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A multi-scale risk assessment for tephra fallout and airborne concentration from multiple Icelandic volcanoes – Part 1: Hazard assessment

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This supplementary material comprises all maps produced to compile the tephra hazard assessment presented in the article *A multi-scale risk assessment for tephra fallout and airborne concentration from multiple Icelandic volcanoes - Part I: hazard assessment* by Biass et al. First, a thorough review of the eruptive history of selected volcanoes is presented. Second, all maps for the probabilistic hazard assessment of far-range atmospheric concentrations are presented and include calculations for the thresholds of $2x10^{-3}$, 0.2 and 2 mg/m^3. The first threshold is used to illustrate the 0-ash tolerance policy, whereas the second and the third are useful for the new threshold approach policy (refer to the text for more details). Conservative maps accounting for the occurrence of ash at any flight level (FL) as well as maps for FL050, FL150 and FL300 are also presented. Finally, results of the deterministic model runs for historical and well-constrained are also presented. All eruptions were set to start on the 14th of April 2010 and were ran for 10 days. Here are shown simulation results at FL050, FL150 and FL300 24, 48, 72, 96, 120, 144, 168 and 192 hours after the onset of the eruption.

Eruptive history of selected volcanoes

Hekla

Hekla volcano is located on the southwest extremity of the EVZ and is one of the most active volcanic systems in Iceland, with 18 eruptions from the central vent and 6 in its vicinity since human settlement in Iceland during the last 1100 years (Table 1). The average recurrence rate of eruptions at Hekla was one to two per century until the 1970's, when the regime drastically changed to a regular 10-year repose time with eruptions in 1970, 1980-81, 1991 and 2000. Since the first historical eruption in 1104, which followed a period of quiescence of 250 years, repose intervals have varied between 10 and 102 years. Interestingly, the repose interval has been recognized as having a strong influence on the magma composition of the following eruption, with a silica content increasing with the length of the interval (Gronvold et al., 1983; Gudmundsson et al., 1992; Höskuldsson et al., 2007; Thorarinsson, 1967). Although voluminous Plinian explosive deposits from pre-historic eruptions of Hekla are recognized in the field (e.g. H1-5 layers; Larsen and Eirìksson, 2008), this study focuses on the eruptive behaviour through historical times, known as "mixed" (Thordarson and Höskuldsson, 2008; Thordarson and Larsen, 2007). Most eruptions are described as being long-lasting (i.e. week to months) including both explosive and effusive activity scattered over three main phases, where the tephra/lava ratio decreases with time. In the first phase, a sub-plinian to Plinian-type plume typically develops few minutes after the onset of the eruption and lasts for about 1 hour. The second phase is a several-hour long transition phase with moderate tephra production and lava fountaining leading to the last phase, characterized by a discrete weeks to months-long Strombolian activity (Thordarson and Höskuldsson, 2008). Here, we model only the first phase known for producing the majority of the tephra.
Based on stratigraphic investigations and reviews of historical reports, Thorarinsson (1967) identified 14 eruptions since the settlement of Iceland (870s A.D., Vésteinsson, 2000) until the eruption of 1947, with major tephra emissions in 1140, 1300, 1510, 1597, 1693, 1766 and 1845. These eruptions, along with the eruption of 1947, show strong similarities in terms of isopach maps, eruptive styles and erupted volumes. Precise eyewitness reports and field studies exist for the eruptions of 1947, 1970, 1980-81, 1991 and 2000. It is clear that the volume produced by the 1947 eruption is larger than that associated with the following eruptions, which exhibit similar volumes and deposition trends (Gronvold et al., 1983; Gudmundsson et al., 1992; Höskuldsson et al., 2007; Thorarinsson, 1967; Thorarinsson and Sigvaldason, 1972).

Katla

The Katla volcanic system lies on the south-eastern sector of the flank zone of the EVZ, at the transition of divergent plate motion (Sturkell et al., 2010). It is composed by a central volcano and an embryonic fissure swarm, about 110 km long with a 100 km2 caldera in the centre of the edifice and covered by the 590 km2 and up to 700 m thick Mýrdalsjökull ice cap (Björnsson et al., 2000; Óladóttir et al., 2008). Three types of eruptive styles are known to have occurred at Katla, which include basaltic explosive eruptions (most typical), silicic explosive eruptions and long-lasting effusive eruptions such as the Eldgjá eruption of 934-940, which curbed the settlement in Iceland (Larsen, 2000). Up to 208 tephra layers are recognized as originating from Katla during the past 8,400 years, amongst which 18 were witnessed during historical times (Larsen, 2000; 2010; Larsen and Eirìksson, 2008; Larsen et al., 2001; Thordarson and Larsen, 2007). Óladóttir et al. (2008) observe two cycles during the Holocene, each involving three plumbing system stages. From 6,600 to 1,700 BP, 12 moderate-size silicic eruptions of dacitic composition took place at Katla, known as the SILK layers (Larsen et al., 2001). In terms of volumes of eruption frequency, Katla is the most productive volcanic system in Iceland (Larsen and Eirìksson, 2008; Óladóttir et al., 2006; Thordarson and Larsen, 2007). The eruption frequency at Katla is about two eruptions per century since 1,500 AD, with a mean repose interval of 47 years (Larsen, 2000). However, due to the preferential conservation of the deposits in the East sector of the volcano related to the presence of an ice cap and a current period of low activity, this estimate can potentially be twice as much throughout the entire Holocene (Óladóttir et al., 2008; Óladóttir et al., 2006). Interestingly, the duration of the repose interval can be correlated with the size of the preceding eruption, where large eruptions lead to long reposes (Eliasson et al., 2006).
Ten eruptions were reported since 1580 AD, all located within the caldera and began during the May-November period (Larsen, 2000; Larsen, 2010; Thordarson and Larsen, 2007; Table 2). The last tephra-producing eruption occurred in 1918, generating a plume rising up to 14 km a.s.l. and a total erupted volume ranging between 0.7-1.5 km3 (Larsen, 2010). Throughout historic time, erupted volumes of freshly fallen tephra have ranged between 0.02-1.5 km3. The largest of these volumes was produced by the K-1755 eruption, which heavily impacted farming activities and caused 50 farms to be abandoned (Larsen, 2000; 2010). Since 1625, eruptions are documented to have lasted from 2 weeks to 5 months, with 80-90% of total tephra generated during the first few days (Larsen, 2010). Since 1918, three crises occurred at Katla in 1955, 1999-

2004 and 2011 accompanied with the generation of jökulhaups and high seismic activity (Soosalu et al., 2006; Sturkell et al., 2010). These crises have been suggested to represent either shallow magma intrusions or small sub-glacial eruptions. Discarding these crises as eruptions, the repose interval since the last eruption is 94 years, which results in a >20% probability of eruption in the next 10 years (Eliasson et al., 2006).

Eyjafjallajökull

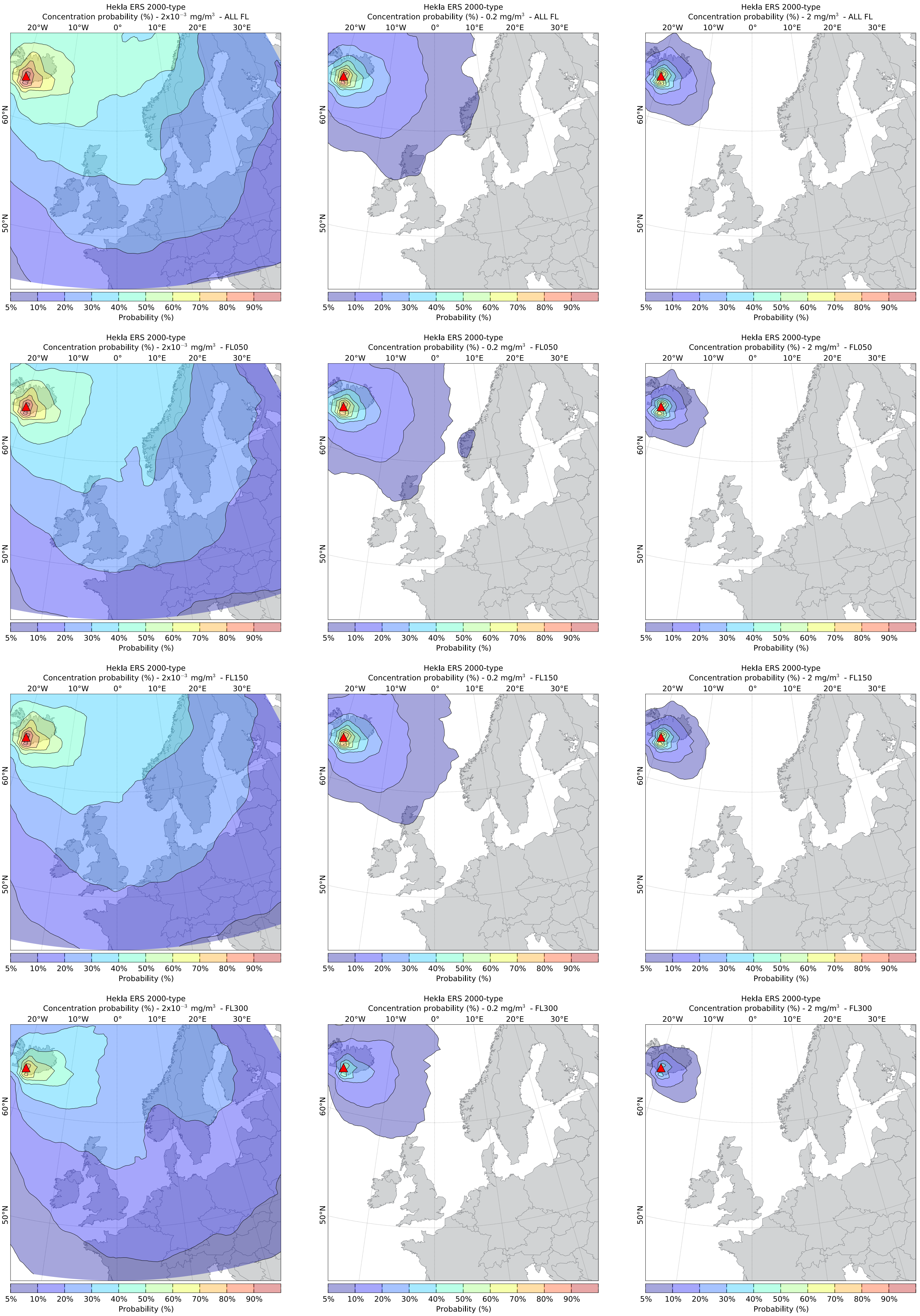
Eyjafjallajökull is located in the central southern part of the EVZ, within the transitional flank zone. The 1651 m high edifice covers a surface of 400 km2 and is capped by a 200 m thick ice cap (Loughlin, 2002; Sturkell et al., 2010). The pre-17th century eruptive history is poorly known, with the knowledge of two eruptions during the 6-7th century and again in 920 AD (Dugmore et al., 2013). Only three eruptions are reported during historical times, namely in 1612, 1821-23 and 2010 (Gudmundsson et al., 2010; Sturkell et al., 2010). All eruptions are considered to be similar in composition and magnitudes, i.e., VEI 3-4 (Gudmundsson et al., 2010).

The long-lasting and pulsating eruption of 2010 started on the 20th of March, following a period of almost 20 years of unrest marked by intrusion-related deformation and seismic crisis in 1994 and 1999 (Gudmundsson et al., 2010; Sigmundsson et al., 2010; Sturkell et al., 2010). The first phase was characterized by a 3-week long basaltic effusive eruption from a flank vent located east of the summit, between the Katla and Eyjafjallajökull volcanoes. Once the activity on the flank vent ceased (around the 12th of April), the activity resumed at the central summit vent on the 14th of April with moderate explosive to effusive activity. The activity of the summit vent can be divided into three phases based on variation in the eruptive styles. During explosive phases, the plume oscillated between 1 and 10 km a.s.l. (Arason et al., 2011; Gudmundsson et al., 2010). The total volume of tephra produced is 0.27 km3, of which 80% was airborne and the remaining 20% was transported by ice and water (Gudmundsson et al., 2012). A precise chronology of the eruption can be found in the works of Arason et al. (2011), Bonadonna et al. (2011) and Gudmundsson et al. (2012).

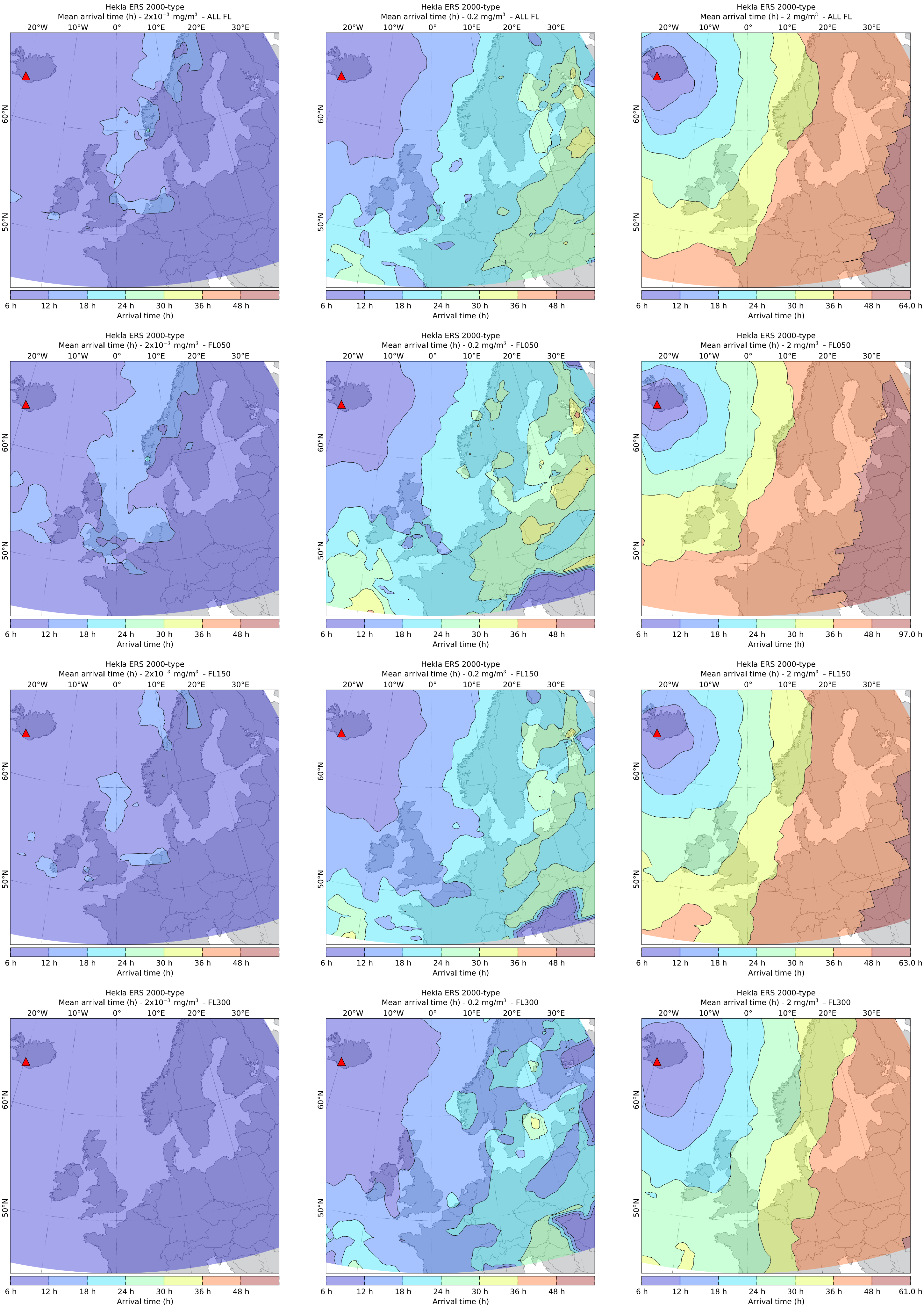
Askja

Askja volcano lies on the southern part of the NVZ, of which it is the largest central volcano (Sparks et al., 1981). Askja volcanic system is composed by a central volcano and a swarm of fissures, faults and crater rows extending 120 km north towards the coast and 30 km south towards Vatnajökull glacier (Hjartardóttir et al., 2009). During historic time, eruptions have occurred both within fissures and the central volcano. The fissure swarm eruptions are all basaltic and effusive, while the central volcano ones are both of the effusive basaltic style as well as rhyolitic and explosive. The most recent activity phase of this volcanic system began in September 1874 and lasted until 1961 with a total of 9 eruptions in 1875, of which one rhyolitic and explosive. During the 20th century a total of 8 eruption have occurred at the volcano, 7 within the central volcano and on south of it (Hartley and Thordarson 2012; Sparks et al., 1981). The most recent explosive eruption was a VEI 5 rhyolitic Plinian eruption, which began on the 28th of March 1875 and lasted for about 17 hours (Hartley and Thordarson 2012; Sparks et al., 1981). More than 95% of the total volume of tephra (i.e. about 2 km3) was produced during the phases Askja C and Askja D, separated by a 30 minute break. Askja C is related to a phreatoplinian activity and is the only historical example of this eruptive style (Carey et al., 2010). It lasted for 1-1.5 hours, produced a plume reaching an altitude of 23 km and a volume of 0.45 km3 of tephra composed of 99 wt.% of particles smaller than 1 mm (Carey et al., 2010; Sparks et al., 1981). The following phase, Askja D, was a dry Plinian eruption which lasted for 4-6 hours, produced a plume reaching an altitude of 26 km and a volume of tephra close to 1.37 km3 (Carey et al., 2010; Sparks et al., 1981). In addition to the 1875 eruption, evidence for another large rhyolitic eruption from Askja dating back to about 10 ka can be observed within the Askja central volcano and along the NE coast of Iceland (Sigvaldason, 2002). The volume of tephra for this event is estimated to be around 5-10 km3 (Larsen and Eirìksson, 2008).

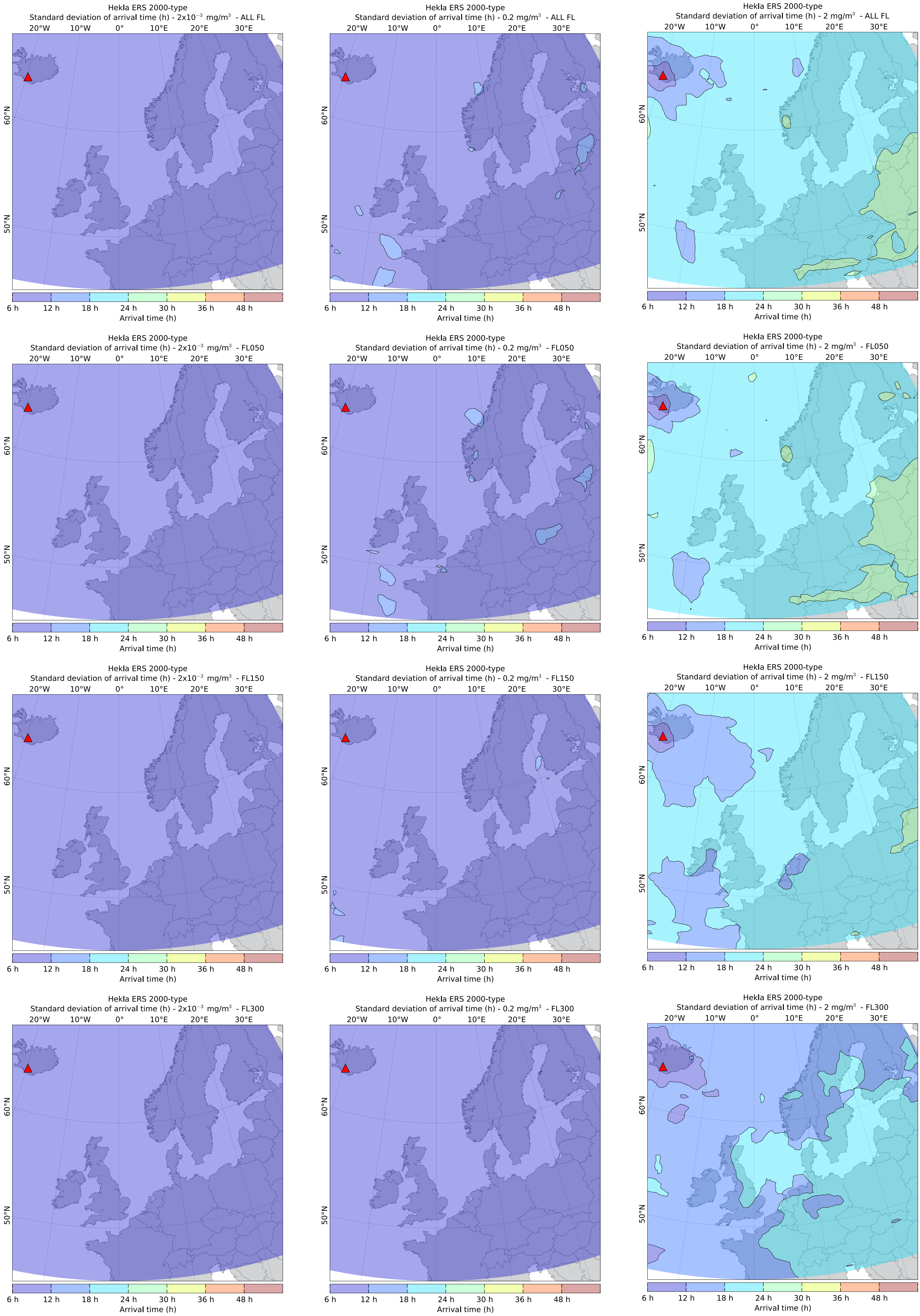
Hekla ERS 2000-type - Concentration probability (%)



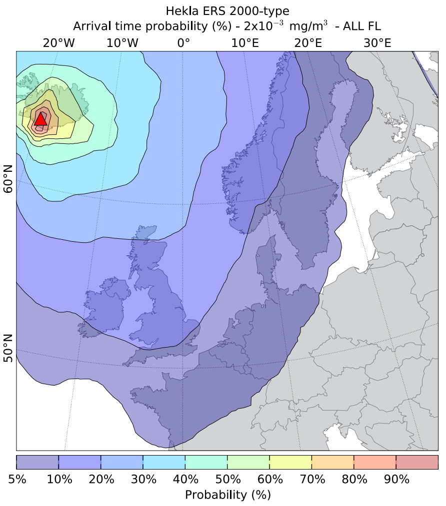
Hekla ERS 2000-type - Mean arrival time (h)

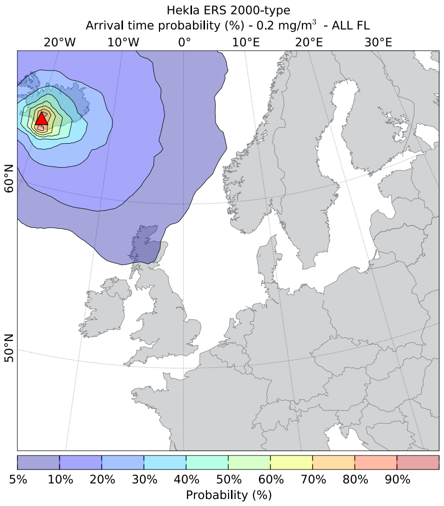


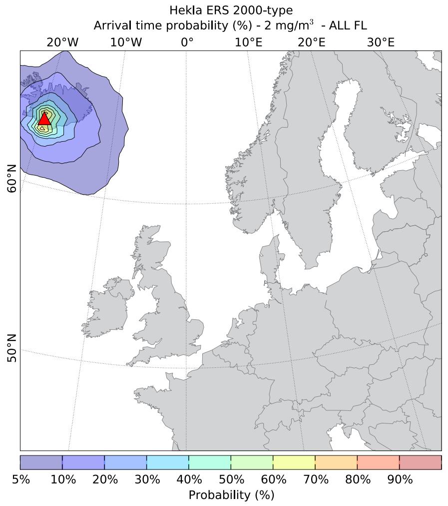
Hekla ERS 2000-type - Standard deviation of arrival time (h)

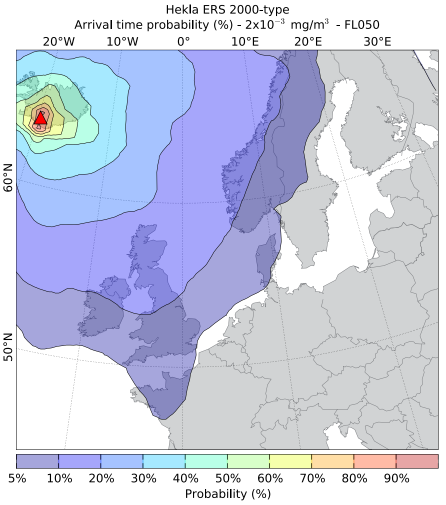


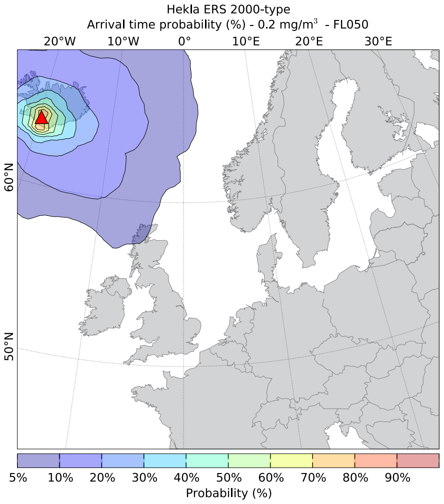
Hekla ERS 2000-type - Probability of arrival time > 24 h (%)

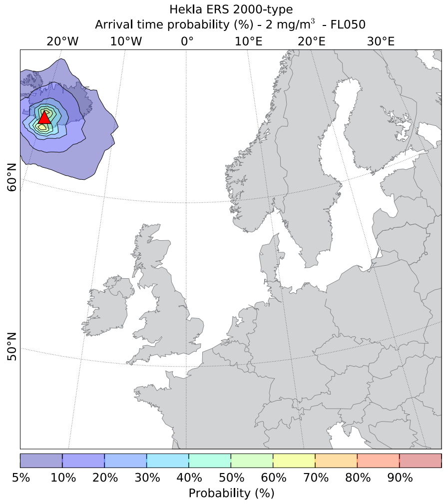


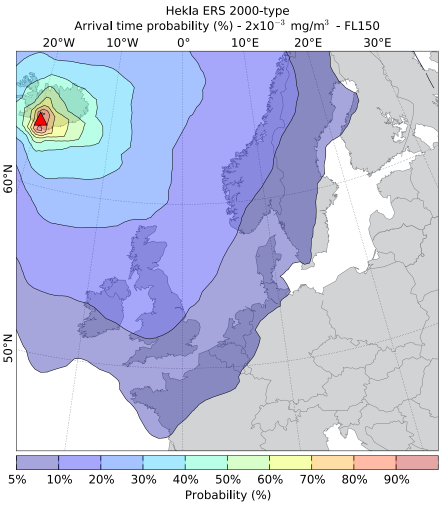


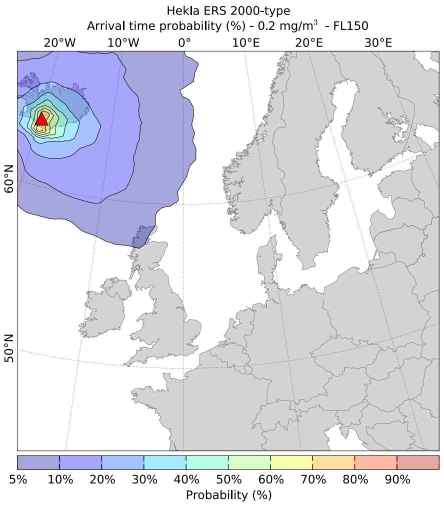


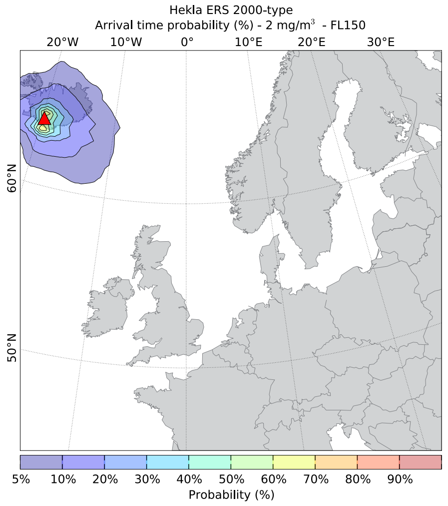


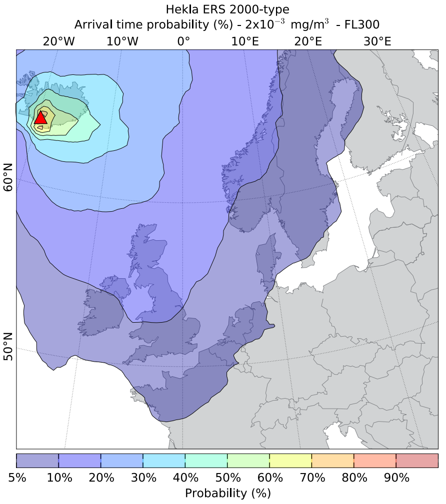


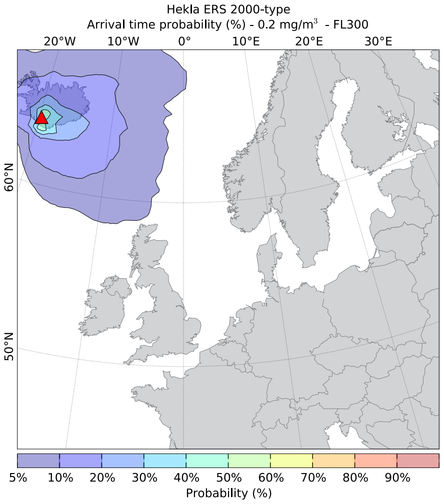


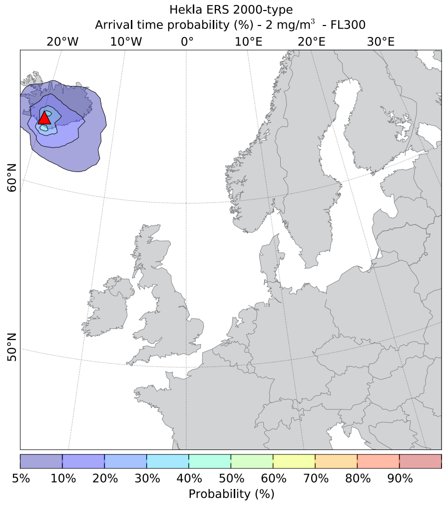




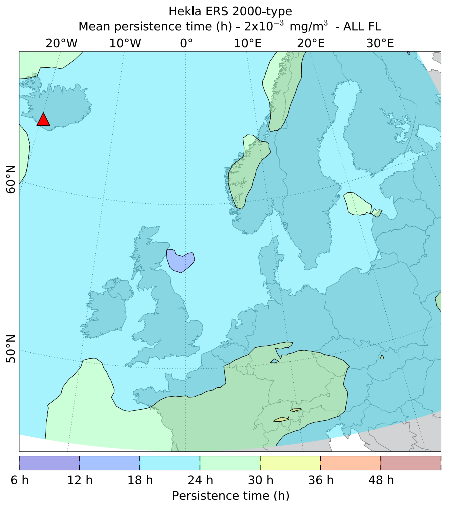


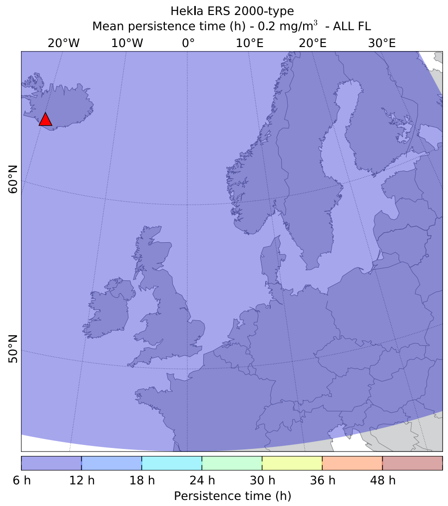


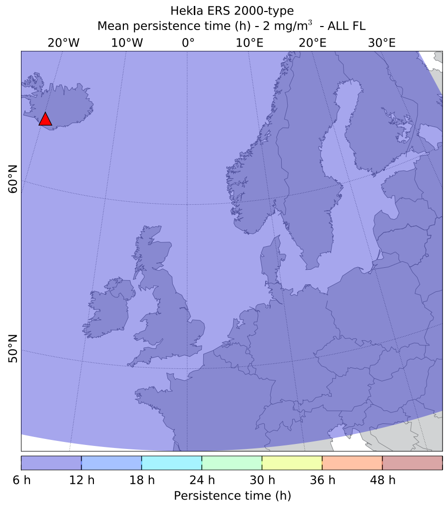


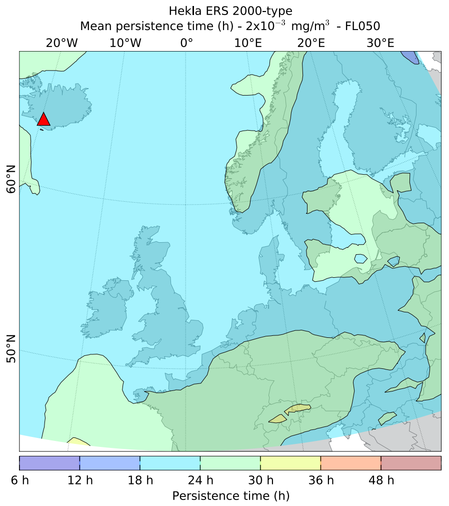


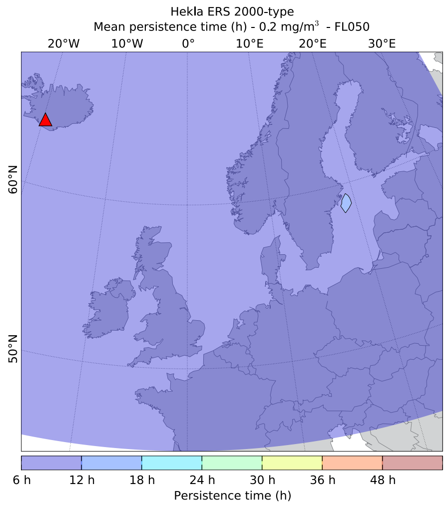
Hekla ERS 2000-type - Mean persistence time (h)

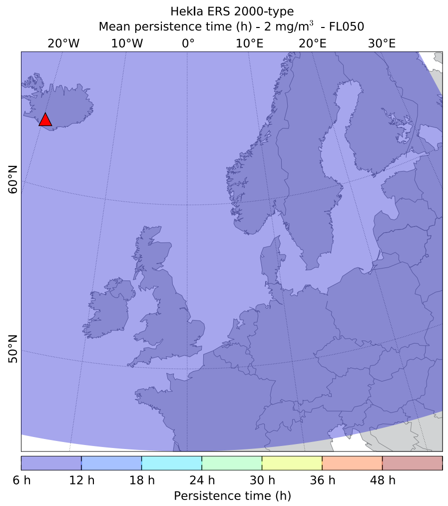


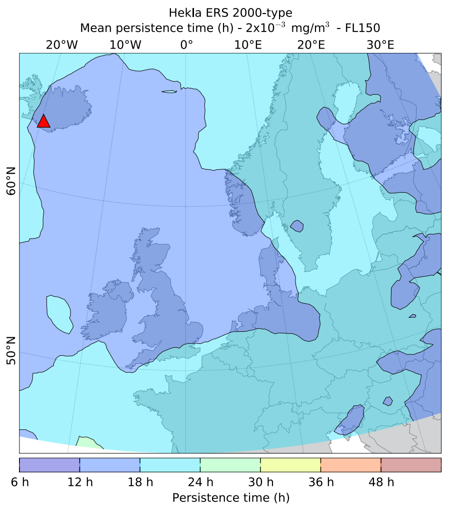


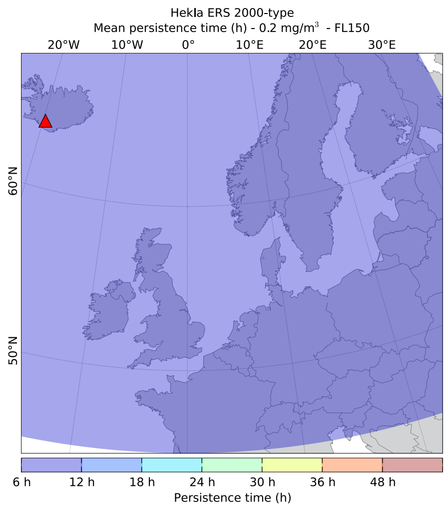


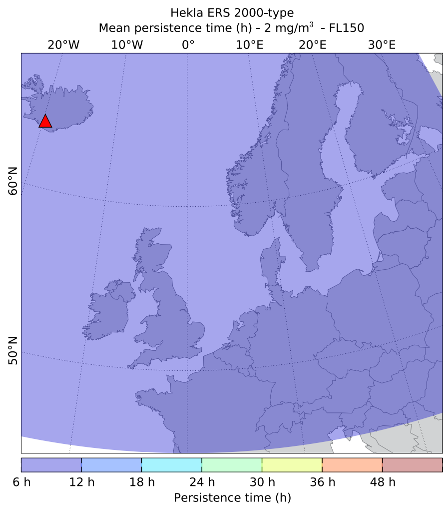


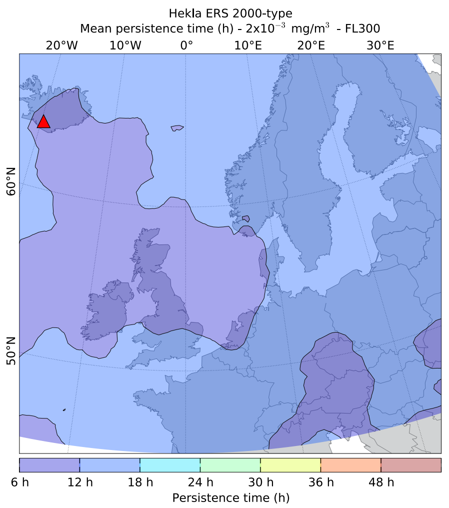


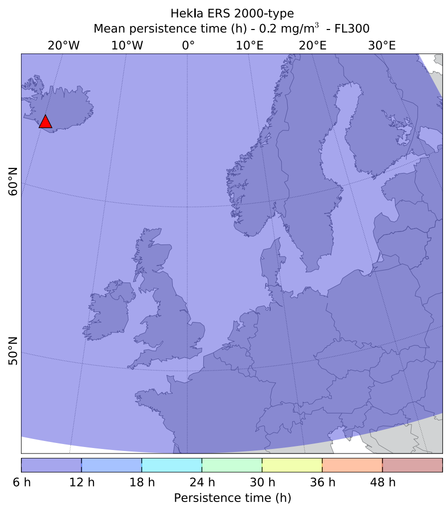


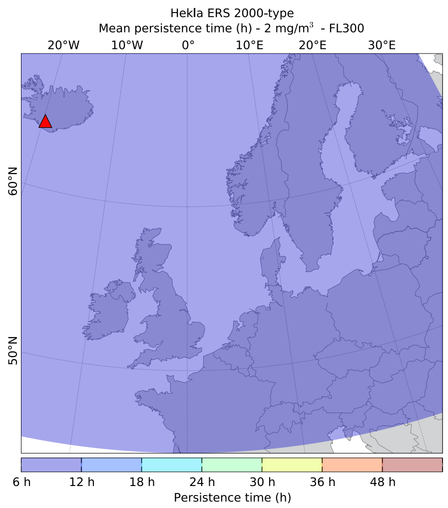




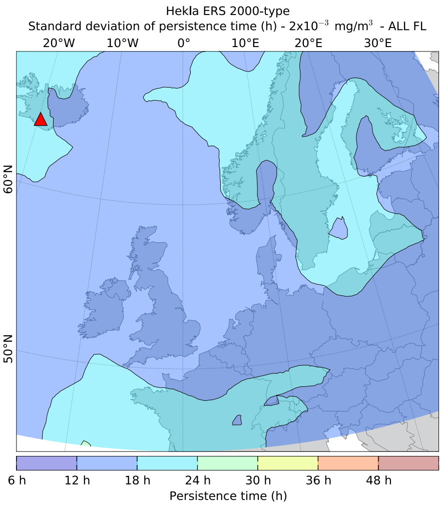


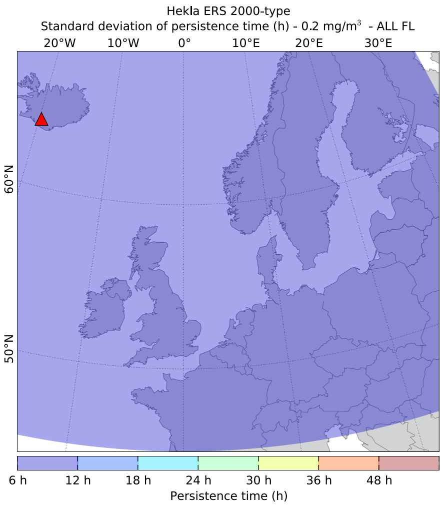


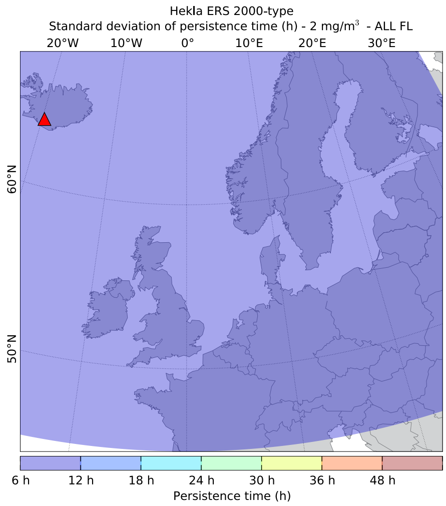


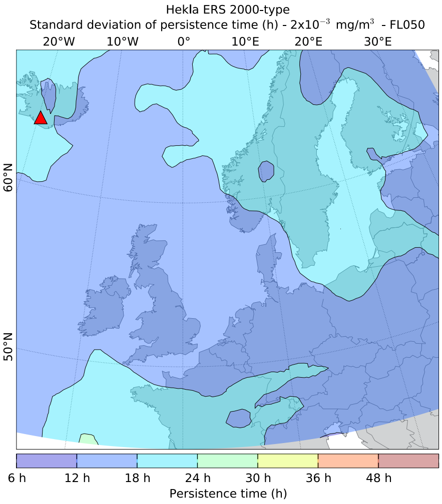


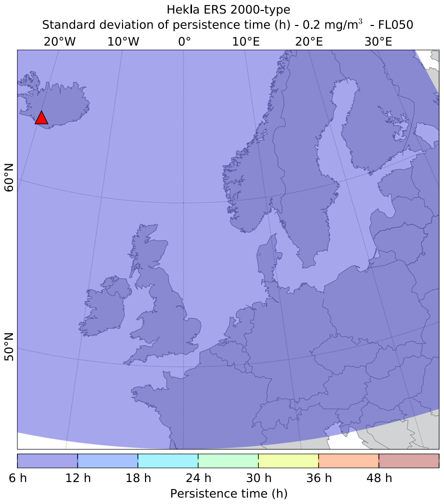
Hekla ERS 2000-type - Standard deviation of persistence time (h)

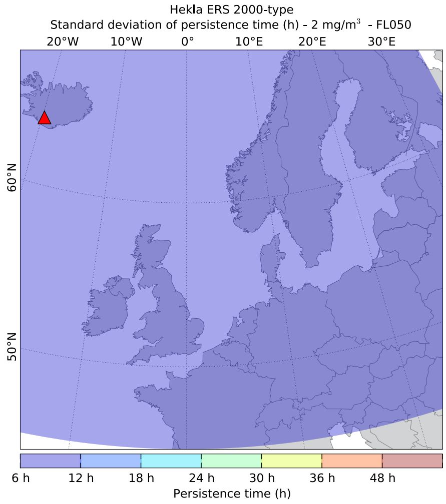


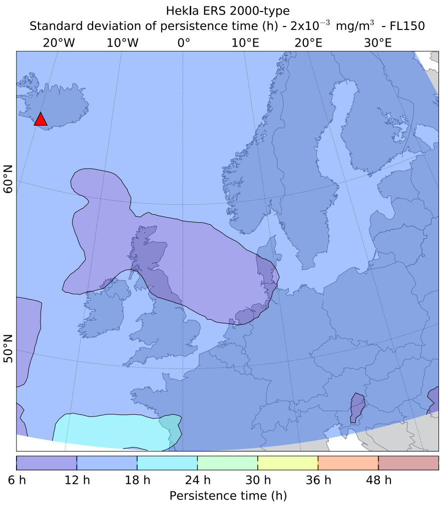


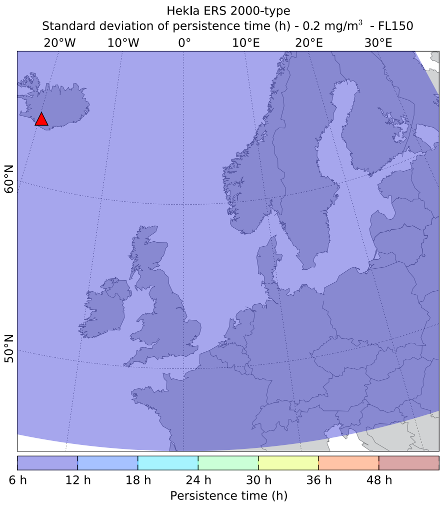


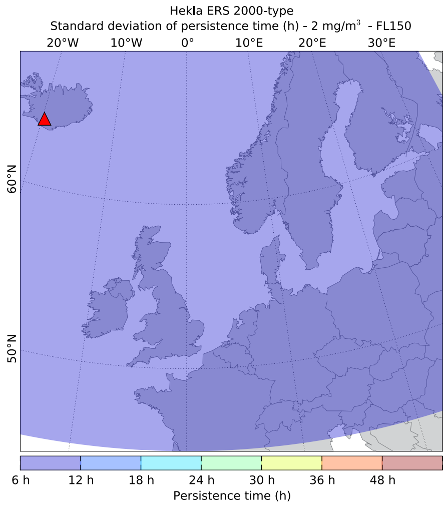


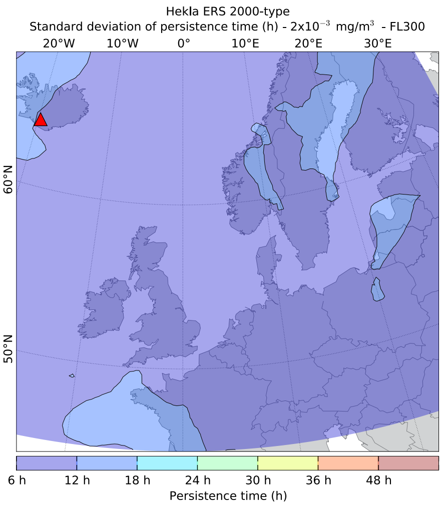


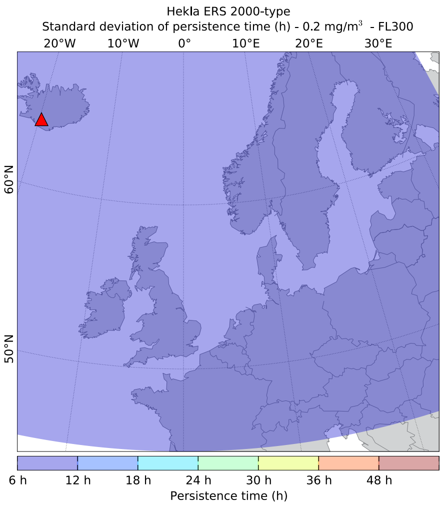


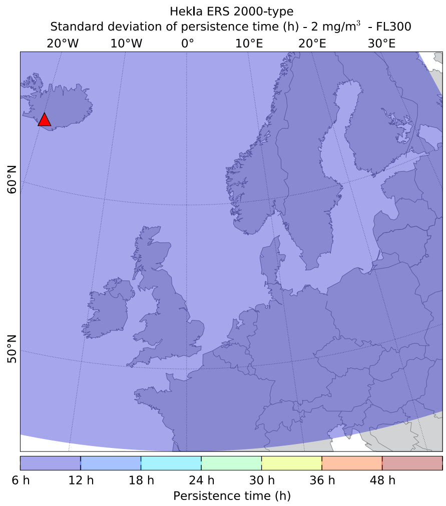




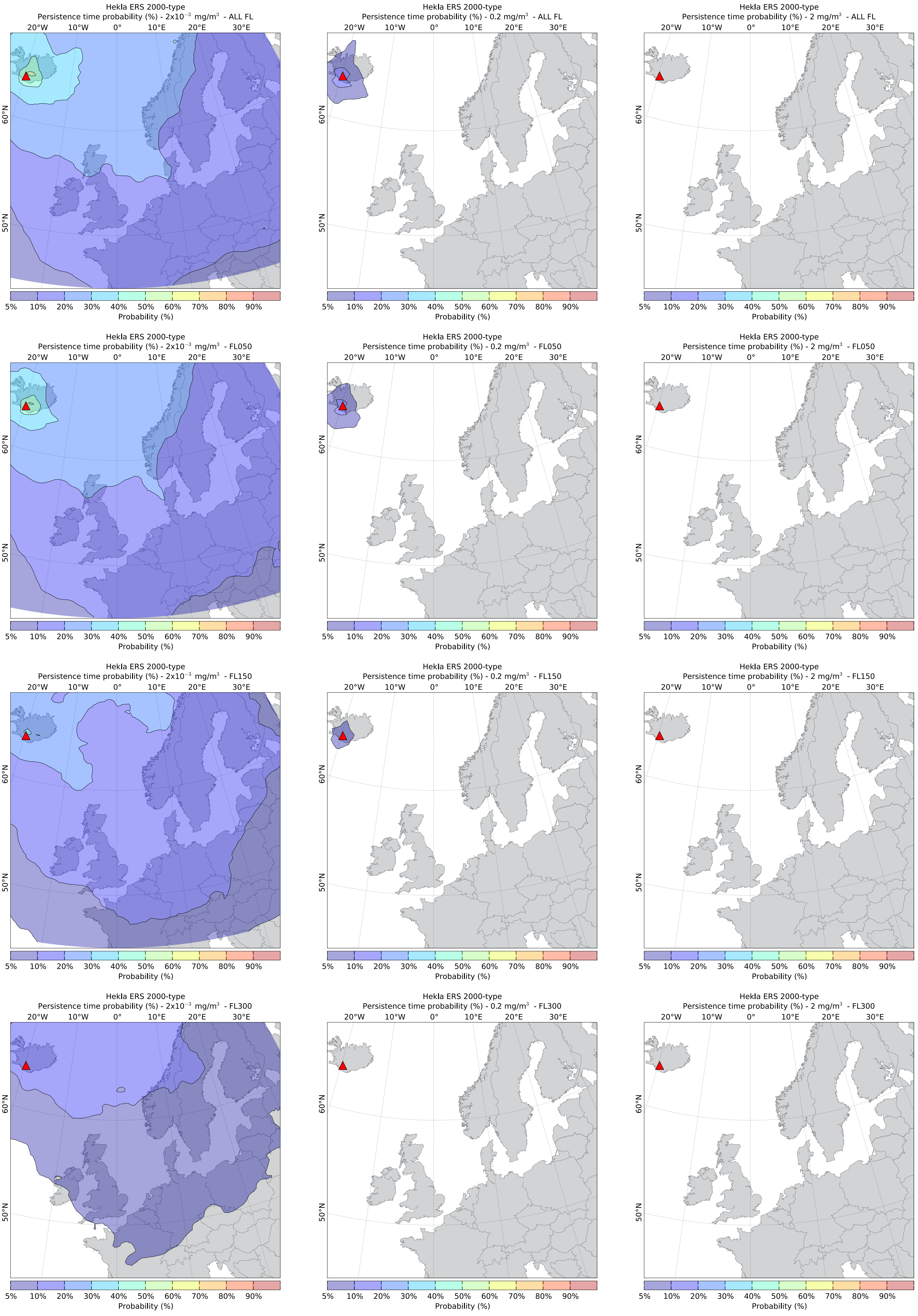




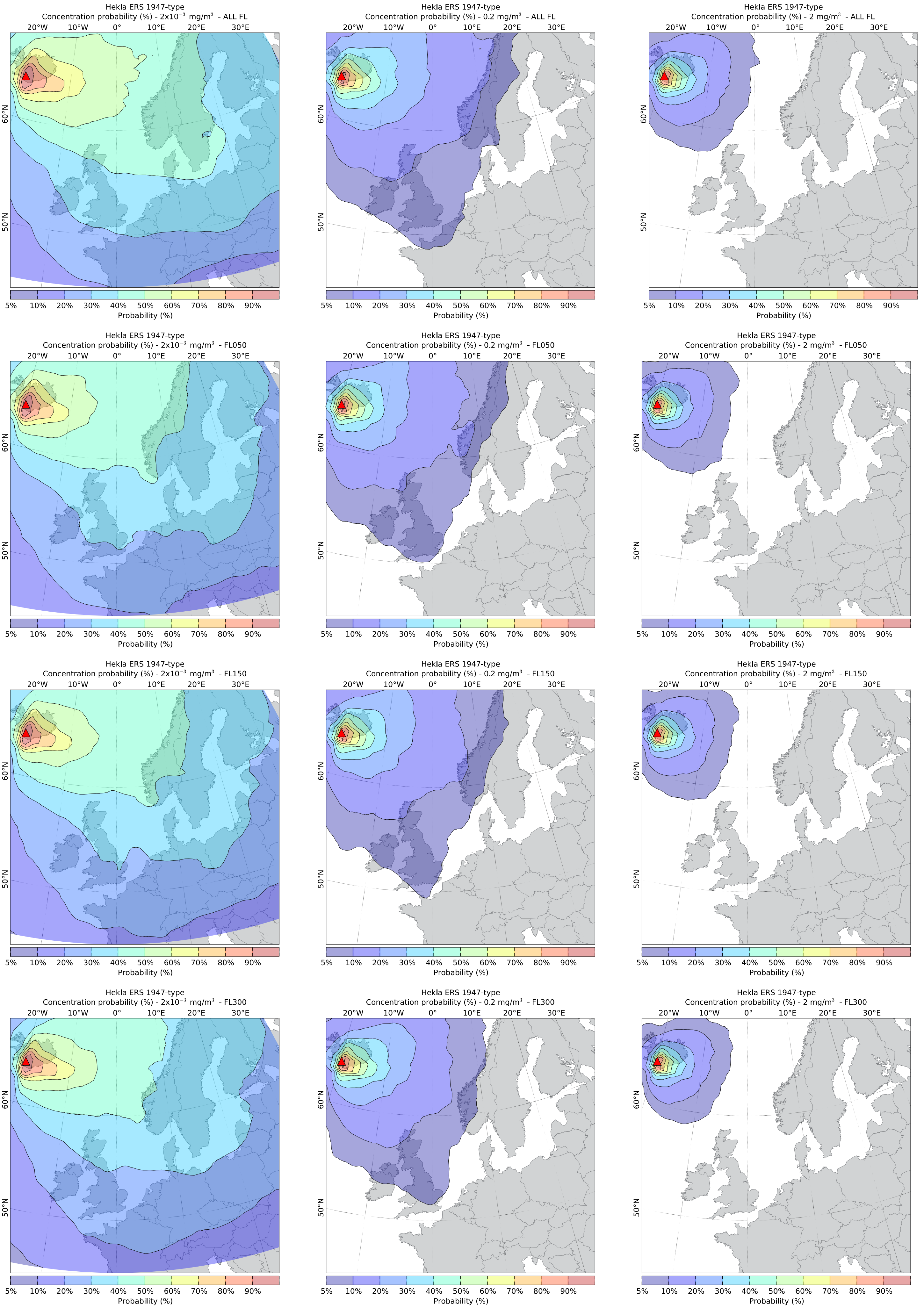




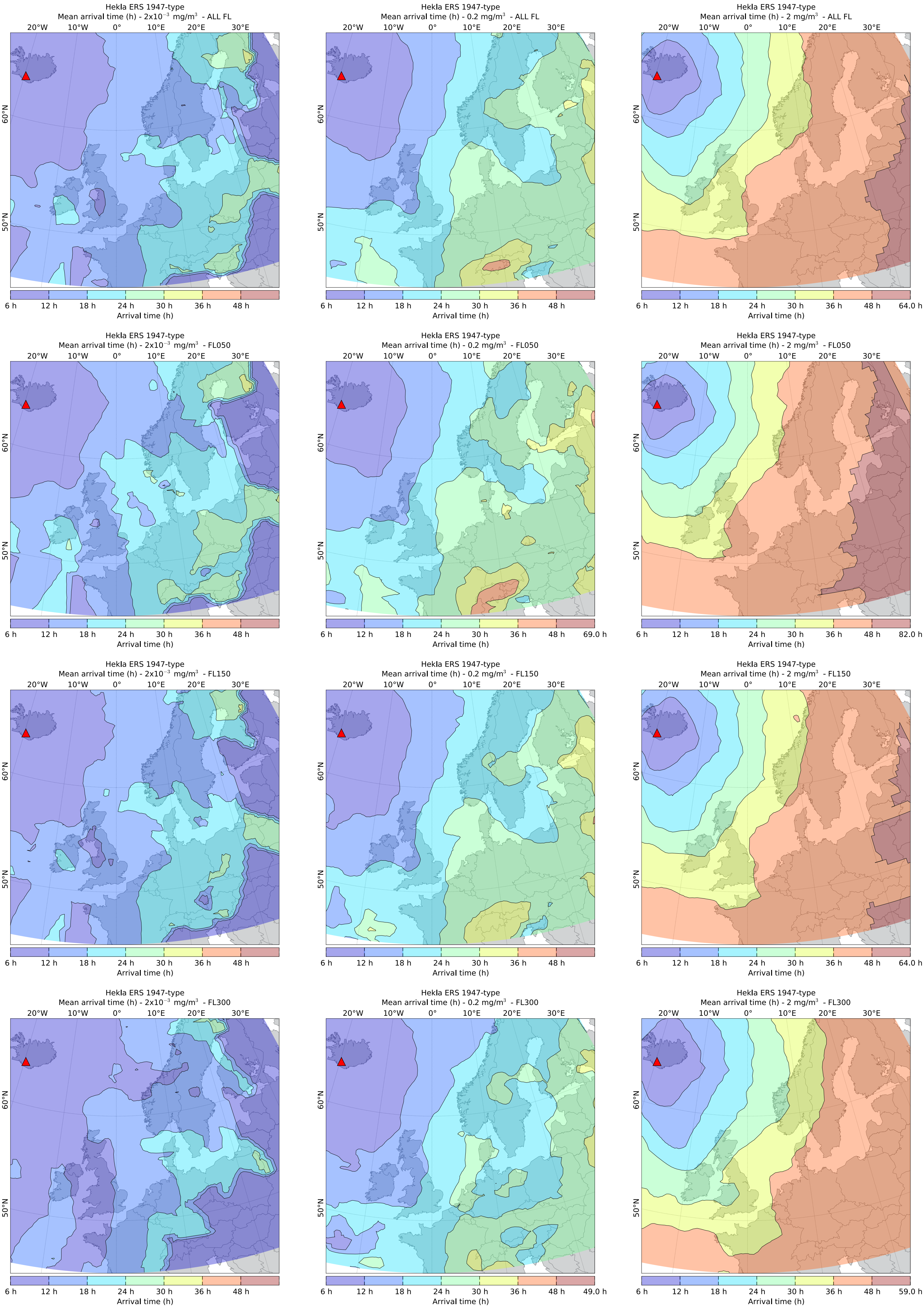
Hekla ERS 2000-type - Probability of persistence time > 12 h (%)



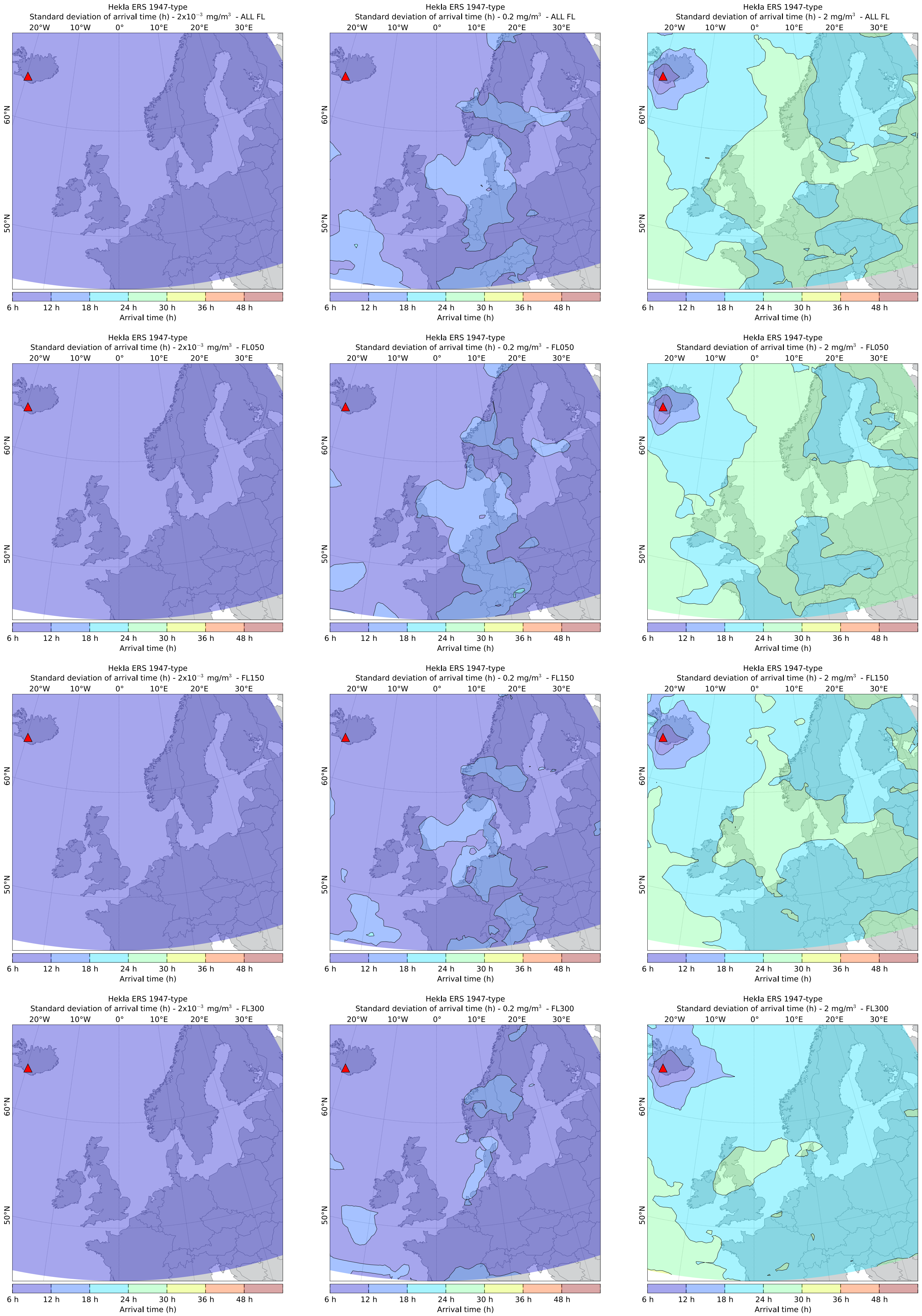
Hekla ERS 1947-type - Concentration probability (%)



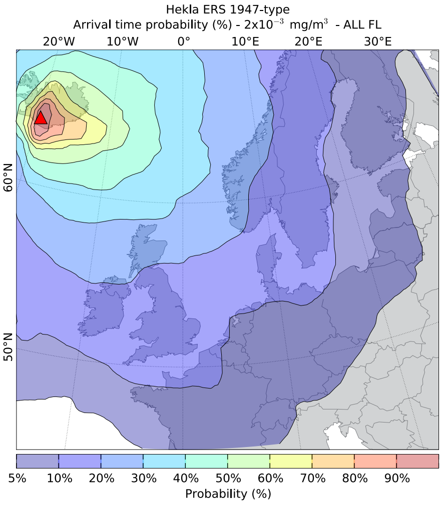
Hekla ERS 1947-type - Mean arrival time (h)

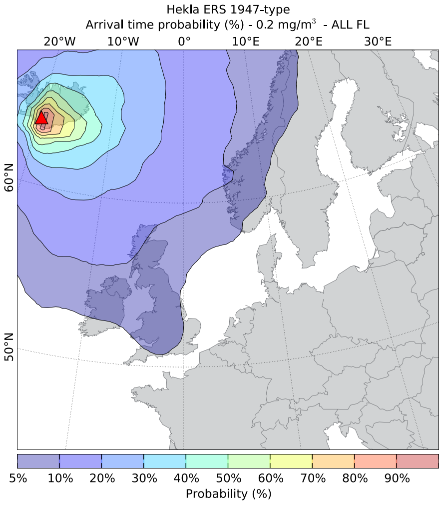


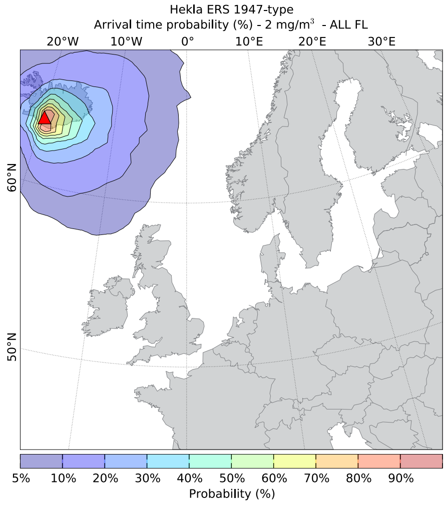
Hekla ERS 1947-type - Standard deviation of arrival time (h)

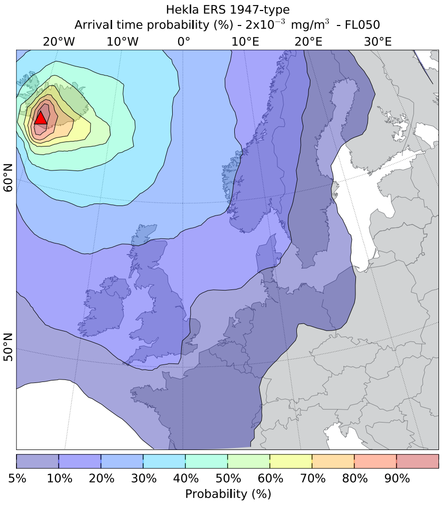


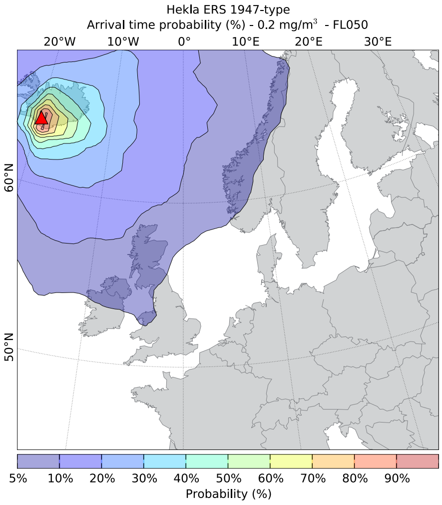
Hekla ERS 1947-type - Probability of arrival time > 24 h (%)

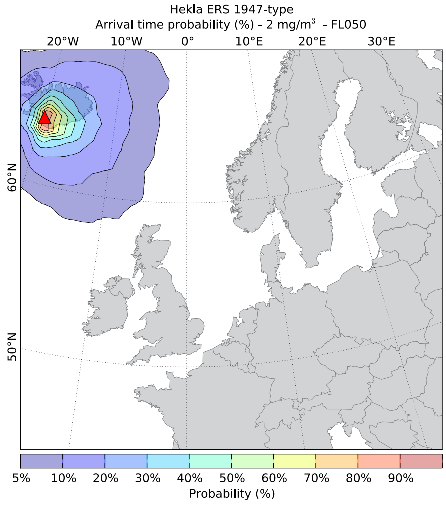


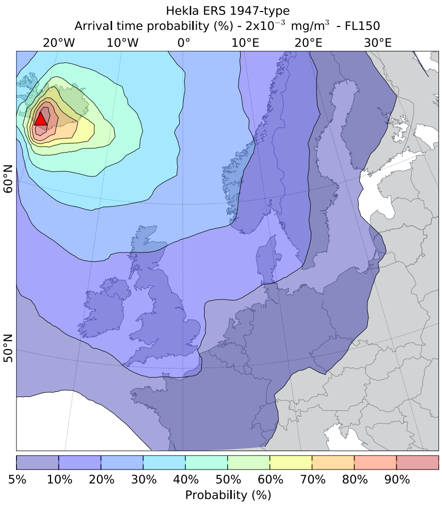


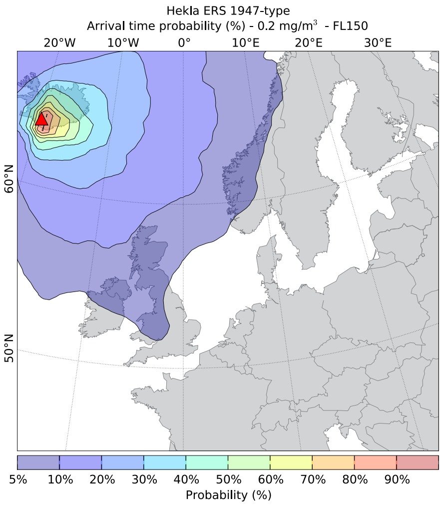


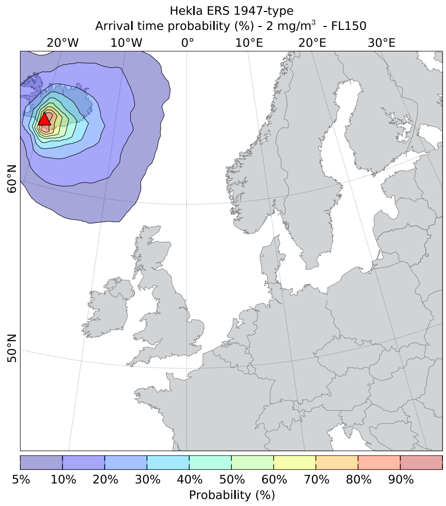


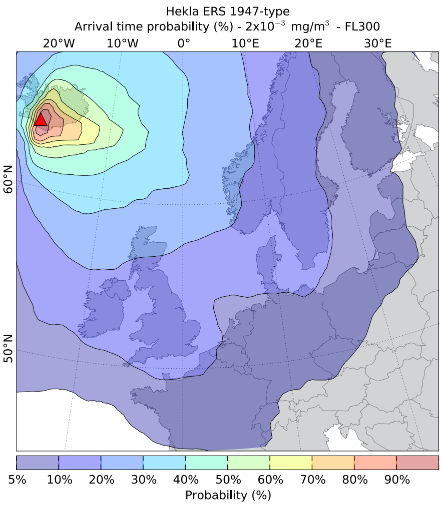


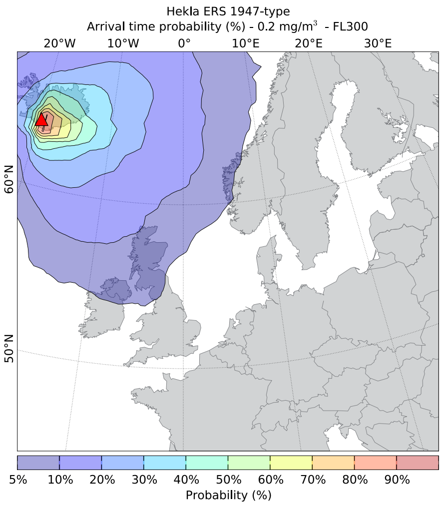


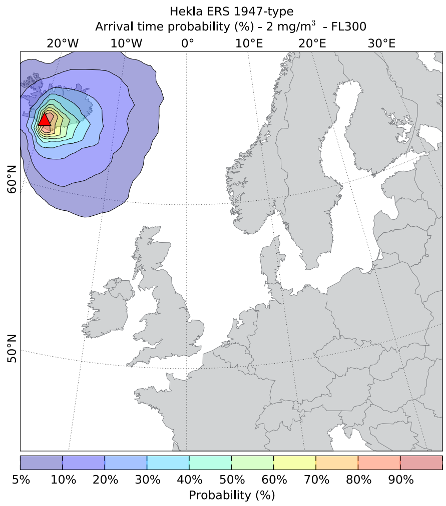




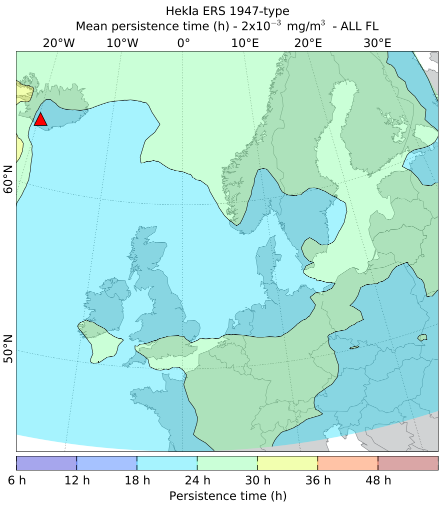


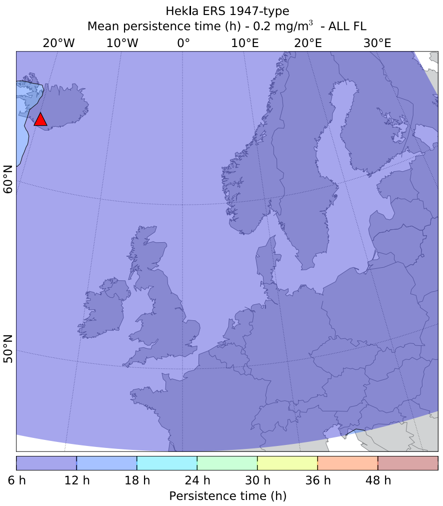


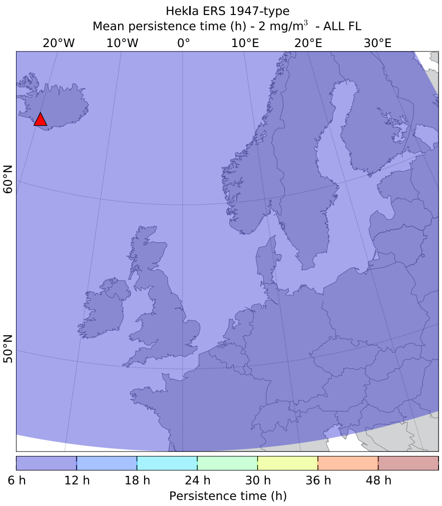


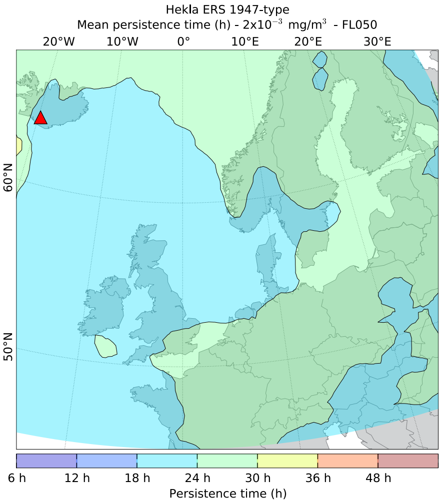


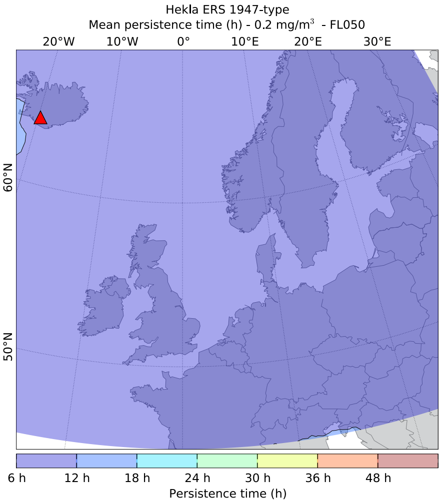
Hekla ERS 1947-type - Mean persistence time (h)

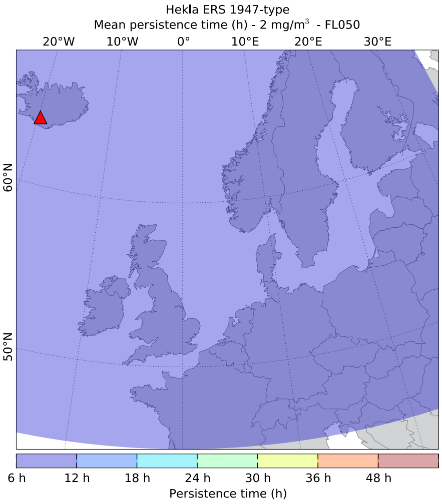


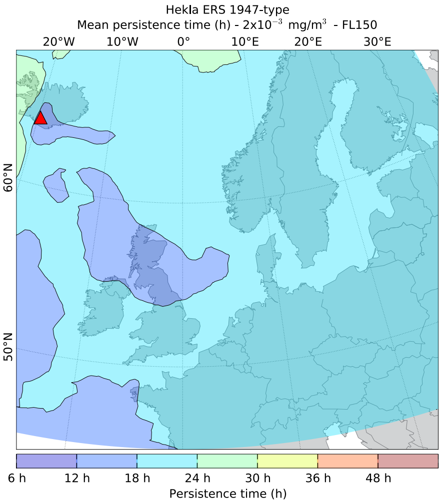


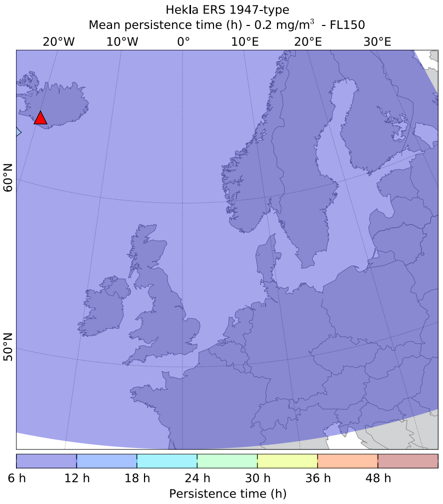


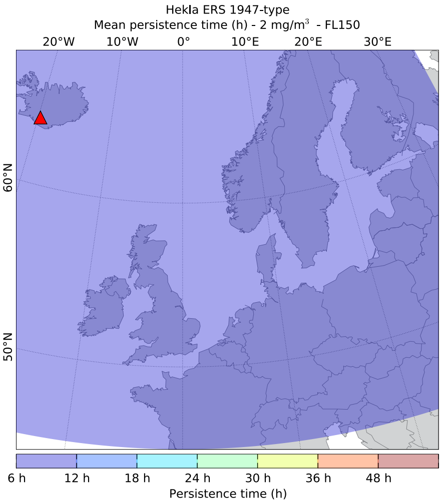


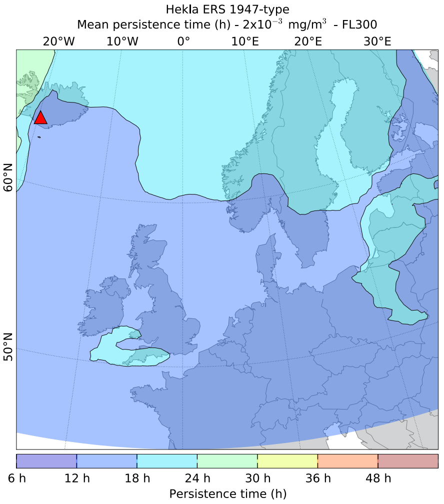


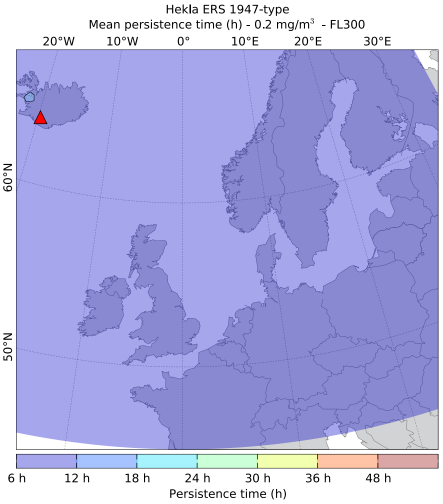


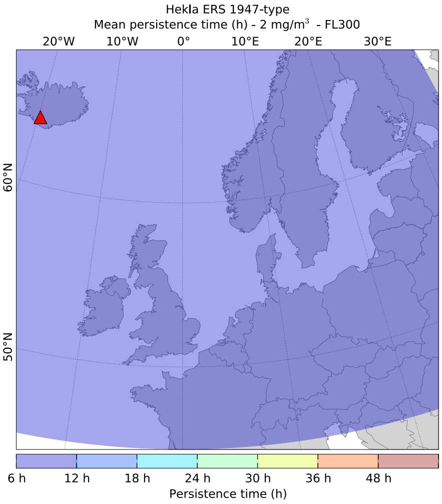




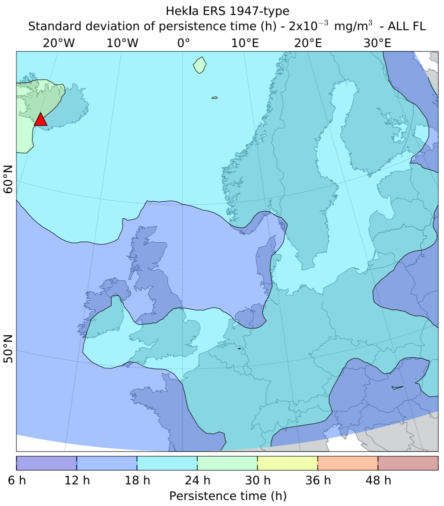


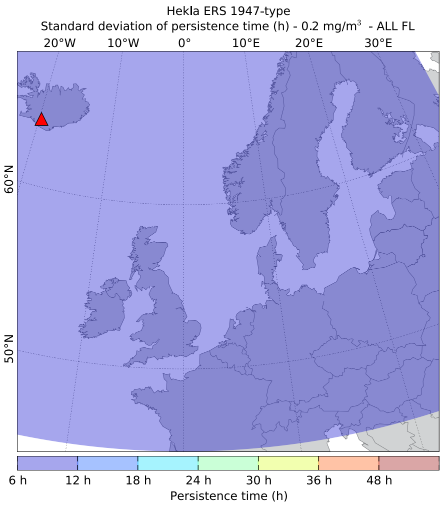


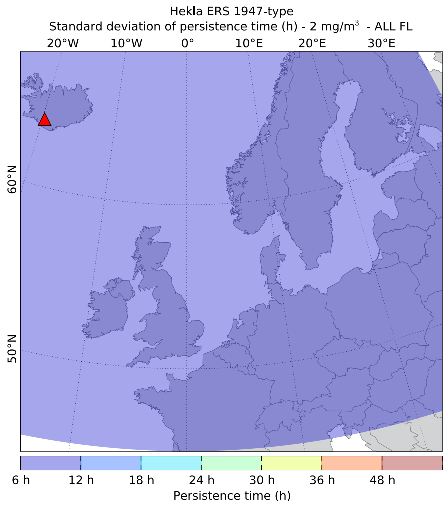


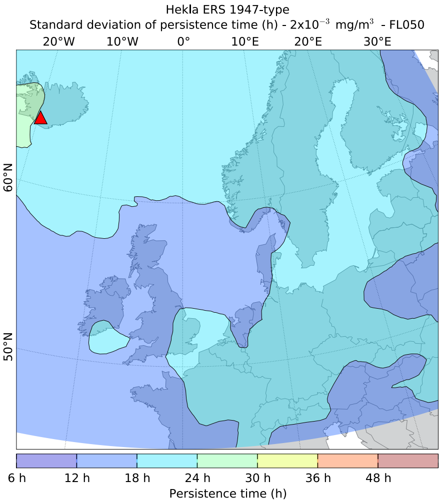


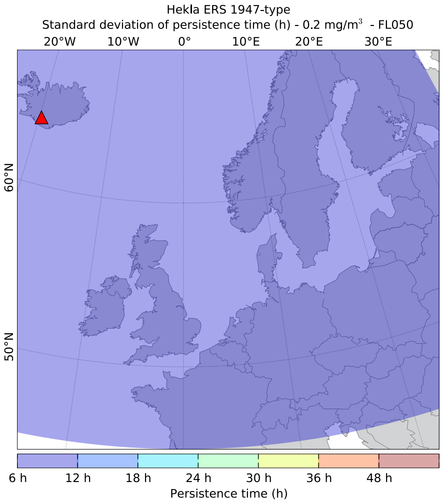
Hekla ERS 1947-type - Standard deviation of persistence time (h)

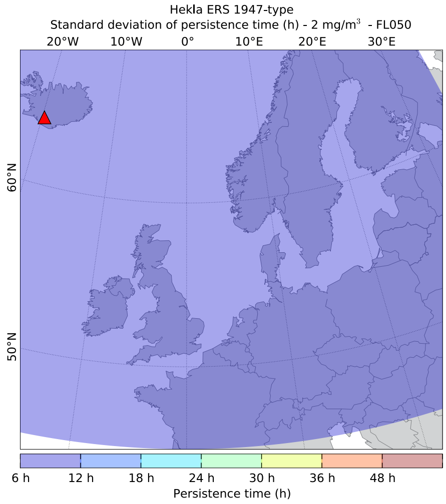


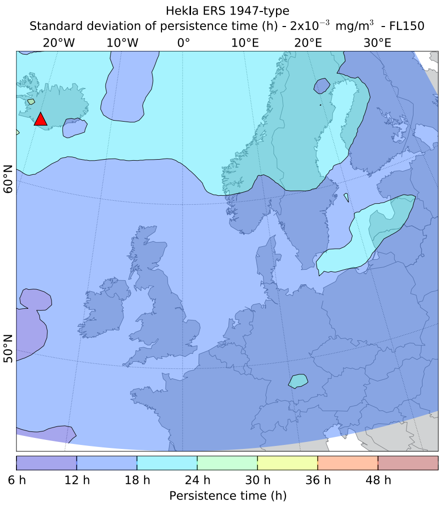


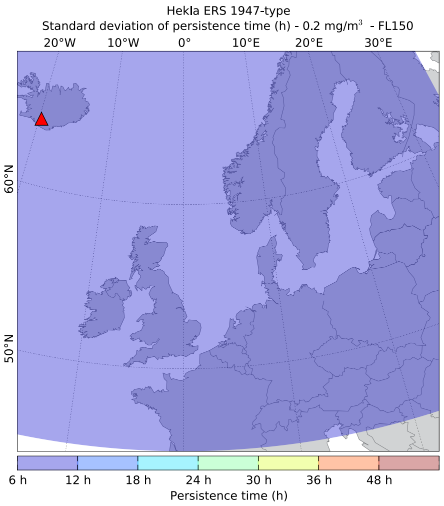


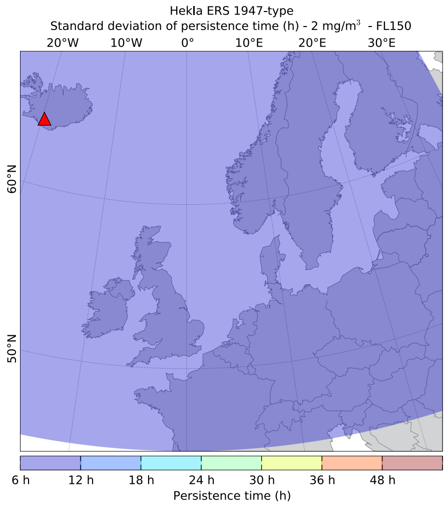


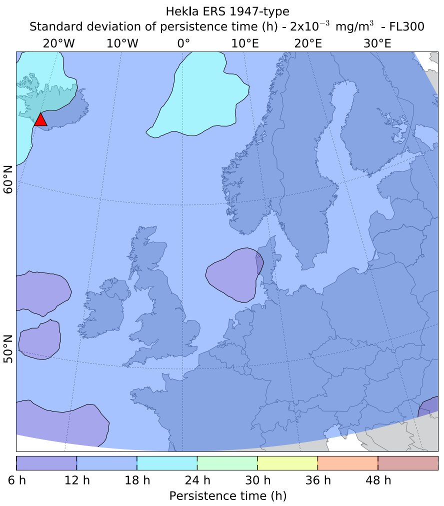


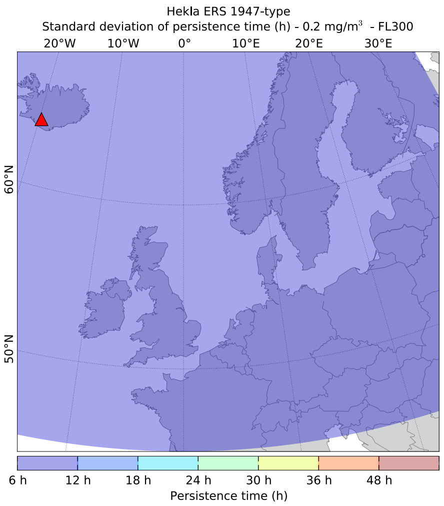


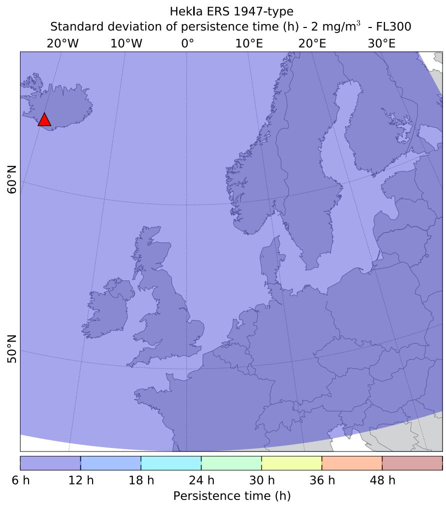




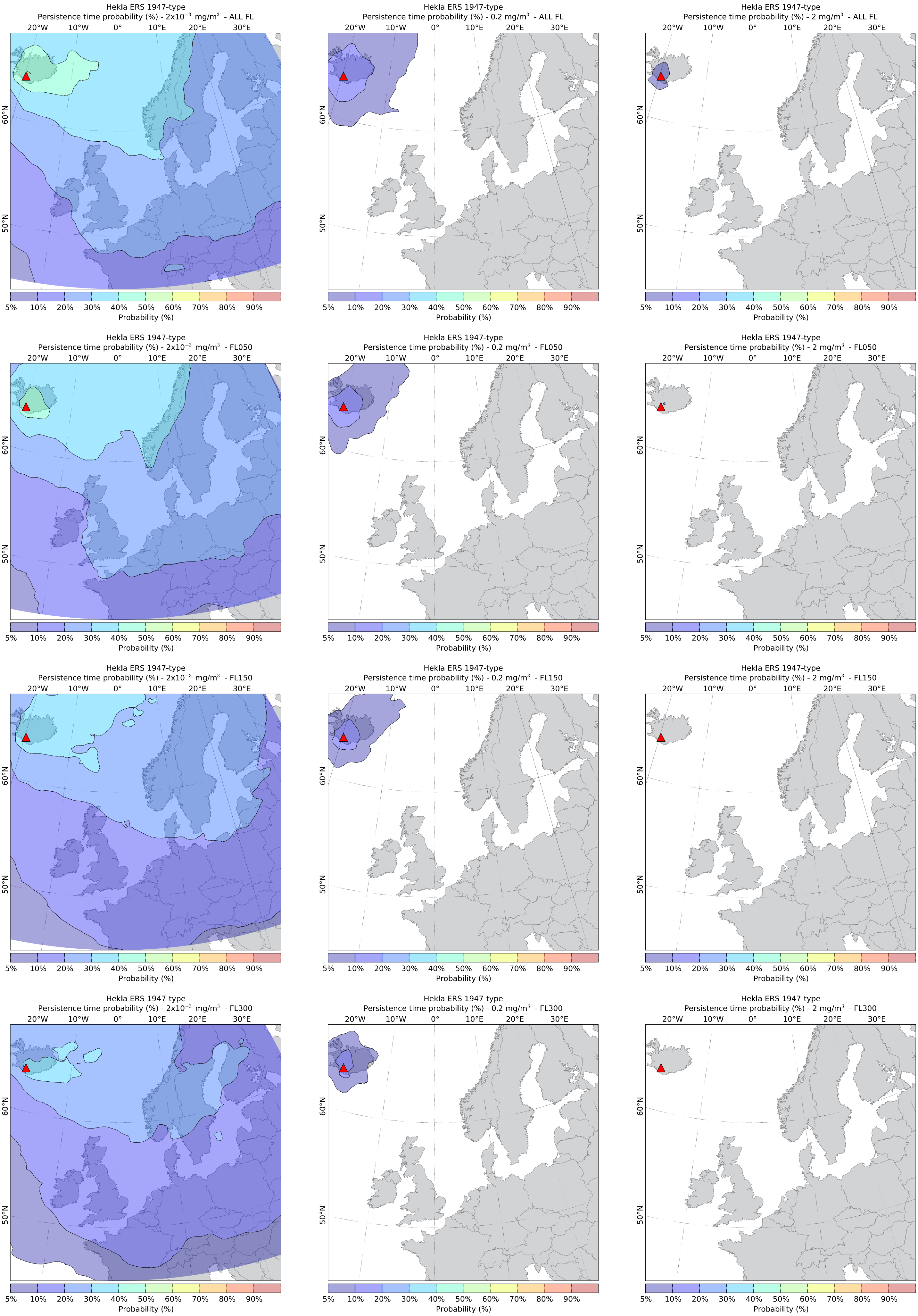




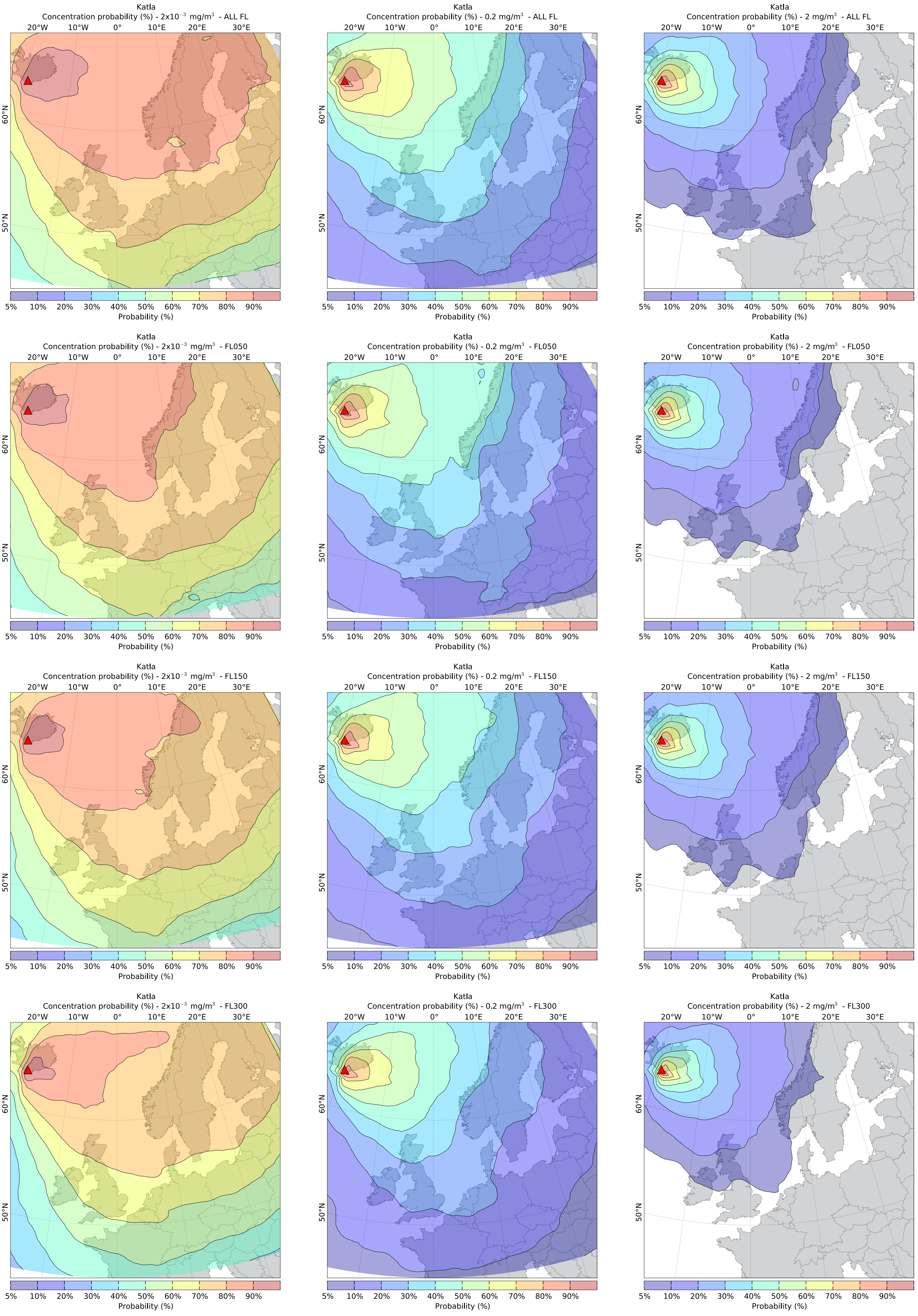




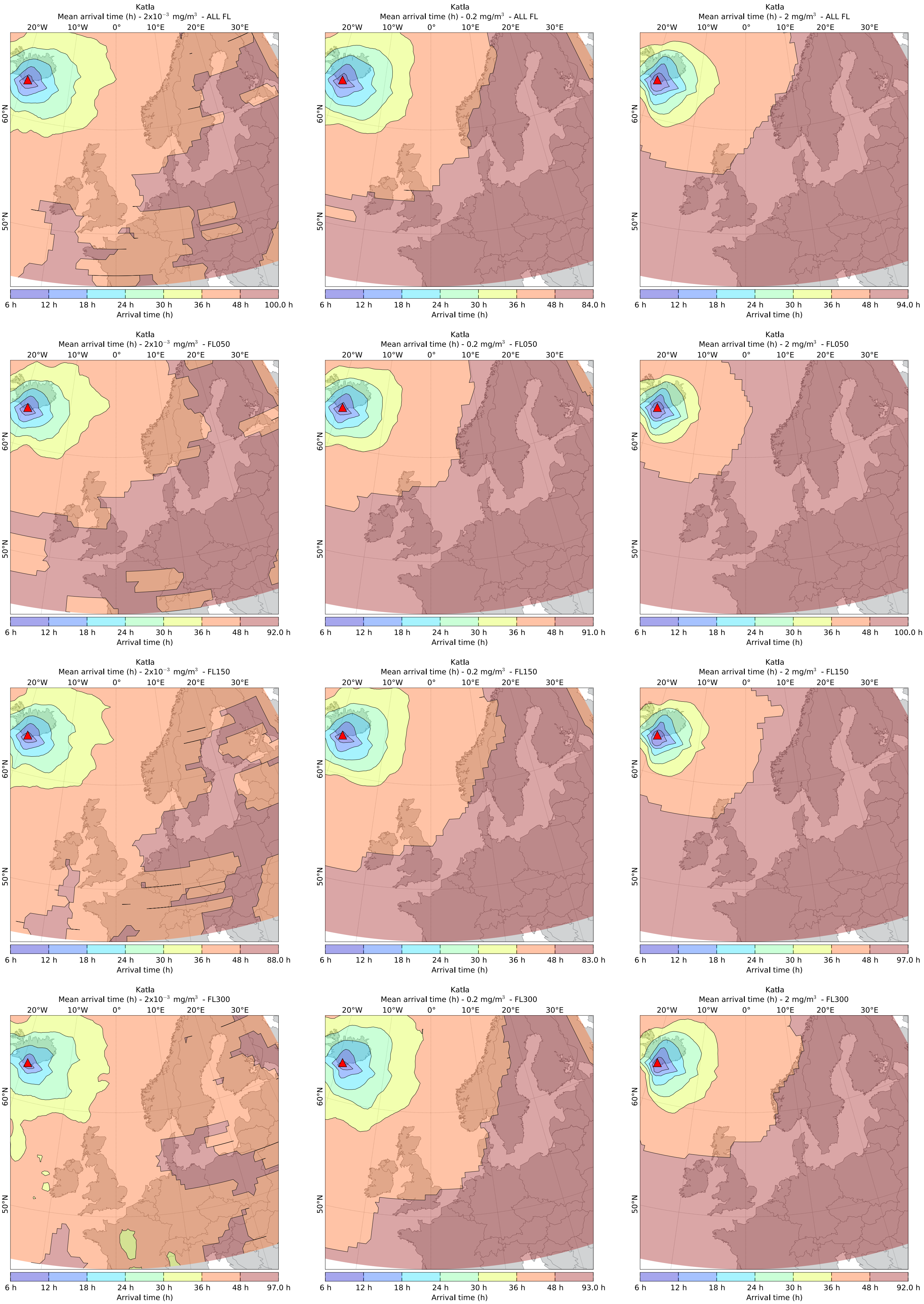
Hekla ERS 1947-type - Probability of persistence time > 12 h (%)



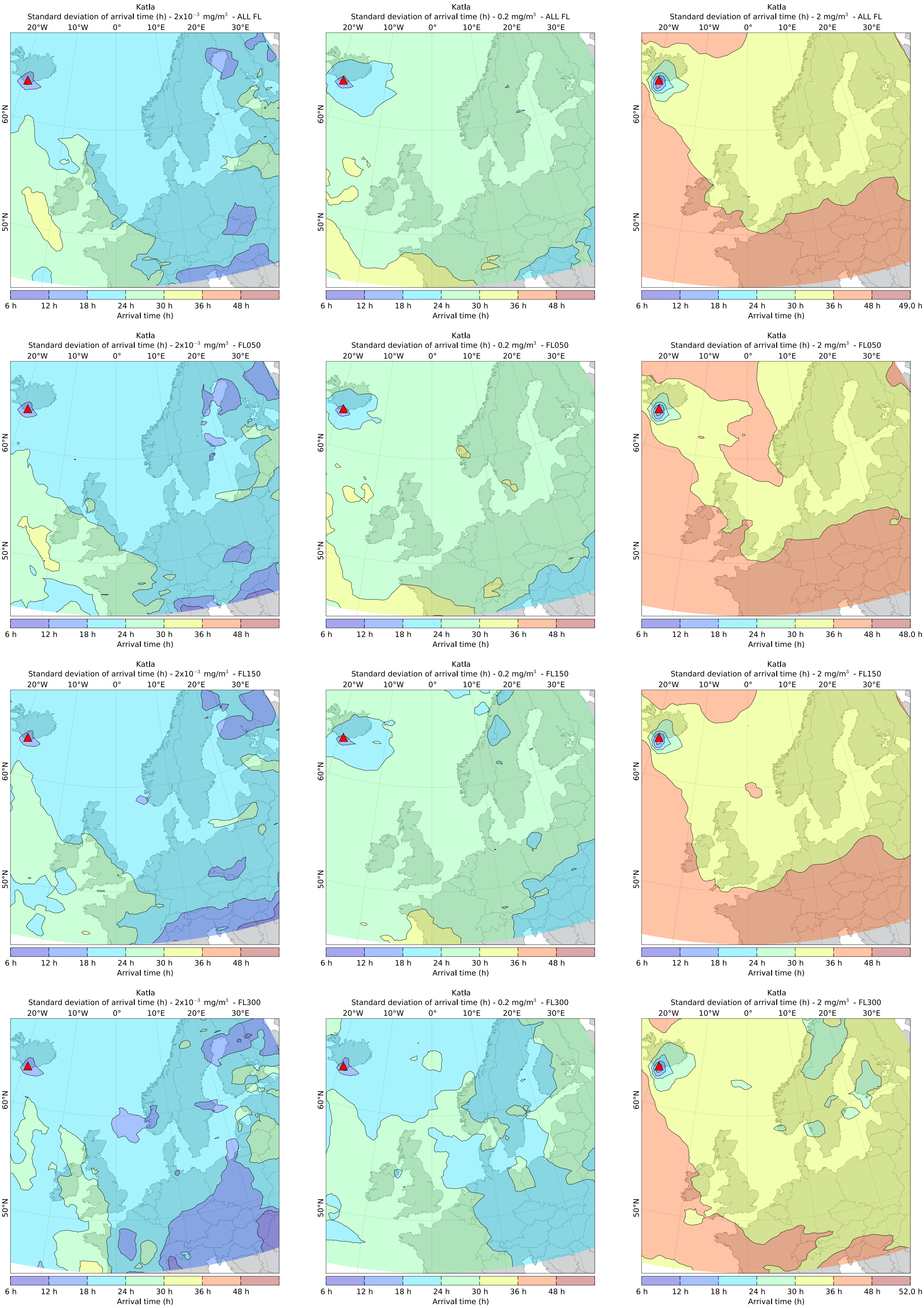
Katla LLERS - Concentration probability (%)



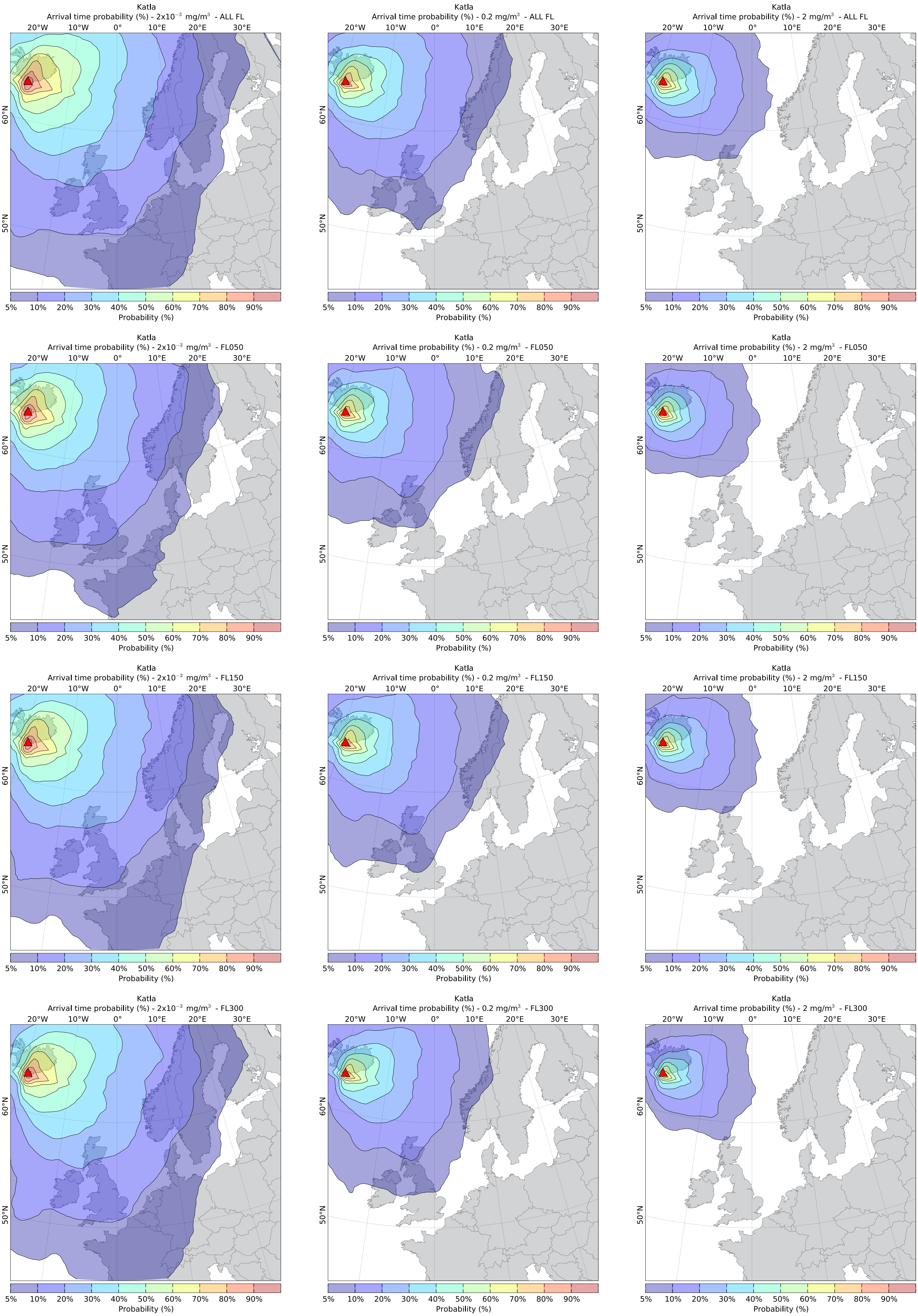
Katla LLERS - Mean arrival time (h)

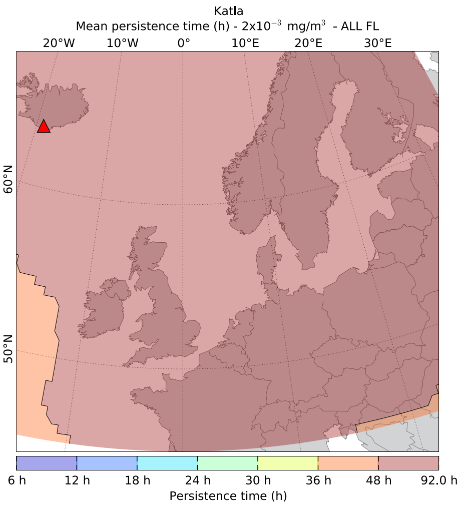


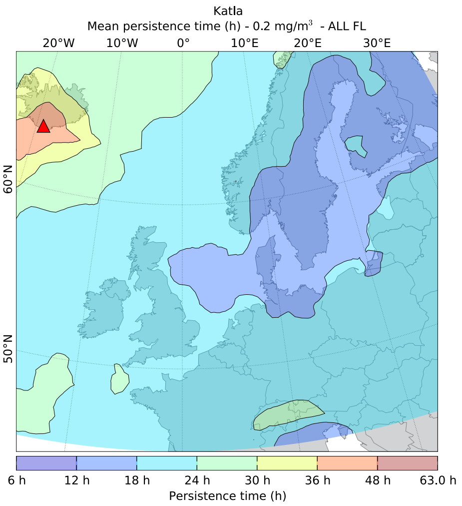
Katla LLERS - Standard deviation of arrival time (h)

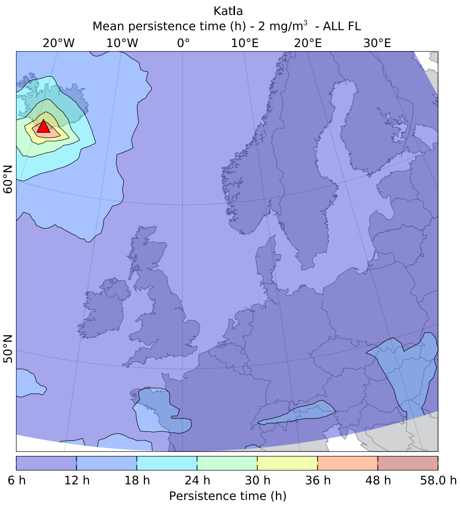


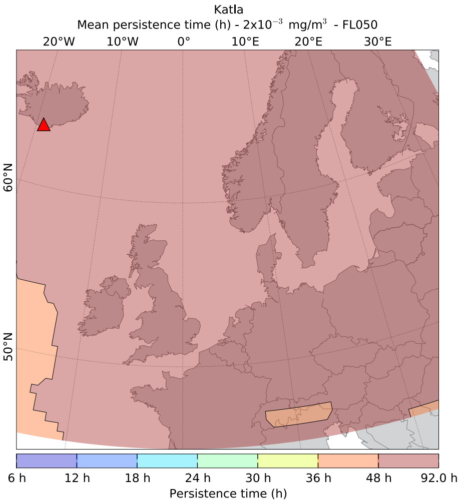
Katla LLERS - Probability of arrival time > 24 h (%)

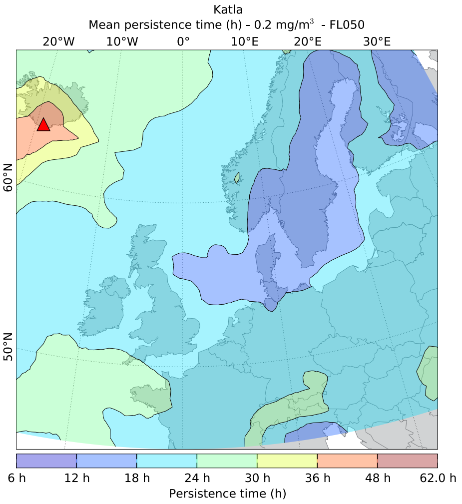


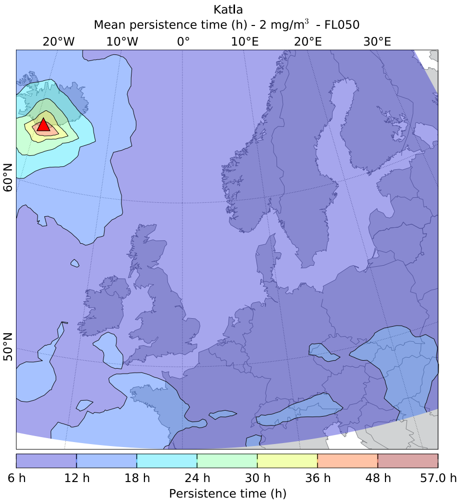

Katla
Mean persistence time (h) - 2x10^{-3} mg/m^3 - ALL FL
20°W 10°W 0° 10°E 20°E 30°E
60°N
50°N
6 h 12 h 18 h 24 h 30 h 36 h 48 h 92.0 h
Persistence time (h)

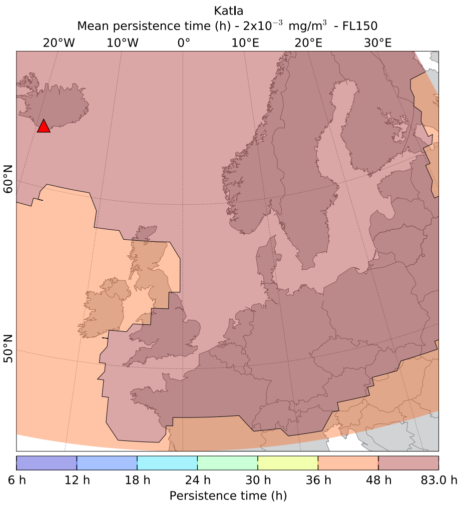

Katla
Mean persistence time (h) - 0.2 mg/m^3 - ALL FL
20°W 10°W 0° 10°E 20°E 30°E
60°N
50°N
6 h 12 h 18 h 24 h 30 h 36 h 48 h 63.0 h
Persistence time (h)

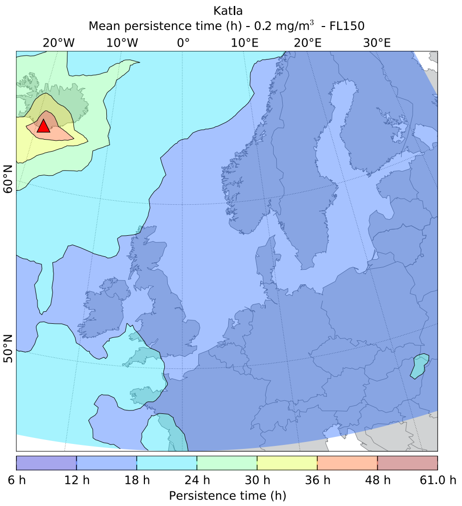

Katla
Mean persistence time (h) - 2 mg/m^3 - ALL FL
20°W 10°W 0° 10°E 20°E 30°E
60°N
50°N
6 h 12 h 18 h 24 h 30 h 36 h 48 h 58.0 h
Persistence time (h)

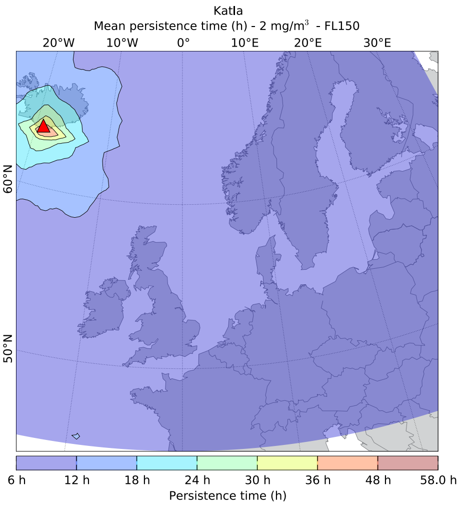

Katla
Mean persistence time (h) - 2x10^{-3} mg/m^3 - FL050
20°W 10°W 0° 10°E 20°E 30°E
60°N
50°N
6 h 12 h 18 h 24 h 30 h 36 h 48 h 92.0 h
Persistence time (h)

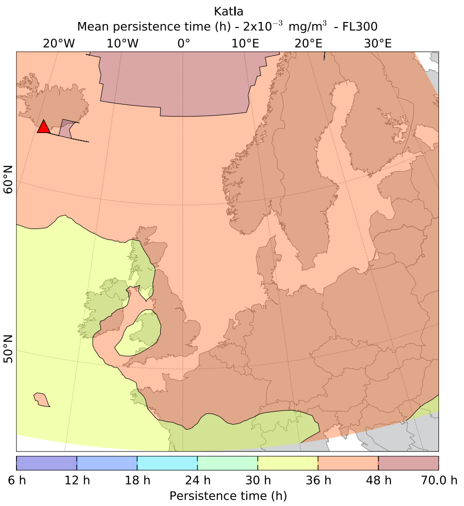

Katla
Mean persistence time (h) - 0.2 mg/m^3 - FL050
20°W 10°W 0° 10°E 20°E 30°E
60°N
50°N
6 h 12 h 18 h 24 h 30 h 36 h 48 h 62.0 h
Persistence time (h)

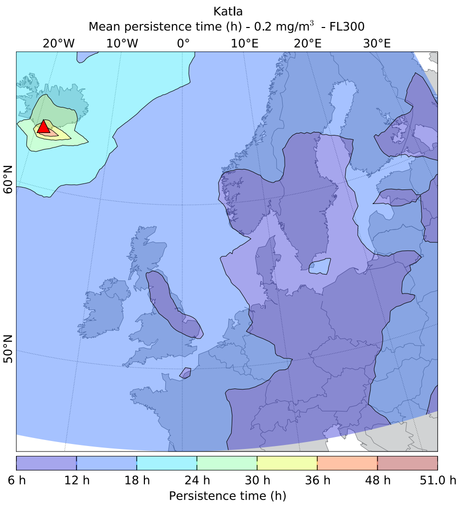

Katla
Mean persistence time (h) - 2 mg/m^3 - FL050
20°W 10°W 0° 10°E 20°E 30°E
60°N
50°N
6 h 12 h 18 h 24 h 30 h 36 h 48 h 57.0 h
Persistence time (h)

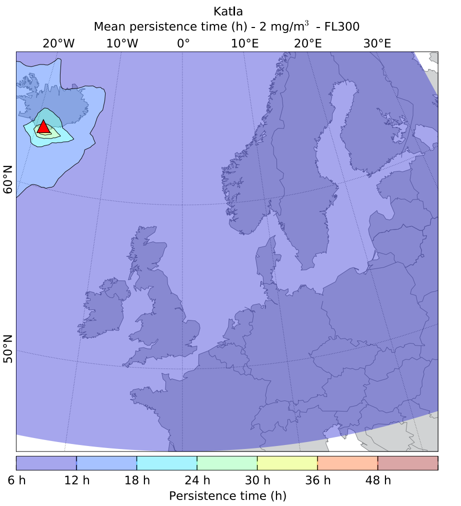

Katla
Mean persistence time (h) - 2x10^{-3} mg/m^3 - FL150
20°W 10°W 0° 10°E 20°E 30°E
60°N
50°N
6 h 12 h 18 h 24 h 30 h 36 h 48 h 83.0 h
Persistence time (h)


Katla
Mean persistence time (h) - 0.2 mg/m^3 - FL150
20°W 10°W 0° 10°E 20°E 30°E
60°N
50°N
6 h 12 h 18 h 24 h 30 h 36 h 48 h 61.0 h
Persistence time (h)

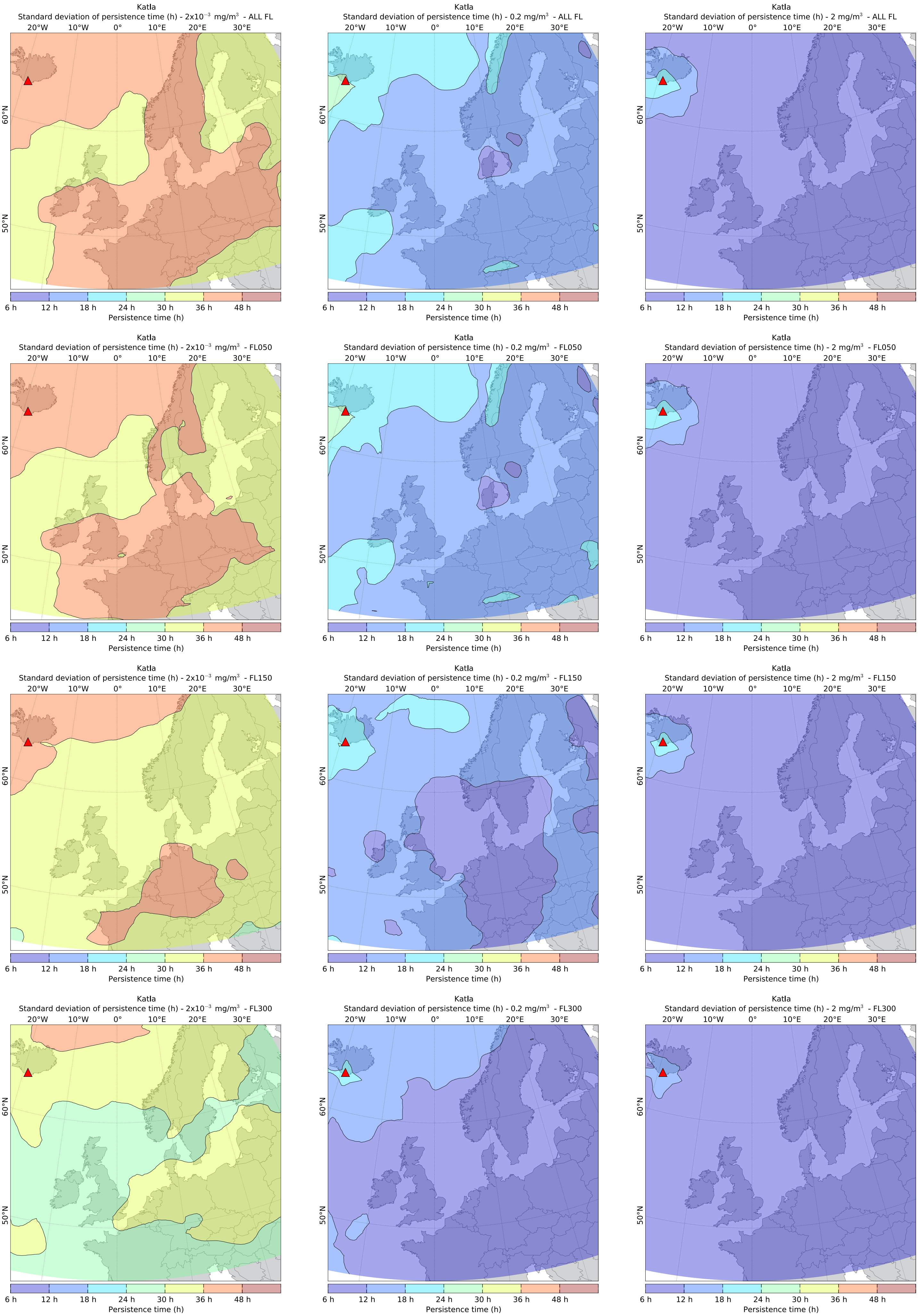

Katla
Mean persistence time (h) - 2 mg/m^3 - FL150
20°W 10°W 0° 10°E 20°E 30°E
60°N
50°N
6 h 12 h 18 h 24 h 30 h 36 h 48 h 58.0 h
Persistence time (h)


Katla
Mean persistence time (h) - 2x10^{-3} mg/m^3 - FL300
20°W 10°W 0° 10°E 20°E 30°E
60°N
50°N
6 h 12 h 18 h 24 h 30 h 36 h 48 h 70.0 h
Persistence time (h)

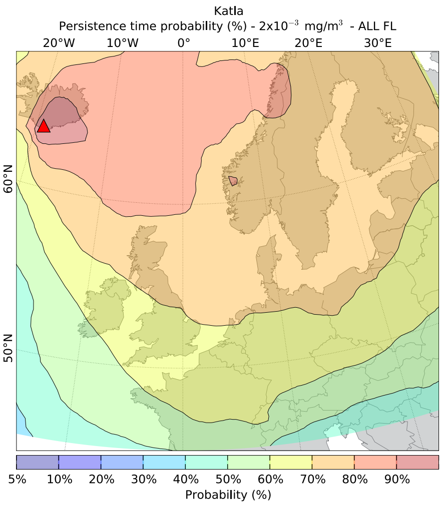

Katla
Mean persistence time (h) - 0.2 mg/m^3 - FL300
20°W 10°W 0° 10°E 20°E 30°E
60°N
50°N
6 h 12 h 18 h 24 h 30 h 36 h 48 h 51.0 h
Persistence time (h)

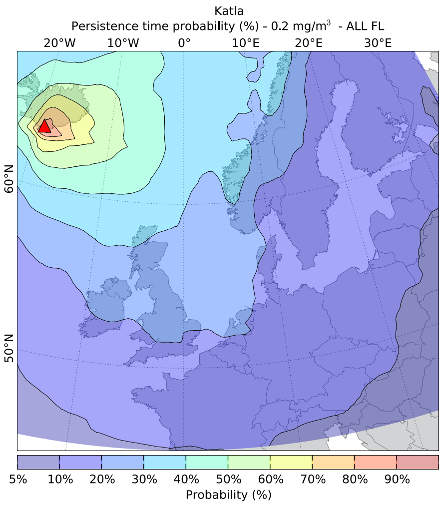

Katla
Mean persistence time (h) - 2 mg/m^3 - FL300
20°W 10°W 0° 10°E 20°E 30°E
60°N
50°N
6 h 12 h 18 h 24 h 30 h 36 h 48 h
Persistence time (h)

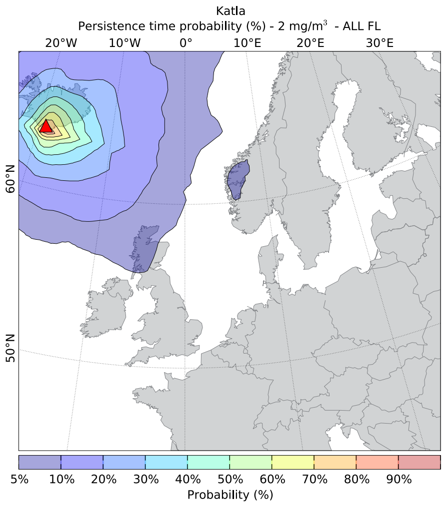
Katla LLERS - Standard deviation of persistence time (h)

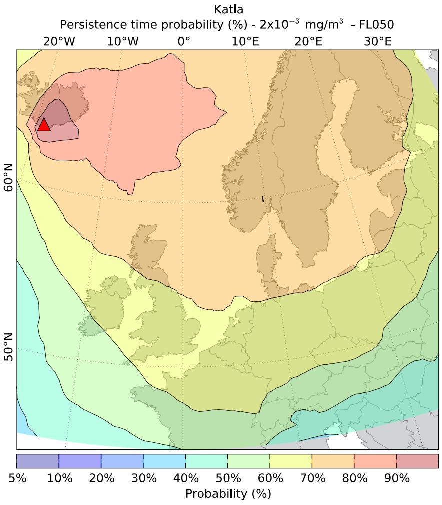


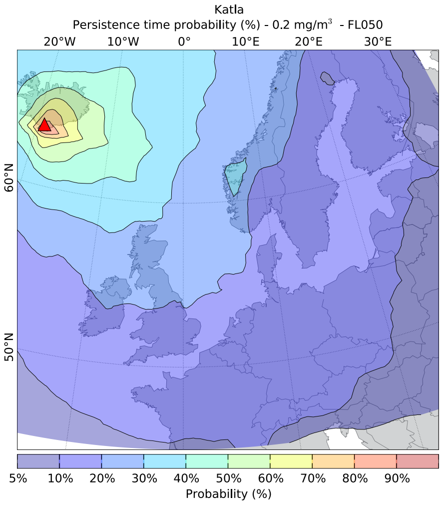
Katla LLERS - Probability of persistence time > 12 h (%)

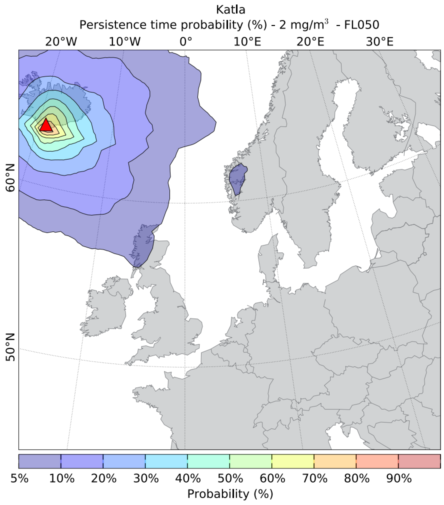


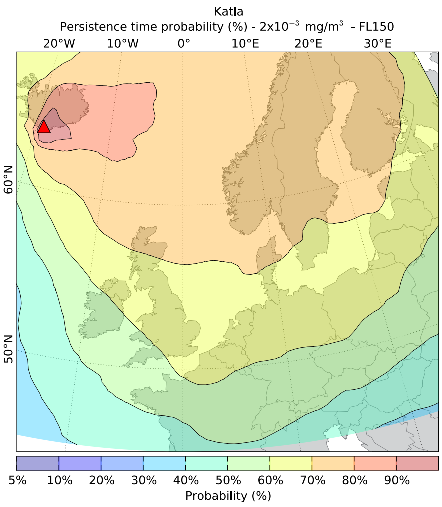


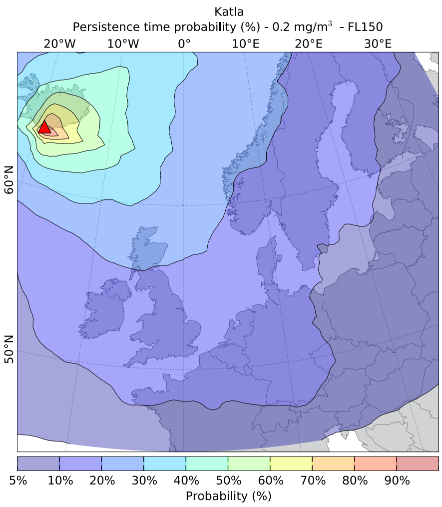


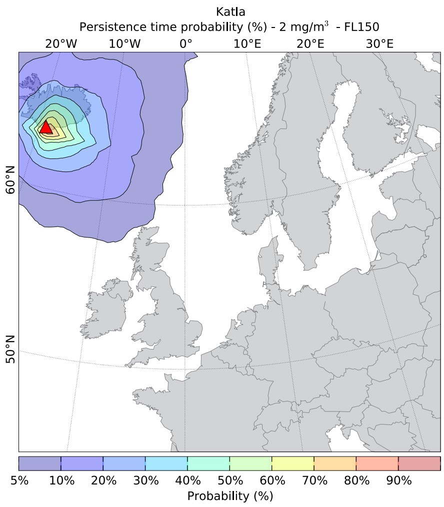


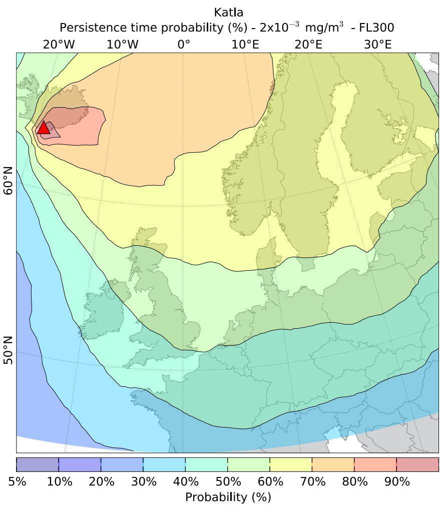


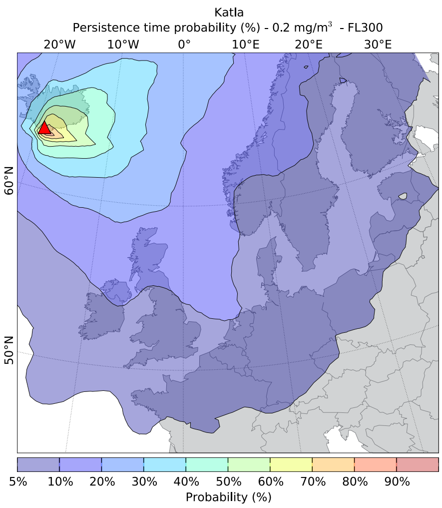


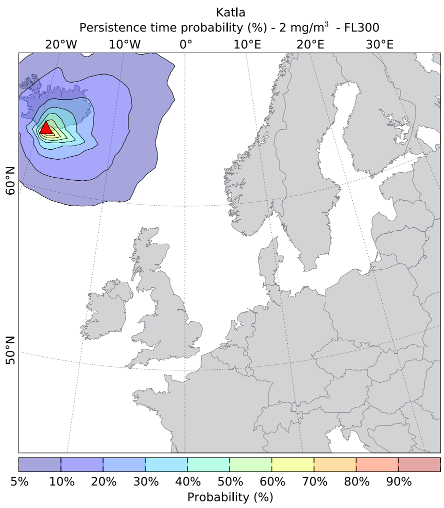




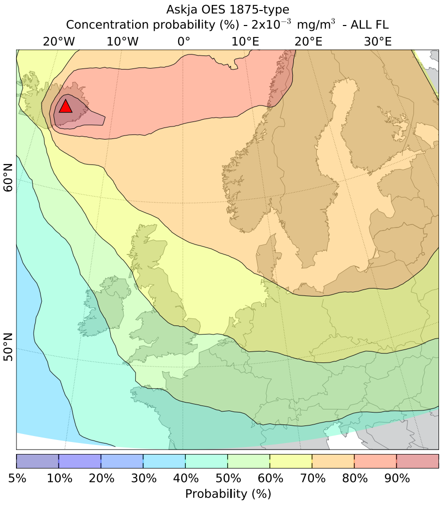


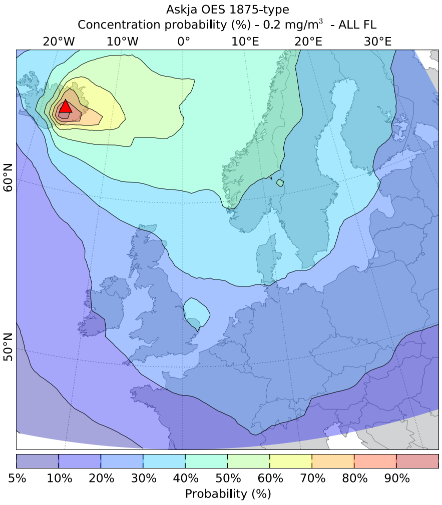


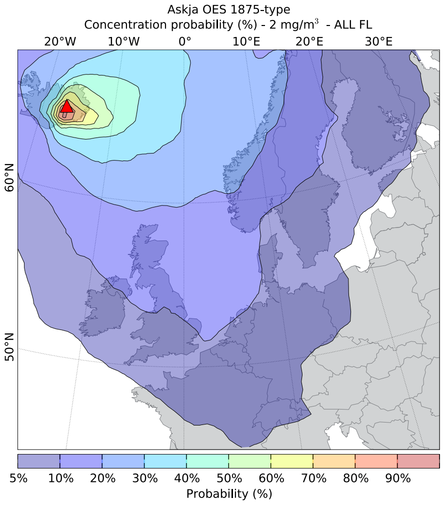


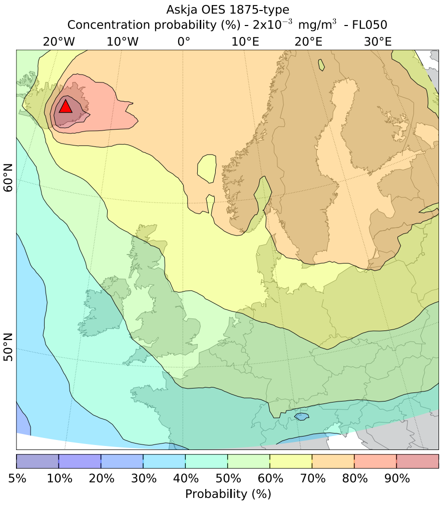


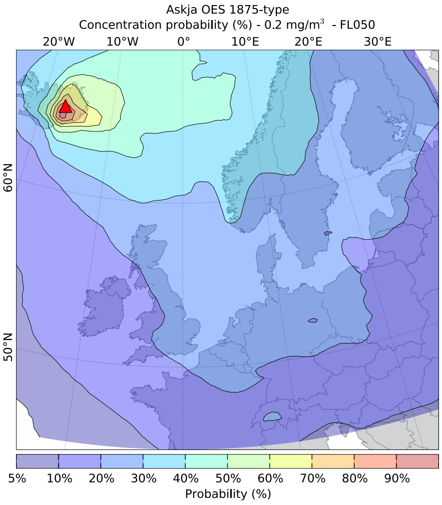
Askja OES 1875-type - Concentration probability (%)

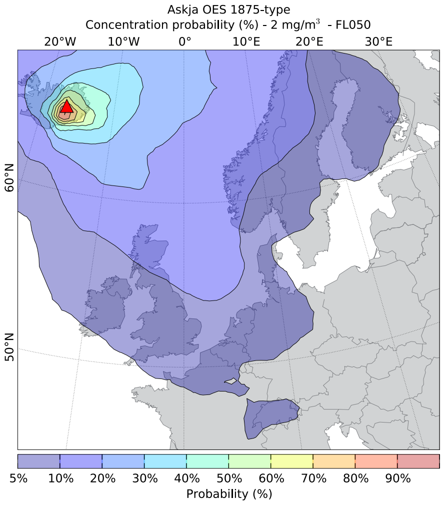


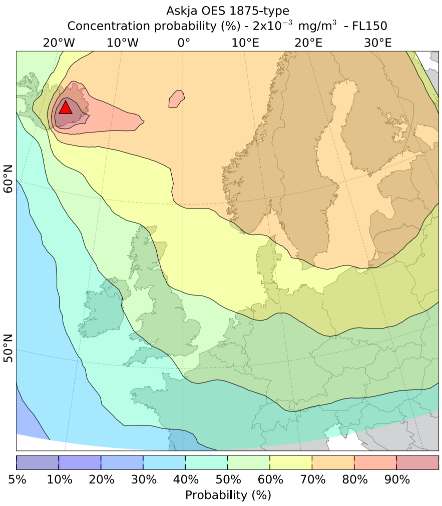


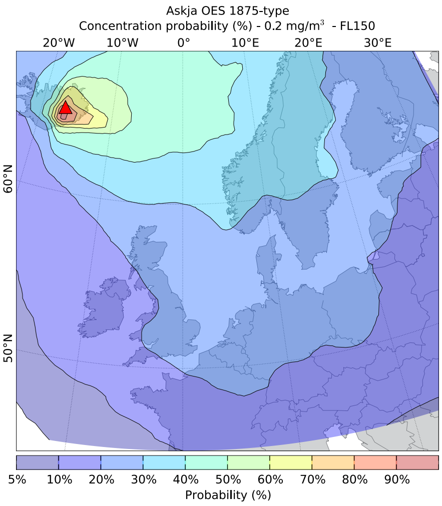


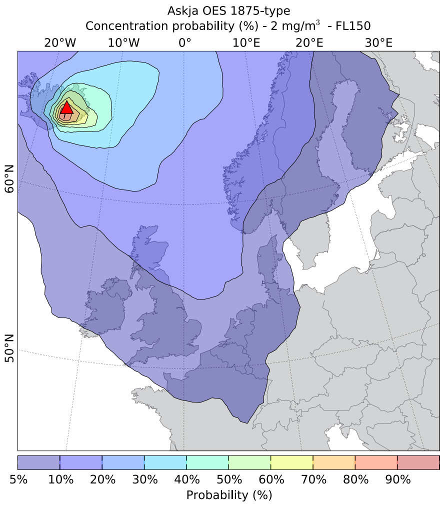


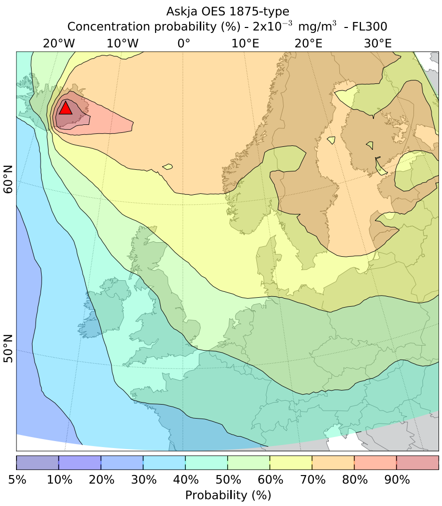


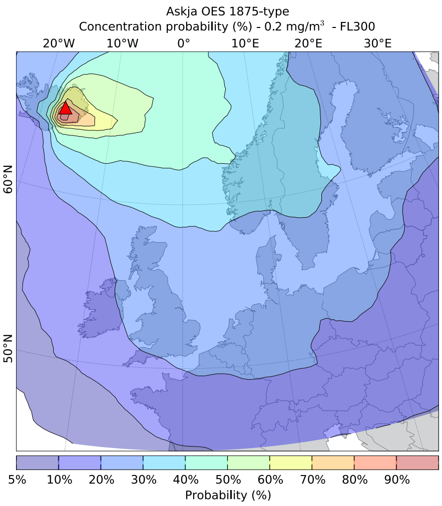


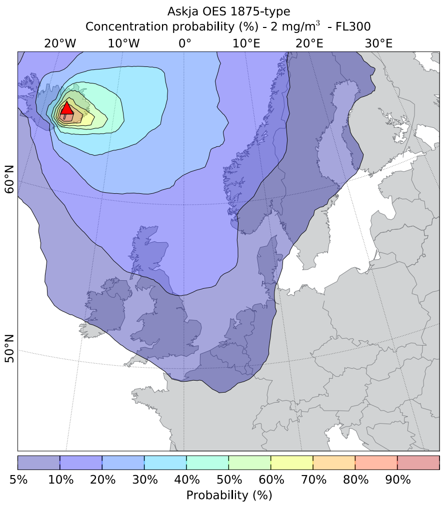




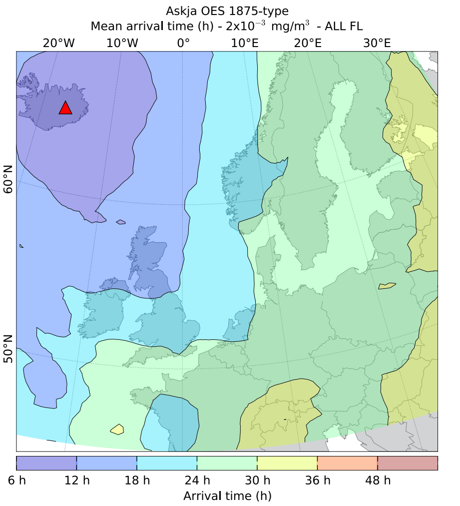


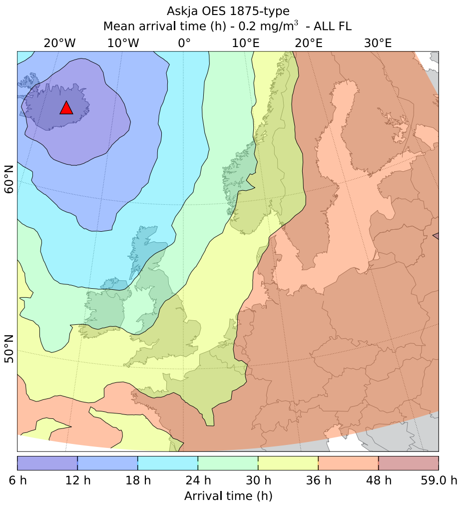


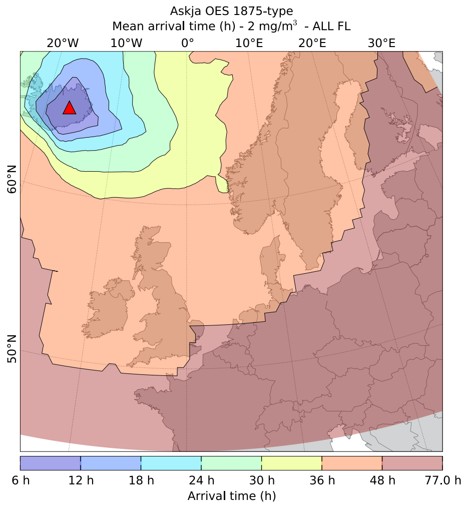


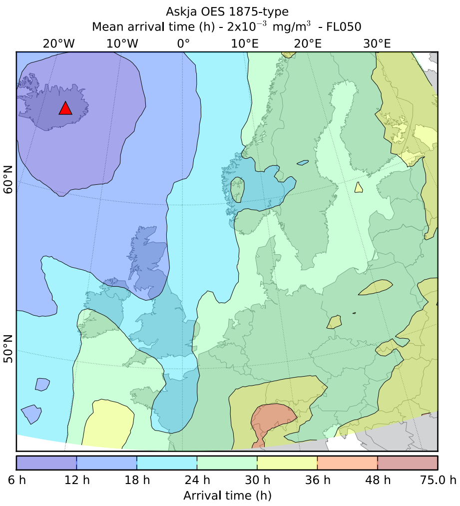


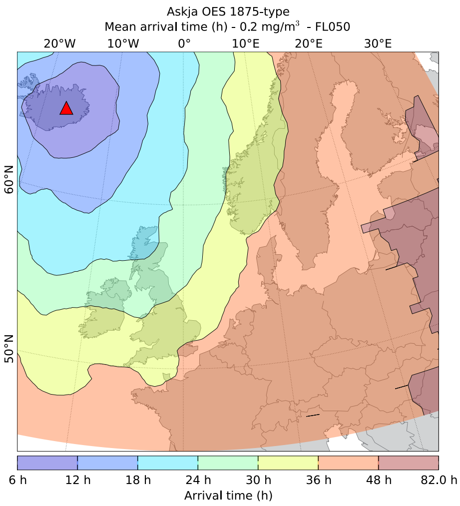
Askja OES 1875-type - Mean arrival time (h)

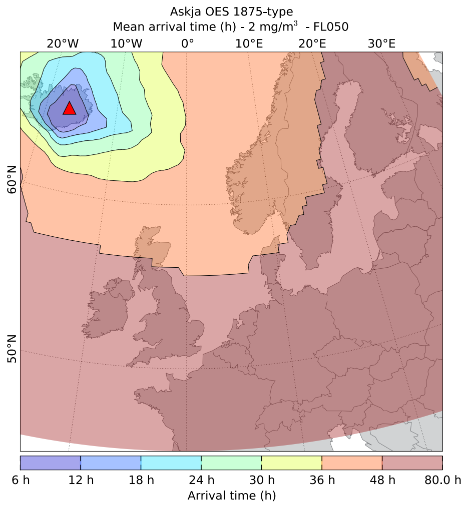


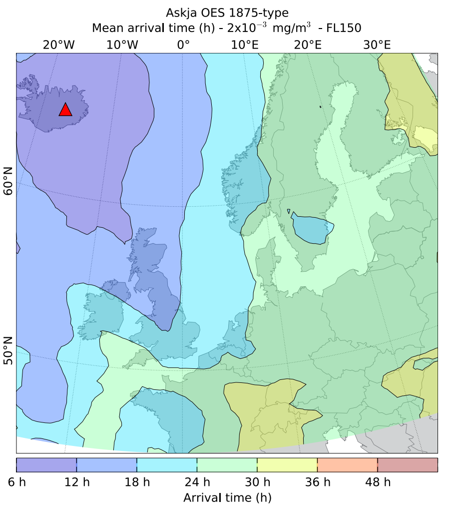


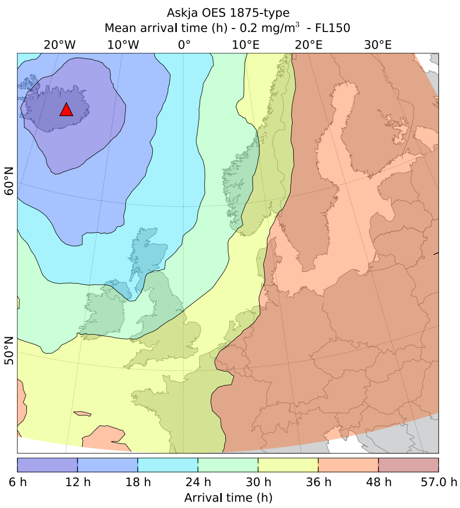


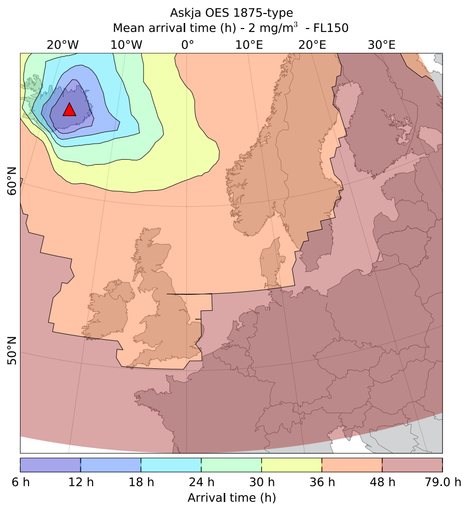


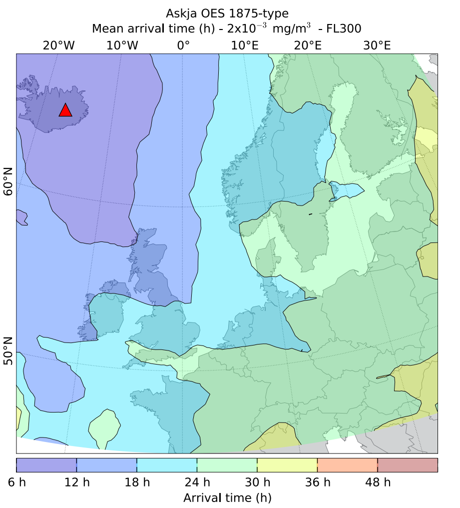


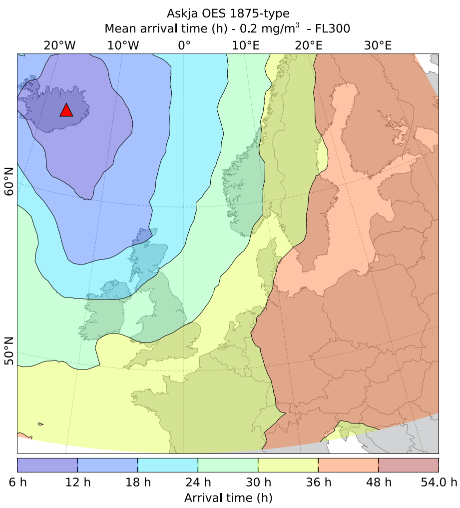


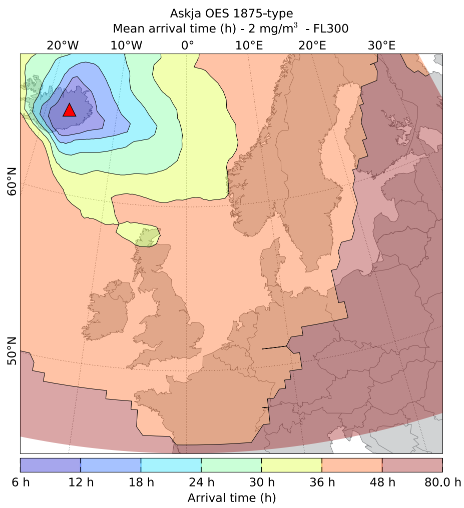




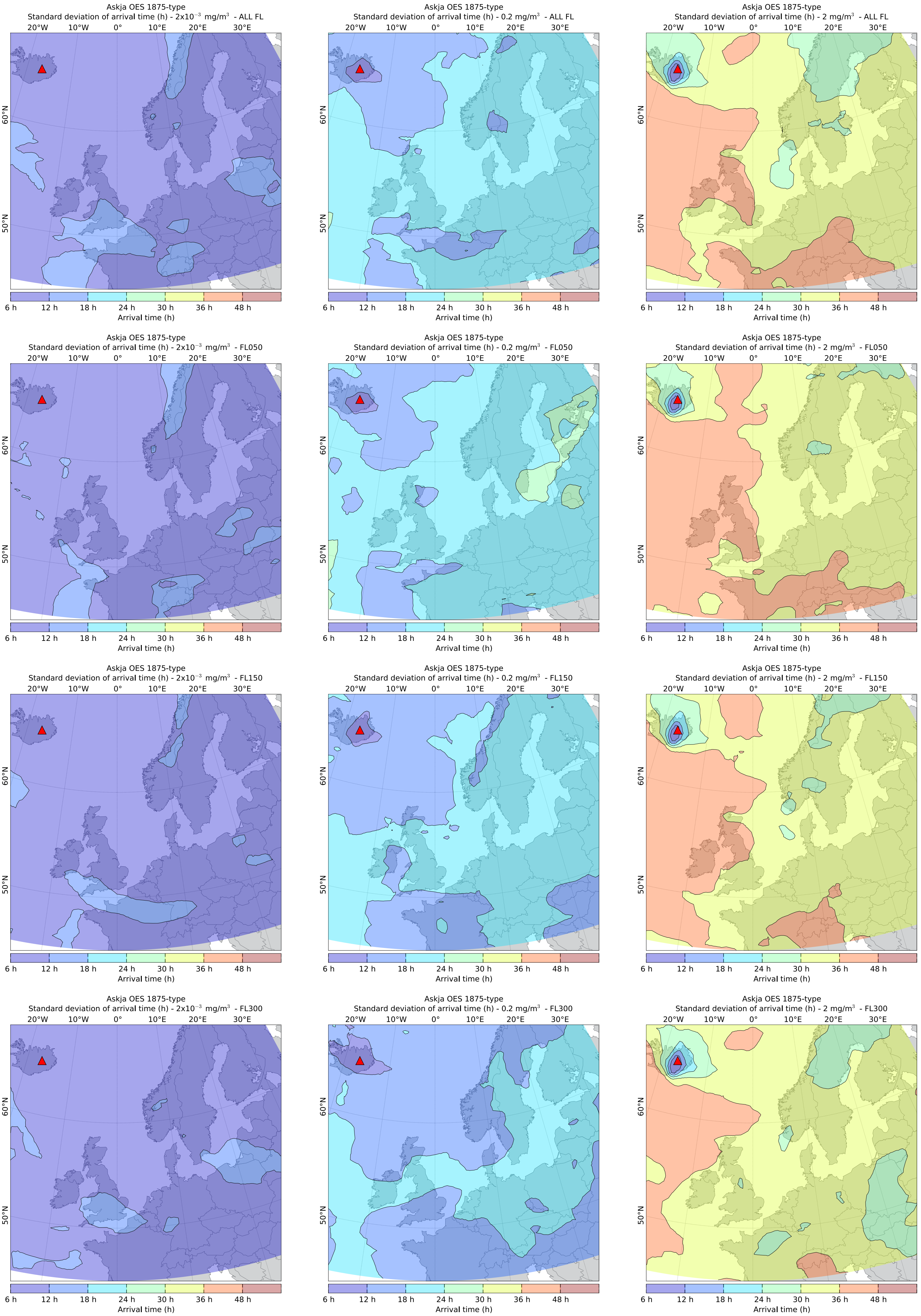




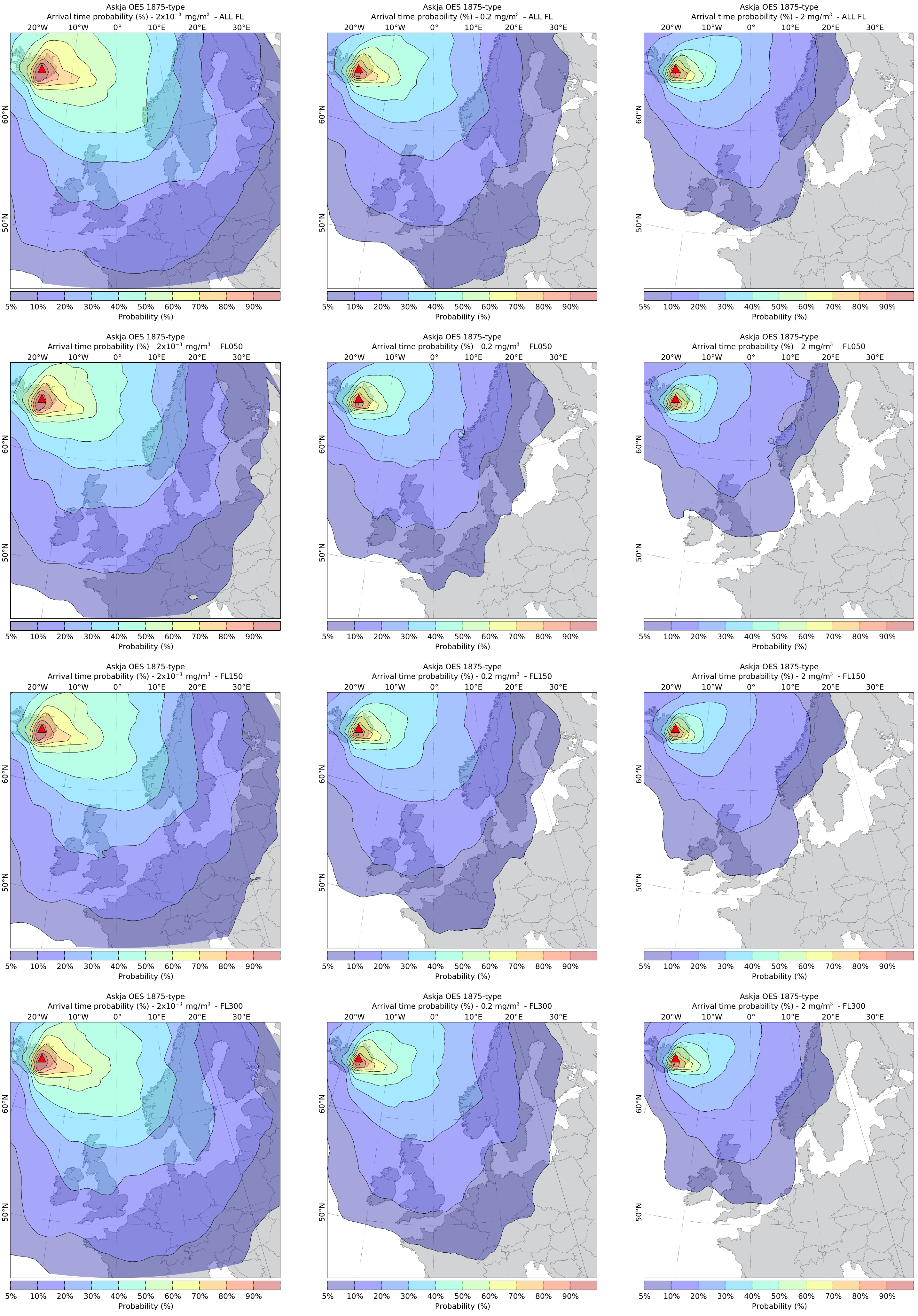




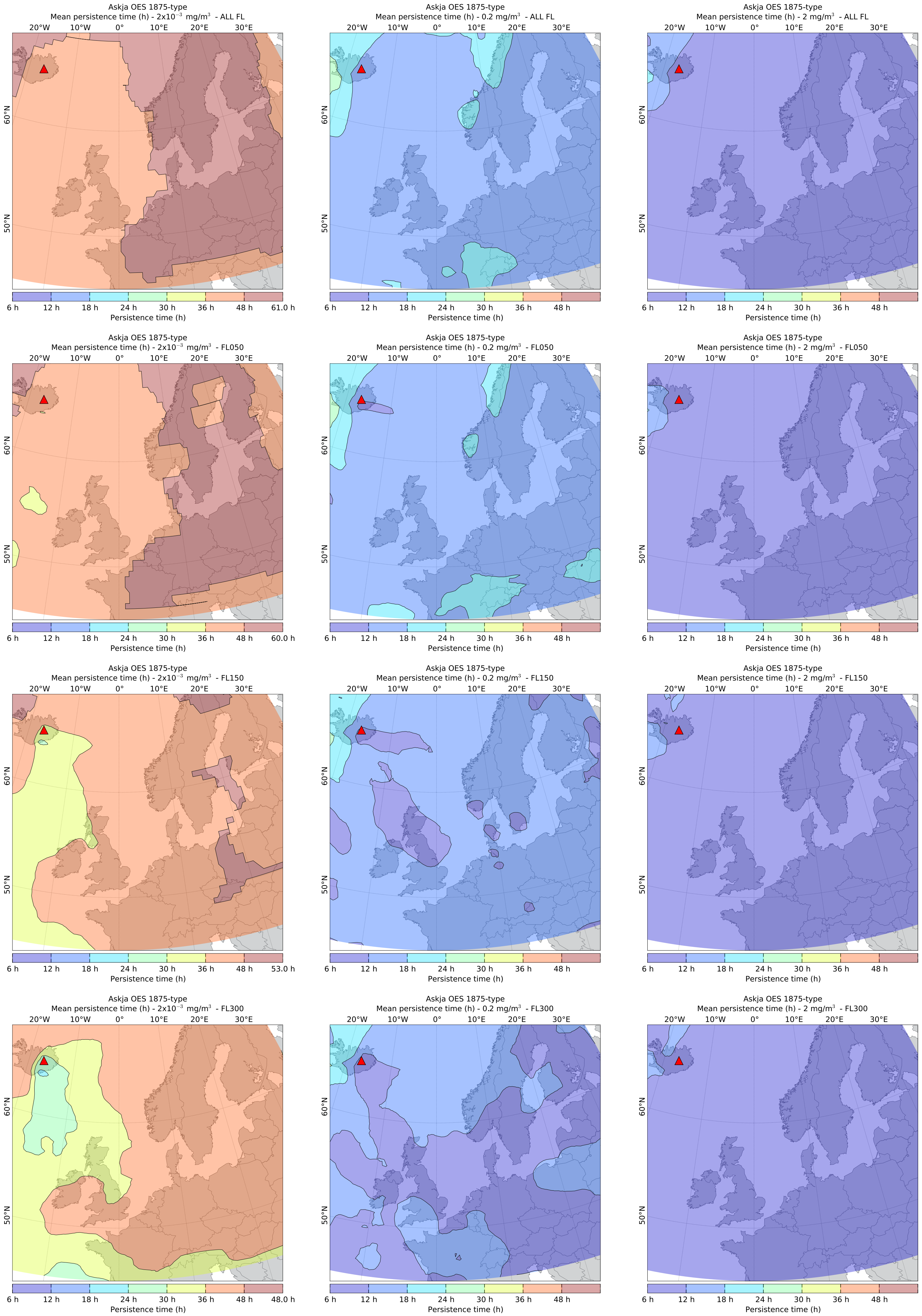
Askja OES 1875-type - Standard deviation of arrival time (h)



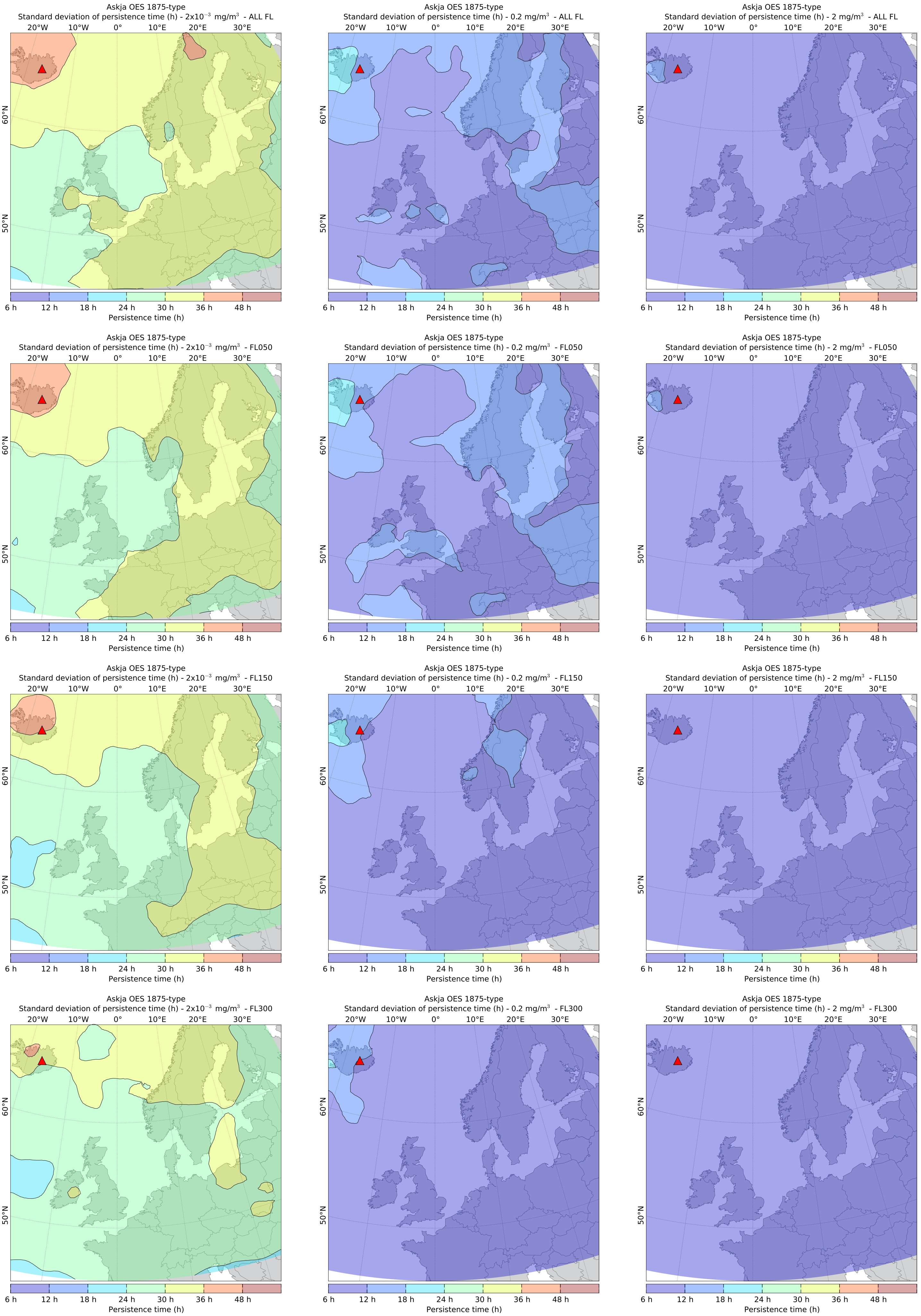
Askja OES 1875-type - Probability of arrival time > 24 h (%)



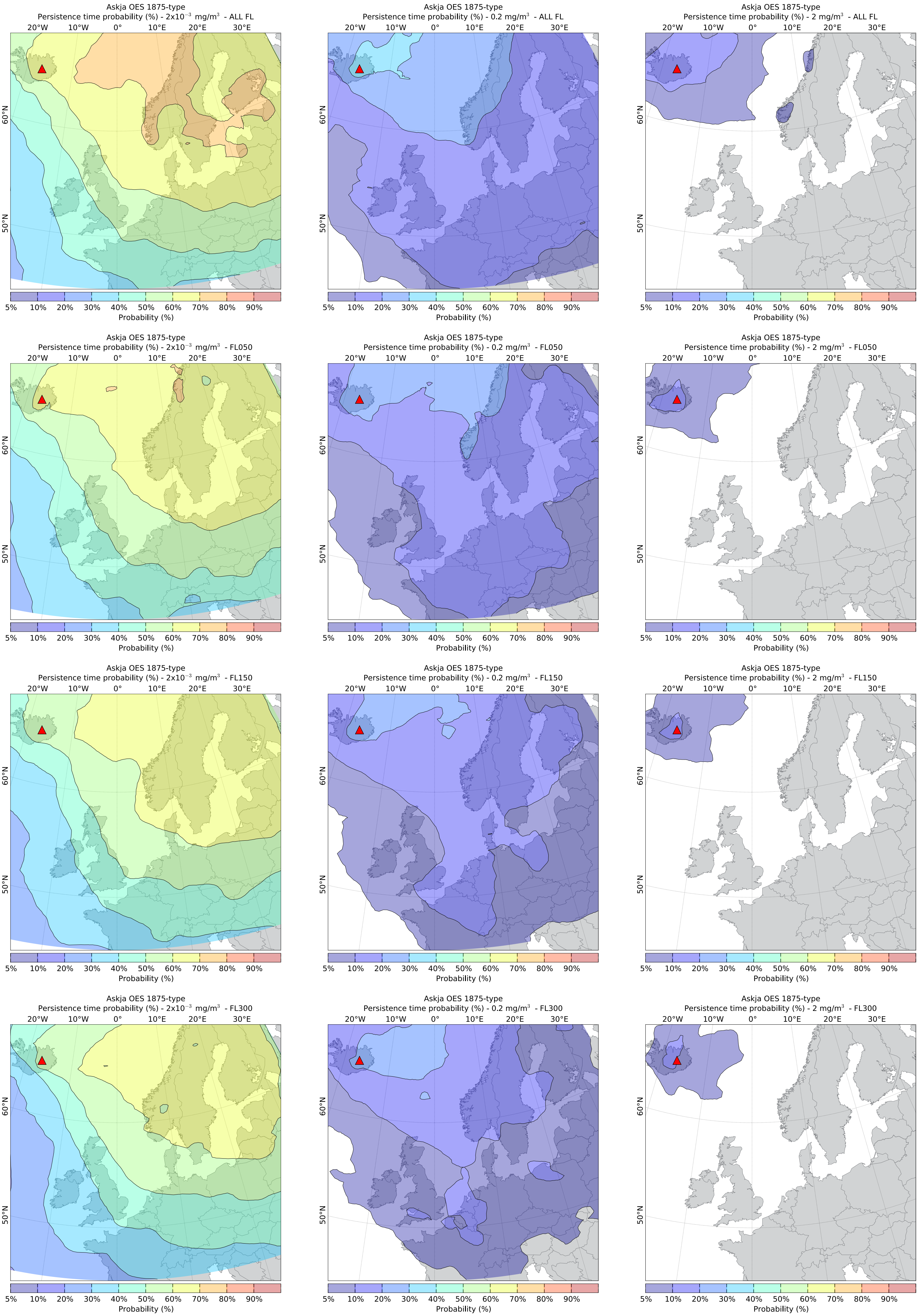
Askja OES 1875-type - Mean persistence time (h)



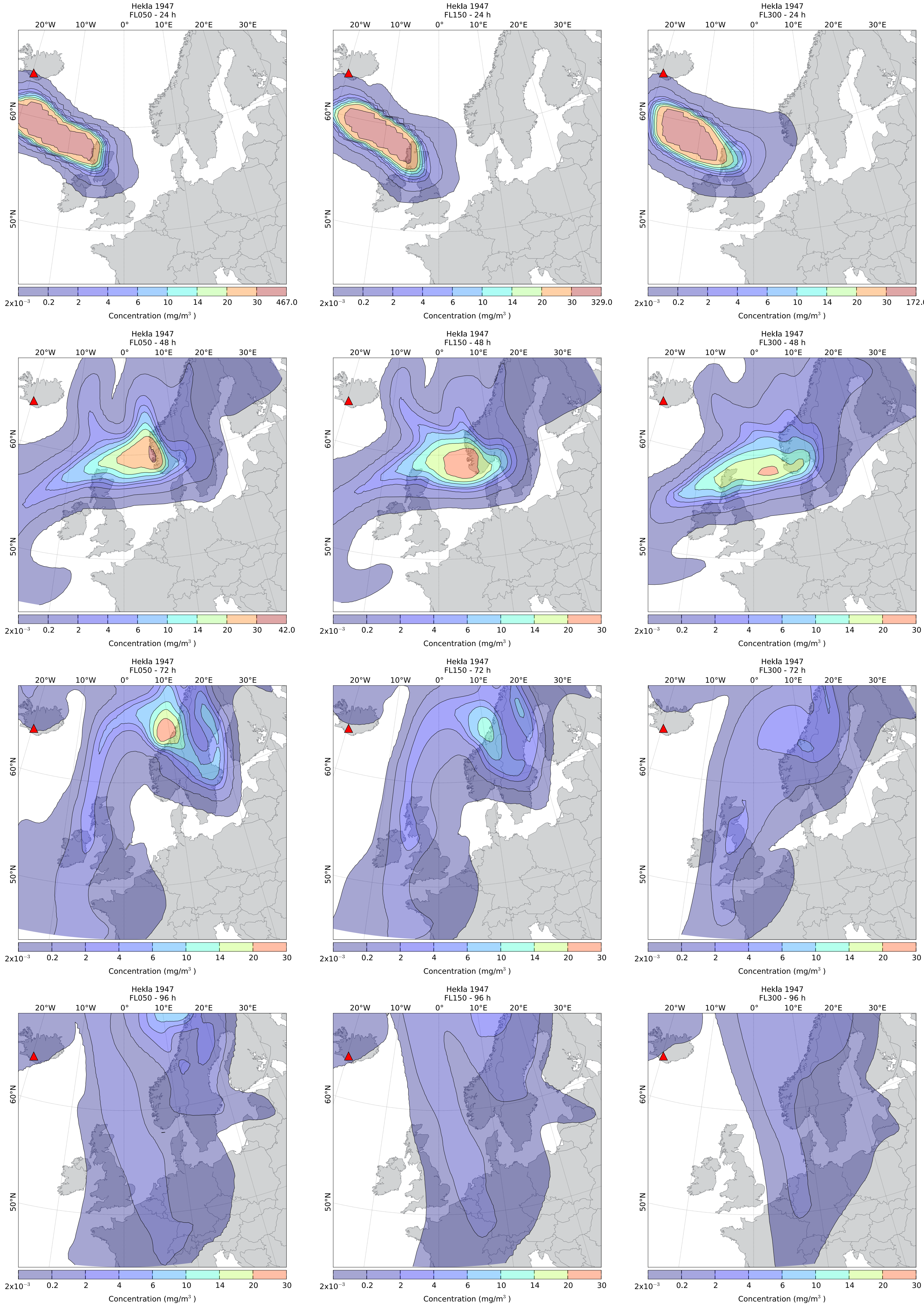
Askja OES 1875-type - Standard deviation of persistence time (h)



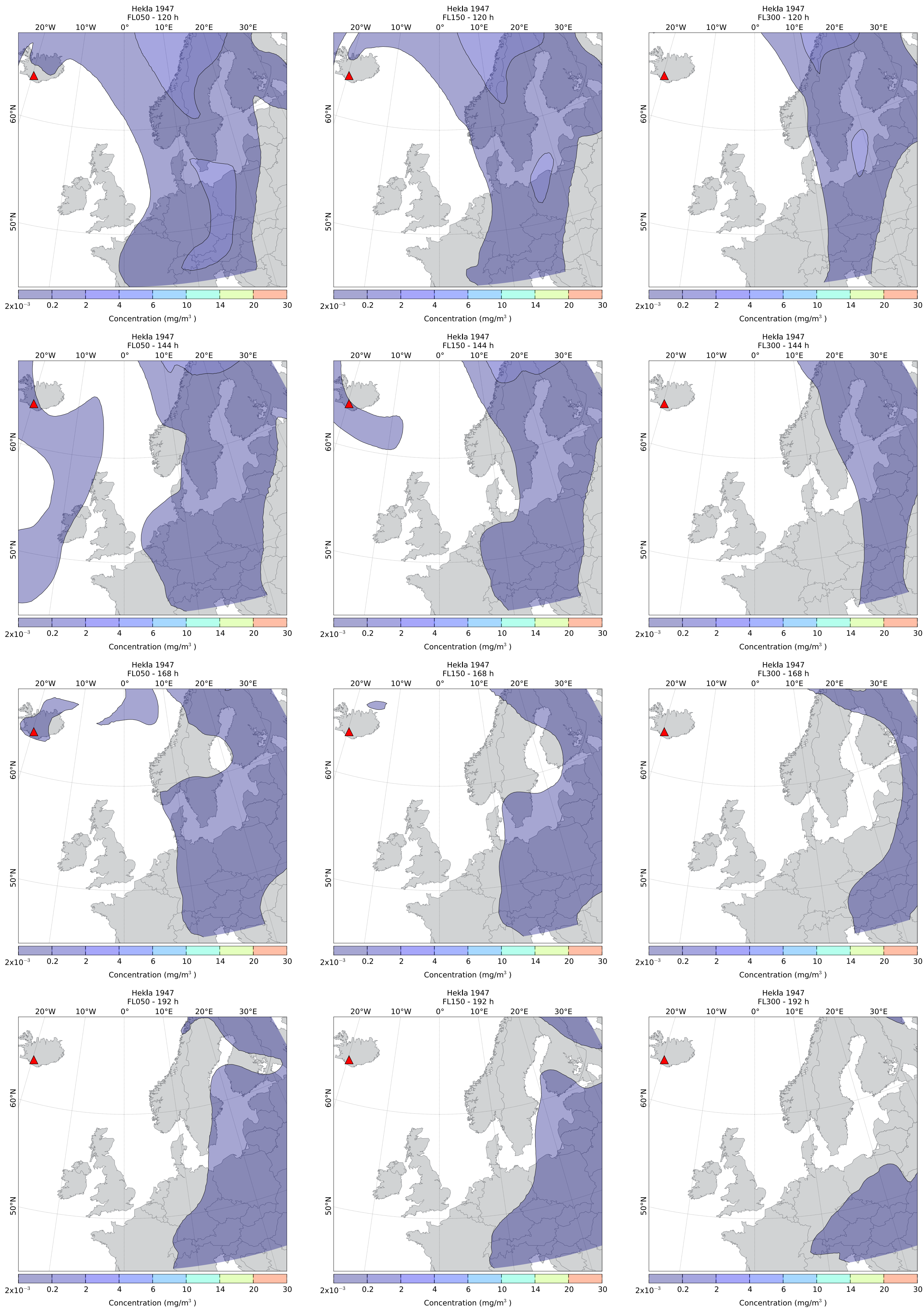
Askja OES 1875-type - Probability of persistence time > 12 h (%)



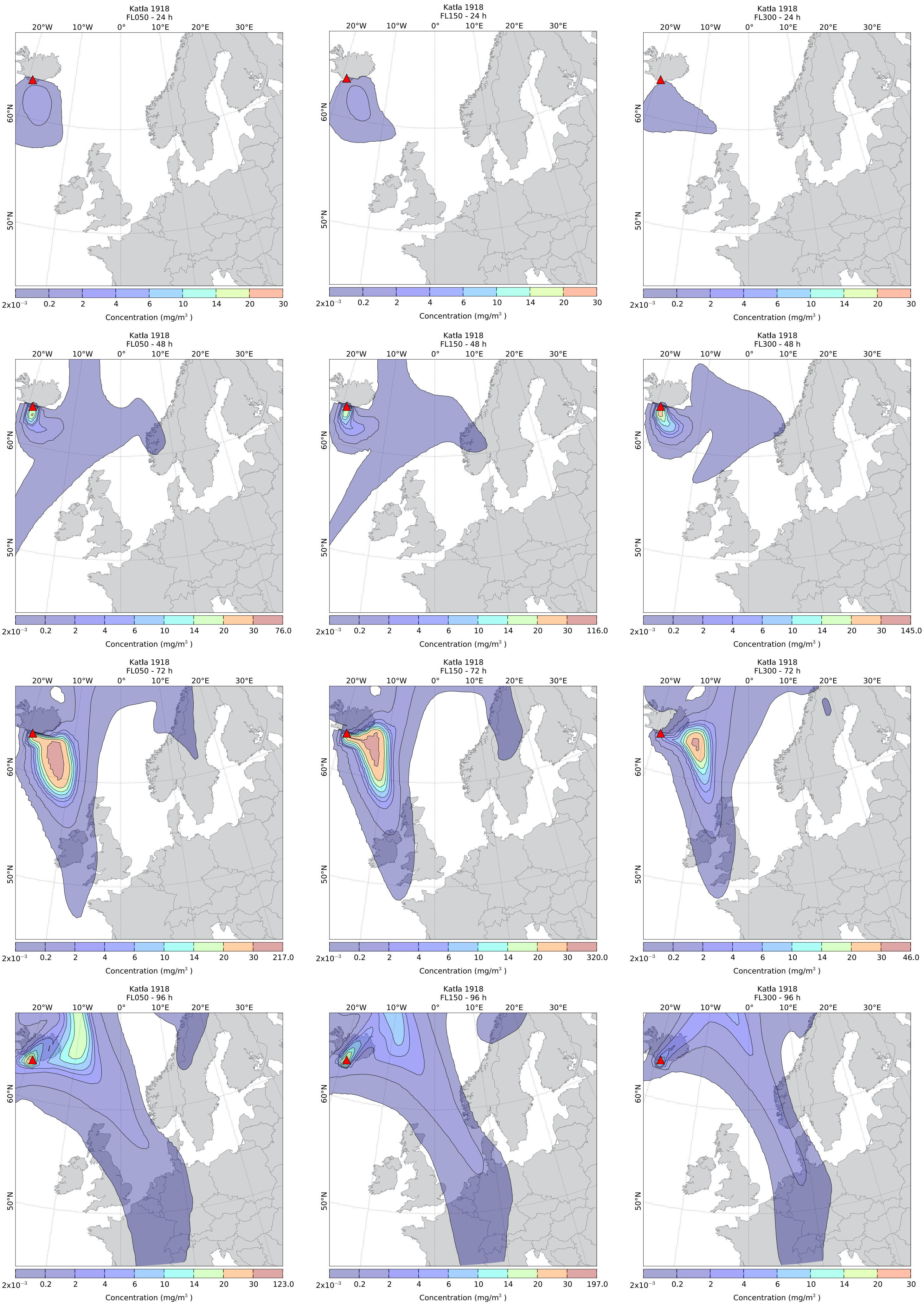
Hekla 1947 - Deterministic approach - Concentration (mg/m^3)



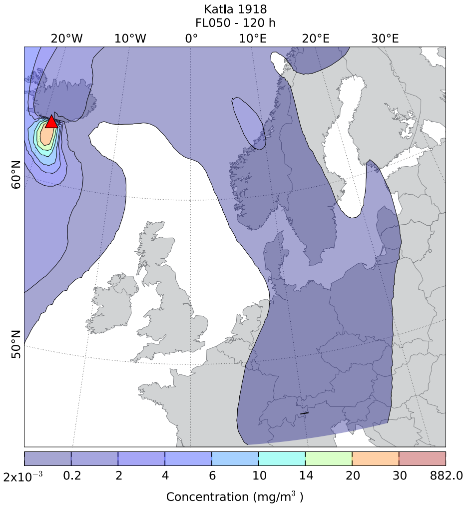
Hekla 1947 - Deterministic approach - Concentration (mg/m^3)

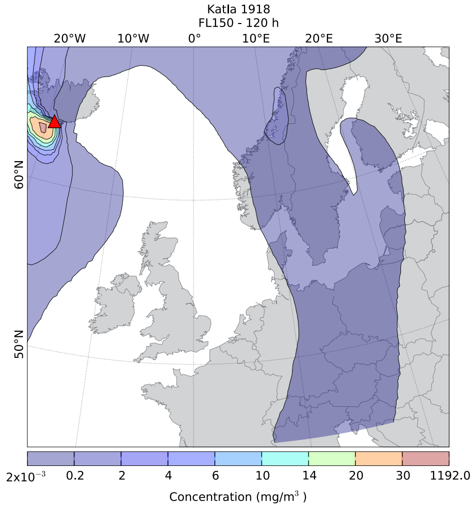


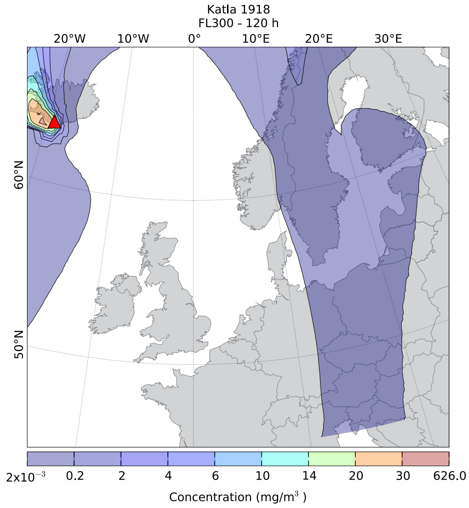
Katla 1918 - Deterministic approach - Concentration (mg/m^3)

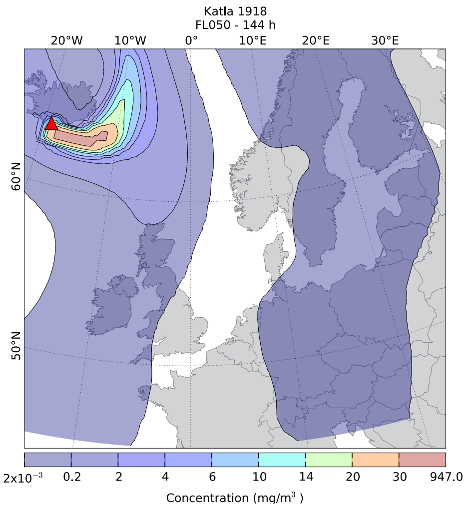


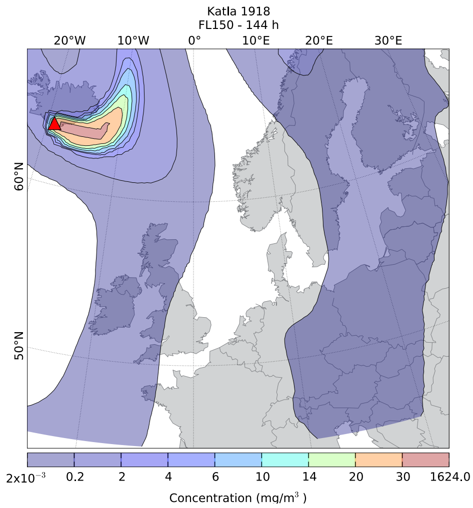
Katla 1918 - Deterministic approach - Concentration (mg/m^3)

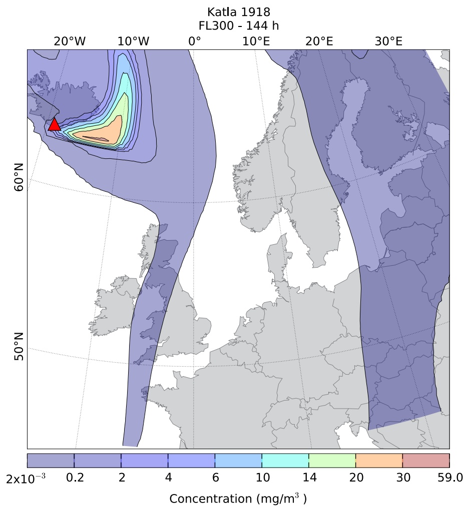


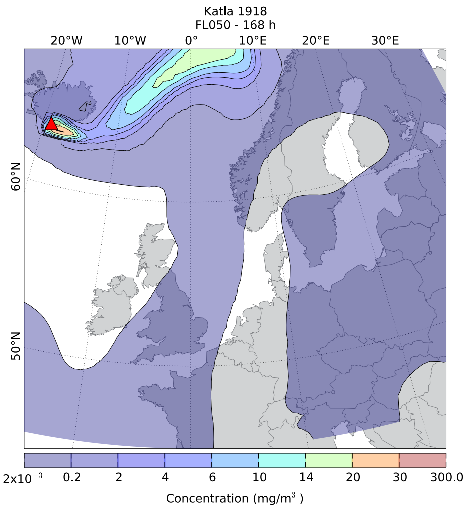


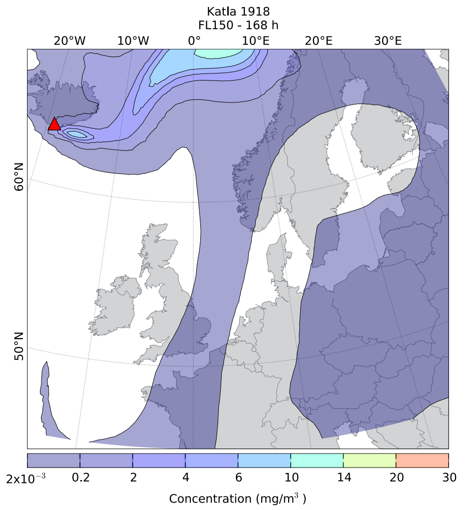


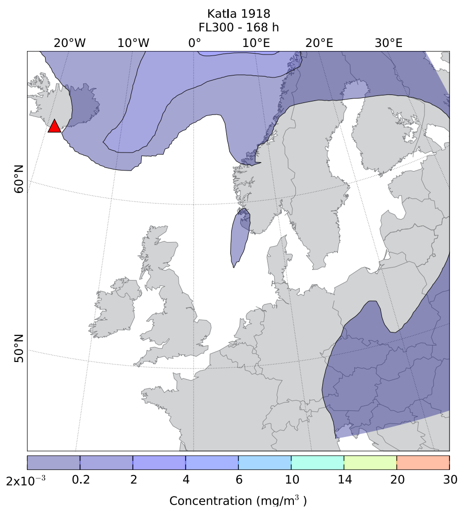


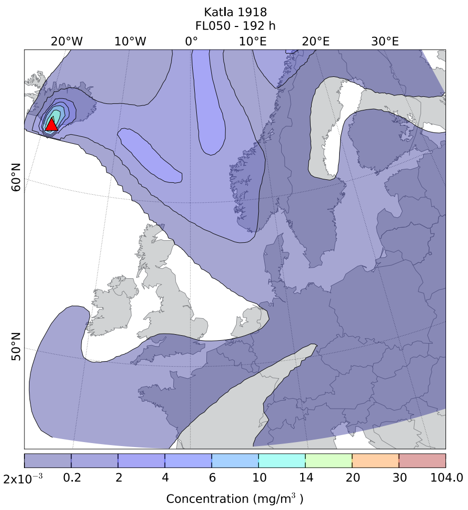


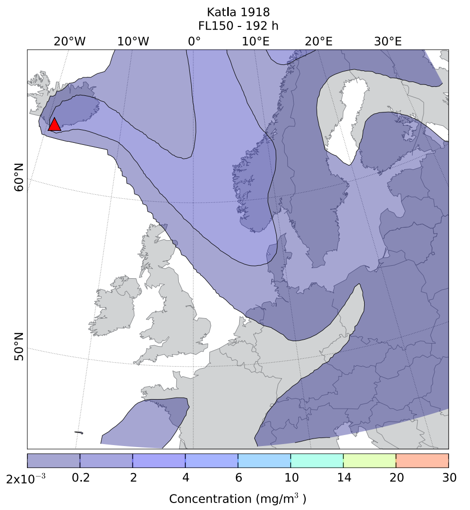


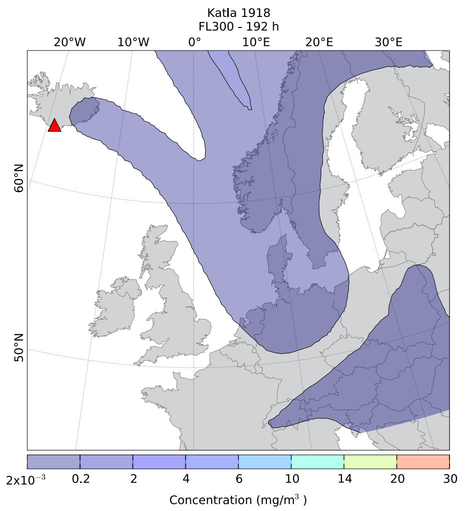




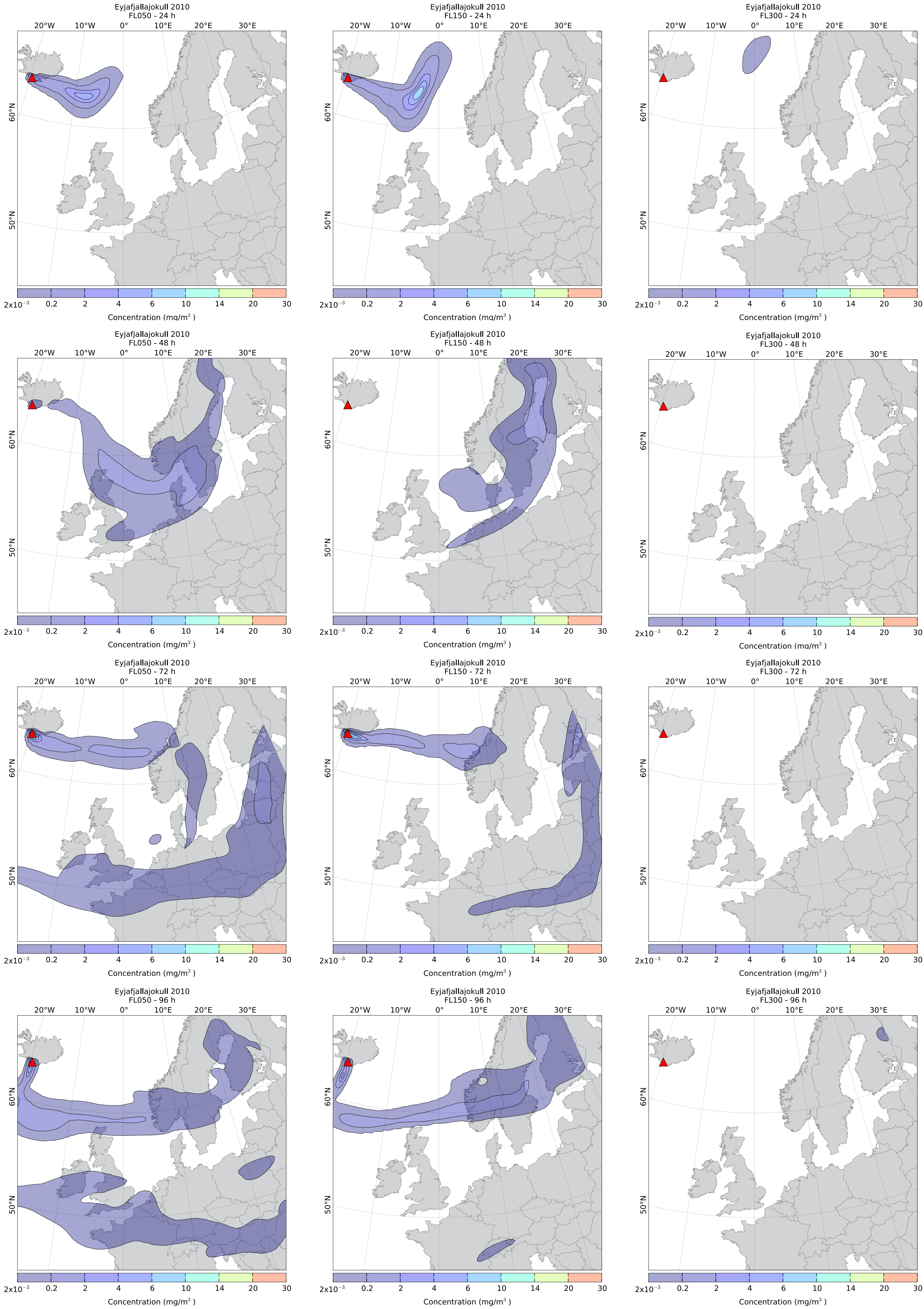




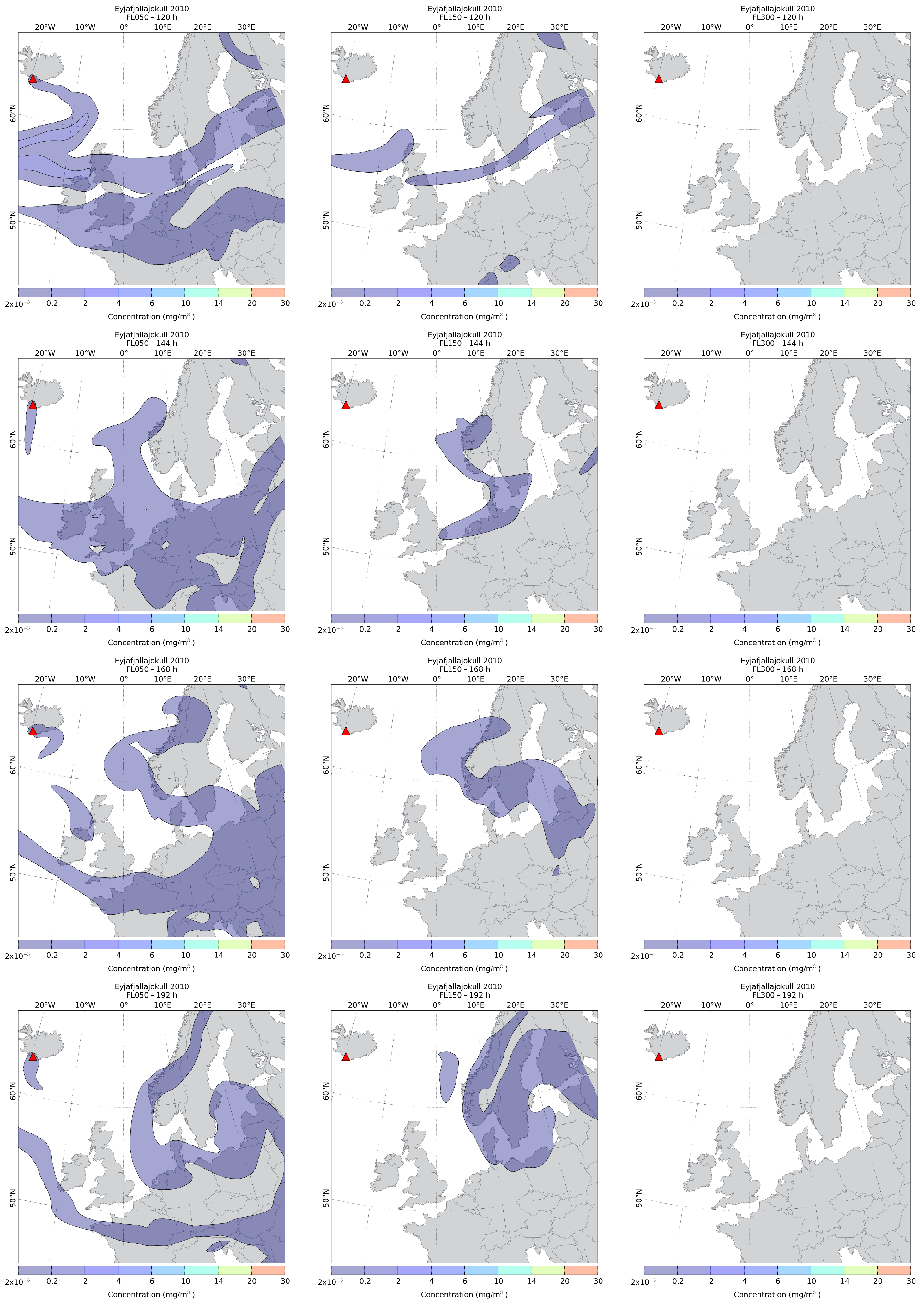


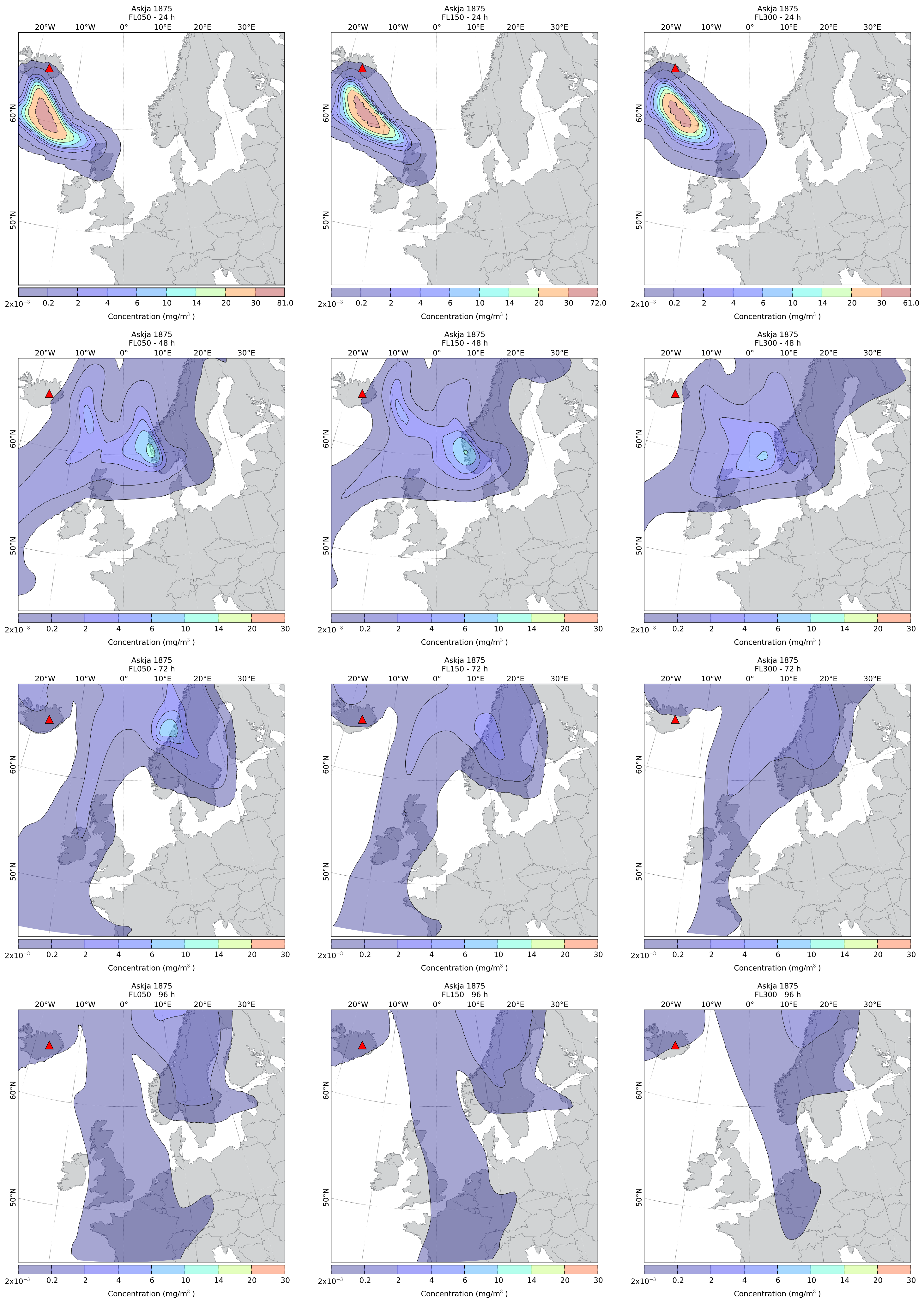


Eyjafjallajökull 2010 - Deterministic approach - Concentration (mg/m^3)

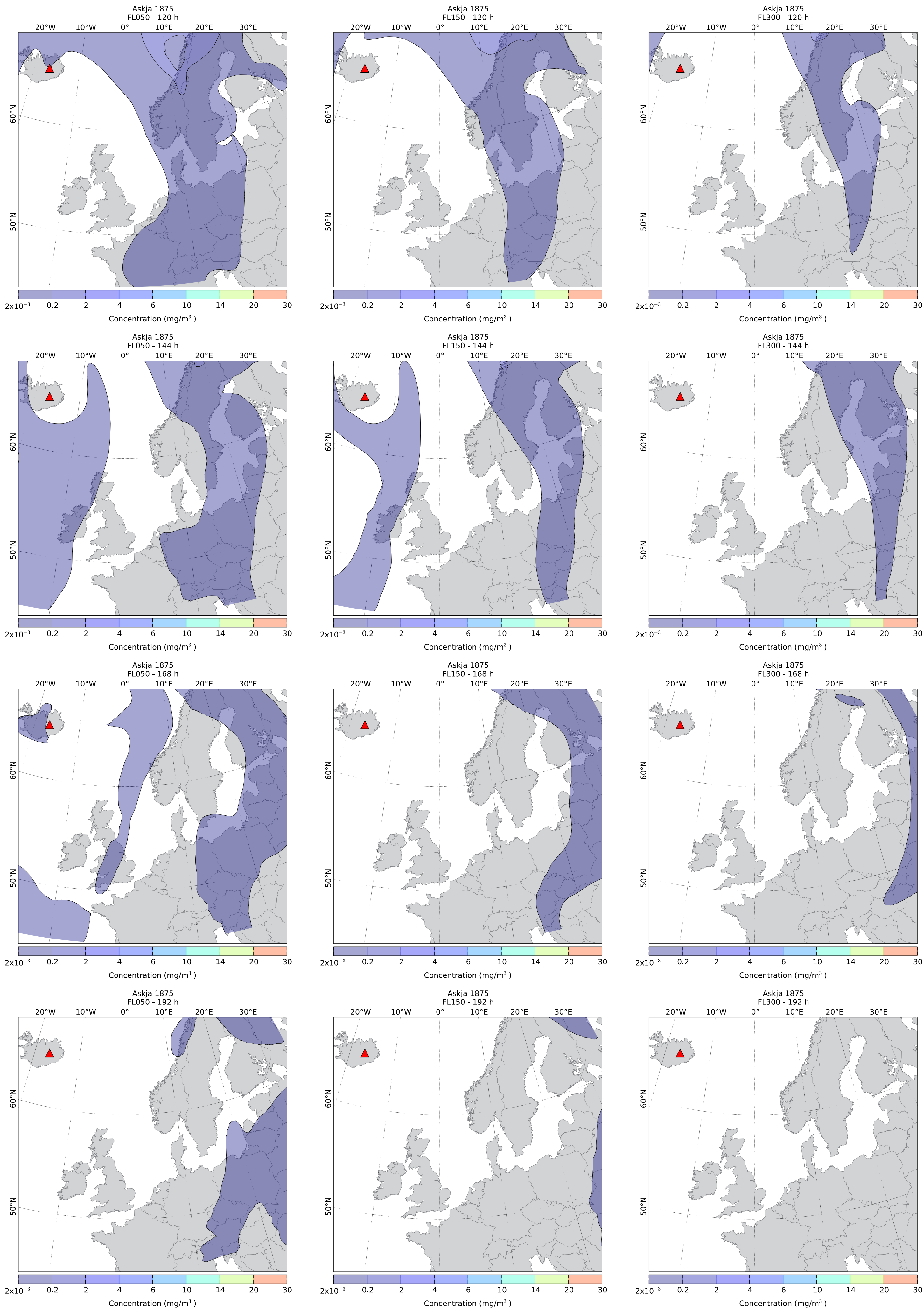


Eyjafjallajökull 2010 - Deterministic approach - Concentration (mg/m^3)

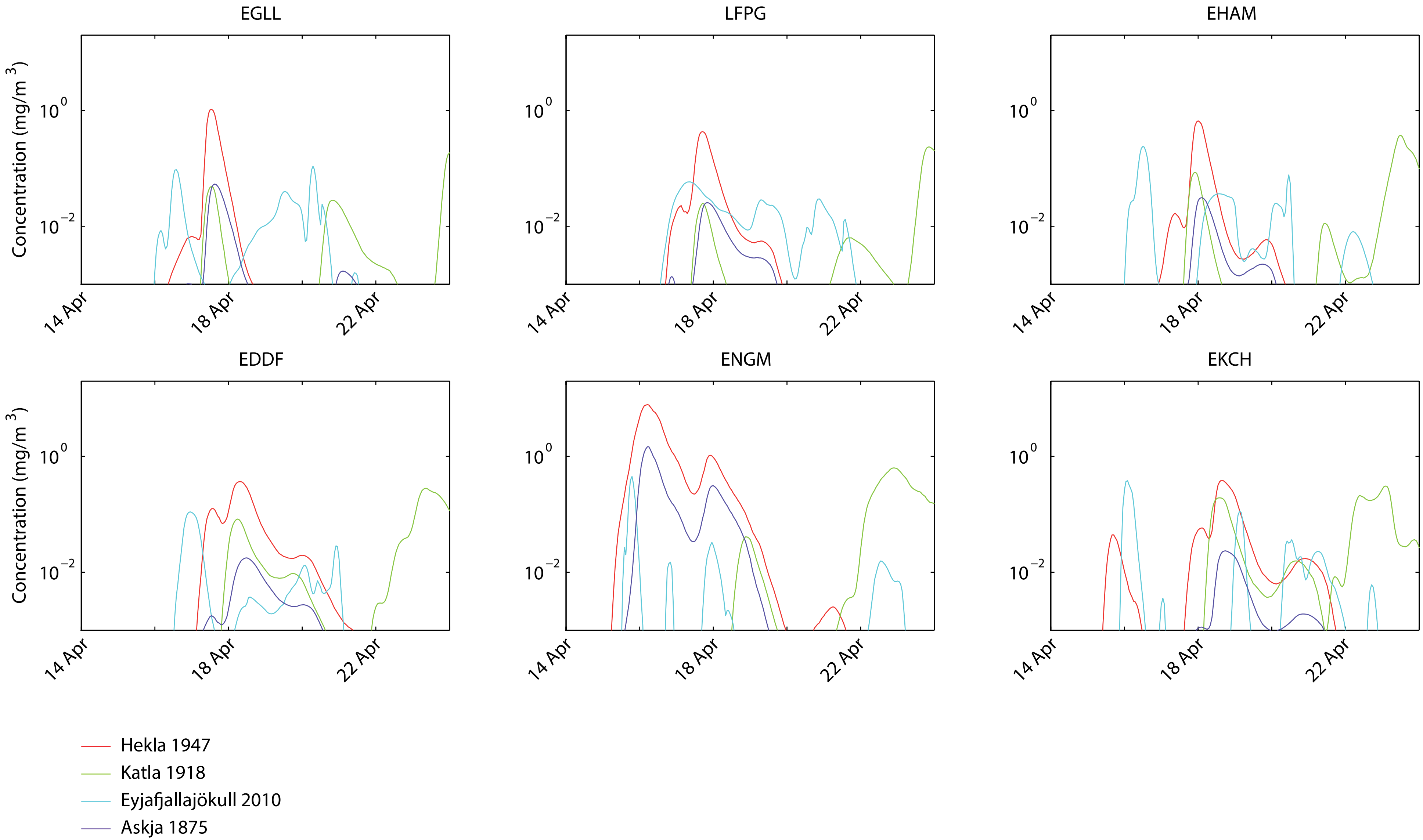




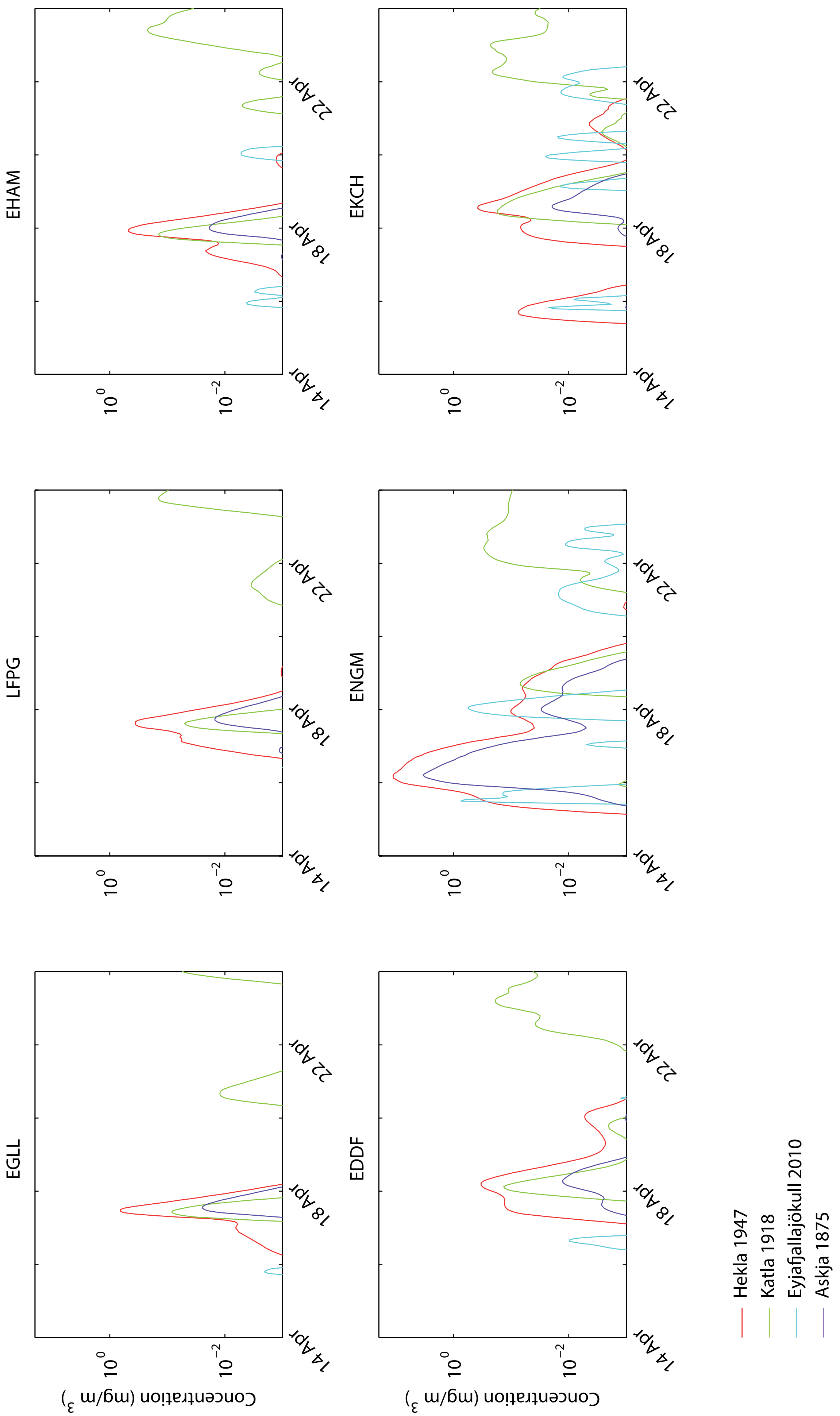
Askja 1875
FL050 - 24 h
Askja 1875
FL150 - 24 h
Askja 1875
FL300 - 24 h
Askja 1875
FL050 - 48 h
Askja 1875
FL150 - 48 h
Askja 1875
FL300 - 48 h
Askja 1875
FL050 - 72 h
Askja 1875
FL150 - 72 h
Askja 1875
FL300 - 72 h
Askja 1875
FL050 - 96 h
Askja 1875
FL150 - 96 h
Askja 1875
FL300 - 96 h
20°W 10°W 0° 10°E 20°E 30°E
60°N
50°N
2x10⁻³ 0.2 2 4 6 10 14 20 30 81.0
2x10⁻³ 0.2 2 4 6 10 14 20 30 72.0
2x10⁻³ 0.2 2 4 6 10 14 20 30 61.0
2x10⁻³ 0.2 2 4 6 10 14 20 30
Concentration (mg/m³)



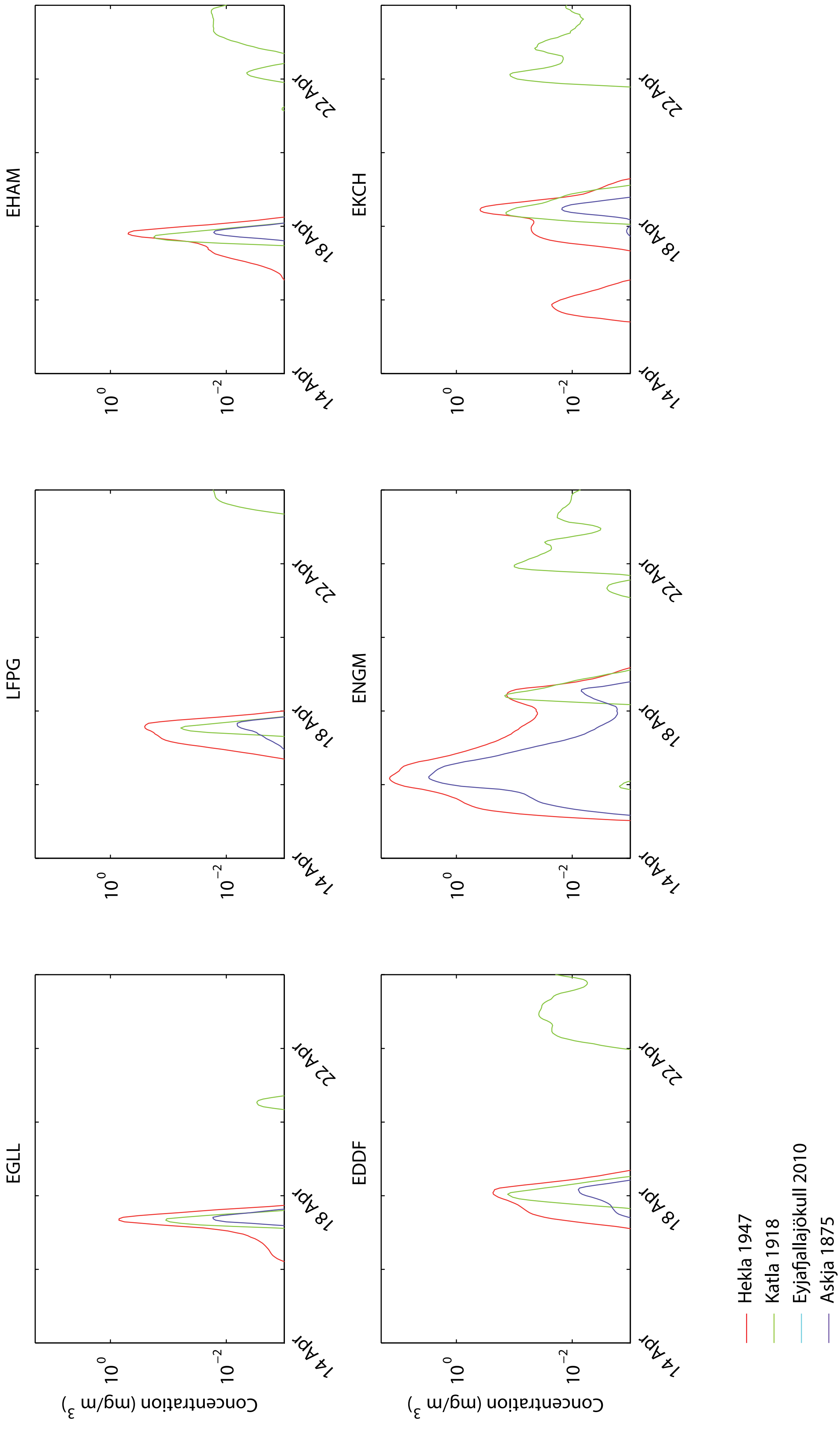
Askja 1875
FL050 - 120 h
Askja 1875
FL150 - 120 h
Askja 1875
FL300 - 120 h
Askja 1875
FL050 - 144 h
Askja 1875
FL150 - 144 h
Askja 1875
FL300 - 144 h
Askja 1875
FL050 - 168 h
Askja 1875
FL150 - 168 h
Askja 1875
FL300 - 168 h
Askja 1875
FL050 - 192 h
Askja 1875
FL150 - 192 h
Askja 1875
FL300 - 192 h
20°W 10°W 0° 10°E 20°E 30°E
60°N
50°N
2x10⁻³ 0.2 2 4 6 10 14 20 30
Concentration (mg/m³)



Concentration over the airports of London Heathrow (EGLL), Paris Charles de Gaulle (LFPG), Amsterdam Schipol (EHAM), Frankfurt (EDDF), Oslo Gardemoen (ENGM) and Copenhagen Kastrup (EKCH) at FL050.



Concentration over the airports of London Heathrow (EGLL), Paris Charles de Gaulle (LFPG), Amsterdam Schipol (EHAM), Frankfurt (EDDF), Oslo Gardemoen (ENGM) and Copenhagen Kastrup (EKCH) at FL150.



Concentration over the airports of London Heathrow (EGLL), Paris Charles de Gaulle (LFPG), Amsterdam Schipol (EHAM), Frankfurt (EDDF), Oslo Gardemoen (ENGM) and Copenhagen Kastrup (EKCH) at FL300.

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