Mapping the Precipitation Type Distribution Over the Contiguous United States Using NOAA/NSSL National Multi-Sensor Mosaic QPE

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***Abstract*—Understanding the Earth's energy cycle and water balance requires an understanding of the distribution of precipitation types and their total equivalent water budget estimation. The fine distribution of precipitation types over the contiguous United States (CONUS) is not yet well understood due to either unavailability or coarse resolution of previous satellite- and ground radar-based precipitation products that have difficulty in classifying precipitation. The newly available NOAA/National Severe Storms Laboratory ground radar network-based National Multi-Sensor Mosaic QPE (NMQ/Q2) System has provided precipitation rates and types at unprecedented high spatiotemporal resolution. Here, four years of 1 km/5 min observations derived from the NMQ are used to probe spatiotemporal distribution and characteristics of precipitation types (stratiform, convective, snow, tropical/warm (T/W), and hail) over CONUS, resulting in assessment of occurrence and volume contribution for these precipitation types through the four-year period, including seasonal distributions, with some radar coverage artifacts. These maps in general highlight the snow distribution over northwestern and northern CONUS, convective distribution over southwestern and central CONUS, hail distribution over central CONUS, and T/W distribution over southeastern CONUS. The total occurrences (contribution of total rain amount/volume) of these types are 72.88% (53.91%) for stratiform, 21.15% (7.64%) for snow, 2.95% (19.31%) for T/W, 2.77% (14.03%) for convective, and 0.24% (5.11%) for hail. This paper makes it possible to prototype a near seamless high-resolution reference for evaluating satellite swath-based precipitation type retrievals and also a potentially useful forcing database for energy–water balance budgeting and hydrological prediction for the United States.**

***Index Terms*—Radar, snow.**

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I. Introduction

ACCURATE identification and classification of precipitation type is the prerequisite to reliably quantify the spatial distribution of precipitation on regional and global scales using ground radar-based or spaceborne observations. A common basic delineation for precipitation type is convective or stratiform [1]. However, for ground radar observations, precipitation can be further classified into five forms (i.e., stratiform (strati), convective (convect), snow, tropical/warm (T/W), and hail) based on the shape of the vertical profile of reflectivity (VPR) and the ground temperature [2], [3]. Radar-based retrieval algorithms heavily depend on the drop size distributions of a given precipitation type, introducing great variation in the relationship between reflectivity (Z) and precipitation rate (R). It is therefore highly advantageous to utilize information on precipitation type to acquire more accurate retrieval. Furthermore, different types of precipitation have different latent heat profiles associated with their specific thermodynamic and microphysical properties. Knowledge of regional and global distributions of precipitation type may advance our understanding on the Earth's energy cycle and water balance, as well as the interrelation between the atmospheric circulation and the thermodynamical and precipitation process [4], [5].

At the present time, continental-scale precipitation classification has largely relied on satellite observations. TRMM Precipitation Radar (PR) provides semiglobal precipitation type products (convective and stratiform) over the tropics and subtropics. However, PR is limited in the aforementioned areas

(38°S–38°N), and its sensitivity does not permit the retrieval of snow and very light rainfall [6]. In addition, the PR has a coarse temporal resolution. NASA CloudSat satellite, carrying a first-of-its-kind W-band (94-GHz) cloud profiling radar [7], provides scientific communities with global snowfall observations [8], [9]. However, it is limited by a swath width of $\sim$1.4 km and a nadir footprint size of $\sim 1.4 \times 1.7$ km, also suffering from low temporal resolution. A few studies have shown that passive microwave (PMW) observations can be used to separate convective and stratiform precipitation [10]–[12], but due to the coarser spatial resolution of PMW sensors, the classification cannot capture small-scale features, particularly convective systems. It is widely known that precipitation frequency is a function of spatial and temporal scales [13]; high-resolution data are needed for more reliable classification of precipitation.

In this paper, we used a recently developed, multiyear, and high-resolution precipitation product over contiguous United States (CONUS). The NOAA/National Severe Storms Laboratory ground radar-based National Multi-Sensor Mosaic QPE (NMQ/Q2) System provides a suite of very high spatiotemporal resolution 1 km/5 min precipitation products, including 2-D and 3-D QPE products over the CONUS, e.g., precipitation rate, precipitation type, and radar reflectivity. [3]. Q2 identifies several precipitation types, including stratiform, convective, snow, T/W, and hail [2], [3]. Because of its high spatiotemporal resolution and large-scale coverage over CONUS, Q2 has been accepted as an ideal platform to evaluate and validate satellite-based observations and products [14]–[16] and has been used to derive a hydrological model for real-time flash flooding simulation and monitoring over CONUS [17]. Therefore, the Q2 products present a unique opportunity to comprehensively understand the characteristics of precipitation in the USA.

The objective of this paper is to reveal the domain characteristics of precipitation, including its occurrence, and the fractional contributions to the total water budget. Hopefully, the effort can provide an evaluation reference for remote sensing of precipitation from space and an aid for hydrological modeling of CONUS, for example, in areas where solid precipitation (snow) and snowmelt are known to be important to river flow, and regions sensitive to flooding from heavy precipitation. This paper is organized as follows. Section II introduces the study domain and the data sets used. Section III provides an analysis of occurrence and contribution of different precipitation types. A summary of key results is given in Section IV.

II. Data and Methods

The NMQ/Q2 precipitation rate products, i.e., precipitation type (Q2PCPFlag) at both 5 min and hourly temporal resolution, from July 2009 to May 2013 have been used in this paper. All the products had high spatiotemporal resolution (1 km/5 min). The hourly gauge-corrected Q2 precipitation rate (Q2RadGC) was applied to correct the 5-min radar-only precipitation rate (Q2Rad5min) and obtain the gauge-corrected 5-min precipitation rate (Q2RadGC5min) [14]–[16]. The precipitation types evaluated in this paper include stratiform, convective, snow, T/W, and hail. The hourly temperature and dew point temperature model analyses from NOAA/National Centers for Environmental Prediction's Rapid Update Cycle (RUC; [18]) were used in the classification of precipitation. The logic of classification is to identify the snow, hail, T/W, convective, or stratiform in sequential order. First, snowfall is identified by using the conditions that: 1) the hybrid scans' reflectivity (i.e., the radar's lowest elevation scan reflectivity that clears the surface) must exceed 5 dBZ; 2) the surface temperature is below 2 °C and the surface wet bulb temperature is below 0 °C. Second, if the precipitation is not snow, then the vertically integrated liquid (VIL) [19] density (VILD) [20] is computed. If the VILD value exceeds 1 gm^{-3}, then the precipitation is hail. Third, if the precipitation is not hail, then the hourly mean volume scan VPRs from each radar are examined to see whether the slope of a VPR below the freezing level is negative (i.e., reflectivity increases as height decreases). If yes, then the radar is identified as T/W PR, and all echoes above an adaptable threshold (default $= 35$ dBZ) within an influence radius of the T/W PR will be classified as T/W precipitation when the surface temperature is greater than 10 °C. Finally, if the precipitation is not classified as snow or T/W or hail, then the composite reflectivity is judged if it is greater than 50 dBZ. If yes, then the precipitation is labeled as convective precipitation; otherwise, the precipitation will be labeled as stratiform precipitation. More details about the classification logic and precipitation retrieval can be found in [2] and [3]. Each precipitation type is computed as instantaneous precipitation rate with unit of millimeters per hour. The precipitation volume of a certain precipitation type in 5 min can be obtained by dividing the instantaneous precipitation rate by 12.

In this paper, it was useful to define two frequencies for each of the five precipitation types. Assuming that at a given grid box, there are N total observations under all weather conditions (both precipitating and clear), and among them, there are total M observations with precipitation observed, i.e., $r > 0$ where r is the precipitation rate, and the numbers of observations for the five types are $T_1, T_2, \ldots, T_5$, respectively, with $\mathrm{M} = T_1 + T_2 + \cdots + T_5$, then the (unconditional) precipitation frequency is

$$P_0 = \frac{\mathrm{M}}{\mathrm{N}}. \quad (1)$$

In addition, for each precipitation type T_i, the (unconditional) frequency is

$$P_i = \frac{T_i}{\mathrm{N}}. \quad (2)$$

The conditional precipitation frequency, defined relative to the total number of precipitating observations, for precipitation type T_i, is defined as

$$P(T_i|\mathrm{r} > 0) = \frac{T_i}{\mathrm{M}}. \quad (3)$$

Moreover, it is related to the unconditional frequency via

$$P(T_i|\mathrm{r} > 0) = \frac{P_i}{P_0}. \quad (4)$$

Similarly, the ratios between the total volume of precipitation from each type and from all types together can be also defined, which we term "volume fractions." For example, in a given

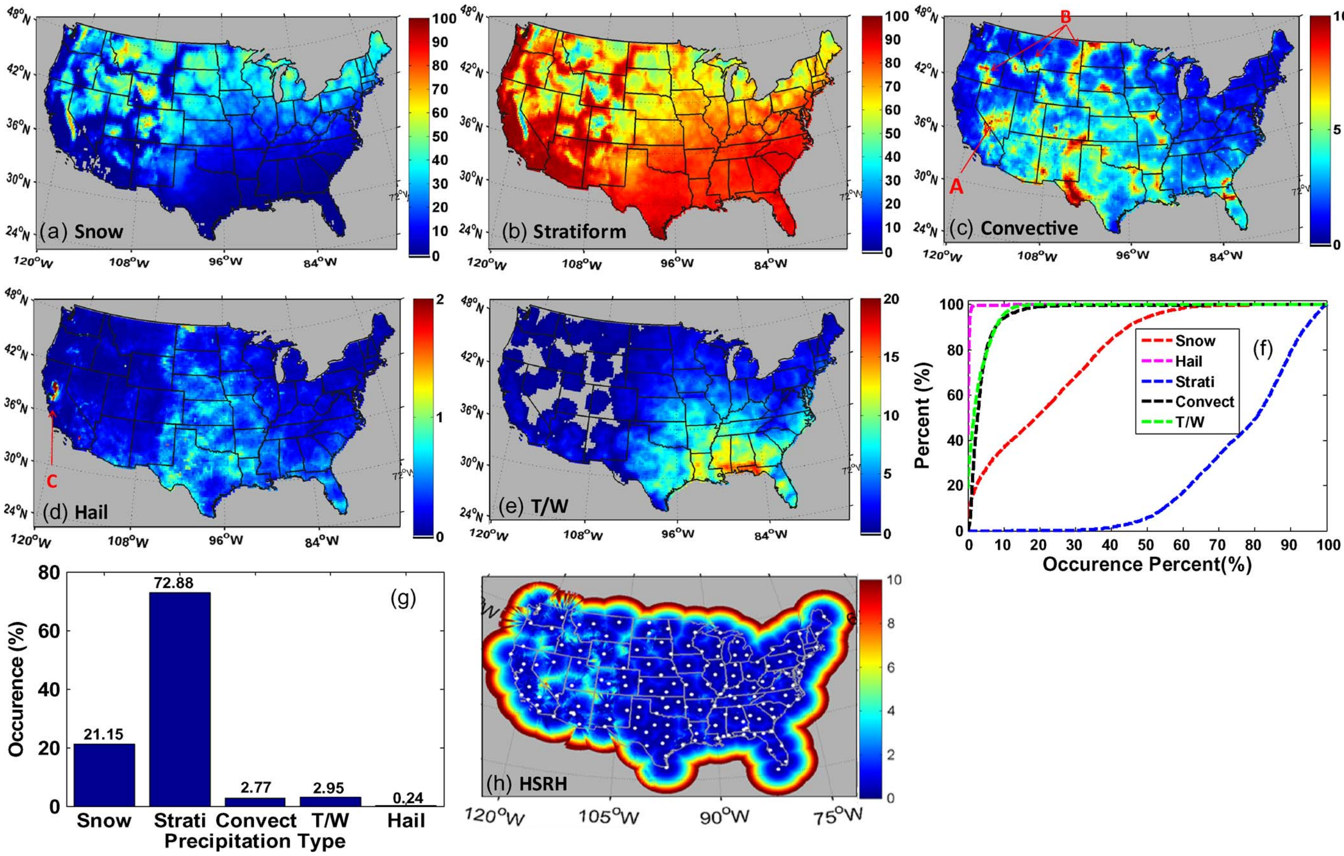

Fig. 1. (a)–(e) Conditional precipitation frequency of different rain types. (f) Cumulative probability distribution of occurrence with interval of 0.1%. (g) Total occurrence of different types over CONUS. (h) HRSH.

period in a given grid box, the five precipitation types have their total precipitation V1, V2, V3, V4, and V5, respectively; then, the total precipitation in the grid box is $\mathrm{V}=\mathrm{V1}+\mathrm{V2}+\mathrm{V3}+\mathrm{V4}+\mathrm{V5}$, and the volume fraction of ith precipitation type is defined as V_i/V. There is no difference in conditional or unconditional volume fractions as the denominator (total precipitation volume) is the same for both. The conditional distributions of occurrence and volume fractions are provided in this paper. In order to obtain enough samples, the spatial conditional distribution of occurrence and volume fractions were defined from $0.25^\circ \times 0.25^\circ$ grids for the four-year and seasonal analyses.

III. Results and Discussion

A. Four-Year Statistics

Fig. 1 shows the spatial distribution of conditional precipitation frequency [see Fig. 1(a)–(e)], the cumulative probability distribution function of occurrence [CDFo; see Fig. 1(f)], and the total occurrence for different precipitation types [see Fig. 1(g)] over CONUS, including a map of hybrid scan reflectivity height (HRSH). The stratiform type dominates with an occurrence rate of 72.88%, followed by snow (21.15%), T/W (2.95%), convective (2.77%), and hail (0.24%). As shown in Fig. 1(f), hail precipitation has low occurrence (< 1%) for almost all over CONUS; convective and T/W precipitation have similar cumulative probability distribution with high percentage ($> 90\%$) of areas seeing low occurrence (< 10%); snow shows most snowfall areas with occurrence between 20% and 50%; and stratiform precipitation has high occurrence ($> 50\%$) over nearly the entire CONUS. It is noted that these precipitation types have different terrain-dependent spatial patterns. Snowfall is common at higher elevations throughout the intermountain west and in northern CONUS (> 40 °N) east of the Rocky Mountains. Snowfall occurrence is higher than 30% for approximately 32% of the snowfall area. Stratiform precipitation prevails over CONUS, particularly in the southeast and western coastal regions. About 98.50% of the domain has a high occurrence of stratiform ($> 40\%$), with nearly 67% of CONUS indicating occurrence ratio above 70%. Convective precipitation mainly occurs in the central USA (e.g., Great Plains) and is scattered over the intermountainous West, with less than 10% occurrence for 94.00% of CONUS. The Great Plains is a climatologically favorable zone for convection. Interaction between developing synoptic lows, topography of the Rocky Mountains, and warm humid air advection from the Gulf of Mexico by a southerly low-level jet can create an environment of high potential instability, associated with an elevated mixed layer and dry-line front. Low-level mass convergence along the dry line is a well-known focus for the initiation of convection [21]. The intermountain western CONUS commonly experiences solar-driven diurnal variation in pressure, which, in conjunction with the topography, provides ascent, promoting scattered convection [22]. Furthermore, large-scale convection in the southwestern USA during summer is associated with the North American Monsoon circulation and onshore flow of humid air from the

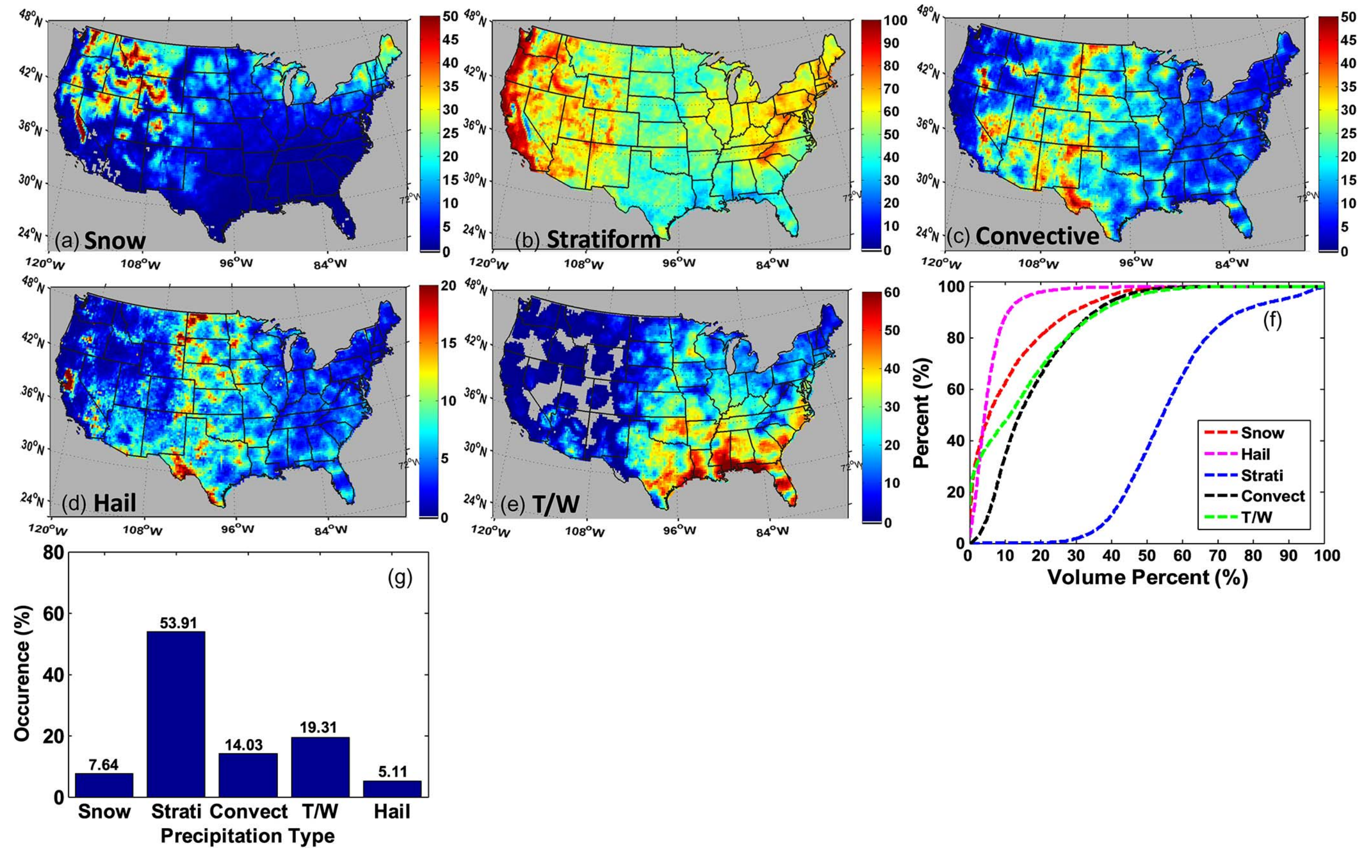

Fig. 2. (a)–(e) Fraction of precipitation volume from each precipitation type. (f) Cumulative probability distribution of volume contribution with interval of 0.1%. (g) Total volume contribution of different types over CONUS.

subtropical Pacific [23]. It should be noted that some localized convection-intensive regions [e.g., areas arrowed by the red letters "A" and "B" in Fig. 1(c)] correspond to the patterns of high HSRH (> 5 km), indicating that the precipitation classification in these regions has high uncertainty and needs further study by incorporating other information (e.g., the VPR derived from spaceborne radar observations). Hail has a similar distribution pattern in central CONUS to convective precipitation and a low occurrence (< 1%) for 98.14% of CONUS. This pattern is likely related to the aforementioned air masses for the Great Plains promoting more vigorous convection and vertical velocities suitable for the growth of hailstones, whereas outside of this region, a greater proportion of nonsevere storms may be observed [24]. In the western mountainous region, disorganized ordinary and multicellular-mode convections are generally most common [25], and the relative absence of severe supercellular convection likely accounts for generally low frequencies of hail. It is noted that there is a hot spot of hail northeast of San Francisco where problematic KPIX radar data were used. KPIX is commercial radar that only provides one tilt of reflectivity data (whereas WSR-88Ds have 5–14 tilts with reflectivity, velocity, and other fields). The limited data of KPIX made it very difficult to segregate precipitation from non-precipitation echoes. This showcases the challenges surrounding using commercial radar as a gap filler, where observations are limited and the radar may not be well calibrated or properly operated, disallowing use of effective quality control. The T/W precipitation dominates the southern CONUS with localized high occurrence (> 10%) in western Louisiana (LA), Mississippi (MS), southern Alabama (AL), and northwestern Florida (FL). This may be due to the contribution to precipitation from landing tropical cyclones. The CDFo shown in Fig. 1(f) also indicates that the T/W precipitation has a less than 10% occurrence for roughly 95% of the T/W area.

Fig. 2 displays the contribution fraction of different precipitation types to the total precipitation [see Fig. 2(a)–(e)], the cumulative probability distribution function of volume [CDFv; see Fig. 2(f)], and the total volume contribution [see Fig. 2(g)]. It is evident that the contributions of different types are not proportional to their occurrence ratios. The total volume contributions are calculated to be: stratiform (53.91%), T/W (19.31%), convective (14.03%), snow (7.64%), and hail (5.11%). Furthermore, the CDFv indicates that hail, convective, and T/W precipitation account for significant constituent of the total precipitation for a lot of areas. Stratiform precipitation has a high contribution (> 60%) in the western and northeastern CONUS and a low contribution (< 60%) in the central and southeastern USA. Along the western coast, stratiform precipitation contributes more than 80%. Snow contributes more than 20% in the northeastern CONUS and more than 40% in the intermountain west. Convective precipitation has high contribution in the central and southwestern CONUS and contributes more than 20% in 34.69% of CONUS. T/W precipitation has a similar CDFv trend with convective precipitation for bins greater than 20% [see Fig. 2(f)]. About 26% of CONUS has a contribution of greater than 20% from T/W precipitation. It is worth noting

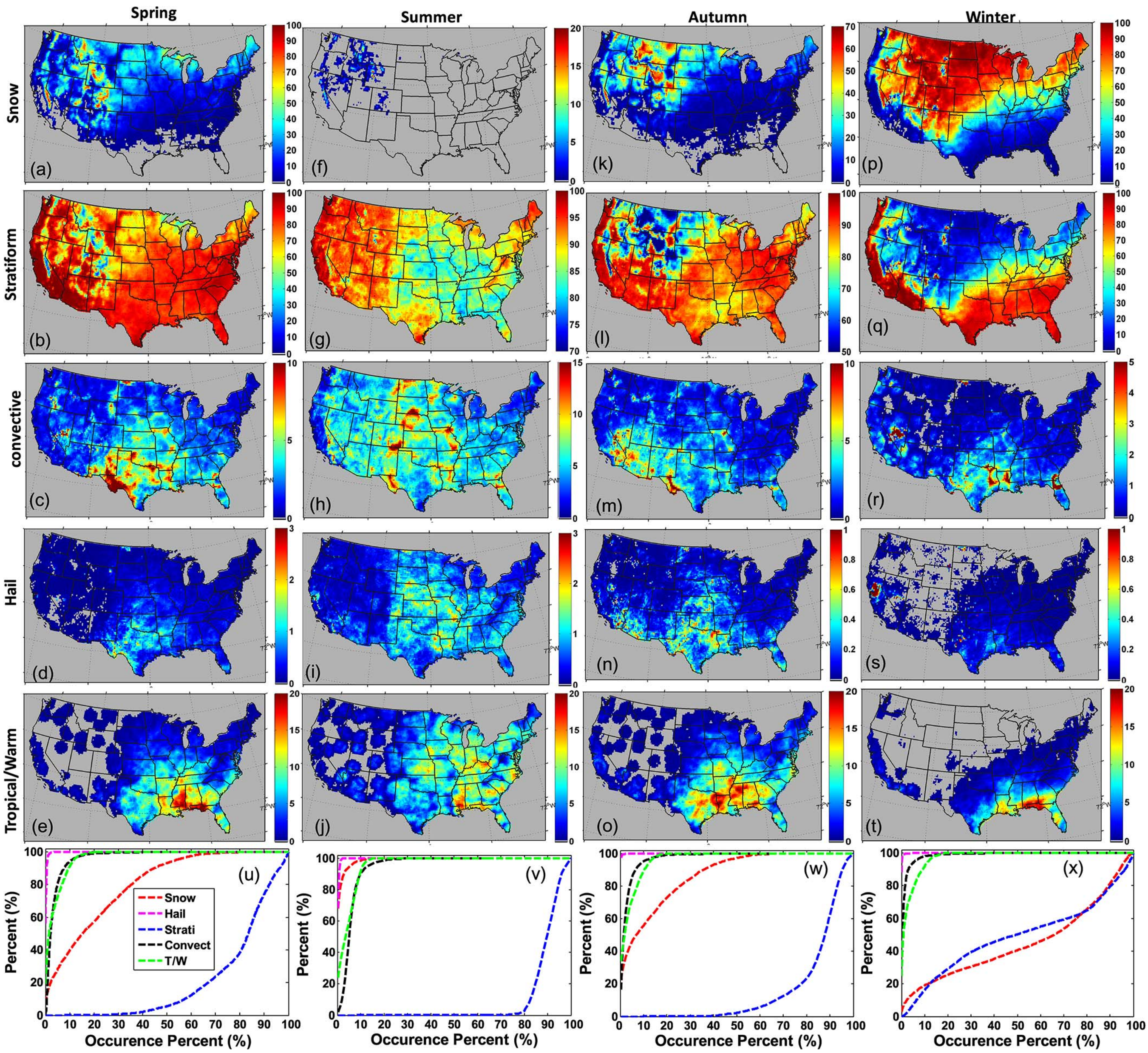

Fig. 3. (a)–(t) Spatial distribution of conditional precipitation frequency for each precipitation type over CONUS in four seasons. (u)–(x) Cumulative probability distributions in four seasons.

that the T/W contribution is much higher than its occurrence in the coastal area of Texas (TX), North Carolina (NC), South Carolina (SC), Georgia (GA), and central/southern FL. This is likely due to large volume of precipitation associated with tropical cyclone activity [26].

B. Seasonal Statistics

Geographical maps of seasonal frequency of precipitation occurrences are shown in Fig. 3(a)–(t) for each precipitation type. The CDFos in each season are illustrated in Fig. 3(u)–(x). Results support some large seasonal changes in the spatial patterns for each type. Snow has a high occurrence ($> 60\%$) in the northern and northwestern CONUS in winter (account for approximately 54% of the total snowfall region). Areas include northeastern Washington (WA), southeastern Oregon (OR), Nevada (NV), Montana (MT), Idaho (ID), Wyoming (WY), Utah (UT), Colorado (CO), northern New Mexico (NM), North Dakota (ND), South Dakota (SD), Nebraska (NE), northwestern Kansas (KS), Minnesota (MN), Iowa (IO), northern Missouri (MO), Wisconsin (WI), northern Indiana (IN), Michigan (MI), northern Ohio (OH), Maine (ME), Vermont (VT), New Hampshire (NH), New York (NY), Massachusetts (MA), Connecticut (CT), and Pennsylvania (PA). In spring and autumn, snowfall mainly occurs in and near the mountainous zones of the northwestern CONUS (MT, ID, and WY) with an occurrence ratio greater than 20%. In summer, the snowfall area is markedly reduced, only being observed for the northwestern mountainous zone. Stratiform precipitation prevails over the whole CONUS during all seasons. It dominates precipitation events with a high occurrence ($> 70\%$ for $\sim 41\%$ of area) over CONUS except in the mountainous northwest in winter where

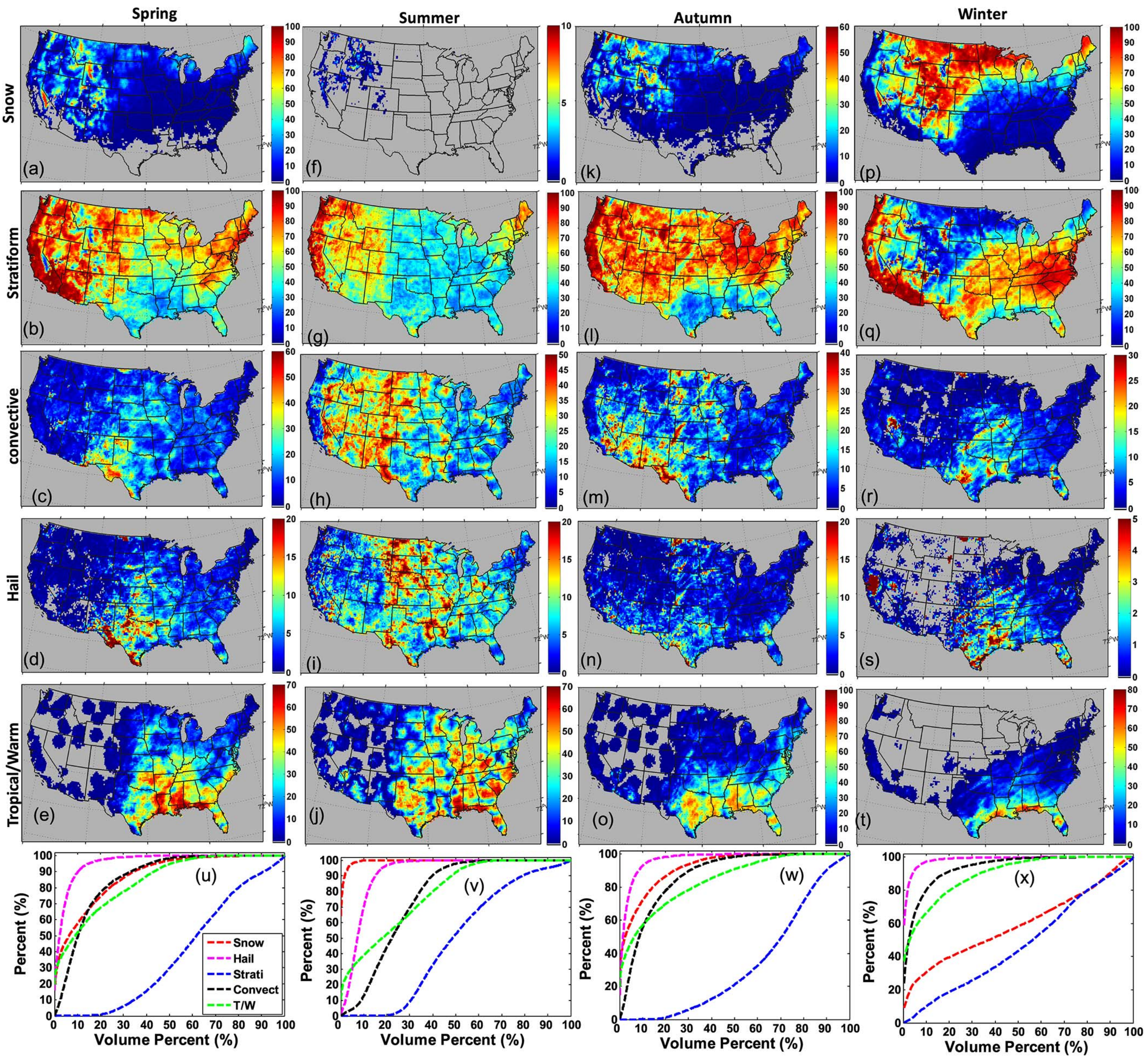

Fig. 4. (a)–(t) Spatial distribution of volume contribution of different precipitation types over CONUS in four seasons. (u)–(x) Cumulative probability distributions.

snow phase precipitation dominates. In summer, stratiform events are most frequent to the western CONUS with an occurrence ratio greater than 90% but still have high occurrence ratio greater than 75% in the eastern USA. In autumn, stratiform precipitation continues to dominate all but mountainous areas in the northwestern CONUS, again due to the greater preponderance of snowfall for the latter region (occurrence $> 20\%$). Convective, hail, and T/W precipitation have low occurrence ratios in every season. The maxima in occurrence of convective precipitation are evident in the southwestern and central CONUS. Convective precipitation is comparatively frequent in the southwestern TX, western, and southern Oklahoma (OK), particularly in the spring associated with the peak in the climatological frequency of severe storms. Hail precipitation has a small occurrence ($< 3\%$) over CONUS and shows a similar spatial pattern to the convective precipitation in central CONUS. The T/W precipitation is mainly distributed in the eastern CONUS from spring to autumn and in the southwestern CONUS in winter. It is noted that the T/W precipitation has a high occurrence ($> 10\%$) strip ranging from the MS to southern Illinois (IL) and northern Kentucky (KY) in summer (potentially from northward transport of subtropical moisture via a low-level jet during episodes of organized precipitation) and has another high occurrence ($> 10\%$) strip extending from southeastern TX northeastward to eastern Arkansas (AR) and northern MS. Since precipitation regimes are geographically and seasonally dependent, the different spatial patterns of occurrences of different precipitation types lead to the differences in the shapes of cumulative probability distribution function of conditions (CDFos) between different precipitation types.

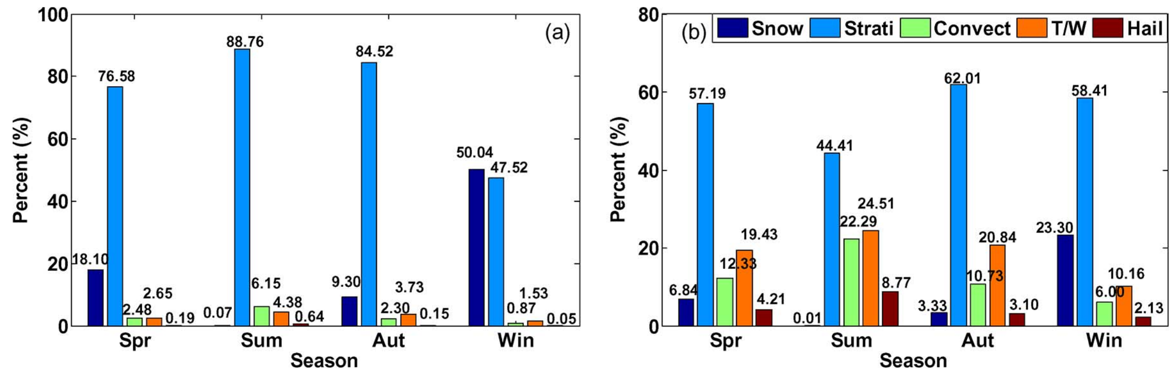

Fig. 5. Seasonal occurrence (volume) percentage for different precipitation types over CONUS.

Fig. 4 illustrates the contributions of the resolved types to the total precipitation volume and the corresponding CDFvs in each season. The spatial patterns of the contributions are generally consistent with the occurrence patterns except that the stratiform contribution in spring in the southern CONUS is much lower than its occurrence ratio. In addition, the snow contribution is slightly lower than its occurrence ratio. Correspondingly, the contributions from convective, hail, and T/W precipitation are much higher than their occurrence ratio. In particular, during summer time, the T/W precipitation contributes more than 20% in 37% area, and hail contributes more than 5% in 68% area. Compared with CDFos in Fig. 3(u)–(x), the CDFvs in Fig. 4(u)–(x) also show corresponding higher contribution ratios than the occurrence ratios. In addition, the different spatial patterns of occurrences of different precipitation types lead to the differences in the shapes of CDFos between different precipitation types.

Fig. 5 shows the overall statistics of seasonal occurrence and contribution. It is noted that the stratiform and snowfall dominate occurrence in spring, autumn, and winter. The total occurrence of other types of precipitation only accounts for less than 10% [see Fig. 5(a)] in all seasons except summer. In terms of contribution, the snow and stratiform have much smaller contributions than their occurrence ratios. In addition, a study by Smalley *et al*. [27] showed that ground radar captured less light snow than CloudSat, which indicates that this underdetection may have little impact on snow volume but can be considerable for fraction of occurrence. Contributions from the three remaining types (convective, hail, and T/W) were calculated as approximately 36% in spring, 56% in summer, 35% in autumn, and 18% in winter. This is consistent with the contribution map shown in Fig. 4.

IV. Discussion

The Q2 data sets used in this paper has unprecedented high spatial and temporal resolution on the continental scale but still possesses limitations including: 1) potentially poor detection of light snow because the quantity control model in the NMQ to filter out weak signals (< 5 dBZ); 2) severe mountain blockage in areas of topography, particularly western CONUS [28]; 3) beam overshooting and broadening of ground radar; and 4) the invariant empirical relation $Z = 75\ R^{2.0}$ applied in Q2 convert reflectivity to snow liquid water equivalent rate (R, in millimeters per hour). In addition, the procedure of correcting 5-min Q2Rad with hourly gauge-corrected Q2RadGC may raise error, particularly with snow because most of the rain gauges in the Hydrometeorological Automated Data System, which are used in NMQ to yield the Q2RadGC, are not suited for snow hourly quantitative estimation. In addition, the NMQ classification has been evolving with time (e.g., the tropical classification has been tuned several times because the tropical rainfall amounts tend to be significantly overestimated relative to observations in north central plains). In addition, to examine the reliability of NMQ's classification scheme, we also compared our results with TRMM PR observations in our previous study [29]. The fraction of stratiform systems is very consistent between the two. However, TRMM PR detected much fewer convective events. These differences are mostly likely caused by the spatial resolution of the two systems. TRMM PR has a horizontal resolution of $\sim$5 km, whereas NMQ has 1 km. Since most convective systems are small and tend to embed in large-scale stratiform systems, the coarser resolution of TRMM PR will underestimate the number of convective systems when compared with the 1-km NMQ data. These factors could degrade Q2's measurement of precipitation (particularly snow) particularly in complex terrain and for light precipitation. However, the study by Chen *et al*. in 2013 [16] showed that the hourly Q2RadGC, when compared with Stage IV, still has promising performance with high correlation coefficient about 0.80, root-mean-square difference about 0.76, and relative difference about -4.09% over one year of observation from December 2009 to November 2010. The precipitation type occurrence and contribution fraction distribution may provide an evaluation reference for remote sensing of precipitation from space and hydrological modeling and provide an improved resource over satellite-only derived data sets. For example, the intermountain snowfall distribution patterns (important to the water budget of the western states) are generally consistent with those of precipitation underestimated by Version 6 and Version 7 real-time multi-satellite precipitation analysis (TMPA-RT; see [16, Fig. 8]. The snowfall distribution east of the Rocky Mountains is also similar to the distribution of precipitation overestimated by the TMPA-RT in northern CONUS (see [16, Fig. 8]). This result indicates that the satellite-only precipitation retrieval algorithm has a certain limitation in accurately estimating the snowfall. In addition, for several reasons, the limited skill of the sensor-level retrieval of snow can contribute to such discrepancies between TMPA-RT and ground observations.

An additional source of uncertainty included areas of high-frequency convective precipitation [marked by "A" and "B" in Fig. 1(c)] corresponding to gaps between radars where the HRSH [see Fig. 1(h)] was relatively high and potentially intersecting the melting layer in the warm season. The enhanced reflectivity in the melting layer (the so-called "bright band" in the radar reflectivity field) might have falsely triggered the convective precipitation identifications sometimes. This limitation of single-polarization radar techniques is likely mitigated by dual-polarization radar techniques that can delineate the bright band more precisely and avoid such false classifications of convection. Otherwise, precipitation classifications in most areas (HSRH < 2 km) showed physically reasonable geographically dependent patterns. Further study by incorporating other kinds of information (e.g., the VPR derived from spaceborne radar observations) will potentially improve the precipitation classifications across multiple modes of topographic variability.

V. Conclusion

This paper has presented a first attempt to investigate the precipitation type distribution over CONUS using four-year (July 2009 to May 2013) high-spatiotemporal-resolution NMQ/Q2 products in order to reveal the spatial distributions and seasonal patterns for five types of precipitation: snow, stratiform, convective, hail, and T/W. Our key findings include.

1) Stratiform dominates the total precipitation occurrence (72.88%), followed by snow (21.15%), T/W (2.95%), convective (2.77%), and hail (0.24%).
2) Stratiform contributes ~54% of total precipitation volume. Contribution from other types of precipitation (nearest integer) includes T/W (19%), convective (14%), snow (8%), and hail (5%).
3) Snowfall mainly occurs in the intermountain west and northern CONUS ($> 40\,^{\circ}$N) east of the Rocky Mountains. Snow accounts for more than 30% of precipitation occurrence for 32% of all snow area. Its occurrence (volume contribution) is 18% (7%) in spring, 0.07% (0.01%) in summer, 9% (3%) in autumn, and 50% (23%) in winter.
4) Stratiform prevails for all seasons over CONUS and particularly in the southeast and along the western coastline. About 98.5% of CONUS has the occurrence ratio greater than 40%. Stratiform has the occurrence (contribution) of 77% (57%) in spring, 89% (44%) in summer, 85% (62%) in autumn, and 47.5% (58.4%) in winter.
5) Convective precipitation is mainly distributed in central CONUS and is scattered over the intermountain West, with less than 10% occurrence for 94% of the domain. It has a high occurrence ratio in southeastern NM, southwestern TX, western and southern OK, southern AR, and eastern LA. From spring to winter, its occurrence (contribution) ratio is 2.5% (12%), 6% (22%), 2% (11%), and 0.9% (6%), respectively.
6) Hail has a similar distribution pattern in central CONUS to convective precipitation and a low occurrence (< 1%) over 98% of CONUS. From spring to winter, its occurrence (contribution) ratio is 0.2% (4%), 0.6% (9%), 0.2% (3%), and 0.05% (2%), respectively.
7) T/W precipitation dominates the southern CONUS with high occurrence (>10%) in localized regions of southeastern TX, western LA, Mississippi, southern AL, and northwestern FL. Its occurrence (relatively higher volume contribution) ratio from spring to winter is 2.6% (19.4%), 4.4% (24.5%), 3.7% (21%), and 1.5% (10%), respectively.

Precipitation type distribution information is useful in benchmarking the accuracy of quantitative precipitation estimate using spaceborne sensors and is helpful for the modeling research of regional and global climate, ecobiology, and hydrology. In particular, this paper makes it possible to prototype a near seamless high-resolution reference for evaluating satellite swath-based precipitation type retrievals and also a useful forcing database for energy–water budgeting and hydrological predictions over many regions of CONUS. However, given the inherent limitations of ground radar network such as beam blockage in mountainous areas, beam broadening as the radar range increases, and the single-polarization algorithms, the characteristics of precipitation occurrence and contribution analyzed in this paper represent only early attempts toward those aforementioned objectives. Fortunately, the NEXRAD network has been upgraded in the second half of year 2013 with dual-polarization capability. The Global Precipitation Measurement (GPM) mission, with more advanced dual-frequency radar onboard, has been launched in early 2014. We can envision that a synthetic approach of incorporating the observations from ground-based dual-polarization radars and spaceborne dual-frequency radars, together with other advanced modeling studies, will greatly advance the understanding of spatiotemporal distribution of regional and global precipitation estimation in rates and types.

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