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Atmospheric Electric Field-Mill Sensor Field Campaign Report

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Acronyms and Abbreviations

AOD	aerosol optical depth
ARM	Atmospheric Radiation Measurement
CC	Carnegie Curve
DJF	December, January, February
ENA	Eastern North Atlantic
ENSO	El Niño-Southern Oscillation
FW	fair-weather
GEC	Global Electric Circuit
GLOCAEM	Global Coordination of Atmospheric Electricity Measurements
JJA	June, July, August
lowess	locally weighted scatterplot smoothing
MAM	March, April, May
NOAA	National Oceanic and Atmospheric Administration
PG	Potential Gradient
SON	September, October, November
SST	sea surface temperature
STD	standard deviation
UTC	Coordinated Universal Time

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1.0 Motivation

The foundation stone of atmospheric electricity is the existence of a Global Electric Circuit (GEC) influencing all of the planet. In fact, global thunderstorm activity acts as a voltage source that imposes a potential difference between the ionosphere (positively charged) and the Earth's surface (negatively charged) of about ~300 kV. Such potential difference is discharged through the poorly conducting atmosphere in fair-weather regions, with atmospheric electric fields of ~100 V/m. First evidence of the GEC was gathered by scientists involved on the *Carnegie* vessel expeditions (early 20th Century), in which they describe a similar daily variation of the atmospheric electric field in different parts of the Pacific Ocean. Such variation become known as the Carnegie Curve (CC).

Nevertheless, aerosols, mainly resulting from pollution, scavenge atmospheric ions and alter the atmosphere's electric properties (making it less conductive). This phenomenon tends to increase the atmospheric electric field and makes it almost impossible to observe the features of the CC at inland locations, especially if measurements are done near urban areas, which is the most common. For that reason, not much research has been done on the CC since the expeditions.

With this in mind, the ARM field campaign, Atmospheric Electric Field-Mill Sensor

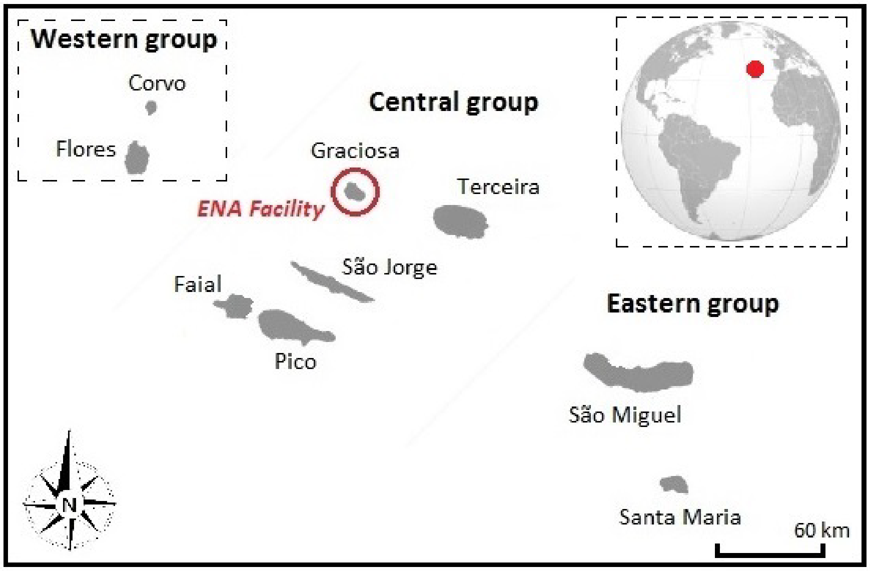

Figure 1. Representation of the Azores Archipelago together with the geographic location of ARM's ENA observatory on Graciosa Island (39º 03.12' N; 27º 57.10' W).

The field-mill used for the local atmospheric electric field measurements, a JCI 131F (Chilworth, United Kingdom), calibrated in December 2013, was installed at 2 m above ground (~31 m from sea level) and at a horizontal distance of 500 m from the seashore. Moreover, this equipment has a flat spectral response up to frequencies of ~100 Hz. A rate of 1-second sampling was used, with 1-minute mean and standard deviation being performed and recorded.

Figure 2 presents a photograph of the installation at the ENA site.

Figure 2. The JCI 131F field-mill (Chilworth, United Kingdom) installed at Graciosa, Azores.

3.0 Campaign and Data

This ARM-ENA campaign was designated as Atmospheric Electric Field-Mill Sensor, reference number AFC06722. It started on September 1, 2014, and was meant to end on August 31, 2021. However, high-quality data only started to be recorded by early 2015 and lasted until late 2020, when the field-mill was unfortunately broken. More details can be found at www.arm.gov/campaigns/ena2014aefms

Data gathered by this instrument were included in the Global Coordination of Atmospheric Electricity Measurements (GLOCAEM) project, which intended to build a database for a network of measurement sites across the world: https://glocaem.wordpress.com

Furthermore, the data were analyzed in two publications referenced below.

4.0 Results and Discussion

An initial assessment of the first year of measurements, starting on April 1, 2015, of the Potential Gradient (PG)[1] on Graciosa Island is depicted in Figure 3. It should be noted that the results discussed in this section are not representative of a long-term change, but can reveal a short-term response of the PG to atmospheric phenomena. In Figure 3a, the raw data of the PG is presented, for the clarity of the representation data is restricted to the range [0, 400] V/m (only ~3% data is out of the plot). Note the high variability characteristic of these measurements. The oscillations can occur due to several local factors such as nebulosity, rain, strong winds, space electrical charges, and even nearby insect or bird activity. This reflects the high sensitivity of the measuring equipment and for that reason only data that comprise fair-weather (FW) days were used further in the analysis; FW days are determined on the basis of the nebulosity index (details given below). Moreover, in Figure 3a, a lowess smoothing curve (solid blackline) is added to the plot as well as the average monthly PG values; these depict well the yearly variation of the PG. Contrary to what is observed in urban environments, where there is a tendency for lower PG values in the summer,[1] no clear annual tendency is observed in Graciosa, with the lower monthly PG value being found for January (~ 64.4 V/m) and higher in October (~102.8 V/m). Monthly PG variability (inset to Figure 2a) does seem to have some degree of seasonal tendency with summer months having lower standard deviation (STD). Nevertheless, the lower STD was found in February (~38.8 V/m) and the higher in September (~472.3 V/m). For the sake of clarity, seasons are separated: spring comprises March, April, and May (MAM); summer includes June, July, and August (JJA); autumn contains September, October, and November (SON); winter involves December, January, and February (DJF). These definitions will be used subsequently.

[1] Potential Gradient is related to the vertical component of the atmospheric electrical field, E_z, by the formula PG = E_z. This guarantees positive values for the PG in fair-weather conditions.

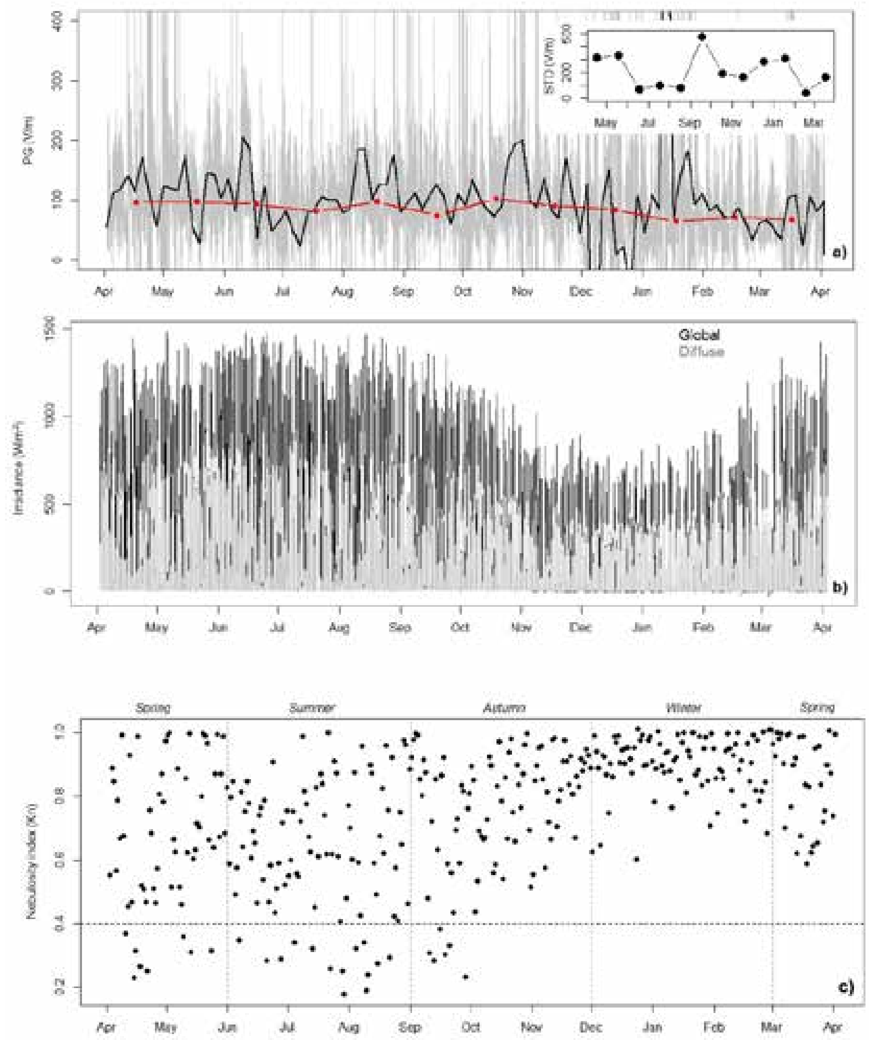

Figure 3. 1-minute raw data of the (a) Potential Gradient (V/m) strict to the [0, 400] V/m interval, (b) Global and Diffuse Irradiance (W/m^2), and the (c) Nebulosity Index (K_n) on Graciosa Island. The solid black line in (a) represents a locally weighted scatterplot smoothing (lowess) curve over the data and the defined PG interval is used to remove outliers that would make data visualization difficult; the dots in that figure represent monthly averages and the inset the monthly standard deviation.

Generically different hypotheses of both a local and global nature may be given to explain PG variability throughout the year at Graciosa. Among the local phenomena that might affect the PG are: (1) the atmospheric electric field can be charged or discharged due to the reduction or increase in the air conductivity, respectively; (2) the influence of clouds, as these are charged and tend to increase the PG.[2] The first hypothesis considers the variation of the air conductivity, which can occur by four different mechanisms: (i) variation in the concentration of small marine ions brought by the sea breeze[3], since the measurements are performed close to the sea (~500 m); (ii) the generation of space-charges due to the burst of water droplets by wave splashing, the so called balloelectric effect[4 and references therein]; (iii) variation of the local ionization by the variation of the emission rate of natural radioactive gases, mainly radon;[5] (iv) reduction or increase of the small ions concentration by an increased or reduced scavenging of the existing ions by water droplets and hygroscopic particles,[6] respectively.

In terms of global effects, the PG values tend to increase or decrease as a result of addition or reduction in the charging of the GEC, respectively, by generators, mainly lightning. The present results do not show a clear seasonality of GEC, in line with the work of Tacza and co-authors[7] who, when analyzing three years of PG data in South America stations, noted that the average daily shape during a month, season, or year repeats similarly for different years, supporting the results here presented. This is in contradiction with the seasonal variations observed in the *Carnegie* expedition data.[8]

Moreover, the analysis for the diurnal variation shows that the PG can be affected by different factors throughout the day. The criteria applied for the selection of the FW days was established on the nebulosity index (K_n), which is defined as the ratio between the diffuse (E_d) and global (E_g) horizontal irradiances (Figure 3b):

$$K_n = \frac{E_d}{E_g}, \tag{1}$$

where the index typically goes from 1 for overcast-sky to ~0.2 in clear-sky conditions. It should be said that radiation measurements are also done at the ENA site. Equation 1 is a simplification of the Perraudeau nebulosity index.[9] The obtained 1-day K_n is depicted in Figure 3c. To apply the nebulosity index in the FW selection, a number of different K_n were considered (Figure 4). The results show a diverse number of FW days and the corresponding average daily PG for each K_n obtained is shown in Figure 4. The nebulosity index that was selected for further analysis was for $K_n < 0.4$, as a trade-off of a statistically representative sample (28 days) and a smooth variation of the average daily PG curve (low relative standard deviation). PG curves for $K_n < 0.5$ and $K_n < 0.6$ are not suitable for FW criteria since they show sharp oscillations between 4 and 6 UTC that might be attributed to disturbed weather conditions. Additionally, an inset with the relative standard deviation (%) for each PG curve corresponding to different K_n is also depicted in Figure 4, as it was obtained through:

$$STD_{rel} = \frac{PG_{Std}}{\overline{PG}} \times 100(\%). \tag{2}$$

The inset plot in Figure 4 shows that the selected nebulosity index ($K_n < 0.4$) presents the best combination between a low relative standard deviation (i.e., a smooth variation from the mean value) and significant statistical samples (in this case, 28 FW days).

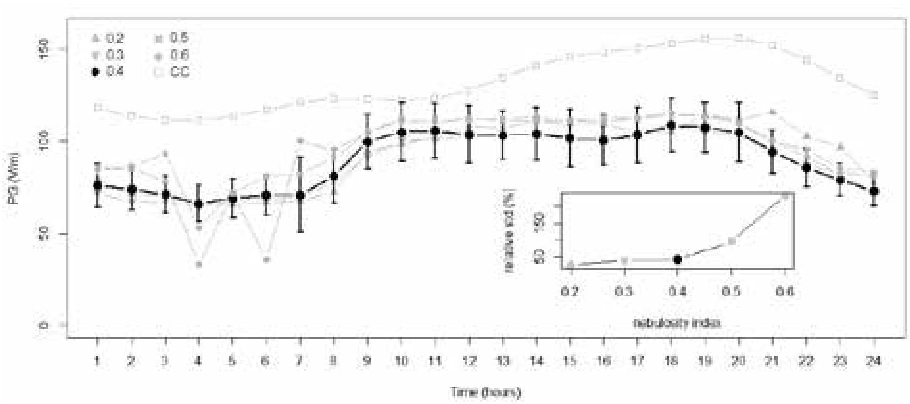

Figure 4. Daily averaged Potential Gradient (V/m) for each daily average nebulosity index K_n below 0.2, 0.3, 0.4, 0.5, and 0.6, together with the general Carnegie Curve (empty squares time series). Error bars are added to the PG curve corresponding to the 0.4 nebulosity index, while the inset shows the relative standard deviation (%) for each PG curve.

A deviation from the Carnegie Curve is observed in the FW PG daily mean curve: lower values with a more pronounced increase in the late morning hours (7 to 10 UTC) and a smooth variation during the afternoon. Additionally, a correlation of ~0.71, with a pvalue < 0.0001, was found between the selected Graciosa PG curve (marked in black) and the Carnegie Curve. The overall lower PG values, as compared with the Carnegie Curve, could be either related to instrumentation or to local effects. One possible local effect is ionization created by natural radioactive gases (radon) that is present over land, but absent in the ocean environment. It is commonly accepted that the two main sources of atmospheric ionization are cosmic rays and radon. To this can be added breaking waves near the seaside;[10,11] this is the case on Graciosa Island. In fact, being a volcanic island might as well promote radon migration from the Earth's surface.[12] Co-located measurements of radon are now being made and future analysis will consider both radon and PG together to explore this suggestion.[12] In the case of measurements in the open ocean like the ones done by the *Carnegie*[8] and other cruises,[13] the only source of ionization is cosmic rays and for that reason lower air conductivity is observed there,[13] and as a consequence of Ohm's law the PG is higher. The presence of natural radioactivity is possibly one of the main differences between the conditions in which the Carnegie Curve was measured and the measurements made in Graciosa Island. Another possibility is the presence of marine ions, as the Carnegie Curve results from measurements taken aboard ships, where there are no breaking waves, contrary to Graciosa, where waves break all along the coastline, allowing the generation of many marine ions. These ions are highly mobile and tend to discharge the local electric field by increasing air's conductivity. This effect has been reported[10] such that when the wind came directly from the sea, there was a greater influence of marine air and the air tended to rise in conductivity.

A closer look into the data, applying the same nebulosity index criteria, but dividing the data into seasons spring (MAM); summer (JJA); autumn (SON); winter (DJF) showed the existence of 8 FW days for spring, 14 FW days for summer, 6 FW days for autumn, and none for winter. The mean daily PG curves and corresponding Carnegie Curves (CC) (obtained from parameters estimated by [8]) for each season are shown in Figures 5a, b, and c. In these plots, we added the mean daily aerosol optical depth (AOD) behavior for the corresponding days of FW used in the PG calculations for each season. Generally, the summer tends to show lower values of AOD coinciding with a better agreement between the PG and CC curves for this season. This could indicate the role that aerosols, as a local effect, might have in the deviation of the measured PG from the signal imposed by the global modulation of the electric field as uttered by the CC.

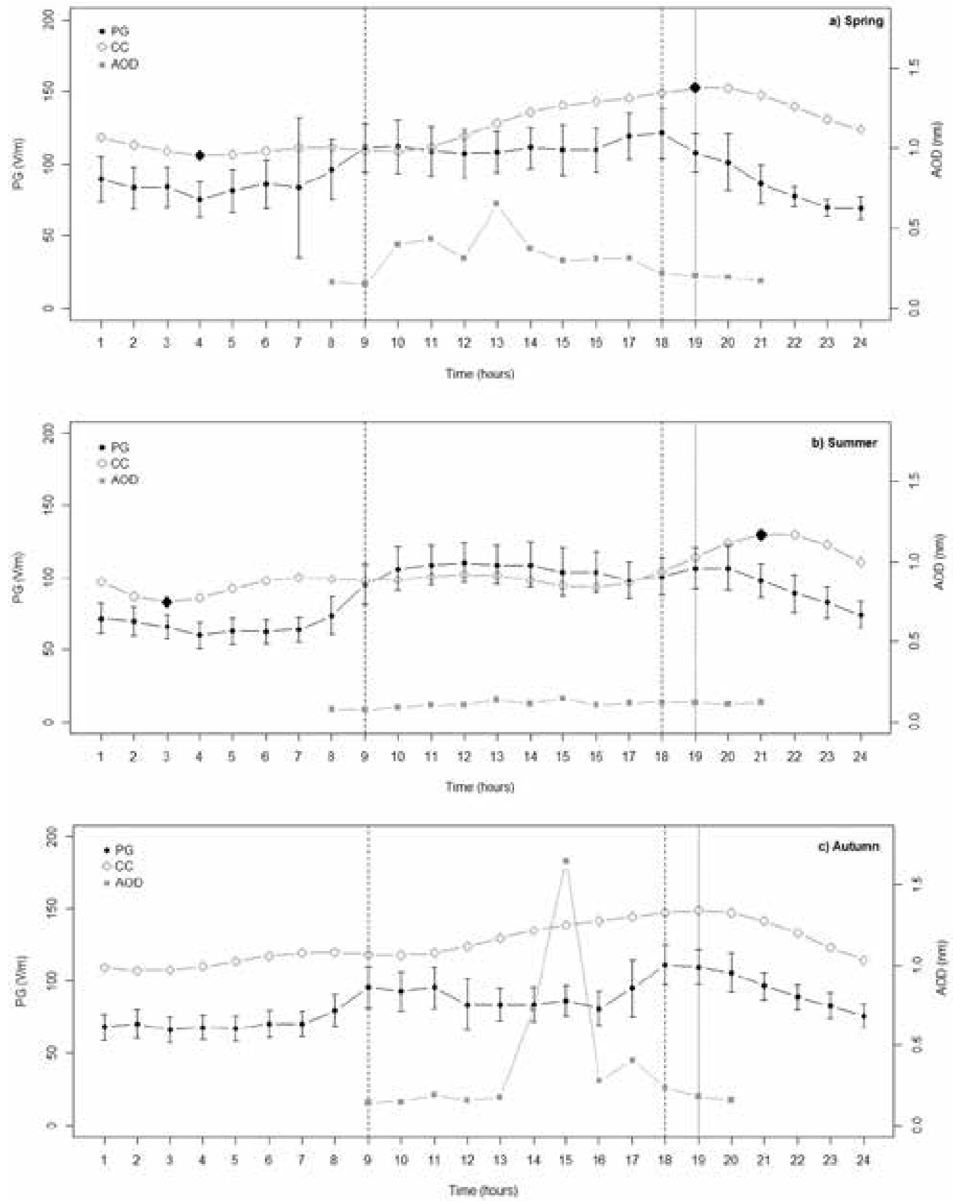

Figure 5. Daily mean Potential Gradient, the corresponding Carnegie Curve, and the daily averaged AOD for: (a) spring; (b) summer, and (c) autumn. Left y-axis corresponds to the PG and the right y-axis to the AOD (440 nm).

Comparing the PG curves in the three seasons, we see that they have similar behavior, showing the expected minima at dawn and the maxima in the evening (in conformity to the minima and maxima observed in CC for each season). The small contrasts observed are probably due to the fact that the PG measurements at Graciosa are more sensitive to thunderstorms in America, Europe, and Africa than to those in Asia and Australia. In the first three regions, thunderstorm activity tends to have its minima later in comparison with the last two ones.[8] In terms of the daily PG maxima, they occur at 18 UTC in spring (second dashed line in the plots), 19-20 UTC in the summer (dotted line in the plots), and 18-19 UTC in autumn. This is approximately one hour earlier than the CC references that have their maxima at

19-20 UTC, 21-22 UTC, and 19 UTC, respectively, for spring, summer, and autumn. This shows that the seasonal change in the time of occurrence of the afternoon PG maximum at Graciosa is consistent with the change of the maximum of the CC references (Figures 5a, b, and c), though the CC maxima occur around one hour later. The fact that PG maxima are recorded earlier in Graciosa Island also suggests the possible influence of the proximity of the European and African continents, where thunderstorm activity peaks are attained around 13 UTC; while American thunderstorm activity peaks around 19 to 20 UTC.[8]

In this context, the effect of the strong 2015 El Niño should help in understanding the seasonal change in the time of occurrence of the PG maximum at Graciosa. In Figure 6 large positive weekly sea surface temperature (SST) anomalies in the Eastern Pacific, Niño 1+2 (0-10° South, 90°-80° West) and Niño 3 (5° North-5°South, 150° -90° West), are clearly identified for 2015, depicting a strong increase during the spring (dashed vertical line) and summer (pointed vertical line) months. El Niño-Southern Oscillation (ENSO) data from 6 January 2010 to 27 July 2016 here presented was retrieved from the National Oceanic and Atmospheric Administration (NOAA)'s website (www.cpc.ncep.noaa.gov). El Niño is known to affect the global distribution of thunderstorms, shifting Pacific thunderstorms eastward, increasing the relevance of the American thunderstorms peak in Graciosa Island. In fact, there is a growth in the intensity of thunderstorm activity between spring and summer over North America[14] that results from the ENSO strengthening that has been occurring since 1996. Comparison with La Niña years will be done in the future.

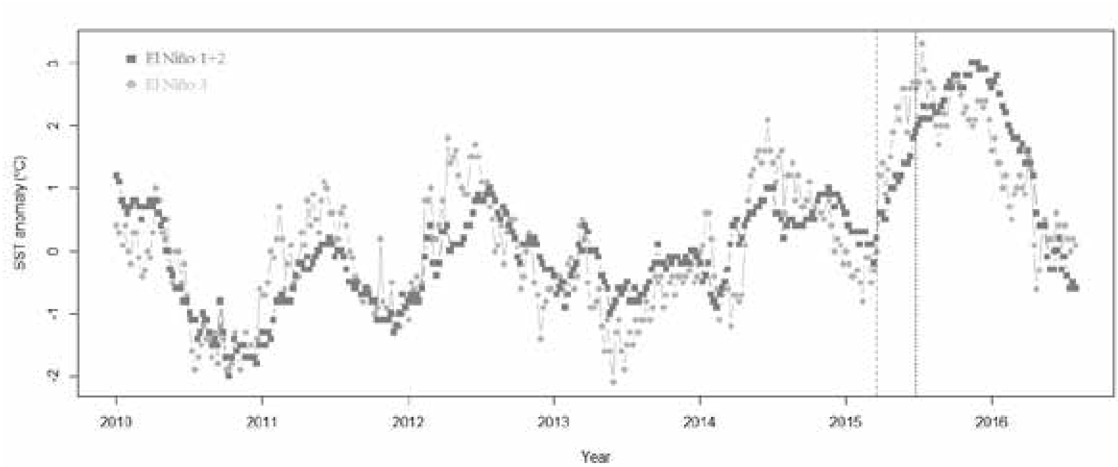

Figure 6. Weekly SST anomalies during ENSO (6 January 2010 to 27 July 2016). Vertical dashed lines mark the beginning of spring and summer seasons during 2015 for El Niño 1+2 (0-10S, 90-80W) and El Niño 3 (5N-5S, 150-90W). The depicted data is available online and can be retrieved from: www.cpc.ncep.noaa.gov/data/indices/wksst8110.for

On the other hand, the first vertical dashed lines mark the observed PG increase during the morning (around 9-10 UTC) for the three curves in Graciosa, but not observed in the Carnegie reference curves that show a smooth increase from the dawn minima to the evening maxima. This deviation of the diurnal Graciosa PG from the CC during the late morning is difficult to interpret in the context of the GEC. Such deviation is expected to be due to near-surface aerosol generated in the island after sunrise, which would reduce the air conductivity in the morning. In some respect, this is a feature common to inland stations in which it is often observed as a double maximum: (1) in the morning, due to the rise of near-surface aerosols; (2) in the evening, due to the GEC. This behavior is particularly clear for the spring and autumn PG curves in Graciosa, Figures 5a and c. Nevertheless, the mean AOD values, also measured at the ENA site, for that time (9-10 UTC) of the day are low (0.15, 0.08, 0.15 for spring, summer, autumn, respectively), corresponding essentially to clean aerosol conditions according to the definition given by[15]: AOD (440 nm) < 0.12. More interesting is the fact that in the period from 10 UTC to 16-17 UTC, while there are relatively high values of AOD, the PG seems to suffer a reduction. In fact, there seems to be an AOD peak (13 UTC in spring and 15 UTC in summer and autumn, reaching 0.65, 0.15, and 1.65, respectively, for each season) accompanied by a PG minimum one to three hours later (16 UTC in spring, 17 UTC in summer, and 16 UTC in autumn, with PG values of 107.7, 98.9, 81.4 V/m, respectively, for each season). Since the AOD data have large standard deviations (not shown here), their relevance to the PG analysis should be considered with particular care.

Nevertheless, the only possibility that can be inferred to explain these observations is that the AOD measurements are measuring aerosols mixed with some sort of charge carriers (which are not accessible to AOD) that would tend to increase the atmospheric electric conductivity (reduce PG), balancing the aerosol effect that is, to reduce atmospheric electric conductivity (increase PG). The measurements are made at the seaside and according to the observations made in similar sites[10,11] the influence of marine ions can be hypothesized to explain the observations. Many studies can be found in the literature dedicated to the formation of space-charge distributions (basically the imbalance between positive and negative small ion clusters) at seaside locations[16,17,18] that might support the present hypothesis. The typical marine cations are H^+, NH_4^+, Na^+, Mg^{2+}, K^+, Ca^{2+} and anions are NO_3^-, Cl^-, SO_4^{2-}, HCO_3^-[19]

Although they should be hydrated by water molecules while remaining in the atmosphere, these ions have high electric mobilities and should, for that reason, increase the atmospheric electric conductivity and, as a consequence of Ohm's law, they should therefore reduce the PG.[10] For this to explain the reduction of the PG while observing a peak in the AOD means that the concentration of marine ions has to be significant. A simple estimation of the amount of space-charge needed for the observed PG minimum can be made for the autumn using the Carnegie value as reference, 141.9 V/m, and the measured PG, 81.4 V/m, at 16 UTC. The difference of the two values is ~60.5 V/m, which if attributed to the space-charge created by the marine ions, allows the use of Equation 8 from [20] (assuming similar parameters) to estimate the space-charge to be nearly ~103 pC/m^3; which is a very reasonable value indeed.[20,21] Taking into account that waves break all along the seashore of the island (with a power around ~20-30 kW/km of wave front), it is easy to understand that those marine ions are constantly being sprayed into the atmosphere. The concentrations can be higher in more convective situations, as is the case for the midday. The same happens for marine aerosols explaining the midday AOD peak, even though the effect of the marine ions on the PG should be prolonged since these ions have large characteristic times of recombination (well above the ~20 s for polluted regions), as this is a very low-pollution environment. After 19 UTC the AOD is again below or near to the 0.12 threshold for clean aerosol conditions and the GEC signal is recovered as it is revealed by the evening maxima in the PG curves for the three seasons (Figures 5a, b, and c), as previously discussed.

In short, unlike the *Carnegie* cruise expeditions, which were entirely ocean based, Graciosa is an island, so it will experience wave-break and wind-blown aerosols and ions in the immediate vicinity of the electric field-mill (~500 m from the shore). This means that the local effects of increased aerosol and ion concentrations after sunrise until sunset are still observed, causing the PG to depart from the GEC signal and approach that of an inland situation. Still, before sunrise and after sunset, the PG at Graciosa tends to reproduce the CC behavior very well, making this period suitable for GEC research.

5.0 Conclusions

For the first time, measurements of the atmospheric electric field have been carried out at the ARM-ENA facility on Graciosa Island (Azores archipelago) as part of a network effort for the study of the Global Electrical Circuit variability. Results show that under fair-weather conditions, the island's Potential Gradient is locally affected by marine air. These conditions tend to alter the diurnal Potential Gradient away from the Carnegie towards that seen at land sites. On a global scale, Graciosa Island appears to be a good place for the study of the GEC because signatures of large-scale systems such as ENSO are apparently observed in the seasonal changes of Potential Gradient.

Further work would have to be dedicated to the analysis of the remaining years of data, from which very promising results are expected. These could not only provide new perspectives on the Global Electric Circuit recent evolution, but also motivate new field campaigns.

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7.0 Publications Related to the Campaign

1. Lopes, F, HG Silva, AJ Bennett, and AH Reis. 2017. "Global Electric Circuit research at Graciosa Island (ENA-ARM facility): First year of measurements and ENSO influences." *Journal of Electrostatics* 87: 203 211, https://doi.org/10.1016/j.elstat.2017.05.001
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