Comparison of characteristics of thunderstorm activity in the south of the Russian Far East according to WWLLN and weather stations data

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Abstract

The work continues the theme of studying of the thunderstorm activity (TA) in the Far East of Russia. A comparison of the characteristics of TA in the south of the Russian Far East (including Sakhalin Island) was carried out according to the data of the World Wide Lightning Location Network (WWLLN) and observational data from 34 weather stations for the period 2009–2018. The estimates of the optimal radius of the region of the WWLLN data sampling in the weather stations vicinity are obtained by two statistical methods. Taking into account the previously published results, the average (median) values of the optimal radius in the south of the Far East of Russia amounted to 23(24) km. Differences in radius estimates for mainland, coastal, and island stations, as well as for night and daytime, are noted. The difference in the average annual TA according to the data of the weather stations and WWLLN varied within ±6 days/year and up to 1.3 days/year, the root mean square deviation were 2.4 days/year and 0.4 days/year, for the first and second methods, respectively. At the same time, the WWLLN data represent the main features of the intra-annual TA variation according to weather station data. It is shown that WWLLN data make it possible to distinguish individual thunderstorms in the course of TA at the diurnal scale, including those not noted in the observational data, and in the spatial distribution of lightning – mesoscale structures formed by thunderstorm rainfall clouds.

1 Introduction

At present, the source of information about thunderstorms in Russia is, first of all, standard weather observations at weather stations of the Roshydromet network (Federal Service for Hydrometeorology and Environmental Monitoring, https://www.meteorf.ru), the results of which are entered into texts of meteorological telegrams and further stored in hydrometeorological archives. Part of the data is freely available from the All-Russian Research Institute of Hydrometeorological Information - the World Data Center (RIHMI-WDC, Obninsk https://www.meteo.ru), however areas with a rare network of weather stations, which include the southern part of the Russian Far East, are poorly covered by such data. As studies have shown (Czernecki et al. 2016; Guide 2008; Permyakov, Potalova, Kleshcheva 2019; Permyakov et al. 2019; Kleshcheva et al. 2021), data from weather stations can be supplemented or even replaced by information from lightning monitoring networks that record radio pulses (atmospherics) emitted by lightning around the clock in a continuous mode over large areas, including those not covered by the ground weather stations network. Such networks include regional and national networks of thunderstorm detection available in a number of countries, as well as the World Wide Lightning Location Network (WWLLN), available at http://wwlln.net/ (Rodger et al. 2006).

Starting to work with databases, one should be aware of the differences in the methods for obtaining information about thunderstorms used by the weather stations and the network of thunderstorm detection. According to the documentation (Instructions 1985; Guide 2008), as the time of the beginning of the thunderstorm, the observer takes “the moment of the first thunderclap, regardless of whether lightning was visible or not”, and for the end time, “the moment of the last thunderclap, provided that in the next 15 minutes the thunder will not be repeated". Since thunder can be heard from 15 to 20 km away from the observer (Instructions 1985), each occurrence of a thunderstorm is represented as a local event that occurred at a weather station, the territory of which is determined by the radius of hearing of thunder in a certain period of time. The disadvantages of visual observations of thunderstorms are obvious: the observer may not hear thunder and may not see lightning and flashes, especially if the thunderstorm passes in the distance; in addition, lightning discharges may not be accompanied by sound, which actually introduces errors in the accuracy of determining the time of a thunderstorm, making the concepts of “first” or “last” very suppositive and subjective. The order of observation of heat lightnings, which is a light phenomenon from a thunderstorm passing in the distance, is not determined by the Instructions (Instructions 1985) at all.

At the same time, WWLLN data are collected in real time and have no spatial restrictions, which makes it possible to use WWLLN data to study a thunderstorm activity in areas that are not covered by a network of weather stations, as well as to study a weather systems and their mesoscale convective structures in the open ocean (Kleshcheva et al. 2021; Permyakov et al. 2019). However, the efficiency of lightning detection by the WWLLN network (the ratio of the number of lightnings registered by the WWLLN network to the number of lightning registered by regional networks) is determined by the state of the ionosphere and local geographic factors, such as topography, conductivity of Earth's surface, the configuration of the network stations, etc. Because of this, network detection efficiency has significant spatial and diurnal variability (Pessi et al. 2009). Therefore, before widely using WWLLN data to study thunderstorm activity in the south of the Russian Far East, it is necessary to compare its characteristics and their spatial and temporal variability obtained from two types of data – visual observations at weather stations and WWLLN data. For this, in turn, it is necessary to determine the size (radius) of the vicinity of the weather station, within which the WWLLN data will be selected, at which the consistency between the weather station data and WWLLN is greatest. When studying thunderstorm activity (TA) in Primorsky Krai (Permyakov, Potalova, Kleshcheva 2019), the radius was set to 25 km for all stations, which we determined by the condition of approximate equality of the number of days with a thunderstorm according to the data of observations and WWLLN. However, estimates of the optimal radius of the WWLLN data sample obtained for 20 weather stations located in the south of the Russian Far East showed that the radius of the vicinity of the stations can range from 12 km to 36 km with an average value of 23 km, while the daytime radius are smaller compared to the nighttime radius, and the average for all stations is 21 km and 26 km, respectively (Kleshcheva et al. 2021). For the North American ECLLN network, the value of the optimal radius for 132 weather stations averaged 17 km during the daytime and 26 km at night (Reap and Orville 1990). For the North European NORDLIS network, the optimal radius was 9–11.3 km (Enno 2015), and for the Polish PERUN network, on average, the optimal radius was 17.5 km (Czernecki et al. 2016). At the same time, the deviation of radius from the average value even by 1 km affects the statistics of thunderstorms (Czernecki et al. 2016; Kleshcheva et al. 2021).

The work continues the study of the TA in the Far East of Russia. The aim of this paper is to compare the characteristics of thunderstorm activity throughout the south of the Russian Far East, including the southern part of the Amur Oblast (AO), Jewish Autonomous Oblast (JAO), southern part of Khabarovsk Krai (KK), Primorsky Krai (PK), and most of the Sakhalin island (SI), according to observations at 34 weather stations and data from the World Wide Lightning Location Network for the period 2009–2018, based on the methods used in previous studies.

2 Data And Methods

The data of observations of atmospheric phenomena at 34 weather stations and data of WWLLN for the period 2009–2018 on the Russian Far Eas territory bounded by the coordinates 42–53° N and 126–145° E were used in the work.

Weather station data were obtained from the RIHMI-WDC archive and contains the date and code of each event, its intensity and the beginning/end time. Information about the "thunderstorm" phenomenon, including the categories "lightning", "thunder" and "thermal lightning", was selected. The coordinates of weather station and their altitude above sea level are given in Table 1. The location of weather stations is shown in Fig. 1, on which 18 mainland stations are highlighted in black (Ekaterino-Nikol'skoe, Krasnyj Jar, Svijagino, Arhara, Habarovsk, Smidovich, Pogranichnyj, Timirjazevskij, Solekul', Mel'nichnoe, Dal'nerechensk, Elabuga, Lermontovka, Konstantinovka, Blagovescensk, Cekunda, Sutur, Nizhnetambovskoe), in blue – 6 coastal stations (Pos'et, Vladivostok, Preobrazhenie, Rudnaja Pristan', Ternej, Sovetskaja Gavan') and in red – 10 stations on the Sakhalin island (Aleksandrovsk-Sahalinskij, Tymovskoe, Pogranichnoe, Uglegorsk, Poronajsk, Mys Terpenija, Ilyinskiy, Nevel'sk, Mys Kril'on, Juzhno-Sahalinsk). It should be noted that the weather station data are periodically corrected and updated, as reported on the official website of the RIHMI-WDC, so July 15, 2020 release was used in this work.

The WWLLN data contains information about the time of a single cloud-to-ground lightning discharge with accuracy to microseconds and its latitude and longitude in degrees with accuracy to the fourth decimal place. This data also contains information about the error in estimating the discharge time in microseconds (Δt, s^{-6}), which makes it possible to estimate the error in determining the lightning coordinates as $\Delta r \sim c\Delta t$ in km, where c is the speed of light. The average (and median) values of Δr obtained for each weather station from WWLLN data samples in its vicinity with a radius of 20 km varied from 3 to 4 km, which is consistent with the global values of the lightning localization error of the WWLLN (Hutchins et al. 2012).

Two statistical methods were used to get the optimal radius of the vicinity of weather stations for WWLLN data sampling (Wilks 2006; Czernecki et al. 2016). The first method is based on the calculation of the Threat Score index (TSI), which is defined as TSI = $a/(a+b+c)$, where a is the number of days, when thunderstorms were detected both by the observer at the weather station and the WWLLN, b is the number of days, when thunderstorms were registered only by the observer at the weather station, c is the number of days, when thunderstorms were registered only by the WWLLN (Wilks 2006; Czernecki et al. 2016). The closer the TSI value is to one, the smaller the contribution of days during which a thunderstorm is recorded either by an observer at a weather station or by WWLLN, which means that there is a better consistency between the weather station and WWLLN data. For the optimal radius (R1), such a radius of the weather station vicinity is taken, at which the value of the TS index will be the largest. The second method, more simple, is based on the calculation of the difference between the total number of days with lightning according to WWLLN and the total number of days with thunderstorms according to weather stations (Czernecki et al. 2016). The optimal radius (R2) is the radius at which this difference is equal to zero. Both radius were calculated from the WWLLN samples obtained in the weather stations vicinity with radius in the range from 5 to 65 km with a step of 0.5 km. A detailed description of these methods can be found in works (Kleshcheva et al. 2021; Czernecki et al., 2016).

3 Results And Discussion

3.1 Optimal radius for sampling WWLLN data

The estimates of optimal radius (rounded values) and TS index obtained by two methods for all 34 weather stations in the Far East, including those previously published in (Kleshcheva et al. 2021), are summarized in Table 1, and Table 2 presents statistical characteristics. Table 2 also separately provides statistics for mainland, coastal, and island (Sakhalin) stations.

Table 1

Results of a comparison the data of thunderstorm observations at weather station and WWLLN data for the period of 2009–2018

Station and it's localization	Coordinates		Station Altitude	1st Method						2nd Method		
	φ,ºN.	λ,º E.	h, m	R1, km	TSI	Day		Night		R2, km	Day	Night
						R1,km	TSI	R1, km	TSI		R2, km	R2, km
1	2	3	4	5	6	7	8	9	10	11	12	13
Mainland												
1. *Nizhnetambovskoe* (KK)	50.92	138.18	24	39	0.60	27	0.62	39	0.51	29	26	39
2. *Cekunda* (KK)	50.87	132.25	271	32	0.69	28	0.66	30	0.59	34	33	32
3. *Blagovescensk* (AO)	50.28	127.48	168	30	0.64	26	0.61	29	0.50	29	27	39
4. *Sutur* (KK)	50.07	132.12	343	21	0.64	21	0.63	28	0.46	20	19	31
5. *Konstantinovka* (AO)*	49.62	127.97	117	29	0.63	27	0.66	50	0.54	36	27	51
6. *Arhara* (AO)*	49.42	130.08	134	22	0.62	22	0.58	18	0.52	25	23	23
7. *Solekul'*(KK)*	49.17	138.05	915	25	0.58	25	0.59	22	0.26	19	19	14
8. *Elabuga* (KK)*	48.82	135.88	62	28	0.61	26	0.58	36	0.51	26	23	28
9. *Smidovich* (JAO)*	48.6	133.83	50	23	0.58	23	0.59	34	0.47	26	21	31
10. *Habarovsk* (KK)*	48.52	135.12	88	23	0.63	17	0.64	25	0.51	22	15	28
11. *Ekaterino-Nikol'skoe* (JAO)*	47.73	130.97	71	13	0.56	13	0.52	16	0.44	14	13	12
12. *Lermontovka* (KK)*	47.15	134.33	75	29	0.67	26	0.66	38	0.52	34	28	44
13. *Krasnyj Jar* (PK)*	46.53	135.3	128	14	0.49	14	0.46	14	0.39	12	12	10
14. *Dal'nerechensk* (PK)*	45.87	133.73	100	27	0.59	27	0.56	37	0.49	27	24	33
15. *Mel'nichnoe* (PK)*	45.45	135.5	331	25	0.62	25	0.61	21	0.44	24	24	22
16. *Svijagino* (PK)*	44.8	133.1	99	19	0.57	17	0.55	21	0.50	19	16	25
17. *Pogranichnyj* (PK)*	44.4	131.38	217	24	0.67	22	0.69	28	0.48	26	24	27
18. *Timirjazevskij* (PK)*	43.88	131.97	34	24	0.60	24	0.62	40	0.44	23	21	31
Coastal												
19. *Sovetskaja Gavan'*(KK)*	49	140.3	21	31	0.63	33	0.66	24	0.49	31	33	28
20. *Ternej* (PK)*	45	136.6	51	30	0.56	30	0.59	23	0.43	26	22	24
21. *Rudnaja Pristan'*(PK)*	44.4	135.9	27	22	0.46	24	0.41	22	0.44	20	20	21
22. *Vladivostok* (PK)*	43.1	131.87	187	20	0.51	15	0.52	27	0.41	18	17	17
23. *Preobrazhenie* (PK)*	42.9	133.9	44	24	0.51	16	0.54	30	0.52	23	18	25
24. *Pos'et* (PK)*	42.65	130.8	41	18	0.45	12	0.45	27	0.40	15	13	14
Sakhalin Island												
25. *Aleksandrovsk-Sahalinskij*	50.9	142.17	30	25	0.43	21	0.38	37	0.42	26	26	25
26. *Tymovskoe*	50.73	142.72	94	30	0.54	22	0.50	31	0.54	27	25	27
27. *Pogranichnoe*	50.4	143.77	6	8	0.37	9	0.35	12	0.39	11	14	8
28. *Poronajsk*	49.22	143.1	7	28	0.41	28	0.52	19	0.32	26	23	25
29. *Uglegorsk*	49.07	142.03	39	21	0.50	21	0.40	20	0.45	25	23	28
30. *Mys Terpenija*	48.65	144.73	33	12	0.49	9	0.54	12	0.38	10	12	8
31. *Ilyinskiy*	47.98	142.2	17	21	0.46	26	0.41	17	0.46	19	21	19
32. *Juzhno-Sahalinsk*	46.95	142.72	22	18	0.50	28	0.48	13	0.48	21	28	15
33. *Nevel'sk*	46.67	141.87	22	24	0.43	24	0.37	13	0.40	20	25	14
34. *Mys Kril'on*	45.9	142.08	34	11	0.37	6	0.39	11	0.33	5	5	5

Note: results marked with "*" particularly were discussed in (Kleshcheva et al. 2021).

In general for the south of the Russian Far East the optimal radius R1 vary from 8 km (Sakhalin, *Pogranichnoe*) to 39 km (KK, *Nizhnetambovskoe*), and the optimal radius R2 range from 5 km (Sakhalin, *Mys Kril'on*) to 36 km (AO, *Konstantinovka*) (Table 1). The average (median) values of both R1 and R2 for the entire territory were 23 (24) km (Table 2). On average, the largest optimal radius were obtained at the mainland stations, where the values of $\overline{R1}$ and $\overline{R2}$ were 25 km each, and the smallest ones – at the Sakhalin stations, where the value of $\overline{R1}$ was 20 km and value of $\overline{R2}$ was 19 km (Table 2). At the coastal stations the values of $\overline{R1}$ and $\overline{R2}$ were 24 and 22 (km), respectively (Table 2).

The maximum values of the TS index at the weather station, from which the optimal radius R1 was determined, show the degree of consistency between the observational data and the WWLLN data, and may reflect their quality and representativeness. For the entire south of the Russian Far East, TSI values varied from 0.37 (Sakhalin, stations *Mys Kril'on* and *Pogranichnoe*) to 0.69 (KK, station *Cekunda*) (Table 1) with a mean (median) value of 0.55 (0.57) (Table 2). On average, the best consistency between the observational data and WWLLN was obtained at the mainland stations (mean TSI = 0.61), lower – at coastal stations (mean TSI = 0.52), and the lowest – at Sakhalin (mean TSI = 0.45) (Table 2). The relatively low consistency between weather station data and WWLLN data on Sakhalin can be explained, firstly, by the small number of days with thunderstorms per year, which distinguishes Sakhalin from the rest of the south of the Russian Far East. As can be seen from Table 2, the average 10-years annual number of thunderstorm days registered at weather stations ($\overline{\mathrm{NM}}$), for Sakhalin stations on average is 6 days/year, which is approximately two times less than at coastal stations ($\overline{\mathrm{NM}}$ ~ 14 days/year), and almost 5 times less than at mainland stations ($\overline{\mathrm{NM}}$ ~ 29 days/year). Thus, we can say that a thunderstorm on Sakhalin is a relatively rare occurrence. Secondly, the insular position here determines foggy, wet weather with a high frequency of low cloudiness (50–60% or more (Reference book, 1968), which, possibly, significantly worsens visibility and affects the quality of visual observations for weather.

Table 2

Statistical characteristics of optimal radius and TSI for mainland, coastal, Sakhalin and all weather stations in the south of the Russian Far East for the period

Region (stations amount)	Base statistics	1st method						2nd method			$\overline{\mathrm{NM}}$, days/year	$\overline{\mathrm{NW1}}$ days/year	$\overline{\mathrm{NW2}}$ days/year	$\overline{\mathrm{NM}}$ - $\overline{\mathrm{NW1}}$ days/year	$\overline{\mathrm{NM}}$ - $\overline{\mathrm{NW2}}$ days/year
		R1, Km	TSI	Day		Night		R2, km	Day	Night					
				R1, km	TSI	R1, km	TSI		R2, km	R2,km					
Mainland (18)	min	13	0.49	13	0.46	14	0.26	12	12	10	17.1	19.4	16.7	-6.3	-0.1
	max	39	0.69	28	0.69	50	0.59	36	33	51	41.5	35.8	40.2	6.4	1.3
	mean	25	0.61	23	0.60	29	0.48	25	22	29	28.6	28.0	28.1	0.6	0.5
	median	24	0.62	24	0.61	28	0.50	25	23	30	27.0	27.9	26.6	0.4	0.4
	σ	6	0.05	5	0.06	10	0.07	7	6	11	6.8	5.4	6.8	3.2	0.4
Coastal	min	18	0.45	12	0.41	22	0.40	15	13	14	11.7	11.7	11.2	-1.3	0.2
Stations	max	31	0.63	33	0.66	30	0.52	31	33	28	15.0	15.2	14.7	0.7	1.0
(6)	mean	24	0.52	21	0.53	25	0.45	22	20	21	13.8	14.0	13.2	-0.2	0.6
	median	23	0.51	20	0.53	25	0.44	22	19	23	14.6	14.4	13.8	0.0	0.5
	σ	5	0.07	9	0.09	3	0.05	6	7	5	1.6	1.3	1.5	0.8	0.3
Sakhalin	min	8	0.37	6	0.35	11	0.32	5	5	5	2.2	1.3	2.0	-2.7	-0.1
(10)	max	30	0.54	28	0.54	37	0.54	27	28	28	9.2	11.1	9.2	1.5	0.5
	mean	20	0.45	19	0.43	18	0.42	19	20	17	6.0	6.3	5.8	-0.3	0.1
	median	21	0.44	21	0.41	15	0.41	20	23	17	6.6	6.0	6.3	-0.5	0.2
	σ	8	0.06	8	0.07	9	0.07	8	7	9	2.7	2.9	2.6	1.4	0.2
All region	min	8	0.37	6	0.35	11	0.26	5	5	5	2.2	1.3	2	-6.3	-0.1
(34)	max	39	0.69	33	0.69	50	0.59	36	33	51	41.5	35.8	40.2	6.4	1.3
	mean	23	0.55	21	0.54	25	0.45	23	21	24	19.5	19.1	19.1	0.2	0.4
	median	24	0.57	23	0.56	24	0.46	24	22	25	19.5	19.4	19.1	0	0.4
	σ	7	0.09	7	0.10	10	0.07	7	6	10	11.8	10.9	11.7	2.4	0.4

Table 1 also shows estimates of the optimal radius and TSI for daytime and nighttime, separated by the moments of sunrise and sunset, calculated using astronomical formulas from (Khrgian, 1978), and Table 2 shows their main statistical characteristics. On average, the entire south of the Russian Far East is characterized by a decrease in the consistency between the data of weather stations and WWLLN at night (Table 2), which, as noted in (Kleshcheva et al., 2021), is most likely due to a deterioration in the quality of visual observations, since the efficiency detection of WWLLN can be two to three times higher at night than during the day (Pessi et al., 2009). For 34 weather stations, the average TSI is 0.54 at day and 0.45 at night. The most significant changes in TSI values were obtained at mainland stations, where the difference between the average daytime (0.6) and nighttime (0.48) TSI values is 2 times greater than the standard deviation (σ) of TSI (0.06 and 0.07). For coastal weather stations, the average values of daytime and nighttime TSI were 0.53 and 0.45 (Table 2), respectively, with only at three stations (*Sovetskaja Gavan'*, *Ternej* and *Vladivostok* stations) decreasing of TSI more than σ. For Sakhalin stations, the average daytime and nighttime TSI values were 0.43 and 0.42, respectively (Table 2), however, a decrease in TSI at night was obtained only for *Poronajsk*, *Mys Terpenija*, and *Mys Kril'on* stations (Table 1). At the other Sakhalin stations, the TSI either does not change (station *Juzhno-Sahalinsk*) or increases insignificantly within σ (Table 1).

On average, the entire south of the Russian Far East is characterized by an increase in the optimal radius at night (Table 2). The average daytime and nighttime R1 radius were 21 and 25 (km) for all weather stations, 23 and 29 (km) for mainland stations, and 21 and 25 (km) for coastal stations, respectively. The average daytime and nighttime R2 radius were 21 and 24 (km) for all weather stations, 22 and 29 (km) for mainland stations, and 20 and 21 (km) for coastal stations, respectively. Thus, the largest difference between the nighttime and daytime values of the optimal radius was obtained at mainland stations, where, on average, the values of R1 and R2 increase at night by ~ 6 and 7 (km), while at coastal stations by ~ 4 and 1 (km). In contrast to the mainland and coastal stations, on Sakhalin one can note a decrease at night of the average optimal radius R1 and R2 by ~ 1 km and 3 km (Table 2). For Sakhalin weather stations, the mean daytime radius R1 and R2 are 19 and 20 (km), respectively, the mean nighttime radius R1 and R2 are 18 and 17 (km). The largest difference between the night and day values of the radius calculated by both methods was obtained at station *Juzhno-Sahalinsk*, where it was − 13 km and − 15 km, and at station *Nevel'sk*, where it was − 11 km each.

3.2 Comparison of thunderstorm activity according to WWLLN data and weather station data

3.2.1 Intra-annual variability of thunderstorm activity

A significant indicator of the quality of WWLLN data is how the data reflects the intra-annual variability of thunderstorm activity in comparison with weather station data. Figure 1 shows graphs of the intra-annual variations of the summary number of days with thunderstorms over ten years according to the weather stations data and similar graphs obtained from lightning WWLLN samples in the stations vicinity with optimal radius R1 and R2. Note that the maximum ordinates on the graphs are 120 days for continental stations and 35 days for Sakhalin stations, since continental regions are characterized by a larger number of days with thunderstorms per year compared to the island (Table 2).

In general, it can be noted that according to visual observations, thunderstorm activity is characterized by 1 maximum at mainland stations (with the exception of *Svijagino* and *Pogranichnyj* stations), 2 maxima at coastal stations (with the exception of *Ternej* station), at Sakhalin stations both by 1 maximum (*Uglegorsk*, *Poronajsk*, *Mys Terpenija*, *Ilyinskiy*, *Nevel'sk*) and 2 maxima (*Aleksandrovsk-Sahalinskij*, *Tymovskoe*, *Pogranichnoe*, *Mys Kril'on and Juzhno-Sahalinsk*). In most cases, graphs based on WWLLN data reflect the main qualitative features of the intra-annual course of TA according to observations at weather stations. At 4 stations, the number of peaks on the graphs does not match, when the graphs based on the data of weather stations have two maxima each, and the graphs based on the WWLLN data have only one (*Svijagino*), and vice versa (*Mys Terpenija*, *Ilyinskiy*, *Nevel'sk*). At some weather stations (*Lermontovka, Krasnyj Jar, Rudnaja Pristan', Vladivostok, Timirjazevskij, Pos'et, Aleksandrovsk-Sahalinskij, Uglegorsk, Mys Terpenija, Juzhno-Sahalinsk*), one can note the asynchrony of the main or secondary maxima of TA. Quantitative difference between the graphs of the intra-annual course according to observations and according to WWLLN data in the sample with R1 varied from − 22 to + 24 days (for R2 varied from − 10 to + 17 days) and the root mean square difference (*rmsd*) was 4.6 (3.5) days.

For each weather station, we calculated the 10-year average values of the number of days with thunderstorms (as a measure of thunderstorm activity) according to observational data ($\overline{\mathrm{NM}}$) and with lightning according to WWLLN data, selected in the vicinity of weather stations with radius R1 ($\overline{\mathrm{NW1}}$) and R2 ($\overline{\mathrm{NW2}}$), and then the difference between them. The statistical characteristics of this average annual thunderstorm activity, both for the entire south of the Russian Far East, and separately for mainland, coastal and Sakhalin stations, are given in Table 2. On average, about 20 days with thunderstorms per year are observed at weather stations of the south of Russian the Far East, 29 days/year at mainland stations, 14 days/year at coastal stations and 6 days/year at Sakhalin stations (Table 2). Thus, the highest thunderstorm activity was observed at mainland stations, where the maximum value of $\overline{\mathrm{NM}}$ (42 days/year) was at weather station *Konstantinovka*, and the lowest TA was at Sakhalin, where the minimum value of $\overline{\mathrm{NM}}$ (2 days/year) was obtained at stations *Mys Terpenija* and *Pogranichnoe*. The difference in the average annual thunderstorm activity according to weather station data and according to WWLLN data in samples with radius R1 and R2 for the entire south of the Russian Far East varied within ± 6 days/year and up to 1.3 days/year, *rmsd* (σ in Table 2) were 2.4 days/year and 0.4 days/year, respectively (Table 2). For mainland stations *rmsd* were 3.2 days/year and 0.4 days/year, for coastal stations *rmsd* were 0.8 days/year and 0.3 days/year, for Sakhalin stations *rmsd* were 1.4 days/year and 0.2 days/year, respectively (Table 2). Thus, the second method for the determining of the optimal radius R2 gives the better results for the estimating of thunderstorm activity according to WWLLN data, if we consider the weather station data as a “reference”.

3.2.2 Diurnal variability of thunderstorm activity

The thunderstorm activity has a clearly defined diurnal variation, especially on land (Zhang et al., 2010). The diurnal variation of TA according to weather station data and according to WWLLN data will differ and their comparison is not entirely correct, since visual observation data are reduced to registering the time of the beginning (that is, the first observed lightning, thunder or flash of light during heat lightning) and the end of a thunderstorm (the last thunder or lightning), while the WWLLN data is the time of registration of each lightning in the vicinity of the station. At the same time, observations of atmospheric phenomena are influenced not only by geographical features (exposure of stations, closeness to the surrounding landscape etc.) and current weather situations (sky conditions, fog, poor or good visibility etc.), but also subjective factors, for example, the state of health of the observer's eyesight and hearing (Instructions 1985; Guide 2008). Therefore, the marks of thunderstorms during the day are several orders of magnitude less than the number of lightnings. To illustrate this, we present three typical examples.

Figures 2a,b show the TA during the period of 7–9 August 2013 in the area of the station *Konstantinovka*, which, according to the surface weather maps of the Japan Meteorological Agency (JMA, http://www.jma.go.jp/), was affected by the front of a stationary cyclone moving from the southwest across the Amur Oblast to the northeast (Fig. 2c). Figure 2a shows the three-day course of the total number of lightning in 0.5 hour windows obtained from the WWLLN data in the square (65 × 65 km) limited by coordinates 49.04° N – 50.21° N and 127.07° N – 128.87° E and in the station vicinity with optimal radius R1 = 29 km and R2 = 36 km. Figure 2a also shows the moments of the beginning and end of the "thunderstorm" phenomenon registered at the station by the observer. The WWLLN graph clearly shows separate periods of lightning activity, which can be distinguished as individual thunderstorms passing over the weather station. In some cases, the marks of the thunderstorm beginning are close to the start of a sharp increase in the number of WWLLN lightning. In general, the time intervals between the marks of the beginning and end cover periods of high WWLLN lightning activity. However, it is possible to distinguish periods when there are no marks of thunderstorms at the weather station, but lightnings is detected by the WWLLN network, for example, 03:00–06:00 UTC on August 7 or from 20:30 UTC to 21:30 UTC on August 9. Figure 2b shows the spatial distribution of lightning in the vicinity of the station for the time intervals 11:00–17:00 UTC on August 7, 08:00–17:00 UTC on August 8, and 02:00–14:00 UTC on August 9. It can be seen from the figure that the areas of thunderstorms shift as the cyclone passes, while the total number of lightning (*N*) increases from 378 to 1711 discharges. On the map for the third time interval, areas of significant lightning density are clearly distinguished, which can be associated with mesoscale structures, such as convective complexes, a multi-cell thunderstorm, or a thunderstorm front.

The second example is thunderstorm activity in the *Pos'et* station area bounded by coordinates 42.07°N – 43.24°N and 130.1°E – 131.6°E on 19–20 October 2017 (Figs. 3a,b), when the weather over the southern coast of Primorsky Krai (Peter the Great Bay) was determined by the passage of atmospheric fronts with short-term precipitation and squally wind (Fig. 3c). During this period, only rain was indicated at *Pos'et* station, while WWLLN data show significant thunderstorm activity from 1600 UTC on October 19 to 09:00 UTC on October 20 (Fig. 3a) southeast of the station (Fig. 3b). Figure 3b shows the lightning distributions in the vicinity of the station in three different periods: 16:00–21:00 UTC and 21:00–24:00 UTC on October 19 and 00:00–03:00 UTC on October 20. It can be seen that the points of lightning discharges formed bands that can be associated with the positions of the thunderstorm front, which was moving to the southeast. Several lightnings were located within the *Pos'et* vicinity with optimal radius R1 = 18 km and R2 = 15 km, i.e. the observer at the weather station could see them. It is possible that the lack of records about the atmospheric phenomenon "thunderstorm" at the weather station was due to poor visibility caused by rain and sea fog, which were indicated in weather reports and marked on weather maps (Fig. 3c). It can also be assumed that the discrepancies in the data are due to the geographical features of the area and the degree of openness of the station. The *Pos'et* station is located on a peninsula between the *Expedition* bay in the west and *Novgorodskaya* bay in the east and is closed from the open sea (i.e. where lightning has been detected) by the *Krabbe* peninsula. It is possible that these reasons determine the relatively low consistency between the WWLLN data and the visual observations data at *Pos'et* station, for which the TSI value is only 0.45 (Table 1).

The third example, shown in Fig. 4, is the thunderstorm activity near *Pos'et* station on 8 September 2014 (Fig. 4a,b), caused by the passage of an occlusive sedentary cyclone (Fig. 4c). Unlike the previous case, this time the thunderstorm was detected by both the WWLLN network and the observer at the weather station, although, for example, in the interval of 11:00–12:30 UTC, only two WWLLN lightnings hit the vicinity with optimal radii, and all other lightnings were detected beyond outside of it. In the field of the spatial distribution of lightning (Fig. 4b) in the interval of 07:42–09:30 UTC to the south, southwest of the station, two areas of high density of discharges can be distinguished. Figure 4d shows part of the IR imagery of the study area received from the geostationary satellite MTSAT on 8 September 2014 at 07:32 UTC and posted on the Tropical Cyclones Archive of the University of Wisconsin—Madison/Cooperative Institute for Meteorological Satellite Studies page (http://tropic.ssec.wisc.edu/archive/). The cloudiness fields in the IR range, combined with the fields of lightning discharges, selected for an image time ± 1 hour, showed that these centers of thunderstorm activity coincide with areas of cold front intense upward movements and cumulonimbus clouds.

The above examples show that WWLLN data can well represent temporal variability of TA at diurnal scales and distinguish individual thunderstorms both in the temporal course and in the spatial distribution of lightning.

4 Conclusions

The characteristics of thunderstorm activity in the south of the Russian Far East, obtained from observations at weather stations and data from the global lightning localization network WWLLN for the period 2009–2018, are compared. For this the estimates of the radius of the best consistency between the data of the weather stations and WWLLN were obtained using two statistical methods. Taking into account the previously published values, the average (median) value of the optimal radius for weather stations of the south of the Russian Far East was 23 (24) km. On average, the optimal radius R1 and R2 were 25 km each at the mainland stations, 24 and 22 (km) at the coastal stations, and 20 and 19 (km) at the Sakhalin stations. On average, the best consistency between the observational data and WWLLN (TS index) was obtained at the mainland stations (0.61), lower – at coastal stations (0.52), and the lowest – at Sakhalin (0.45). On average, the entire south of the Russian Far East is characterized by a decrease in the TS index (from 0.54 to 0.45) and by an increase in the optimal radius at night (from 21 to 25 (km)).

It is shown that at most weather stations the intra-annual variability of the summary number of days with thunderstorms over ten years according to the data of WWLLN samples in the stations vicinity with optimal radius R1 and R2 reflects its main qualitative features according to visual observations, namely the presence of 1 maximum at mainland stations, 2 maxima at coastal stations, both 1 and 2 maxima at Sakhalin stations. The root mean square deviations in intra-annual variability of the total days with thunderstorms over ten years were 4.6 and 3.5 (days) for all weather stations with vicinity of R1 and R2, respectively.

It was obtained that on average about 20 days with thunderstorms per year are observed at weather stations of the south of the Russian Far East, 29 days/year at mainland stations, 14 days/year at coastal stations and 6 days/year at Sakhalin stations. The difference in the average annual thunderstorm activity according to weather station data and according to WWLLN data in samples with radius R1 and R2 varied within ± 6 days/year and up to 1.3 days/year, the root mean square deviation were 2.4 and 0.4 (days/year), respectively.

Using examples of specific situations, it is demonstrated that WWLLN data make it possible to distinguish individual thunderstorms in the diurnal TA variation and mesoscale structures formed by thunderclouds in the spatial distribution of lightning. At the same time, WWLLN data make it possible to determine the duration of thunderstorms, which, as data from individual stations showed, is not always possible with auditory and visual observation at weather stations. The results confirm the WMO opinion that in order to increase the reliability of information on the characteristics of thunderstorm activity, the use of automated observing systems, including regional and global lightning localization systems, should be expanded (Guide 2008).

Declarations

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Data Availability: Weather stations data are obtained from the archives of the All-Russian Research Institute of Hydrometeorological Information - the World Data Center (RIHMI-WDC) where they are freely available at https://www.meteo.ru. The lightning data stored on the World Wide Lightning Location Network was obtained from the website http://wwlln.net/ with the special permission of the Director Professor R.H. Holzworth and is not shared to further distribution. Weather maps and satellite (MTSAT) images were obtained from the Japan Meteorological Agency (http://www.jma.go.jp/) and the University of Wisconsin—Madison/Cooperative Institute for Meteorological Satellite Studies page (http://tropic.ssec.wisc.edu/archive/) sites where they are freely available.

Code availability: Not applicable.

Author Contributions: All authors contributed to the study conception, material preparation, data collection and analysis. All authors read and approved the final manuscript.

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Figures

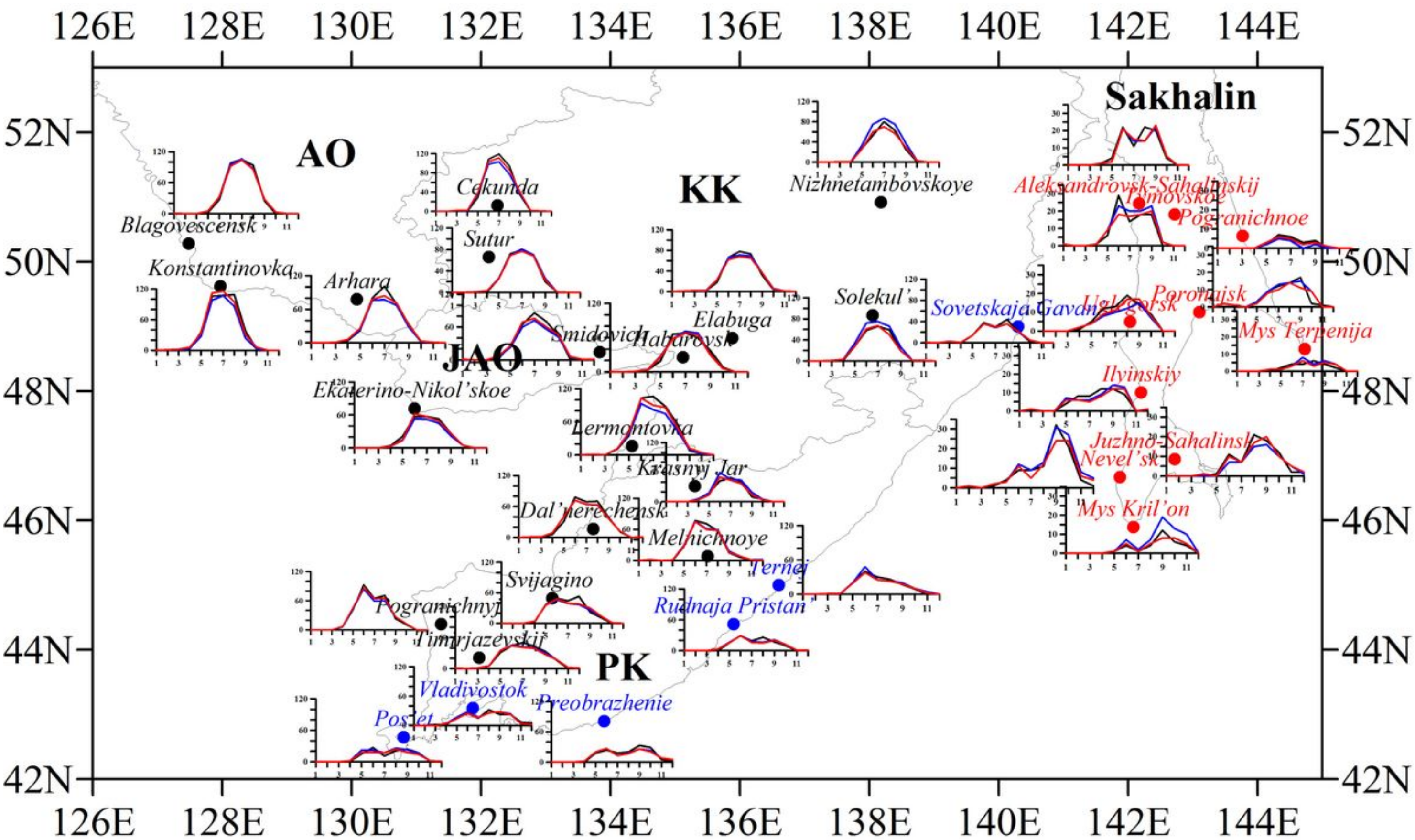

Figure 1

Intra-annual variability of the total number of days with thunderstorms according to the data of the weather stations and WWLLN for the period 2009–2018. Black lines - according to weather stations data, blue and red lines - according to WWLLN data in areas with radius R1 and R2, respectively; colored dots - the position of the stations

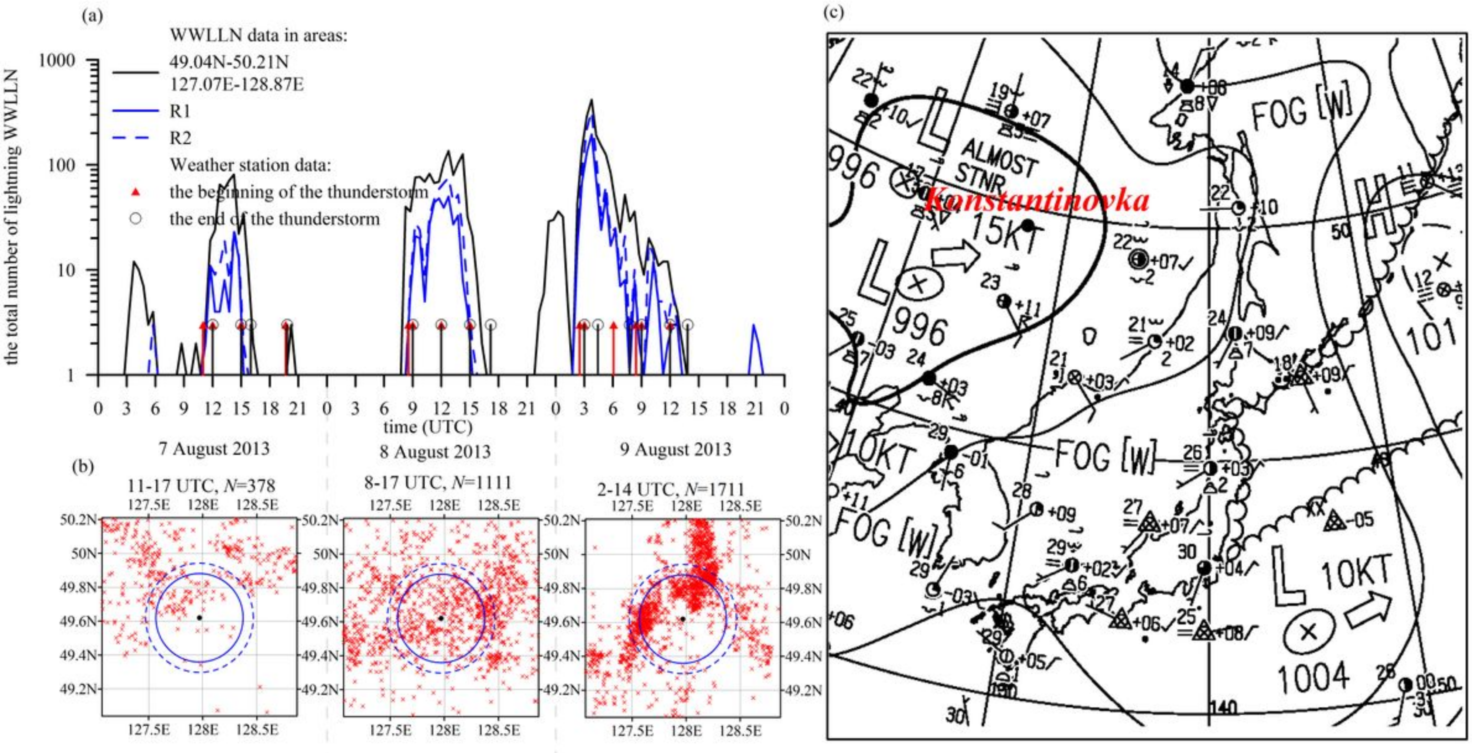

Figure 2

Thunderstorm activity near the *Konstantinovka* weather station on 7–9 August 2013. (a) Variation of the total number of WWLLN lightnings in the weather station vicinity; (b) Spatial distribution of WWLLN lightning in the weather station vicinity; (c) Part of the JMA surface weather map for 7 August 2013 (12:00 UTC).

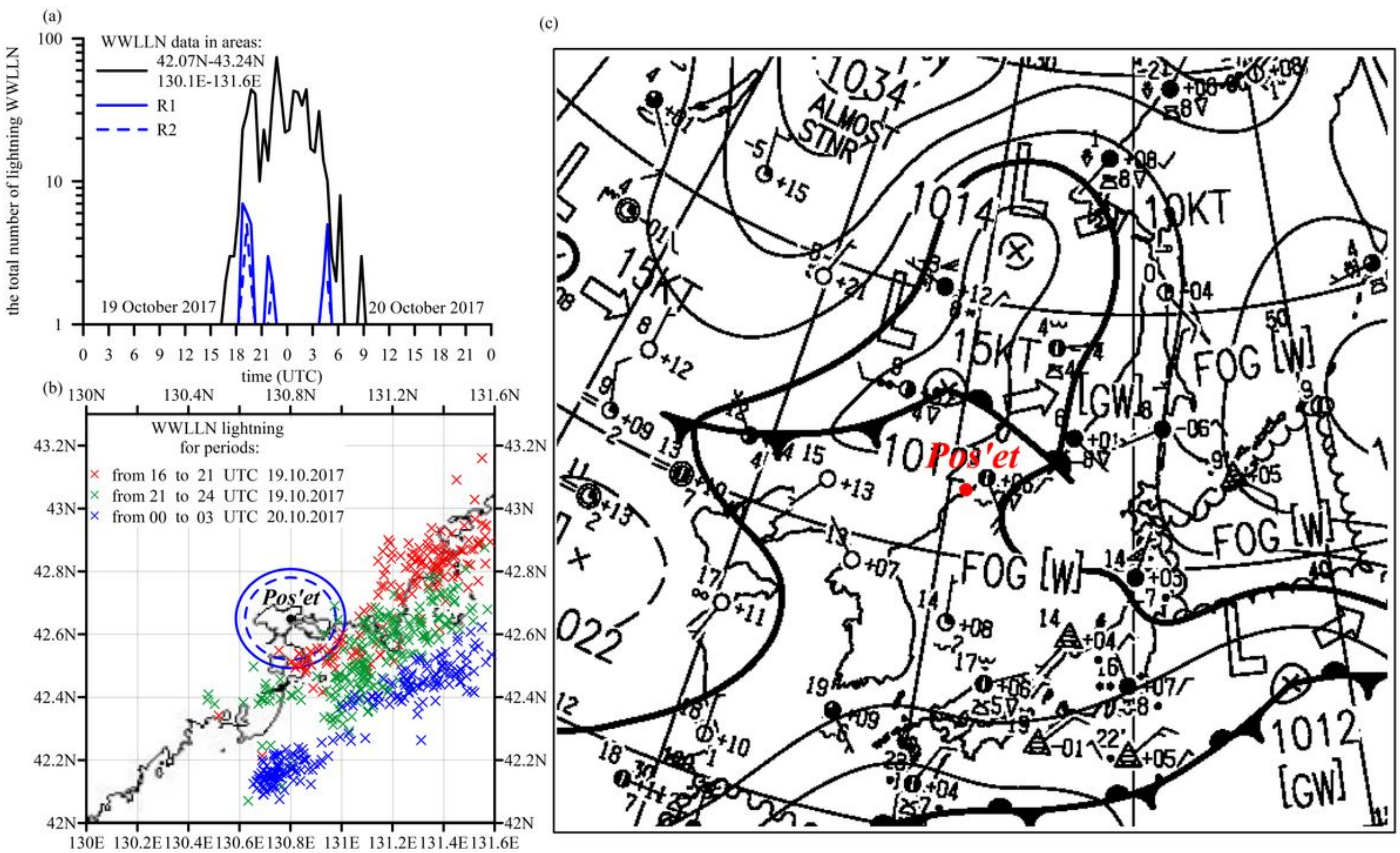

Figure 3

Thunderstorm activity near the *Pos'et* weather station on 19–20 October 2017. (a) Variation of the total number of WWLLN lightnings in the weather station vicinity; (b) Spatial distribution of WWLLN lightnings in the weather station vicinity; (c) Part of the JMA surface weather map for 20 October 2017 (12:00 UTC).

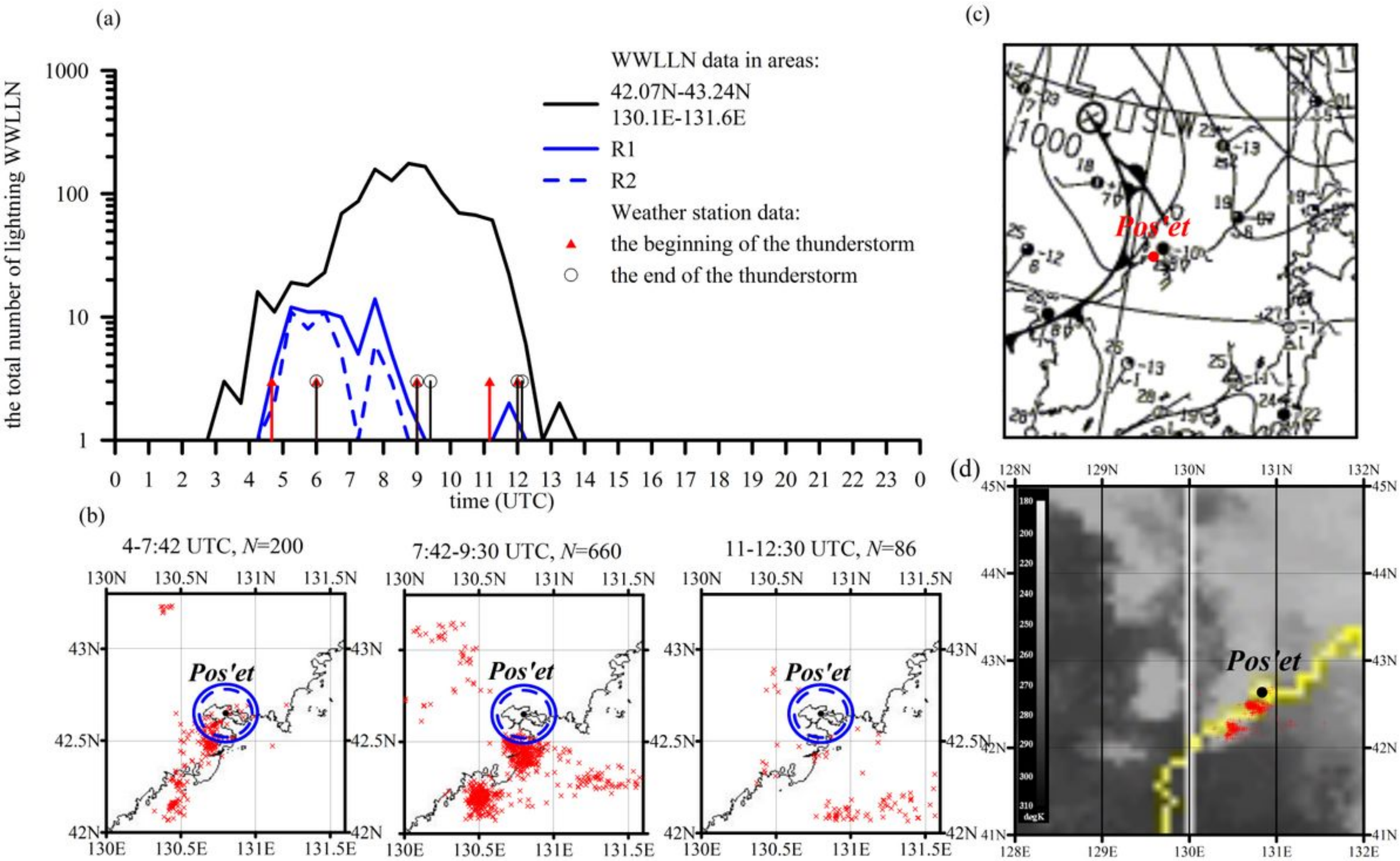

Figure 4

Thunderstorm activity near the *Pos'et* weather station on 8 September 2014. (a) Variation of the total number of WWLLN lightnings in the weather station vicinity; (b) Spatial distribution of WWLLN lightnings in the weather station vicinity; (c) The part of the JMA surface weather map for 8 September 2014 (06:00 UTC); (d) The part of the MSAT IR imagery at 07:32 UTC on 8 September (the yellow line is the coastlines).