Estimation of heat, water, and black carbon fluxes during the fire induced by the Hiroshima A-bomb in 1945

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Abstract

The amount of flammable materials in traditional Japanese houses in the Hiroshima region in the 1940s is estimated to calculate heat, water and carbon fluxes during the induced urban fire by the Hiroshima A-bomb in 1945. Traditional houses remaining in the Fukuyama region were examined to estimate the total amount of flammable resources in each house classified into three categories based on number of stories and size of the houses. The density of wood was estimated to be 112 kg m^{-2} for one-story houses while it was 72 kg m^{-2} for two-story houses (Okada and Aoyama, 2011). Then, the amount of flammable materials in traditional Japanese houses in each 50-m grid was estimated based on a digital map of the entire city of Hiroshima just before the atomic bombing and a detailed damage distribution map which were both created from the aerial photographs (Koizumi et al., 2011) and . The amount of flammable materials was converted to heat, water, and black carbon fluxes based on the duration of the fire induced by the A-bomb as a function of time and space. The average heat flux in the region was 14.4 kJ s^{-1} m^{-2}, and it ranged from 0.5 to 96.5 kJ s^{-1} m^{-2}. The average heat flux obtained in this study is about half of a value used in previous study (Yoshikawa, 1999) and is 7 times larger than that in Shouno, 1953. The total heat released during the fire was 7 PJ. In total, 0.22 Tg of water was produced and released during the fire. The total amount of black carbon produced and released during the fire was 0.02 Tg, when we assume that 10% of the fuel was under reducing conditions. To confirm this assumption for under reducting conditions, we prepared dummy black rain sample of which black carbon concentration ranged from 1 % to 70 % and asked witnesses of black rain to choose one of the samples as most similar one with black rain they observed in 1945. 37 replies were obtained and the 34 of 37 replies concentrated with a range from 5 % to 15 %. The time-dependent fluxes of heat, water, and carbon were also calculated.

1. Introduction

To simulate the clouds and precipitation due to the Hiroshima A-bomb, it is necessary to estimate the heat, water, carbon dioxide, and black carbon fluxes during the fire induced by the bomb as a function of time and space. It already passed two decades from the first numerical model simulation of fallout of the Hiroshima A-bomb in 1990, it might possible to conduct improved numerical model simulations using latest chemical transport models and high performance super computers. If so, heat flux and water flux during the induced urban fire by the Hiroshima A-bomb are important to simulate the clouds and precipitation due to the Hiroshima A-bomb.Therefore, the amount of flammable materials in traditional Japanese houses in the Hiroshima region in the 1940s is estimated to calculate heat, water and carbon fluxes during the induced urban fire by the Hiroshima A-bomb in 1945.

2. Method

The amount of flammable materials in traditional Japanese houses in the Hiroshima region in the 1940s is estimated to calculate heat, water and carbon fluxes during the induced urban fire by the Hiroshima A-bomb in 1945. Traditional houses remaining in the Fukuyama region were examined to estimate the total amount of flammable resources in each house classified into three categories based on number of stories and size of the houses. The density of wood was estimated to be 112 kg m^{-2} for one-story houses while it was 72 kg m^{-2} for two-story houses (Okada and Aoyama, 2011). Then, the amount of flammable materials in traditional Japanese houses in each 50-m grid was estimated based on a digital map of the entire city of Hiroshima just before the atomic bombing and a detailed damage distribution map which were both created from the aerial photographs (Koizumi et al., 2011) and . The amount of flammable materials was converted to heat, water, and black carbon fluxes based on the duration of the fire induced by the A-bomb as a function of time and space. The details of this estimation are described in Aoyama et al., 2011.

3. Results and discussion

3.1 Heat flux

In Figures 1 and 2, distributions of average heat flux (MJ s^{-1} m^{-2}) in each 50-m grid within the 4 km × 4 km and 8 km × 8 km are shown, respectively. A part of the destroyed area located southwest of the hypocenter could not be analyzed because clouds covered the area when the aerial photographs were taken. Although the average heat flux in the region was 14.4 kJ s^{-1} m^{-2}, it ranged from 0.5 to 96.5 kJ s^{-1} m^{-2} as shown in the Figures 1 and 2. When we look at within 1 km × 1 km region from the hypocenter, the averaged heat flux at north-west region is relatively high rather than those in north-east, shouth-west and south-east regions.

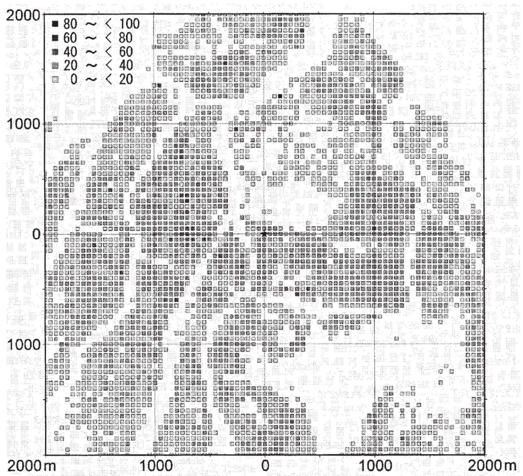

Figure 1 Distribution of average heat flux in each 50 m grid within 4 km × 4km area of hypocenter of the A-bomb as a same area as shown in figure 1. A star marked at a location (0 m, 0 m) is the hypocenter of A-bomb. Unit: MJ s^{-1} m^{-2} (Figure 4 in Aoyama et al., 2011)

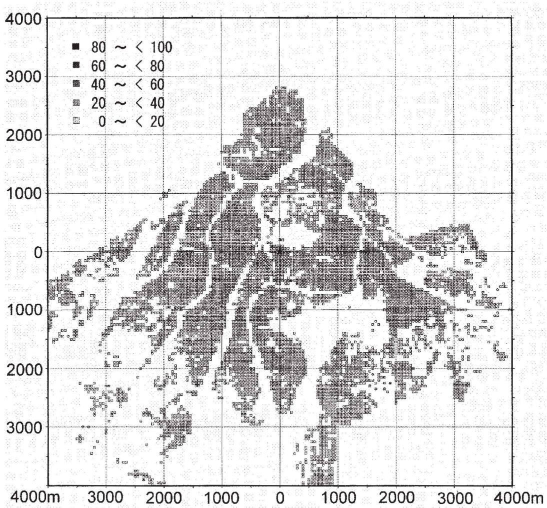

Figure 2 Distribution of average heat flux in each 50 m grid within 8 km x 8 km area of hypocenter of the A-bomb. A star marked at a location (0 m, 0 m) is the hypocenter of A-bomb. Unit: MJ s^{-1} m^{-2} (Figure 5 in Aoyama et al., 2011)

We estimated the total mass of flammable materials to be 0.39×10^9 kg, such that the total heat released during the fire induced by the A-bomb was estimated to be 7.02×10^{15} J (see Table 1 for representative values from nine grids). A part of the destroyed area located southwest of the hypocenter could not be analyzed because clouds covered the area when the aerial photographs were taken. Therefore, our estimation of total mass of flammable materials and some resulting values might be underestimated by a few percent. In the database, the average value of the mass of flammable materials in a 50-m grid will be inserted for the area lacking data.

Table 1. Examples of the total area of houses, coverage, total mass of flammable materials, total heat produced, heat produced per unit area, and average heat flux for nine 50-m grids around the hypocenter of the A-bomb.

Distance	Direction	Area	Coverage	Total mass of flammable materials	Total heat produced	Heat produced per unit area	Average heat flux
(m)	(degree)	(m^2)	(%)	(10^3 kg)	(TJ)	(MJ m^{-2})	(MJ s^{-1} m^{-2})
0	0	553	22	70	1.24	498	0.017
50	0	928	37	104	1.86	744	0.026
50	90	763	31	85	1.53	612	0.021
50	180	1192	48	96	1.72	688	0.024
50	270	601	24	47	0.84	335	0.012
71	45	988	40	82	1.47	587	0.020
71	135	1276	51	95	1.70	681	0.024
71	225	1029	41	120	2.15	858	0.030
71	315	1195	48	137	2.45	981	0.034

(Table 3 in Aoyama et al., 2011)

For the time-dependent heat flux, we assumed that the progress of combustion of houses follows a scenario as described by DiNenno et al. (1995b). In general, compartment fires are discussed in terms of the following stages: ignition, growth, flashover, fully developed fire, and decay. Because no fire control measures were undertaken due to the total destruction of fire control systems in Hiroshima after the A-bomb, we assumed the fire followed this scenario. We assumed that the growth period was about 3 h, based on the analysis by Kawano et al. (2011), which shows good agreement with DiNenno et al. (1995b), when we consider a larger opening factor. A scenario of the rate of heat release is shown in Figure 3.

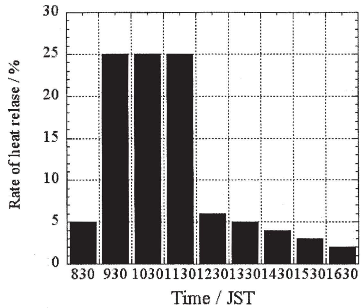

Figure 3 A scenario of a rate of heat release for the urban fire of which duration is 8 hours just after A-bomb explosion. (Figure 6 in Aoyama et al., 2011)

Therefore using total mass of flammable materials in each grid and the times that the fire began and ended in each grid, the time-dependent heat flux can be calculated, as shown in Table 2.

Table 2. Examples of time-dependent heat flux for nine 50-m grids around the hypocenter of the A-bomb. The bomb was dropped at 08:15 h.

Distance (m)	0	50	50	50	50	71	71	71	71
Direction (degree)	0	0	90	180	270	45	135	225	315
Time of day	Time-dependent heat flux (MJ s^{-1} m^{-2})								
08:30	0.028	0.041	0.034	0.038	0.019	0.033	0.038	0.048	0.054
09:30	0.035	0.052	0.043	0.048	0.023	0.041	0.047	0.060	0.068
10:30	0.035	0.052	0.043	0.048	0.023	0.041	0.047	0.060	0.068
11:30	0.035	0.052	0.043	0.048	0.023	0.041	0.047	0.060	0.068
12:30	0.008	0.012	0.010	0.011	0.006	0.010	0.011	0.014	0.016
13:30	0.007	0.010	0.009	0.010	0.005	0.008	0.009	0.012	0.014
14:30	0.006	0.008	0.007	0.008	0.004	0.007	0.008	0.010	0.011
15:30	0.004	0.006	0.005	0.006	0.003	0.005	0.006	0.007	0.008
16:30	0.003	0.004	0.003	0.004	0.002	0.003	0.004	0.005	0.005
Average	0.017	0.026	0.021	0.024	0.012	0.020	0.024	0.030	0.034

(Table 4 in Aoyama et al., 2011)

The heat produced by the fire would have been proportional to the oxygen condition, which is unknown. Given our assumption that 10% of the fuel was under reducing conditions, the total produced heat of 7.02×10^{15} J is decreased to 6.32×10^{15} J.

3.2 Water flux

An estimate of the water flux from the fire induced by the A-bomb was calculated based on the total mass of flammable materials in each grid and the production constant of water . The distribution of averaged water flux for the region is shown in Figure 4.

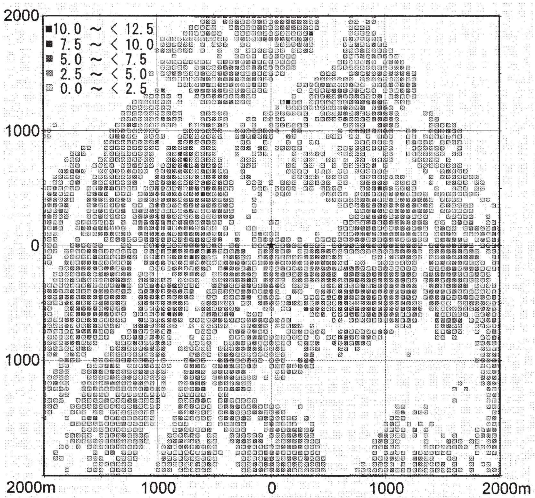

Figure 4 Distribution of average water flux in each 50 m grid within 4km × 4km area of hypocenter of the A-bomb. A star marked at a location (0 m, 0 m) is the hypocenter of A-bomb. Unit: mm h^{-1} m^{-2}(Figure 7 in Aoyama et al., 2011)

3.3 Black carbon flux

The estimated carbon flux from the fire induced by the A-bomb was calculated based on the total mass of flammable materials in each grid and the production constant of black carbon. As discussed above, heat and water are produced in proportion to the amount of flammable materials, whereas the amount of carbon produced depends upon the oxygen condition during the fire, which is unknown. We assumed that 10% of flammable materials was under reducing conditions; thus, the total amount of black carbon produced and released during the fire was estimated to be 0.02 Tg.

To confirm this assumption for under reducting conditions, we prepared dummy black rain sample of which black carbon concentration ranged from 1 % to 70 % and asked witnesses of black rain to choose one of the samples as most similar one with black rain they observed in August 1945. 37 replies were obtained and the 34 of 37 replies concentrated with a range from 5 % to 15 %.Therefore we concluded that about 10 % would be appropriate as under reducting condition for heat, water, black carbon flux estimation.

4. Conclusion

The average heat flux in the region was 14.4 kJ s^{-1} m^{-2} and it ranged from 0.5 to 96.5 kJ s^{-1} m^{-2}.

The total heat released during the fire was 7 PJ. The average heat flux obtained in this study is about half of a value used in previous study (Yoshikawa, 1999) and the total heat flux is 7 times larger than that in Shouno, 1953. In total, 0.22 Tg of water was produced and released during the fire. The total amount of black carbon produced and released during the fire was 0.02 Tg, when we assume that 10% of the fuel was under reducing conditions.

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References

1. Aoyama, M., N. Kawano, T. Koizumi , T. Okada, Y. Okada, M. Ohtaki, T. Tanikawa. 2011. Estimation of heat, water, and black carbon fluxes during the fire induced by the Hiroshima A-bomb, 47-58. In: M. Aoyama and Y. Oochi (Eds.), Revisit the Hiroshima A-bomb with a Database: Latest Scientific View on Local Fallout and Black Rain, Hiroshima City, Hiroshima.
2. DiNenno, Philip J., Craig L. Beyler, Richard L. P. Custer, W. Douglas Walton, John M. Watts, Dougal Drysdale, John R. Hall (Eds.). 1995. Table 3-6.11: Examples of gas temperature-time curves of post-flashover compartment fires for different values of the fire load density and the opening factor, 3-144. In: SFPE Handbook of Fire Protection Engineering, 2nd ed. The National Fire Protection Association, Quincy, Massachusetts.
3. Hiroshima City . 1971. Hiroshima Genbaku Sen Vol. 21 (Hiroshima Atomic Bomb Damages). (in Japanese)
4. Kawano, N., M. Ohtaki, T. Okada. 2011. Visualized map of a fire field near epicenter of Hiroshima A-bomb in August 6, 1945, 19-28. In: M. Aoyama and Y. Oochi (Eds.), Revisit the Hiroshima A-bomb with a Database: Latest Scientific View on Local Fallout and Black Rain, Hiroshima City, Hiroshima.
5. Koizumi, T. 2011. Digital mapping of urban area of Hiroshima City just before and after the atomic bombing, 29-40. In: M. Aoyama and Y. Oochi (Eds.), Revisit the Hiroshima A-bomb with a Database: Latest Scientific View on Local Fallout and Black Rain, Hiroshima City, Hiroshima.
6. Okada, Y., M. Aoyama. 2011. Resources of heat, water and carbon fluxes for an induced urban fire in 1945 Hiroshima based on field research of Japanese traditional houses, 41-46. In: M. Aoyama and Y. Oochi (Eds.), Revisit the Hiroshima A-bomb with a Database: Latest Scientific View on Local Fallout and Black Rain, Hiroshima City, Hiroshima.
7. Petterson, R.C., 1984. The chemical composition of wood, 7-126. In: Wowell, R. M. (Ed) "The Chemistry of SolidWood". Advances in Chemistry Series 207. American chemical society. Washington, D.C.