Chronological Studies of the Interlink of Air Pollutants with Geomagnetic Indices and Meteorological Factors on Eclipse Days

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Abstract: Solar eclipse has become a point of interest since the ancient ages of times. It occupies important places in mythological, scientific and biological studies. Solar eclipse impacts the solar radiation, geomagnetic activities, air quality in significant ways and drastic difference at this time can be noted than normal days. Monitoring air pollution during solar eclipses gives an unusual angle on how the atmosphere behaves when solar energy suddenly shifts. Solar eclipses cause sudden drops in temperature and light intensity, which influence how chemicals react and how air pollution, propagate. Because of a drop-in photochemical activity and air turbulent conditions, studies have found brief decreases in surface ozone (O_3), changes in nitrogen dioxide (NO_2) and other chemical compounds and particulate matter ($PM_{2.5}$, PM_{10}) during eclipse periods. Further study in this field helps to improve atmospheric models and forecast pollutant behaviour in the presence of fluctuating solar circumstances. This paper enquires the dynamics between the solar eclipse, geomagnetic indices, meteorological factors and air pollutant components. The analysis records the important observations noted during eclipse time since 1940 to present. The evolution of geomagnetic indices implying geomagnetic activities, changes in ionosphere and magnetosphere, alteration in pollutant concentration in air, changes in temperature, humidity, wind speed etc. Have been analytically reviewed in this paper.

Key Words: Geomagnetic Storm, Ionosphere, Meteorological parameters, Solar Corona, Ventilation Coefficient

Introduction

The indistinct outer atmosphere of the Sun, termed as corona, comes into view while experiencing a full solar eclipse, when the moon completely obscures the Sun's apparent disk. Just before the event, the thinner and brighter red chromosphere of atmosphere of the sun appears for a very short period of time, typically for few seconds at the edges of the solar disc. After that the chromosphere vanishes and the corona comes into view. Far beyond the Moon's dark disk, Pearly white coronal streamers can be seen. Solar Corona is much fainter than the dark disk of the Sun, which can't be seen in bare eye in broad daylight. That's why observations and records are made by scientist when the corona becomes prominent. Coronagraph is invented by Bernard Lyot in 1930, this is a special type of telescope that can create an artificial eclipse of the Sun[1].The corona can be studied any day when thehalo around the sun was not especially bright. The sky at daytime is darker during the time of eclipse than other normaldays. Up to mid-1970s, till the availability of suborbital rocket and satellite observatories, the total solar eclipse continued to provide the chances to observe and study the outer atmosphere of sun.[2]A number of significant advantagesare possessed by the observatories in space over the surface-based instruments, as they have immunities to the disturbances in weather and the distorting effects of Earth's atmosphere. But these methods are excessively expensive and requires decades of planning. It is relatively more affordable to set up a temporary observation station within the eclipse's trajectory toward totality. Therefore, despite theconstraints they face, observations that are surface-based continue to play a vital role in gathering newer knowledge about the Sun during total solar eclipse. Among the significant developments which were created during past full eclipses, three significant events can serve as examples—the discovery of helium[3], empirical evidences for the general theory of relativity[4] and the finding that the Sun's corona is highly warm[5]. It has also been seen that although for short time but significant changes have been noticed in air condition. Due to partial or full blockage of the sun, temperature has reduced significantly[6]. During solar eclipse the atmospheric Ozone (O_3) also get reduced[7]. Also, the vertical air mixing, pollutant dispersion or ventilation has been slowed down[8]. In a word the atmosphere has become calmer and cooler during the eclipse.

Following shows the time line review based on geomagnetic indices, ionosphere perturbations, impact on meteorological factors and quality of air in regards of pollution etc. During the occurrence of solar eclipse. Starting from the work on geomagnetic indices of Bartels in 1939, solar quiet current variation, Dst variations and atmospheric changes, the following review covers the striking events happened till now.

Time line review of solar eclipse, geomagnetic indices, meteorological factors and air components

In the years 1940-1950

- Ozone concentration was measured during the solar eclipse, happened on 9th July, 1945. Which was seen to be decreased after the termination of eclipse by 0.1 cm.[9]
- At this time, the methodology was introduced to calculate K_s and K_p indices, developed upon the previous indices, specifically the global $K_{(m)}$ index, as well as the lessened K_r and global K_w indices. [10-12]
- In the year 1949, Bartels developed a method to convert K indices into standardized K_s indices using conversion tables. These tables assign integer values between 0

and 27 to each K index for every three hour Universal Time (UT) interval and for each of the three Lloyd seasons equinoxes, June solstice, and December solstice.[11-13]

In the year 1951-1960

- A measurement by Dobson spectrophotometer made on the eclipse day of 2nd October,1959 claims an increase in ozone concentration by an amount of 4% before 20 minutes of the peak phase of the eclipse.[14]
- Geomagnetic storms were classified according to their severity and they were assigned a numerical index. Dst variation were noted for sudden commencement of the storms.[12]
- Prior to the discovery of the solar wind, geomagnetic variations were believed to result from solar particle radiation.[15]

In the year 1961-1970

During the annular solar eclipse, happened on 20th May, 1966 observation and measurement by ozone spectrophotometer claimsan increase of 25–30 m atm-cm of Ozone concentration during the maximum phase of the solar eclipse. Applying the dark-limb correction the amount reduced to 14 m atm-cm.[16]

In the year 1971-1980

- The development of Dst index was initiated by Bartel to monitor the equatorial ring current. A delayed response was shown by the ring current which is compared to the variation in the solar wind that caused the geomagnetic storm to commence. The atmospheric instability was found to be reduced than the normal value during observation from Tarapur, India, at the time of the solar eclipse occurred on 16th February,1980.[18]
- During the eclipse happened in 1973, observed from Chinguetti, Mauritania, measurement were done on pressure, wind speed, temperature. The pressure showed no difference. There were maximum changes of 3.5°C and 4.5m/s in temperature and wind speed respectively.[19]

In the year 1981-1990

- At the time of eclipse, adrop in electron density was observedin the ionosphere particularly at the E and F1 region. However, for the F2 region, some investigations report a decrease, while others report an increase in electron density.[20]
- The total content of NO_2 in the vertical air column is increased during the solar eclipse, especially during the maximum phase.[21]

In the year 1991-2000

- The deterioration of the ring current during the recovery phase of geomagnetic stormwas considered a non-K-variation .[22]

- The development of standardized Ks and planetary Kp are specific to each observatory.[23]
- During the solar eclipseon 24th October, 1995, it was noticed that the ozone concentration is decreased by 16% in comparison to a normal day at the time of maximum obscuration[22].
- One parameter that provides precious information on the ionosphere's response is the TEC (Total Electron Content). TEC measurements during solar eclipse in the year 1999 across Europe clearly depicted the movement of an area with reduced electron content.[25]
- Measurement during the solar eclipse occurred on 11th August, 1999 using differential absorption lidar (DIAL) claims that there was a drop in ozone concentration during the eclipse[26].
- Another study based on the same eclipse of Aug, 1999 claims a change in temperature up to 5K of the air level close to the surface during the eclipse. Also, the Thermal stability was more stable during the event.[27]

In the year 2001-2010

- Observations of solar eclipses have been the focus of intense study since the initiation of the space age. The majorly used observation technique has been vertical sounding with ionospheric stations, known as ionosondes.[27]
- The Dst index is commonly considered as an indicator of the ring current intensity of Earth, although it also responds to variations in the partial ring current.[29]
- Study showed that Dst does not reflect the dynamics of the particle population, that were in the radiation belts.[30]
- There will be the gradual weakening of current field of the ring at the recovery stage of the geomagnetic storm.[31]
- Investigation on the distribution of cold plasma density within the plasma-sphere was carried out.[32]
- The energy associated with the precipitation of auroral particles is represented by Kp.[32,33]
- The geomagnetic field variation, measured at a geomagnetic observatory can be represented as the sum of two components: K-variation and non-K-Variation. K-variation is composed of the irregular disturbances of the geomagnetic field which is occurred by solar particle radiation within the 3-hourly UT interval, and includes phenomena such as geomagnetic storms (with the exception of the recovery phase geomagnetic pulsations, bays or sub storms, sudden commencements), and other geomagnetic disturbance resulting from fast changes in the ring-current and other currents of magnetosphere and ionosphere. On the other hand, non-K-variation encompasses the phenomena which are related to the energetic electromagnetic solar radiation (EUV, X-ray), such as the solar and lunar quiet variation, occurring daily and the rare solar flare effects.[34]

- During a solar eclipse on 29th march, 2006 observed from Athens, Greece a study claims that the solar ultraviolet radiation of wavelength 312nm and 365nm reached 97% and 93% respectively. The temperature and the wind speed decreased and the relative humidity was increased. There was an increase in the NO_2 concentration also.[35]
- During the same eclipse, observed from Side, Turkey, measurement was done on relative humidity and temperature. The temperature was decreased by 5.0°C from initial phase to peak phase of the eclipse and after that till termination it was increased by 4.5°C. Whereas relative humidity showed inverse trend to the temperature.[36]
- It was reported that the luminosity and the UV component from the sun towards the surface of earth significantly reduced during the time of solar eclipse on July 22, 2009. A drop in temperature and increase in humidity was also noticed. A short period fading at 27 KHz frequency was noted.[37]
- There was also a sudden drop in the measurements of surface meteorological parameters and intensity of cosmic ray at thesame time of the obscuration. The drop was noted after 51 min and 12 sec of the happening of the first contact and it recovered with a delay of 2 hours after the termination of the eclipse.[38]
- During the same solar eclipse but observed from South Korea on 22nd July, 2009, the temperature of air decreased a little bit more or less unchanged but after the termination of eclipse it rose by 2.5^{0}C-4.5°C. Apart from this there was an increase in relative humidity and decease in Ozone concentration of ground level and wind speed.[39]
- Another study made on a partial eclipse occurred on 15th January,2010 observed from Udaipur, India claims that the surface ozone concentration and CO concentration in air varies respectively from -9 to -2 ppb and from -180 to -80 ppb than normal days. The observed change in the value of Black Carbon is -3.3 to -0.5 µg/m3. During the eclipse hour the planetary boundary layer height and wind speed were also seen to be decreased. Therefore, a change in Ventilation coefficient has also been noted.[40]
- During the same eclipse observed from Kannur, a coastal city in Indiaresearchers claimed the sharp decrease of surface ozone concentration, probably due to the decrease in NO_2 photolysis during the eclipse. There was an increase in NO_x concentration up to 62.5%. Air temperature, relative humidity and wind speed were also found to be reduced.[41]

In the year 2011-2020

- Gravity wave measurements at the same location during eclipse in the year 2006 and1999 are compared. The results showed similar behaviour during both eclipses, with fluctuations observed in the gravity measurements and a decrease in magnetic field intensity. Further analysis of the magnetic data of low-pass filter revealed peculiarities during the eclipse that were correlated with the observed gravity field fluctuations.[42]

- The ionospheric disturbance at the eclipse kind of solar perturbation propagates vertically at a supersonic speed.[43,44]
- Kp is of great importance in physics-based geospace models, particularly in models that simulate the magnetosphere and plasma sphere. The VERB-3D model is a good example of such models.[45]
- The generation of a large number of electrons by solar radiation leads to the creation of high-density electron regions. These electrons, along with the ionic plasma in motion, form electric currents. The magnetic field induction in the ionospheric E layer is also attributable to the presence of these currents.[46,47]
- The cross-tail current is studied from the existence of the ring current.[48-50]
- The fluctuations in thermospheric density, which are crucial for atmospheric drag and spacecraft re-entry, are modulated by changes inthe geomagnetic activity represented by the Kp index.[51,52]
- The activity of waves with ultra-low frequency (ULF) while propagating through the ionosphere was investigated.[53]
- Investigation on the impact of the partial solar eclipse thathappened on March 20, 2015 on the mid-latitude ionospheric parameters and physical processes in geospace over Kharkiv (49.60° N, 36.30° E) is carried out. This analysis revealed that the solar eclipse caused a significant restructuring of the thermal and dynamic state of the ionospheric plasma over Kharkiv [49.60° N, 36.30° E).[54]
- Investigation through Chorus/VLF wave activity in the lower frequency range within the ionosphere was carried out.[55,56]
- Some fluctuations in atmospheric pressure were observed during the time of solar eclipse, happened on 20th March,2015 over Kaliningrad (54^0 N, 20^0 E). They are claimed by the study as the source of Acoustic Gravity Wave (AGW). The wave is produced at the lower atmosphere then tends to transfer to the upper part. Some increased activities were noted for a period of 4 minute 20 second in the lower atmosphere after the solar eclipse. AGWs were dissipated to the upper atmosphere which created some disturbances there for a period of 50 minutes. The disturbances were opposite to the movement of solar eclipse region along the Earth's surface. The computational results are in sync with the observation of the disturbances of ionosphere.[57]
- During the solar eclipse on August 21, 2017, a vast network of Global Navigation Satellite System (GNSS) receivers at approximately 2,000 locations in North America generated precise and expansive observations of the ionosphere. This resulted in a data-rich set of eclipse information that enabled the detection of ionospheric bow waves as disruptions in EC over central and eastern United States. In addition, it was uncovered that substantial ionospheric perturbations that

moved at supersonic velocities during the maximum solar obscuration were too rapid to be ascribed to known as gravity wave.[58]

- During the annular solar eclipse occurred on 26th December,2019, observed from Kannur, a coastal city in India it was observed that there was a significant change in the pollutant level and meteorological parameters. The solar radiation was decreased by 93%, the temperature and wind speed was reduced by 16.3% and 36.1% respectively. The surface O_3 concentration and column O_3 concentration were reduced by 61.5% and 11.8% respectively, during the maximum phase of eclipse. There was significant increase in CO and NO_2 and increase in SO_2, PM_{10} and $PM_{2.5}$.[59]
- During the same eclipse another study claims increase in ozone concentration at different altitudes. The drop in temperature at altitude 94-98 Km was also correlated to the increase in concentration of CO_2 at the same altitude.[60]
- As per another study on the same event the Ozone (O_3) concentration was decreased by 48% and NO_2 was increased to 8 times after 52 minutes of maximum phase.[61]
- At the time of the solar eclipse of 21st June, 2020 observations were made from 8 stations of India claims that the overall ozone concentration was changing proportionally with the intensity of eclipse. The ozone concentration was lowest at the maximum phase of eclipse.[62]

From the year 2021 – present

- Solar Eclipse triggered extensive studies due to its occurrence during daytime ionospheric activity and proximity to geomagnetic disturbances. An investigation claims the mid-latitude F2-layer ionosphere during PartialSolar Eclipse on 25 October 2022 using vertical sounding techniques. They observed a notable daytime dip in electron density, a reduction superimposed on post-storm effects from a preceding magnetic disturbance. Their study revealed that solar eclipse effects compounded with residual geomagnetic perturbations, altering the natural diurnal variation in ionospheric density and dynamics.[63]
- A study explored the D-region ionospheric changes through the study of signals of very low frequency (VLF) during the same eclipse. The analysis along the DHO path (Germany) showed that VLF amplitude increased during the greatest eclipse (GE) phase, indicating increased D-region ionization due to decreased solar radiation. Importantly, geomagnetic activity had no significant effect on the VLF responses on that date, distinguishing eclipse-induced ionospheric changes from storm-driven disturbances.[64]
- To evaluate spatial dependence of ionospheric effects, researchers analysed Total Electron Content (TEC) using GNSS observations. A study documented changes in GPS-derived TEC during both the 25 October 2022 and 14 October 2023 eclipses.

Their results illustrated that:

- In zones with 20% eclipse cover, TEC dropped by ~11.76%.
- In zones with 60–80% cover, reductions ranged from 22% to 44%.
- The correlation between eclipse obscuration and TEC depression confirmed the localized and magnitude-dependent nature of ionospheric reactions.[65]

- A study documented disturbances during the intense geomagnetic storm on 23 April 2023 (Dst ≈ −212 nt). Using ionosonde and VLF data across Europe, they identified significant D- and F-region anomalies. These hemispheric-scale responses served as a comparative framework to distinguish storm-induced effects from those due to eclipses.[66]
- An analysis claims the TEC variations during multiple solar eclipses over Ethiopia.
  - TEC dropped by 38%.
  - The magnitude of reduction depended on eclipse path, timing, and station location.
  - This African-focused study reinforced the universal suppression of ionization during solar eclipses, modulated by eclipse geometry and solar zenith angle.[67]
- A multi-instrumental study (GNSS, ionosondes, irradiance sensors) was conducted to assess eclipse-driven atmospheric and ionospheric impacts:
  - Solar irradiance dropped by 78–92% in shortwave and 4–6% in longwave.
  - Air temperature fell by ~2 °C at ground level.
  - In the ionosphere, O+ recombination exceeded photoionization, results in aincrease in the O/N_2 ratio and post-eclipse generation of Traveling Ionospheric Disturbances (tids).[68]

These results underscore how thermospheric chemistry and dynamics are impacted by sharp variations in solar input, reinforcing the multi-layer coupling within geospace during eclipses.

- Analysis was done on the records of 14th December, 2020 eclipse which claims a significant decrease of around 10-15nt in the intensity of horizontal field at southern hemisphere. This may be due to the change of conductivity in the E region due to the changing ionization process of ionosphere during the eclipse.[69]
- During a total solar eclipse, occurred on 8th April, 2024, observed from New York reveals that, air temperature was reducedby 2.8°C on an average and 6.8°C maximum. Calmer winds, reduced vertical mixing, reduced planetary boundary layer were also observed.[70]
- The Kp is calculated based on data from 13 specific geomagnetic observatories where the current Kp-stations along with their positional longitudes,K9-limits, quasi-dipole (QD) latitudes, and corresponding weights in Kp are provided. The QD coordinates were determined using IGRF-13.[34]
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Conclusions:

The body of work spanning nearly eight decades underscores the complexity and interconnectedness of solar, geomagnetic, and atmospheric phenomena. Solar eclipses have proven to be natural laboratories for studying the ionosphere's behaviour, consistently revealing reductions in electron content, modified geomagnetic field components, and disruptions in atmospheric circulation. Geomagnetic indices such as Dst and Kp have evolved not only as classification tools for storm intensity but also as parameters essential for empirical modelling and forecasting. The progression from ground-based ionosonde observations to satellite-supported and magnetospheric models highlights a maturing scientific landscape that increasingly integrates multi-scale, multi-variable data. During eclipse there happens a lot of change in the atmosphere. Due to the full or partial blocking of the sun by the moon there is a change in solar direct radiation (SDR) at the time of eclipse than other time of the day and normal days as well. Therefore, the temperature drops by significant amount during or just after the eclipse[72]. The reduction in SDR and temperature disturbs the photochemical reaction producing ozone (O_3). That's why significant reduction of a secondary pollutant component Ozone can be observed during eclipse. Due to reduced SDR and drop in temperature, the turbulent mixing in atmospheric boundary layer gets reduced. Resulting in decreased amount of momentum flux, heat flux and turbulent kinetic energy. The atmospheric boundary layer becomes more stable and its overall height decreases. The study also claims that the wind speed reduces significantly. Hence the reduced wind speed and reduced ABL results to reduction in ventilation coefficient. Which means the power of air to disperse the pollutant becomes decreased. That's why several pollutant components such as particulate matter ($PM_{2.5}$, PM_{10}), SO_2 concentration get enhanced. As the solar radiation received by the atmosphere is reduced the photolysis process which breaks NO_2, decelerates which results in more amount of Nitrogen Oxide compounds in air during solar eclipse. As the incoming total solar radiation is reduced during eclipse, the amount of radiation absorbed and scattered by the aerosols also changes which in turn changes the properties of aerosols, such as Aerosol optical depth (AOD).

Scopes of research: The primary motto of the study was to comprehend the correlation between the solar dynamics, meteorological parameters and the air pollution. This timeline of research offers critical perspectives on space weather impacts and lays the groundwork for future studies, particularly in improving predictive capabilities and understanding Earth's dynamic response to solar forcing.

But there are other aspects of the solar eclipse also. E.g. The inter terrestrial relationship of different astronomical object during the eclipse, the cultural and historical aspect since the ancient times, Biological and environmental aspects which includes public health and general safety during the eclipse.

There is a broad scope of further research in the above-mentioned areas as these short time changes can also be far reaching.

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