The FEH22 rainfall depth-duration-frequency (DDF) model

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List of acronyms

AMAX	Annual maximum
CNC	Cyfoeth Naturiol Cymru (Natural Resources Wales)
DDF	Depth-duration-frequency
DfI	Department for Infrastructure (Northern Ireland)
EA	Environment Agency
FEH	Flood Estimation Handbook
FORGEX	FOcused Rainfall Growth EXtension
FSR	Flood Studies Report
mAOD	Metres above ordnance datum
NERC	Natural Environment Research Council
RMED	Median annual maximum rainfall
RMSE	Root-mean-square error
SAAR	Standard-period (1961-1990) average annual rainfall
SEPA	Scottish Environment Protection Agency
UKCEH	UK Centre for Ecology & Hydrology
UTC	Coordinated universal time
WHS	Wallingford HydroSolutions

1. Introduction

This report provides a high-level summary of the FEH22 rainfall depth-duration-frequency (DDF) model. For more detailed information on the model, please refer to Vesuviano & Stewart (2021) and Vesuviano *et al.* (2021), as the model is unchanged since this documentation (some variable parameter values are changed; these are documented here).

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2. Background

The first national rainfall depth-duration-frequency (DDF) model was set out in the 1975 Flood Studies Report (FSR: NERC 1975). This model was superseded in 1999 by the Flood Estimation Handbook (FEH) DDF model (Faulkner 1999), now referred to as FEH99. A new model (FEH13: Stewart *et al.* 2013) was released in 2015, incorporating more data and enhanced methods. FEH13 is the current UK industry-standard method to generate design storm rainfall (e.g. Environment Agency 2022).

The FEH13 DDF model relates the depth, duration and frequency of rainfall events as they vary spatially across the UK. Rainfall depth is calculated for a given duration and frequency using depth-duration-frequency relationships derived from statistical analysis of annual maximum rainfalls. This depth is then translated into a design storm rainfall event using a design storm profile, using methods set out in Faulkner (1999). It is also used for post-event analysis of real storms (to find the frequency of an observed event from its depth and duration). It is delivered via the FEH Web Service (https://fehweb.ceh.ac.uk) for durations from 5 minutes to 8 days, and frequencies (or return periods) from 1 to 100,000 years.

The FEH13 model is calibrated to daily rainfall data from the period 1853-2005 and hourly rainfall data from the period 1881-2006 (though less than 5% of daily and hourly data precede 1930 and 1960 respectively). As a result, many recent large storms were unused in its calibration, including the record-breaking events at Seathwaite Farm (November 2009) and Honister Pass (December 2015), and other significant non-record-breaking events (e.g. East Wretham, Norfolk, August 2020).

Due to recent significant events leading to flooding, UKCEH was approached by several organizations, independently and at different times, each requesting a local recalibration of FEH13 for a specific area of the UK. One of these, for Cumbria, has been published (Vesuviano & Stewart 2021, Vesuviano *et al.* 2021). Independently, in 2021, the Hydro-JULES project (https://hydro-jules.org) received period-of-record data for over 2500 hourly rain gauges operated by the Environment Agency (EA), Scottish

Environment Protection Agency (SEPA), Cyfoeth Naturiol Cymru (CNC) and Met Office, with the intention to make these available open-access (Northern Ireland's Department for Infrastructure was unable to contribute data to the Hydro-JULES project at the same time). This forms the dataset underpinning the updated FEH22 rainfall DDF model. Due to the demand for recalibration and the supply of hourly rainfall data, it was decided to recalibrate the FEH13 model across the entire UK.

3. FEH22 calibration data

3.1 Data description

The FEH22 model benefits from a much greater quantity of input data than FEH13, especially hourly data (Table 1). This is compared per country in Table 2.

Table 1 Comparison of FEH13 and FEH22 calibration datasets.

Model	1-hour gauges (gauge-years)	1-day gauges (gauge-years)
FEH13	970 (17,018)	6504 (171,910)
FEH22	1704 (35,218)	7910 (213,849)

Table 2 Comparison of FEH13 and FEH22 calibration datasets (per country).

Country	1-hour gauges FEH22 / FEH13	1-day gauges FEH22 / FEH13
England	1176 / 669	5619 / 4607
Scotland	313 / 162	1345 / 1113
Wales	180 /107	647 / 487
Northern Ireland	34 / 31	280 / 279
Isle of Man	1 / 1	19 / 18

While the quantity of daily data is increased somewhat, with a 20-25% increase in both the number of gauges and gauge-years, the quantity of hourly data is increased signifcantly, with a more than 75% increase in the number of usable gauges and more than double the number of usable gauge-years. The FEH22 data extend to more recent years than the FEH13 data; the FEH13 dataset extended to 2005 for daily data and 2006 for hourly data, while the FEH22 includes daily data up to December 2020, and hourly data up to December 2013 in Northern Ireland, August 2017 in England, July 2018 in Wales, and December 2020 in Scotland. The time periods represented by the FEH22 dataset cover the dates of occurrence of many recent events of concern, though it should be noted that coverage in Scotland during 2017-2020 is limited to 16-44 valid hourly gauges per year, there are no valid annual maxima in England for the part-year 2017 and none in Wales for the part-year 2018. Hence, some very recent events may be captured only partly by hourly gauges, by daily gauges only, or not at all.

Table 2 shows that the additional gauges in FEH22 are not evenly distributed across the UK. In particular, Northern Ireland gains very few additional gauges, because the (Northern Ireland) Department for Infrastructure (DfI) was unable to contribute data to the Hydro-JULES project in time for ingestion to the FEH22 dataset. As a percentage increase, Scotland gains the most hourly gauges (+93%, vs 76% and 68% in England and Wales respectively). This is because Scotland, as a whole, was a focus area for maximizing the quantity of hourly data for local calibration of FEH13, under a specific project. Wales gains the most daily gauges as a percentage (+33%, vs 22% and 21% in England and Scotland respectively).

Figure 1 and Figure 2 show the spatial distribution and total number of daily and hourly gauges suitable for use in the FEH22 project in ten specific years from 1881 to 2020. The top two rows in each figure show gauges used to develop FEH13 while the bottom two rows show gauges used to develop FEH22. Despite the main motivation behind the development of FEH22 being the much greater availability of hourly data, Figure 1 shows that the number of usable daily gauges is also much improved, particularly from 1961 onwards (e.g. 3081 gauges provide the FEH13 model with data for 1961, while 4603 gauges provide the FEH22 model with data for the same year). Conversely, Figure 2 shows that the number of hourly gauges is largely unchanged in earlier years (especially pre-1981). This is attributed to the fact that the few hourly gauges in operation before then were almost all administered by the Met Office, and the data for these were already readily available.

The density of Met Office daily gauges peaked in 1974, with 5741 suitable sites operating, and has been declining since then. Areas that remain particularly well covered into 2020 include the south and north-west of England. Scotland is covered more uniformly by daily gauges than it was in 1961, though at a lower density.

The density of suitable hourly gauges is still increasing, and is currently highest in Devon/Cornwall, London, Kent/Sussex, Lancashire, Glamorgan, and Scotland's Central Belt. The north-west of England has a high hourly gauge density as additional Environment Agency gauges were provided for an FEH13 recalibration requested over Cumbria (Vesuviano & Stewart 2021, Vesuviano *et al.* 2021), one of the earlier projects built upon by FEH22. The density of hourly gauges is lowest in Northern Ireland, for reasons stated above.

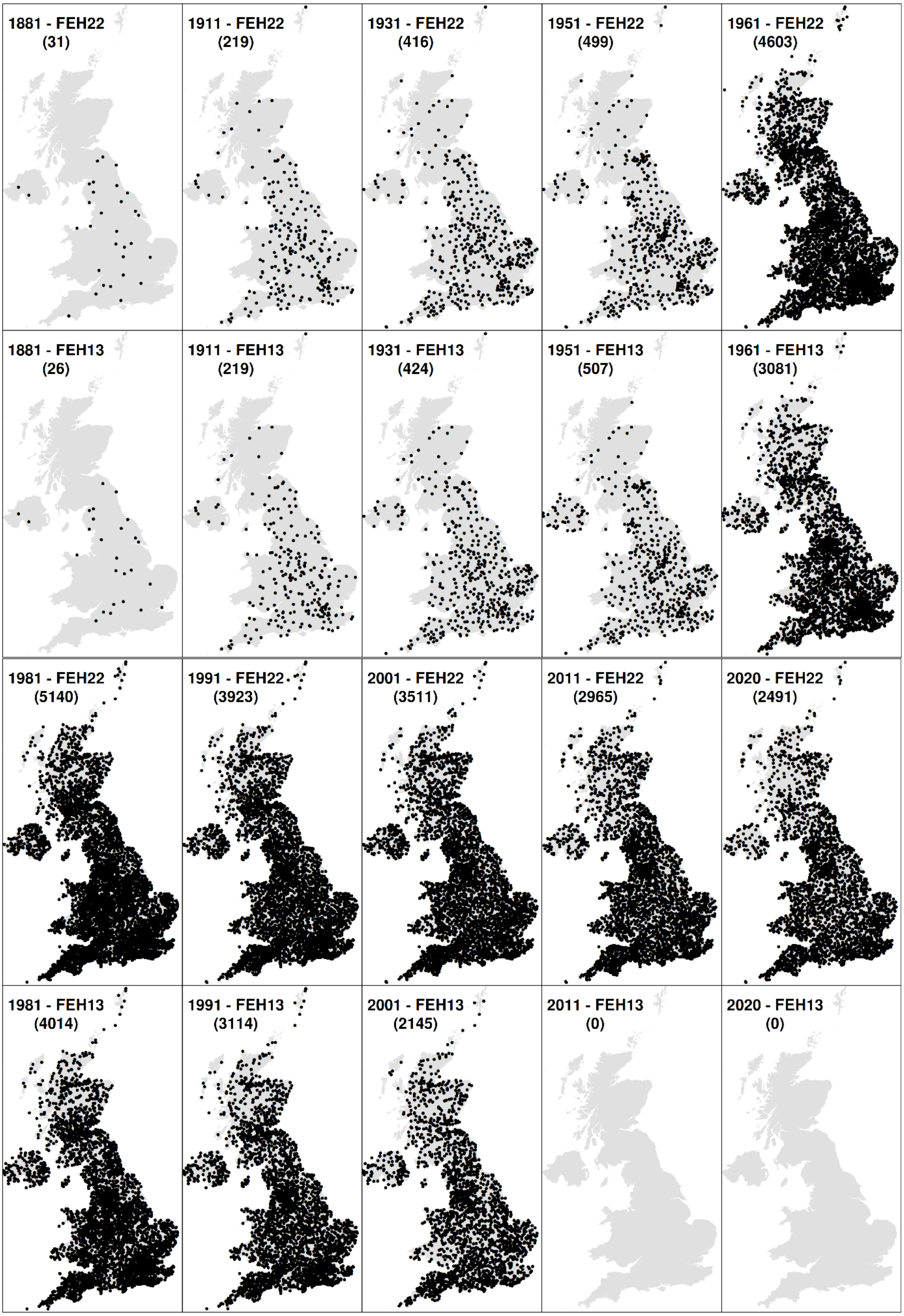

Figure 1 **Spatial distribution of daily rainfall gauges used in FEH13 and FEH22 at individual years between 1881 and 2020.**

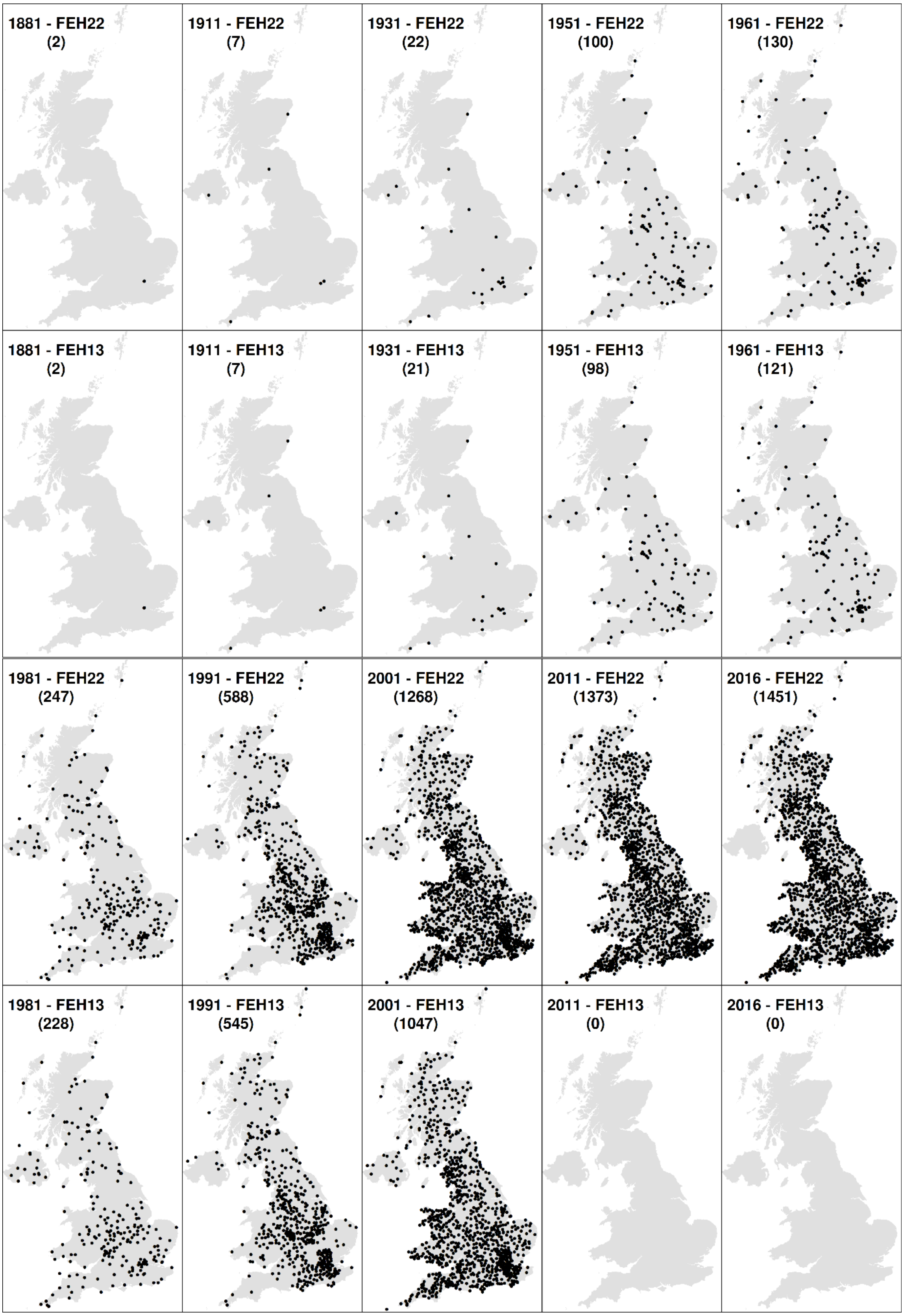

Figure 2 **Spatial distribution of hourly rainfall gauges used in FEH13 and FEH22 at the individual years between 1881 and 2020.**

3.2 Data quality review

For model outputs to be accurate, it is essential that the model calibration data are accurate. After all annual maxima were extracted, several automated deletions were performed. First, unrealistically large or small AMAX were deleted:

- More than 341.4 mm in 24 hours (59 values)
- More than 135 mm in 1 hour (77 values)
- Less than 3 mm in 1 hour (33 values)

When these were deleted, all other-duration maxima belonging to the same event at the same gauge were also deleted.

Next, AMAX of over 50 mm in 1 hour (204 values) were compared against daily totals from the three nearest daily gauges and categorized according to whether:

- They were used previously, in either FEH13 or the Cumbria-specific recalibration (47 values)
- They were new to this dataset, but:
    - one (or more) of the three nearest daily gauges recorded an equal or greater depth over a three-day total centred on the same day (37 values)
    - none of the three nearest daily gauges recorded an equal or greater depth over a three-day total centred on the same day (120 values) – these were deleted, along with all other-duration maxima belonging to the same event at the same gauge.

Finally, rainfalls over 100 mm in 6 hours were identified. These were similarly categorized, though only 32 events did not also correspond to events of over 50 mm in 1 hour.

All of the identified events over 50 mm in 1 hour or 100 mm in 6 hours that were not deleted were sent to the relevant measuring authority for review (Environment Agency for events recorded in England, Scottish Environment Protection Agency for events recorded in Scotland and Cyfoeth Naturiol Cymru for events recorded in Wales). The results of this review are shown in the appendix.

All AMAX of over 50 mm in 1 hour or 100 mm in 6 hours recorded by a sub-daily Met Office gauge were automatically accepted. This is because Met Office data are continually quality controlled, whereas large portions of the measuring authority data have never been made available before. As all daily data used in this project were provided by the Met Office, and quality controlled by both the Met Office and UKCEH before delivery, they were all automatically accepted. Some examples of events recorded by a Met Office gauge, used to calibrate FEH13, and subsequently revised or deleted by the Met Office include the 1958 1-day AMAX at Hurn, West Hampshire (reduced from 117.3mm to 38.9 mm), the 1989 1-day AMAX at Swallowcliffe (reduced from 110.4 mm to 40.8 mm), the 1998 1-day AMAX at Worleston S. Wks (reduced from 108.8 mm to 20.8 mm) and the 2004 1-day AMAX at Nantwich, Reeseheath Hall (deleted). Because the Met Office is continually revising data, it is possible that some AMAX values recorded by a Met Office gauge and used to calibrate FEH22 will be revised or deleted in the future.

4. FEH22 model

4.1 Model description

The FEH22 rainfall DDF model uses calibration data, as described in Section 3, to relate rainfall depth, duration and frequency across the UK. A single model is used for durations from 1 to 192 hours and return periods from 1 to 100,000 years, but the parameterization of the model varies at each point where the model is calibrated (in 1-km steps in both easting and northing across the UK). The model structure and procedure are identical to those presented in detail in an earlier UKCEH report (Vesuviano & Stewart 2021) and summarized in an open-access *Journal of Flood Risk Management* article (Vesuviano *et al.* 2021), both of which reported on the recalibration of the FEH13 DDF model for Cumbria. As both sources are freely available, only a brief restatement of the modelling procedure (how calibration data are turned into DDF estimates) is presented below:

1. *RMED* (the median, 2-year or 50% annual exceedance probability annual maximum rainfall) is estimated at all gauges with six or more valid annual maxima of duration 1, 2, 4, 6, 12, 18, 24, 48, 96 and 192 hours.
2. *RMED* is modelled as a function of *SAAR*, easting, northing and duration on a regular 1-km grid across the United Kingdom (Northern Ireland uses the Irish National Grid, while Great Britain, the Isle of Man and other islands use the British National Grid).
3. All valid gauged annual maxima are standardized by *RMED*, *SAAR* and, for durations of one day or longer, northing. *RMED* of each duration has a standardized depth of 1, while an event *x* times as large may or may not have a standardized depth near *x*, depending on *SAAR* and (for day-plus durations) northing.
4. FORGEX is applied on a regular 1-km grid across the United Kingdom. In simple terms, this is a method that is used to estimate depth-frequency relationships for much rarer events than could be estimated by single gauges, by combining records from multiple gauges to find the largest standardized event per year and assigning it a return period based both on its rank within the combined record and on the number of gauge-years that were required to find that event, searching outwards from the grid point.
5. A DDF model, consisting of a weighted sum of two gamma distributions raised to a power, is fitted jointly to all (now unstandardized) FORGEX outputs at each location. All DDF model parameters are functions of duration.
6. The DDF model outputs are smoothed to avoid large jumps in estimated rainfall depth corresponding to similar locations, durations and frequencies.

4.2 Differences between FEH22 model and model reported by Vesuviano & Stewart (2021)

Differences between the FEH22 model and the model reported in detail by Vesuviano & Stewart (2021) are minimal. The only differences are between individual constants used in the model, which are solely a direct consequence of the different calibration datasets used. Individual constant values, and one very minor bug fix (also discussed in Vesuviano & Stewart 2021), are also the only differences between the FEH22 model and the FEH13 model available through the FEH Web Service.

The *RMED* grids are used as a standardizing variable for rainfalls of the same duration in the FEH13 and FEH22 model. Due to differences in the calibration data, updated *RMED* grids were produced for FEH22. The fitting statistics for the FEH22 grids are compared to the FEH99 grids in Table 3. The values are not compared to FEH13, as the fitting statistics for the "FEH13" model on this dataset would be identical to those shown in this table for FEH22.

Table 3 *RMED* regression model fitting statistics.

Duration	Number of sites	RMSE (FEH99)	RMSE (FEH22)	R^2 (FEH99)	R^2 (FEH22)
1h	2043	0.14641	0.13641	0.0888	0.2091
2h	2001	0.13362	0.12209	0.2361	0.3622
4h	1955	-	0.11351	-	0.5740
6h	1980	0.15586	0.11397	0.3568	0.6560
12h	1955	0.15363	0.11314	0.5164	0.7377
18h	1953	-	0.11618	-	0.7659
24h	1958	0.15980	0.11813	0.5915	0.7768
1d	9205	0.16636	0.10405	0.4107	0.7695
2d	9205	0.15977	0.10189	0.5492	0.8166
4d	9232	0.16262	0.09602	0.6438	0.8758
8d	9219	0.17219	0.09490	0.6800	0.9028

The regression models used to estimate *RMED* in the FEH22 model are clearly superior to those used in FEH99. The fitting statistics are comparable to, but very slightly lower than, those reported by Vesuviano & Stewart (2021) for the recalibrated FEH13 model, which were themselves comparable to, but very slightly lower than, those reported for the original FEH13 model. The reason for this slight decline is likely because the regression model is tuned to the FEH13 dataset; the dataset used by Vesuviano & Stewart (2021) contains many of the same values, but also many new values, so the model is no longer optimal, but still good enough that the loss in performance is small. The FEH22 dataset differs again, so there is another small loss in performance. Similarly, the FEH22 dataset covers a longer period than any other dataset so may be trying to incorporate greater climate change effects into the stationary *RMED* model.

Because the dataset and regression are different, the error due to sampling variance and extra estimated real variation are different too. The sampling error in the rainfall data and extra estimated real variation are used by the *RMED* fitting program, so the fitting must be performed at least twice: once with placeholder values, and once with the values output after the first fitting. If the values output by the second fitting match those output by the first fitting, then a third fitting will not be required as it will not change the *RMED* regressions further. In FEH22 development, and all previous FEH13 recalibrations, only two fittings were required.

In the FORGEX model, dimensionless standardized annual maxima (AMAX) are used in place of the raw (mm) depth values. The standardization first divides each AMAX by RMED (discussed above), then rescales the resulting values by a factor based on the site's SAAR value and northing. The coefficients for these factors were recalculated from the FEH22 calibration dataset and are presented in Table 4.

Table 4 Regression coefficients for AMAX standardization equation.

Duration	Number of sites	*a*	*b*	*c*
1h	1704	1.2614530	0.3606247	0
2h	1677	0.8728392	0.5088426	0
4h	1634	0.6624730	0.5188423	0
6h	1659	0.6349850	0.4835181	0
12h	1634	0.7062640	0.3979469	0
18h	1631	0.7512002	0.3742421	0
24h	1636	0.7915471	0.3407812	0
1d	7910	0.6997293	0.4038119	0.1093301
2d	7910	0.6122815	0.3735633	0.2358151
4d	7936	0.4442113	0.3798064	0.2920338
8d	7914	0.4176303	0.3391930	0.2617659

5. Model outputs

5.1 Case study: Cumbria

Table 5 compares return periods estimated for the record-breaking November 2009 and December 2015, and significant October 2021, events in Cumbria using:

- FEH22,
- the local recalibration of FEH13 produced for the Environment Agency in Cumbria,
- the FEH13 model available on the FEH Web Service, and
- the FEH99 model.

In each case, the return period given is for the closest 1-km grid point to the named gauge. The FEH22 return period estimates of these events are comparable to the “Cumbria” return period estimates. However, due to the additional occurrence of non-extreme events during the period 2016-2020, the FEH22 return periods are almost always slightly longer. It is possible that the FEH22 return periods would be slightly shorter if the rainfall on 27 October 2021 (369.0 mm in 38 clock hours at Honister Pass) were included in the calibration dataset. However, they would not be shorter than those estimated by the Cumbria model, as the October 2021 rainfall was not record-breaking.

Throughout Table 5, “clock” days always refer to time periods beginning and ending at 0900 UTC, whereas “clock” hours always refer to time periods beginning and ending at the start of an hour (i.e. both refer to “fixed” rather than “sliding” durations). This is why Thirlmere has identical rainfall depths for the 38-hour and 2-day December 2015 event. However, the return periods estimated for each event in the table do take account that each total was recorded over a “fixed” period. Figure 3 presents the locations of Honister Pass, Thirlmere and Seathwaite Farm gauges within Cumbria.

Table 5 Estimated return periods for record-breaking Cumbrian events using FEH22, FEH13 (Cumbria update), FEH13 and FEH99 rainfall DDF models. The two italicized events were not real events; they are presented to show what the return period of an event recorded at either Honister Pass or Seathwaite Farm would be if it had been recorded at the other.

Location	Date	Depth (mm)	Duration	Return period			
				FEH22	Cumbria	FEH13	FEH99
Honister Pass	Oct 2021	222.6	1 clock day	31	31	118	266
Honister Pass	Oct 2021	343.0	2 clock days	39	38	376	464
Honister Pass	Oct 2021	399.2	3 clock days	35	35	431	541
Honister Pass	Oct 2021	369.0	38 clock hours	67	63	651	658
Honister Pass	Dec 2015	341.4	24 clock hours	146	131	988	1118
Seathwaite Farm	*Dec 2015*	*341.4*	*24 clock hours*	*279*	*253*	*1911*	*236*
Thirlmere	Dec 2015	322.6	24 clock hours	4849	4336	37872	2607
Thirlmere	Dec 2015	405.0	38 clock hours	9163	8293	>100k	4017
Thirlmere	Dec 2015	405.0	2 clock days	7678	7020	>100k	4751
Seathwaite Farm	Nov 2009	316.4	24 clock hours	163	150	980	160
Honister Pass	*Nov 2009*	*316.4*	*24 clock hours*	*92*	*84*	*538*	*757*
Seathwaite Farm	Nov 2009	392.6	36 clock hours	208	192	2604	172
Seathwaite Farm	Nov 2009	456.4	3 clock days	134	132	3224	133
Seathwaite Farm	Nov 2009	495.0	4 clock days	113	113	2847	109

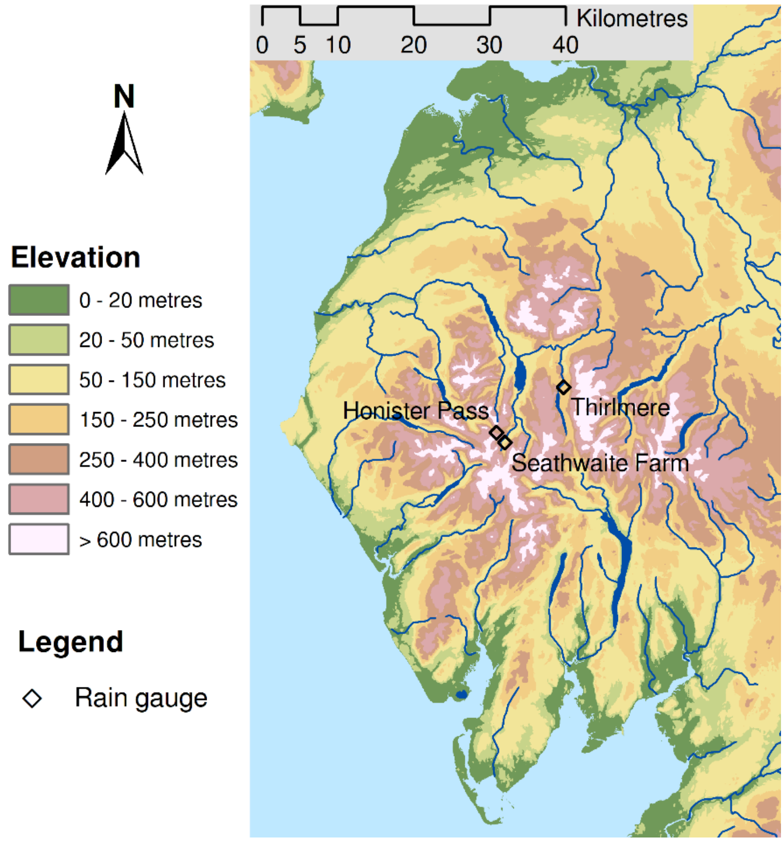

Figure 3 **Map of Cumbria and immediate surrounding area, with locations of Honister Pass, Seathwaite Farm and Thirlmere hourly recording gauges.**

This report is the first to present the return periods of the October 2021 event at Honister Pass, as estimated using FEH DDF methods. In common with the December 2015 event, the return period estimated by FEH13 is shorter than that estimated by FEH99. This is the opposite of what occurs at most locations in the UK, including Seathwaite Farm, which is less than 2 km away. In general, FEH99 estimates are more similar to FEH22 at Seathwaite Farm but more similar to FEH13 at Honister Pass, while the ratios of return periods at Honister Pass to Seathwaite Farm are around 5:1 for FEH99 and 2:1 for each of FEH13 and FEH22. The 5:1 ratio for FEH99 provides an example of the “unsmoothed” spatial behaviour that the FEH13 model was designed to attenuate, and since the Cumbria and FEH22 models are almost identical to the FEH13 model, these also present more gradual spatial changes in DDF relationships than FEH99. Return periods at Seathwaite Farm and Honister Pass are not expected to be overly similar, as Seathwaite Farm is at the bottom of a valley, at 129 mAOD, while Honister Pass is at the top of the pass, at 358 mAOD. However, the two sites may not be so different, as both have similar SAAR (3150 mm at Seathwaite Farm, 3350 mm at Honister Pass) and both have (and fulfilled) the potential for record-breaking rainfalls.

Thirlmere is around 10 km away from Seathwaite Farm and Honister Pass, so all models from FEH99 to FEH22 permit a less-similar DDF relationship. This is justified, as *SAAR* is approximately 2200 mm at Thirlmere. The FEH13 return period of the

December 2015 event at Thirlmere (over 100,000 years) seems particularly questionable, although it is reiterated that the event was not used in calibration of the FEH13 model. The standardized depth of the December 2015 event at Thirlmere event is 4.274, compared to 2.441 for the same event at Honister Pass, so there should be a significant difference in return periods between the two sites. However, the FEH22 model estimates for these two locations do differ by a factor of more than 50, compared to less than five using the FEH99 model (and more than 100 using the FEH13 model).

Vesuviano *et al.* (2021) presented a spatial map of return periods given by the FEH13 and Cumbria models for the maximum 36-hour fall during the November 2009 event. This is not repeated here as, visually, the spatial map of return periods given by the FEH22 model is almost indistinguishable from that given by the Cumbria model. The maximum return period, however, is increased from 503 to 542 years.

5.2 UK overview

FEH22 rainfall depths for four durations (1, 6, 12 and 48 hours) and two return periods (30 and 100 years) are presented in Figure 4 to Figure 11. The range of depths for each of these events is shown in Table 6.

Table 6 Minimum and maximum FEH22 rainfall depths for six representative events.

Event	Minimum depth (mm)	Maximum depth (mm)
1-hour, 30-year	22.2	52.3
1-hour, 100-year	30.3	67.3
12-hour, 30-year	47.3	213.5
12-hour, 100-year	58.1	263.8
48-hour, 30-year	64.1	447.0
48-hour, 100-year	78.8	552.6

The largest 1-hour events for a given return period occur both in very wet areas of the UK (e.g. the Scottish Highlands, Snowdonia) but also in hotter areas that are more likely to experience intense summer convective events (e.g. southern and eastern England). Larger 12- and 48-hour events are much more associated with higher altitudes and average annual rainfalls, especially for the longer (100-year) return period. FEH22 1-hour estimates are driven by data from the hourly gauge network, while 48-hour estimates use data from the daily gauge network. 6- and 12-hour rainfall estimates used for calibration are obtained from the hourly network, but the DDF model is designed to smooth the transition between the daily and hourly networks, so 6- and

12-hour DDF model outputs can be influenced by both (12-hour more so than 6-hour, as 12 hours is closer to 24 hours than is 6 hours).

The FEH22 rainfall depth as a fraction of the FEH13 rainfall depth is presented for five durations (1, 6, 12, 24 and 48 hours) and six return periods (2, 30, 100, 200, 1000 and 10000 years) in Figure 12 to Figure 41. Blue shades represent areas where the FEH22 estimate exceeds the FEH13 estimate, while red shades indicate the opposite.

In general, FEH22 is more similar to FEH13 for longer durations: mean changes from FEH13 to FEH22 are +0.8%, +1.0% and +1.7% for the 24-hour, 30-, 100- and 1000-year events respectively. FEH22 usually gives smaller estimates than FEH13 for shorter durations: mean changes from FEH13 to FEH22 are -2.8%, -5.4% and -11.6% for the 1-hour, 30-, 100- and 1000-year events respectively. The greatest positive changes from FEH13 to FEH22 occur in regions that experienced large rainfalls after 2005/6 (e.g. Cumbria and north Aberdeenshire/Moray) while the greatest negative changes occur in regions where quality control has resulted in the deletion or reduction of large events that were used to calibrate FEH13 (e.g. Cheshire and West Hampshire). The closer (further away) a site is from the location of an added, deleted or revised AMAX, the more the effect of this change is seen at shorter (longer) return periods.

Independently of this, differences between the models typically increase as return period increases, as more extrapolation from the input dataset is required: the mean daily and hourly record lengths are 27 and 21 years respectively, while the record periods are 168 (daily) and 137 (hourly) years; two daily gauges, in Oxford and Armagh, include 168 valid AMAX, for all years from 1853 to 2020 inclusive, while the longest hourly record, at Eskdalemuir, includes 105 valid AMAX for all years from 1910 to 2016 inclusive, except 1938 and 1939. Differences are also greater for shorter durations, for three reasons. Firstly, the change in gauging density and data availability is greater for hourly than daily gauges (Table 1 and Table 2), not only because completely new gauges were made available, but also because some gauges that had insufficient data to contribute to FEH13 had gained sufficient data in the intervening years to contribute to FEH22. Secondly, the increased density of hourly gauges means that the effects of large rainfalls do not propagate as far in the FEH22 model as in FEH13. This is a function of the FORGEX methodology, which assigns return periods to extreme events based on the number of effective gauge-years existing in a radius between the site of interest and the site at which the extreme event was recorded. Increasing the gauging density effectively places an extreme event “further away”, in terms of gauge-years, from a given distant point. Thirdly, the Environment Agency, SEPA and Cyfoeth Naturiol Cymru performed a review on recorded rainfall event data for all extracted annual maximum rainfalls larger than 50 mm in 1 hour or 100 mm in 6 hours. These threshold values were chosen as a level of “extreme” that included the events with the largest range of influence but excluded smaller events that appeared more plausible and had a smaller range of influence. This review resulted in the rejection of several large rainfalls that were used to calibrate the FEH13 model (the full review is included in this report’s Appendix). The largest changes between FEH22 and FEH13 do not necessarily occur exactly at sites where new extreme values were recorded (or existing ones were removed); they may also occur at sites between those where several extreme values were added or removed. In general, the effects of adding/deleting/revising individual significant AMAX values are greater than the effects of increased gauging density or record length, as a “further away” event still has an effect, whereas a deleted one doesn’t.

Smaller differences between the FEH22 and FEH13 estimates generally relate to sampling variability. The mean record lengths in the FEH13 model were 26.4 (daily) and 17.5 (hourly) years. Hence, the addition of just a few years to any record could significantly alter the distribution of the maxima. Finally, since the FEH22 and FEH13 models were fitted jointly to all durations, there is a gradual change in behaviour as duration increases from 1 to 24 hours, as the influence of the daily gauging network is introduced gradually.

At a few locations (Isle of Man, Cumbria, Skye, Shetland/Orkney, Aberdeenshire/Banffshire, and Norfolk), FEH22 presents consistently increased rainfall depth estimates over FEH13, even at the shortest durations and longest return periods. In all cases, this is the result of the FEH22 dataset capturing extreme events that were either missed by the FEH13 dataset or had not yet occurred by 2006. Particular FEH22-only extreme events include Seathwaite Farm/Honister Pass (2009 and 2015), Ronaldsway, Isle of Man (2011), Alltdearg House, Skye (new gauge record added to FEH22), Fair Isle (2014) and East Wretham, Norfolk (2020). The large increases in Aberdeenshire/Banffshire are the combined effect of several FEH22-only events, in Bogmuchalls, Aberdeenshire (2014 and 2017), Dipple, Banffshire (2009 and 2014) and Keith, Banffshire (2009).

The FEH22 rainfall depth is presented as a fraction of the FEH99 rainfall depth for the same five durations and six frequencies in Figure 42 to Figure 71. There is more variation in these fractions, especially over short distances in wet areas, as FEH99 estimates can vary greatly over short distances in wet areas; the post-processing applied to both the FEH13 and FEH22 model outputs smooths over the most extreme short-distance variations. Additionally, the FEH99 model structure is very different from, and simpler than, the FEH22/FEH13 model structure, so larger differences that do not strictly follow the patterns of recent extreme events or increased gauging density are expected.

FEH22 estimates are generally larger than FEH99 estimates for shorter durations and return periods. As return periods increase to 1000 years, the areas where FEH22 estimates exceed FEH99 estimates at all durations recede to Aberdeenshire/Banffshire and Shetland/Orkney, both areas that have experienced extreme events since 2006 and were sparsely gauged during FEH99 development. For longer durations, other areas where FEH22 exceeds FEH99 include Cumbria and Norfolk, which experienced extreme events post-2006, and Devon/Cornwall, which was very sparsely gauged for FEH99. FEH22 estimates also exceed FEH99 estimates across Northern Ireland for all durations.

For the 10000-year return period, FEH22 estimates are almost uniformly smaller than FEH99 estimates, often greatly so. This is unsurprising as, for extrapolation, FEH99 fits a linear relationship between the logarithm of rainfall depth and the logarithm of return period, while FEH22 and FEH13 fit a linear relationship between untransformed rainfall depth and the logarithm of return period. The FEH99 relationship results in FEH99 rainfall depths growing massively for return periods above 1000 years, its design limit. The small areas where FEH22 10000-year estimates exceed FEH99 10000-year estimates include Fair Isle and Aberdeenshire/Banffshire, due to improved gauging and recent extreme events, and also around Edinburgh and Strangford Lough, Northern Ireland, at specific durations. It is restated here that, between the release of FEH99 and FEH13, the Institution of Civil Engineers returned to recommending the use of the FSR DDF model for 10000-year return period events (ICE 2015).

Finally, FEH22 1000:100-year growth factors are compared to FEH13 1000:100-year growth factors in Figure 72 to Figure 76. As suggested by the separate maps of 1000- and 100-year FEH22 versus FEH13 rainfall depth, FEH22 growth curves are generally flatter than FEH13 growth curve for short durations, but the two are more similar for daily and longer durations. In north Scotland, Cumbria, Anglesey and the Isle of Man, FEH22 growth curves are generally steeper than FEH13 growth curves for all durations. This is due to the influence of recent extreme events recorded in both the hourly and daily data, as identified in previous paragraphs.

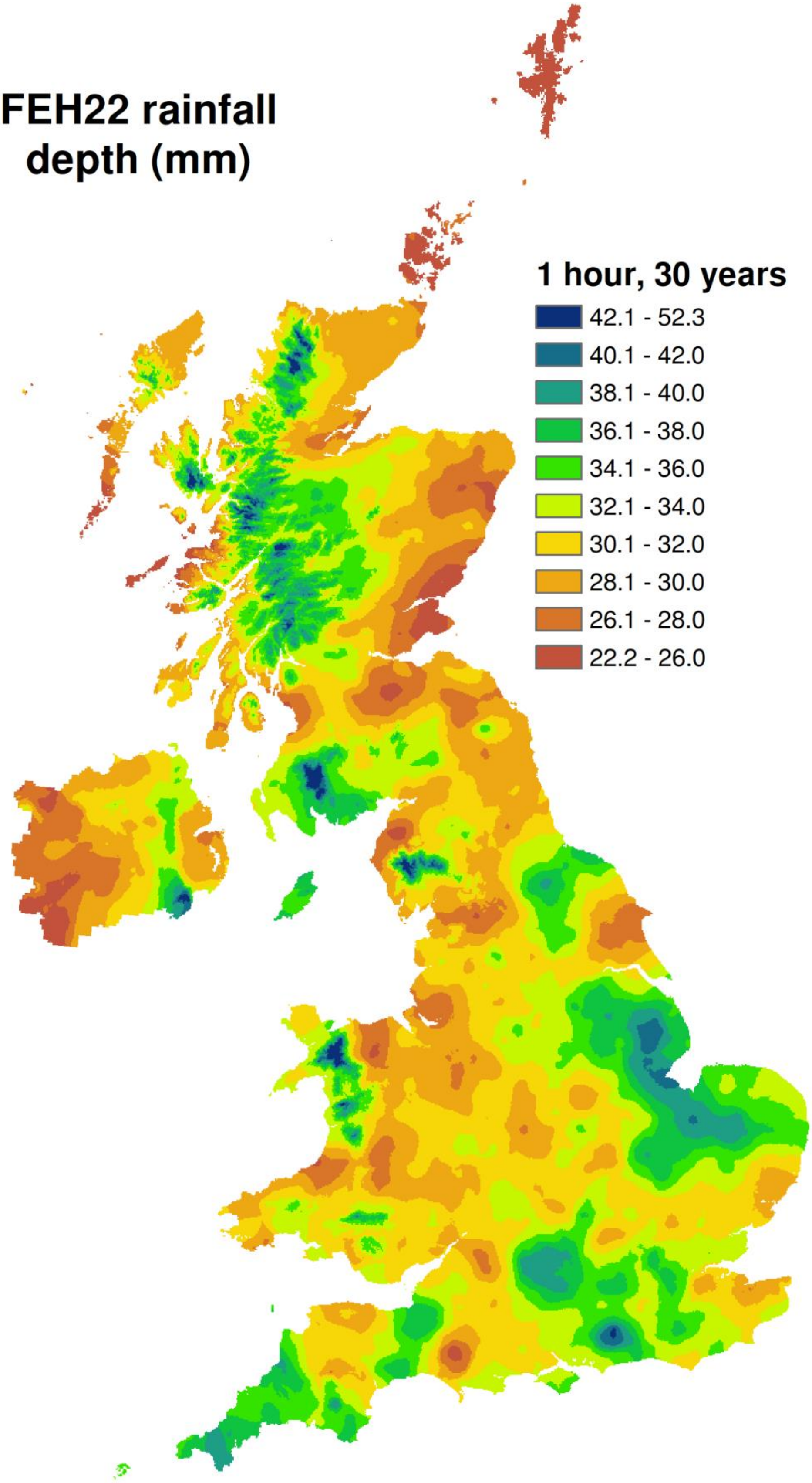

Figure 4 FEH22 rainfall depth (mm): 1-hour, 30-year event.

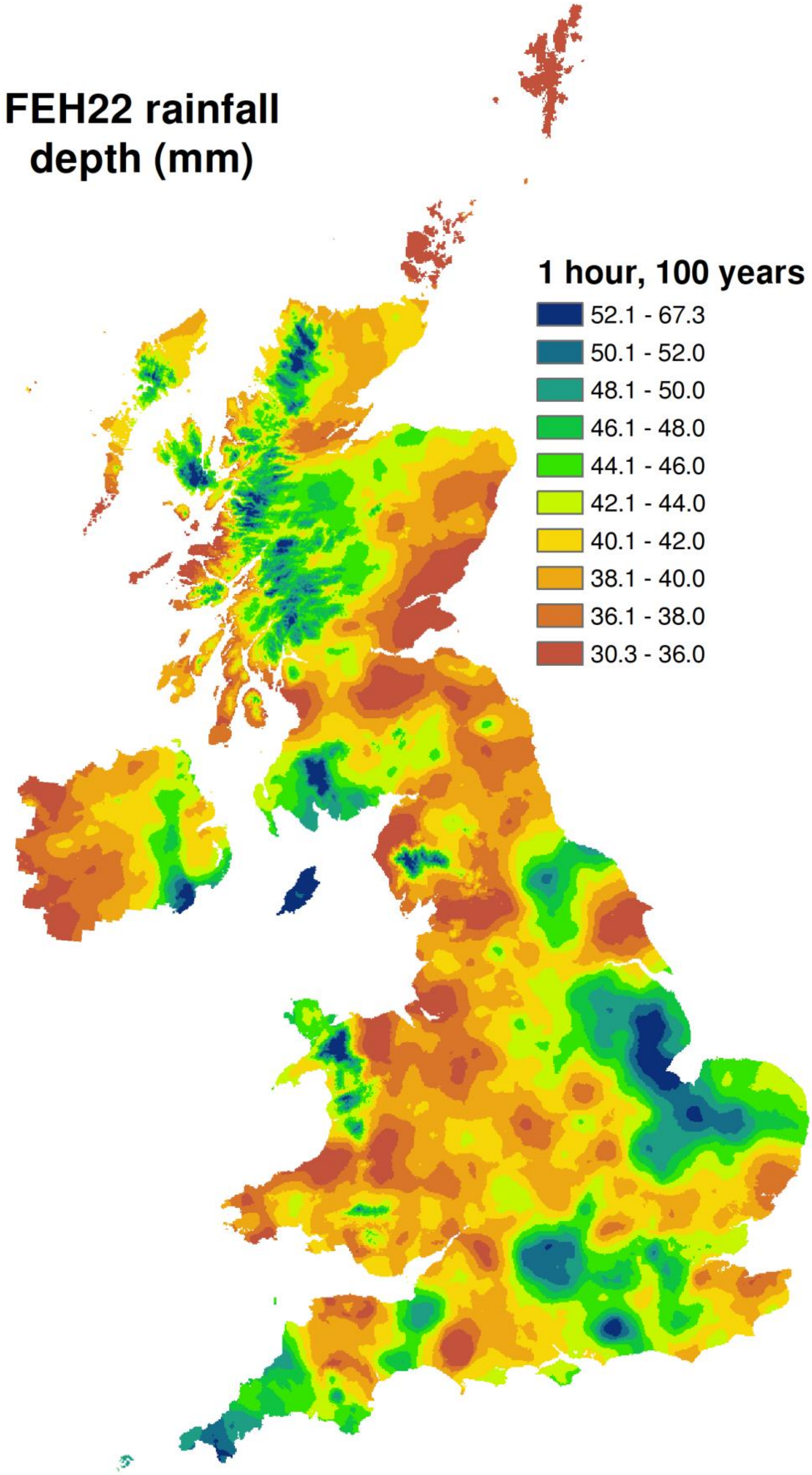

Figure 5 FEH22 rainfall depth (mm): 1-hour, 100-year event.

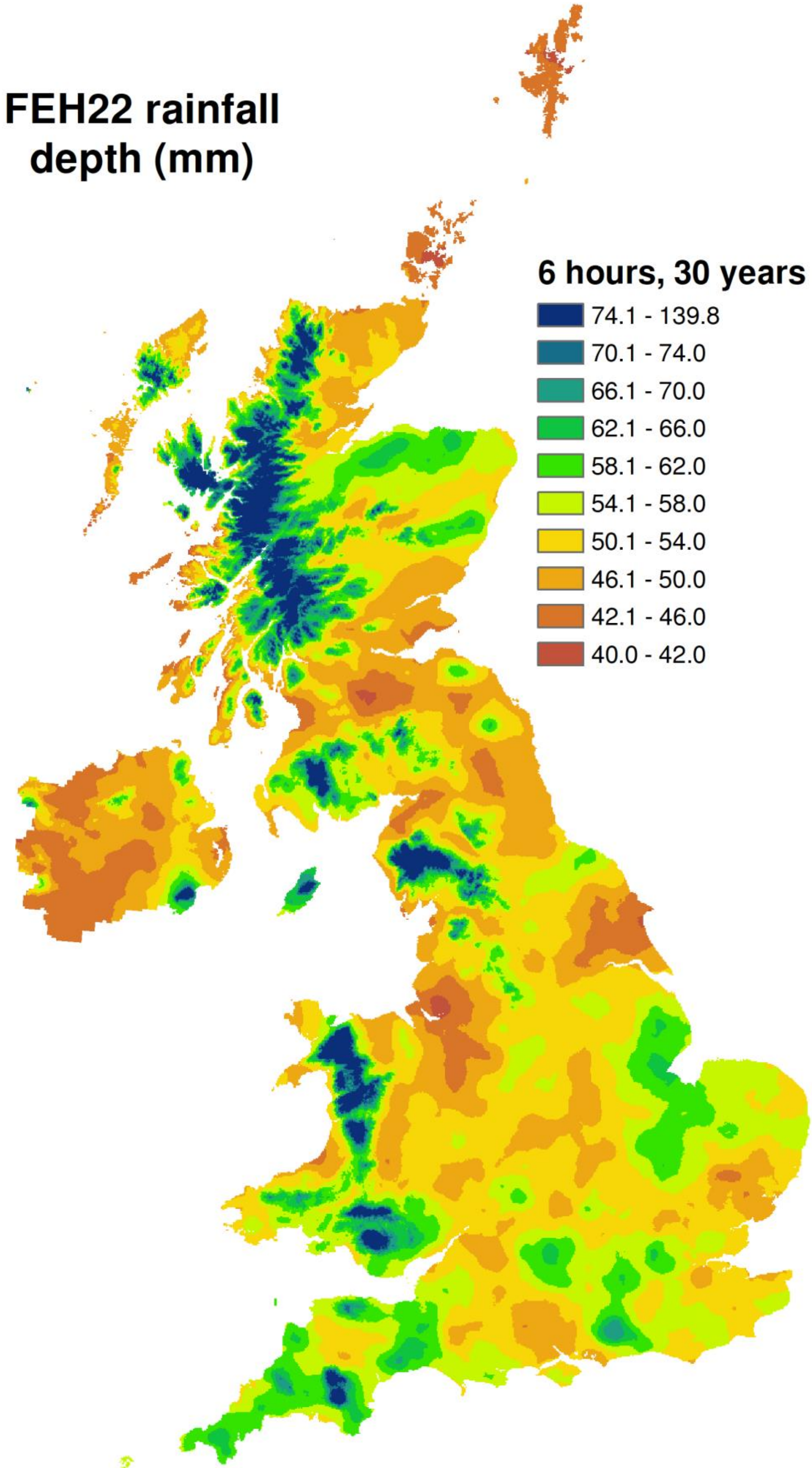

Figure 6 FEH22 rainfall depth (mm): 6-hour, 30-year event.

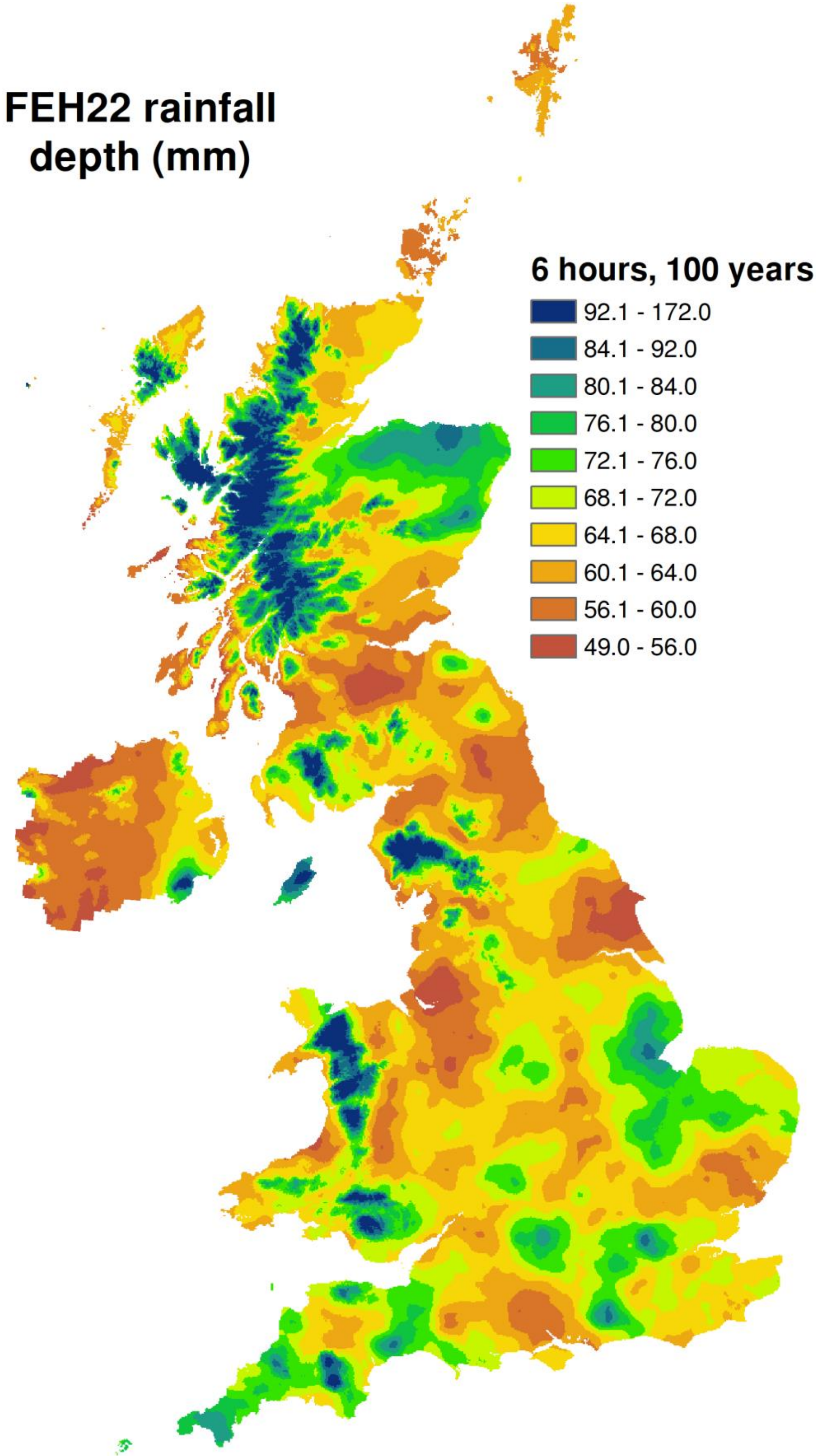

Figure 7 FEH22 rainfall depth (mm): 6-hour, 100-year event.

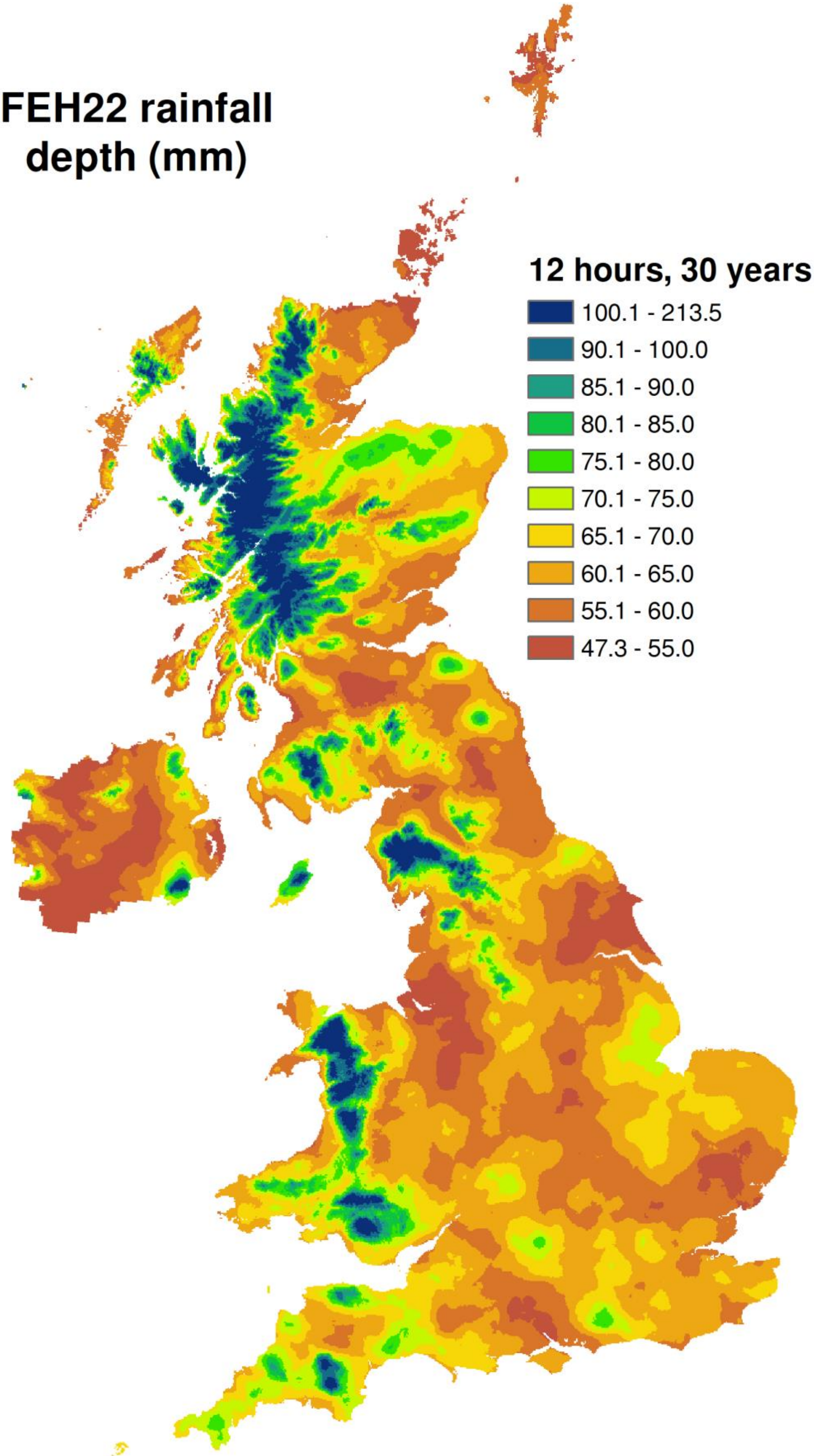

Figure 8 FEH22 rainfall depth (mm): 12-hour, 30-year event.

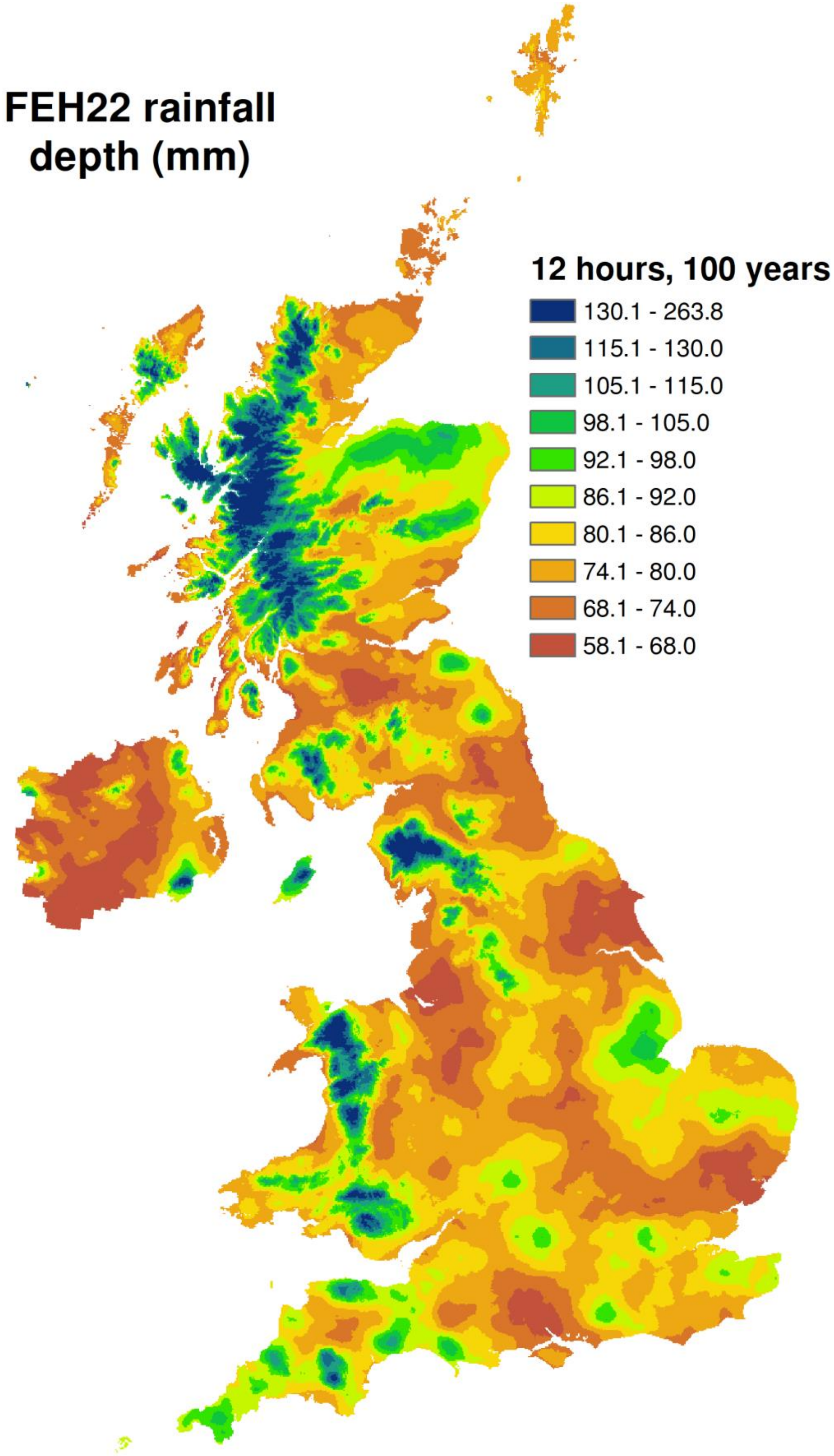

Figure 9 FEH22 rainfall depth (mm): 12-hour, 100-year event.

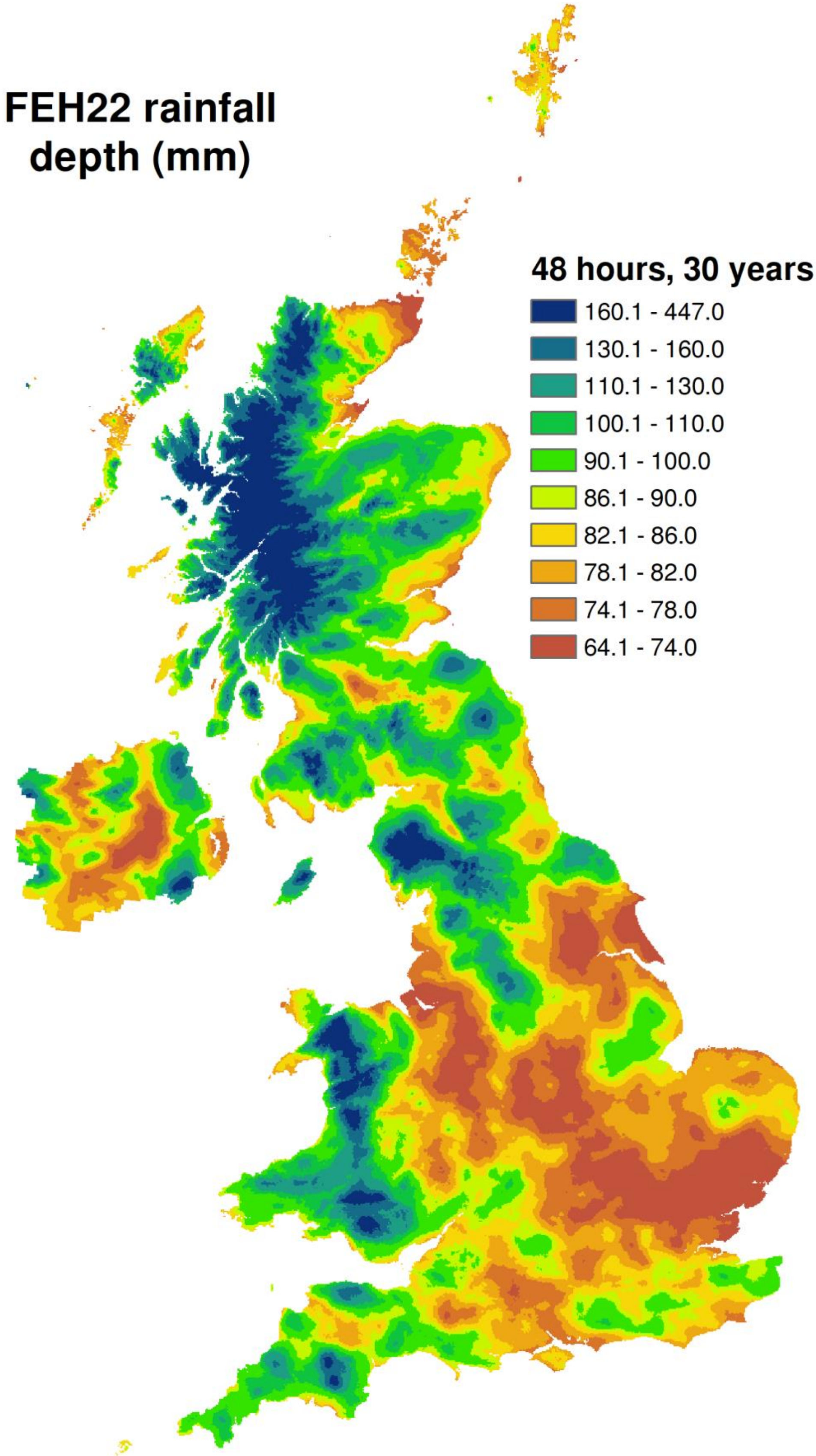

Figure 10 FEH22 rainfall depth (mm): 48-hour, 30-year event.

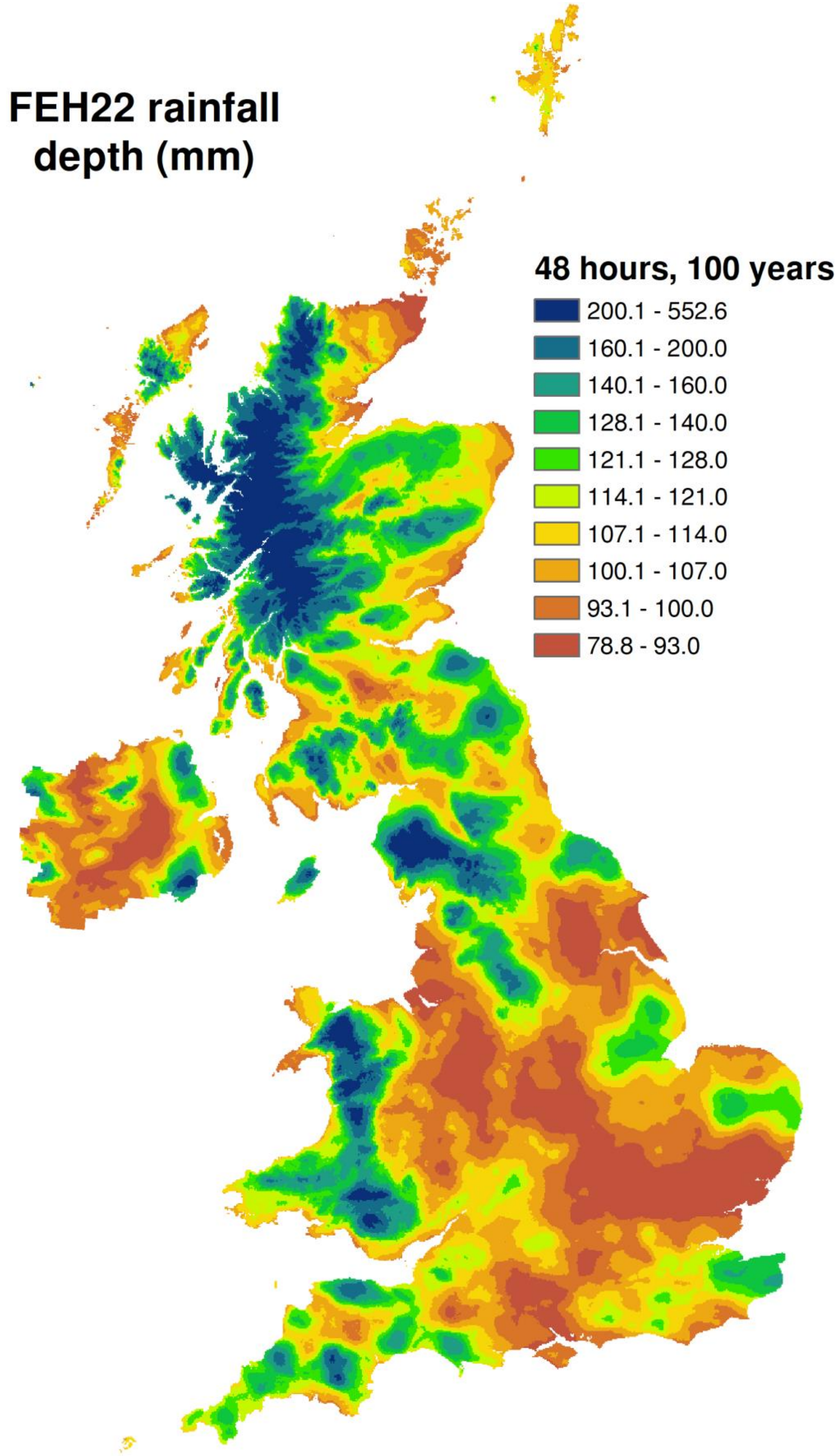

Figure 11 FEH22 rainfall depth (mm): 48-hour, 100-year event.

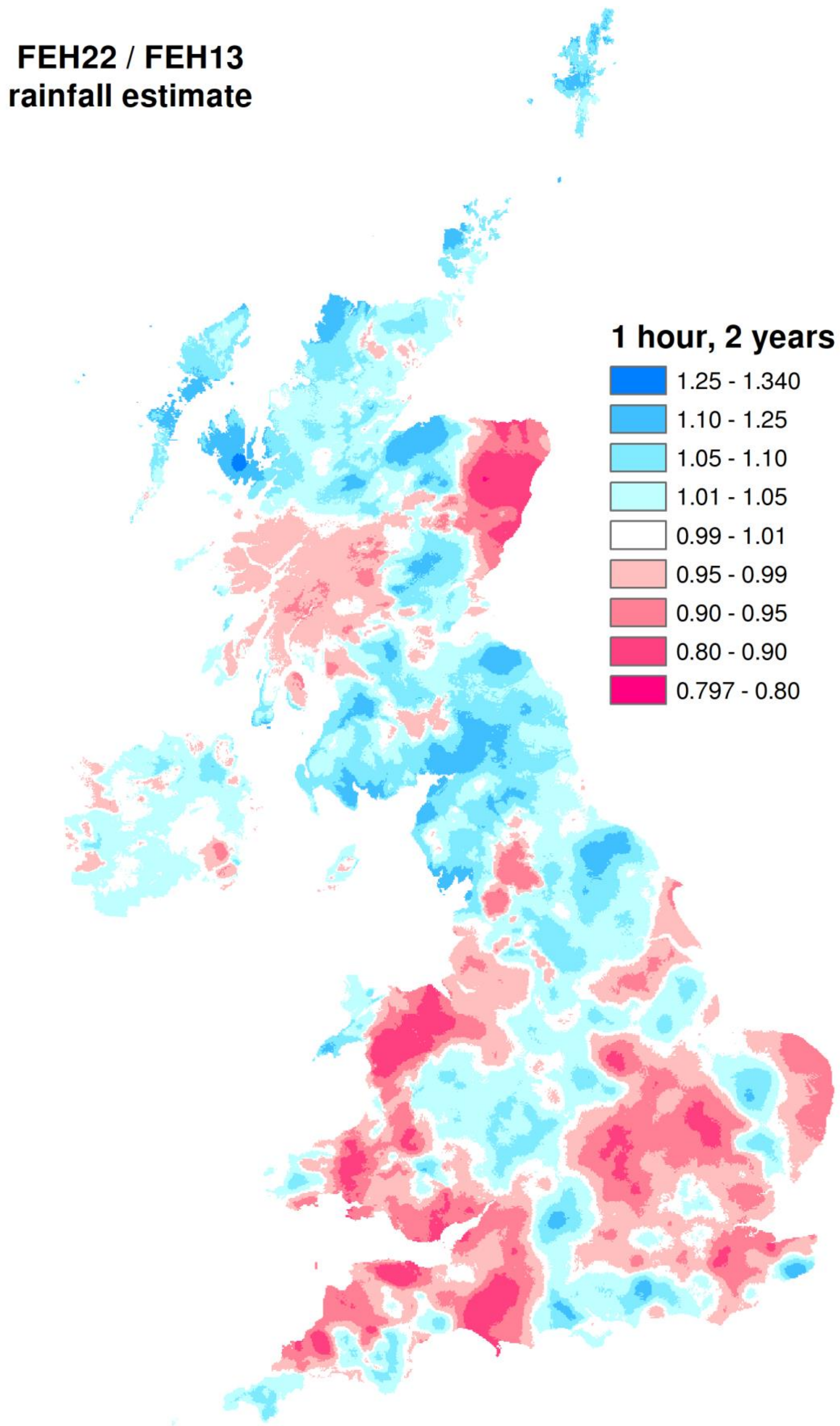

Figure 12 **FEH22 rainfall depth as fraction of FEH13 rainfall depth: 1-hour, 2-year event.**

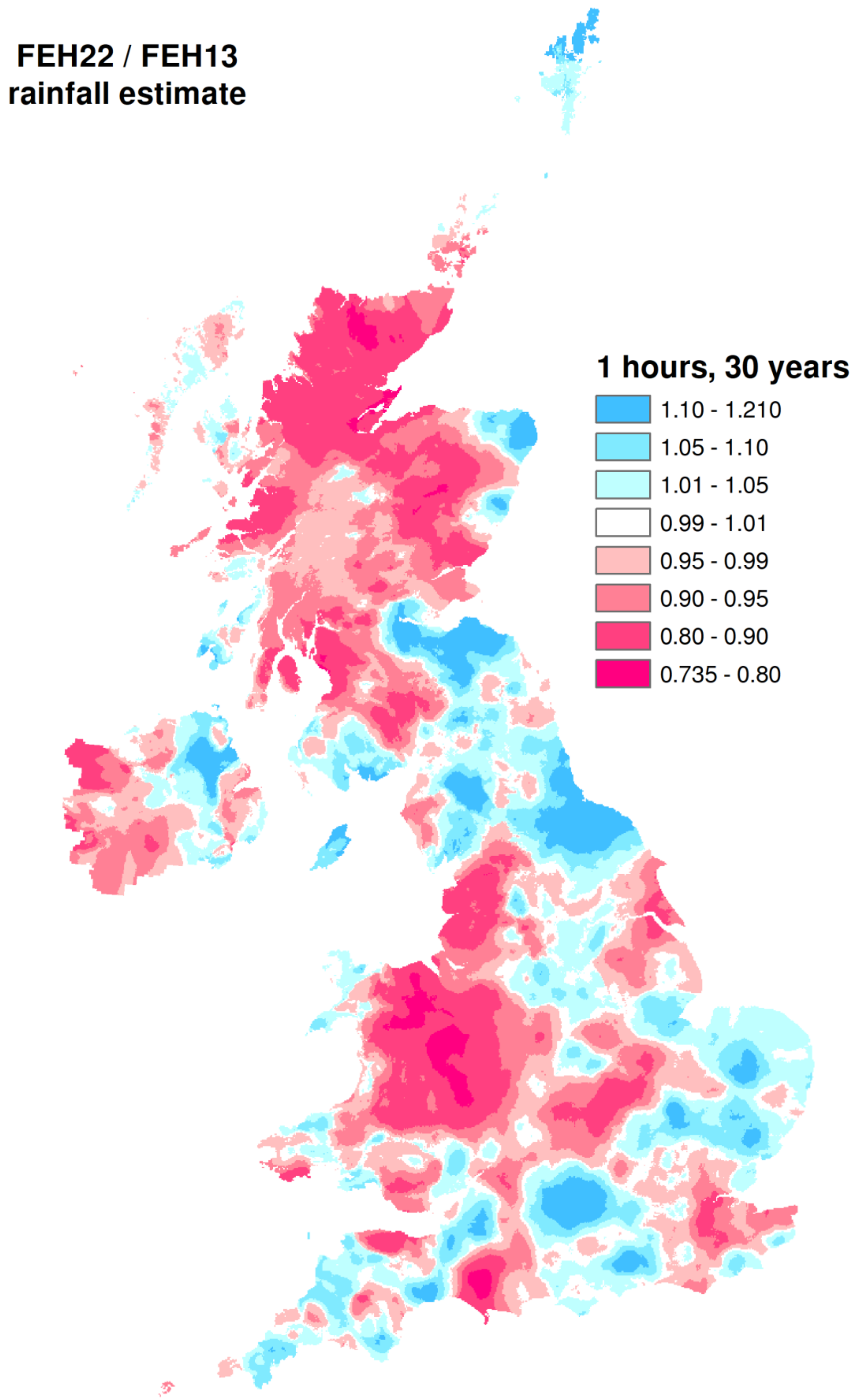

Figure 13 FEH22 rainfall depth as fraction of FEH13 rainfall depth: 1-hour, 30-year event.

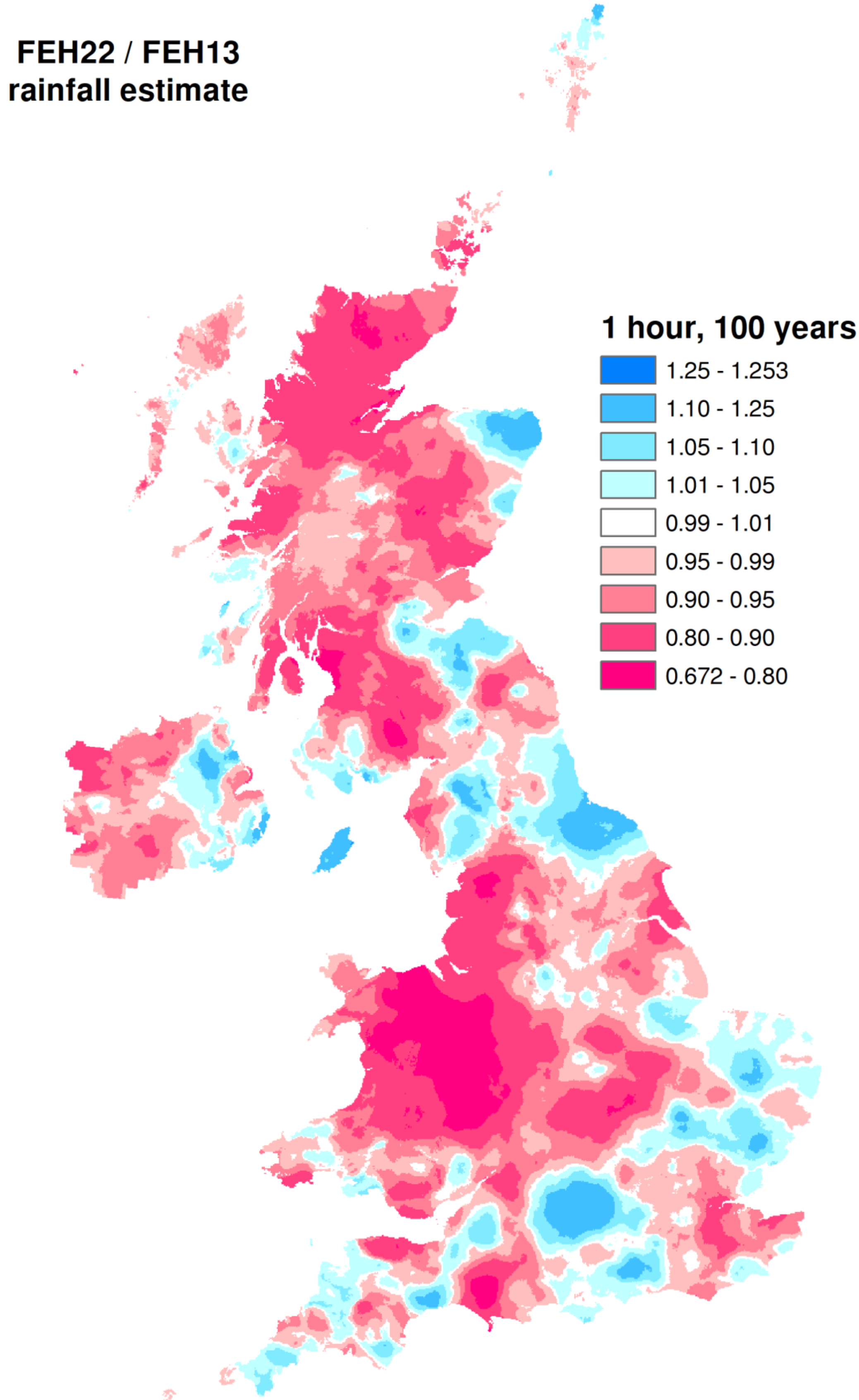

Figure 14 **FEH22 rainfall depth as fraction of FEH13 rainfall depth: 1-hour, 100-year event.**

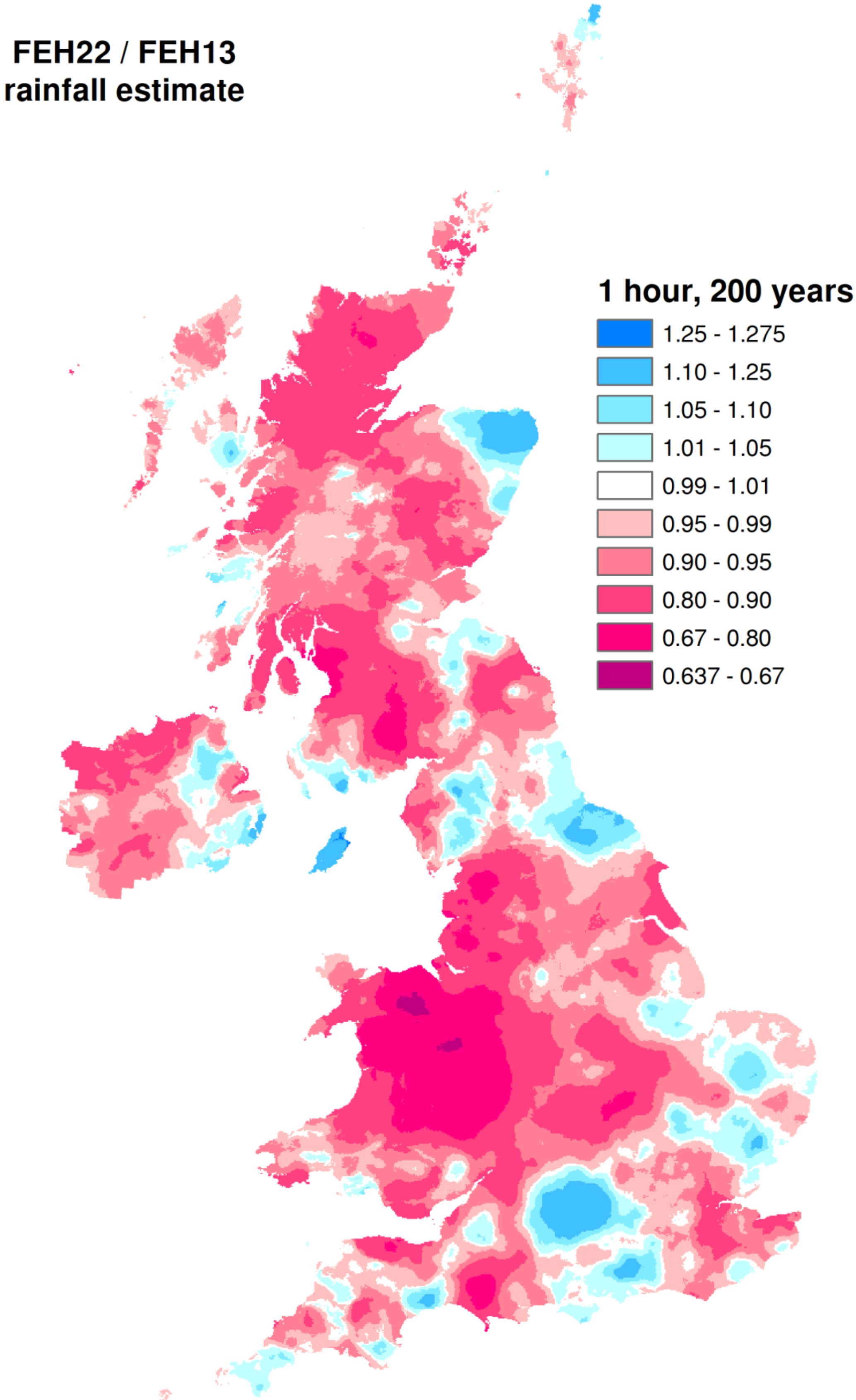

Figure 15 FEH22 rainfall depth as fraction of FEH13 rainfall depth: 1-hour, 200-year event.

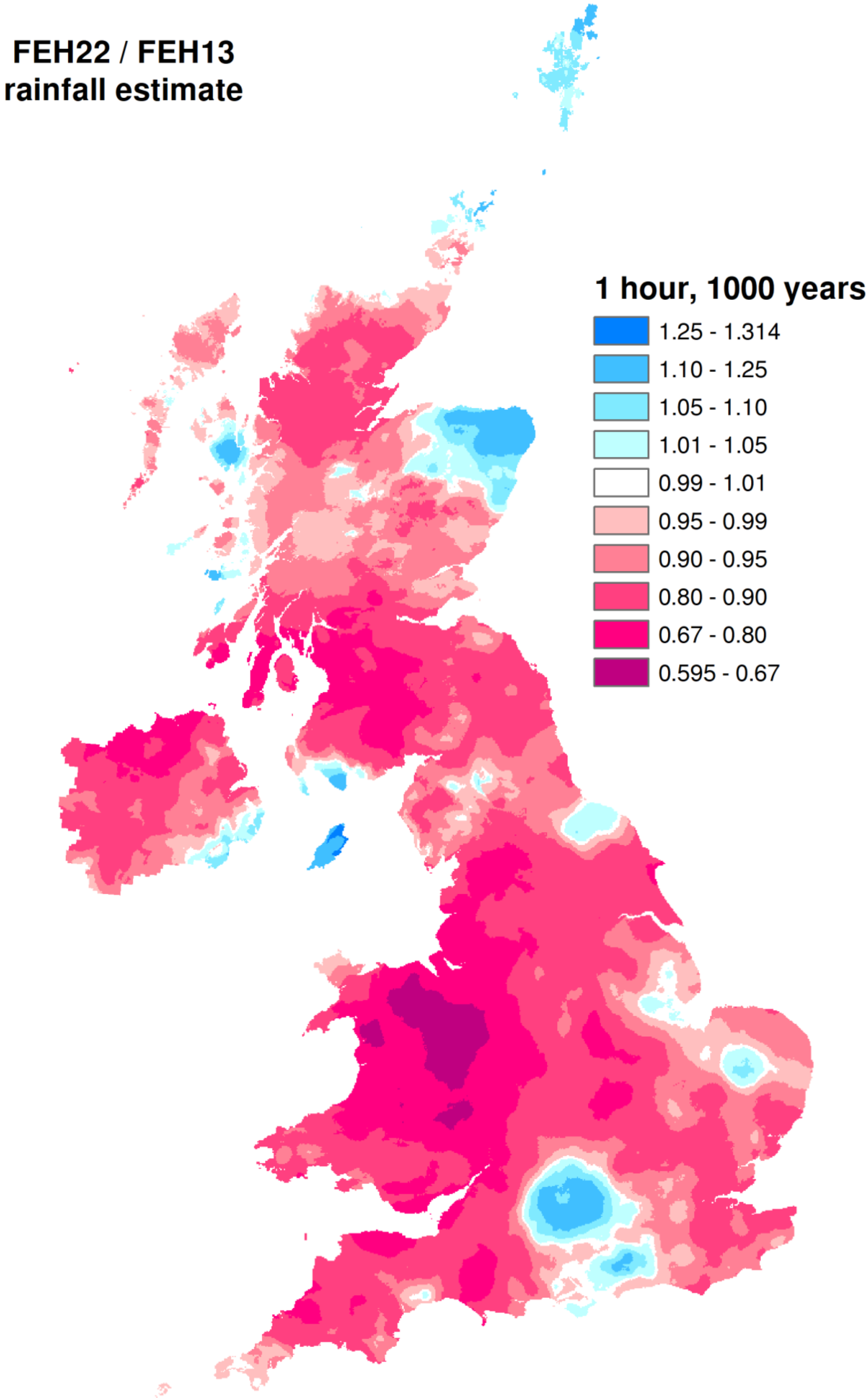

Figure 16 **FEH22 rainfall depth as fraction of FEH13 rainfall depth: 1-hour, 1000-year event.**

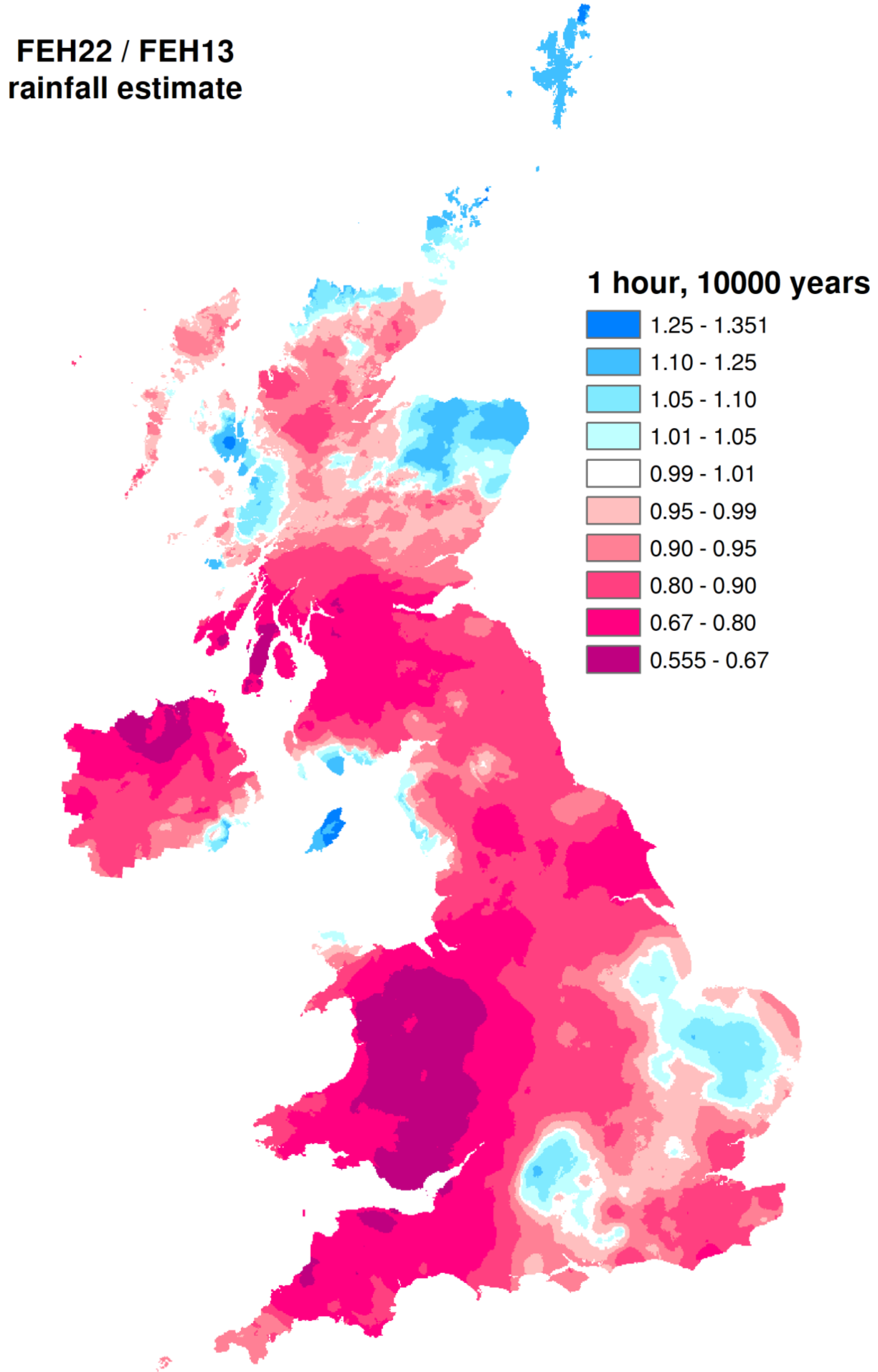

Figure 17 **FEH22 rainfall depth as fraction of FEH13 rainfall depth: 1-hour, 10000-year event.**

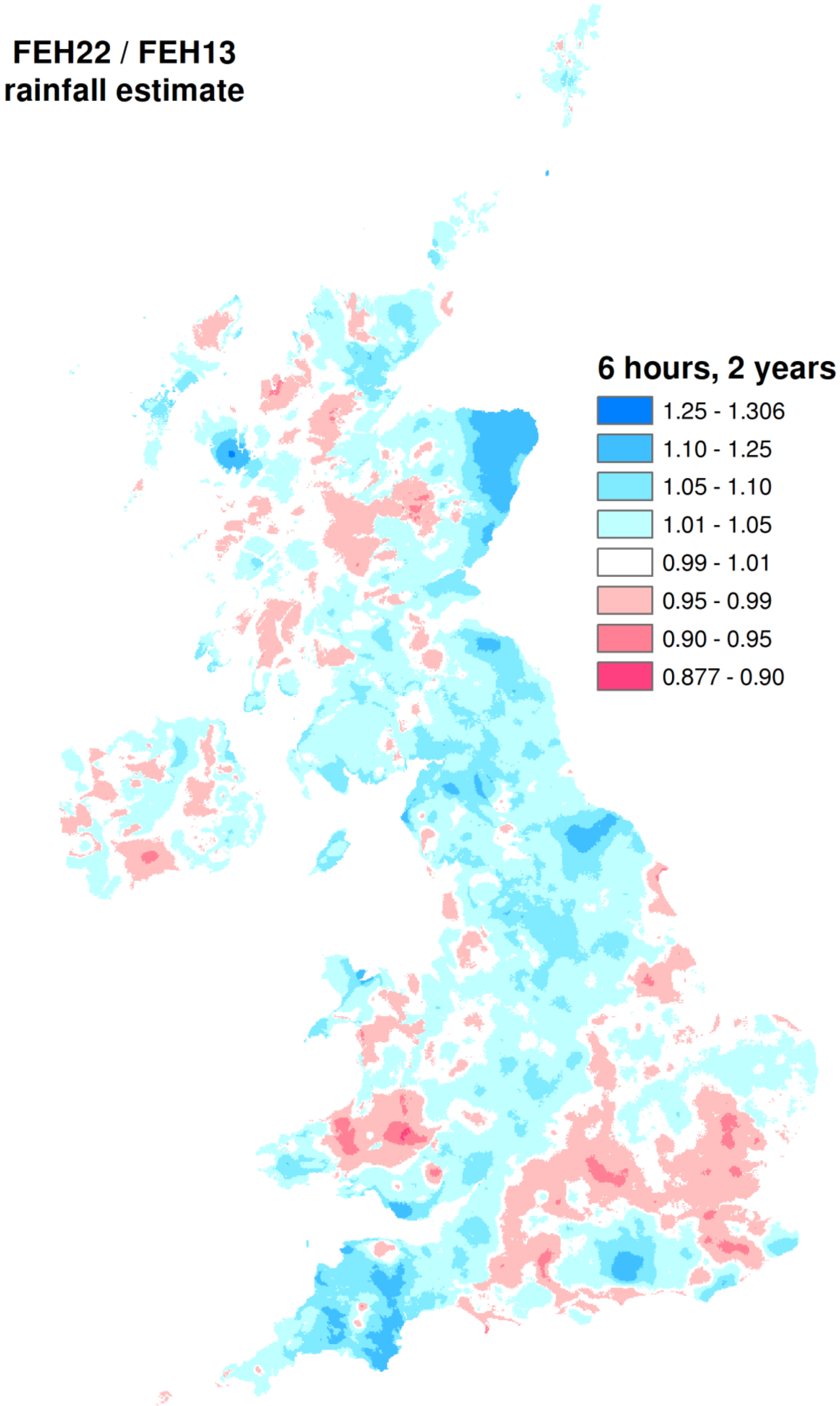

Figure 18 FEH22 rainfall depth as fraction of FEH13 rainfall depth: 6-hour, 2-year event.

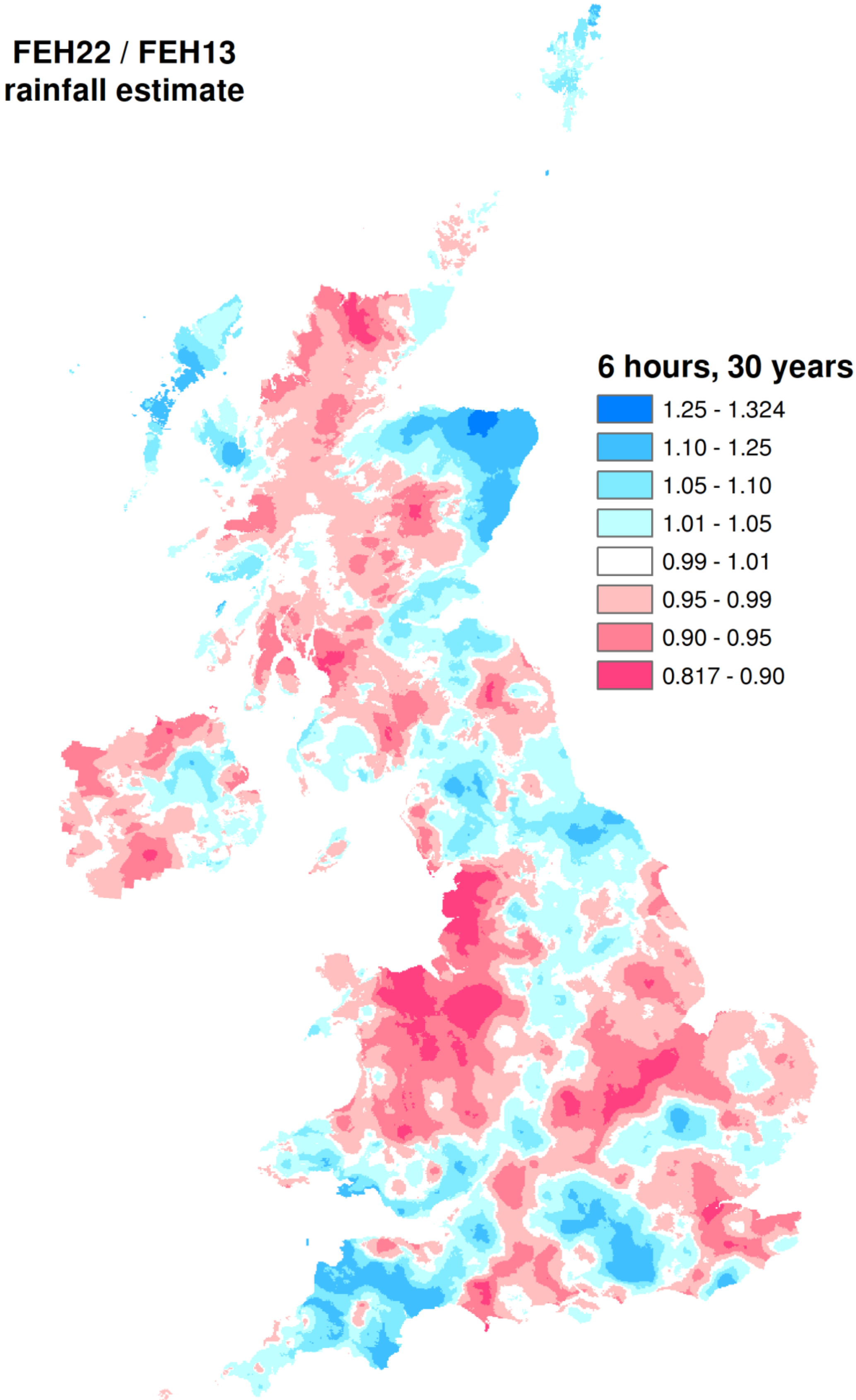

Figure 19 **FEH22 rainfall depth as fraction of FEH13 rainfall depth: 6-hour, 30-year event.**

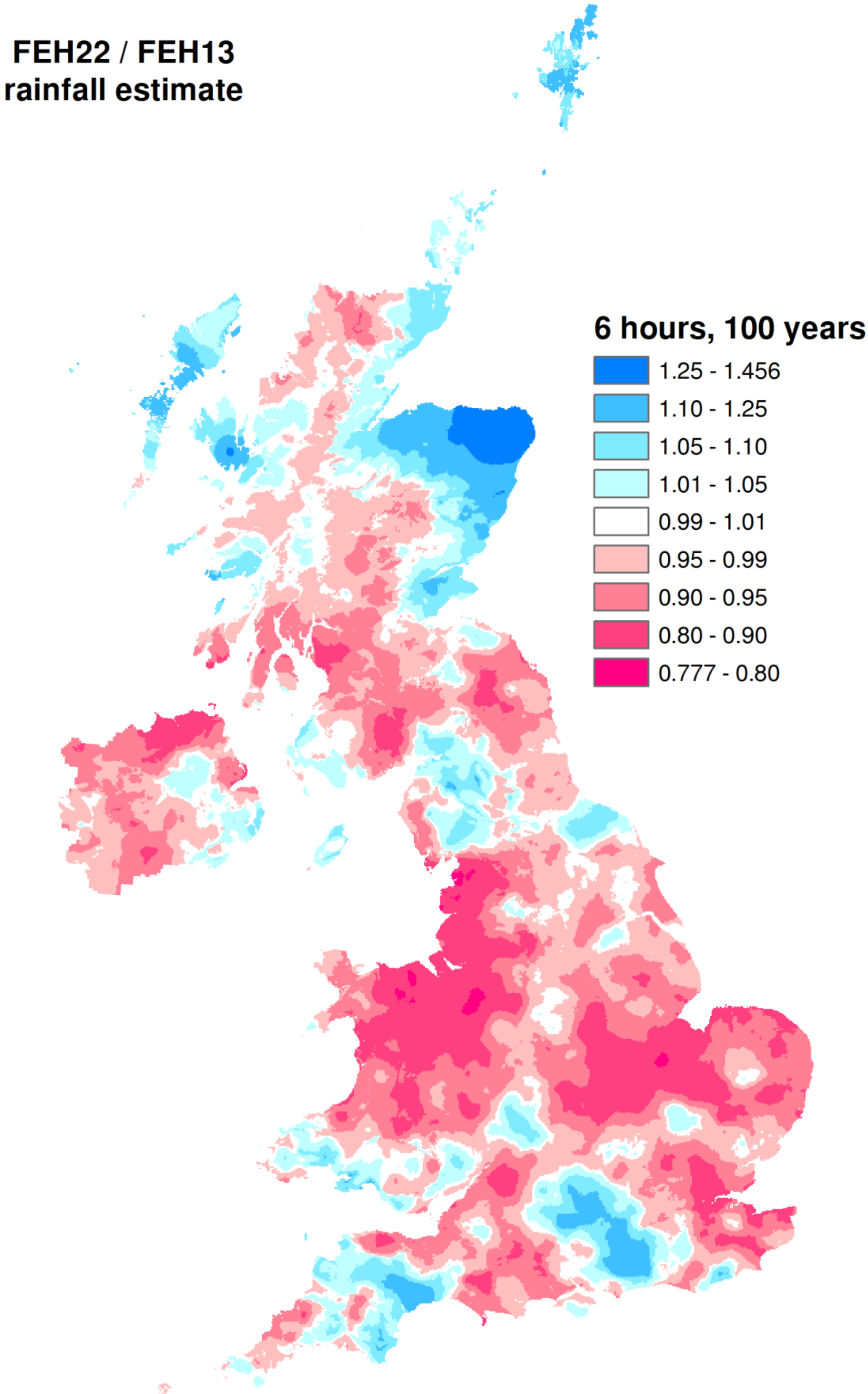

Figure 20 FEH22 rainfall depth as fraction of FEH13 rainfall depth: 6-hour, 100-year event.

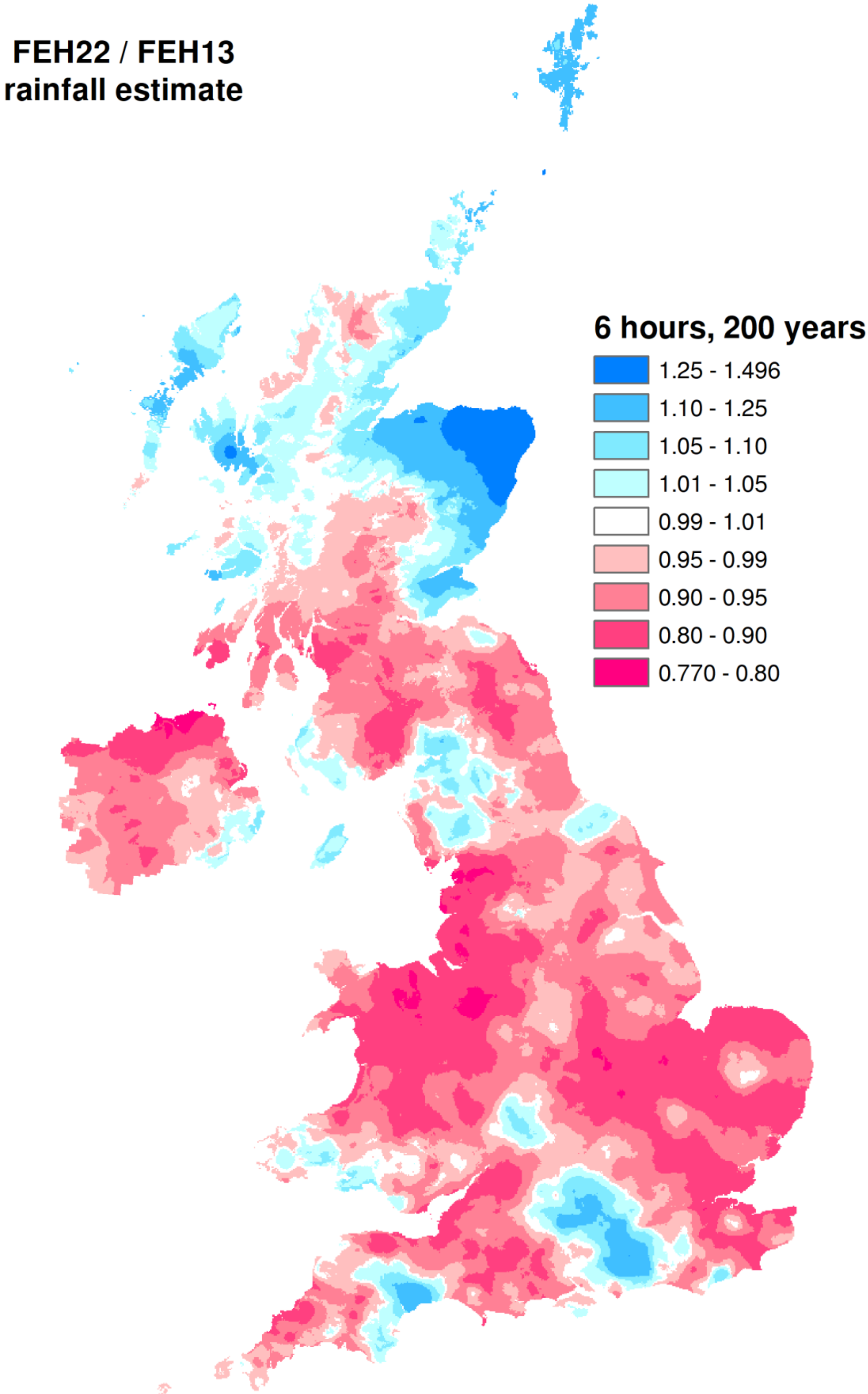

Figure 21 FEH22 rainfall depth as fraction of FEH13 rainfall depth: 6-hour, 200-year event.

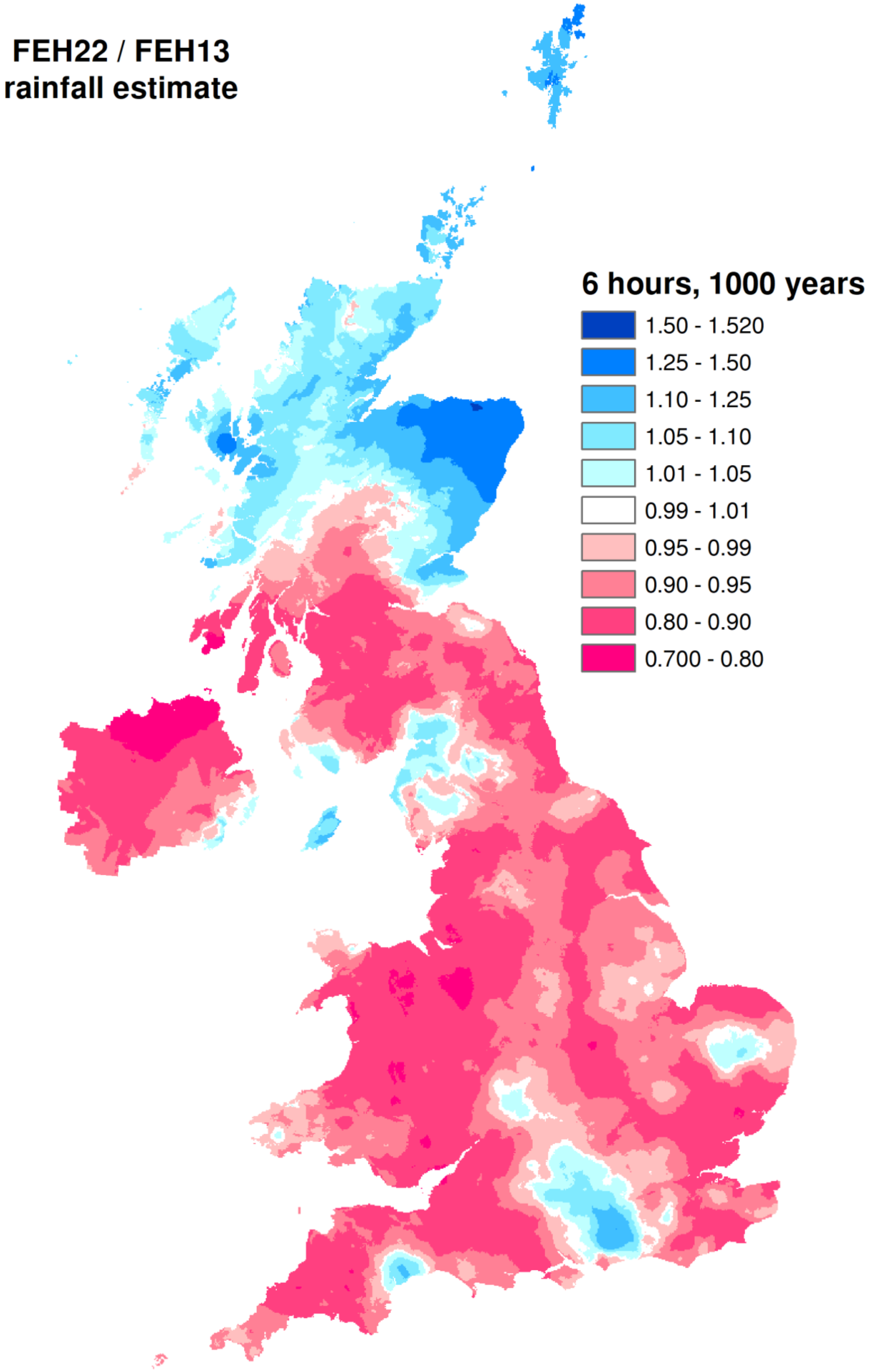

Figure 22 **FEH22 rainfall depth as fraction of FEH13 rainfall depth: 6-hour, 1000-year event.**

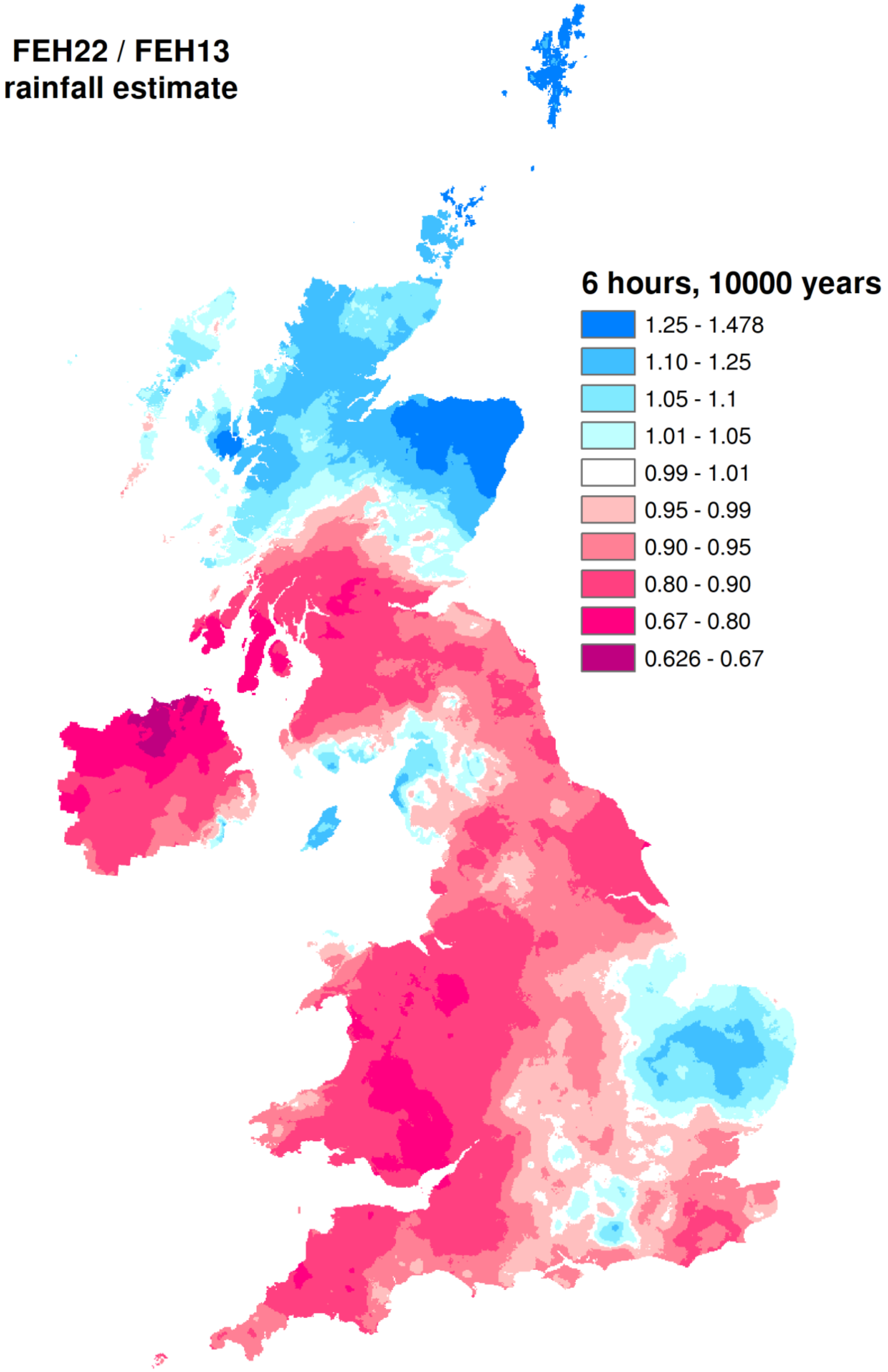

Figure 23 **FEH22 rainfall depth as fraction of FEH13 rainfall depth: 6-hour, 10000-year event.**

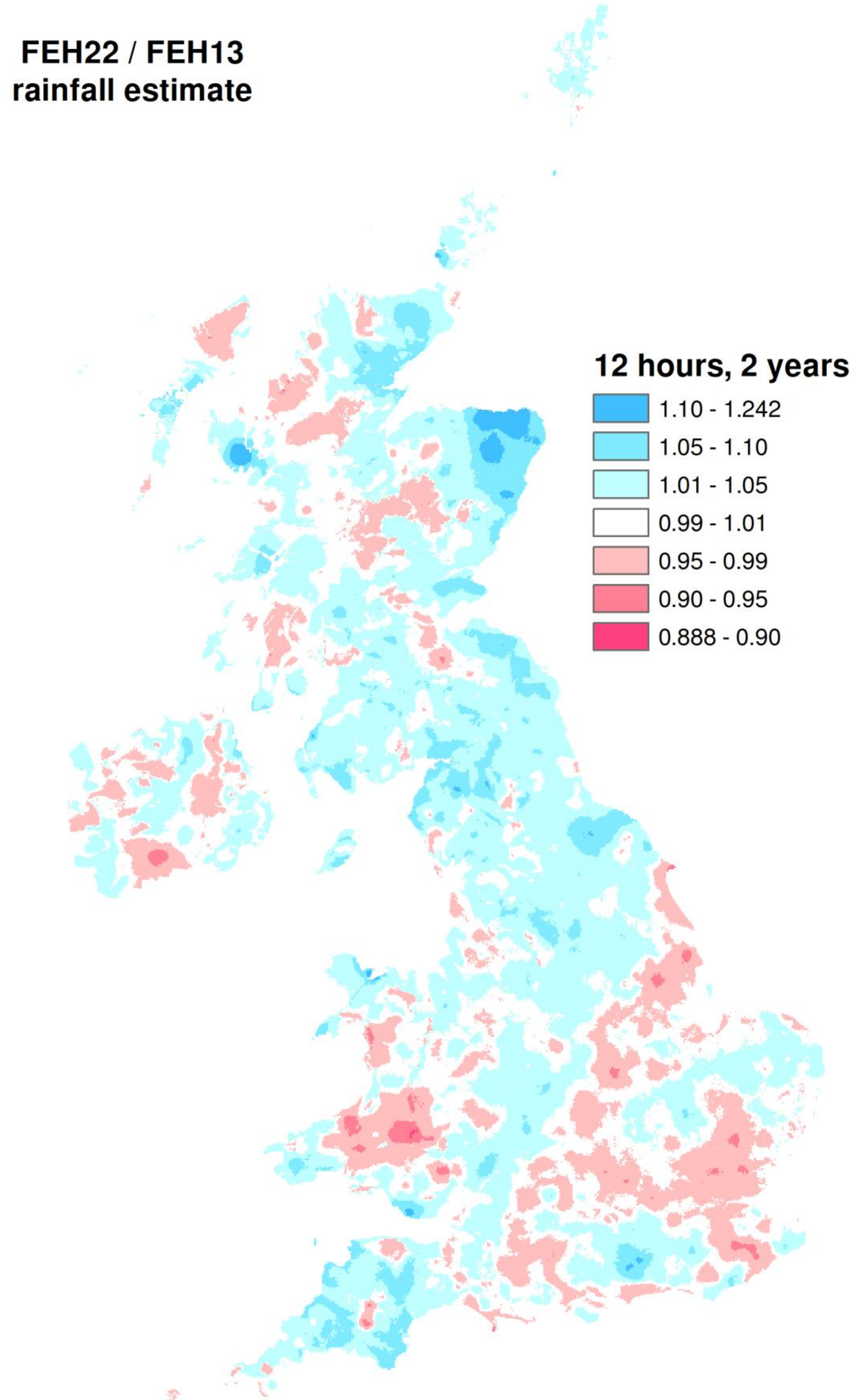

Figure 24 FEH22 rainfall depth as fraction of FEH13 rainfall depth: 12-hour, 2-year event.

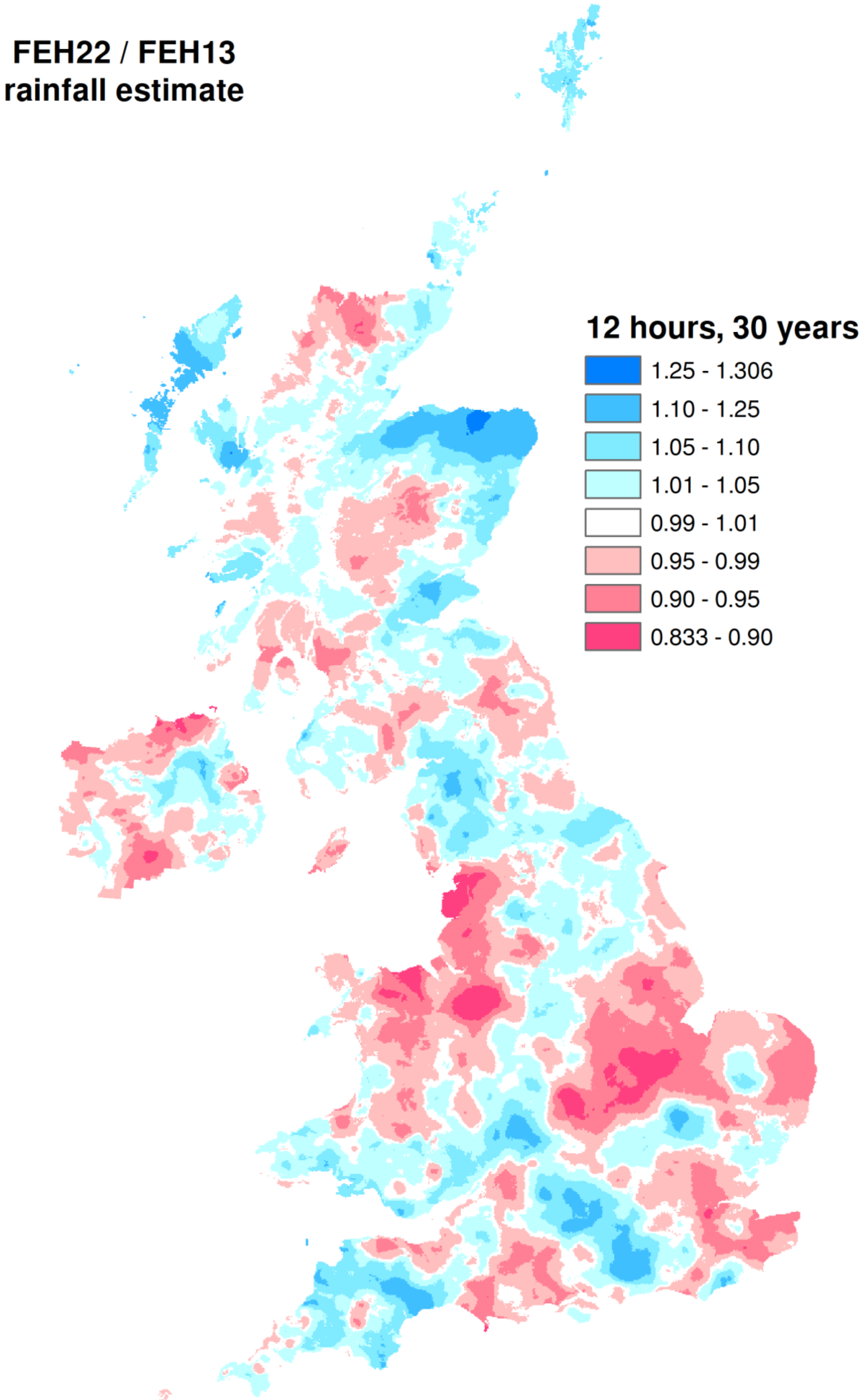

Figure 25 FEH22 rainfall depth as fraction of FEH13 rainfall depth: 12-hour, 30-year event.

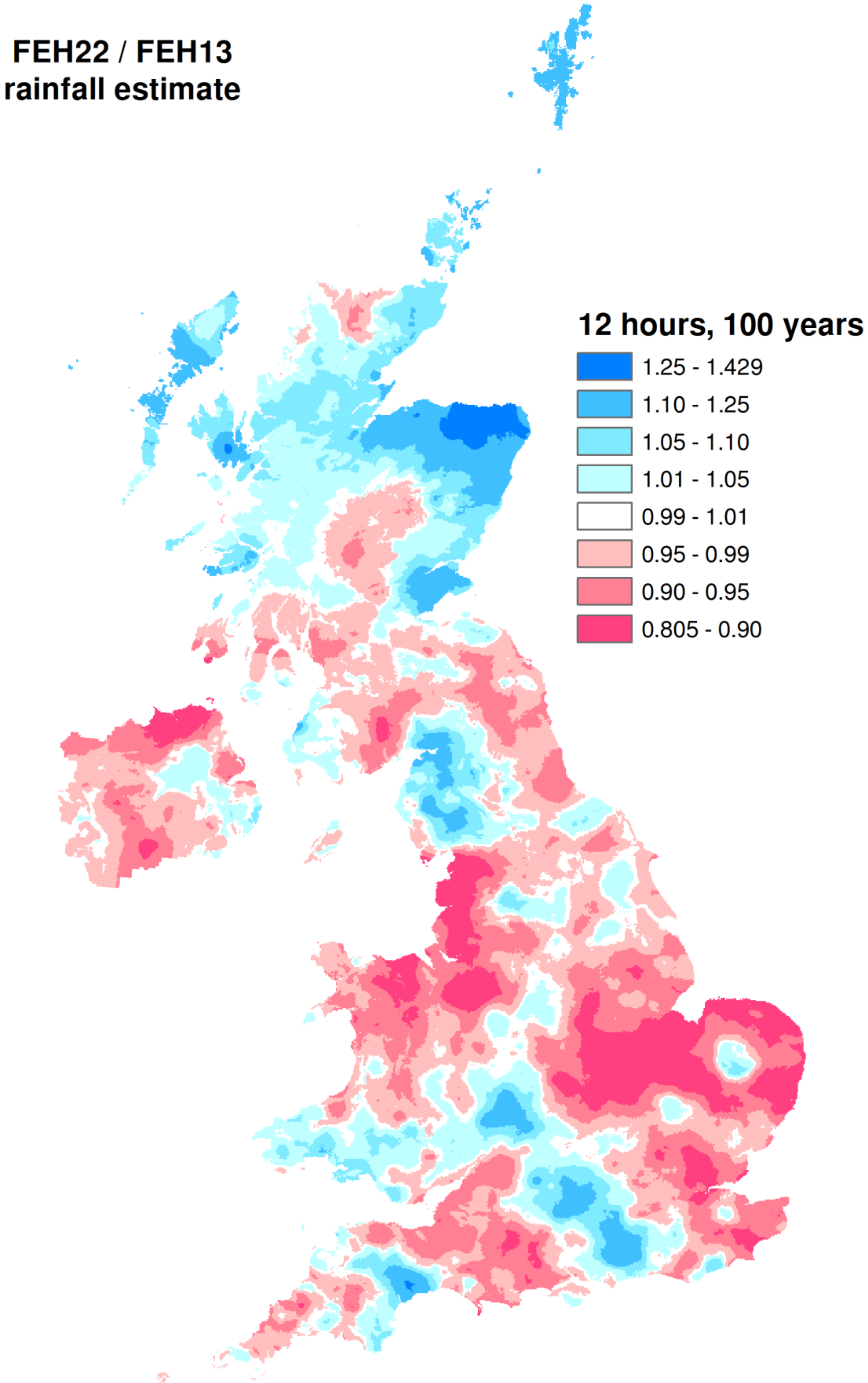

Figure 26 **FEH22 rainfall depth as fraction of FEH13 rainfall depth: 12-hour, 100-year event.**

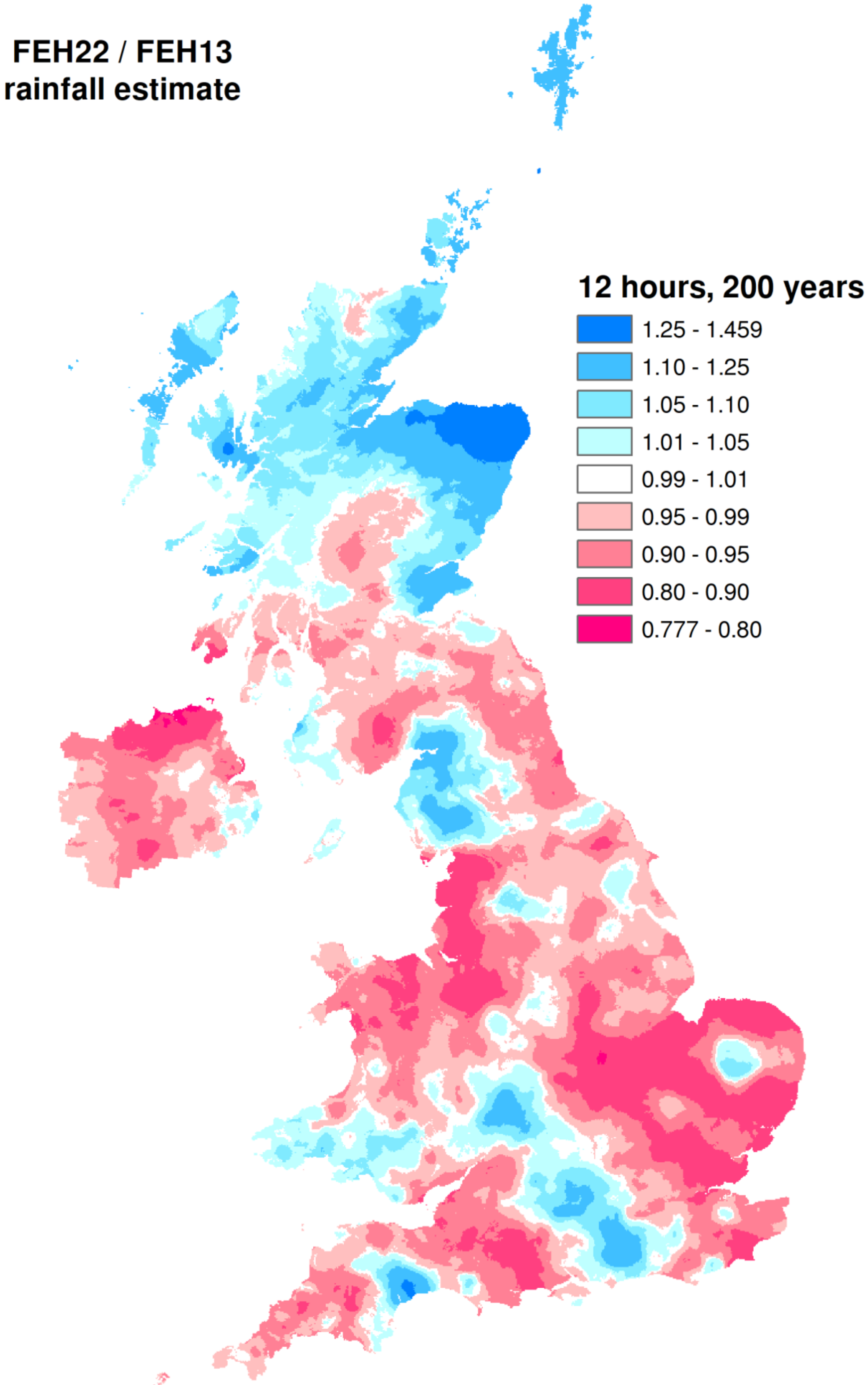

Figure 27 FEH22 rainfall depth as fraction of FEH13 rainfall depth: 12-hour, 200-year event.

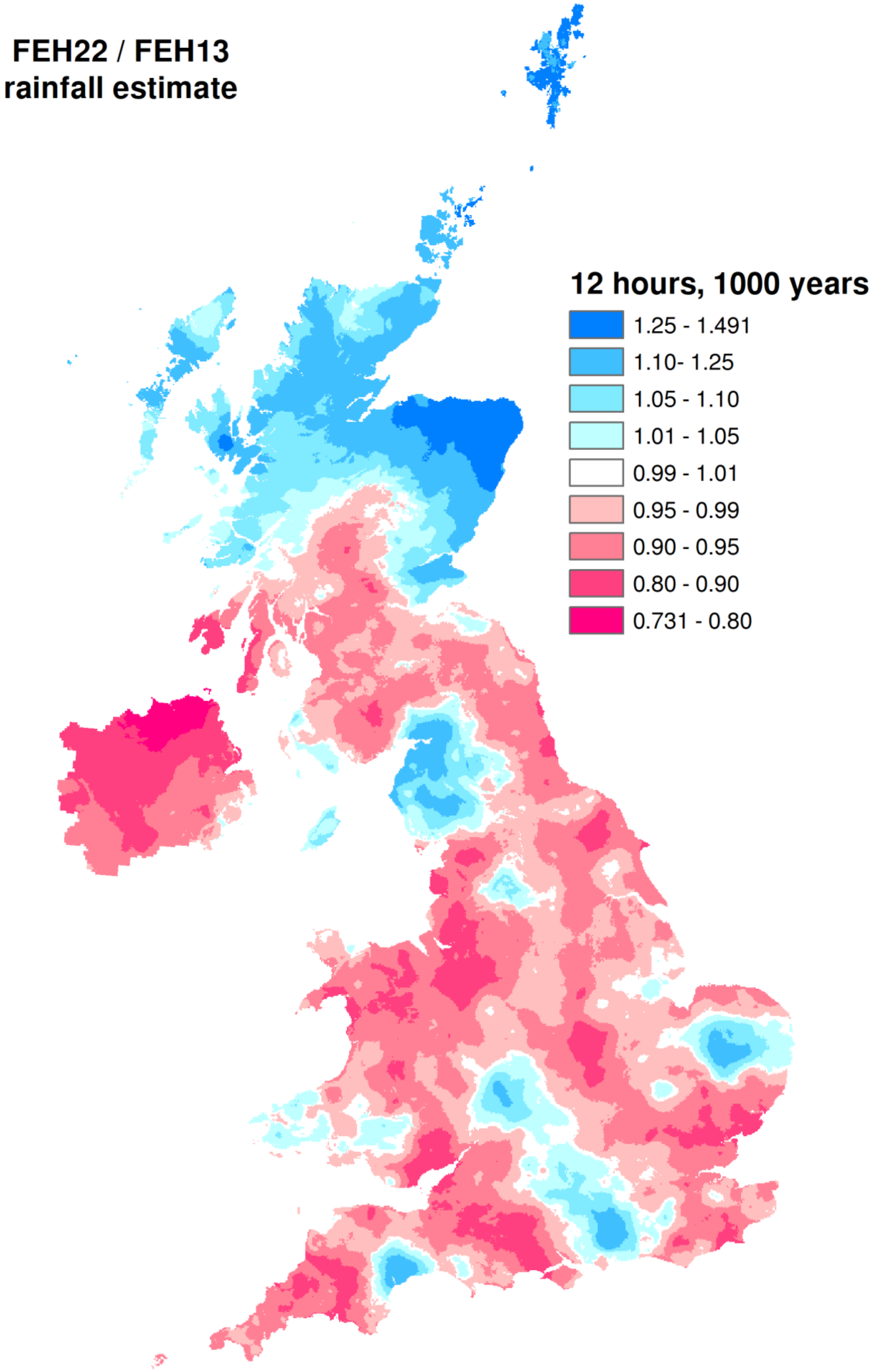

Figure 28 **FEH22 rainfall depth as fraction of FEH13 rainfall depth: 12-hour, 1000-year event.**

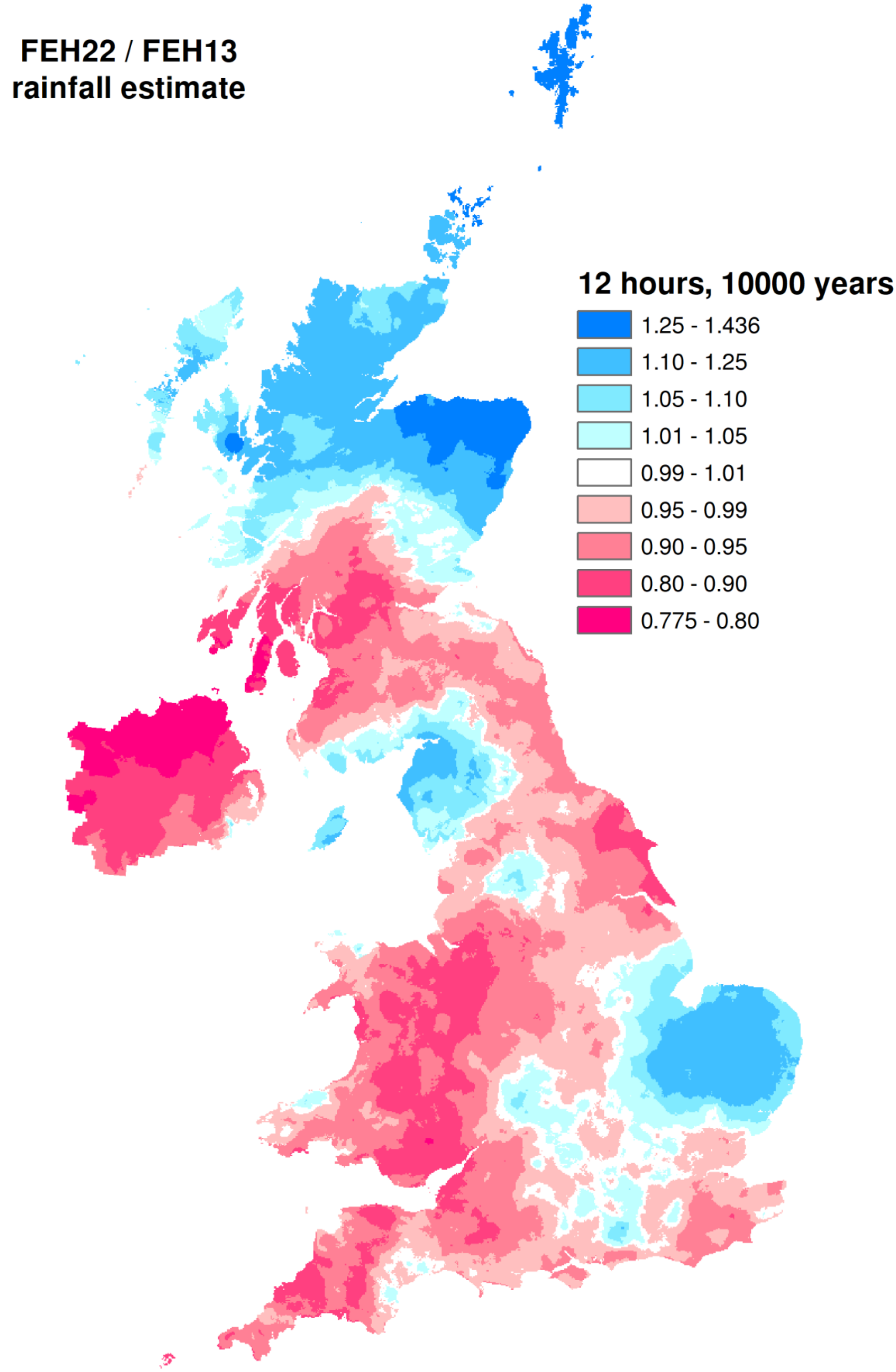

Figure 29 **FEH22 rainfall depth as fraction of FEH13 rainfall depth: 12-hour, 10000-year event.**

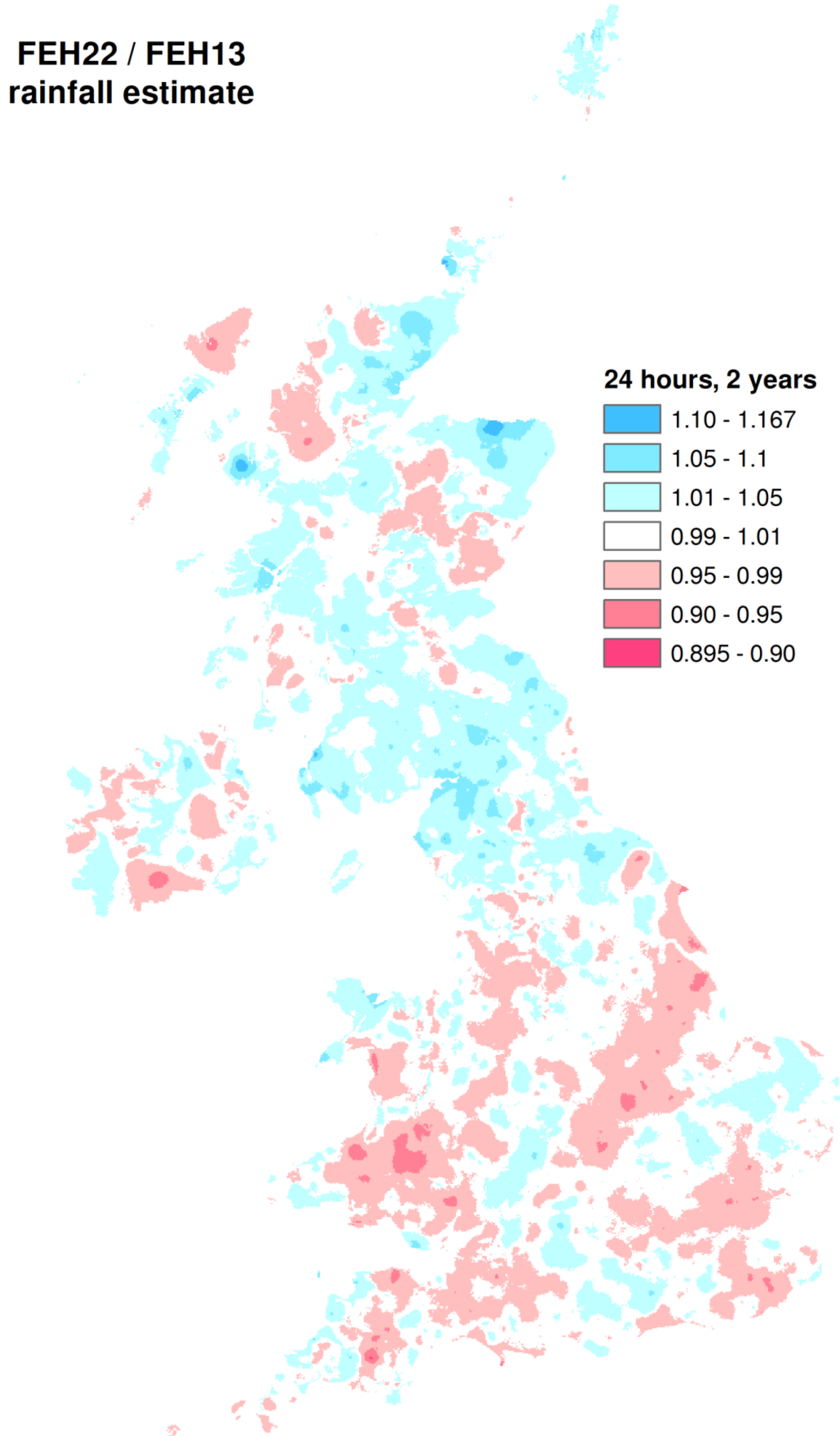

Figure 30 FEH22 rainfall depth as fraction of FEH13 rainfall depth: 24-hour, 2-year event.

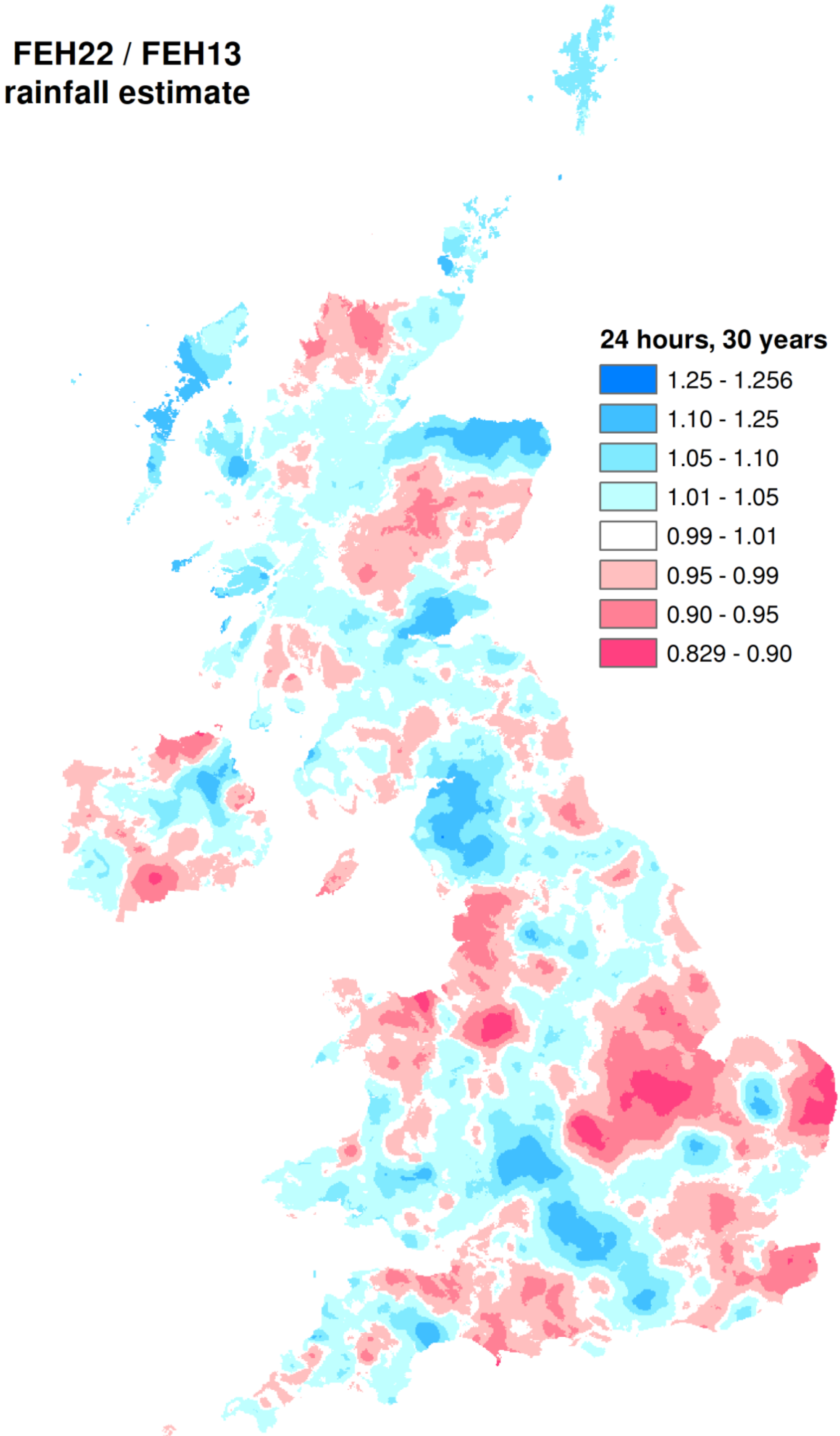

Figure 31 **FEH22 rainfall depth as fraction of FEH13 rainfall depth: 24-hour, 30-year event.**

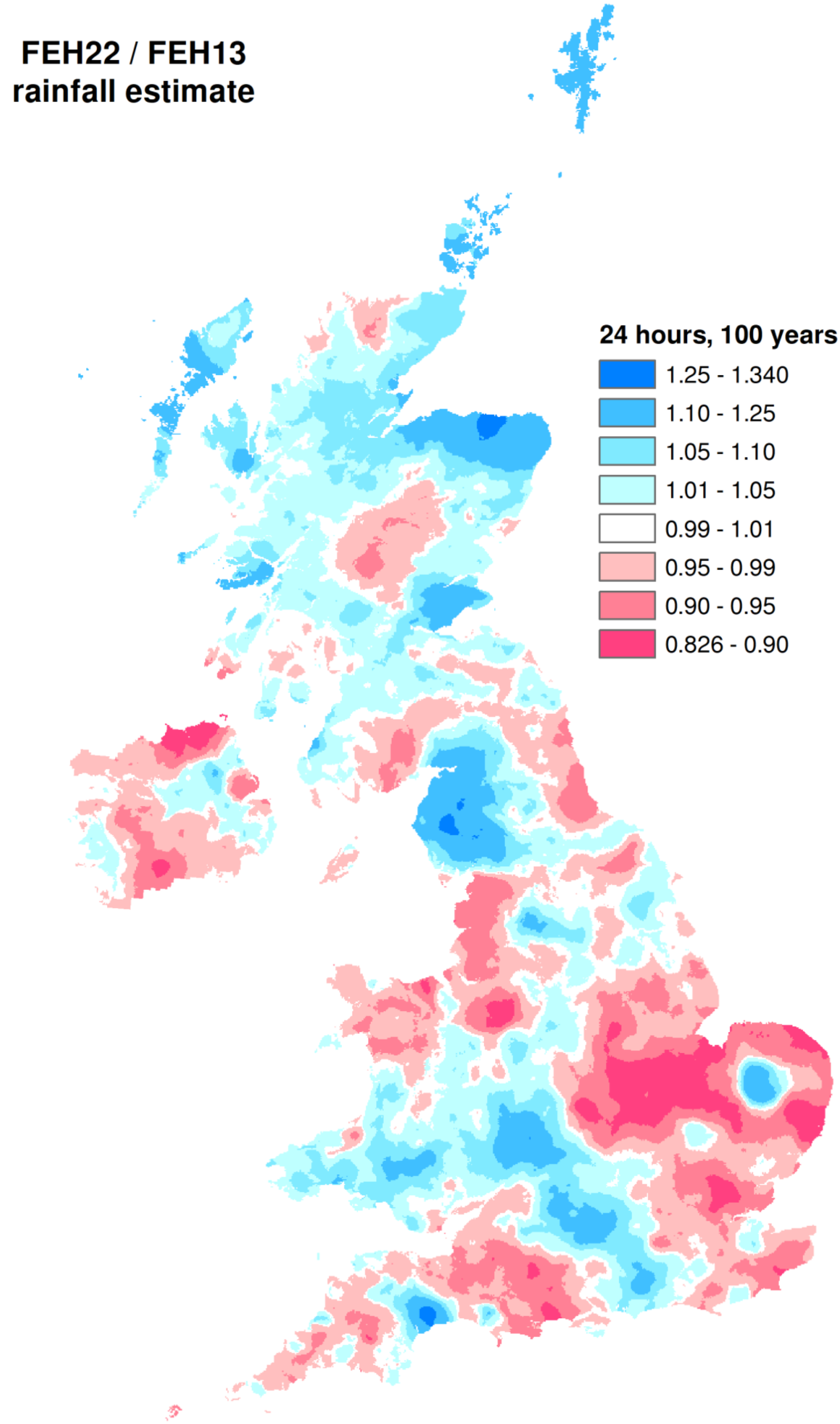

Figure 32 FEH22 rainfall depth as fraction of FEH13 rainfall depth: 24-hour, 100-year event.

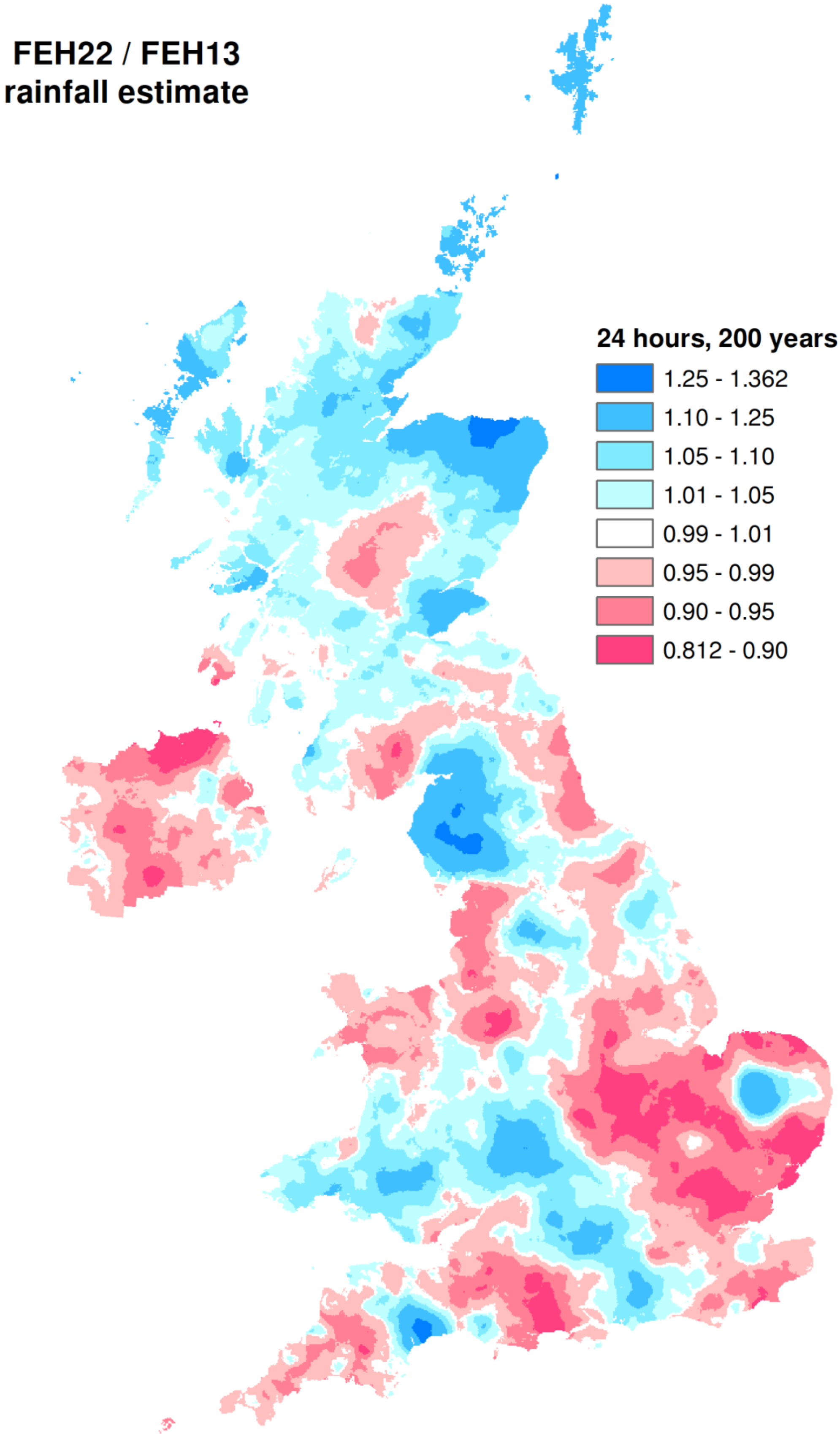

Figure 33 **FEH22 rainfall depth as fraction of FEH13 rainfall depth: 24-hour, 200-year event.**

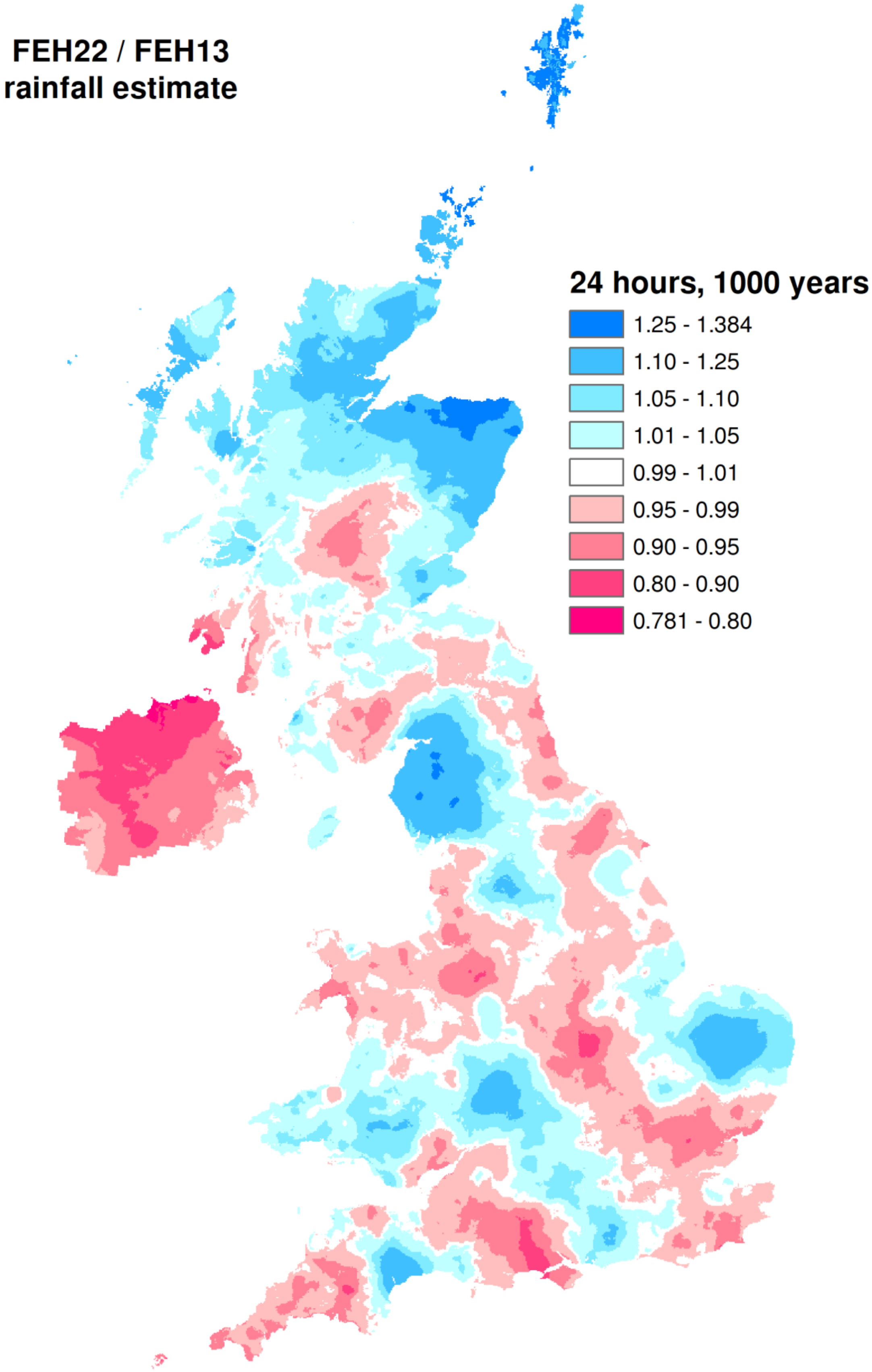

Figure 34 **FEH22 rainfall depth as fraction of FEH13 rainfall depth: 24-hour, 1000-year event.**

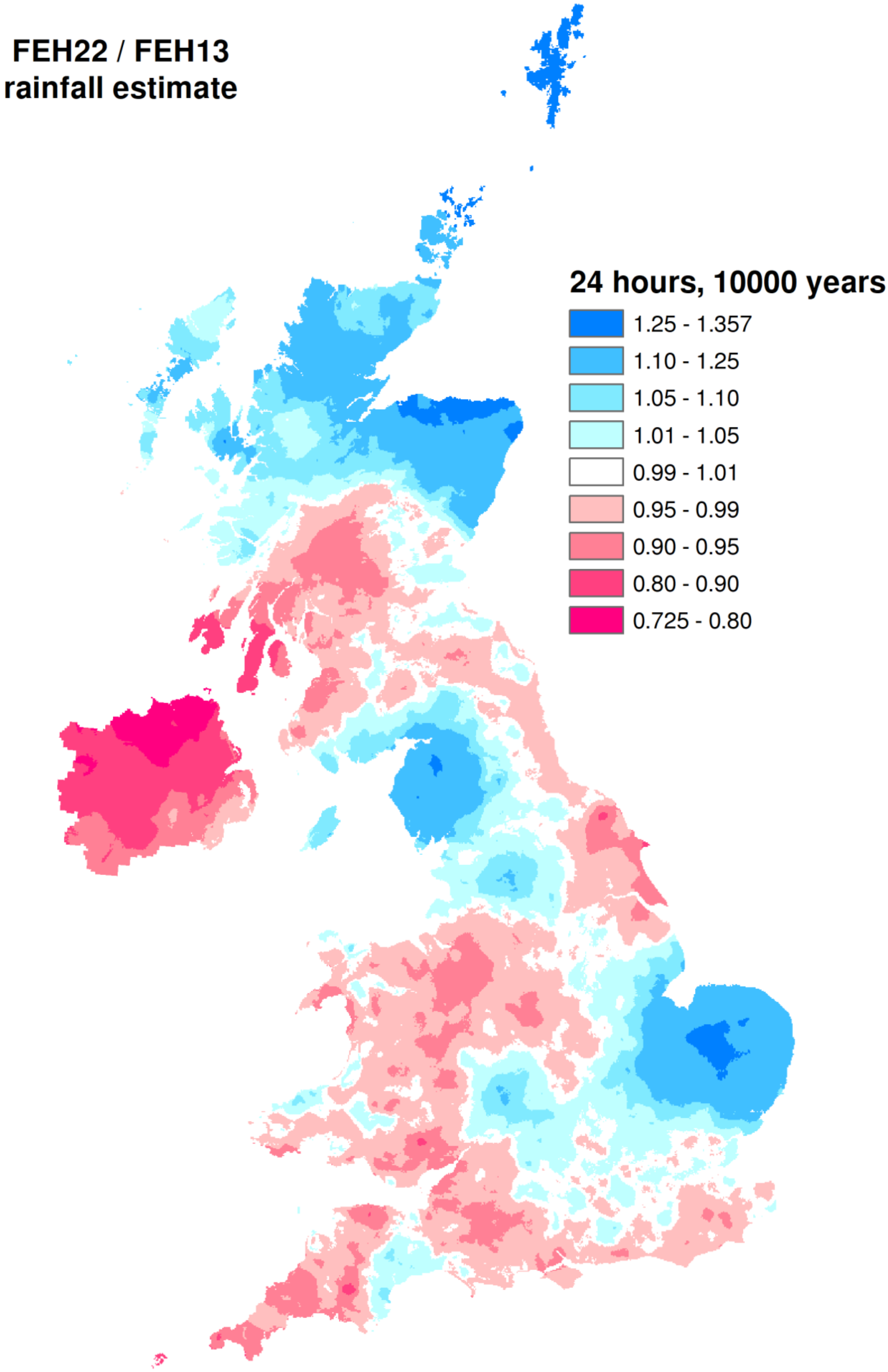

Figure 35 **FEH22 rainfall depth as fraction of FEH13 rainfall depth: 24-hour, 10000-year event.**

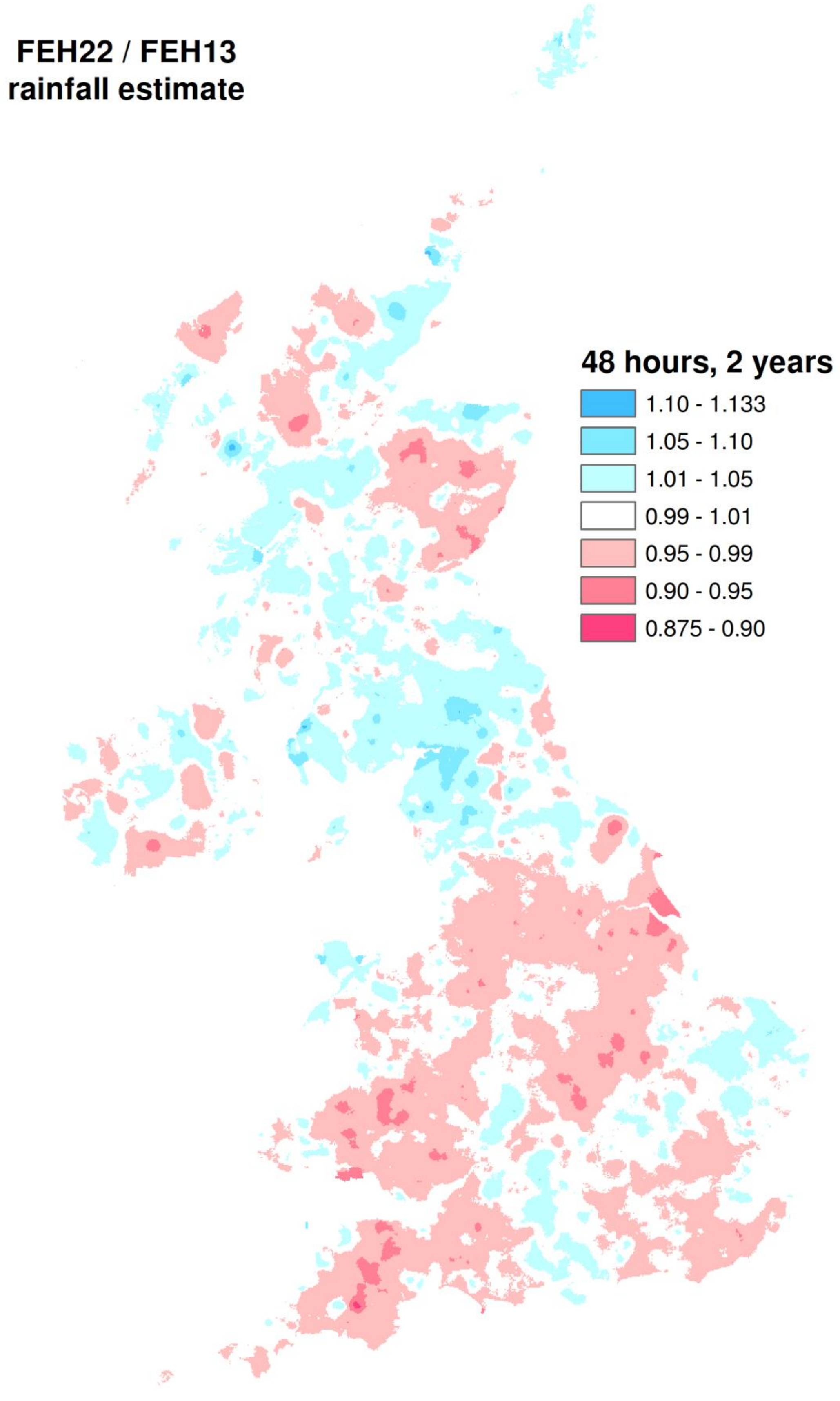

Figure 36 **FEH22 rainfall depth as fraction of FEH13 rainfall depth: 48-hour, 2-year event.**

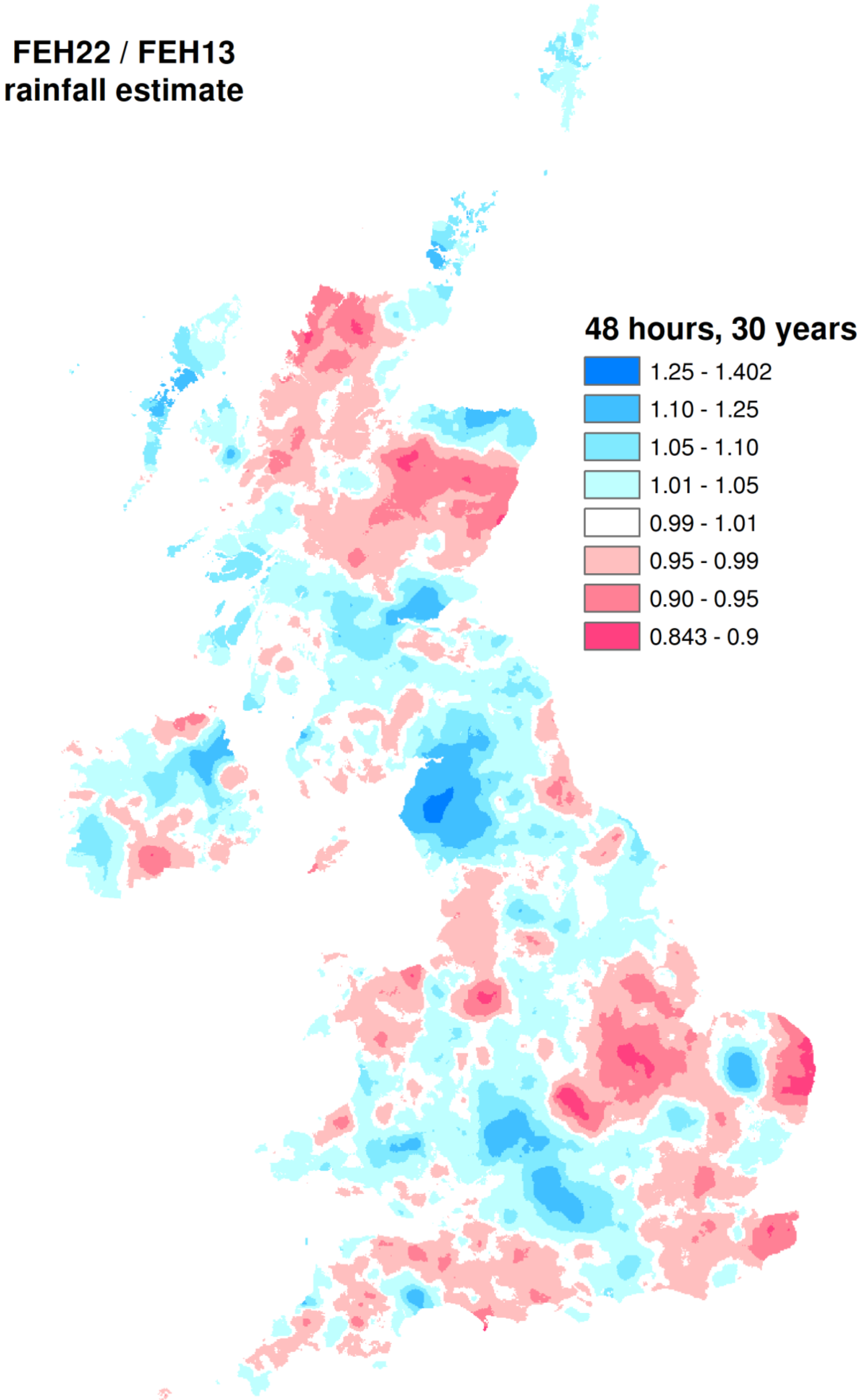

Figure 37 FEH22 rainfall depth as fraction of FEH13 rainfall depth: 48-hour, 30-year event.

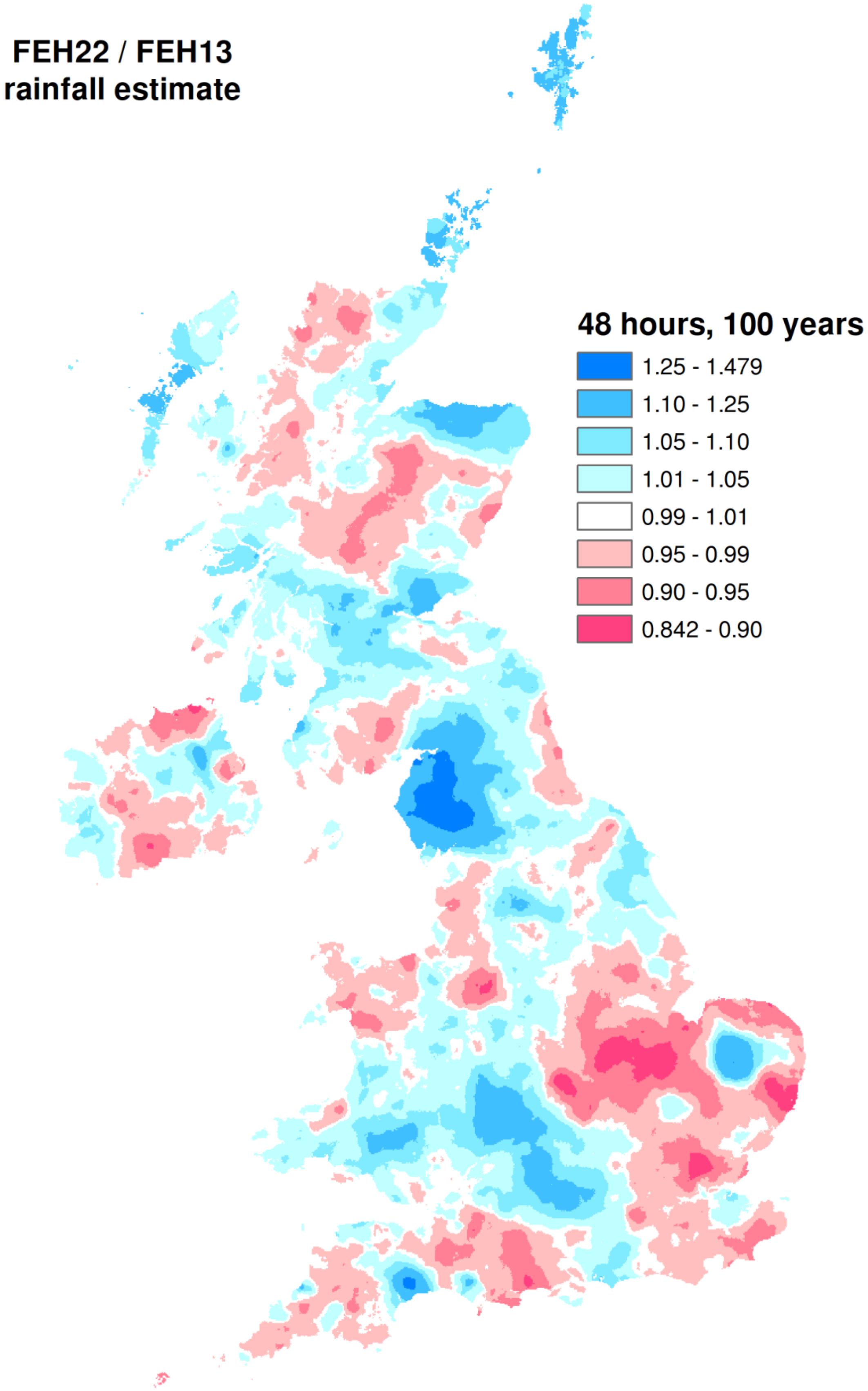

Figure 38 **FEH22 rainfall depth as fraction of FEH13 rainfall depth: 48-hour, 100-year event.**

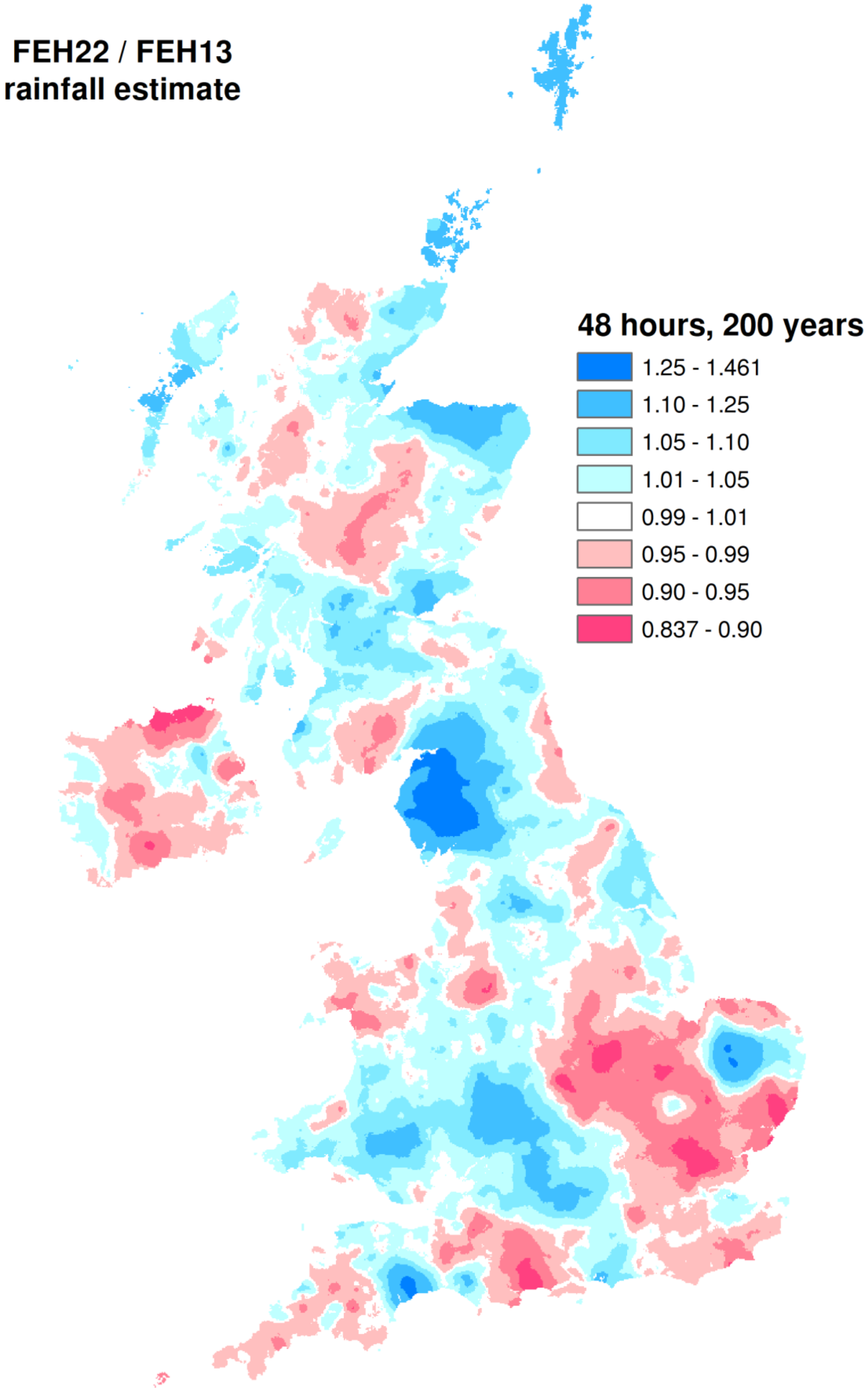

Figure 39 **FEH22 rainfall depth as fraction of FEH13 rainfall depth: 48-hour, 200-year event.**

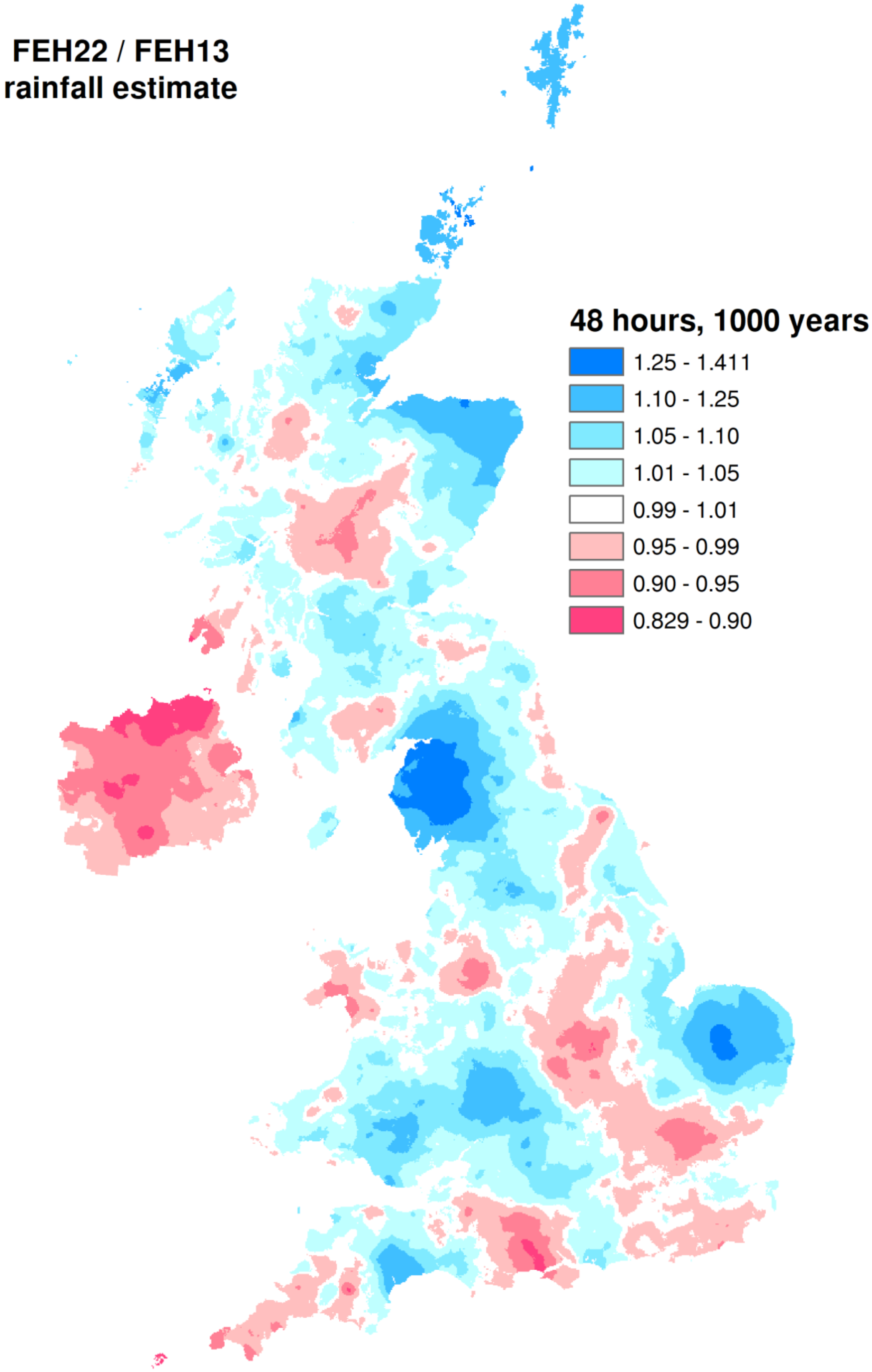

Figure 40 **FEH22 rainfall depth as fraction of FEH13 rainfall depth: 48-hour, 1000-year event.**

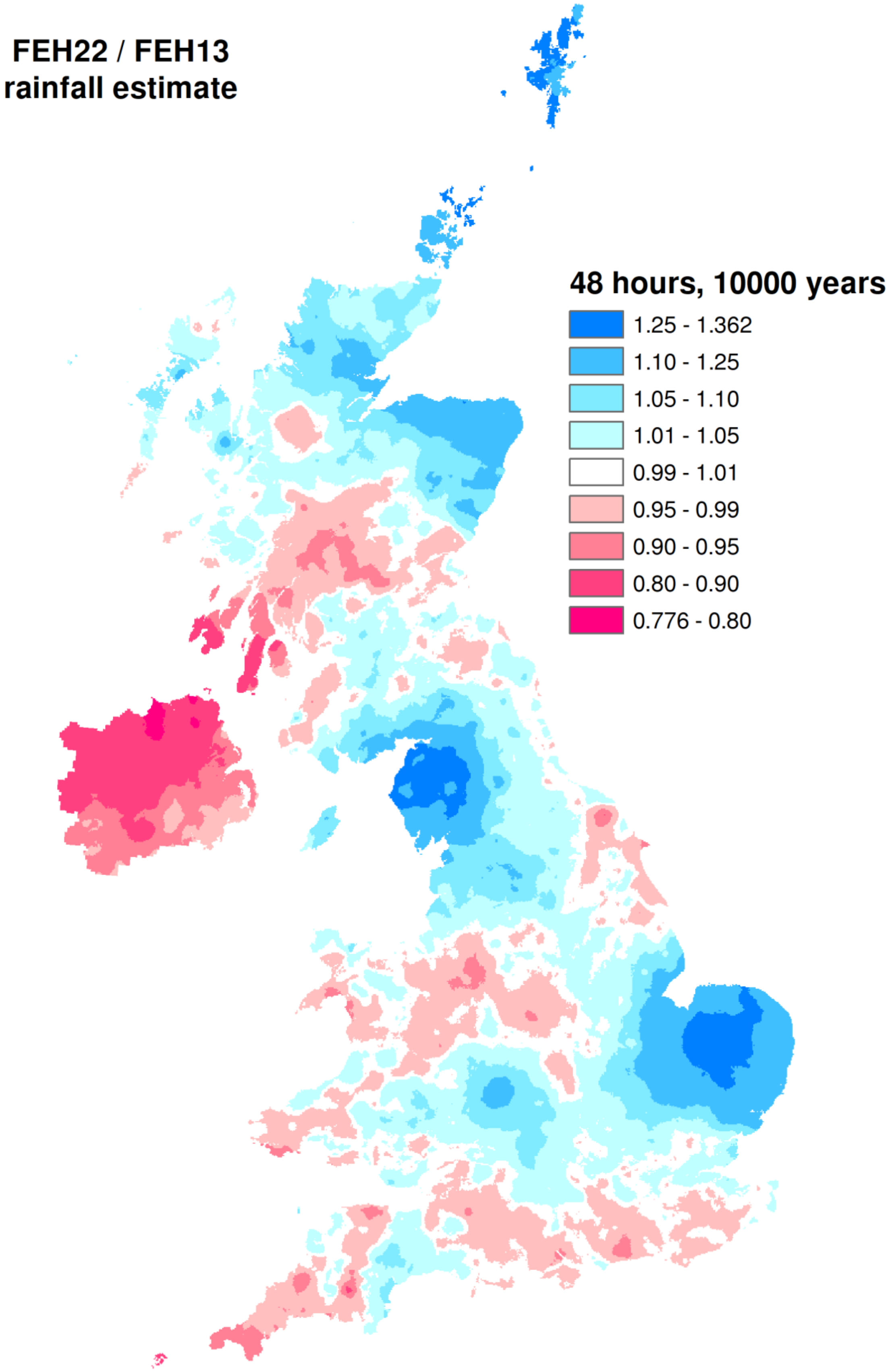

Figure 41 **FEH22 rainfall depth as fraction of FEH13 rainfall depth: 48-hour, 10000-year event.**

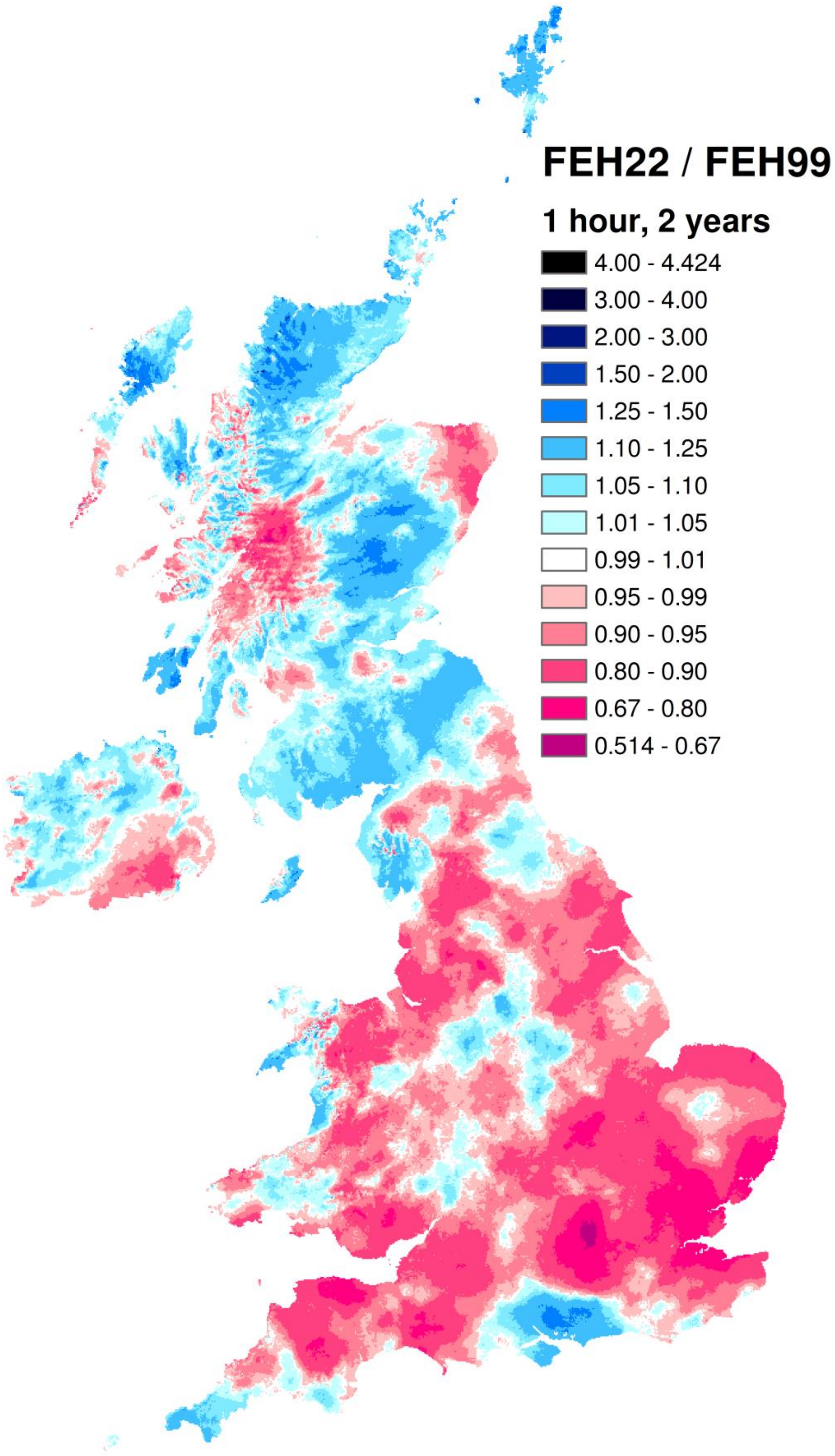

Figure 42 FEH22 rainfall depth as fraction of FEH99 rainfall depth: 1-hour, 2-year event.

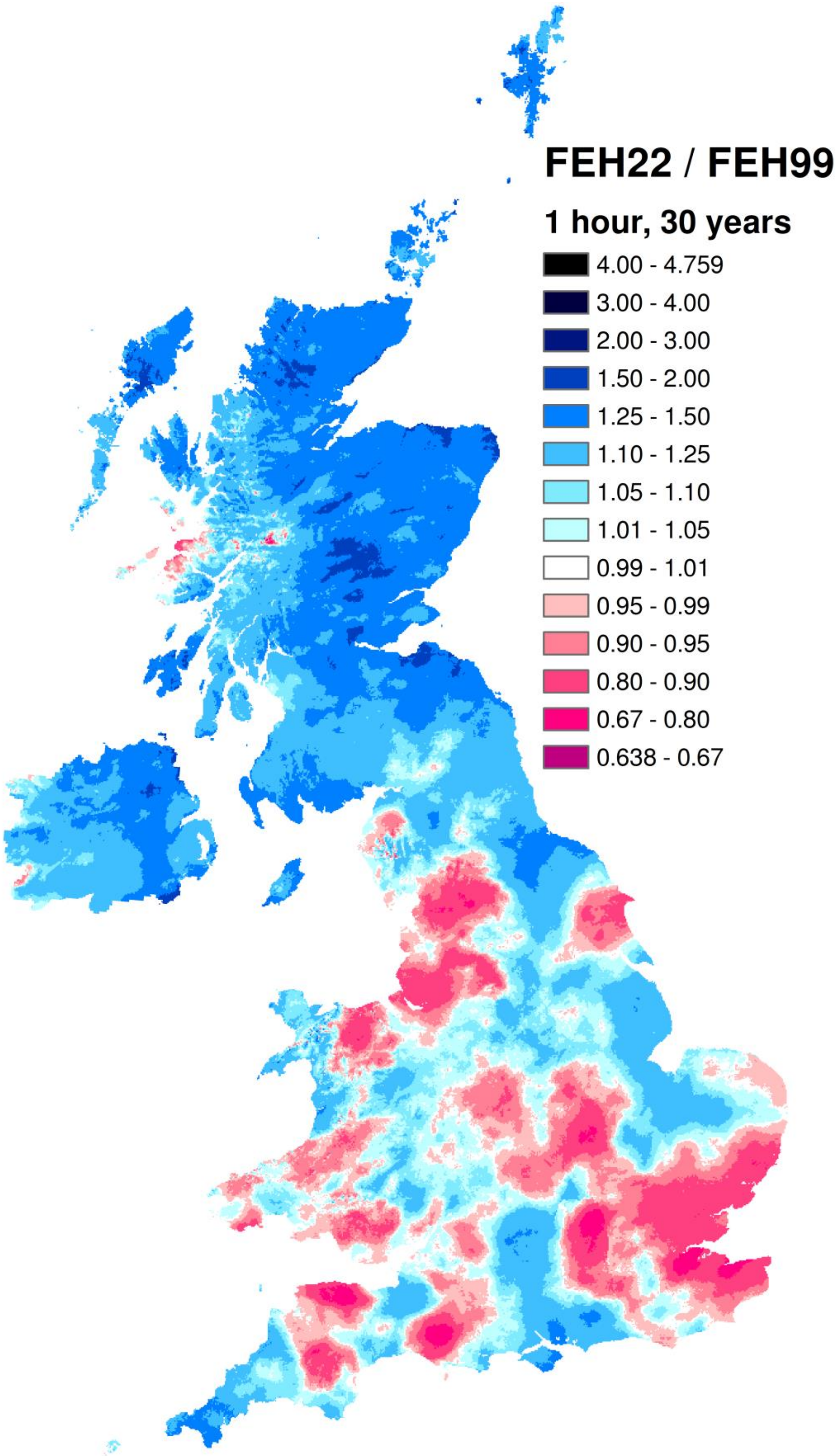

Figure 43 FEH22 rainfall depth as fraction of FEH99 rainfall depth: 1-hour, 30-year event.

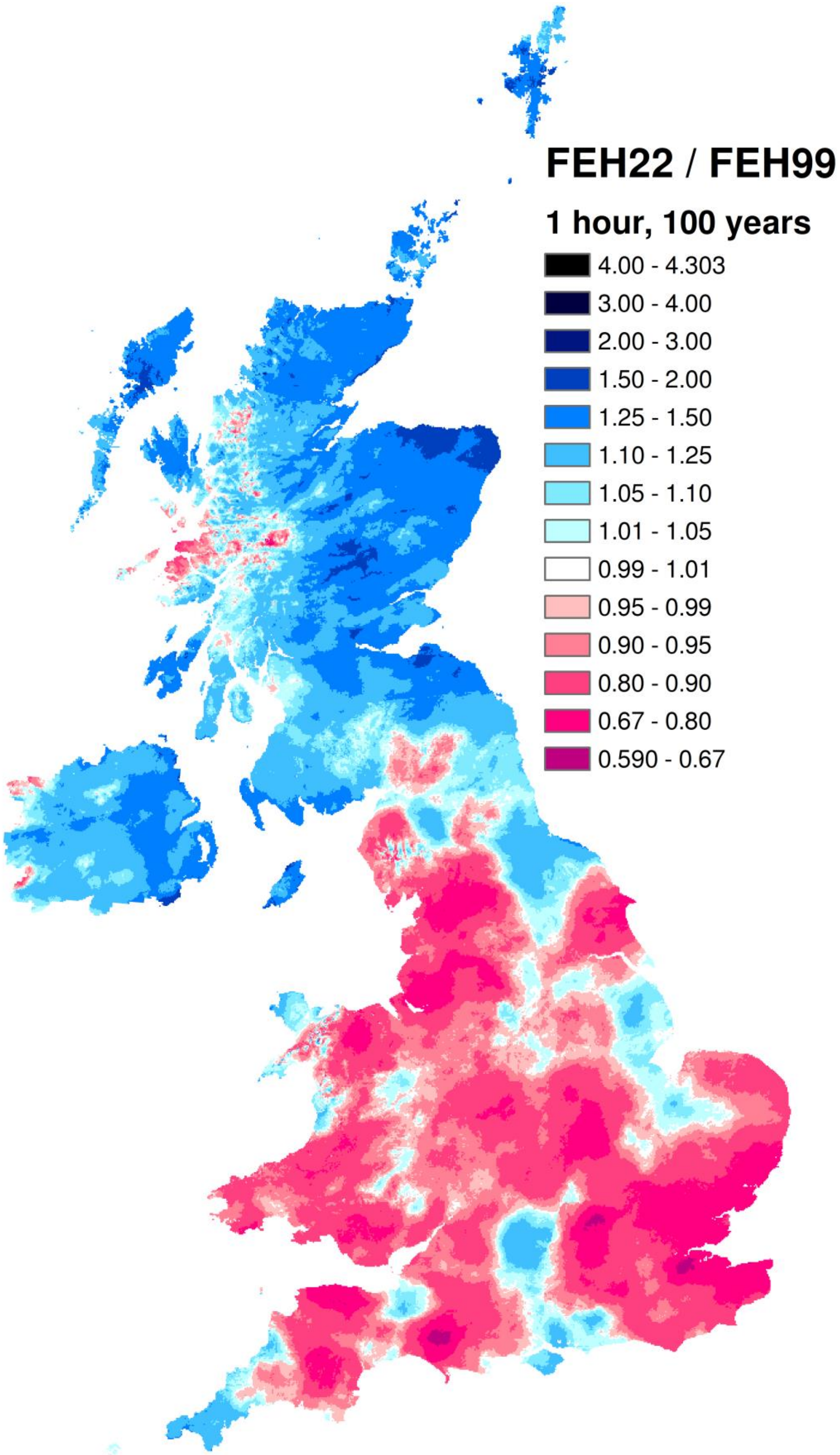

Figure 44 FEH22 rainfall depth as fraction of FEH99 rainfall depth: 1-hour, 100-year event.

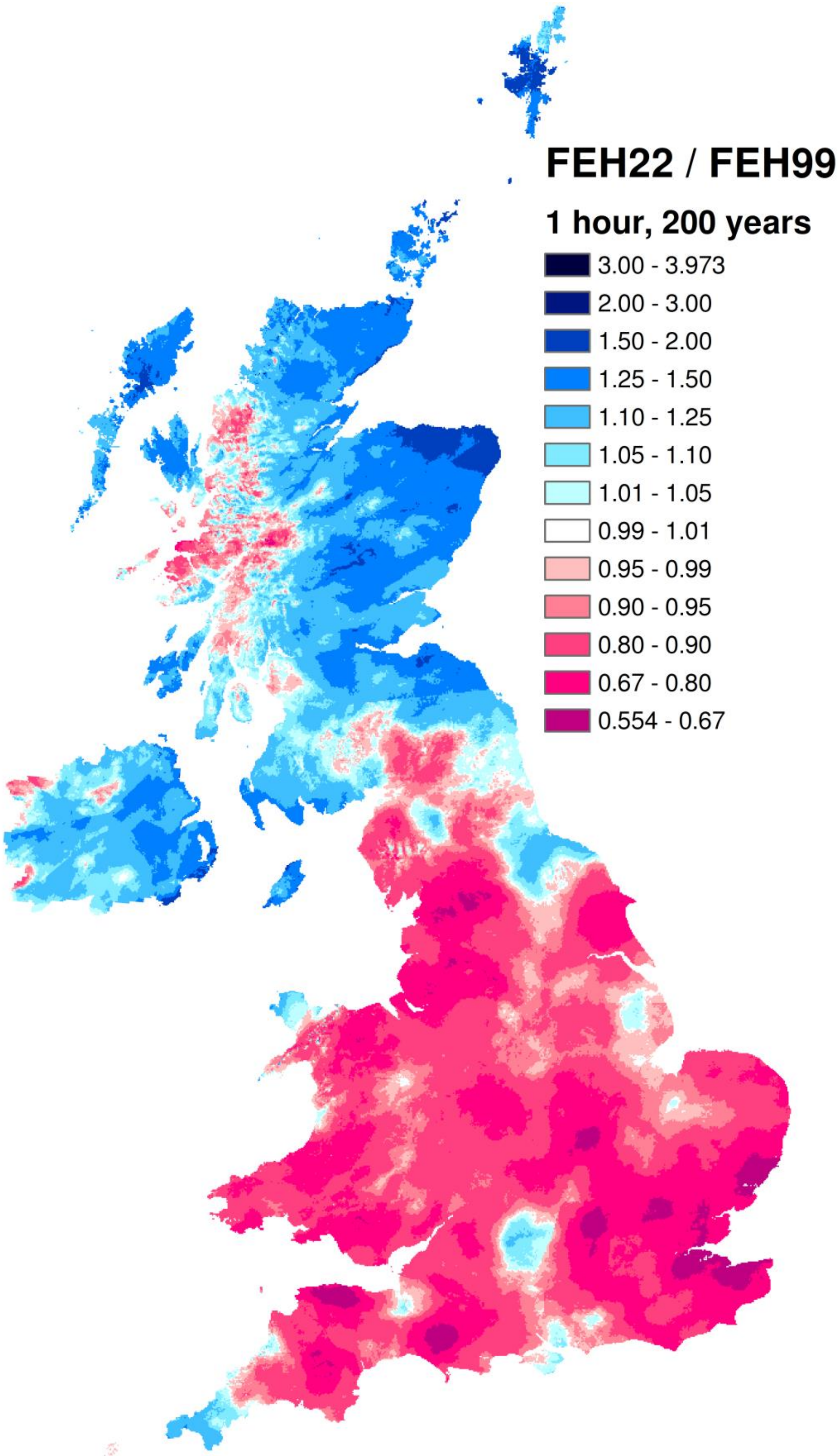

Figure 45 **FEH22 rainfall depth as fraction of FEH99 rainfall depth: 1-hour, 200-year event.**

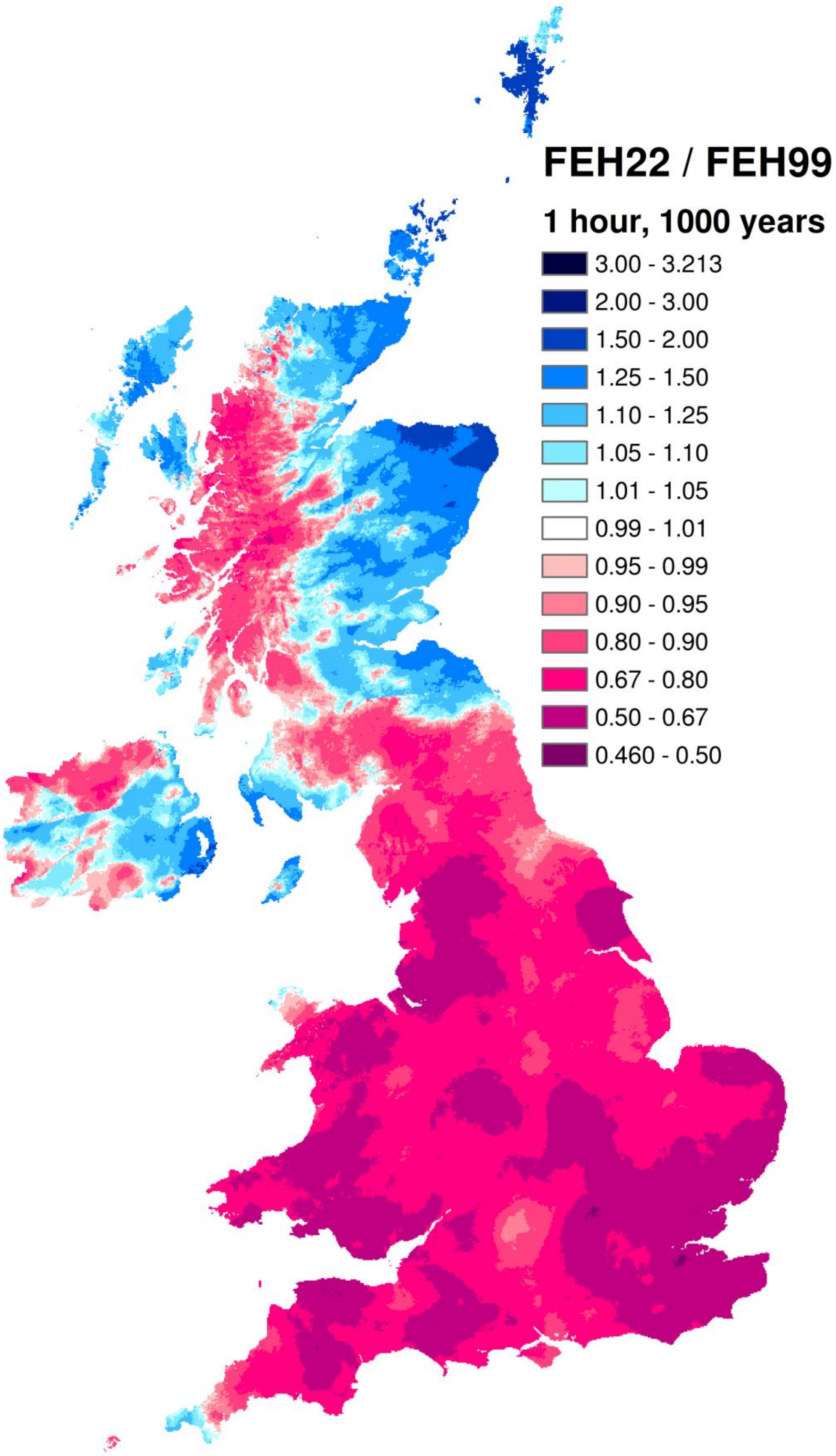

Figure 46 **FEH22 rainfall depth as fraction of FEH99 rainfall depth: 1-hour, 1000-year event.**

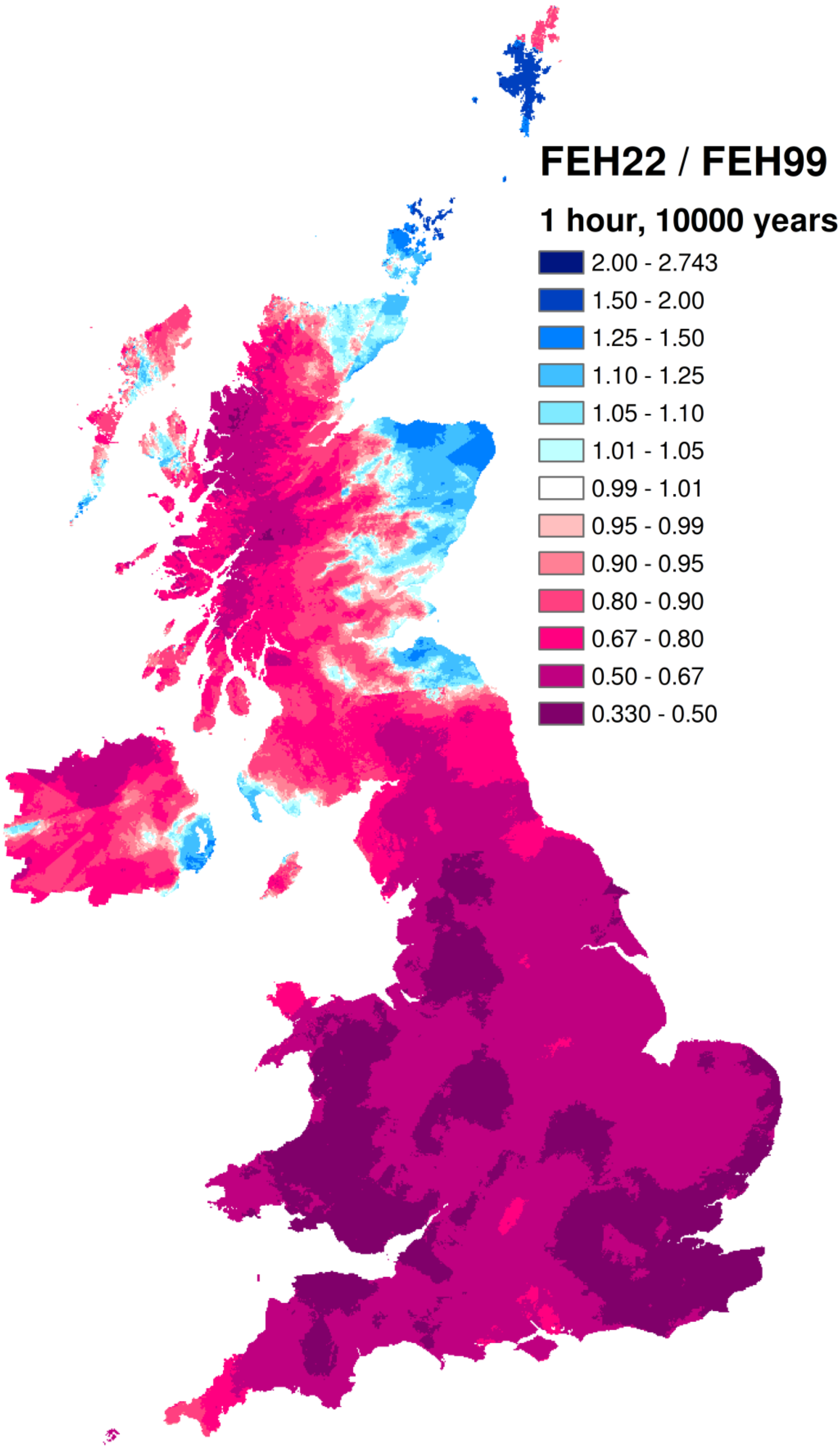

Figure 47 FEH22 rainfall depth as fraction of FEH99 rainfall depth: 1-hour, 10000-year event.

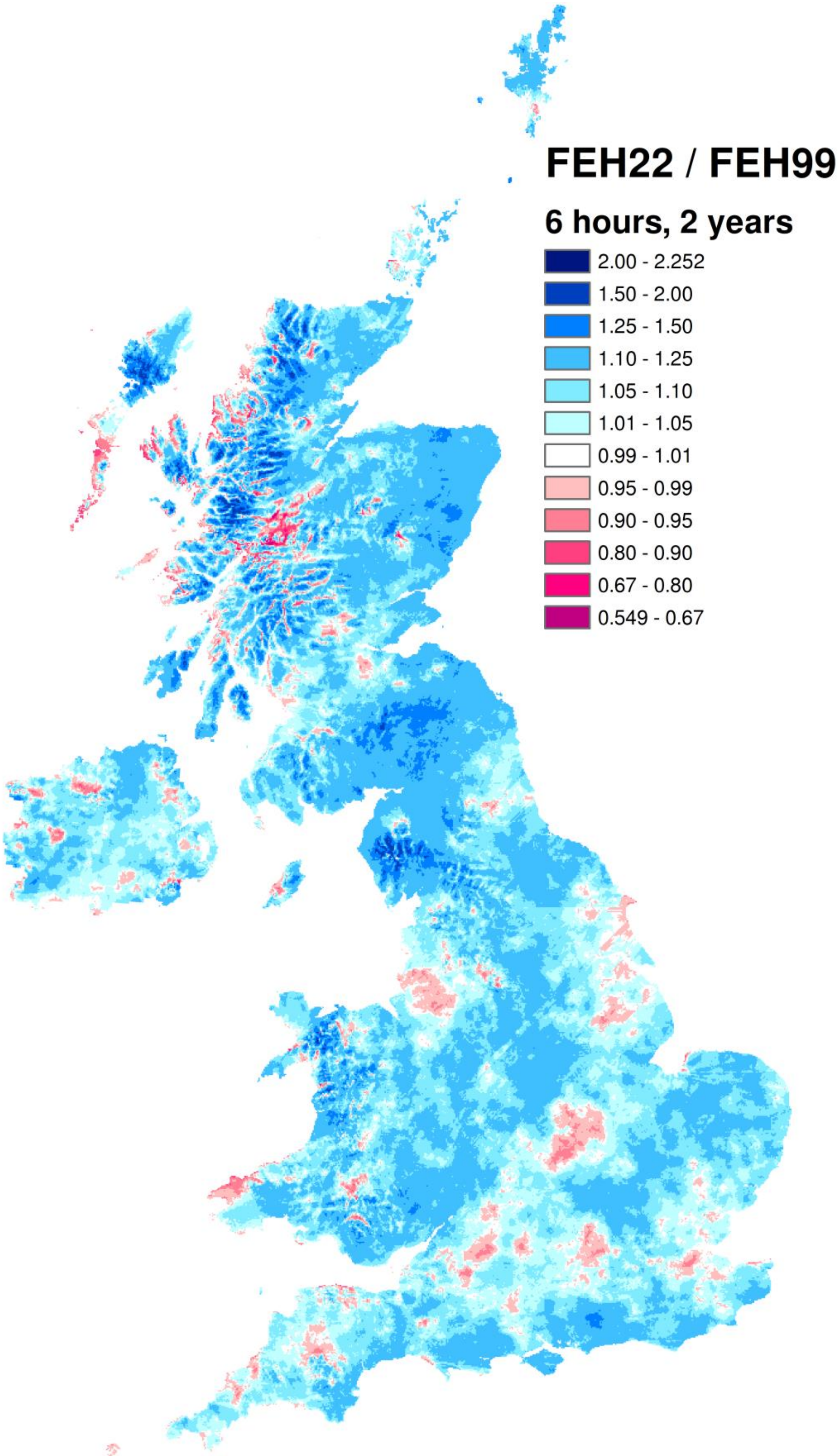

Figure 48 FEH22 rainfall depth as fraction of FEH99 rainfall depth: 6-hour, 2-year event.

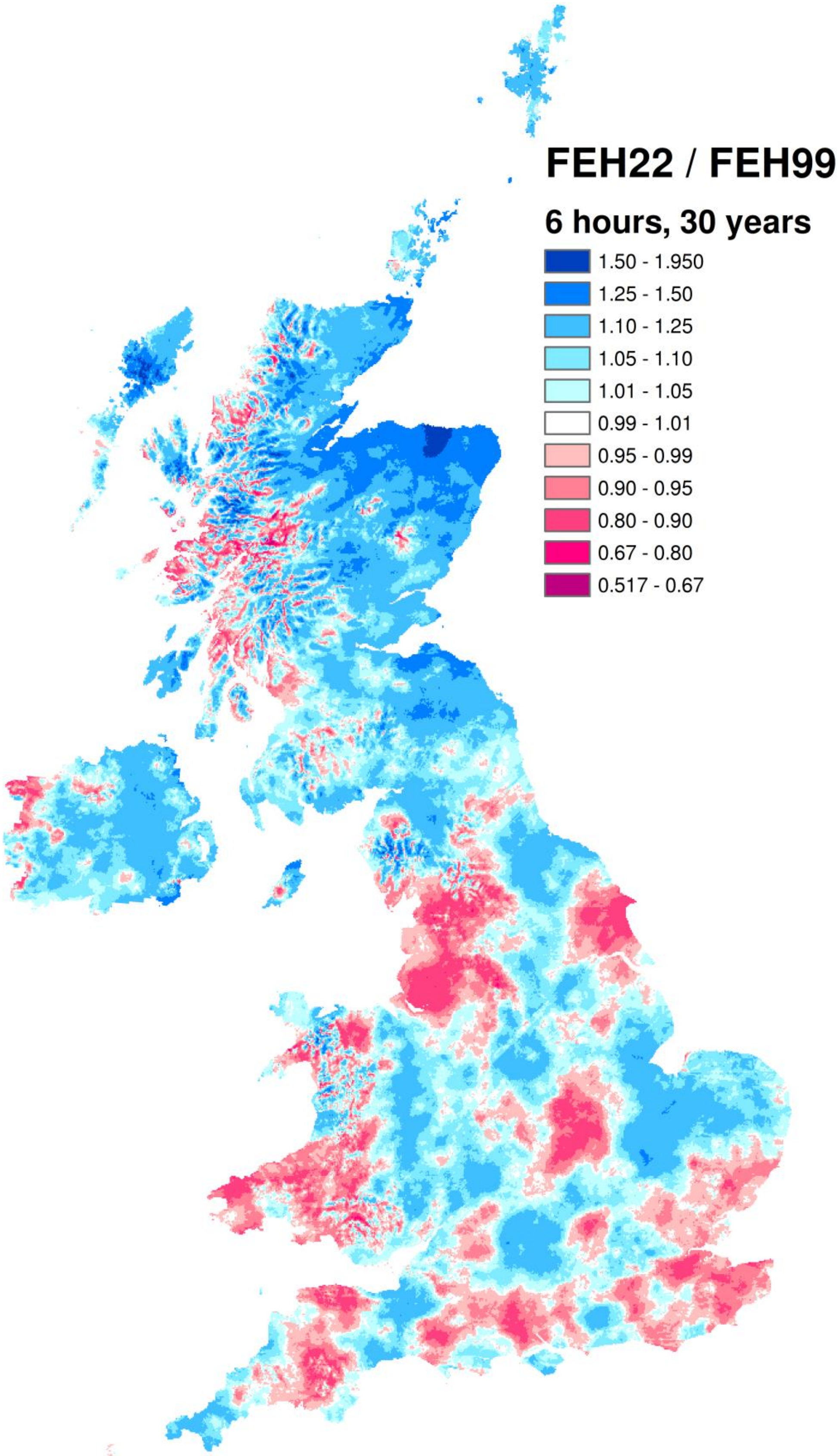

Figure 49 FEH22 rainfall depth as fraction of FEH99 rainfall depth: 6-hour, 30-year event.

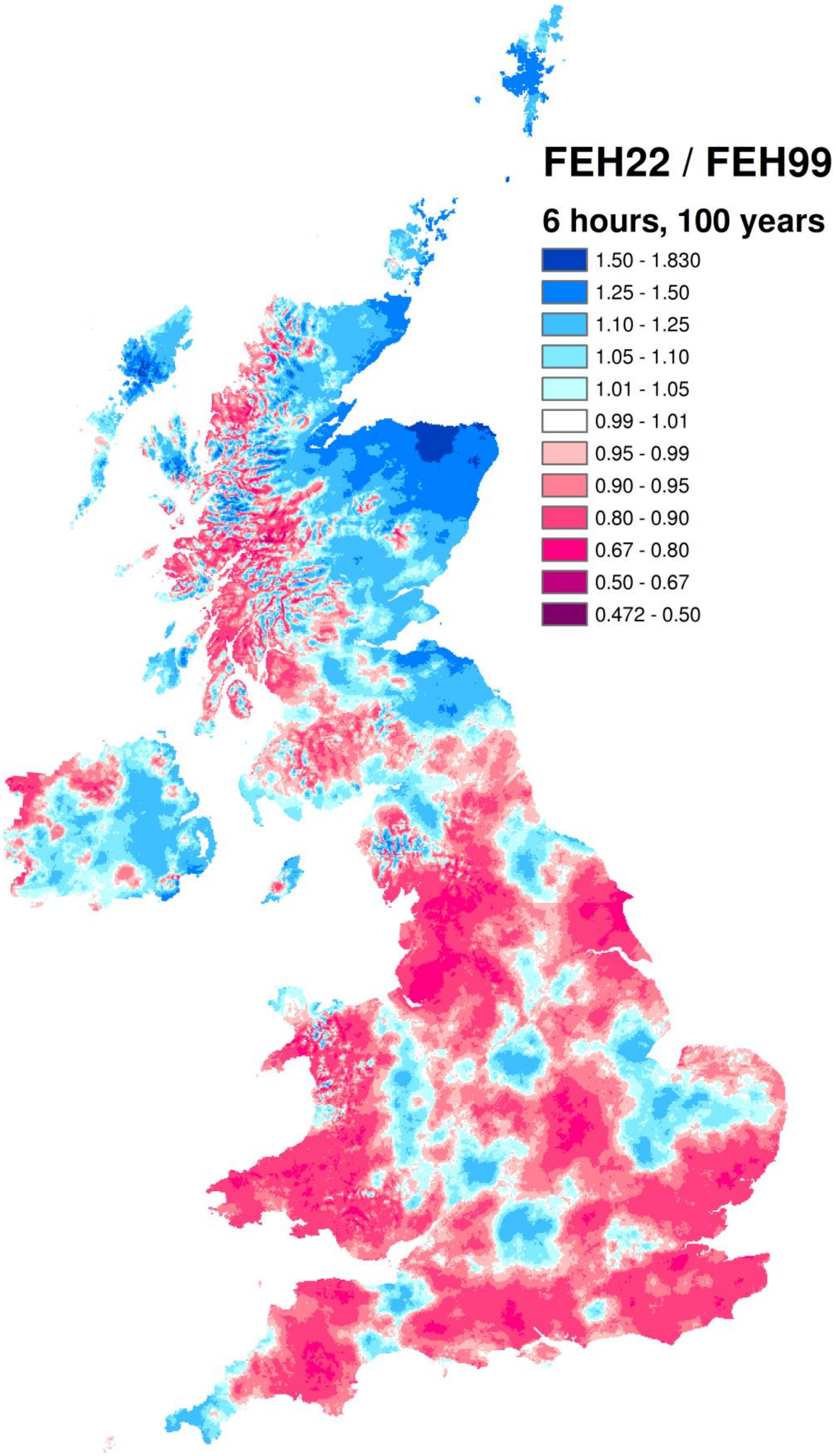

Figure 50 FEH22 rainfall depth as fraction of FEH99 rainfall depth: 6-hour, 100-year event.

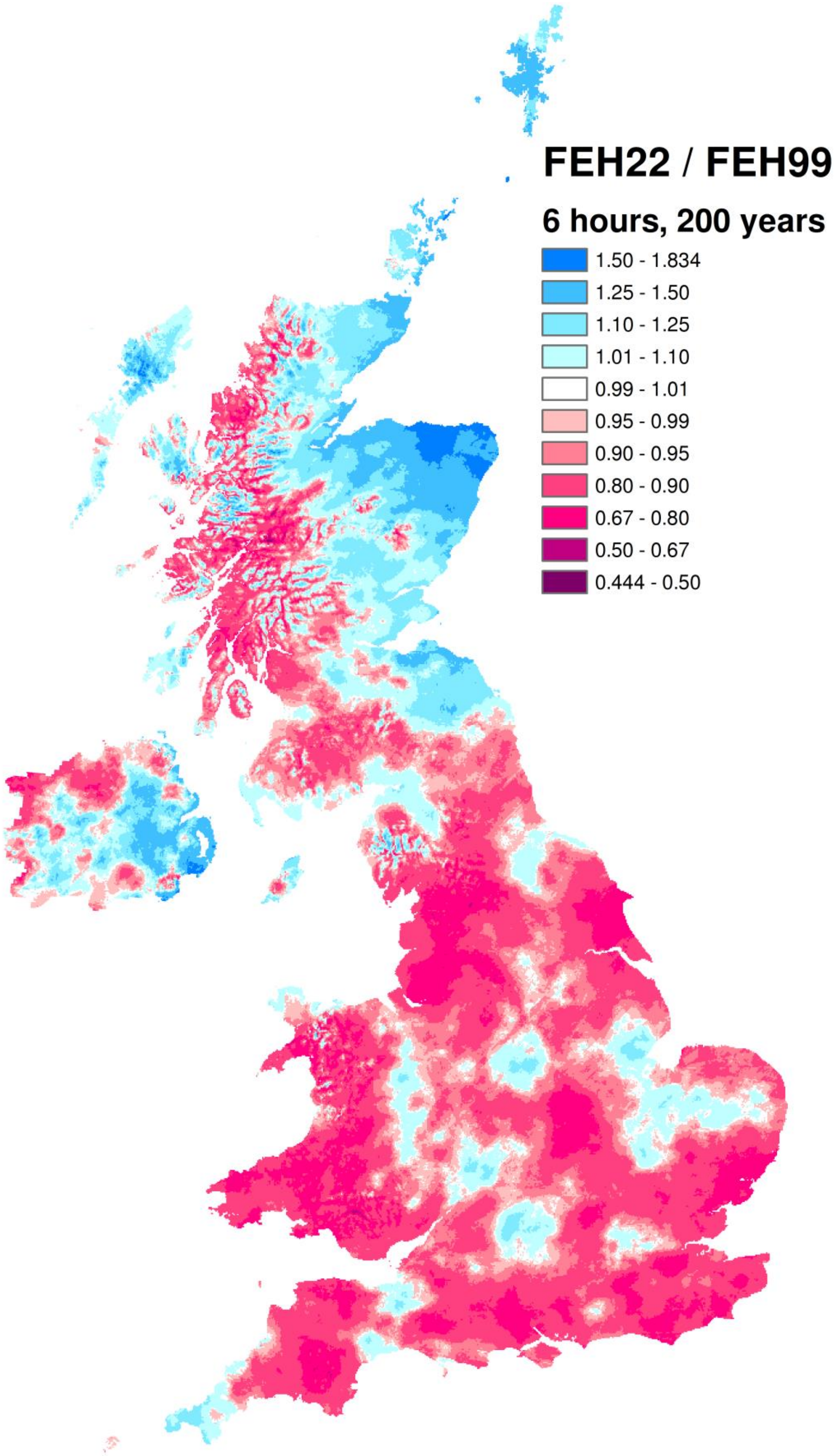

Figure 51 FEH22 rainfall depth as fraction of FEH99 rainfall depth: 6-hour, 200-year event.

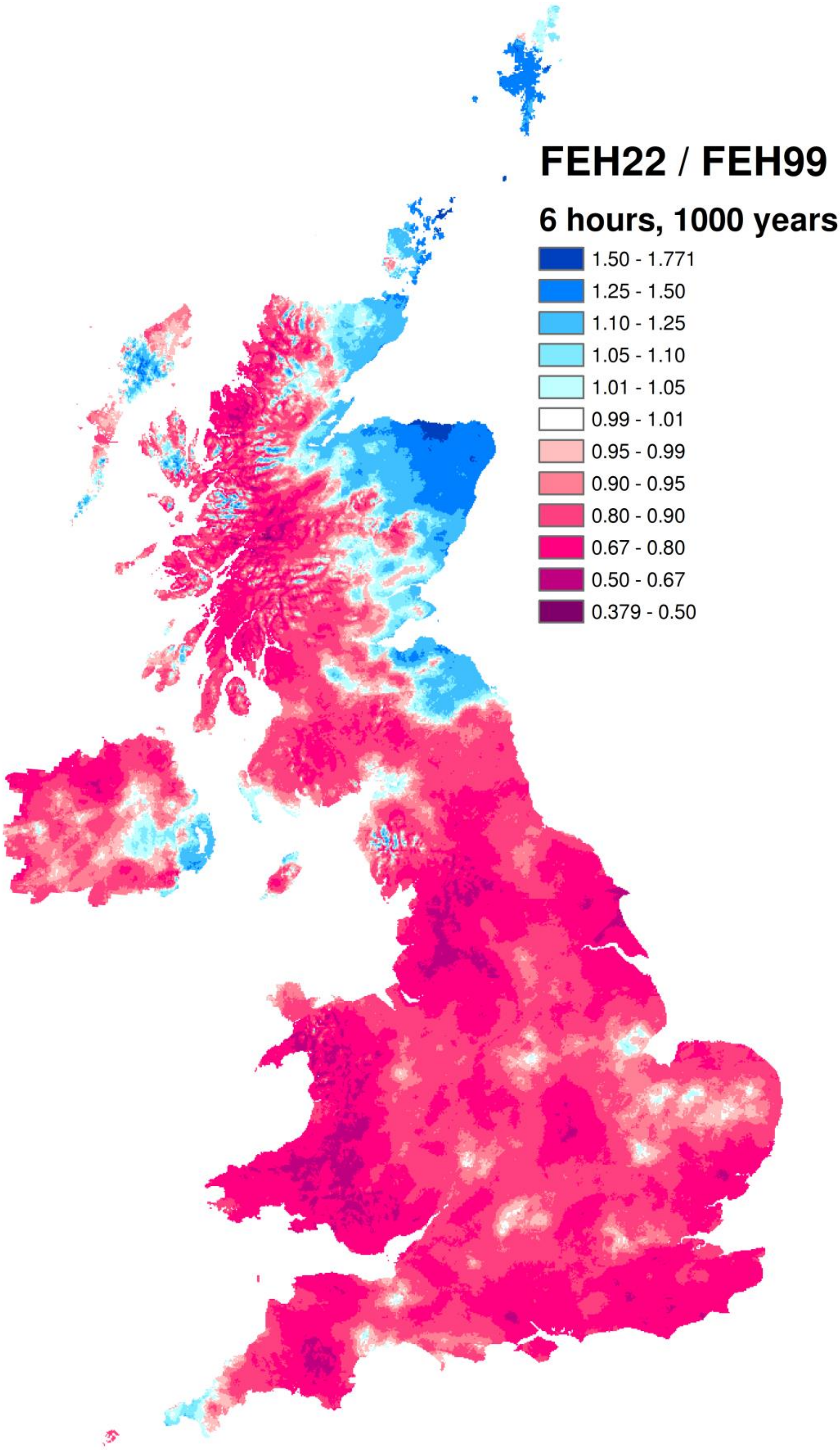

Figure 52 **FEH22 rainfall depth as fraction of FEH99 rainfall depth: 6-hour, 1000-year event.**

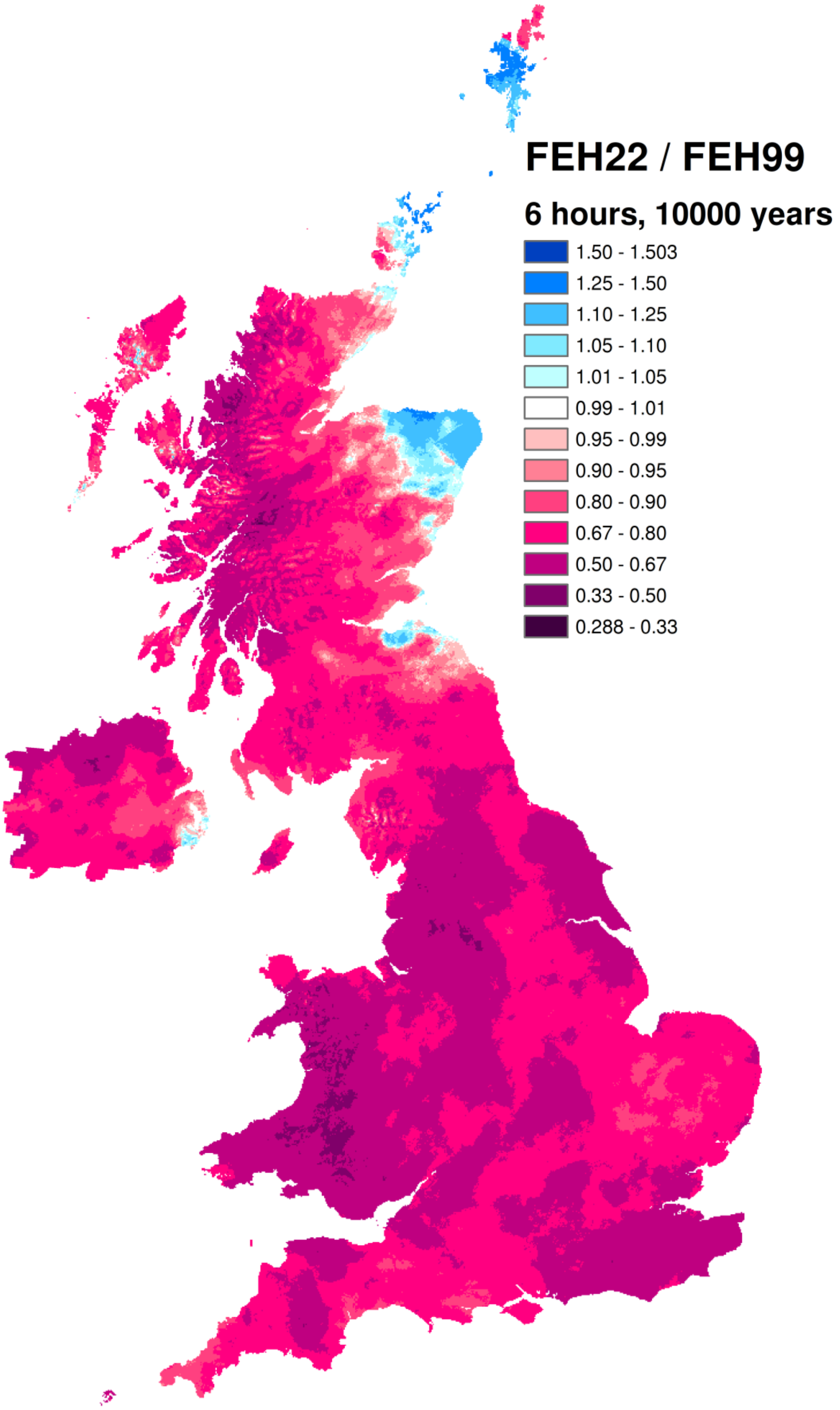

Figure 53 **FEH22 rainfall depth as fraction of FEH99 rainfall depth: 6-hour, 10000-year event.**

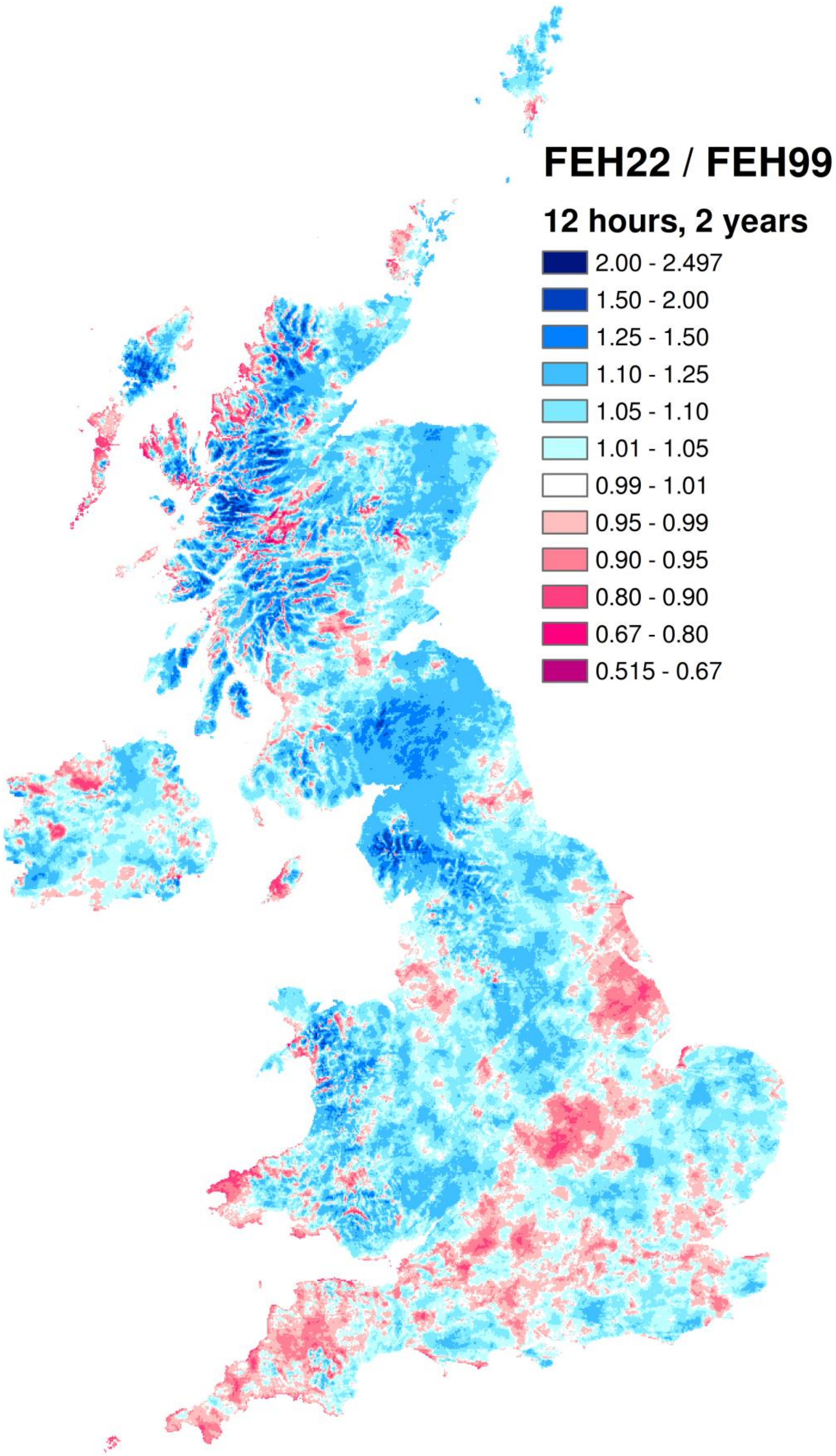

Figure 54 FEH22 rainfall depth as fraction of FEH99 rainfall depth: 12-hour, 2-year event.

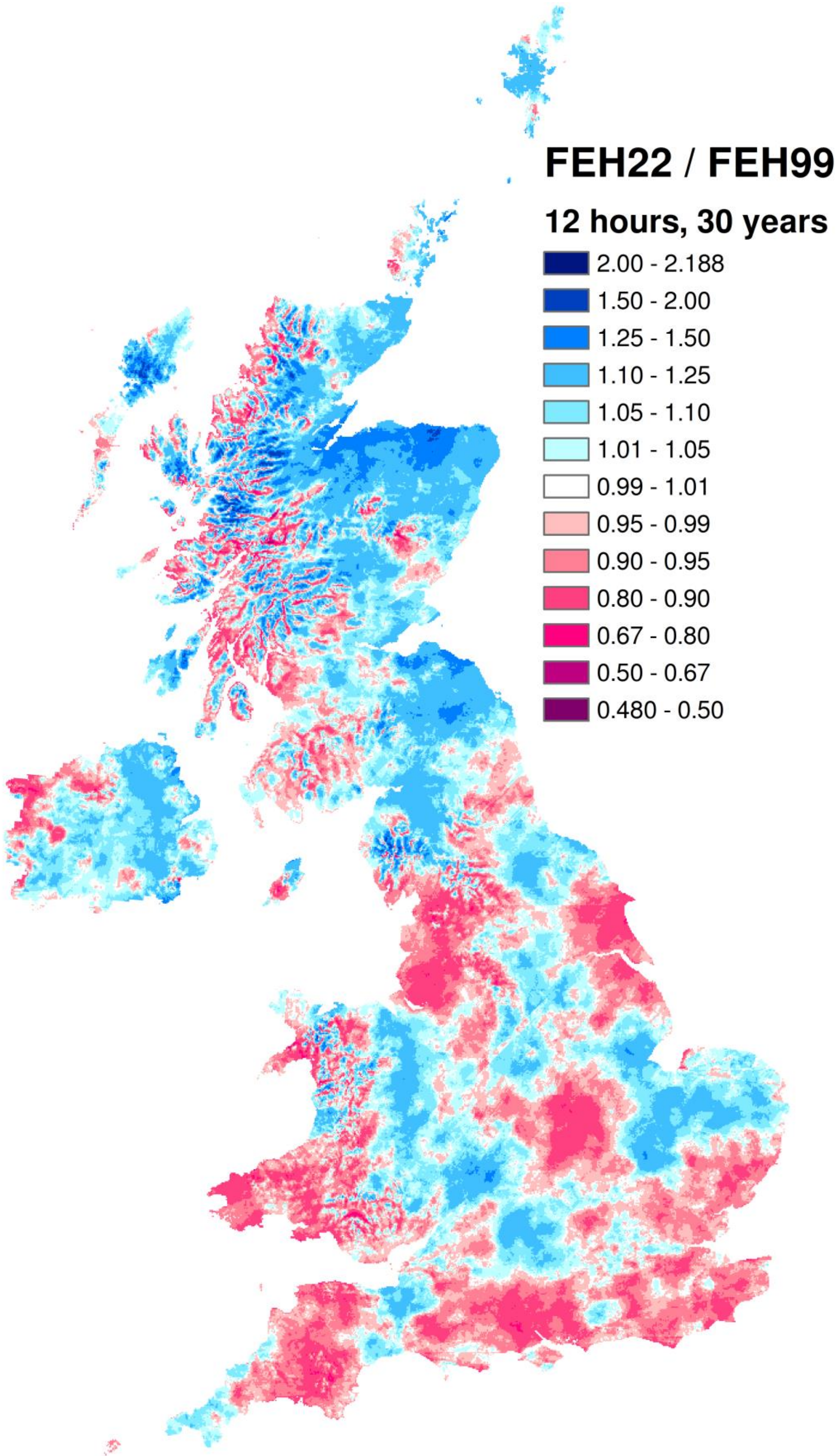

Figure 55 FEH22 rainfall depth as fraction of FEH99 rainfall depth: 12-hour, 30-year event.

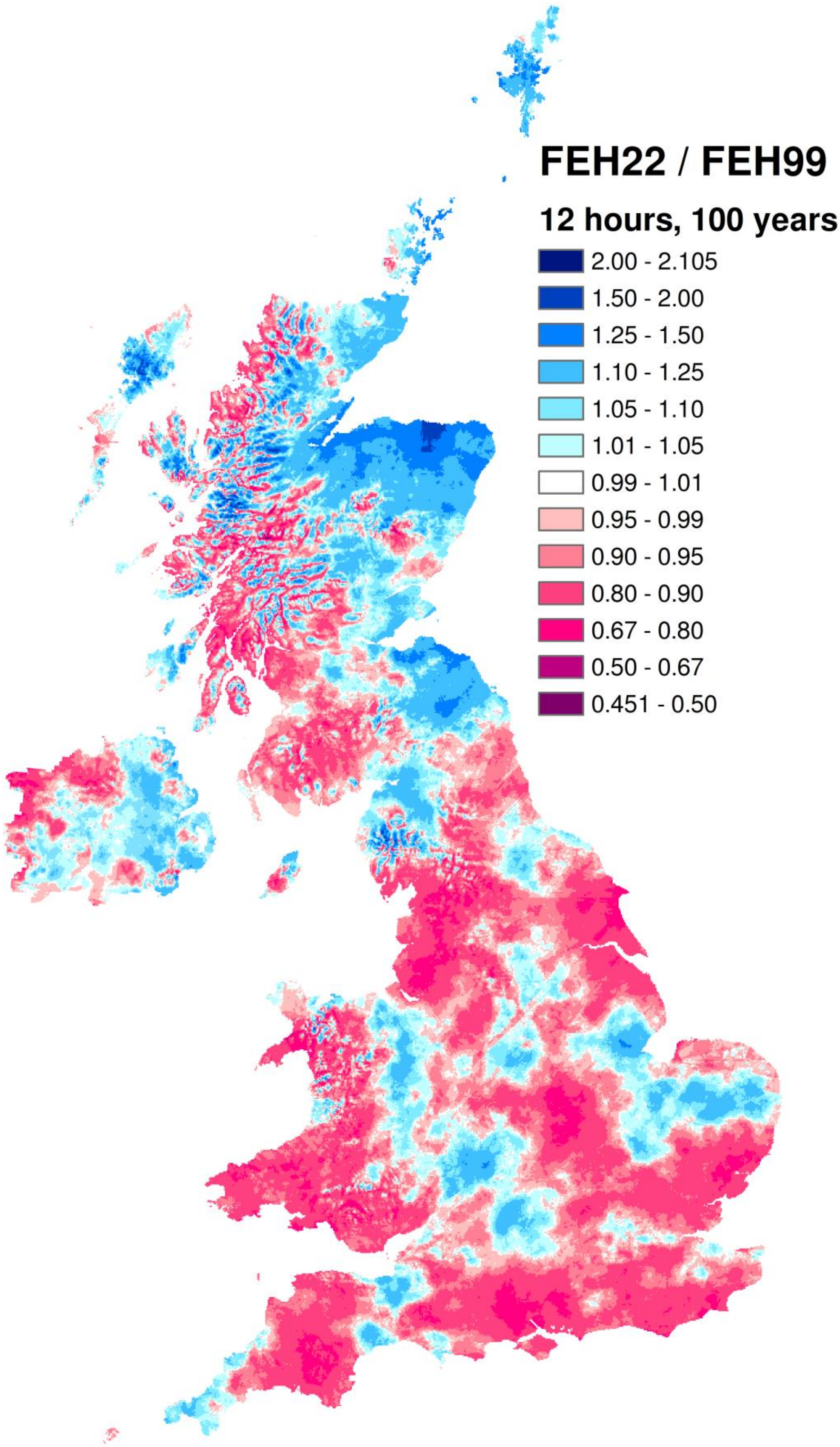

Figure 56 FEH22 rainfall depth as fraction of FEH99 rainfall depth: 12-hour, 100-year event.

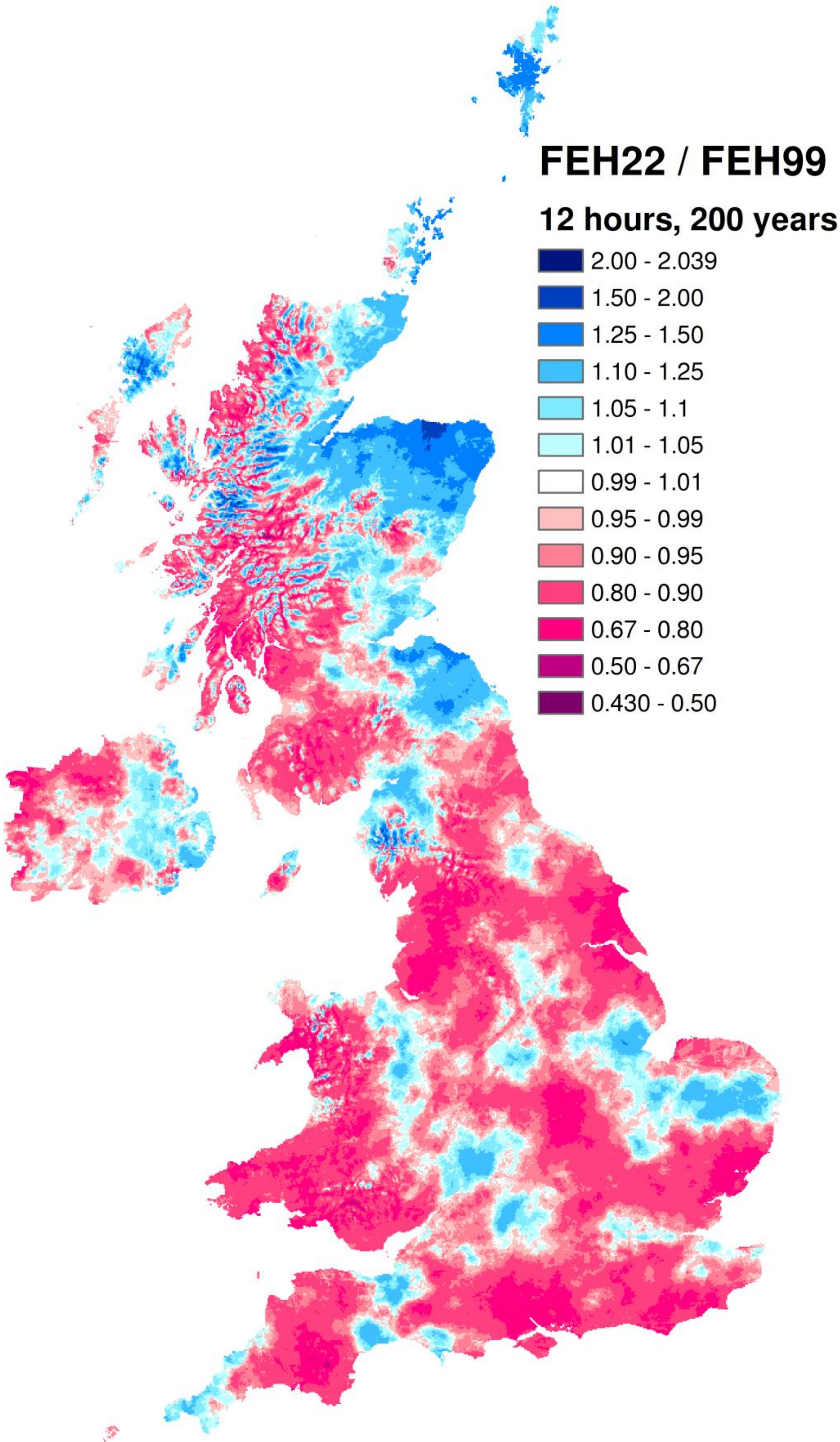

Figure 57 **FEH22 rainfall depth as fraction of FEH99 rainfall depth: 12-hour, 200-year event.**

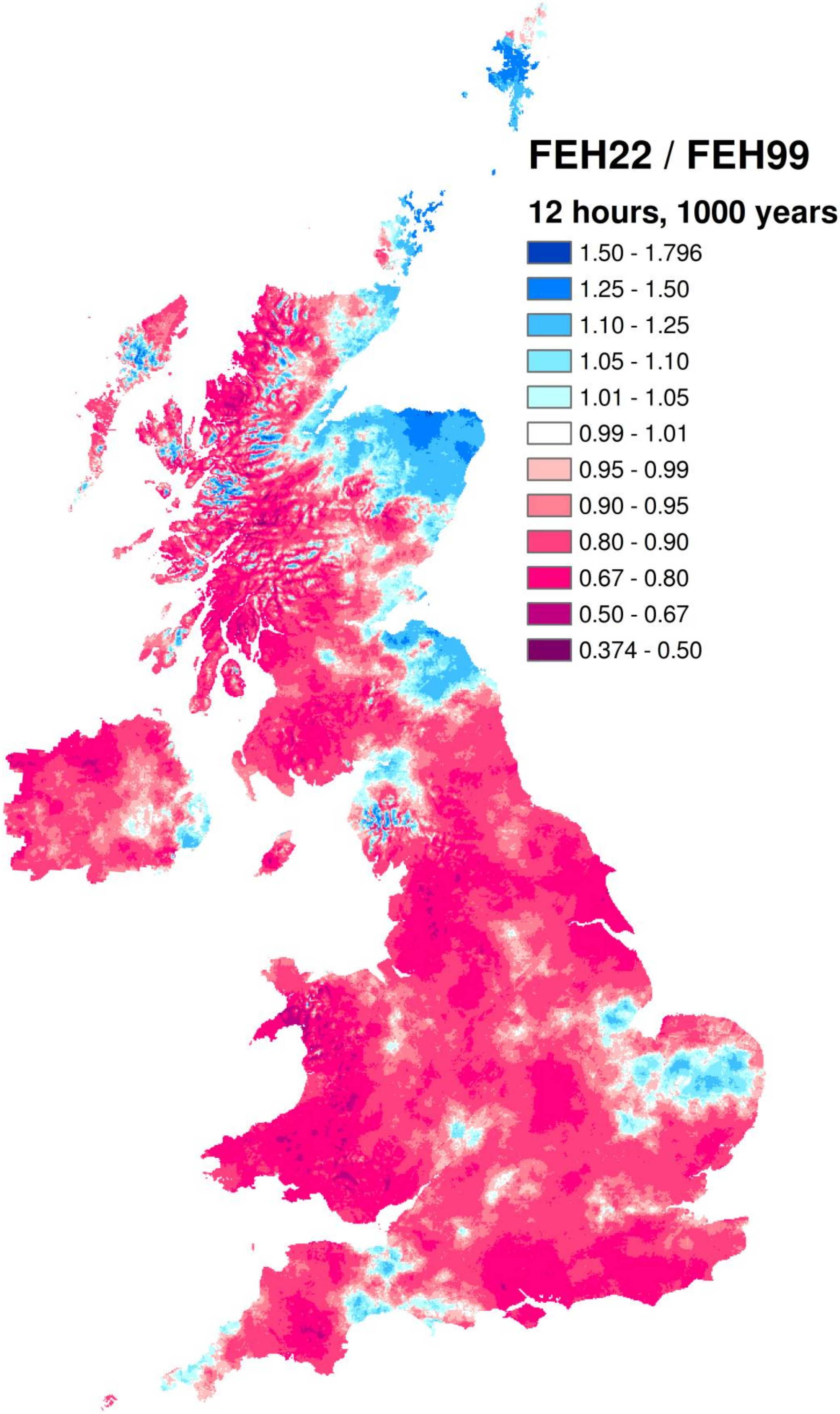

Figure 58 **FEH22 rainfall depth as fraction of FEH99 rainfall depth: 12-hour, 1000-year event.**

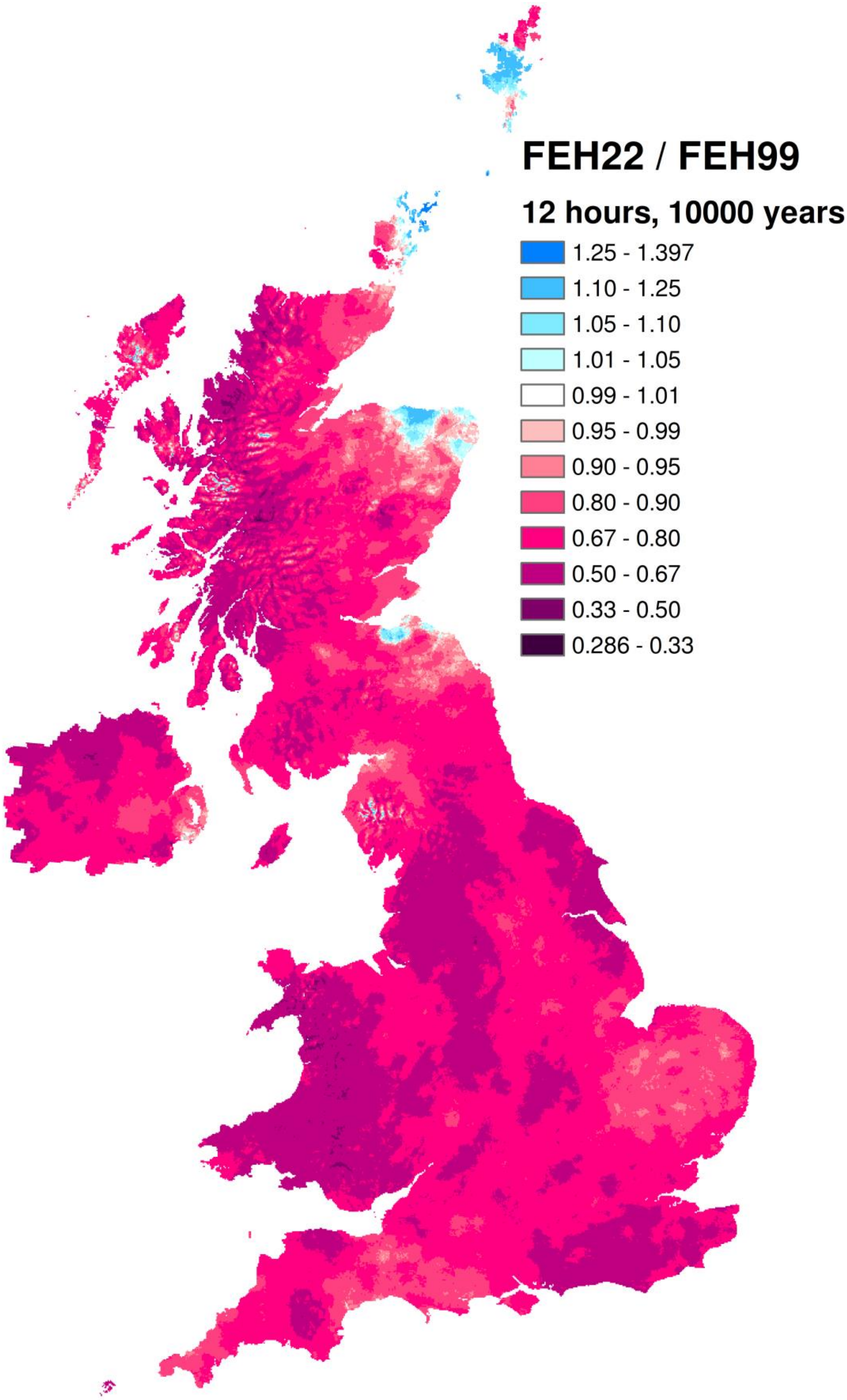

Figure 59 **FEH22 rainfall depth as fraction of FEH99 rainfall depth: 12-hour, 10000-year event.**

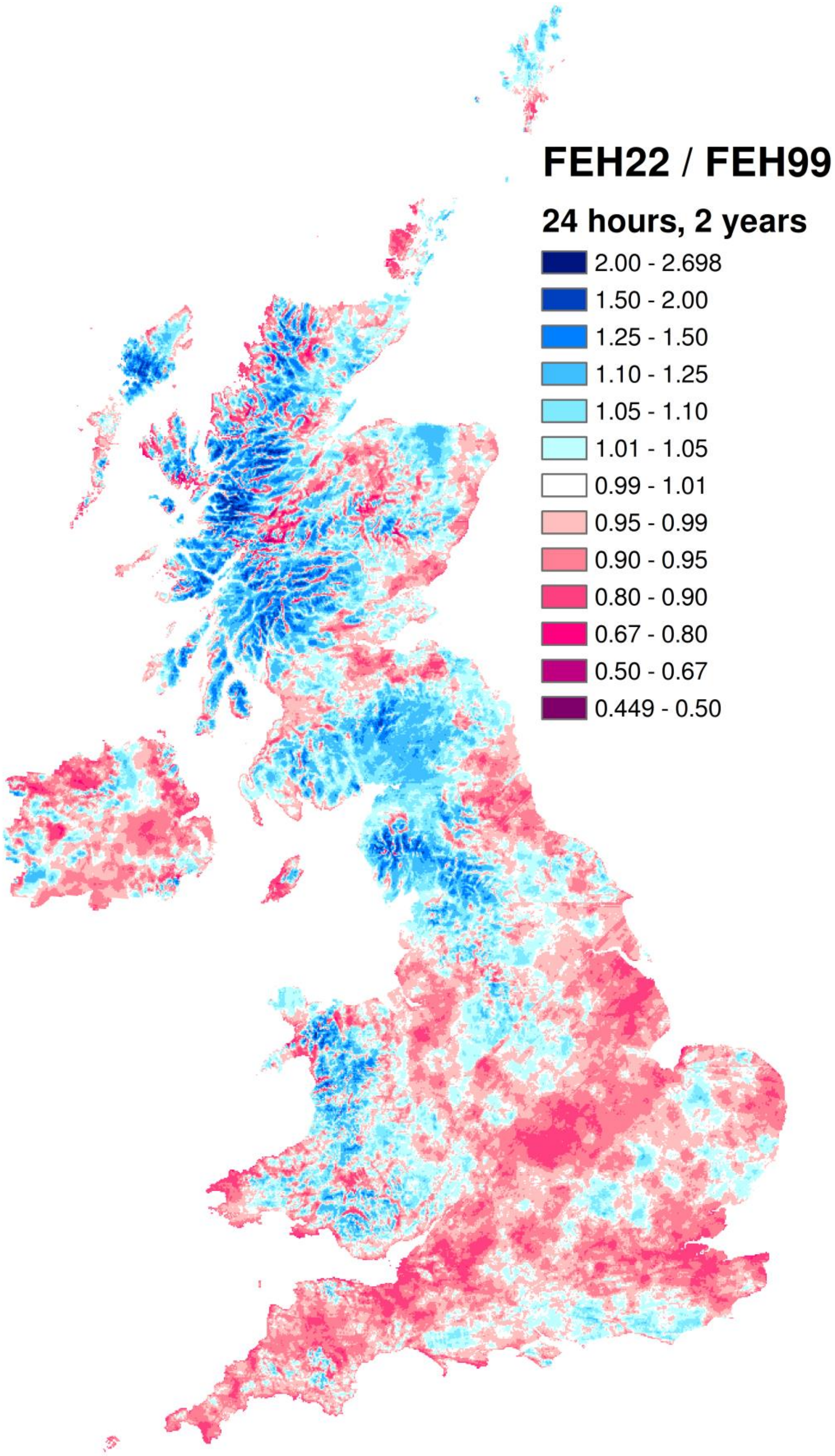

Figure 60 **FEH22 rainfall depth as fraction of FEH99 rainfall depth: 24-hour, 2-year event.**

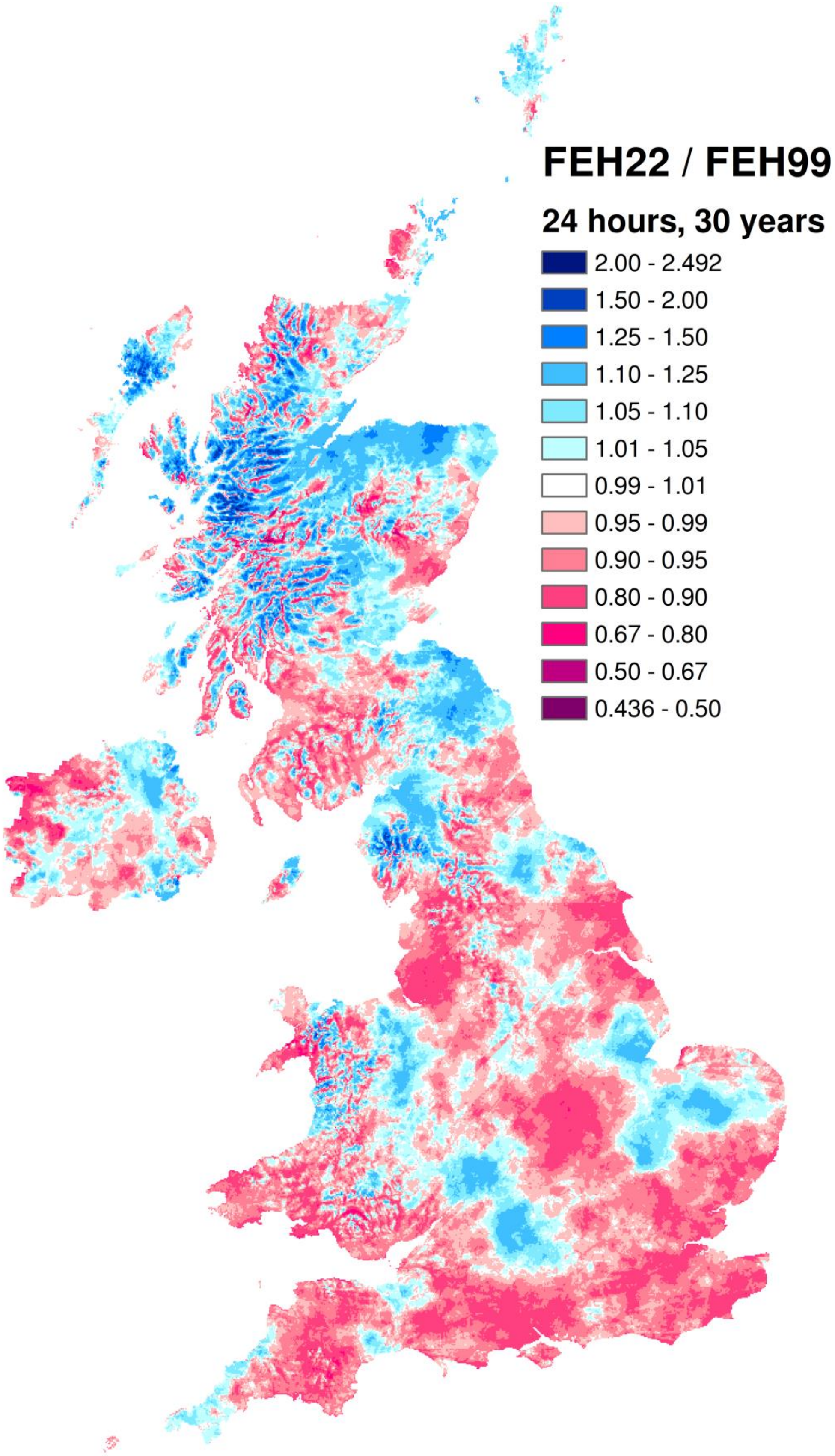

Figure 61 **FEH22 rainfall depth as fraction of FEH99 rainfall depth: 24-hour, 30-year event.**

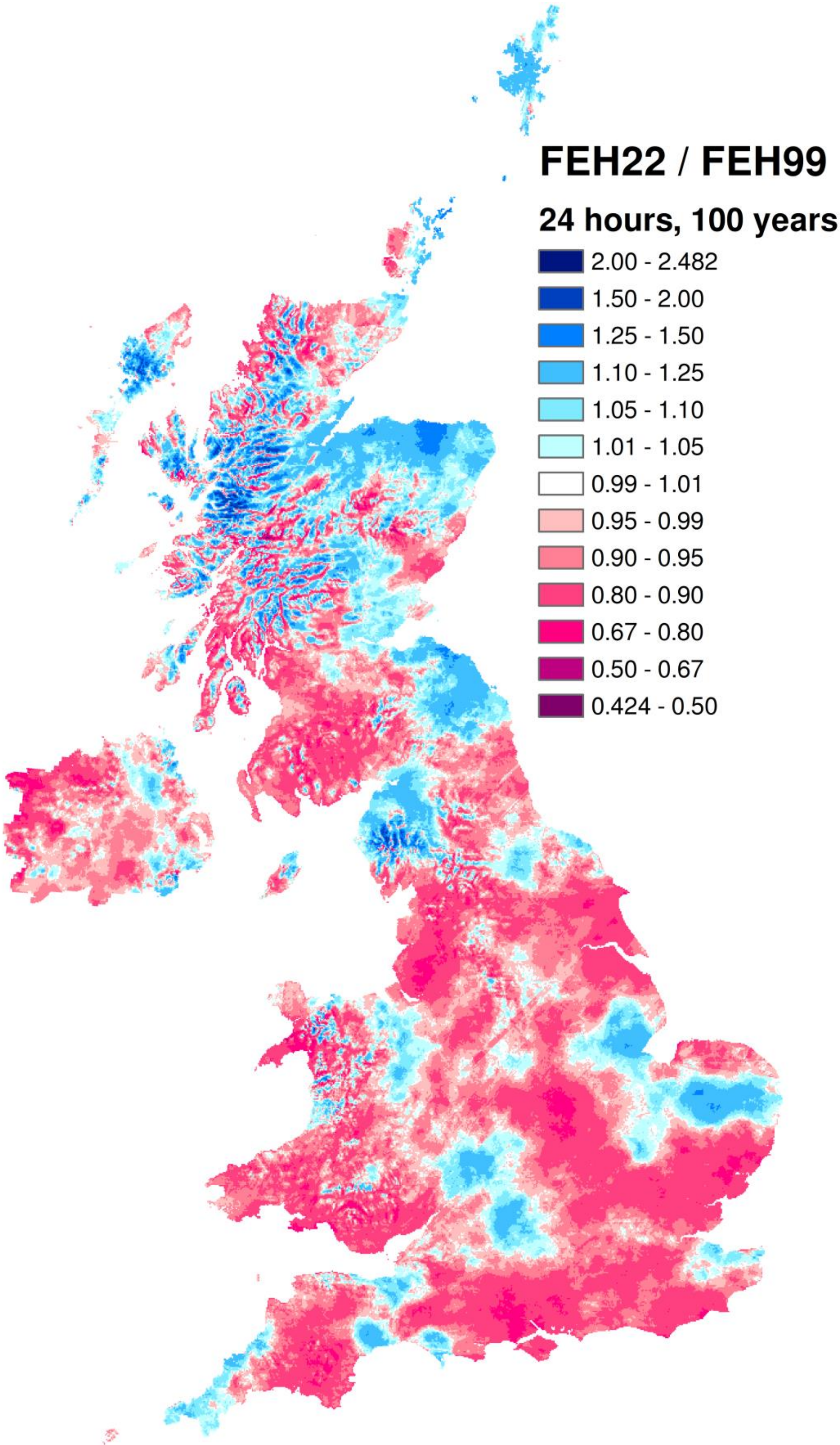

Figure 62 **FEH22 rainfall depth as fraction of FEH99 rainfall depth: 24-hour, 100-year event.**

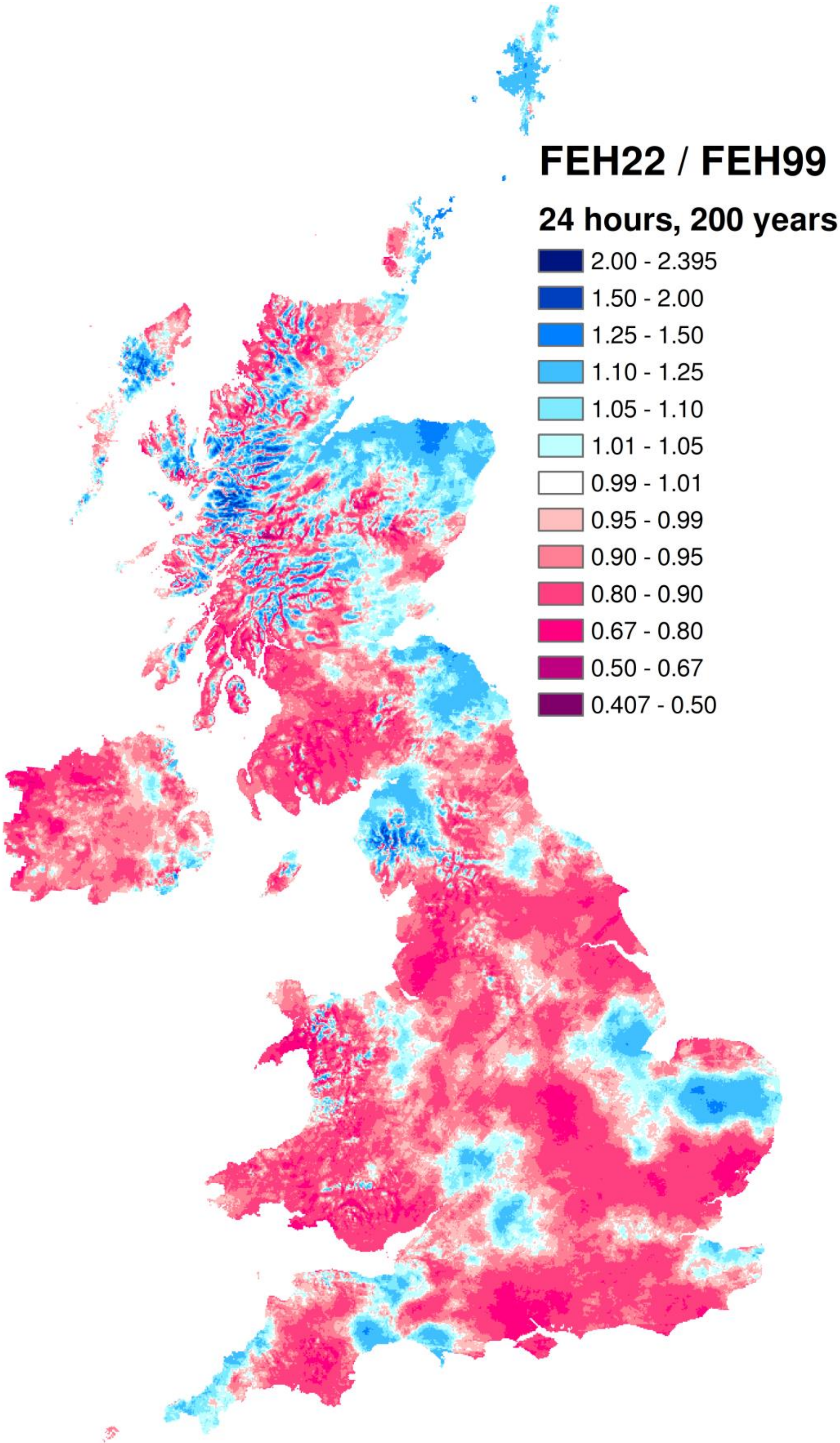

Figure 63 **FEH22 rainfall depth as fraction of FEH99 rainfall depth: 24-hour, 200-year event.**

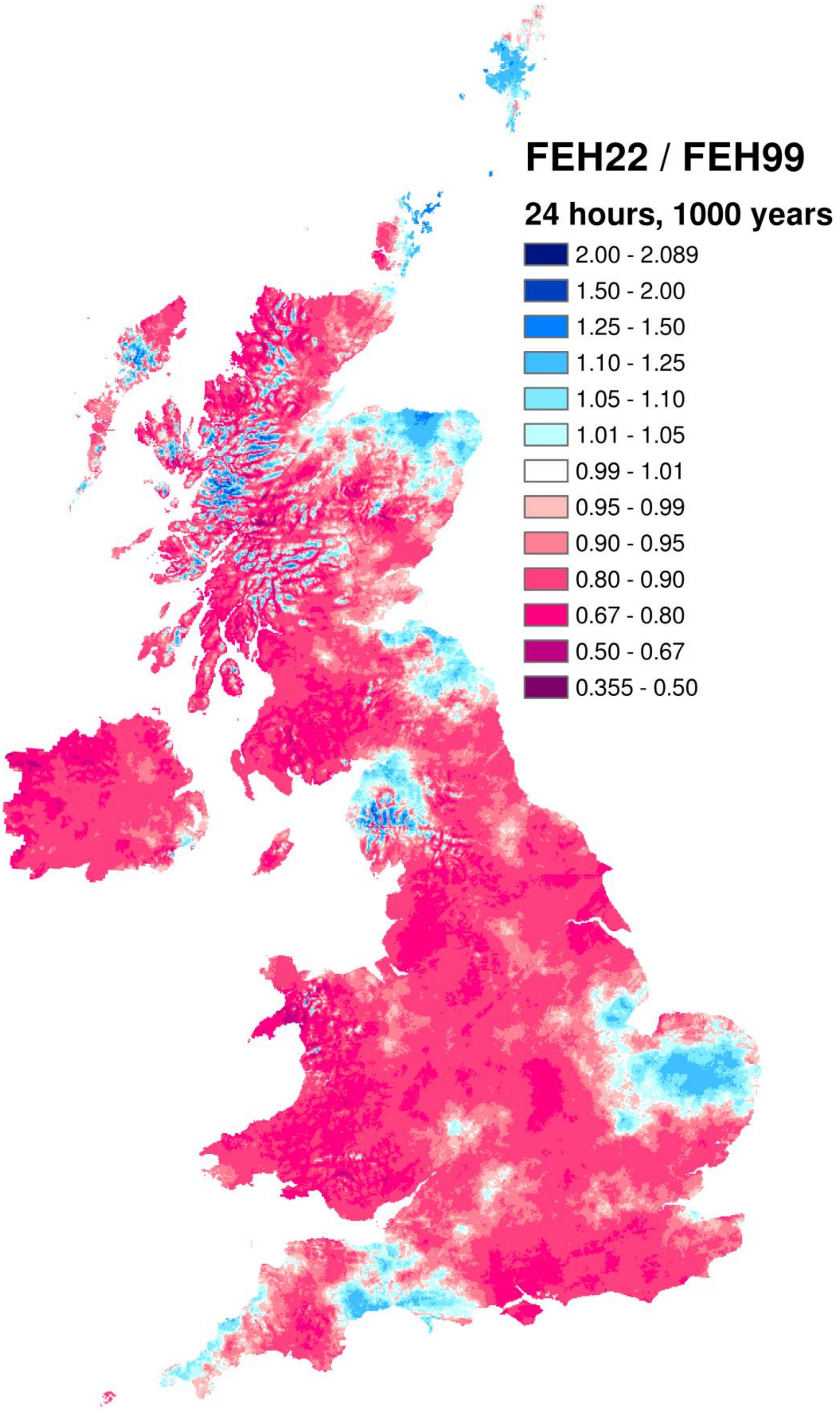

Figure 64 **FEH22 rainfall depth as fraction of FEH99 rainfall depth: 24-hour, 1000-year event.**

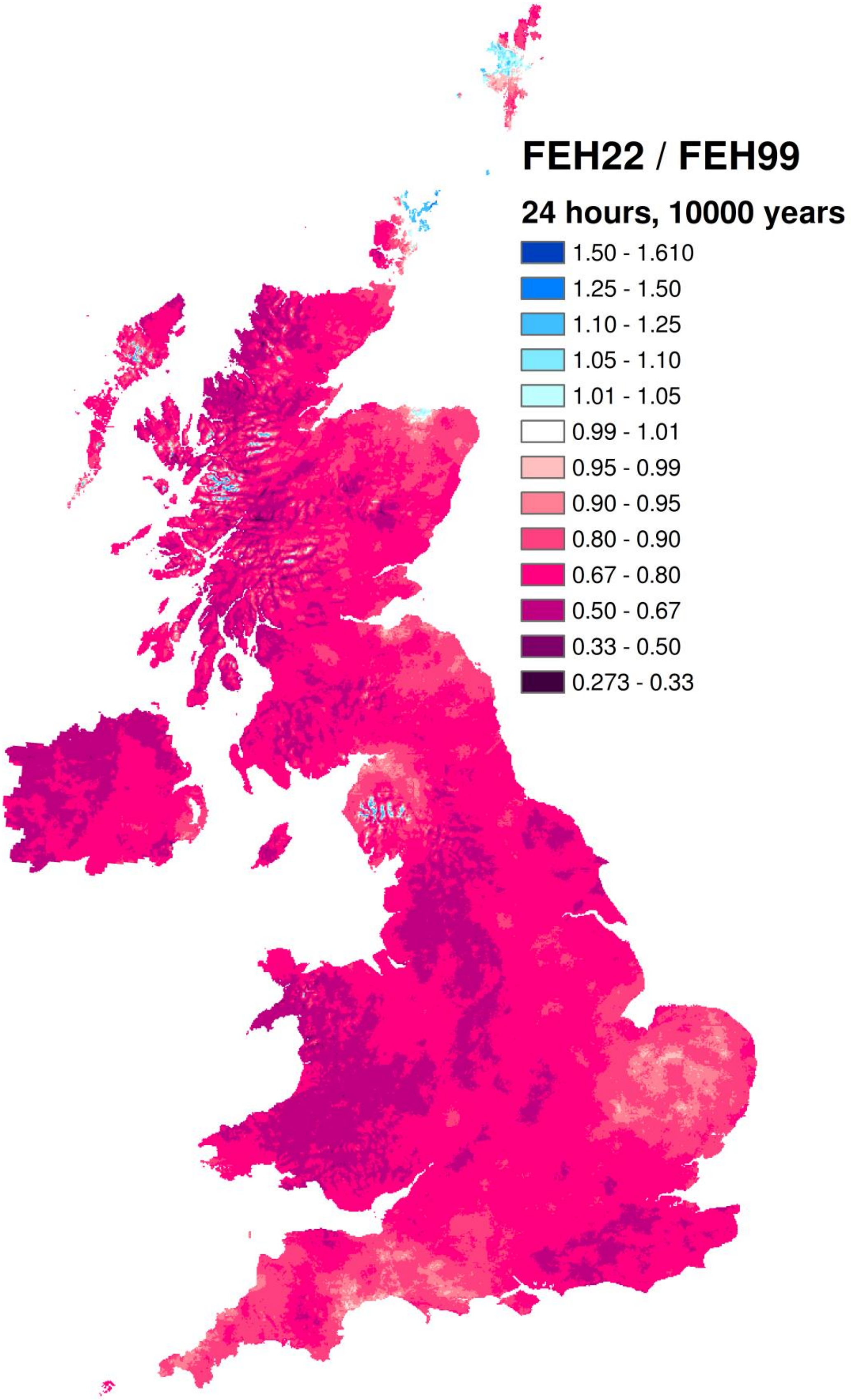

Figure 65 FEH22 rainfall depth as fraction of FEH99 rainfall depth: 24-hour, 10000-year event.

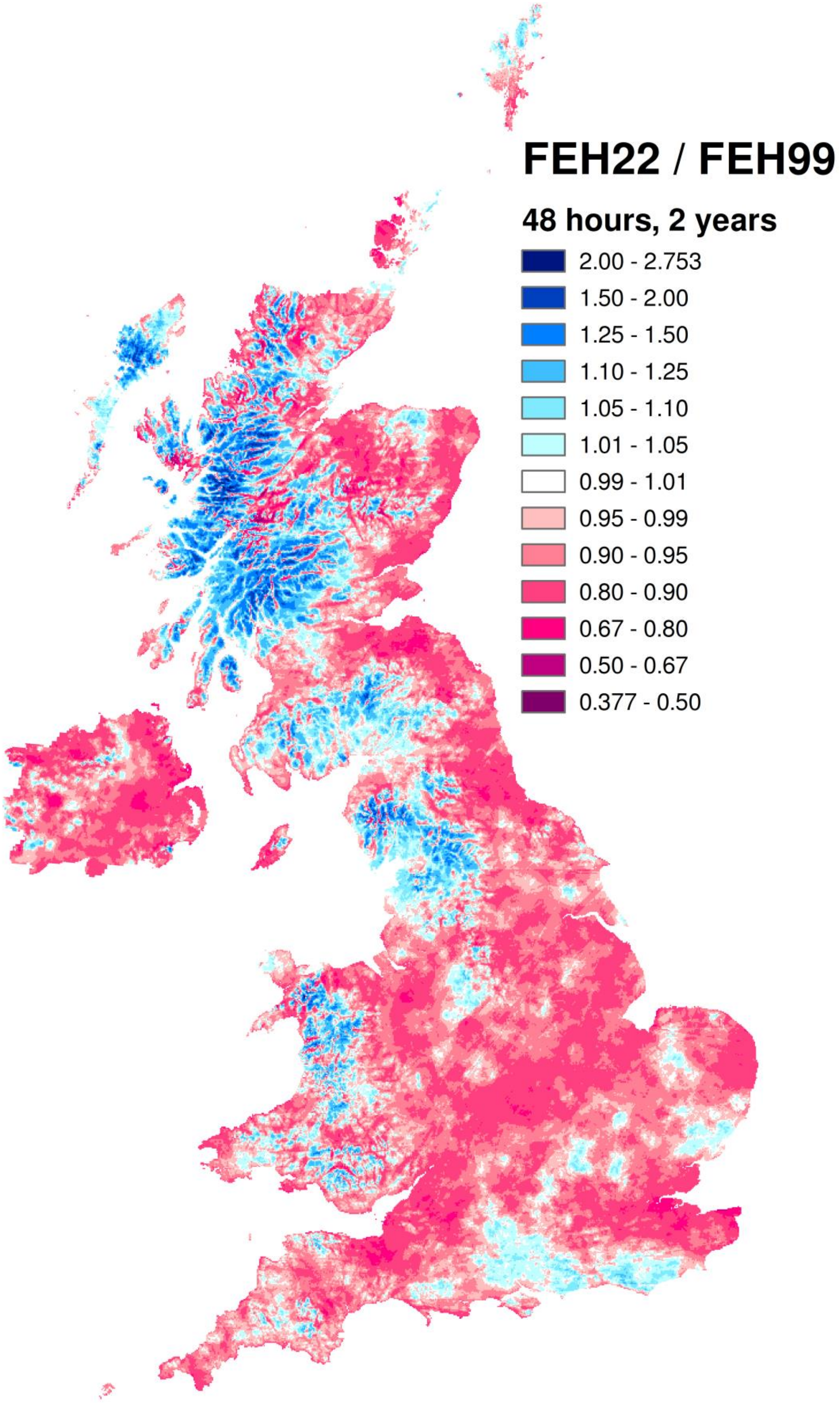

Figure 66 FEH22 rainfall depth as fraction of FEH99 rainfall depth: 48-hour, 2-year event.

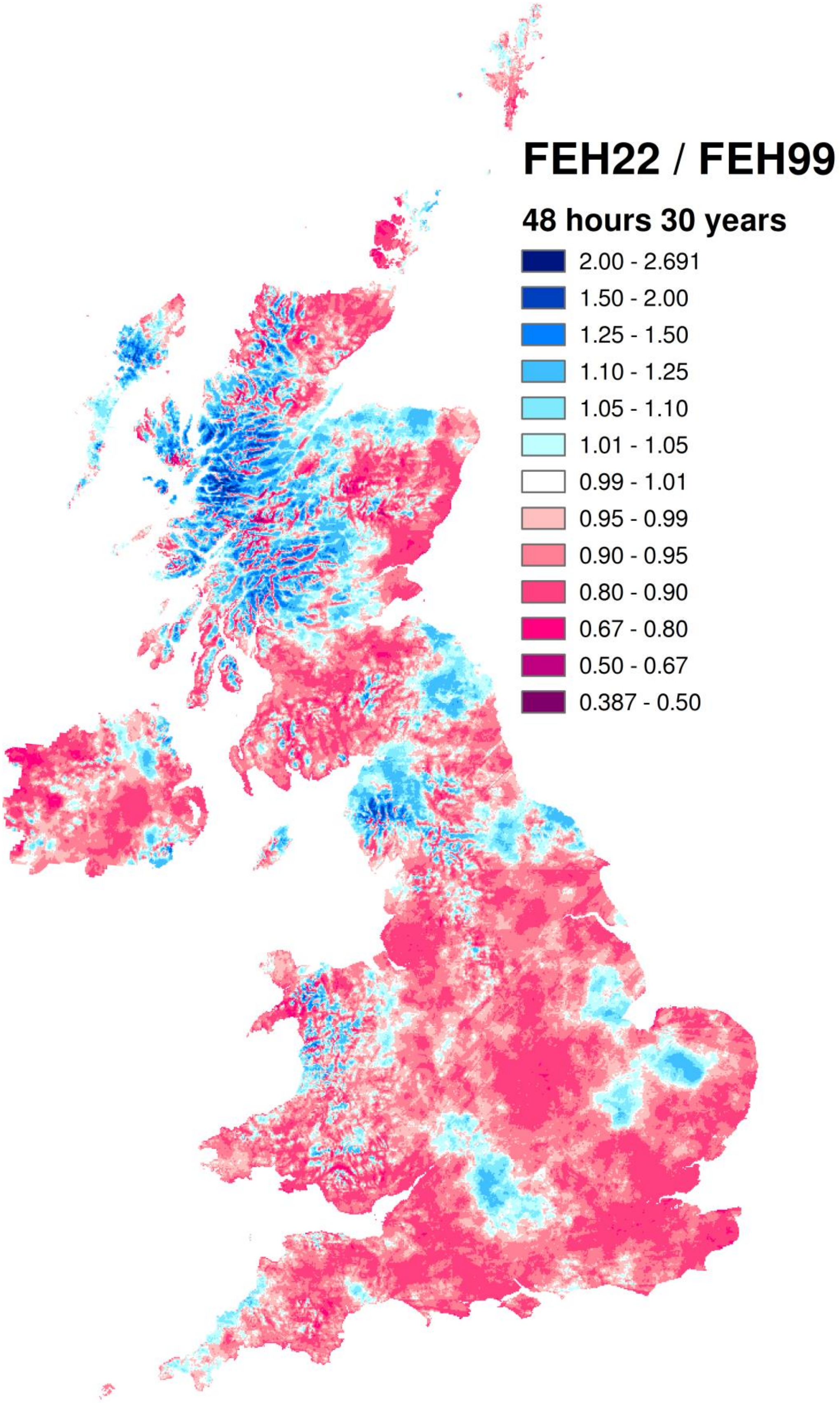

Figure 67 FEH22 rainfall depth as fraction of FEH99 rainfall depth: 48-hour, 30-year event.

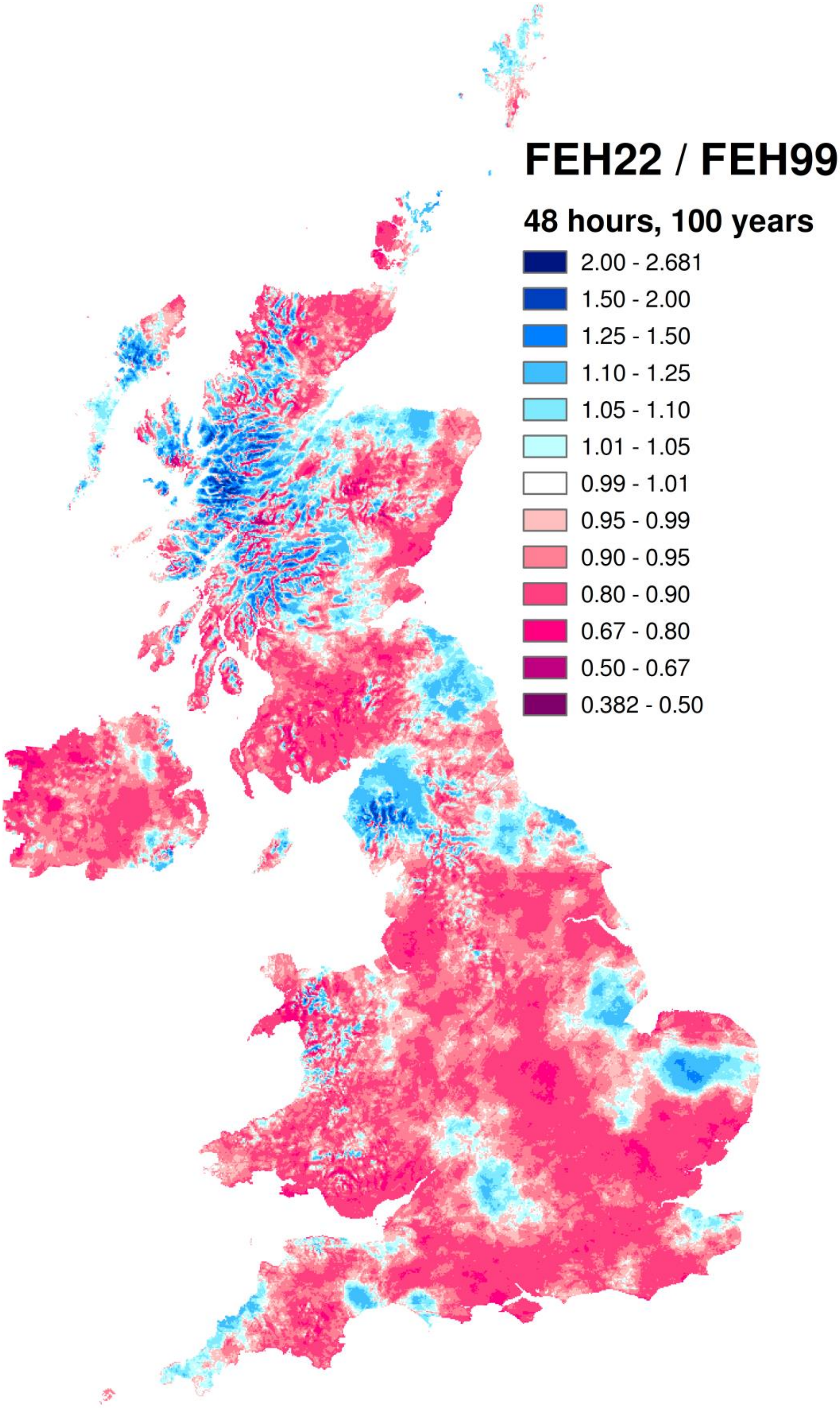

Figure 68 **FEH22 rainfall depth as fraction of FEH99 rainfall depth: 48-hour, 100-year event.**

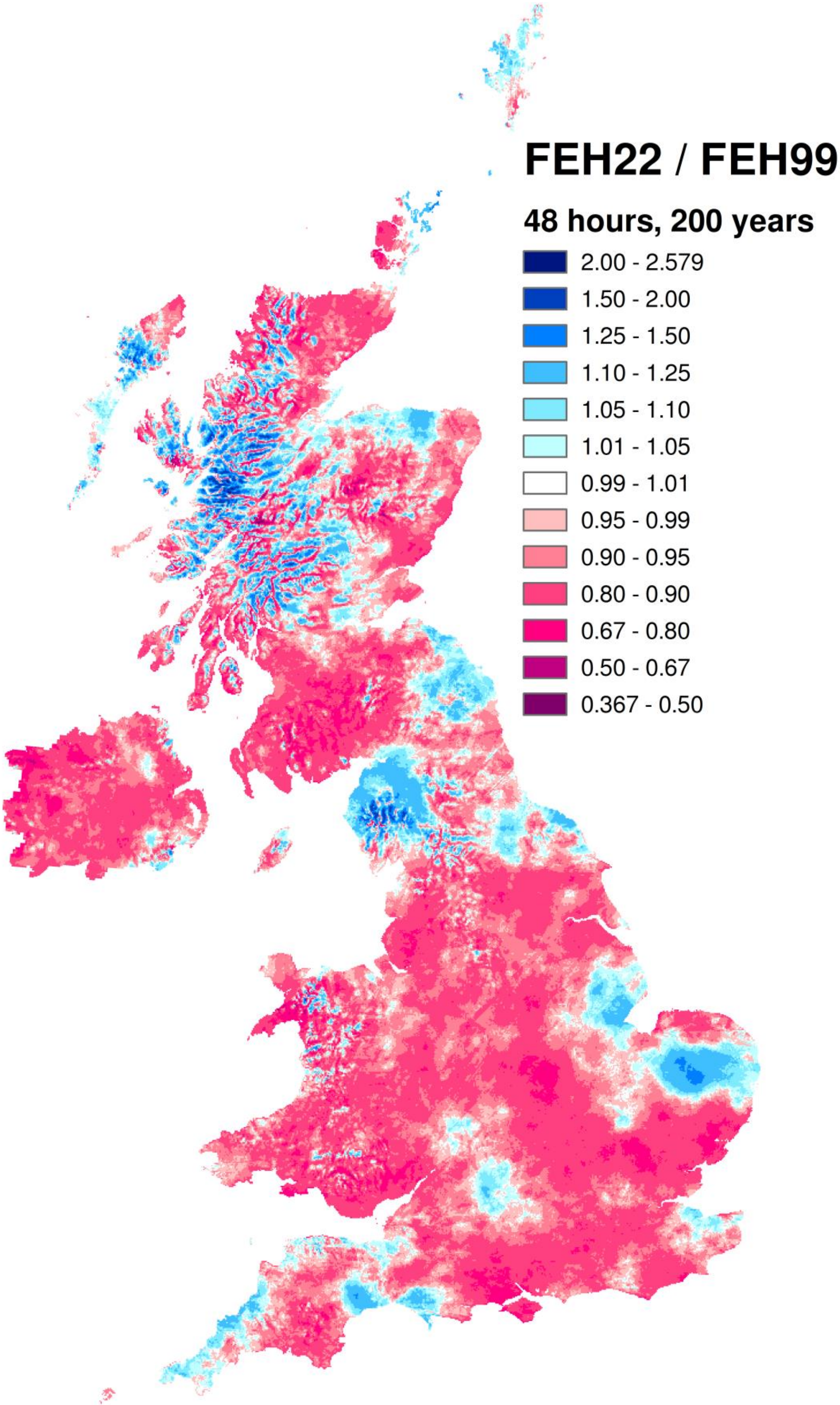

Figure 69 FEH22 rainfall depth as fraction of FEH99 rainfall depth: 48-hour, 200-year event.

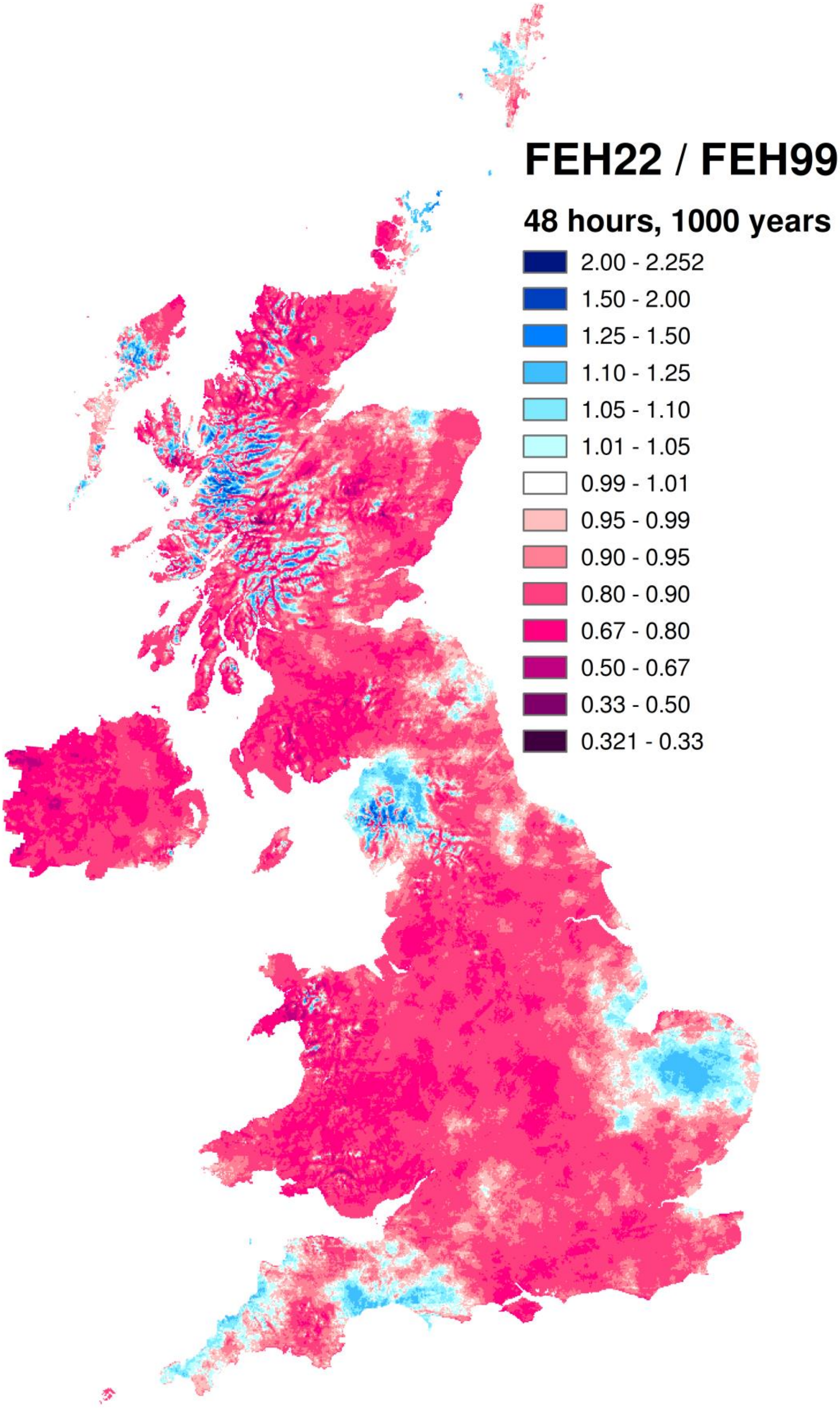

Figure 70 **FEH22 rainfall depth as fraction of FEH99 rainfall depth: 48-hour, 1000-year event.**

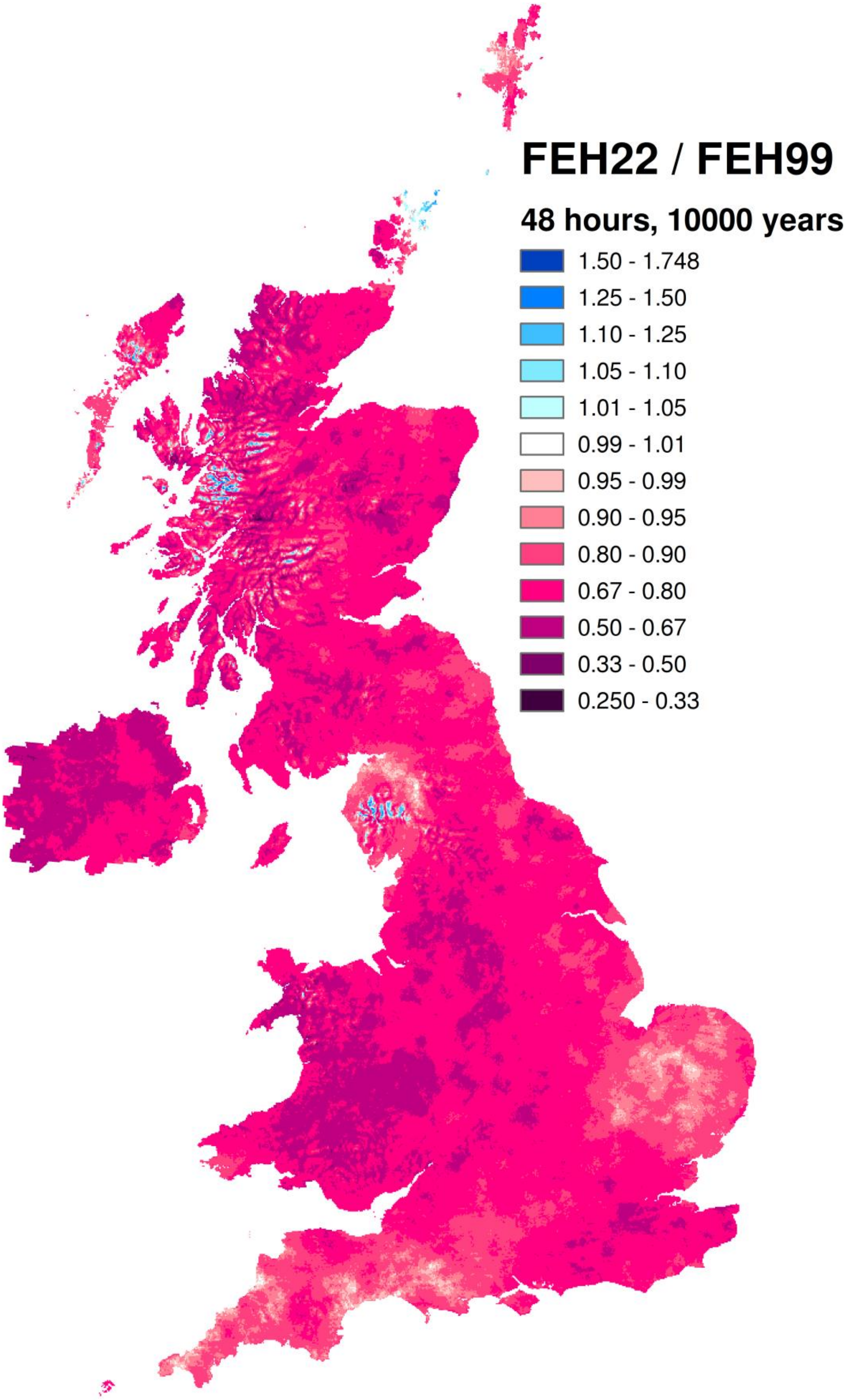

Figure 71 FEH22 rainfall depth as fraction of FEH99 rainfall depth: 48-hour, 10000-year event.

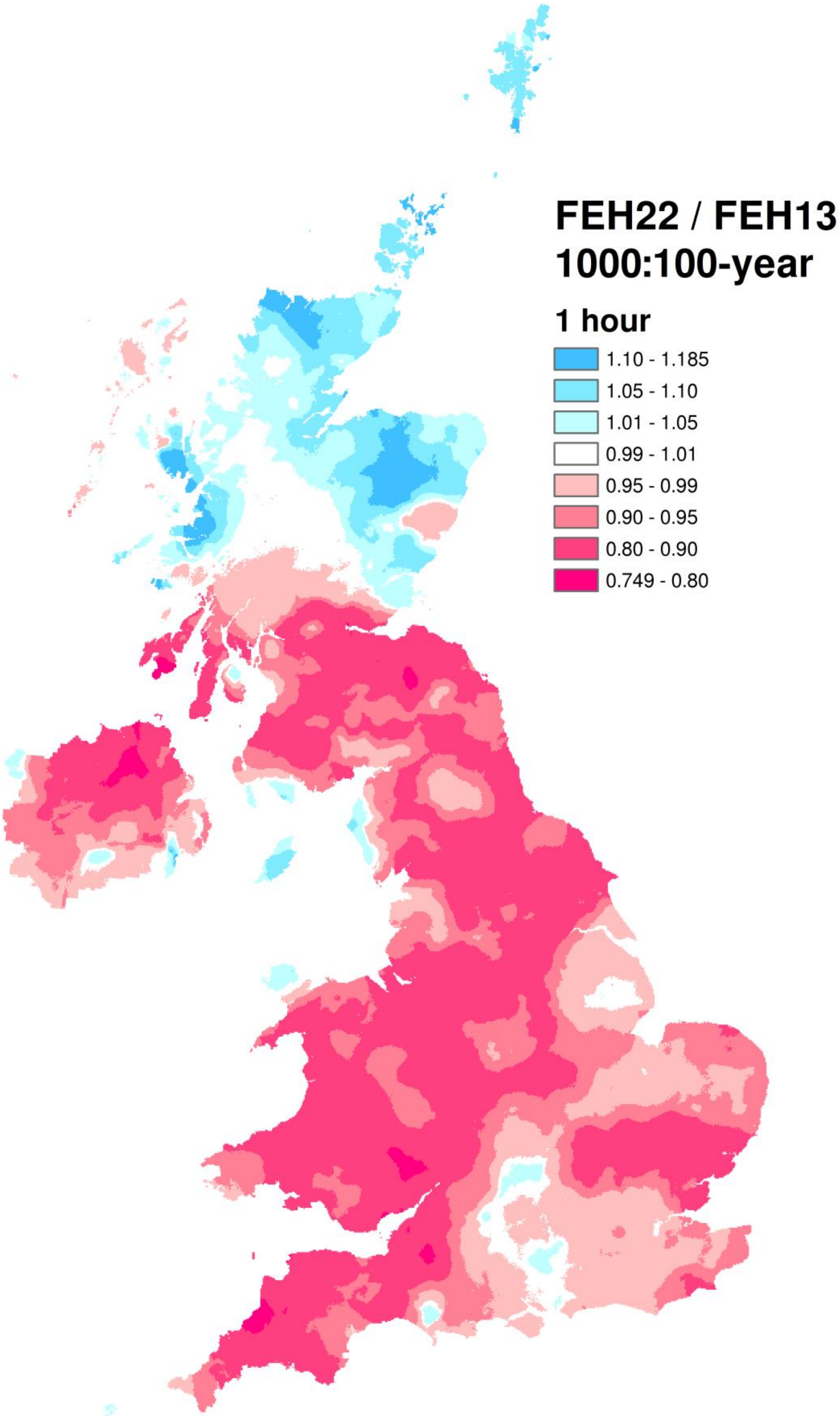

Figure 72 **FEH22 1000:100-year rainfall depth as fraction of FEH13 1000:100-year rainfall depth: 1-hour.**

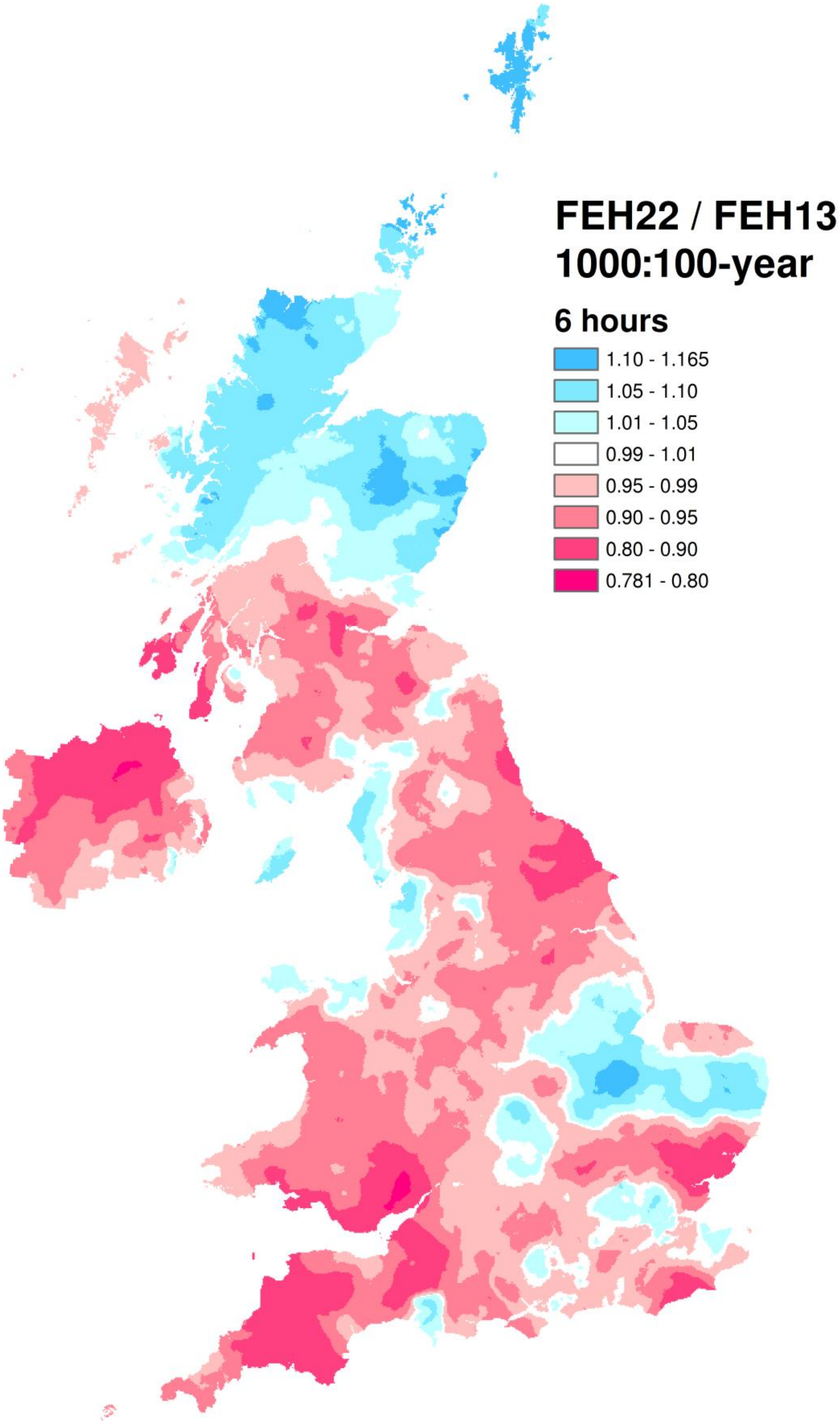

Figure 73 FEH22 1000:100-year rainfall depth as fraction of FEH13 1000:100-year rainfall depth: 6-hour.

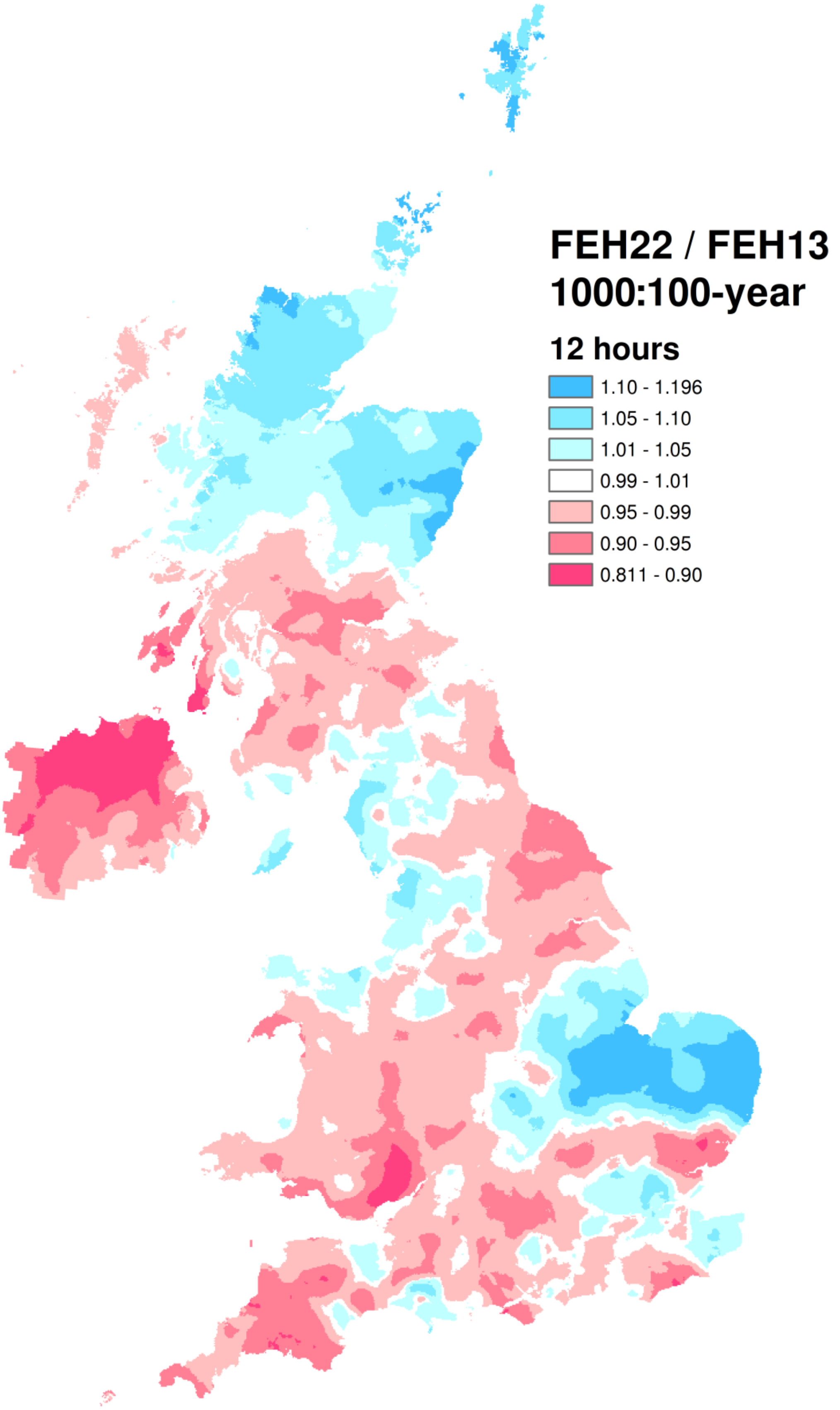

Figure 74 FEH22 1000:100-year rainfall depth as fraction of FEH13 1000:100-year rainfall depth: 12-hour.

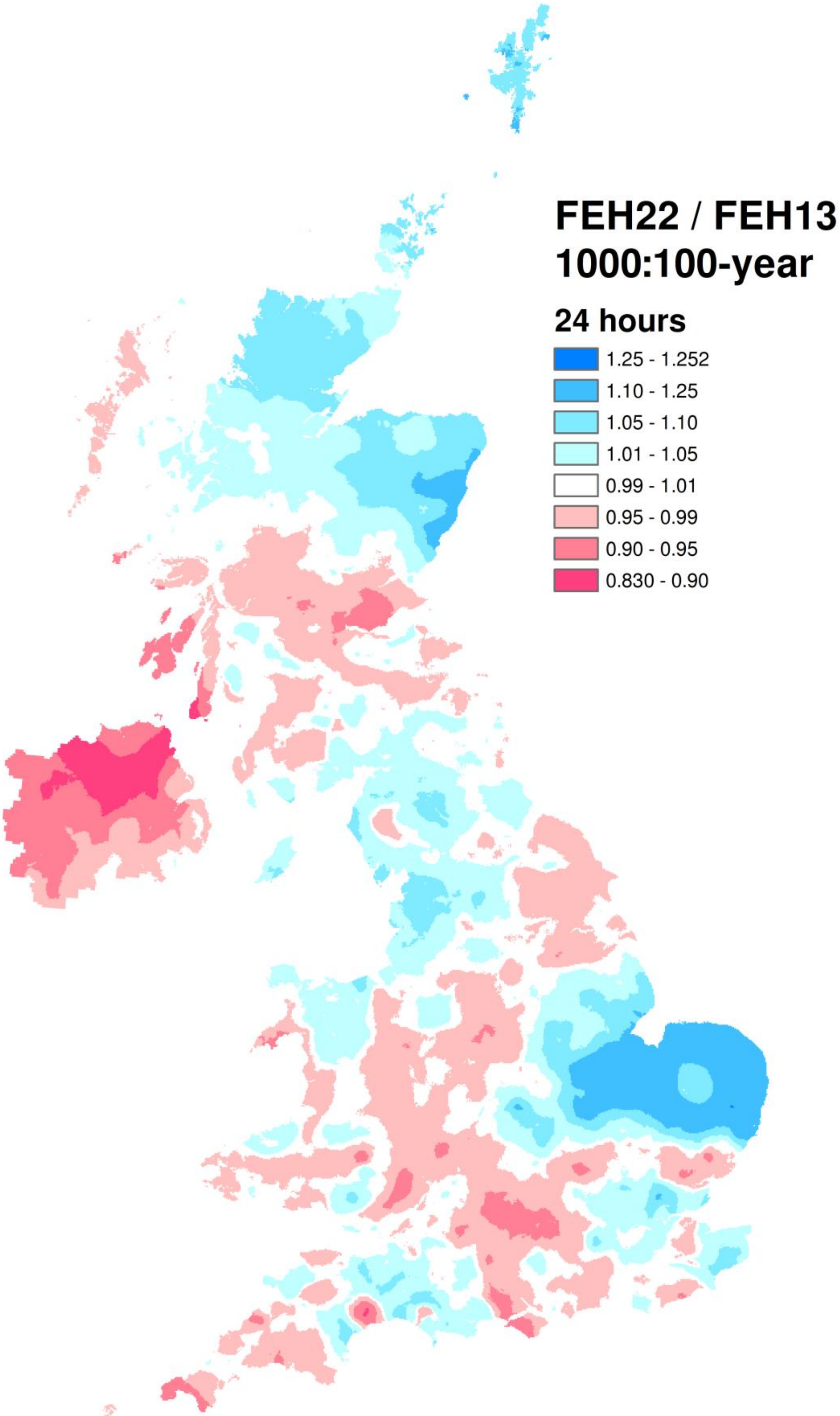

Figure 75 **FEH22 1000:100-year rainfall depth as fraction of FEH13 1000:100-year rainfall depth: 24-hour.**

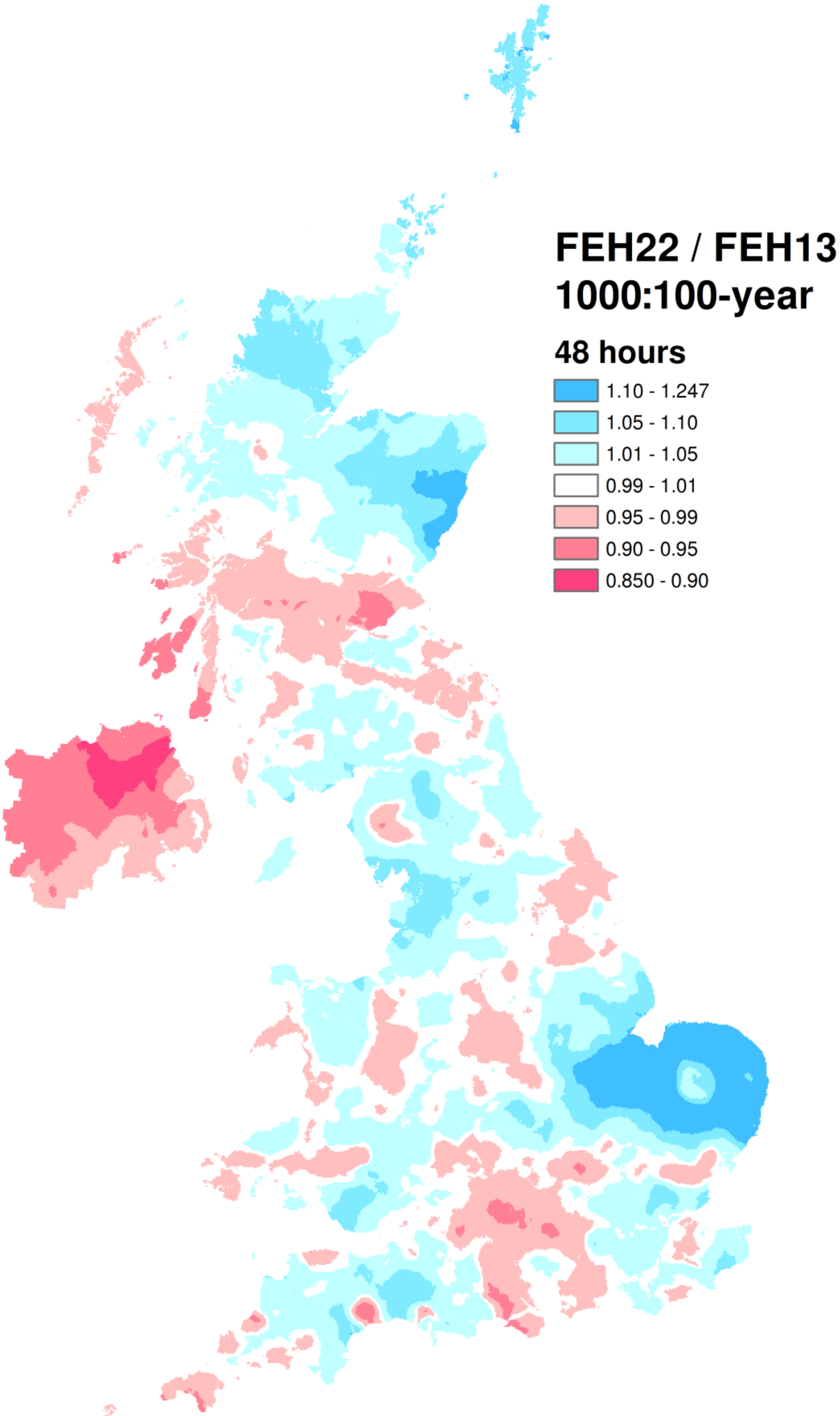

Figure 76 FEH22 1000:100-year rainfall depth as fraction of FEH13 1000:100-year rainfall depth: 48-hour.

6. Assumptions, limitations and uncertainty

A number of assumptions must be made during development of any model, some of which lead to limitations in the model. Additionally, uncertainty from multiple sources, some of which may or may not be possible to mitigate, is an unavoidable part of any study.

6.1 Assumptions (climate change and non-stationarity)

In common with the FEH99 and FEH13 models, the FEH22 depth-duration-frequency model assumes stationarity in all calibration data. Hence, it assumes no temporal trends in the data used for calibration. The most recent Government climate change risk assessment (CCRA3) points to some evidence for recent increases in occurrence of extreme UK rainfall, but states that records are too short for the evidence of trends to be conclusive (Slingo, 2021). HadUK-Grid data suggest that significant changes, particularly increases in seasonal rainfall extremes, have occurred (Cotterill *et al.* 2021). However, the HadUK-Grid data set is based only on daily rainfall, so it cannot be used to infer trends in sub-daily extremes. Because it is a stationary model, FEH22 makes no explicit account of such potential changes in recent rainfall and how this could affect design rainfall estimates. However, by including significantly more events and recent data, confidence in the model outputs capturing any recent climate shifts is improved, hence FEH22 serves as an improved baseline for flood risk assessment. The uncertainty in potential inclusion of any recent climatic shifts, which clearly remains uncertain, is fundamentally outweighed by the improvement gained through significant increases in gauged data. This “updated stationarity” approach can be shown to have advantages over models that model non-stationarity explicitly, independently of what trends exist (e.g. Luke *et al.* 2017).

It is important to note that a decrease or increase in rainfall estimates from FEH22 to FEH13 should not be interpreted to indicate a change in climatic conditions. The changes are primarily due to the addition of extra data and improved quality assurance removing erroneous data, from both the recent *and* historical records. Future work will set out to explore the effects of recent climate shifts on extreme rainfall, how this can be more explicitly represented in the rainfall model, and how climate change allowances that account for variable baseline data and design storm estimates can be systematically applied.

6.2 Other assumptions

The *RMED* grids that are used in standardization of rainfall depths assume that the gauged values of *RMED* are not the “true” values, but subject to sampling variability. This is a reasonable assumption that was also made in FEH99 and FEH13 model development. Similarly, standardization of AMAX is clearly required, and the form of standardization used in FEH22, in which AMAX are not only divided by *RMED*, but further scaled to so that all series have more similar *L*-moments, is an improvement over that used in FEH99, in which AMAX were divided by *RMED* only. However, the exact forms of the standardizations used in each model must be assumed and, while improvements have been noted from FEH99 to FEH13 and FEH22, it is impossible to know the “true” correct forms.

Unlike some point-interpolation procedures, the FEH22 (and FEH13 and FEH99 models) do not assume that storm centres are captured; it is possible for a rainfall depth captured at one gauge to be translated to a greater depth at a nearby ungauged location. However, it is not possible for a *standardized* depth at a gauged location to be translated to a greater *standardized* depth at an ungauged location.

6.3 Limitations

The FEH22 calibration data set contains the largest amount of data ever used to calibrate a UK DDF model, with double the amount of hourly data used to calibrate FEH13 and about five times the amount used to calibrate FEH99. Daily data quantity is also greatly increased over both FEH13 and FEH99. However, there is potential to increase the data set further, through digitizing more pre-1961 rainfall data, obtaining rainfall records from Met Éireann for the whole island of Ireland, using rainfall radar data to revise events where the greatest standardized depth was not captured by a ground gauge, and (subject to comprehensive data quality checks) incorporating data from private observers, such as that published to the Met Offices Weather Observations Website (https://wow.metoffice.gov.uk).

6.4 Uncertainty

Sampling variability is a significant source of uncertainty in every rainfall record. Uncertainty due to sampling variability is greater in AMAX series with fewer data points, and also in series that have exactly one outlier. Figure 77 demonstrates this using the 17-year series of 1-hour AMAX at Tyndrum № 3, which has exactly one outlier (AMAX1 = 69.2 mm, AMAX2 = 20.2 mm). in this series, the return period of the largest event is estimated at 87 years. However, the interquartile range of return periods from 1000 balanced resamples of the original series ranges from 56 to 81200 years for the same event (horizontal line on Figure 77a). Repeating this procedure 1000 times, the lower quartile return period is stable, around 50-80 years (Figure 77b), the mean return period is consistently between 89 and 92 years (Figure 77c), but the upper quartile estimate of return period ranges from 25000 to 1.12 million years (Figure 77d). The reason for such a large range in return period estimates is due to the inclusion (or not) of the outlier event in each resample: in Figure 77a, these fall into “bands” corresponding to how many duplicates of the outlier event are in each resample. The large scatter of shallower lines correspond to resamples without the outlier event, while each consecutive band to the left of this includes one more copy of the outlier event than the last. Clearly, the presence of an outlier event reduces the estimated return period of that event considerably more than the presence of more than one outlier (however, if there are multiple outliers, it is questionable if they really are “outliers”).

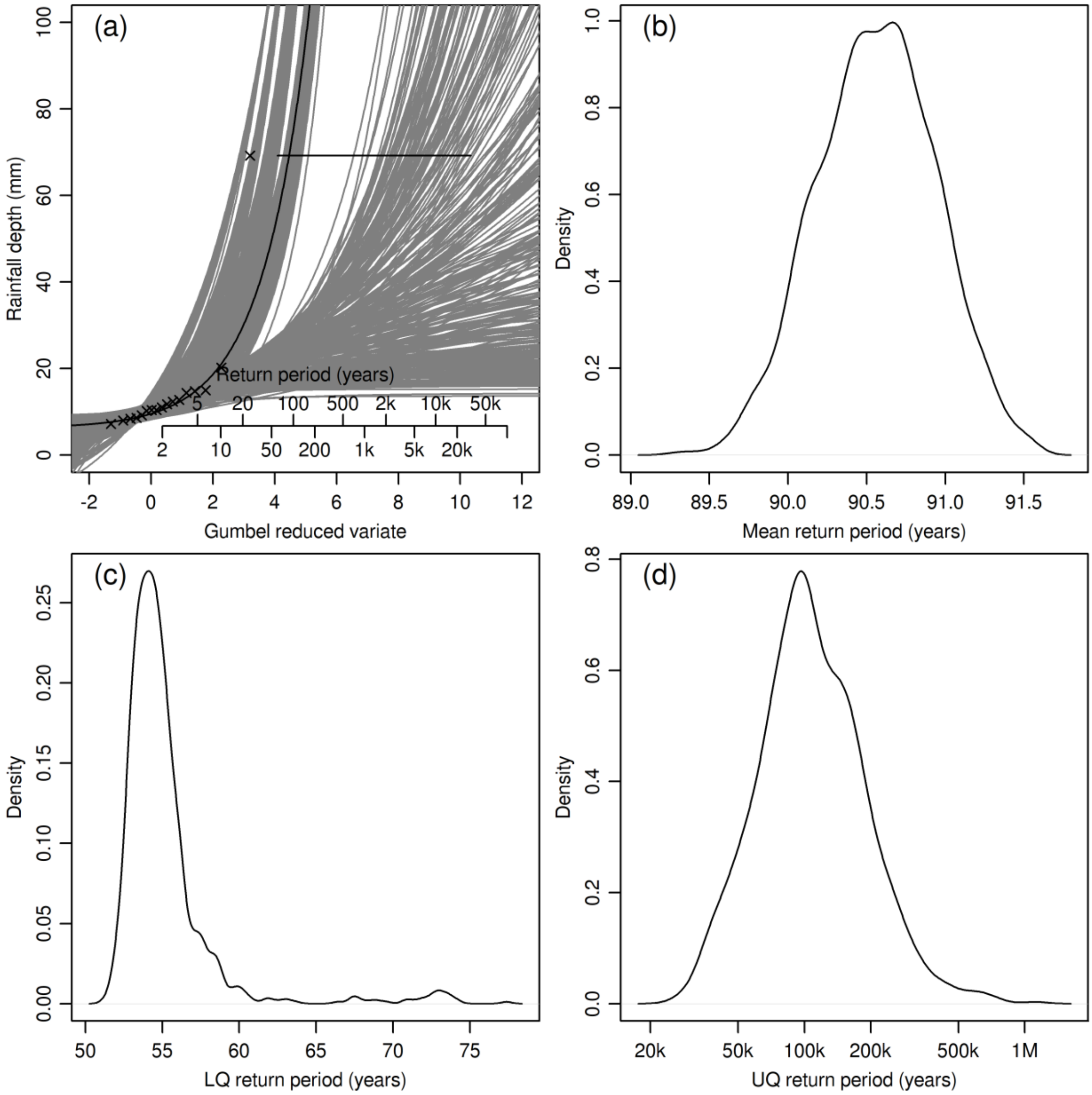

Figure 77 **Extreme value plot: 17 valid 1-hour AMAX at Tyndrum № 3 using Gringorten plotting position (black crosses), with generalized extreme value distribution fitted to AMAX (black curve) and 1000 balanced examples of the AMAX (grey curves), and interquartile range of return periods for largest AMAX (black horizontal line) (a). Mean (b), lower quartile (c) and upper quartile (d) of return period associated with largest AMAX, from 1000 replications of the procedure shown in (a).**

7. Recommendations

Despite the great advances in data availability made during the FEH22 project, various additional sources of rainfall data were mentioned in the previous section (digitization of old records, Met Éireann, radar, private observers). It is recommended to investigate all of these sources fully.

While the FEH22 data set is the largest ever used to calibrate a UK DDF model, several recent large events are known to be excluded, either because they occurred too recently, or because they were captured by gauges that do not have long enough records for inclusion in calibration. It is therefore recommended that new DDF models are produced more regularly: 24 years passed between the FSR and FEH99, then another 16 between the FEH99 and widespread availability of FEH13. Because extreme events can occur at any time, and it is very unlikely that a model calibration data set will be able to include any events occurring less than a year or two before the model's release date, updates should continue indefinitely.

Inclusion of more pre-1961 data could extend the main focus of the dataset from the last 60 years to a longer period, while regular inclusion of new events as time goes on extends the temporal range. Both could increase the amount of observable non-stationarity in the data set. Future work will explore the effects of recent climate shifts on extreme rainfall, how these can be more explicitly represented in a rainfall DDF model, and how climate change allowances that account for variable baseline data and design storm estimates can be applied systematically.

8. Acknowledgements

This update to the FEH DDF model - FEH22 - has been funded by re-investment of income from the FEH Web Service and builds on specific projects funded by the Environment Agency (Local recalibration of FEH13 depth-duration-frequency (DDF) model for Cumbria, Boosting Action on Surface Water – Local Surface Water Mapping) and Scottish Water (Improved understanding of short-duration rainfall intensity and its impacts on storm sewer flooding in Scotland). The sub-daily rainfall dataset includes data that were collated within the Hydro-JULES project, funded by the UK Natural Environment Research Council (NE/S017380/1).

The FEH Web Service is provided by the UK Centre for Ecology & Hydrology (UKCEH), a not-for-profit research charity, and is developed, maintained and made available by its agent, Wallingford HydroSolutions (WHS), for use by the flood hydrology community. Income generated by the FEH Web Service users funds the operation, maintenance and development of the FEH Web Service platform itself and is also re-invested into its underpinning scientific research to ensure continual advancement in the FEH evidence base. These advancements are guided by regular consultation with the UK regulatory agencies, and liaison with the wider scientific and user community, along with the availability of data.

The development of and reporting on the FEH22 DDF model has benefited greatly from regular engagement with scientists, practitioners, and regulators. It has been supported by contributions from UKCEH (Lisa Stewart, James Miller, Oliver Robertson, Caroline Cowan) and Wallingford HydroSolutions (Jude Jeans, Tracey Haxton, Chris Nicholls, Laura Anne Cox). We would like to acknowledge review of this report by the Environment Agency (Clare Waller, Donna Wilson, Katie Muchan), Cyfoeth Naturiol Cymru (Owain Sheppard, Sophie Lucas), Scottish Environment Protection Agency (Becky Wilson, David Fadipe, Alistair Cargill, Leila Farkhondeh), and Wallingford HydroSolutions (Jude Jeans, Tracey Haxton).

9. References

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Appendix

This Appendix shows all extreme events reviewed by the Environment Agency (EA) in England, SEPA in Scotland and Cyfoeth Naturiol Cymru (CNC) in Wales. Measuring authorities were requested to review all annual maxima consisting of 50 mm or more in 1 hour, or 100 mm in 6 hours (italicized values in this appendix are 6-hour totals). Where a 1-hour or 6-hour total was rejected, all annual maxima from 1 to 24 hours were rejected for that year and gauge. In addition to rejecting or accepting individual values, "replaced" values were those for which either a new, lower value (or a replacement 15-minute record suitable to derive one) was provided. In these cases, all annual maxima from 1 to 24 hours were replaced for that year and gauge. The EA rejected 28 of 56 extreme values, including 14 of the 21 extreme values used in FEH13, while SEPA rejected or replaced all 5 values used in FEH13 (accepting 4 and providing 3 replacement values for the total set of 26), and CNC rejected all (10 of 10) extreme values (4 used in FEH13, 6 new). This is one of the reasons why FEH22 estimates for short durations and longer return periods are lower than the equivalent FEH13 estimates, particularly in Wales. Met Office extreme rainfalls and tabulated data used in the FEH99 model were not reviewed.

Review of extreme rainfalls in England (56)

Gauge	Easting	Northing	Date	Rain (mm)	In FEH13	Decision
HILBOROUGH HALL	582700	300300	19/06/1973	50.8	No	Rejected
HORSHAM	516000	130200	28/12/1979	55.5	No	Rejected
HORSHAM	516000	130200	20/09/1980	51.2	No	Rejected
HOVE	529400	105900	10/10/1980	64.3	No	Rejected
OUNDLE STW (L)	503800	289700	09/01/1981	69.5	**Yes**	Rejected
HORSHAM	516000	130200	13/04/1981	86.3	No	Rejected
CORBY S.T.W (T)	490600	288900	26/04/1981	75.0	**Yes**	Rejected
SWAFFHAM S.WKS	583700	306600	05/06/1982	77.5	No	Rejected
UPTON (L)	487700	386800	22/06/1982	62.0	**Yes**	Accepted
HOLBEACH S.T.W. (L)	535800	325800	23/08/1987	63.0	**Yes**	Accepted
CASTOR (T)	512600	298200	10/06/1992	50.5	**Yes**	Rejected
KIRK LANGLEY	429300	339200	08/12/1993	67.5	**Yes**	Accepted
March STW (T)	544100	299100	03/02/1994	*120.0*	**Yes**	Rejected
DODFORD (T)	462700	260700	21/11/1996	50.6	**Yes**	Rejected
Kelsey Park *	537400	169200	01/08/1998	54.0	**Yes**	Accepted

ABBEYSTEAD RESR NO 2	355614	453877	25/11/1998	52.2	**Yes**	Rejected
DITTON PRIORS	360400	288300	12/06/1999	91.5	**Yes**	Rejected
HONISTER PASS	322503	513484	11/01/2000	*101.8*	**Yes**	Accepted
HILLERTON	272700	98100	17/09/2000	70.0	**Yes**	Rejected
PRINCES MARSH TBR	477200	127000	01/05/2001	57.6	**Yes**	Rejected
HUCKWORTHY	253100	70500	03/07/2001	54.0	**Yes**	Rejected
PAINS HILL RES RTS	541200	151700	18/11/2001	*119.8*	**Yes**	Rejected
STICKLEPATH	264700	94800	26/11/2002	77.0	**Yes**	Rejected
BONEHAYNE	321600	94700	01/01/2003	66.0	**Yes**	Rejected
CRAVEN ARMS	343700	281100	03/08/2004	53.0	**Yes**	Accepted
WILMINGTON	321600	100100	11/08/2004	53.0	**Yes**	Accepted
LANREATH R7505_FW	218078	56729	11/08/2004	50.8	No	Accepted
BUTTOCK	380722	440098	30/10/2004	53.4	**Yes**	Rejected
HAWNBY TBR	454255	489426	19/06/2005	59.8	No	Accepted
BELLEVER	265700	77600	24/06/2005	*115.5*	No	Rejected
PEEL COMMON TBR	456560	103460	18/08/2005	50.2	No	Accepted
HONISTER PASS	322503	513484	24/08/2005	*131.8*	No	Accepted
ENNERDALE, BLACK SAIL	319365	512483	24/08/2005	*104.6*	No	Accepted
CHIEVELEY RG	446952	173862	10/09/2005	73.6	No	Accepted
KENTMERE HALLOW BANK	346556	505409	05/07/2006	60.6	No	Accepted
COWBEECH TBR (TEL)	561000	114900	09/11/2006	*114.6*	No	Rejected
HAYWARDS HEATH TBR	530235	123793	19/07/2007	52.0	No	Accepted
NORTH CHAPEL RG	495177	129075	20/07/2007	*106.8*	No	Accepted
HONISTER PASS	322503	513484	25/10/2008	*124.6*	No	Accepted
COPLEY LOGGER STA.	408498	525452	01/07/2009	53.0	No	Accepted
SEATHWAITE	323579	512167	19/11/2009	*102.4*	No	Accepted
Marlborough R33	418400	168200	11/12/2009	*104.4*	No	Rejected
TEMPLE EWELL TBR	628293	144420	05/03/2010	*101.4*	No	Rejected
HEMINGBY BRIDGE	523461	374316	20/12/2012	*105.8*	No	Rejected
OAREFORD (TBR)	281179	145909	29/01/2013	*104.8*	No	Accepted
ASHFORD HALL	420070	369870	27/07/2013	*110.2*	No	Rejected
ENNERDALE, BLACK SAIL	319365	512483	25/10/2013	*114.6*	No	Accepted

CHALE RG	449005	80549	13/05/2014	*152.7*	No	Rejected
UTTONS DROVE TBR	536717	265326	08/08/2014	52.9	No	Accepted
RAITHBY	532070	386540	08/08/2014	51.6	No	Accepted
ASHFORD HALL	420070	369870	08/08/2014	61.8	No	Rejected
BROTHERSWATER TEL	339884	512059	05/12/2015	*103.6*	No	Accepted
THIRLMERE, ST JOHNS BECK	331321	519470	05/12/2015	*118.8*	No	Accepted
HONISTER PASS	322503	513484	05/12/2015	*120.2*	No	Accepted
CHOBHAM TBR	497662	161057	15/09/2016	53.0	No	Accepted
WEST ILSLEY	445642	182926	15/09/2016	55.7	No	Accepted

Review of extreme rainfalls in Scotland (26)

Gauge	Easting	Northing	Date	Rain (mm)	In FEH13	Decision
TOWNFOOT (GLENCAPLE)	299720	567810	31/10/1968	50.5	No	Rejected
TOWNFOOT (GLENCAPLE)	299720	567810	13/12/1969	51.6	No	Rejected
TOWNFOOT (GLENCAPLE)	299720	567810	31/10/1977	53.4	No	Rejected
TOWNFOOT (GLENCAPLE)	299720	567810	01/10/1981	53.1	No	Rejected
TOWNFOOT (GLENCAPLE)	299720	567810	04/01/1982	67.6	No	Rejected
PORTLING	288143	554302	18/10/1988	56.6	No	Rejected
South Moorhouse	252500	651200	01/01/1993	75.2	**Yes**	Rejected
Dosmucheran TBR	220400	860200	14/03/1994	53.8	**Yes**	Rejected
Polhollick	334300	796500	17/05/1997	56.2	**Yes**	Replaced
TOWNFOOT (GLENCAPLE)	299720	567810	20/10/1998	56.3	No	Rejected
Killin Monemore	256400	732100	01/03/2000	51.6	**Yes**	Rejected
TOWNFOOT (GLENCAPLE)	299720	567810	21/10/2002	68.2	No	Rejected
GORDON ARMS	330908	624757	21/10/2002	58.4	No	Replaced
TOWNFOOT (GLENCAPLE)	299720	567810	10/08/2004	61.1	No	Rejected
Gatelawbridge TBR	290000	596500	06/12/2004	52.7	**Yes**	Rejected
Little Assynt TBR	214700	925000	05/01/2005	55.8	No	Rejected
SHIELSKNOWE	371349	611070	11/10/2005	76.5	No	Rejected
Spey Dam	258200	793500	28/12/2007	48.0	No	Accepted
Spey Dam	258200	793500	18/01/2008	*126.6*	No	Rejected
Monyquil Farm	193779	634919	22/02/2008	*125.6*	No	Rejected
BORELAND	316081	590605	19/08/2009	61.5	No	Rejected

KIRRIEREOCH	236207	587069	04/04/2010	102.0	No	Rejected
LOW CREOCH	259728	558729	06/06/2010	59.4	No	Accepted
Luib	213100	854700	22/01/2015	*124.2*	No	Accepted
SCARDROY NO3	221271	851572	07/06/2016	52.4	No	Replaced
HUNGRY SNOUT 2 (WHITEADDER RESERVOIR)	366291	663325	20/07/2016	55.2	No	Accepted

Review of extreme rainfalls in Wales (10)

Gauge	Easting	Northing	Date	Rain (mm)	In FEH13	Decision
ABERNANT MAIN	289139	246449	04/01/1991	*133.0*	No	Rejected
VYRNWY EXP. STN.	301700	318800	14/05/1991	51.0	**Yes**	Rejected
COWBRIDGE STW TELEMETRY RG	299675	173689	22/06/1991	51.0	No	Rejected
VYRNWY EXP. STN.	301700	318800	18/04/1992	61.0	**Yes**	Rejected
COWBRIDGE STW TELEMETRY RG	299675	173689	13/08/1992	*153.0*	No	Rejected
COWBRIDGE STW TELEMETRY RG	299675	173689	09/11/1993	*140.9*	No	Rejected
LLANNERCH YRFA TELEM MAIN	283619	255503	27/01/1995	*109.4*	**Yes**	Rejected
COYCHURCH	293200	179600	22/12/2003	53.5	**Yes**	Rejected
UPPER USK TBR	283397	228956	01/07/2007	57.8	No	Rejected
MARGAM PARK	280900	185400	20/02/2016	*184.8*	No	Rejected

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