Remote Sensing Properties of Freezing Rain Events From Space

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Abstract Four years (2014 April to March 2018) of Global Precipitation Measurement (GPM) Precipitation Features data along with colocated the Modern Era Retrospective-Analysis for Research and Applications-2 model data are used to identify Freezing Rain Features (FRFs). A Precipitation Feature with presence of both melting layer (maximum temperature of the vertical column > 4 °C) and a layer of subfreezing air (2-m temperature < 0 °C) adjacent to the surface is considered an FRF. During 4 years of observations, GPM and Modern Era Retrospective-Analysis for Research and Applications-2 identify approximately 3,096 FRFs globally (65°S–65°N). Most of them are observed over Northern Hemispheric land in the winter season. The majority of FRFs originates through the “melting process,” whereas only 35% are associated with “warm rain” process. The locations and seasonal and diurnal distribution patterns of the FRFs over the United States are well matched with the ground-based observations. The ground-based observations verify approximately 70% of the FRFs over the United States. Ku-band radar properties show that FRFs are found shallower (2–5 km) and less intense (<27 dBZ) than precipitation features in general but deeper and more intense than Snow Features. Passive microwave properties show that FRFs Tbs and Polarization-Corrected Temperature are warmer than Snow Features at all GPM Microwave Imager channels with the largest differences in 166 GHz. The enhancement in Tbs are more distinct with warm rain FRFs. FRF Tb tends to decrease as echo top height increases at all GPM Microwave Imager channels except for 183 GHz, where Tbs have lack of dependence on echo top height.

1. Introduction

Winter storms often produce frozen precipitation (such as snow or ice pellets) and occasionally produce freezing precipitation (such as freezing rain or drizzle). Freezing rain is any form of liquid precipitation that freezes on contact or coats the frozen ground or exposed objects with a glaze of ice (Czys et al., 1996; Huffman & Norman, 1988; Stewart, 1985; Stewart & King, 1987). It occurs when a thermal stratification layer of a warm and moist air overlays over a shallow subfreezing layer of air and causes a temperature inversion. The presence of thermal stratification in the midlayer is caused by strong baroclinic systems that transport warm and moist air over the subfreezing layer of air near the subfreezing surface (Cortinas, 2000; Holle & Watson, 1996; Keeter et al., 1995; Stuart & Isaac, 1999). This is a relatively uncommon phenomena when compared to all season precipitation, but it can cause severe impact in higher latitude countries such as the United States, Canada, many European countries including Russia, east Asia, and occasionally lower latitude regions as well (Cortinas et al., 2004; Zhou et al., 2011). The main impacts are disruption of transportation, powerlines, communications, and aircraft performances, as well as damage to trees, livestock and agriculture, water and sewers, and more, that not only causes billions of dollar loss but also causes fatalities every year (Bendel & Paton, 1981; Changnon, 2003a, 2003b; Cortinas, 2000; DeGaetano, 2000; Forbes et al., 1987; Jones & Mulherin, 1998; Irland, 1998; Rauber et al., 1994). Thus, a proper understanding of such events could help to improve forecasts and to save human lives.

The generally accepted freezing rain formation mechanism is either through the “melting process” (Forbes et al., 1987; Martner et al., 1993; Rauber et al., 1994; Rauber et al., 2000) or the “warm rain” process (Bocchieri, 1980; Huffman & Norman, 1988; Ohtake, 1963; Rauber et al., 2000). The melting process is a classical approach where freezing rain starts with ice hydrometeors, which completely melt during their fall through a warm air layer, then become supercooled when they pass through a subfreezing or subzero layer adjacent to the earth surface (hereafter referred to as a subfreezing layer), and freezes on contact with exposed objects. The “warm rain process” is similar to the melting process, but precipitation is formed by the collision and coalescence process where the precipitation starts as rain instead of ice hydrometeors because of the warm cloud top temperatures.
Several studies have been carried out in the past over the United States, Canada, Europe, and some other countries to highlight the climatology, synoptic and environmental conditions, and thermodynamic behaviors of freezing rain events. Over the United States, several research studies about freezing rain can be found in the literature (e.g., Bennett, 1959; Bernstein, 2000; Changnon & Karl, 2003; Cortinas, 2000; Gay & Davis, 1993; Robbins & Cortinas, 2002; Zerr, 1997). Bennett (1959) was one of the earliest reports, where his survey shows that freezing rain events are more frequent east of the Rocky Mountains and in the northern half of the country, and the frequency of occurrence increases toward the eastern part (Cortinas, 2000; Rauber et al., 2001). These events are more frequently observed from the Texas panhandle to Michigan, the Catskill and Allegheny Mountain region of the Northeast, the eastern side of the Appalachian Mountains, central New York, North Carolina, Virginia, the central United States from southwest Missouri to Pennsylvania, and the Pacific Northwest (Forbes et al., 1987; Bernstein, 2000; Robbins and Cortinas, 1996; Robbins & Cortinas, 2002). These studies revealed that freezing rain mostly occurs before the sunrise in December to March. They last usually for a short period of time, typically less than 1 hr (Cortinas, 2000; Steenburgh et al., 1997). Robbins and Cortinas (2002) used 15 years of surface observation data over the United States to examine the local and synoptic conditions associated with freezing rain events. They found that the most common conditions during those events are nearly saturated air near the surface, midlevel upward vertical motion, a deep low-level warm layer (~1.3 km), and a shallow (~600 m) subfreezing surface layer. The median maximum temperature of the vertical column (T-MAX) is about 3.2 °C at a median height of ~1,100 m with a median depth of ~1,300 m. The subfreezing layer near the surface is found to have a median depth of 600 m, with −1 °C median surface temperature. Rauber et al. (2001) were able to summarize common synoptic patterns over the United States by analyzing 411 freezing rain cases. The four most common synoptic patterns include Arctic front anticyclone, warm front occlusion, cyclone-anticyclone, and west quadrant of Arctic high pressure.

Freezing rain is also common in Canada in all seasons with relatively high frequencies of occurrences in the colder seasons (McKay and Thompson, 1969; Strapp et al., 1996; Stuart & Isaac, 1999). With 42 years of observations in 27 stations, Kochtubajda et al., (2017) have shown that about 1.4% of the precipitation events in Canada were associated with freezing rain and most of the events were short lived (<2 hr). Central and eastern Canada are the most affected regions where eastern Canada especially newfound land andes more than 100 hr of freezing rain annually. The frequency of freezing rain events decreases toward northern Canada because the surface temperature is often too cold. Freezing rain occurs most often when the surface temperature is near zero, especially between 0 and −5 °C (Cortinas et al., 2004; Groisman et al., 2016; Kochtubajda et al., 2017). Most Canadian regions experience freezing rain in colder seasons with higher frequency in March and April, but it is limited to the far north during summer months (Stuart & Isaac, 1999). The topographical features, proximity to water bodies, and storm tracks locations are influential to the geographical distribution of freezing rain events (Cortinas et al., 2004).

In addition to the Northern American continent, there have been a few climatological studies on freezing rain over Europe. Carrière et al. (2000) studied three winter seasons’ SYNOP data over central and western Europe. Their study showed that the occurrence of freezing precipitation (including freezing drizzle and ice pellets) is approximately 1% over central Europe especially Southern Germany, Hungary, Croatia, and Bosnia. The most active season is found to be winter (December to February). They also revealed that approximately 60% of the events are associated with the melting process, whereas the rest are formed through the warm rain process. Bezrukova et al. (2006) and Groisman et al. (2016) used several years of ground station observations and constructed a climatology of freezing rain and riming events including mean annual and monthly occurrences of freezing rain over Russia and Eastern Europe. Groisman et al. (2016) claimed that the frequency of these events has increased substantially in recent years. Kämäräinen et al. (2017) developed a method to detect freezing rain events over Europe by using gridded atmospheric data sets. They used ERA-I reanalysis data set with threshold of near-surface temperature colder than 0.09 °C, T-MAX warmer than −0.64 °C, surface precipitation greater than 0.39 mm/6 hr, and so forth to define freezing rain events. Their results show that freezing rain is more common in central and Eastern Europe, and the peak months are during September to April, which are in good agreement with previous climatological studies (Carrière et al., 2000; Groisman et al., 2016). These previous studies use surface station data to generate the climatology and associated weather patterns over certain regions or
the continent. To our knowledge, there is no complete global freezing rain climatology found in current literature because of unavailability of data and/or proper measurement techniques.

In recent years, satellite-based precipitation measurement techniques are becoming more popular and are the only practical way to estimate precipitation on a global scale (Tian & Peters-Lidard, 2010). This includes not only the rain events but also the various types of winter precipitation such as snow (Adhikari et al., 2018; Kulie & Bennartz, 2009; Kulie et al., 2016; Liu, 2008) and thundersnow (Adhikari & Liu, 2019). After the launch of Global Precipitation Measurement (GPM) core satellite (Hou et al., 2014; Skofronick-Jackson et al., 2017) in February 2014, measurement of solid precipitation events in near-global (65°S–65°N) scale became possible because of its middle to high latitude coverage. This study aims to summarize the characteristics of freezing rain events by utilizing the GPM Ku-band Precipitation Radar (KuPR), GPM Microwave Imager (GMI), and Modern Era Retrospective-Analysis for Research and Applications (MERRA)-2 reanalysis data. After identifying freezing rain events from satellite and reanalysis data, this study attempts to address the following scientific questions.

1. What are the geographical distributions of freezing rain events observed by the GPM and MERRA-2 data?
2. How do freezing rain events from satellite measurements compare with ground observations in the United States?
3. What are the characteristics of freezing rain in space borne radar and passive microwave observations?

To answer the above questions, we have defined Freezing Rain Features (FRFs) by using 4 years of GPM KuPR and MERRA-2 data. The FRFs over the United States are validated with freezing rain reports from ground stations. Then, the properties of FRFs shown by radar and passive microwave observations are summarized.

2. Data and Methods

2.1. GPM PF Data

The GPM core observatory satellite, which is the follow-up mission of the Tropical Rainfall Measuring Mission (Kummerow et al., 1998), was launched in a non-Sun synchronous polar orbit in late February 2014 (Hou et al., 2014; Skofronick-Jackson et al., 2017). The onboard instruments include the Dual-Frequency Precipitation Radar functioning at Ku band (13.5 GHz) and Ka band (35.5 GHz) and a multifrequency GMI operating at 13 various frequency channels ranging from 10–183 GHz. The highly inclined orbit (65°S–65°N) and improved minimum detectable sensitivity of Dual-Frequency Precipitation Radar (~12 dBZ; Hamada & Takayabu, 2016) enable light precipitation as well as falling snow-related research in mid-high latitudes. The near-surface radar reflectivity is used to retrieve the precipitation rate and types (Seto et al., 2013). Four years (March 2014 to February 2018) of GPM precipitation data are used to define Precipitation Features (PFs), which are defined by grouping at least four contiguous precipitation pixels (>0.1 mm/hr; Liu et al., 2008, Liu, 2016) observed by the GPM KuPR. A PF better represents the storm system than the individual pixels. The PF properties are derived from both radar and passive microwave observations. Radar properties include the highest near-surface reflectivity and maximum radar echo top height, and properties derived from passive microwave observations include minimum Tb or polarization-corrected Tb (PCT; Spencer et al. 1989) from various frequencies channels. From 4 years of GPM observation, more than 8.5 million PF samples are collected. The PF data set along with input from collocated MERRA-2 surface and upper air thermodynamic variables is used to define FRFs, as defined in the following section 2.1.

2.2. Defining FRFs

Each PF is collocated with MERRA-2 surface and upper air thermodynamic variables such as 2-m temperature, surface pressure, and vertical temperature profile spatially and temporally by the nearest neighbor method. MERRA-2 is relatively new atmospheric reanalysis data that deploys an upgraded version of the Goddard Earth Observing System-5 and the Global Statistical Interpolation scheme (Gelaro et al., 2017). It has 0.5° × 0.625° spatial resolution with hourly surface data and 3 hourly upper air data at 42 pressure levels. MERRA-2 2-m temperature can be used to identify snow events with about 15% of false alarm rate (Adhikari & Liu, 2019).

After finding the collocated MERRA-2 temperatures, T-MAX is determined. T-MAX is defined as the T-MAX from surface to 500-hPa pressure level. Any precipitation features with collocated MERRA-2
surface temperature below freezing (<0 °C) with a warm melting layer (T-MAX > 4 °C) is defined as an FRF. Note that freezing rain is rare and sensitive to the temperature; to be able to identify them at individual fields of view, we need to have vertical temperature profiles at such a resolution (5 km) globally and almost near real time, which is not available. Even if we propose a methodology of detection freezing rain (at the moment, we do not believe that we can), there is no way we can validate it at individual fields of view. By grouping features, we created a buffer to collocate to the surface freezing rain reports that can be somewhat validated. The T-MAX warmer than 4 °C ensures that hydrometeors would completely melt on the way to the surface, and the 2-m surface temperature below freezing provides the supercooled environment adjacent to the surface and sufficient surface conditions to freeze the hydrometeor when it comes in contact with any object. The mean and standard deviation of ”warm nose” (>0 °C) are approximately 1,380 and 465 m, respectively. Those statistics represent the depth of warm nose in the vertical column where temperature is warmer than 0 °C (note that each column’s T-MAX is warmer than 4 °C). We believe that on the given average depth, hydrometeors would completely melt. The criteria of T-MAX warmer than 4 °C excludes most of the sleet cases at all melting depths (Zerr, 1997) and would provide enough depth to melt a hydrometeor.

Various FRF properties from both KuPR and GMI, such as KuPR maximum reflectivity, maximum echo top height, minimum Polarization-Corrected Temperature (Spencer et al., 1989) at 37 and 89 GHz, and minimum Tbs at 166- and 183-GHz channels, are summarized. To differentiate FRFs from snow, FRFs properties are compared with Snow Features (SFs) properties. Note that SFs are defined following Adhikari et al. (2018), where at least four contiguous solid precipitation pixels are grouped, and those with collocated MERRA-2 2-m temperature colder than 0 °C are considered SFs. The 2-m surface temperature restriction is used to ensure the GPM defined “near-surface snow” is indeed snow at the surface. At or below 0 °C temperature, the probability of snow is more than 85% both over land and ocean (Sims & Liu, 2015).

Figure 1a shows an example of an FRF in North Carolina, United States, in 1 March 2015.

First, all the contiguous precipitation pixels are grouped together to define the PF, and then collocated MERRA-2 variables are used to identify it as an FRF. During the event, the MERRA-2 2-m temperature of the center of the feature is below −1 °C and T-MAX is −6 °C. Figure 1b shows the corresponding sounding at the center of the feature marked with a red triangle in Figure 1a. The MERRA-2 temperature profile shows there is an elevated melting layer between 800 and 950 hPa with a subfreezing layer near the ground. It is clear from this figure that the precipitation all started as snow, completely melted when it passed through the melting layer (~6 °C), and finally became supercooled again near the subfreezing surface before it hit the frozen surface (approximately −10 °C). A layer of maximum temperature warmer than 4 °C is an indicator of the melting layer that ensures the precipitation hydrometeors completely or partially melt before reaching the subfreezing layer adjacent to the surface. A deep warm layer above the frozen surface provides the thermal stratification conditions necessary to generate the freezing rain events (Cortinas, 2000). Out of 8.5 million PFs between March 2014 and February 2018, approximately 3,096 features satisfy the freezing rain criteria and, therefore, are identified as FRFs. This method might exclude many freezing rain events that have T-MAX colder than 4 °C or are without a melting layer, but we are confident that the FRFs defined using these strict criteria are indeed freezing rain cases. To avoid ground clutter from high terrain regions, features over mountains with higher than 1.5-km elevation are not considered in this study.

2.3. Freezing Rain Events From Surface Stations

The locations of FRFs are validated with Freezing Rain events (FZRA) from the ground station data. Four years (2014–2017) of hourly National Centers of Environmental Information (NCEI) data from more than 2,000 ground stations over the United States are used. The NCEI data mainly use the Integrated Surface Database to archive the meteorological variables and weather conditions. The NCEI observations include both manual and automated observations such as data from the Automated Weather Observing System stations, synoptic data, measurements from airways, Meteorological Terminal Aviation Routine Weather Reports (METARs), coastal and marine information, and buoy data (Smith et al., 2011). In this study, hourly FZRA events are retrieved by decoding the METAR data. The METAR data are decoded by following the standard norms of World Meteorological Organization and National Weather Service.
3. Results

In the first part of this section, the global locations of the GPM FRFs are identified and then validated with FZRA reports from the ground-based observations over the United States. In the second part of this section, properties of FRFs are summarized from GMI and KuPR observations. The FRF properties are further compared to SF properties to examine the radar echoes and passive microwave signatures during snow and freezing rain events.

3.1. Geographical Distributions of FRFs

During 4 years of GPM KuPR observations along with input from MERRA-2 reanalysis, approximately 3,096 FRFs are identified from 8.5 million PFs globally (65°S–65°N; Figure 2). As expected, these events are rare and occur mainly over continental regions. Since most ocean surface are warmer than land and are mostly above freezing temperatures, FRFs are rarely identified over water surface, except over southern oceans at high latitudes (south of 60°S). The majority of the FRFs occurs over North America and Europe, and a few events occur over the eastern coast of China. On a global scale, the majority of events (~41%) occur in the spring season (MAM), following by the winter (DJF) season (~28%), and autumn (SON) season (~24%).

The geographical distribution in Figure 2 is consistent with the literature. Ground station observations reported freezing rain events over United States mainly occur east of the Rocky Mountains and the frequency of occurrence increases toward the eastern states (Cortinas, 2000; Rauber et al., 2001). In Canada, freezing rain events are more common in all seasons, with maximum occurrence in March and April and limited occurrence in summer months in the far North (Stuart & Isaac, 1999). Approximately 1% of European precipitation occurs as a freezing rain, and most frequently occurs over Germany and Central Europe including Hungary, Croatia, and Bosnia (Carrière et al., 2000). In addition to North America and Europe, freezing rain events occasionally occur over Asian countries such as Japan (Matsushita and Nishio, 2004), Korea (Park and Byun, 2015), southern China (Chen et al., 2011; Sun & Zhao, 2010), and so forth. In China, it occurs most frequently over mountainous area such the Guizhou, Hunan, Jiangxi, and Hubei provinces (Sun and Zhao, 2010; Ye et al., 2007).

3.2. Validation of GPM FRFs Over the United States

Over the United States, 328 PFs are identified as FRFs from 4 years of GPM data. The majority of them occurs in the winter season (Figure 2). The most favorable locations are the central United States including

Figure 1. An example of a freezing rain event in North Carolina, United States, on 1 March 2015. (a) Color-filled contours are GPM Ku-band Precipitation Radar near-surface reflectivity pixels, and black and red dashed contour lines represent collocated MERRA-2 2-m temperatures (T2m) and maximum temperature of the vertical column from 500 hPa to surface (TMAX), respectively. The bold black and red solid lines represent 0 and 4 °C isotherm for T2m and TMAX, respectively. (b) A skew-T diagram at the location marked with red triangle on (a) from MERRA-2 data set. MERRA-2 = Modern Era Retrospective-Analysis for Research and Applications-2.
northeast Texas, central Arkansas, eastern Oklahoma, central Missouri, and the Kansas-Iowa boarder; the eastern United States including South Carolina, Virginia, New York, Ohio, and Pennsylvania; and the western United States including Oregon and Washington (Figure 3a).

To validate the locations of FRFs over the United States, fractions of FZRA from the ground stations are calculated. Four years (2014–2017) of hourly FZRA events from more than 2,000 ground stations are retrieved from NCEI. The fraction of the FZRA event in each station is calculated by dividing total FZRA hours by total sample hours (for all weather conditions) and is presented in Figure 3b. The highest fractions of FZRA events are found to be approximately 0.5–0.6% and occasionally up to 0.9%. The locations of these higher fractions of FZRA are over northeast Texas, Arkansas, Oklahoma, Kansas, Ohio, Michigan, New York, Pennsylvania, South Carolina, Oregon, and Washington (Figure 3b). These higher fractions values are consistent with Cortinas et al., 2004) who reported an annual median of Hours 40 or more of FZRA in the above-mentioned locations. Changnon (2003a, 2003b) and Changnon and Karl (2003) reported FZRA maxima occur in the Northeast region including a portion of New York and Pennsylvania, the central United States, along the eastern Appalachians, and in the Pacific Northwest. In general, the FZRA frequency increases toward the eastern part of the United States that might be related to the high climatological frequency of cyclones that follow the same pattern in the Central and eastern regions (Angel & Isard, 1997; Cortinas, 2000). The Southwestern region reports little or no FZRA events from both observations, which is consistent with previous ground report observations (Cortinas, 2000; Changnon & Karl, 2003; Cortinas et al., 2004). The important point to note here is that the higher fractions of FZRA events from the ground stations are well captured by the GPM and MERRA-2 and are consistent with previous studies. While comparing these two figures, another point to keep in mind is that Figure 3a just provides the locations of FRFs and Figure 3b provides the fractions of FZRA from the ground stations. Although it does not show a “head-to-head” comparison and magnitudes between FRFs and FZRA, it provides important information that most of the FRF locations are the regions where ground stations show higher fractions. The FRFs locations are further validated with ground stations data by finding the closest stations and their weather reports. From the center location of the FRFs, nearest stations are collocated within 2.5° longitude and latitude range and within 6 hr of time span. For 283 FRFs (April 2014 to December 2017) over the United States, approximately 270 nearest surface stations are identified. Approximately 70% (189 out of 270) of the surface stations report freezing rain events (Table 1). The 30% of the stations have either data missing or the other kind of weather reports. Given the strong temperature dependence of FZRA events and spatial variations of temperature in 2.5°, 70% of event confirmation provides the confidence on the FRF identification method implemented here.

Figure 2. Geographical distribution of FRFs identified by GPM Ku-band radar and Modern Era Retrospective-Analysis for Research and Applications-2 temperatures over 65°S–65°N. For 4 years (March 2014 to February 2018) of observations, approximately 3,096 features are identified as FRFs. GPM = Global Precipitation Measurement; FRF = Freezing Rain Feature.
3.3. Seasonal and Diurnal Variations Over the United States

The seasonal variation of 328 FRFs over the United States is calculated by dividing the number of FRFs in each monthly bin by the total number of FRFs. Temporally, it is clear that most of the FRFs occur in January and February (Figure 4a, black solid line). More than 70% of the FRFs occur in the winter season including approximately 42% in January and ~20% in February. To examine the seasonal peak of FRFs, seasonal variations of FZRA from ground stations are calculated by dividing total number of FZRA events by total samples (for all the events) at each station. GPM = Global Precipitation Measurement; FRF = Freezing Rain Feature.

![GPM FRFs](image1)

![Fraction of FZRA](image2)

Figure 3. (a) Geographical distributions of FRFs identified by GPM Ku-band radar and Modern Era Retrospective-Analysis for Research and Applications-2 temperatures over the United States. (b) Fraction of Freezing Rain (FZRA) events at the ground stations over the United States. Four years of hourly data from more than 2,000 ground stations are used to calculate the fraction. Note that the fraction is calculated by dividing total FZRA events by total samples (for all the events) at each station. GPM = Global Precipitation Measurement; FRF = Freezing Rain Feature.

| Table 1 Total Population of PFs and FRFs for 4 Years (March 2014 to February 2018) of Global Precipitation Measurement and Modern Era Retrospective-Analysis for Research and Applications-2 Observations |
|---|---|---|---|---|---|---|
| Total PFs | Total FRFs | FRFs through “melting process” | FRFs through “warm rain process” | Total FRFs over the United States | Nearest ground stations found | Station that reports FZRA |
| ~8.5 million | 3,096 | 3,061 | 35 | 283 | 270 | 189 (~70%) |

Note. Over the United States, each FRFs are validated with nearest ground stations report. From the center of FRFs, the nearest ground stations are collocated within 2.5° longitude and latitude range and within 6 hr of time span. PF = Precipitation Feature; FRF = Freezing Rain Feature.
that the winter is the peak season of FZRA events. More than 70% of the FZRA events occur in winter season including ~25% in each of the winter months. Although the magnitude of few winter months is different, the pattern and magnitude in seasonal distribution of the FRF are consistent with that of FZRA. Previous studies show a wintertime seasonal peak of FZRA over the United States. Changnon and Karl (2003) and Cortinas et al., (2004) reported winter is the season when most of the United States’ freezing rain cases occur, with the eastern and western regions peaking during January and December, respectively. A relatively high frequency of low-pressure centers and Arctic fronts over the United States during the winter season might be related to the peaks in FZRA events during those months (Changnon & Karl, 2003; Rauber et al., 2001).

The diurnal variations of FRFs and FZRA are calculated for each 1-hr bin based on the local time (Figure 4b). The FRF events tend to occur during the early morning. More specifically, the FRF frequency starts increasing at sunset, reaches its peak (~10–12%) in the early morning, then starts decreasing at sunrise. The diurnal variation of FRFs, including the nighttime and early morning peak in FRFs, is somewhat similar with the snowfall (Adhikari et al., 2018) and lake effect snow (Grim et al., 2004; Kristovich & Spinar, 2005) peaks, likely related to the surface heating (Chronis & Koshak, 2017). Similarly, diurnal variations of FZRA events follow a pattern similar to FRFs with a larger amplitude. The limitation in sensitivity of Ku-band radar and small sample size (~200) of FRF might lead to the difference in the amplitudes. The diurnal peak is consistent with Cortinas et al., (2004), who had shown that the FZRA peak is just before sunrise and the minimum is near sunset. Despite the fact that these results in Figure 4 are produced using two different methodologies on data sets of different sample sizes, both the seasonal and diurnal variations except midnight peak of FRFs are consistent with the FZRA events derived from the ground-based stations.

3.4. Two Types of FRFs

There are two types of FRFs based on two different formation mechanisms that can be roughly separated by temperature vertical distribution and radar echo tops. The first is through melting process where ice hydrometeors melt and refreeze on surface. In this case, radar Echo Top Temperature (T_{ET}) is below freezing (<0 °C). Another mechanism is the warm rain process where the liquid hydrometeors freeze on supercooled surface, which has T_{ET} warmer than 0 °C. In both cases, there needs to be a warm layer (>4 °C) above a subfreezing layer (T_{2m} < 0 °C) near the surface.

Based on the T_{ET}, all FRFs are separated into these two types, and their temperature profiles are presented in Figure 5. The melting process is more common, out of 3,096 FRFs, approximately 3,061 features are identified as forming through this process (Figure 5a). This process includes the hydrometeors that started either as snow or as supercooled particles, insuring that, in either case, the hydrometeors are continuously supercooled or frozen during their growth. These cold clouds whose T_{ET} is subfreezing may contain ice crystals, supercooled water drops, or both. In this situation, preexisting ice crystals may act as freezing nuclei (Huffman & Norman, 1988). Although an event with T_{ET} between 0 and −10 °C is not necessarily a sufficient condition for ice crystals, about 12-dBZ minimum detection by KuPR ensures that precipitation size...
Hydrometeors exist at subfreezing level for these cases. On the other hand, the warm rain process is very rare; only 35 features are identified globally (Figure 5b). In this process, hydrometeors grow into a precipitation particle by vapor condensation and via the collision-coalescence process because the cloud is wholly warm (Huffman & Norman, 1988). The warm rain process is still possible at levels with TET between 0 and −10 °C, but measurements of ice particles concentrations in clouds show that its role is somewhat unclear (Rouber et al., 2000). So we define the warm rain process with TET relative to the 0 °C isotherm, which makes it easy to compare the formation of droplets either with involving active ice nucleation or without.

3.5. Remote Sensing Properties

In this section, the radar (KuPR) and passive microwave (GMI) properties of FRFs are summarized. KuPR properties include max echo top height, maximum reflectivity, and near-surface reflectivity and GMI properties include Tb or PCT of various frequency channels. These properties are further compared to SFs properties (Adhikari et al., 2018). The comparison between the properties of FRFs and SFs helps to separate the precipitation systems that produce freezing rain from those that produce snow, from a spaceborne radar and passive microwave prospective. Since FRFs are mostly observed over land except very few over high-latitude Southern Ocean, the following analysis is restricted to land only.

3.5.1. Radar Properties

Previous studies show that snow clouds are shallower when compared to rain clouds. Most of these systems have maximum echo top height less than 4 km (Adhikari et al., 2018). Figure 6a compares the histogram of maximum echo top height of SFs and FRFs. Note that the comparison is made only over the Northern Hemispheric land. Most of the SFs have shallower echo top height (~80% are shallower than 4 km), and the peak maximum echo top height (~20%) is found near 2.5 to 3 km. This result is consistent with previous snow studies (such as Adhikari et al., 2018; Kulie et al., 2016; Liu, 2008). Significantly higher values of maximum echo top heights are observed during FRFs than during SFs. Approximately 40% of the FRFs are deeper than 4 km, and the peak maximum echo top height is found near 3–3.5 km. This shows that the systems that produce freezing rain are shallower than the systems which produce snow but deeper than snow systems. However, in terms of near-surface reflectivity, FRFs are more consistent with SFs. The near-surface reflectivity associated with FRFs are relatively less intense, with the peak frequency being found near 22 dBZ, which is comparable with SFs. Histogram (Figure 6b) shows that slightly higher values of near-surface reflectivity (beyond ~27 dBZ) are more common in FRFs than in SFs.

Furthermore, KuPR properties of FRFs are compared with SFs over Northern Hemispheric land and are shown in cumulative two-dimensional histograms in Figure 7. Figure 7a shows that FRF echo top heights range from 1.5 to 7 km, where majority of them are found in 2.5–5 km with maximum near-surface
reflectivity being 20–30 dBZ. FRFs are occasionally (~15% of the time) found to have deeper than 6-km echo top heights. More intense (>30 dBZ) FRFs are mainly found in deeper (>4 km) systems. Approximately 20% of FRFs are deeper than 4 km with maximum near-surface reflectivity greater than 35 dBZ (Figure 7a). SF echo top heights are lower than the FRF echo top heights. Approximately 20% of SFs are found to be shallower than 1.5 km with maximum near-surface reflectivity below 25 dBZ.

A two-dimensional cumulative histogram of the maximum KuPR reflectivity of FRFs and SFs with altitude are plotted in Figure 7b. Note that maximum reflectivity is the maximum value of reflectivity in each altitude bin and altitude is the vertical distance from mean sea level. The vertical KuPR reflectivity profile shows that FRFs are mainly centered at 500–2-km altitude (Figure 7b). Although there are many FRFs cases found deeper than 4-km echo top heights, the maximum reflectivity values are mostly centered below 2-km altitudes (Figure 7b), and those reflectivity become more intense when approaching toward the surface. Since precipitation particles are originates through snow or supercooled droplets, their reflectivity values are lower at higher altitudes. Once they fall into the melting layer, hydrometeors become coated with water. Because of this, higher values of radar reflectivity are observed due to the increased scattering from water

Figure 6. Histogram of (a) maximum echo top height and (b) maximum near-surface GPM Ku-band Precipitation Radar reflectivity of FRFs. Blue line represents SFs, and red represents FRFs. FRF = Freezing Rain Feature; SF = Snow Feature.

Figure 7. (a) Cumulative 2-D histogram of FRFs (color filled) and SFs (contour) as a function of the max echo top height and max near-surface reflectivity. (b) Vertical GPM Ku-band Precipitation Radar reflectivity profile. FRF = Freezing Rain Feature; SF = Snow Feature.
surface of hydrometeors. Also, the KuPR maximum reflectivity and echo top height of FRFs are more intense and deeper when compared with the SFs, respectively.

3.5.2. Passive Microwave Properties

The above result demonstrates that most of the FRFs are observed when the maximum echo top height is 2–5 km (Figures 5a and 6a) and MERRA-2 2-m surface temperature is colder than 0 °C but warmer than −5 °C (figure not shown). So the FRFs with echo top heights between 2 and 5 km and MERRA-2 surface 2-m temperatures between 0 and −5 °C are chosen to analyze the GMI properties. The GMI properties of FRFs, such as minimum PCT at 37 and 89 GHz and minimum Tb at 166 GHz (both horizontal [H] and vertical [V]) and at 183 ± 3 and 183 ± 7 GHz, are analyzed and compared with SFs. FRFs formed via the “melting” and warm rain processes are considered separately in this analysis, and histograms of each frequency's measurement are presented in Figure 8. The comparisons of all the GMI frequency channels help us to understand the channels that are more sensitive to FRFs. Histogram of minimum 37-GHz PCT shows that the FRF PCT is warmer than that of SFs and warm rain FRFs are found to be even warmer than the rest (Figure 8a). The microwave radiance at low-frequency channels (such as 37 GHz) is more sensitive to the emission from liquid droplets than scattering by solid particles. The radiance from the liquid droplets adds to the radiation coming from the earth surface, and the lower-frequency channels should report higher values of

![Figure 8](image-url)
radiance from clouds with mostly liquid than from those that have larger amounts of solid particles. The histogram of FRFs at 89-GHz PCT shows a peak (approximately 18%) near 265-K PCT (Figure 8b). The SF histogram at minimum 89-GHz PCT is relatively flat when compared to the FRF histogram, and the maximum frequency (~10%) is found near 260 K. Although warm FRFs have a smaller sample size, it is clear that the histogram is shifted to the warmer side. Higher-frequency channels (89 GHz or higher) are “scattering channels” because they are primarily sensitive to ice scattering than emissions. Because of the scattering, there should be a depression in the radiance, and colder values of Tb are expected for clouds with large amount of ice particles. A similar trend is observed in Tb at 166 GHz (both H and V), but the difference is larger than above-mentioned lower-frequency channels. The maximum FRFs occurrence (~10%) is observed at 260-K Tb, which is approximately 10 K warmer than the SF Tb at its peak frequency (Figures 8c and 8d). The “warm” FRFs at both frequency channels have less ice scattering than the others and are shifted to the warmer side of the spectrum. The warm FRFs Tb enhancement of higher-frequency channels (89 and 166 GHz) are associated with presence of supercooled water and emission from the cloud droplets. It is noted that the higher-frequency channels are also very sensitive to the emission of
cloud droplets and that emission contribution from cloud droplets increases with increasing the frequency (Kneifel et al., 2010; Panegrossi et al., 2017). Presence of water vapor during freezing rain is further demonstrated by histogram of total column water vapor (TCWV) presented in Figure 8g. The majority (~80%) of FRFs (warm FRFs) have TCWV depth deeper than 10 mm (15 mm), whereas TCWV depth of majority of SFs is less than 10 mm. The distribution of T-MAX for SFs, FRFs, and warm FRFs is presented in Figure 8h. Similarly, minimum Tb at 183 ± 7 GHz shows consistent results with lower-frequency channels, but the difference is smaller (Figure 8f). There are no clear differences between FRFs, and warm FRFs are observed in minimum Tb at 183 ± 3 GHz (Figure 8e). The depression of Tb in higher-frequency channels is related to the amount of the ice in the vertical column (Vivekanandan et al., 1991) and is also an indicator of convective intensity (Zipser et al., 2006). Comparing Tb or PCT at all the above-mentioned frequency channels, minimum Tb at 166 GHz (H and V) shows a larger difference between SFs and FRFs (~10 K) than the rest. This might be explained by the fact that the 166 GHz channel is more sensitive to falling snow than the other GMI channels (You et al., 2017). These results could be useful to distinguish freezing rain from snow in the GPM precipitation algorithm.

Further differences between FRFs and SFs are demonstrated by using cumulative two-dimensional histogram as a function of maximum echo top height and minimum Tb or PCT at all before-mentioned frequency channels. As we demonstrated earlier, FRFs are warmer than SFs at all GMI frequency channels. A negative trend in the region of the highest probability (>63%; red colors in Figures 9a and 9b) shows that FRFs PCTs at minimum 37 and 89 GHz tend to decrease with increasing echo top height, which is more evident for the high-frequency channels (166 GHz). However, colder FRFs PCTs (<250 K) are occasionally found to be associated with shallower (<5 km) echo top heights. On the other hand, SFs occasionally have higher echo top heights, but most of them are shallower and colder than the FRFs. For 166 GHz and higher channels, colder Tbs are found to be associated with deeper echo top height in both FRFs and SFs (Figures 9c–9e). No significant Tb differences are observed between SFs and FRFs at 183 ± 3-GHz channel (Figure 8e). The 183 ± 3-GHz channel also shows a very weak dependency on shallow echo top (<6 km) for both SFs and FRFs (Figure 9e). It is possible that cloud signal from the shallow clouds are blocked by water vapor emission/absorption in the atmosphere because at this channel, the weighting function peaks above the cloud except for very dry conditions (Panegrossi et al., 2017).

4. Summary

This study utilizes 4 years of both GPM core observatory satellite data and MERRA-2 reanalysis data to define FRFs. The locations of FRFs are mapped globally and are validated with FZRA events obtained from ground station observations over the United States. Remote sensing properties from both radar (KuPR) and GPM passive microwave imager (GMI) are summarized. The FRFs properties are further compared with SFs properties. The main scientific findings are summarized as follows:

1. The Ku-band radar precipitation data from GPM satellite and MERRA-2 reanalysis data are used to define FRFs. Any features with at least 0.1 mm/hr precipitation, MERRA-2 2-m surface temperature colder than 0 °C, and maximum temperatures of the vertical column warmer than 4°C are defined as FRFs. Globally, during 4 years of observation, approximately 3,096 features are qualified to be considered as FRFs. Most FRFs are found over continental regions specially United States, Europe, and central Russia. The majority of FRFs are found during Spring (41%) and Winter (28%) seasons.

2. The FRFs over the United States are validated with hourly FZRA events reported from NCEI surface stations. In general, locations with higher fractions of FZRA occurrence are well captured by GPM and MERRA-2 observations. Both methods show that the central United States including northeast Texas, central Arkansas, eastern Oklahoma, central Missouri, and the Kansas-Iowa boarder; the eastern United States including South Carolina, Virginia, New York, Ohio, and Pennsylvania; and the western United States including Oregon and Washington are prone to freezing rain events. FRFs and FZRA over the United States show consistent seasonal and diurnal variations with the peak of occurrence during the winter season and nighttime, respectively. Approximately 70% the GPM freezing rain events are verified by the surface observations over the United States.

3. Most of FRFs are formed through the melting process, whereas only a few (35 out of 3,096) are associated with the warm rain process. Ku-band radar shows that FRFs are shallower than the systems that produce rain but deeper than SFs. The majority of FRFs are found to have radar echo top between 2
4. GM properties of FRFs were compared to SFs properties for all frequency channels. Both emission and scattering channels have demonstrated the FRFs Tbs are warmer than those of SFs. The Tb difference between FRFs and SFs is higher in 166-GHz vertical and horizontal channels. At 37- and 89-GHz channels, the minimum PCTs tend to decrease with increasing in echo top heights, which is more evident for high-frequency channels (166 GHz). At 166- and 183-GHz channels, colder Tbs are found to be associated with deeper echo top height for both FRFs and SFs. However, at 37- and 85-GHz channels, the warmer FRFs are generally associated with a wide range (2–7 km) of FRF depths.

This study utilizes satellite and reanalysis data to study the global freezing rain events. The criteria that was implemented to define freezing rain events shows promising result and well matched with the surface observation reports over the United States. However, the method might exclude some of the freezing rain cases that have T-MAX colder than 4 °C. The KuPR may not detect some of the light precipitation events because of its sensitivity issue. The uncertainties in MERRA-2 temperatures might lead to detect either false events or miss the real events especially when the surface temperature is near 0 °C. Despite the potential uncertainties, this study generates the first ever global freezing rain climatology and summarizes its radar and passive microwave properties.

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