Potential earthquake precursory pattern from space: the 2015 Nepal event as seen by magnetic Swarm satellites

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Abstract

A large earthquake of 7.8 magnitude occurred on 25 April 2015, 06:26 UTC, with the epicenter in Nepal. Here, taking advantage of measurements provided by the Swarm magnetic satellites, we investigate the possibility to detect some series of pre-earthquake magnetic anomalous signals, likely due to a lithosphere-atmosphere-ionosphere coupling, that can be a potential earthquake precursory pattern. Different techniques have been applied to Swarm data available during two months around earthquake occurrence. From the detected magnetic anomalies series (during night and magnetically quiet times or with an automatic detection algorithm), we show that the cumulative number of anomalies follows the same typical power-law behavior of a critical system approaching its critical time, and hence recovers as the typical recovery phase after a large event. The similarity of this behavior with the one obtained from seismic data analysis and the application of the analyses also to another period without significant seismicity do support a lithospheric-linked origin of the observed magnetic anomalies. We suggest that they might be connected to the preparation phase of the Nepal earthquake.

1. Introduction

The lithosphere, under the stress due to the plate tectonics, releases most of its energy with some rapid ruptures: the earthquakes (EQs). Intense shallow EQs are usually very destructive. Their seismic release requires a long time of preparation before it occurs so suddenly, when a particular fault cannot longer sustain the increasing deformation [e.g. *Scholz* 2002]. Recently, it has been shown that the ionosphere keeps the signature of seismic fault shortly after an

earthquake [e.g. *Occhipinti et al.*, 2013, and references therein]. This offers the possibility to retrieve seismic information from ionospheric observations.

An important and debated question arises about the possibility that, during the phase of EQ preparation, electromagnetic waves and/or particles could be transferred from the solid Earth (in particular the lithosphere) to the atmosphere, with a particular effect in the ionosphere, above around 50 km [e.g. *Pulinets and Boyarchuk*, 2004; *Freund*, 2011; *Pulinets and Ouzounov*, 2011; *De Santis et al.*, 2015]. One of the most general models of coupling is based on the emission of a radioactive gas [*Pulinets and Boyarchuk*, 2004] or metallic ions [*Freund*, 2011] before a large earthquake, which may change the distribution of electric potential above the surface of the Earth and then up to the ionosphere [e.g., *Pulinets and Boyarchuk*, 2004; *Sorokin et al.*, 2001]. Penetration of the electric field to the ionosphere could produce ionospheric plasma density and/or conductivity anomalies, which are observed above seismic zones [e.g., *Liu et al.*, 2006; *Kon et al.*, 2011]. An alternative explanation is that the radon emitted before an earthquake would increase the conductivity of air at ground level and that the ensuing increase of current in the fair weather global circuit would lower the ionosphere [*Harrison et al.* 2010]. Therefore, it is expected that low Earth orbiting (LEO) satellites could be the best possible dedicated platforms of sensors to detect any electromagnetic, acoustic or infrared seismic-linked precursors. Certainly, space observations have to be investigated together with ground (and near-surface) seismic and other geophysical observations, in order to have a more complete picture of the possible involved phenomena.

Few attempts have been made to deeply investigate pre-EQ ionospheric perturbations. The French satellite mission, DEMETER (Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions), was suitably designed and launched (2004-2010) for searching electromagnetic anomalies likely anticipating large earthquakes [Parrot, 1995]. Systematic analyses over parts of the mission data [Němec et al., 2008] or the full life-time of satellite [Piša et al., 2013; Li and Parrot, 2013] have showed a significant statistical correlation between ionospheric anomalies and large events, within a few days before the event, although no undisputed precursor evidence has been proved.

The opportunity to investigate the ionosphere perturbation is currently due to the new Swarm constellation [Friis-Christensen et al., 2006]. From the end of 2013 the three Swarm satellites measure the Earth's magnetic field with an unprecedented accuracy. Since then, a few large EQs occurred, but here we focus on the EQ occurred on 25 April 2015, 06:26 UTC, in Nepal region, 77 km NW of Kathmandu, with a magnitude Mw 7.8 (hypocenter 28.15°N, 84.71°E at a depth of 15 km), in an area characterized by a persistent seismicity [Parameswaran et al. 2015]. According to the USGS, the fault rupture plane was 295° and the dip 10°NNE; the rupture surface was approximately 100 km along the strike and 80 km along the downdip (135km × 100 km, according to Wu et al., [2016]). Seventeen days later (May 12, 2015), a strong aftershock followed, approximately 77km NE of Kathmandu, with a smaller estimated magnitude of Mw 7.3 [Parameswaran et al. 2015].

This very damaging EQ has been studied using different geophysical datasets. For example, Galetzka et al. [2015] performed a detailed geodetic imaging of earthquake ruptures. They used

Global Positioning System (GPS) and interferometric synthetic aperture radar (SAR) data to model the earthquake rupture and found that the smooth slip onset caused moderate ground shaking at high frequencies (>1 Hz) and minimized damage to vernacular dwellings, while whole-basin resonance at a period of 4 to 5 seconds caused the collapse of tall structures. *Chen et al. [2016]* found a significant gravity anomaly before the EQ which could be an important precursor; indeed, the broad source region derived from gravity data is consistent with the idea that a broad region of crust in southern Tibet is involved in the storing of elastic strain energy driving the Himalayan earthquakes [*Feldl and Bilham, 2006*]. Another intriguing feature comes from some atmospheric parameters, such as the aerosol optical depth (AOD) and the columnar ozone (NO_2) found to be higher than 40% and 6%, respectively prior to the occurrence of the earthquake [*Galguly, 2016*]. The UV aerosol index, AOD and the columnar NO_2 increased, while columnar ozone and sea level pressure dropped following the earthquake. This result, if confirmed, might support a coupling between the lithosphere and the atmosphere, during the phase of preparation of the Nepal EQ. Finally, let us note that this EQ seems to have released only a fraction of the energy still trapped in the underlying fault, so that the area has still the potential to host another large earthquake in the near future [*Avouac et al., 2015*].

In this paper, we explore a possible pre-EQ lithosphere-atmosphere-ionosphere (LAI) coupling by analyzing magnetic and ionospheric data from the Swarm satellites, applying different methods over different intervals of time around the 2015 Nepal EQ occurrence. Firstly, we shortly describe the used Swarm data, together with ground seismic data, and the applied methods. In the following, we present the obtained results based on: i) the comparison of the average power in Pc3 frequency band (0.022-0.1 Hz; *Saito, [1969]*) for a 2 month period in 2015

with that of the previous year, when no large earthquake occurred in the area of interest; and ii) the search for the single “anomalies” and then of the temporal behavior of the cumulative number of anomalies. Finally, we specify the main results based on a comparison from the latter analysis with an analogous method applied to the ground seismic data, and a confutation analysis to the Swarm magnetic data in another no significant seismic period, before concluding.

2. Data

Swarm satellite observations

Swarm is an ESA (European Space Agency) satellite mission of three satellites devoted to the study of the geomagnetic field and its dynamics [Friis-Christensen *et al.*, 2006]. The main objectives of the mission are to deliver the best survey of the geomagnetic field and its temporal variation, and to acquire a characterization of the internal field sources and of the ionospheric-magnetospheric current systems, due to the very high accuracy of the onboard instruments¹. This constellation was designed to derive the first global representation of the geomagnetic field variations on times scales from an hour to several years, addressing the crucial problem of source separation.

The three Swarm satellites are identical, and the constellation consists of two satellites (A and C) flying almost side-by-side (longitude separation of 1.4° at equator) at an altitude close to 450 km, and inclination of 87.4° . The third satellite (B) flies above, close to 510 km, on a more polar orbit (inclination of 88°) and has allowed for a progressive Local Time (LT) separation with respect to A and C, of about three hours, in the beginning of 2016. The three satellites are also named

¹ http://esamultimedia.esa.int/docs/SP_1279_6_Swarm.pdf

Alpha, Bravo and Charlie. This specific constellation allows the scientists to observe the small space-scale variations of the geomagnetic field, particularly those linked to the lithospheric field. The main mission sensors are a couple of magnetometers, i.e. an Absolute Scalar Magnetometer (ASM) providing, in nominal mode, measurements of the field intensity and a Vector Field Magnetometer (VFM) mounted halfway along the boom on an optical bench together with the Star Trackers, providing field directions. Other sensors complete the payload of each satellite, in particular, two electric field and particle sensors (Langmuir Probes), a GPS antenna and an accelerometer.

The previous magnetic satellite missions were single satellite systems. With Swarm data taken at three different orbits and two altitudes, it is possible to investigate for distinctive seismogenic signatures in the ionosphere from non-seismic external (ionospheric and/or magnetospheric) electromagnetic signals, providing that proper analysis are applied in order to extract the wealth of information that underlies the data.

In this study we have analyzed the magnetic VFM (Low Resolution) and the ASM Level1B 1Hz data², and the electron density N_e 2 Hz data¹, along the tracks that crossed a circular region within $R=2750$ km from the Nepal EQ epicenter. The distance R is the so-called Dobrovolsky radius strain [Dobrovolsky et al., 1979], $R=10^{0.43M}$. This distance was initially defined as the distance from the impending EQ fault where the strain due to the preparation EQ phase reaches the terrestrial tides background level. Some later works (e.g. Plastino et al., 2002; Vizzini and Brai, 2012) showed that precursory phenomena occur within this distance. Since, an uncertainty of around 0.2 units is noted in the estimated magnitude as given by different agencies (e.g. while

² <ftp://swarm-diss.eo.esa.int>

USGS estimated M7.8, the Chinese Earthquake Administration provided M8.1; Zao, 2016), here, we have considered a Dobrovolsky area corresponding to a magnitude $M=8$.

Seismic Data

Seismic catalogues represent fundamental data sources for earthquake and seismic hazard studies: they contain the earthquake source parameters (e.g. origin time, hypocenter, magnitude etc.) and may be created by single Countries or international Agencies. For this study, we have used data extracted from the USGS Catalog³: in particular, we have collected events from 1 April to 10 May, 2015 with magnitude $M4+$ occurred within the above defined Dobrovolsky region.

3. Results

Considering the available Swarm data around the time of EQ, two specific analyses have been performed, and they are presented here.

3.1. Pc3 activity in 2014 and 2015

Magnetospheric ultra low frequency (ULF) waves in the topside ionosphere are typically transmitted from magnetospheric and upstream solar wind sources. Oscillations with quasi-sinusoidal waveform are called pulsations continuous (Pc). Those with waveforms that are more irregular are named pulsations irregular (Pi) and are associated with magnetospheric substorms. In particular (Jacobs et al., 1964), continuous pulsations with frequencies in the range 1 mHz to 5 Hz, denoted as Pc1–2 (100 mHz–5 Hz), Pc3 (20–100 mHz), Pc4 (7–20 mHz), and Pc5 (1–7 mHz), have been extensively studied using measurements from both space-borne and ground-

³ <http://earthquake.usgs.gov>

based instruments for many years (for a recent review see Menk, 2011). They are broadly of two types, depending on whether their energy source originates in the solar wind on the dayside or from processes within the magnetosphere (e.g., substorms and other instabilities in the magnetotail) on the nightside.

The low Earth orbit (LEO) CHAMP satellite has been one of the most successful missions for the study of the Earth's magnetic field, with high-sensitivity and accuracy magnetometer measurements orbiting within an altitude range 450–300 km for more than a decade (July 2000–September 2010). For the first time long-term statistical studies on the occurrence of ULF wave events in the topside ionosphere were possible. LEO observations of ULF waves can only be reliably done and without too much spatial aliasing for the Pc1/Pi1 and Pc2/3 waves (frequency ~ 22–100 mHz). Due to the fast motion through field lines in a LEO orbit lower frequency Pc4-5 waves (1–10 mHz) cannot be accurately determined by LEO satellites, their period being longer than the spacecraft transition time through the wave region (Heilig et al., 2007; Balasis et al., 2012). Though Pi2 waves have lower frequencies (frequency ~ 2–25 mHz), thanks to their large spatial scales at low latitudes, they have also been detected by LEO satellites. A spatial scale of Pi2 waves along an orbit becomes comparable with the scale of lithospheric magnetic anomalies (Maus et al., 2007). Therefore, to reveal reliably Pi2 signatures from LEO satellite data the knowledge of a detailed magnetic model of the Earth (e.g., Maus et al., 2007) is necessary. Therefore, the most prominent LEO observations of ULF waves are usually made in the Pc3 frequency range (20–100 mHz) as also show recent studies using data from the Swarm mission [Balasis et al., 2015; Heilig and Sutcliffe, 2016].

There have been several studies suggesting that ULF pulsations may be associated with earthquakes [*Fraser-Smith* et al., 1990; *Hayakawa* et al., 1996]. The majority of these studies refers to the detection of these signals in ground-based magnetometer measurements [*Hayakawa* et al., 2015; *Contoyiannis* et al., 2016; *Potirakis* et al., 2016 and references therein]. On the other hand, there is only a handful of studies that have been attempted to correlate ULF pulsations with seismic activity from space-borne measurements [e.g., *Balasis and Manda*, 2007 for CHAMP satellite and *Walker* et al., 2013 for DEMETER satellite].

In this analysis, we have used the low resolution ASM data with a sampling rate of 1 Hz and hence we have limited our analysis to the Pc3 class, covering frequencies from 20 mHz (period of 50 sec) to 100 mHz (10 sec). An electromagnetic wave of higher frequency, e.g. at 200 mHz (5 sec), would be captured in the low resolution data by a pulsation with a period of merely 5 data points, making the analysis statistically questioning.

Our method involves two steps [see also *Balasis* et al., 2015]. The first step is to build a database of daily power spectra, while the second turns to the actual wave detection. For every day in the time interval of interest, i.e., approximately one month before and after the Nepal EQ both in 2014 and 2015: this time interval could have been extended into a longer time period, however, the neighboring months of March and June 2015 were both dominated by strong geomagnetic activity associated with two intense magnetic storms occurred one at each month as witnessed by the Dst index⁴.

The hourly Disturbance storm-time (Dst) geomagnetic activity index is computed from an average over 4 mid-latitude magnetic observatories, and hence serves as a proxy for the

⁴ http://wdc.kugi.kyoto-u.ac.jp/dst_provisional/201503/index.html;
http://wdc.kugi.kyoto-u.ac.jp/dst_realtime/201506/index.html

magnetospheric ring current, and thus magnetic storm occurrence [http://wdc.kugi.kyoto-u.ac.jp/dst_realtime/presentmonth/index.html]. The two intense magnetic storms occurred on 17 March and 23 June 2015 with minimum Dst index of -223 nT and -204 nT, respectively.

Then, we have performed the following analysis. First, the magnetic data are downloaded, along with the files of the previous and the next day. Since all spectral methods are plagued by edge effects [Torrence and Compo, 1998], we have appended the magnetic field time series of the current day, with a few hours from the previous and next day. Whatever edge effects appear they might affect these additional "margins", which can be then safely removed from the process, getting the spectral data of the day under processing clean of edge effects. From the magnetic time series of the ASM instrument we have derived the magnitude of the magnetic field and applied a Chebysev type II, zero-phase, high-pass filter with a cutoff frequency of 20 mHz to remove all lower frequency components from the signal and bring the Pc3 range in the spotlight [Williams and Taylors, 1988]. Using the wavelet method, with the Morlet mother function, we have produced the power spectrum of the magnetic field series, for 50 logarithmically spaced frequencies from 20 to 100 mHz [Balasis et al., 2013] and removed the aforementioned margins. In parallel to that, the positional vector of the spacecraft is extracted from the files and converted to magnetic coordinates (magnetic latitude, longitude and local time), as well as the electron density series from the Swarm electric field instrument (EFI) data files of the same day. The final spectrum, along with the time series of the magnetic field, the electron density and all positional information are then exported in a daily file and saved in the database.

The second step refers to the wave detection, which begins by reading the daily output files and segmenting them in tracks (half-orbits) from -90 to +90 degrees in magnetic latitude. For each

such track, the maximum power per second (stored in the spectrum) is calculated and all segments of consecutive points that exceed a threshold of $0.5 \text{ (nT}^2 / \text{Hz)}$ (which roughly corresponds to a pulsation with a minimum amplitude of 0.15 nT) are labeled as "candidate events". Each candidate is tested against a series of criteria that help rule out artificial signals that might result from instrument or telemetry errors. As such, for the candidate event to not be discarded it must i) exhibit a duration at least two times its peak period, ii) have an amplitude that does not exceed a given limit (10 nT) and iii) be smooth enough to constitute a continuous pulsation, so its difference series must always be smaller than 1 nT. In order to avoid traces of activity from lower Pc classes (below 20 mHz) that have not been completely eliminated by the filtering process, the peak of the wave activity has to be at a frequency that does not lie at the limits of the examined range, so only pulsations with a peak frequency that lies well above 21 mHz are accepted. Lastly, if the candidate is detected when the satellite is located at the nightside sector, an additional criterion must be met, namely that its electron density series must not display abrupt changes. If it does, then the candidate is classified as belonging to the Plasma Instability class, which includes (but is not limited to) equatorial spread-F (ESF) events [Stolle et al., 2006] at low latitudes and activity related to field aligned or auroral currents at higher latitudes. If the electron density profile is smooth enough, or the wave event takes place at the dayside sector then it is classified as a Pc3 Wave.

For the production of wavemaps the coordinate space, i.e., geographical latitude vs longitude is divided into a 50 by 50 grid, which provides a resolution of 3.6 degrees in latitude and 7.2 degrees in longitude. For every second in the duration of an event, its total Pc3 power is calculated and added to the appropriate grid point that the measurement belongs, based on the

satellite location at the same moment, thus allowing the entire extent of the wave to be accurately represented. In order to make the resulting maps less dependent on the satellite orbit (the number of times it passes from each sector of local time) we have divided the summed power by the number of seconds the satellite spends in each grid point.

Having produced the wavemaps for the months April to May 2014 and 2015, we then have divided them, point by point, to remove the wave power due to a normal Pc3 wave activity, which should be statistically similar in both cases reflecting a period of quiet geomagnetic activity as in our case. Figure 1 shows, on global scale, the difference in the Pc3 wave power between 2015 and 2014, as estimated from Swarm A and Swarm B data, limited to 1 April to 31 May of each year. In the map based on the Swarm A data we notice an anomalous difference just above the Nepal EQ epicenter and its magnetic conjugate point. On the map based on Swarm B no clear anomaly is noticeable in this area, probably because this latter satellite is at a higher altitude, and, supposing a simple model of lithospheric source with geometrical attenuation with the distance, the effect is dramatically minimized.

Figure 1. Pc3 difference in Wave Power 2015-2014 for Swarm A satellite (bottom) and Swarm B satellite (top), both cases, in the period 1 April to 31 May of each year to avoid periods of magnetic storms. The northern hemisphere and southern hemisphere red stars are the positions of the 2015 Nepal EQ epicentre and its conjugate point, respectively. The black line indicates the magnetic equator at both panels.

Please note that, by construction, the wavemaps depict average values of the wave activity for the entire two-month period that was examined. Thus, the activity from many local times that correspond to the same latitude-longitude grid point will have been averaged together and so it is impossible to extract the notion of local time from these graphs. An alternative approach would be to construct the maps on a latitude vs local-time grid, which would show any such behavior, but in this case activity from many longitudes would have been averaged together, thus making it impossible to associate any observations with the EQ epicenter. We think the way we chose to construct the above wavemaps is the best compromise.

3.2. Analysis of magnetic satellite data and seismic data

Previous analysis points toward a possible coupling between lithosphere and ionosphere. To verify this assessment, we have performed another study to enforce the idea of a coupling between lithosphere and ionosphere occurring before the large Nepal EQ.

We have performed an analysis on the vector data provided by Swarm A. We have considered all magnetic X (North), Y (East), Z (vertical) and F (field intensity) measurements and computed the first time difference along the night orbital tracks (between 2200 to 0600 LT). This procedure removes most of the slow fluctuations of the magnetic signal. Then, we have adjusted and removed the best fit curve obtained by a series of cubic-splines with knot points every 20 s and plot the obtained track residuals. These residuals are very sensitive to any abrupt change in the original signal, or in its slope. Finally, we have examined the obtained plots to identify clear anomalies with the following characteristics: i) peak-to-peak amplitude ≥ 0.3 nT/s and persistence for at least ten seconds (so well inside the ULF band); ii) occurrence during very magnetic quiet night-times (the absolute value of the Dst index lower than 10 nT and $a_p \leq 12$ nT)⁵; iii) situated within the Dobrovolsky circular area around the epicenter. We notice that the best clear anomalies generally occur in the Y-component. Once identified, we plot for each anomaly, at its occurrence time t , the subsequent cumulative number, $N(t)$, i.e. the order of the N -th earthquake until time t . An example of chosen track with an anomaly is shown in Figure 2a, while Figure 2b shows as example a track without significant anomalies.

⁵ <https://www.ngdc.noaa.gov/stp/geomag/indices.html>

Figure 2a Specific plots (dX/dt , dY/dt , dZ/dt from fluxgate magnetometer and dF/dt from scalar magnetometer of Alpha satellite; and geographic map of the satellite track where the yellow star is the EQ epicentre) of one of the corresponding chosen night-time tracks with anomalies used in Fig 3 (bottom). The presumed anomaly is evidenced by a red oval. Above are indicated: date, # of track (half-orbit), mean Local time, UTC, and the values of the geomagnetic indices Dst and a_p .

Figure 2b Specific plots (dX/dt , dY/dt , dZ/dt from fluxgate magnetometer and dF/dt from scalar magnetometer of Alpha satellite; and geographic map of the satellite track where the yellow star is the EQ epicentre) of a night-time track without anomalies. Above are indicated: date, # of track (half-orbit), mean Local time, UTC, and the values of the geomagnetic indices Dst and a_p .

This technique is used because of its sensitivity to anomalous deviations with respect to a typical random process whose cumulated value has a statistical linear increase. In particular, in case of critical phenomena we would expect more frequent anomalies when they approach the critical point, and less frequent anomalies after, so providing an accelerating power law before it and a decelerating recovery after, such as:

$$N(t) = A + B |t_f - t|^m \quad (1)$$

with A and B two constants, and $0 < m < 1$ or $m > 1$ in the acceleration or deceleration phase, respectively [e.g. *De Santis*, 2014].

The bottom of Figure 3 shows the temporal behavior of $N(t)$, denoted here as N (magnetic anomalies). We indeed notice a power-law temporal behavior before the EQ (its occurrence is indicated by a vertical dashed line) with an upper concavity and a subsequent power-law behavior after, with an opposite concavity. Same figure shows the best fit power-laws before or after the Nepal main-shock. This behavior is compared with the analogous of the cumulative number of M4+ earthquakes, $N(\text{EQs})$, occurred before and after the Nepal EQ, in the Dobrovolsky region. The two plots are very similar, both identifying the phases before and after the large EQ, and supporting the hypothesis that the noticed magnetic anomalies in Swarm data are mostly of internal origin, due to a LAI coupling. This process can be linked to the preparation phase of a large EQ and on the aftershocks phase [Pulinets and Boyarchuk, 2004; Pulinets and Ouzounov, 2011].

Figure 3 Cumulative number of magnetic anomalies detected by Swarm satellite A versus time. Red and blue curves are the best power-law fits before and after the Nepal main-shock, respectively (bottom); Cumulative number of M4+ earthquakes occurred within Dobrovolsky area versus time (top).

The cumulative count of the magnetically quiet tracks (Figure 4) indicates a similar behavior, especially after the EQ. This means that our previous result could be due, in some unknown amount, to a modulation of the daily distribution of quiet times intervals used in the satellite data selection.

Figure 4. Cumulative number of magnetically quiet satellite tracks.

This possibility cannot be fully excluded so a more robust approach is required. The proposed one is based on an automatic selection of anomalies, only on the basis of a given number of standard deviations, with no consideration of night or day, quiet or disturbed times. As partial justification of relaxing the quiet time criterion of selection, we remind the recent paper by *Currie and Waters* [2014], which refutes the widely spread misbelief that ULF variations and geomagnetic activity are closely correlated, rather it leaves space to the assumption that sometimes ULF activity may be related to internal lithospheric processes, like, for instance,

microcracks, shallow fluid migration and/or particle emissions associated with earthquake preparation phase.

When considering, independently from the quiet index selection, only those anomalies above 3.5 standard deviations (with a standard deviation estimated along the entire track from 55°N to 55°S geomagnetic latitude, to avoid the auroral and polar disturbances), we obtain almost the same type of “critical” curve (Figure 5), at the cost of less detected anomalies, because of the more stringent criterion of selection. Let us note that: i) when two detected anomalies occur in the same day, we indicate it as one single point, but we add two counts in the cumulative value (this explains why, although the detected anomalies are 17, there are 11 points in the plot); ii) although most of anomalies (15 out of 17) occur during rather quiet magnetic times (both $|Dst|$ and a_p less than 20 nT), there are two exceptions on the same day (i.e. 17 April 2015) with anomaly occurrence during some slightly perturbed periods ($Dst=-34$ and -36 nT, although $a_p=7$ nT). This means that even in a perturbed day, the detected anomaly clearly emerges.

In Figure 5, for simplicity, instead of two power-law functions before and after the main-shock, as (1), the complete “critical curve” around the large earthquake is approximated with a generalized sigmoid function:

$$S(t) = a + \frac{b-a}{\left(1 - e^{\frac{t-t_f}{c}}\right)} \quad (2)$$

where t_f , a , b and c are given constants calculated by the fitting, with t_f the inflection point of the function.

Figure 5. Cumulative number of magnetic anomalies (empty circles) which are above 3.5 standard deviation. Red curve is the best sigmoid fit over the experimental data while the dashed line is the best linear fit. Vertical thin line is the time of the Nepal earthquake, while the vertical thick line is the predicted time given by the sigmoid fit. Both C-factor and the corrected Akaike information point to a sigmoid function as a fitting model, better than the linear one.

Although this function is not a rigorous solution for a dynamical equation satisfying the approach of a system to its critical point, it is a sound representation of the correct solution, with the advantage of no singular point in its first time derivative. We have performed the fit in a unique solution over all periods of time around the main-shock, without the intention of making predictions of the impending EQ from the precursory magnetic anomalies, rather to invoke a LAI coupling.

Another advantage of using the sigmoid fit is the estimation of the time t_f . Despite the used function is only approximated, the parameter t_f is a reasonable estimation of the time of the radical change of the critical dynamical system, i.e. its critical point. In this specific case, the obtained values are: $t_f = 27.26 (\pm 1.37)$ days from April 1st, 2015, that is surprisingly close to the actual time (25.27 days) of the Nepal EQ. Certainly, this complete analysis can be performed only once the event is occurred, because the sigmoid needs to be computed over a significant time around the EQ. To understand whether the fit with the sigmoid function is robust, we have compared it with that of a straight line. The sigmoid fit is clearly better than the linear one: their Pearson's correlation coefficients, r_p , are 0.9950 and 0.9848, respectively. In addition, we have introduced the *C-factor* as the ratio between the RMS (root mean squares) of the sigmoid fit and the RMS of the best line (e.g. *Bowman* et al., [1998] define the *C-factor* for a power-law and a line) or equivalently:

$$C = \sqrt{(1 - r_p^2[\text{sigmoid}]) / (1 - r_p^2[\text{line}])} \quad (3)$$

The lower than 1 the *C-factor* is, the better performance of the sigmoid fit with respect to the linear one is obtained. In the present case, with $C = 0.57$, it appears that the fit of the sigmoid function is significantly better than the linear fit.

Though the sigmoid function contains four parameters instead of the two for a line, we can prove that it is more efficient than the line, in terms of the corrected Akaike information AIC_c [*Akaike*, 1973; *Cavanaugh*, 1997]: the corresponding criterion affirms that the best function is the one with lower AIC_c . Thus, we have calculated AIC_c for both fitting functions, and represented in

Figure 5. For the two functions we have found that $AIC_c(\text{line}) \gg AIC_c(\text{sigmoid})$, confirming that the sigmoid function is more appropriate to model the data than a simple linear fit. If the cumulative number of magnetic anomalies is reproducing the effect of the LAI coupling before and after a large EQ, the sigmoid fit also provides an estimate of the time of change of this coupling, i.e. the time of occurrence of a large EQ.

4. Confutation analysis

The region of interest that includes the Dobrovolsky area around the 2015 Nepal EQ is very seismic and it is rather difficult to find long periods of complete seismic inactivity. Table S1 (Supplemental Material) shows, in the interval 1 Jan. 2014- 30 June 2016, the 3 periods with no M5.5+ EQs, which are longer than 60 days. Here, we present the results of a confutation analysis for a non seismic situation: i) the wavelet power analysis of the Swarm magnetic data as observed all over the world over the same two months April and May, but in another year (2016) and ii) a track-by-track anomaly detection in the same region (Dobrovolsky area for the Nepal EQ), but in another 60-day period. In the former case no large M6+ seismicity was present in the considered Dobrovolsky area, while in the latter no M5.5+ earthquakes occurred (Table S1). Figures S1 and S2 (Supplemental Material) show the comparison of the wavelet power result in 2015 with that in 2016 and then the wavelet power result in 2014 with that in 2016, respectively. If we examine the area around the Nepal EQ epicentre and its conjugate point, we notice that the regional anomaly found in Alpha satellite, in the comparison 2015-2014 is still present in 2015-2016, while it is not present in the comparison 2014-2016, confirming the uniqueness of the anomaly in the period of time before the EQ. Regarding the second kind of analysis, and looking at the Table S1, excluding the second period, that includes the analysed EQ, and the third that is

too close with the aftershocks activity of the same EQ, it remains only the first period useful for the confutation analysis of this kind of method, i.e. from 1 June to 30 July 2014. We call this dataset as “false” case, because no significant M5.5+ earthquakes occurred over the period. Figure S3 (Supplemental Material) shows that the corresponding cumulative numbers of EQs behave more linearly than as a sigmoid ($C\text{-factor}=1.1$), and in any case more linearly than the real case, confirming that the results obtained around the Nepal EQ in 2015 are not merely due by chance.

5. Conclusions

In this paper we have analysed the Swarm satellite data around the time of 25 April 2015 Nepal EQ. Two different analyses suggest that this EQ involved a physical coupling between the lithosphere and ionosphere in its preparation phase. The comparison of the Pc3 wave power of the same two month period over three years (the EQ year together with the previous one and the next one) shows some anomalous differences in the region around the EQ epicentre. A more sophisticated technique based on the theory of critical systems, allows us to establish a clear change in the behavior of the cumulative number of magnetic anomalies, which is analogous with that found for the cumulative number of EQs occurred in the same region. This analogy permits us to suggest that the potential LAI coupling would extend over a rather large interval of time, i.e. around a month before and after the 2015 Nepal main-shock. This analysis is also confirmed as not obtained by simple chance after a confutation analysis during an almost aseismic 60-day period in the same region, but in the previous year.

From the above analyses, it appears that the Nepal event probably affected the ionosphere before the EQ occurrence.

We think that our paper represents an important step moving from the search of single anomalies, which is still a difficult task, to the search of anomalous patterns, likely related to EQs. The use of the cumulative number of anomalies is the solution we propose here, but we do not exclude other strategies that can address better and more efficiently the same goal.

In addition, more case studies should be undertaken in some other tectonic settings. The reader is reminded that the objective of the present analyses is not a retrospective prediction of an impending EQ, rather an emphasizing of a potential LAI coupling during its preparation phase.

We would expect however, that the use of an accelerating power-law might be more suitable than the sigmoid, though with some resulting frequent false alarms. A specific further study should be done in order to assess whether information on the magnitude of the EQ could be deduced from the number or the amplitude of the magnetic anomalies. In addition, only with the simultaneous and combined analysis of many different physical parameters in the space, time and frequency domains we can advance in this subject [De Santis et al., 2015]. A more detailed analysis would require the investigation of some other large EQs; currently, this is beyond the scope of this first Swarm data analysis, however this will be an important matter for future work.

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