



Rainfall erosivity in catchments contaminated with fallout from the Fukushima Daiichi nuclear power plant accident

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Abstract. The Fukushima Daiichi nuclear power plant (FDNPP) accident in March 2011 resulted in the fallout of significant quantities of radiocesium over the Fukushima region. After reaching the soil surface, radiocesium is quickly bound to fine soil particles. Thereafter, rainfall and snowmelt run-off events transfer particle-bound radiocesium downstream. Characterizing the precipitation regime of the fallout-impacted region is thus important for understanding post-deposition radiocesium dynamics. Accordingly, 10 min (1995–2015) and daily precipitation data (1977–2015) from 42 meteorological stations within a 100 km radius of the FDNPP were analyzed. Monthly rainfall erosivity maps were developed to depict the spatial heterogeneity of rainfall erosivity for catchments entirely contained within this radius. The mean average precipitation in the region surrounding the FDNPP is 1420 mm yr^{-1} (SD 235) with a mean rainfall erosivity of $3696 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$ (SD 1327). Tropical cyclones contribute 22 % of the precipitation (422 mm yr^{-1}) and 40 % of the rainfall erosivity ($1462 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$ (SD 637)). The majority of precipitation (60 %) and rainfall erosivity (82 %) occurs between June and October. At a regional scale, rainfall erosivity increases from the north to the south during July and August, the most erosive months. For the remainder of the year, this gradient occurs mostly from northwest to south-

east. Relief features strongly influence the spatial distribution of rainfall erosivity at a smaller scale, with the coastal plains and coastal mountain range having greater rainfall erosivity than the inland Abukuma River valley. Understanding these patterns, particularly their spatial and temporal (both inter- and intraannual) variation, is important for contextualizing soil and particle-bound radiocesium transfers in the Fukushima region. Moreover, understanding the impact of tropical cyclones will be important for managing sediment and sediment-bound contaminant transfers in regions impacted by these events.

1 Introduction

In March 2011, the Great Tohoku earthquake triggered a giant tsunami that resulted in the release of the largest amount of radioactive material since Chernobyl from the Fukushima Daiichi nuclear power plant (FDNPP) (Chino et al., 2011; Thakur et al., 2013). After the decay of short-lived radionuclides (e.g. ^{131}I , $^{110\text{m}}\text{Ag}$, ^{129}Te), the radionuclide with the most serious short- and long-term human health concerns is radiocesium ($t_{1/2}$ ^{134}Cs – 2 years; ^{137}Cs – 30 years) (Kitamura et al., 2014; Saito et al., 2015).

Radiocesium is rapidly bound to fine soil particles and remains stored within the top 0–5 cm of the soil profile (Tamura, 1964; Sawhney, 1972; Kato et al., 2012). As radiocesium is adsorbed to soil particles in the upper layer of the soil profile, soil erosion and particle transport processes are considered to be the main processes responsible for transferring radiocesium downstream (Saito and Onda, 2015; Yamashiki et al., 2014; Evrard et al., 2015). Rainfall drives erosion by detaching particles from the soil surface, primarily through the kinetic energy of raindrops (Wischmeier and Smith, 1958; Renard and Freimund, 1994). The potential of rainfall to erode soils is referred to as rainfall erosivity. Quantifying rainfall erosivity is important to determine the climatic vulnerability of a region, like Fukushima, to rainfall-driven soil erosion (Mello et al., 2013).

The Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) and its revised edition (RUSLE) (Renard et al., 1997) are two of the most broadly adopted soil erosion modelling frameworks (Oliveira et al., 2013). The USLE predicts average annual soil loss with six factors pertaining to soil, topography, vegetation, management and rainfall erosivity, known as the R factor. The R factor estimates rainfall erosivity as a combined function of event frequency, intensity and rainfall amount (Wischmeier and Smith, 1958). It sums event-based erosivity individually calculated through multiplying each storm's total kinetic energy with its maximum measured 30 min rainfall intensity. To incorporate variations in interannual rainfall, the R factor is averaged over long temporal periods (~ 20 years) (Renard and Freimund, 1994; Wischmeier and Smith, 1978).

When all other factors in the (R)USLE are held constant, there is a proportional relationship between soil loss and the R factor (Lu and Yu, 2002; Wischmeier and Smith, 1958, 1978). The utility of the R factor is reflected in its global application (McFarlane et al., 1986; Ma et al., 2014; Oliveira et al., 2013; Moore, 1979; Panagos et al., 2015), including Asia in general (Lee and Heo, 2011; Shamshad et al., 2008; Yu et al., 2001) and Japan in particular (Shiono et al., 2013).

There are limitations to the application of the R factor and the USLE (Kinnell, 2010). Although the USLE and R factor were developed from plot-scale soil erosion research (Wischmeier and Smith, 1978), they have been applied at the catchment scale (Wilkinson et al., 2009; Kitamura et al., 2014; Belyaev et al., 2005). A debate about the applicability of the USLE within catchment-scale modelling frameworks and the universality of the R factor is beyond the scope of this current research. What is important is that the R factor and a thorough characterization of the precipitation regime are useful to contextualize local soil erosion, which represents the first step of potential downstream particle-bound contaminant transfers.

Research in the Fukushima region has clearly indicated that precipitation drives downstream radiocesium migration (Evrard et al., 2015). In fact, the majority of soil erosion and concomitant radiocesium migration was reported to coincide

with extreme rainfall events (Mouri et al., 2014; Nagao et al., 2013; Onishi et al., 2014). For example, Yamaguchi et al. (2014) reported that most sediment-bound radiocesium migration occurs in flood events that may only occur 1 to 2 times per year. Tropical cyclones in this region likely transfer significant quantities of radiocesium from hillslopes to the Pacific Ocean (Evrard et al., 2015).

As improved estimates of rainfall erosivity result in more accurate modelling results (Renard et al., 1991; Lee and Heo, 2011), a comprehensive examination of rainfall erosivity, including the impact of tropical cyclones on erosivity, may improve our understanding of sediment and radiocesium dynamics in the Fukushima region. Therefore, the objective of this research is to evaluate the spatial and temporal (monthly and interannual) precipitation and rainfall erosivity in general, and from tropical cyclones in particular, for catchments contained entirely within a 100 km radius of the FDNPP accident. Rainfall erosivity maps (monthly and annual) are provided for the Fukushima region, along with precipitation and rainfall erosivity data for all events selected by the RUSLE criteria and information summarizing tropical cyclone events impacting the area since 2011, in the Supplement.

2 Methods

2.1 Study area

Most of the terrestrial fallout from the FDNPP accident occurred over the coastal catchments of the Fukushima Prefecture (Fig. 1). Soil contamination $> 25 \text{ kBq kg}^{-1}$ of $^{134+137}\text{Cs}$ occurred within small catchments ($< 700 \text{ km}^2$) draining to the Pacific Ocean, with the highest contamination levels in the coastal mountain range northwest of the FDNPP. The coastal mountain range is separated from the larger westernmost mountain range by the Abukuma River catchment ($\sim 5200 \text{ km}^2$) extending on a SSW–NNE direction and characterized by a $^{134+137}\text{C}$ soil contamination $< 25 \text{ kBq kg}^{-1}$.

The region has a humid, subtropical climate along the Pacific coast (Cwa in the Köppen–Geiger climate classification; Peel et al., 2007), transitioning to a humid continental climate (Dfa) to the west. The westward continental region has large differences in seasonal temperatures, with hot and humid summers and cold winters. The subtropical coastal region has slightly warmer winters, along with hot humid summers and more precipitation in the summer months, compared to relatively dry winters. There is tropical-cyclone-driven precipitation in the Fukushima region that results in high volumes and intensities of precipitation occurring during extreme events (Evrard et al., 2014; Chartin et al., 2013). The Japanese tropical cyclone season occurs between May and October with the peak activity occurring between July and September. The mean annual temperature in the Fukushima region is 11.3°C (SD 1.7), ranging from a mean of 0.0 (SD 2.1) in January to 23.4 (SD 1.4) in August.

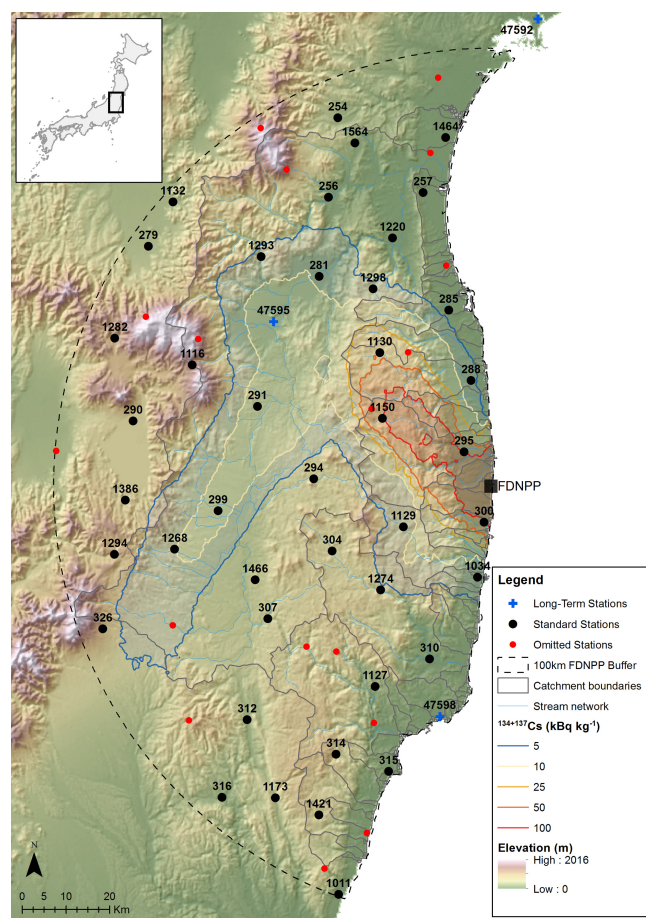


Figure 1. Standard, omitted and long-term stations in the Fukushima region, along with catchments (grey lines) contained entirely within a 100 km buffer around the FDNPP (dashed line); $^{134+137}\text{Cs}$ activities are from Chartin et al. (2013).

2.2 Meteorological stations

All precipitation monitoring stations within a 100 km radius of the FDNPP were analyzed (Fig. 1). Fourteen stations within this 100 km radius were omitted due to an operation period of less than 7 years ($n = 5$) or operation pause during winter months ($n = 9$). Up to 21 years were available for the 10 min (1995–2015) and 39 years for daily precipitation data (1977–2015) for 42 stations. Daily precipitation was also analyzed from three additional long-term stations (including one located within a 115 km radius of the FDNPP) as they had similar data available from 1890 to 2015. The long-term stations were excluded from the R factor and daily rainfall calculations due to high levels of missing data (mean 33 % daily) and short temporal periods (7 years–10 min). All data were downloaded from the Japan Meteorological Agency’s (JMA) website (<http://www.jma.go.jp/jma/index.html>).

Daily precipitation data were examined for breakpoints and homogeneity with the RHTest program from the Meteorological Service of Canada (Wang et al., 2010). No sig-

nificant breakpoints required correction. Duan et al. (2015) similarly did not report significant breakpoints for the JMA daily precipitation data. No homogenization analyses were performed on the 10 min precipitation data due to the difficulties in assessing heterogeneity in 10 min precipitation data and the potential to overcorrect the data. Shiono et al. (2013) similarly did not correct 10 min JMA data. For the daily data, there was an average of only 0.23 % of missing data (SD 0.20 %, maximum 0.94 %) compared to 0.30 % (SD 0.20 %, maximum 0.78 %) for the 10 min data.

2.3 R factor calculations

The Rainfall Intensity Summarisation Tool (RIST) software (USDA, 2013) was used to calculate the R factor, which is a product of the kinetic energy of an event (E) and its maximum 30 min intensity (I_{30}) (Renard and Freimund, 1994):

$$R = \frac{1}{n} \sum_{j=1}^n \sum_{k=1}^{m_j} (EI_{30})_k, \quad (1)$$

where R equals the annual average rainfall erosivity in $\text{MJ mm ha}^{-1} \text{h}^{-1} \text{yr}^{-1}$, n represents the number of years of data utilized, m_j is the number of erosive events in year j and EI_{30} was calculated as

$$EI_{30} = \left(\sum_{r=1}^o e_r v_r \right) I_{30}, \quad (2)$$

where e_r represents rainfall energy per unit depth of rainfall in $\text{MJ ha}^{-1} \text{mm}^{-1}$, v_r is the volume of rainfall (mm) during a given time interval (r) and I_{30} is the maximum rainfall intensity over a 30 min period of the rainfall event (mm h^{-1}). For each time interval, e_r was calculated as

$$e_r = 0.29 \left[1 - 0.72^{(-0.05i_r)} \right], \quad (3)$$

where i_r is rainfall intensity (mm h^{-1}) (Renard and Freimund, 1994).

To calculate the annual and monthly R factors, erosive rainfall events were summed for each monitoring station for the considered period (months or year). Two criteria within the RIST software were used to define an erosive event: (1) cumulative rainfall of a given event is > 12.7 mm; (2) accumulations < 1.27 mm over a 6 h period separates events into two different periods.

To consider the impact of snowfall, precipitation was removed from R factor calculations when the temperature dropped below 0°C for 31 stations (Meusburger et al., 2012). When removing precipitation that may have occurred as snowfall, there was not a significant difference in the R factor (t test p : 0.469) with a mean difference of $26 \text{ MJ mm ha}^{-1} \text{h}^{-1} \text{yr}^{-1}$ (SD 35). Due to the limited impact of potential snowfall on R factor calculations, 11 stations that did not record temperature were included in the analyses.

To examine the impact of tropical cyclones on precipitation and rainfall erosivity, the best track data of all tropical cyclones from the JMA Tokyo-Typhoon Center (JMA, 2016) were cross-referenced with regional events that occurred from 1995 to 2015. Each cyclone path and summary information was also reviewed in the Wikipedia Pacific typhoon database (Wikipedia, 2016). Furthermore, news reports on tropical cyclones in the region (from Google news searches) were also examined to provide complimentary information. A database was then created that allowed for the quantification of the precipitation and rainfall erosivity that occurred during tropical-cyclone-related events. In the Northwest Pacific Ocean, tropical cyclones are referred to as tropical depressions, tropical storms and typhoons depending on the sustained wind speed. Tropical cyclones are non-frontal synoptic-scale systems that have organized convection along with cyclonic surface wind circulation. Typhoons, tropical storms and tropical depressions are all referred to as tropical cyclones in the remainder of this paper.

2.4 R factor spatial interpolation

Annual and monthly *R* factor data were used to derive maps of annual and monthly rainfall erosivity at a resolution of 250 m over the eastern part of the Fukushima Prefecture. Rather than interpolation by kriging, a regression approach, based on relationships established between the *R* factor and spatially distributed covariates, was used to produce these maps in order to identify the environmental covariates that are driving the spatial distribution of rainfall erosivity.

The covariates used for the spatial interpolation of annual and monthly *R* factors over the study area are described below.

- Climatic data (i.e. monthly mean precipitation and mean temperature) from the WorldClim database reported for the period 1950–2000 and with a 30 arcsec resolution (equivalent to 1 km resolution) (Hijmans et al., 2005) were used for the monthly models (Panagos et al., 2015). From the monthly data, annual mean precipitation and mean temperature were derived to be included as covariates in the annual *R* factor model. These covariates are expected to impact the spatial distribution of rainfall erosivity.
- Based on their known influence on spatial patterns and intensities of rainfall, different morphometric attributes have been included as covariates in the mapping procedure, as proposed by Daly et al. (2002). Precipitation varies strongly with elevation (Barry and Chorley, 2009). Conceptually, relief features can induce different precipitation–elevation gradients depending partially on their ability to block and uplift moisture-bearing air (Daly, 2002). In mountainous areas, the steepest features oriented perpendicular to the air flow are more likely to produce a greater elevation–precipitation gra-

dient than gentle sloping areas parallel to the air flux, such as coastal plains. Moreover, hillslopes experience different climate regimes depending on their orientation, relative to air currents at large scales (i.e. leeward and windward sides of mountains), and solar radiation. Areas located at similar elevations may thus have different precipitation intensities.

Accordingly, a 90 m resolution digital elevation model (DEM) was obtained from Shuttle Radar Topography Mission (SRTM) of NASA (Jarvis et al., 2008). Considering the local relief in the fallout-affected region (Fig. 1), the DEM was smoothed with a Gaussian filter to two wavelengths of 5 and 20 km. From the 20 km wavelength smoothed DEM, slope and aspect were derived. The slope layer was used in the modelling procedure to account for potential impact of large relief features on moisture-bearing air. The aspect layer derived from the same 20 km wavelength smoothed DEM was used to delineate the opposite sides of mountains and represent leeward and windward sides. Then, this aspect layer was inserted in the model as a categorical covariate (i.e. a two-value layer, one value for each leeward and windward “facets”). From the 5 km wavelength smoothed DEM, the easting and northing were computed to represent the degree to which aspect is close to the east and the north, respectively (Zar, 2010). These two layers were used as covariates in the modelling procedure to account for slope orientation at a smaller scale than the entire side of a mountains range at the coarser scale.

- Distance to the Pacific Ocean coast (*DC* is the distance to the coast) was calculated for each pixel by using the Euclidean distance tool from ArcGis 10 (ESRI, 2011) as the proximity of the ocean, a major source of moisture, may influence the spatial distribution of precipitation.

Before the fitting of the models, the continuous covariates presented above were rescaled at a 250 m resolution in ArcGIS10 (ESRI, 2011) with bilinear interpolation, which determined the output value of a cell based on a weighted distance average of the four nearest input cell centres. Then, the spatial variation of rainfall erosivity in the study region was modelled with generalized additive models (GAMs; Hastie and Tibshirani, 1986), implemented in the *mgcv* package in *R* (Wood, 2001). The GAM regression technique is a generalization of linear regression models (GLMs) in which the coefficients may be a set of smoothing functions. GAMs consider the nonlinearity that may exist between the target variable (*Y*) and covariates (*X*), providing more flexibility to the model fitting than a GLM.

As for GLMs, GAMs specify a distribution for the response variable *Y* and use a link function *g* relating the conditional mean $\mu(Y)$ of the response variable to an additive

function of the selected predictors:

$$g[\mu(Y)] = \alpha + f_1 X_1 + f_2 X_2 + \dots + f_p X_p, \quad (4)$$

where Y is the response variable, X_1, X_2, \dots, X_p represent the covariates and the f_i is the smooth (non-parametric) functions.

Based on monthly and annual mean values for each of the 42 stations, 13 GAMs were fitted to spatially model the R factor over the study area (i.e. one model per month and one model for the year). A Gaussian distribution model incorporated the conditional mean $\mu(Y)$ and, due to the predominant logarithmic distribution of the monthly and annual data, a log-linear link function $g(\mu) = \log(\mu)$ was implemented. The smoothing functions of the models were built using regression splines fitted by penalized maximum likelihood to avoid over-fitting (Wood, 2001). An extra penalty was added to each smoothing term so that each could potentially be set to zero during the fitting process, especially in the case of multi-collinearity or multi-concurvity. The interaction of geographical coordinates was then added to each model (as a two-dimensional spline on latitude and longitude) to incorporate spatial trends of the target variable at the regional scale.

A model including all the covariates was first developed (the “full” model), based on each of the total data sets (13 data sets of $n = 42$). Next, a backward stepwise procedure was applied to select the appropriate covariates, where each of the covariates was sequentially removed from the full model (Poggio et al., 2013; de Brogniez et al., 2015). The difference (Δ AIC) between AIC values (Akaike’s information criterion; Akaike, 1974) was calculated for the “full model” and compared with AIC values obtained when removing sequentially each of the covariates from the model in order to evaluate the influence of each covariate on the overall capabilities of model prediction.

Explained variance was calculated during the procedure to assess the evolution of “fitting performance” and to support the decision to keep or remove a covariate into the final model. Once the final model was obtained, a Bayesian approach was used to compute standard errors for the predictions as proposed in the mgcv package. A leave-one-out cross-validation (LOOCV) procedure was applied to each fitted model. Predicted and observed values were compared with the calculation of the root mean square errors (RMSEs) and the coefficient of determination (R^2). Finally, maps were delineated according to the limits of the target area, i.e. entire hydrological basins contained within the 100 km radius of around the FDNPP.

3 Results

3.1 Precipitation

Mean annual precipitation ranged from 1098 mm yr⁻¹ at station 281 to 2201 mm yr⁻¹ at station 1116 (Table 1; Fig. 2a). Mean annual precipitation was 1420 mm yr⁻¹ (SD 235 mm yr⁻¹) (Fig. 2a) with a coefficient of variation (CV) of 17%. Between 1977 and 2015, regional mean annual precipitation ranged from 869 mm in 1984 to 1844 mm in 2006 (Fig. 3a) with a CV of 15%. This interannual variation in precipitation was maintained over a longer period (Fig. 4), with a mean annual precipitation for the long-term stations (126 yr) of 1159 mm yr⁻¹ (SD 187 mm) with a 16% CV. The 5-year running average for these long-term stations demonstrates that the region experiences prolonged wet and dry periods that last approximately 5–10 years. Note that these long-term stations plot near or below 1 standard deviation on the annual precipitation mean for all of the stations, and therefore they may not be indicative of all precipitation trends in the region.

The majority of precipitation (60%) occurs between June and October (Fig. 5a) coinciding with a wet season that includes tropical cyclones. In fact, 39% of the precipitation occurred between July and September alone, compared to only 22% between March and May and 17% between November and February. The monthly precipitation also varied spatially. For example, the mean monthly maximum precipitation was 318 mm m⁻¹ at site 1116 in July compared to 256 mm m⁻¹ for site 281 in July.

The highest daily maximum precipitation recorded was 607 mm in 1998 at site 326, compared to the lowest daily maximum precipitation of 38 mm in 1984 at site 294 (Fig. 6a). The mean daily maximum precipitation for all the stations and every year was 115 mm (SD 27 mm). The highest mean daily maximum precipitation for all the stations (169 mm) was recorded in 2011 compared to a minimum of 62 mm in 1984. Although the maximum daily precipitation is not an optimal indicator of precipitation depth due to the probability of events occurring over multiple days, the year of the FDNPP accident (2011) had the highest daily maximum precipitation as a result of Typhoon Roke.

3.2 Rainfall erosivity

The annual R factor ranged from 1972 MJ mm ha⁻¹ h⁻¹ yr⁻¹ at station 290 to 8274 MJ mm ha⁻¹ h⁻¹ yr⁻¹ at station 326 (Table 1 – Fig. 2b). The mean R factor for the 42 stations was 3696 MJ mm ha⁻¹ h⁻¹ yr⁻¹ (SD 1327) with a CV of 36%. The CV was double the corresponding CV for annual average precipitation indicative of more spatial variability.

The regional mean annual R factor ranged from a minimum of 1866 MJ mm ha⁻¹ h⁻¹ yr⁻¹ in 1996 to a maximum of 7159 MJ mm ha⁻¹ h⁻¹ yr⁻¹ in 1998 (Fig. 3c). The annual R factor standard deviation was 1252 MJ mm ha⁻¹ h⁻¹ yr⁻¹

Table 1. Station coordinates along with the mean and standard deviation (SD) of annual precipitation, *R* factor and kinetic energy (KE).

Station	Latitude	Longitude	Annual precipitation (mm)		<i>R</i> factor (MJ mm ha ⁻¹ h ⁻¹ yr ⁻¹)		KE (MJ ha ⁻¹ yr ⁻¹)	
			Mean	SD	Mean	SD	Mean	SD
254 ^{A,4}	38.178	140.635	1429	302	3295	3045	167	61
256	38.015	140.612	1292	243	2497	1296	149	42
257	38.025	140.858	1256	259	2922	1313	148	38
279	37.912	140.143	1343	221	2049	572	142	28
281	37.852	140.588	1098	172	2045	792	121	26
285	37.783	140.925	1350	266	3859	1928	171	48
288*	37.638	140.983	1333	272	3819	1527	173	39
290	37.552	140.108	1265	242	1972	1029	124	35
291	37.583	140.430	1176	219	2337	1206	136	33
294	37.435	140.577	1168	210	2718	1355	141	36
295	37.492	140.965	1493	299	4327	1694	196	43
299	37.368	140.330	1154	176	2465	982	130	30
300 ^{*,D}	37.347	141.017	1532	295	4249	1517	203	40
304	37.287	140.625	1231	200	2984	1361	145	31
307	37.147	140.460	1280	205	3405	1530	157	34
310*	37.065	140.877	1426	281	4425	2105	193	49
312	36.938	140.408	1399	234	4342	2145	182	46
314*	36.868	140.637	2001	380	7177	2405	274	55
315	36.833	140.772	1472	247	4126	1629	185	42
316 ¹⁰	36.778	140.345	1419	204	5075	2370	193	39
326	37.123	140.035	1954	373	8274	8491	279	78
1011	36.580	140.645	1474	232	4406	2002	191	37
1034	37.233	141.000	1568	280	4530	1545	205	45
1116 ³	37.668	140.260	2201	355	5056	2385	262	57
1127 ^{C,6}	37.008	140.737	1435	285	3636	1263	178	46
1129	37.337	140.808	1444	250	4193	2115	185	42
1130	37.695	140.747	1307	245	2989	1563	157	41
1132 ¹⁰	38.003	140.207	1254	199	2350	1380	127	34
1150 ^{*,10}	37.560	140.753	1341	239	3470	1369	165	35
1173 ^{*,10}	36.778	140.482	1437	234	4432	1981	191	42
1220 ¹⁰	37.932	140.778	1262	245	2878	1234	149	40
1268 ^{*,8}	37.288	140.218	1366	256	3680	2595	170	50
1274 ^{*,8}	37.207	140.750	1440	272	4156	1812	181	43
1282 ⁹	37.722	140.058	1762	316	3351	1764	200	49
1293 ⁹	37.892	140.437	1363	178	2361	916	144	29
1294 ⁹	37.277	140.063	1568	281	3914	2567	190	51
1298 ^{*,8}	37.827	140.728	1462	270	3765	2209	175	46
1386 ^{*,7}	37.388	140.090	1311	231	2726	1569	142	39
1421 ^{*,5}	36.743	140.593	1851	284	6448	2422	249	50
1464 ^{B,2}	38.138	140.917	1129	174	2742	1522	133	27
1466 ^{B,2}	37.227	140.427	1232	213	3150	1055	146	33
1564 ^{A,1}	38.127	140.680	1356	170	2647	1030	154	26

* No temperature data available.

For *R* factor, ^A 10 years of data available, ^B 13 years, ^C 14 years and ^D 18 years.

For precipitation analyses, ¹ 10 years available, ² 13 years, ³ 21 years, ⁴ 28 years, ⁵ 30 years, ⁶ 32 years, ⁷ 33 years, ⁸ 36 years, ⁹ 37 years and ¹⁰ 38 years.

with a CV of 34 %. The CV again was more than double that of the annual precipitation.

The highest monthly *R* factors occurred in the summer months and early fall (Fig. 5b), coinciding with the wet sum-

mer and the peak tropical cyclone season (July–September). In fact, 82 % of the rainfall erosivity occurred between June and October in the Fukushima region, an increase of 22 % compared to the amount of precipitation during this period.

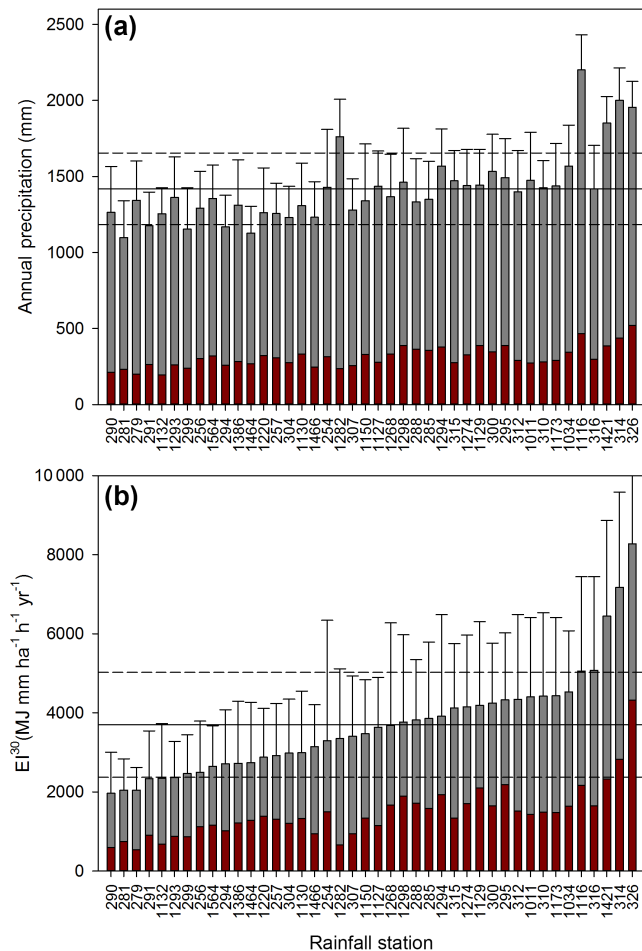


Figure 2. Total (grey) and typhoon-related (red) mean annual precipitation (a) and R factor (b) with the solid line representing the mean and the dashed lines being 1 standard deviation from the mean. The error bars indicate 1 standard deviation from the mean for individual stations.

In particular, 64 % of the rainfall erosivity occurs between July and September. Winter (November–February) only contributes 6 % of the total annual R factor with spring (March–May) contributing the remaining 12 %.

3.3 Spatial distribution of rainfall erosivity

The variance explained by the final erosivity models produced by the calibration procedure (from the total data set of $n = 42$) varied from 82.5 % for September to 97.7 % for April and was 95.5 % for the annual R factor model (Table 2). Predicted values produced with the LOOCV procedure for the 42 stations showed similar distributions as the observed values (Table 2) for the year and for the months between October and June. For the months between July and September, which includes the tropical cyclone season, the standard deviations of predicted values were smaller than for the observed values. For mean observed

values ranging from 778.7 to 799.7 $\text{MJ mm ha}^{-1} \text{h}^{-1} \text{m}^{-1}$ between July and September, the RMSE varied between 165.3 and 313.6 $\text{MJ mm ha}^{-1} \text{h}^{-1} \text{m}^{-1}$ with a R^2 between 0.56 and 0.67. The model fitted for August demonstrated a bias by underestimating the R factor (mean observed values = 778.7 $\text{MJ mm ha}^{-1} \text{h}^{-1} \text{m}^{-1}$ and mean predicted values = 755.2 $\text{MJ mm ha}^{-1} \text{h}^{-1} \text{m}^{-1}$).

For the months between October and June, and for the year, the differences between mean observed and predicted values remained relatively low relative to corresponding observed values and their variability. For these periods, the R^2 produced by the validation procedure varied between 0.62 in April and 0.86 in October, with a R^2 of 0.77 for the annual model. In general, the annual map and the months with higher erosivity had lower R^2 values. Contrarily, months with lower erosivity often had higher R^2 . This is possibly due to localized impacts of high precipitation events.

For all of the monthly models, the categorical variable facets, was selected as one of the most influential explanatory covariates, whereas facets were less influential in the annual model (Table 3). The selection of facets highlights how opposite sides of the mountain ranges in this region have different rainfall erosivity regimes.

For 10 of the 13 models, mean precipitation, for the considered period, was selected as a significant explanatory covariate. Mean temperature was selected by the procedure for the three models for which mean precipitation was not retained as significant covariates (i.e. February, November and December). Mean temperature and mean precipitation was selected for the annual R factor model. According to the ΔAIC , mean precipitation and mean temperature capture the most R factor spatial variability within the final models (Table 3). Easting and/or northing was selected in all the other models, except July and September, accounting for the influence of hillslope aspects at smaller scales than entire mountain sides. The selection of elevation, slope and/or the distance to the coast as significant explanatory variables varied in some of the final models.

Although elevation, slope and distance to the coast may influence precipitation patterns and intensities, their inconsistent selection in the final models does not mean that they potentially do not influence rainfall erosivity. Covariates have the potential not to be retained in the final model when there may be multi-collinearity or multi-concurvity between covariates. The non-selection of covariates signifies that other covariates likely have a similar, though stronger, mathematical relationships with the target variable. To achieve parsimony, only selected variables from the original set of covariates are included in the final model.

The annual R factor has a predominantly positive gradient from north-northwest to south-southeast (Fig. 7a) and is impacted by the relief of the region. The coastal plain receives lower rainfall erosivity than the adjacent coastal mountain range, both of which have greater rainfall erosivity than the inland Abukuma River valley. The south-southeast-

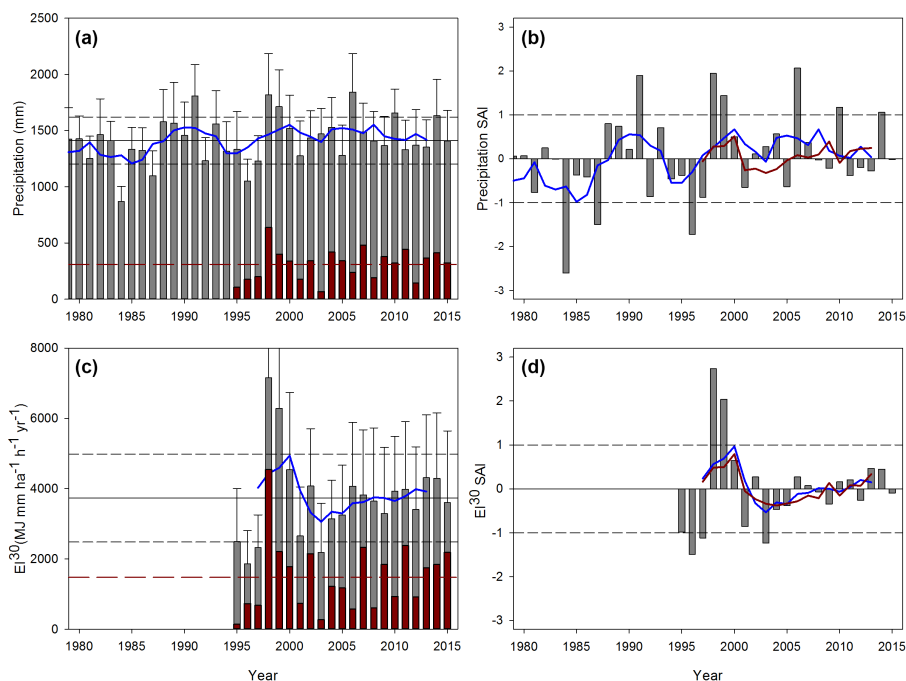


Figure 3. Annual (grey) and typhoon-related (red) mean annual precipitation (a) and corresponding standardized anomaly index (SAI – b) and the annual (grey) and typhoon-related (red) R factor (c) and the R factor's SAI (d). The grey solid line represents the regional mean (including typhoons) and the grey dashed lines represent 1 standard deviation from the total mean, whereas the red dashed line represents the mean contribution from typhoon events. The blue (total) and red (typhoon) solid lines depict the 5-year running average.

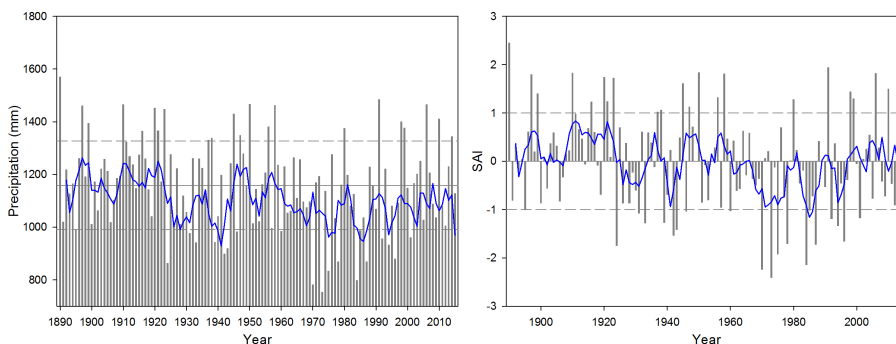


Figure 4. Mean annual precipitation (a) and the standardized anomaly index (SAI – b) for three long-term rainfall stations including mean annual precipitation (solid line), the standard deviation (dashed line) for the entire period and the 5-year running average (blue line).

oriented side of the westernmost mountain range bordering the Abukuma valley has lower rainfall erosivity than the easternmost side of this valley. The CV of modelling errors is rather low, predominantly under 10% in the study area (Fig. 7b).

In July and August, the most erosive months of the year, rainfall erosivity increases mainly from the north to the south of the region, while during the rest of the year this gradient occurs mostly from northwest to southeast. The spatial patterns relative to the relief features are also observed in the monthly rainfall erosivity distributions with the coastal plains and coastal mountain range receiving higher rainfall erosivity

than the parallel Abukuma River valley. The maps of errors associated with each monthly R factor models are available in the Supplement (Fig. S1). The coastal plain and coastal mountainous ranges, including the FDNPP and a large part of the contamination plume with high levels of radiocesium contamination, have greater rainfall erosivity than the less contaminated Abukuma River valley.

3.4 Tropical cyclones

In the Fukushima region, tropical cyclones contributed 22% (331 mm yr^{-1}) of the total annual precipitation (Fig. 3a).

Table 2. Observed and predicted mean and standard deviation (SD) for monthly (in MJ mm ha⁻¹ h⁻¹ m⁻¹) and annual *R* factors (in MJ mm ha⁻¹ h⁻¹ yr⁻¹) with GAM performance parameters (RMSE: root mean square error; *R*²: coefficient of determination).

Month or year	Observed <i>R</i>		Predicted <i>R</i>		Variance explained (%)	Model performance (LOOCV)	
	Mean	SD	Mean	SD		RMSE	<i>R</i> ²
Year	3696	1327	3696	1293	96	640	0.77
January	43	26	44	25	90	16	0.77
February	24	16	23	15	90	9	0.68
March	64	31	64	30	93	13	0.83
April	160	104	165	97	92	66	0.62
May	206	160	214	163	98	75	0.80
June	312	124	312	116	88	66	0.72
July	800	283	800	244	83	167	0.65
August	779	469	755	305	92	314	0.56
September	785	287	781	263	83	165	0.67
October	368	247	374	237	95	92	0.86
November	73	28	72	25	90	12	0.80
December	83	66	84	62	93	33	0.76

Table 3. Results from the backward stepwise procedure used to select covariates to include in final GAMs for annual and monthly *R* factor maps computation. The values (Δ AIC) correspond to the difference in AIC scores obtained when the particular covariate is dropped from the “full” model, i.e. the model containing all the covariates. Scores in bold indicate which covariates were selected in the final models.

Model	Δ AIC							
	Elevation	Slope	DC*	Easting	Northing	Rainfall	Temperature	Facets
Annual	8.7	1.0	10.8	12.1	2.8	13.6	10.1	5.6
January	0.0	6.1	2.1	0.7	0.0	8.3	0.0	4.0
February	2.2	0.0	0.1	2.7	2.6	0.2	4.6	8.6
March	0.0	9.9	0.0	1.3	0.1	5.3	0.0	3.2
April	3.7	0.0	17.6	0.0	0.5	17.3	0.0	14.0
May	0.1	8.5	0.0	0.7	4.5	8.4	0.0	10.9
June	0.4	0.3	0.0	0.2	1.4	8.6	0.0	12.6
July	0.0	0.3	5.5	0.0	0.0	13.2	0.0	13.8
August	0.7	1.6	0.0	0.0	8.6	8.8	0.1	7.8
September	0.0	0.4	5.5	0.0	0.0	13.2	0.0	13.8
October	0.4	4.8	1.2	0.0	5.7	16.3	0.0	19.8
November	0.0	26.3	2.7	3.0	0.2	0.2	11.2	8.8
December	0.3	0.2	0.0	3.2	0.4	0.6	11.7	5.5

* Distance to coast.

This contribution varies from only 5 % (68 mm yr⁻¹) in 2003 to 35 % (639 mm yr⁻¹) in 1998. In September, 60 % of the precipitation is derived from tropical-cyclone-related events (119 mm m⁻¹) compared to 43 % in October (64 mm m⁻¹), 28 % in August (49 mm m⁻¹) and 25 % in July (47 mm m⁻¹). During the remainder of the year there is less than a 15 mm m⁻¹ contribution from tropical cyclones (< 11 % of the month precipitation totals) (Fig. 5a).

Although tropical cyclones only contribute 22 % of the annual precipitation in the region, they contribute 40 % of the annual rainfall erosivity (1462 MJ mm ha⁻¹ h⁻¹ yr⁻¹). This contribution varies from 6 % (142 MJ mm ha⁻¹ h⁻¹ yr⁻¹) in 1995 to 64 % in

1998 (4547 MJ mm ha⁻¹ h⁻¹ yr⁻¹) (Fig. 3b). In September, 75 % of the rainfall erosivity (589 MJ mm ha⁻¹ h⁻¹ m⁻¹) is derived from tropical cyclone activity, followed by 57 % in October (208 MJ mm ha⁻¹ h⁻¹ m⁻¹), 41 % in August (321 mm ha⁻¹ h⁻¹ m⁻¹), 32 % in July (257 mm ha⁻¹ h⁻¹ m⁻¹) and 19 % in June (59 mm ha⁻¹ h⁻¹ m⁻¹) (Fig. 5b). Tropical cyclones, which only occurred on average 3.9 times per year (SD 2.0), contributed 40 % of the rainfall erosivity in the Fukushima region.

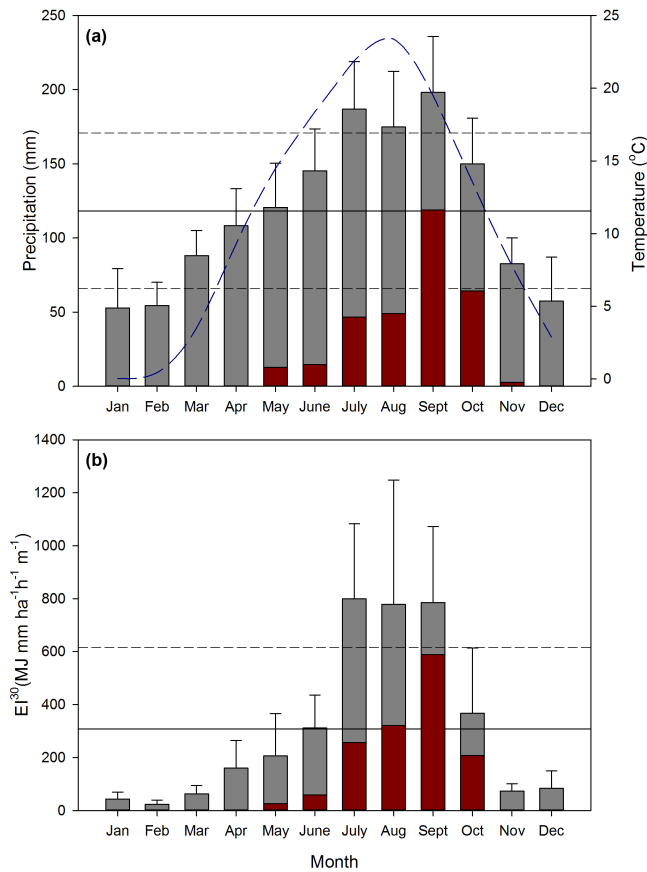


Figure 5. Total (grey) and typhoon-related (red) mean monthly rainfall (a) and R factor (b) with error bars indicating 1 standard deviation from the mean, the solid line representing the monthly mean and dashed lines representing 1 standard deviation from the mean. The mean monthly temperature is plotted (red line) along with mean monthly rainfall (a).

4 Discussion

4.1 Precipitation

The location and intensity of annual tropical cyclones influence the spatial and temporal (intra- and interannual) variation in precipitation in the Fukushima region. The majority of precipitation occurs in the summer months, the result of the high humidity and seasonal tropical cyclone activity. Long-term climatic oscillations (e.g. El Niño) also influence the precipitation patterns, illustrated by the 5- to 10-year running average reported in the long-term analyses (Fig. 4). Duan et al. (2015) reported periodic variations in extreme precipitation though at frequencies of 2–3 and 5–13 years.

The average precipitation in the Fukushima region (1420 mm yr^{-1}) is $\sim 250 \text{ mm}$ less than the mean annual precipitation in Japan (1684 mm yr^{-1}) (Kim et al., 2010). Along the western and southeastern coast of Japan, annual precipitation may be greater than 3000 mm yr^{-1} (Kim et al., 2010).

In the southeast of Japan, the elevated annual precipitation is related to an increasingly tropical climate progressing southwards and the increased occurrence of tropical cyclones in these warmer climates with higher precipitation intensities during summer months.

4.2 Rainfall erosivity

Rainfall erosivity varied spatially and temporally (monthly and interannually) in the Fukushima region. Rainfall erosivity has similarly varied in other regions of the world, e.g. the Mediterranean region (Capolongo et al., 2008) and the Middle East (Eltaif et al., 2010). Although researchers have demonstrated relationships between precipitation and rainfall erosivity (Ma et al., 2014), in the Fukushima region the relationship was positive, though not significant ($r^2 = 0.39$). The lack of significant relationship was likely the result of rainfall erosivity varying more than precipitation. There are also possibly decadal variations in rainfall erosivity, similarly to precipitation, that require long-term analyses to investigate.

There have been a range of R factors reported for Japan and the Fukushima region. In the Fukushima region, between 17 July 2011 and 18 November 2012, Yoshimura et al. (2015) calculated an R factor of $3677 \text{ MJ mm ha}^{-1} \text{ h}^{-1}$ (SD 463) for three sites near Kawamata town, $\sim 13 \text{ km}$ from station 1130. Although station 1130 recorded a similar R factor for this time period ($3853 \text{ MJ mm ha}^{-1} \text{ h}^{-1}$), the R factor recorded at this station was 40 % lower than the regional average for this period ($6559 \text{ MJ mm ha}^{-1} \text{ h}^{-1}$, SD 3232). This demonstrates the potential impact of the spatial heterogeneity on rainfall erosivity and limitations of extrapolating data from one sampling point to the entire region.

Yamaguchi et al. (2014) quantified an average annual R factor of $3366 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$ for 23 JMA stations in this region for a 10-year period between 2001 and 2011. For a sensitivity analysis, these authors also modelled a maximum case of $4217 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$ and a minimum case of $1986 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$. The average annual R factor reported by Yamaguchi et al. (2014) was 9 % lower than that reported for our current research, likely the result of the longer temporal period and the high levels of rainfall erosivity in the late 1990s not being included in the calculations of Yamaguchi et al. (2014). Further, there was only a $120 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$ difference between our minimum cases, though our maximum case was 41 % higher ($7159 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$) in 1998 than Yamaguchi et al. (2014) and again 33 % higher ($6288 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$) than their maximum case in 1999.

Around Japan a variety of R factors have been reported, for example $5880 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$ in the Onga River basin (Fukuoka Prefecture in southern Japan) (Tran et al., 2011), $4568 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$ in the Shiraska River catchment (Aichi Prefecture in Central Japan) (Karki and Shibano, 2006) and $2890 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$ in

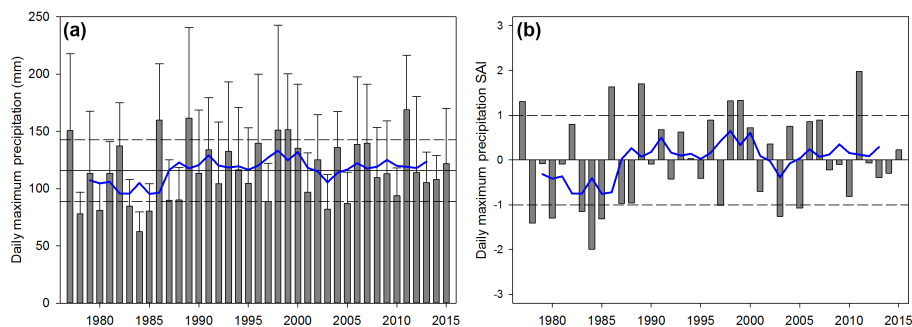


Figure 6. Mean maximum daily precipitation (a) and corresponding SAI (b) with error bars indicating 1 standard deviation from the mean for each station, along with the mean (solid) and 1 standard deviation from the mean (dashed line) for the daily rainfall analysis period; the blue solid line depicts the 5-year running average.

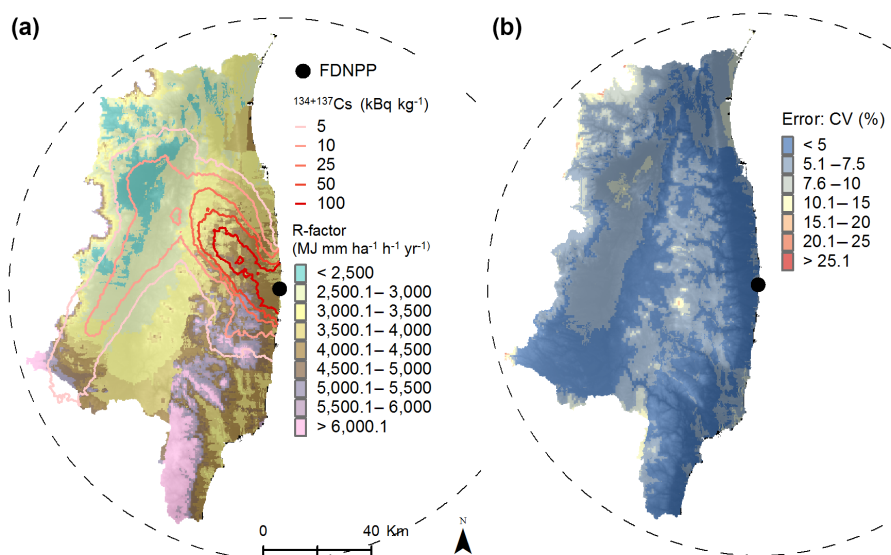


Figure 7. Annual *R* factor (a) and model errors depicted as the coefficient of variation (i.e. $CV = (\text{standard error}/\text{mean}) \cdot 100$) (b) for catchments entirely contained within a 100 km radius of the FDNPP. $^{134+137}\text{Cs}$ activities are from Chartin et al. (2013).

the Hirose River catchment (Miyagi Prefecture in northern Japan) (Takeuchi and Ishidaira, 2001). Shiono et al. (2013) found that rainfall erosivity varied from 721 to 35 299 $\text{MJ mm ha}^{-1} \text{h}^{-1} \text{yr}^{-1}$ across Japan with a mean of 5130 $\text{MJ mm ha}^{-1} \text{h}^{-1} \text{yr}^{-1}$. In our current analyses, rainfall erosivity in the Fukushima region was found to be similar to the results of Shiono et al. (2013), who spatially depicted rainfall erosivity in the Fukushima region between 2500 and 5000 $\text{MJ mm ha}^{-1} \text{h}^{-1} \text{yr}^{-1}$.

Shiono et al. (2013) also demonstrated that rainfall erosivity in the Fukushima region is relatively low compared to the rest of Japan. Similarly to annual precipitation, there is a rainfall erosivity gradient in Japan from north to south, particularly along the Pacific coast with rainfall erosivity increasing southwards from the colder temperate/subarctic regions in the north towards the tropical regions in the south. Importantly, the rainfall erosivity of the Fukushima region is

projected, by Shiono et al. (2013), to increase significantly as a result of climate change.

The difference between Shiono et al. (2013) and our current research is the comprehensive analysis of precipitation, and rainfall erosivity at a scale relevant to the fallout from the FDNPP accident. In particular, our current research highlights that the coastal mountain range, which received a significant amount of radiocesium fallout, has higher rainfall erosivity relative to the remainder of the fallout-impacted region, with a large proportion of this rainfall erosivity being derived for tropical cyclones.

4.3 Tropical cyclones

Regions subject to tropical cyclones generally have much high rainfall erosivity. In Mexico, the mean annual rainfall erosivity was 6525 $\text{MJ mm ha}^{-1} \text{h}^{-1} \text{yr}^{-1}$ (García-Oliva et al., 1995). In Peninsular Malaysia, the *R* factor was shown

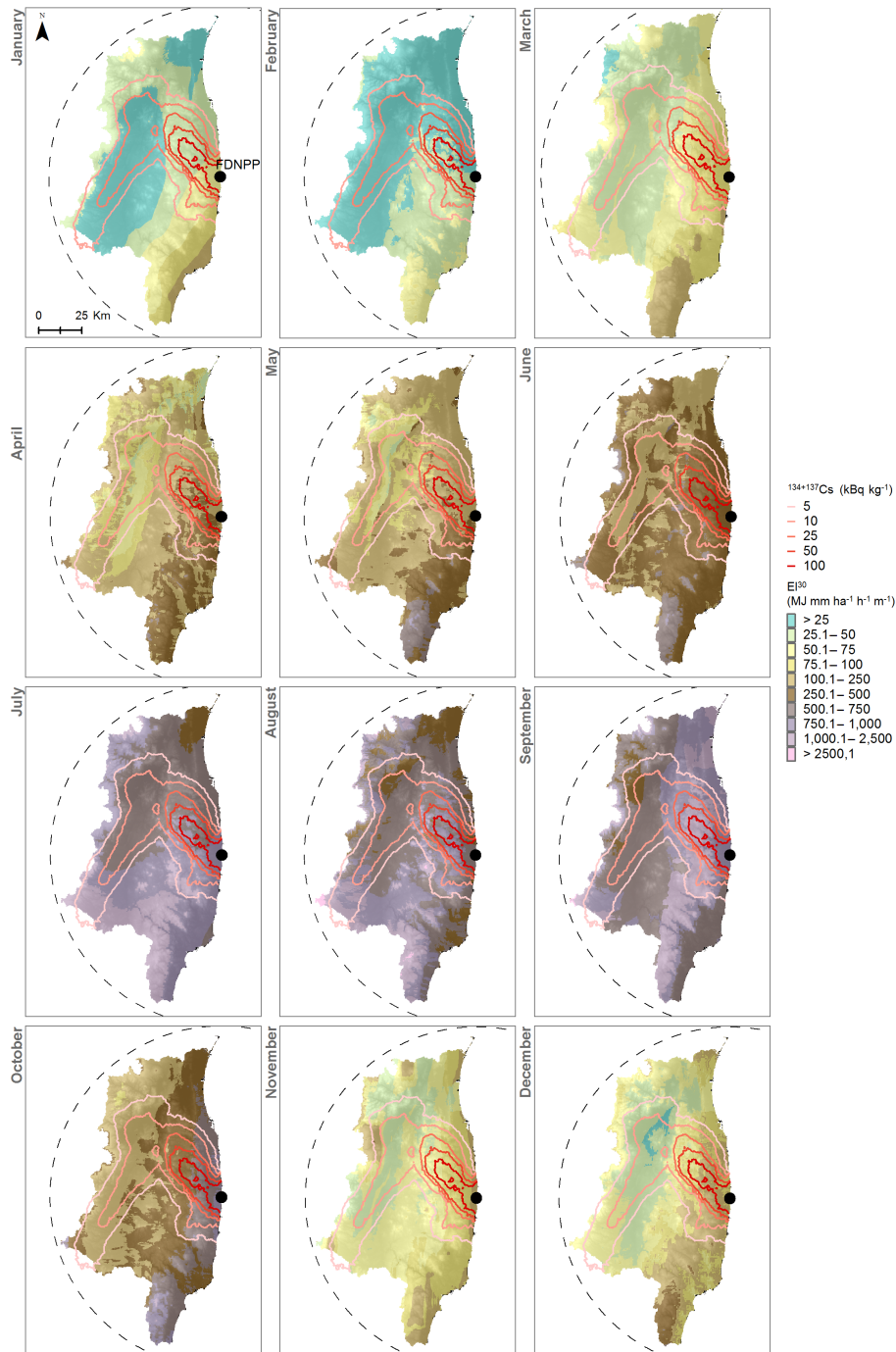


Figure 8. Monthly R factor distribution for catchments contained entirely within a 100 km radius of the FDNPP. $^{134}\text{+}^{137}\text{Cs}$ activities are from Chartin et al. (2013).

to range between 9000 and 14 000 $\text{MJ mm ha}^{-1} \text{h}^{-1} \text{yr}^{-1}$ (Shamshad et al., 2008) in one study and between 1360 and 21 600 $\text{MJ mm ha}^{-1} \text{h}^{-1} \text{yr}^{-1}$ in another (Yu et al., 2001). In these regions, the majority of the annual precipitation and rainfall erosivity may be derived from only a few storms (García-Oliva et al., 1995). In the Fukushima region, this cur-

rent research demonstrated that 40 % of the rainfall erosivity is derived from tropical cyclones. According to model erosion and contaminant transfers in the Fukushima region, it may be important to focus on the spatial distribution of rainfall erosivity from major tropical cyclone events (Chartin et al., 2016).

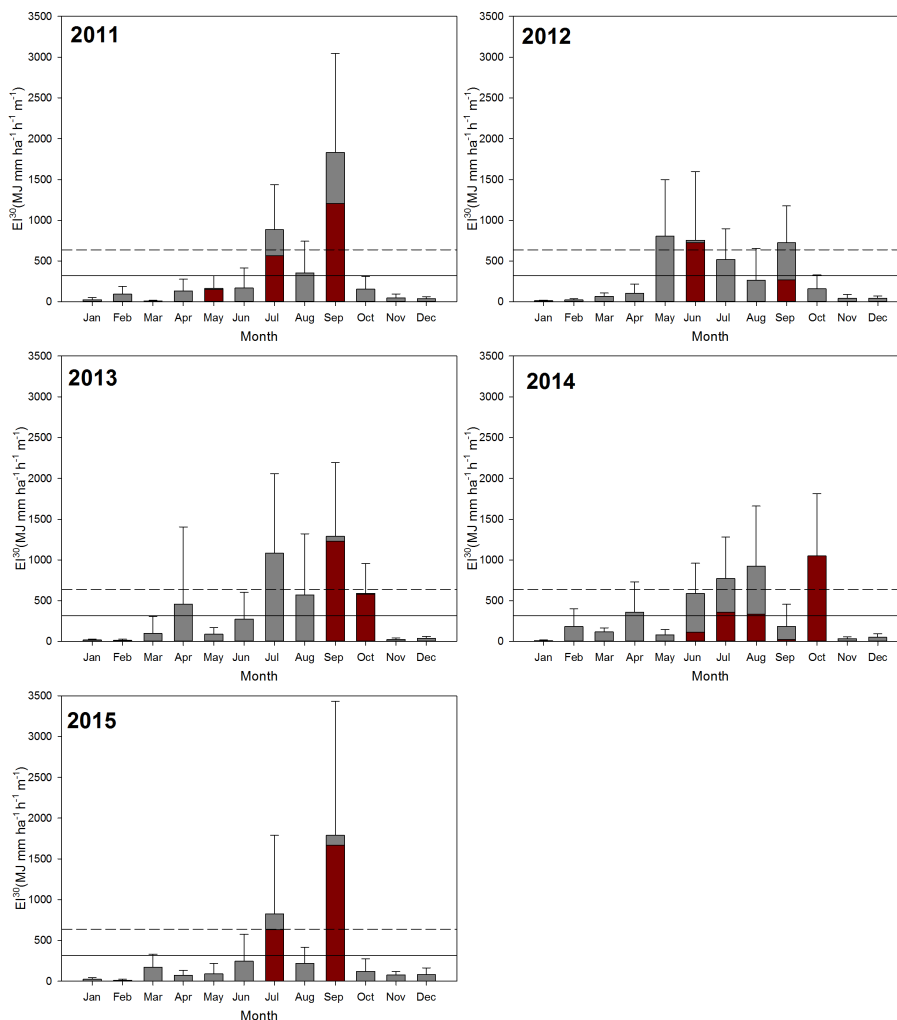


Figure 9. Total (grey) and typhoon-related (red) monthly rainfall erosivity from 2011 to 2015 with the mean line representing mean monthly rainfall erosivity and the dashed line being 1 standard deviation from the mean for the period of 1995–2015 for the 42 rainfall stations analyzed.

4.4 Implications for radiocesium dynamics

Precipitation characteristics, such as rainfall erosivity, are fundamental inputs into a variety of approaches to modelling downstream contaminant transfers (Karydas et al., 2015; Yamaguchi et al., 2014; Rosa et al., 1996). Although precipitation and rainfall erosivity alone are insufficient to directly model downstream radiocesium migration, their characterization is important to improve our understanding of radiocesium dynamics. In the Fukushima region, rainfall drives three major contaminant transfer processes: (i) wet fallout of particle from the atmosphere to the surface controls the spatial distribution of deposited contaminants; (ii) rainfall splash effects trigger the detachment of particle-bound contaminants; (iii) detached particles are potentially transported by overland flow generated by rainfall when infiltration capacity is exceeded or when the soil is saturated with water. In addition,

the timing and intensity of events in general, and tropical cyclones in particular, are likely of particular importance for understanding these and other post-fallout radiocesium dynamics in the Fukushima region (Fig. 9).

The Fukushima region has been demonstrated to be highly reactive to major precipitation events (Evrard et al., 2013), with the climate driving a massive and episodic transfer of radiocesium downstream (Chartin et al., 2013). In fact, Yamaguchi et al. (2014) state that the majority of sediment and radiocesium is transferred downstream in 1–2 major events each year. In Fig. 9, the potential impact of major events is quickly evident. In each year, the rainfall erosivity from tropical cyclones is greater than the mean monthly rainfall erosivity (individual tropical cyclone and tropical storm data for events since 2011 are presented in Table S1 in the Supplement).

Although the Chernobyl and Fukushima regions have similar humid continental climates (Dfb), the tropical cyclones and other significant summer rainfall events result in a higher precipitation (~ 2 times) and rainfall erosivity in the Fukushima region (~ 3 – 4 times). In the Kharkiv region of Ukraine, the mean annual precipitation is 460 mm yr^{-1} (Nazarok et al., 2014); in Odessa it is $< 500 \text{ mm yr}^{-1}$ (Svetlitchnyi, 2009) compared to 1420 mm yr^{-1} for the Fukushima region. In Ukraine, the region within a 100 km radius from Chernobyl has a rainfall erosivity that ranges from 830 to $1250 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$ (Larionov, 1993). Within 100 km from the FDNPP accident, the R factor is ~ 3 to 4 times higher ($3696 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$). As there is positive relationship between rainfall erosivity and soil loss, when other factors are held equal, higher erosion rates and therefore a more rapid radiocesium export are anticipated in the Fukushima region compared to Chernobyl, based on these differences in their climatic contexts.

R factor maps focusing on the region impacted by fallout from the FDNPP accident that depict the annual and monthly variation in the R factor are important for research and modelling of radiocesium dynamics in this region. These R factor maps are thus provided (data set 1). Further, all the event data (total precipitation, rainfall erosivity and kinetic energy) are included in the Supplement (data set 2). These two data sets are included in the Supplement. More research is nevertheless required to examine the impact of different raindrop size distributions and resultant variations in kinetic energy in this region.

5 Conclusions

Rainfall erosivity is an important indicator of a region's climatic vulnerability to rainfall-driven soil erosion and also the potential downstream transfer of sediment and sediment-bound contaminants. Rainfall erosivity in the Fukushima region is $3696 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$ and the region receives 1420 mm yr^{-1} of precipitation. Although these are below average values for Japan, the rainfall erosivity is more than 3 – 4 times higher than in Chernobyl. The majority of precipitation (60%) and rainfall erosivity (86%) occurs between June and October. Major tropical cyclone events are responsible for 22% of the precipitation (422 mm yr^{-1}) and 40% of the rainfall erosivity ($1462 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$, SD 637). The highest areas of contamination in the coastal mountain range correspond to the contaminated area that receives high rainfall erosivity.

The R factor maps demonstrate that areas most contaminated with radiocesium with the highest rainfall erosivity are located along the coastal mountain range of the Pacific Ocean west of the FDNPP. Catchments in these areas will have the highest sensitivity to rainfall-induced soil erosion and thus potential concomitant radiocesium transfers to downstream catchments and ultimately to the Pacific Ocean. The high-

est rainfall erosivity in these areas occurs during the tropical cyclone season (July–September). Monitoring radiocesium transfers after major events will be important. In other catchments that may be impacted by future radiocesium contamination it will be important to similarly investigate the climatic context, as precipitation strongly influences post-fallout radiocesium dynamics.

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