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*Research Article*

# The Contribution of Geomagnetic Activity to Polar Ozone Changes in the Upper Atmosphere

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Energetic particle precipitation (EPP) has significant impacts on ozone depletion in the polar middle atmosphere during geomagnetic activity. It is well known that solar ultraviolet (UV) radiation plays an important role in ozone generation. Therefore, it is interesting to compare the contributions of EPP and solar UV to ozone changes in the polar upper atmosphere. In this article, we use the annual average $A_p$ index to denote the annual-mean magnitude of the geomagnetic activity, which is closely correlated with the EPP flux, and the annual average $F_{10.7}$ index to denote the annual-mean magnitude of the solar radiation, which is somewhat related to the solar UV. We adopt the 5° zonal annual-mean ozone profile dataset to study the statistical characters between the ozone dataset and the $A_p$, $F_{10.7}$ indices. Multiple regression analysis shows that the contributions of geomagnetic activity are not negligible and are of a similar order of magnitude as the solar UV radiation in the polar upper atmosphere (above 10 hPa). The results also show that high-speed solar-wind-stream-induced and coronal-mass-ejection-driven geomagnetic activity is of the same order of magnitude. There are interhemispheric differences according to our multiple regression analysis. We discuss the possible causes of these differences.

## 1. Introduction

It is well known that energetic particle precipitation (EPP) during geomagnetic activity has the potential to play an important role in the catalytic process of polar ozone depletion (OD). Particle deposition into the upper atmosphere generates odd nitrogen ($NO_x$) and hydrogen ($HO_x$) families, which cause ozone loss [1–7]. Many investigations of EPP–OD effects for different levels of geomagnetic activity have been carried out, and the impact of EPP on polar ozone has been modeled and observed [8–27]. Solar ultraviolet (UV) radiation has a significant direct and indirect impact on high-latitude ozone through ion chemistry processes and atmospheric transport mechanisms [28, 29]. Geomagnetic activity is also modulated by the 11-year solar cycle, just like solar UV radiation. The main difference is that the frequency peak of the geomagnetic activity driven by coronal mass ejection (CME) occurs around the maximum of the solar cycle like solar UV radiation whereas the geomagnetic activity induced by high-speed solar wind streams (HSSWS) occurs mostly during the declining phase of the solar cycle [30]. High-latitude ozone is important for the polar climate because ozone affects the radiative balance, temperature, and dynamics of the middle atmosphere [31, 32]. Thus, it would be interesting to examine how EPP effects that influence annual polar ozone changes compare with the impact of solar UV variations.

To this end, we conducted a preliminary statistical study using high-latitude ozone observations based on a number of space-weather indices. Since the EPP levels are modulated by geomagnetic activity [33–35], we use the $A_p$ index (which is calculated based on measurements of the magnetic-field

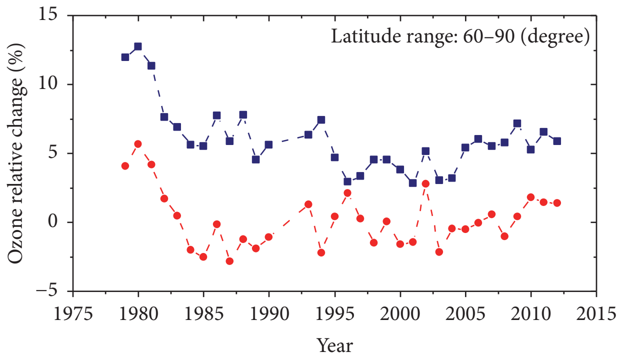


Figure 1: The annual-mean ozone thickness anomalies relative to 40 DU (Dobson Unit) above 10 hPa over latitude range from 60° to 90° from 1979 to 2012. We averaged ozone data in this latitude range with considering the latitude weight. The blue squares and red spots connected with dash lines denote the data points of the NH and the SH, respectively.

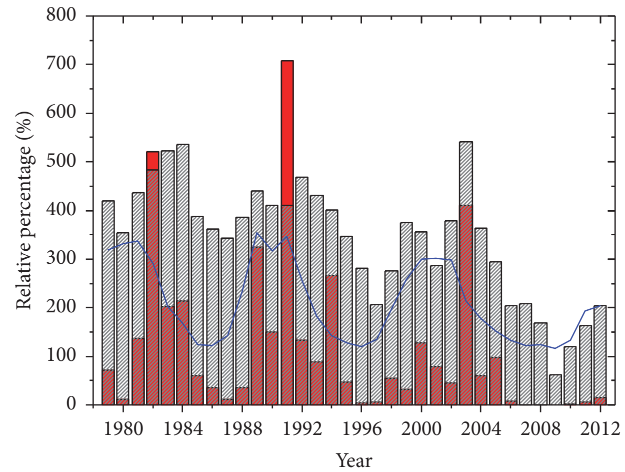


Figure 2: The annual-mean EI (Energy Index, see it in Section 2.3) anomalies of $A_p$ (histograms) and $F_{10.7}$ (blue line) indices relative to $A_p = 5$ and $F_{10.7} = 60$, respectively. The red and shadow columns denote $A_p$-HSSWS and $A_p$-CME, respectively.

components at 13 high-latitude geomagnetic observatories [36]) of the geomagnetic activity as a proxy for EPP, because we do not have enough long-term EPP observations. This method is mentioned and applied by Seppälä et al. [34, 35]. We apply the $F_{10.7}$ index of the solar radio flux as a proxy for solar UV flux because of the good correlation between these quantities. In this paper, we introduce the ozone observations and the multiple regression analysis method used in Section 2, we present the statistical analysis results for both hemispheres in Section 3, and we discuss the possible causes of interhemispheric differences in Section 4.

## 2. Data and Methods

*2.1. SBUV Dataset.* The Solar Backscatter Ultra Violet (SBUV and SBUV/2) instruments onboard the National Oceanic and Atmospheric Administration's (NOAA) satellites apply the solar UV backscatter technique, which has been developed for 40 years since the 1970s [37–39], to derive the ozone profile from ground level (at an altitude of ~1 km) to the top of the atmosphere (~100 km). We use the 5° zonal annual-mean ozone profile SBUV dataset from 1979 to 2012. This dataset was calculated based on the V8.6 SBUV MOD Profile Layer Data Products [40], and the accuracy of the profile ozone data is approximately 2%–5%, depending on the instrument [41, 42]. The regions of interest are at high latitudes (60°–90°; geodetic latitude) and the upper atmosphere (above 10 hPa). Figure 1 presents the annual-mean ozone thickness relative anomalies above 10 hPa at high latitudes in both hemispheres. The ozone thickness above 10 hPa ranges from 38 DU to 46 DU (with an average value of ~40 DU). We use 40 DU as the threshold and derive the anomaly changes relative to this value.

*2.2. $A_p$ and $F_{10.7}$ Indices.* The $A_p$ and $F_{10.7}$ indices were derived by the World Data Center for Geomagnetism, Kyoto (http://wdc.kugi.kyoto-u.ac.jp/index.html) and NASA's Goddard Space Flight Center (https://omniweb.gsfc.nasa.gov/form/dx1.html). We divided the $A_p$ index into two groups according to their values: one, $A_p$-CME for $A_p \geq 30$, denotes that the geomagnetic activity is driven by CME; the other, *Ap*-HSSWS, denotes that the geomagnetic activity is induced by HSSWS. This is a simple but quick classification method we use in the field of space-weather forecasting to distinguish what drives the geomagnetic activity for a given event. According to Gonzalez et al. [43], the most acceptable classification of geomagnetic storms is a Dst (Disturbance Storm Time) index < −200 nt for severe events, −200 nt < Dst < −100 nt for strong events, −100 nt < Dst < −50 nt for moderate events, and −50 nt < Dst < −30 nt for weak events. Moderate and weak geomagnetic storms (Dst < −100 nt) are often induced by HSSWS. We also refer to the Space Weather Prediction Center's criteria for geomagnetic storms, which define that an event is below the G1 level (minor storm) when the *Kp* index ≤ 5 (approximately equivalent to Dst < −100 nt and $A_p < 32$). In general and considering the conversion relationships among the Dst, *Kp,* and *Ap* indices, we choose $A_p = 30$ as a key value for the classification of the driving source of the geomagnetic activity. In this paper, we use the annual-mean relative anomalies of these indices to analyze correlations between polar ozone changes and solar activity in the upper atmosphere. Figure 2 presents the indices used as a function of time during the solar cycle. There are still some differences between the red and shadow columns, in the sense that the typical peaks of the $A_p$-CME and $F_{10.7}$ indices are tied to solar maximum, but the HSSWS-induced geomagnetic activity occurs most often during the solar cycle's declining phase.

*2.3. Analytical Approach.* We used the multiple regression analysis method. We defined the Energy Index (EI) such that $\text{EI}_{F10.7} = F_{10.7}$, $\text{EI}_{\text{CME}} = (A_p\text{-CME})^2$, and $\text{EI}_{\text{HSSWS}} = (A_p\text{-HSSWS})^2$, which represent the energy inserted into the atmosphere by solar UV radiation, EPP driven by CMEs, and EPP induced by HSSWS, respectively. We constructed a regression model following (1) below, which implies that

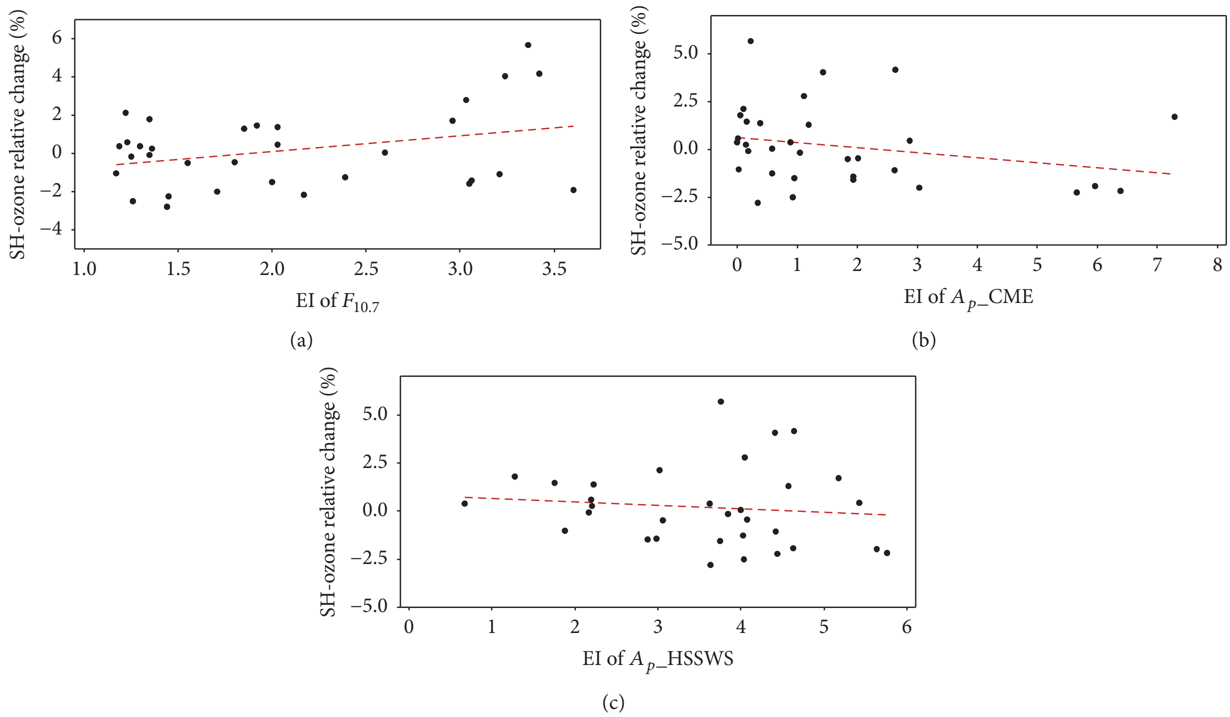


FIGURE 3: The energy index (EI) of $F_{10.7}$ (a), CME (b), and HSSWS (c) versus the polar ozone relative anomalies in the SH. The red dash lines are linear fittings of the points.

ozone anomaly changes ($O_{var}$) are relevant to the energy inserted by solar UV radiation and geomagnetic activity.

$$O_{var} = A_0 + A_1 EI_{CME} + A_2 EI_{HSSWS} + A_3 EI_{F10.7}. \quad (1)$$

Note that we use different annual intervals in both hemispheres when we analyze annual-mean values associated with the ozone data and the $A_p$ and $F_{10.7}$ indices. In the southern hemisphere (SH), we apply normal annual intervals (YYYY ranges from Jan. YYYY to Dec. YYYY); in northern hemisphere (NH), we apply half-yearly moving annual intervals (YYYY ranges from Jul. YYYY to Jun. YYYY + 1) to avoid the influence of the northern polar night on the ozone observations between years (we tried to move the period of the northern polar night to the middle of the analysis year as for the SH). During polar nights, no ozone observations are obtained. The period of the polar night is at mid-year (Jun. to Aug.) in the SH but during the interannual time (Dec. to Feb.) in the NH. By moving the boundaries of our analysis periods, we attempt to balance the impact of the polar night on the ozone observations in both hemispheres. In the NH, the starting point is on Jul. 1 and the end point is on Jun. 30 of the next year. This moves the polar night period in the NH to mid-year, as for the SH.

## 3. Results

*3.1. Southern Hemisphere.* Figure 3 shows that the solar UV flux and geomagnetic activity cause the positive and negative forcing on the southern polar ozone, respectively. We derive the regression equation as in equation (2) below. We derive the impact proportion = $|A_1| : |A_2| : |A_3| = 43 : 10 : 131$. This means that the impact of the geomagnetic activity is close to 40% of the solar UV flux effect. CME-driven geomagnetic activity contributes to the effects of the overall geomagnetic activity. The energetic particles in CME-driven and HSSWS-induced geomagnetic activity have different energy spectra, affecting different levels in the atmosphere [44–48]. This means that the higher energy of the particles, the lower into the atmosphere they can reach [49]. High geomagnetic activity driven by CMEs is associated with more higher-energy particles compared with that induced by HSSWS. Therefore, the impact of the CME-driven geomagnetic activity should exceed the impact of the HSSWS-induced geomagnetic activity. However, the EPP impact on the polar atmosphere also depends on the dynamical situation in the polar middle atmosphere, which may cause interhemispheric differences [48–51]. SH-$O_{var}$ is calculated as follows:

$$\text{SH-}O_{var} = -1.45 - 0.43 EI_{CME} - 0.10 EI_{HSSWS} + 1.31 EI_{F10.7}. \quad (2)$$

*3.2. Northern Hemisphere.* The situation in the NH may be complicated. The distribution of human activity in the NH is significantly different from that in the SH, and the impact of anthropogenic emissions on the northern polar ozone must be pronounced. Anthropogenic emissions can be represented by data of the equivalent effective stratospheric chlorine (EESC). Many previous studies [52–57]

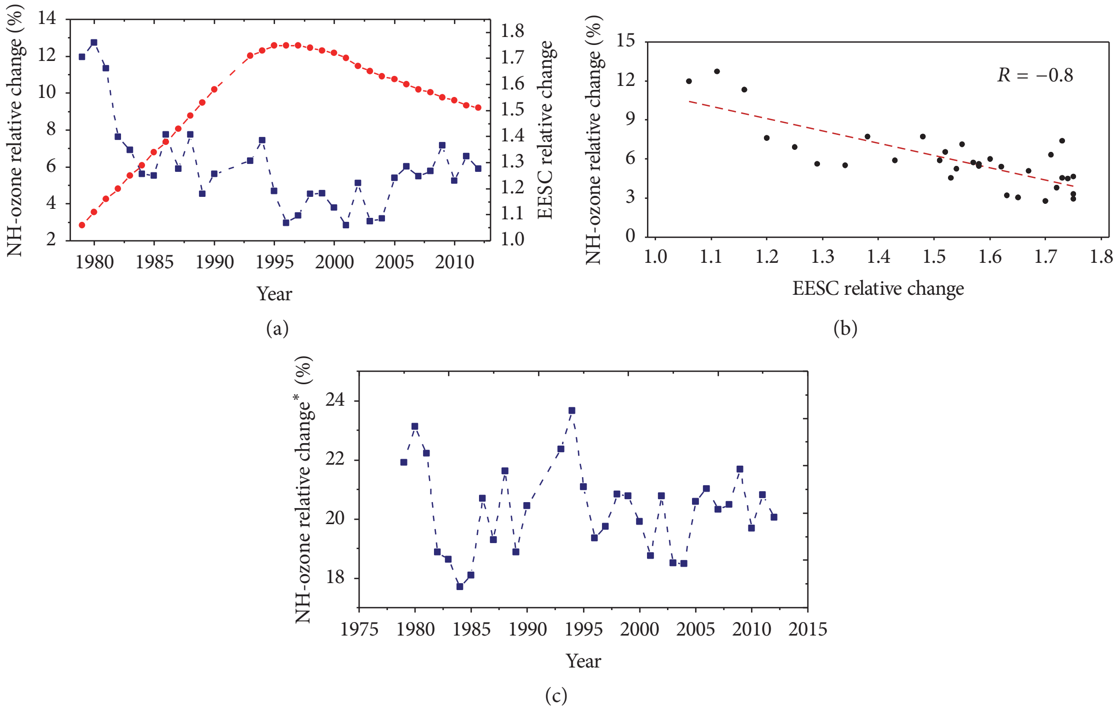


Figure 4: (a) The northern polar ozone relative anomalies (blue squares connected with dash lines) and the EESC data (red spots connected with dash lines); (b) the correlation between the northern polar ozone relative anomalies and the EESC data, the red dash line is the linear fitting of the points; (c) the northern polar ozone relative anomalies after detrending the EESC effects (blue squares connected with dash lines). NH-$O^*_{var}$ denotes that the ozone data of NH has detrended the EESC effects.

have reported a negative relationship between EESC and northern polar ozone. We also found that the northern polar ozone relative anomalies show a good relationship with EESC, which means that the northern polar ozone concentration in the upper atmosphere may be affected by human activity. Figure 4(a) shows the northern polar ozone relative anomalies and the EESC data. Figure 4(b) shows the negative correlation between the ozone relative anomalies and the EESC data, with a correlation coefficient, $R = -0.8$, which is consistent with the results derived by [58] at 60°–65°N (although their study focused on total ozone). Therefore, we detrended the EESC effects from the northern polar ozone relative anomalies (see Figure 4(c)). The EESC data used here can be calculated and downloaded from the website of NASA's Goddard Space Flight Center (http://acdb-ext.gsfc.nasa.gov/Data_services/automailer/index.html), for which we chose 3 years for the age of the air, 1.5 years for the air spectrum width distribution, and the Br coefficient ($\alpha = 60$). Figure 5 shows that the solar UV flux and geomagnetic activity lead to positive and negative forcing on the northern polar ozone (after detrending the EESC effects), respectively, similar to the results in the SH. We derived a regression equation, shown in (3). From (3), we derived the impact proportion = $|A1| : |A2| : |A3| = 9 : 15 : 48$. This suggests that the impacts of CME-driven and HSSWS-induced geomagnetic activities are similar to each other and reach 50% of the solar UV flux effects. However, note that the general impact of natural forcing in the NH is not as significant as that in the SH.

NH-$O^*_{var}$ (which has detrended the EESC effects) is calculated as follows:

$$\text{NH-O}^*_{var} = 20.0 - 0.09\text{EI}_{\text{CME}} - 0.15\text{EI}_{\text{HSSWS}} + 0.48\text{EI}_{F10.7}. \quad (3)$$

## 4. Discussion

We applied multiple regression analysis to investigate the contribution of geomagnetic activity to polar ozone changes compared with solar UV flux in the upper atmosphere. The results show that the observations coincide with the theory; that is, solar UV radiation exhibits positive forcing and geomagnetic activity reveals negative forcing on polar ozone in both hemispheres, the effects of geomagnetic activity are of the same order of magnitude as the solar UV flux effects, and the impact of geomagnetic activity on polar ozone changes in the upper atmosphere is more significant in the SH than in the NH.

We detrended the EESC effects from the NH data to remove anthropogenic forcing in the northern polar upper atmosphere, which implies that human influence is not negligible in this region. The conclusion of this work is not significantly different from those of previous studies; that is, that the impact of geomagnetic activity on ozone is of the same order of magnitude as that of solar UV radiation. Callis et al. [59] and Rozanov et al. [60] used numerical models to calculate the indirect effects of EPP and reached the conclusion

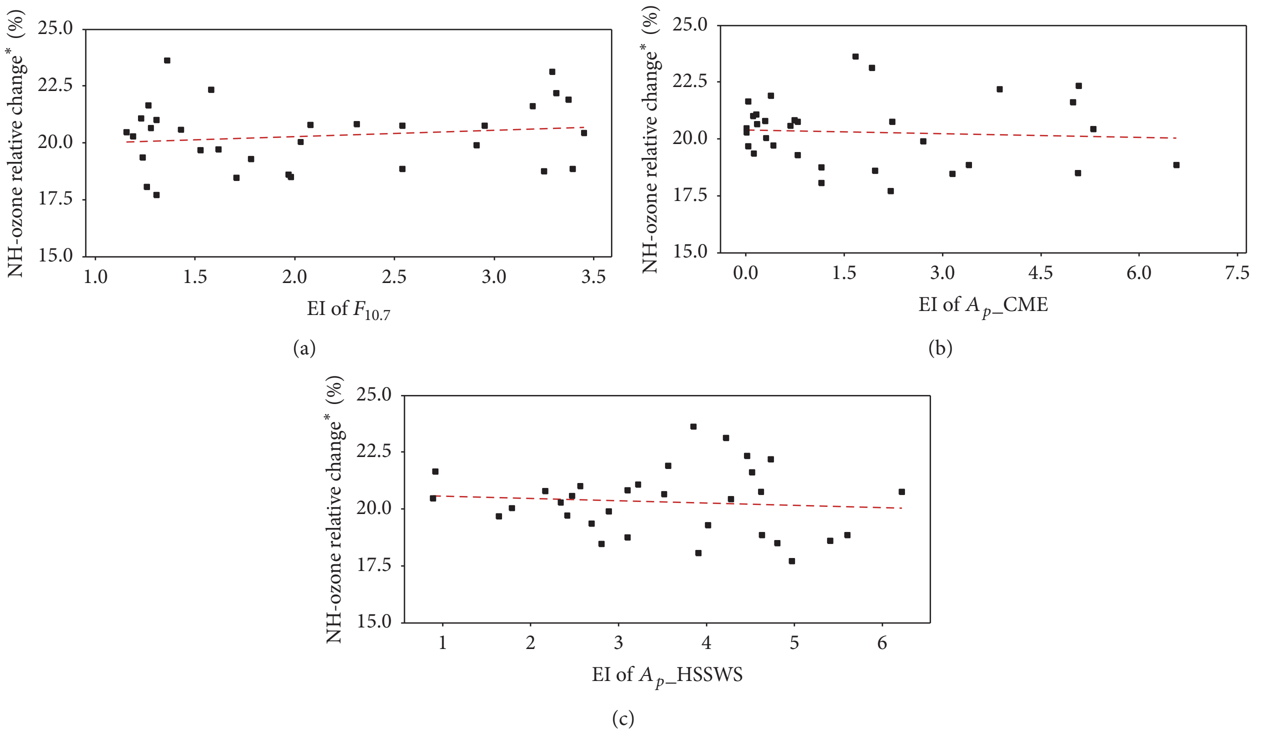


FIGURE 5: As Figure 3, but for the northern polar ozone (after detrending EESC effects). NH-$O^{*}_{var}$ denotes that the ozone data of NH has detrended the EESC effects.

that indirect EPP effects on ozone are of the same order of magnitude as those associated with the solar UV flux. To some extent, our results are in agreement with their conclusions. The differences between the hemispheres may relate to local photochemical conditions, transport processes, and the geomagnetic field [26, 27, 49, 51, 61–63]. The result regarding the apparent hemispheric differences (i.e., the impact of geomagnetic activity on polar ozone changes in the upper atmosphere is more significant in the SH than in the NH) is in general agreement with previous studies [49–51], in the sense that more stable vortices in the SH can help the EPP effects propagate from high levels downward to low levels in the southern polar upper atmosphere. This work is a preliminary statistical study of the impact of geomagnetic activity on polar ozone in the upper atmosphere. Assessment of the underlying physical mechanism is left for future studies.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Acknowledgments

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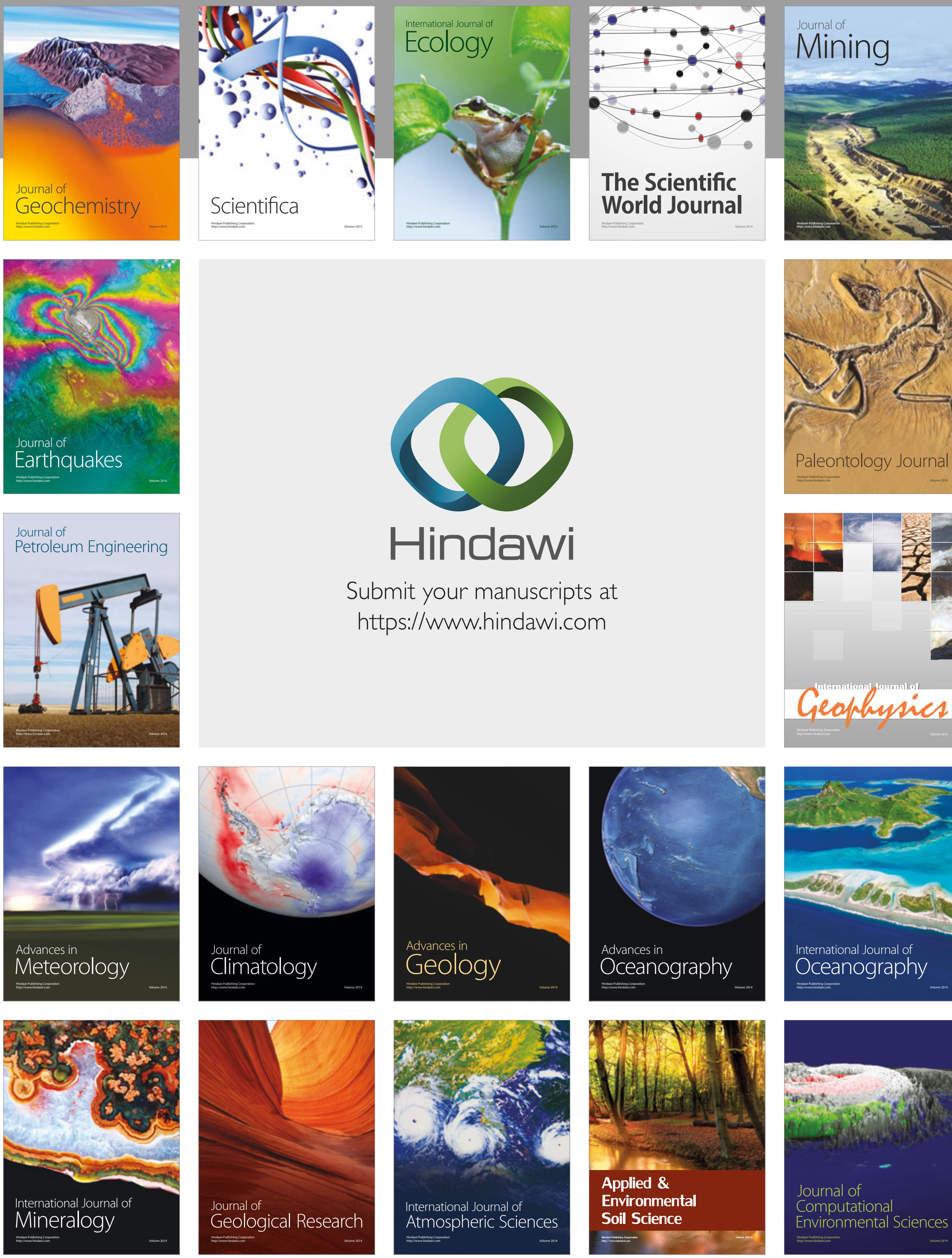
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