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ARTICLE

Atmospheric Meteorological Parameters and Ionospheric F2 Layer Critical Frequency (foF2) Observation for 6th December, 2016 Indonesia Earthquake (M 6.5): A Case Study

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ABSTRACT

On 6th December, 2016, an earthquake with M 6.5 occurred at the tectonic plate boundary, southwest of Sumatra, Indonesia (Latitude: 0.5897°S, Longitude: 101.3431°E). In this case, ionospheric critical frequency of F2 layer (foF2) variations and meteorological parameters, viz., air temperature, relative humidity, atmospheric pressure and wind speed variations were investigated so as to detect any anomalies. Data are obtained from different websites freely available for researchers. In the absence of real ionosonde foF2 data, IRI 2016 model data were used. For each parameter, anomaly window were defined when values fell beyond ± 6 °C, < 70 %, ± 4 mb and ± 3.5 km h^{-1} from the event day value and one third of total foF2 values broke the limits of the upper and lower bounds. Certain random anomalies in temperature, relative humidity, pressure, wind speed and foF2 frequencies were observed different days prior to occurrence of the quake but each parameter showed anomalies 12 days before the occurrence. Also, geomagnetic tranquility was justified through Kp and Dst indices. This study reveals that continuous monitoring of atmospheric meteorological parameters and regular ionospheric foF2 observations might help us to predict an earthquake about a week prior to the occurrence.

1. Introduction

On the environmental hazards one has no control but one can take some precautions for such events (like Earthquakes, Typhoons, cyclones etc.) if the occurrences of the events could be predicted few days earlier. On the basis of the research during last two decades, it is established to some extent that electromagnetic waves (in the ULF-ELF-VLF bands), that propagate within earth-ionosphere waveguide, prior to the occurrence of any earthquakes, show deviations from their normal diurnal behavior[1-6]. But fruitful indication of earthquake prediction has still been challenging to scientists. The analyses of catastrophic earthquakes (M > 5) have shown the importance of the development and

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perfection of forecast methods in the recent past. The earthquake precursor research has shown that the impact of earthquakes simultaneously affect both the surface of the Earth and the upper atmosphere.

Attempts to predict earthquakes set up long ago, using different methods and analyzing data from various stations all over the globe. Researchers detected precursors in different geophysical parameters in the event of earthquakes. Techniques of monitoring and forecasting the earthquakes deal mainly with physical effects on the Earth's surface, viz., thermal anomalies, magnetic disturbances, radio signal anomalies, ionospheric and sub-ionospheric signal propagation disorders, electron density fluctuations[1-9]. Over the past few decades, great efforts have been presented all over the world, of impending earthquake precursory signals in search of potential - both geophysical and geochemical methods in a variety of different nature have been adopted in non-seismic monitoring parameters.

In the recent past, perturbation of critical frequency of layer F2 (foF2) has been used as a precursor to earthquakes by many researchers. It is also observed that the enhancement as well as bite out of foF2 anomalies was fairly well detected prior to Ahmedabad earthquake. For Chi-Chi and Rei-Li earthquakes, foF2 analyses showed significant decrease in foF2 for 2-3 days prior to these events. Ionospheric precursors were detected at Multan and Karachi 1−15 days before the occurrence of Dalbandin earthquake [10-13]. However, for less strong earthquakes (M < 5), the decrease of foF2 towards the day of event may not be found[14]. Thus, ionospheric parameters as a precursor to earthquakes is a complicated issue and for this further observations to search for ionospheric perturbations related to pre-earthquake seismic activity are urgently needed.

This paper deals with the satellite data to investigate the nature of variations of different atmospheric parameters, viz., air temperature, humidity, pressure and wind speed and variations of foF2 frequency along with kp and Dst indices during 6th December, 2016 Indonesia earthquake preparation and exploration. Significant variations are observed; those are presented below and discussed.

2. Event, Data and Methodology of Analyses

An earthquake occurred at the tectonic plate boundary, southwest of Sumatra, Indonesia (Latitude: 0.5897°S, Longitude: 101.3431°E) on 6th December, 2016 with M 6.5. The tectonic collision zone extends 8000 km from Papua in the east to the Himalayan front in west. This convergence is responsible for the intense seismicity and volcanism in Sumatra. The Sumatra Fault, a major transform structure that two division of Sumatra accommodates the northwest-increasing lateral component of relative plate motion. The diffuse deformation zone of the Indian Ocean belongs to these events are Chagos-Laccadive Ridge and the Sumatra Trench both rotation between the Indian and the Australian plates[15-17]. The depth of the main shock is about 18-27 km. Fault rupture and volcanoes, i.e, fault-volcano interaction is suspected for acting to trigger each other. Now-a-days, scientific community believes that the association is based on changes in the state of stress around the volcano due to the energy released by rupture to the fault, and vice-versa. The relation between earthquakes and volcanic eruption are understood but reasons of dormancy of volcanoes are still a question for scientists. Mount Sinabung has several volcanoes along in Sumatra Trench which is the subduction zone of the Indian Ocean. It is also part of the Ring of Fire. Map of location of volcanoes in relation to Sumatra Trench is shown in Figure 1. Green Star represents the earthquake occurrence place while thick red lines with black coloured triangles represent great Sumatran fault system along with volcanoes. Movement of Sumatra trench towards northeast direction is shown by black arrow-headed thick lines. Large subduction type earthquakes can reactivate volcanic arcs because they change the types and amounts of tectonic stress underground which are released after a subduction, this can lead to strike and slip motions and other types of tectonic stress. This could create mega-thrust earthquake.

Figure 1. Location of volcanoes in relation to Sumatra Trench along with earthquake occurrence zone. ★ represents place of occurrence of earthquake; ▲, the volcanoes; ▬, the Great Sumatran Fault System and ▲ represents the tectonic movement

In Figure 2, the Kp index for 20th November, 2016 to 20th December, 2016 is plotted. Quiet magnetic conditions are defined by Kp index values ranging 0 to 4. On 6th December, 2016, it was 3 (marked by down arrow), while average was smaller than this, which indicate that the day was geomagnetically tranquil. The value was obtained as 5 on 24th November, 2016 few days earlier before the occurrence of the earthquake. Figure 3 shows the variation of Dst index during 20th November, 2016 to 20th December, 2016 with the day of seismic event marked by down arrow. Dst index did not cross the value of -50 during the period of observations. So the geomagnetic situation was favourable for investigating the ionospheric behavior before this Indonesia earthquake.

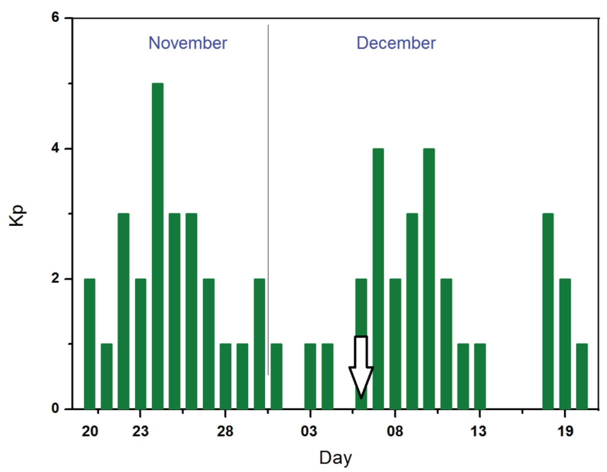

Figure 2. Variation of Kp index during November and December, 2016 (31 day observation prior to and post occurrence of the 6th December, 2016 Indonesia earthquake). Down arrow represents the day of seismic event

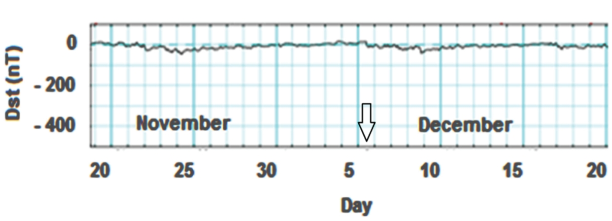

Figure 3. Variation of Dst index during November and December, 2016 (31 day observation prior to and post occurrence of the 6th December, 2016 Indonesia earthquake). Down arrow represents the day of seismic event

The data of air temperature, relative humidity, atmospheric pressure and wind speed monitoring are collected from https://www.underground.com/history/wmo/96009/2016/12/6/DailyHistory. html?req_city=Reuleuet&req_state=AC&req_statename=Indonesia&reqdb.zip=00000&reqdb.magic=1932&reqdb.wmo=96009. Also little relevant information about this earthquake is taken from https://earthquake.usgs.gov/earthquakes/eventpage/us10007ghm#region-info and http:// www.sagaingfault.info/. Kp and Dst indices related data are collected from http:// wdc.kugi.kyoto-u.ac.jp/kp/index.html and foF2 data is excerpted from https:// ccmc.gsfc.nasa.gov/modelweb/ models/iri2016_vitmo.php. Obviously, the real local ionosondes foF2 data could provide more real statistics instead of what is used here from IRI model. This is only because of non availability of data from this end. But, to obtain a meaningful foF2 data from IRI model, the inputs were given as: Year = 2016, Month = 11, Day = 06, Hour = 5., Time_type = Local, Coordinate_type = Geographic, Latitude = -1., Longitude = 113.9213, Height = 100; Start = 1. Stop = 30, Step= 1; For Month = 12, Start = 1, Stop = 31, Step = 1; and selected output parameters were taken as Day and foF2 in MHz. Then all data were analyzed through Origin 8.1 and eventually plotted.

Now, the question arises that whether there is any possibility of changing the atmospheric as well as ionospheric conditions due to the occurrence of seismic event? The earthquake preparation zone has been modeled by the following relationship [18]:

$$\rho = 10^{0.43M} \text{ km} \tag{1}$$

Where, ρ is the radius of the earthquake preparation zone and M is the magnitude [19]. The radius of the earthquake preparation zone is shown in Table 1.

Table 1. The magnitude vs. the related radius of earthquake preparation zone

Magnitude	3	4	5	6	7	8	9
ρ (km)	19.5	52.5	141	380	1022	2754	7413

In this event, radius of the earthquake preparation zone, ρ=$10^{0.43\times6.5}$=624 km gives an area covered by the earthquake about 10^6 km^2. Thus, the effect of this earthquake affects the atmosphere as well as the ionospheric conditions of whole Indonesia and surrounding places.

To identify the abnormal behavior of the plasma frequency of layer F2, foF2 data have been analyzed by using the bound statistical technique [19]. In this technique, the median (2nd Quartile) X for the period of 31 days (20th November, 2016 to 20th December, 2016) foF2 data and associated inter quartile range (IQR) are calculated to construct the upper and lower bound by the following mathematical relationships.

$$\text{Upper Bound} = X + IQR \tag{2}$$

$$\text{Lower Bound} = X - IQR \tag{3}$$

Where X is the median, i.e., 2nd Quartile, defined earlier and IQR = (UQ − LQ), the associated inter quartile range of the selected data set. LQ and UQ are the first and the third quartiles.

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Table 2. Detail of anomalies before and after the occurrence of the earthquake event

Atmospheric Parameters	Anomaly Window	Value on the event day (0 day)	Precursory signatures, before (negative day)	Post-seismic signatures, after (positive day)
Temperature (°C)	± 6 °C	30 °C	15, 13, 12, 11, 6, 2, 1	1, 12, 14
Relative Humidity (%)	< 70 %	97 %	15, 13, 12, 11, 6, 2	1, 12
Atmospheric Pressure (mb)	± 4 mb	1009 mb	11, 6, 2, 1	12, 14
Wind Speed (km h^{-1})	± 3.5 km h^{-1}	7.5 km h^{-1}	16, 15, 13, 11, 6, 2, 1	1, 12, 14
foF2 (MHz)	> 3.71 MHz and < 3.074 MHz	3.371 MHz	12	No

3. Observational Results and Analyses

Air temperature, relative humidity, atmospheric pressure and wind speed data for the 31 day observation prior to and post occurrence of the 6th December, 2016 Indonesia Earthquake between 20th November, 2016 and 20th December, 2016 is shown in Figure 4 through panels (a) to (d) respectively. Down arrow in blue shade, grey and rose shades represent respectively the day of seismic event, background environment and before & after event. In each panel, data have been plotted in three hour interval. Some data are missing in few plots due to non availability.

Now, different ranges are defined for temperature, relative humidity, atmospheric pressure and wind speed expected to be used as the earthquake precursors and post-seismic anomalies accordingly as ± 6 °C, < 70 %, ± 4 mb and ± 3.5 km h^{-1} respectively. Table 2 shows the detail of anomalies before and after the occurrence of the seismic event. The event day, i.e, 6th December, 2016 is defined as (0 day) and before and after the event days are negative and positive respectively.

In current study, ionospheric variations have also been examined. For this event, foF2 values observed from local geographic position have been examined for the period of November and December 2016. Figure 5 shows the anomalies with respect to Upper Bound (UB) and Lower Bound (LB) limits. Figure also demonstrates anomalies w.r.t. 1st and 3rd Quartile values. The day is said to be an anomalous one when 1/3 of foF2 values across the UB and LB limits. On 24th November, 2016, a positive foF2 value was obtained beyond UB which might be treated as earthquake precursor. But few positive and negative anomalies are said to occur beyond 3rd and 1st Quartile values. These are obtained 7 days prior to and 6 days post earthquake occurrence. Down arrow shows the earthquake occurrence date (Figure 5).

4. Discussion and Conclusion

Atmospheric temperature starting from few days earlier reached maximum about 30 °C on the day of event, while on the day of occurrence of earthquake, relative humidity

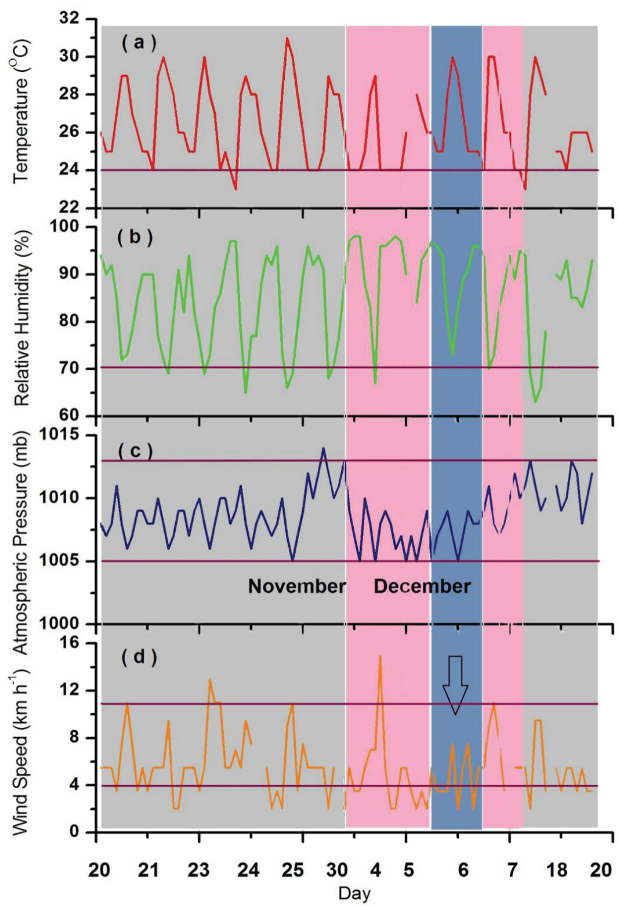

Figure 4. Temperature, Relative Humidity, Atmospheric Pressure and Wind Speed variations for the 31 day observation prior to and post occurrence of the 6th December, 2016 Indonesia Earthquake. Down arrow in blue shade represents the day of seismic event. Background environment and before & after event are represented by grey and rose shades

decreased from 95% to 75% ; pressure increased from 1005 mb to 1009 mb and again decreased and wind speed showed fluctuation within the range of 2 to 7 km h^{-1} (Figure 4). It generally shows the chance of repetition of earthquakes after the main shock near the epicenter, but fortunately no such occurrences are reported within a couple of days.

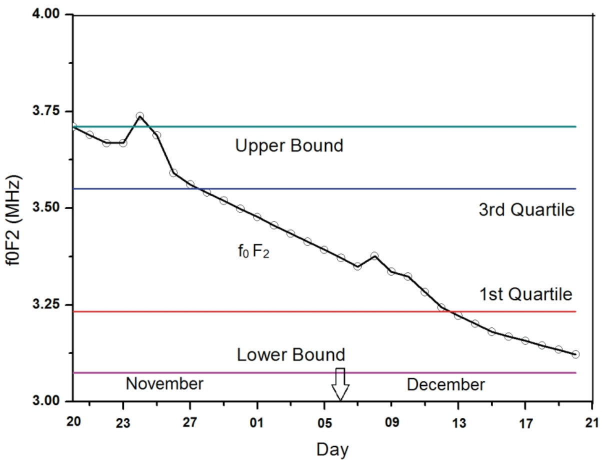

Figure 5. Variation of foF2 at Indonesia (Latitude: 0.5897 °S, Longitude: 101.3431 °E). —— and —— show Upper and Lower Bound respectively and —o— represents the daily foF2 value. 1st and 3rd Quartiles are represented by —— and —— respectively. Down arrow represents the day of seismic event.

Also, ionosphere modification, caused by geomagnetic storm activity, can endorse amplification or weakening of the seismo ionospheric symptom. To ascertain that the daily variations of air temperature, relative humidity, atmospheric pressure and wind speed as narrated in this work and foF2 anomalies are involved exclusively with this earthquake and not evolved by any natural processes along with geomagnetic activities, the quotidian variation of Kp and Dst indices for the stated duration had been checked (Figures 2 and 3) and found that the geomagnetic situation was favorable for investigating the ionosphere behavior before this Indonesia earthquake. All these ensure that the disorderliness portrayed in this paper might be exclusively evolved by this earthquake and not due to any other natural or geomagnetic events.

Now the task is to check whether the observed alterations are within the normal range of magnitudes of stated meteorological parameters or not. In an earlier work, one such technique was described. It has been shown that standard deviations (σ) for temperature, relative humidity and pressure except wind speed are not only well away from mean but also in opposite sense [20]. Thus, it may be concluded that there is anomaly in meteorological parameters during this earthquake. In Table 2, the anomaly ranges for different parameters are defined. During the 31 day observational period, anomalies in temperature, relative humidity, atmospheric pressure and wind speed variations started to show their signatures 15, 15, 11 and 16 days earlier and post-seismic anomalies continued till 14, 12, 14 and 14 days respectively. Though, the alterations of these parameters followed regular diurnal trends.

The physical mechanisms responsible for these observed meteorological anomalies and abnormal behaviour of foF2 during any earthquakes are not well understood. But to make it out some basic hypotheses of lithosphere ionosphere coupling have been proposed by different researchers [6,10,12-14,20]. During the occurrences of earthquakes, vertical electric field of seismogenic origin with amplitude of several to tens of mV m^{-1} is generated within the upper atmosphere due to seismo-ionospheric coupling phenomena.

In case of strong earthquakes, the atmospheric layer close to the Earth's surface becomes ionized and generates electric field which introduces particle acceleration thereby exciting local plasma instabilities. Several days before the occurrence of the earthquake, electron density of plasma in the upper ionosphere over the epicentre also increases abnormally. The ionospheric disturbances are due to action of upward propagation of the electric field which is produced by tectonic movement which enables the electric charges to appear at the surface of the earth and modify the current in the atmosphere-ionosphere system[21]. Anomalous electric fields can penetrate into the lower ionosphere and can then be transmitted along the geomagnetic field to the F2 region of ionosphere and cause the foF2 perturbations.

Thus, there being two processes of lithosphere-ionosphere coupling before earthquakes. During the first process, the upward streaming ionosphere plasma flows occur with the decrease of the recombination process and an increase of foF2. During the second process, the upward streaming plasma flow also occurs, but the overwhelming processes are heating and smearing out of the maximum electron density of the F2-layer due to diffusion[14]. Also, a recent study reveals that Earthquake lights (EQLs) occur before, during and occasionally after any earthquakes[22]. In relation to meteorological as well as foF2 anomalies presented in this event, strong electric currents are assumed to be produced inside the Earth during earthquakes. It results different configurations of current dipoles inside the Earth.

In this work, the effects of 6^{th} December, 2016 Indonesia earthquake event on atmospheric temperature, relative humidity, pressure, wind speed and ionospheric foF2 frequency have been investigated to detect anomalies. The day was treated as an anomalous day when temperature, relative humidity, atmospheric pressure and wind speed values fell beyond ± 6 °C, < 70 %, ± 4 mb and ± 3.5 km h^{-1} respectively from the event day value and one third of total foF2 values broke the limits of the upper and lower bounds. It is concluded that there are certain anomalies in all the

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parameters and few specific signatures are detected as precursors 12 days before the occurrence of the Indonesia earthquake. Still, there are ample scopes to enhance the level of confidence and quality of analysis in this field to predict the occurrence of any earthquake.

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