Relating electrified cloud properties to Wilson currents: an oceanic and continental case study

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SOARS® Summer 2012

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ABSTRACT

Thunderstorms and other electrified, non-lightning producing clouds are thought to play an important role in maintaining the potential difference between Earth's surface and upper atmosphere. These clouds are responsible for producing Wilson currents between cloud tops in the troposphere and the electrosphere which help sustain the Global Electric Circuit (GEC). Estimates of Wilson currents for oceanic and continental electrified clouds were recently derived from data collected over two decades during multiple field campaigns involving the NASA ER-2 aircraft. It was found that the strength of Wilson currents varies by storm type and, on average, is higher for oceanic storms than their continental counterparts. This study builds upon findings made from the ER-2 data set and investigates relationships between the dynamical and microphysical properties of electrified clouds alongside their ER-2 Wilson current estimates. Variations of these properties were also studied during the lifecycles of one oceanic and two continental storms from 19 September 2001. Maximum reflectivity measured by the Next Generation Radar (NEXRAD) and ER-2 Doppler radars, along with radar derived precipitation ice mass and ice water path, updraft volume, maximum updraft velocity and echo top height were compared to the Wilson current estimates. Some cloud properties, such as ice water path and updraft volume, correlated well to the Wilson currents. Cloud top heights, however, did not have such a strong correlation. Further research is needed to determine if these results are robust. If proven, they could be utilized as Wilson current parameterizations in a modeling framework of the GEC.

This work was performed under the auspices of the Significant Opportunities in Atmospheric Research and Science Program. SOARS is managed by the University Corporation for Atmospheric Research and is funded by the National Science Foundation, the National Oceanic and Atmospheric Administration, the Cooperative Institute for Research in Environmental Science, the University of Colorado at Boulder, and by the Center for Multiscale Modeling of Atmospheric Processes.

1. Introduction

An electric field exists between Earth's surface, which holds a net negative charge, and the electrosphere (i.e. the ionosphere and magnetosphere), which holds a net positive charge (Saunders 1993). It is believed that thunderstorms and electrified shower clouds (ESCs) play an important role in maintaining the potential difference between the upper atmosphere and the earth's surface (Rycroft et al. 2000). These clouds are responsible for producing conduction currents, specifically Wilson currents, from the cloud tops in the troposphere to the electrosphere (see Figure 1) (Bering et al. 1998). With around 1000-2000 thunderstorms simultaneously occurring globally at all times and each producing a current ranging from -1.3 to 9.9 amperes (Rycroft et al. 2000; Mach et al. 2010), thunderstorms and ESCs generate enough current to maintain the potential difference between the earth's surface and the upper atmosphere and are thus thought to play an important role in the Global Electric Circuit (GEC).

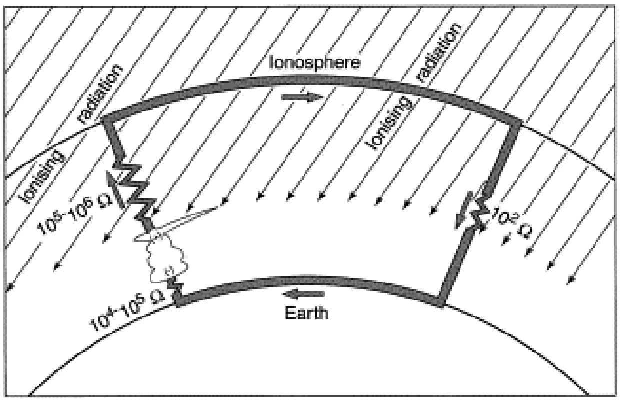

Figure 1 A schematic of the Global Electric Circuit (GEC) showcasing a Wilson current and the fair weather current from globally averaged thunderstorms (Fig. 3 Rycroft et al. 2000)

As an equalizing response to Wilson currents, the potential difference between earth's upper atmosphere and surface creates a fair weather current estimated at 2x10^{-12} amperes/meter^2 towards the surface (Rycroft et al. 2000). This weakens the potential difference whereas Wilson currents strengthen it. Lightning, galactic cosmic rays, magnetospheric coupling, and possibly transient luminous events such as sprites all modify the potential difference and GEC as well (see Figure 2). The exact details on the strength of impacts from all components in the GEC are still under investigation (Bering et al. 1998).

There is strong evidence from field and laboratory observations, as well as from modeling studies, that precipitation based charging plays a major role in thunderstorm electrification. The precipitation based non-inductive charge-transfer process is thought to contribute significantly to thunderstorm electrification and does not require a pre-existing electric field. In this process, collisions between riming hydrometeors (graupel) and ice crystals in the presence of supercooled water produce enough charge to electrify a storm (e.g. Saunders 1993). The magnitude of the charge transfer relies on temperature, impact velocity of the colliding ice particles, size of the ice crystals, and the liquid water content. Experiments from Takahashi (1978) and Saunders et al. (1991) suggest that graupel becomes negatively charged below -10°C

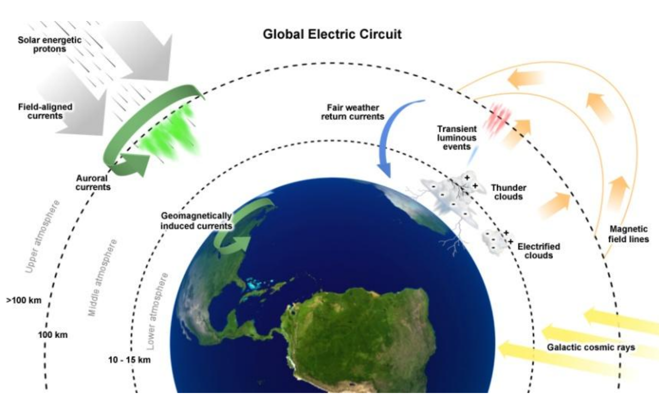

Figure 2 The GEC and all of the contributing processes which form it. Notice the Wilson currents in orange and the fair weather currents in blue (FESD: ECCWES)

(depending on the liquid water content of the cloud) and ice crystals become positively charged as a result of these collisions. This non-inductive charging process can explain the classical model of the charge structure observed in a thunderstorm (see Figure 3). Through gravitational size sorting, positively charged ice crystals are carried upward by the updraft to form a main positive charge region at the top of the thunderstorm. The heavier negatively charged graupel particles create a main negative charge region around -20°C. Warmer temperatures and higher liquid water contents near the cloud base often form a smaller net positive charge region as well.

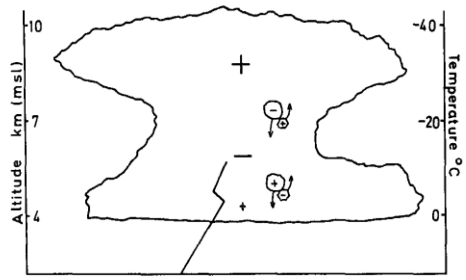

Figure 3 A tripole thunderstorm structure after collisions of negatively charged graupel and positively charged ice crystals aloft and the reversed charges near the cloud base. Updrafts are able to lift the ice crystals, rather than heavier graupel particles, to higher portions of the cloud (Fig. 2 Saunders 1993).

Inverted dipoles in which the main negative charge is at the cloud top, with positive charges below, have also been observed in the continental United States and China, and may occur elsewhere. Disrupting the normal flux of current in the GEC, inverted dipole structures produce Wilson currents that short the circuit. The occurrence of these structures is not well known and they are unidentifiable without further data analysis (Williams et al. 2008; Mach et al. 2010).

From 1915-1929, the research ship *Carnegie* sailed around the world measuring the diurnal variation of the fair weather electric field (Bering et al. 1998). These climatological diurnal variations are referred to as the Carnegie Curve (depicted in Figure 4). In 1936, Whipple and Scrase discovered that the diurnal variation of thunderdays matched the Carnegie Curve fairly well, with the exception of a difference in amplitude (Mach et al. 2011). New technology, such as the Optical Transient Detector (OTD) and Lightning Imaging Sensor (LIS), allowed researchers to better represent the curve when they compared it to the global variation of the diurnal flash rate. Mach et al. (2011) found that they could match the amplitude of the Carnegie Curve within 4% for most of the time period when they combined the OTD and LIS data with their measurements of Wilson currents from different storm types. They measured continental

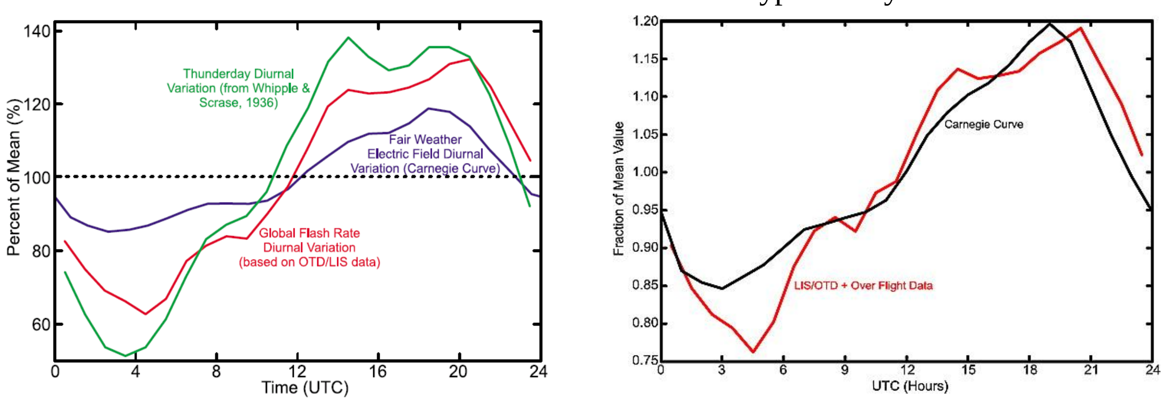

Figure 4 Left: The Carnegie Curve in blue compared with the diurnal thunderday variation in green and the diurnal variation in global flash rate in red (Fig. 1 Mach et al. 2011). Right: The Carnegie Curve overlaid with the total Wilson current from overflights of various storm types and environments combined with the LIS/OTD data (Fig. 10 Mach et al. 2011).

thunderstorms to have mean Wilson currents of approximately 1.0 kA while oceanic thunderstorms contributed 1.6 kA. In contrast, continental ESCs produced only 0.13 kA while oceanic ESCs produced 0.39 kA (Mach et al. 2011).

Liu et al. (2012) confirmed previous findings that lightning flash rates correlate well with radar reflectivity in the mixed phase region of a thunderstorm. Storms with reflectivities greater than 30, 35, and 40 dBZ had high correlations, but these relationships varied significantly between oceanic and continental storms. Land thunderstorms had an average flash rate of 2.2 flashes/minute while oceanic storms had an average rate of only 0.8 flashes/minute. Therefore, oceanic storms have a lower flash rate, but higher mean Wilson current (Mach et al. 2011). A further examination of electrified cloud properties, such as updraft strength and ice microphysics, may explain why these storms differ in the strength of their Wilson currents and thus contribute differently to the GEC.

This paper examines one oceanic multi-cell and two continental single-cell thunderstorm events from 19 September 2001, near the Florida peninsula. By analyzing electrified cloud properties, a correlation may be determined between these properties and the Wilson currents measured by Mach et al. (2009-2011). This relationship may then be used in a modeling framework to determine the role of electrified clouds in the GEC globally. Section 2 of this paper will describe the data used to determine the cloud microphysical and dynamical properties and how these properties were computed. Results will be presented and discussed in Section 3 followed by a conclusion of the research in Section 4.

2. Methods and Data Sets

a. NEXRAD Reflectivity

Full volume reflectivity scans from the 10 cm wavelength, Next Generation Radar (NEXRAD) at Miami, Florida (KAMX) were examined. This was done for thunderstorms for which Wilson current estimates were derived from the ER-2 electric field and conductivity measurements (Mach et al. 2009). Using this data along with the Integrated Data Viewer (IDV) and the National Corporation for Atmospheric Research (NCAR) SOLOIII radar editing software, the following fields were determined: echo top height, maximum reflectivity, and stage of storm evolution. Mach et al. (2009, 2010) found that strong Wilson currents often occurred with high cloud tops; however, weak currents also occurred with high cloud tops. Though the two variables are not strongly correlated, Mach et al. (2010) did determine that strong currents required the high cloud tops in order to form.

In addition, maximum radar reflectivity above the melting level is a measure of storm intensity which may relate to thunderstorm electrification. Liu et al. (2012) found that high lightning rates often occurred with reflectivities greater than 30 dBZ above the melting level. This suggests that precipitation ice plays a role in thunderstorm electrification. Stronger updrafts are able to enhance the production of graupel, hail, and ice crystals and lift these hydrometeors to higher altitudes. Allowing for increased particle collisions, both the updraft and gravity help spur charge separation and creation of charge regions in a thundercloud (Section 1).

The KAMX NEXRAD reflectivity data was also used to determine the storm’s stage in its lifecycle. Comparing storm evolution to the intensity of the Wilson currents produced may provide insight as to how variable the currents are during the storm's lifecycle. As shown in Figure 5, the 19 September 2001 oceanic case was a multicellular storm which the ER-2 sampled during its mature and dissipating stages. The two continental cases were both single cells and were sampled during their mature stage only.

b. EDOP Radar Reflectivity

In addition to the NEXRAD data, the ER-2 Doppler (EDOP) radar measures a vertical profile of radar reflectivity and radial velocities along the flight path of the ER-2 aircraft. Although this 3 cm wavelength, X-Band radar cannot provide full volume scans of the storms, by flying over the core it can give insight on updraft intensity. ER-2 derived vertical velocity was determined by subtracting the hydrometeor fall speed from the downward measured radial velocity. Fall speeds were estimated above and below the melting layer with different fall speed-radar reflectivity relationships. Maximum reflectivity, storm evolution, and echo top height were also calculated with this radar.

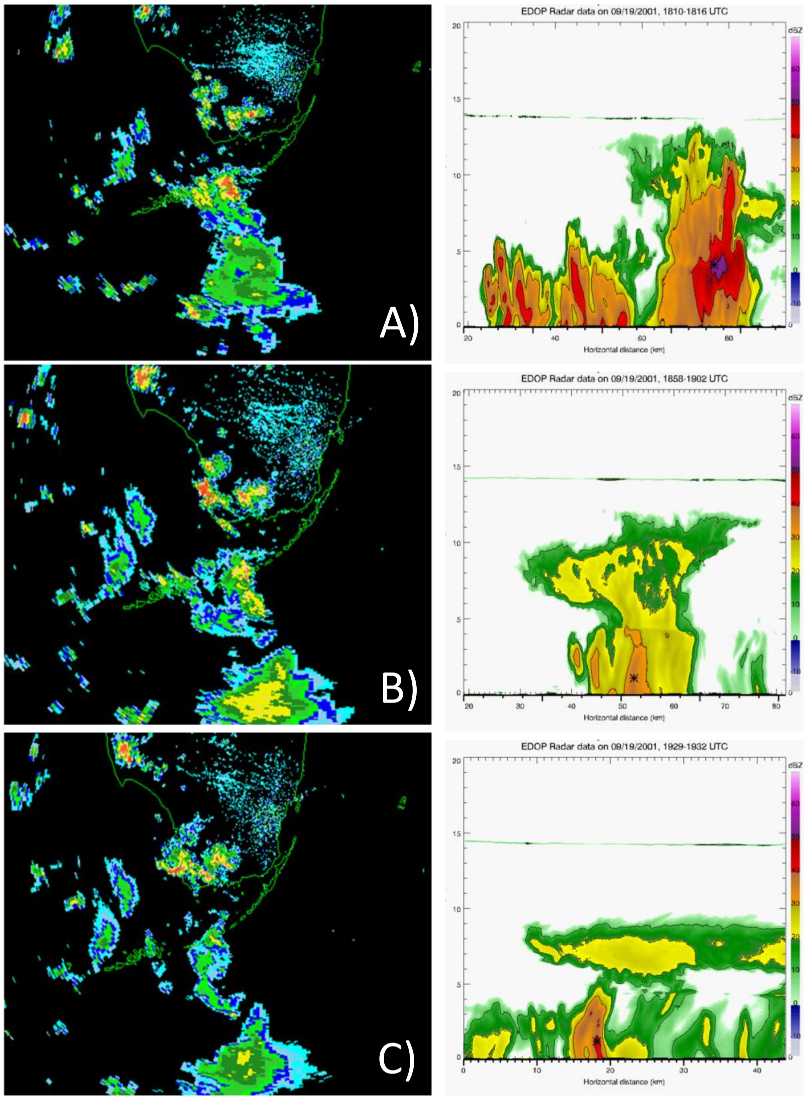

Figure 5 A through C compares the oceanic multicell NEXRAD reflectivity (left) to the EDOP reflectivity (right) throughout the storm's lifecycle. A shows the storm at 1810 UTC during its mature stage. The EDOP had a direct overflight over the updraft core. B shows the beginning of the dissipating stage from 1856 UTC. EDOP did not have a direct overflight, thus the core was actually stronger than what is depicted. C shows the dissipating stage from 1931 UTC with a direct overflight from EDOP.

c. Conduction Current Data

The Wilson current data used in this study was provided by Mach et al. (2009-2011). From overflights of the NASA ER-2 high altitude aircraft, they determined storm total Wilson currents within 10 km of the peak Wilson current (Heymsfield et al. 2001; Hood et al. 2006). This aircraft collected data during various field projects over a period of twelve years (1993-2005) for numerous oceanic, continental, and coastal electrified clouds. Onboard the ER-2, two to eight electric field mills, also known as rotating vane electric field meters, as well as conductivity probes collected information on the ambient electric field and conductivity of the air. This data was used to estimate the Wilson currents.

b. Ice Water Path Computations

Petersen et al. (2005) found a high correlation between ice water path (IWP) and lightning flash density. Thus, the IWP is a good candidate as a microphysical indicator of cloud electrification. This study compares IWP to the Mach et al. (2009-2011) determined storm total Wilson currents. Following Petersen et al. (2005), IWP measured in kilograms/meters^2, is computed by vertically integrating the ice water content (IWC) in a column starting from the height of the -10ºC level. IWC is computed with the following equation:

$$\mathrm{IWC} = \pi \rho_i N_\circ^{\frac{3}{7}} \left(\frac{5.28*10^{-18}}{720} Z\right)^{4/7} \text{ kg m}^{-3}$$

where $N_o = 4*10^6$ m^{-4} and $\rho_i = 917$ kg m^{-3} (Petersen and Rutledge 2001). IWP was determined from both the NEXRAD and EDOP radars. The stationary NEXRAD determined storm total IWP, whereas the EDOP radar computed IWP within a 10 km radius around the maximum Wilson currents. Some Wilson current estimates were taken just outside of this updraft core and are identified in the analysis.

c. Precipitation Ice Mass Computations

Deierling et al. (2008) and others found a strong correlation between precipitation ice mass above the -5°C level and total lightning activity. Precipitation ice mass is thus another candidate for examining the electrification state of a cloud and was compared to estimated Wilson currents in this study. Similar to IWP, this variable was derived from both the NEXRAD and EDOP radars and from the following Z-M relationship:

$$\text{Precipitation Ice (Graupel): } M = 0.0052Z^{0.5}$$

where M is in kg and Z is in mm^6/m^3 (Heymsfield and Palmer 1986; Heymsfield and Miller 1988).

d. Maximum Updraft and Updraft Volume Computations

In accordance to the non-inductive charging process, stronger updrafts should be able to initiate the development of large hydrometeors in the mixed phase region of a storm. A large updraft volume would then initiate more collisions and thus create more charge. Deierling and Petersen (2008) found a high correlation between updraft volumes above the -5ºC and -10ºC levels with vertical velocities greater than 5 ms^{-1} and total lightning rates. Relating to the electrification state of a cloud, this dynamical parameter was also compared to estimated Wilson currents. Maximum updraft (ms^{-1}) and updraft volume (m^3) were derived from the EDOP radar for the 0ºC, -5ºC, and -10ºC levels of each storm.

4. Results

During the field campaigns of the ER-2, some storms took more precedence than others. Since the oceanic multicell storm of 19 September 2001 was more vigorous than the single cell continental storms of the same day, the ER-2 flew over the oceanic storm more frequently. Thus, the data set for the oceanic case was much larger and more representative of the storm system. It also shows clearer relationships than the continental cases. As such only the oceanic data is displayed in the next few graphs. Additionally, due to the size and limitations of these data sets, any correlations discussed only represent one storm. Supplemental data is needed to form any robust conclusions. Since NEXRAD derived products encompass the entire storm, those results for maximum reflectivity, IWP, precipitation ice mass, and echo top height were the main focus of the following discussion.

a. Maximum Reflectivity and Storm Evolution

Figure 6 depicts Wilson current (A) compared to NEXRAD measured maximum reflectivity (dBZ) over time. Wilson current peaks around 1800 UTC which was around the time of the storm's maximum intensity. After this point, there is a steady decline in the strength of the current which corresponds to the weakening of the oceanic storm. Overall, the two variables had a correlation coefficient r of 0.63. Since the ER-2 did not fly over the updraft core consistently, EDOP measurements on maximum reflectivity were sometimes lower than the NEXRAD measurements. Nonetheless, EDOP reflectivity of the oceanic storm still had a correlation of r = 0.75 to Wilson currents. This suggests that although the measurements were not exact, the ER-2 sampled the storm well enough to capture the storm's evolution.

b. Precipitation Ice Mass

Next, a time series of Wilson current and precipitation ice mass (kg) above the -10°C level computed from NEXRAD data is shown in Figure 7. Though past research by Deierling et al. (2008) showed a strong correlation between lightning activity and precipitation ice mass, this study shows a weak correlation of 0.46 between precipitation ice mass and Wilson currents. It remains to be seen if this holds up with a larger data set.

c. Echo Top Height

Another NEXRAD product that was compared to Wilson currents is echo top height (km) over time as shown in Figure 8. In agreement with Mach et al. (2010) there does not appear to be a strong correlation between the radar derived echo top heights and the conduction current (r = -0.28).

d. Maximum Updraft Velocity and Updraft Volume

EDOP derived dynamical storm properties such as maximum updraft velocity and updraft volume were the next variables compared to Wilson currents. The peak in maximum updraft velocity (ms^{-1}) above the -5°C level occurred around 1730 UTC, just before the peak in Wilson current (see Figure 9). In contrast, the peak in updraft volume (m^3) above the -5°C level and greater than 5 ms^{-1} aligned well with the peak in Wilson current (see Figure 10). This study found correlation coefficients of 0.70 and 0.74 for -5°C maximum updraft velocity and updraft volume respectively. Updraft characteristics were also compared at the 0°C and -10°C levels. Correlation coefficients of 0.70 and 0.68 were computed between Wilson currents and the 0°C level maximum updraft velocity or updraft volume respectively. For -10°C, both maximum updraft velocity and updraft volume had a correlation coefficient of 0.70.

e. Ice Water Path

NEXRAD IWP (g/m^2) above the -10°C level compared to Wilson current over time is shown in Figure 11. The IWP correlates well to the conduction current with a correlation coefficient of 0.81. This is a promising result; however, more data is needed to investigate if IWP can be used to describe the production of Wilson currents.

f. Oceanic and Continental Comparisons

Figure 12 compares the Wilson currents and IWPs (above -10°C) of not only the oceanic multicell storm, but also the two continental singe cells. There is a distinct difference between these relationships where the Wilson current and IWP measurements for the oceanic storm are generally higher than those of the continental storms. This relationship, however, is due to the difference in storm type rather than location. Since multicells have many updrafts functioning as a system to lift and support hydrometeor development, the oceanic storm was able to produce a higher IWP and stronger Wilson current than the single cells. The continental single cell storms simply lacked the intensity and force of the oceanic multicell storm.

Analogous to Figure 12, Figure 13 shows a similar trend as it compares Wilson current to updraft volume (above the -5°C level and greater than 5 ms^{-1}) for both oceanic and continental storms. Continental storm B is not pictured as it did not have an updraft volume greater than 5 ms^{-1} above -5°C. The oceanic storm shows a positive trend where Wilson current increases as updraft volume increases.

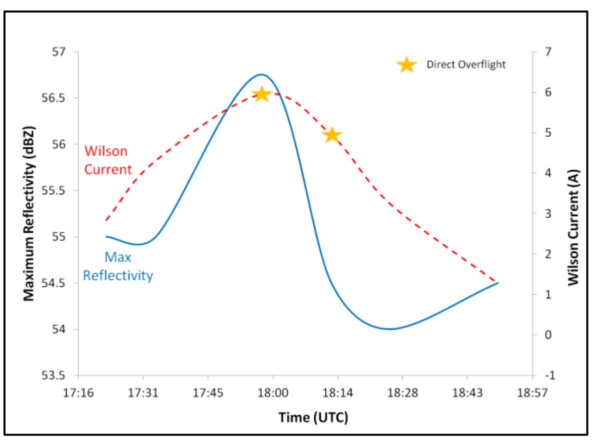

Figure 6 NEXRAD maximum reflectivity (dBZ) and Wilson current (A) over time for the oceanic case. Shows change in Wilson current with storm evolution.

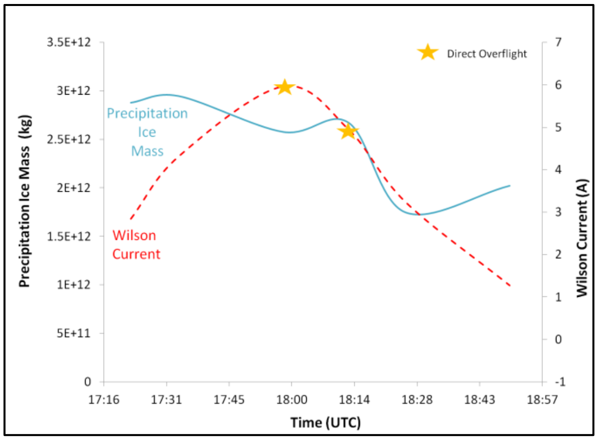

Figure 7 NEXRAD precipitation ice mass (kg) and Wilson current (A) over time for the oceanic case. Past research by Deierling et al. (2008) found a strong correlation between precipitation ice mass and total lightning.

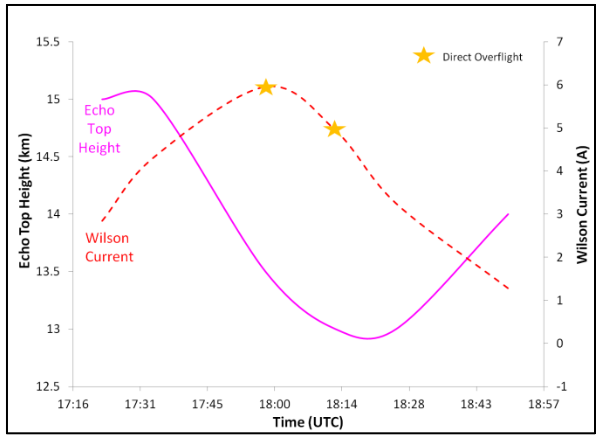

Figure 8 NEXRAD echo top height (km) and Wilson current (A) over time for the oceanic case. This cloud property had the lowest correlation (-0.28) with Wilson currents.

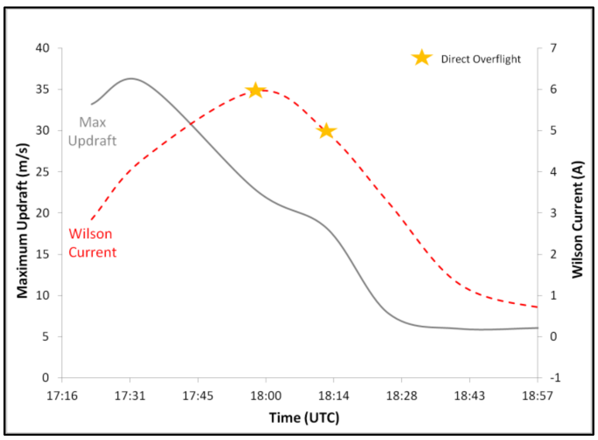

Figure 9 EDOP maximum updraft above the -5°C height (ms^{-1}) and Wilson current (A) over time for the oceanic case.

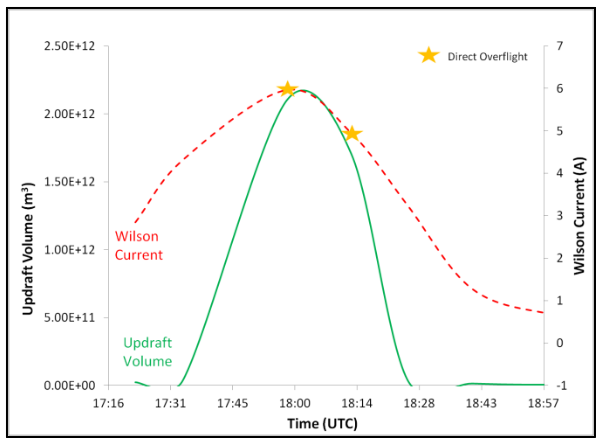

Figure 10 EDOP updraft volume (m^3) above the -5°C height with vertical velocities greater than 5 ms^{-1} and Wilson current (A) over time for the oceanic case.

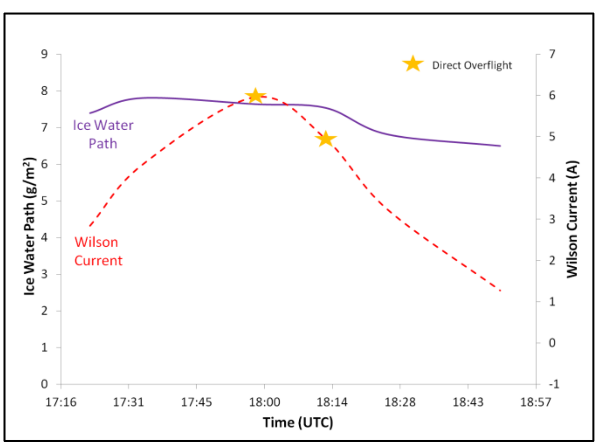

Figure 11 NEXRAD ice water path (IWP) (gm^{-3}) and Wilson current (A) over time for the oceanic case. Past research by Petersen et al. (2005) found a strong correlation between IWP and lightning activity.

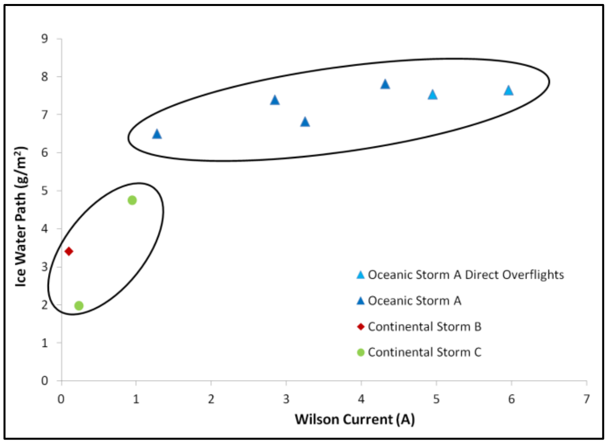

Figure 12 NEXRAD IWP (gm^{-3}) versus Wilson current (A) for both oceanic and continental storms. Circles discriminate between the oceanic multicell storm and the two continental single cells.

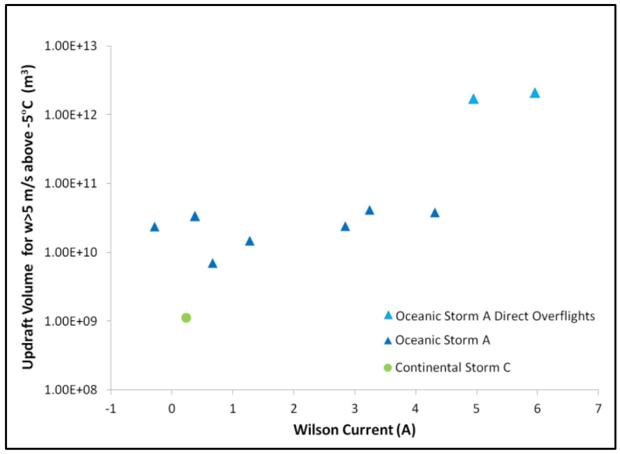

Figure 13 EDOP updraft volume (m^3) with vertical velocities greater than 5 ms^{-1} and above the -5°C level versus Wilson current (A) for both oceanic and continental storms. Continental Storm B is not depicted since it did not have an updraft volume with these parameters.

5. Conclusions

This study used the Wilson current data set derived by Mach et al. (2009-2011) to compare it to the microphysical and dynamical properties of electrically charged clouds. Examining the lifecycles of three different storms from 19 September 2001 and two different radars (NEXRAD and EDOP), comparisons were made between Wilson currents and the following radar derived products: maximum reflectivity, ice water path, precipitation ice mass, echo top height, maximum updraft velocity, and updraft volume.

Most of these variables correlated well with the conduction current estimates, however, precipitation ice mass and cloud top height did not. This may be due to the limited amount of data available for the three storms being investigated. Strong relationships were found between maximum reflectivity, IWP (above -10°C), maximum updraft velocity (above -5°C), updraft volume (above -5°C and greater than 5 ms^{-1}) and Wilson currents. Maximum reflectivity helps illustrate the storm's evolution and shows the Wilson current's tie to the storm's lifecycle. IWP, maximum updraft velocity and updraft volume then show the dependency of Wilson current to the strength of the updraft and the amount of ice crystals and graupel the updraft is able to support. The comparisons between oceanic and continental storms showed more of a relationship between storm type rather than storm location. Since the oceanic case was a multicell with many updrafts supporting hydrometeor development, it had higher Wilson currents than the continental storms which were only single cells with one updraft.

For any of these results to be implemented in a modeling framework of the GEC, much more research is needed. The ER-2 field campaigns created a huge data set of thunderstorms which when analyzed, will help make these preliminary findings more robust. More comparisons such as those conducted here will help to define relationships between electrified cloud properties and Wilson currents. To solidify the findings of this study in particular, more research is needed on discriminating Wilson current strength between storm type as well as regime.

Acknowledgements

I would like to thank all of the co-authors for their invaluable support and mentoring throughout this project. A huge thank you also goes to Douglas Mach for providing the Wilson current data sets and Daniel Cecil for his programming expertise. Also, to the SOARS program and all of its committee members for allowing this research to happen and for selecting me as a protégé. Finally, I extend my gratitude to all of the SOARS protégé's for their support and advice.

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