European Icing Frequency Derived From Surface Observations

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Abstract — **In this study, several approaches are applied to historical surface observations to assess the frequency of icing conditions in Europe.**

The first approach is an examination of surface observations of fog at sub-freezing temperatures. The frequency of reports of freezing fog provides one direct indication of the occurrence of icing at the surface. However, examination of historical records indicates that at many stations, fog was often not indicated as "freezing fog" despite occurring at temperatures well below 0°C. Large databases of such "cold fog" observations are compared to those of "freezing fog" in terms of their geographical and temporal frequency.

In the second approach the frequency of freezing fog was determined for the 150 m level above ground based on observations of surface temperature and the height of cloud base. Such frequencies are particularly relevant in assessing the problems causes by icing on wind turbines.

The third approach was to determine frequencies of freezing precipitation. This too was done by two methods: directly from present weather observations and indirectly from precipitation and temperature data. The results of these two methods are somewhat different and the nature of the difference depends on the region.

I. Nomenclature

CFG = "cold" fog (FG at T<0°C, including FZFG).
FG = fog
FZFG = explicit observations of freezing fog.
Glaze1= freezing precipitation as observed and reported in the form of the WMO Present Weather Code.
Glaze2 = freezing precipitation as theoretically deduced based on the Present Weather Code and the wet bulb temperature.
Rime = icing from supercooled clouds is expected.
Rime 150 = rime for the height of 150 m AGL.
SLD = Supercooled Large Drops.
SLW = Supercooled Liquid Water.

II. Introduction

With the rapid growth of the wind power industry, there is increasing interest in the occurrence of icing conditions at and near ground level. Ice growth on wind turbines can decrease their efficiency, damage the systems and present a hazard to people and property in the vicinity of the blades when ice falls from or slings off of them. Such ice is formed by the exposure of the blades to supercooled liquid water (SLW). SLW drops come in a variety of sizes, from "cloud sized" to precipitation-sized drops. At the ground level, these conditions are known as freezing fog (FZFG), freezing drizzle (FZDZ) and freezing rain (FZRA), and they are reported in routine surface observations at airports and other weather stations around the globe.

The frequencies of FZDZ and FZRA have been estimated for North America and Russia [1-5], while FZFG frequencies in addition to those for FZDZ and FZRA have been estimated for Western Europe [6] and for the Northern Hemisphere [7]. In recent studies of the frequency of icing conditions aloft, the frequency of surface FZDZ and FZRA has been documented for North America [8], while frequencies of surface FZDZ, FZRA and FZFG were documented for Europe and Asia [9].

Overall, FZDZ and FZRA were found to be uncommon across these continents. Peak frequencies tended to be found in areas with subfreezing surface temperatures and either a) strong maritime influences (FZDZ only) or b) frequent warm frontal activity. Though the lack of sub-freezing temperatures at the surface in areas with (a) and/or (b) may have resulted in little FZDZ and/or FZRA at the surface, it did not necessarily mean that SLD (supercooled large drops) were infrequent aloft. In fact, some areas that appeared to have large SLD frequencies aloft rarely had FZDZ or FZRA at the surface [8,9]. The same was true for large icing frequencies and the FZFG at the surface. Elevated freezing levels tended to relegate these conditions to altitudes well above the surface. Only stations at significant elevations showed indications of these phenomena at the surface [6,8,9,10].

III. Datasets and Methodology

In this study, several approaches are applied to historical surface observations to assess the frequency of these conditions. The first approach is an examination of fifteen years of surface observations from a NOAA Techniques Development Laboratories (TDL) database for the period from 1980 to 1994. Twelve-hourly observations from 0000 and 1200 UTC each day were used, resulting in as many as 11,000 observations per site. Data from stations across the world were tested, but the results to be discussed here are limited to those from Europe and bordering areas (Fig. 1).

The present weather fields were searched for observations of explicit FZFG as well as fog at subfreezing temperatures ("cold fog", hereafter referred to as "CFG"). For each station, distributions of the occurrence of FZFG and CFG versus elevation, month and temperature were generated to examine

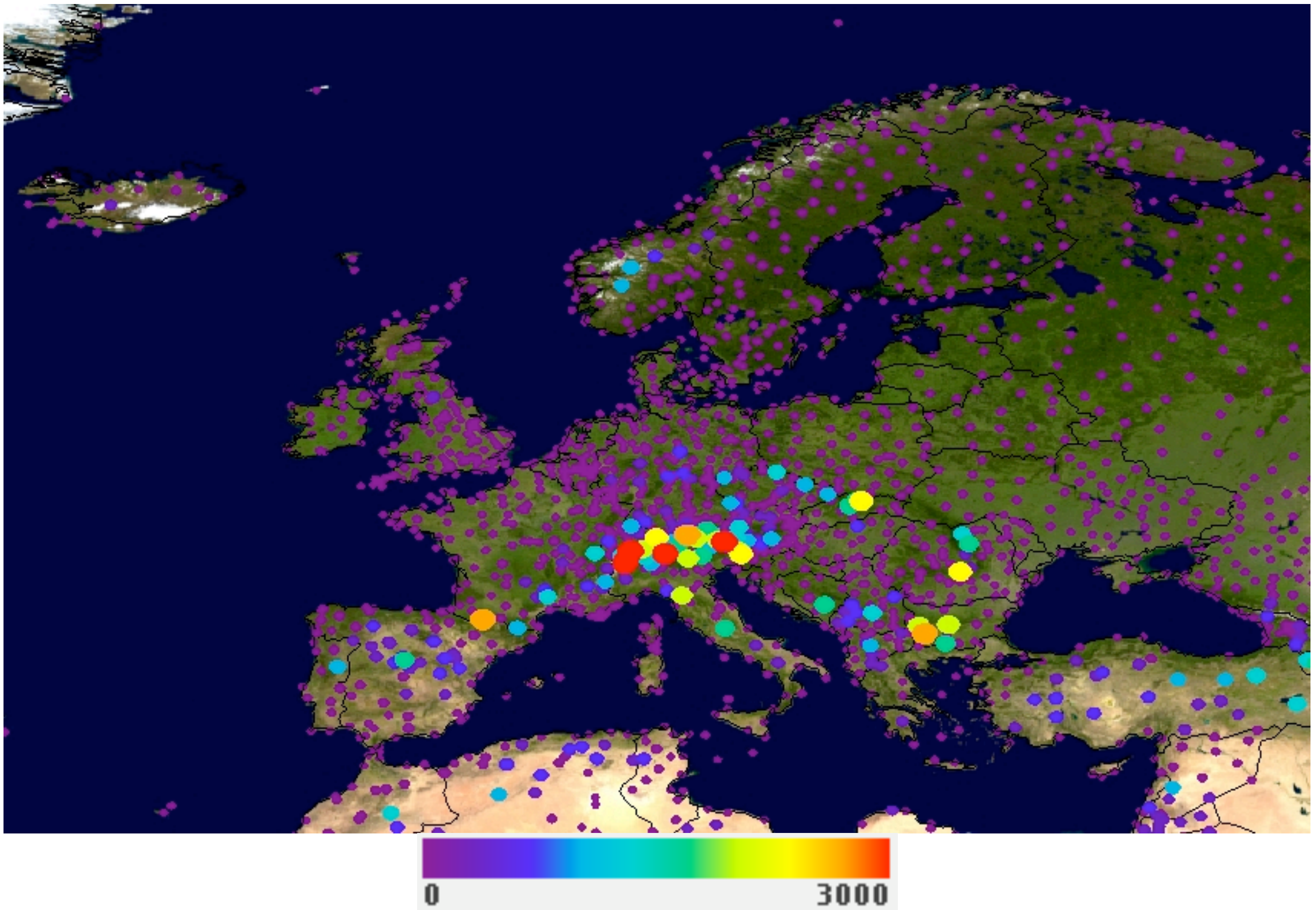

Fig. 1. Station elevations (m MSL).

not only their frequency, but also their seasonal patterns and some hints at the meteorological patterns behind their occurrence. Results for the first method are limited to the surface, but are likely to be relevant to the frequency of icing at locations only 150 m AGL (above ground level). They will be compared to the results from the second and third methods (described below) and to recent results published on the inferred frequency of icing aloft from soundings and nearby surface observations [9]. Care has been taken to be sure that the surface frequencies of FZFG and CFG were from stations that were not used in the merged sounding/surface-based analysis of icing aloft.

The second and third approaches used a 16-year NOAA National Climatic Data Center database of surface observations at airports [11] covering the period 1982-1997. Geographic coverage was global, except for Canada, with a

TABLE I
DESCRIPTION OF FIELDS USED IN SECOND AND THIRD METHODS. CODES REFER TO THE INTERNATIONAL SURFACE WEATHER OBSERVATION DATA FORMAT BY THE WORLD METEOROLOGICAL ORGANIZATION WMO.

Field	Meaning	Criteria
Glaze 1	Explicitly reported freezing precipitation	Pwx = 48, 49, 56, 57, 66, 67 **or** Ix (M 27) = 7 and Pwx = 35, 47, 48, 54, 55, 56, 65, 65, 66
Glaze 2	Theoretically deduced freezing precipitation based on Pwx and T_w	$T_w < 0^oC$ **and** either Pwx (M 14 69) = 42-47, 50-55, 58-65, 68-69, 80-84, 87-90 **or** Ix (M 27) = 7 and Pwx = 3-34, 43-44, 57-58, 67-68, 81-84
Rime	Cloud icing based on cloud base height and surface air temperature between -15 and 0°C.	Cloud base height (Hb) (M04 35) = 00 or (M09 50) = 90 **and** T_a (M21 95) = 2581 < T_a < 2731
Rime 150	Rime at 150 m, includes all cases of “rime” and those where cloud base height is less than 150 m with surface temperature between -15 and +1°C.	Rime cases plus Cloud base height (Hb) (M04 35) = 01-05 or (M09 50) = 91-92 **and** T_a (M21 95) = 2581 < T_a < 2741

lower density of surface stations over Europe than the dataset used for the first method. The second method assessed the frequency of icing conditions at 150 m AGL, based on observations of surface temperature and the height of the observed cloud base. Such frequencies are particularly relevant in assessing the problems causes by icing on wind turbines. The third approach was to determine frequencies of freezing precipitation (FZDZ + FZRA). This too was done by two methods: Directly from present weather observations and indirectly from precipitation and temperature data (Table 1). The results of these methods are somewhat different and the nature of the difference depends on the region.

IV. Results – Method #1

A. FZFG versus CFG

Figures 2a and 2b clearly demonstrate that there is a significant difference in the frequency of the reporting of explicit FZFG and the surrogate field CFG from station to station (and perhaps even by country, region or station type). It seems that the disparity was caused by the fact that a large number of CFG observations were recorded or coded as simple FG, despite the presence of subfreezing temperatures (Fig. 3). Some stations may not have reported FG of any type, even when it was occurring.

B. Geographic and vertical distribution of CFG

Because CFG appears to more effectively capture the occurrence of conditions that are conducive to icing at the surface, results from method #1 will focus on this parameter. Fig. 2b appears to indicate that CFG is most common across southeastern and central Europe, especially in the mountains of southwestern Poland, the Czech Republic, Yugoslavia, Slovakia, Bulgaria, and Romania. Peak values were also found on mountaintops in Norway, Germany, and even a few stations in Italy, France and northern England.

It is not surprising that there is some tendency for CFG values to be maximized at stations with significant elevation. This result corroborates those found in an earlier climatology of FZFG observations [6] and an inferred climatology of icing aloft from merged sounding and surface observations [9], which showed that icing is less common across Europe at elevations below 1 km (as in Fig. 4). A scatter plot of CFG (%) versus elevation for the domain shown in Figs. 1 and 2 (hereafter "the European domain") shows that nearly all occurrences of CFG > 5% and > 10% occurred at elevation > 750 m and > 1000 m MSL, respectively (see Fig. 5).

Statistically, the correlation between these two parameters is weak (0.59) for the European domain. This may be caused by the fact that this domain covers a large range of latitudes and numerous climate zones and locations relative to major storm tracks, but may be more strongly driven by the fact that some stations did not report FG at all. The correlation coefficient improves slightly to 0.65 when the only heart of the CFG domain is considered (40-55^{o}N, 0-30^{o}E). By eliminating stations within the sub-domain that had CFG <

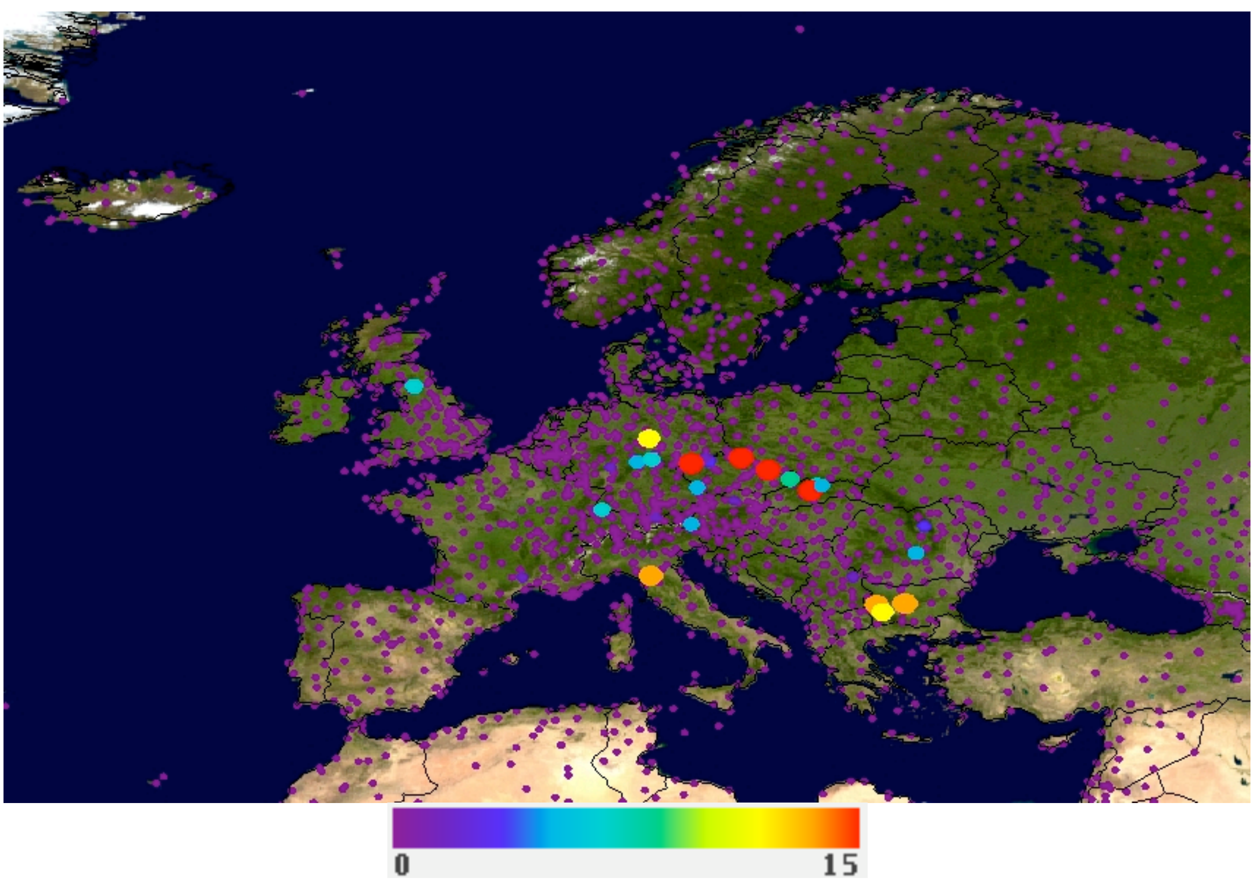

Fig. 2a. FZFG frequencies (% of all observations).

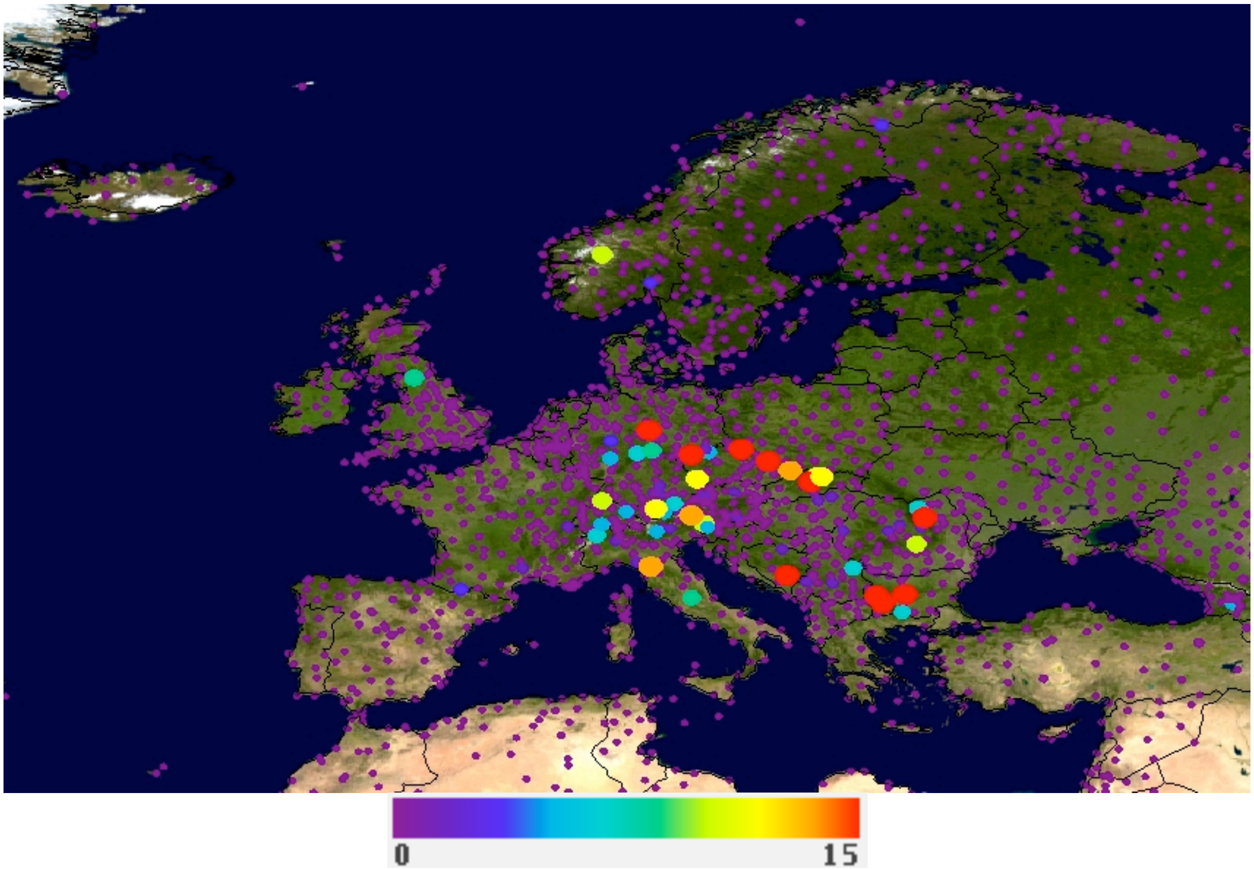

Fig. 2b. CFG frequencies (% of all observations).

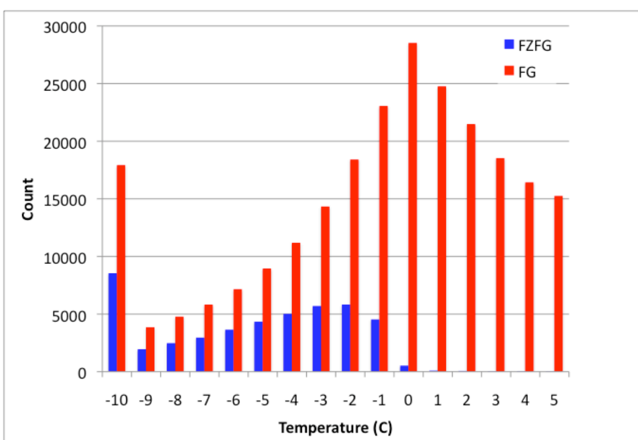

Fig. 3. Temperature (°C) distribution of FZFG and FG for all stations within the area shown on Fig. 1. The temperature listed is the maximum value for each 1°C bin. The -10°C bin includes all temperatures less than or equal to -10°C.

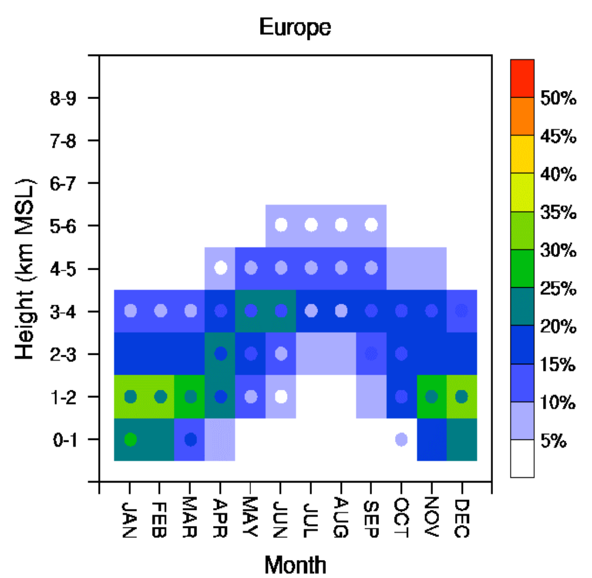

Fig. 4. Inferred frequency of icing by month and height (km MSL) for Europe (from Ref. [9]).

0.5% of the time (including stations that never reported FG), the correlation coefficient increased to 0.74, showing that there is some reasonable correlation between icing frequency and elevation in this region. Given the pattern in Fig. 4, it is likely that such a correlation would be reversed beyond ~2-3 km MSL, overall, and that it would reverse at lower altitudes during the cool season.

C. *Seasonal comparisons by station*

At most mountain stations, the frequency of CFG observations tends to vary strongly by season (Fig. 6a). As expected, frequencies are maximized at most locations

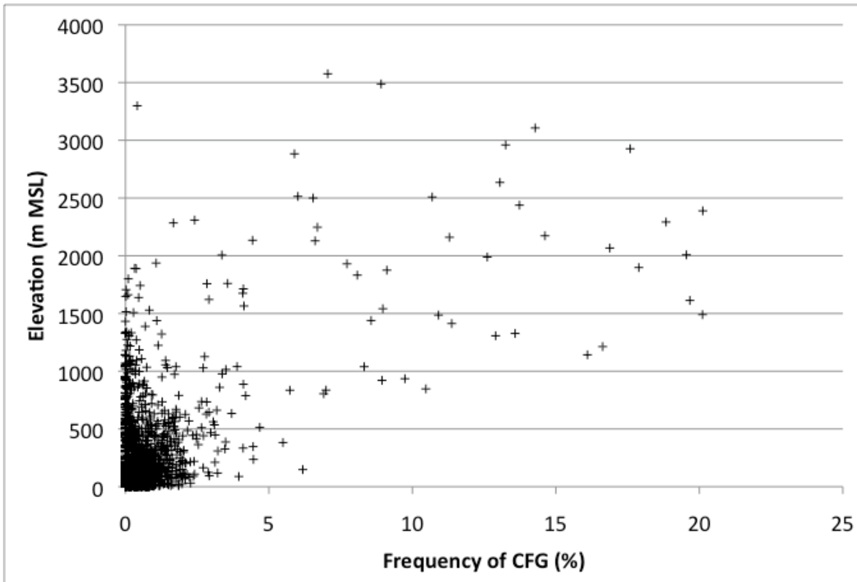

Fig. 5. Scatter plot of CFG (%) versus station elevation (m MSL) for stations with the area shown on Fig. 1.

between November and March, and minimized in July and August. Peak CFG frequencies last somewhat longer at mountain sites in Bulgaria, the Czech Republic, Poland and Romania. They also start earliest there. The largest CFG frequencies were found at Praded Mountain, Czech Republic, located at an elevation of 1490 m. Its overall, annual CFG frequency was 20.1%, which matched very closely to the inferred annual icing frequency of ~20.5% estimated for the 1-2 km altitude bin over the Wroclaw, Poland sounding site located to its north (not shown).

The icing season starts slightly later in the fall at Botev Peak, Bulgaria (2389 m), but CFG frequencies rise sharply to surpass 28% in November and are 32-36% from December to April, before dropping off sharply in May. This pattern, which was also found in ref. [10], compares quite well with the frequencies of icing inferred between 2 and 3 km above the Sofia, Bulgaria sounding site, nearby to the west (Fig. 7; ref. [9]). Notice that there was a slight minimum in both the CFG frequency at Botev Peak and the icing frequency above Sofia in January, when conditions may be at their coldest. This is

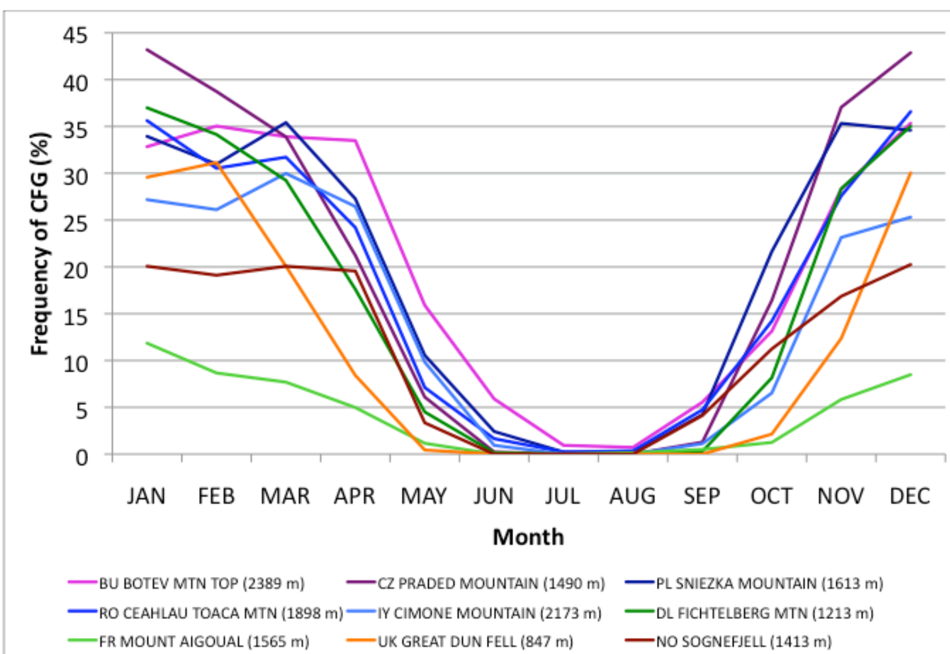

Fig. 6a. Monthly frequencies of CFG (%) at Botev (Bulgaria), Praded Mountain (Czech Republic), Sniezka Mountain (Poland), Ceahlau Toaca (Romania), Cimone Mountain (Italy), Fichtelberg Mountain (Germany), Mount Aigoual (France), Great Dun Fell (England) and Sognefjell (Norway).

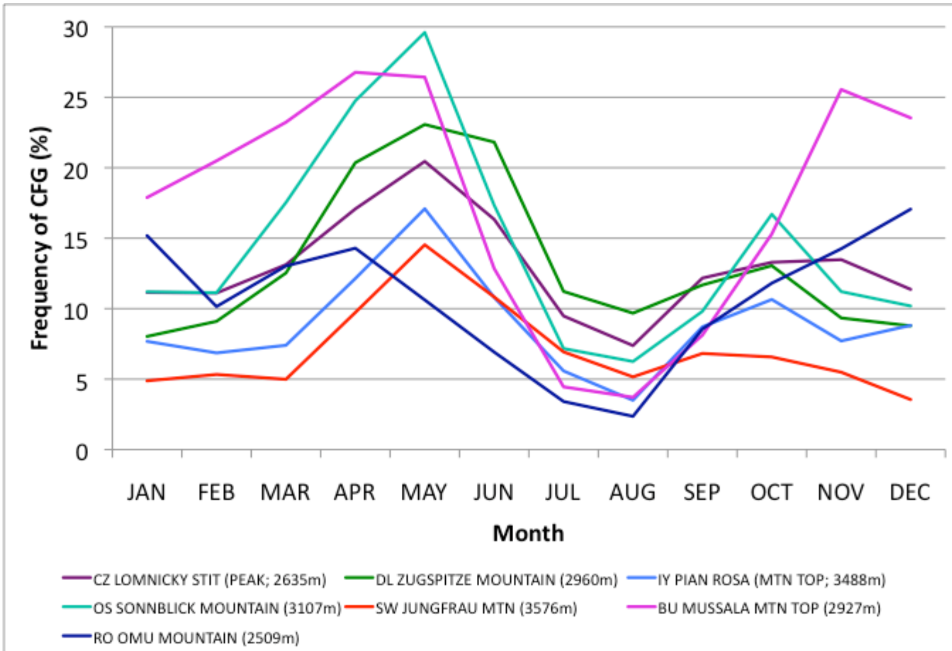

Fig. 6b. Monthly frequencies of CFG (%) at Lomnicky Peak (Czech Republic), Zugspitze (Germany), Pian Rosa (Italy), Sonnblick Mountain (Austria), Jungfrau (Switzerland), Mussala (Bulgaria) and Omu Mountain (Romania).

also the month of the peak CFG frequency at the Sofia surface station (1.75%; not shown). Sofia's surface CFG frequencies only exceed 1% during December and January; the same months when icing frequencies exceed 5% below 1 km.

Similar comparisons are found for sounding sites near other stations shown in Fig. 6a, including strong similarities in the frequencies and seasonal patterns of CFG at the Sognefjell, Norway surface station and icing in the ~1-2 km (3,000-6,000 ft) range over the Orland, Norway sounding site to its northeast (not shown; see [12]). At an elevation of 847 m, Great Dun Fell, England proved to be the only station in the U.K. with CFG > 2% of the time, annually. It had CFG 10.5% of the time and this matched well to interpolated icing frequencies from the Boulmer sounding site (not shown). Italy had several sites with significant full-year CFG frequencies, including Cimone Mountain (2173 m; 14.6%; see Fig. 6a), Terminillo Mountain (1875 m; 9.1%) and Pian Rosa (3488 m, 8.9%). Though FG is common at lower altitudes in northern Italy's Po River valley, CFG is only observed at sites like Milan (211 m) between November and March, with CFG found in more than 10% of all January observations.

The seasonal CFG patterns at most elevated sites across Italy look like those in Fig. 6a, but the particularly high Pian Rosa site had a distinct peak in the spring and a weaker peak in the fall. In fact, spring and fall peaks in the seasonal CFG pattern were found at nearly every European station at elevations in excess of 2500 m (Fig. 6b). This pattern is likely caused by the tendency for ideal icing temperatures ($-15^oC < T < 0^oC$) to pass through such altitudes in the spring and fall, simultaneous with adequate moisture, especially in the spring. In winter, temperatures are likely to often be cooler than normal for icing at these elevations, causing CFG frequencies to decrease there while they tend to peak at altitudes not far below (800-2400 m; Fig. 6a), where temperatures are likely to be more ideal for icing. In summer, temperatures are too warm for icing at the lower sites in Fig. 6a, but they were occasionally still cool enough at the sites above 2500 m. Note that although the seasonal pattern matches those of other high elevation sites, CFG frequencies at Jungfrau (Switzerland) appear to be anomalously small. It is expected that they would be larger than those found at Pian Rosa, to the south.

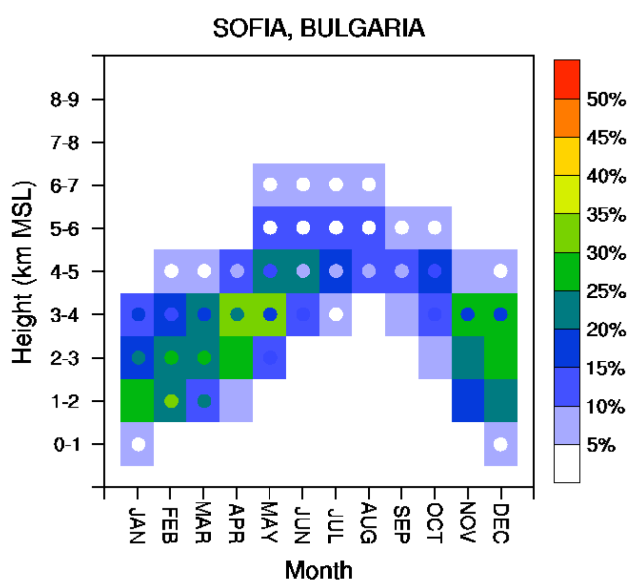

Fig. 7. Inferred frequency of icing by month and height (km MSL) over Sofia, Bulgaria (from Ref. [9]).

V. Results – Method #2

The second method estimated the frequency of "rime" ice based upon whether the following criteria were met: 1) the height of cloud base was less than 150 m AGL and 2) the air temperature at the surface was between -15°C and 1°C, implying that the temperature at 150 m was likely to be in an ideal range for icing (about -15°C to 0°C). This method is similar to that used by Makkonen and Ahti [13] in their assessment of icing frequencies and ice loads over Finland.

Results are generally similar to those from method #1, within the highest icing frequencies (triangles in Fig. 8) found in areas with significant elevation (compare to Fig. 1). Thanks to smaller gradations between the symbols used in Fig. 8, it allows for a better opportunity to visualize area of relatively low icing frequencies (e.g. green dots in Fig. 8 are for <72 hours per year, which translates to <~0.8% of all observations, assuming that hourly observations were taken; all values less than 1% were within the lowest gradation in Fig. 2; magenta dots cover the range ~0.8-2.7%; blue dots ~2.7-5.5%, red dots ~5.5-11.4%; red triangles >11.4%).

Using this more sensitive scale, we see that rime icing occurrences extend well beyond elevated terrain to areas of lower terrain, especially across Central Europe. Most of the area from southeastern England and central France eastward to western and even central Russia had frequencies in excess of 72 hr/year. This swath includes a large area from the Alps and Balkans northward to southern and eastern Scandinavia that had at rime icing at 150 m at least 240 hr/year. Scattered areas with >480 hr/year of rime icing were present within this area, including along the Norway-Sweden border, across southern Finland, western Russia and Ukraine.

Impressive values exceeding 1000 hr/year (>11.4%) appear to occur in the same general locations as the largest CFG frequencies. As mentioned earlier, many of these sites appear to be in areas of elevated terrain. Note, however, that the stations used in method #2 are all at airports which are usually not located in very rough terrain or high in the mountains. Therefore, Fig. 8 should be interpreted with caution keeping in mind that higher than indicated rime icing frequencies may exist locally.

Two important areas of disparity between methods #2 and #1 are the presence of relatively high values of rime-150 (>5.5%) over southern Finland and western Russia, where CFG values are generally less than 3%, if not less than 1%. Makkonen and Ahti [13] noted that the similarly large icing frequencies that they found over southern Finland were contradictory to the experience of those that live in this area of low elevation (e.g. Helsinki). This was due to the fact that

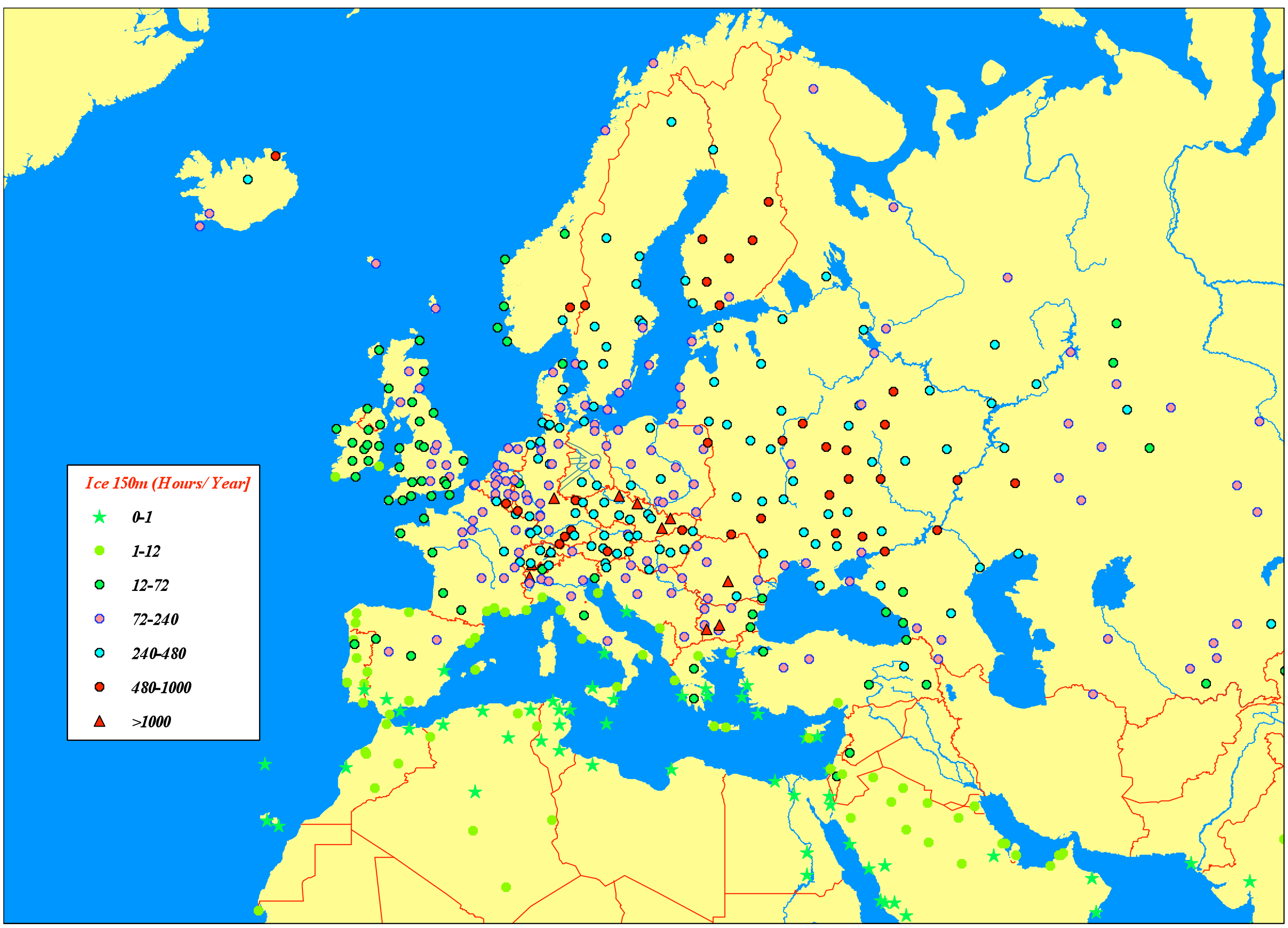

Fig. 8. Frequency of "Rime-150" conditions (hours/year).

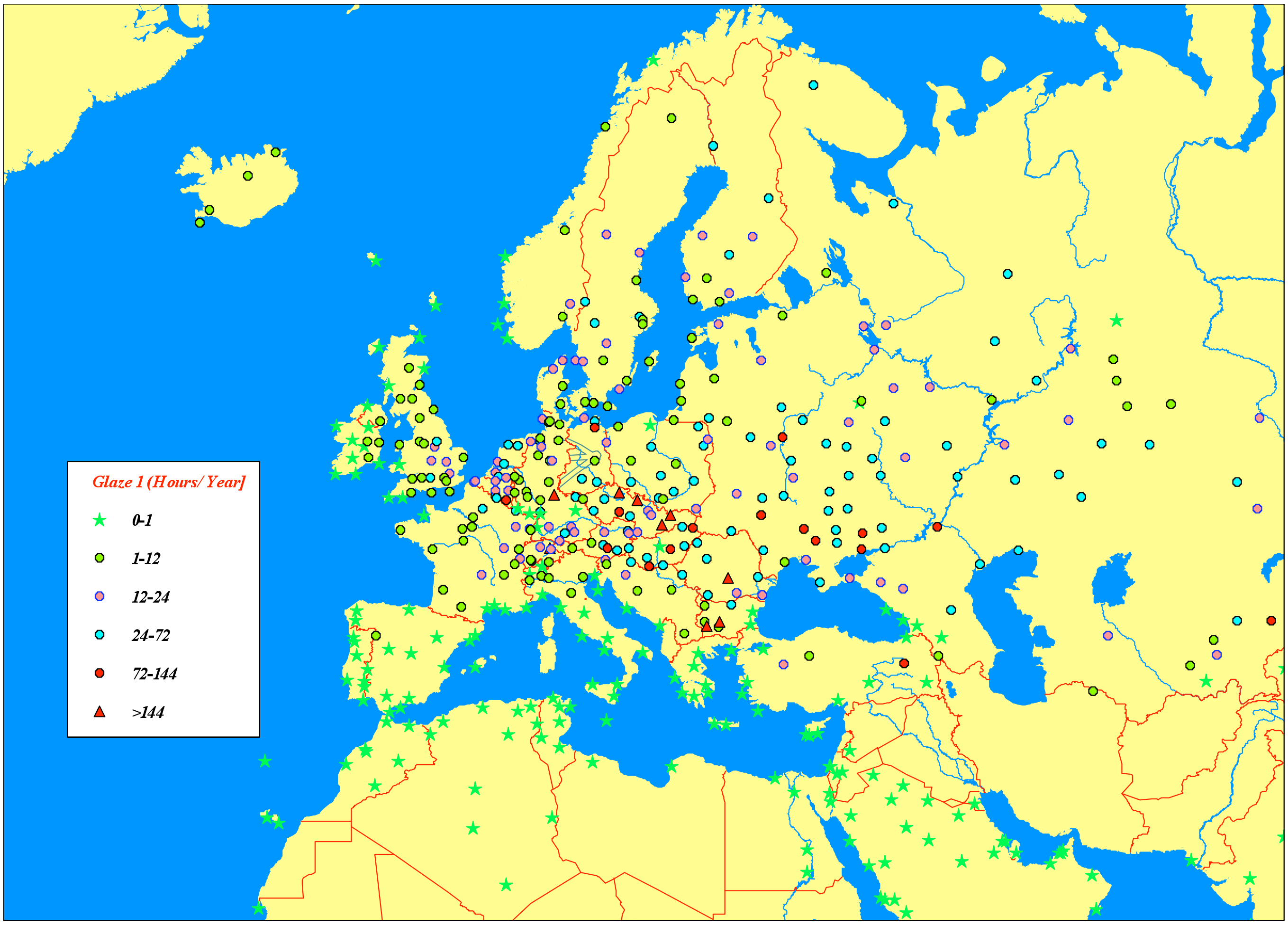

Fig. 9. Frequency of "Glaze-1" conditions (hours/year).

surface icing is extremely rare in this region, giving credence to the low CFG values in this area (Figs. 1, 2b).

Rime-150 frequencies were also significantly larger than for CFG across much of western Russia and Ukraine. Rime-150 frequencies exceeding 5.5% were scattered across this area, while most CFG frequencies were <1% and a few sites in the southern part of this domain were on the order of 1-3%. Cloudy skies and icing aloft have been found to be quite common over these areas [9], but such conditions do not often seem to reach the ground. The general geographical patterns of rime icing from method #2 are mostly similar to the WECO-analysis presented by Dobesch et al. [14].

VI. Results – Method #3

The third method estimated the frequency of "glaze" icing based upon the frequency of either a) freezing precipitation at the surface ("glaze-1") or b) a theoretical deduction of freezing precipitation based upon the combination of sub-freezing wet bulb temperatures with either freezing precipitation or non-freezing liquid precipitation (rain, drizzle) at the surface ("glaze-2").

Patterns were generally similar to those for rime-150 and CFG, except that overall frequencies were much lower for both glaze-1 and glaze-2 (Figs. 9, 10). Nearly all stations had frequencies < 144 hours/year (<1.65%), though a few mountain sites exceeded this value. Similar results were found in previous European climatologies of FZDZ and FZRA [6, 9].

It is interesting to note that glaze-2 frequencies were significantly higher than those for glaze-1 over much of the U.K., Denmark, Scandinavia and Iceland. Glaze-2 values often exceeded 72 hours/year in these areas, while glaze-1 values were typically <24 hours/year. Bernstein and LeBot [9] found that these areas were within the European SLD maximum aloft, thanks to the influence of maritime air masses. Much of the SLD was thought to occur not far above the surface, though it rarely seemed to reach the ground at most sites.

VII. Summary/Conclusions

The comparison of reports of FZFG and the CFG shows that any regional analysis using only explicit reports of FZFG would be incomplete. Clearly, cases with reported FG at subfreezing temperature need to be included in order to cover all rime icing cases at the ground level.

Sub-freezing fog at the ground level appear to occur with large frequency only in mountainous regions. Such fogs may well be considered "clouds". The absence of sub-freezing fogs

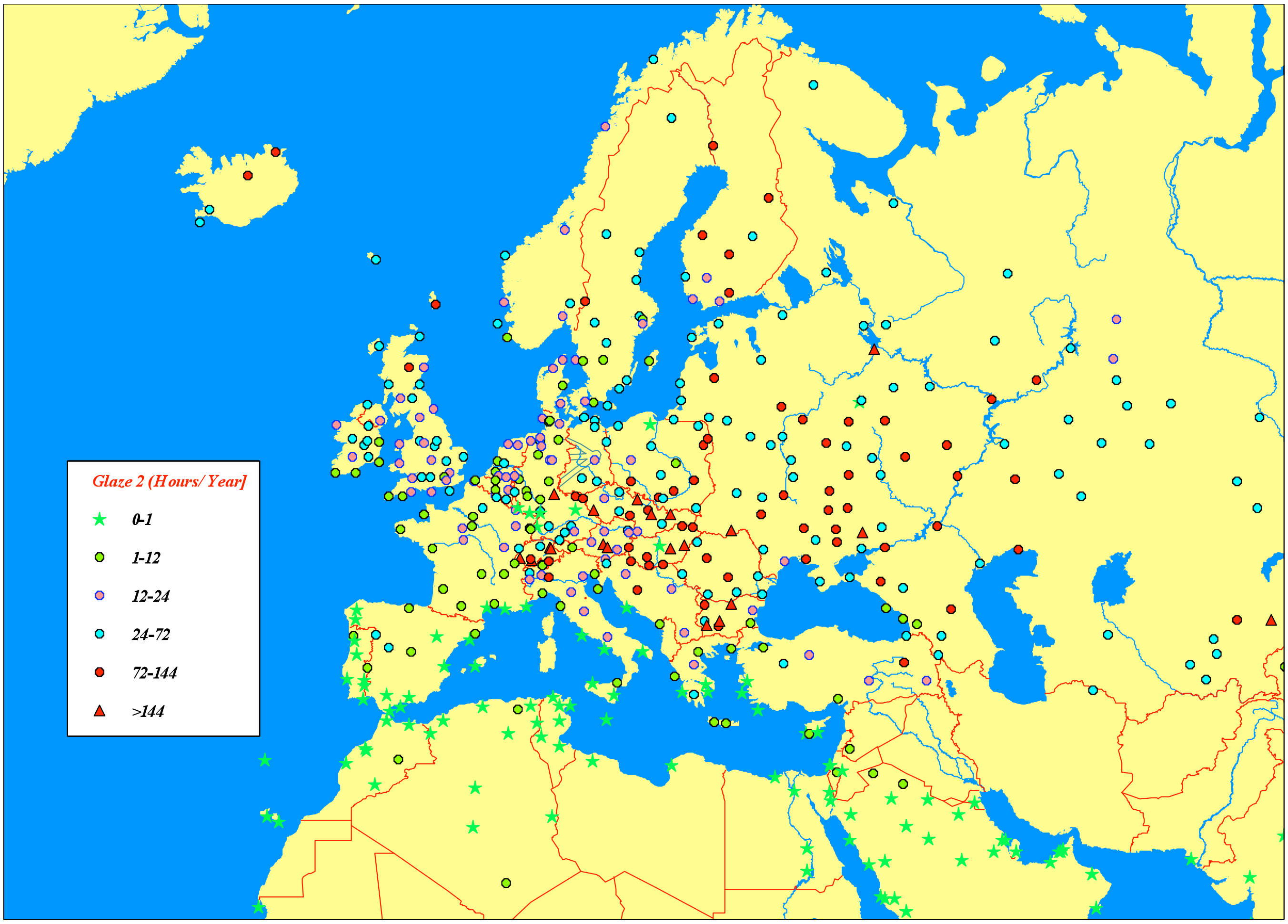

Fig. 10. Frequency of "Glaze-2" conditions (hours/year).

of any sort and consequent rime icing at low elevations is striking considering the high frequency of warm fogs at some of these locations. The main reason for this is sublimation on the surface of snow on the ground, as well as the tendency for freezing levels to be elevated.

The results show that there is a limited correlation between CFG and station elevation. This result may be related to the inclusion of multiple climate zones in the generation of those statistics, and the facts that some stations were at elevations above the typical range for icing over Europe and that some stations may not have reported FG of any type. Another important reason may be rooted in the properties of the atmospheric boundary layer. In particular, that cloud base level tends to "follow" the terrain. Consequently, there is a much stronger correlation between the icing frequency and *relative* altitude (in respect to the surrounding terrain) than between icing frequency and the absolute elevation ASL, as shown by Makkonen and Ahti [13]. This puts the accuracy of the multiple regression model mapping method by Dobesch et al. [14] in doubt.

The dependence of rime icing frequency on the elevation above ground is so great that there are many regions in Europe at which significant icing occurs at 150 m while practically no icing occurs at the ground level. This is an important aspect to recognize when planning wind turbine systems, for example, since historical surface observations in these areas may give the false impression that icing conditions should not be expected.

In many parts of Europe, glaze icing as deduced from precipitation and air temperature appears to be much more frequent than the freezing precipitation as reported by observers. This is probably mostly related to inadequate observations as well as the different cultures of taking observations in various countries. In any case, this shows that it can be difficult to measure, or even provide a standard definition for freezing precipitation.

VIII. ACKNOWLEDGMENT

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