Associating an ionospheric parameter with major earthquake occurrence throughout the world

D GHOSH¹ and S K MIDYA^{1,2,*}

¹*Department of Atmospheric Science, University of Calcutta, Kolkata 700 009, India.*

²*Indian Centre for Space Physics, 43 Chalantika, Garia Station Road, Kolkata 700 084, India.*

**Corresponding author. e-mail: drskm06@yahoo.co.in*

With time, ionospheric variation analysis is gaining over lithospheric monitoring in serving precursors for earthquake forecast. The current paper highlights the association of major ($M_s \geq 6.0$) and medium ($4.0 \leq M_s < 6.0$) earthquake occurrences throughout the world in different ranges of the Ionospheric Earthquake Parameter (IEP) where ‘ M_s ’ is earthquake magnitude on the Richter scale. From statistical and graphical analyses, it is concluded that the probability of earthquake occurrence is maximum when the defined parameter lies within the range of 0–75 (lower range). In the higher ranges, earthquake occurrence probability gradually decreases. A probable explanation is also suggested.

1. Introduction

Lithospheric disturbances or crust vibrations affecting ionosphere are an established fact at present. This coupling is more prominent during seismo-tectonics of higher magnitude. An earthquake being one of the most devastating natural calamities, is still unpredictable and thus to predict or forecast earthquakes based on ionospheric precursors has become a highlighted section of research.

Chakrabarti *et al.* (2005) presented the observations of ionospheric variability by continuous monitoring of VLF signals during the Sumatra–Andaman earthquake in 2004 and reported that the delay in sunset time occurred 24 hrs prior to the occurrence of earthquake. Study of surface latent heat flux (SLHF) and night-time subionospheric low frequency (LF) radio soundings showed anomalous fluctuations before earthquake. Both SLHF and night-time LF showed complementary nature with SLHF variations being prominent near the epicentral region of coastal

earthquake (Cervone *et al.* 2006). Pulinets and Dunajevka (2007) reported using LAIC (Lithosphere–Atmosphere–Ionosphere Coupling model) and experimental data of using remote sensing satellites that thermal anomalies due to radon emission in the area of earthquake preparative zone can produce variations of air temperature and relative humidity.

Ganguly (2009) reported that column ozone concentration over a location reaches its lowest value on the day of the major earthquake, increases gradually after the calamity and attains its peak value. Afterwards ozone concentration was found to be normal. *Quasi-static* electric field anomaly in the upper ionosphere before an earthquake had been observed as an ionospheric precursor (Gousheva *et al.* 2009). According to LAIC model (Lithosphere–Atmosphere–Ionosphere Coupling model), geochemical, atmospheric and ionospheric parameters are united by a common physical mechanism (Pulinets 2009a, b). Using IAP (ionospheric plasma analyzer) and ISL (Langmuir probe) on DEMETER satellite and GPS

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data analysis, Akhoondzadeh *et al.* (2010) showed that electron and ion density variations in the ionosphere occurred over locations prior to strong earthquakes. Jain *et al.* (2010) reported the anomalies in slab thickness of ionospheric F-region for some days before the main seismic event. They concluded that it may be due to the seismogenic electric field developed above the surface of the earth. Recent investigation has shown that major earthquake ($M_s \geq 6.0$ Richter scale) occurrence within 48 hrs is expected when geomagnetic index K_p attains its minimum value (Midya *et al.* 2011).

Till date, scientists are continuously trying to discover more and more reliable earthquake precursors so that earthquake prediction may be possible in the near future. The purpose of this paper is to introduce a new parameter – Ionosphere

Earthquake Parameter (IEP) and its close association with the occurrence of major and medium earthquakes throughout the globe.

2. Data and methodology

Our data catalogue has been made from websites <http://earthquake.usgs.gov/> (for earthquake data) and <http://www.ngdc.noaa.gov/> (for SID data) for the period 2000–2006. IEP has been defined on the basis of Kleczek index of sun – the parameter which represents daily solar activity. Kleczek index-Q (Kleckzek 1952; Atac 1987), describing the flare activity over 24 hr period is defined by,

$$Q = i \times t$$

Figure 1. Yearly occurrence of major earthquakes throughout the world plotted in different ranges of IEP of previous day for the period 2000–2006. (a) 2000, (b) 2001, (c) 2002, (d) 2003, (e) 2004, (f) 2005 and (g) 2006.

where i represents the intensity scale of importance of a flare and t is the duration of the flare in minutes. In relation to the above defined index, the IEP is defined by

$$\text{IEP} = i_a \times t_d$$

where i_a is the actual importance of the sudden ionospheric disturbance (SID) and ' t_d ' is the duration of the disturbance in minutes. On days with multiple SIDs, average value of the IEP throughout the day has been considered. The ionospheric disturbances are measured by ground observatories over different locations throughout the globe (locations are mentioned on the datasheet of SID obtained from NOAA website).

SID is an abnormal variation in ion/plasma density in the lower ionospheric region (generally D-region). Upper ionospheric effect, magnetospheric coupling and lower atmosphere (troposphere) primarily affect these ionospheric disturbances. Flare effect includes the blast of intense ultraviolet and X-ray radiation during the solar flare hitting the dayside of the earth, ionizing atmospheric particles, leading to plasma variation and ionospheric disturbance. Earth's magnetic field or the magnetosphere covers a vast area in space thereby preventing earth from the harmful effects of the solar flare. Due to its large cross-section, magnetospheric effect in the ion density variation is also very low. The SID's generally result in sudden increase in radio-wave absorption – most severe in the upper medium frequency (MF) and lower high frequency (HF) ranges and as a result it often interrupts telecommunication systems leading to signal fadeout or communication gap.

3. Results and discussion

3.1 Results

The occurrence probability of major earthquakes throughout the globe within the defined IEP ranges is depicted in figure 1, where IEP of the previous day of earthquake occurrence is considered. The IEP values obtained are divided into number of slabs with '75' being the slab-width starting from zero. The number of major earthquakes ($M_s \geq 6.0$) occurrence throughout the globe is plotted along the ordinate while IEP range along the abscissa. The figure clearly points out the maximum occurrence probability of earthquakes in the lower IEP range, with probability decreasing with the increase in IEP value. Similar probability trend is also observed for medium earthquakes ($4.0 \leq M_s < 6.0$), shown in figure 2, with two-year (2000–2001) variations being presented.

Figure 2. Frequency distribution of medium earthquakes for different ranges of IEP.

The lithospheric crust/cement is a combination of various plates floating over the molten magma. Thus it is under continuous motion throughout the year. So, minor earthquakes ($M_s \leq 4.0$) which are occurring large in number (nearly 33,00,000/year) are not a section to be worried about (Midya *et al.* 2011). As minor earthquakes occur frequently, it is quite expected that in all the ranges of IEP value, the number of minor earthquakes will be higher. So, data from medium earthquakes ($4.0 \leq M_s < 6.0$) is considered as these earthquakes can also cause massive destruction depending upon the topography of the location where the shock is experienced.

Figure 3 presents the daily variation of IEP with earthquake occurrence shown by arrows. The figure at a glance reflects that the trend of occurrence of major earthquake in the lower region of IEP value is greater compared to other regions. The observation is validated using Chi-square (χ^2) test analysis technique with the analysis details given in table 1. Yearly expected occurrence, actual occurrence and no occurrence of major and medium earthquakes are shown in table 2 with their trend of variation shown in figure 4. From this figure it is clear that occurrences of major and medium earthquakes nearly follow our expected trend.

3.2 Discussion

Discovery of the ionosphere in the early 19th century led to completion of the Global Electric Circuit (GEC) model; though it does not serve as a perfect conductor parallel to the Earth, but the huge potential difference (150–600 kV) along with finite electric currents and field which is being maintained between the two spheres bears contributions not only from solar and cosmic radiations but also from electrical processes occurring at the lower atmosphere (Roble and Tzur 1986). But the number density of the charged particles

Figure 3. Daily variation of IEP for the year 2002. Upward and downward arrows indicate the occurrence of major earthquakes.

in the ionosphere (total electron content, ion disturbance, etc.) is observed to undergo anomalous behaviour before a major earthquake occurrence. These disturbances are experienced due to the negative field vector intrusion into the ionosphere from the preparative zone of the earthquake, controlled fruitfully through the GEC model by a horizontal ion drift process with a positive downfield through a thunderstorm activity, discharging over regions of fair weather (Pulinets and Boyarchuk 2004; Pulinets 2009a, b). The generation of the negative vertical electric field is mainly attributed to the increased emanation of excited radon molecules from the ground.

3.2.1 Pathway for radon emission

Radioactive decay of nuclear materials (U^{238} , Th^{232} , etc.) underneath the soil surface leads to formation of radons (illustrated below), which get entrapped within the various layers of the soil. A fraction of the formed radon is with held by the solid matrix while the left over fraction migrates through the pores and faults underneath. High density (9.73 kg/m^3) and lower mobility ($\leq 10^{-3} \text{ cm/s}$) restricts radon flow through the porous soil layers by diffusion and advection. Thus the carrier gas mixture also termed as ‘geogas’ (CH_4 , CO_2 , N_2 , etc.) (Etiope and Martinelli 2002) guides radons to the surface. Since the fault zone provides greater pathways, gas migration is facilitated through these channel faults instead of the pore channels.

Before a seismic activity, the increase in stress and strain of the underneath surface strata and rock layers leads to the development of new faults and fissures along with the existing one. The increase in stress within the different tectonic

plates guides the fluid underneath to rise to the surface (Khilyuk *et al.* 2000; Ghosh *et al.* 2009). The solubility property of radon in water (King 1980; Khilyuk *et al.* 2000) allows it to migrate to different and distant locations of the earth about to experience quake shocks following the bubble flow theory which is recognized as the most rapid gas migration mechanism (Vårhegyi *et al.* 1992). Radons emanate continuously from the surface throughout the year, with concentration anomaly observed near and around the epicentral zone a few days before the main shock.

3.2.2 General mechanism for ion cluster formation

The emitted radon molecules from the earth’s surface strata are highly excited, energized particles. They collide with the atmospheric constituents [viz., aerosols and other gaseous components (CO_2 , SO_x , NO_x , etc.)] of the planetary boundary layer making them activated and charged. By this collisional process the mobility of the activated and energized aerosol particles increases. But the mobility of those particles is checked as these highly charged particles including radons become centres of water condensation. Thus, the mobility of the particles getting hydrated decreases {ionic mobility is given by $\mu = q/m_i\nu_i$, where μ is the ionic mobility, q is the ion charge, m_i is the ion mass and ν_i is the ion-collision frequency}. Nearly 100 to 200 water molecules get attached to a single ion but sometimes over 1000

Table 1. Statistical calculation of expected and unexpected occurrence of major earthquakes (monthwise) and occurrence percentage.

Year	Month	Expected occurrence (no. of days)	Actual occurrence (no. of days)	χ^2 for expected major earthquake (monthwise)	Unexpected occurrence (no. of days)	Actual occurrence (no. of days)	χ^2 for unexpected major earthquake (monthwise)
2000	Jan	17	4	1.46	14	0	1.82
	Feb	14	0	1.82	15	0	1.95
	Mar	17	0	2.21	14	0	1.82
	Apr	17	0	2.21	13	0	1.69
	May	14	2	0.02	17	0	2.21
	June	14	8	21.04	16	1	0.56
	July	19	3	0.12	12	1	0.20
	Aug	17	2	0.02	14	0	1.82
	Sept	19	0	2.47	11	0	1.43
	Oct	15	2	0.00	16	2	0.00
	Nov	18	1	0.76	12	1	0.20
	Dec	21	2	0.19	10	2	0.38
2001	Jan	14	1	0.37	17	1	0.66
	Feb	21	5	1.90	7	0	0.91
	Mar	22	3	0.01	9	1	0.02
	Apr	10	0	1.30	20	2	0.14
	May	16	1	0.56	15	2	0.00
	June	14	1	0.37	16	3	0.41
	July	11	0	1.43	20	0	2.60
	Aug	19	1	0.87	12	2	0.13
	Sept	13	0	1.69	17	1	0.66
	Oct	16	2	0.00	15	1	0.46
	Nov	11	0	1.43	19	0	2.45
	Dec	14	2	0.02	17	1	0.66
2002	Jan	19	1	0.87	12	1	0.20
	Feb	20	0	2.60	8	0	1.04
	Mar	15	3	0.57	16	0	2.08
	Apr	16	1	0.56	14	1	0.37
	May	17	2	0.02	14	1	0.37
	June	15	2	0.00	15	1	0.46
	July	13	0	1.69	18	1	0.76
	Aug	23	2	0.33	8	0	1.04
	Sept	19	1	0.87	11	1	0.13
	Oct	17	5	3.54	14	0	1.82
	Nov	23	2	0.33	7	3	4.81
	Dec	20	1	0.98	11	0	1.43
2003	Jan	19	1	0.87	12	0	1.56
	Feb	17	1	0.66	11	0	1.43
	Mar	19	5	2.60	12	0	1.56
	Apr	22	2	0.26	8	0	1.04
	May	10	1	0.07	21	4	0.60
	June	13	4	3.17	17	3	0.29
	July	14	2	0.02	17	1	0.66
	Aug	17	0	2.21	14	0	1.82
	Sept	18	4	1.18	12	0	1.56
	Oct	16	3	0.41	15	0	1.95
	Nov	19	1	0.87	11	1	0.13
	Dec	16	0	2.08	15	2	0.00

Table 1. (Continued.)

Year	Month	Expected occurrence (no. of days)	Actual occurrence (no. of days)	χ^2 for expected major earthquake (monthwise)	Unexpected occurrence (no. of days)	Actual occurrence (no. of days)	χ^2 for unexpected major earthquake (monthwise)
2004	Jan	17	0	2.21	14	0	1.82
	Feb	15	1	0.46	14	1	0.37
	Mar	20	0	2.60	11	0	1.43
	Apr	18	4	1.18	12	0	1.56
	May	23	3	0.00	8	1	0.00
	June	19	3	0.12	11	1	0.13
	July	13	1	0.28	18	3	0.19
	Aug	13	0	1.69	18	0	2.34
	Sept	7	2	1.31	23	3	0.00
	Oct	16	3	0.41	15	0	1.95
	Nov	19	4	0.95	11	1	0.13
	Dec	15	1	0.46	16	1	0.56
2005	Jan	16	3	0.41	15	4	2.16
	Feb	16	5	4.11	12	0	1.56
	Mar	14	5	5.57	17	0	2.21
	Apr	14	5	5.57	16	3	0.41
	May	18	3	0.19	13	1	0.28
	June	12	2	0.13	18	3	0.19
	July	10	1	0.07	21	0	2.73
	Aug	13	1	0.28	18	0	2.34
	Sept	12	1	0.20	18	0	2.34
	Oct	5	0	0.65	26	1	1.67
	Nov	6	1	0.06	24	3	0.00
	Dec	7	3	4.81	24	0	3.12
2006	Jan	10	3	2.23	21	1	1.09
	Feb	8	0	1.04	20	0	2.60
	Mar	12	2	0.13	19	0	2.47
	Apr	15	5	4.79	15	1	0.46
	May	5	0	0.65	26	1	1.67
	June	8	1	0.00	22	0	2.86
	July	5	1	0.19	26	0	3.37
	Aug	13	3	1.02	18	0	2.34
	Sept	1	1	5.83	29	0	3.76
	Oct	9	5	12.57	22	0	2.86
	Nov	13	3	1.02	17	0	2.21
	Dec	11	2	0.23	20	3	0.06
Total sum		1248	162	132.40	1309	73	105.44

Expected occurrence percentage = 12.98% while unexpected occurrence percentage = 5.58%. From the above table, chi-square for expected = 132.40, while for unexpected = 105.44.

H₂O molecules can bind to a single ion depending upon the charge density of the ion and water availability in the surrounding atmosphere. With the increase in ion hydration, the ion size and mass increase significantly resulting in the decrease in columnar conductivity of the non-conductive air {the drop in ion mobility is immediately reflected in the electrical conductivity σ ; given by $\sigma = n|q|\mu$, where n is the collision frequency, q is ion charge and μ is ionic mobility} where the above

charge clusters are formed about 4–5 m above the ground thereby developing an electric field near the surface (Pulinets 2004, 2009a, b).

3.2.3 Vertical electric field intrusion

In normal atmosphere, with minimum ion clusters at the surface, the columnar conductivity increases with altitude exponentially (Roble and Tzur 1986).

Table 2. Data for expected, actual and no occurrence of major and medium earthquake for the period 2000–2006*.

Year	Total expected occurrence	Actual occurrence of major earthquake	Actual occurrence of medium earthquake	Total occurrence of major and medium earthquake	No occurrence of major and medium earthquake
2000	202	24	144	168	32
2001	181	16	140	156	25
2002	217	20	150	170	47
2003	200	24	132	156	44
2004	195	22	130	152	43
2005	143	30	78	108	35
2006	110	26	68	94	16

*Figures corresponding to each year in the table above represent number of days.

Figure 4. Occurrence trends of expected, actual and no major and medium earthquakes for the period 2000–2006.

But with the decrease in atmospheric columnar conductivity by the formation of ion clusters near the surface, the vertical electric field of the column therefore increases before major earthquakes (since conductivity and electric field are inversely proportional) over the preparative zone.

Ionospheric disturbances are related to ion or electron concentration variations in the lower ionosphere, measured as frequency signals emitted from the disturbance. The preparative zone experiences a decrease in total electron count (TEC) before strong earthquakes (Liu *et al.* 2001; Namgaladze *et al.* 2009). The two way interaction of lower electron content with upward electric field results in the net lowering of IEP value prior to strong earthquakes. Cases registered with increase in TEC

Figure 5. Variation of IEP with K_p geomagnetic index for 2000–2003.

value (Pulinets and Tsybulya 2010; Klimenko *et al.* 2011) actually led to results with higher IEP value before major earthquakes. Geological structures and topographical conditions play a vital role in varying radon concentrations. Sometimes the concentration of radons may not be sufficient to create the significant large-scale variations within the ionosphere. Instead, ‘scintillations’ of the columnar resistance and a corresponding regional variability will be observed in the ionosphere.

In figure 5, contribution of earth’s geomagnetic index ‘ K_p ’ to IEP is studied. Low correlation co-efficient value ($R^2 = 8 \times 10^{-4}$) and slope (-0.1478) of the linear fit curve clearly depicts that these two parameters (IEP and K_p) are independent of each other. Thus, magnetospheric contribution in ionospheric disturbance is quite negligible. Similar independent relationship is obtained in figures 6 and 7 where solar effects on IEP are studied with sunspot numbers and X-ray flux. With the same statistical calculation, very low R^2 value [2×10^{-3} (with sunspot) and 2.17×10^{-2} (with X-ray flux)] in both the cases is observed

Figure 6. Variation of IEP with sunspot number for 2000–2003.

Figure 7. Variation of IEP with X-ray flux for 2000–2003.

reflecting low flare contribution over IEP. Variation of IEP is thus considered separately for associating major earthquake occurrence. Our presented analysis shows that the probability of major earthquake is greater when IEP value lies between zero and 75.

4. Conclusion

It is concluded that the probability of major earthquake occurrences throughout the world is maximum when the defined parameter lies within the range of 0–75 (lower range). In the higher ranges, earthquake occurrence probability decreases. It is shown that geomagnetic disturbance index (K_p), sunspot numbers and X-ray flux variations have no inter-relationships with IEP. Earthquake occurrence in the lower value of IEP may be due to the interaction of total electron content decrease over the preparative zone in the ionosphere and vertical field intrusion from the ground.

This two way interaction results in net lowering of the duration of SID and finally of IEP value.

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