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Summary of Almost 20 Years of Storm Overflight Electric Field, Conductivity, Flash Rate, and Current Statistics

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ABSTRACT: We present total conduction (Wilson) currents for more than 1000 high-altitude aircraft overflights of electrified clouds acquired over nearly two decades. The overflights include a wide geographical sample of storms over land and ocean, with and without lightning, and with positive (i.e., upward-directed) and negative current. Peak electric field, with lightning transients removed, ranged from -1.0 kV m^{-1} to 16. kV m^{-1}, with mean (median) of 0.9 kV m^{-1} (0.29 kV m^{-1}). Total conductivity at flight altitude ranged from 0.6 pS m^{-1} to 3.6 pS m^{-1}, with mean and median of 2.2 pS m^{-1}. Peak current densities ranged from -2.0 nA m^{-2} to 33.0 nA m^{-2} with mean (median) of 1.9 nA m^{-2} (0.6 nA m^{-2}). Total upward current flow from storms in our dataset ranged from -1.3 to 9.4 A. The mean current for storms with lightning is 1.7 A over ocean and 1.0 A over land. The mean current for electrified shower clouds (i.e. electrified storms without lightning) is 0.41 A for ocean and 0.13 A for land. About 78% (43%) of the land (ocean) storms have detectable lightning. Land storms have 2.8 times the mean flash rate as ocean storms (2.2 versus 0.8 flashes min^{-1}, respectively). Approximately 7% of the overflights had negative current. The mean and median currents for positive (negative) polarity storms are 1.0 and 0.35 A (-0.30 and -0.26 A). We found no regional or latitudinal-based patterns in our storm currents, nor support for simple scaling laws between cloud top height and lightning flash rate.

1. INTRODUCTION

The quasi-steady state current flow from the tops of electrified clouds, often called the Wilson current, has long been considered a critical component of the global electric circuit [e.g., Wilson, 1920; Whipple, 1929; Whipple and Scrase, 1936]. Although estimates of the Wilson current have been derived in numerous studies [e.g., Gish and Wait, 1950; Stergis et al., 1957; Vonnegut et al., 1966; Blakeslee et al., 1989; Thomas et al.,2009], these prior estimates only provided a few dozen values for the Wilson current. In this paper, we greatly expand upon that previous limited set of observations by presenting statistics of flash rates, electric fields, conductivity, and storm current derived from over 1000 high-altitude aircraft overflights of electrified clouds spanning nearly two decade. In addition, these measurements provide important insights based on storm location (e.g., land versus ocean), polarity and flash rate. This paper encapsulates previous results [Mach et al., 2009; Mach et al., 2010], as well as new observations obtained in a 2010 hurricane campaign using the NASA Global Hawk aircraft. These results represent the airborne statistical component used in Mach et al., 2011a,b.

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2. OBSERVATIONS

2.1 Instrumentation

The aircraft used to collect data for this study were the NASA high altitude ER-2 and Global Hawk (GH), and the General Atomics Aeronautical Systems Inc. Altus-II. We obtained the aircraft electric field observations from sets of rotating vane electric field mills [Bateman et al., 2007], calibrated using the technique in Mach and Koshak [2007] . The conductivity data were derived from Gerdien capacitor conductivity probes [Mitchell et al., 1990; Bailey et al., 1999]. More detailed information about the field mills and the conductivity probes are contained in Mach et al. [2009].

2.2 Data Sets

Our data set consists of overflights of electrified clouds spanning a 17 year period from 1993 to 2010 (Table 1). Typically each aircraft flight includes multiple overpasses of storms. The storms that do not produce lightning are referred to as electrified shower clouds (ESC), and constitute 42% if the total overflown. Most of the statistics presented in this paper reflect the 12 year period ending in 2005 since the analysis of the 2010 campaign is still in progress. The regions sampled include the Southeastern United States, the Western Atlantic Ocean, the Gulf of Mexico, Central America (and adjacent oceans), Central Brazil, and the South Pacific. References describing the field campaigns and the location of the overpasses can be found in Mach et al., 2009.

3. RESULTS

3.1 Peak Electric Fields

The peak electric field, with lightning transients removed, ranged from ranged from -1.0 kV m^{-1} to 16. kV m^{-1}, with mean (median) of 0.9 kV m^{-1} (0.29 kV m^{-1}). When the aircraft did not pass over the exact charge center, we estimated the true magnitude of the peak electric field at the point of closest approach to the storm center (when $E_X = 0$) assuming $E_{Peak} = (E_Z^2 + E_Y^2)^{1/2}$, and setting the polarity of E_M to be the same as that of E_Z.

3.2 Conductivity and Peak Current Density

The total conductivity was obtained by measuring the contribution of both positive and negative ions. Total conductivity at flight altitude ranged from 0.6 pS m^{-1} to 3.6 pS m^{-1}, with mean and median of 2.2 pS m^{-1}. Multiplying the peak electric field by the total conductivity yielded the peak current density. The mean (median)

Table 1 Summary of field campaigns, aircraft platforms and data used in this study

Field Campaign	Flights Analyzed	Total Overpasses (with Lightning)	Aircraft/ Mean Altitude (km)	Peak E (kV/m)	Max Flash Count	Mean Wilson Current (A)
TOGA-COARE (1993)	6	78 (14)	ER-2/19.6	1.5	15	0.3
CAMEX-1 (1993)	3	38 (13)	ER-2/19.3	1.6	11	0.5
CAMEX-2 (1995)	3	36 (29)	ER-2/20.4	1.7	65	1.2
TEFLUN-A (1998)	6	47 (39)	ER-2/19.7	1.1	130	0.5
TEFLUN-B (1998)	3	38 (35)	ER-2/19.6	4.7	65	1.5
CAMEX-3 (1998)	6	75 (37)	ER-2/19.9	4.6	40	1.1
TRMM-LBA (1999)	13	255 (192)	ER-2/19.4	8.8	78	0.9
CAMEX-4 (2001)	10	87 (52)	ER-2/20.0	4.2	80	1.2
ACES (2002)	6	98 (76)	Altus/15.1	15.9	107	0.1
TCSP (2005)	12	98 (55)	ER-2/20.1	5.1	10	1.3
GRIP (2010)	5	190 (65)	GH/18.5	1.5	70	TBD
TOTAL	73	1040 (607)				

value is 1.9 nA m^{-2} (0.6 nA m^{-2}), and the values ranged from from -2.0 nA m^{-2} to 33.0 nA m^{-2}. Almost 90% of the data is contained in the range from -0.13 nA m^{-2} to 9.1 nA m^{-2}.

*3.3 **Total Storm Current***

Total storm current flow is obtained by integrating current densities over the complete storm. We accomplished this by using the peak electric fields, a median field falloff with distance based on all overflights, and assuming cylindrical storm symmetry. Total upward current flow from storms in our dataset ranged from -1.3 to 9.4 A. Figure 1 summarizes the total storm current results as a function of land/ocean and lightning/non-lightning ESC. The mean current for storms with lightning is 1.7 A over ocean and 1.0 A over land. The mean current for electrified shower clouds (i.e. electrified storms without lightning) is 0.41 A for ocean and 0.13 A for land. Thus, on average, land storms with or without lightning have about half to a third the mean current as their corresponding oceanic storm counterparts, while land (ocean) storms with lightning produce 7.7 (4.1) times the mean current as storms without lightning.

*3.4 **Flash Rate, Storm Polarity, Regional Patterns, and Scaling Laws***

Over three quarters (78%) of the land storms had detectable lightning, while less than half (43%) of the oceanic storms had lightning. When only lightning storms are considered, land storms have 2.8 times the mean

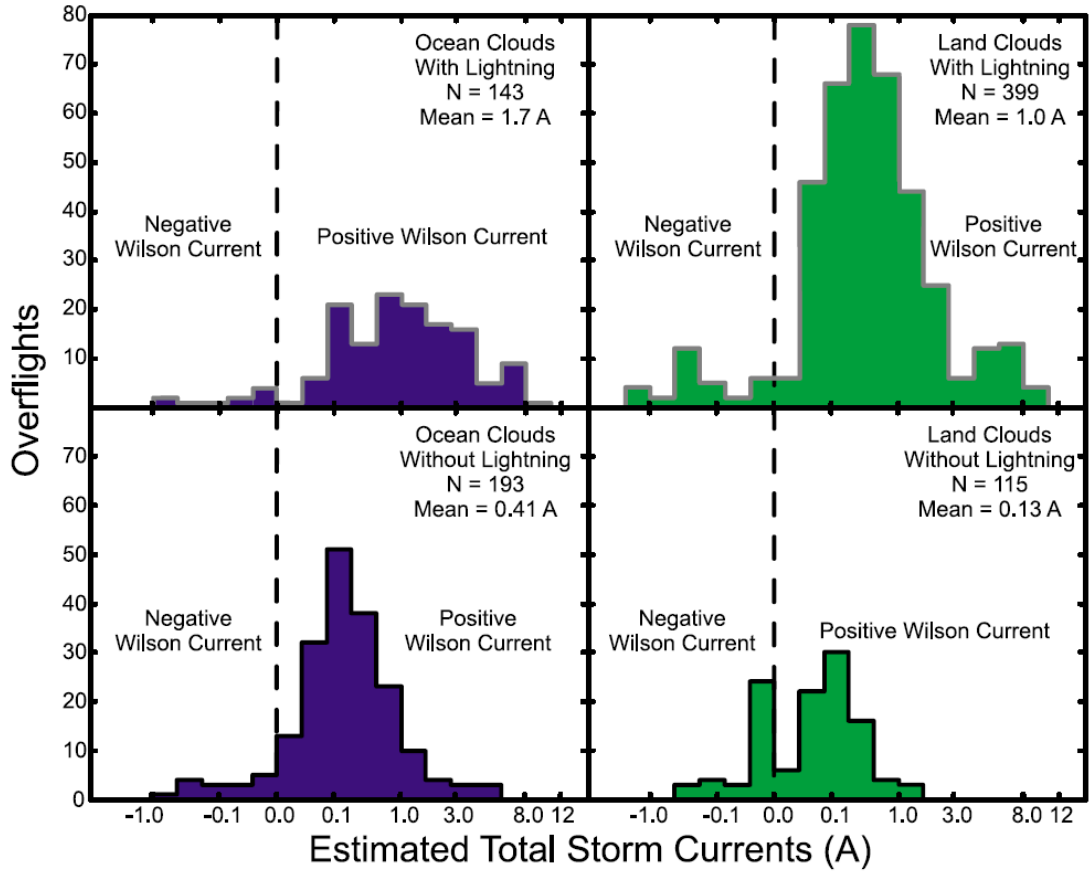

Figure 1. Total storm currents for ocean/land and lightning/nonlightning electrified clouds. The upper (bottom) two panels are for storms with lightning (without lightning). The left (right) panels are for ocean (land) storms. Left (right) of the dashed line are negative (positive) total storm currents representing global circuit sinks (sources). Vertical scale is overflight counts. Horizontal scale is cube root compressed.

flash rate as ocean storms (2.2 versus 0.8 flashes min^{-1}, respectively). Approximately 7% of the overflights had negative current. The mean and median currents for positive (negative) polarity storms are 1.0 and 0.35 A (-0.30 and -0.26 A). Finally, we found no regional or latitudinal-based patterns in our storm currents, nor support in the data for simple scaling laws between cloud top height and lightning flash rate.

4. SUMMARY

We have determined the flash rate, electric field, conductivity and current densities for over 1000 storm overflights, and used those data, along with some simple assumptions, to estimate the Wilson current flow. We find that new insights are gained and the Wilson current differences are clearer when the data are subdivided into the four subsets of oceanic storms with lightning, oceanic storms without lightning, land storms with lightning, and land storms without lightning., and are key in understanding the global electric circuit (Mach et al.,2011b).

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