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DEVELOPMENT OF TYPICAL YEAR WEATHER DATA FOR CHINESE LOCATIONS

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ABSTRACT

Since their development starting in the late 1970's, computer simulations have become accepted as the most detailed way to calculate the dynamic behavior and energy use of a building over an entire year. Their use in a large developing country such as China, however, has been hampered by the absence of detailed hourly weather data. For computer simulations, the weather data must have hourly records of at least temperature, humidity, wind speed, and both direct and total solar radiation. Furthermore, to avoid the random variations in weather from year to year, the weather data should be for a hypothetical typical year, rather than an actual year of record.

In support of the development of residential building energy standards for the Hot Summer Cold Winter region in central China, the authors have recently developed Typical Meteorological Year (TMY) weather data for 28 Chinese locations that will eventually be expanded to 69. These TMY weather data have been produced from 16 years of historical weather (1982-1997) reported by Chinese airports and obtained from the U.S. Climatic Data Center (NCDC). Since the weather data records only cloud conditions at various heights, a substantial effort was made towards estimating the total and direct solar radiation from the cloud information, combined with information on temperature, humidity, and wind speed. Comparisons of the estimated solar to measured hourly solar radiation for two locations resulted in an R^2 of 0.87, while comparisons of annual global and diffuse solar radiation for 9 locations showed standard deviations of 5% and 12%, respectively.

The creation of the artificial TMY uses a similar methodology to that used for the United States TMY data, with a four-step process to select the most representative month from the 16 available historical months. The 12 representative months were then combined to form the Typical Meteorological Year for each city. These Chinese TMY weather files will be made public on a CD as part of a technical document to be published in Japan in 2002.

INTRODUCTION

Weather is one of the primary determinants of indoor thermal conditions and space conditioning energy use. In particular, dynamic simulations using modern computer programs such as DOE-2 or HASP (Winkelmann et al. 1993, Inooka et al. 1985) require hourly data of weather conditions such as solar radiation, dry-bulb temperature, dew-point temperature or humidity, atmospheric pressure, wind direction, and wind speed. Since weather conditions can vary significantly from year to year, researchers in many countries have devised Typical Meteorological Year (TMY) data to represent long-term typical weather conditions over a year (Matsuo et al. 1974, Akasaka et al. 1999, NCDC 1981, Clarke 1985, Marion and Urban 1995). Although their development may differ in detail, such weather data share the same principle whereby twelve months judged to have weather conditions most representative of that month are combined into a single synthetic "typical year" weather file.

So far, there have been very few reports of TMY weather data developed for Chinese locations. There are three major barriers in the development of such weather data: (1) although the Chinese weather service has recorded weather data for all major cities for several decades, the data are not in a digital format, making their transcription and purchase prohibitively expensive, (2) with the exception of very few stations such as Beijing, the data are not recorded hourly, but rather at six hour intervals, plus the daily maximum and minimum dry-bulb temperatures, and (3) solar data, when available, consist of daily total horizontal and diffuse solar radiation. Matsuo et al. (1974) tried to produce TMY data for Beijing and Shanghai using such data, but encountered problems in interpolating between the six-hour intervals. In 1992, one of the authors (Lang) obtained TMY weather files for Beijing and Shanghai developed by colleagues at the China Academy of Building Research (Lang and Huang 1993). The Beijing TMY weather file has been used extensively by the authors and others, but the Shanghai TMY weather file did not match long-term climate normals and was never used.

In the early 1990's, Lang obtained paper copies of weather data for over 20 major cities from the Chinese weather service. These data contained one year's record of dry-bulb temperatures and relative humidity at six-hour intervals, and daily totals for global and diffuse horizontal solar radiation for each city. Although the data were not used directly in the current effort, they were useful for corroborating the temperatures from and, more importantly, verifying the solar radiation estimated from the NCDC data.

In 1999, Lang was authorized by China's Ministry of Construction to co-chair a Code Compilation Committee to develop a national energy standard for residential buildings in the Hot Summer Cold Winter region of China. Huang and several other U.S. experts provided technical assistance to this effort (Hogan et al. 2001). The Hot Summer Cold Winter region covers a broad area across central China corresponding roughly to the Yangtze River basin, with a population of 500 million and some of the most economically developed areas of China (see boundary line in Figure 2). As implied in its name, the climate in the Hot Summer Cold Winter region is characterized by cold winters with occasional snowfall along with hot humid summers with 0.4% design temperatures reaching as high as 35ºC (95ºF) dry-bulb and 28ºC (83ºF) wet-bulb. To accurately calculate building cooling loads, the Code Compilation Committee decided to use the DOE-2 building energy simulation program, which necessitated the development of hourly TMY weather files for locations within this region. The study described in this paper was done to meet this need. Although the raw weather data obtained permitted the development of TMY weather files for up to 69 Chinese locations, we decided to create first a set of 28 files covering most of the provincial capitals in China, and then create a second set of the remaining 41 files as time and resources permit. The first set of 28 were completed in the Fall of 2000, just in time for its use in the building standards work. The second set is expected to be completed by mid-2002.

In roughly the same time frame as this effort, ASHRAE supported a research project to develop International Weather for Energy Calculations (IWEC) files for 227 non-North American locations (Thevenard and Brunger 2002a, 2002b). A brief comparison of the IWEC weather files for 8 Chinese cities to the TMY weather files from this project follows in this paper.

SOURCE DATA FOR TMY WEATHER FILES

The TMY weather files for 28 major Chinese cities were developed from a large data base of International Surface Weather Observations (ISWO) released as a set of 5 CD's by NCDC (1998). The ISWO data set contains the same stations (583 U.S. and 907 non-U.S.) that were compiled by NCDC for use by the American Society of Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) to update the design climate tables in Chapter 26 of ASHRAE's *Handbook of Fundamentals* (ASHRAE 1997). The original data set provided to ASHRAE covered the twelve year period 1982-1993, while the ISWO data set was expanded to sixteen years, 1982 through 1997. As a member of ASHRAE's Weather Information Technical Committee (TC 4.2), Huang participated in the selection of non-US locations included in the ASHRAE data set, among which are 70 Chinese locations. The original source for the ISWO data are weather observations from local stations transmitted internationally via the Global Telecommunications System (GTS) and archived by the AFCCC (Air Force Combat Climatology Center) in Asheville, NC. Therefore, although the data base was obtained from a US government organization, the weather data themselves should be consistent with local records. When the ISWO data are compared to those obtained previously by Lang from the Chinese weather service for the same city and time period, the recorded dry-bulb temperatures were found to be virtually identical (see Figure 1).

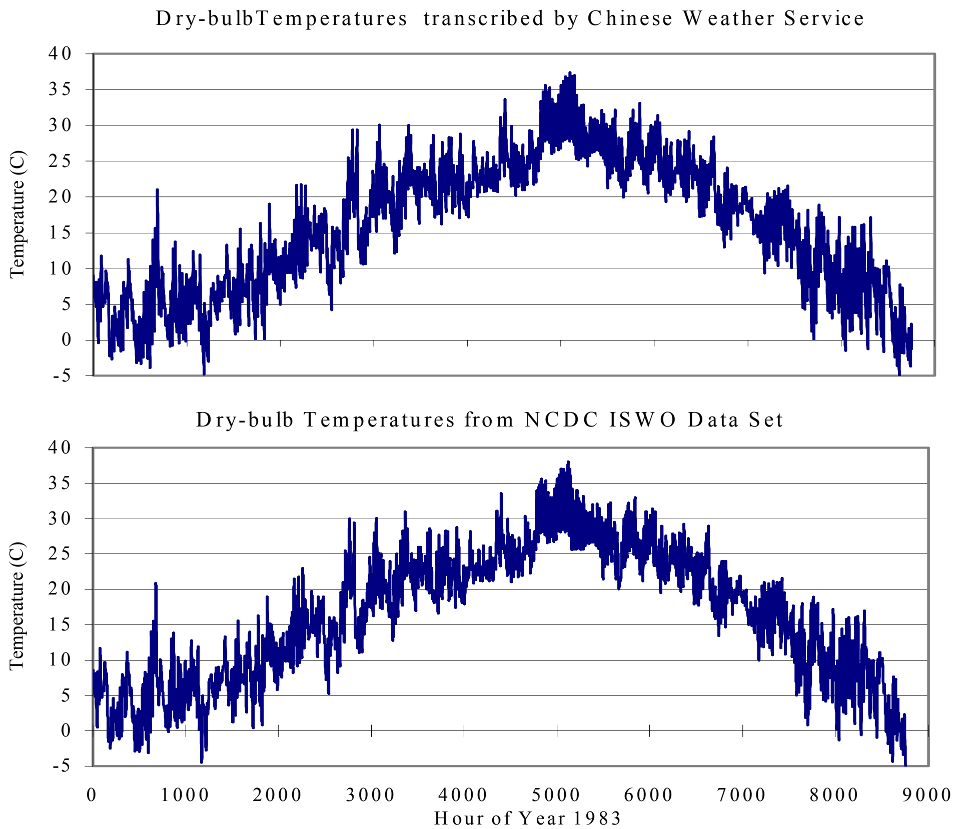

Figure 1. Comparison of dry-bulb temperature records transcribed by the Chinese Weather Service and recorded in NCDC's ISWO data set for Shanghai 1983

The weather variables recorded in the ISWO data base include dry-bulb and dew-point temperatures, atmospheric pressure, wind speed and direction, and the amounts of cloud cover at various heights. With the exception of three cities, the ISWO data for Chinese locations were all reported at three-hour intervals. Starting in 1988, the weather data for Beijing, Shanghai, and Guangzhou were reported at one-hour intervals. In order to produce hourly records from the three-hour data, interpolation methods had to be developed and tested.

Because the ISWO data do not contain solar radiation data, we developed methods adapted from previous work by Japanese researchers to estimate 1) total solar radiation from reported dry-bulb temperature, temperature change from previous hours, relative humidity, cloud cover and wind speed, and 2) the split between direct and diffuse solar from the solar angle and ratio of total to extraterrestrial solar radiation. The ISWO data also contain information on cloud type and amount of low cloud cover that can be very useful in predicting solar radiation, but these data were not used in this study due to the large amount of missing data. To verify the accuracy of these models and adapt them to Chinese climate conditions, the authors obtained measured direct hourly solar radiation for three Chinese locations (Beijing, Harbin, and Guangzhou) and used them to calibrate the coefficients in the solar models. Further comparisons of the estimated daily global horizontal and diffuse solar radiation were done against two sources of measured data: 1) the meteorological data obtained by Lang for 20 cities mentioned earlier, and 2) daily totals for global and diffuse radiation for 10 Chinese cities from the World Radiation Data Center (WRDC) online archive (WRDC 2001).

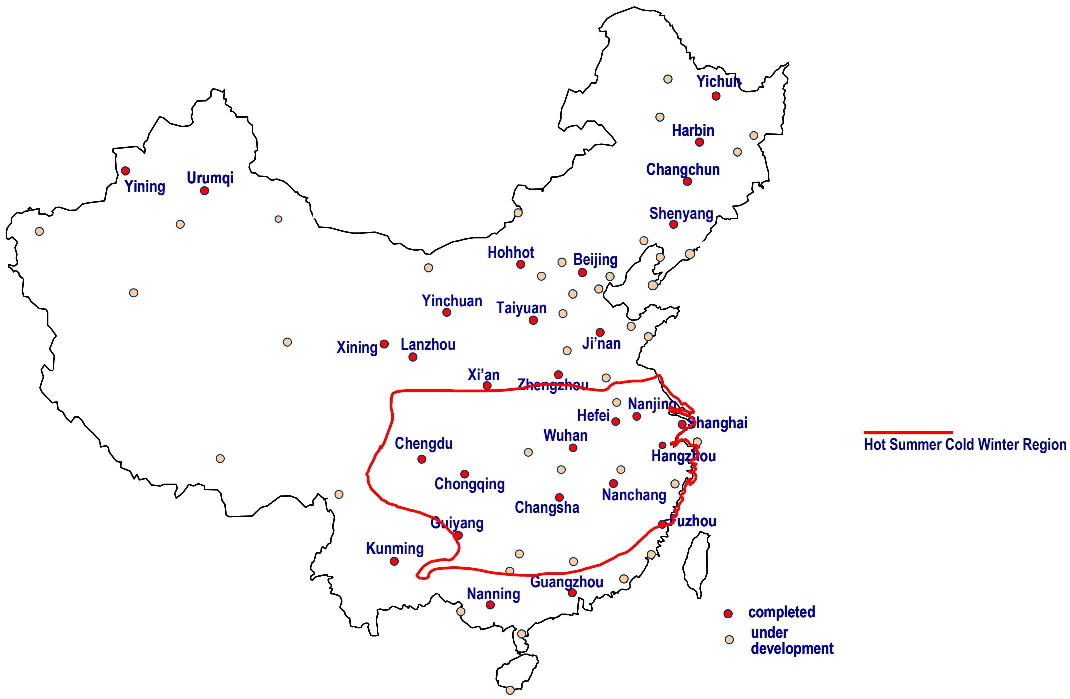

Figure 2. Sketch map of Chinese TMY weather data locations

The selection of Typical Meteorological Months was based on how closely the climate variables of a month matched the long-term average values over the 16 years of record (1982-1997), following the criteria developed by the US National Renewable Energy Laboratory (NREL) in the early 1980's to create TMY weather files for US locations (NCDC 1981). Table 1 lists in bold the 28 cities for which TMY weather files have already been developed, along with the additional 41 cities in the ISWO data set for which the authors intend to create additional TMY weather files in the near future using the same methodology. The same list of cities is shown on the map in Figure 2. These files will provide architects and engineers with typical weather conditions of temperature, humidity, pressure, wind speed and direction, cloud cover, and solar radiation for all major Chinese cities that can be conveniently used in building energy simulation programs.

MODEL FOR ESTIMATING SOLAR RADIATION

As mentioned above, there is no observed data on solar radiation in the ISWO data base. Therefore, it was necessary in this study to develop a method for estimating the amount of solar radiation based on other available climate parameters.

Of the recorded climate parameters, cloud cover is the most influential for estimating the amount of solar radiation. Moreover, low-level cloud cover can affect the solar radiation a great deal. Nevertheless, we chose not to include low-level cloud cover in our solar model because this climate parameter was often not reported in the weather data. On the other hand, since the rate of increase in dry-bulb temperature is correlated to the amount of solar radiation, it can be used as a secondary parameter for estimating solar radiation. Conversely, a recent study has also shown that relative humidity has a negative correlation to solar radiation (Cui et al. 1996). Ma et al. (1993) developed a model to estimate solar radiation based on cloud cover, dry-bulb temperature difference between sequential observations, relative humidity and wind speed that was then applied to climate data recorded at 6-hour intervals. There were two problems with this approach: 1) the impact of the long six-hour interval on the accuracy of the solar model could not be determined, and 2) the model overestimated at low values and underestimated at high levels of solar radiation.

Table 1. Years from which the Typical Weather Months are selected
(28 locations with completed TMY files shaded)

Location	Lat. (N)	Lon. (E)	Jun.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Sep.	Dec.
Andirlan	37 56	83 39	86	90	82	88	86	92	92	92	84	88	88	93
Anyang	36 07	114 22	87	89	87	86	88	93	83	84	89	84	85	86
Baoding	38 51	115 34	88	91	86	85	87	82	91	93	92	93	91	86
Bayan Mod	40 45	104 30	83	85	91	82	90	93	89	82	88	88	87	83
Beijing	39 56	116 17	93	91	82	85	89	86	95	84	86	93	83	90
Bengbu	32 57	117 22	92	89	82	90	90	89	84	88	89	88	87	90
Changchun	43 54	125 13	91	94	82	92	82	90	90	90	90	89	89	88
Changsha	28 14	112 52	85	94	89	83	87	89	91	91	85	85	91	90
Chengdu	30 40	104 01	85	85	89	95	86	83	93	82	92	90	93	87
Chongqing	29 33	196 30	88	98	98	97	95	94	97	95	87	96	87	95
Dalian	38 54	121 38	93	91	82	85	91	86	83	93	92	94	89	89
Dandong	40 03	124 20	93	91	82	82	82	85	88	90	92	92	91	84
Datong	40 06	113 20	88	91	83	82	84	83	83	87	91	89	83	88
Deqen	28 30	98 54	85	86	90	87	84	84	87	86	85	93	83	86
Dinghai	30 02	122 07	83	83	93	86	90	88	86	85	91	84	86	90
Erenhot	43 39	112 00	83	85	83	92	84	82	82	83	83	83	82	82
Fuzhou	26 05	119 17	85	85	93	85	90	90	87	91	89	90	89	85
Golmud	36 25	94 54	91	86	82	91	83	87	84	83	90	90	88	85
Guangzhou	23 08	113 19	85	82	84	92	93	85	91	83	82	86	85	86
Guilin	25 20	110 18	85	85	94	83	87	83	88	91	89	90	83	90
Guiyang	26 35	106 43	92	85	84	93	89	87	93	83	93	90	82	90
Hami	42 49	93 31	92	83	87	88	87	89	88	87	86	86	88	91
Hangzhou	30 14	120 10	83	83	82	93	90	94	86	82	92	93	93	86
Harbin	45 45	126 46	93	86	82	85	82	91	85	85	90	82	82	89
Hefei	31 52	117 14	83	86	83	90	93	87	85	93	92	90	88	92
Hohhot	40 49	111 41	85	92	86	85	90	82	89	85	87	85	82	87
Ji'nan	36 41	116 59	93	89	83	82	87	89	85	82	90	87	85	93
Jingdezhen	29 18	117 12	92	94	82	90	87	94	86	84	84	89	89	90
Jinzhou	41 08	121 07	91	91	82	85	86	87	83	88	92	93	84	90
Jixi	45 17	130 57	93	86	82	94	82	86	93	90	86	85	82	93
Kashi	39 28	75 59	91	89	91	86	91	88	91	82	92	88	88	82
Korla	41 45	86 08	93	85	87	93	87	86	89	88	83	90	84	83
Kunming	25 01	102 41	82	89	87	86	85	89	87	89	82	88	86	89
Lanzhou	36 03	103 53	85	82	92	84	90	83	93	90	93	90	93	91
Lhasa	29 40	91 08	85	94	82	93	84	94	87	92	88	83	89	94
Liuzhou	24 21	109 24	88	82	89	89	87	90	82	83	89	88	93	89
Longzhou	22 22	106 45	92	85	84	90	86	82	87	83	89	87	91	89
Mudanjiang	44 34	129 36	93	86	94	94	89	89	90	84	90	85	82	89
Nanchang	28 36	115 55	90	94	83	93	87	86	87	90	84	93	85	83
Nanjing	32 00	118 48	83	94	83	90	90	91	91	97	91	94	89	86
Nanning	22 49	108 21	88	85	89	90	86	91	91	91	89	91	93	85
Nenjiang	49 10	125 14	83	91	85	85	93	84	84	90	84	85	84	87
Qingdao	36 04	120 20	82	91	82	86	84	89	83	91	91	84	92	93
Qiqihar	47 23	123 55	88	86	83	90	83	84	84	90	85	85	82	84
Shanghai	31 10	121 26	83	85	86	90	91	86	83	83	82	90	87	82
Shantou	23 24	116 41	85	94	92	86	86	86	90	94	82	84	89	93

Table 1. Years from which the Typical Weather Months (TMMs) are selected (continued)
(28 locations with completed TMY files shaded)

Location	Lat. (N)	Lon. (E)	Jun.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Sep.	Dec.
Shaoguan	24 48	113 35	85	85	84	89	90	89	90	82	82	84	86	89
Shenyang	41 46	123 26	93	94	82	83	86	86	83	90	94	94	89	84
Shijiazhuang	38 02	114 25	88	91	86	85	87	89	83	93	88	87	82	90
Tangshan	39 40	118 09	82	91	82	86	86	91	91	87	92	83	91	90
Tianjin	39 06	117 10	88	87	92	85	88	82	91	87	93	88	89	90
Urumqi	43 47	87 37	91	90	92	93	84	83	89	85	82	83	89	91
Weifang	36 42	119 05	93	94	92	82	84	89	87	82	89	94	87	94
Wenzhou	28 01	120 40	83	94	83	93	90	90	86	92	82	84	89	89
Wuhan	30 37	114 08	88	89	89	90	87	86	82	83	88	89	85	86
Xiamen	24 29	118 05	85	88	93	93	90	86	90	91	85	89	85	93
Xi'an	34 18	108 56	92	85	89	83	87	85	93	84	89	91	87	88
Xining	36 37	101 46	89	89	92	84	90	83	87	90	87	87	87	85
Xuzhou	34 17	117 09	87	94	83	86	87	85	87	82	91	84	87	91
Yaxian	18 14	109 31	85	91	88	83	83	91	86	91	91	91	91	88
Yichang	30 42	111 18	85	85	87	87	88	86	82	83	88	84	85	90
Yichun	47 43	128 54	91	92	82	84	92	84	90	84	93	89	84	89
Yinchuan	38 29	106 13	83	85	87	82	90	86	89	83	89	85	85	83
Yingkou	40 40	122 12	93	91	92	84	82	91	89	92	90	89	82	93
Yining	43 57	81 20	91	90	92	86	84	88	85	86	83	85	84	85
Yueyang	29 23	113 05	83	94	89	90	88	83	86	91	91	84	85	82
Zhangjiakou	40 47	114 53	86	91	83	90	88	89	86	82	92	87	91	90
Zhanjiang	21 13	110 24	92	88	84	83	83	89	84	83	87	86	89	85
Zhengzhou	34 43	113 39	83	89	89	93	87	89	87	83	89	93	85	86

Table 2. Format of TMY weather files for Chinese locations

Item	Columns	Format	Parameter	Units
1	1-6	6I	WMO Station Number	(0 if interpolated data)
2	7-12	6I	Year	
3	13-18	6I	Month	
4	19-24	6I	Day	
5	25-30	6I	Hour	
6	31-36	6.2F	Local solar time	(hours)
7	37-42	6I	Dry bulb temperature	(0.1*K)
8	43-48	6I	Dew-point temperature	(0.1*K)
9	49-54	6I	Absolute humidity	(*0.1g/kg)
10	55-60	6I	Relative humidity	(%)
11	61-66	6I	Total horizontal solar radiation	(W/m^2)
12	67-72	6I	Direct normal solar radiation	(W/m^2)
13	73-78	6I	Diffuse horizontal solar radiation	(W/m^2)
14	79-84	6I	Wind direction	(degrees, 0=N, 90=E, 180=S, 270=W)
15	85-90	6I	Wind speed	(*0.1m/sec)
16	91-96	6I	Cloud cover	(tenths)
17	97-102	6I	Atmospheric pressure	(Pa)
18	103-108	6.2F	Cos Z (solar angle)	

Table 3. Summary statistics for 28 completed TMY weather files

			Degree Days and Degree Hours				Temperatures				Average Daily Solar Radiation	
Location	Lat (N)	Lon (E)	HDD 18°C	CDD 18°C	CDD 26°C	CDH 26°C	Max. (°C)	Avg. Daily Max (°C)	Avg. Daily Min. (°C)	Min. (°C)	Total Horiz. (W/m²)	Direct Normal (W/m²)
Beijing	39.9	116.3	2684	874	72	3633	39.3	32.1	-8.4	-12.8	3996	4134
Changchun	43.9	125.2	4820	375	0	520	30.8	26.6	-21.5	-25.4	3564	3583
Changsha	28.2	112.9	1556	1352	280	7340	39.2	34.2	0.3	-2.2	2752	1534
Chengdu	30.7	104.0	1426	887	31	2055	33.2	28.3	3.1	-1.3	2422	1094
Chongqing	28.2	112.9	1068	1388	251	6830	38.4	33.1	4.0	2.5	2045	652
Fuzhou	26.1	119.3	800	1605	319	6692	38.8	32.7	5.1	2.4	3011	1607
Guangzhou	23.1	113.3	389	2074	365	8639	35.9	32.4	7.1	4.8	2936	1395
Guiyang	26.6	106.7	1536	735	3	817	31.3	27.3	1.0	-1.7	2615	1195
Hangzhou	30.2	120.2	1649	1235	208	5430	36.9	32.0	-1.3	-3.6	3046	1847
Harbin	45.8	126.8	5360	318	0	351	30.3	25.8	-24.8	-32.4	3459	3551
Hefei	31.9	117.2	1863	973	113	3388	36.4	32.0	-2.9	-5.3	3080	2007
Hohhot	40.8	111.7	4301	300	0	782	33.8	26.3	-19.2	-23.1	4332	4638
Ji'nan	36.7	117.0	2279	1197	155	5334	37.4	32.4	-6.8	-9.5	3844	3375
Kunming	25.0	102.7	1255	340	0	31	29.9	23.0	-9.6	-35.3	3995	3154
Lanzhou	36.1	103.9	3170	367	0	1195	35.4	26.3	-15.0	-18.3	3746	3052
Nanchang	28.6	115.9	1470	1413	264	6566	37.5	33.0	-1.9	-3.6	2938	1550
Nanjing	32.0	118.8	1994	1123	178	4933	36.6	32.5	-1.9	-5.7	3202	2193
Nanning	22.8	108.4	431	2088	405	9252	38.1	31.8	8.2	4.5	2822	1260
Shanghai	31.2	121.4	1707	1075	165	4303	37.3	32.8	-0.4	-3.5	3051	1903
Shenyang	41.8	123.4	3955	584	15	1491	32.3	28.4	-17.2	-22.2	3650	3500
Urumqi	43.8	87.6	4442	467	12	1634	36.3	32.8	-21.6	-24.6	3760	3593
Wuhan	30.6	114.1	1694	1249	221	5833	37.3	32.8	-0.6	-2.9	3005	1732
Xi'an	34.3	108.9	2336	839	82	3529	38.1	30.3	-5.4	-9.6	3294	2336
Xining	36.6	101.8	3984	39	0	84	30.0	21.1	-12.2	-19.2	4061	3785
Yining	44.0	81.3	3671	462	6	2174	36.7	28.0	-16.6	-24.3	3764	3766
Yinchuan	38.5	106.2	3639	416	2	1131	33.4	27.0	-14.9	-19.9	4169	4057
Yichun	47.7	128.9	6145	208	0	576	31.6	24.9	-27.5	-36.0	3330	3413
Zhengzhou	34.7	113.7	2262	1016	106	4467	37.6	30.4	-5.8	-10.8	3711	3114

For this study, we developed a solar model similar in form to the Ma model, with total cloud cover, dry-bulb temperature, relative humidity, and wind speed as the independent variables (see Equation 1), and calculated the constants with multi-parameter analyses against measured hourly total horizontal solar radiation for Beijing and Guangzhou in 1993 obtained from another colleague (Yang 1999). Measured solar radiation data for a third city, Harbin, was also obtained but not used due to its poor data quality.

$$I = [I_0 \cdot \sin(h) \cdot \{c_0 + c_1(CC) + c_2(CC)^2 + c_3(T_n - T_{n-3}) + c_4\varphi + c_5 V_W\} + d]/k \quad \text{when } I > 0$$
$$= 0 \quad \text{when } I < 0 \qquad (1)$$

where I = estimated hourly solar radiation in $J/(m^2h)$
I_0 = solar constant, 1355 W/m^2
h = solar altitude angle, i.e, the angle between the horizontal and the line to the sun
CC = cloud cover in tenths
φ = relative humidity in %
T_n, T_{n-3} = dry-bulb temperature at hours n and n-3, respectively
V_w = wind speed in m/s.
c_0, c_1, c_2, c_3, c_4, c_5, d, k = regression coefficients

The constants determined from multi-parameter analyses against the 1993 measured data for Beijing and Guangzhou are as follows:

$$c_0 = 0.5598,\ c_1 = 0.4982,\ c_2 = -0.6762,\ c_3 = 0.02842,\ c_4 = -0.00317,$$
$$c_5 = 0.014,\ d = -17.853,\ k = 0.843.$$

The relationship between the observed solar radiation and the values from Equation 1 is shown in Figure 3. The correlation coefficient (R) is 0.93, which implies that Equation 1 can be used to estimate the hourly total horizontal solar radiation with good accuracy in both Beijing and Guangzhou. To verify the accuracy of Equation 1 when applied to other locations and times, the total daily global solar radiation estimated using Equation 1 are compared to measured totals for Beijing 1984, Shanghai 1983, and Chongqing 1988 (see Figures 4, 5, and 6). Based on these figures, it is reasonable to conclude that Equation 1 can be used to estimate the global solar radiation on the horizontal surface for other Chinese locations as well.

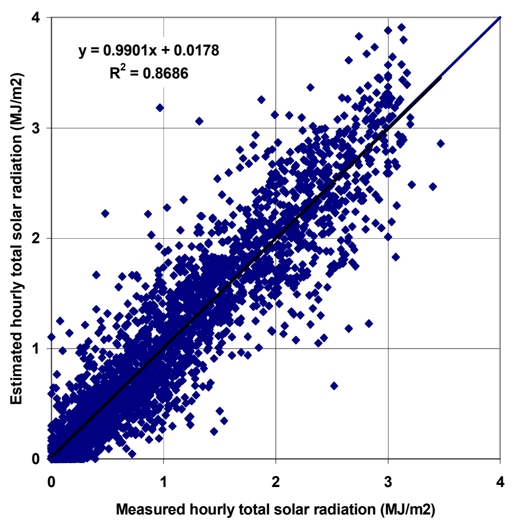

Figure 3. Comparison of estimated to measured hourly total solar radiation on a horizontal surface for Beijing and Guangzhou 1993

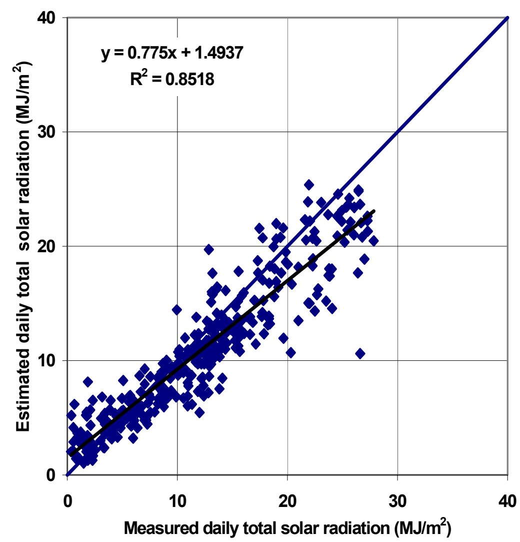

Figure 4. Comparison of estimated to measured daily total solar radiation on a horizontal surface in Beijing 1984

For building energy simulations, it is necessary to separate the total global solar radiation into direct and diffuse components. In this study, we used the following model developed by Watanabe et al. (1983) for Japanese locations:

$$K_T = I/(I_0 \sin h),\quad K_{TC} = 0.4268 + 0.1934 \cdot \sin h$$
$$K_{DS} = K_T - (1.107 + 0.03569 \cdot \sin h + 1.681 \cdot \sin^2 h)(1 - K_T)^2 \qquad \text{when } K_T \geq K_{TC}$$
$$K_{DS} = (3.996 - 3.862 \cdot \sin h + 1.540 \cdot \sin^2 h) K_T{}^3 \qquad \text{when } K_T < K_{TC}$$
$$DH = I_0 \cdot \sin h \cdot K_{DS}(1 - K_T)/(1 - K_{DS})$$
$$SH = I_0 \cdot \sin h (K_T - K_{DS})/(1 - K_{DS}) \qquad (2)$$

where I = global solar radiation on the horizontal surface in W/m^2
DH = direct solar radiation on the horizontal surface in W/m^2
SH = diffuse radiation in W/m^2.

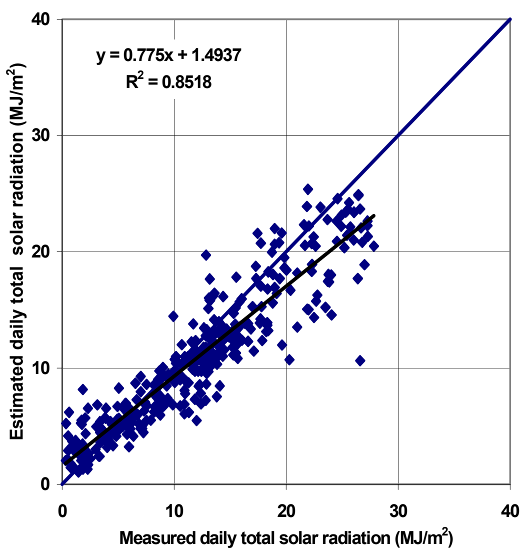

Figure 5: Comparison of estimated to measured daily total solar radiation on a horizontal surface for Shanghai 1983

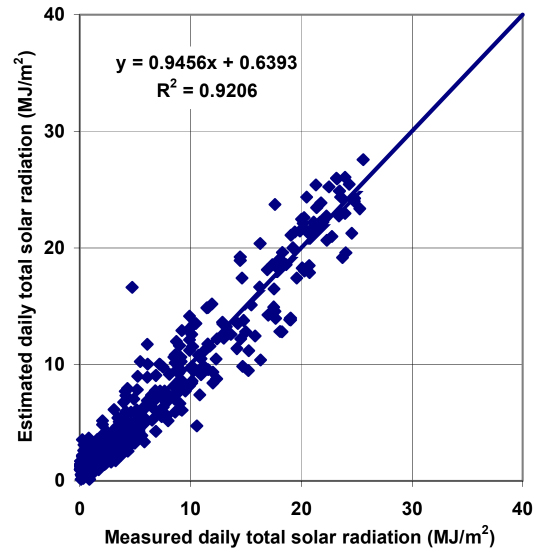

Figure 6. Comparison of estimated to measured daily total solar radiation on a horizontal surface for Chongqing 1988

Because we were unable to obtain hourly data on measured diffuse solar radiation, we can only compare daily total diffuse solar radiation estimated using Equation 2 to measured daily totals for various cities (see Figure 7 for Beijing 1984 and Figure 8 for Chongqing 1988). The estimated values agree with the measured ones fairly well throughout the year except for less than 10% of the days. We also investigated the use of other models developed in the US (Erbs et al. 1982, Perez et al. 1992), but did not find any improvement in the results. Therefore, the Watanabe method for separating global solar radiation into direct and diffuse components was used in all the generated weather files.

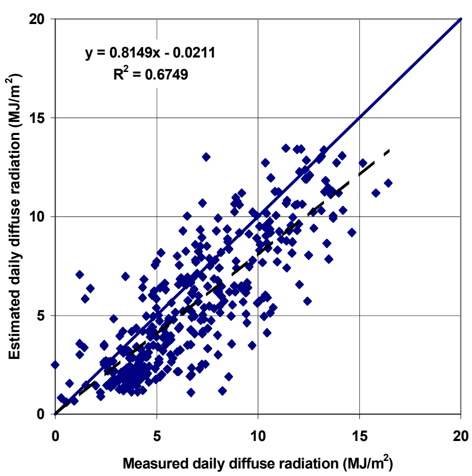

Figure 7: Comparison of estimated to measured daily diffuse solar radiation for Beijing 1984

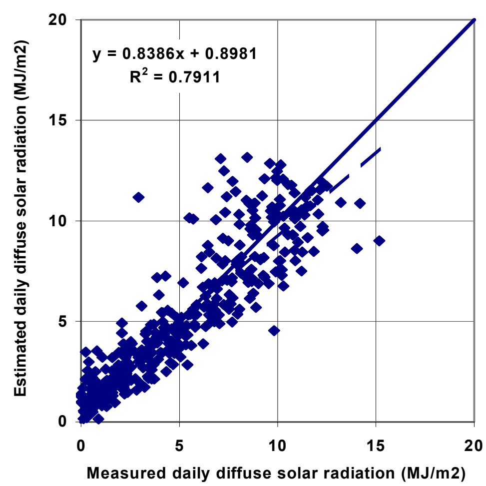

Figure 8. estimated to measured daily diffuse solar radiation for Chongqing 1988

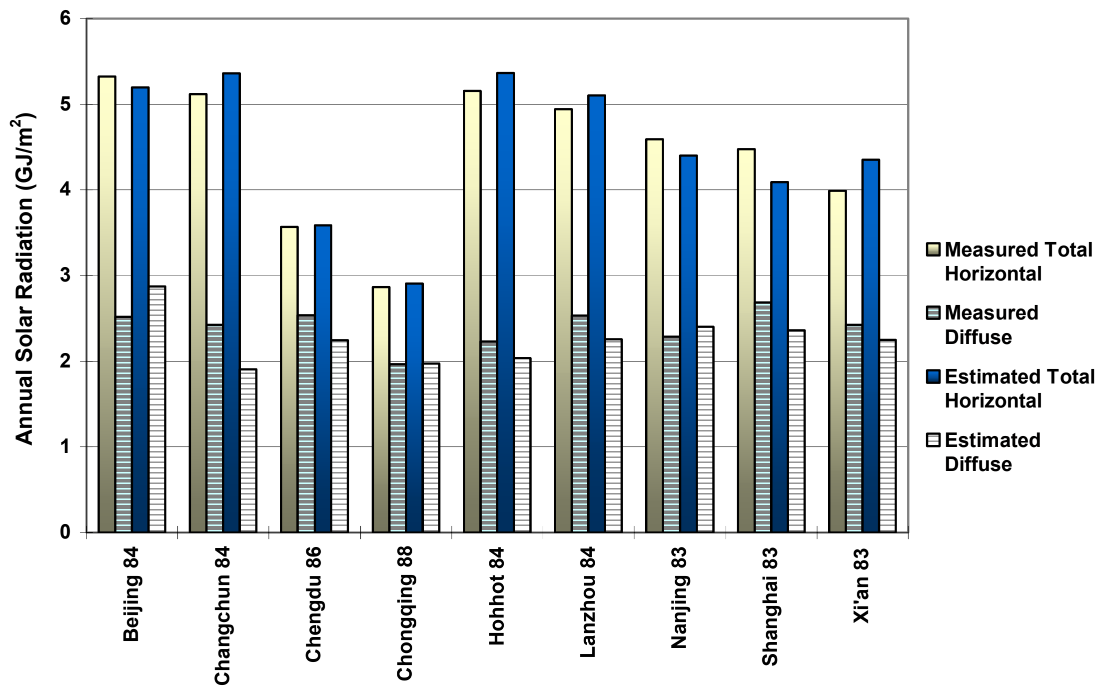

Figure 9. Comparison of measured and estimated annual solar radiation for various cities and years

Figure 9 and Table 4 show the comparison of estimated to measured annual totals for global horizontal and diffuse solar radiation in nine cities. The estimated annual global solar radiation on a horizontal surface agrees with the measured annual totals to within 10% in all nine cities, and often to within 5%. The error in estimating the annual diffuse solar radiation is significantly larger than for global solar radiation, but still well within 20% with the single exception of Changchun (21%). The reason for the increased error is that the estimation of diffuse solar radiation is based on the data of global solar radiation; therefore, any errors in the estimation of the global solar radiation will be propagated into the estimation of the diffuse solar radiation.

Table 4. Comparison of measured and estimated annual solar radiation for various cities and years (same data as shown in Figure 9)

		Measured Solar Radiation (GJ/m^2)		Estimated Solar Radiation (GJ/m^2)		Differences in solar radiation (%)	
Location	Year	Total Horizontal	Diffuse	Total Horizontal	Diffuse	Total Horizontal	Diffuse
Beijing	1984	5.32	2.52	5.20	2.87	2.4	-14.1
Changchun	1984	5.12	2.42	5.36	1.91	-4.6	21.3
Chengdu	1986	3.57	2.54	3.59	2.24	-0.5	11.5
Chongqing	1988	2.86	1.97	2.91	1.97	-1.6	-0.1
Hohhot	1984	5.15	2.23	5.37	2.03	-4.1	8.9
Lanzhou	1984	4.94	2.53	5.10	2.26	-3.2	10.8
Nanjing	1983	4.59	2.29	4.40	2.40	4.1	-5.0
Shanghai	1983	4.47	2.69	4.09	2.36	8.6	12.1
Xi'an	1983	3.99	2.42	4.35	2.25	-9.0	7.1
				Standard deviations (%)		5.3	12.3

Table 5. Comparison of weather statistics from IWEC and TMY weather files for nine Chinese locations (diff. = IWEC – TMY)

				Degree Days and Degree Hours				Temperatures				Average Daily Solar Radiation	
	Lat (N)	Lon (E)	Weather Type	HDD 18°C	CDD 18°C	CDD 26°C	CDH 26°C	Max. (°C)	Avg. Daily Max (°C)	Avg. Daily Min. (°C)	Min. (°C)	Total Horiz. (W/m²)	Direct Normal (W/m²)
Beijing	39.9	116.3	IWEC	2689	891	62	3073	35.0	30.5	-10.5	-14.0	3791	3292
			TMY	2684	874	72	3633	39.3	32.1	-8.4	-12.8	3996	4134
			diff.	5	17	-10	-560	-4	-2	-2	-1	-205	-842
Guangzhou	23.1	113.3	IWEC	381	2086	396	9010	36.0	31.9	5.0	3.8	2990	1895
			TMY	389	2074	365	8639	35.9	32.4	7.1	4.8	2936	1395
			diff.	-8	12	31	371	0	-1	-2	-1	54	500
Harbin	45.8	126.8	IWEC	5202	388	3	695	33.1	27.5	-24.8	-30.6	3735	3411
			TMY	5360	318	0	351	30.3	25.8	-24.8	-32.4	3459	3551
			diff.	-158	70	3	344	3	2	0	2	276	-140
Kunming	25.0	102.7	IWEC	1180	377	0	81	29.9	23.5	1.0	-2.4	3986	2617
			TMY	1237	340	0	31	29.9	23.0	3.8	-0.4	3995	3154
			diff.	-57	37	0	50	0	1	-3	-2	-9	-537
Lanzhou	36.1	103.9	IWEC	3184	394	12	1238	35.1	28.6	-8.2	-13.4	3941	3169
			TMY	3170	367	0	1195	35.4	26.3	-15.0	-18.3	3746	3052
			diff.	14	27	12	43	0	2	7	5	195	117
Shanghai	31.2	121.4	IWEC	1691	1131	165	4018	38.0	32.8	-1.1	-3.2	3422	2392
			TMY	1707	1075	165	4303	37.3	32.8	-0.4	-3.5	3051	1903
			diff.	-16	56	0	-285	1	0	-1	0	371	489
Shenyang	41.8	123.4	IWEC	4036	566	18	1269	33.3	29.9	-24.4	-28.2	3512	2526
			TMY	3955	584	15	1491	32.3	28.4	-17.2	-22.2	3650	3500
			diff.	81	-18	3	-222	1	2	-7	-6	-138	-974
Urumqi	43.8	87.6	IWEC	4377	521	22	1876	37.1	30.8	-22.3	-24.8	3803	3412
			TMY	4442	467	12	1634	36.3	32.8	-21.6	-24.6	3760	3593
			diff.	-65	54	10	242	1	-2	-1	0	43	-181

SELECTION OF TYPICAL METEOROLOGICAL MONTHS

The TMY weather file contains measured data for 12 historical months, between which some of the variables have been smoothed to avoid abrupt changes. Different methods have been developed to select the Typical Meteorological Months (TMMs) by NREL (NCDC 1981), and Matsuo et al. (1974). The NREL method has the problem of being subjective in the weights given various climate parameters, while the Matsuo method uses the calculated air-conditioning loads of a model building as the last stage of the selection procedure. Matsuo et al. made a large number of computer simulations to evaluate the impact of different climate parameters on air-conditioning loads and determined that the 0.50 weighting for solar radiation used in the NREL method was much too large. In this study, we used a method that combined elements from both methods.

The characteristics of this method are as follows: First, it considered both the average values and the data structure of all the variables to ensure the selected months not only are close to the average of the period of the weather observation, but also have a similar structure with the average month; second, it avoids the procedure of air-conditioning load calculation. The procedure is as follows:

1. Select the months whose monthly average dry-bulb temperature, dew-point temperature, solar radiation and wind speed are within the range of 0.6 times the standard deviation. If there is only one candidate left after Step 1, the only candidate is selected as the TMM. If there is no candidate left, go to Step 2. If there is more than one candidate after step 1, go to Step 4.
2. Select the months whose monthly average dry-bulb temperature, dew-point temperature, solar radiation and wind speed are within the range of 0.8 times the standard deviation. If there is only one candidate left after Step 2, the only candidate is selected as the TMM. If there is no candidate left, go to Step 3. If there is more than one candidate after Step 2, go to Step 4.

3. Select the months whose monthly average dry-bulb temperature, dew-point temperature, solar radiation and wind speed are within the range of one standard deviation. If there is only one candidate left after Step 3, the only candidate is selected as the TMM. If there is more than one candidate left after Step 3, go to Step 4.
4. Compare the WS values of the remaining months, and select the month whose WS is the smallest as the TMM.

The value of WS is calculated as follows:

$$WS = \sum w_i \cdot FS_i \tag{3}$$

where FS_i means the Finkelstein-Shafer (*FS*) statistic (Finkelstein and Shafer 1971). The smaller the FS, the closer the structure of a variable will be to the average year. The weights w_i applied to the different climate parameters are the same as those used by NCDC in the development of the original TMYs (NCDC 1981), i.e.,

Dry-bulb temperature: Max 1/24, Min 1/24, Mean 2/24
Dew-point temperature: Max 1/24, Min 1/24, Mean 2/24
Wind speed: Max 2/24, Mean 2/24
Solar Radiation: 12/24

In a few cases, it might possible that no candidate exists after Step 3. If that happens, the criterion for wind speed or dew-point temperature should be relaxed so that at least one candidate TMM remains.

Table 1 is a list of years from which the TMMs have been selected for 69 of the 70 Chinese locations in the ISWO data set, with one location dropped due to poor data completeness. Very few TMMs have been taken from the years 1993 to 1997, due not to their climate characteristics, but because there were too much missing data that could not be reliably filled.

INTERPOLATION PROCEDURES FOR MISSING DATA

The great majority of the weather data in the ISWO data base are at three-hour intervals. For use in thermal simulations or annual energy calculations, the data must be interpolated to one-hour intervals. Although one option would be to do the interpolation for the entire 16 years of record for each station, to save work we first selected the TMMs using the statistics from the actual recorded data, and then interpolated the missing hours for only the selected TMMs.

We developed interpolation procedures for the following climate variables: dry-bulb temperature, dew-point temperature, solar radiation, wind speed, and total cloud cover. We did not attempt to interpolate atmospheric pressure because it is only measured at a few stations and its impact of building energy use is secondary.

To interpolate for dry-bulb temperatures, we used two separate equations depending on the time of day. Since the change in dry-bulb temperature is periodic, we tried to approximate it with a Fourier Series as follows:

$$\theta(t) = b_0 + \sum \{b_n \cos(n\frac{\pi}{12}t) + a_n \sin(n\frac{\pi}{12}t)\} \tag{4}$$

where $b_0 = \frac{1}{8}\sum_{k=1}^{8}\theta(k)$

$$b_n = \frac{1}{4}\sum_{k=1}^{8}\theta(k)\cos\frac{n\pi k}{4}$$

$$a_n = \frac{1}{4}\sum_{k=1}^{8} \theta(k) \sin \frac{n\pi k}{4}$$

n = nth term of the Fourier series

k = sequential number of observed dry-bulb temperature from 1 to 8 at three-hour intervals

$\theta(k)$ = k_{th} observed dry-bulb temperature

t = local standard time, here meaning Beijing Standard Time.

In a previous study using Japanese weather data, we found that Equation 4 approximated measured dry-bulb temperatures most closely with n=3 or n=4. However, we found that dry-bulb temperatures during the period from 20:00 to 5:00 the next day cannot be approximated by a Fourier Series such as Equation 4, because a Fourier Series assumes that the temperature function is periodical, i.e., the temperature at the beginning of the series, i.e., day, must be equal to that at the end of the series, i.e., day. When this assumption is not true, Equation 4 has difficulty in producing reasonable interpolated values. Therefore, to interpolate dry-bulb temperatures in the period between 20:00 and 5:00, we use the following equation based on regression analyses with measured weather data from Sapporo, Tokyo, and Kagoshima (Zhang and Asano 2000).

$$\theta_j = \theta_{j-1} - 0.3419 + 0.2449(\theta_{j+2} - \theta_{j-1}) + 0.2282 \bullet CC + 0.03243 \bullet CC^2 \quad (j=21,24,3)$$

$$\theta_j = \theta_{j-2} - 0.5617 + 0.6900(\theta_{j+1} - \theta_{j-2}) + 0.07229 \bullet CC + 0.02331 \bullet CC^2 \quad (j=22,1,4) \qquad (5)$$

where θ_j is the dry-bulb temperature (ºC) at local time j, and CC the cloud cover in tenths.

To illustrate this interpolation procedure, two examples using Equations 4 and 5 are shown in Figures 10 and 11. Figure 10 compares measured to interpolated dry-bulb temperatures using Equation 4 for the period from 6:00 to 19:00 and Equation 5 for the period from 20:00 to 5:00 for a summer day, while Figure 11 shows a similar comparison for a winter day in Tokyo. These figures show that dry-bulb temperatures can be interpolated satisfactorily using this combined approach.

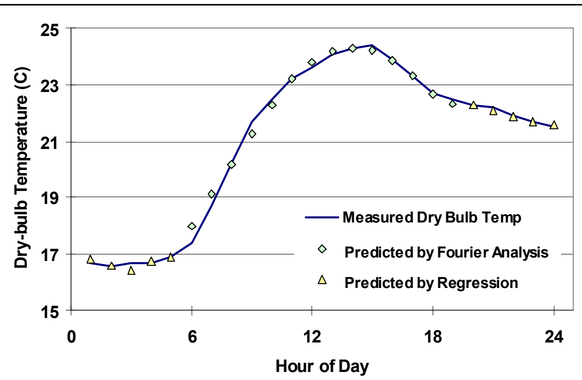

Figure 10. Example of dry-bulb temperature interpolation for Tokyo, June 21

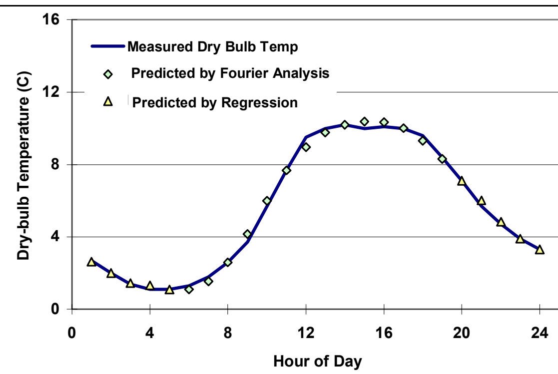

Figure 11. Example of dry-bulb temperature interpolation for Tokyo, Dec 21

To interpolate for dew-point temperatures, we also used a Fourier Series like Equation 4 for the daytime hours, but a simple linear interpolation for the nighttime hours instead of Equation 5. Simple linear interpolations were done for wind speed and cloud cover. Solar radiation is calculated by Equations 1 and 2 using the interpolated values of temperature, humidity, wind speed, and cloud cover.

DESCRIPTION OF TMY WEATHER FILES

Summary statistics of the 28 TMY weather files completed to date are listed in Table 3. The files have been saved as ASCII files containing 8760 hourly records in the format shown in Table 2. A snippet of the first day's data for the Beijing TMY weather file is shown in Figure 12. The authors are aware this format differs from other commonly found such as TMY2, IWEC, or EnergyPlus and have written small scripts in the awk programming language (Aho et al. 1988) to convert the weather files to those other formats.

Figure 12. Sample of Chinese TMY weather file for Beijing, Jan. 1

```
     0  1993     1     1     1   .70  2715  2635    17    54     0     0     0    40    24     6 10257   .00
545110  1993     1     1     2  1.70  2718  2634    17    53     0     0     0    40    20     9 10252   .00
     0  1993     1     1     3  2.70  2714  2633    18    54     0     0     0    40    20     7 10246   .00
     0  1993     1     1     4  3.70  2711  2631    17    54     0     0     0    40    20     4 10238   .00
545110  1993     1     1     5  4.70  2709  2628    16    54     0     0     0    90    20     0 10230   .00
     0  1993     1     1     6  5.70  2698  2630    17    59     0     0     0    90    14     0 10230   .00
     0  1993     1     1     7  6.70  2688  2631    17    64     0     0     0    90     8     0 10231   .00
545110  1993     1     1     8  7.70  2679  2633    17    70     0     0     0     0     0     0 10231   .05
     0  1993     1     1     9  8.70  2687  2652    20    76    38     9    36     0     3     0 10231   .21
     0  1993     1     1    10  9.70  2705  2673    24    78   138    86   109     0     7     0 10232   .33
545110  1993     1     1    11 10.70  2727  2681    25    71   264   273   151   340    10     0 10232   .42
     0  1993     1     1    12 11.70  2746  2673    24    58   350   483   131   340    13     0 10223   .45
     0  1993     1     1    13 12.70  2758  2656    21    47   358   547   115   340    17     0 10212   .44
545110  1993     1     1    14 13.70  2764  2644    19    41   290   460   112   270    20     0 10201   .39
     0  1993     1     1    15 14.70  2765  2645    19    41   177   297    92   270    23     0 10202   .29
     0  1993     1     1    16 15.70  2761  2658    21    46    50    57    42   270    27     0 10203   .15
545110  1993     1     1    17 16.70  2753  2672    23    55     0     0     0   180    30     0 10204   .00
     0  1993     1     1    18 17.70  2742  2679    25    63     0     0     0   180    24     0 10208   .00
     0  1993     1     1    19 18.70  2730  2678    25    68     0     0     0   180    18     0 10213   .00
545110  1993     1     1    20 19.70  2722  2675    24    70     0     0     0   340    10     0 10217   .00
     0  1993     1     1    21 20.70  2718  2674    24    72     0     0     0   340    10     0 10221   .00
     0  1993     1     1    22 21.70  2719  2673    24    71     0     0     0   340    10     0 10224   .00
545110  1993     1     1    23 22.70  2718  2670    23    70     0     0     0   360    10     0 10228   .00
     0  1993     1     1    24 23.70  2708  2670    24    75     0     0     0   360    10     0 10232   .00
------------------------------------------------------------------------------------------------------------
     |   |      |     |     |  |     |     |     |     |     |     |     |     |     |     |  |      |
     | Year  Month  Day   Hour |     |     |     |     |     |     |     |     |     |     |  |      cos(Z)
   Station                     |     |     |     |     |     |     |     |     |     |     |Atmos.pressure(Pa)
                               |     |     |     |     |     |     |     |     |     |   Clound cover
                               |     |     |     |     |     |     |     |     |   Wind speed(*0.1)
                               |     |     |     |     |     |     |     |  Wind direction
                               |     |     |     |     |     |     |  Diffuse solar radiation(W/m2)
                               |     |     |     |     |     |  Direct solar radiation(W/m2)
                               |     |     |     |     |  Total solar radiation(w/m2)
                               |     |     |     |  Relative humidity(%)
                               |     |     | Absolute Humidity(*0.1g/kg')
                               |     |  Dew point(K)
                               |   Dry bulb(K)
                    Real local solar time
```

COMPARISON TO ASHRAE IWEC WEATHER FILES

The work described in this report was done concurrently with ASHRAE Research Project RP-1015, "the Development of Typical Weather Years for International Locations", that produced International Weather for Energy Calculations (IWEC) files for 227 non-U.S. locations (Thevenard and Brunger. 2002a, 2002b). Although the authors had some technical correspondence with the researchers on RP-1015, this happened when both projects were nearing completion and did not affect the work on either project. Among the 227 IWEC weather stations, there are 8 Chinese locations, all of which are among the 28 weather files developed in this study (Harbin, Urumqi, Lanzhou, Shenyang, Beijing, Kunming, Shanghai, Guangzhou). Table 5 compares the summary weather statistics and estimated solar radiation for these 8 IWEC files to the respective files from this study.

The differences in heating and cooling degree days and hours are relatively small and often within 5% in locations with significant numbers of degree days. The largest discrepancy was found in Shanghai, where the IWEC showed 7% fewer cooling degree hours than did the TMY weather file. The differences in extreme temperatures are random and due primarily to the selection process for the typical months. The differences in annual total solar radiation range from 0% in Kunming to 11% in Shanghai, with the other locations mostly agreeing within 5%. The differences in annual direct normal solar radiation are the most pronounced, with the IWEC and TMY weather files often disagreeing by more than 20%, or in one case 39% (Shenyang).

CONCLUSIONS

The main conclusions from this study are:

1. A set of Typical Meteorological Year (TMY) data have been developed for 28 Chinese locations, with a second set of 41 to follow
2. A model to estimate global solar radiation on a horizontal surface has been developed, and found to be fairly reliable for locations with measured daily solar radiation;
3. A method to select Typical Meteorological Months (TMM) from the period of record has been developed and applied to all 69 Chinese locations in the ISWO data base;
4. A method to interpolate dry-bulb temperatures using a Fourier Series for the daytime and a linear regression for the nighttime has been applied to fill in missing data, primarily between the three-hour observation intervals.

These Chinese TMY weather files will be made public on a CD as part of a technical document to be published in Japan in 2002.

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