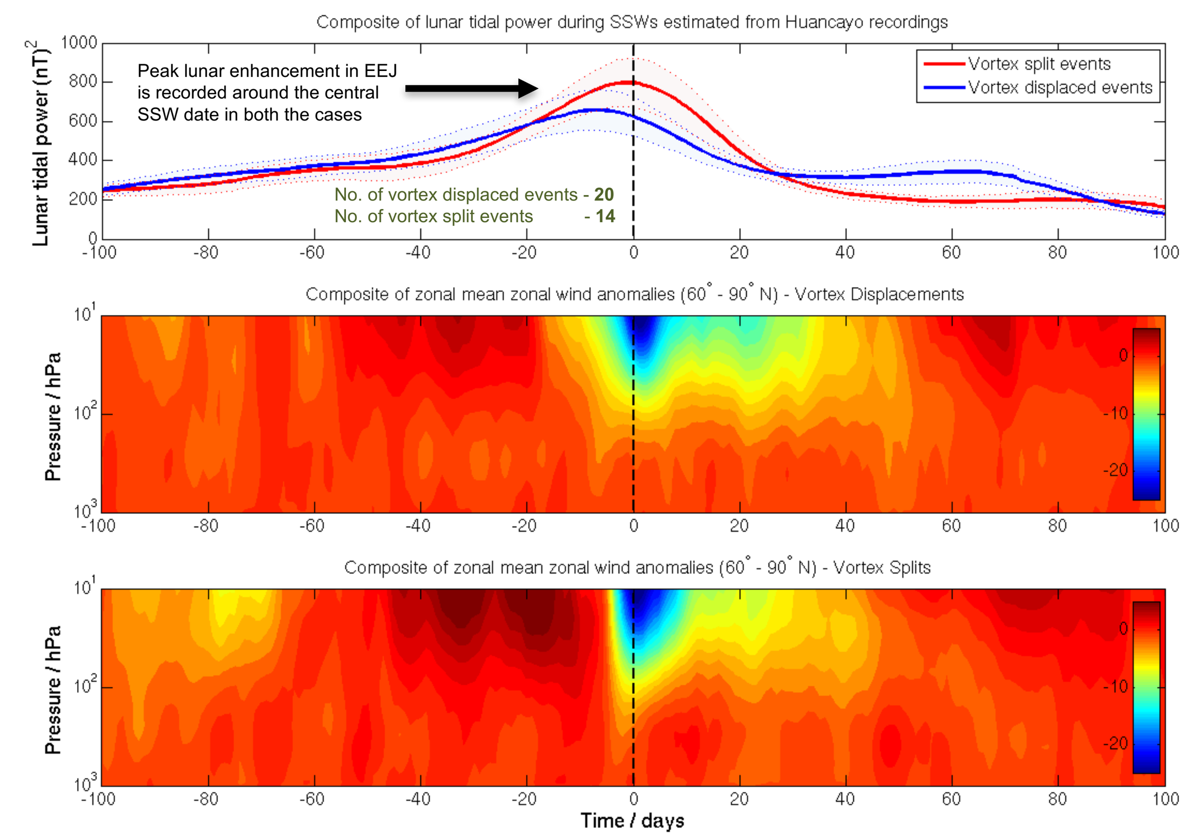


List of SSW events recorded between 1958-2013

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	E	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	S	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	S	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	S	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

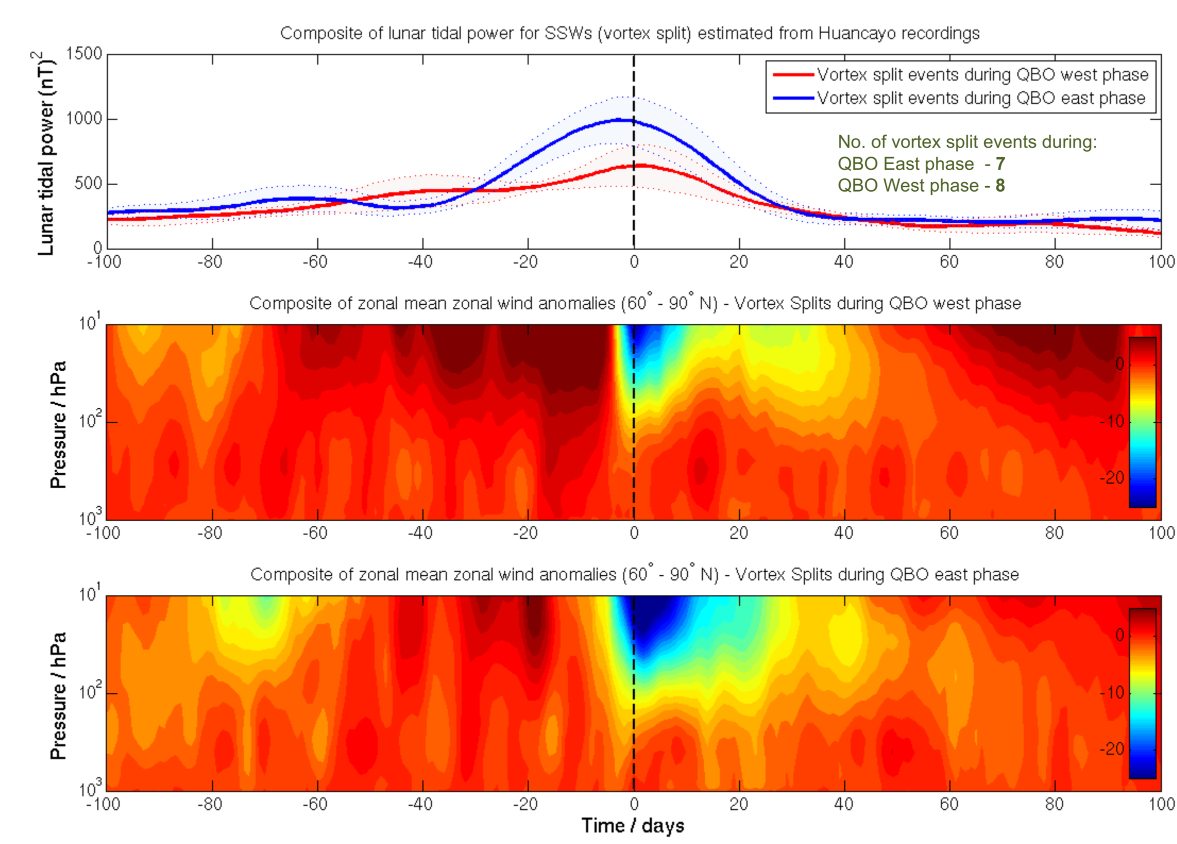


Peak lunar tidal power for **vortex split** SSWs is approximately 21% greater than **vortex displaced** SSWs

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

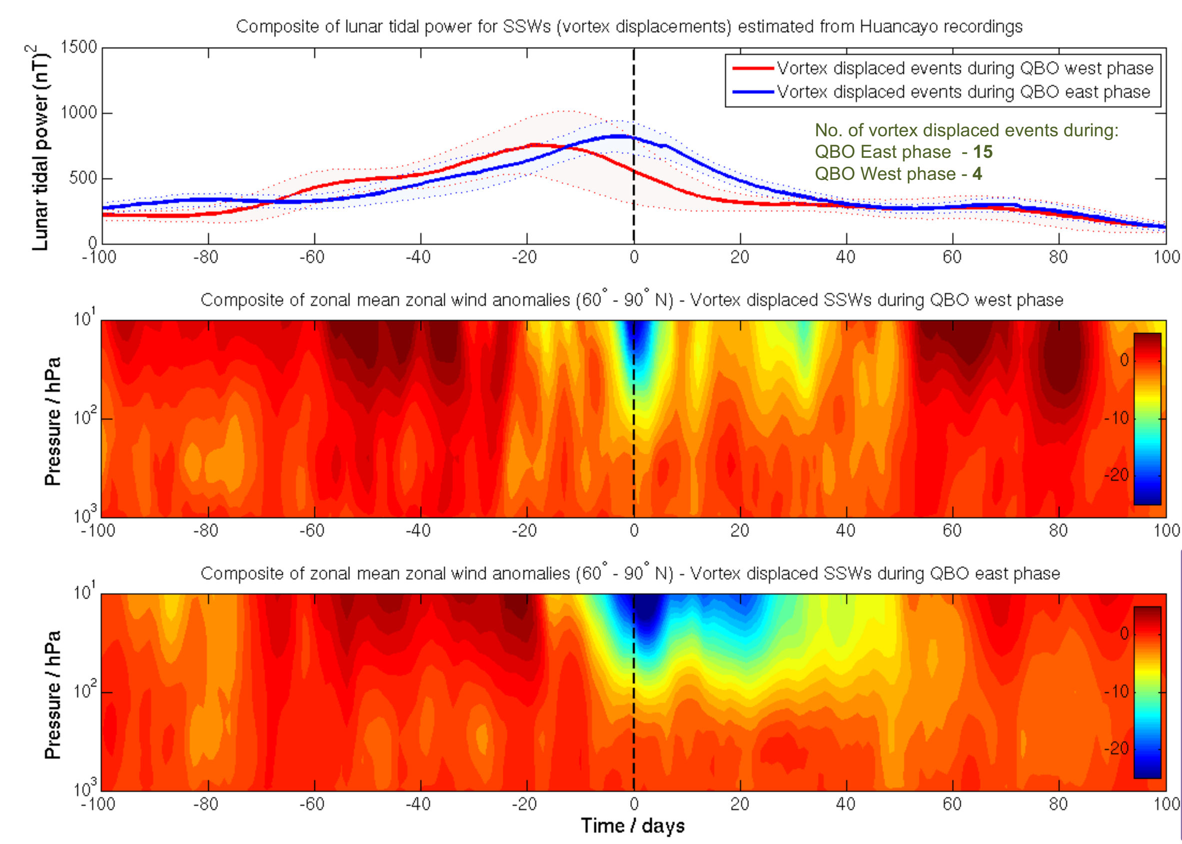
Vortex Split



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 greater and recorded earlier than the vortex splits recorded in the QBO west phase

Vortex displaced



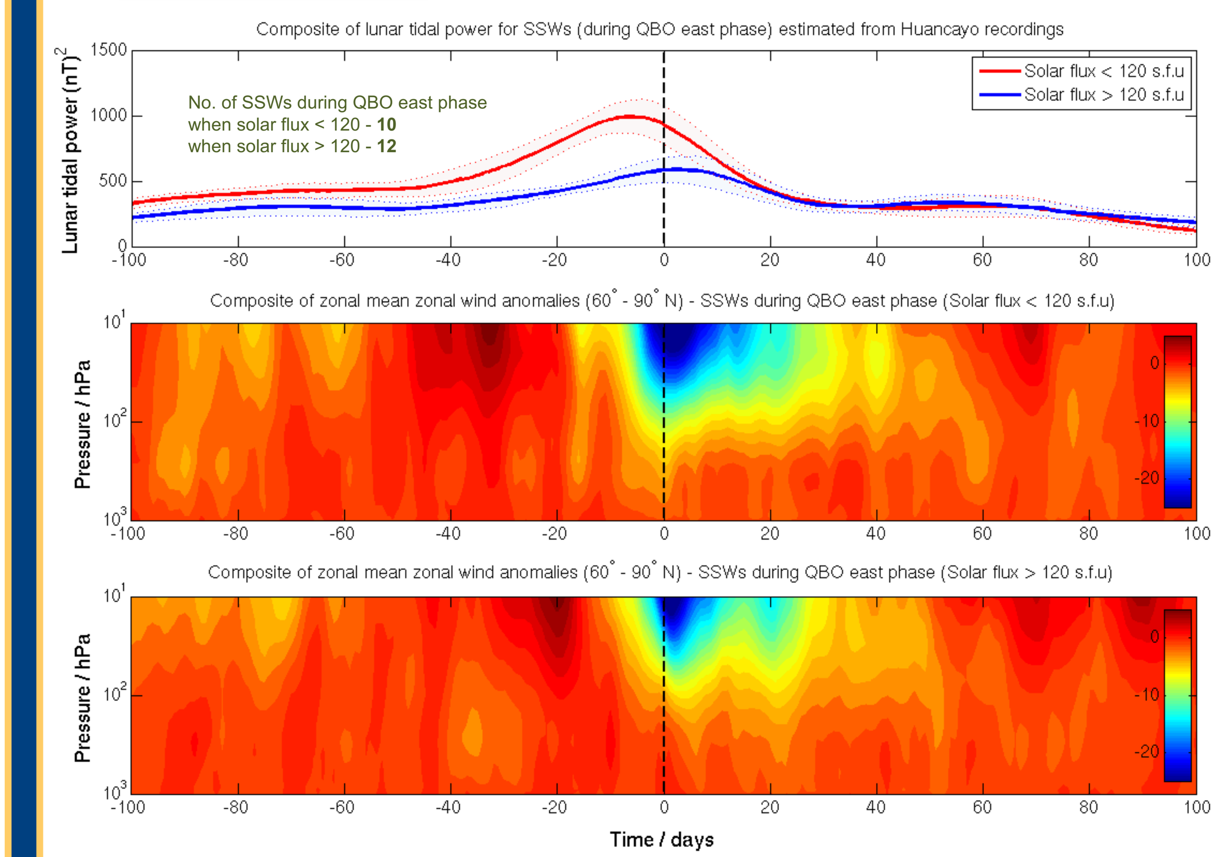
Peak lunar tidal power for **vortex displaced** SSWs recorded during QBO east phase is greater compared to the QBO west phase

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

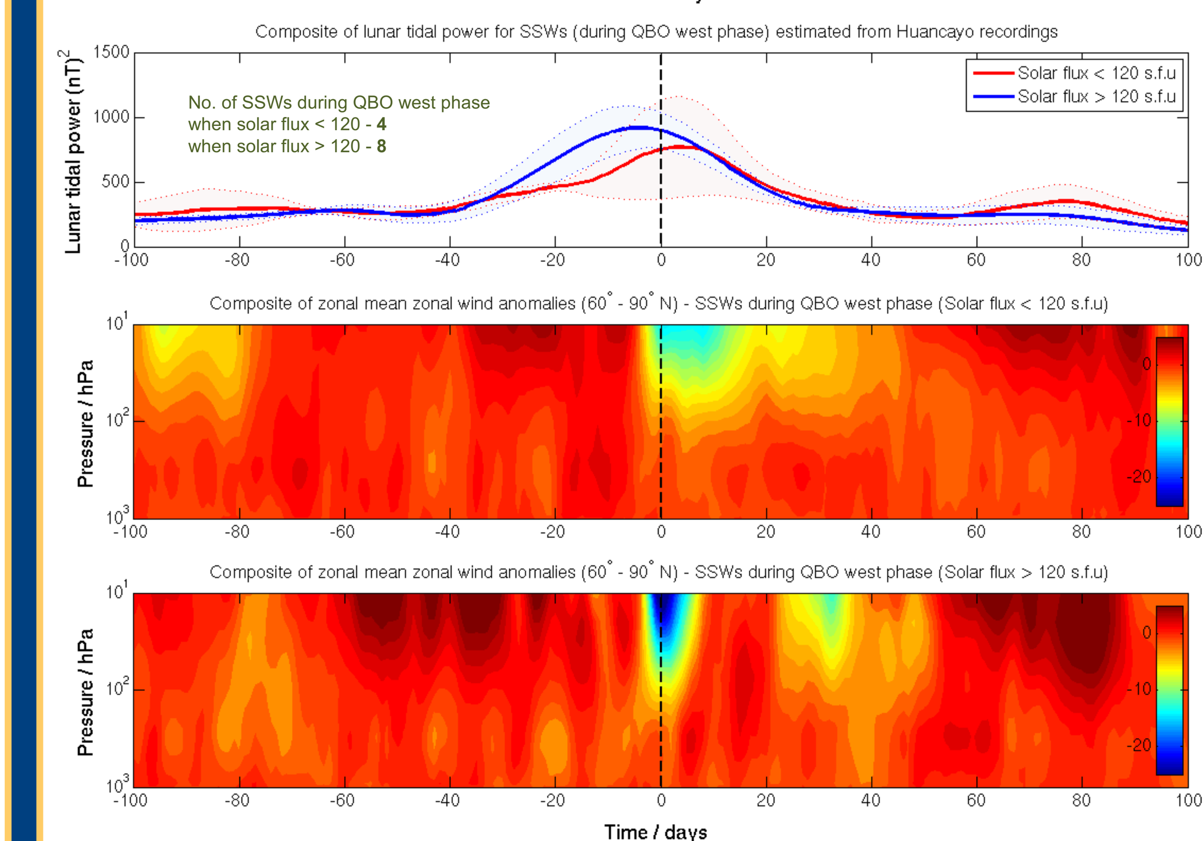


Lunar tidal power in the east phase of QBO is significantly larger under low solar flux conditions than under moderate to high solar flux conditions

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.

Deceleration of the zonal mean wind anomalies is stronger under low solar flux conditions, meaning that stronger SSWs are recorded in the QBO east phase under these conditions

QBO west phase



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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Acknowledgments

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