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Key Points:
- We discuss the SSI index as indicator of earthquakes precursors
- We show that SSI preearthquake changes may be explained as geomagnetic effects
- We show that SSI is not reliable indicator of precursory effects of earthquakes

Correspondence to:
F. Masci,
fabrizio.masci@ingv.it

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On the reliability of the Spatial Scintillation Index to detect earthquake precursors in the ionosphere

F. Masci[1] and J. N. Thomas[2,3,4]

[1]Istituto Nazionale di Geofisica e Vulcanologia, L'Aquila, Italy, [2]NorthWest Research Associates, Redmond, Washington, USA, [3]Department of Electrical and Computer Engineering, DigiPen Institute of Technology, Redmond, Washington, USA, [4]Department of Earth and Space Sciences, University of Washington, Seattle, Washington, USA

Abstract The scientific literature includes many reports of ionospheric phenomena that are retrospectively identified prior to seismic events. These disturbances of the Earth's ionosphere are considered to be possible precursors of the impending earthquakes. However, a causal relationship between ionospheric phenomena and earthquakes has never been definitively demonstrated, and attempts at identifying precursory effects in the ionosphere have been called into question by several studies. Among the candidate indicators of ionospheric precursors there is the Spatial Scintillation Index (SSI) proposed by Pulinets et al. (2007). The usefulness of this index in the search for precursory effects of earthquakes has been criticized by Thomas et al. (2012) and Masci (2013). In a recent report, Pulinets and Davidenko (2014) attempt to briefly respond to the remarks of these researchers. Here we cast doubt that Pulinets and Davidenko (2014) have shown that SSI is a reliable indicator of precursory effects of earthquakes in the ionosphere.

1. Introduction

Disturbances in ionospheric parameters are usually observed a few minutes after earthquakes caused by atmospheric waves induced by the motion of the ground [see, e.g., *Astafyeva et al.*, 2013; *Calais and Minster*, 1995; *Komjathy et al.*, 2012]. On the contrary, a clear demonstration of the occurrence of earthquake precursors in the ionosphere has not yet been provided [see, e.g., *Cohen and Marshall*, 2012; *Masci*, 2012; *Masci and Thomas*, 2014; *Masci et al.*, 2014; *Rishbeth*, 2006a; *Thomas et al.*, 2012]. *Pulinets* [2007], in a communication in the EOS newsletter of the American Geophysical Union, maintain that as previously reported by *Pulinets et al.* [2007], the 16 October 1999 M_w 7.1 Hector Mine, California (U.S.), earthquake could have been predicted by monitoring changes of the total electron content (TEC) in the ionosphere above the fault zone. *Pulinets* [2007] concludes that this type of ionospheric phenomena will be useful in the future for predicting an earthquake. In *Pulinets et al.* [2007] the authors introduce a new index in an effort to describe the variability of the ionosphere on a regional scale. They call this index regional variability index, indicating it with ΔTEC. More recently, *Pulinets and Davidenko* [2014] have renamed this index Spatial Scintillation Index (SSI). Hereinafter, we will use SSI also referring to *Pulinets et al.* [2007]. SSI is obtained by calculating the difference between the maximum value and the minimum value of the vertical TEC (VTEC) from GPS measurements in the receivers within the area of the analysis [*Pulinets et al.*, 2007]. Global Positioning System (GPS) satellite signals (1575.42 and 1227.60 MHz carrier phase frequencies) are transmitted to ground receivers through the ionosphere. The phase of these signals are affected by the number of electrons, known as slant TEC (STEC), integrated over the path between the receiver and the GPS satellite (1 total electron content unit, $1\,\text{TECU} = 10^{16}\,\text{el m}^{-2} = 10^{16}\,\text{electrons/m}^2$). VTEC is derived from STEC and represents the integrated electron density in the vertical column above the receiver [*Komjathy et al.*, 2005]. According to *Pulinets* [2007], SSI is a special index which is sensitive to earthquake-related TEC changes and much less sensitive to TEC variations induced by the geomagnetic activity.

Pulinets et al. [2007], by a retrospective analysis of VTEC data from 13 GPS receivers near the Hector Mine area, assert to have identified changes in SSI that are precursory signatures of the 16 October 1999 earthquake. According to them, the 13 GPS receivers cover an area that may be identified with the "preparation zone" of the Hector Mine earthquake as suggested by *Dobrovolsky et al.* [1979]. The theoretical relationship reported by *Dobrovolsky et al.* [1979] between the size of the alleged preparation zone of an earthquake and its magnitude estimates that the preparation of the Hector Mine earthquake took place in the area having a radius of more than 1100 km centered to the epicenter. What *Pulinets* [2007] claims is in contrast with the previous study of *Afraimovich et al*. [2004] in which the authors analyze TEC data from 125 GPS receivers in the southwest U.S., including the 13 GPS stations considered in *Pulinets et al*. [2007]. *Afraimovich et al*. [2004] conclude that TEC variations above the Hector Mine area were controlled by solar and geomagnetic activity and not by seismicity. More recently, *Masci and Thomas* [2014] have shown that the temporal and spatial analyses of TEC data reported by *Su et al*. [2013] do not show evidence of any clear relationship between the documented ionospheric changes and the 16 October 1999 Hector Mine earthquake.

The reviews of *Thomas et al*. [2012] and *Masci* [2013] have put into question the idea that the SSI changes reported by *Pulinets et al*. [2007] before the Hector Mine earthquake is of seismogenic origin. *Thomas et al*. [2012] demonstrate that the TEC changes before this earthquake were not anomalous but normal variations on global scale not related to the localized seismicity of the Hector Mine area. They have shown that at the time of the Hector Mine earthquake, the SSI time series calculated from two GPS stations located far from the epicentral area, in Canada, is very similar to that calculated by using the same GPS stations used by *Pulinets et al*. [2007]. *Masci* [2013] confirms the results of *Afraimovich et al*. [2004] and *Thomas et al*. [2012] by comparing the SSI of *Pulinets et al*. [2007] with the 3 h global geomagnetic *Kp* index. The *Kp* index is calculated as the average value of the disturbance level in the horizontal component of the geomagnetic field by combining data from 13 selected magnetometer stations located at middle and high latitudes. *Kp* is considered representative of the average geomagnetic disturbances on planetary scale [*Menvielle and Berthelier*, 1991]. *Masci* [2013] concludes that before the Hector Mine earthquake there is a close correspondence between SSI and *Kp* time series which is further evidence that at the time of this earthquake the TEC variability over the Hector Mine area was driven by Sun-Earth interactions.

Pulinets and Davidenko [2014], not accepting the criticism of *Thomas et al*. [2012] and *Masci* [2013], have tried to reiterate their thought that SSI is a good predictor of earthquakes. Papers like *Pulinets* [2007], *Pulinets et al*. [2007], *Pulinets and Davidenko* [2014], and other similar papers [see, e.g., *Le et al*., 2011; *Li and Parrot*, 2013; *Pulinets*, 2009; *Su et al*., 2013] showing ionospheric anomalies, claimed to be precursory signals of pending earthquake, have a great social impact. They remain influential in the search for earthquake precursors, and, more importantly, they motivate the idea that earthquake prediction one day will be possible. Considering the importance of earthquake prediction, in the following section we are motivated to further comment on the usefulness of the SSI index of *Pulinets*.

2. The Spatial Scintillation Index and Earthquakes

In Figure 1a we show the SSI index at the time of the 1999 Hector Mine earthquake as reported by *Pulinets et al*. [2007] and recently republished in *Pulinets and Davidenko* [2014, Figure 13a]. These authors claim that the increase of SSI during the week before the 16 October Hector Mine earthquake had seismogenic origin. Here similarly to *Masci* [2013], we have superimposed the *Kp* index time series onto the original figure. It can be seen that there is a close correspondence between the SSI increase and the *Kp* index. According to *Masci* [2013] this demonstrates that the TEC variability over the Hector Mine area at the time of the 16 October 1999 earthquake had a global origin in response to Sun-Earth interactions. We also calculated the Pearson's correlation coefficient between SSI and *Kp* during 1–20 October. We excluded data starting from 21 October just before the onset of a geomagnetic storm. The value of the correlation coefficient is 0.77. This is a reasonable value since, due to the global averaging used to calculate the geomagnetic index *Kp*, we do not expect a strict correlation between *Kp* and SSI but just a close correspondence, and, in any case, this correspondence is not expected always and everywhere. Refer to *Thomas et al*. [2012] and *Masci* [2013] for a more exhaustive discussion on the SSI changes above the Hector Mine area during October 1999.

Pulinets and Davidenko [2014], in response to the results of *Thomas et al*. [2012] and *Masci* [2013], assert that these authors have interpreted the SSI index as a one-point parameter, whereas, since SSI is obtained by combining TEC data derived from many GPS receivers, it describes the variability of the ionosphere on regional scale. According to *Pulinets and Davidenko* [2014] this led *Thomas et al*. [2012] and *Masci* [2013] to wrong conclusions. Even if we consider the remark of *Pulinets and Davidenko* [2014] not relevant, we would like to point out that we have not interpreted SSI as one-point parameter because, e.g., in Figure 1a

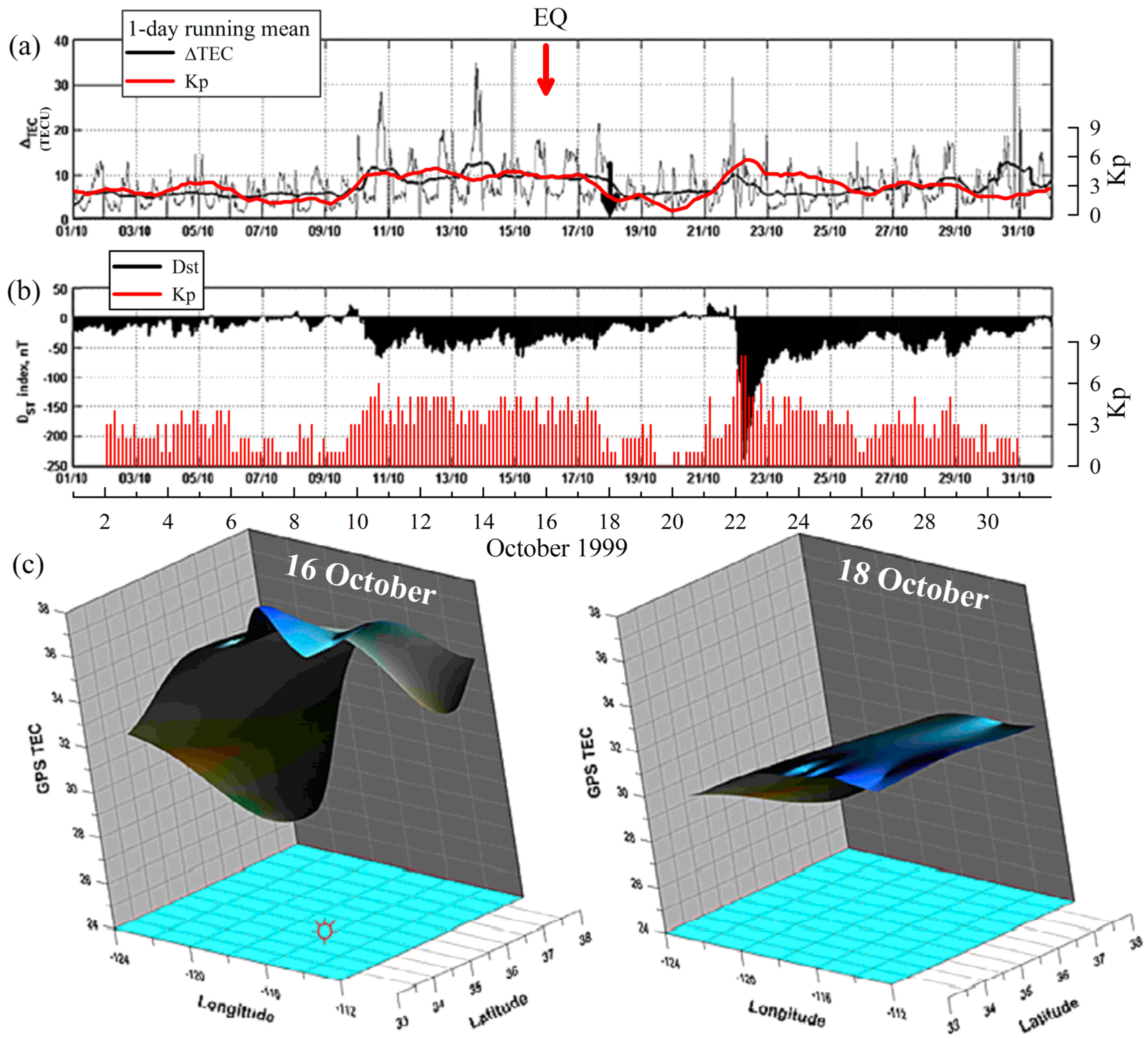

Figure 1. A reproduction of Figure 13 by *Pulinets and Davidenko* [2014]. (a) Ionospheric SSI index (ΔTEC) during October 1999. The red arrow indicates the date of the 16 October 1999 Hector Mine earthquake that in the original figure was erroneously indicated with the black arrow. (b) Geomagnetic *Dst* index. In Figures 1a and 1b the *Kp* index time series has been superimposed onto the original views. (c) Distribution of the GPS vertical TEC over the Hector Mine area on (left) 16 October 1999 and on (right) 18 October 1999. See text for details.

we have compared SSI with a global (i.e., *Kp*), and not local, indicator of the geomagnetic activity level. More interesting for us is that the correspondence we have found between SSI and *Kp* demonstrates that SSI may be strongly affected by the effect of global geomagnetic changes.

In order to demonstrate the reliability of SSI as indicator of precursory effects in the ionosphere, *Pulinets and Davidenko* [2014] investigate the spatial distribution of the GPS TEC over a large area, which includes the Hector Mine area as well, on the day of the earthquake and during 2 days after the shock. In Figure 1c we show the TEC distribution as reported by *Pulinets and Davidenko* [2014] for 16 and 18 October 2009. They found a strong spatial variability of TEC during 16 October. In contrast, during 18 October the spatial distribution of TEC is almost constant. According to *Pulinets and Davidenko* [2014] the similarity of the geomagnetic condition during these 2 days, that they have deduced from the *Dst* index time series, demonstrates that the stronger TEC variability during 16 October, as well as the increase of SSI during the period before the Hector Mine earthquake, originated seismogenic.

We disagree with the claims of *Pulinets and Davidenko* [2014]. Their method for checking the geomagnetic conditions just by a visual inspection of the *Dst* index in their Figure 13a (here Figure 1b) is not sufficiently rigorous and led them to unfounded conclusions. In Table 1 we have reported for 16 and 18 October 1999

Table 1. Global Geomagnetic Indices *Kp*, Σ*Kp*, and the Mean Value of the *Dst* Index During 16 and 18 October 1999

	Kp	Σ*Kp*	$\overline{Dst}$
16 October 1999	4 5− 3+ 4− 4− 5− 4− 3	31−	−33 nT
18 October 1999	1 1+ 0+ 2− 2+ 2− 2+ 2	13−	−16nT

the geomagnetic indices *Kp*, Σ*Kp*, and, even if it is redundant, the daily mean value of the *Dst* index. Contrary to what is stated by *Pulinets and Davidenko* [2014], it is evident that during 16 and 18 October the geomagnetic conditions were significantly different. We focus our attention on the *Kp* index that is indicative of the global geomagnetic conditions, whereas *Dst* is designed to monitoring the strength of the Equatorial Electroject, and it is usually used as indicator of the geomagnetic storm level and ring current intensification [*Mayaud*, 1980]. In Table 1 we see that during 18 October the *Kp* index shows low values in all the 3 h periods; note that maximum *Kp* value is 2+. Therefore, 18 October can be classified as geomagnetic quiet day. In contrast, 16 October is a more active day since *Kp* shows values between 4− and 5− during six of the eight 3 h periods. Thus, it is highly likely that the TEC variability during 16 October was related to the higher geomagnetic activity and cannot be considered as a possible seismogenic effect. Note that *Kp* shows high values (up to 6−) also during the week before the shock when the SSI increase occurs (see http://swdcwww.kugi.kyoto-u.ac.jp/). Further evidence that TEC distribution over the Hector Mine area during 16 October was strongly affected by global geomagnetic effects, and not necessarily by the seismicity, is that the high variability of TEC spreads over a very large area. As we can see from Figure 1c, on 16 October the area in which TEC shows a strong variability ranges between (33–39)°N and (112–124)°W. Was the ionosphere above such a wide area disturbed by seismogenic effects? Taking into account the tectonic context, we think this is unlikely. Probably, *Pulinets and Davidenko* [2014] were misled by the assumption that precursory effects of the Hector Mine earthquake may be observed in the ionosphere above an area which radius, according to *Dobrovolsky et al*. [1979], is about 1130 km. *Masci and Thomas* [2014] have pointed out that the theoretical formula proposed by *Dobrovolsky et al*. [1979] is not supported by the experimental evidence. The surface fault rupture (both offset and slip) generated by the 1999 Hector Mine earthquake was observed at a maximum distance of few tens of kilometers (~50 km) from the epicenter [see, e.g., *Chen et al*., 2015; *Jónsson et al*., 2002; *Treiman et al*., 2002]. Furthermore, during the Parkfield Earthquake Prediction Experiment along the San Andreas Fault in California, high-precision borehole strain and pore pressure observations were obtained close to the epicenter of the 28 September 2004 M_w6.0 Parkfield earthquake. No precursory accelerating strain or pore pressure changes during the weeks before the main shock were observed [*Johnston et al*., 2006]. They also showed that the earthquake nucleation region of the Parkfield earthquake was very small. More recently, *Johnston* [2015] reported that (i) earthquakes are multiple events controlled by the mechanical properties of the fault, (ii) irregularities in the fault geometry and its frictional characteristics control the starting and stopping of the earthquake rupture, (iii) the fault failure nucleation size for $M > 5$ earthquakes is extremely small (<10 cm) compared with the size of the earthquake and does not scale with earthquake magnitude, and (iv) the observed stress has no measurable changes prior to earthquakes that might indicate the initiation of fault failure. Therefore, as *Johnston* [2015] points out, any small earthquake could degenerate into a stronger earthquake and the size of an earthquake is determined by how it is stopped and not by how it starts. This behavior, where the physical phenomena leading the fault in the critical state act in a small volume, and poorly known local characteristics control the size of an earthquake, raises serious doubts about the realization of future short-term earthquake prediction. Therefore, the notion of a large-earthquake preparation zone has no physical basis, and we conclude that, if ionospheric precursory disturbances emerged prior to the Hector Mine earthquake, but this has yet to be demonstrated, it is very unlikely that they had extension as large as suggested by *Pulinets and Davidenko* [2014]. On the contrary, the large extension of the high TEC variability during 16 October may support global geomagnetic origin for the ionospheric disturbances.

If, however, we accept that earthquake precursory signals may be observed in the area estimated by the *Dobrovolsky*'s formula, this raises some doubts regarding the usefulness of precursors for earthquake prediction. The search for precursory signals, indeed, is aimed toward the development of short-term prediction capability of catastrophic earthquakes. A prediction is a deterministic statement that a future earthquake of magnitude *M* will occur in a particular geographic region and in given period of time. For the M_w9.0 Tohoku-Oki, Japan, earthquake of 11 March 2011, e.g., the Dobrovolsky's formula estimates a

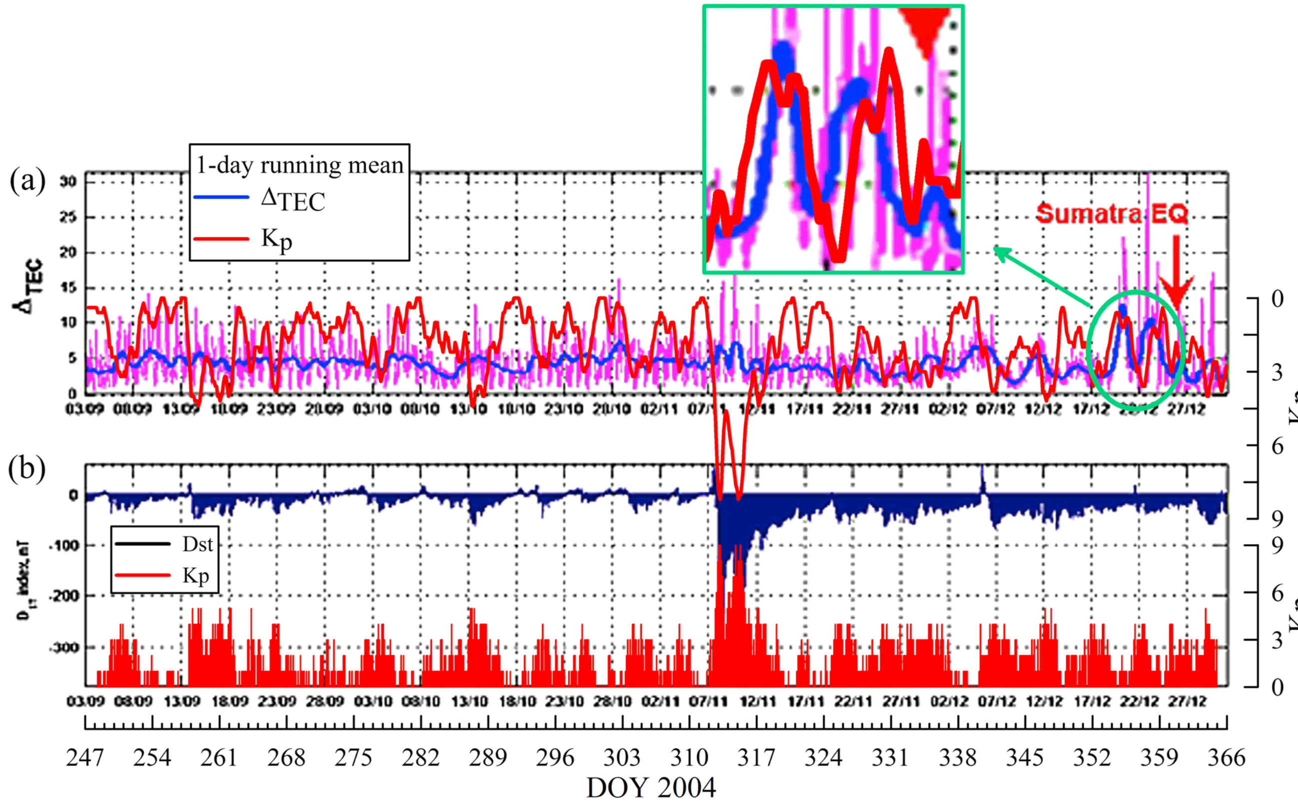

Figure 2. A partial reproduction of Figure 14 by *Pulinets and Davidenko* [2014]. (a) SSI index (ΔTEC) at the time of 26 December 2004 Sumatra Andaman earthquake. (b) Geomagnetic *Dst* index. The *Kp* index time series has been superimposed onto the original views.

radius for the alleged preparation zone of 7413 km. Note that this area is about one thirds of the Earth's surface. A precursor observed within this very wide area would not have been useful for predicting the Tohoku-Oki earthquake.

In support of their conclusions, *Pulinets and Davidenko* [2014] briefly introduce three selected examples of SSI changes in correspondence of earthquakes. SSI time series have been reported at the time of the 26 December 2004 M_w9.1 Sumatra Andaman offshore earthquake, the 27 February 2010 M_w8.8 Chile offshore earthquake, and the 6 April 2009 M_w6.3 L'Aquila earthquake. We note that, however, in their short discussion *Pulinets and Davidenko* [2014] do not specify how many GPS receivers they used and where these receivers are located around the epicentral area of each investigated earthquake. Therefore, it is not possible for us to precisely reproduce and evaluate the results for these additional cases. In Figures 2–4 we show the three examples as reported by *Pulinets and Davidenko* [2014]. What they note is the increase of the SSI index before the shock that seems to be common to the three selected earthquakes. This was enough to argue that SSI is one of the most reliable ways in understanding the coupling between ionosphere and seismic activity. Similarly to the Hector Mine earthquake, however, *Pulinets and Davidenko* [2014] have not taken seriously into account the possible effect of the geomagnetic activity. With the exception of L'Aquila earthquake, where they compare SSI with the *Ap* index (*Ap* is the average daily value of the *ap* index, a global geomagnetic index which is directly related to the *Kp* index [*Mayaud*, 1980]), in the other two examples they have improperly used the *Dst* index as exhaustive indicator of the geomagnetic activity level.

Now we are going to briefly discuss the three selected examples reported by *Pulinets and Davidenko* [2014]. In Figure 2a we show the SSI index (raw data and 1 day running average) at the time of the 2004 Sumatra Andaman earthquake. *Pulinets and Davidenko* [2014], as well as previously *Pulinets* [2009], suggest that the two humps in the SSI time series before the earthquake may be seismogenic. In Figure 2 we have superimposed onto the original views the global geomagnetic index *Kp*. Even if we cannot see a strict

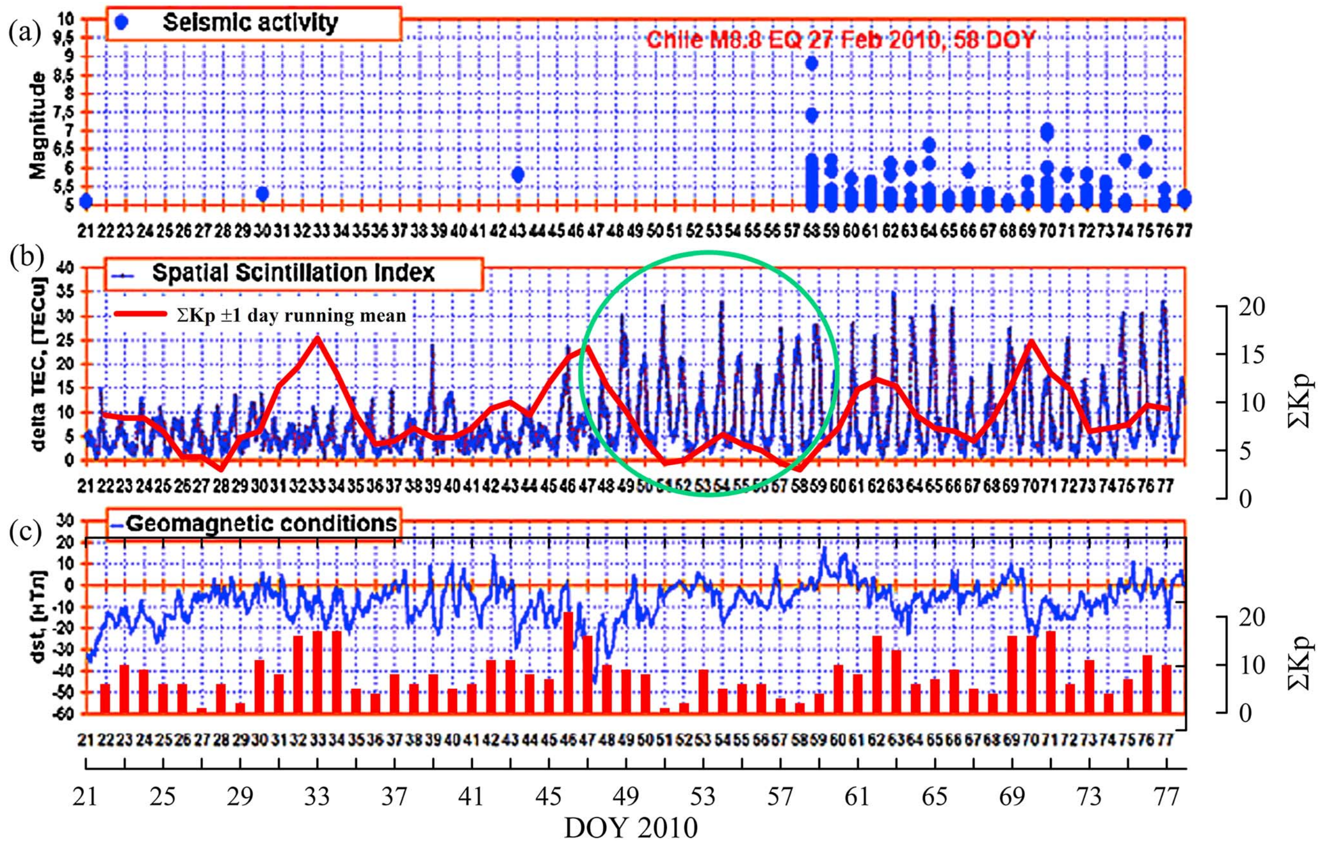

Figure 3. A partial reproduction of Figure 14 by *Pulinets and Davidenko* [2014]. (a) Seismic activity at the time of the 27 February 2010 Chile earthquake. (b) SSI index (delta TEC). (c) *Dst* index. The Σ*Kp* index time series has been superimposed onto Figures 3b and 3c.

correlation between SSI and *Kp* over all the investigated period of time, we note that there is a close inverse correspondence between *Kp* and the two preearthquake SSI increases hypothesized to be seismogenic by *Pulinets and Davidenko* [2014] (see the enlarged view in Figure 2a). Therefore, it is evident that the days before the earthquake the SSI index is influenced by global geomagnetic effects. However, we should not expect, in general, a good correlation between SSI variations and changes of the geomagnetic activity level always and everywhere because, contrary to the global geomagnetic *Kp* index, SSI was not designed to measure changes of the global geomagnetic activity. Still, we can see that before the Sumatra Andaman earthquake the correspondence between SSI and *Kp* is inverse and not positive as before the Hector Mine earthquake.

In Figure 3b we show the SSI index at the time of the 2010 Chile earthquake as reported by *Pulinets and Davidenko* [2014]. According to them, the increase of the amplitude of the SSI daily maxima before and after the 27 February 2010 Chile earthquake may have seismogenic origin. In Figure 4a we show the daily value of the SSI index at the time of the 6 April 2009 L'Aquila earthquake. Also, in this case *Pulinets and Davidenko* [2014] note an increase of SSI before the earthquake. In Figures 3 and 4 we have superimposed the Σ*Kp* and *Ap* global geomagnetic indices time series, respectively. In these two examples we do not see obvious correspondence between SSI and the geomagnetic activity level, even if, however, it can be noted that, as for the 2004 Sumatra Andaman event, the SSI increase before the earthquakes coincides with slow decreases and low level of the geomagnetic activity (see the green circles in Figures 3 and 4). This may be just a coincidence, but at the same time the SSI increases before Chile and L'Aquila earthquakes may be a coincidence as well. We would like to point out once again that a good correlation between SSI variations and changes of the geomagnetic activity level is not expected always and everywhere. Changes in solar and geomagnetic activity may cause not only global alteration of the ionosphere but also may control local perturbations of ionospheric parameters such as TEC variations on regional scales [see *Afraimovich et al.*, 2004; *Afraimovich and Astafyeva*, 2008; *Rishbeth*, 2006b]. Local ionospheric condition may also be determined by other factors such as meteorological events, anthropogenic effects, atmospheric gravity

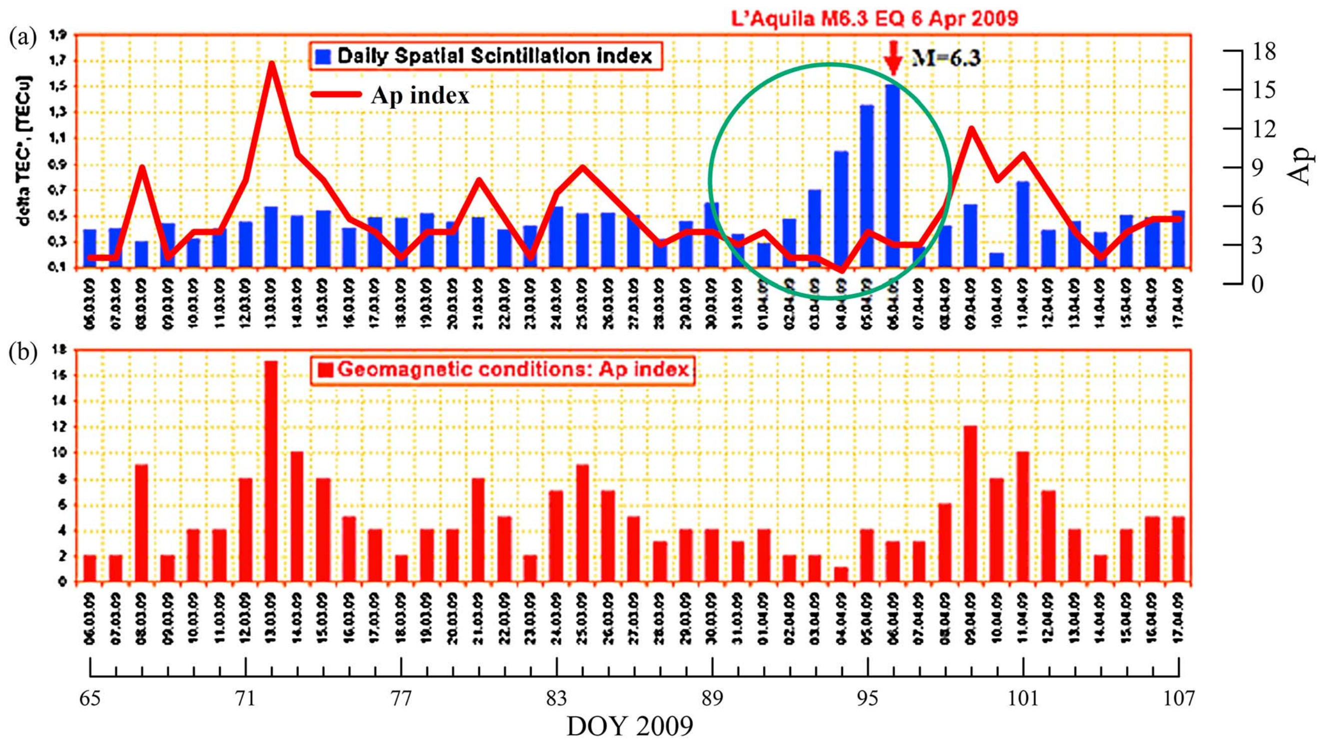

Figure 4. A partial reproduction of Figure 14 by *Pulinets and Davidenko* [2014]. (a) SSI index (delta TEC) at the time of the 6 April 2009 L'Aquila earthquake. The *Ap* index time series has been superimposed onto the original view. (b) Geomagnetic *Ap* index.

waves, and travelling ionospheric disturbances [*Hocke and Schlegel*, 1996]. The ionosphere also shows normal seasonal, day-to-day, and diurnal variations. Still, we cannot say whether a possible correspondence between SSI and geomagnetic indices should be positive or inverse. This could depend on how in a particular region SSI responds to global effects, since it may also be strongly affected by the number of the GPS stations used for its calculation and by their location in the investigated zone. Thus, how SSI responds to changes of the geomagnetic conditions may be different for different areas. Still, there is no physical reason to suggest that SSI may increase before an earthquake in order to be indicator of precursory disturbances in ionospheric data, and the reports by *Pulinets* and coauthors never provided actual evidence of the influence of seismic activity on SSI variations. On the other hand, if we find that SSI changes reported to occur prior to earthquake have a positive or inverse correspondence to changes in the global geomagnetic conditions, it is highly likely that the regional TEC variability during this period was driven by solar-terrestrial interactions and not by seismicity.

3. Conclusions

We have discussed the findings of *Pulinets and Davidenko* [2014] which, in response to the criticism of *Thomas et al.* [2012] and *Masci* [2013], tried to provide new relevant evidence in support of the reliability of the Spatial Scintillation Index as indicator of precursory effects of earthquake in the ionosphere. Here we have shown that the additional findings provided by *Pulinets and Davidenko* [2014] in support of the Hector Mine precursor of *Pulinets et al.* [2007] are unfounded. The incorrect use of the *Dst* index as indicator of the geomagnetic conditions on a global scale led them to wrong conclusions on the SSI changes they reported. We have shown that the high variability of TEC before the Hector Mine earthquake, claimed by *Pulinets and Davidenko* [2014] in support of the reliability of the SSI index as indicator of precursory effects of earthquakes, can be an effect of the increase of the global geomagnetic level. We do not agree that the three additional selected preearthquake SSI changes reported by *Pulinets and Davidenko* [2014] had seismogenic origins. We have shown that particularly during the period before the Sumatra Andaman earthquake there is a close inverse correspondence between SSI and the *Kp* index. However, this is in contrast to the Hector Mine earthquake before which this correspondence is positive.

We find that the SSI index introduced by *Pulinets et al.* [2007] is not a special index that may be useful to detect specific ionospheric TEC variability induced by seismicity. In the two examples reported in Figures 1 and 2, indeed, we have shown that the preearthquake SSI increases claimed to be earthquake precursors by *Pulinets and Davidenko* [2014] are effects induced by global geomagnetic activity rather than seismogenic. At the same time, however, even if in Figures 1 and 2 we see that SSI agrees with *Kp* for several weeks, it cannot be considered a reliable indicator of the geomagnetic conditions. This is because SSI sometimes shows positive correspondence with the geomagnetic activity, whereas other times this correspondence is inverse or the correspondence is not so obvious. However, if before earthquakes, when significant changes of the SSI index are reported, we find a correspondence (positive or inverse) between SSI and the geomagnetic condition, it is unlikely that these changes have seismogenic origin. We conclude that *Pulinets and Davidenko* [2014] have not provided any new relevant evidence that SSI is one of the most reliable ways to identify precursory signals of earthquakes in the ionosphere.

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References

Afraimovich, E. L., and E. I. Astafyeva (2008), TEC anomalies—Local TEC changes prior to earthquakes or TEC response to solar and geomagnetic activity changes?, *Earth Planets Space*, *60*, 961–966, doi:10.1186/BF03352851.

Afraimovich, E. L., E. I. Astafyeva, M. B. Gokhberg, V. M. Lapshin, V. E. Permyakova, G. M. Steblov, and S. L. Shalimov (2004), Variations of the total electron content in the ionosphere from GPS data recorded during the Hector Mine earthquake of October 16, 1999, California, *Russ. J. Earth Sci.*, *6*, 339–354, doi:10.2205/2004ES000155.

Astafyeva, E., S. Shalimov, E. Olshanskaya, and P. Lognonné (2013), Ionospheric response to earthquakes of different magnitudes: Larger quakes perturb the ionosphere stronger and longer, *Geophys. Res. Lett.*, *40*, 1675–1681, doi:10.1002/grl.50398.

Calais, E., and J. B. Minster (1995), GPS detection of ionospheric perturbations following the January 17, 1994, Northridge earthquake, *Geophys. Res. Lett.*, *22*, 1045–1048, doi:10.1029/96GL01256.

Chen, T., S. O. Akciz, K. W. Hudnut, D. Z. Zhang, and J. M. Stock (2015), Fault-slip distribution of the 1999 M_w 7.1 Hector Mine earthquake, California, estimated from postearthquake airborne lidar data, *Bull. Seismol. Soc. Am.*, *105*(24), 776–790, doi:10.1785/0120130108.

Cohen, M. B., and R. A. Marshall (2012), ELF/VLF recordings during the 11-March-2011 Japanese Tohoku earthquake, *Geophys. Res. Lett.*, *39*, L11804, doi:10.1029/2012GL052123.

Dobrovolsky, I. P., S. I. Zubkov, and V. I. Miachkin (1979), Estimation of the size of earthquake preparation zones, *Pure Appl. Geophys.*, *117*, 1025–1044, doi:10.1007/BF00876083.

Hocke, H., and K. Schlegel (1996), A review of atmospheric gravity waves and travelling ionospheric disturbances: 1982–1995, *Ann. Geophys.*, *14*, 917–940, doi:10.1007/s00585-996-0917-6.

Johnston, M. J. S. (2015), On earthquake fault failure, 26th IUGG General Assembly, Prague, Czech Republic, 22 June–2 July.

Johnston, M. J. S., D. Borcherdt, A. T. Linde, and M. T. Gladwin (2006), Continuous borehole strain and pore pressure in the near field of the 28 September *M* 6.0 Parkfield, California earthquake: Implications for nucleation, fault response, earthquake prediction, and tremor, *Bull. Seismol. Soc. Am.*, *96*, S56–S72, doi:10.1785/0120050822.

Jónsson, S., H. Zebker, P. Segall, and F. Amelung (2002), Fault slip distribution of the 1999 M_w 7.1 Hector Mine, California, earthquake, estimated from satellite radar and GPS measurements, *Bull. Seismol. Soc. Am.*, *92*, 1377–1389, doi:10.1785/0120000922.

Komjathy, A., L. Sparks, B. Wilson, and A. J. Mannucci (2005), Automated daily processing of more than 1000 ground-based GPS receivers to study intense ionospheric storms, *Radio Sci.*, *40*, RS6006, doi:10.1029/2005RS003279.

Komjathy, A., D. A. Galvan, P. Stephens, M. D. Butala, V. Akopian, B. Wilson, O. Verkhoglyadova, A. J. Mannucci, and M. Hickey (2012), Detecting ionospheric TEC perturbations caused by natural hazards using a global network of GPS receivers: The Tohoku case study, *Earth Planets Space*, *64*, 1287–1294, doi:10.5047/eps.2012.08.003.

Le, H., J. Y. Liu, and L. Liu (2011), A statistical analysis of ionospheric anomalies before 736 *M*6.0+ earthquakes during 2002–2010, *J. Geophys. Res.*, *116*, A02303, doi:10.1029/2010JA015781.

Li, M., and M. Parrot (2013), Statistical analysis of an ionospheric parameter as a base for earthquake prediction, *J. Geophys. Res. Space Physics*, *118*, 3731–3739, doi:10.1002/jgra.50313.

Masci, F. (2012), The study of ionospheric anomalies in Japan area during 1998–2010 by Kon et al.: An inaccurate claim of earthquake-related signatures?, *J. Asian Earth Sci.*, *57*, 1–5, doi:10.1016/j.jseaes.2012.06.009.

Masci, F. (2013), Further comments on the ionospheric precursor of the 1999 Hector Mine earthquake, *Nat. Hazards Earth Syst. Sci.*, *13*, 193–196, doi:10.5194/nhess-13-193-2013.

Masci, F., and J. N. Thomas (2014), Comment on "Temporal and spatial precursors in ionospheric total electron content of the 16 October 1999 M_w 7.1 Hector Mine earthquake," by Su et al. (2013), *J. Geophys. Res. Space Physics*, *119*, 6994–6997, doi:10.1002/2014JA019896.

Masci, F., J. N. Thomas, F. Villani, J. A. Secan, and N. Rivera (2014), On the onset of ionospheric precursors 40 minutes before strong earthquakes, *J. Geophys. Res. Space Physics.*, *120*, 1383–1393, doi:10.1002/2014JA020822.

Mayaud, P. N. (1980), *Derivation, Meaning, and Use of Geomagnetic Indices*, *Geophys. Monogr.*, vol. 22, AGU, Washington D. C.

Menvielle, M., and A. Bethelier (1991), The *K*-derived planetary indices: Description and availability, *Rev. Geophys.*, *29*(3), 415–432, doi:10.1029/91RG00994.

Pulinets, S. A. (2007), Natural radioactivity, earthquakes, and the ionosphere, *Eos Trans. AGU*, *88*, 217–224, doi:10.1029/2007EO200001.

Pulinets, S. A. (2009), Physical mechanism of the vertical electric field generation over active tectonic faults, *Adv. Space Res.*, *44*, 767–773, doi:10.1016/j.asr.2009.04.038.

Pulinets, S. A., and D. Davidenko (2014), Ionospheric precursors of earthquakes and Global Electric Circuit, *Adv. Space Res.*, *53*, 709–723, doi:10.1016/j.asr.2013.12.035.

Pulinets, S. A., N. Kotsarenko, L. Ciraolo, and I. A. Pulinets (2007), Special case of ionospheric day-to-day variability associated with earthquake preparation, *Adv. Space Res.*, *39*, 970–977, doi:10.1016/j.asr.2006.04.032.

Rishbeth, H. (2006a), Ionoquakes: Earthquake precursors in the ionosphere?, *Eos Trans. AGU*, *87*(32), 316, doi:10.1029/2006EO320008.

Rishbeth, H. (2006b), *F*-region links with the lower atmosphere?, *J. Atmos. Sol. Terr. Phys.*, *68*, 469–478, doi:10.1016/j.jastp.2005.03.017.

Su, Y. C., J. Y. Liu, S. P. Chen, H. F. Tsai, and M. Q. Chen (2013), Temporal and spatial precursors in ionospheric total electron content of the 16 October 1999 M_w 7.1 Hector Mine earthquake, *J. Geophys. Res. Space Physics*, *118*, 6511–6517, doi:10.1002/jgra.50586.
Thomas, J. N., J. J. Love, A. Komjathy, O. P. Verkhoglyadova, M. Butala, and N. Rivera (2012), On the reported ionospheric precursor of the 1999 Hector Mine, California earthquake, *Geophys. Res. Lett.*, *39*, L06302, doi:10.1029/2012GL051022.
Treiman, J., K. J. Kendrick, W. A. Bryant, T. K. Rockwell, and S. F. McGill (2002), Primary surface rupture associated with the M_w 7.1 16 October 1999 Hector Mine earthquake, San Bernardino County, California, *Bull. Seismol. Soc. Am.*, *92*(4), 1171–1191, doi:10.1785/0120000923.