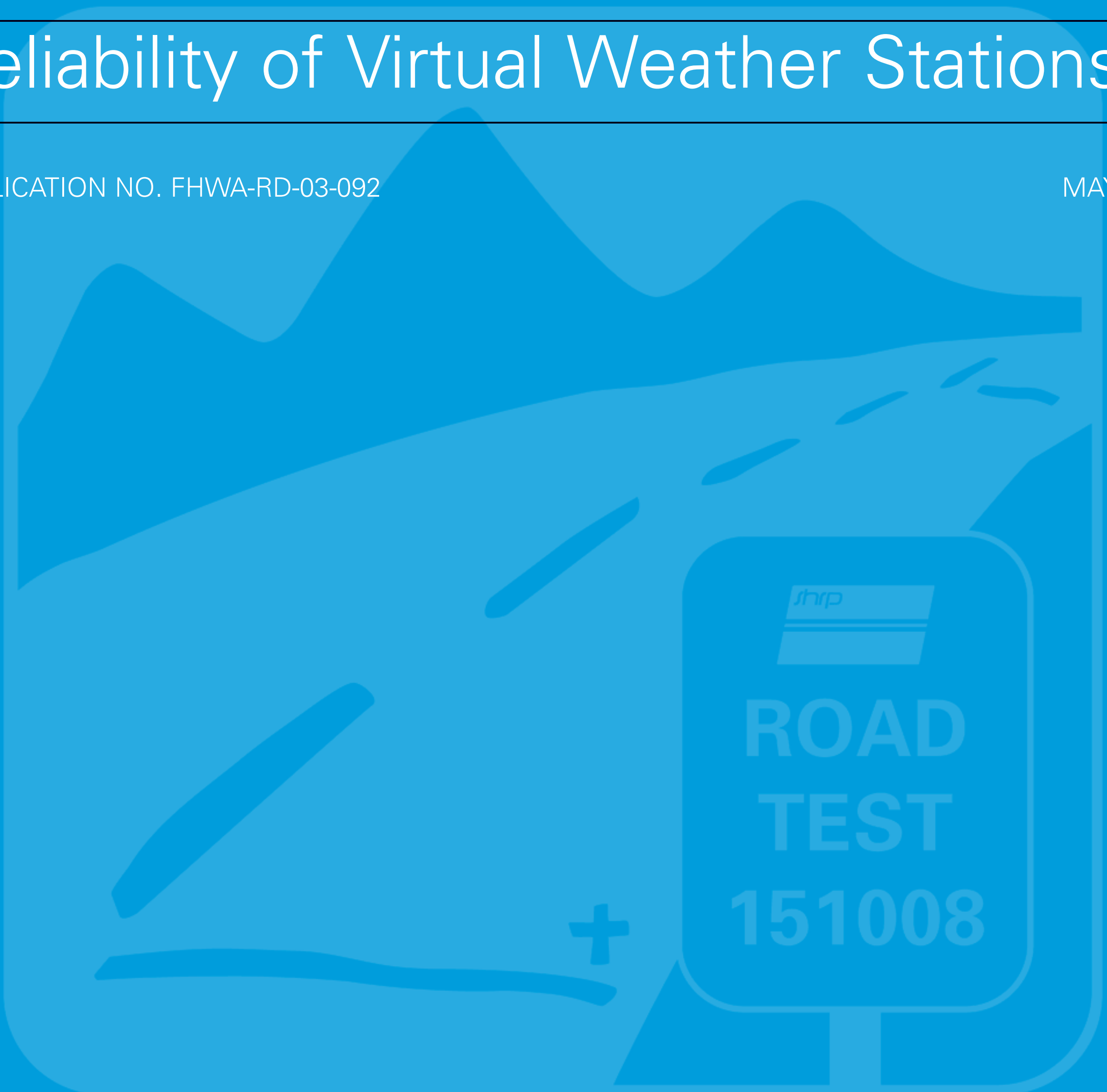
Verification of Long-Term Pavement Performance Virtual Weather Stations: Phase I Report—Accuracy and Reliability of Virtual Weather Stations

PUBLICATION NO. FHWA-RD-03-092

MAY 2006



U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

LTPP

FOREWORD

Within the Long-Term Pavement Performance (LTPP) program, two sources of data are used to characterize the climatic conditions for each test section. For the majority of the test sections, data for nearby national weather stations are obtained from the National Climatic Data Center (NCDC) and are used to compute estimated data for a virtual test section located at the test section. In addition, onsite instrumentation is used to obtain site-specific climatic data for the test sections included in the Seasonal Monitoring Program and for the Specific Pavement Studies (SPS)–1, –2, and –8 project sites.

This report documents a study undertaken to examine the reliability and accuracy of the LTPP climatic data. The study confirmed that accurate daily, monthly, and yearly estimates of climatic data for a project location can be derived by using the NCDC weather data for several nearby weather stations. The variation in the climatic data also was characterized.

Gary L. Henderson
Director, Office of Infrastructure
Research and Development

NOTICE

This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The U.S. Government assumes no liability for its contents or use thereof. This report does not constitute a standard, specification, or regulation.

The U.S. Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein only because they are considered essential to the objective of this document.

QUALITY ASSURANCE STATEMENT

The Federal Highway Administration (FHWA) provides high-quality information to serve Government, industry, and the public in a manner that promotes public understanding. Standards and policies are used to ensure and maximize the quality, objectivity, utility, and integrity of its information. FHWA periodically reviews quality issues and adjusts its programs and processes to ensure continuous quality improvement.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-RD-03-092		

4. Title and Subtitle	5. Report Date
Verification of Long-Term Pavement Performance Virtual Weather Stations: Phase I Report—Accuracy and Reliability of Virtual Weather Stations	May 2006
	6. Performing Organization Code
7. Author(s)	**8. Performing Organization Report No.**
Alaeddin Mohseni, Ph.D., P.E.	
9. Performing Organization Name and Address	**10. Work Unit No. (TRAIS)**
Alaeddin Mohseni, Ph.D., P.E. 6105 Maiden Lane Bethesda, MD 20817	**11. Contract or Grant No.** DTFH61-95-Z-00086
12. Sponsoring Agency Name and Address	**13. Type of Report and Period Covered**
Office of Infrastructure R&D Federal Highway Administration 6300 Georgetown Pike McLean, VA 22101-2296	Final Report March 2001–January 2002
	14. Sponsoring Agency Code

15. Supplementary Notes

Contracting Officer's Technical Representative (COTR): Monte Symons, HRDI-13

16. Abstract

Within the Long-Term Pavement Performance (LTPP) program, two sources of data are used to characterize the climatic conditions for each test section. For the majority of the test sections, data for nearby national weather stations are obtained from the National Climatic Data Center (NCDC) and are used to compute estimated data for a virtual test section located at the test section. In addition, onsite instrumentation is used to obtain site-specific climatic data for the test sections included in the Seasonal Monitoring Program and for the Specific Pavement Studies (SPS) –1, –2, and –8 project sites.

This report documents a study undertaken to examine the reliability and accuracy of the LTPP climatic data. The study confirmed that accurate daily, monthly, and yearly estimates of climatic data for a project location can be derived by using the NCDC weather data for several nearby weather stations. The variation in the climatic data was also characterized.

17. Key Words	18. Distribution Statement
Pavements, weather stations, LTPP, climatic data, temperature, precipitation.	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	91	

Form DOT F1700.7 (8-72) Reproduction of completed page authorized

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

TABLE OF CONTENTS

LIST OF FIGURES

Figure 18. Graph. Mean minimum temperature difference versus distance for NCDC sites. 47

LIST OF TABLES

Acronyms and Abbreviations

AWS	Automated Weather Stations
CCC	Canadian Climatic Center
CLM	Climatic Module
COV	Coefficient of Variation
FHWA	Federal Highway Administration
FI	freezing index
GPS	General Pavement Studies
IMS	Information Management System
LTPP	Long-Term Pavement Performance
NCDC	National Climatic Data Center
OWS	Operating Weather Stations
SHRP	Strategic Highway Research Program
SMP	Seasonal Monitoring Program
SPS	Specific Pavement Studies
VWS	Virtual Weather Stations

INTRODUCTION

Several climatic measurements are taken during the Long-Term Pavement Performance (LTPP) program. Onsite weather data are collected during the Seasonal Monitoring Program (SMP) for 63 General Pavement Studies (GPS) and Specific Pavement Studies (SPS) sections. Climatic data are also collected for 35 SPS–1, –2, and –8 sections using onsite automated weather stations (AWS). In the Information Management System (IMS) database, the climatic conditions for 880 SPS and GPS sites are estimated using data from as many as 5 nearby national weather stations. These estimates are referred to as virtual weather stations (VWS).

The study of onsite and estimated climatic data in the LTPP database can help determine the reliability and accuracy of climatic data and identify any possible discrepancies in the data. It will also help determine the quality of VWS estimates and the accuracy with which the site's weather conditions can be estimated.

BACKGROUND

The climatic database for the LTPP program was originally developed by the Strategic Highway Research Program (SHRP) in 1992[(1)] and was later revised and expanded by the LTPP program in 1997.[(2)] The climatic data in the LTPP database were derived from the U.S. National Climatic Data Center (NCDC) and the Canadian Climatic Center (CCC) databases. For each GPS test section and SPS project site, up to five nearby weather stations were selected and used to estimate site-specific climatic conditions. These estimates are referred to as VWS. The VWS climatic data are estimated by averaging data from up to five nearby weather stations (see figure 1) using a $1/R^2$ weighting scheme as shown in figure 2.

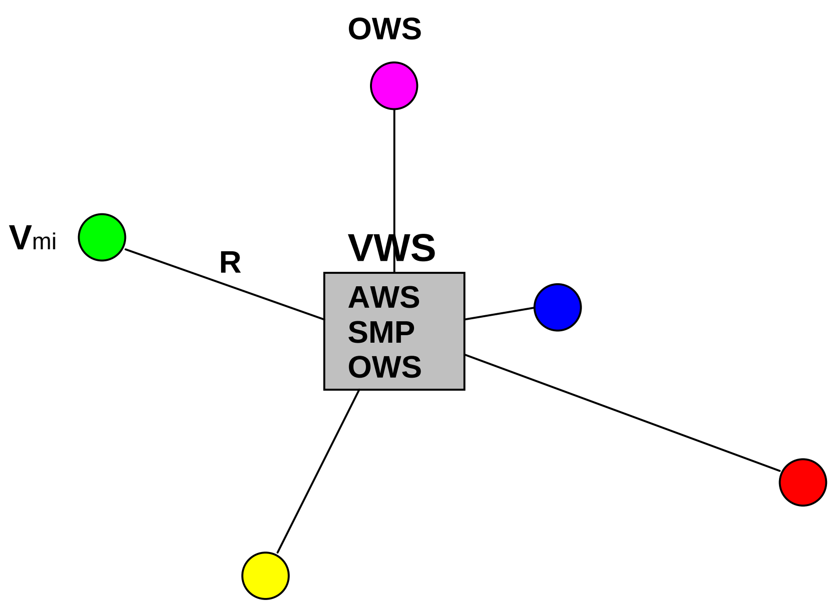


Figure 1. Diagram. Schema of VWS concept.

$$V_m = \frac{\sum_{i=1}^{k}\left(\frac{V_{mi}}{R_i^2}\right)}{\sum_{i=1}^{k}\left(\frac{1}{R_i^2}\right)}$$

Figure 2. Equation. Estimating climatic data.

where:

V_m = Calculated data element for day *m* for the VWS.
k = Number of weather stations associated with the project site (up to five).
V_{mi} = Value of a data element on day *m* for weather station *i*.
R_i = Distance of weather station *i* from the pavement project site.

The monthly and yearly estimates of several climatic parameters for every LTPP section are developed and stored in several tables in the climatic module (CLM) of the LTPP database. Between 13 and 57 years of data through 1996 are available for the LTPP test sections.

OBJECTIVES

The objectives of the study are to:

- Characterize the variation between the estimated virtual weather data and onsite measurements to determine the accuracy of virtual weather data and compare it with the accuracy of within-site measurements and yearly variation.

- Investigate factors affecting the VWS estimates and propose changes to the existing algorithm that can improve the accuracy of the estimates.

- Report any anomalies found in the measured and estimated weather data during the conduct of the project.

TASKS

The project was conducted in four tasks:

Task 1: Obtain and summarize climatic data.

Task 2: Compare estimated and onsite climatic data.
Compare daily temperatures.
Compare monthly temperatures.
Compare monthly precipitation.
Compare monthly freezing index.
Compare all other parameters.

Task 3: Determine the accuracy of VWS estimates and verify the VWS algorithm.

- Identify suspect data (outliers).
- Determine the accuracy of VWS data.
- Determine the factors affecting VWS estimates.
- Recommend modifications to the VWS concept.

Task 4: Prepare Phase I report.

TASK 1: OBTAIN AND SUMMARIZE CLIMATIC DATA

DATA SOURCES

Climatic data needed for the conduct of this project were obtained from various sources and collected into several working databases. Five sources of information were used in this study as follows.

SMP Daily Temperature and Precipitation

The daily temperature and precipitation data for seasonal monitoring sections were taken from the DataPave 2.0 software on CD-ROM. The daily temperature and precipitation data were stored in the SMP_ATEMP_RAIN_DAY table. There were data for 63 SMP sites in this table.

IMS Virtual Weather Estimates in Climatic Module

The monthly and yearly climatic summaries for VWS in the LTPP database were also extracted from DataPave 2.0. The monthly temperature data were stored in table CLM_VWS_TEMP_ MONTH, which contained data for 880 SPS and GPS sites. The daily VWS data, which are kept offline, were obtained from LTPP program customer service (CLM_VWS_DATA_DAILY table).

Automated Weather Stations

Onsite weather stations are installed at several SPS–1, –2, and –8 sites. Data from these weather stations were available in the AWS module of the database included in DataPave 2.0. The daily temperature and precipitation data were extracted from the AWS_DAILY_DATA table, which contained data for 35 SPS sites.

Operating Weather Stations (OWS)

OWS data, stored offline, were obtained from LTPP program customer service and were used in this project (owsdaily.txt file). This file contained daily temperature, precipitation, humidity, and wind data for up to five OWS near each GPS section or SPS site.

National Climatic Data Center Cooperative Data

The weather station data for 1994 through 1996 from the NCDC cooperative program were used to verify daily temperature and precipitation estimates. Data for more than 8000 weather stations existed in this database.

SUMMARY CLIMATIC DATABASES

After obtaining the needed data files, data were extracted for the desired time period and locations, and were combined into several user-friendly databases for further analysis. Four summary databases were initially developed as explained below.

VWS Daily Database

A database was developed that contained VWS daily data for SMP and AWS sites. The database contained the climatic parameters listed in table 1 (except for the mean daily temperature and snowfall). This database, which contained data for 58 SMP sections (table 2) and 24 AWS sites (table 3) was used for verification of the precision and bias of the VWS data in the LTPP database.

Table 1. Climatic data elements included in owsdaily.txt data file.

Data Element	Variable Name	Units
Daily mean air temperature	MEAN_DAY_TEMP	ºC
Daily maximum air temperature	MAX_DAY_TEMP	ºC
Daily minimum air temperature	MIN_DAY_TEMP	ºC
Daily maximum relative humidity	MAX_DAY_HUM	%
Daily minimum relative humidity	MIN_DAY_HUM	%
Daily precipitation	DAY_PRECIPITATION	mm
Daily snowfall	DAY_SNOWFALL	mm
Daily mean windspeed	MEAN_DAY_WIND_SPD	m/s
Daily maximum gust windspeed	MAX_DAY_WIND_SPD	m/s

mm – millimeters
m/s – meters/second

NCDC Daily Database

A database was developed from the NCDC cooperative weather station data for daily maximum and minimum temperature and precipitation. This database contained data for more than 8000 weather stations and was used for verification of the accuracy of estimated climatic data and for investigating factors affecting VWS estimates.

SMP Daily Database

This database contained daily SMP climatic data, and VWS estimates and OWS data for up to five nearby weather stations. It included maximum and minimum temperatures and precipitation for 58 SMP sections (table 2). The database was used to verify VWS calculations for SMP sites and to study factors affecting climatic estimates for a site.

Table 2. List of SMP sections used in this study.

No.	State Code	SHRP ID	Installation Date	No.	State Code	SHRP ID	Installation Date
1	1	0101	24-Jul-95	30	32	0204	09-Oct-96
2	1	0102	25-Jul-95	31	33	1001	14-Oct-93
3	4	0113	15-Aug-95	32	35	1112	05-Apr-94
4	4	0114	16-Aug-95	33	36	0801	22-Aug-95
5	4	0215	24-Aug-95	34	36	4018	27-Oct-93
6	4	1024	21-Aug-95	35	37	1028	17-May-95
7	6	3042	12-Jul-95	36	40	4165	29-Mar-94
8	8	1053	01-Jul-93	37	42	1606	09-Aug-95
9	9	1803	19-Aug-93	38	46	0804	14-Jul-94
10	10	0102	04-Oct-95	39	46	9187	18-Jul-94
11	13	1005	07-Aug-95	40	48	1060	30-Nov-93
12	13	1031	02-Aug-95	41	48	1068	01-Nov-93
13	13	3019	31-Jul-95	42	48	1077	25-Oct-93
14	16	1010	30-Sep-93	43	48	1122	22-Nov-93
15	18	3002	07-Sep-95	44	48	3739	06-Dec-93
16	20	4054	24-Aug-95	45	48	4142	08-Nov-93
17	23	1026	15-Sep-93	46	48	4143	17-Nov-93
18	24	1634	11-May-95	47	49	1001	05-Aug-93
19	25	1002	01-Sep-93	48	49	3011	03-Aug-93
20	27	1018	24-Aug-93	49	50	1002	06-Oct-93
21	27	1028	08-Sep-93	50	51	0113	23-Oct-95
22	27	4040	21-Sep-93	51	51	0114	23-Oct-95
23	27	6251	14-Sep-93	52	53	3813	18-Jul-95
24	28	1016	18-Jul-95	53	56	1007	10-Aug-93
25	28	1802	20-Jul-95	54	83	1801	12-Oct-93
26	30	8129	12-Aug-92	55	83	3802	14-Oct-93
27	31	0114	07-Aug-95	56	87	1622	22-Sep-93
28	31	3018	10-Aug-95	57	89	3015	29-Sep-93
29	32	0101	08-Oct-96	58	90	6405	06-Oct-93

AWS Daily Database

A database similar to the SMP daily database was developed for the AWS data. This database had data for 24 sites (table 3) and was used to verify VWS data for sections equipped with AWS.

Table 3. List of AWS sites used in the analysis.

No.	AWS ID	Installation Date	Latitude, degrees	Latitude, minutes	Longitude, degrees	Longitude, minutes	Elevation, meters
1	010101	07-Feb-95	32	36	85	15	46
2	040100	16-Feb-95	35	24	114	16	1122
3	040200	21-Jul-94	33	27	112	43	334
4	050113	09-May-95	35	42	90	34	14
5	080200	15-Sep-95	39	58	104	44	1552
6	100100	15-Nov-95	38	49	75	26	14
7	120101	11-Jun-96	26	31	80	41	57
8	200100	06-Aug-96	37	36	99	16	737
9	200200	07-Aug-96	38	59	96	59	342
10	300800	17-Nov-94	46	8	112	53	1221
11	310100	07-Aug-96	40	5	97	36	542
12	320200	19-May-95	40	43	117	2	1417
13	350101	21-Sep-95	32	40	107	4	1373
14	350801	09-Aug-96	32	11	108	18	1689
15	360800	22-Nov-95	42	21	77	53	79
16	370200	04-Aug-94	35	50	80	16	233
17	380200	13-Jan-95	46	52	97	13	298
18	390200	08-Sep-94	40	22	83	4	765
19	460800	24-Oct-96	45	55	100	24	569
20	480801	02-Oct-96	30	46	96	23	101
21	490800	18-Nov-96	40	33	111	8	1977
22	510100	26-Oct-95	36	39	79	21	198
23	530200	05-Apr-95	47	3	118	25	557
24	530800	05-May-95	46	16	117	52	551

DATA COMPLETENESS

The available climatic data in DataPave 2.0 were reviewed to assess the adequacy and completeness of the data, and to identify the areas where the quality and quantity of LTPP climatic data can be improved. This review resulted in identification of missing or incomplete climatic data in the LTPP database.

Seasonal Monitoring Program Climatic Data

Some climatic data are collected as part of the SMP. Air temperature is collected on an hourly basis and is summarized for the day. The daily summary includes mean air temperature and minimum and maximum air temperature. Total daily precipitation is also recorded at the end of the day.

Table 4 presents the number of days of available data for minimum and maximum air temperature and the total precipitation for 68 SMP installations. Some LTPP sections have more than one SMP installation since sensors are reinstalled after each overlay. The installation date for each construction event and the first and last date of reported data (SMP_DATE) are also included in table 4. The following are some general observations regarding SMP data completeness:

- Most SMP installations provided sufficient climatic data for this analysis.
- There typically is more precipitation than air temperature data.
- Some SMP sites were missing significant temperature data (e.g., sections 131031-2, 133019-1, and 390204-1).
- Data for sections 370201-1, 370205-1, 370208-1, and 370212-1 were suspect.
- Data feedback reports outlining the problems in detail were submitted to the LTPP program.

Automated Weather Station Data

Table 5 presents counts of data for 8 different climatic parameters presently collected from 35 AWS installations. The following are some observations on data completeness:

- With few exceptions, the AWS installations provided sufficient data for analysis.
- The precipitation data for section 190100 are completely missing. The windspeed data are also deficient.
- Precipitation data are deficient for section 260100.
- Some of the precipitation and almost half of the wind and solar radiation data are missing for section 260200.
- Precipitation data from 8/14/96 to 8/26/97 are missing for section 530200.

Table 4. Counts of available SMP climatic data in DataPave 2.0.

SHRP ID Const. No.	GPS_SPS	Experi-ment_No.	Install_ Date	Beginning SMP_ Date	Ending SMP_ Date	Days of Data	Days of Min_Air_ Temp-erature	Days of Max_Air_ Temp-erature	Days of Total_ Rain
010101-1	S	1	07/24/95	07/24/95	11/16/98	725	684	684	725
010102-1	S	1	07/25/95	07/25/95	11/20/98	820	816	816	820
040113-1	S	1	08/15/95	08/15/95	11/16/98	645	628	628	645
040114-1	S	1	08/16/95	08/17/95	11/17/98	678	673	673	678
040215-1	S	2	08/24/95	10/13/95	11/19/98	653	647	647	653
041024-1	G	1	08/21/95	08/28/95	11/18/98	669	663	663	669
063042-1	G	3	07/12/95	07/12/95	11/23/98	643	637	637	643
081053-1	G	1	07/01/93	10/15/93	09/25/97	873	869	869	873
091803-1	G	1	08/19/93	01/20/94	10/15/97	826	823	823	815
100102-1	S	1	10/04/95	11/18/95	06/07/99	904	899	899	867
131005-1	G	1	08/07/95	08/08/95	11/17/98	787	783	783	787
131031-1	G	1	08/02/95	08/02/95	10/16/96	344	342	342	344
131031-2	G	6S	05/31/97	10/15/97	09/13/98	303	210	210	303
133019-1	G	3	07/31/95	07/31/95	04/27/98	554	355	355	554
161010-1	G	1	09/30/93	10/22/93	05/11/97	749	744	664	749
183002-1	G	3	09/07/95	09/07/95	06/15/98	486	482	482	486
204054-1	G	4	08/24/95	08/24/95	11/18/98	577	526	526	577
231026-1	G	1	09/15/93	12/17/93	06/25/95	556	555	555	556
231026-2	G	6B	09/26/96	10/15/96	10/20/97	350	348	348	350
241634-1	G	2	05/11/95	05/13/95	04/07/98	822	817	817	822
251002-1	G	1	09/01/93	01/18/94	10/14/97	862	859	859	862
271018-1	G	1	08/24/93	09/23/93	08/28/94	291	289	289	291
271018-2	G	1	08/29/94	08/29/94	09/07/97	881	738	738	881
271028-1	G	1	09/08/93	09/09/93	09/09/97	1318	1314	1314	1318
274040-1	G	4	09/21/93	09/21/93	09/08/97	932	921	921	932
276251-1	G	1	09/14/93	09/14/93	09/09/97	1226	1219	1219	1226
281016-1	G	2	07/18/95	07/18/95	10/18/96	459	458	458	459
281802-1	G	2	07/20/95	07/20/95	11/12/98	803	797	797	803
308129-1	G	1	08/12/92	08/31/93	09/30/97	925	922	922	925
310114-1	S	1	08/07/95	08/07/95	11/17/98	615	604	604	615
313018-1	G	3	08/10/95	08/10/95	11/16/98	596	590	590	596
320101-1	S	1	10/08/96	11/10/96	09/09/97	287	284	284	287
320204-1	S	2	10/09/96	11/09/96	09/08/97	303	302	302	303

Table 4. Counts of available SMP climatic data in DataPave 2.0 (continued).

SHRP ID Const. No.	GPS_SPS	Experi-ment_No.	Install_ Date	Beginning SMP_Date	Ending SMP_Date	Days of Data	Days of Min_Air_ Temp-erature	Days of Max_Air_ Temp-erature	Days of Total_ Rain
331001-1	G	1	10/14/93	12/28/93	10/21/97	925	923	923	925
351112-1	G	1	04/05/94	06/20/94	09/08/97	565	560	560	565
360801-1	S	8	08/22/95	09/26/95	03/25/99	910	906	906	902
364018-2	G	4	10/27/93	12/30/93	10/13/97	926	923	923	926
370201-1	S	2	10/18/93	08/04/94	02/22/99	1302	98*	98*	1302*
370205-1	S	2	10/18/93	09/23/94	02/22/99	1142	98*	98*	1142*
370208-1	S	2	10/17/93	06/24/97	02/22/99	369	98*	98*	369*
370212-1	S	2	10/17/93	09/23/94	02/22/99	1066	98*	98*	1066*
371028-1	G	1	05/17/95	05/18/95	10/19/98	906	900	900	906
390204-1	S	2	07/20/95	02/10/98	05/17/99	400	60	60	400
404165-1	G	2	03/29/94	03/29/94	09/10/97	752	748	748	752
421606-1	G	4	08/09/95	08/10/95	10/26/98	782	780	780	782
460804-1	S	8	07/14/94	07/14/94	09/21/97	679	673	673	679
469187-2	G	1	07/18/94	07/18/94	09/22/97	609	600	600	609
481060-1	G	1	11/30/93	11/30/93	09/29/97	828	807	807	828
481068-1	G	1	11/01/93	12/16/93	09/16/97	846	844	844	846
481077-1	G	1	10/25/93	12/15/93	09/15/97	867	865	865	867
481122-1	G	1	11/22/93	01/25/94	06/15/97	674	670	670	674
483739-1	G	1	12/06/93	12/06/93	09/25/94	294	293	293	294
483739-2	G	1	09/26/94	09/26/94	01/29/95	126	126	126	126
483739-3	G	1	01/30/95	01/30/95	09/30/97	444	442	442	444
484142-1	G	4	11/08/93	11/09/93	09/25/97	840	835	835	840
484143-1	G	4	11/17/93	02/15/94	09/24/97	719	714	714	719
491001-1	G	1	08/05/93	11/04/93	05/03/95	442	436	436	442
493011-1	G	3	08/03/93	11/02/93	09/21/97	875	870	870	875
501002-1	G	1	10/06/93	01/12/94	10/22/97	903	901	901	851
510113-1	S	1	10/23/95	10/25/95	04/19/99	814	809	809	814
510114-1	S	1	10/23/95	01/25/96	06/04/99	802	796	796	802
533813-1	G	3	07/18/95	07/28/95	12/08/98	735	699	701	735
561007-1	G	1	08/10/93	10/19/93	06/18/97	756	672	672	756
831801-1	G	1	10/12/93	11/12/93	04/04/99	1619	1588	1588	1619
833802-1	G	3	10/14/93	10/14/93	11/05/98	908	900	900	908
871622-1	G	1	09/22/93	12/13/93	10/29/97	893	890	890	893
893015-1	G	3	09/29/93	12/15/93	11/05/97	1184	1067	1067	1184
906405-1	G	1	10/06/93	10/06/93	09/18/97	794	789	789	794

Data marked with an asterisk (*) appears to be unusable.

Table 5. Counts of AWS collected data for selected climatic parameters.

AWS_ID	Installation Date	From Date	To Date	Days of Min_ Day_ Temp.	Days of Max_ Day_ Temp.	Days of Total_ Day_ Precip.	Days of Min_ Day_ Hum-idity	Days of Max_ Day_ Hum-idity	Days of Mean_ Day_ Wind_ SPD	Days of Max_ Day_ Wind_ SPD	Days of Mean_ Day_Solar
010101	02/07/95	02/07/95	03/31/98	1147	1147	1149	1072	1072	1147	1147	1147
040100	02/16/95	05/04/95	11/30/98	1306	1306	1307	1304	1304	1306	1306	1306
040200	07/21/94	07/21/94	11/30/98	1592	1592	1594	1590	1590	1592	1592	1592
050113	05/09/95	05/10/95	08/31/98	1186	1186	1188	1118	1118	1186	1186	1186
050803	09/25/97	09/25/97	08/31/98	339	339	341	339	339	339	339	339
05A601	05/20/97	05/21/97	04/30/98	343	343	345	304	304	343	343	343
080200	09/15/95	09/15/95	11/30/98	1163	1163	1043	1150	1150	1163	1163	1163
100100	11/15/95	11/15/95	11/30/98	1110	1110	1083	1111	1111	1071	1071	1111
120101	06/11/96	06/12/96	02/28/98	620	620	623	599	599	620	620	620
190100*	03/04/97	03/05/97	09/30/98	575	575	0*	573	480	403*	403*	575
190200	03/03/97	03/03/97	05/21/98	444	444	445	444	444	444	444	444
200100	08/06/96	08/06/96	07/31/98	724	724	725	724	721	724	724	724
200200	08/07/96	08/07/96	07/31/98	723	723	724	723	716	723	723	723
220113	10/14/97	10/14/97	08/31/98	249	249	305	249	249	249	249	249
260100*	09/04/96	02/27/97	09/30/98	580	580	398*	580	558	580	580	580
260200*	09/05/96	07/26/97	09/30/98	432	432	343*	432	423	236*	236*	236*
300100	05/20/98	05/20/98	11/30/98	194	194	195	194	194	193	193	194
300800	11/17/94	11/18/94	11/30/98	1473	1473	1246	1473	1473	1473	1473	1473
310100	08/07/96	08/07/96	08/31/98	754	754	755	754	754	754	754	754
320200	05/19/95	05/19/95	11/30/98	1272	1272	1274	1268	1268	1272	1272	1272
350101	09/21/95	09/27/95	01/31/98	847	847	848	847	847	833	833	847
350801	08/09/96	08/10/96	01/31/98	530	530	533	528	528	530	530	530
360800	11/22/95	11/22/95	10/31/98	1059	1059	1060	1059	1059	1055	1055	1059
370200	08/04/94	08/04/94	07/31/97	1008	1008	1010	1008	987	1002	1002	981
370800	03/10/98	03/11/98	05/31/98	82	82	82	82	82	82	82	82
380200	01/13/95	01/13/95	09/30/98	1046	1046	1048	1046	1007	1046	1046	1046
390200	09/08/94	09/08/94	08/31/98	1179	1179	1182	1179	1094	1179	1179	1179
400113	05/29/97	05/29/97	12/31/97	216	216	217	210	210	216	216	216
460800	10/24/96	10/24/96	09/30/98	706	706	707	706	704	620	620	706
480113	08/26/97	08/26/97	02/28/98	186	186	187	186	186	186	186	186
480801	10/02/96	10/02/96	02/28/98	513	513	437	470	470	513	513	513
490800	11/18/96	11/18/96	11/30/98	742	742	743	740	740	742	742	742
510100	10/26/95	10/26/95	08/31/98	970	970	963	970	924	964	964	970
530200*	04/05/95	04/05/95	11/30/98	1335	1335	958*	1320	1320	1335	1335	1335
530800	05/05/95	07/18/95	11/30/98	1231	1231	1232	1223	1223	1231	1231	1231
Total		07/21/94	11/30/98	27876	27876	26290	27575	27248	27352	27352	27654

*Identifies deficient data.

LTPP VWS Estimates in Climatic Module

Monthly data for selected VWS parameters were reviewed for completeness. Different temperature, precipitation, humidity, and windspeed data provided with DataPave 2.0 were considered. Table 6 includes a list of VWS parameters that were reviewed.

Table 6. List of selected VWS climatic parameters reviewed for data completeness.

IMS Table	IMS Field	Abbreviation
CLM_VWS_TEMP_MONTH	MIN_MON_TEMP_AVG	Temp_Min
	MAX_MON_TEMP_AVG	Temp_Max
	DAYS_BELOW_0_C_MONTH	Temp_Cold
	DAYS_ABOVE_32_C_MONTH	Temp_Hot
	FREEZE_INDEX_MONTH	Temp_FI
	FREEZE_THAW_MONTH	Temp_FT
CLM_VWS_PRECIP_MONTH	TOTAL_MON_PRECIP	PRC_Total
	WET_DAYS_MONTH	PRC_Wet
	TOTAL_SNOWFALL_MONTH	PRC_Snow
CLM_VWS_HUMIDITY_MONTH	MIN_MON_HUM_AVG	Humid_Min
	MAX_MON_HUM_AVG	Humid_Max
CLM_VWS_WIND_MONTH	MEAN_MON_WIND_AVG	Wind_Mean
	MAX_MON_WIND_SPD	Wind_Max

GPS Data Counts

The Administration module of the LTPP database contains an Experiment_Section table that is considered the master control section for the database. All test sections are supposed to have entries in the table. The table thus is both a source of data and provides a cross check on data from other areas of the database. For GPS sections, the link between the VWS climatic tables and the Experiment_Section table is fairly complete. Table 7 shows total data counts (in months) for selected parameters listed in table 6. Out of the 790 GPS sections currently in the Experiment_Section table, 788 sections had VWS data; however, data for 2 GPS sections could not be located. These sections (both GPS–1) are listed in table 8. One GPS section (section 481094), also listed in table 9, had VWS estimates, but was not listed in the Experiment_Section table.

Table 7 shows that 788 GPS sections had adequate temperature and precipitation data. There are slightly more data for precipitation than for temperature (211,523 and 211,458 months, respectively). Humidity and windspeed data, on the other hand, were missing for more than 40 percent of the sections. Minimum and maximum humidity were missing for 328 sections, average windspeed was missing for 310 sections, and maximum windspeed was missing for 348 sections. For the sections that had humidity and windspeed data, the average number of records per section was almost half of the temperature and precipitation data. This indicates that these data are incomplete during the data collection period.

Table 7. Record count of selected parameters for 788 GPS sections.

Parameter	Total Records (months of data)	Number of GPS Sections With Data	Average Months of Data per Section
Temp_Min	211,458	788	268
Temp_Max	211,458	788	268
Temp_Cold	211,458	788	268
Temp_Hot	211,458	788	268
Temp_FI	211,458	788	268
Temp_FT	211,458	788	268
PRC_Total	211,523	788	268
PRC_Wet	211,523	788	268
PRC_Snow	211,523	788	268
Humid_Min	71,893	460	156
Humid_Max	71,893	460	156
Wind_Mean	68,963	478	144
Wind_Max	93,336	440	212

Table 8. GPS sections and SPS sites without VWS estimates.

Experiment Type	Experiment No.	LTPP ID
GPS	1	481061
	1	901802
SPS	8	370800
	1	550100
	2	550200
	8	550800
	9	55C900
	9	81A900
	9	89A900

Table 9. Sections with VWS data but not in the Experiment_Section table.

Experiment Type	Experiment No.	LTPP ID
GPS	unknown	481094
SPS	4	32B400
	6	470600
	9	50900
	9	90900
	9	120900
	9	180900
	9	200900
	9	270900
	9	280900
	9	310900
	9	350900
	9	370900
	9	390900
	9	480900
	9	550900, 55A900, 55B900

SPS Data Counts

For SPS sites, the link between the VWS climatic data and the Experiment_Section table is not direct. The CLM_SITE_VWS_LINK table is designed to provide the link between the VWS data and other tables. However, this table currently only includes data for GPS sections and SPS control sections. Expanding this table to other SPS sections (noncontrol sections and SPS sections that are linked to GPS) can significantly improve the VWS data accessibility for SPS.

Out of the 200 SPS sites that are represented in the Experiment_Section table, 120 sites are linked to GPS through the SPS_GPS_Link table. Data for these sections are the same as the GPS data. Data for seven SPS sites were not located. These sections are listed in table 8. The data counts for the other 74 SPS sites are listed in table 10. There is also one site that is both linked to GPS and has VWS data (VWS_ID 340900 linked to GPS section 341011). SPS sections listed in table 9 had VWS data, but were not listed in the Experiment_Section table. These data were not included in this review since pertinent data could not be located.

As with the GPS data, almost half of these SPS sites were missing humidity and windspeed data. The average months of data per section for these data were about 40 percent less than the temperature data, indicating incomplete coverage.

Table 10. Record count for selected parameters for 74 SPS sites.

Parameter	Total Records (months of data)	Number of SPS Sites With Data	Average Months of Data per Section
Temp_Min	18,332	74	248
Temp_Max	18,332	74	248
Temp_Cold	18,332	74	248
Temp_Hot	18,332	74	248
Temp_FI	18,332	74	248
Temp_FT	18,332	74	248
PRC_Total	18,336	74	248
PRC_Wet	18,336	74	248
PRC_Snow	18,336	74	248
Humid_Min	5,822	39	149
Humid_Max	5,822	39	149
Wind_Mean	5,842	42	139
Wind_Max	6,814	34	200

Data Coverage and Adequacy

Climatic data coverage was calculated from the first and last month of climatic data for a section and shows the maximum number of years of climatic data available for every section. Table 11 shows the distribution of years of climatic data for 862 GPS sections and SPS sites. This table shows that about half of the sections (408 sections) have between 16 and 20 years of climatic data, while the other half of the sections have more than 20 years of data. The most extensive data are for the SPS site (ID 810500), with more than 56 years of data. Two GPS sections (ID 541640 and ID 134111), each with about 13 years of data, have the least data.

Data adequacy was only evaluated to identify the quantity of the missing data in the LTPP database and is not relevant to the analysis of the data. Data adequacy for each parameter is assessed by the percentage of the available data for the period covered. This value is derived by dividing the number of months of available data by the number of months of data coverage. Table 12 includes the distribution of data adequacy for GPS and SPS sections for different climatic parameters. The precipitation data for all 862 sections cover the entire data period (100 percent adequacy) for all parameters. For temperature parameters, 859 sections were 100 percent complete, while 3 sections had data for 95 percent of the covered period. Humidity data for 363 sections and mean windspeed for 342 sections were missing (not available), and the remaining data had less than 80 percent adequacy (no section had data for the entire data coverage). The maximum windspeed was missing for 388 sections; however, about 15 percent of the sections were 100 percent complete, while another 15 percent were 95 percent complete.

Table 11. Distribution of years of climatic data for GPS and SPS sections.

Years of Climatic Data (Coverage)		Number of Sections		
From	To	GPS	SPS	All
12	16	2	0	2
16	20	356	52	408
20	24	124	1	125
24	28	136	8	144
28	32	63	8	71
32	36	50	2	52
36	40	30	1	31
40	44	13	1	14
44	48	7	0	7
48	52	7	0	7
52	56	0	0	0
56	60	0	1	1
All		**788**	**74**	**862**

Table 12. Distribution of data coverage for different climatic parameters.

Adequacy, % of coverage	Temperature-Related Parameters						Precipitation			Humidity and Windspeed			
	Temp_Min	Temp_Max	Temp_Cold	Temp_Hot	Temp_FI	Temp_FT	PRC_Total	PRC_Wet	PRC_Snow	Humid_Min	Humid_Max	Wind_Mean	Wind_Max
0	0	0	0	0	0	0	0	0	0	363	363	342	388
5	0	0	0	0	0	0	0	0	0	1	1	13	7
10	0	0	0	0	0	0	0	0	0	2	2	12	4
15	0	0	0	0	0	0	0	0	0	2	2	1	4
20	0	0	0	0	0	0	0	0	0	2	2	1	2
25	0	0	0	0	0	0	0	0	0	3	3	3	1
30	0	0	0	0	0	0	0	0	0	5	5	13	1
35	0	0	0	0	0	0	0	0	0	8	8	21	3
40	0	0	0	0	0	0	0	0	0	13	13	38	3
45	0	0	0	0	0	0	0	0	0	44	44	28	10
50	0	0	0	0	0	0	0	0	0	65	65	51	11
55	0	0	0	0	0	0	0	0	0	42	42	35	8
60	0	0	0	0	0	0	0	0	0	44	44	37	13
65	0	0	0	0	0	0	0	0	0	25	25	23	20
70	0	0	0	0	0	0	0	0	0	22	22	26	17
75	0	0	0	0	0	0	0	0	0	35	35	36	37
80	0	0	0	0	0	0	0	0	0	186	186	182	29
85	0	0	0	0	0	0	0	0	0	0	0	0	23
90	0	0	0	0	0	0	0	0	0	0	0	0	38
95	3	3	3	3	3	3	0	0	0	0	0	0	140
100	859	859	859	859	859	859	862	862	862	0	0	0	103

Data Quality

The number of weather stations on which VWS estimates are based is related to the quality of the estimated data since better estimates are made from five weather stations rather than a single weather station. This fact was demonstrated by comparing different estimates (refer to the discussions for table 27).

Table 13 shows the average number of contributing weather stations for each VWS table. Data in table 13 show that the temperature and precipitation estimates are generally made based on data from more than the four closest weather stations. The humidity and windspeed estimates, however, are based on data from a single weather station.

Table 13. Total record counts and number of contributing weather stations for AWS estimates.

IMS Table	Total Records (months of data)	Average Number of Contributing Weather Stations
CLM_VWS_TEMP_MONTH	233,846	4.5
CLM_VWS_PRECIP_MONTH	233,915	4.6
LM_VWS_HUMIDITY_MONTH	79,722	1.0
CLM_VWS_WIND_MONTH	118,406	1.0

TASK 2: COMPARE ESTIMATED AND ONSITE CLIMATIC DATA

During this task, climatic estimates in the LTPP database were compared to the measured data. The daily, monthly, and yearly VWS data estimates were compared to the onsite SMP and AWS measured data. The results of the comparisons were presented in various charts and graphs for numerical and visual verification of the accuracy of the VWS estimates. An explanation of the comparisons for each climatic parameter follows.

MINIMUM AND MAXIMUM TEMPERATURES

Daily and monthly temperature estimates (minimum and maximum) were compared to AWS and SMP measured data for the same periods. The results are presented below.

Precision and Bias of Estimate

The VWS estimates in the database were compared to the daily measured data from the AWS and SMP sites. For every SMP and AWS site, the collected daily low (minimum) and high (maximum) air temperatures were compared to the current VWS estimates in table CLM_VWS_DATA_DAILY, which is based on up to five nearby weather stations. Figures 3 through 5 show the estimated versus measured maximum daily temperature for three sample sites. Figure 3 shows a close relationship between the estimated and collected data, while the data shown in figure 4 show more variation between the two. Figure 5 is an example of a relationship that is close, but has a shift in the data.

The mean and standard deviation of the difference between the estimated and measured data (error of estimate) were used for the purpose of numerical comparison of the data. The mean of the error was used as an estimate bias and shows a shift in the data (e.g., figure 5). The standard deviation of the error was used as estimate variation, which relates to the precision of the estimated data (low precision for data in figure 3 and higher precision in figure 4).

Comparing Daily Minimum and Maximum Temperatures

Table 14 includes the mean and standard deviation of error (bias and precision of estimate) for minimum and maximum temperatures for AWS and SMP sites. There are data for 82 sites (24 AWS and 58 SMP sites) in this table. The mean error for the maximum temperature ranged from –1.2 to 6.3 degrees Celsius (°C), with an average of 0.57 °C. The overall mean error was 0.51 °C (for all days of data). The standard deviation of error for the maximum temperature ranged from 0.73 to 5.8 °C, with an average of 2.75 °C per section. The standard deviation for all days of data (overall) was 3.14 °C. The overall value is usually higher than the average per section since it includes the effect of bias, while this effect is removed by averaging standard deviations for the sections. The average mean error per section and the overall mean error, however, are usually comparable.

The mean error for the minimum temperature was between –2.6 and 2.8 °C, with an average of –0.13 °C per section (–0.14 °C overall), and the standard deviation of error was between 1.0 and 7.0 °C, with an average of 2.26 °C per section (2.55 °C overall).

More than one set of climatic instrumentation was installed at some LTPP project sites. For example, the first three sections in table 14 were in the same vicinity since they were all installed at the same SPS–1 site (typically within a 1.6-kilometer (km) stretch). Despite their proximity, some differences in the precision and bias of the estimated value were evident. For example, the mean error for the minimum temperature estimate was between 0 and 1.33 °C, and the standard deviation ranged from 2.06 to 2.41 °C.

Similarly, SMP section numbers 4–8, 15–16, 37–38, 41–42, 47–48, 56–57, and 71–73 are built within the same project site. Data for these sites may be used to determine the variation between onsite measurements and thus the precision and bias of the measured data within a site. This provides a useful reference for comparing onsite and estimated data, and for determining the required accuracy of the estimated data.

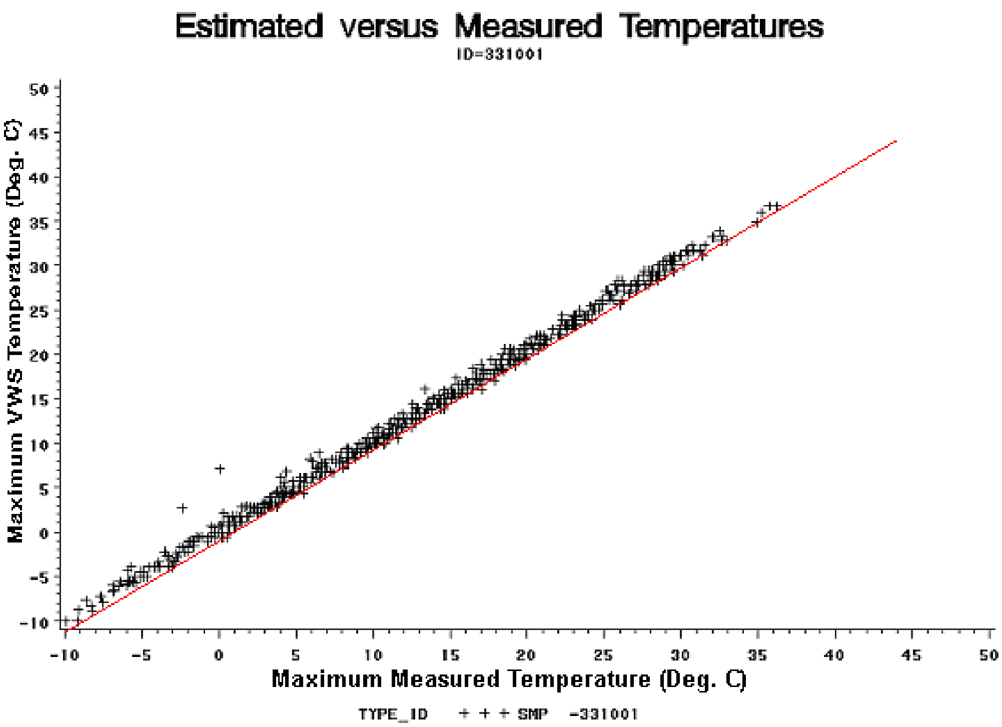


Figure 3. Graph. Estimated versus measured maximum temperature for section 331001.

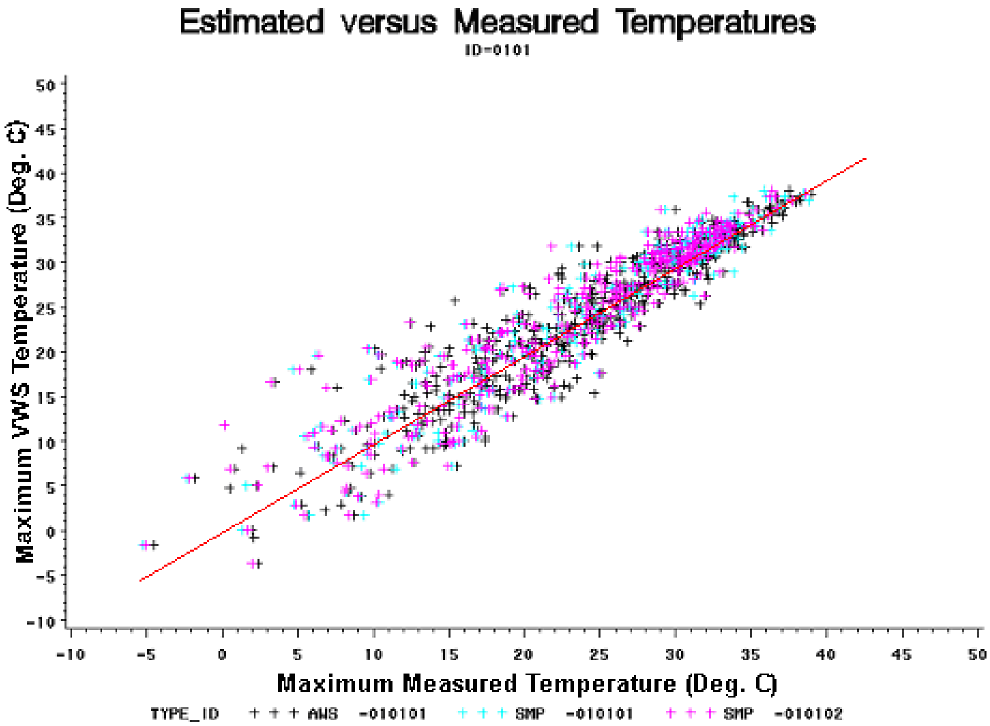


Figure 4. Graph. Estimated versus measured maximum temperature for site 010100.

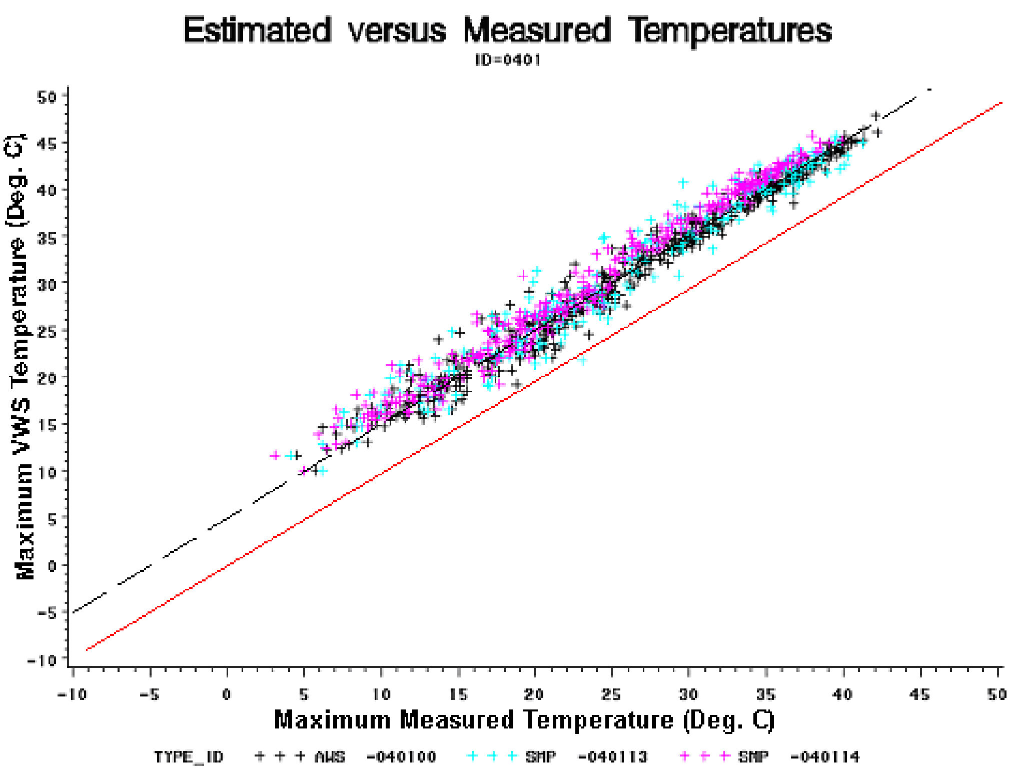


Figure 5. Graph. Estimated versus measured maximum temperature for site 040100.

Table 14. Summary statistics for error of daily temperature estimates.

No.	SHRP ID	Source of Measured Data	Days of Data	Error (Measured-Estimated), °C			
				Max. Temperature		Min. Temperature	
				Mean	Std. Dev.	Mean	Std. Dev.
1	10101	AWS	686	-0.08	3.03	-0.01	2.06
2	10101	SMP	313	0.35	3.34	-0.10	2.41
3	10102	SMP	442	0.47	3.17	1.33	2.09
4	40100	AWS	606	4.98	1.28	2.23	2.34
5	40113	SMP	253	5.47	1.93	-0.02	3.01
6	40114	SMP	330	6.28	1.28	-0.36	3.15
7	40200	AWS	892	1.25	1.61	-0.79	1.59
8	40215	SMP	310	2.00	1.45	-1.26	1.63
9	41024	SMP	286	1.85	1.26	-2.59	2.66
10	50113	AWS	601	-0.01	3.19	-0.49	2.02
11	63042	SMP	295	2.03	1.90	-0.40	1.03
12	80200	AWS	459	-0.39	5.83	-0.99	2.76
13	81053	SMP	600	0.65	3.50	0.59	2.52
14	91803	SMP	599	0.26	0.85	0.18	1.15
15	100100	AWS	410	-0.24	2.58	1.47	1.94
16	100102	SMP	335	0.38	2.47	1.09	1.83
17	120101	AWS	201	0.05	2.23	-0.26	1.20
18	131005	SMP	395	-0.26	2.74	-0.84	1.90
19	131031	SMP	342	-0.14	3.38	0.22	2.16
20	133019	SMP	353	0.27	3.31	1.87	2.28
21	161010	SMP	519	1.45	1.94	1.05	1.92
22	183002	SMP	287	1.38	3.56	-0.27	2.57
23	200100	AWS	147	-0.53	5.04	-1.35	2.96
24	200200	AWS	146	0.46	2.75	0.76	1.78
25	204054	SMP	302	1.40	3.25	0.43	2.04
26	231026	SMP	629	0.44	2.91	0.48	2.54
27	241634	SMP	502	1.28	1.58	0.19	1.32
28	251002	SMP	569	-0.21	3.29	-2.03	2.10
29	271018	SMP	898	1.44	3.17	1.12	1.99
30	271028	SMP	1057	0.89	2.50	0.11	2.27
31	274040	SMP	730	0.85	4.36	-0.05	3.42
32	276251	SMP	979	-0.61	4.33	-0.08	3.71
33	281016	SMP	457	0.13	3.23	-0.46	2.53
34	281802	SMP	410	-1.06	2.09	0.94	1.84
35	300800	AWS	763	1.37	2.51	-1.74	2.40
36	308129	SMP	692	0.94	2.88	-0.36	2.43
37	310100	AWS	143	-0.43	4.14	-0.50	2.41
38	310114	SMP	309	0.59	4.73	-1.08	2.99
39	313018	SMP	313	0.61	5.72	-1.49	2.90
40	320101	SMP	51	0.37	1.93	0.45	1.91
41	320200	AWS	571	0.84	1.51	-0.57	1.95
42	320204	SMP	52	0.22	1.92	0.01	1.89

Table 14. Summary statistics for error of daily temperature estimates (continued).

No.	SHRP ID	Source of Measured Data	Days of Data	Error (Virtual-Measured), °C			
				Max. Temperature		Min. Temperature	
				Mean	Std. Dev.	Mean	Std. Dev.
43	331001	SMP	624	0.45	0.73	-1.15	1.21
44	350101	AWS	458	-0.11	2.46	-1.69	1.96
45	350801	AWS	142	0.34	1.37	-1.72	1.66
46	351112	SMP	356	0.92	1.57	-0.11	1.71
47	360800	AWS	403	0.56	2.31	-0.19	1.71
48	360801	SMP	355	1.15	2.46	0.06	1.79
49	364018	SMP	636	0.20	3.25	-0.83	2.92
50	370200	AWS	877	0	1.60	0.01	1.95
51	371028	SMP	464	0	1.78	1.02	1.68
52	380200	AWS	402	0.47	4.05	-0.28	2.75
53	390200	AWS	635	-0.41	4.31	-0.28	3.19
54	404165	SMP	495	0.86	3.79	0.51	2.58
55	421606	SMP	362	0.02	2.03	-0.26	1.27
56	460800	AWS	68	-0.24	1.64	0.51	2.14
57	460804	SMP	406	0.52	1.73	-0.34	1.81
58	469187	SMP	342	0.15	3.46	0.70	1.71
59	480801	AWS	90	0.69	2.07	-0.35	1.90
60	481060	SMP	577	0.86	1.44	0.92	1.53
61	481068	SMP	583	-0.39	4.04	-1.01	2.75
62	481077	SMP	605	-0.02	2.82	-0.09	1.85
63	481122	SMP	535	-0.01	3.05	-0.79	2.59
64	483739	SMP	601	-0.46	3.03	0.49	2.41
65	484142	SMP	611	-1.20	4.06	-0.27	3.18
66	484143	SMP	447	0.59	4.06	0.63	6.97
67	490800	AWS	43	2.25	2.29	2.76	2.86
68	491001	SMP	536	0.17	1.36	-1.71	1.66
69	493011	SMP	603	1.55	2.09	-0.07	1.98
70	501002	SMP	604	-0.43	2.97	-0.24	2.99
71	510100	AWS	362	-0.32	4.49	-0.86	3.06
72	510113	SMP	324	0.19	4.36	0.65	2.70
73	510114	SMP	266	0.75	4.27	-0.51	2.88
74	530200	AWS	631	-0.58	3.07	-0.89	1.82
75	530800	AWS	526	-0.35	3.66	-0.33	1.60
76	533813	SMP	356	0.80	2.97	-1.19	1.60
77	561007	SMP	588	0.48	3.96	-1.05	3.37
78	831801	SMP	973	0.02	1.29	-0.16	1.39
79	833802	SMP	575	-0.18	1.35	-0.12	2.61
80	871622	SMP	582	0.23	1.25	0.12	1.78
81	893015	SMP	782	0.19	1.60	0.33	2.09
82	906405	SMP	606	0.23	1.69	0.68	2.02
All Days			**38,665**	**0.51**	**3.14**	**-0.14**	**2.55**
Average Section			**471.5**	**0.57**	**2.75**	**-0.13**	**2.26**

The distribution of errors for maximum and minimum temperatures is shown in figures 6 and 7 for AWS sites. Figures 8 and 9 show the same distribution for SMP sites. It shows that errors in these figures are approximately normally distributed.

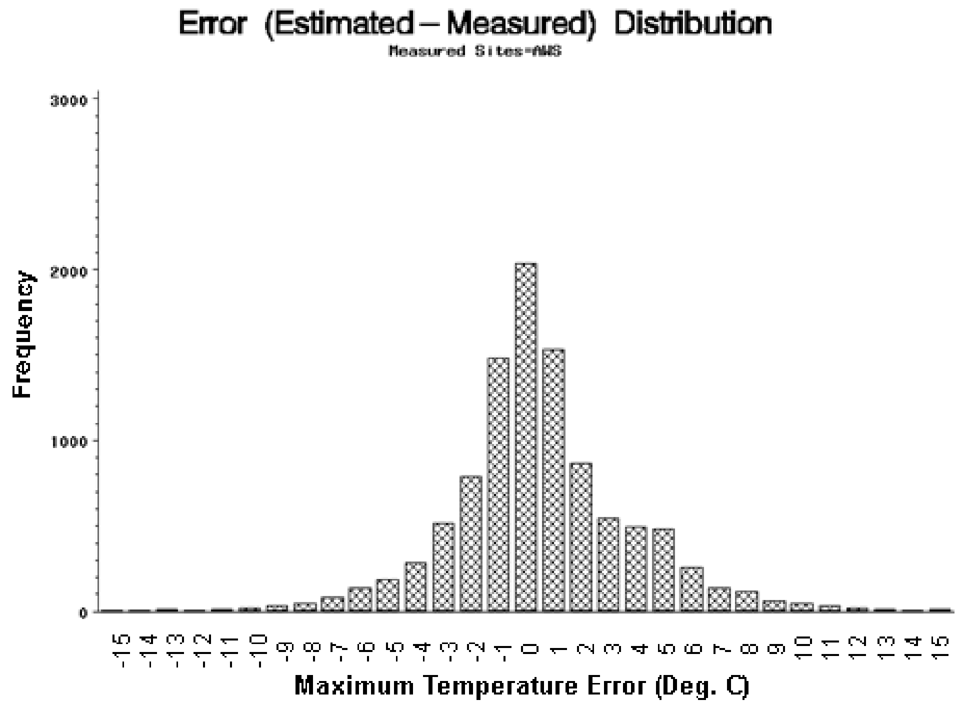


Figure 6. Bar chart. Error distribution of maximum temperature estimates for AWS sites.

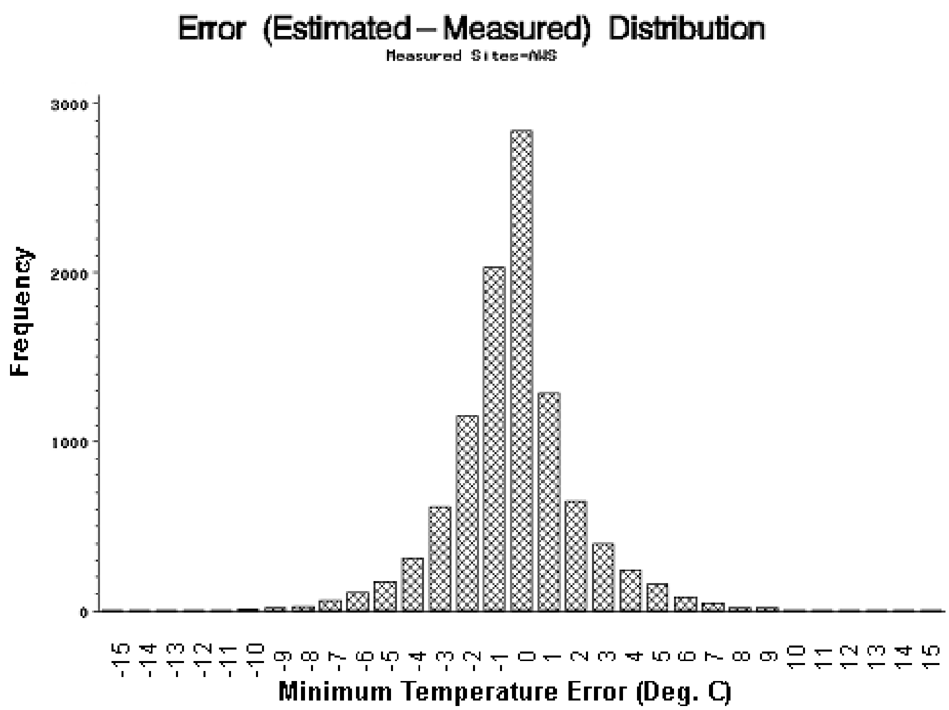


Figure 7. Bar chart. Error distribution of minimum temperature estimates for AWS sites.

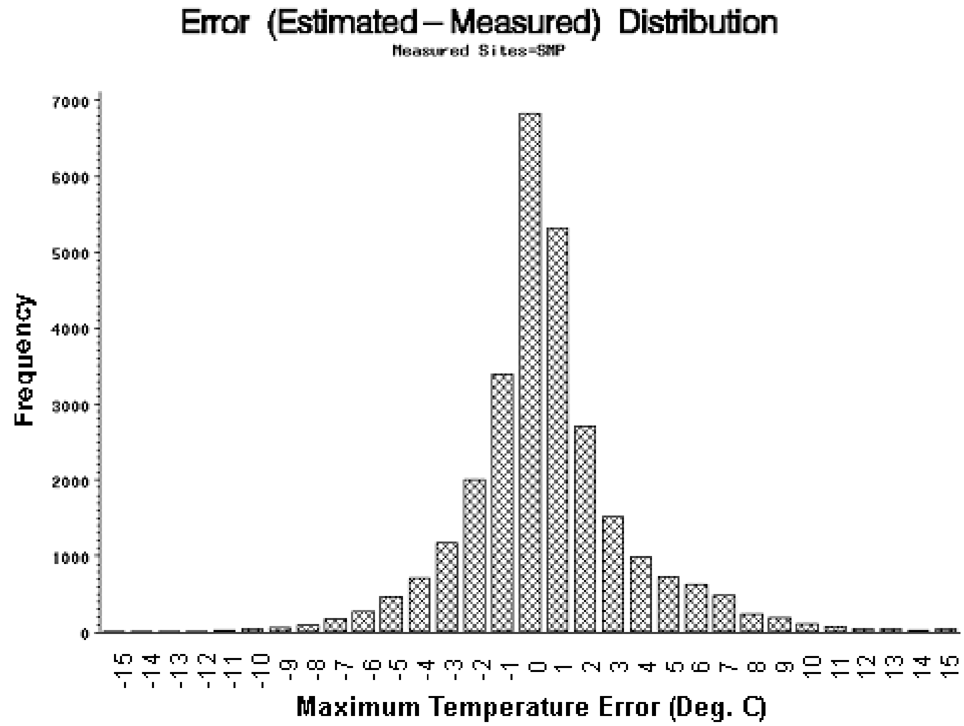


Figure 8. Bar chart. Error distribution of maximum temperature estimates for SMP sites.

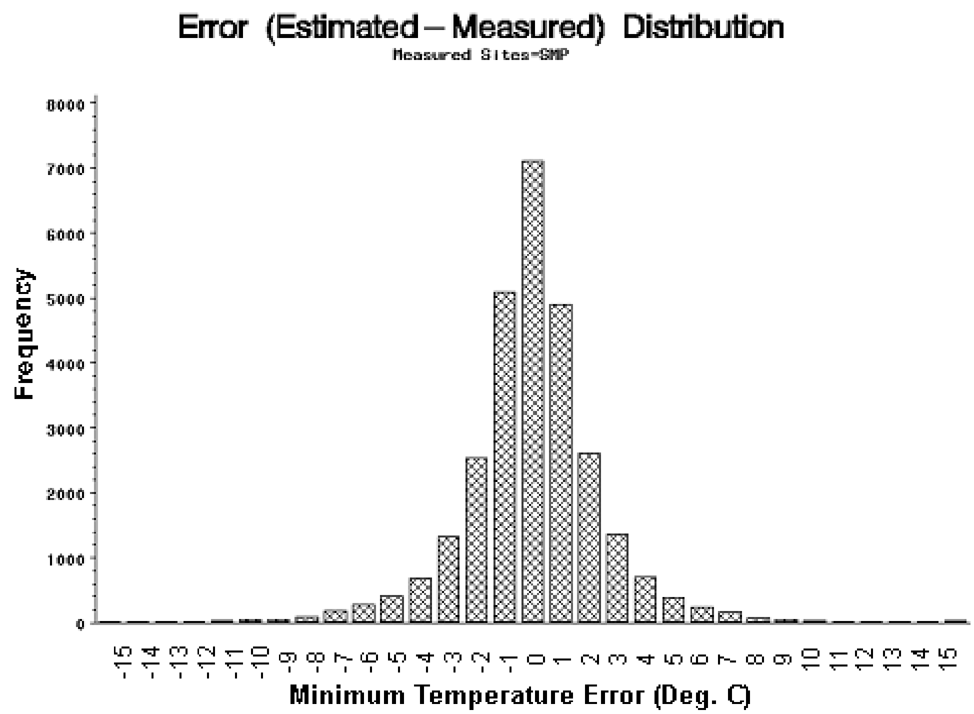


Figure 9. Bar Chart. Error distribution of minimum temperature estimates for SMP sites.

Comparing Monthly Minimum and Maximum Temperatures

The monthly average maximum and minimum daily temperatures were calculated for all SMP and AWS sites and were compared with the monthly estimates in LTPP database table CLM_VWS_TEMP_MONTH. Table 15 shows the mean and standard deviation of error (estimated minus measured) for all AWS and SMP sites and contains 1120 months of measured and estimated data. Some sections had as few as 1 month of data and some had as many as 32 months.

The mean error for the maximum temperature ranged from –1.2 to 6.26 °C, with an average of 0.58 °C. The overall mean error was 0.51 °C. The highest mean error (bias) belongs to site 040100 (section numbers 4–6). The bias is mainly caused by the high elevation difference between the site and the five closest weather stations and can be somewhat improved.

The standard deviation of error for the maximum temperature for the sections ranged from 0.19 to 1.11 °C, with an average of 0.47 °C. The overall standard deviation for all 1120 months of data was 1.2 °C. The standard deviation for the majority of the sites was less than 0.5 °C.

The mean error (bias) for the minimum temperature ranged from –2.5 to 2.55 °C, with an average mean error of –0.14 °C. The standard deviation of error for the sections ranged from 0.11 to 2.22 °C, with an average of 0.53 °C. The overall standard deviation for all months of data was almost twice as much (1.04 °C).

The average estimated bias (mean error) for the daily and monthly maximum temperatures is very close (0.57 and 0.58 °C, respectively). This was also the case for the minimum temperature (–0.13 and –0.14 °C, respectively). The average standard deviation (used as an estimate of precision) for the monthly maximum temperature estimate was substantially less than the daily estimates (0.47 versus 2.75 °C, respectively). The same is true for the minimum temperature (0.53 versus 2.26 °C, respectively).

Table 15. Summary statistics for error of monthly temperature estimates.

No.	SHRP ID	Source of Measured Data	Months of Data	Error (Virtual-Measured), °C			
				Max. Temperature		Min. Temperature	
				Mean	Std. Dev.	Mean	Std. Dev.
1	10101	AWS	22	-0.05	0.41	0.02	0.38
2	—	SMP	8	0.35	0.35	-0.21	0.56
3	10102	SMP	14	0.46	0.33	1.34	0.40
4	40100	AWS	19	4.96	0.45	2.18	0.56
5	40113	SMP	6	5.61	0.32	0.04	1.07
6	40114	SMP	9	6.26	0.57	-0.36	0.80
7	40200	AWS	29	1.25	0.26	-0.79	0.58
8	40215	SMP	9	1.97	0.24	-1.26	0.71
9	41024	SMP	7	1.97	0.45	-2.50	1.31
10	50113	AWS	19	-0.02	0.41	-0.48	0.35
11	63042	SMP	8	1.95	0.98	-0.50	0.34
12	80200	AWS	14	-0.42	0.58	-1.01	0.33
13	81053	SMP	17	0.71	1.03	0.67	1.11
14	91803	SMP	18	0.26	0.49	0.19	0.42
15	100100	AWS	13	-0.25	0.31	1.47	0.38
16	100102	SMP	10	0.34	0.51	1.09	0.44
17	120101	AWS	6	0.08	0.51	-0.30	0.18
18	131005	SMP	11	-0.24	0.36	-0.91	0.29
19	131031	SMP	10	-0.15	0.30	0.20	0.23
20	133019	SMP	10	0.27	0.31	1.87	0.32
21	161010	SMP	13	1.46	0.58	1.07	0.72
22	183002	SMP	8	1.41	0.50	-0.23	0.42
23	200100	AWS	4	-0.67	0.28	-1.51	0.27
24	200200	AWS	4	0.64	0.43	0.73	0.19
25	204054	SMP	8	1.48	0.51	0.54	0.33
26	231026	SMP	19	0.43	0.38	0.44	0.56
27	241634	SMP	15	1.25	0.47	0.16	0.25
28	251002	SMP	16	-0.24	0.52	-2.03	0.57
29	271018	SMP	22	1.68	0.78	1.26	0.44
30	271028	SMP	32	0.88	0.42	0.11	0.55
31	274040	SMP	22	0.98	0.49	-0.09	0.54
32	276251	SMP	29	-0.61	0.43	-0.15	0.82
33	281016	SMP	14	0.15	0.61	-0.46	0.65
34	281802	SMP	12	-1.08	0.56	0.99	0.42
35	300800	AWS	25	1.39	0.61	-1.74	1.02
36	308129	SMP	21	0.98	0.60	-0.33	0.85
37	310100	AWS	3	-0.43	0.24	-0.65	0.11
38	310114	SMP	7	0.66	0.36	-0.99	0.40
39	313018	SMP	8	0.62	0.40	-1.57	0.62
40	320101	SMP	1	0.30	—	0.54	—
41	320200	AWS	17	0.84	0.39	-0.57	0.73
42	320204	SMP	1	0.03	—	0.20	—

Table 15. Summary statistics for error of monthly temperature estimates (continued).

No.	SHRP ID	Source of Measured Data	Months of Data	Error (Virtual-Measured), °C			
				Max. Temperature		Min. Temperature	
				Mean	Std. Dev.	Mean	Std. Dev.
43	331001	SMP	18	0.49	0.41	-1.08	0.36
44	350101	AWS	15	-0.13	0.58	-1.71	0.54
45	350801	AWS	4	0.45	0.59	-1.72	0.27
46	351112	SMP	9	0.91	0.58	-0.13	0.30
47	360800	AWS	13	0.57	0.94	-0.19	0.63
48	360801	SMP	11	1.13	1.11	0.05	0.77
49	364018	SMP	20	0.20	0.24	-0.83	0.30
50	370200	AWS	28	0.02	0.47	0.01	0.46
51	371028	SMP	12	-0.01	0.36	1.05	0.62
52	380200	AWS	12	0.45	0.40	-0.33	0.27
53	390200	AWS	19	-0.38	0.38	-0.29	0.39
54	404165	SMP	14	0.93	0.45	0.55	0.34
55	421606	SMP	11	0.03	0.20	-0.23	0.20
56	460800	AWS	2	-0.32	0.27	0.45	0.44
57	460804	SMP	10	0.51	0.57	-0.41	0.42
58	469187	SMP	8	0.15	0.28	0.63	0.35
59	480801	AWS	3	0.70	0.50	-0.34	0.71
60	481060	SMP	18	0.89	0.32	0.90	0.36
61	481068	SMP	16	-0.33	0.58	-0.91	0.66
62	481077	SMP	17	-0.03	0.30	-0.15	0.38
63	481122	SMP	16	-0.03	0.44	-0.85	0.63
64	483739	SMP	18	-0.49	0.43	0.49	0.40
65	484142	SMP	17	-1.20	0.93	-0.28	0.48
66	484143	SMP	11	0.63	0.40	-0.01	2.22
67	490800	AWS	1	1.95	—	2.55	—
68	491001	SMP	12	0.13	0.66	-1.75	0.80
69	493011	SMP	16	1.58	0.58	-0.16	0.72
70	501002	SMP	18	-0.45	0.48	-0.25	0.80
71	510100	AWS	11	-0.29	0.33	-0.87	0.49
72	510113	SMP	8	0.09	0.35	0.65	0.24
73	510114	SMP	8	0.76	0.41	-0.49	0.41
74	530200	AWS	20	-0.58	0.80	-0.90	0.41
75	530800	AWS	17	-0.34	0.40	-0.32	0.37
76	533813	SMP	10	0.80	0.49	-1.08	0.52
77	561007	SMP	17	0.47	1.01	-1.10	1.15
78	831801	SMP	28	0.02	0.31	-0.16	0.29
79	833802	SMP	16	-0.18	0.28	-0.13	0.53
80	871622	SMP	17	0.27	0.19	0.16	0.40
81	893015	SMP	22	0.17	0.40	0.34	0.49
82	906405	SMP	17	0.23	0.30	0.64	0.31
All Days			**1120**	**0.51**	**1.21**	**-0.15**	**1.04**
Average Section			**13.7**	**0.58**	**0.47**	**-0.14**	**0.53**

PRECIPITATION AND FREEZING INDEX

The monthly and yearly precipitation estimates in the LTPP database were compared with the monthly SMP and AWS measured values, and the results are presented below.

Comparing Monthly Precipitation and Freezing Index

Table 16 includes the mean and standard deviation of error for the monthly precipitation and the freezing index (FI) estimates for 82 SMP and AWS sections. There were between 1 and 28 months of data for each section and a total of 1120 months of data. The overall values (mean and standard deviation for all months of data) and the average values per section are highlighted at the end of table 16.

The mean error of the precipitation estimate was between –5.8 and 38 millimeters (mm), with an average of 9.1 mm per section. The overall mean error for all months of data was 8.58 mm, which is not significantly different. The standard deviation of error was between 1.3 and 84.3 mm, and the average standard deviation per section was 18.6 mm. The overall standard deviation (22.3 mm) was higher.

The FI was calculated as the sum of all the mean daily temperatures less than 0 °C and is reported as °C-days. The mean error of the FI ranged from –8.6 to 55.8 °C-days, and the average mean error per section was 1.7 °C-days (overall average was 0.97 °C-days). The standard deviation of error was between zero and 26.8 °C-days, and the average standard deviation per section was 4.7 °C-days (overall standard deviation was 8.4 °C-days).

Comparing Yearly Precipitation and Freezing Index

Table 17 includes the mean and standard deviation of error for yearly total precipitation and the FI estimates for SMP and AWS sites. Only 37 sites had 1 or 2 years of measured and estimated (VWS) data, and 7 sites had 2 years of data.

As shown in table 17, the average of the mean error of the yearly precipitation estimates per section was 99.8 mm (overall mean was 97.5 mm), and the average standard deviation per section was 31.5 mm (overall standard deviation was 78.7 mm).

The average mean error of the FI estimate was about 9.4 °C-days (8.1 °C-days overall), and the average standard deviation per section was 9.5 °C-days. This value was substantially less than the overall standard deviation (around 50 °C-days).

Since precipitation and FI are accumulated values (rather than monthly mean values in the case of temperature), their variation is higher for yearly estimates (since yearly values accumulate the error). For this reason, both the average per section and the overall yearly statistics are significantly higher than the monthly estimates.

Table 16. Summary statistics for error of monthly precipitation and FI estimates.

No.	SHRP ID	Source of Measured Data	Months of Data	Error (Virtual-Measured)			
				Precipitation, mm		Freezing Index, °C	
				Mean	Std. Dev.	Mean	Std. Dev.
1	10101	AWS	22	8.68	26.91	-0.15	1.40
2	—	SMP	8	26.85	20.22	-0.19	1.81
3	10102	SMP	14	23.14	19.65	0.35	1.88
4	40100	AWS	19	-3.27	4.88	0	0
5	40113	SMP	6	-3.62	6.26	0	0
6	40114	SMP	9	-3.88	7.53	0.01	0.02
7	40200	AWS	29	0.08	7.95	0	0
8	40215	SMP	9	-0.41	8.20	0	0
9	41024	SMP	7	2.40	8.29	2.01	5.03
10	50113	AWS	19	-2.58	21.42	-0.38	1.98
11	63042	SMP	8	3.02	13.18	0	0
12	80200	AWS	14	8.80	8.12	-3.93	5.68
13	81053	SMP	17	2.49	8.14	-0.29	12.13
14	91803	SMP	18	4.94	34.97	1.18	1.71
15	100100	AWS	13	9.95	23.13	4.53	6.00
16	100102	SMP	10	29.91	48.86	4.56	6.19
17	120101	AWS	6	10.63	49.70	0	0
18	131005	SMP	11	10.37	17.66	-0.73	1.85
19	131031	SMP	10	19.97	25.88	-0.07	0.22
20	133019	SMP	10	12.91	21.41	1.19	2.27
21	161010	SMP	13	10.52	9.37	9.90	15.62
22	183002	SMP	8	7.77	13.17	8.32	9.33
23	200100	AWS	4	-4.25	11.30	-4.68	7.51
24	200200	AWS	4	7.30	7.70	6.52	9.66
25	204054	SMP	8	9.39	7.56	13.54	16.21
26	231026	SMP	19	12.84	23.73	3.27	6.20
27	241634	SMP	15	9.08	31.70	1.32	2.41
28	251002	SMP	16	4.56	16.62	-4.99	11.65
29	271018	SMP	22	8.13	18.71	16.43	16.97
30	271028	SMP	32	11.68	14.81	6.70	7.45
31	274040	SMP	22	12.23	12.96	3.61	7.43
32	276251	SMP	29	9.90	15.45	-8.55	14.14
33	281016	SMP	14	6.11	26.35	0.49	2.35
34	281802	SMP	12	15.78	37.61	0.32	1.08
35	300800	AWS	25	4.74	7.00	2.62	7.48
36	308129	SMP	21	1.67	10.39	10.19	12.25
37	310100	AWS	3	-3.40	4.43	-0.67	1.15
38	310114	SMP	7	12.29	22.19	-1.13	5.33
39	313018	SMP	8	1.80	14.97	-5.62	5.83
40	320101	SMP	1	23.50	—	8.20	—
41	320200	AWS	17	3.85	13.18	1.18	3.25
42	320204	SMP	1	20.60	—	4.70	—

Table 16. Summary statistics for error of monthly precipitation and FI estimates (continued).

No.	SHRP ID	Source of Measured Data	Months of Data	Error (Virtual-Measured)			
				Precipitation, mm		Freezing Index, °C	
				Mean	Std. Dev.	Mean	Std. Dev.
43	331001	SMP	18	0.72	15.40	-2.77	3.87
44	350101	AWS	15	5.04	16.12	-0.24	0.58
45	350801	AWS	4	3.25	2.49	0.01	0.02
46	351112	SMP	9	-1.70	20.41	0.32	0.64
47	360800	AWS	13	2.58	27.33	-4.82	7.70
48	360801	SMP	11	12.21	28.39	-3.71	6.15
49	364018	SMP	20	24.38	36.83	-1.84	5.02
50	370200	AWS	28	6.48	12.97	0.23	1.05
51	371028	SMP	12	4.83	19.69	1.55	2.61
52	380200	AWS	12	14.43	24.04	0.15	3.56
53	390200	AWS	19	13.51	23.69	-1.18	6.01
54	404165	SMP	14	7.22	18.31	1.60	3.24
55	421606	SMP	11	4.48	16.91	1.82	2.41
56	460800	AWS	2	26.10	1.27	2.55	3.39
57	460804	SMP	10	7.08	10.34	-2.73	5.66
58	469187	SMP	8	12.59	13.52	4.12	7.76
59	480801	AWS	3	2.30	4.37	-0.08	0.14
60	481060	SMP	18	6.47	32.21	0	0
61	481068	SMP	16	4.62	27.95	-0.62	1.63
62	481077	SMP	17	1.36	13.64	0.31	2.29
63	481122	SMP	16	4.29	18.08	0	0
64	483739	SMP	18	8.41	14.18	0	0
65	484142	SMP	17	15.11	37.33	-0.13	0.52
66	484143	SMP	11	3.52	24.17	-0.09	0.30
67	490800	AWS	1	28.10	—	55.80	—
68	491001	SMP	12	0.57	3.74	-2.61	5.22
69	493011	SMP	16	6.81	6.65	8.79	10.08
70	501002	SMP	18	21.46	25.32	-0.59	6.77
71	510100	AWS	11	16.68	25.38	-1.07	1.93
72	510113	SMP	8	12.84	15.52	-0.13	0.33
73	510114	SMP	8	3.34	22.41	-0.21	0.73
74	530200	AWS	20	-5.83	14.56	-4.43	8.85
75	530800	AWS	17	9.11	14.18	0.87	5.90
76	533813	SMP	10	38.04	84.33	-0.15	2.29
77	561007	SMP	17	5.71	5.79	-2.43	26.76
78	831801	SMP	28	12.32	14.84	-0.27	4.15
79	833802	SMP	16	18.96	24.27	-1.10	3.46
80	871622	SMP	17	23.46	25.70	1.87	5.30
81	893015	SMP	22	6.61	18.61	0.29	7.05
82	906405	SMP	17	13.24	10.03	7.29	9.15
All Months			**1120**	**8.58**	**22.31**	**0.97**	**8.4**
Average Section			**13.7**	**9.10**	**18.60**	**1.7**	**4.7**

Table 17. Summary statistics for error of yearly precipitation and FI estimates.

No.	SHRP ID	Source of Measured Data	Years of Data	Error (Virtual-Measured)			
				Precipitation, mm		Freezing Index, °C	
				Mean	Std. Dev.	Mean	Std. Dev.
1	10101	AWS	2	84.65	36.98	-1.03	6.61
2	40100	AWS	1	-69.10	—	0	—
3	40200	AWS	2	4.50	8.63	0	0
4	50113	AWS	1	-2.60	—	-3.95	—
5	80200	AWS	1	109.40	—	-26.30	—
6	91803	SMP	1	138.50	—	7.75	—
7	100100	AWS	1	139.40	—	44.60	—
8	161010	SMP	1	91.60	—	142.45	—
9	231026	SMP	1	184.10	—	13.00	—
10	251002	SMP	1	15.50	—	-97.65	—
11	271018	SMP	1	28.70	—	144.95	—
12	271028	SMP	2	113.75	14.50	56.27	5.55
13	274040	SMP	1	118.20	—	37.65	—
14	276251	SMP	2	117.55	43.91	-72.10	28.71
15	300800	AWS	2	53.85	26.38	32.27	5.62
16	308129	SMP	1	-2.00	—	108.65	—
17	320200	AWS	1	44.20	—	22.45	—
18	331001	SMP	1	35.70	—	-39.10	—
19	350101	AWS	1	74.70	—	-2.50	—
20	360800	AWS	1	11.60	—	-44.95	—
21	364018	SMP	1	160.30	—	-13.15	—
22	370200	AWS	2	86.90	1.41	3.20	1.41
23	380200	AWS	1	106.60	—	14.10	—
24	481060	SMP	1	117.30	—	0	—
25	481068	SMP	1	33.80	—	-9.65	—
26	481077	SMP	1	3.10	—	13.60	—
27	481122	SMP	1	102.10	—	0	—
28	483739	SMP	1	147.70	—	0	—
29	484142	SMP	1	153.90	—	-0.40	—
30	501002	SMP	1	323.90	—	-45.80	—
31	530200	AWS	1	226.30	—	-79.30	—
32	530800	AWS	1	125.70	—	12.95	—
33	561007	SMP	1	49.70	—	57.60	—
34	831801	SMP	2	135.50	88.67	-11.65	17.82
35	833802	SMP	1	269.10	—	-15.40	—
36	871622	SMP	1	236.10	—	14.85	—
37	906405	SMP	1	124.00	—	84.85	—
All Years			**44**	**97.50**	**78.70**	**8.10**	**50.30**
Average Section			**1.2**	**99.80**	**31.50**	**9.40**	**9.40**

HUMIDITY

The daily estimates of maximum and minimum humidity in the LTPP database were compared with the AWS measured humidity to assess the accuracy of the estimated humidity values. Only 10 AWS sections had both measured and estimated humidity data. These data were combined into a database that had data for about 4100 days.

Comparing Daily Maximum and Minimum Humidity

Table 18 includes the mean error and standard deviation for daily maximum and minimum humidity estimates. The average mean error of the maximum humidity per section was –4.8 percent (–4.2 percent overall), and the standard deviation (Std. Dev. column) was 6.1 percent (7.3 percent overall).

The average mean error of the minimum humidity was 2.1 percent (2.5 percent overall), and the standard error was 7.8 percent (8.6 percent overall). The results indicated that the maximum humidity estimates were made slightly more accurately than the minimum humidity estimates. Generally, daily humidity estimates were within 10 percent of the measured data.

Table 18. Summary statistics for error of daily maximum and minimum humidity estimates.

AWS ID	Error (Virtual-Measured), percent					
	Maximum Humidity			Minimum Humidity		
	Mean	Std. Dev.	Days	Mean	Std. Dev.	Days
010100	-5.5	6.8	674	4.2	7.3	674
120100	-9.3	7.5	201	6.0	7.5	201
200100	-2.6	4.6	147	1.4	7.7	147
200200	-2.4	5.6	146	5.4	6.6	146
310100	-2.1	3.9	146	2.8	6.1	146
360800	1.6	5.3	405	1.9	10.4	405
370200	-6.6	7.6	859	4.2	7.1	869
380200	-3.0	3.9	408	0.6	7.0	408
390200	-5.8	6.7	567	-3.6	8.2	635
530800	-6.3	9.1	526	1.8	10.5	526
All Days	**-4.8**	**7.3**	**4079**	**2.1**	**8.6**	**4157**
Average Section	**-4.2**	**6.1**	**407.9**	**2.5**	**7.8**	**415.7**

Comparing Monthly Maximum and Minimum Humidity

The mean error and standard deviation of the monthly humidity estimates (minimum and maximum) are shown in table 19. This table includes 142 months of data (from 5 to 29 months per site).

The average mean error per section was similar to the daily estimates (–4 percent and 2.6 percent for maximum and minimum humidity, respectively); however, the average standard deviation was less than half of the daily estimates (2.1 percent and 3.4 percent for maximum and minimum humidity, respectively).

Table 19. Summary statistics for error of monthly maximum and minimum humidity estimates.

AWS ID	Error (Virtual-Measured), percent					
	Maximum Humidity			Minimum Humidity		
	Mean	Std. Dev.	Months	Mean	Std. Dev.	Months
010100	-5.5	3.1	23	4.5	3.2	23
120100	-9.1	3.0	7	6.1	3.3	7
200100	-2.5	1.0	5	1.6	4.3	5
200200	-2.3	1.0	5	5.5	1.8	5
310100	-2.0	1.0	5	2.9	2.2	5
360800	1.9	2.1	14	2.2	4.1	14
370200	-6.5	3.0	29	4.3	2.8	29
380200	-2.9	1.7	14	0.7	3.2	14
390200	-5.2	2.8	22	-3.5	4.9	22
530800	-6.3	2.2	18	2.1	3.9	18
All Months	**-4.6**	**3.7**	**142**	**2.3**	**4.5**	**142**
Average Section	**-4.0**	**2.1**	**14.2**	**2.6**	**3.4**	**14.2**

WINDSPEED

The daily and monthly windspeed estimates were compared to the measured AWS data. As with humidity, only 10 AWS sites had both average windspeed estimates (VWS) and measured data. However, only four sites had maximum windspeed estimates and measured data. This is mainly a result of the lack of data for maximum windspeed in the VWS monthly table.

Comparing Daily Average and Maximum Windspeeds

Table 20 includes the mean error and standard deviation for the daily average and maximum windspeeds. There were 4183 days with estimated and measured average windspeed data, but only 1365 days for maximum windspeed (because of lack of estimates).

The mean error of the average daily windspeed estimate was 1.4 kilometers per hour (km/h), and the standard deviation was 1.1 km/h. The mean error of the maximum daily windspeed was

1.5 km/h, and the standard deviation was 2.2 km/h. The average per section values was similar to the overall values.

These data indicate that the daily windspeed estimates were estimated within 1 to 2 km/h of the measured values.

Table 20. Summary statistics for error of daily average and maximum windspeed estimates.

SHRP ID	Error (Virtual-Measured), km/h					
	Average Windspeed			Maximum Windspeed		
	Mean	Std. Dev.	Days	Mean	Std. Dev.	Days
010100	1.3	0.7	691	—	—	0
120100	2.0	1.1	201	—	—	0
200100	2.0	0.8	146	—	—	0
200200	1.6	0.9	146	—	—	0
310100	0.8	0.7	146	—	—	0
360800	2.4	1.1	404	3.3	2.4	219
370200	2.0	0.9	875	2.3	1.7	420
380200	1.3	0.8	408	1.4	1.9	287
390200	0.3	0.7	634	0.1	1.8	439
530800	0.6	0.9	532	—	—	0
All Days	**1.4**	**1.1**	**4183**	**1.5**	**2.2**	**1365**
Average Section	**1.4**	**0.9**	**418.3**	**1.8**	**2.0**	**136.5**

Comparing Monthly Average and Maximum Windspeeds

Table 21 includes the mean error and standard deviation for the monthly average and maximum windspeeds. There are 142 months of estimated and average windspeed data and only 47 months of data for the maximum windspeed.

The mean error of the average and maximum monthly windspeeds was similar to the daily data (1.3 and 1.5 km/h). However, the standard deviations were lower for the monthly data (0.8 and 1.3 km/h). The average per section mean error was similar to the overall error; however, the average standard deviation was less than half of the overall value.

In general, the monthly windspeed estimates were estimated within 1 km/h of the measured values.

Table 21. Summary statistics for error of monthly average and maximum windspeed estimates.

SHRP ID	Error (Virtual-Measured), km/h					
	Average Windspeed			Maximum Windspeed		
	Mean	Std. Dev.	Months	Mean	Std. Dev.	Months
010100	1.3	0.3	23	—	—	0
120100	2.0	0.4	7	—	—	0
200100	1.9	0.3	5	—	—	0
200200	1.6	0.3	5	—	—	0
310100	0.8	0.2	5	—	—	0
360800	2.4	0.4	14	3.2	0.5	8
370200	2.0	0.3	29	2.3	0.5	14
380200	1.2	0.2	14	1.4	0.3	10
390200	0.3	0.5	22	0.1	0.6	15
530800	0.6	0.2	18	—	—	0
All Months	**1.3**	**0.8**	**142**	**1.5**	**1.3**	**47**
Average Section	**1.4**	**0.3**	**14.2**	**1.8**	**0.5**	**4.7**

SUMMARY OF COMPARISONS

A summary of all of the comparisons performed between the estimated (VWS) and measured (AWS and SMP) LTPP climatic data is presented in table 22. This table includes the per section average for the mean and standard deviation of the error. Depending on the parameter, the results are shown either for daily and monthly or monthly and yearly estimates. The following are some general observations drawn from the comparisons:

- Daily and monthly temperatures were estimated within 2.5 and 0.5 °C, respectively.
- Monthly and yearly precipitation were estimated within 19 and 32 mm, respectively.
- Monthly and yearly FI were estimated within 5 and 10 °C-days.
- Daily and monthly humidity were estimated within 7 and 3 percent.
- Daily and monthly windspeeds were estimated within 2 and 0.5 km/h.

Table 22. Summary statistics for error of various LTPP VWS estimates for AWS and SMP sites.

Parameter	Unit	Period	Number	Error (Measured-Estimated)	
				Mean	Std. Dev.
Maximum Temperature	°C	Daily	38665	0.57	2.75
	°C	Monthly	1120	0.58	0.47
Minimum Temperature	°C	Daily	38665	-0.13	2.26
	°C	Monthly	1120	-0.14	0.53
Precipitation	mm	Monthly	1120	9.10	18.60
	mm	Yearly	44	99.80	31.50
Freezing Index	°C	Monthly	1120	1.70	4.70
	°C	Yearly	44	9.40	9.40
Maximum Humidity	%	Daily	4079	-4.20	6.10
	%	Monthly	142	-4.00	2.10
Minimum Humidity	%	Daily	4157	2.50	7.80
	%	Monthly	142	2.60	3.40
Average Windspeed	km/h	Daily	4183	1.40	0.90
	km/h	Monthly	142	1.40	0.30
Maximum Windspeed	km/h	Daily	1365	1.80	2.00
	km/h	Monthly	47	1.80	0.50

TASK 3: DETERMINE ACCURACY OF VWS ESTIMATES AND VERIFY THE VWS ALGORITHM

Under this task, the accuracy of the measured temperature data, year-to-year variation in data, and factors affecting VWS estimates were studied. Also, different methods of estimating weather data were presented and their effects on accuracy were determined.

ACCURACY OF MEASURED TEMPERATURE DATA

Some LTPP sites are instrumented with both AWS and SMP probes. For some sites, the SMP and AWS measured temperatures agreed very well, while for others, it did not. Figure 10 shows the AWS versus SMP measured maximum daily temperatures for SPS–1 site ID 010100. The two measurements were quite close for this section. Figure 11 shows the same information for SPS–1 site ID 040100 (Arizona). It shows that there is some variation between the two measurements.

The difference between the SMP and AWS measurements is used to determine the accuracy of the measured data within a site. Table 23 includes the mean and standard deviation of the difference for the maximum and minimum daily temperatures and precipitation for eight LTPP sites. Six sites had one AWS and one SMP installation, and two sites had one AWS and two SMP installations (these sites are shaded and identified with duplicate AWS IDs). A total of 2661 days of common SMP and AWS data exist in this database. There were 52 to 436 days of data (266 days on average) for each site.

The average mean difference per section for the maximum temperature was –0.6 °C (overall mean was –0.7 °C). The average standard deviation per section was 0.8 °C (1 °C overall). The mean difference for the minimum temperature was 0.3 °C, and the standard deviation was 1.1 °C (0.2 and 1.8 °C overall, respectively). The standard deviation of the daily difference for precipitation was 2.1 mm (2.7 mm overall).

Table 24 includes the monthly data for the maximum and minimum temperatures, precipitation, and FI. Comparing with the daily difference, the standard deviations of the differences for the monthly minimum and maximum temperatures were less and the mean differences were the same. The mean difference for precipitation was –4.6 mm, and the standard deviation was 18 mm. The mean difference for the FI was 0.3 °C, and the standard deviation was 1.9 °C.

This comparison shows that different climatic measurements within the same site are not identical and show some differences. These differences are related to differences in instrumentation and operation. When determining the accuracy of the climatic estimates from nearby weather stations, the instrumentation variation should also be taken into account. The instrument variation was around 1 °C for LTPP sites (0.8 °C for maximum and 1.1 °C for minimum temperatures). This variation is about 40 percent of the variation of the VWS estimates, which are 2.75 and 2.26 °C for maximum and minimum temperatures, respectively, in table 14.

Table 23. Summary statistics for daily differences between SMP and AWS data.

AWS ID	SMP ID	Number of Days	Difference (AWS-SMP)					
			Maximum Temperature, °C		Minimum Temperature, °C		Precipitation, mm	
			Average	Std. Dev.	Average	Std. Dev.	Mean	Std. Dev.
10101	10102	436	-0.4	0.4	-1.2	0.9	-0.4	4.0
40100	40113	253	-0.5	2.3	2.0	2.5	0.0	1.0
=	40114	329	-1.5	0.4	2.4	1.6	0.0	0.9
40200	40215	310	-0.8	0.3	0.5	0.7	-0.1	1.2
100100	100102	333	-0.7	0.9	0.3	0.6	-0.2	3.4
320200	320204	52	0.1	1.0	0.0	0.8	-0.5	2.4
360800	360801	298	-0.5	0.7	-0.2	0.6	-0.3	1.7
460800	460804	62	-0.2	0.5	0.8	0.9	0.1	0.6
510100	510113	322	-0.4	0.7	-1.5	1.7	0.0	4.3
=	510114	266	-1.0	0.7	-0.3	0.8	0.2	1.7
All Days		2661	-0.7	1.0	0.2	1.8	-0.1	2.7
Average Section		266.1	-0.6	0.8	0.3	1.1	-0.1	2.1

Table 24. Summary statistics for monthly difference between SMP and AWS data.

AWS ID	SMP ID	Months of Data	Difference (AWS-SMP)							
			Maximum Temperature, °C		Minimum Temperature, °C		Precipitation, mm		Freezing Index, °C	
			Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
10101	10102	16	-0.4	0.2	-1.2	0.3	-10.3	20.4	0.5	0.9
40100	40113	12	-0.6	0.3	2.3	1.0	0.9	4.3	0.0	0.0
=	40114	13	-1.5	0.3	2.4	0.6	0.1	5.4	0.0	0.0
40200	40215	11	-0.8	0.2	0.5	0.3	-2.5	9.5	0.0	0.0
100100	100102	12	-0.7	0.5	0.3	0.2	-16.4	30.5	-0.2	0.7
320200	320204	2	0.1	0.2	0.0	0.2	-11.6	8.9	0.4	2.3
360800	360801	11	-0.5	0.2	-0.1	0.2	-12.4	16.8	2.2	2.9
460800	460804	3	-0.2	0.2	0.8	0.2	2.7	1.7	-5.6	5.8
510100	510113	13	-0.4	0.3	-1.5	0.5	-0.2	24.9	0.7	1.4
=	510114	10	-1.0	0.4	-0.3	0.2	5.9	8.7	0.6	1.1
All Months		103	-0.7	0.5	0.3	1.4	-4.6	18.3	0.3	1.9
Average Section		10.3	-0.6	0.3	0.3	0.4	-4.4	13.1	-0.1	1.5

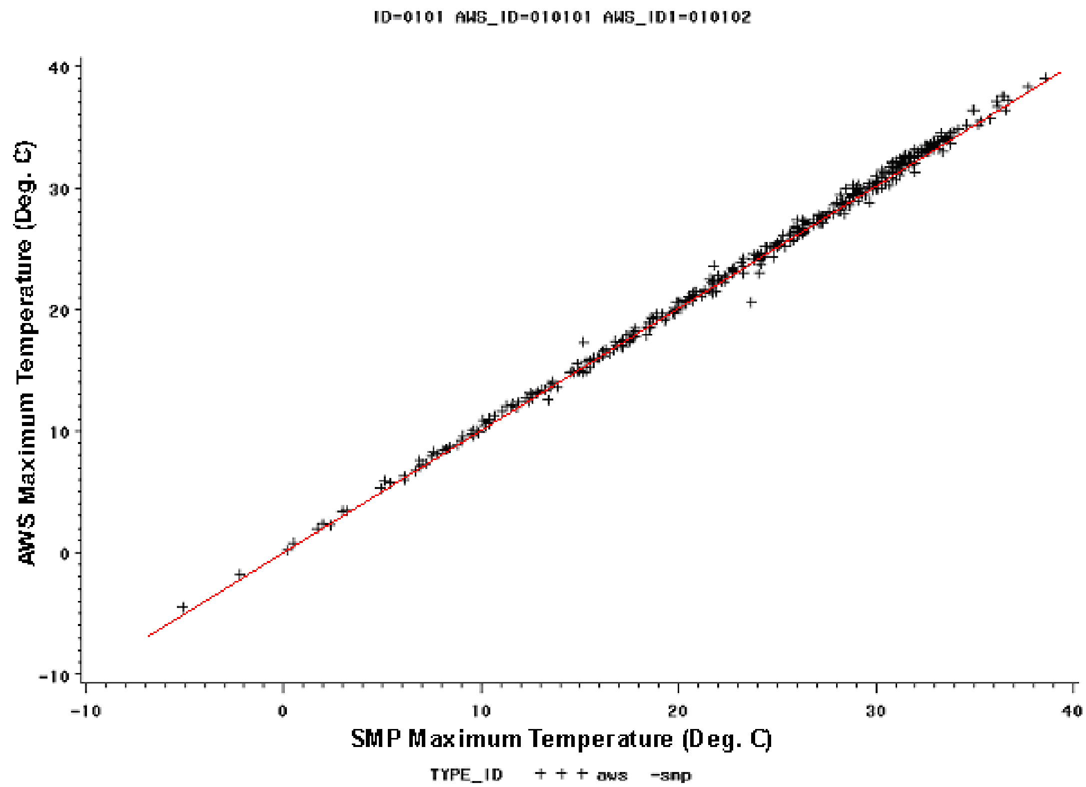


Figure 10. Graph. AWS versus SMP measured maximum temperature for site 010100.

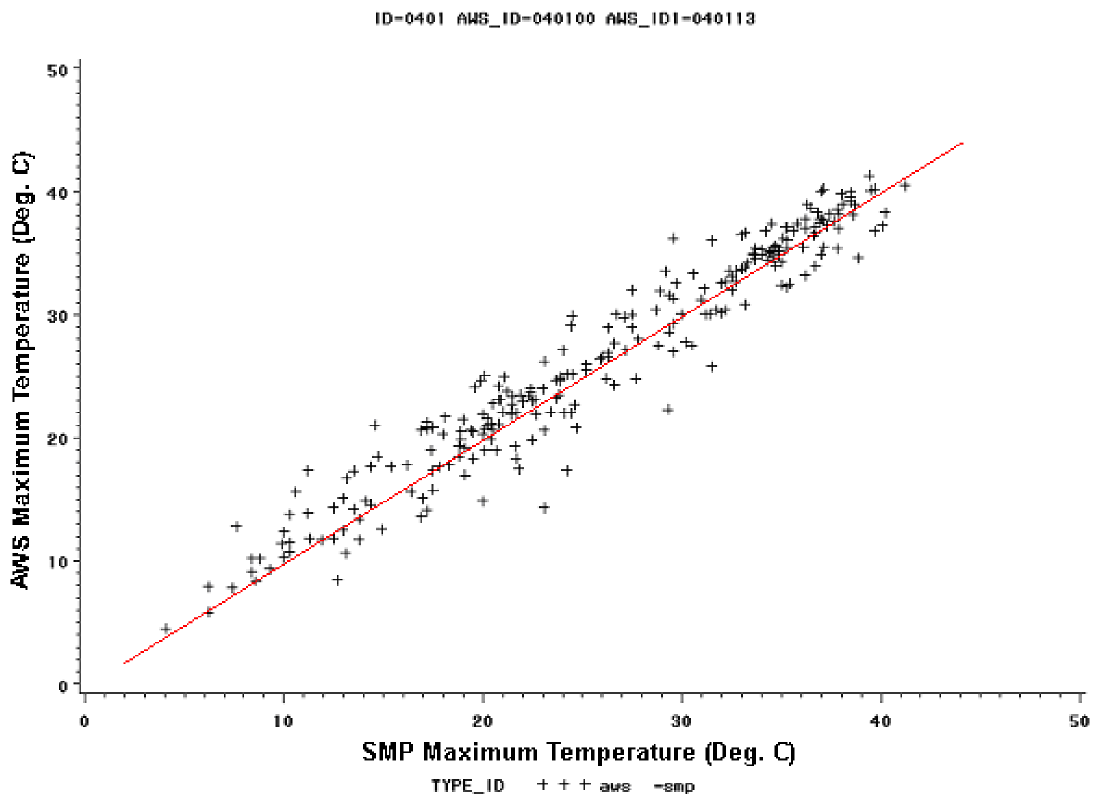


Figure 11. Graph. AWS versus SMP measured maximum temperature for site 040100.

YEARLY VARIATION OF CLIMATIC DATA

The year-to-year variation in climatic data also should be considered when determining the required accuracy of the climatic estimates. The monthly and yearly climatic data are used in most pavement design procedures. These data should be corrected for the yearly variation.

Table 25 shows the coefficient of variation (COV = Standard Deviation * 100 / Mean) for yearly maximum and minimum temperatures, precipitation, and FI estimates in the IMS. The table shows that there is a considerable year-to-year variation for the FI (34 percent) and yearly precipitation (21 percent). The yearly variations of the yearly maximum and minimum temperatures were 4.8 and 8.6 percent, respectively. The monthly temperature data, however, showed higher variation (7 percent for mean monthly maximum temperature as compared to 4.8 percent yearly).

The standard deviation of the yearly and monthly data also shows that there is a considerable variation in the FI and precipitation data. The mean standard deviation for the FI was 153 °C-days, and the mean standard deviation for precipitation was 171 mm.

Table 25. Year-to-year variation of virtual weather data.

Parameter	Period	Unit	Frequency	Mean Value	Mean COV	Mean Std. Dev.
Maximum Temperature	Yearly	°C	880	19.2	4.8	0.8
Minimum Temperature	Yearly	°C	711	7.8	8.6	0.7
Precipitation	Yearly	mm	880	903	21	171
Freezing Index	Yearly	°C-days	496	555	34	153
Maximum Temperature	Monthly	°C	5280	26.7	7	1.7

The year-to-year variation in the FI and precipitation were 34 and 21 percent, respectively. The monthly and yearly temperature variation is around 7 percent (4.8 to 8.6 percent). Therefore, the year-to-year variation in the climatic data is significant and should be considered when determining the required accuracy of the climatic parameters.

The required precision for estimating a climatic parameter is related to instrument variation and the year-to-year variation in the climatic data.

FACTORS AFFECTING VWS ESTIMATES

Several factors were studied during this project to identify their effects on the precision and bias of the VWS estimates. In addition, the wisdom of using the $1/R^2$ weight for computing the VWS data was investigated in this part of the project.

The following factors were considered to investigate their effects on the precision and bias of the estimated climatic data:

- Distance from the weather station to the site.
- Elevation difference between the weather station and the site.
- North-south distance (latitude).

The effects of these factors were investigated using the following three databases:

- LTPP AWS database (contains 24 sections).
- LTPP SMP database (contains 58 sections).
- NCDC cooperative weather station database (contains more than 5000 weather stations throughout the United States).

A brief explanation of each factor and their effect on the estimated temperatures are discussed below.

Effects of Distance (From the Weather Station to the Site)

To determine the effects of the distance from the weather station to the site on the accuracy of the estimate, the differences between the temperatures at a site and each of the five closest weather stations were determined and graphed versus distance to the site. Figure 12 shows a sample graph for the maximum temperature at site 460800.

As figure 12 shows, the weather station located farthest from the site (a distance of 41 km) has a mean difference of 0.3 °C and a standard deviation of 1.2 °C. This weather station has the lowest bias and the highest precision of all of the weather stations and thus provides the most accurate estimate of maximum temperature. A study of the data for the other AWS and SMP sites reveals that the most accurate weather station is located closest to the site only one out of five times, thus making it a random event.

Figures 13 through 16 show the mean and standard deviation of the temperature difference (maximum and minimum) for the five closest weather stations to the SMP and AWS sites. It can be seen from these figures that neither the precision nor the bias of the estimate is related to distance. Figures 17 through 20 show the same information for more than 5000 NCDC sites, which confirms that neither the precision nor the bias is significantly related to distance within the 60-km range.

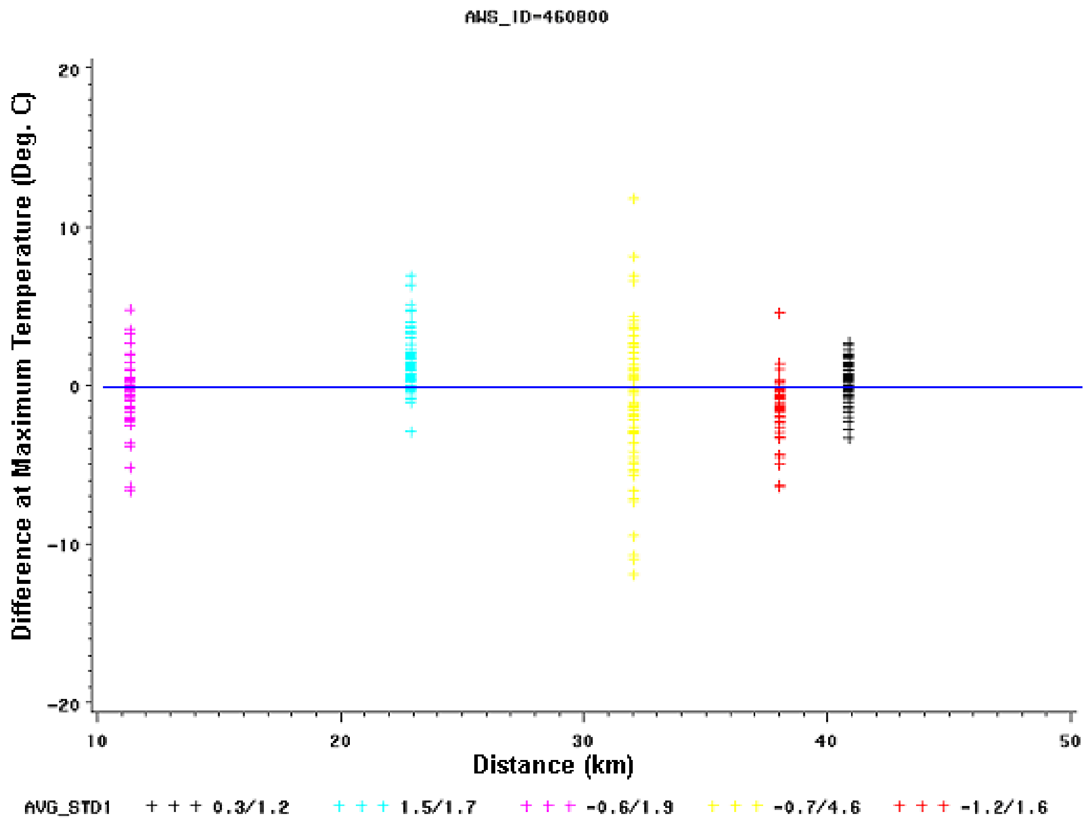


Figure 12. Graph. Temperature difference between site 460800 and nearby weather stations versus distance.

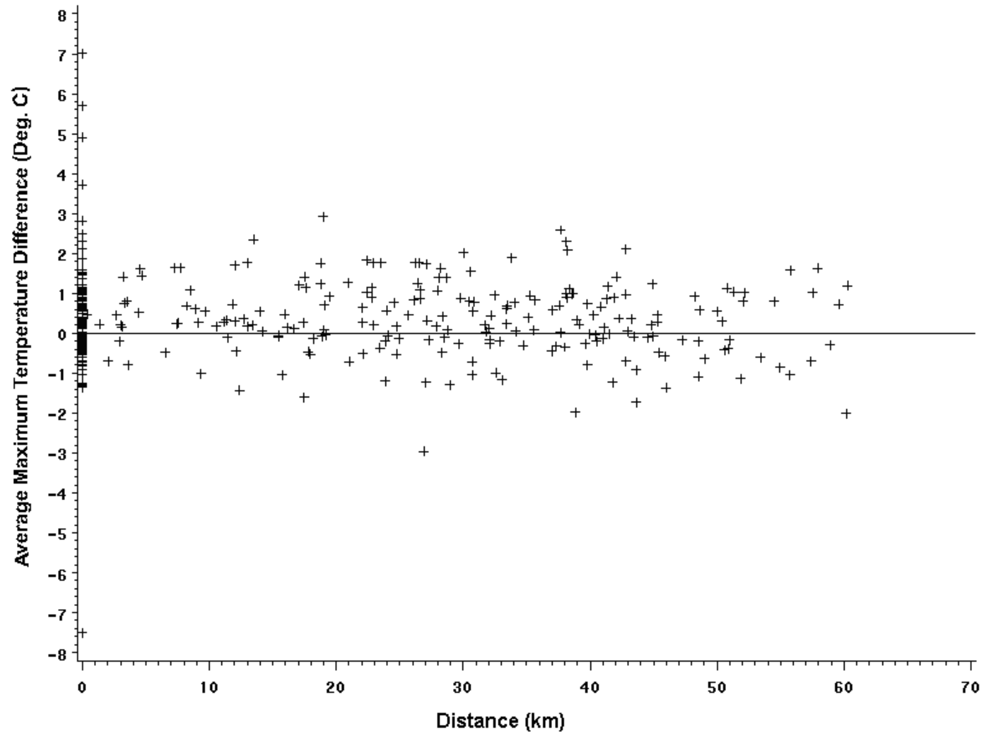


Figure 13. Graph. Mean maximum temperature difference versus distance for AWS and SMP sites.

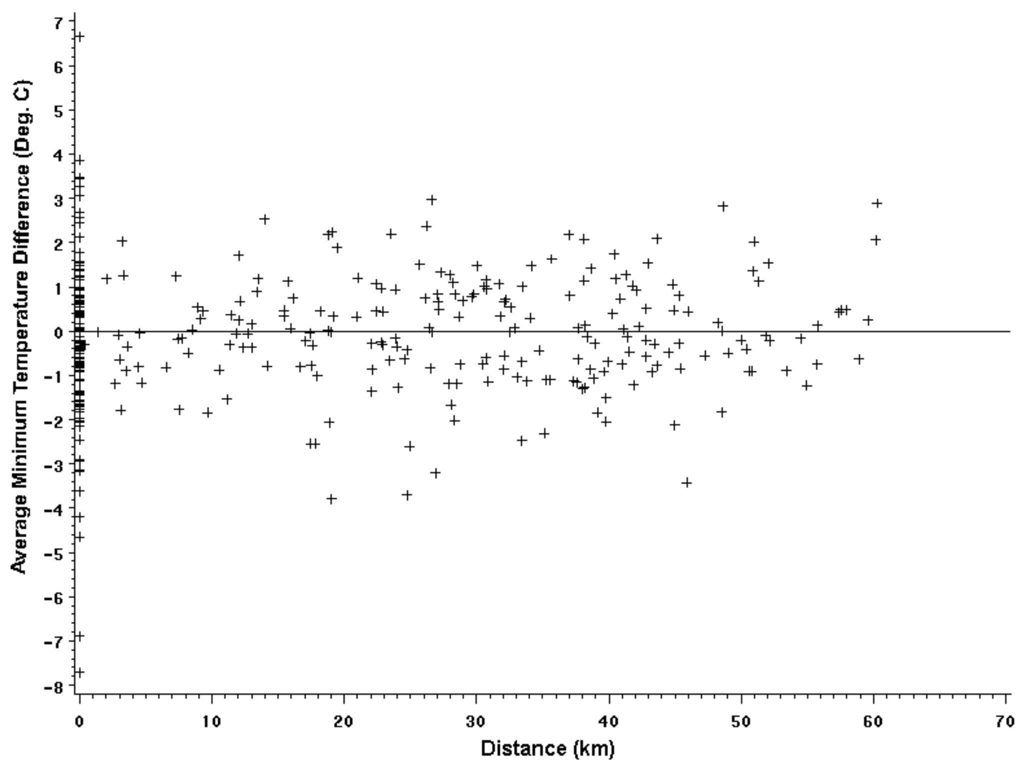


Figure 14. Graph. Mean minimum temperature difference versus distance for AWS and SMP sites.

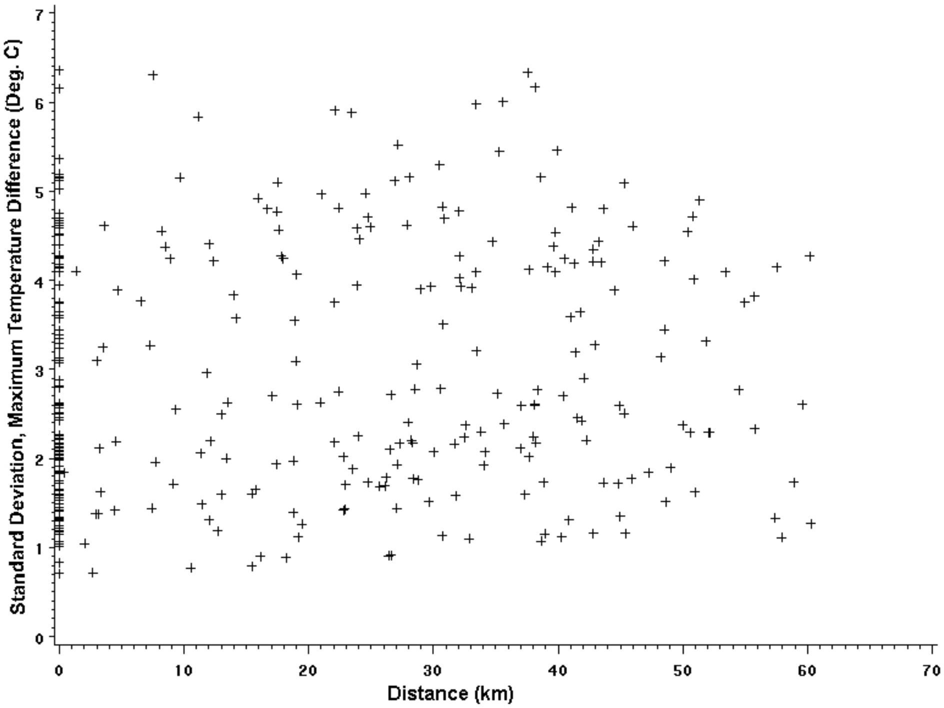


Figure 15. Graph. Standard deviation of maximum temperature difference versus distance for AWS and SMP sites.

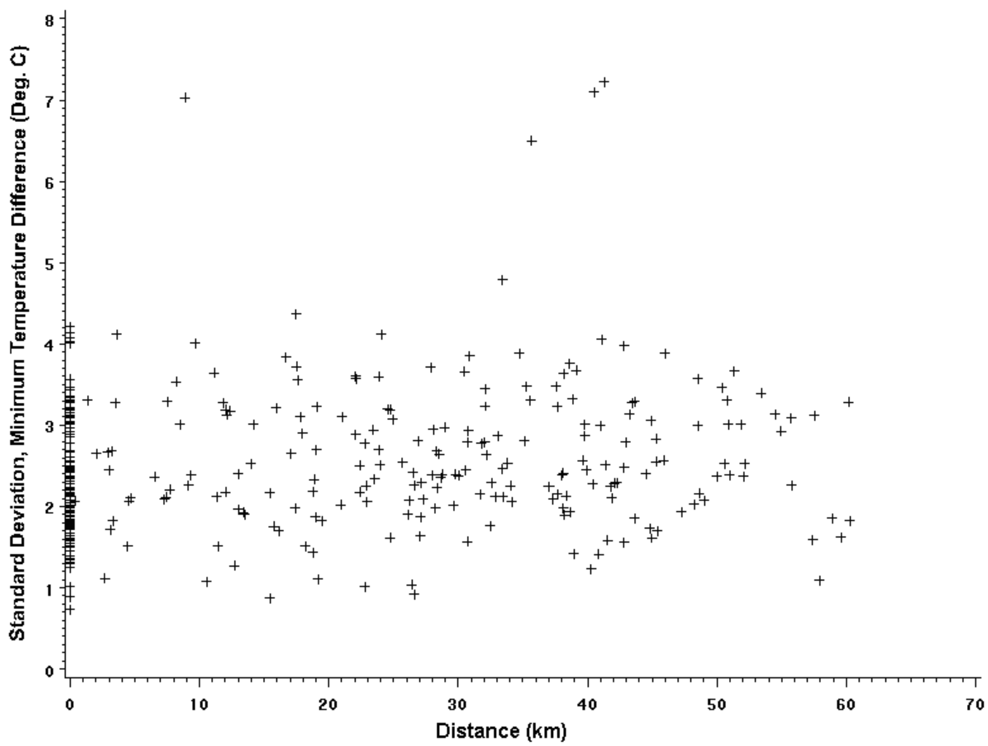


Figure 16. Graph. Standard deviation of minimum temperature difference versus distance for AWS and SMP sites.

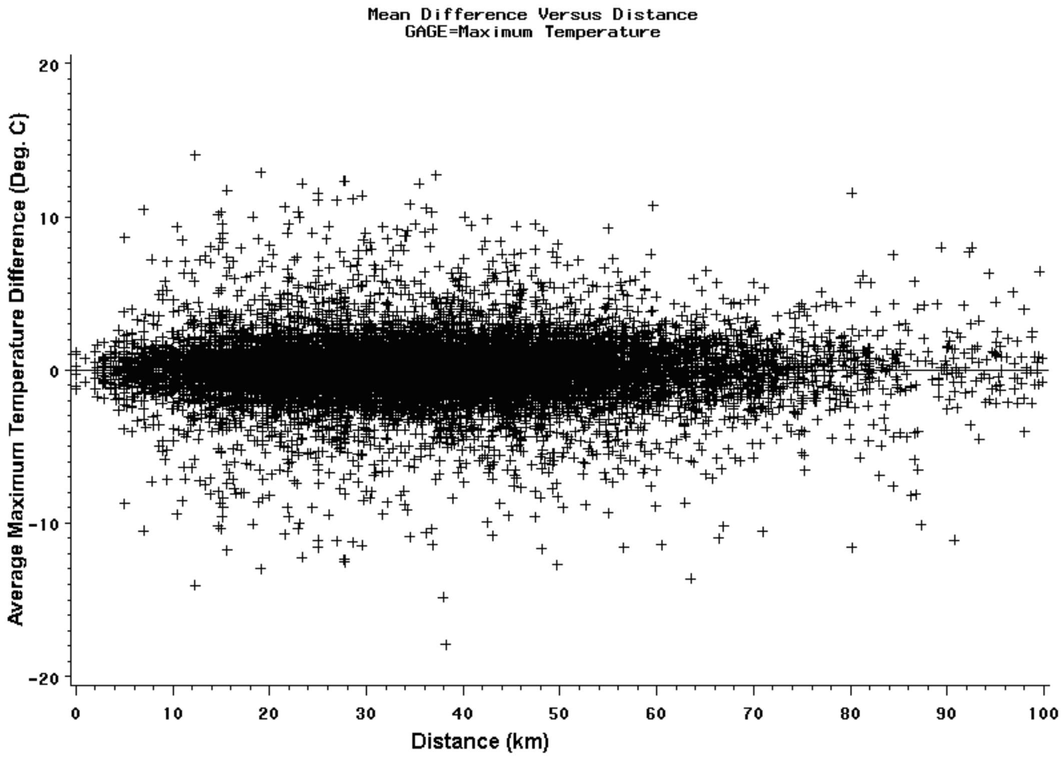


Figure 17. Graph. Mean maximum temperature difference versus distance for NCDC sites.

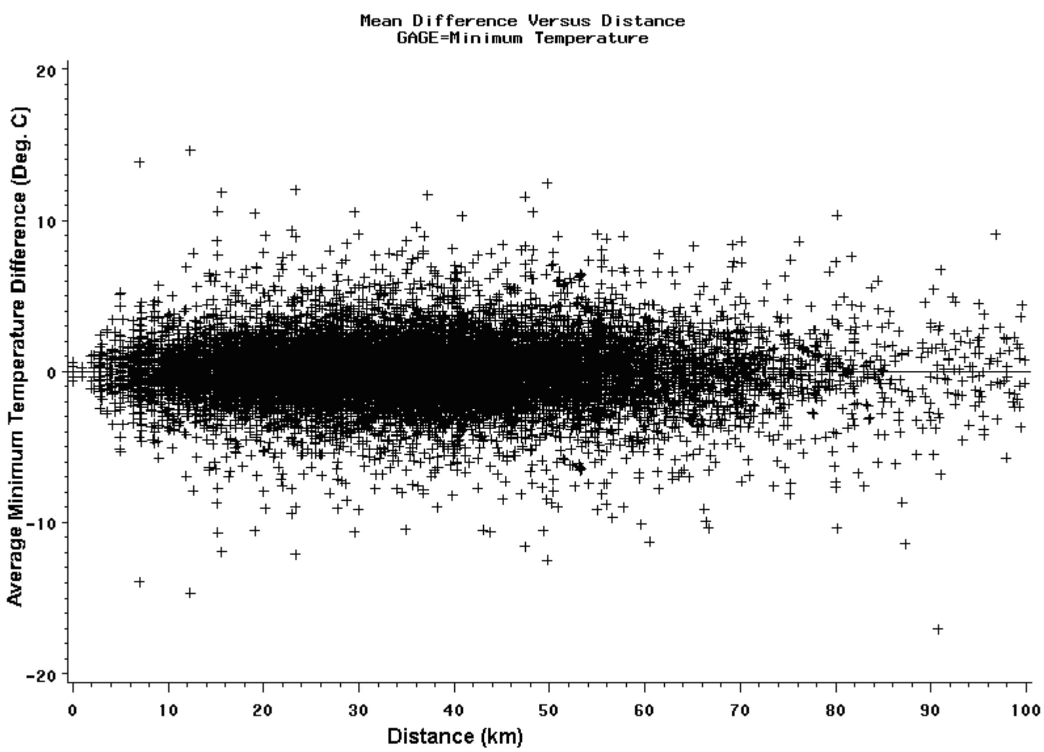


Figure 18. Graph. Mean minimum temperature difference versus distance for NCDC sites.

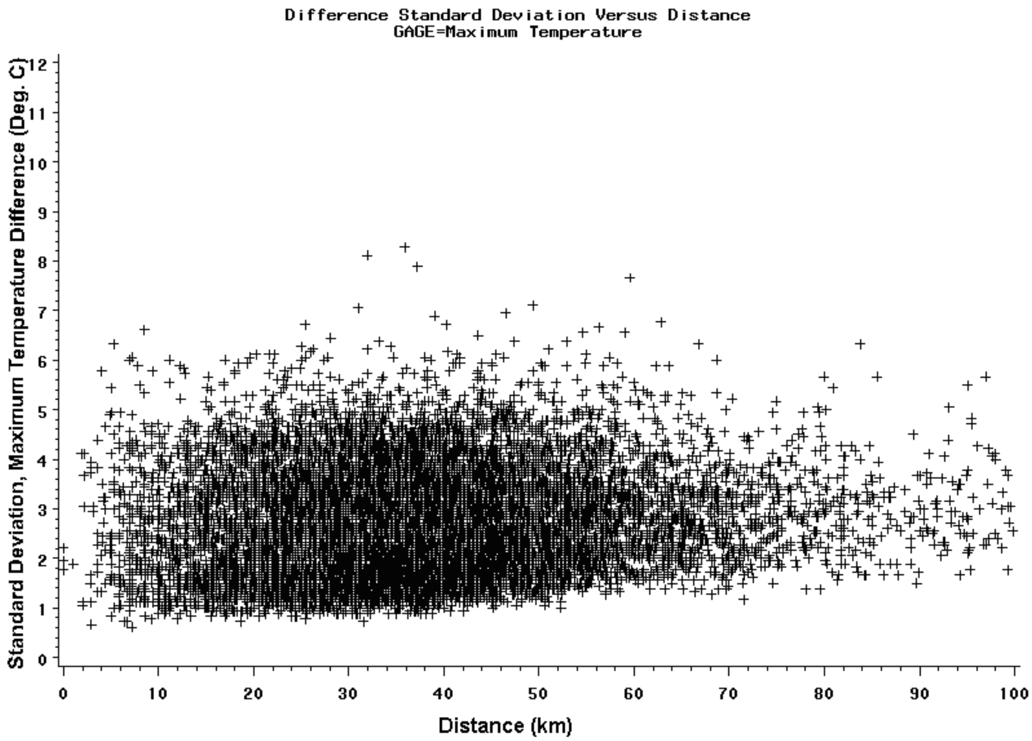


Figure 19. Graph. Standard deviation of maximum temperature difference versus distance for NCDC sites.

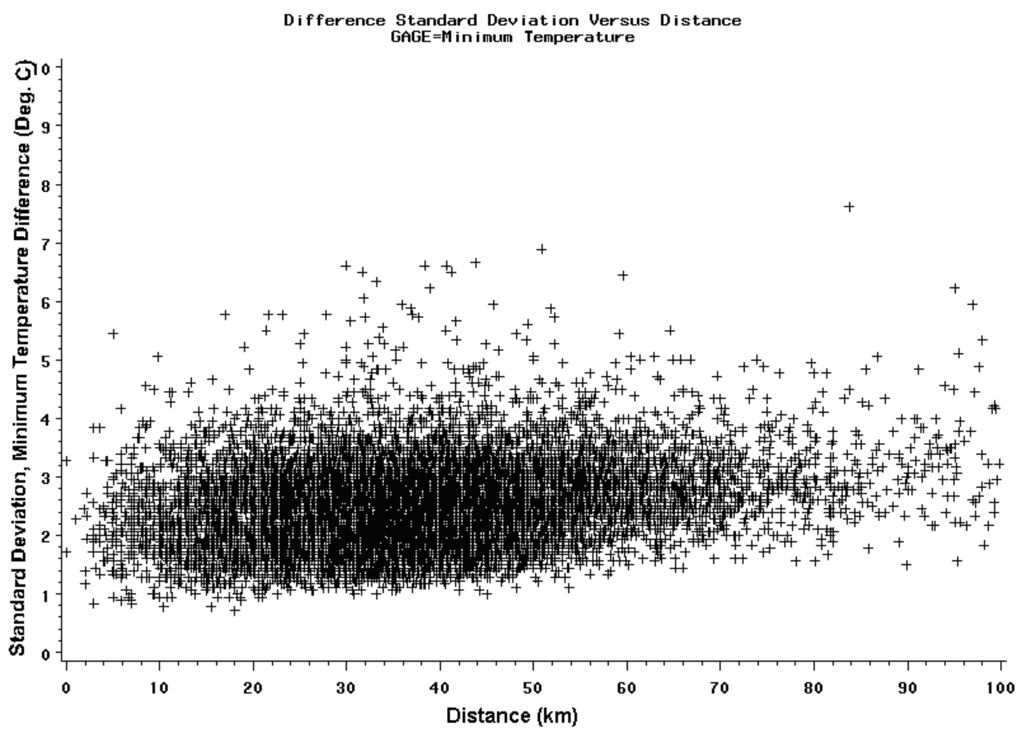


Figure 20. Graph. Standard deviation of minimum temperature difference versus distance for NCDC sites.

Elevation Difference (Between the Weather Station and the Site)

Graphs similar to those presented in the previous section were developed to show the effects of the elevation difference on the precision and bias of the SMP and AWS sites (see figures 21 through 25). Figures 21 and 22 show that the elevation difference affects the bias of the estimate at elevation differences higher than ±250 meters (m). On the other hand, table 26, for NCDC sites, shows that the elevation difference does not affect the precision of the estimate.

For all of the NCDC weather stations, the mean and standard error of the difference between the temperature at each of the weather stations and the five closest weather stations were determined. This resulted in five average values and standard deviations for every weather station (an average of up to 1096 days of data for each weather station). Table 26 shows the average and standard deviation of the temperature difference grouped by the elevation difference.

As can be seen from table 26, the mean difference (bias) for the maximum and minimum temperatures is highly related to the elevation difference. Figure 25 shows the mean temperature difference (bias) versus the elevation difference for the maximum temperature. This figure shows that the elevation difference is highly correlated with the mean temperature difference (bias). Figure 26 shows the same trend, but with higher variation for the minimum temperature. The result of this study shows that correcting for the elevation difference in the VWS calculation may substantially improve the bias of the estimate.

Table 26. Mean and standard deviation of temperature difference between NCDC site and the five nearby weather stations.

Elevation Difference, m	Number of Sites	Number of Days	Mean Difference for Closest Weather Stations, °C			
			Maximum Temperature		Minimum Temperature	
			Average	Std. Dev.	Average	Std. Dev.
-1750	6	6,566	13.0	3.5	11.1	3.2
-1500	38	39,442	10.2	3.8	7.3	3.4
-1250	42	44,381	9.1	3.7	5.6	3.7
-1000	90	90,373	7.4	3.3	4.6	3.5
-750	166	162,637	5.3	3.2	3.3	3.3
-500	512	498,127	3.9	2.9	2.4	3.2
-250	1,668	1,633,880	2.1	2.9	1.5	3.0
0	32,378	31,412,843	0	2.7	0	2.4
250	1,630	1,593,219	-2.3	2.9	-1.4	3.0
500	560	553,288	-4.2	3.0	-2.6	3.2
750	170	167,828	-5.7	3.2	-3.4	3.4
1000	82	77,840	-7.8	3.3	-4.8	3.5
1250	46	48,914	-9.9	3.6	-7.3	3.7
1500	32	32,794	-11.2	3.9	-7.4	3.7
1750	2	2,183	-14.1	3.2	-14.7	3.3
2000	2	2,012	-17.9	3.3	-8.9	3.0
All Days	37,424	36,366,327	0	2.7	0	2.5

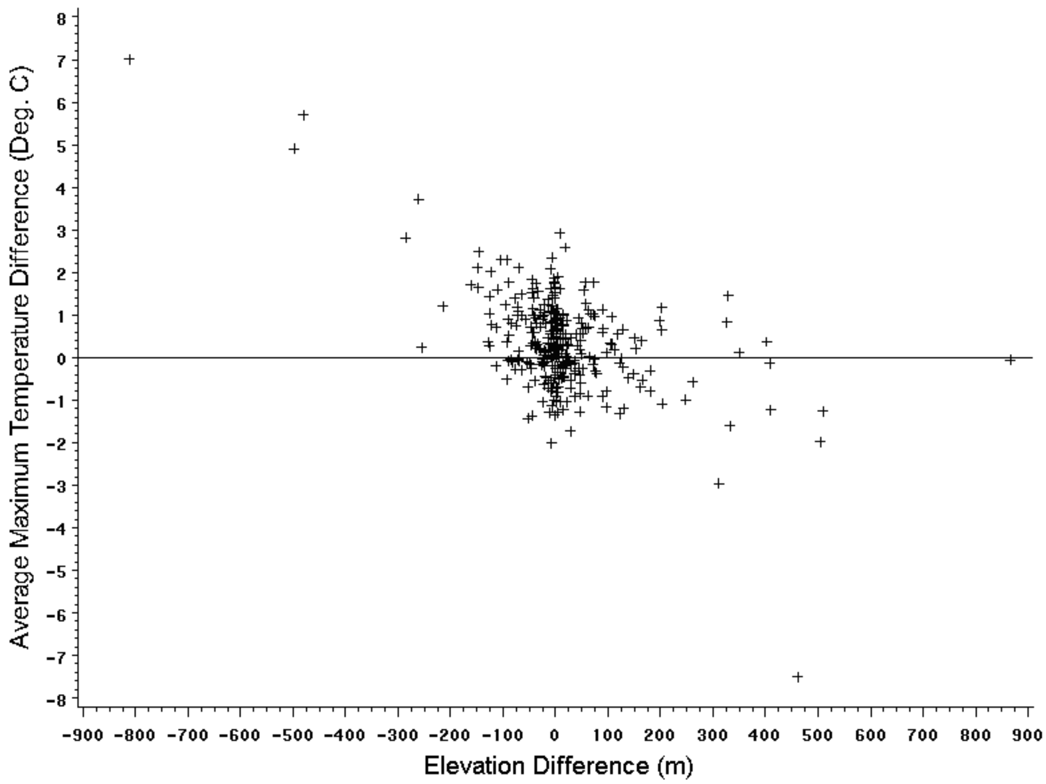


Figure 21. Graph. Average maximum temperature difference versus elevation difference for AWS and SMP sites.

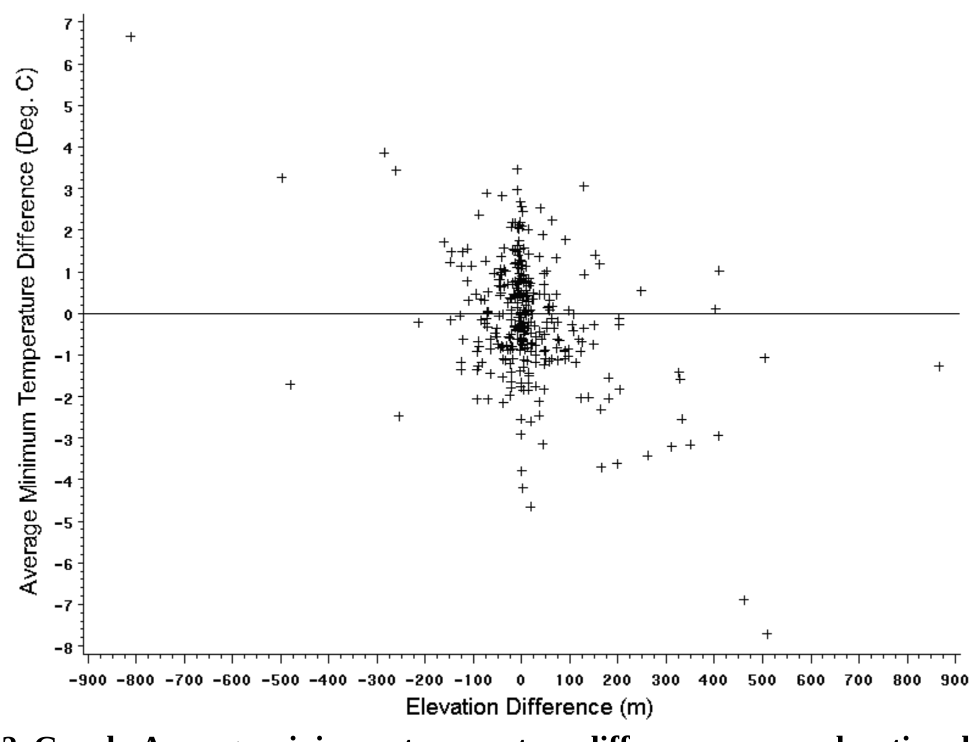


Figure 22. Graph. Average minimum temperature difference versus elevation difference for AWS and SMP sites.

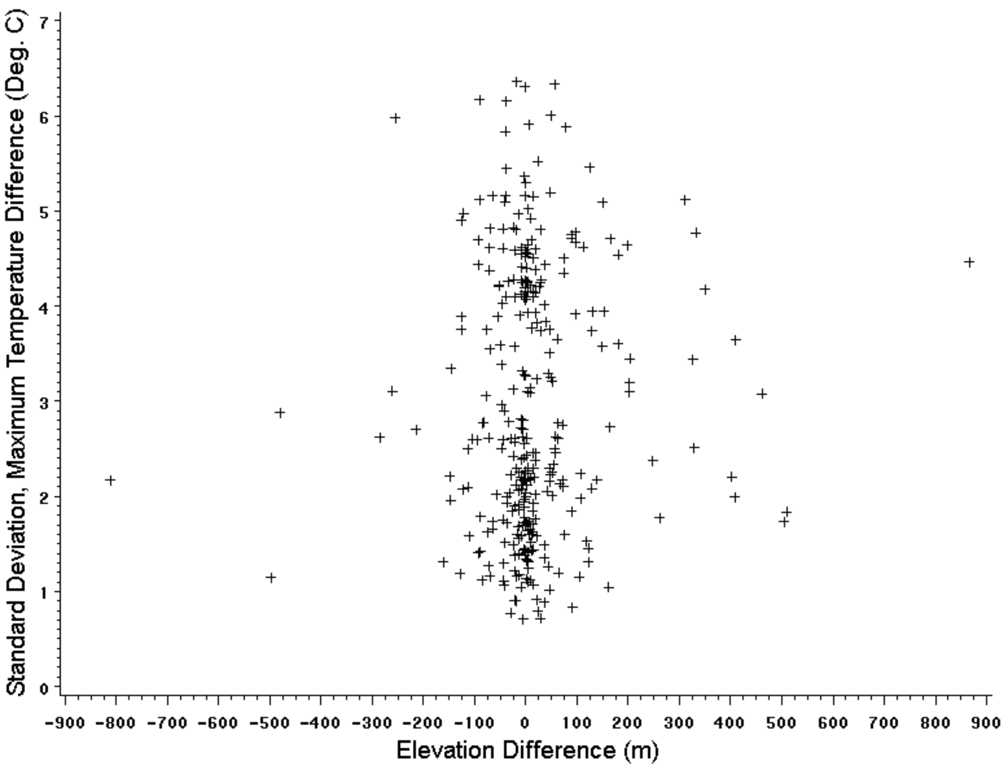


Figure 23. Graph. Standard deviation of maximum temperature difference versus elevation difference for AWS and SMP sites.

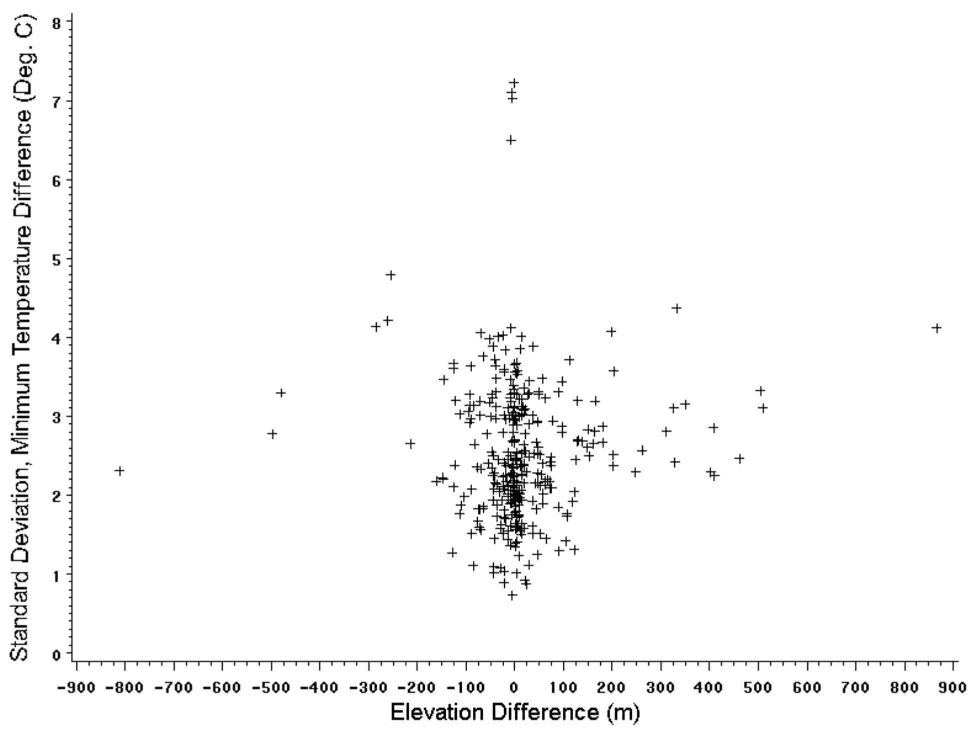


Figure 24. Graph. Standard deviation of minimum temperature difference versus elevation difference for AWS and SMP sites.

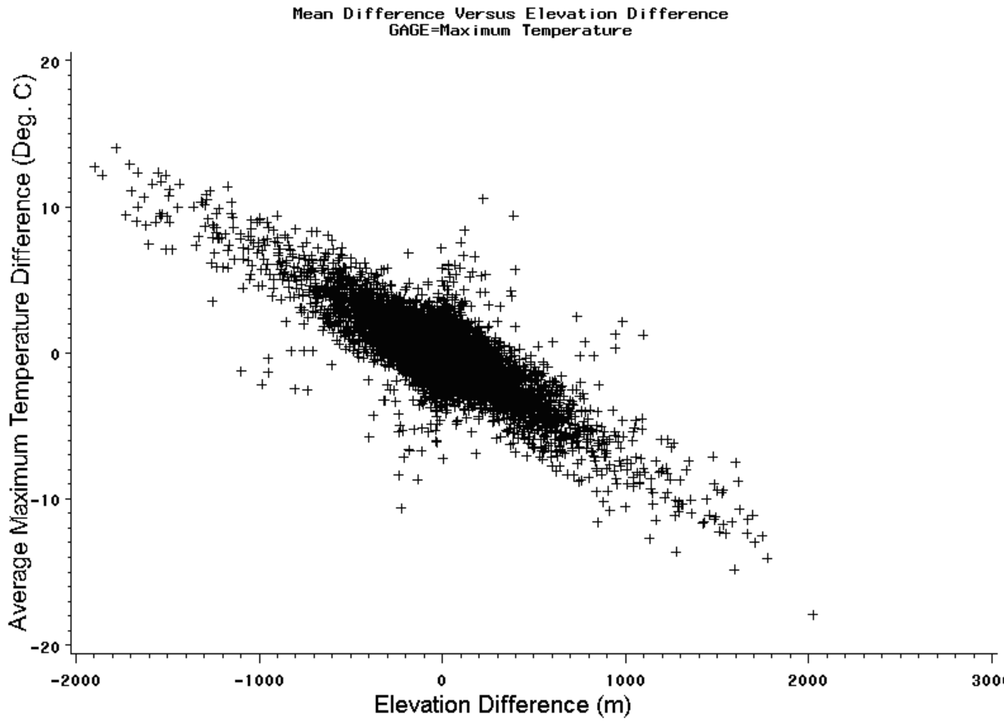


Figure 25. Graph. Mean maximum temperature difference versus elevation difference for NCDC sites.

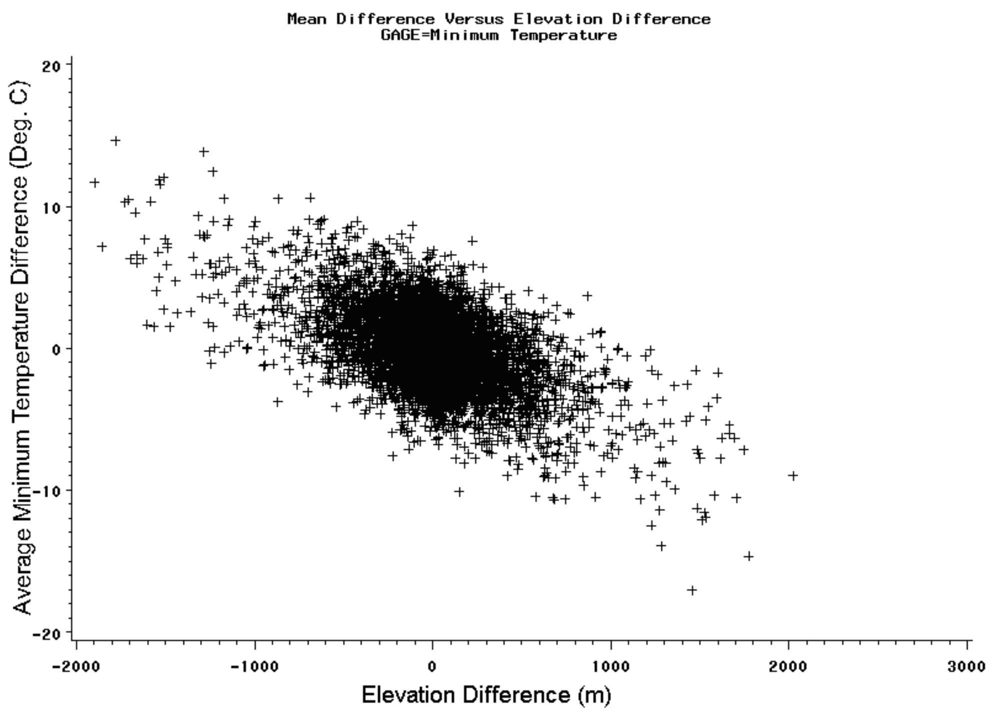


Figure 26. Graph. Mean minimum temperature difference versus elevation difference for NCDC sites.

North-South Distance (Latitude) Effects

Since air temperature generally decreases when going north, this change may affect the climatic estimates from the nearby weather stations. To investigate the effects of the latitude difference, the mean and standard deviation of the temperature difference between the site and the weather stations were graphed versus the north-south distance to the weather station. The north-south distance was calculated from the distance and the bearing to the site.

Figures 27 and 28 show the average temperature difference versus the north-south difference for the maximum and minimum temperatures, respectively. No particular trend was evident between the latitude and the average temperature difference (bias).

Figures 29 and 30 show the standard deviation of the temperature difference versus the north-south distance. The effects of latitude on the standard deviation of the temperature difference (a measure of precision) also were not clear from these graphs.

As with distance, the north-south distance does not seem to affect the precision or bias of the estimate. This may be explained by the fact that within the 60-km range, the effects of distance are mainly random. These effects may be more important at greater distances from the site.

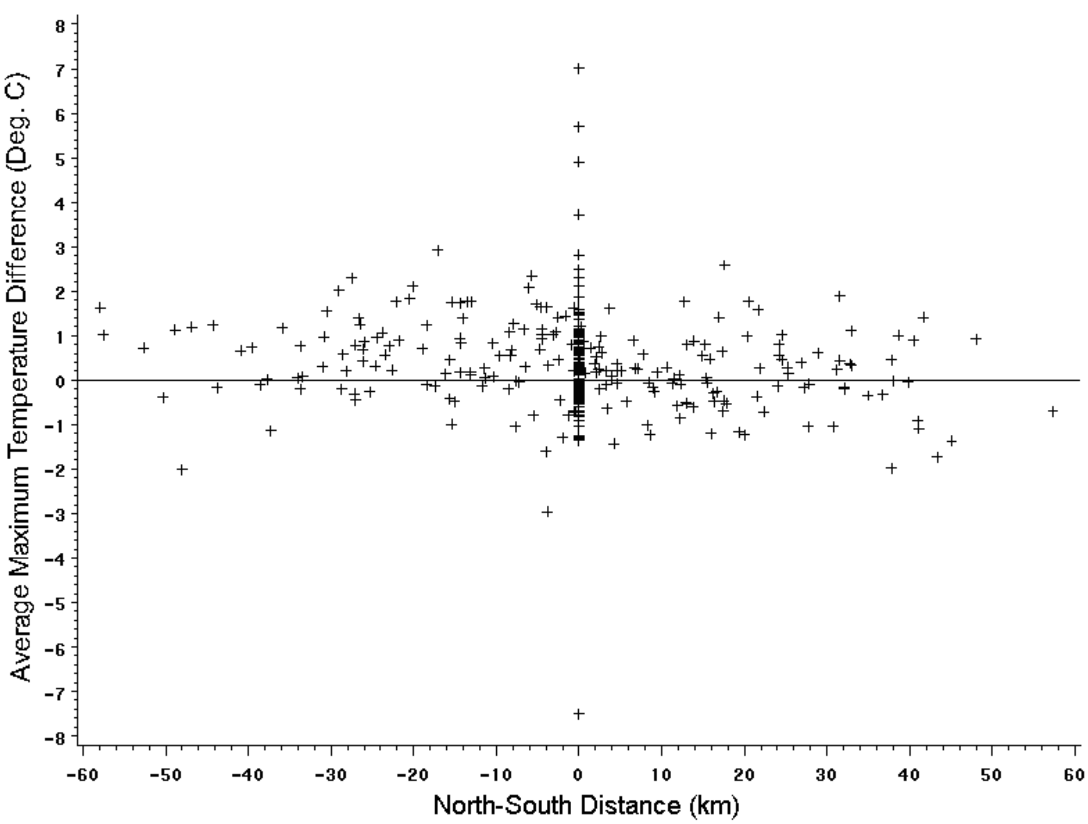


Figure 27. Graph. Mean maximum temperature difference versus north-south distance for AWS and SMP sites.

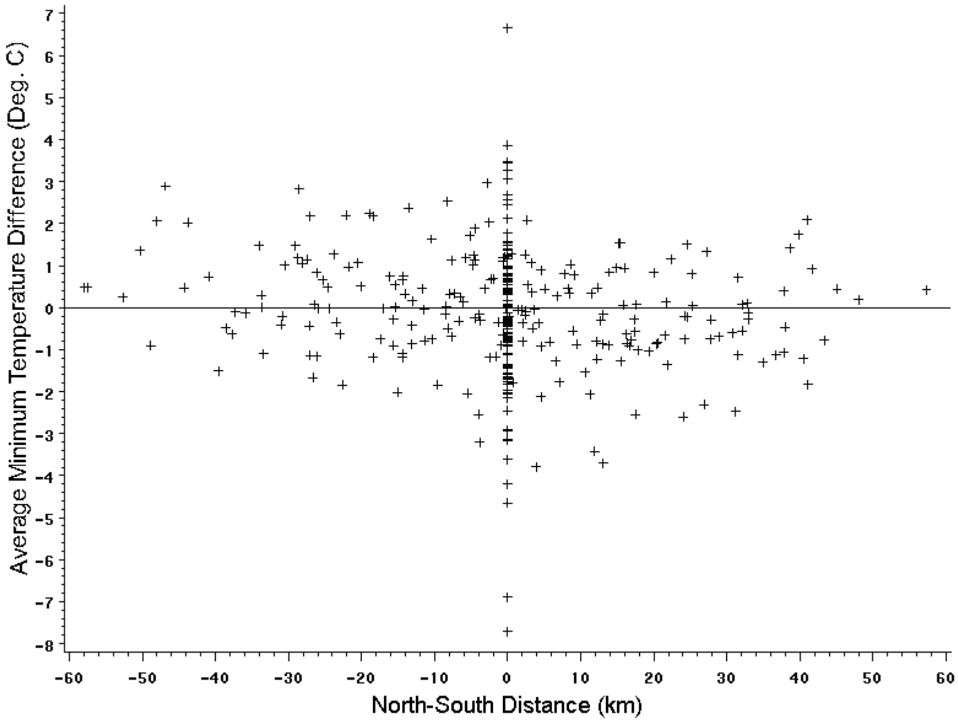


Figure 28. Graph. Mean minimum temperature difference versus north-south distance for AWS and SMP sites.

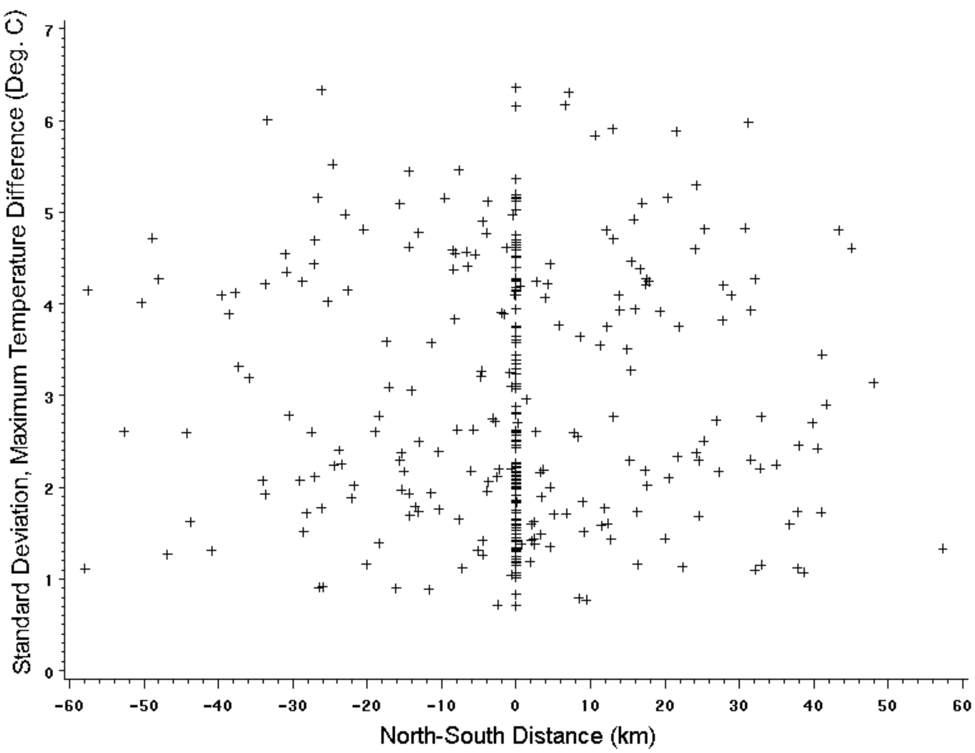


Figure 29. Graph. Standard deviation of maximum temperature difference versus north-south distance for AWS and SMP sites.

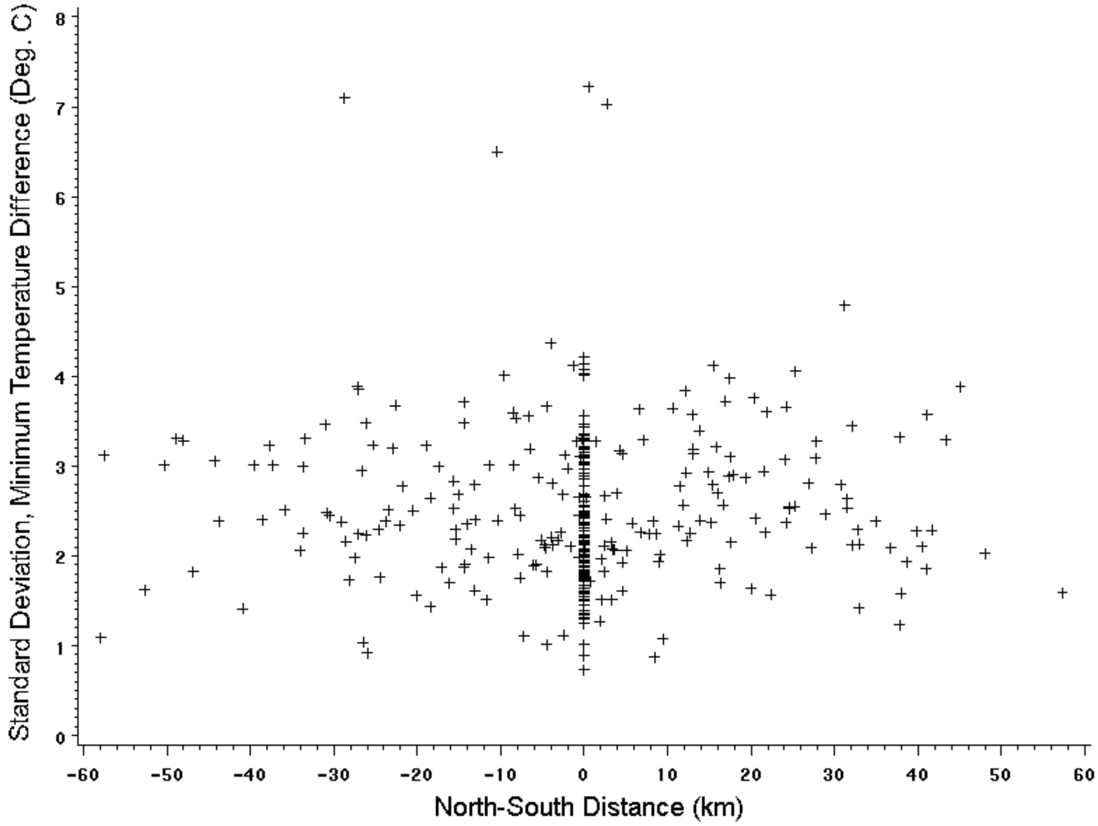


Figure 30. Graph. Standard deviation of minimum temperature difference versus north-south distance for AWS and SMP sites.

COMPARING DIFFERENT METHODS OF CALCULATING VWS ESTIMATES

Climatic data from five weather stations (OWS) near SMP and AWS sites were compared to the collected SMP and AWS data. The daily data for the five closest weather stations (OWS data) were averaged using three different methods: (1) without using a weight, (2) by using the inverse distance square ($1/R^2$) weight, and (3) by using the inverse distance ($1/R$) weight. Also, estimates were made based on the data from the closest weather station. The resulting estimates were then compared with the LTPP VWS estimates and SMP and AWS measured data.

Different Methods of Calculating VWS

Four different methods of calculating VWS were compared with the LTPP VWS estimates currently available in the IMS database to investigate the possibility of improving the current LTPP methodology. The four methods of estimating climatic conditions at a site using data from nearby weather stations were:

1. Closest: Estimate climatic conditions based on data from the closest weather station.
2. Weight $1/R^2$: Estimate the climatic parameter based on averaging the data for up to five of the closest weather stations weighted by the inverse squared distance.
3. Weight $1/R$: Similar to the previous method; however, weighting by the inverse distance.
4. No Weight: Calculate estimates based on a simple average without using any weight, as shown in figure 31.

$$V_m = \frac{\sum_{i=1}^{k} V_{mi}}{n}$$

Figure 31. Equation. Average temperature calculation.

where:

V_m = Calculated data element for day *m* for the VWS.
k = Number of weather stations associated with the project site (up to five).
V_{mi} = Value of a data element on day *m* for weather station *i*.

Figure 32 shows the distribution of the percent contribution of the closest weather station to the estimated value for all 880 LTPP sites when using the $1/R^2$ rule. The percent contribution is the ratio of the weight ($1/R^2$) of the closest weather station to the sum of the weights for all of the weather stations. It shows that the closest weather station contributed more than 70 percent to the VWS estimate for half of the LTPP sites. For this reason, the LTPP VWS estimates are closer to data from the closest weather station. Figure 33 shows results for the $1/R$ rule. It shows that the contribution of the closest weather station to the estimate is significantly less (less than 50 percent half of the time) with this method. This method provides results that are close to using a simple average.

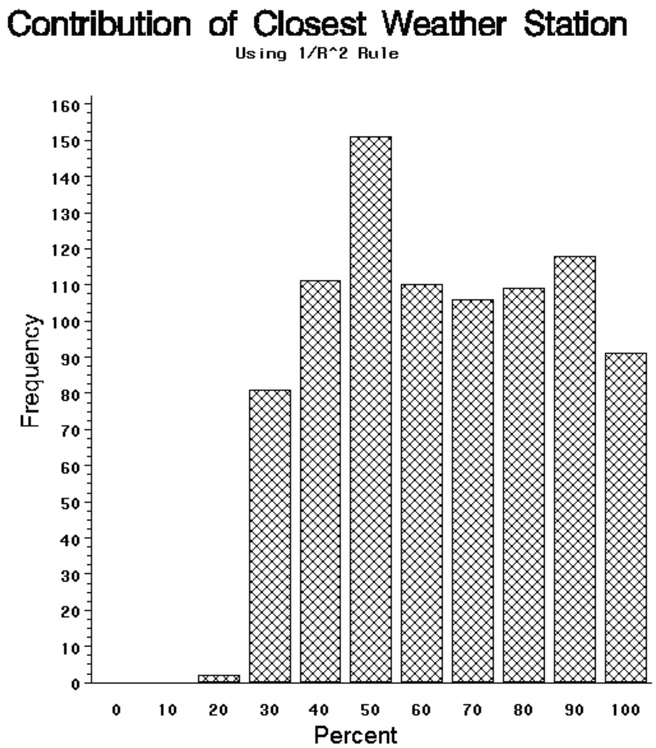


Figure 32. Bar chart. Percent contribution of closest weather stations to VWS using the 1/R^2 rule.

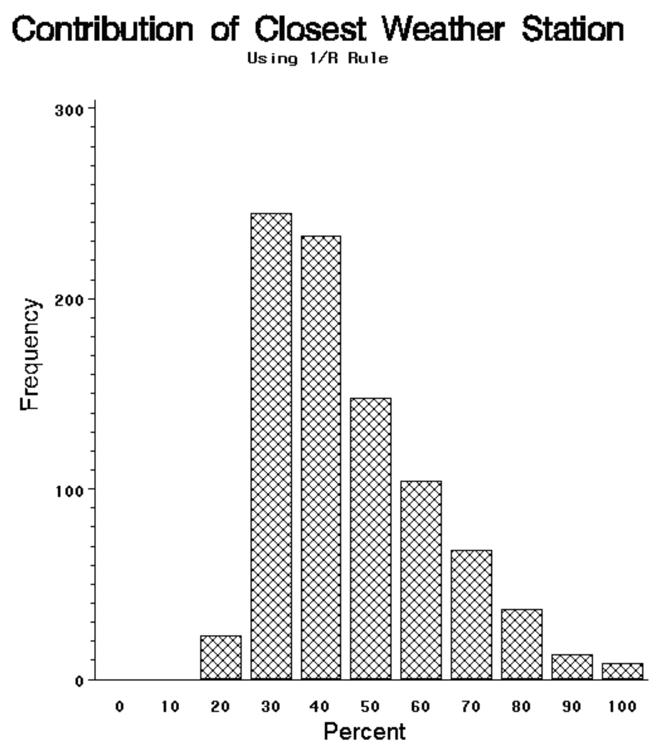


Figure 33. Bar chart. Percent contribution of closest weather stations to VWS using the 1/*R* rule.

The overall daily and monthly summaries for the AWS and SMP sections combined are shown in table 27.

Table 27. Summary statistics for error of daily and monthly estimates of AWS and SMP maximum temperature using five different calculation methods.

Temp.	Period	Freq.	Mean Error (Estimated-Measured), °C					Standard Deviation Error, °C				
			IMS VWS	Closest	Weight 1/*R*^2	Weight 1/*R*	No Weight	IMS VWS	Closest	Weight 1/*R*^2	Weight 1/*R*	No Weight
Max.	Daily	30601	0.41	0.47	0.45	0.41	0.34	3.13	3.41	3.03	2.81	2.69
Min.	Daily	30601	-0.14	-0.11	-0.03	-0.06	-0.12	2.58	3.05	2.65	2.43	2.33
Max.	Monthly	1170	0.41	0.48	0.44	0.4	0.33	1.14	1.44	1.26	1.12	0.99
Min.	Monthly	1170	-0.14	-0.11	-0.03	-0.06	-0.11	1.44	1.85	1.59	1.45	1.40

The following observations were made from table 27:

- The simple average method (No Weight column) provided the lowest standard deviation of all the methods for the daily and monthly estimates.
- The next lowest standard deviation was provided by the inverse distance method (Weight 1/*R* column), which provided more precise estimates (lower standard error) than the inverse distance squared method (Weight $1/R^2$ column).
- The estimate based on the closest weather station (Closest column) gave the highest standard error and the highest mean error. This method provided the poorest climatic estimates.
- All methods gave a similar mean error of the estimate for the daily and monthly estimates.
- The overall standard deviation of error of the simple average method was at least 10 percent lower than the inverse squared distance method (Weight $1/R^2$ column).

In summary, the SMP and AWS data showed that the simple average method was the best method, while weighting by 1/*R* was the next best. Estimates from the closest weather station were the poorest. This validates the use of multiple weather stations in estimates.

Comparing Different Methods of Estimating

The four different methods of estimating daily climatic data explained in the previous section and the VWS estimates currently in the IMS were compared with the climatic data for the AWS sections. Table 28 includes the mean and standard deviation of error (difference between the AWS measured and estimated temperatures) for the maximum air temperature for the five different methods of estimating the daily temperature. Table 29 includes the same data for minimum temperature. Similar data for SMP sites are included in tables 30 and 31.

Table 28. Summary statistics for error of daily estimates of AWS maximum temperature using three different calculation methods.

No.	AWS ID	Days of Data	Mean Error (AWS-Estimate), °C					Standard Deviation Error, °C				
			IMS VWS	Closest	Weight 1/*R*^2	Weight 1/*R*	No Weight	IMS VWS	Closest	Weight 1/*R*^2	Weight 1/*R*	No Weight
1	10101	673	-0.05	-0.39	-0.05	-0.02	0	3.03	3.58	3.05	2.97	2.90
2	40100	604	4.98	7.02	6.56	5.63	4.14	1.28	2.18	2.03	1.80	1.52
3	40200	643	1.29	1.49	1.29	1.16	1.04	1.62	1.66	1.62	1.57	1.52
4	50113	579	0.05	0.29	-0.02	-0.08	-0.14	3.20	4.26	3.46	3.27	3.13
5	80200	443	-0.45	-0.48	-0.44	-0.31	-0.07	5.82	6.37	5.84	4.44	2.74
6	100100	395	-0.26	-0.43	-0.26	-0.21	-0.17	2.59	2.04	2.55	2.49	2.29
7	120101	201	0.05	0.23	0.04	-0.13	-0.33	2.23	2.43	2.23	2.03	1.82
8	200100	144	-0.58	-0.12	-0.12	-0.12	0.46	5.09	1.45	1.44	1.31	2.69
9	200200	141	0.45	1.20	0.50	0.18	-0.14	2.75	2.11	2.78	3.08	3.28
10	300800	706	1.40	1.47	1.41	1.14	0.65	2.48	2.51	2.48	2.44	2.69
11	310100	139	-0.38	-0.55	-0.37	-0.17	0.05	4.14	5.16	4.17	3.29	2.45
12	320200	547	0.82	1.06	0.83	0.61	0.35	1.51	1.45	1.50	1.67	1.98
13	350101	150	0.40	0.96	0.40	0.14	-0.08	2.69	3.13	2.71	2.55	2.45
14	350801	141	0.33	2.11	1.68	0.98	0.03	1.37	2.21	1.96	1.73	1.63
15	360800	391	0.58	0.67	0.59	0.57	0.56	2.33	2.46	2.35	2.46	2.67
16	370200	863	0	0	0	-0.03	-0.17	1.60	1.60	1.60	1.63	1.81
17	380200	389	0.48	0.50	0.48	0.46	0.44	4.06	4.40	4.09	3.03	1.59
18	390200	611	-0.42	-0.53	-0.42	-0.20	0.10	4.33	4.59	4.33	3.84	3.20
19	460800	66	-0.25	-0.60	-0.26	-0.15	-0.14	1.66	1.91	1.65	1.60	1.64
20	480801	69	0.89	1.45	0.90	0.72	0.55	1.36	0.71	1.35	1.93	2.57
21	490800	40	2.39	1.86	2.35	2.43	2.49	2.25	2.17	2.28	2.35	2.42
22	510100	358	-0.30	-0.05	-0.29	-0.45	-0.54	4.47	4.62	4.48	4.17	3.70
23	530200	597	-0.55	-0.90	-0.47	-0.14	0.21	3.07	3.65	2.95	2.48	2.07
24	530800	497	-0.35	-0.20	-0.21	-0.25	-0.40	3.61	2.10	2.08	2.12	2.77
All Days		**9387**	**0.5**	**0.69**	**0.64**	**0.55**	**0.40**	**3.36**	**3.74**	**3.43**	**3.04**	**2.69**
Avg. Section		**391.1**	**0.44**	**0.67**	**0.59**	**0.49**	**0.37**	**2.86**	**2.86**	**2.71**	**2.51**	**2.40**

Table 29. Summary statistics for error of daily estimates of AWS minimum temperature using three different calculation methods.

No.	AWS ID	Days of Data	Mean Error (AWS-Estimate), °C					Standard Deviation Error, °C				
			IMS VWS	Closest	Weight 1/*R*^2	Weight 1/*R*	No Weight	IMS VWS	Closest	Weight 1/*R*^2	Weight 1/*R*	No Weight
1	10101	673	-0.01	-0.75	-0.01	0.01	-0.01	2.07	2.60	2.07	2.01	1.98
2	40100	604	2.24	6.66	5.21	3.02	0.22	2.34	2.31	2.23	2.22	2.35
3	40200	643	-1.01	-1.46	-1.01	-0.55	0	1.54	1.83	1.54	1.39	1.34
4	50113	579	-0.47	-0.77	-0.82	-0.66	-0.45	2.03	3.01	2.23	2.02	1.83
5	80200	443	-1.05	-1.09	-1.06	-0.98	-0.93	2.70	2.97	2.70	2.06	1.51
6	100100	395	1.45	1.26	1.44	1.61	1.75	1.96	1.94	1.96	1.90	1.77
7	120101	201	-0.26	-0.35	-0.26	-0.15	0.05	1.20	1.35	1.20	1.12	1.20
8	200100	144	-1.36	-0.93	-0.93	-0.94	-0.61	2.98	1.31	1.30	1.24	1.61
9	200200	141	0.77	1.38	0.81	0.55	0.32	1.81	1.74	1.83	1.90	1.94
10	300800	706	-1.67	-1.58	-1.66	-1.98	-2.48	2.35	2.42	2.35	2.15	2.21
11	310100	139	-0.53	-0.81	-0.54	-0.29	-0.02	2.42	2.97	2.42	1.93	1.50
12	320200	547	-0.58	-0.62	-0.58	-0.57	-0.58	1.95	2.12	1.95	1.85	1.82
13	350101	150	-1.25	-0.88	-1.27	-1.47	-1.66	1.87	2.23	1.87	1.78	1.76
14	350801	141	-1.71	1.23	0.49	-0.52	-1.70	1.67	2.23	1.93	1.72	1.72
15	360800	391	-0.21	0.08	-0.19	-0.31	-0.44	1.71	1.89	1.72	1.74	1.83
16	370200	863	0.01	0.03	0.01	-0.15	-0.35	1.94	1.96	1.94	1.75	1.51
17	380200	389	-0.26	-0.33	-0.26	-0.05	0.24	2.76	2.97	2.77	2.13	1.42
18	390200	611	-0.27	-0.39	-0.27	-0.04	0.28	3.19	3.46	3.19	2.74	2.25
19	460800	66	0.49	0.38	0.50	0.54	0.57	2.17	2.44	2.17	2.06	1.98
20	480801	69	-0.04	0.96	-0.03	-0.43	-0.80	1.16	0.74	1.16	1.67	2.21
21	490800	40	2.88	2.69	2.82	2.88	2.97	2.92	2.97	2.96	3.01	3.09
22	510100	358	-0.86	-0.32	-0.84	-1.22	-1.51	3.06	3.19	3.06	2.80	2.41
23	530200	597	-0.89	-1.09	-0.71	-0.33	0.13	1.85	2.18	1.81	1.65	1.62
24	530800	497	-0.34	0.77	0.72	0.49	-0.36	1.62	1.76	1.70	1.50	1.45
All Days		**9387**	**-0.30**	**0.01**	**-0.02**	**-0.15**	**-0.34**	**2.40**	**3.09**	**2.68**	**2.27**	**2.05**
Avg. Section		**391.1**	**-0.21**	**0.17**	**0.07**	**-0.06**	**-0.22**	**2.14**	**2.27**	**2.09**	**1.93**	**1.85**

Table 30. Summary statistics for error of daily estimates of SMP maximum temperature using three different calculation methods.

No.	SMP ID	Days of Data	Mean Error (SMP-Estimate) , °C					Standard Deviation Error, °C				
			IMS VWS	Closest	Weight 1/*R*^2	Weight 1/*R*	No Weight	IMS VWS	Closest	Weight 1/*R*^2	Weight 1/*R*	No Weight
1	100102	325	0.39	0.21	0.34	0.39	0.41	2.47	2.00	2.02	2.09	2.22
2	131005	392	-0.28	-0.48	-0.29	-0.18	0	2.73	3.77	2.80	2.45	2.32
3	133019	345	0.26	0.56	0.26	0.19	0.19	3.31	3.84	3.32	3.03	2.63
4	161010	499	1.43	0.80	0.83	0.97	1.25	1.92	3.25	3.16	2.78	2.23
5	183002	164	1.48	1.41	1.47	1.48	1.48	3.90	5.10	3.94	3.66	3.44
6	204054	293	1.40	2.35	1.43	1.06	0.74	3.27	2.63	3.31	3.69	3.98
7	231026	608	0.47	0.11	0.44	0.48	0.54	2.92	4.80	3.04	3.01	3.07
8	241634	493	1.28	1.75	1.30	1.19	1.08	1.58	1.97	1.61	1.66	1.75
9	251002	397	-0.22	-0.53	-0.20	-0.23	-0.27	3.48	4.71	3.49	3.50	3.54
10	271018	871	1.45	1.63	1.45	0.95	0.26	3.20	3.27	3.20	3.02	2.84
11	271028	744	0.76	0.65	0.75	0.74	0.71	2.23	2.19	2.23	2.36	2.53
12	274040	700	0.89	0.47	0.47	0.48	0.73	4.36	1.84	1.84	1.83	3.30
13	276251	659	-0.77	-0.78	-0.77	-0.69	-0.57	4.59	4.62	4.59	4.37	3.71
14	281016	275	0.20	0.20	0.54	0.49	0.18	3.09	3.10	1.78	1.77	2.03
15	281802	405	-1.05	-1.05	-1.07	-1.04	-0.97	2.09	1.66	1.78	2.10	2.56
16	308129	660	0.96	1.20	0.98	0.82	0.67	2.85	2.70	2.85	2.87	2.85
17	310114	293	0.59	0.29	0.59	0.90	1.22	4.70	5.84	4.72	3.73	2.80
18	313018	279	0.42	0.53	0.50	0.66	0.95	5.54	1.41	2.16	2.72	3.30
19	320204	50	0.18	0.28	0.19	0.10	-0.02	1.92	1.94	1.88	1.89	2.02
20	331001	586	0.47	0.47	0.46	0.44	0.24	0.71	0.72	0.71	0.79	2.18
21	351112	350	0.93	1.72	1.28	1.33	1.40	1.58	1.31	1.12	1.20	1.42
22	360801	345	1.18	1.27	1.18	1.16	1.15	2.48	2.63	2.49	2.59	2.77
23	364018	594	0.20	-0.69	-0.67	-0.51	-0.02	3.28	1.05	1.04	1.15	2.67
24	371028	454	0.03	1.06	0.05	-0.04	-0.12	1.79	2.41	1.86	1.91	1.98
25	404165	487	0.84	0.47	0.83	1.02	1.19	3.76	4.92	3.77	3.19	2.71
26	421606	348	0.02	-0.06	0.03	0.03	0.01	1.98	0.79	1.95	2.46	2.89
27	460804	394	0.52	0.33	0.51	0.54	0.50	1.73	2.06	1.74	1.66	1.68
28	469187	262	0.22	1.83	0.75	0.62	0.50	3.55	4.81	3.87	3.73	3.58
29	481060	563	0.85	0.84	0.84	0.84	0.84	1.45	1.69	1.45	1.44	1.45
30	481068	570	-0.37	-0.53	-0.37	-0.31	-0.30	4.06	4.25	4.06	3.96	3.89
31	481077	539	0	-0.13	-0.01	0.10	0.20	2.27	0.89	2.26	2.48	2.58
32	481122	529	0	0.04	0	-0.07	-0.16	3.06	3.58	3.06	2.62	2.24
33	483739	410	-0.56	-1.02	-0.97	-0.84	-0.69	2.89	2.56	2.50	2.48	2.70
34	484142	602	-1.17	0.22	0.20	0.02	-0.46	4.06	4.10	4.05	3.72	3.28
35	484143	445	0.60	0.61	0.60	0.57	0.53	4.07	4.24	4.07	3.76	3.46
36	491001	525	0.17	0.16	0.17	0.17	-0.02	1.37	1.38	1.37	1.34	1.55
37	493011	582	1.56	1.62	1.58	1.41	0.95	2.12	2.19	1.83	1.76	1.93
38	501002	519	-0.48	-1.61	-0.52	-0.29	0.02	3.16	4.77	3.23	2.83	2.30
39	510114	263	0.78	1.08	0.78	0.56	0.40	4.22	4.38	4.23	3.93	3.48
40	533813	218	1.14	1.44	1.15	0.78	0.39	3.29	3.89	3.30	2.68	2.17
41	561007	556	0.47	0.56	0.47	0.39	0.29	3.95	5.15	3.99	3.94	4.04
42	831801	938	0.03	0.18	0.04	0.01	-0.03	1.28	1.74	1.29	1.23	1.16
43	833802	544	-0.18	-0.19	-0.09	0.04	0.11	1.37	1.38	1.23	1.30	1.30
44	871622	545	0.25	0.23	0.24	0.26	0.27	1.26	1.44	1.28	1.22	1.23
45	906405	594	0.23	-0.45	-0.21	-0.08	0.05	1.70	2.20	1.91	1.79	1.72
All Days		**21214**	**0.37**	**0.37**	**0.36**	**0.34**	**0.31**	**3.02**	**3.25**	**2.83**	**2.70**	**2.70**
Avg. Section		**471.42**	**0.39**	**0.42**	**0.39**	**0.38**	**0.35**	**2.81**	**2.91**	**2.61**	**2.53**	**2.57**

Table 31. Summary statistics for error of daily estimates of SMP minimum temperature using three different calculation methods.

No.	SMP ID	Days of Data	Mean Error (SMP-Estimate), °C					Standard Deviation Error, °C				
			IMS VWS	Closest	Weight 1/*R*^2	Weight 1/*R*	No Weight	IMS VWS	Closest	Weight 1/*R*^2	Weight 1/*R*	No Weight
1	100102	325	1.07	0.90	1.34	1.60	1.85	1.84	1.93	1.86	1.86	1.91
2	131005	392	-0.82	-0.82	-0.81	-0.76	-0.62	1.87	2.36	1.87	1.71	1.71
3	133019	345	1.88	2.52	1.89	1.67	1.56	2.28	2.53	2.29	2.16	1.98
4	161010	499	1.08	-0.89	-0.78	-0.36	0.35	1.92	3.27	3.15	2.69	2.10
5	183002	164	-0.44	-0.77	-0.45	-0.40	-0.37	2.79	3.72	2.85	2.65	2.51
6	204054	293	0.43	1.18	0.47	0.15	-0.12	2.05	1.91	2.10	2.22	2.29
7	231026	608	0.50	-0.80	0.44	0.69	0.97	2.56	3.84	2.66	2.61	2.64
8	241634	493	0.19	0.02	0.19	0.25	0.30	1.33	2.18	1.33	1.30	1.30
9	251002	397	-2.21	-3.70	-2.22	-2.18	-2.14	2.05	3.19	2.19	2.17	2.16
10	271018	871	1.14	1.26	1.14	0.78	0.27	2.01	2.10	2.01	1.79	1.57
11	271028	744	0.16	-0.27	0.15	0.16	0.13	2.10	2.88	2.10	2.08	2.12
12	274040	700	-0.04	-0.31	-0.31	-0.30	-0.24	3.40	2.07	2.07	2.02	2.63
13	276251	659	-0.34	-0.35	-0.34	-0.21	0.22	4.07	4.11	4.08	3.82	3.28
14	281016	275	-0.64	-0.64	0.19	0.14	-0.34	2.44	2.45	1.45	1.43	1.64
15	281802	405	0.95	1.12	0.93	0.82	0.66	1.85	1.76	1.61	1.72	1.97
16	308129	660	-0.35	-0.22	-0.36	-0.42	-0.46	2.46	2.65	2.47	2.49	2.58
17	310114	293	-1.16	-1.54	-1.16	-0.81	-0.45	2.95	3.64	2.96	2.36	1.81
18	313018	279	-1.56	-0.80	-1.02	-1.05	-1.02	2.8	1.51	1.46	1.54	1.73
19	320204	50	-0.02	-0.05	-0.03	-0.03	-0.07	1.89	1.98	1.91	1.90	1.99
20	331001	586	-1.18	-1.19	-1.18	-1.11	-0.77	1.10	1.12	1.10	0.97	1.39
21	351112	350	-0.08	1.71	0.78	0.64	0.56	1.70	2.18	1.71	1.60	1.53
22	360801	345	0.08	0.32	0.08	-0.03	-0.17	1.81	2.02	1.82	1.84	1.92
23	364018	594	-0.84	1.19	1.15	0.78	-0.38	2.84	2.65	2.61	2.25	2.36
24	371028	454	1.04	1.28	1.04	1.03	1.03	1.68	2.38	1.69	1.68	1.68
25	404165	487	0.50	0.06	0.49	0.70	0.83	2.56	3.21	2.57	2.29	2.10
26	421606	348	-0.27	0.34	-0.25	-0.50	-0.76	1.25	0.88	1.24	1.55	1.84
27	460804	394	-0.36	-0.31	-0.35	-0.38	-0.40	1.80	2.13	1.81	1.66	1.58
28	469187	262	0.83	1.08	0.92	0.85	0.77	1.72	2.50	1.77	1.73	1.70
29	481060	563	0.90	0.74	0.90	0.94	0.97	1.54	1.91	1.54	1.51	1.50
30	481068	570	-1.00	-1.02	-1.00	-0.98	-0.94	2.76	2.91	2.77	2.72	2.72
31	481077	539	-0.03	0.45	-0.02	-0.13	-0.24	1.63	1.51	1.63	1.67	1.70
32	481122	529	-0.79	-0.78	-0.79	-0.78	-0.74	2.61	3.01	2.61	2.29	2.06
33	483739	410	0.47	0.47	0.46	0.50	0.60	2.36	2.39	2.30	2.16	2.22
34	484142	602	-0.26	-0.01	-0.01	0	0.01	3.18	3.31	3.27	3.01	2.73
35	484143	445	0.66	0.54	0.66	0.88	1.16	6.98	7.03	6.98	6.89	6.82
36	491001	525	-1.73	-1.78	-1.73	-1.49	-1.17	1.66	1.72	1.67	1.42	1.62
37	493011	582	-0.08	-0.04	-0.10	-0.18	-0.32	2.00	2.07	1.83	1.78	1.84
38	501002	519	-0.36	-2.54	-0.44	-0.13	0.26	3.13	4.37	3.22	2.95	2.62
39	510114	263	-0.51	0.03	-0.49	-0.86	-1.14	2.89	3.01	2.88	2.63	2.26
40	533813	218	-1.09	-1.17	-1.09	-1.05	-1.07	1.75	2.10	1.76	1.45	1.33
41	561007	556	-1.00	-1.84	-1.03	-0.96	-1.02	3.30	4.01	3.32	3.28	3.35
42	831801	938	-0.17	-0.43	-0.16	-0.21	-0.27	1.39	1.61	1.39	1.40	1.41
43	833802	544	-0.09	-0.09	-0.13	-0.19	-0.28	2.64	2.66	2.65	2.52	2.06
44	871622	545	0.12	-0.17	0.12	0.37	0.63	1.81	2.11	1.81	1.73	1.83
45	906405	594	0.68	0.67	0.68	0.70	0.72	2.03	3.13	2.58	2.34	2.17
All Days		**21214**	**-0.08**	**-0.16**	**-0.03**	**-0.02**	**-0.02**	**2.66**	**3.03**	**2.63**	**2.50**	**2.44**
Avg. Section		**471.42**	**-0.11**	**-0.15**	**-0.05**	**-0.04**	**-0.04**	**2.33**	**2.62**	**2.29**	**2.17**	**2.14**

Comparing Measured Daily Temperatures to Estimates from a Simple Average

The same approach used for SMP and AWS sites was used here to determine the precision and bias of estimates for 5347 locations throughout the United States. For this purpose, the climatic data for all cooperative weather stations from the NCDC between 1994 and 1996 (1096 days) were used. For every weather station, the five closest weather stations were determined and the estimated daily weather data were calculated by simply averaging data for the five closest weather stations, without using distance as a weight or eliminating weather stations with a high elevation difference. The estimated data were then compared with the measured data at the site.

Table 32 shows the mean and standard deviation error for minimum and maximum temperatures by elevation. The results in table 32 indicate that the mean error (estimate bias) increases with elevation. This is because elevation differences between the weather stations are more probable at higher elevations. The lowest mean error was for elevations of less than 250 m; however, the standard deviation did not significantly differ. Below this elevation, the overall standard deviation was 2.1 °C for maximum and 1.9 °C for minimum temperatures. Almost 40 percent of the weather stations in the United States are located below a 250-m elevation. Figures 34 through 37 show the distribution of the mean and standard deviation of the errors for maximum and minimum temperatures.

The overall precision and bias of maximum (2.2 and 0.2 °C, respectively) and minimum (2.0 and 0.1 °C, respectively) temperatures are comparable to the results from the AWS and SMP sections. Since the estimated bias increases with the elevation difference, the bias can be remedied by correcting the temperature for the elevation difference.

Table 32. Summary statistics of mean error for maximum and minimum temperatures versus weather station elevation.

Elevation	Number of Sites	Number of Days	Error (Estimated-Measured), °C			
			Maximum Temperature		Minimum Temperature	
			Mean	Std. Dev.	Mean	Std. Dev.
0-250	2168	2,214,330	-0.1	2.1	-0.1	1.9
250-500	1231	1,258,811	0	2.3	0	2.1
500-750	470	473,303	0.2	2.4	0.2	2.1
750-1000	316	326,772	0.2	2.3	0.2	2.0
1000-1250	267	276,052	0.4	2.3	0.3	2.0
1250-1500	312	325,627	0.2	2.3	0.1	2.1
1500-1750	213	219,487	0.6	2.4	0.6	2.3
1750-2000	162	166,121	0.9	2.3	0.5	2.4
2000-2250	107	106,261	1.4	2.2	0.9	2.4
All Days	5347	5,471,796	0.2	2.2	0.1	2.0

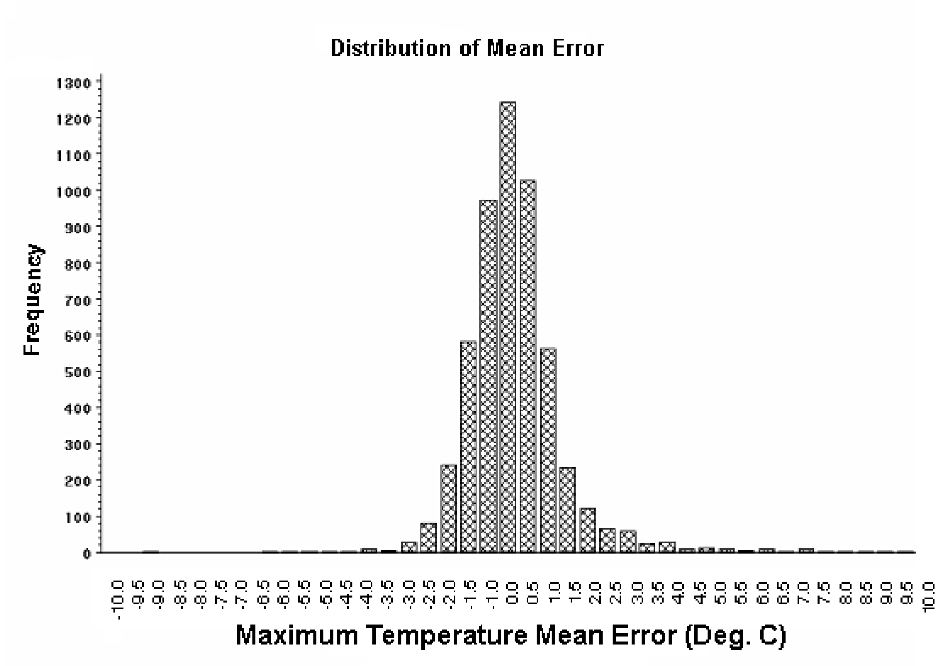


Figure 34. Bar chart. Distribution of mean error for maximum temperature (NCDC data).

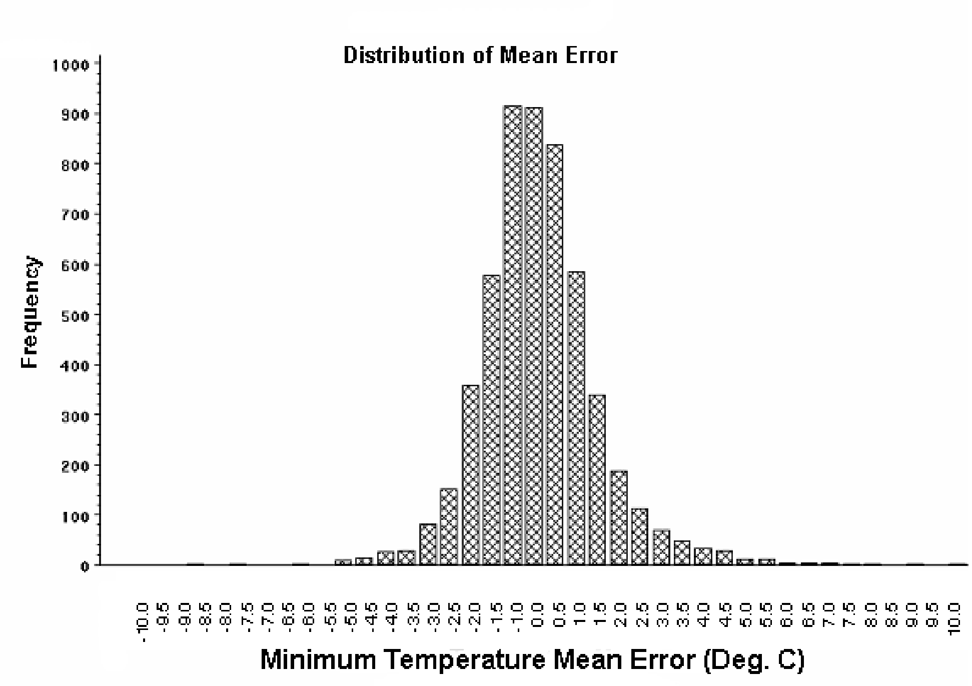


Figure 35. Bar chart. Distribution of mean error for minimum temperature (NCDC data).

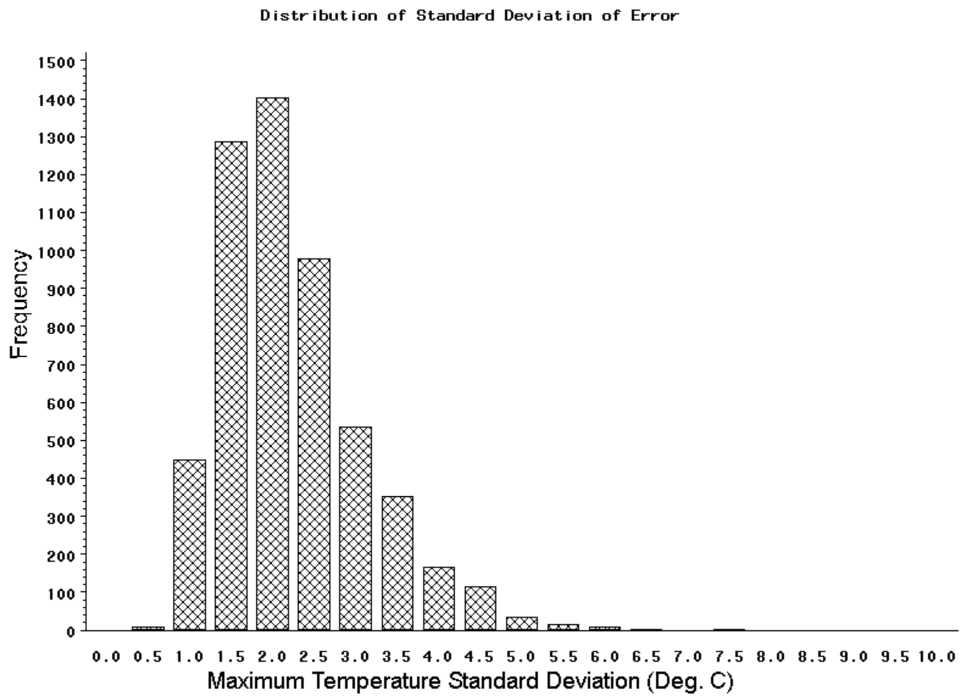


Figure 36. Bar chart. Distribution of standard deviation of error for maximum temperature (NCDC data).

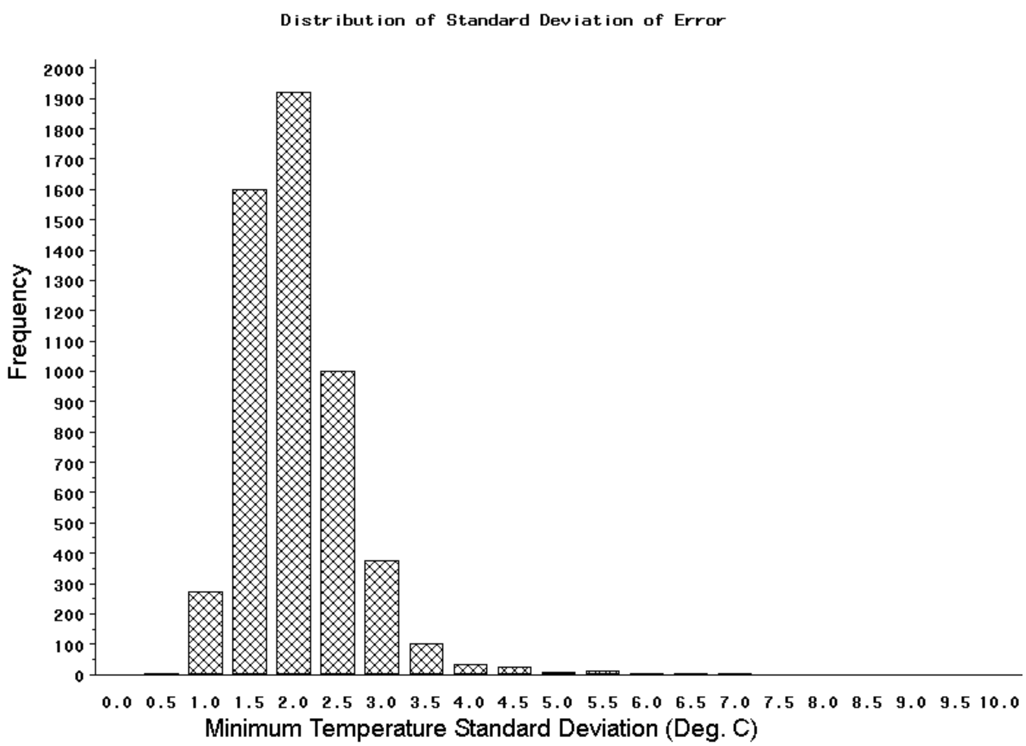


Figure 37. Bar chart. Distribution of standard deviation of error for minimum temperature (NCDC data).

Correcting Temperature for Elevation Difference

In this part of the study, maximum temperatures were corrected for elevation differences and the results of the corrected and uncorrected errors were compared. The LTPP AWS and SMP databases were used for the study and the maximum temperature was corrected using the following algorithm derived from the analysis of the elevation differences in table 26:

1. Temperature correction was applied to elevation differences between 250 and 1000 m (higher and lower elevation differences).

2. For every 100-m increase in elevation, 0.75 °C was subtracted from the temperature (0.75 °C was added for elevation decrease) as Corrected Maximum Temperature = Maximum Temperature – Elevation Difference (km) * 7.5 °C.

Table 33 includes the mean and standard deviation of error for maximum temperature estimates using a simple average (corrected and uncorrected). Table 34 includes the same data for SMP sections. In both cases, correcting the maximum temperature dramatically reduced the bias, while the standard deviation did not change significantly.

Table 33. Summary statistics of error for AWS sections (corrected for elevation).

No.	AWS ID	Days of Data	Mean Error (AWS-Estimate), °C			Standard Deviation Error, °C		
			IMS VWS	No Weight	Corrected No Weight	IMS VWS	No Weight	Corrected No Weight
1	10101	686	-0.1	0	0	3.0	2.9	2.9
2	40100	606	5.0	4.1	3.2	1.3	1.5	1.6
3	40200	892	1.3	1.0	1.0	1.6	1.5	1.5
4	50113	601	0	-0.2	-0.2	3.2	3.1	3.1
5	80200	459	-0.4	-0.1	-0.1	5.8	2.7	2.7
6	100100	410	-0.2	-0.1	-0.1	2.6	2.3	2.3
7	120101	201	0.1	-0.3	-0.3	2.2	1.8	1.8
8	200100	147	-0.5	0.5	0.5	5.0	2.7	2.7
9	200200	146	0.5	-0.1	-0.1	2.8	3.3	3.3
10	300800	763	1.4	0.7	-1.5	2.5	2.7	2.7
11	310100	143	-0.4	0.1	0.1	4.1	2.4	2.4
12	320200	570	0.8	0.4	0.4	1.5	2.1	2.1
13	350101	458	-0.1	-0.3	-0.3	2.5	2.4	2.4
14	350801	142	0.3	0	-0.6	1.4	1.6	1.7
15	360800	403	0.6	0.5	0.2	2.3	2.7	2.7
16	370200	877	0	-0.2	-0.2	1.6	1.8	1.8
17	380200	402	0.5	0.4	0.4	4.1	1.6	1.6
18	390200	635	-0.4	0.1	0.1	4.3	3.2	3.2
19	460800	68	-0.2	-0.1	-0.1	1.6	1.6	1.6
20	480801	90	0.7	0.4	0.4	2.1	3.0	3.0
21	490800	43	2.3	2.3	2.3	2.3	2.4	2.4
22	510100	362	-0.3	-0.6	-0.6	4.5	3.7	3.7
23	530200	631	-0.6	0.2	0.2	3.1	2.1	2.1
24	530800	525	-0.4	-0.4	-0.4	3.7	2.9	2.9
All Days		10260	0.48	0.39	0.15	3.31	2.67	2.64
Average Section		427.5	0.41	0.35	0.18	2.88	2.42	2.43

Table 34. Summary statistics of error for SMP sections (corrected for elevation).

No.	SMP ID	Days of Data	Mean Error (Estimate-SMP), °C			Standard Deviation Error, °C		
			IMS VWS	No Weight	Corrected No Weight	IMS VWS	No Weight	Corrected No Weight
1	100102	335	0.4	0.4	0.4	2.5	2.3	2.3
2	131005	395	-0.3	0	0	2.7	2.3	2.3
3	131031	342	-0.1	-0.4	-3.5	3.4	2.6	2.6
4	133019	353	0.3	0.2	0.2	3.3	2.6	2.6
5	161010	518	1.4	1.3	1.3	1.9	2.2	2.2
6	183002	287	1.4	1.4	1.4	3.6	3.3	3.3
7	204054	302	1.4	0.7	0.7	3.3	4.0	4.0
8	231026	627	0.4	0.5	0.5	2.9	3.1	3.1
9	241634	502	1.3	1.1	1.1	1.6	1.8	1.8
10	251002	569	-0.2	-0.3	-0.4	3.3	3.4	3.4
11	271018	898	1.4	0.3	0.3	3.2	2.8	2.8
12	271028	1057	0.9	0.8	0.8	2.5	2.8	2.8
13	274040	727	0.8	0.7	0.7	4.4	3.4	3.4
14	276251	979	-0.6	-0.5	-0.5	4.3	3.5	3.5
15	281016	457	0.1	0.1	0.1	3.2	2.3	2.3
16	281802	410	-1.1	-1.0	-1.0	2.1	2.6	2.6
17	308129	692	0.9	0.6	0.6	2.9	2.9	2.9
18	310114	309	0.6	1.2	1.2	4.7	2.8	2.8
19	313018	313	0.6	1.1	1.1	5.7	3.6	3.6
20	320204	52	0.2	0	0	1.9	2.0	2.0
21	331001	624	0.5	0.2	0.2	0.7	2.2	2.2
22	351112	356	0.9	1.4	1.4	1.6	1.4	1.4
23	360801	355	1.2	1.1	1.1	2.5	2.8	2.8
24	364018	636	0.2	0	-1.7	3.3	2.7	2.7
25	371028	464	0	-0.2	-0.2	1.8	2.0	2.0
26	404165	495	0.9	1.2	1.2	3.8	2.7	2.7
27	421606	362	0	0	0	2.0	3.0	3.0
28	460804	406	0.5	0.5	0.5	1.7	1.7	1.7
29	469187	342	0.2	0.4	0.4	3.5	3.5	3.5
30	481060	577	0.9	0.9	0.9	1.4	1.4	1.4
31	481068	583	-0.4	-0.3	-0.3	4.0	3.9	3.9
32	481077	605	0	0.2	0.2	2.8	2.8	2.8
33	481122	535	0	-0.2	-0.2	3.1	2.2	2.2
34	483739	601	-0.5	-0.6	-0.6	3.0	2.9	2.9
35	484142	611	-1.2	-0.5	-0.5	4.1	3.3	3.3
36	484143	447	0.6	0.5	0.5	4.1	3.5	3.5
37	491001	536	0.2	0	-0.9	1.4	1.6	1.6
38	493011	603	1.6	0.9	0.9	2.1	1.9	1.9
39	501002	597	-0.5	0	-0.8	3.0	2.2	2.2
40	510114	266	0.8	0.4	0.4	4.3	3.5	3.5
41	533813	356	0.8	0.2	0.2	3.0	2.2	2.2
42	561007	588	0.5	0.3	0.3	4.0	4.1	4.1
43	831801	973	0	0	0	1.3	1.2	1.2
44	833802	575	-0.2	0.1	0.1	1.4	1.3	1.3
45	871622	581	0.2	0.3	0.3	1.3	1.2	1.2
46	893015	782	0.2	0.5	0.5	1.6	1.4	1.4
47	906405	605	0.2	0.1	0.1	1.7	1.7	1.7
All Days		24585	0.35	0.30	0.17	3.02	2.70	2.76
Average Section		523.1	0.37	0.33	0.19	2.81	2.57	2.57

COMPARING CLIMATIC ESTIMATES FROM NCDC DATA

Estimated climatic data were developed for NCDC weather station sites and were then compared to the measured NCDC data. Climatic estimates were developed by averaging data for the five closest weather stations for each NCDC site without using a weight. Table 35 includes the overall average and standard deviation of error (measured minus estimated) for the daily, monthly, and yearly climatic estimates of 5347 NCDC sites throughout the United States. The data period covers 1994 through 1996 and included 1096 days of data for each site. The following are some observations from the results:

- Using a simple average of data from the five closest weather stations, maximum and minimum daily temperatures can be estimated within 2.2 °C.
- Monthly minimum and maximum temperatures can be estimated within 0.7 °C.
- Yearly minimum and maximum temperatures can be estimated within 0.6 °C.
- Monthly and yearly precipitation can be estimated within 29 mm and 147 mm, respectively.
- Yearly FI can be estimated within 56 °C-days.

These statistics were calculated using all observations and are overall values. The overall values are generally higher than the average per section values, especially for accumulated data such as precipitation and FI. This is caused by the effect of bias on the standard deviation (locations with a high bias will contribute more to the standard deviation).

Table 35. Overall mean and standard deviation of error of daily, monthly, and yearly estimates for NCDC sites.

Parameter	Period	Frequency	Error (Estimated-Measured)	
			Mean	Std. Dev.
Maximum Temperature, °C	Daily	5,471,796	0.1	2
	Monthly	178,840	0	0.7
	Yearly	15,631	0	0.6
Minimum Temperature, °C	Daily	5,471,796	0.2	2.2
	Monthly	175,411	0	0.7
	Yearly	15,622	0	0.6
Precipitation, mm	Monthly	235,286	-3.4	28.6
	Yearly	22,929	-35	147.3
Freezing Index, °C	Yearly	23,969	-17.5	55.8

DATA ANOMALIES

Four different data problems were found during the course of this study and were reported to the LTPP program. These problems are related to the raw OWS daily data file, daily VWS calculations in the IMS, and SMP data problems. Following is a description of each data problem.

Duplicate Records in OWS Daily Data

The review of the OWS daily data in the owsdaily.txt file revealed that sometimes the temperature and precipitation data for 2 or more consecutive days were identical (duplicates). Duplicate records were identified when identical data for parameters were repeated for 1 or more days. It was found that fewer than 1 percent of the data were duplicates.

Duplicate records were probably used by NCDC to remedy the missing climatic data for some days. Although duplicate records may not affect the calculation of monthly data estimates, it may affect the daily climatic estimates.

Problems in VWS Data Calculations

The daily VWS data in the IMS were compared to the VWS data that were calculated from the original daily OWS data, and some differences were observed. While the VWS data for most SMP and AWS sections in the study (tables 28 through 31) matched the $1/R^2$-weight estimated values, the results for some of the sections were different (e.g., AWS site 200100 in table 28). A more detailed study of the problem indicated that the difference was caused by a number of weather stations used in the calculation of the VWS data in CLM_VWS_OWS_LINK. Some weather stations were eliminated from the calculations, but still were counted in the number of contributing weather stations shown in the table.

Table 36 shows the VWS daily maximum temperatures, the corresponding AWS daily data, and the data for the five closest OWS to AWS site ID 200100 (from the owsdaily.txt file). The first row of data (August 7, 1996) shows that the estimated VWS Max_Day_Temp was 33.2 °C and the measured AWS temperature was 26.5 °C. The weighted average of the five closest OWS was 26.72 °C. It was found by trial and error that the data for the closest weather station (KS02164, distance R = 264 m) were eliminated from the VWS calculations, but were still counted as a contributing weather station. Therefore, the Contribute_WS_No is actually only four (not five as reported in the CLM_VWS_DATA_DAILY table).

The maximum temperature for the eliminated weather station actually agreed closely with the measured AWS data (26.5 versus 26.7 °C). The VWS estimate is almost identical to the data for station no. 2 (KS03239, R = 4783 m) because this station is much closer to the AWS site compared to station nos. 3 through 5. Eliminating the closest weather station for this site has resulted in a much higher VWS estimate.

Table 36. VWS, AWS, and OWS maximum temperatures for AWS site 200100.

Virtual Weather Station			AWS	Operating Weather Stations					
VWS_Date	MAX_ DAY_ TEMP	CONTRI-BUTE_ WS_NO	MAX_ DAY_ TEMP	(1) KS02164 *R*=264 m	(2) KS03239 *R*=4783 m	(3) KS01704 *R*=37771 m	(4) KS04333 *R*=37588 m	(5) KS06549 *R*=40734 m	Weight $1/R^2$
07-Aug-96	33.2	5	26.5	26.7	33.3	30.0	33.9	32.2	26.72
08-Aug-96	25.7	5	28.6	27.8	25.6	27.8	27.8	28.3	27.79
09-Aug-96	27.2	5	24.6	23.9	27.2	25.0	30.0	27.2	23.91
10-Aug-96	26.1	5	26.8	27.2	26.1	28.3	25.0	26.7	27.20
11-Aug-96	25.7	5	26.0	26.7	25.6	27.8	28.3	27.2	26.70
12-Aug-96	25.7	5	24.5	24.4	25.6	27.8	27.8	25.6	24.40
13-Aug-96	24.6	5	28.7	28.3	24.4	28.3	27.2	28.3	28.29
14-Aug-96	28.4	5	30.6	30.0	28.3	30.6	28.9	30.6	29.99
15-Aug-96	30.1	5	30.6	28.9	30.0	30.6	31.1	32.2	28.90
16-Aug-96	30.0	5	29.3	28.3	30.0	29.4	32.2	29.4	28.31
17-Aug-96	30.5	5	28.4	27.2	30.6	28.3	29.4	28.9	27.21
18-Aug-96	31.1	5	32.4	32.2	31.1	32.2	28.9	32.2	32.20
19-Aug-96	31.8	5	34.5	33.3	31.7	33.9	32.8	33.9	33.30
20-Aug-96	33.8	5	27.3	26.1	33.9	29.4	35.0	32.2	26.12
21-Aug-96	27.9	5	31.4	30.6	27.8	31.1	28.9	32.2	30.59
22-Aug-96	31.1	5	32.1	30.6	31.1	31.7	31.7	32.8	30.60
23-Aug-96	31.1	5	29.4	27.2	31.1	30.6	33.3	30.0	27.21
24-Aug-96	28.9	5	29.7	28.3	28.9	28.9	30.0	28.9	28.30
25-Aug-96	29.4	5	27.6	27.8	29.4	26.7	30.6	28.3	27.80
26-Aug-96	27.8	5	27.3	25.6	27.8	26.1	28.9	27.8	25.61
27-Aug-96	27.2	5	27.6	27.2	27.2	28.9	26.7	27.2	27.20
28-Aug-96	27.2	5	27.8	27.8	27.2	25.6	28.9	28.3	27.80
29-Aug-96	26.8	5	29.4	28.9	26.7	28.9	28.3	29.4	28.89
30-Aug-96	28.8	5	26.9	23.3	28.9	27.2	28.9	28.9	23.32
31-Aug-96	26.8	5	25.6	25.0	26.7	26.1	31.1	31.7	25.01
01-Sep-96	25.6	5	26.0	24.4	25.6	25.6	25.6	28.9	24.40
02-Sep-96	25.7	5	28.6	28.3	25.6	28.3	26.7	29.4	28.29

The daily VWS temperature data that were calculated from the owsdaily.txt raw data for the AWS and SMP sections did not agree with the VWS data estimates in the IMS table CLM_VWS_DATA_DAILY for about 10 percent of the AWS and SMP sections. The criteria used to eliminate the weather stations in the CLM_VWS_OWS_LINK table are not known. While this problem has affected the daily VWS data, the effect on the monthly averages is not as significant. The stated number of contributing weather stations, however, is sometimes higher than the actual number.

Anomalies in Daily SMP Data

Different problems in daily SMP air temperature and precipitation data (table SMP_ATEMP_ RAIN_DAY) for some SMP sections were found. These problems are listed below:

- **Entire Data Suspect:** All data for sections 370201, 370205, 370208, and 370212 are either missing or zero. The minimum and maximum temperature times are set to 0001.

- **Zero Minimum and Maximum Temperatures:** The minimum and maximum temperatures for section 161010 (from 9/29/96 to 1/17/97) are zero. The minimum and maximum temperature times are set to 0001. For the following sections, the minimum and maximum temperature times are both set to midnight, as shown in table 37.

Table 37. Sections with anomalies in daily SMP time data.

ID	SMP_DATE	MAX_ATEMP_TIME	MIN_ATEMP_TIME
271018	11/27/96	2400	2400
831801	12/10/96	2400	2400
493011	11/02/94	2400	2400
833802	11/10/93	2400	2400
276251	11/04/93	2400	2400
276251	11/03/95	2400	2400
469187	11/10/96	2400	2400

- **Unreasonable Temperature Change:** Temperature differences of more than 20 °C in less than an hour are listed in table 38. Either the air temperature or the time is suspect.

Table 38. Sections with anomalies in daily SMP temperature change data.

ID	SMP_DATE	MAX_AIR_TEMPERATURE	MIN_AIR_TEMPERATURE	Temperature Difference	MAX_ATEMP_TIME	MIN_ATEMP_TIME
510113	11/19/97	14.1	-6.3	20.4	0803	0826
561007	02/06/94	-0.5	-23.0	22.5	0009	0000
271028	04/06/97	5.5	-14.6	20.1	0101	0100
533813	03/28/98	12.1	-44.5	56.6	1442	1452
533813	04/25/98	15.4	-36.9	52.3	1608	1555
274040	09/29/96	28.0	4.1	23.9	0055	0000
484143	09/08/94	25.9	-15.5	41.4	0908	0941
276251	02/19/94	6.8	-15.3	22.1	0005	0000
276251	01/14/96	-5.5	-27.3	21.8	0001	0000

- **Unreasonable Daily Temperatures:** Daily temperature differences of more than 50 °C are listed below in table 39. It appears that the minimum air temperature is unreasonable.

Table 39. Sections with anomalies in daily SMP temperature data.

ID	SMP_DATE	MAX_AIR_ TEMPERATURE	MIN_AIR_ TEMPERATURE	Daily Temperature Difference, °C
533813	05/01/98	30.4	-41.4	71.8
131031	05/17/98	30.1	-36.2	66.3
131031	04/20/98	21.4	-44.5	65.9
533813	03/13/98	19.0	-46.0	65.0
533813	05/04/98	22.6	-39.4	62.0
533813	04/19/98	16.6	-45.2	61.8
484143	08/15/94	34.3	-24.3	58.6
533813	03/28/98	12.1	-44.5	56.6
533813	01/01/98	9.4	-45.1	54.5
533813	11/17/97	12.6	-41.1	53.7
533813	04/25/98	15.4	-36.9	52.3
484143	09/04/94	33.3	-17.3	50.6
484143	09/07/94	31.3	-19.1	50.4
533813	12/29/97	8.1	-42.3	50.4

Data Inconsistency from Two SMP Installations

The daily climatic data for LTPP sites with more than one simultaneous SMP installation were compared to verify data consistency. A study of the collected data using different instruments in the same location can reveal the data consistency. During this study, collected daily maximum and minimum air temperatures in the SMP_ATEMP_RAIN_DAY table for sections within an SMP site were compared. While most data were within a close range, for some sections, major differences in the temperatures were observed.

Figure 38 shows the maximum air temperatures for SMP site 010101 versus similar temperatures collected at SMP site 010102. Both SPS sections are located within the same site. As can be seen from figure 38, data for some days do not correspond very well.

Figure 39 includes the graph of minimum air temperatures for the same two sections. This figure also shows that SMP collected minimum temperatures for some days do not agree well. The temperature data for temperature differences of 8.5 °C and greater, which correspond to the part of the data with high scatter, are shown in table 40. The first row in table 40 shows a minimum temperature difference of 15.2 °C for data collected on 10/03/98. The difference in the maximum temperature was also significant (11.3 °C).

The same process was repeated for all SMP sites with more than one simultaneous installation, and similar, but less significant, inconsistency was observed for SMP sections 040113 and 040114.

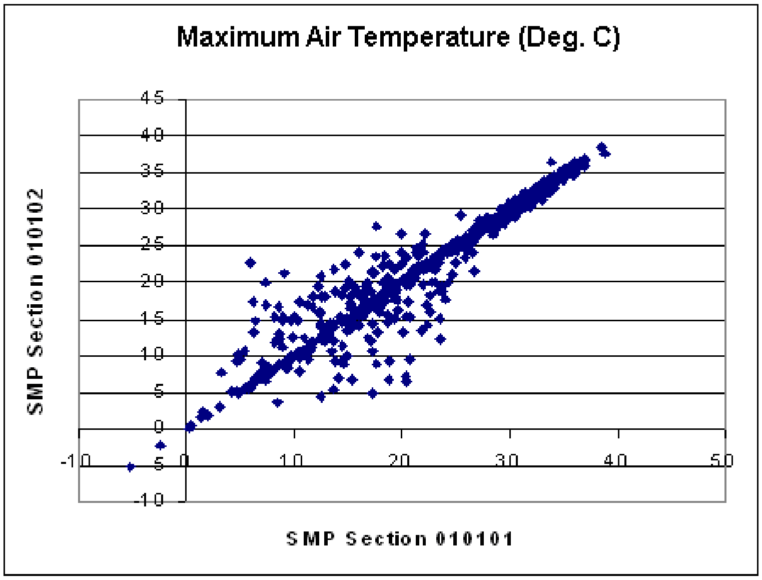


Figure 38. Graph. Maximum air temperature for SMP sections 010101 versus 010102.

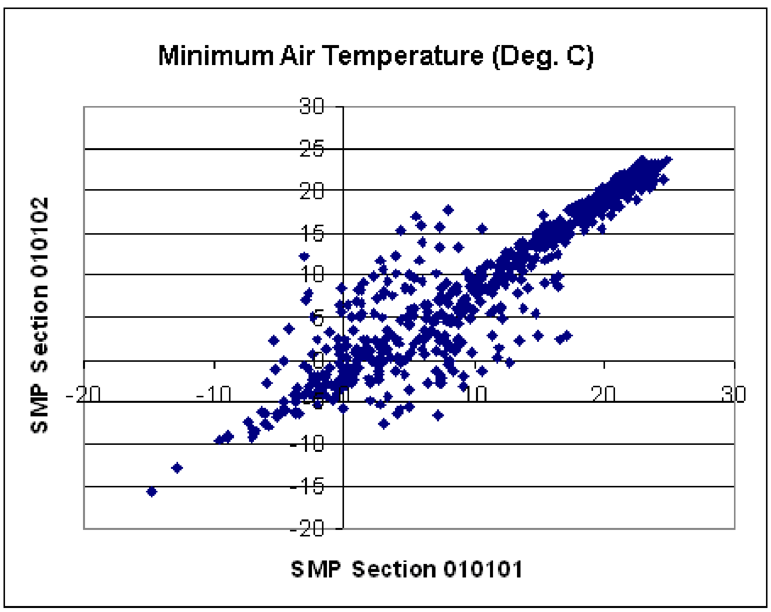


Figure 39. Graph. Minimum air temperature for SMP sections 010101 versus 010102.

Table 40. Temperature data for two SMP installations within the same site.

SMP Section 010101				SMP Section 010102				Difference	
SMP_ DATE	MAX_ AIR_ TEMPER-ATURE	MIN_ AIR_ TEMPER-ATURE	TOTAL_ RAIN	SMP_ DATE	MAX_ AIR_ TEMPER-ATURE	MIN_ AIR_ TEMPER-ATURE	TOTAL_ RAIN	Maximum Temper-ature, °C	Minimum Temper-ature, °C
10/03/98	6.2	-3.0	0	10/03/98	17.5	12.2	0	11.3	15.2
15/04/98	25.8	16.6	0.2	15/04/98	23.4	2.4	0.1	2.4	14.2
06/01/98	19.3	17.1	21.7	06/01/98	21.7	2.9	20.1	2.4	14.2
04/01/98	22.6	7.2	0	04/01/98	16.1	-6.6	0	6.5	13.8
05/01/98	18.7	12.7	7.8	05/01/98	20.7	-0.3	7.6	2.0	13.0
06/03/98	16.5	9.2	10.9	06/03/98	17.0	-3.1	12.5	0.5	12.3
08/04/98	22.0	14.9	40.2	08/04/98	24.2	2.8	39.3	2.2	12.1
13/01/98	14.7	10.6	2.1	13/01/98	19.2	-1.4	2.0	4.5	12.0
09/01/98	9.1	5.5	0.4	09/01/98	21.3	17.0	0.3	12.2	11.5
21/11/97	20.6	11.8	18.9	21/11/97	17.5	0.3	20.3	3.1	11.5
01/11/97	21.0	13.5	34.3	01/11/97	21.8	2.3	28.0	0.8	11.2
22/11/97	18.4	9.2	0	22/11/97	19.0	-2.0	0	0.6	11.2
05/04/98	21.4	4.4	0	05/04/98	24.8	15.2	0	3.4	10.8
25/01/98	12.5	-2.7	0	25/01/98	14.2	7.9	0	1.7	10.6
03/01/98	20.7	3.1	0	03/01/98	9.6	-7.5	0	11.1	10.6
14/03/98	18.8	5.0	0	14/03/98	6.7	-5.5	0	12.1	10.5
14/04/98	18.4	11.9	26.4	14/04/98	23.7	1.4	27.8	5.3	10.5
15/03/98	21.8	4.1	0	15/03/98	13.4	-6.2	0	8.4	10.3
09/12/97	10.4	4.3	1.2	09/12/97	7.9	-5.9	1.0	2.5	10.2
22/01/98	12.9	7.5	19.7	22/01/98	12.1	-2.6	20.5	0.8	10.1
27/11/97	20.7	7.3	0	27/11/97	15.2	-2.6	0	5.5	9.9
16/11/97	8.2	-2.9	0	16/11/97	12.0	7.0	0	3.8	9.9
22/08/96	33.3	5.9	0	22/08/96	32.5	15.8	0	0.8	9.9
16/02/98	20.5	8.4	50.6	16/02/98	15.5	-1.4	46.8	5.0	9.8
11/02/98	18.6	7.4	7.9	11/02/98	15.6	-2.4	8.4	3.0	9.8
20/12/97	19.3	8.3	0	20/12/97	17.7	-1.4	0	1.6	9.7
08/01/98	18.9	8.0	1.1	08/01/98	19.9	17.7	1.3	1.0	9.7
23/01/98	13.7	7.5	0.1	23/01/98	14.5	-2.2	0.1	0.8	9.7
05/03/98	13.5	7.4	6.5	05/03/98	10.6	-2.1	7.0	2.9	9.5
28/04/98	17.5	14.7	0	27/04/98	23.6	5.4	0	6.1	9.3
02/02/98	9.7	6.5	39.8	02/02/98	14.8	-2.7	35.9	5.1	9.2
22/12/97	15.5	9.8	8.1	22/12/97	19.5	0.8	7.2	4.0	9.0
09/03/98	12.4	2.8	0.1	09/03/98	15.8	11.8	0.1	3.4	9.0
28/11/97	21.9	7.3	0	28/11/97	19.7	-1.7	0	2.2	9.0
10/12/97	20.3	7.3	0.5	10/12/97	7.3	-1.6	0.6	13.0	8.9
10/01/98	12.3	-0.2	0	10/01/98	19.5	8.4	0	7.2	8.6
25/03/98	24.3	8.0	0	25/03/98	20.1	-0.5	0	4.2	8.5
27/01/98	8.6	5.0	2.4	27/01/98	12.2	-3.5	2.6	3.6	8.5
27/02/98	21.3	11.3	0.4	27/02/98	24.0	2.8	0.2	2.7	8.5

CONCLUSIONS

During this project, the LTPP virtual weather data for SMP- and AWS-instrumented sites were compared with the measured data. Different methods of developing climatic estimates for the SMP, AWS, and NCDC weather stations were considered and evaluated. Factors affecting the precision and bias of the climatic estimates were investigated. The following are the major findings of this project:

- Daily, monthly, and yearly climatic estimates for anywhere in North America can be developed with reasonable accuracy.

- Using several nearby weather stations for estimating the climatic parameters for a project site provides more accurate estimates than using the closest weather station.

- A simple average of the data (without a weight) for the five closest weather stations provides the best overall estimate for temperature. Weighting the average by the inverse distance provides closer estimates than weighting by the inverse square distance.

- Elevation differences (between the project site and the nearby weather station) of more than 250 m significantly affect the climatic estimates. In this case, temperatures could be corrected to reduce the bias of the estimate. A relationship was proposed for correcting the maximum temperature by the elevation difference.

- The estimated climatic parameters are not severely affected by either the distance or the latitude (north-south distance) of the contributing weather stations within the 60-km range.

- The variation of the measured climatic data (calculated from two or more instruments in one location) was around 40 percent of the variation of the estimated data from the five nearby weather stations.

- Significant year-to-year variation in climatic data was observed. The year-to-year variation (COV) of the yearly precipitation was 21 percent and the FI was 34 percent. On average, the year-to-year variation of the monthly temperature data was 6 percent.

- Review of the VWS data for completeness showed that the quality and quantity of the windspeed and humidity data are significantly lower than the temperature and precipitation data.

- Several data anomalies in VWS, SMP, and AWS data were found and reported.

- LTPP VWS estimates were found to be within a reasonable range, considering the within-site variation of the measured data and also the year-to-year variation of the data.

RECOMMENDATIONS

The following recommendations are given for future work:

- The VWS concept can be used to provide reasonable climatic estimates at any site.
- In developing the climatic estimates, the elevation differences of the nearby weather stations should be limited to 250 m. The temperature could be corrected for the elevation difference using an algorithm similar to what was developed in this study.
- A simple average (no weight) or inverse distance weight ($1/R$) should be used for developing the VWS estimates. The inverse distance square rule ($1/R^2$) and the estimates based on the closest weather stations should be avoided as much as possible.
- The VWS concept provides reasonable estimates regardless of the proposed improvements.
- The most accurate characterization of the year-to-year variation of the climatic data should be made. This variation should be considered when estimating climatic data for an average year at a project site.
- Because of the year-to-year variation of the climatic data, the estimated yearly climatic parameter for a typical year should be made with reliability.
- The within-site variation of the measured climatic data should be further investigated.
- SMP data anomalies discovered during this study should be fixed.
- The quality and quantity of the windspeed and humidity data in the LTPP database should be improved.
- It is highly recommended that the procedures developed in this study be used to develop a user-friendly climatic database for the LTPP program. Such a database can provide daily, monthly, yearly, and multiyear climatic estimates for existing and new sections, and will be updated easily.

REFERENCES

1. *Development of the LTPP Climatic Database*, Report No. SHRP-P-621, Strategic Highway Program, National Research Council, Washington, DC, 1992.

2. *LTPP Climatic Database Revision and Expansion*, FHWA-RD-00-133, Federal Highway Administration, McLean, VA, 2002.

Recycled
Recyclable

HRDI-13/05-06(WEB)E