POSSIBLE SOLAR INFLUENCE ON ATMOSPHERIC ELECTRIC FIELD

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ABSTRACT

A physical hypothesis for the electrical coupling of the troposphere, ionosphere and magnetosphere has been proposed. It is shown that the vertical mass exchange takes place in the troposphere, ionosphere and magnetosphere by the gravity wave feedback mechanism through a chain of eddy systems. The vertical mass exchange gives rise to a vertical aerosol current which is responsible for the generation and maintenance of atmospheric electric field and also the variations in the H-component of the geomagnetic field. Any perturbation in the troposphere would be transmitted to ionosphere and vice versa. A global perturbation in ionosphere, as the one caused by solar variability, is transmitted to troposphere influencing weather systems/geomagnetic/atmospheric electrification processes.

The theory relating to the above physical mechanism is discussed. Also, results of analysis of atmospheric electrical field data for Colaba, Bombay (8°53' 56" N, 72° 48' 54" E, 9.8 m ASL) and solar activity indices (A_p index, D_{ST} index and MSB crossing dates) for the 31 year period from 1936–1966 which provide statistical evidence for solar influence on atmospheric electrification processes are presented.

I. INTRODUCTION

Recent experimental investigations relating to the electrical coupling between the troposphere, ionosphere and magnetosphere suggest the possible solar modulation of atmospheric electrification. Analysis of the 1200 hrs of stratospheric balloon data has indicated correlation between the vertical electric field and the magnetic activity parameters (D'Angelo et al., 1982). Markson (1978) observed correlation between the earth-ionospheric potential variations deduced from airplane soundings and the solar wind parameters. Evidence suggests that higher solar wind speeds yield higher potential differences. Holzworth and Mozer (1979) from the study of the stratospheric balloon data obtained during the August 1972 solar flare have concluded that the solar proton shower occurred during the event 'compressed' the ionosphere down to a level below 30 km. The solar proton fluxes have been found to be correlated with a decrease in the local vertical field component near 30 km. The above observations provide the evidence for the downward coupling of high altitude processes into the middle atmosphere and the troposphere. Similarly upward coupling of the tropospheric processes into the middle atmosphere has been noticed from the following observations. Balloon data in the stratospheric region display classic fair weather vertical electric field magnitudes modulated by the solar wind effects (Kelly, 1983). During thunderstorms large enhanced fields are seen in the horizontal components as well as large and reversed vertical fields (Holzworth, 1981). Direct coupling of discharge electric field into the ionosphere has been recently detected in a multiple platform (three rockets, a stratospheric balloon, an airplane and ground-based detectors) during a thunderstorm. Numerous electrical discharges have been recorded simultaneously by all the sensors located in different platforms. Transient fields of tens of mv m^{-1}

have been observed in the mesosphere and the ionosphere. Large transient fields have been seen at stratospheric heights.

In this paper a physical mechanism for the electrical coupling of the troposphere, ionosphere and the magnetosphere has been discussed along with the results of analysis of atmospheric electrical field for Colaba, Bombay (8° 53' 56''N, 72°48' 54'' E, 9.8 m asl) and geomagnetic data (D_{ST} index, A_p index and MSB crossing dates) for the 31 year period from 1936–1966. Based on the above theoretical and observational results possible solar modulation of atmospheric electrification has been investigated.

II. PHYSICAL MECHANISM

A gravity wave feedback mechanism for the troposphere-ionosphere coupling has been proposed (Mary Selvam et al., 1982, 1984a). Vertical mass exchange in the troposphere-ionosphere-magnetosphere takes place through a chain of eddy systems. Any perturbation in the troposphere would be transmitted to the ionosphere and vice versa. A global perturbation in ionosphere, as the one caused by solar variability, is transmitted to troposphere influencing weather systems/geomagnetic/atmospheric electrification processes.

The atmospheric boundary layer (ABL) contains large eddies (vortex rolls) which carry on their envelopes turbulent eddies of surface frictional origin (Fig. 1). It is shown that the buoyant production of energy by microscale-fractional-condensation (MFC) in turbulent eddies is responsible for the sustenance and growth of large eddies (Mary Selvam et al., 1983b). The circulation speed of the large eddy is related to that of the turbulent eddy according to the following expression.

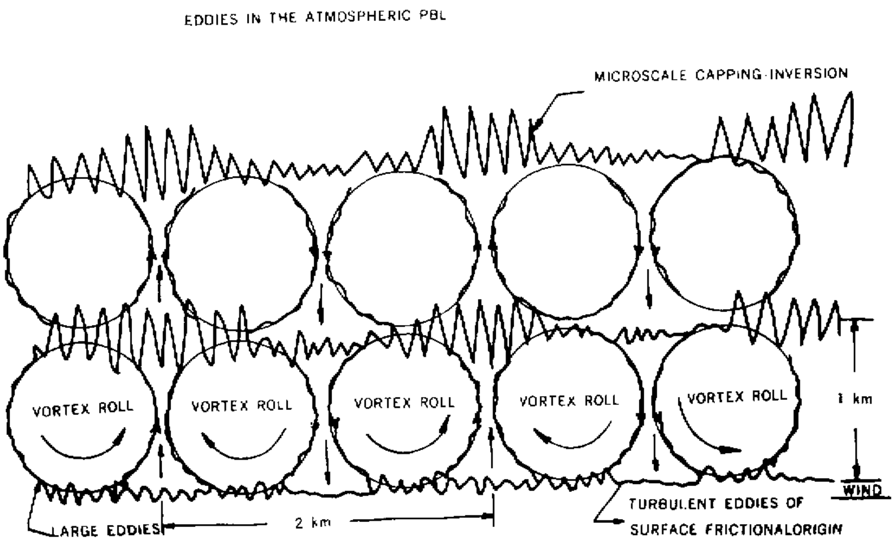


Fig. 1. Eddies in the atmospheric boundary layer.

$$W^2 = \frac{2r}{\pi R} \cdot w^2 \ , \qquad (1)$$

where W and w are respectively the r.m.s. circulation speeds of the large and turbulent eddies and R and r their respective radii. The buoyant production of turbulent energy by the MFC process is maximum at the crest of the large eddies and results in the warming of the large eddy volume. The turbulent eddies at the crest of the large eddies are identifiable by a microscale-capping-inversion (MCI) which rises upwards with the convective growth of the large eddy in the course of the day. This is seen as the rising inversion of the day time ABL in the echosonde records.

As the parcel of air corresponding to the large eddy rises in the stable environment of the MCI, Brunt Vaisala oscillation is generated (Mary Selvam et al., 1983a, 1984b). Thus the large eddy growth is associated with generation of a continuous spectrum of gravity (buoyancy) waves in the atmosphere. The slopes of temperature and wind spectra were theoretically shown to be equal to -1.8 for the eddy scale ratio (z) i.e. $R/r=10$ (Mary Selvam et al., 1984c) and it is in agreement with the observed spectral slopes in the troposphere-stratosphere-ionosphere-magnetosphere (Weinstock, 1980; Dewan. 1979; Keskinen et al., 1980; Tsurutani et al., 1981; Garter and Balsley, 1982; Van Zandt. 1982).

1. *Vertical Mixing*

The dilution by environmental mixing of the large eddy volume by turbulent eddy fluctuations across unit cross-section of the large eddy surface is derived as follows.

The ratio of the upward mass flux of air in the turbulent eddy to that in the large eddy across unit cross-section per second $=w_*/dW$, where

w_* = increase in vertical velocity per second of the turbulent eddy due to the MFC process and

dW = corresponding increase in vertical velocity of large eddy.

This fractional volume dilution of the large eddy occurs in the environment of the turbulent eddy. The fractional volume of the large eddy which is in the environment of the turbulent eddy where dilution occurs $=r/R$. Therefore, the total fractional volume dilution K of the large eddy per second across unit cross section can be expressed as

$$K = \frac{w_*}{dW} \cdot \frac{r}{R} \qquad (2)$$

The value of $K=0.4$ when $R/r=10$ since $dW=0.25w_*$ (Eq. 1).

In Equation (2), dW is the increase in vertical velocity of the large eddy per second as a result of w_*. The height interval in which this incremental change in the vertical velocity occurs is dz which is equal to r (Fig. 2).

Using the above expressions Eq. (2) can be written as follows

$$dW = \frac{w_*}{K} \frac{dz}{z} \qquad (3)$$

Integrating Equation (3) between the height interval r and R the following relation for W can be obtained

$$W = \int_r^R \frac{w_*}{K} \frac{dz}{z} = \frac{w_*}{K} \ln \frac{R}{r} \ . \qquad (4)$$

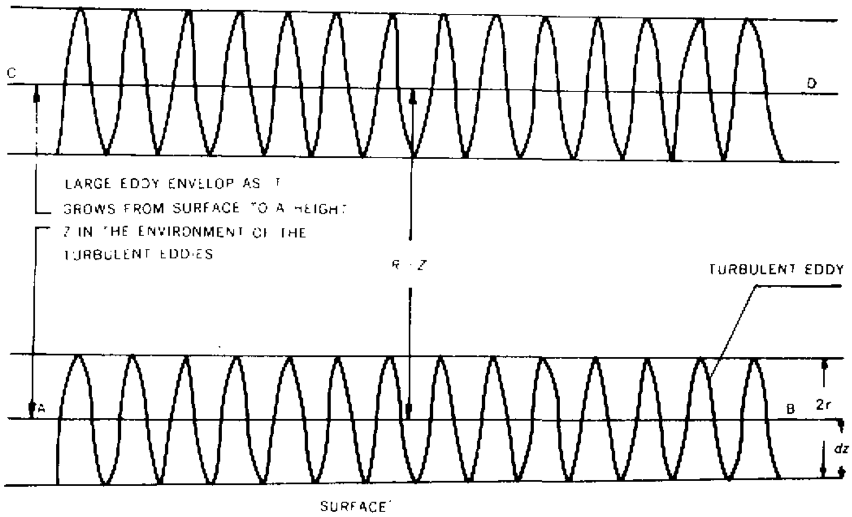


Fig. 2. Growth of large eddy in the environment of the turbulent eddy.

In the above expression for W it is assumed that w_* is constant for the height interval of integration.

A normalised height z with reference to the turbulence scale r can be defined as

$$z=\frac{R}{r}. \tag{5}$$

Using the above expression Equation (4) can be written as follows:

$$W=\frac{wr_*}{K}\cdot \ln z. \tag{6}$$

The value of K is constant for a fixed value of R/r. As defined earlier K represents the fractional volume dilution rate of the large eddy by turbulent eddy fluctuations across unit cross-section on its envelope and is constant for a fixed value of the scale ratio z.

It is well known from observations and from existing theory of eddy diffusion (Holton, 1979) that the vertical wind profile in the atmospheric ABL follows the logarithmic law which is identical to the expression shown in Eq. 6. The constant K for the observed wind profile is called the Von Karman constant. The value of K as determined from observations is equal to 0.4 and has not been assigned any physical meaning in the literature.

The new theory relating to the eddy mixing in the ABL proposed in the present study enable us to predict the observed logarothmic wind profile without involving any assumptions as in the case of existing theories of eddy diffusion processes. Also it is shown that the Von Karman constant is associated with a specific physical process. It is the fractional volume dilution rate of the large eddy by the turbulent scale eddies for the scale ratio of 10.

Identifiable large eddies can grow in the atmospheric ABL only for scale ratios $z \geq 10$ since for smaller scale ratios, the volume dilution rate by turbulent eddy mixing is more than 0.5. The convective scale eddy of radius R_c evolves from the turbulence scale eddy of radius r for scale ratio (z) i.e., $R_c/r=10$. This type of successive decadic scale range eddy mixing generates the convective. meso-, synoptic- and planetary scale eddies starting from the turbulence scale as the basic unit (Mary Selvam et al., 1984c).

Observation evidence for the tropospheric eddy chain linking up with ionosphere is seen in satellite observations which indicate that increased currents at ionospheric levels are accompanied by a simultaneous increase in wind speed at lower levels. Measurements with Poker Flat radar and instruments at Alaska and with NOAA radar at Fairbanks support this contention. From the motions of chemically released ions and neutral clouds it is apparent that neutral winds in the high latitude ionosphere are driven principally by ion drag forces. Observations of infrasonic waves following sudden ionization enhancements indicate the existence of momentum transfer (Heppner, 1975). Carter and Ralsley (1982) have reported correlation between short term fluctuations in the wind field near the mesopause (~83–90 km) and the intensity variations of the auroral electrojet (~110–115 km).

2. *Troposphere-Ionosphere Coupling*

It is postulated that a vertical chain of eddy system exists in the atmosphere with the convective scale as the smallest unit (Fig. 1). Turbulent eddies of surface frictional origin ride on the envelopes of these convective scale eddies and reach up to ionospheric levels.

This stack of convective scale eddies will be associated with microscale-capping-inversion layers at intervals equal to the convective scale size i. e. 2 R_B (2-20 km). The layered structure of the atmospheric PBL with thin sheets/layers of turbulence has been observed by aircraft. echosonde, MST radars throughout the atmospheric PBL extending up to ionospheric levels (Gage, 1979, Carter and Balsley, 1982).

This vertical stack of convective scale eddies results in vertical mass exchange throughout the column extending from the surface to the ionospheric levels. This upward propagation of convective scale eddies derives energy from (i) microscale-fractional-condensation process in the turbulent eddies and (ii) the exponential decrease of atmospheric density with height. In the upper troposphere and up to ionospheric levels the eddy amplification occurs mainly as $\rho^{-1/2}$ where ρ is the atmospheric density (Beer, 1975).

The vertical mass exchange between surface to ionospheric levels by the eddy stack is the coupling mechanism which transmits solar activity controlled variation of the ionosphere to the lower troposphere and thus influences the weather systems and other atmospheric process.

3. *Observational Evidence for the Vertical Eddy Chain*

Weinstock (1981) has shown that the energy dissipation rate of turbulence in the stable free atmosphere can be expressed by the following relation:

$$\varepsilon = 0.4 N_B W_B^2 . \tag{7}$$

W_B^2 is the variance of the vertical velocity and N_B the Brunt-Vaisala frequency. Observations indicate that the above relation for ε holds good for the atmospheric PBL up to the stratosphere. The new theory of atmospheric eddy mixing can be used to derive the relation as follows:

The dominant eddies in the atmospheric PBL are the Brunt-Vaisala eddies since they are generated and sustained by the microscale-fractional-condensation process in the turbulent eddies.

Let W_B = root mean square value of the vertical velocity of the large eddy i. e., for one complete cycle of the large eddy oscillation. Let N_B = Brunt-Vaisala frequency associated with the large eddy.

Thus ε, the dissipation rate per second of the vertical velocity variance associated with the Brunt-Vaisala eddy is given as follows:

ε = dilution per second of the large eddy volume by turbulent mixing $\times$ variance per second of the Brunt-Vaisala eddy.

The variance per second of the large eddy of frequency $N_B = N_B W_f$.

$$\varepsilon = kN_B W_f^2. \tag{8}$$

The value of $k = 0.4$ for size ratio $z = 10$. Thus the predicted relation for ε at Eq .8 is identical to the observed relation for ε at Eq. (7) providing proof for the existence of a vertical eddy chain with convective scale as the basic unit.

III. ATMOSPHERIC ELECTRIC AND GEOMAGNETIC FIELDS

In the following it is shown that the atmospheric electric field and geomagnetic field variations are also manifestations of the vertical mass exchange process between the lower troposphere and ionosphere.

The vertical mass exchange on the sunlit hemisphere gives rise to upward transport of surface air. The nuclei in the surface air layers contain a net positive space charge and thus there is an aerosol current i_{a*} in the upward direction from the surface layers which is expressed as

$$i_{a*} = w_* \sigma^*,$$

σ^* = net positive space charge density in the surface layer.

As the large eddy grows there is upward transport of net positive space charge from surface layers the concentration decreasing with height due to dilution of the large eddy volume by turbulent mixing as explained earlier.

The fractional mass flux f of the surface air in the vertical can be derived as follows:

Across unit cross-section of the large eddy surface at normalized height z the ratio of the upward mass flux of air to the upward mass flux at surface level $= W/w_*$. This excess upward mass flux occurs in the environment of the turbulent eddy and hence the fractional volume of the large eddy associated with this dilution $= r/R = 1/z$. Hence the fractional mass flux f of surface air at normalized height z is given as

$$f = \frac{1}{z} \cdot \frac{W}{w^*}.$$

Earlier (Eq. 6) it was shown that the wind profile of the large eddy is logarithmic with height.

Thus
$$f = \sqrt{\frac{2}{\pi z}} \ln z, \tag{9}$$

f gives the fractional upward mass flux of surface air at any level z across unit area.

Under steady state conditions a fraction f of surface air will be found at normalized height z.

The atmospheric nuclei and thus space charge concentration originate from the surface layers. Thus the net positive space charge concentration σ at any level can be expressed in terms of the surface concentration σ^* as follows:

$$\sigma = \sigma^* f. \tag{10}$$

The atmospheric electric field F at any level is given as

$$F = 4\pi\sigma, \tag{11}$$

where σ is the net positive space charge density at that level. F and σ are expected to decrease with height according to the f distribution (Eq. 9). The vertical profile of f is shown in Fig. 3 and it is similar to the observed F and nuclei profile (Imyanitov and Chubarina, 1967) in the atmosphere (Fig. 4). The value of f has been computed assuming that the dominant turbulent eddy radius (r) is equal to 100 m and 1 m respectively below and above the lifting condensation level (LCL).

The aerosol current at any level z is given by

$$i_a = \sigma^* f z \cdot w_* f z\,,$$
$$i_a = i_{a*} f^2 z^2\,. \qquad (12)$$

Thus the aerosol current i_a produced by the vertical mass exchange generates the observed atmospheric electric field. The conventional air-earth conduction current cannot discharge the atmospheric electric field and thus be produced since the dynamic charge transport by the vertical mass exchange process is faster than the ion mobilities by more than one order of magnitude.

The vertical distribution of the aerosol current i_a follows the f^2z^2 distribution.

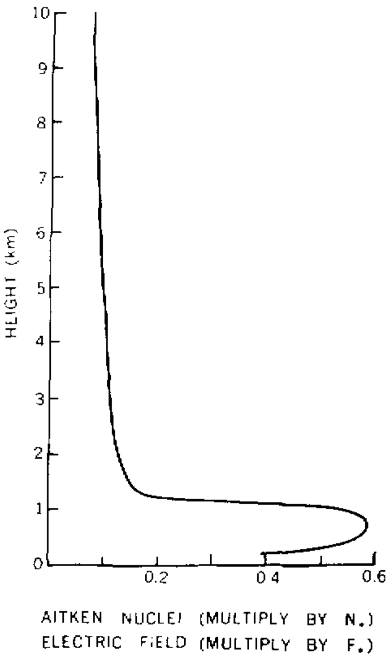


Fig. 3. Computed profiles of Aitken nuclei and electric field.

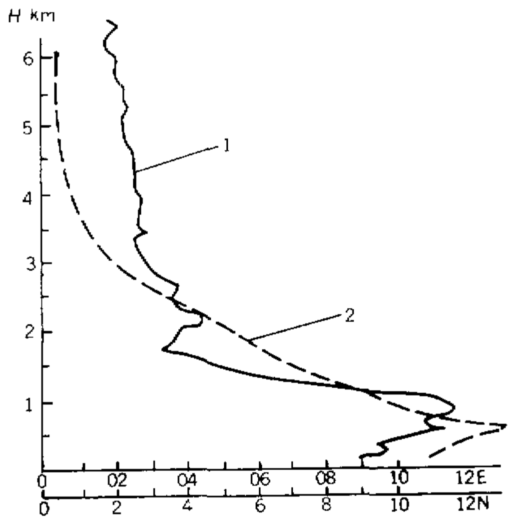


Fig. 4. Observed profiles of atmospheric condensation nuclei and electric field in USSR (after Imyanifov and Chubarina, 1967) where (1) and (2) refer respectively to the Aitken nuclei and electric field profiles.

The convective scale (2 km²) aerosol current can be computed and shown to be 10^5 times larger and is in opposite direction to the conventional air-earth conduction current from Eq.12. The vertical aerosol currents are of the right order of magnitude and direction as those of the vertical currents postulated to exist in the atmosphere by Bauer (1920) and Schmidt (1924) in their hypothesis for explaining the variations in the H component of the global geomagnetic field. The aerosol currents occur over convective scale i. e., 1 km^2 and thus were not detected by conventional spot observations.

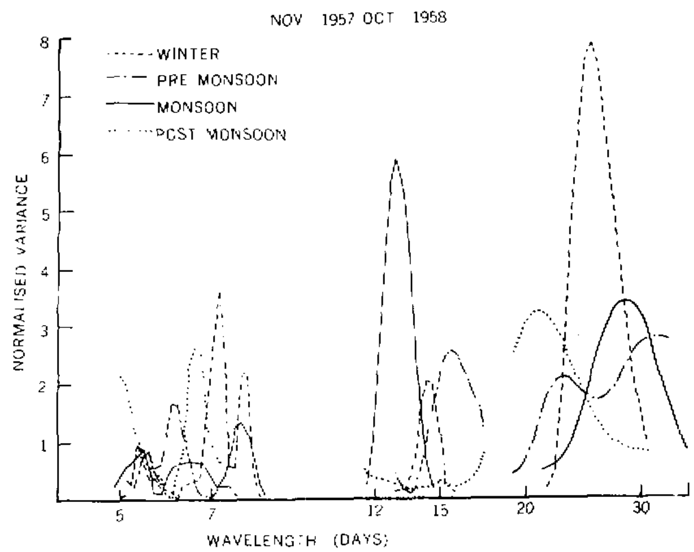
Lanzerotti et al. (1982) found the fluctuations with periods less than one day in the powering voltage on a transatlantic cable which are predominantly produced by fluctuations in the geomagnetic field. Enhancements at similar frequencies are seen in both voltage and magnetic field spectra. These observations corroborate the hypothesis proposed in this paper.

The results of the analysis of the surface electric field data for Colaba for the period 1936–1966 are discussed below.

1. *Interplanetary Magnetic Field (IMF) and Electric Field*

Continuous periodogram analysis of the daily values of surface atmospheric electric field data for Colaba, Bombay (8° 53'56'' N, 72° 48'54''E, 9.8 m ASL) for the 31-year period (1936–1966) was carried out after grouping the data into the four seasons, (i) Winter (November-February), (ii) pre-monsoon (March-May), (iii) monsoon (June-August) and (iv) post-monsoon (September-October).

The results of the harmonic analysis of the electric field data showed a fundamental peak with a period of 6 to 7 days. This period corresponds to the average time interval between any two successive MSB crossing events. Periodicities of 12–15 days and 21–23 days are also present in the electric field. The peaks in the negative D_{ST} index occurred when maximum values of the positive electric field are present. Results of the cross-spectral analysis of the electric field data and the daily mean equatorial D_{ST} index suggested negative correlation between electric field and IMF for all significant wave lengths less than 30 days with



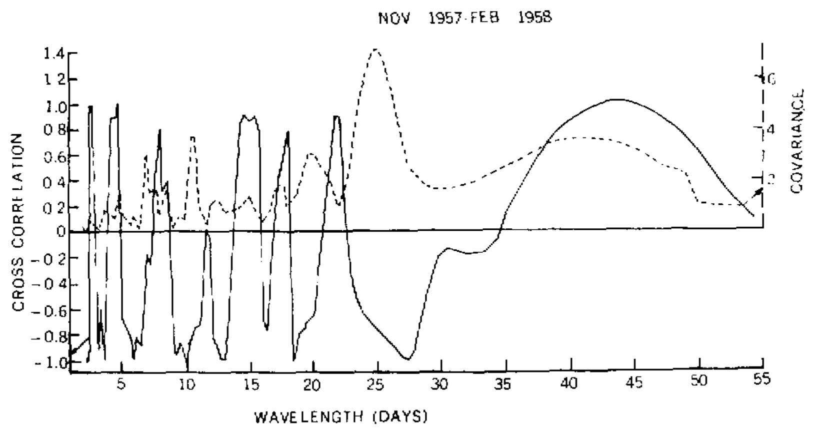


Fig. 5. Results of the spectrum and cross spectrum analysis of the surface atmospheric electric field and the D_{ST} index.

maximum being centred around 27 days, which may roughly correspond to one solar rotation period. A positive correlation between surface electric field and IMF is found in the wave length range 35-55 days with maximum at about 47 days. This appears to correspond with two solar rotation periods. The results indicate a strong association between surface electric field and IMF.

2. *Geomagnetic Storms and Electric Field*

The association between atmospheric electric field and global geomagnetic storms was studied by the superposed epoch method of analysis of the atmospheric electric field data for Colaba, Bombay for the 31-year period from 1936 to 1966.

Results of the analysis of the electric field, major geomagnetic storms (with A_p index$>$ 100) and the selected meteorological parameters (surface pressure, wind, humidity, temperature and rainfall) indicate the following. Geomagnetic storms are followed by a decrease in the electric field during a 6-day period following the data of occurrence of the storm. During the summer monsoon (June-September) geomagnetic storms are followed by a decrease in surface pressure, increases in wind velocity and rainfall. The results of the study corroborate the hypothesis that there is a two-way interaction between the ionospheric S_q current systems and the meteorological parameters i. e., a geomagnetic storm in association with a major solar flare can enhance the vertical mass exchange resulting in enhancement of existing weather systems. This in turn feeds back energy into the S_q current system which is manifested as a delayed geomagnetic storm (sub-storm) following the solar flare induced sudden storm commencement (SSC).

3. *Interplanetary Magnetic Sector Boundary (MSB) Crossing Events and Electric Field*

Association between the MSB crossing events and the surface atmospheric electric field data for Colaba, Bombay was investigated by the superposed epoch method of analysis.

The results indicate that an MSB crossing for which there is a negative to positive polarity change is associated with a decreasing surface electric field for a total period of about 4 days inclusive of the MSB crossing date (Fig. 6). An MSB crossing event for which the polarity changes from positive to negative is associated with a distinct peak in the surface atmospheric electric field within 2 days of the MSB crossing event. The above results are in agreement with those reported by other investigators (Herman and Goldberg, 1978).

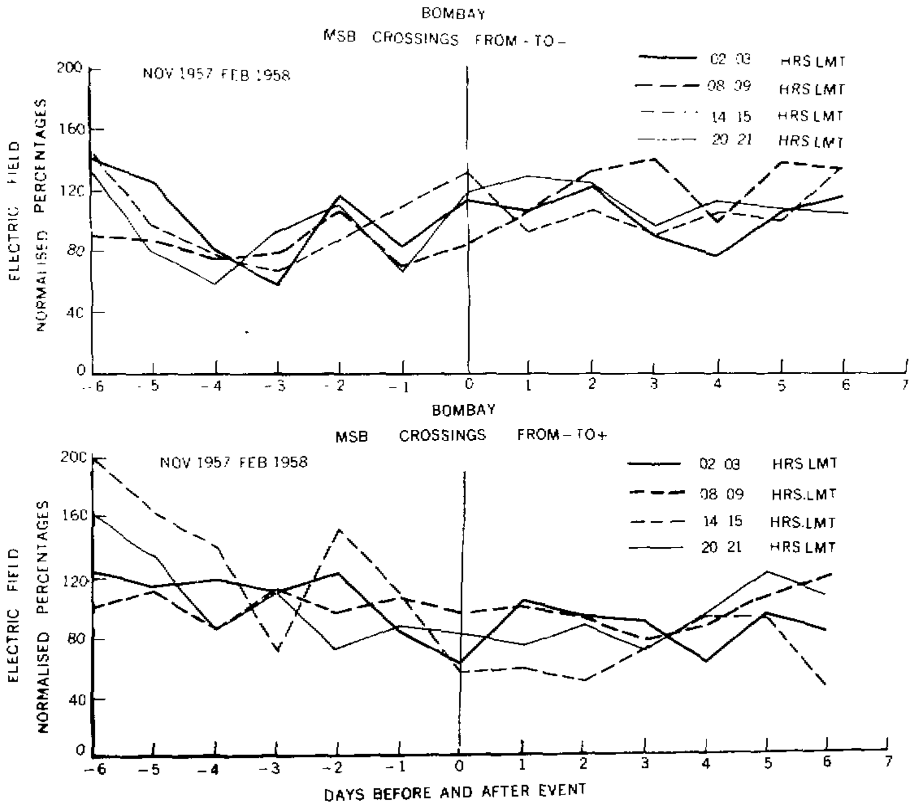


Fig. 6. Variations in the electric field with the MSB crossing events.

4. *Lunar Phases and Electric Field*

The association between surface atmospheric electric field and lunar phases was investigated by the superposed epoch method of analysis using surface atmospheric electric field data for the 31 year period from 1936 to 1966. From the analysis it is found that a peak occurs in the atmospheric electric field within ± 2 days of the full moon occurrence. A possible explanation is that the magnetohydrodynamic wake of the moon at full phase (analogous to earth's magnetotail) produced by the solar wind interacts with the earth's magnetotail to promote energetic particle precipitation, into the ionosphere, thereby setting up electric currents that perturb the magnetic field. Such disturbances are seen in the atmospheric electric field (Herman and Goldberg, 1978).

REFERENCES

Bauer, L.A., (1920), Vertical electric currents and the relation between terrestrial magnetism and atmospheric electricity, *Terr. Magn. Atmos. Elec.*, **25**:145–162.

Beer, T., (1975), Atmospheric Waves, Adam Hilger, London, pp. 300.

Carter, D.A. and B.B. Balsley, (1982), The summer wind field between 80 and 93 km observed by the MST radar at Poker Flat, Alaska (65°N), *J. Atmos. Sci.*, **39**:2905–2915.

D'Angelo, N., J.B. Iversen and M.M. Madsen, (1982), Influence of the dawn-dusk potential drop across the polar cap on the high-latitude atmospheric vertical current, *Geophys. Res. Letts.*, **9**:773–776.

Dewan, E.M., (1979), Stratospheric wave spectra resembling turbulence. *Science*, **204**:832–835.

Gage, K.S., (1979), Evidence for a $K^{-5/3}$ inertial range in mesoscale two-dimensional turbulence. *J. Atmos. Sci.*, **36**: 1950–1954.

Heppner, J.P., (1975), High-latitude ionospheric winds related to solarinterplanetary conditions. In 'Possible relationships between solar activity and meteorological phenomena' National Aeronautics and Space Administration Report, *Washington D.C.*, 167–170.

Herman, J.R. and R.A. Goldberg, (1978): Sun, weather and climate, NASA Report SP–426, *Washington D.C.*, pp.360.

Holton, J.R., (1979), An introduction to dynamic meteorology, Academic Press, New York, pp. 391.

Holzworth, R.H., (1981), High latitude stratospheric electrical measurements in fair and foul weather under various solar conditions. *J. Atmos. Terr. Phys.*, **43**:1115–1125.

Holzworth, R.H. and F.S. Mozer, (1979), Direct evidence of solar flare modification of stratospheric electric fields. *J. Geophys. Res.*, **84**:363–367.

Imyanitov, I.M. and E.V. Chubarina, (1967), Electricity of the free atmosphere, Israel Program for Scientific Translations. Jerusalem, pp. 212.

Kelley, M C., (1983), Middle atmospheric electro-dynamics, *Reviews of Geophysics and Space Physics*, **21**:273–275.

Keskinen, M.J., S.L. Ossakow and B.E. McDonald, (1980), Non-linear evolution of diffuse auroral F. region ionospheric irregularities. *Geophys, Res. Betts.*, **7**:573–576.

Lanzerotti, L.J., A. Meloni and L.V. Medford, (1982), Induction in a transatlantic cable at periods between 20 minutes and one day, *Geophys. Res. Letts.*, **9**:439–441 .

Markson, R., (1978), Solar modulation of atmospheric electrification and possible implications for the sun-weather relationship, *Nature*, **273**:103–109.

Mary Selvam, A., G. K. Manohar, S. S. Kandalgaonkar, A.S.R. Murty and Bh. V. Ramana Murty, (1982), Electrical and dynamical characteristics of summer monsoon clouds. Preprint Volume Regional Conference on Tropical Meteorology, Tsukuba, Japan, 18–22 October 1982, WMO, Geneva, 249–250.

Mary Selvam, A., A.S.R. Murty and Bh. V. Ramana Murty, (1983a), Surface frictional turbulence as an agent for the maintenance and growth of large eddies in the atmospheric boundary layer. Preprint Volume VIth Symposium on Turbulence and Diffusion, 22-25 March, 1983, Boston, *Mass., Amer. Meteor. Soc.*, 106–109.

Mary Selvam, A., A.S.R. Murty, Poonam Sikka and Bh. V. Ramana Murty, (1983b), Some physical and dynamical aspects of warm monsoon clouds and their modification. Proc. Indian Academy of Sciences (Submitted).

Mary Selvam, A., A.S.R. Murty, G.K. Manohar, S.S. Kandalgaonkar and Bh. V. Ramana Murty, (1984a), A new mechanism for the maintenance of fair weather electric field and cloud electrification. Preprint Volume VIIth International Conference on Atmospheric Electricity, 4–8 June 1984, Albany, New York, *Amer. Met. Soc.*

Mary Selvam, A., A.S. R. Murty and Bh. V. Ramana Murty, (1984b), A new hypothesis for vertical mixing in clouds. Preprint Volume 9th International Cloud Physics Conference, 21–28 August 1984, Tallinn, USSR.

Mary Selvam, A., A.S.R. Murty and Bh. V. Ramana Murty, (1984c), Role of frictional turbulence in the evolution of cloud systems. Preprint Volume 9th International Cloud Physics Conference, 21–28 August, 1984, Tallinn, USSR.

Schmidt, A., (1924), Zur Frage der elektrischan Vertikalstrome, Z. Geophys., **1**: 281–284.

Tsurutani, B.T., E.J. Smith, R.M. Thorne, R.R. Anderson, D.A. Gumett, G.K. Parks, C.S. Lin and C.T. Russell, (1981), Wave particle interactions at the magnetopause contributions to the dayside aurora, *Geophy. Res. Letts.*, **8**: 183–186.

Van Zandt, T.E., (1982), A universal spectrum of buoyancy waves in the atmosphere, *Geophys. Res. Letts.*, **9**:

575-578.

Weinstock, J., (1980). A theory of gaps in the turbulence spectra of stably stratified flow, *J. Atmos. Sci.*, **37**:1542-1549.

Weinstock, J., (1981). Energy dissipation rates of turbulence in the stable free atmosphere, *J. Atmos. Sci.*, **38**: 880-883.