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Observed impact of land uses and soil types on cloud-to-ground lightning in Castilla-Leon (Spain)

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Abstract

The impact of land use on lightning activity has mainly been studied for urban areas, however the number of authors addressing the impact of vegetation on lightning is fairly limited. The relationship of different types of land use and soil (thirteen categories of land use and fourteen major soil types were considered) on cloud-to-ground lightning activity was studied in the Spanish region of Castilla-León from 2000 to 2010. To do this, urban, mining, and industrial areas were found to be associated with enhanced CG-lightning activity. With respect to natural land uses, forest and shrubland were the categories where CG-lightning was seen to be increased. By contrast, non-agricultural vegetated areas and pastures displayed the lowest CG-lightning activity. When the major soil types are considered, rendzinas, podzols, and phaeozems were found to be associated with a slight increase in CG-lightning activity and gleysols and solonchaks seems to decrease it. Assuming there are a plethora of factors which can indirectly affect the charging electromicrophysics and cloud dynamics, the authors provide evidence that soil type show a significant correlation on CG-lightning flash density and weather characteristics are affected by land uses. It is suggested that the influence of vegetation and soil on surface moisture is one of the main effects contributing to explain the impact of land cover on CG-lightning.

Keywords: Lightning/land index; land cover; soil types.

1. Introduction

Many studies (e.g. Pielke et al., 2011; Bounoua et al., 2010; Raddatz, 2007; Hirota et al., 2011; Giannakopoulou and Toumi, 2012) have reported that surface weather characteristics, even at large scale, are influenced by the moisture balances of the surface and the atmosphere and by the energy budget of the surface. The physiological and physical properties of the vegetation and their impact on soil moisture affect the transfer of heat, moisture, and momentum between the surface and the atmosphere. Arora and Boer (2014) stated that the main physiological parameters are leaf area, stomatal resistance and rooting depth, and that the main physical properties are albedo and surface roughness. There is a considerable body of literature that addresses the ways in which the land surface affects weather and climate (e.g. Raddatz, 2007 and references therein), including modelling (at global and regional scales) and observational studies. Almost all of these studies have focused on the effect of the transformation of natural vegetation.

The impact of land use on lightning activity has mainly been studied for urban areas. Increased cloud-to-ground lightning over urban areas and/or downwind has been reported both for large cities (e.g. Wescott, 2006; Kar and Liou, 2014) and small urban areas (Rivas Soriano and de Pablo, 2002). However, the number of authors addressing the impact of vegetation on lightning is fairly limited. Kilinc and Beringer (2007) analyzed the effect of vegetation on lightning in the Northern Territory of Australia and reported an increase in lightning strike density from woodland to shrubland to grassland, explaining this in terms of the greater surface heating of grassland with respect to other vegetation types. Kotroni and Lagouvardos (2008) studied the impact of the vegetation cover on lighting activity in the Mediterranean and found that for woodland areas lightning increased while over bare ground lightning activity was low.

They suggested that the maintenance of soil moisture in forested and wooded areas, especially during the Mediterranean dry, warm period, might explain their findings. Ray et al. (2011) reported that in agricultural areas adjacent to the natural vegetation in Southwest Australia, cumulus clouds were more frequent over areas with the highest soil moisture content. By contrast, we have not found any previous study exploring the impact of soil types on lightning activity, although the impact of lightning activity as a geomorphic agent has been studied (Kinght and Grab, 2014). Nevertheless, some of the causes invoked to explain the influence of land use on lightning, as maintenance of soil moisture and greater surface heating, could also act for some soil types. In fact, Liu and Shao (2013) found that soil-layer has a great impact on the simulated atmospheric boundary layer dynamics. Lightning science is very complex, and in regards to the soil types, there is no demonstration of how the soil affects. It is known that the flash rates to ground are explicitly determined by a complex combination of physical (outside and within the cloud), kinematic and dynamic processes occurring within the cloud give rise to electric fields structure conductive to cloud-to-ground lightning activity. However, the development of convective clouds is affected by the state of the boundary layer, which is influenced by the ground-atmosphere interaction which, in turns, depends on the soil type.

We note that the objective of present study is not to provide evidence of how environmental changes caused by land and soil types affect the electrical development of storms. Otherwise we explore the relationship of different categories of land use, and for the first time soil types, on cloud-to-ground (CG) lightning activity in the Spanish territory of Castilla-Leon (CL, see section 2). It is worth mentioning that CL is located on the Spanish plateau, which has been recognized as one of the regions in Europe of greatest frequency of severe thunderstorms (Brooks, 2013).

2. Area of study and data

The area considered in this study is CL, which is one of the 17 regions in which Spain is organized. It is located in the northwestern Iberian Peninsula (IP) (Figure 1), extending from 40ºN/1ºW to 42ºN/7ºW, with a total area of 94,193 km^2. The orography of CL is complex. It is a plateau at approximately 700 m above the sea (the Northern Plateau of the IP), surrounded by mountain systems: the Cordillera Cantabrica (northern), the Sistema Ibérico (northern and northeastern), the Sistema Central (southern and southeastern) and the Portuguese mountains (western). The Duero is the most important river and it crosses the region from east to west.

The CG lightning data used here belong to the time period spanning from 2000 to 2010. The lightning data were obtained from the lightning detection network operated by Spanish Meteorological Agency (Agencia Estatal de Meteorologia, AEMET). This network consists in 15 sensors model IMPACT (14 in the IP and 1 in the Balearic Islands). In January 2003, 4 Portuguese sensors were incorporated to the network (Perez Puebla, 2004). The probability of detecting a lightning flash occurring within an ellipse of 700 m^2 of area is 50%, 90% for an area of 2 km^2, and 99% if the area is lower than 5 km^2. Only the CG lightning data of highest quality were considered in this study. To obtain these data, the full database was filtered taken (chi-square) $\chi^2<3$ as threshold value, and the major and minor semi-axes of the error ellipse of less than 1 km and 0.5 km respectively. From a total of 570,382 CG lightning flashes counted by detection network over CL, the above mentioned filter retained 367,714.

Land use types and major soils were obtained from the CORINE land cover (CLC) raster data (CLC 2007 release, available at http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster) (Büttner et al., 2002) and AEMET

(Figure 2). These dataset provides a high-resolution description of land use patterns and major soils Figure 2 shows that are numerous different categories, especially of soil types, in the domain studied. However, several categories cover small percentages of area in the studied zone and their impact on CG-lightning activity is therefore expected to be no significant and, in consequence, they are not taken into account. We finally selected 13 categories of land use (urban, mining, industrial, non-agricultural vegetated areas, arable land, permanent crops, pastures, heterogeneous agricultural areas, forest, shrubland, open spaces, inland wetland, and water) (see figure 2b), and the 16 of soil types (luvisol, litosol, combisol, regosol, gleysol, rendzina, ranker, arenosol, fluvisol, acrisol, podzol, vertisol, solonchak, solonetz, kastanozem, phaeozem) (see figure 2a) present in the domain studied at a spatial resolution of 100 x100 m^2. Information about the characteristics of the different soil types can be found in Driessen et al. (2001).

3. Results and discussion

The spatial pattern of CG flash density in CL is depicted in Figure 3. The mean flash density is 0.5 fl km^{-2} yr^{-1}, ranging from 0 fl km^{-2} yr^{-1} to 3.4 fl km^{-2} yr^{-1}, and Figure 3a shows that CG-lightning activity tended to be concentrated over mountainous areas. Generally, lightning strike frequency increases with increased land surface elevation (i.e. mountain height), and shows strong seasonal and diurnal patterns related to the timing of the most intense convective storms (Rivas Soriano et al., 2005; Mattos and Machado, 2011). This is clearly seen in Figure 3b, where the relationship between the total (2000-2010) CG flash density and altitude is shown. CG-lightning activity increases from 750m to approximately 2100 m. It is worth mentioning that altitudes higher than 2100 m and lower than 700 m are rare in CL. It should be noted the outlier point over 2500m, which is probably caused by the very small area of the domain studied with altitude around 2500m. The increase of convective activity over complex terrain has been reported in a number of studies (e.g. Bartholtt et al., 2006; Santos et al., 2013), associated with orographic lift and mesoscale circulations generated by temperature discontinuities (e.g. Mohr and Kunz, 2013). The different land uses and soil types are not homogeneously distributed over the altitude range of the domain studied as is shown by comparing Figures 1 and 2 (for example the land use category forest and the rendzina soil type tend to predominate at high altitudes). Therefore, the orographic effect on CG-lightning activity masks the possible impact associated with the type of surface. Moreover, the area occupied by each land use and soil type is different (for example shrubland and arenosol are, respectively, the most widespread in CL, Figure 2a). This means that the effect associated with the differences in altitude and area must be filtered in order to analyze the possible influence of the land use and soil type in CG-lightning activity. To achieve this, we propose the index (henceforth referred to as *LLI*: lightning/land index) defined for each type j of land cover and soil type as:

$$LLI_j = \frac{F_j / A_j h_j}{F_T / A_T h_T},$$

where F, A, and h, are the number of CG-flashes, area, and mean altitude respectively, and the subscript T indicates the total spatial domain. For a given category j, A_j is the total area occupied by that category, h_j its mean altitude, and F_j the number of CG-flashes detected within the area A_j. *LLI* defines a kind of potential of each land use and soil type for the "generation" of lightning. Values of $LLI \sim 1$ would mean that the percentage of CG-lightning over each category of land use and soil type is equal to the percentage of area covered by each category with respect to the total area if the altitude were uniform over the area. Accordingly, when *LLI* > (<) 1, CG-lightning activity would tend to be enhanced (suppressed).

Figure 4a shows the *LLI* values for each land use category. The urban areas, and other areas strongly modified by the human activity, as mining and industrial areas, show *LLI* values clearly higher than 1. The increase of lightning activity associated with urban areas has been reported in a number of studies (e.g. Wescott, 2006; Pinto et al., 2004), and has also been found for cities in the domain considered here (Rivas Soriano and de Pablo, 2002). The urban effect on lightning activity has been associated with pollution (e.g. Bell et al., 2009) and frictional lifting (e.g. Atkinson, 2003; Farias et al., 2014). These arguments are also valid to explain the enhancement of CG-flash density in mining and industrial areas. Upon considering natural land covers, forest and shrubland are the types with *LLI* values clearly higher than 1. Both land cover types tend to retain soil moisture during the warm and dry period of the year, which is the period with the highest CG-lightning activity in CL (Rivas Soriano et al., 2005). Thus, over forested areas, the specific humidity of the convective boundary layer tends to increase. This generally results in strong increase in CAPE (Convective Available Potential Energy), especially if the boundary layer was previously moist (Pielke, 2013). This could explain that *LLI* > 1 for these land uses. Moreover, forested areas may act as a barrier for air flow, enhancing the upward movement, as indicated by Kotroni and Lagouvardos (2008). The lowest *LLI* values were found for non-agricultural vegetated areas and pastures, which display almost the opposite characteristics to those of forested areas: they do not retain soil moisture during the warm and dry season and neither have sufficient roughness to induce frictional lift.

Figure 4b shows the *LLI* values for each soil type. Rendzinas, Podzols, and Phaeozems exhibit *LLI* clearly higher than 1, suggesting that these soil types tend to increase CG-lightning activity. Rendzinas contain calcium carbonate (more than 40%), which absorbs water and favors high moisture content in this soil type. Accordingly, Rendzinas could behave like forested areas as regards enhancing CG-lightning activity. Moreover, Rendzinas are dark soils, which can reach higher temperatures than other zones due to solar heating, thus generating temperature discontinuities that may contribute to the development of local convection. Podzols and Phaeozems have high levels of organic matter, whose decomposition increases the concentration of positive and negative ions. This could explain the enhanced CG-lightning activity over these soils. The lowest values of *LLI* were seen for the Gleysols and Solochaks soils type, which are characterized by high permeability, generating groundwater and removing moisture from the surface levels.

4. Conclusions

This study explores the impact of different types of land cover and, for the first time, soil types on CG-lightning activity over the Spanish territory of CL. Eleven-year lightning data (2000 to 2010), and 13 categories of land use and 16 major soil types were considered. Urban, mining, and industrial areas were associated with enhanced CG-lightning activity. This was expected, considering the results found for cities in a number of studies. Forested and wooded areas also tend to enhance CG-lightning whereas, by contrast, non-agricultural vegetated areas and pastures tend to suppress it. With respect to the major soil types, rendzinas, podzols, and phaeozems can be associated with increased CG-lightning activity and gleysols and solonchaks seems to decrease it. The impact of vegetation and soil on land moisture is suggested to be the main cause of the incidence of on CC-lightning on such areas, although dark soils and increases in conductivity may also contribute.

There are a lot of factors that can indirectly affect the electro-microphysics loading and cloud dynamics, and this study only shows a correlation between land use/soil type and cloud to CG-lightning activity, and a possible explanation of the observations. More research is necessary to perform a comprehensive evaluation of how environmental changes caused by land uses and soil types affect the electrical storm development.

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Figure captions

Figure 1. Left: Location of the study area. Right: Orography of Castilla-Leon.

Figure 2. (a) Classification of the soils in Castilla y León according to WRB. (b) Land cover in Castilla -León. [Source: http://atlas.itacyl.es].

Figure 3. (a) Annual average cloud-to-ground flash density (flashes km^{-2} per year; resolution 1 km x 1 km). (b) Total (2000-2010) cloud-to-ground flash density (flashes km^{-2}) versus altitude (m).

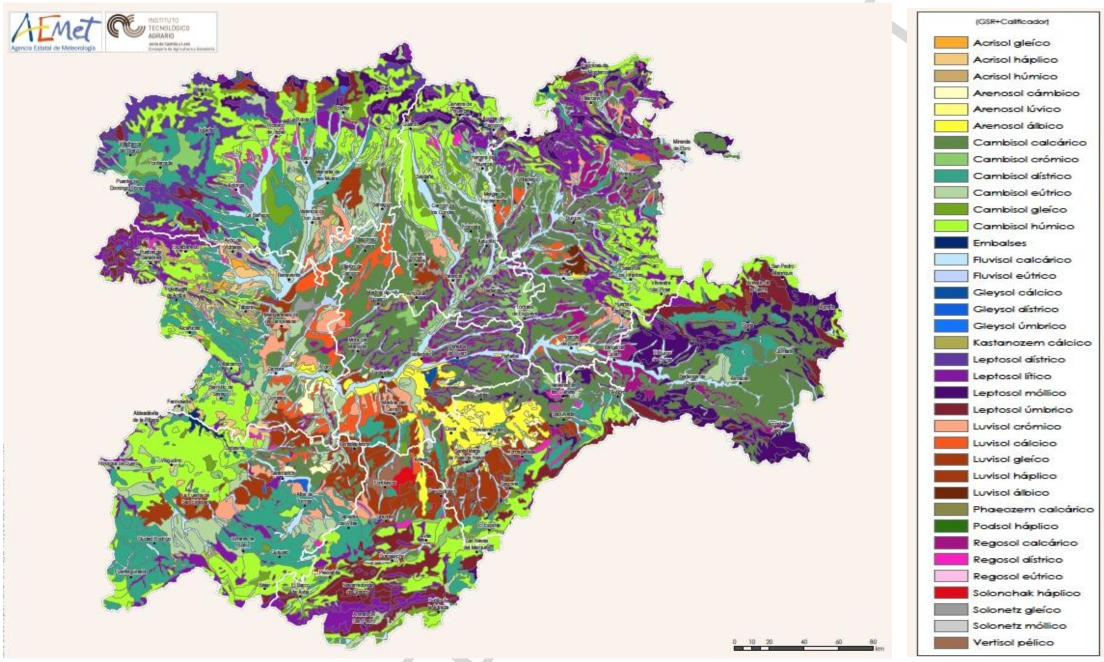
Figure 4. Lightning/land index (*LLI*) for each type of (a) land use and (b) major soil

Figure 1


NO
SE
IE
UK
NL
BE
LU
DE
PL
CZ
SK
SZ
SI
HR
BIH
SM
MC
IT
AD
PT
ES
MT
PICOS DE EUROPA
MONTES DE LEÓN
Sª ANCARES
León
Sª TELENO
Sª CABRERA
Burgos
Sª DEMANDA
Palencia
PICOS DE URBIÓN
Sª MONCAYO
Valladolid
Soria
Zamora
Sª AYLLÓN
Segovia
Salamanca
Sª PEÑA FRANCIA
Ávila
Sª GUADARRAMA
Sª BÉJAR
Sª GREDOS

Figure 2

(a)


(GSR+Calificador)
Acrisol gleíco
Acrisol háplico
Acrisol húmico
Arenosol cámbico
Arenosol lúvico
Arenosol álbico
Cambisol calcárico
Cambisol crómico
Cambisol dístrico
Cambisol eútrico
Cambisol gleíco
Cambisol húmico
Embalses
Fluvisol calcárico
Fluvisol eútrico
Gleysol cálcico
Gleysol dístrico
Gleysol úmbrico
Kastanozem cálcico
Leptosol dístrico
Leptosol lítico
Leptosol móllico
Leptosol úmbrico
Luvisol crómico
Luvisol cálcico
Luvisol gleíco
Luvisol háplico
Luvisol álbico
Phaeozem calcárico
Podsol háplico
Regosol calcárico
Regosol dístrico
Regosol eútrico
Solonchak háplico
Solonetz gleíco
Solonetz móllico
Vertisol pélico

(b)

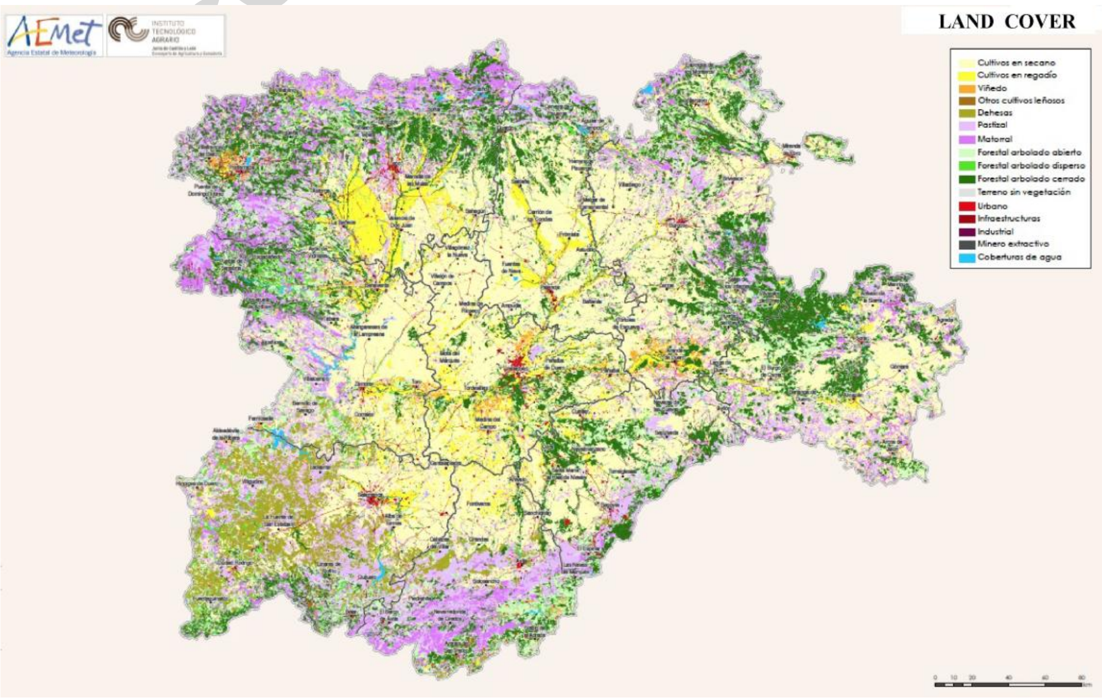
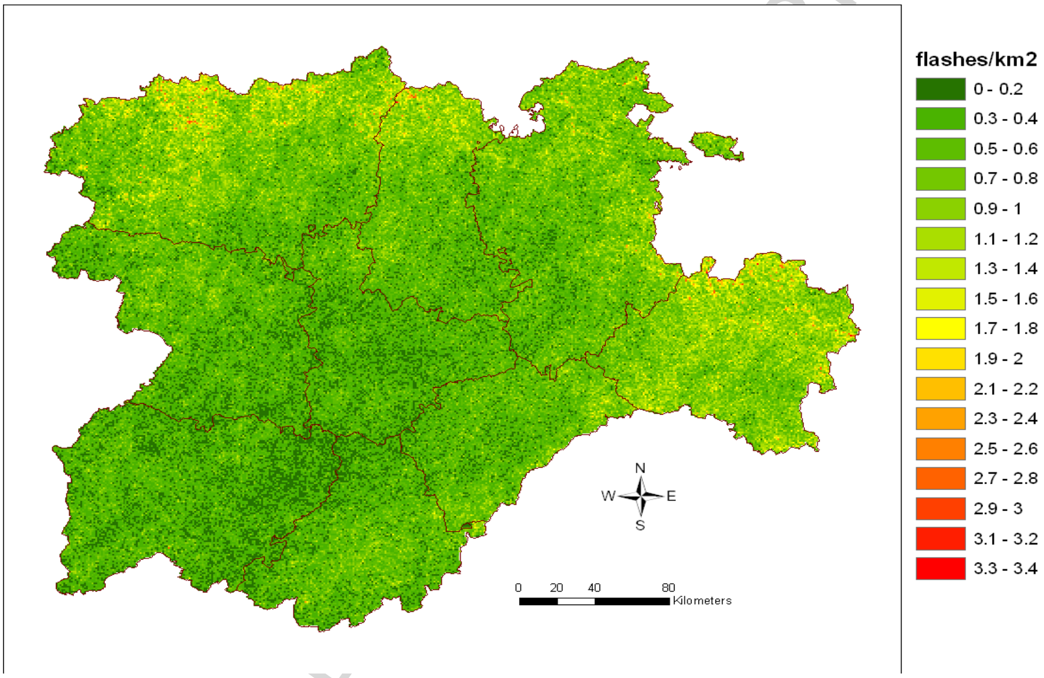

LAND COVER
Cultivos en secano
Cultivos en regadío
Viñedo
Otros cultivos leñosos
Dehesas
Pastizal
Matorral
Forestal arbolado abierto
Forestal arbolado disperso
Forestal arbolado cerrado
Terreno sin vegetación
Urbano
Infraestructuras
Industrial
Minero extractivo
Coberturas de agua

Figure 3

(a)


flashes/km2
0 - 0.2
0.3 - 0.4
0.5 - 0.6
0.7 - 0.8
0.9 - 1
1.1 - 1.2
1.3 - 1.4
1.5 - 1.6
1.7 - 1.8
1.9 - 2
2.1 - 2.2
2.3 - 2.4
2.5 - 2.6
2.7 - 2.8
2.9 - 3
3.1 - 3.2
3.3 - 3.4
N
W
E
S
0 20 40 80
Kilometers

(b)

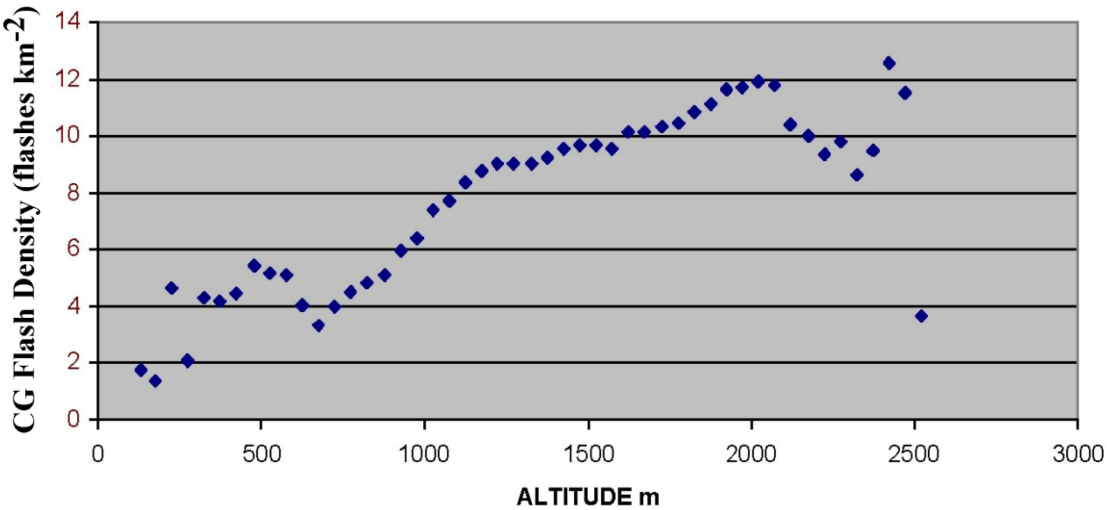
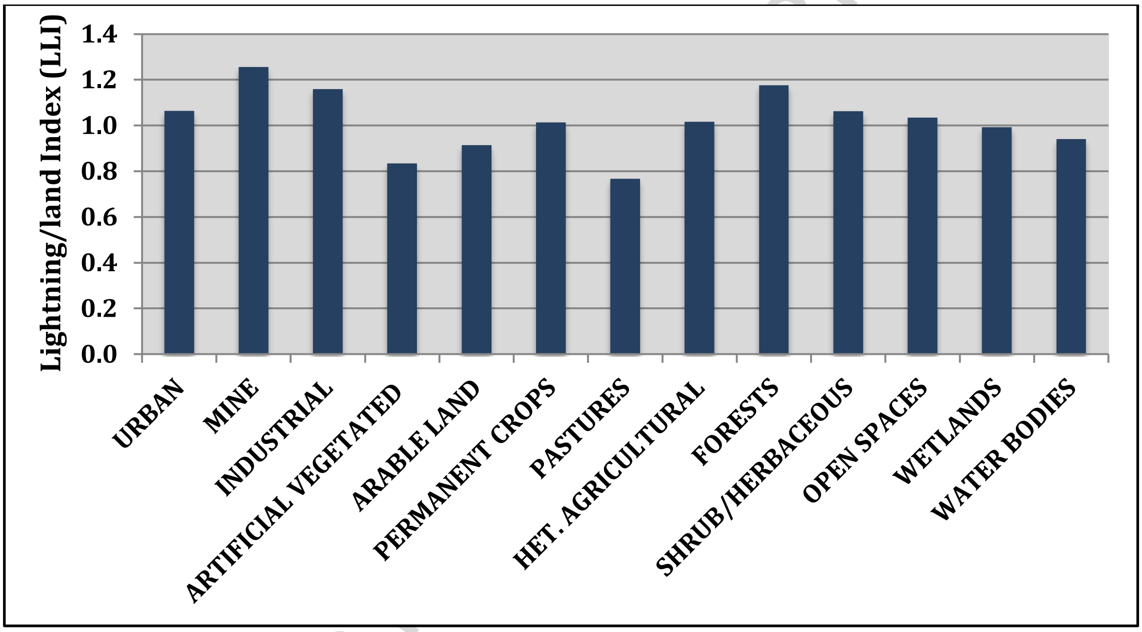
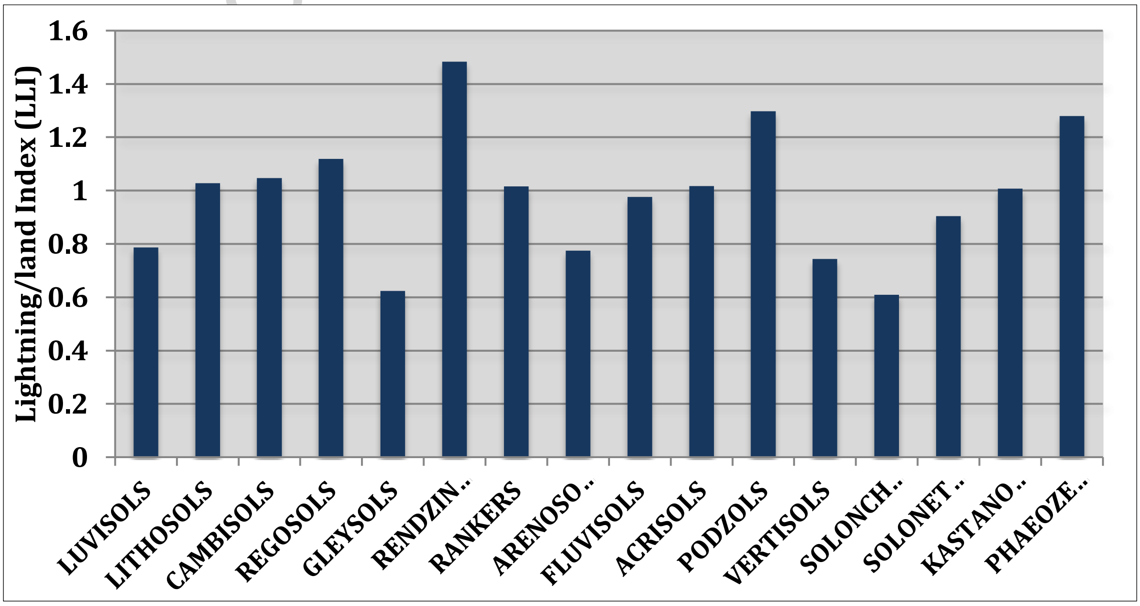

CG Flash Density (flashes km-2)
0
2
4
6
8
10
12
14
0
500
1000
1500
2000
2500
3000
ALTITUDE m

Figure 4

(a)


Lightning/land Index (LLI)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
URBAN
MINE
INDUSTRIAL
ARTIFICIAL VEGETATED
ARABLE LAND
PERMANENT CROPS
PASTURES
HET. AGRICULTURAL
FORESTS
SHRUB/HERBACEOUS
OPEN SPACES
WETLANDS
WATER BODIES

(b)


Lightning/land Index (LLI)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
LUVISOLS
LITHOSOLS
CAMBISOLS
REGOSOLS
GLEYSOLS
RENDZIN...
RANKERS
ARENOSO...
FLUVISOLS
ACRISOLS
PODZOLS
VERTISOLS
SOLONCH...
SOLONET...
KASTANO...
PHAEOZE...

Highlights

- The relationship of land use and soil types on CG-lightning activity is studied.
- An index was designed to filter out the effects associated by each category.
- Forest and shrubland were the categories of land uses where CG-lightning increases
- Rendzinas (soil types) were associated with an increase in CG-lightning activity.
- The influence of vegetation on surface moisture is the main effect on CG-lightning.