Chapter 3 Appendix 1

ESTIMATION OF HUMIDITY AT VARIOUS ALTITUDES ON THE DAYS OF EXPLOSION IN HIROSHIMA AND NAGASAKI

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The moisture content of the air is an extremely important parameter in the dose calculation of the atomic bombs in Hiroshima and Nagasaki. The leakage neutrons from the bombs collided with the atomic nucleus of air compositions to produce secondary gamma rays by neutron capture processes. In the present reevaluation of the A-bomb dose, the Oak Ridge National Laboratory (ORNL) group[1] has used atmospheric conditions in several layers of air from ground zero to the burst point in Hiroshima and Nagasaki. Also, the Lawrence Livermore National Laboratory (LLNL) group has calculated the A-bomb doses assuming the atmospheric condition at any altitude to be same as the surface condition. The purpose of the present study is to estimate the water vapour content from ground zero to the altitude of the burst point in Hiroshima and Nagasaki at the time of the explosions.

General Weather Conditions

On 6 and 9 August 1945 when the A-bombs were detonated over Hiroshima and Nagasaki,

It should be noted that this report was revised and the values in the tables were recalculated.

an anticyclone covered almost the whole of Japan and in general the weather was fine with light wind and good visibility. Tables 1 and 2 give the surface weather conditions in Hiroshima and Nagasaki,[2] respectively, on the day of the explosion. According to these tables, in Hiroshima, it remained clear from midnight of the 5th and became slightly cloudy from around 0600 hours. It was almost calm until 0805 hours of the 6th, when the sea breeze set in to replaced a land breeze.

In Nagasaki, in view of the time-course percent of possible sunshine, it seems to have been relatively cloudy, but the clouds decreased by 1103 hours when the bomb was detonated.

Table 1. Surface Weather Conditions in Hiroshima, 6 August 1945

Time (hr)	Air Pressure (mb)	Air Temperature (°C)	Relative Humidity (%)	Wind Velocity ($m\ s^{-1}$)	Cloud Amount (tenth)
01	1016.0	25.0	88	NNE 2.0	0
02	1016.1	24.7	90	NNE 2.0	0
03	1016.1	24.2	92	NNE 1.5	2
04	1016.7	23.9	93	NNE 2.5	2
05	1016.9	23.7	93	NNE 2.3	4
06	1017.5	23.6	94	NNE 2.3	8
07	1018.0	24.7	89	NNE 1.3	8
08	1018.1	26.7	80	N 0.8	10
09	1018.0	27.3	79	SW 1.7	9
10	1018.5	29.3	67	SW 2.5	7
11	1017.7	30.0	65	W 2.8	5
12	1016.7	30.7	64	SSW 3.3	6
13	1016.1	30.7	64	SW 3.7	8
14	1015.9	31.0	66	SW 3.2	6
15	1015.3	30.3	70	SW 3.8	7
16	1015.2	30.7	65	SW 4.0	5
17	1015.1	29.7	72	SW 5.5	4
18	1015.5	28.3	78	SW 5.2	4
19	1016.1	28.2	77	SSW 3.0	9
20	1016.4	27.5	83	SSE 5.2	9
21	1017.3	26.9	79	S 3.7	10
22	1017.2	26.7	78	S 2.3	9
23	1017.3	26.6	78	SW 1.5	10
24	1016.9	26.5	75	WSW 2.5	10

Cloud amount is the proportion of the sky covered by clouds, and is expressed in tenths of the entire dome of the sky.

Selection of the Days Equivalent to those of the Explosions

In spite of the necessity to analyze the meteorological conditions in the upper air of Western Japan for the days of the A-bomb detonations, there are no aerological data of the upper atmosphere for these days. But there are valuable aerological data of the upper atmosphere which were recorded routinely five times a day at Koenji in Tokyo by the former Japanese Army Meteorology Division. On the basis of these data, Kerr et al[1] estimated the humidity in Hiroshima and Nagasaki at the altitude of the detonation. The humidity in question, evaluated by altitude from different data, is reported here. Aerological observation was resumed at various locations in Japan after the end of the war. The days in summer

Table 2. Surface Weather Conditions in Nagasaki, 9 August 1945

Time (hr)	Air Pressure (mb)	Air Temperature (°C)	Relative Humidity (%)	Wind Velocity (m s⁻¹)		Possible Sunshine (%)
01	1015.0	24.0	88		0.0	
02	1015.0	24.7	90		0.0	
03	1014.8	23.5	91	ESE	0.7	
04	1014.7	23.2	90	E	3.2	
05	1014.6	23.2	87		0.0	
06	1015.0	23.1	90		0.0	0.00
07	1015.0	24.3	94	ESE	2.2	1.00
08	1015.0	25.7	91	ESE	1.2	1.00
09	1015.3	27.3	76	ESE	1.8	1.00
10	1015.3	28.0	76		0.3	0.70
11	1014.0	28.8	71	SW	3.0	0.69
12	1013.9	29.4	68	SW	3.7	1.00
13	1013.6	29.9	58	SW	4.2	
14	1013.3	29.9	65	SW	4.3	
15	1013.0	29.9	63	SW	5.0	
16	1012.7	29.3	66	WSW	6.0	
17	1012.7	28.5	68	SW	3.3	
18	1012.8	27.2	73	SW	6.2	
19	1012.7	26.4	80	SW	7.2	
20	1013.0	25.7	84	WSW	2.0	
21	1013.2	25.2	88	WSW	5.0	
22	1013.5	24.9	91	SW	1.5	
23	1013.0	24.7	91	SSW	0.8	
24	1013.1	24.6	91	SSW	0.8	

Possible sunshine is observed by means of the Jordan sunshine recorder, and is total hours of sunshine given in percent of possible total hours of sunshine.

were selected when the weather conditions were analogous to those of the days of the detonations from the available aerological data of the upper atmosphere. The estimation was based on the assumption that the weather factors of the selected days approximated those of the days of the explosions. It is desirable for validity of this assumption that the weather conditions be stable. Fortunately, on the days of the explosions, Japan was covered with the summer monsoon pattern, high in the south and low in the north. This situation had continued for more than one week. Under such atmospheric conditions, Japan is widely covered homogeneously with a hot and humid maritime air mass. It is the so-called tropical maritime air mass and it controls the weather in summer in Japan. Thus, the analogous days could be selected in the summer season from the previously observed surface weather maps which showed the summer monsoon pattern indicative of Japan being covered by a tropical maritime air mass.

The analogous days thus selected were 4 to 9 August 1960, 6 to 11 August 1973, and 1 to 6 August 1975.[3] Here the water vapour content is estimated using the aerological data in the upper atmosphere in Western Japan for these selected days together with the surface weather data in Hiroshima and Nagasaki at the explosion days.

Equivalency of the Selected Days

In this section, the equivalency of the selected days to the explosion days is examined

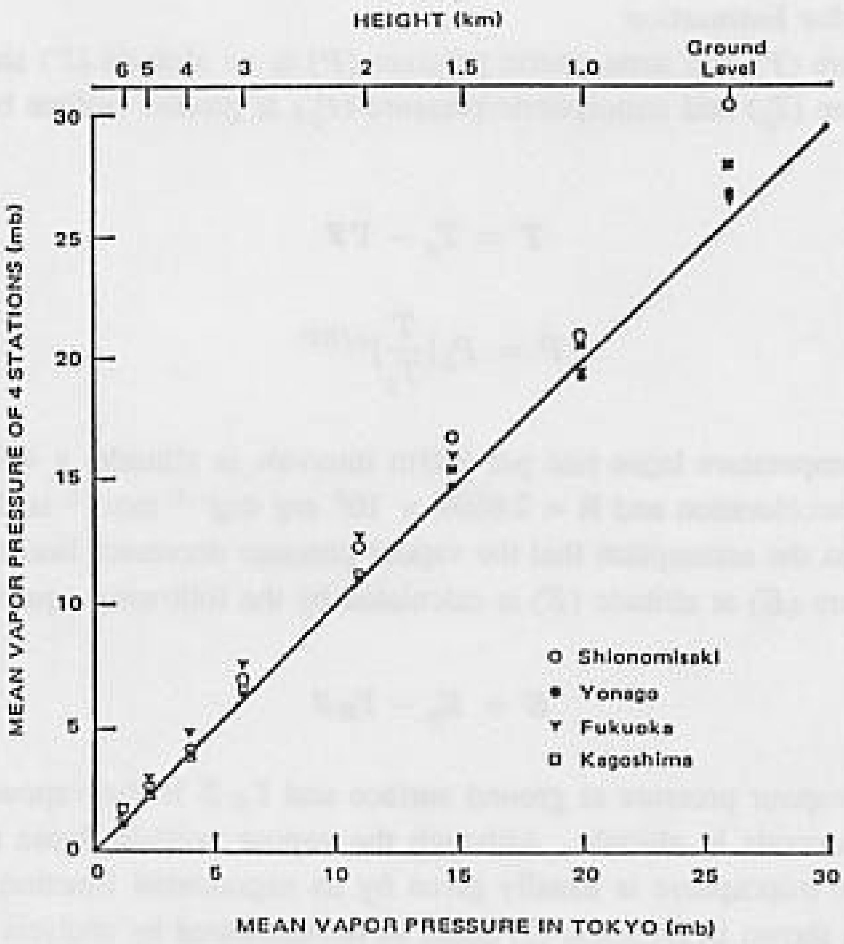

Figure 1. Comparison of mean vapour pressure

in the sense of weather conditions in the upper atmosphere. Vapour pressure was used as a factor characteristic of the air mass. Since there are no aerological data of the upper atmosphere of Western Japan for the explosion days, they were represented by the data observed in Tokyo. The aerological data compared with the Tokyo data were the vapour pressure at four stations in Western Japan (Shionomisaki, Yonago, Fukuoka, and Kagoshima) where the observations of the upper atmosphere have been made since the end of the war. Figure 1 shows comparison of the average vapour pressure measured at these stations. The abscissa of the figure indicates the average vapour pressure in Tokyo. This is the average of the five daily mean vapour pressures, calculated from the temperature and humidity observed on 6 and 9 August. The ordinate indicates the vapour pressure averaged over the selected days at the four stations in Western Japan. The vapour pressure was calculated from the temperature and humidity observed at 0900 hours. The figure shows that the equivalency of the mean vapour pressure are well established between Tokyo on the explosion days and four stations, particularly Yonago. The standard deviation of vapour pressure in Yonago against Tokyo is 0.46 mb. The other stations also show a good correlation at a altitude of 1500 m and over. The average standard deviation for the four stations is 0.58 mb.

The weather conditions (air mass) in the upper air on the days selected are considered to be closely equivalent to those of the explosion days. These selected days are referred to as "equivalent days".

Equations Used for Estimation

Air temperature (T) and atmospheric pressure (P) at an altitude (Z) are calculated using air temperature (T_0) and atmospheric pressure (P_0) at ground surface by the following equations:

$$T = T_0 - \Gamma Z \qquad (1)$$

$$P = P_0 \left(\frac{T}{T_0}\right)^{g/R\Gamma} \qquad (2)$$

where Γ is the temperature lapse rate per 100 m intervals in altitude, g = 980 cm sec^{-2} is the gravitational acceleration and R = 2.8699×10^6 erg deg^{-1} mol^{-1} is the universal gas constant. Then, on the assumption that the vapour pressure decreases linearly with altitude, the vapour pressure (E) at altitude (Z) is calculated by the following equation:

$$E = E_0 - \Gamma_E Z \qquad (3)$$

where E_0 is the vapour pressure at ground surface and $\Gamma_E Z$ is the vapour pressure lapse rate per 100 m intervals in altitude. Although the vapour pressure lapse rate in standard atmosphere in the troposphere is usually given by an exponential function of altitude, the linear function as shown in Equation (3) could be demonstrated by analysis of the data as a good approximation for the present case. Figure 2 shows variation of vapour pressure profile

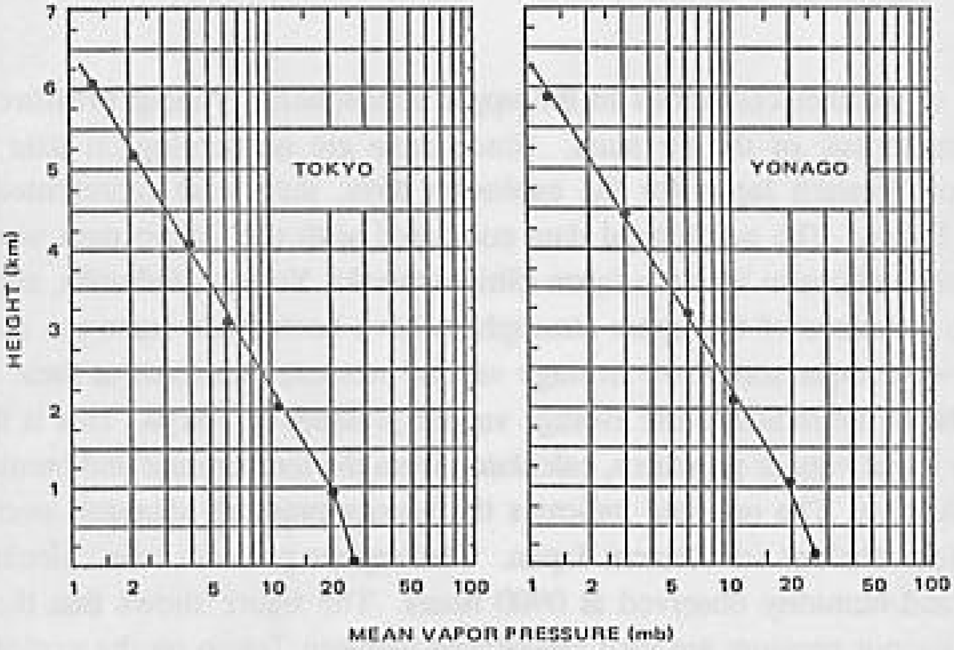

Figure 2. Variation of vapour pressure profiles of Tokyo and Yonago at the time of explosion

of Tokyo at the explosion time and that of Yonago on the equivalent days on a semilog diagram. The mean vapour pressure of Tokyo was calculated as shown previously and Yonago was selected as a representative location in Western Japan on account of its proximity to Hiroshima. As shown in Figure 2, vertical distribution of vapour pressure in the upper atmosphere gives exponential functions which differ from those in the lower atmosphere, with the point of inflection being at 1000 m for both Tokyo and Yonago. Detailed study of the lower atmosphere indicated that the distributions were linear against altitude rather than exponential. Therefore, the linear form as shown by Equation (3) was used for the present study.

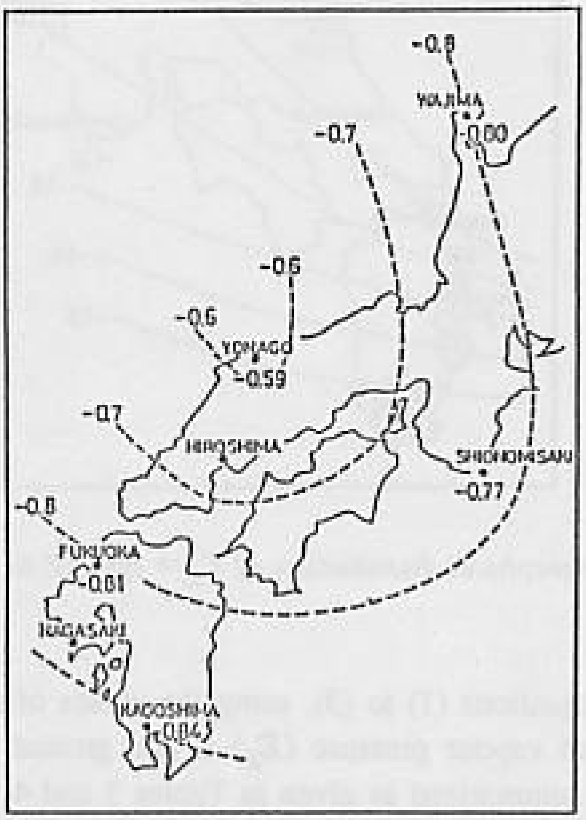

Figure 3. Geographical distribution of $\Gamma = \Delta T/\Delta Z$ in °C per 100 m

Determination of Γ and Γ_E

In order to obtain air temperature and vapour pressure at an altitude (Z), the temperature lapse rate (Γ) and vapour pressure lapse rate (Γ_E) in Equations (1) and (3) must be determined. The temperature lapse rates were calculated for all equivalent days, and the mean lapse rate for each location was plotted on the map to show the geographical distribution as shown in Figure 3. The temperature lapse rates of Hiroshima and Nagasaki were read from this distribution giving Γ = 0.67°C/100 m for Hiroshima and Γ = 0.83°C/100 m for Nagasaki. Figure 4 shows the geographical distribution of the mean vapour presure lapse rate calculated in a manner similar to that of temperature lapse rate. Thus, the vapour pressure lapse rates for Hiroshima and Nagasaki as obtained from Figure 4 are Γ_E = 0.80 mb/100 m and 1.20 mb/100 m, respectively.

Estimation of the Atmospheric Pressure and Water Vapour Content

The atmospheric pressure (P) and water vapour content at 100 m intervals from the ground surface to the altitude of the burst point are estimated by substituting the obtained

Figure 4. Geographical distribution of $\Gamma_E = \Delta E/\Delta Z$ in mb per 100 m

values of Γ and Γ_E in Equations (1) to (3), using the values of atmospheric pressure (P_0), air temperature (T_0), and vapour pressure (E_0) at the ground surface of Hiroshima and Nagasaki. These can be summarized as given in Tables 3 and 4.

The dry air density ρ_d (kg m^{-3}) in Tables 3 and 4 was calculated by the following formula:

$$\rho_d = \frac{P_d}{RT_a} \tag{4}$$

where P_d, T_a, and R_d are atmospheric pressure of dry air, absolute temperature and the universal gas constant, respectively. The moist air density ρ_m (kg m^{-3}) was calculated by the following equation:

$$\rho_m = \frac{P}{RT_a}(1 - 0.378\frac{E}{P}) \tag{5}$$

where P is total pressure and E is vapour pressure.

Discussion

As given in Tables 3 and 4, the air pressure and water vapour content at the time of explosions in Hiroshima and Nagasaki were estimated as a function of height to the burst points based on the weather conditions of the equivalent days. In order to check the reliability of these estimates, another calculation was made using measured values on 9 August 1945

Table 3. Estimated Value of Air Pressure and Water Vapour Content as a Function of Altitude, Hiroshima

Altitude (m)	Air Pressure (mb)	Relative Humidity (%)	Absolute Humidity ($g\ m^{-3}$)	Moist Air Density ($kg\ m^{-3}$)	Dry Air Density ($kg\ m^{-3}$)
30.3	1018.1	80	20.3	1.171	1.150
100	1006.4	80	19.8	1.161	1.141
200	995.8	81	19.2	1.151	1.132
300	983.9	82	18.7	1.141	1.122
400	972.2	83	18.1	1.130	1.111
500	962.2	83	17.5	1.120	1.103
580	952.4	84	17.2	1.112	1.094

Table 4. Estimated Values of Air Pressure and Water Vapour Content as a Function of Altitude, Nagasaki

Altitude (m)	Air Pressure (mb)	Relative Humidity (%)	Absolute Humidity ($g\ m^{-3}$)	Moist Air Density ($kg\ m^{-3}$)	Dry Air Density ($kg\ m^{-3}$)
26.7	1014.0	71	20.2	1.160	1.139
100	1003.0	71	19.4	1.151	1.131
200	990.7	72	18.6	1.140	1.122
300	979.9	72	17.8	1.131	1.113
400	959.2	71	16.9	1.122	1.105
503	957.2	71	16.1	1.112	1.096

Table 5. Surface Weather Conditions at Onsendake, 9 August 1945

Time (hr)	Air Pressure (mb)	Air Temperature (°C)	Relative Humidity (%)	Wind Velocity ($m\ s^{-1}$)	Possible Sunshine (%)
10	921.9	22.8	88	– 0.3	1.00
11	921.8	23.0	87	NNW 1.5	0.20
12	921.4	25.3	77	NW 2.0	1.00
13	921.4	26.5	74	NW 3.0	1.00
14	920.7	26.6	73	NW 3.0	0.20
15	920.6	27.9	71	NW 3.0	–
16	920.6	23.6	68	NW 2.0	–
17	920.2	22.5	81	NW 1.8	–
18	920.2	21.8	80	NW 2.5	–
19	920.4	21.3	80	NW 3.3	–
20	920.6	20.8	86	NNW 0.8	–
21	920.8	21.0	84	0.5	–
22	921.0	21.1	85	– 0.2	–
23	921.1	20.8	90	NNW 1.0	–
24	919.8	20.5	92	NNW 1.0	–

Possible sunshine is observed by means of the Jordan sunshine recorder, and is total hours of sunshine given in percent of possible total hours of sunshine.

at Onsendake Meteorological Station (presently Unzendake Meteorological Station) that is located approximately 40 km west of Nagasaki city at an altitude of 853 m from sea level.

Table 5 gives the measured values of surface weather conditions at Onsendake. The lapse rates of temperature and vapour pressure at Nagasaki city were estimated from these values assuming that the differences of temperature and vapour pressure between Onsendake and Nagasaki are due to the difference in altitude from the sea level. The resultant lapse rates are given as follows:

$$\Gamma_E = 0.70\,\text{mb}/100\,\text{m} \text{ and } \Gamma = 0.58°C/100\,\text{m}$$

The relative humidity and absolute humidity were calculated as shown in Table 6 using these lapse rates. Comparison of Tables 4 and 6 shows that there is good agreement of relative

Table 6. Estimated Values of Air Pressure and Humidity as a Function of Altitude, Nagasaki

Altitude (m)	Air Pressure (mb)	Relative Humidity (%)	Absolute Humidity (g m^{-3})
26.7	1014.0	71	20.2
100	1002.2	72	19.7
200	990.5	72	19.3
300	980.8	73	18.8
400	968.0	73	18.3
503	958.0	74	17.9

Table 7. Comparison of Air Density and Water Vapour Content in Hiroshima and Nagasaki between Present Data and Data of Kerr et al[1]

	Hiroshima			Nagasaki		
	Present Data	Kerr et al	Δ (%)	Present Data	Kerr et al	Δ (%)
Relative Humidity (%)						
Ground level	80	80	–	71	71	–
Burst height	84	75	10.7	71	67	5.6
Moist air density (kg m^{-3})						
Ground level	1.171	1.170	0.1	1.160	1.158	0.2
Burst height	1.112	1.110	0.1	1.112	1.106	0.5
Dry air density (kg m^{-3})						
Ground level	1.151	1.150	0.1	1.139	1.137	0.2
Burst height	1.094	1.094	0.0	1.096	1.090	0.5
Absolute humidity (kg m^{-3})						
Ground level	0.0203	0.02025	–	0.0202	0.02018	–
Burst height	0.01720	0.01564	9.0	0.01610	0.01613	0.0
Mean density (kg m^{-3})						
Moist air	1.141	1.140	0.1	1.136	1.132	0.4
Dry air	1.122	1.122	0.0	1.118	1.114	0.4
Water vapour	0.01869	0.01785	4.0	0.01817	0.01808	0.5

and absolute humidity between the two calculations at altitudes lower than 300 m, but at higher altitudes, the calculated values using the measured weather factors are higher by 2 to 3% for relative humidity and 1 to 2 g for absolute humidity. However, considering the errors inherent in the original data, the values of the two tables can be considered to be in a good agreement.

The present values are compared with the values of Kerr et al[1] as given in Table 7. Both estimations seem to be in good agreement.

References

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