Initial balloon soundings of the electric field in winter nimbostratus clouds in the USA

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[1] Presented are the first known vertical profiles of electric field, E, in six winter nimbostratus clouds in the USA. No lightning was detected while the E profiles were collected. Deep convection was embedded in one of the clouds that had been a thunderstorm. The maximum magnitude of the vertical component of the electric field, E_z, in the profiles ranged from 1 to 12 kV m^{-1}; the maximum horizontal component ranged from 0.2 to 28 kV m^{-1}. The latter indicates that the charge in the cloud was not horizontally homogeneous. The E_z versus altitude profiles have 1–3 peaks inside the clouds. From the profiles, we inferred up to four charge regions stacked vertically. Peaks in E_z are found in regions of melting as evidenced by radar bright bands: Both polarities of charge are inferred in the bright bands. Three nimbostratus clouds without melting precipitation also were electrified. *INDEX TERMS:* 3304 Meteorology and Atmospheric Dynamics: Atmospheric electricity; 3399 Meteorology and Atmospheric Dynamics: General or miscellaneous; 3324 Meteorology and Atmospheric Dynamics: Lightning. **Citation:** Rust, D., and J. Trapp, Initial balloon soundings of the electric field in winter nimbostratus clouds in the USA, *Geophys. Res. Lett.*, *29*(20), 1959, doi:10.1029/2002GL015278, 2002.

1. Introduction

[2] The vertical structure of the electric field, E, in winter clouds remains very sparsely studied, especially in stratiform clouds. The largest body of research on stratiform clouds was done in and by scientists of the former USSR in the 1950s and 1960s. They used instrumented aircraft and flew spiral patterns to get vertical profiles of E, e.g., see *Imyanitov et al.* [1972]. Of relevance here is that in nimbostratus clouds >2 km thick, they found three or more charge regions stacked vertically. Japanese researchers have done most of the vertical soundings of electrical structure of winter clouds with balloon-borne instrumentation, and there are a few quantitative electric field profiles in winter thunderstorms in Japan [e.g., *Magono et al.*, 1982]. There are also several profiles of electric field polarity (not magnitude) in nonthunderstorm "snow clouds" in Japan [e.g., *Magono et al.*, 1983]. In a review of electrical aspects of winter clouds, *MacGorman and Rust* [1998] noted that the total number of soundings with good spatial resolution and a quantitative measurement of the vertical profile of the electric field still numbers only a few. They further noted that there are no published vertical profiles of the electric field in winter clouds in the USA.

[3] Our objective was to make a few soundings in an initial effort to begin documenting the interior electrical structure of winter clouds in the United States. To do this, in February 2000 we participated in the Intermountain Precipitation Experiment (IPEX) [*Schultz et al.*, 2002] in the region around Salt Lake City, Utah. From that has come the only known profiles of electric field in winter clouds in the United States. They are summarized here.

2. Instrumentation

[4] We obtained the vertical soundings of electric field using mobile ballooning procedures [*Rust*, 1989; *Rust and Marshall*, 1989]. This included an NSSL mobile laboratory containing a mobile GPS/LORAN atmospheric sounding system (MGLASS) for receiving radiosonde data. We operated both fixed-base and in a fully mobile, i.e., storm intercept, mode. In this mode, we were guided from the coordination center located in the Salt Lake City National Weather Service forecast office. The instruments flown beneath a helium-filled, 1200-g rubber balloon were an electric field meter and a Vaisala RS80-15GH radiosonde, which has GPS wind finding. The sonde measured the thermodynamic variables and the GPS portion of the sounding system provided the wind and balloon latitude and longitude. The electric field meter, originally developed by *Winn and Byerley* [1975], and the instrument train are summarized in *MacGorman and Rust* [*pp 127–131*, 1998]. The E data were processed to yield both the vertical and horizontal components of E. The mobile laboratory, NSSL5, was equipped with standard surface meteorological sensors and a downward-looking electric field mill, which was calibrated to give the value of E at the ground, E_{gnd}. The polarity convention for both E_{gnd} and E aloft is that a positive E points in the direction a positive charge will move. Other instrumentation relevant here was the National Lightning Detection Network [*Cummins et al.*, 1998] and a 3-cm wavelength, mobile Doppler radar [*Wurman et al.*, 1997].

3. Observations

[5] We made six soundings, and there are differences among the electric field profiles, even in this small data set.

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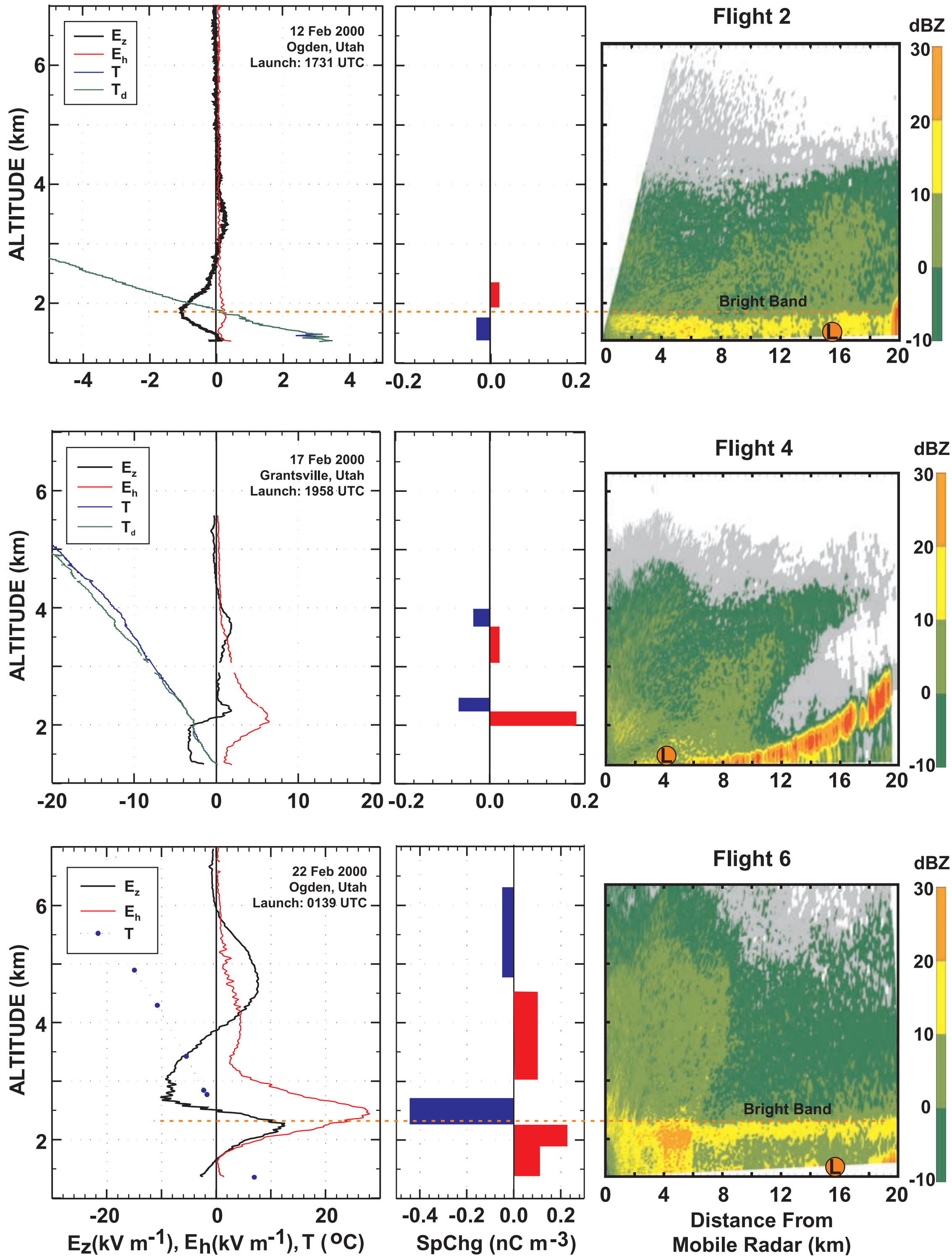

Figure 1. Example soundings in winter nimbostratus clouds. For each flight: Left panels are profiles of the vertical (E_z) and horizontal (E_h) components of the electric field, temperature (T), and dewpoint (T_d); middle panels are the space charge density inferred using Gauss's law; and right panels are the range-height-indicator radar reflectivity through the balloon launch location, L. All altitudes are MSL. The orange dashed line is the approximate top of the radar bright band. The >20 dBZ values in Flight 4 from 6–20 km and at 19 km in Flights 2 and 6 are from the foothills terrain.

The generalities of the six E profiles are contained in three examples in Figure 1, with all six summarized in Table 1. The profiles show that there can be a significant horizontal component of the electric field, E_h, that can be comparable in magnitude to the vertical component, E_z, even though the clouds appear very stratiform on radar. In Figure 1, the radar images are vertical sections near the time of launch and approximately through the balloon launch location. Three of

Table 1. Summary of All Six Soundings of Electric Field and Inferred Charge Layers in Winter Nimbostratus Clouds

Flight No., Date, and Launch Time	E_z max in cloud ($kV\ m^{-1}$)	E_h max in cloud ($kV\ m^{-1}$)	Charge Layer ($nC\ m^{-3}$), Altitude Span (km)	Temps of Alt Spans to the Left (°C)	Alt of 0°C level (km)	Bright Band Observed?
1: 11 Feb 00 0800 UTC	+1.5	0.5	−0.06, 1.48–1.79	3.9/19	2.12	yes
			+0.19, 1.35–1.48	4.7/3.9		
2: 12 Feb 00 1731 UTC	−1	0.3	+0.02, 1.93–2.35	−0.2/−2.9	1.89	yes
			−0.03, 1.39–1.76	3.2/0.8		
3: 17 Feb 00 1840 UTC	−1	0.5	+0.03, 1.89–2.03	−2.3/−2.6	1.46	no
			−0.02, 1.48–1.89	−0.2/−2.3		
4: 17 Feb 00 1958 UTC	−3	6	−0.04, 3.68–3.99	−11/−12.4	1.34	no
			+0.02, 3.06–3.68	−7.9/−11		
			−0.07, 2.23–2.47	−3.6/−4.8		
			+0.18, 1.99–2.23	−2.7/−3.6		
5: 17 Feb 00 2250 UTC	−1	0.2	− (?), 2.1–2.3	−4.2/−4.8	1.39	no
			+ (?), 1.6–2.1	−1.3/−4.2		
6: 22 Feb 00 0239 UTC	+12	28	−0.05, 4.78–6.32	no data	estimated 2.7	yes
			+0.1, 3.04–4.52			
			−0.44, 2.26–2.71			
			+0.20, 1.38–2.26			

The ? denotes values too small for us to be confident they are real (arbitrarily set at <0.01 $nC\ m^{-3}$).

the six soundings penetrated clouds in which the temperature was warmer than 0°C and hence in which frozen precipitation was melting. ‘Bright bands’ in the corresponding radar reflectivity data (Figure 1, Flights 2 and 6) confirm the existence of a melting layer; maximum radar reflectivities within and outside the bright bands here are typical for those in stratiform clouds, e.g., *House* [1993].

[6] A brief description of each example balloon flight follows. Flight 2, 12 Feb 2000 at 1731 UTC (Figure 1, top) was launched at Ogden, Utah, in light rain. Flight 2 was through a nimbostratus cloud, with a well-defined bright band. The temperature measurement of 0°C by the sonde is in good agreement with the top of the bright band as seen in the figure. Cloud top above the launch site is estimated from radar data to have been about 4.5–5 km MSL. There was no nearby lightning observed around the time or place of this sounding.

[7] Flight 4, 17 February 2000 at 1958 UTC (Figure 1, middle) was launched 2 km east of Grantsville, Utah. This was the second of three flights on this day and was the result of storm intercept/mobile operations during which we deployed the NSSL5 mobile laboratory and a mobile Doppler radar to the Tooele Valley, southwest of Salt Lake City. The balloon was inflated in, and launched from, our high-wind launch tube. The temperature at the ground was ≈0°C. There was moderate to heavy snowfall, and ≈2 cm more accumulated during the 40-min flight, adding to the 12 cm of snow already on the ground. The cloud top above the launch site was at about 5.5 km MSL. The cloud had a subzero temperature profile and no bright band in the radar reflectivity. Thus, we conclude no significant precipitation melted within the cloud. The profile has a peak in E_z of ≈ $-3\ kV\ m^{-1}$ and an E_h maximum of about $6\ kV\ m^{-1}$. There was no nearby lightning observed around the time or place of this sounding.

[8] Flight 6, 22 February 2000 at 0139 UTC (Figure 1, bottom) was launched from Ogden into the most electrified cloud in which we obtained soundings. Although the National Lightning Detection Network recorded more that 50 ground flashes in the hour prior to launch, none were nearby during or after the flight. The flashes closest in time were at 15 min prior to launch, but at a distance to the ground strike point of 94 km, and at 36 min before launch at 16 km from the launch site. One last ground flash from the entire system occurred >100 km away and after the sounding was over.

[9] The balloon disappeared and presumably entered the cloud about 64 s after launch, which indicates a cloud base ≈1.6 km MSL. The data indicate the electric field meter was swinging extensively, perhaps because one of the two instrument train let-down reels malfunctioned. The E_z data have been filtered to reduce the artifact. A computer malfunction resulted in loss of all the radiosonde data except for a few data points we had logged during the flight. These are shown in the figure. Note that this caused us to have to estimate the altitude versus time for the E profile. The reconstructed balloon altitudes were linearly interpolated from the manually entered pressures during Flight 6 and a subsequent sounding at Ogden launched at 0245 UTC under similar weather conditions as was Flight 6.

[10] Light rain was occurring at the launch of Flight 6. The rain resulted from the melting of frozen precipitation within a layer whose top was at about 2.7 km MSL, as evidenced by the extensive bright band. A ‘core’ of higher radar reflectivity (Figure 1) at ranges ≤6 km was associated with a band of relatively deep (cloud top ≈7.5 km MSL) convection embedded with the nimbostratus cloud. As conceptualized by *House* [*p 211*, 1993], such deep convective cells play a formative role in the nimbostratus, specifically, by providing a source of ice particles that fall slowly once outside the updrafts in the cells. The band of cells represented in Figure 1, bottom was in a decaying stage of its evolution. The band's lifetime determined from radar was ≲1 h. Rough estimates using wind data from other soundings suggest that the trajectory of Flight 6 might have passed through or at least very near the band of cells.

4. Discussion

[11] We recognize that any conclusions are very tentative owing to the small size of the data set. In addition to the observations shown in Figure 1 and Table 1, we show the inferred charge regions calculated from a one-dimensional version of Gauss's law, which uses the change of E_z with height to determine the charge density (for a discussion on using Gauss's law, see *MacGorman and Rust* [*pp 130–131*,

1998]). Only the larger inferred charge densities (arbitrarily set at >0.01 nC m^{-3}) in the cloud are shown, since they are the ones in which we are most confident. The shallow charge layers that sometimes extended a few tens of meters above the ground are not shown, since they generally were below cloud base. The inferred charge structure in Flight 2 consists of only two charge regions, in contrast to Flights 4 and 6 that each may have had four regions of charge. In contrasts to other flights, Flights 1 and 2 had charge regions vertically stacked in the opposite order of polarity. During Flights 4 and 6, there were large E_h, whose presence makes more uncertain the magnitude of the two lowest charge layers inferred from Gauss's law. However, the number of peaks in the E_z profile, which is an observable that requires no assumptions, varied from one to three, indicating a difference in charge structure complexity. There are different arrangements in the peaks of E_z among the six profiles.

[12] *Shepherd et al.* [1996] reported that in warm season stratified clouds associated with mesoscale convective systems, the largest E in the profile was often at or near the top of the bright band. However, whether melting had a role in creating the electric field was not clear because they found both polarities of E_z and inferred charge are seen in the cases with bright bands. The same holds for our winter cases with bright bands.

[13] The electric field magnitudes in all six profiles are well below those generally associated with lightning. Except prior to Flight 6, no lightning was recorded by any sensor, including no ground strikes within hundreds of kilometers for several hours around the sounding time. Thus, we classify all clouds, but that in Flight 6, as electrified, nonthunderstorm clouds, or more precisely, nimbostratus. Flight 6 passed through or near a decaying band of convective—and previously thunderstorm—cells that were embedded within a nimbostratus.

[14] Comparison of the Flight 4 E profile with Flight 3 (not shown), launched 1 h 20 min earlier and a few kilometers to the east, indicates that the polarities of the charges in different regions in the cloud were oppositely stacked. Hence, from the six E profiles reported here, we see that there can be significant electrification in nimbostratus clouds, and even though the cloud seems stratified, the charge apparently can be nonuniform in its horizontal, as well as its vertical, distribution. *Imyanitov et al.* [1972] reported such heterogeneities in winter nimbostratus clouds. In the case of Flight 6, however, the heterogeneities likely include those associated with the presence of convective cells embedded within that winter nimbostratus.

[15] We examined some of our E_{gnd} data to see if we could corroborate the finding by *Reiter* [1965] of a link between polarity of E_{gnd} and the temperature, which he measured at various heights up a mountain side. He reported that in more than 80% of the cases, the polarity of both the charge on precipitation and E_{gnd} was positive if T >0°C. In our limited examination and small number of cases, we found that the polarity of E_{gnd} often changed while the temperature remained constant (and a few degrees >0°C). The behavior of E_{gnd} was not an objective of this study, but our limited analysis agrees with Reiter's finding that the simple relationship between E_{gnd} and temperature is not always the case.

[16] Although the melting of particles and the radar bright band seem linked with a relatively large peak in E_z, we are not sure if charge separation from any melting mechanism was taking place because opposite polarities of charge occurred in the bright bands of Flights 2 and 6. There are, however, more than one charging mechanism associated with melting, which may account for the difference. Furthermore, evidence that the electrification could not have been solely from melting comes from the electrified cloud with temperatures everywhere colder than 0°C, and thus no melting inside. The clouds we observed contained multiple layers of charge, as in earlier observations in Japan and Russia. Even in this data base of only six E profiles, we find diversity in electrical structure in winter nimbostratus clouds and hints at significance in particle charging by melting in mixed-phase, nimbostratus clouds.

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References

Cummins, K. L., M. J. Murphy, E. A. Bardo, W. L. Hiscox, R. B. Pyle, and A. E. Pifer, A combined TOA/MDF technology upgrade of the U.S. national lightning detection network, *J. Geophys. Res.*, *103*, 9035–9046, 1998.

House, R. A., Jr., *Cloud Dynamics*, Academic Press, San Diego, 1993.

Imyanitov, I. M., Ye. V. Chubarina, and Ya. M. Shvarts, *Electricity of Clouds*, 122 pp, NASA Tech. Translation, NASA TT F-718, of *Elektrichestvo oblakov.*, Hydrometeorological Press, Leningrad, 1971, 1972.

MacGorman, D. R., and W. D. Rust, *The Electrical Nature of Storms*, Oxford University Press, New York, 1998.

Magono, C., T. Endoh, and T. Taniguchi, The mirror image relation in the vertical distributions of electric field and precipitation charge in winter thunderclouds, *J. Meteor. Soc. Jpn.*, *60*, 1188–1193, 1982.

Magono, C., T. Endoh, and T. Shigeno, The electrical structure of snow clouds Part I: Relationship to their precipitation-physical properties, *J. Meteor. Soc. Jpn.*, *61*, 325–338, 1983.

Reiter, R., Precipitation and cloud electricity, *Q. J. Roy. Meteor. Soc.*, *91*, 60–72, 1965.

Rust, W. D., Utilization of a mobile laboratory for storm electricity measurements, *J. Geophys. Res.*, *94*, 13,305–13,311, 1989.

Rust, W. D., and T. C. Marshall, Mobile, high-wind, balloon-launching apparatus, *J. Atmos. Oceanic Tech.*, *6*, 215–217, 1989.

Schultz, D. M., W. J. Steenburgh, R. J. Trapp, J. Horel, D. E. Kingsmill, L. B. Dunn, W. D. Rust, L. Cheng, A. Bansemer, J. Cox, J. Daugherty, D. P. Jorgensen, J. Meitin, L. Showell, B. F. Smull, K. Tarp, and M. Trainor, Understanding Utah winter storms: The intermountain precipitation experiment, *Bull. Amer. Meteor. Soc.*, *83*, 189–210, 2002.

Shepherd, T. R., W. D. Rust, and T. C. Marshall, Electric fields and charges near 0°C in stratiform clouds *Mon. Wea. Rev.*, *124*, 919–938, 1996.

Winn, W. P., and L. G. Byerley III, Electric field growth in thunderclouds, *Q. J. Roy. Meteor. Soc.*, *101*, 979–994, 1975.

Wurman, J., J. Straka, E. Rasmussen, M. Randall, and A. Zahrai, Design and deployment of a portable, pencil-beam, pulsed, 3-cm Doppler radar, *J. Atmos. Oceanic Technol.*, *6*, 1502–1512, 1997.

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