JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 99, NO. 10, PAGES 19,475–19,483, OCTOBER 1, 1994

Observations of ionospheric electric fields above atmospheric weather systems

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Abstract. We report on the observations of a number of quasi-dc electric field events associated with large-scale atmospheric weather formations. The observations were made by the electric field experiment onboard the San Marco D satellite, operational in an equatorial orbit from May to December 1988. Several theoretical studies suggest that electric fields generated by thunderstorms are present at high altitudes in the ionosphere. In spite of such favorable predictions, weather-related events are not often observed since they are relatively weak. We shall report here on a set of likely E field candidates for atmosphere-ionosphere causality, these being observed over the Indonesian Basin, northern South America, and the west coast of Africa; all known sites of atmospheric activity. As we shall demonstrate, individual events can often be traced to specific active weather features. For example, a number of events were associated with spacecraft passages near Hurricane Joan in mid-October 1988. As a statistical set, the events appear to coincide with the most active regions of atmospheric weather.

Introduction

In this paper we shall present examples of quasi-dc electric field events occurring above intense atmospheric weather systems observed at ionospheric altitudes. These events are observed by double floating probe experiment onboard the San Marco D satellite. Thunderclouds are known sources of dc electric fields. However, the enhanced conductivity of the ionosphere is thought to shield much of the quasi-dc fields from the upper ionosphere and magnetosphere. The observations presented here suggest the ionosphere shielding is effective but not perfect, thus allowing the weather-related quasi-dc electric fields to be observed as high as 270 km above the ground.

The typical, mature thundercloud is an electric dipole consisting of an accumulation of negative charge near the low-altitude cloud base and positive charge near the high-altitude cloud top. Large upward directed electric fields exist both above and below the thundercloud which drives current upward from the Earth to the ionosphere through the resistive atmosphere. In the simplest global circuit model, like that shown in Figure 1, the Earth and ionosphere can be considered highly conductive, redistributing charge at their surfaces in association with the inducing thundercloud electric field. In the ionosphere the charge redistribution can shield the electric field so that the field is not observed at higher altitudes. However, the effectiveness of this shielding is dependent on the ionospheric conductivity. The global circuit is completed by the downward directed electric field which drives current from the ionosphere back to the Earth through the resistive atmosphere. At any given time, approximately 2000 thunderstorms are active on the Earth surface, giving rise a downward current of approximately 10^{-12} A/m^2 and electric field of -100 V/m at the ground in fair-weather regions. A thorough review of this process is found in the work by *Volland* [1984].

Paper number 94JA01135.
0148-0227/94/94JA-01135$05.00

In the simple global circuit model the ionosphere is treated as a highly conductive plate which effectively "shorts" the electric field at the ionosphere base. Compared to the resistive atmosphere, the ionosphere is indeed highly conductive. However, the ionosphere is not a perfect conductor. The reaction of the ionosphere to external electric fields, like those created by thunderstorms, is a complicated function depending upon diurnal effects, incident frequency, external solar activity, etc. Because the conductivity values are finite, quasi-dc electric fields should be detectable at high altitudes.

Balloon experiments passing over thunderstorms at stratospheric altitudes (~35 km) indicate the presence of strong electric fields aligned upward, in a direction opposite to the typical fair-weather field [*Holzworth*, 1981; *Bering et al.*, 1980]. The field strengths at these altitudes can be 10 V/m. It has also been demonstrated that the local conductivities above thunderstorms is altered from fair-weather values [*Holzworth et al.*, 1986; *Pinto et al.*, 1988]. Theoretical studies using realistic ionosphere conductivities suggest that such fields should be detectable at ionospheric altitudes, albeit attenuated from their low-altitude values [*Park and Dejnakarintra*, 1973; *Dejnakarintra and Park*, 1974;

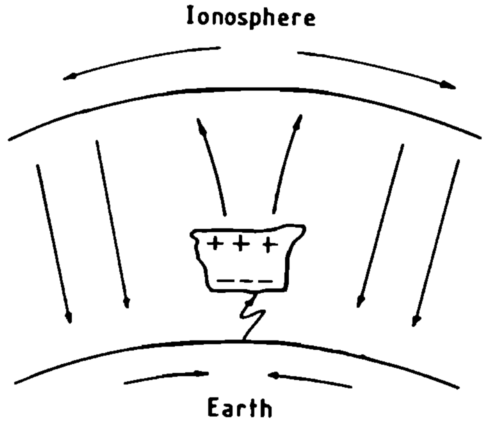

Figure 1. An illustration of the global circuit (adapted from *Volland* [1984]).

Greifinger and Greifinger, 1976]. For example, *Dejnakarintra and Park* [1974] indicate that a quasi-dc electric field detected at a horizontal distance of 5 km from the cloud charge and a vertical distance of 20 km altitude will be reduced by 60 dB at 70 km altitude and 140 dB at 100 km altitude (see their Figure 5). Thus an initial 100 V/m field at 20 km will be reduced to 0.1 V/m at 70 km and 10 μV/m at 100 km. *Greifinger and Greifinger* [1976] predict a similar attenuation. However, they demonstrate that while the vertical component of the electric field quickly decreases with altitude, the horizontal component should remain nearly constant with altitude above about 85 km, with values of about 10 μV/m for each Coulomb of cloud charge (i.e., for a typical value of 20 C following a discharge, the field above 85 km is about 0.2 mV/m). Thus theoretical predictions suggest ionospheric *E* field values of about 10–100 μV/m above a thundercloud.

Despite theoretical predictions of observation, detection of storm-related dc electric fields at ionospheric altitudes are rarely made. During the Thunder rocket campaign, storm-related quasi-dc electric field signals were detected above the cloud tops by *E* field instruments onboard both the Thunder Hi and Thunder Lo rockets [*Kelley et al.*, 1985]. These signals were of a transient nature, lasting of the order of a tenth of a second and coincided exactly with higher-frequency sferic observations. The Thunder-lo payload at 88 km easily detected the event, but the Thunder-hi payload at 142 km detected a much weaker signal. As described by *Kelley et al.* [1985], this attenuation is consistent with the theoretical predictions. However, the transient nature of the event is not at all like the longer-lasting spatially large *E* fields detected by balloons over storms or like the events reported here.

In this paper we report on intense quasi-dc electric field events associated with large atmospheric weather systems by the San Marco D spacecraft, these being observed between 188 and 270 km altitude. Such events at these high altitudes have not been reported previously. These observations suggests that strong weather-related dc *E* fields can be observed at high altitudes. A most unusual characteristic of the cases presented is that their intensity is over 20 dB greater than that predicted from theory. We shall discuss some potential mechanisms for these enhanced intensities.

Instrument Description

The San Marco D satellite was launched on May 25, 1988, into an elliptical orbit of 610 km apogee and 275 km perigee and 2.9° inclination. The satellite successfully returned data until reentry into the atmosphere, this occurring on December 5, 1988. The apogee/perigee history of the spacecraft is shown in Figure 2. The satellite was oriented such that its spin axis (+*Z* axis) pointed toward the south geographic pole. As a consequence, the spacecraft spin plane was nearly aligned with the equatorial plane and approximately contained the spacecraft zenith and nadir directions. The spacecraft spin rate was at 0.1 rps.

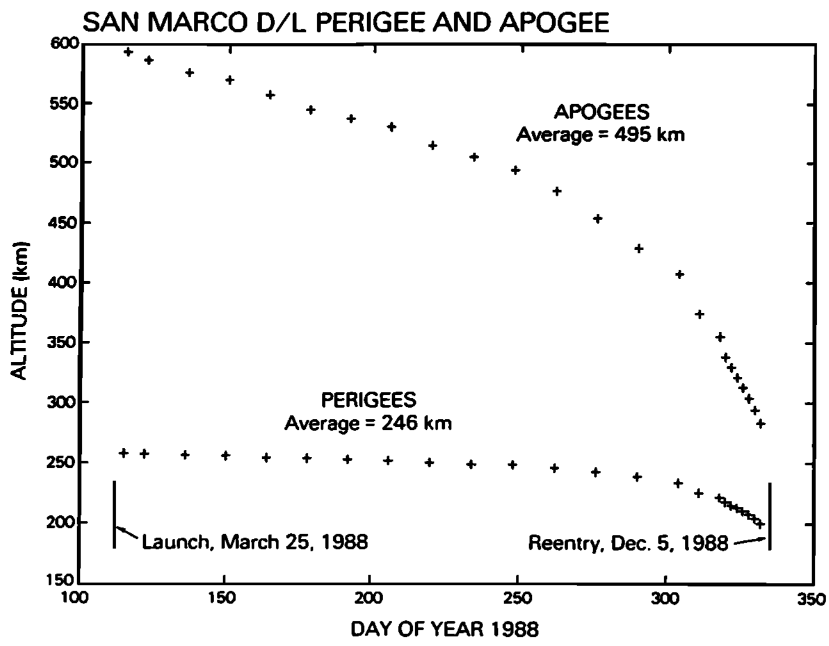

Figure 2. The apogee and perigee history for the San Marco D satellite.

Two pairs of 20-m antennae were deployed in the spacecraft spin plane. These antennas were insulated for the first 14.5 m and last 0.5 m, allowing 5 m of exposed surface centered 17 m from the spacecraft. This geometry allowed each antenna pair to be configured as cylindrical double probe antenna with 35-m baseline. Antennas along the spin axis were also employed, but these were too short (i.e., 2.5 m) to make reliable dc *E* field measurements. The San Marco D antenna configuration is shown in Figure 3. Signals from these antennas drive both a quasi-dc and ac electric field packages. The instrument package is very similar to that onboard DE 2. Specifically, the quasi-dc electric fields are measured at a rate of 16 vector samples per second, with 14-bit resolution. The ac electric fields are monitored using a 20-channel comb filter system covering a frequency range between 4 Hz and 512 kHz. All frequency bands are characterized by a sixth-order Butterworth filter response and possess an approximately 70-dB instantaneous dynamic range. For further information on the details of these packages, refer to the DE 2 instrument description found in the work by *Maynard et al.* [1981].

The quasi-dc electric field data returned to the ground is a vector measurement obtained in the spinning spacecraft frame of reference. Data analysis includes despining the measurements using spacecraft altitude information, resulting in an inertially defined *E* field vector quantity. In order to observe details the **V** × **B** electric field created by the spacecraft moving at velocity **V** through the terrestrial magnetic field is vectorially subtracted from the measurements. This **V** × **B** electric field can be as large as 200 mV/m, but upon removal, reliable values to 0.75 mV/m are obtained. It is this despun, **V** × **B**-subtracted data set that is highlighted in this paper. Removing the spin effect from the measurements is not always perfect and sometimes leaves a residual spin modulation in the data. Some examples of residual spin modulation are described below.

Figures 4 and 5 show examples of the data display. The E_x and E_y measurements are obtained from transforming the signals from the long 20-m antennas located in the spin plane to a vertical and longitudinal coordinate system. The top panel of the figures contains the E_x measurements, where x is directed in the nadir direction. The middle panels display the E_y measurements, where y is directed in the geographic east direction. Residual spin modulation in E_y due to small inaccuracies in the despin process is clearly evident between 1513:00 and 1513:40 UT in Figure 4. The spin axis antennas measuring in the latitudinal direction are not very sensitive and thus are not used in the analysis. The bottom panel of the figure shows the measured ion density obtained from a biased, axially symmetric ring collector mounted on top of

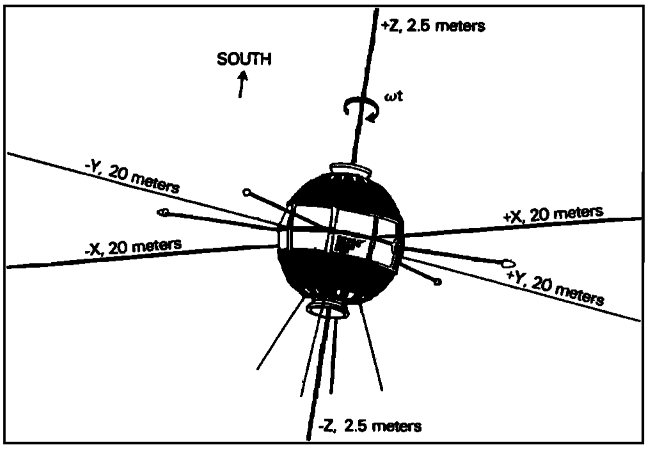

Figure 3. An illustration of the San Marco D spacecraft, showing the various antennae.

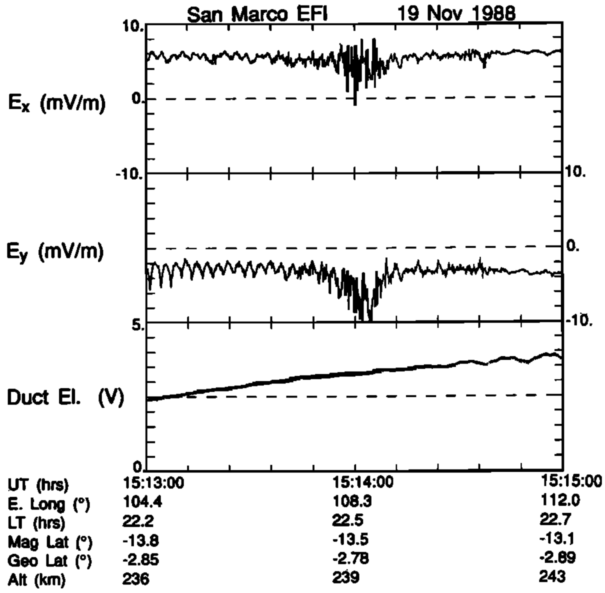

Figure 4. The measured quasi-dc electric field event on November 19. The top panel of the figure contains the E_x measurements, where x is directed in the nadir direction. The middle panel displays the E_y measurements, where y is directed in the geographic east direction. The bottom panel shows the measured ion density obtained from a biased, axially symmetric ring collector mounted on top of the spacecraft about the $+Z$ axis.

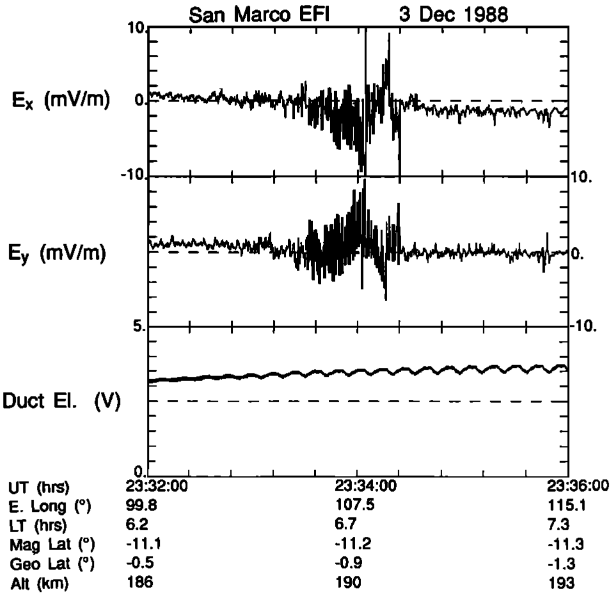

Figure 5. A similar event as shown in Figure 4, observed 14 days later over nearly the same location.

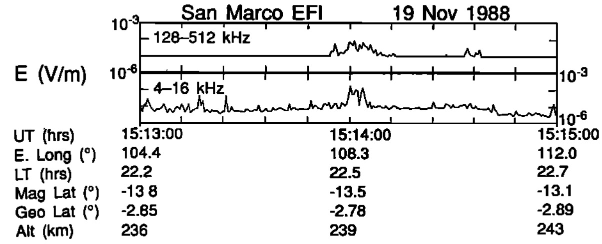

Figure 6. The associated AC electric field measurements during the same event as shown in Figure 4.

the spacecraft about the $+Z$ axis. In spite of the symmetric geometry the sensor still displays a noticeable spin effect, which is believed to be due to contamination of part of the ring surface [*Aggson et al.*, 1992]. This spin effect is quite apparent after 1514:30 UT in Figure 4 and throughout the event in Figure 5. It should be noted that when the ion density drops below about 10^4 cm^{-3}, capacitive coupling of the double-probe antenna to the plasma becomes important, introducing a phase shift in the measurements of several degrees. This error is difficult to remove. Thus E field values measured in regions where the density is below this critical value are considered suspect. This critical density is identified by the dashed line in the bottom panel. For details concerning this capacitive coupling phase shift, see the appendix in the work by *Aggson et al.* [1992].

For comparison with the San Marco measurements, we will often refer to terrestrial microwave images obtained by the Special Sensor Microwave/Imager (SSM/I) onboard the F-8 Defense Meteorological Satellite Program (DMSP). The SSM/I measures the incident and reflected microwave emission at 19.4, 22.2, 37.0, and 85.5 GHz. The brightness temperature as measured by the instrument is a function of radiation emitted from the Earth's surface and the constituents within the intervening atmosphere. Large raindrops and ice associated within electrically-charged convective cells will tend to scatter microwave radiation [*Norville et al.*, 1991; *Ziegler et al.*, 1991], giving rise to an apparent cool region. Thus convective cells that contain large raindrops and ice are easily identifiable features in the microwave regime. *Negri et al.* [1989] devised a method for displaying an image of the 85.8- and 37.0-GHz channel in false color for emphasis of storm-related cool spots. We used such images in storm identification and display some composites showing the storm cell location relative to the San Marco feature of interest.

Observations

The most abundant feature detected by the San Marco E field experiment was the equatorial spread-F [*Aggson et al.*, 1992], density bubbles observe in the F layer at equatorial latitudes resulting from a Rayleigh-Taylor instability occurring in the lower-altitude region of the layer [*Haerendel*, 1973]. The San Marco spacecraft passed directly through regions where this phenomena is most prevalent and the E field and corresponding density perturbation are easily identifiable in the data set. Specifically, *Aggson et al.* [1992] found that events satisfied, to the first order, the *Ossakow and Chaturvedi* [1978] relationship between electric field and density,

$$E_y = -\frac{Bg}{\nu_{\rm in}}\left(1 - \frac{n_0}{n}\right) + \frac{n}{n_0 - n} E_0 \qquad (1)$$

where B is the magnetic field strength (about 0.3 G), g is the acceleration of gravity, $\nu_{\rm in}$ is the ion/neutral collision frequency (about 1 s^{-1} near 250 km), n_0 and E_0 are the ambient electron density and electric field, and n is the density in the middle of the spread-F bubble. The first term in the expression originates from the Rayleigh-Taylor instability and is dominate at high ionospheric altitudes (>300 km). The second term is derived from the drift instability, which tends to dominate at lower altitudes. Also, by monitoring the E_x and E_y field components of individual bubbles, *Aggson et al.* [1992] established the relative convective motion of the features.

In the San Marco data set, spread-F events are easily recognizable. However, a number of dc E field events not immediately recognizable also appeared in the data set. A typical example is shown in Figures 4 and 5. These events could be characterized by the following:

1. The events lasted of the order of 0.1–1 min.
2. the events are observed at night.
3. the typical event, on average, possessed a strong underlying upward component (E_x value was reduced) but could be either eastward or westward directed (E_y value varied from event to event, and sometimes varied during the event itself). This effect is particularly noticeable in Figure 5.
4. The events are not related to any detectable density perturbation (see bottom panel), thus ruling out spread-F. For example, (1) above suggests the perturbed electric field below 300 km in the spread-F bubble should vary as

$$\Delta E = \frac{\Delta n}{n} E_0. \qquad (2)$$

Since E_0 is of the order of 1 mV/m, an observed electric field disturbance of 10 mV/m near 250 km should be associated with a corresponding factor of 10 density reduction within a spread-F bubble. Such a density depletion would be clearly visible on Langmuir probe time series displays like those shown in Figures 4 and 5. The fact that no corresponding density perturbation is observed is strong evidence that something unusual (i.e., anomalous) is occurring.

5. About 70% of the events are accompanied by signals at high frequencies between 128 and 512 kHz. Figure 6 shows the ac electric field activity for the same time period as that of Figure 4. Note that wave activity in this channel is occurring simultaneously with the quasi-dc field structures.
6. A most interesting feature, once recognized, is that the dc electric field events tended to be clustered in both time and space. Events often reoccurred for up to two weeks as the spacecraft passed over the same geographic region. For example, Figure 5 shows a similar dc E field event from near the same location as that in Figure 4 (i.e., near 100° east longitude), only observed 14 days later. In fact, a set of seven events were observed associated with this location for an approximately 2-week period. This clustering in both space and time is a common feature of these anomalous events.
7. There seems to be evidence that the location and time of the E field events is coincident with unusually large atmospheric weather systems. As we shall demonstrate, statistically, the set of events tend to be observed over

Table 1. Weather-Related *E* Field Events

Date	UT	East Longitude, deg	Local Time, hour	Magnetic Latitude, degree	Geographic Latitude, deg	Altitude, km	Intensity, mV/m
May 16	0533	300	1.5	12	2.5	266	2
May 17	0303	300	23.0	11	1.5	270	5
May 24	0405	353	3.7	−11	1.0	258	11
July 13	0846	278	3.3	9	−2.8	253	5
July 16	0438	351	4.0	−15	−2.9	256	4
Oct. 16	0714	289	2.5	13.8	1.3	239	2.5
Oct. 17	0910	287	4.3	14.6	2.7	252	4
Oct. 17	1044	278	5.2	14.8	2.9	267	1.5
Oct. 18	1104	274	6.0	15.2	2.9	271	1
Oct. 19	0946	288	5.1	15.1	3.0	249	5
Oct. 27	1017	290	5.6	12.3	0.1	236	2
Oct. 29	0909	287	4.7	11.7	−0.1	258	1.5
Nov. 4	1104	104	18.0	−6.7	2.9	322	3
Nov. 17	1030	105	17.9	−11.3	−1.6	217	5
Nov. 19	1514	110	22.6	−13.3	−2.8	241	8
Nov. 21	0755	287	3.1	13.3	0.9	286	5
Nov. 23	1010	120	18.0	−13.0	−2.9	219	3
Nov. 30	1028	113	18.0	−11.6	1.5	231	2
Nov. 30	2305	108	6.3	−9.0	1.0	224	4
Dec. 1	1439	54	18.3	−10.2	−0.7	224	6
Dec. 2	0953	118	18.0	−9.7	−0.3	221	4
Dec. 3	2333	105	6.6	−11.2	−0.8	188	20

regions known for a high occurrence of severe weather systems. Individually, the occurrence of many events can be traced to large weather systems that magnetically map to the location of observation.

In all, 22 events like those described above were found in the San Marco D *E* field data set. Table 1 lists the time and locations of these events. Note from the table that events are indeed clustered over certain locations at certain times, consistent with point 6 above. For example, in the last 2 weeks of October, a number of events occurred as the spacecraft passed through east longitudes between 270° and 290°, and in November, a number of events were clustered near 100° E. As we shall demonstrate, both sites are known for their unusual atmospheric weather. Figure 7a is the global distribution of the 22 events shown in Table 1. Note that the dc *E* field detections tend to be clustered over three geographic regions: The Indonesian basin, the northern coast of South America, and the western coast of Africa. These sites are also well known for there large number of active weather systems. Figure 7b, adapted from *Herman* [1968], shows the typical number of thunderstorm days between September and November, which identifies these same three regions as atmospherically active. Similar global distributions of optical lightning flashes [see *Volland*, 1984, Figure 6.3] and 9.18-MHz radio noise [see *Herman et al.*, 1973, Figure 11] also confirms these regions as atmospherically active. It should be recognized that the San Marco trajectory is primarily equatorial, and thus atmospheric activity at high latitudes is not observed. However, some of the most active weather sites occur at equatorial latitudes and thus are observable by San Marco. As evident in Figure 7, the distribution in longitude of the anomalous events correspond closely to the regions where atmospheric weather is most active.

However, the evidence relating the quasi-dc *E* field events to atmospheric weather is more than just statistical. In many instances the events track well-defined and identifiable weather features. One of the best examples is a set of events detected in mid-October 1988 occurring in association with the very strong tropical cyclone Joan. Of all the Atlantic tropical cyclones in 1988, Joan extended most southerly (i.e., nearest to the spacecraft trajectory), had the lowest pressure (932 mbar), and had a very high sustained wind speeds (143 mph (88.7 km) [*Lawerence and Gross*, 1989]. The San Marco spacecraft repeatedly passed near the system during both its tropical storm and hurricane stages. As a result, during this period a number of *E* field events were observed. Figure 8 displays the location of these events and the tropical cyclone. In two of the cases (October 16 at 1714 UT and October 17 at 0910 UT) the SMM/I made a north-to-south observational pass very near the *E* field event location within about 4 hours of the event time. In each case, significant atmospheric convective cells were observed within 5° of the *E* field observation point. In both instances the convection cells were associated with clusters of storms that extended south of the cyclone. There were no SSM/I data within a corresponding reasonable time for the three other events shown in Figure 8.

A similar situation occurred at near the end of November and early December of 1988. During this time a number of large convective systems developed off the coast of Sumatra. Typically, this region becomes convectively active due to its association with the ascending branch of the Walker circulation in the Pacific basin [*Simpson et al.*, 1988]. A series of dc electric field events were detected in association with spacecraft passages over this location.

As an example, Figure 9 shows a composite from an SSM/I image obtained within about two and a half hours of the San Marco *E* field detection occurring on December 3. The spacecraft was passing nearly due west at a geographic latitude of −0.8° and an altitude of only 190 km. Because of atmospheric drag, the spacecraft perigee was steadily decreasing during this period (spacecraft reentry occurred two days after this event). We assume that the quasi-dc *E* fields

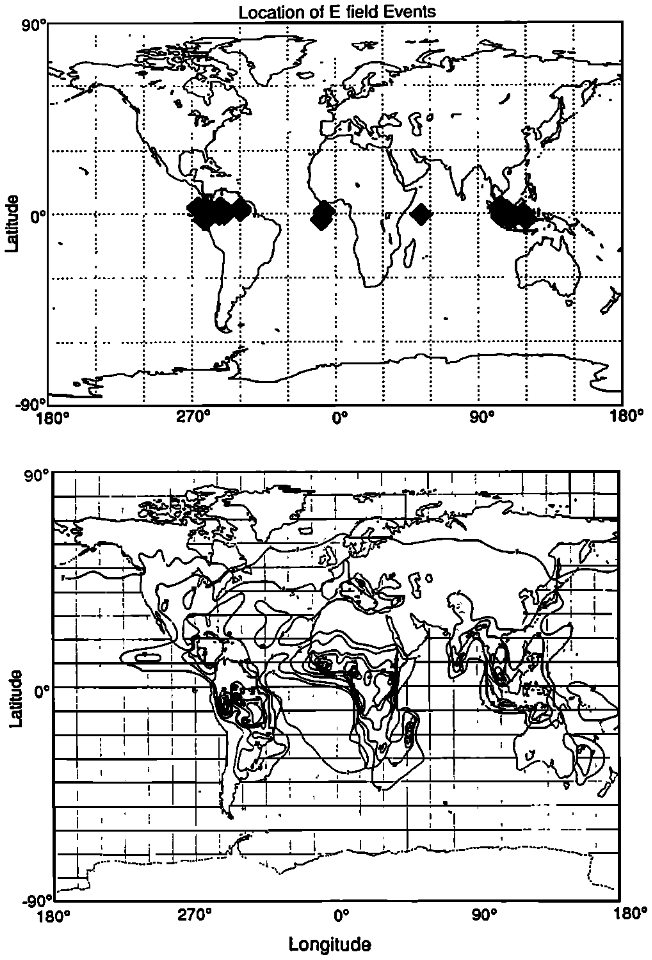

Figure 7. (a) The global distribution of the 22 quasi-dc E field events observed by San Marco D and (b) the global distribution of thunderstorm days between September and November (adapted from *Herman* [1968]).

map vertically to a height of 100 km, to the ionospheric base. However, because of the enhanced parallel conductivity, the fields become directed along geomagnetic field lines at higher altitudes. Given this scenario, we have mapped the geomagnetic field lines coincident with the spacecraft at both the beginning and the end of the December 3 E field event down to the ionosphere base, and this magnetic footprint is shown in Figure 9. Note that a large convective system lies within 100 km south of the spacecraft magnetic footprint and is a likely candidate for driving the quasi-dc fields observed at high altitudes.

Comparing San Marco and SSM/I data, only 10 SSM/I images were available that included a full north-south observational pass very near or directly over the San Marco E field observation point within 5 hours of the event. The other images were either at much later times or distant from the observation point. Assuming that a convective storm remains active for 5 hours and moves no more than 100 km/h, we should expect the E field-generating storm system to lie in close proximity to the San Marco E field event location (i.e., within a few degrees, depending on the specifics of the mapping of the storm to the spacecraft). In fact, 9 out of 10 images showed a major convective feature within 5° of the observation point.

Possible Mechanisms for the dc E Fields

There are two possible scenarios for observing weather-related electric fields at ionospheric altitudes: The observation of the accumulated cloud charge (i.e., direct process) or the measurement of a local phenomena coupled to the weather system below (i.e., indirect process). Both cases have been discussed previously in the literature.

Considering the former first, theory [*Dejnakarintra and Park*, 1974; *Greifinger and Greifinger*, 1976] suggests that the dc E fields from a single thundercloud should be directly observable in the ionosphere at values between 10–100 μV/m. However, such values are barely detectable by spacecraft like San Marco. After removing the large motional $\mathbf{V} \times \mathbf{B}$ electric field, the reliable instrument resolution is about 750 μV/m. The low-intensity fields from a single charged cloud would be difficult to observe and may explain the lack of previous satellite observations of this phenomena. However, large convective storm systems have a large number of thunderstorms in relatively close proximity. The combined effect of many clouds could conceivably increase the field values from the predicted 100 μV/m to the observed 10 mV/m.

A set of active thunderstorms in close proximity within a large convective storm system may even act as coherent ULF radiators. As described by *Greifinger and Greifinger* [1976] immediately following a discharge, a charge Q is left in the cloud that relaxes of the order of minutes. A ULF electric field develops as a result of effects of both charge relaxation and the redistribution of charge in the ionosphere. Typically, the field abruptly changes immediately after the discharge but slowly returns to predischarge levels in approximately a minute. The typical postdischarge disturbance is illustrated in Figure 2 of *Dejnakarintra and Park* [1974]. If a number of charged clouds are acting in close proximity, their effect may become coherent (vary as N^2) which will amplify values above the single charged cloud scenario modeled in theory. Thus the effects of ionospheric attenuation may be overcome by the coherence of the atmospheric ULF radiators.

Another effect that might enhance the directly measured electric fields is a change in ionospheric conductivity over large weather systems. Balloon payloads have indicated that conductivity changes can occur over thunderstorms at about

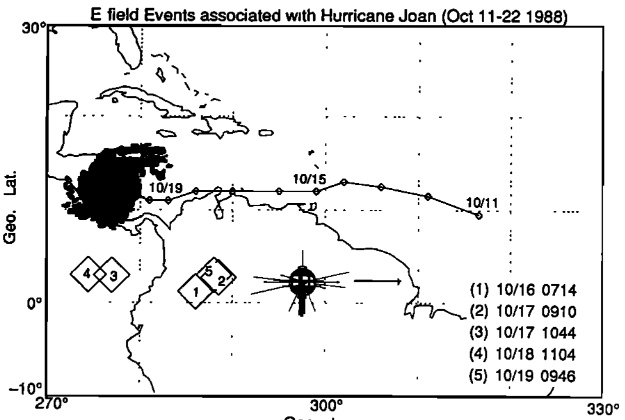

Figure 8. The quasi-dc E field events associated with Hurricane Joan.

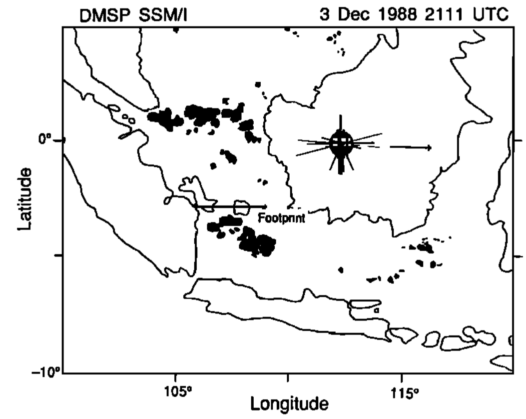

Figure 9. A composite of an SSM/I image showing intense convective storm systems over Indonesia. This system maps directly to the San Marco spacecraft during the observation of the anomalous dc E field event on December 3.

30 km [*Holzworth et al.*, 1986; *Pinto et al.*, 1988]. It might also be possible that a similar effect occurs in the ionosphere. This alteration may allow for the easier propagation of disturbances to higher altitudes. The calculations performed by *Dejnakarintra and Park* [1974] and *Greifinger and Greifinger* [1976] assume a normal fair-weather conductivity profile above the convective storm, which may not be very accurate in the vicinity of the storm.

However, indirect process may also be responsible for the observed electric fields by San Marco. In this case the coupling of the atmosphere and ionosphere is more complicated. The electric fields are not measured directly from storm but instead are created via some secondary conversion process related to the storm. For example, *Gherzi* [1950] and *Bauer* [1958] demonstrated that the reflection height of the F layer decreased with the passage of Hurricanes. Similar ionospheric modifications have also been observed with passing cold fronts [*Bauer*, 1957]. *Bauer* [1957] suggests that tropospheric disturbances affect the ionosphere, primarily because the approximately 100 km barrier separating the two regions is not overly effective as an acoustic wave shield, particularly at longer wavelengths. As hypothesized by *Bauer* [1957], weather-generated acoustic disturbances reaching ionospheric altitudes would create irregularities in the electron density that would appear similar to the spread-F phenomena. Radio scintillations associated with weather-related ionospheric disturbance have been observed by the S-66 satellite, confirming the presence of such density structures [*Arendt and Frisby*, 1968] and adding further evidence for an acoustic/electrostatic wave conversion process. Along similar lines, *Woodman and Kudeki* [1984] and *Kelley et al.* [1984] also describe the generation of explosive spread-F associated with lightning discharge events.

Rather than an acoustic/electrostatic wave coupling as envisioned by *Bauer* [1957], *Park and Helliwell* [1971] suggest that the electric fields associated with charged clouds map directly to the ionosphere. However, the resulting $\mathbf{E} \times \mathbf{B}$ force creates an electron density vortex that gives rise to density fluctuations (i.e., depletions and enhancements) aligned parallel to the geomagnetic field. They further speculate that lightning-generated VLF emissions (i.e., whistlers) propagate through the ionosphere and into the magnetosphere via the $\mathbf{E} \times \mathbf{B}$-created enhancements.

However, the San Marco dc E field observations cannot verify either the direct or indirect wave scenario. On the basis of discussion above, we see that direct processes tend to generate electromagnetic disturbances while indirect processes tend to generate electrostatic disturbances. ULF magnetic wave measurements would aid in the identification process. Unfortunately, a magnetometer was not included in the instrument complement. Thus the exact nature of the E field events is unknown at this time, making the identification of the corresponding process difficult.

Discussion

It should be noted that the E fields described here are not detected above every large-scale weather system. As an example, *Burke et al.* [1992] recently described the observation of a strong VLF spheric signal observed by DE 2 above Hurricane Debbie at an altitude of about 300 km. However, there were no observable quasi-dc E field structures associated with the passage of the spacecraft over the Hurricane. This lack of observation places an upper limit on the quasi-dc E field values at less than 0.5 V/m at this altitude.

One possible explanation for the lack of observation by the DE 2 satellite is the observing altitude. The San Marco observations suggests the intensity of events are dependent on altitude (see Figure 10). Although the San Marco spacecraft traversed from 600 km to below 200 km in altitude, the anomalous E field events became apparent only at altitudes below about 300 km. Further, the events appear to intensify (in a statistical sense) with decreasing altitude. For example, the most intense event occurred on December 3, just 2 days prior to reentry, when the spacecraft was at an altitude of about 188 km (see Figure 5). On the basis of the altitude dependence shown in Figure 10, it appears the probability of detecting an event above 300 km diminishes significantly. As stated previously, the events are observed at night, at altitudes below the peak ionospheric densities near 300 km. On the basis of Figure 10 we suspect that emission attenuation is strong in this peak density region and thus may explain why the event are not observed at higher altitudes.

As described previously, nearly 70% of the anomalous dc E field events possessed high frequency activity between 128 and 512 kHz. An example of this wave activity is shown in Figure 6. In each case the wave emission occurs in coincidence with the dc field structures. Also, emission in the VLF regime (4–16 kHz) is commonly detected with the events. These MF and VLF emissions observed by San Marco are believed to be in the whistler mode and are suspected to be originally generated by lightning discharges. Typically, spheric signals possess peak amplitudes near 10 kHz, and vary like $1/f^2$ at higher frequencies [*Le Vine and Meneghini*, 1978]. Thus, for spheric-generated emission, one might expect the relative power in the 128–512 kHz channel to be reduced by a factor of 10–100 as compared to the power levels in the 4–16 kHz channel. When the channel bandwidths are included, the measurements shown in Figure 6 and the other cases appear consistent with a spheric-generated emission. Specifically, in Figure 6, the wave power spectral density in the 4–16 kHz channel during the

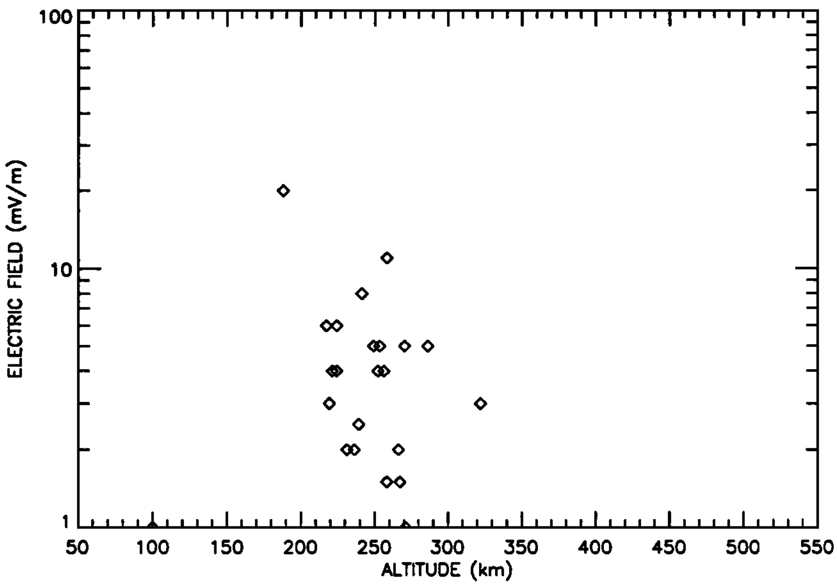

Figure 10. The dependency of the San Marco quasi-dc *E* field events with altitude.

event is about 10^{-12} V^2 m^{-2} Hz^{-1}, while the values are more like 10^{-14} V^2 m^{-2} Hz^{-1} in the 128–512 kHz channel. A frequency-versus-time radio spectrogram of the signal levels above background is shown in Plate 1 for the same time period as that shown in Figure 6. Note that during the *E* field event, the most intense signals are observed between 1 and 10 kHz, consistent with the peak intensities of spheric signals.

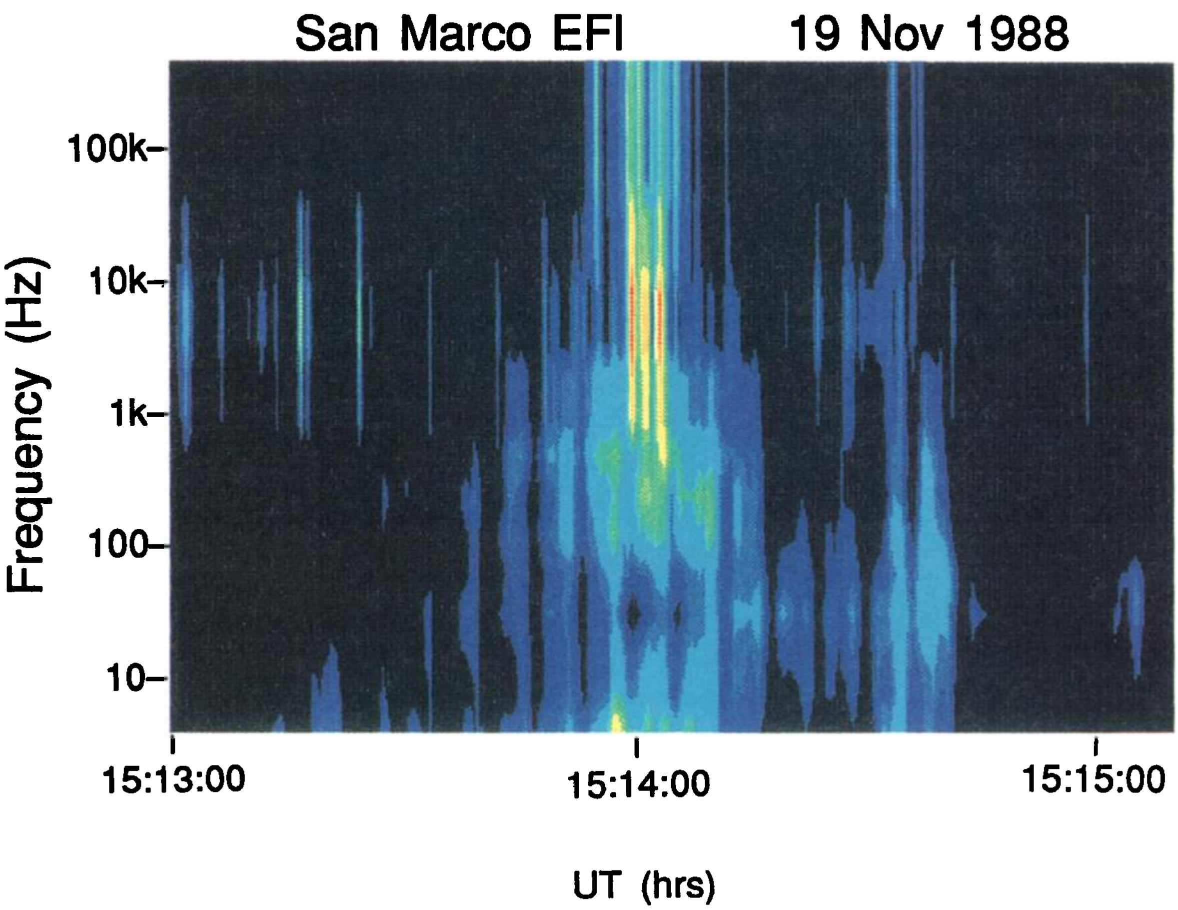

Plate 1. Frequency versus time radio spectrogram during an anomalous *E* field events showing the enhanced wave activity between 1 and 10 kHz.

Conclusion

We have presented observations from the San Marco electric field instrument of anomalous ionospheric electric fields that are now believed to originate from large atmospheric weather systems. Individual events are identified by their upward directed electric field (consistent with directions above thunderclouds), no correlated density perturbation, and their clustering in both time and space. Events appear to reoccur in approximately the same location for up to 2 weeks in association with the passages of the spacecraft by magnetic field lines that map to large storm systems. The 22 candidate events, as a statistical set, correspond nicely to locations where atmospheric weather systems are prevalent.

Theory has predicted that such events could be observed, albeit at low intensities. The observations by San Marco are typically larger than theoretical values. However, the cumulative effect of many simultaneous storms or an alteration in the ionospheric conductivity might accounts for the larger values.

The approach in this work has been to examine a set of ionospheric anomalous *E* field events and attempt to determine their possible causality with weather below. However, the inverse approach is also possible: Given data on a large number of convective storm systems, determine the coincidence of *E* field events observed by passing spacecraft. Clearly, the latter approach would be most definitive in determining the relationship between atmospheric and ionospheric electrical disturbances. However, such an approach involves a considerable data analysis effort involving a large number of both weather and ionospheric data sets. Such a large-scale study is beyond the scope of this introductory work but should be considered in the future.

Acknowledgments. We gratefully thank Carlo Arduini at Centro Ricerche Aerospaziali in Italy for forwarding Drag Balence measurements for comparison studies. We thank Fred Herraro for a number of useful suggestions concerning the analysis and interpretation of the events. We also are very grateful to Judy Johnson and Stan Cobb for data analysis support.

The Editor thanks N. C. Maynard and U. S. Inan for their assistance in evaluating this paper.

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(Received November 2, 1993; revised March 10, 1994;
accepted April 20, 1994.)