GEORGIA DOT RESEARCH PROJECT 16-10

FINAL REPORT

IMPROVEMENT OF CLIMATE DATA FOR USE IN MEPDG CALIBRATION AND OTHER PAVEMENT ANALYSIS

GDOT
Georgia Department of Transportation

OFFICE OF PERFORMANCE-BASED
MANAGEMENT AND RESEARCH
15 KENNEDY DRIVE
FOREST PARK, GA 30297-2534

1. Report No.: FHWA-GA-19-1610	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle Improvement of Climate Data for Use in MEPDG Calibration and Other Pavement Analysis	5. Report Date January 2019 6. Performing Organization Code
7. Author(s) Stephan A. Durham, Ph.D., P.E., Bora Cetin, Ph.D., Charles Schwartz, Ph.D., Barton Forman, Ph.D., P.E., and Leela Sai Praveen Gopisetti	8. Performing Organization Report No.
9. Performing Organization Name and Address University of Georgia College of Engineering Driftmier Engineering Center, Athens, GA 30602 Phone: (706) 542-9480 Email: sdurham@uga.edu	10. Work Unit No. (TRAIS) 11. Contract or Grant No. PI#0014920
12. Sponsoring Agency Name and Address Georgia Department of Transportation Office of Performance-Based Management and Research 15 Kennedy Drive Forest Park, GA 30297-2534	13. Type of Report and Period Covered Final; September 2016-January 2019 14. Sponsoring Agency Code

15. Supplementary Notes:
Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract

This study compares the predicted distresses of asphalt concrete (AC) and jointed plain concrete pavement (JPCP) using four different climate data sources: (1) ground-based weather station (GBWS) data, (2) the North American Regional Reanalysis (NARR) data, and (3 and 4) the Modern-Era Retrospective Analysis for Research and Applications (MERRA) versions 1 and 2 (MERRA-1 and MERRA-2) data. The results indicate that pavement performance predictions generated using these data showed disagreement among some of the climate data sources, especially for MERRA-2. Comprehensive diurnal and time-series analyses of the raw climate data found significant disagreements in the percent sunshine data. Percent sunshine is used in the Pavement ME Design environmental effects model to semi-empirically estimate the shortwave radiation reaching the pavement surface, the major driver for pavement heating and cooling. The MERRA-1 and MERRA-2 data independently provide direct predictions of surface shortwave radiation (SSR); these values were found to agree with “ground truth” measurements of SSR from the U.S. Climate Reference Network (USCRN). The direct model predictions of SSR were used to back calculate “synthetic” percent sunshine for input into the Pavement ME Design software. Use of the synthetic percent sunshine derived from predicted SSR eliminated nearly all discrepancies in predicted pavement performance using MERRA-1 vs. MERRA-2 data. Based on these results, the authors recommend SSR rather than percent sunshine to be used as input into the Pavement ME Design software.

17. Keywords Pavement Analyses, Climate Effects, Mechanistic-Empirical Pavement Design Guide (MEPDG), Ground-based Weather Station (GBWS), Modern-Era Retrospective Analysis for Research and Applications (MERRA), North American Regional Reanalysis (NARR)	18. Distribution Statement

19. Security Classification (of this report) Unclassified	20. Security Classification. (of this page) Unclassified	21. No. of Pages 123	22. Price

Form DOT 1700.7 (8-69)

GDOT Research Project No. 16-10

Final Report

IMPROVEMENT OF CLIMATE DATA FOR USE IN MEPDG CALIBRATION AND OTHER PAVEMENT ANALYSIS

By

Stephan A. Durham, Ph.D., P.E.
Associate Professor – University of Georgia

Bora Cetin, Ph.D.
Assistant Professor – Iowa State University

Charles W. Schwartz, Ph.D.
Charles W. Schwartz and Associates, LLC

Barton Forman, Ph.D., P.E.
Charles W. Schwartz and Associates, LLC

and

Leela Sai Praveen Gopisetti
Graduate Student – Iowa State University

Contract with

Georgia Department of Transportation

In cooperation with

U.S. Department of Transportation
Federal Highway Administration

January 2019

TABLE OF CONTENTS

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

EXECUTIVE SUMMARY

Hourly climate data is one of the principal inputs (i.e. traffic, pavement structure, and material properties) in AASHTOWare Pavement ME Design, which applies the principles of engineering mechanics to predict critical pavement responses. Hourly data are used in the Enhanced Integrated Climate Model (EICM) to predict temperature and moisture distributions in the pavement over depth and time. The EICM is a one-dimensional coupled heat and moisture flow program that simulates changes in pavement, and subgrade characteristics and behavior in conjunction with environmental conditions over numerous years of service. It simulates the upper boundary conditions of a pavement soil system by generating patterns of cloud cover, rainfall, wind speed, air temperature, and solar radiation.

This study compares the predicted distresses of asphalt concrete (AC) and jointed plain concrete pavement (JPCP) using four different climate data sources: (1) ground-based weather station (GBWS) data supplied with early versions of the Pavement ME Design software, (2) the North American Regional Reanalysis (NARR) data supplied with the July 2016 version of the Pavement ME Design software, and (3 and 4) the Modern-Era Retrospective Analysis for Research and Applications (MERRA) versions 1 and 2 (MERRA-1 and MERRA-2) data from the National Aeronautical and Space Administration (NASA).

Comparisons of flexible pavement distresses predicted by AASHTOWare Pavement ME Design using old MEPDG (GBWS) vs. current MEPDG (NARR) vs. MERRA-1 vs. MERRA-2 weather data were conducted to predict total rutting, AC rutting, alligator fatigue cracking, and roughness (International Roughness Index [IRI]).

In most cases, the pavement distresses predicted via MERRA-2 were relatively higher than those predicted with the other climate data sources. Moreover, both MERRA sources resulted in higher pavement distress for flexible pavements as observed in previous studies. The use of MERRA-2 almost doubled the AC layer rutting distresses. This is due to the considerable differences in percent sunshine values predicted by the different climate data sources and it being one of the most sensitive input parameters directly related to pavement performance predictions in AC pavements.

Comparisons of rigid JPCP pavement performance as predicted by the AASHTOWare Pavement ME Design software using old MEPDG vs. NARR vs. MERRA-1 vs. MERRA-2 weather data were conducted to predict transverse cracking, joint faulting, and roughness (IRI). Similar to AC pavements, the MERRA-2 predicted distresses were relatively higher compared to those predicted via the other climate data sources. The agreement of the distress predictions using the four climate data series is slightly less in rigid pavements compared to AC pavements. IRI predictions for rigid pavements were more scattered compared to asphalt concrete pavements. This was expected because IRI in JPCPs is slightly more sensitive to slight climate data changes compared to joint faulting and transverse cracking. Transverse cracking distresses using NARR were observed to be very low compared to those predicted with other climate data sources. The reason for this could be high wind speed values recorded for NARR compared to other sources and wind speed being the second-most sensitive parameter, especially at high traffic conditions. This is the same for all the locations across the United States. For joint faulting, AASHTOWare Pavement ME Design reports the predictions in 0 to 0.25 cm precision. This indicates that climate influences in joint faulting predictions are very negligible.

Environmental conditions impact the pavement performance and its service life significantly. Therefore, it is important to take the effects of environmental conditions into account during pavement design analyses. Previous studies mostly focused on predicting pavement temperature using air temperature. There are many models developed for this purpose. However, these models did not take shortwave radiation parameters into account while modeling the pavement temperature. Shortwave radiation directly impacts the pavement temperature, as well as air temperature, and changes the pavement surface reflectivity, which can ultimately alter the shortwave absorptivity of the pavement upper layer and change the temperature of the pavement structure. The climate model embedded in the MEPDG software uses percent sunshine as an input. Percent sunshine values collected from GBWS are estimated from percent cloud cover, which does not provide the actual shortwave radiation values. On the other hand, MERRA provides direct estimates of surface shortwave radiation (SSR) instead of using percent cloud cover in GBWS in order to estimate the percent sunshine. Surface shortwave radiation provides more accurate, physics based, and reliable input for use in MEPDG design in the future. This study developed a shortwave radiation model to predict the synthetic percent sunshine by back calculation through a shortwave radiation regression equation. The comparisons show tremendous improvement in agreements between various climate sources.

Based on the findings from this study, the authors recommend abandonment of the percent sunshine approach currently used in Pavement ME Design. Percent sunshine as obtained from percent cloud cover, whether measured or predicted, is a non-fundamental derived property that is just too imprecise for use in pavement performance modeling. Instead, the authors recommend converting to SSR as the direct input for pavement environmental modeling. In the context of the Pavement ME Design software, this is entirely consistent with the planned migration to MERRA-2 climate data. The modifications to the Pavement ME Design code necessary to effect this change are trivial.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support for this work provided by the Georgia Department of Transportation (GDOT). The authors thank the many GDOT personnel who assisted with this study. Special thanks are given to Mr. Ian Rish, P.E; Mr. Binh Bui; and Mr. David Jared, P.E., for their research support and valuable input.

LIST OF ABBREVIATIONS AND NOTATIONS

AASHO:	American Association of State Highway Officials
AASHTO:	American Association of State Highway and Transportation Officials
AC:	Asphalt Concrete
AOGCM:	Atmosphere–Ocean General Circulation Model
ASOS:	Automated Surface Observing System
AWOS:	Automated Weather Observing System
CMS:	Climate, Materials, Structures
COOP:	Cooperative Observer Program
CRREL:	Cold Regions Research and the Engineering Laboratory
EICM:	Enhanced Integrated Climate Model
FHWA:	Federal Highway Administration
GAEMN:	Georgia Automated Environmental Monitoring Network
GBWS:	Ground-Based Weather Stations
GDOT:	Georgia Department of Transportation
GIS:	Geographical Information System
GOES:	Geostationary Operational Environmental Satellites
GSA:	Global Sensitivity Analyses
GSI:	Gridpoint Statistical Interpolation
HMA:	Hot Mix Asphalt
IAU:	Incremental Analysis Update
IDM:	Infiltration and Drainage Model
IDW:	Inverse Distance Weighted Interpolation

IEM: Iowa Environment Mesonet

IRI: International Roughness Index

JPCP: Jointed Plain Concrete Pavement

LTPP: Long-Term Pavement Performance

MEPDG: Mechanistic-Empirical Pavement Design Guide

MERRA: Modern-Era Retrospective Analysis for Research and Applications

NARCCAP: North American Regional Climate Change Assessment Program

NARR: North American Regional Reanalysis

NASA: National Aeronautical and Space Administration

NCDC: National Climatic Data Center

NCHRP: National Cooperative Highway Research Program

NOAA: National Oceanic and Atmospheric Administration

NSI: Normalized Sensitivity Index

NSRDB: National Solar Radiation Data Base

NWS: National Weather Service

OAT: One At a Time

PCC: Portland Cement Concrete

PRECIP: Precipitation

QCLCD: Quality Controlled Local Climatological Data

RCC: Regional Climate Centers

RWIS: Road Weather Information Systems

SCAN: Soil Climate Analysis Network

SIRS: Solar Infrared Radiation Station

SSR:	Surface Shortwave Radiation
ULCD:	Unedited Local Climatological Data
USCRN:	United States Climate Reference Network
USDA:	United States Department of Agriculture

1. INTRODUCTION

1.1. Overview

The American Association of State Highway Officials (AASHO) Road Test was a milestone in understanding how pavements perform. Data from the AASHO Road Test were used to develop the original empirical American Association of State Highway and Transportation Officials (AASHTO) pavement design procedure in the early 1960s. Although enhanced periodically, this empirical procedure has served as the standard method for the structural design of highway pavements for over 50 years. Today, pavement design is modernizing from this empirical approach to a more theoretical mechanistic–empirical (M–E) methodology. The *Mechanistic-Empirical Pavement Design Guide* (MEPDG), originally released in 2004 as part of National Cooperative Highway Research Program (NCHRP) Project 1-37A, considers climate, traffic, pavement structure, and material property input parameters that influence pavement performance, and applies the principles of engineering mechanics to predict critical pavement responses. These critical response parameters, in turn, serve as inputs to empirical pavement distress models for predicting field performance.

The MEPDG provides significant improvements over the 1993 AASHTO Guide. It provides more realistic characterization of in-service pavements and gives uniform guidelines for designing the in-common features of flexible, rigid, and composite pavements. In addition, it offers procedures for evaluating existing pavements and designing rehabilitation treatments. Most importantly, MEPDG:

- implements an integrated analysis approach for predicting pavement condition over time (including fatigue, rutting, and thermal cracking in asphalt pavements, and cracking and faulting in concrete pavements) that accounts for the interaction of traffic, climate, and pavement structure;

- allows consideration of special loadings with multiple tires or axles; and
- provides a means for evaluating design variability and reliability. The MEPDG allows pavement designers to make better-informed decisions and take cost-effective advantage of new materials and features. The software can also serve as a forensic tool for analyzing the condition of existing pavements and pinpointing deficiencies in past designs.

The MEPDG and its implementation in the AASHTOWare Pavement ME Design software (http://me-design.com/MEDesign/) represent a major improvement over its predecessors, particularly in its comprehensive coverage of climate impacts on pavement performance. Accuracy and reliability of the input data play a very important role in the M–E prediction of pavement performance. Climatic factors affect the behavior of all layers in the pavement system and have a direct influence on several deterioration processes, including thermal cracking, frost heaving, and thaw weakening, and rutting.

The M-E design is performed through an iterative process. If the output of distress predictions exceeds a user-specified desirable level, the trial pavement structure is modified, and the M–E performance predictions are repeated. The structural design is revised until the structure meets all user-specified performance criteria. Ideally, a life cycle cost analysis of alternative solutions is performed. The Enhanced Integrated Climate Model (EICM) component of the MEPDG methodology uses climatic data to simulate changes in material properties caused by environmental factors.

There have been serious concerns about the reliability and the accuracy of the climate data (GBWS) provided with the MEPDG software until the NARR data was included for analysis in July 2016. Zaghloul et al. (2006) predicted the performance of flexible pavements in New Jersey by using the MEPDG-provided climate data (version 0.7) from 8 weather stations located between 19 and 97 km from the project site. They found significant discrepancies in the predicted performances, depending on which weather stations were used in the analyses. These discrepancies are troubling given the relatively uniform topography and weather patterns over the small state of New Jersey. They suggested that the quality of the weather data provided with the MEDPG should be carefully evaluated and that more reliable and accurate climate data may be needed from alternative sources.

GDOT’s locally calibrated MEPDG weather database contains only 17 stations throughout Georgia. There are other sources of data from ground-based weather stations (GBWS) available for Georgia, but as described later, most are deficient in important ways. No efforts have been initiated until now to compile these climate data. Consequently, the objectives of this project are to evaluate the reliability and adequacy of the North American Regional Reanalysis (NARR) climate data included in the MEPDG software (version 2.3.1.) at the time of this study and additional data collected from GBWS in Georgia. A particular emphasis in this study is on alternative future sources of climate data that are more reliable and easier to collect and update.

The Modern-Era Retrospective Analysis for Research and Applications (MERRA) product developed by the National Aeronautical and Space Administration (NASA) is considered in this study as an alternative source of high-quality weather data.

MERRA is a global climate reanalysis product that combines computed model fields with ground-, ocean-, atmospheric-, and satellite-based observations. The Federal Highway Administration (FHWA) Long-Term Pavement Performance (LTPP) program has recently adopted MERRA as the source for hourly climate data. MERRA has several key advantages over GBWS data. Unlike GBWS data that are compiled at irregularly spaced geographic locations, the hourly MERRA data are provided at a 0.5 degree (latitude) by 0.67 degree (longitude) horizontal spatial resolution (approximately 50 by 66 km at mid-latitudes) and at multiple atmospheric elevations, ranging from the ground surface up to the outer atmosphere. MERRA provides continuous hourly climate estimates from 1979 onward, whereas most GBWS data span only the last 10 years and often have gaps in the time series data. Further, unlike GBWS data, MERRA data does not require any additional quality checks since NASA performs rigorous checks for its own internal purposes. MERRA-2, which is the latest version of the series, is considered for comparisons and analysis in this study. MERRA-2 includes improved precipitation modeling, enhanced data assimilation, and improved horizontal resolution compared to MERRA-1.

Pavement temperature is an important factor influencing pavement performance and design. Pavement temperature is a function of surface shortwave radiation (SSR), air temperature, wind speed, humidity, surface shortwave absorptivity (inverse of albedo), material thermal properties, and other factors. Of these, SSR is the most important driver for pavement heating. However, the climate model embedded in the MEPDG software does not use SSR as a direct input, but instead estimates it using percent sunshine measurements. Percent sunshine values are calculated from percent cloud cover values collected by GBWS. As shown later in this report, percent cloud cover is a problematic metric for this purpose. MERRA, on the other hand, provides direct estimates of surface shortwave radiation separate from percent cloud cover. This can provide more accurate, physics based, and reliable input for use in MEPDG design in the future. A major task of this study is to evaluate the improvements in pavement performance predictions using direct surface shortwave radiation inputs as compared to values estimated using percent cloud cover.

The work summarized in this report includes an extensive comparison of the pavement distresses predicted using the AASHTOWare Pavement ME software, version 2.3.1, via:

- weather data collected from GBWS throughout Georgia;
- weather data embedded with the MEPDG software, NARR; and
- MERRA (versions 1 and 2) weather data.

Comparisons of the pavement distresses for both flexible and rigid pavements predicted using MEPDG weather data (NARR) vs. GBWS, MERRA vs. GBWS data, and MERRA vs. current MEPDG weather data (NARR) are evaluated.

1.2. Study Objectives

The objective of this study is to evaluate MERRA data as an alternative climate source to the current climate inputs in the MEPDG in order to improve pavement designs in Georgia. Version 2.3.1 of the AASHTOWare Pavement ME design software was used for all pavement analysis completed in this study and as such, all future references to Pavement ME Design Software implies the use of version 2.3.1 unless stated otherwise. The major tasks completed in this study include:

- evaluation of the quality and adequacy of the weather station data currently embedded with the MEPDG software, NARR, for the state of Georgia;
- comparison of the predicted pavement performances using the weather data in the MEPDG software weather database, weather data from GBWS throughout Georgia, and weather data from MERRA;
- completion of statistical comparisons of weather data from GBWS and the closest MERRA grid cell; and
- calculation of synthetic percent sunshine from MERRA surface shortwave radiation estimates for better pavement performance predictions.

Implementation of this work will result in the enhancement of the AASHTOWare Pavement ME Design database for GDOT. MERRA data will be used in future versions of the AASHTOWare Pavement ME Design software. Existing research-grade code for extracting and downloading MERRA data from the NASA servers, extracting the data elements required by AASHTOWare Pavement ME Design, and generating the weather data files will be refined for production usage by GDOT. The recently released LTTP online extraction tool for accessing MERRA data complements this code.

1.3. Project Scope

Chapter 2 of this report summarizes a literature review examining the effect of climate in M–E pavement performance predictions and assessments of the adequacy of climate data provided with the AASHTOWare Pavement ME Design software. Chapter 3 provides additional assessments of the reliability, accuracy, and adequacy of climate data currently provided with the Pavement ME Design software for the state of Georgia. During the study, the research team identified issues with the weather data provided within the current version of Pavement ME Design, identified alternative climate data sources, and assessed their availability and quality for use in M–E pavement design in Georgia; this is documented in Chapter 4. Chapter 5 describes the impact of shortwave radiation on pavement performance and the use of the shortwave radiation model to back calculate synthetic percent sunshine. Chapter 6 provides the conclusions of the research and recommendations for future studies.

2. LITERATURE REVIEW

The major objective of the MEPDG is to provide the highway community with a state of the practice for the design of new and rehabilitated pavement structures based on mechanistic–empirical principles (National Cooperative Highway Research Program, 2004). The design guide requires climate, traffic, and material properties for the performance prediction. Collecting data for each input has been a major challenge for agencies. Climate input affects the overall pavement performance, as critical material properties change with fluctuating moisture and temperature conditions (Andrey et al., 2013).

The incorporation of the Enhanced Integrated Climate Model allows the MEPDG to consider the temperature and moisture profiles in the subgrade and pavement structure over the design life of a pavement (Li et al., 2011b). The EICM is a one-dimensional coupled heat and moisture flow program that simulates changes in the behavior and characteristics of pavement and subgrade materials in conjunction with climatic conditions (Quintero, 2007). Being an integral part of the MEPDG, the EICM simulates climatic conditions, as well as pavement characteristics. This program requires wind speed (miles/hour), air temperature (Fahrenheit), precipitation (inches), relative humidity (%), and percent sunshine (%) as its inputs for designs and validations in the MEPDG (Bulut et al., 2013).

The development of the EICM started in the 1960s at the University of Illinois through an initiative of programming the Climate, Materials, Structures (CMS) model (Richter, 2006). The actual model was later created at the Texas Transportation Institute and Texas A&M University in 1989 after combining the CMS model with a rainfall precipitation model (PRECIP), the infiltration and drainage model (IDM), and the frost heave and thaw settlement model developed by the United States Army Cold Regions Research and Engineering Laboratory (CRREL). The final version of the EICM 3.2 was developed by the collaboration of Applied Research Associates and the University of Illinois after the addition of the unsaturated moisture flow model developed by Arizona State University, as well as the Thornthwaite Moisture Index developed to evaluate base course moisture boundary conditions. The combination of different models allows exchange of information to develop new calculations.

2.1. Previous Efforts to Study Deficiencies in Climate Data from Various Sources

One of the principal inputs to the AASHTOWare pavement ME is hourly climate data. To reduce the deficiencies in the data collected from the Ground Based Weather Stations (GBWS), continuous efforts have been put to search for an alternative source (Rada et al. 1989; Tarefder and Rodriguez-Ruiz 2013; Schwartz et al. 2015, Cetin et al. 2017). Climate inputs affect the overall pavement performance as the material properties tend to change with fluctuating moisture and temperature conditions (Andrey et al. 2013; Li et al. 2012; Gopisetti 2017). Climatic factors affect the behavior of all layers in the pavement system and have a direct influence on several deterioration processes in pavements including thermal cracking, frost heave and thaw weakening, rutting, infiltration potential, and decreasing drainability of pavement layers (Hossain et al. 2017). Therefore, the transportation community is investigating more accurate, reliable and continuous climate data sources.

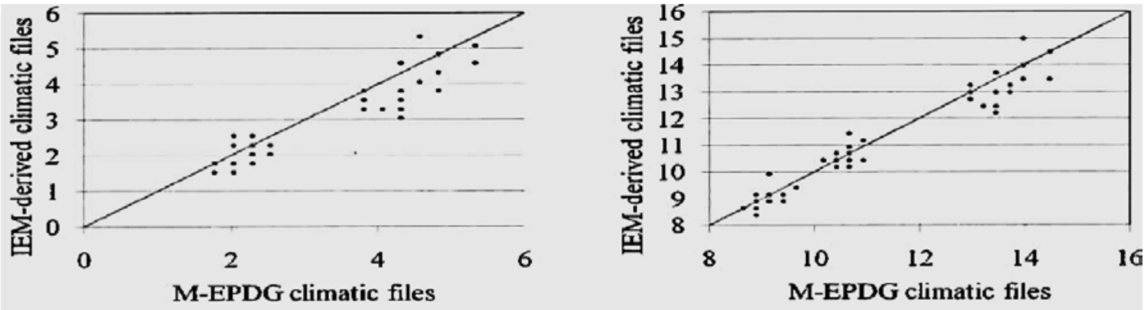
Johanneck and Khazanovich (2010) compared MEPDG pavement performance predictions for composite pavements consisting of asphalt concrete over portland cement concrete (PCC) for 610 locations across the United States. This study assessed the quality of climate data available in the MEPDG and concluded that the database is non-uniform and that low-quality data are being used. The study further compared the data by creating a virtual weather station created through interpolation and demonstrated a simple, practical approach for the evaluation of data quality. The only limitation of this study is the methodology may not be reliable in mountainous regions.

Breakah et al. (2011) investigated the effects of accuracy of climatic data (GBWS) on pavement performance through the MEPDG (version 1.0). They further analyzed and compared climatic files available with the design guide and those developed based on the historical information for counties in the state of Iowa through a source called the Iowa Environmental Mesonet (IEM). Data from 24 counties across Iowa were used to represent the climate for Iowa's 99 counties, and design guide simulations were performed for each of these counties using both the MEPDG default climatic files and the IEM climatic files. The following conclusions were drawn from that study:

- For all the distresses, the IEM files provide a more detailed variation because they use a specific file for each county, compared to the design guide files that are interpolated from surrounding stations.
- The distresses achieved from using the IEM-derived climatic files are statistically different from the results achieved from the climatic files that were interpolated from the data available within the design guide.
- The climatic data interpolated from data available within the design guide predicted higher rutting, lower thermal cracking, and lower International Roughness Index (IRI) compared to the IEM-derived climatic files.

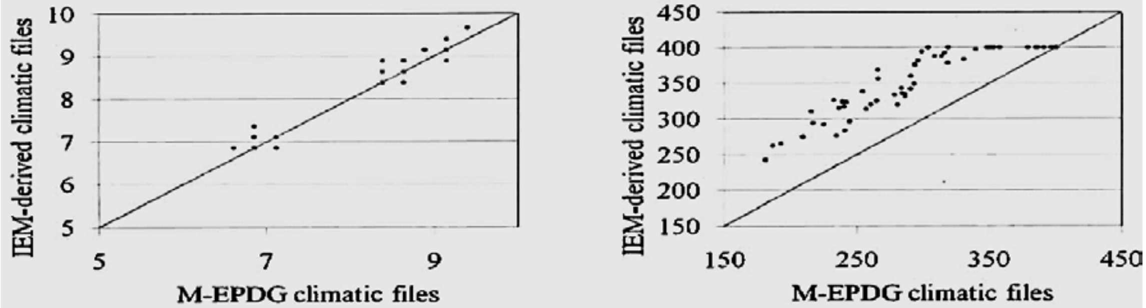
In addition, the differences between the datasets developed from the IEM and the default MEPDG climatic files resulted in nearly 17% more transverse cracking (low temperature distress) and nearly 10% less rutting (high temperature distress). Figure 1 shows the comparison between the results from the MEPDG climatic files and the IEM-derived climate files.

Heitzman (2007) presented an approach that builds a virtual climate database by using all the available broader historical trends that can better project historical cycles than any 10- to 20-year historical climate record. This method is an excellent replacement for conventional methods, such as interpolation and repetition of the climate databases after every short period. Heitzman et al. (2011) extended the study at Mississippi State by applying climate science for developing virtual climate models using historic climate files and accepted models of long-term changes in global climate, aiming to examine how the improved climate data input files impact the pavement performance prediction. The method used in that study to build virtual climate files is only one of several approaches that depend upon the changing climate patterns in a particular state. Table 1 summarizes the possible processes for developing the virtual climate files. The new historic climate files used the hourly data of 23 stations from the Automated Surface Observing System (ASOS), the Automated Weather Observing System (AWOS), and the daily data of over 100 stations from the Cooperative Observer Program (COOP). These weather databases were combined to generate a more accurate 40-year historic climate input data file for each of the 82 counties, creating over 30 times more climate input data.



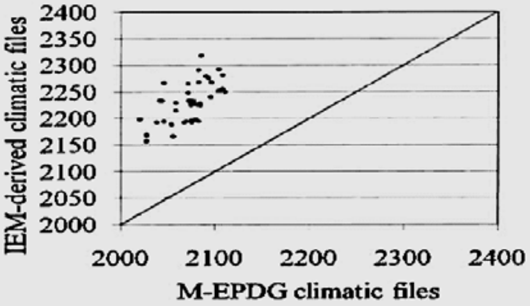
a. Rutting in the asphalt layer, mm

b. Total pavement rutting, mm



c. Pavement rutting in non-asphalt layers, mm

d. Transverse cracking, m/km



e. IRI, mm/km

FIGURE 1

Comparison Between the Results from MEPDG Climatic Files and IEM Climatic Files (Breakah et al., 2011)

TABLE 1

Summary of Methods to Build Virtual Climate Files (Heitzman et al., 2011)

Process Name	Description	Discussion
No Change	Use the historic climate data as the future climate data.	The predicted future pavement performance will not account for any projected long-term changes in future climate.
Adjusted Historic Climate (used for the project)	Apply projected changes in climate from global and regional models to the 40-year historic climate data.	The predicted future pavement performance will reflect long-term climate changes, but will still use the historic year-to-year trends.
Random Adjusted Climate	The 40-year historic data are randomly re-sorted to change the chronologic sequence of extreme annual periods. The projected change in climate from global and regional models is applied to the re-sorted climate data.	The predicted future pavement performance will reflect long-term climate change and reflect an un-biased series of trends.
Biased Adjusted Climate	The 40-year historic data are re-sorted to match extreme annual climate periods with the weakest pavement conditions. The projected change in climate from global and regional models is applied to the re-sorted climate data.	This is a conservative approach that would examine predicted future pavement performance based on a worst-case climate scenario. (Example: extreme high temperatures within the first 3 years and extreme low temperatures between 10 and 15 years for a hot mix asphalt [HMA] pavement)
Multi-Adjusted Historic Climate	Apply projected changes in climate from global and regional models to the 40-year historic climate data. Also, apply projected changes in the severity and duration of the climate events.	The predicted future pavement performance will reflect long-term climate change in value, severity, and duration, but will still use the historic year-to-year trends.
Statistically Generated Climate	Use the statistical parameters of the 40-year historic data to build a random virtual climate data file.	This approach is more complicated and may not capture daily and weekly extremes.

The sensitivity analysis by Heitzman et al. measured the impact of the three different climate input files (MEPDG (GBWS), historic, and virtual) on three common types of pavements (i.e., jointed PCC, thick HMA, and thin HMA) used in Mississippi. The analysis showed that repeating the limited data in the MEPDG climate input files to predict pavement distress over a typical 20- to 40-year analysis period resulted in significantly higher predicted distress in some cases. A similar study was also performed by Heitzman and Wei (2017) for the Louisiana DOT, in which the historic climate files for each parish (i.e., territorial division corresponding to county in other states of the U.S.) were developed in the format required for input into the MEPDG model. The length of time for these data was established as 1970 through 2009 and sources used to generate the data were the ASOS and the COOP. The study demonstrated steps involved in developing a random future climate file for each parish, containing a complete set of data from 2010 to 2050. Random climate files were prepared by dividing the 40-year historic climate file into 4- to 7-year temperature cycles and randomly re-sorting the cycles into a modified 40-year data set. This process randomly changes the chronologic sequence of extreme annual temperature periods. The modified file was adjusted by the future global and regional models to create a random future climate file.

2.2. Previous Efforts on Sensitivity Analysis

Sensitivity analysis is considered to be one of the important steps for any study with multiple inputs. The sensitivity index will help researchers understand which input is most influencial and which input is least significant with respect to the output. It is significant to ensure that each parameter is independent. Previous studies show different methods of sensitivity analysis and different results based on the quality of the data available for any input. Schwartz et al. (2011) conducted a study to determine the sensitivity of the pavement performance predicted by the MEPDG to variability of the design input values for both flexible and rigid pavements. ‘One at a time’ (OAT) and ‘Global Sensitivity Analyses’ (GSA) methodologies were explored and thoroughly explained in this study, along with the neural network surface response models that were used to quantify the distribution of design input sensitivities across the entire problem domain. The study conducted over 41,000 MEPDG runs and over 1 million evaluations of the neural network response surface models, not limiting to climate inputs but evaluating all the design inputs available in the MEPDG. This study is used as a reference in adopting methodologies and considering steps in evaluating the sensitivity analysis for the current research purposes, which is fully described in the subsequent sections of this report.

Schwartz et al. (2015) quantified the sensitivity of MEPDG predictions to specific characteristics of the climate inputs. The climate inputs considered in the study were relative humidity, precipitation, wind speed, percent sunshine, average daily temperature range, average annual temperature range and average annual temperature. Three climate scenarios—temperate, hot dry, and cold wet—and three traffic levels—low, medium, and high—were considered to assess sensitivity over a broader range. The local OAT sensitivity analysis approach was applied and over 300 MEPDG runs were conducted. The sensitivity results for flexible pavements showed that pavement performance is most sensitive to average annual temperature and average annual temperature range followed by percent sunshine and wind speed as the next most sensitive climate parameters. The low sensitivity was observed for average daily temperature range and precipitation.

Similarly, key observations from jointed plain concrete pavement (JPCP) rigid pavement analyses showed that average annual temperature range and average daily temperature range exhibited the highest sensitivity values, followed by percent sunshine, wind speed, and relative humidity. Precipitation exhibited the least sensitivity to JPCP rigid pavement performance predictions, similar to the flexible pavements results, and the expected reason was that the EICM does not include the effects of surface precipitation and infiltration in its modeling of temperature and moisture within the pavement. Li et al. (2013) also presented a study to quantify the sensitivity of MEPDG pavement with respect to climate inputs. Their study explored the differences between OAT analyses and GSA. According to this study, GSA are more appropriate for complex nonlinear models with many inputs, and local OAT evaluations are suitable for exploratory analysis and for simpler models with few input parameters.

In addition, Cetin et al. (2015) conducted quantitative evaluation of the sensitivity of MEPDG pavement performance predictions on three different pavement types: (1) asphalt concrete (AC), (2) JPCP, and (3) rehabilitation of asphalt concrete over rubblized concrete (AC over JPCP). A summary of results shows that all three types of pavements were most sensitive to air temperature, moderately sensitive to percent sunshine and wind speed, and least sensitive to precipitation, as concluded in the other studies as well. Pavement designs require depth of ground water table to be considered as a major factor. Impact on unbound soil layers is a major occurrence due to the groundwater table. When the groundwater table is raised, the rate of both asphalt rutting and total rutting in the pavement is increased and permanent deformation is accelerated. The saturated unbound layers lose stiffness. Cetin et al. took an extra step and conducted sensitivity analyses on the groundwater table on all three types of pavements at three different water table levels (2, 5, and 10 ft) and results showed that groundwater did not exhibit significant impact on the pavement distress unless the water table is at the ground surface. It was concluded that the MEPDG failed to quantify the impact of groundwater table level on the pavement distress predictions.

Yang et al. (2015) also conducted a comprehensive study for the state of Michigan, selecting six representative geographic sites and two typical traffic levels to evaluate the sensitivity of AASHTOWare Pavement ME to individual climatic inputs available in the software using the OAT approach. Almost similar results were observed as described in the other studies, showing temperature as the most sensitive; wind speed, relative humidity, and percent sunshine as moderately sensitive; and precipitation as least sensitive to distress prediction.

2.3. Previous Efforts on Shortwave Radiation Model

One of the major tasks in this study was to evaluate the impact of shortwave radiation on pavement performance. Previous studies mostly focused on predicting the pavement temperature using air temperature. Shortwave radiation has never been considered before for evaluation of the pavement temperature through the MEPDG. Shortwave radiation directly impacts the pavement temperature in addition to the air temperature, and it changes the pavement surface reflectivity, which ultimately alters the shortwave absorptivity of the pavement upper layer and changes the temperature of the pavement structure.

Walker and Anderson (2016) determined the influence of cloud-type groups (i.e., properties of clouds on short time periods and small spatial scales) on pavement temperature and surface radiation and analyzed the correlations among pavement temperature, surface radiation, and cloud-type groups. A case study was conducted in the Great Plains where surface radiation data were obtained from the High Plains Regional Climate Center's Automated Weather Data Network stations, and pavement temperature data were obtained from the Meteorological Assimilation Data Ingest System for better understanding of how cloud cover affects pavement temperature through influencing surface radiation. Results showed that pavement temperatures and surface radiation observations were strongly correlated, with a maximum correlation coefficient of 0.83.

2.4. Climate Data Sources

The original MEPDG software included climate data from more than 800 GBWS across the United States. These data were obtained from two products provided by the National Climatic Data Center (NCDC):

- Unedited Local Climatological Data (ULCD) – Data prior to January 1, 2005
- Quality Controlled Local Climatological Data (QCLCD) – Data after January 1, 2005

The climate data from these sources are the general inputs for the EICM, which serve as default values for pavement design simulations conducted through the software. However, frequent reviews conducted on the ULCD and the QCLCD show that additional quality control steps are required on these products due to errors in measurement, data coding, and gaps in time intervals, which force the transportation agencies to find alternative sources that provide accurate data for their designs.

One such alternative source considered is the Cooperative Observer Program. Through this program, the National Weather Service (NWS) and the NCDC are working together to assess strategies for low-cost standardized climate observing systems capable of supporting federal and local agency requirements. Monthly data from around 5800 COOP stations are provided by the NCDC, out of which 1220 stations have data for the past 80 years or more (National Oceanic and Atmospheric Administration, 2000). Program operations, including data acquisition, maintenance, and training, are managed by the NWS.

The United States Climate Research Network (USCRN), another source of climate change tracker, was developed by the National Oceanic and Atmospheric Administration (NOAA). High-quality data of temperature, precipitation, surface skin temperature, solar radiation, relative humidity, and surface winds are collected from around 120 research-grade stations (Bell et al., 2013). The USCRN initiated monitoring soil observations, including soil moisture and soil temperature at five standard depths (5, 10, 20, 50, and 100 cm). This program aims at collecting data for over 50 years.

Another important source, the Department of Energy’s Solar Infrared Radiation Station (SIRS), provides ground-based radiometer measurements with the collaboration of the Atmospheric Radiation Measurement Program (Schwartz et al., 2015). This program provides direct estimates of shortwave radiation that could be used for comparisons against the shortwave radiation estimates generated by the model evaluated in this study. Other climate data sources include NOAA’s Regional Climate Centers (RCC), ASOS, Road Weather Information Systems (RWIS), solar radiation data from the National Solar Radiation Database (NSRDB) and Geostationary Operational Environmental Satellites (GOES).

The past studies and reports show the importance of climate as an input for pavement designs. However, questions are raised even today regarding the adequacy of the climate data available in the MEPDG (GBWS), as well as the reliability of the alternative sources used for data accommodation to fill in the gaps of the climate database. Federal and state transportation agencies and research centers are putting extensive efforts into improving the climate databases for pavement designs.

2.5. Other Climate-related Studies

Climate changes increase critical risk for the pavements with anticipating alterations in the frequency and severity levels of road failures and the duration of each failure. Daniel et al. (2014) concluded that pavements face failures from a combination of temperature and water impacts. Higher temperatures decrease the stiffness of the asphalt concrete pavements, increasing susceptibility to rutting. Freeze and thaw cycles would increase the damage from frost heaves and increase thermal fatigue cracking. Also, the moisture content of the granular sublayers beneath the pavement surface is increased with excessive precipitation, which can further weaken the pavement subgrade and base, resulting in increased cracking and rutting on the pavement surface due to the loss of underlying support.

Li et al. (2011a) explored the impacts of potential climate change and its effects on pavement performance. Their study concluded that temperature changes resulted in thermal cracking and pavement distortion comprising rutting, shoving, and corrugation. Subsurface moisture resulted in growth of ice lenses beneath pavements in wet-freeze regions and potentially influenced the amount and rate of the frost heave. Precipitation-related pavement distresses were characterized by cracking, excessive deflection, concrete deterioration due to durability cracking, and reduced load-bearing capacity. Freeze and thaw cycles resulted in the formation of voids and tensile stresses at the surface of the pavement due to accumulation of ice underneath the pavement surface.

Willway et al. (2008) summarized the future climate scenarios into four categories: wetter and milder winters, drier and hotter summers, more extreme rainfall events and storms, and rising sea levels. These climate change scenarios suggest that higher mean and extreme temperatures, excess water, and high soil moisture deficit are the major climate hazards for road pavements. The extent of the risk to pavement condition and maintenance will largely depend on the change in the future climate and other factors such as pavement type, soil type, condition, and drainage. Actions that could help minimize the risk include: (a) protecting the surface of the pavements when laying during excessively wet weather, (b) laying deformation-resistant asphalt mixes in thin layers in hot weather, and (c) restricting laying periods to the cooler part of the day to allow materials to cool and reduce the effect of extreme temperatures on the work force.

Mills et al. (2009) developed two future climate scenarios to investigate how climate change affects the frequency, severity, and duration of three deterioration processes and their impact on pavement performance. The deterioration processes included thermal cracking, frost heave, and thaw weakening and rutting. Climate change scenarios were derived from experiments using coupled atmosphere–ocean general circulation models (AOGCMs). AOGCMs and regional dynamic climate models nested within AOGCMs are the most advanced tools presently available to quantitatively estimate the transient global climate response to scenarios of future greenhouse gases, sulfate aerosols, and other elements that affect climate forcing. The first climate scenario analysis involved examining a sample of deterioration-relevant climate indicators that are routinely applied in the management of pavement infrastructure. The second analysis employed the MEPDG to simulate pavement deterioration and performance over time for selected sites. The study concluded that rutting issues will become worse due to climate change, and that further maintenance, rehabilitation, and reconstruction will be required earlier in the design life for the affected pavements.

Meagher et al. (2012) presented a method to assess the impacts of forecasted climate change on pavement deterioration. The method was illustrated with a case study that used future climate model temperature data from three North American Regional Climate Change Assessment Program (NARCCAP) scenarios at four sites across New England. The cumulative distribution function transformation method was used to probabilistically downscale the NARCCAP temperature data to site-specific data for use in the MEPDG. The study concluded that the potential impact of future temperature changes on pavement performance is modest for AC rutting and negligible for alligator cracking, which raises the question as to whether future predictions should be considered.

Ankit et al. (2011) categorized environmental-associated factors that exert significant impact on the pavement performance into two types: (a) external factors, such as precipitation, temperature, humidity, freeze–thaw cycles, and depth of the water table; and (b) internal factors, such as susceptibility of the pavement materials to moisture, freeze–thaw damage, and infiltration potential of the pavement. The models developed and analyzed in the study concluded that resilient modulus of the pavement layers is very sensitive to change in stress conditions and moisture content. The study also recommended the use of techniques such as the finite element method, artificial neural networks, the genetic algorithm, and cellular automata for investigating the effects of environmental factors on pavement performance models.

Zapata and Houston (2008) conducted a study on 30 sites to evaluate, calibrate, and validate the moisture predictive capabilities of the EICM. A total of 84 sand cone tests were performed by coring 84 HMA test locations, along with 165 tube samples for asphalt and soil characterization. The study concluded that hydraulic conductivity was found to be too low to account for any significant water infiltration through the HMA mix layers. Very few cracks were found at the 30 sites. In a few cases where cracks were found, the water content adjacent to the crack was measured and found to be not statistically significantly higher than other locations away from the crack.

Hozayen and Fouad (2015) studied the effect of hot environmental conditions on overlay thickness of the asphalt pavement. Minimum, maximum, and average pavement temperatures at a range of depths during the various months of the year were observed and recorded. The study concluded that the pavement temperature in summer is about 2.5 times the pavement temperature in winter and also is directly related to the major climate factors of air temperature and solar radiation.

Overall, the literature review provides sufficient information and background required for further tasks in this study. It is evident that climate data used for pavement designs is crucial, and careful evaluation of data is very significant for qualitative and adequate data. Multiple studies have concluded that sources with missing data can drastically change pavement performance predictions, and it is recommended that climate sources should be carefully adopted for research purposes.

3. ASSESSMENT OF THE ADEQUACY OF CLIMATE DATA EMBEDDED IN THE AASHTOWARE PAVEMENT ME DESIGN SOFTWARE

Under this task, the research team assessed the reliability, accuracy, and adequacy of climate data embedded in the AASHTOWare Pavement ME Design software. The climate data files previously embedded in the AASHTOWare Pavement ME Design software were derived from two data products provided by the NCDC: (a) the UCLD that provide data prior to January 1, 2005, and (b) the QCLCD that provide data after January 1, 2005. Climate data from 15 different GBWS in Georgia were provided with the previous AASHTOWare Pavement ME Design software. Table 2 summarizes the ground-based weather stations (old MEPDG) in Georgia, including the starting and ending date of the data available for each weather station. AASHTOWare Pavement ME Design requires a minimum of 2 years of continuous climate data to make runs, but such a short duration is an incomplete representation of actual climate variability. Even 10 years of data may be impacted by outliers and may not be sufficient to represent the real climatic conditions at a specific project site. Hence, alternative climate data sources were investigated and compared.

As summarized in Table 3, other GBWS in Georgia were investigated and the research team observed that these climate data sources had serious deficiencies either in terms of time series duration or the completeness of the data required for the AASHTOWare Pavement ME Design analyses. Moreover, the majority of these climate data sources do not have good and uniform spatial coverage, as shown in Figure 2. Therefore, the research team further investigated other alternative climate data sources, including NARR’s hourly climate data, NASA’s Modern-Era Retrospective Analysis for Research and Applications, and USCRN’s ground-truth data, for comparisons.

TABLE 2
AASHTOWare Pavement ME Design Ground-based Weather Stations in Georgia

Station ID	City	Latitude	Longitude	Elevation (m)	First Date	Last Date
03813	Macon	32.688	−83.654	104.242	1996-07-01	2006-02-28
03820	Augusta	33.37	−81.965	40.233	1996-07-01	2006-02-28
03822	Savannah	32.119	−81.202	7.62	1996-11-01	2006-02-28
03888	Atlanta	33.779	−84.521	244.145	1998-11-01	2006-02-28
13837	Augusta	33.467	−82.039	125.578	1996-07-01	2006-02-28
13869	Albany	31.536	−84.194	57.912	2001-01-01	2006-02-28
13870	Alma	31.536	−82.507	58.82	2000-12-01	2006-02-28
13873	Athens	33.948	−83.327	243.84	1996-07-01	2006-02-28
13874	Atlanta	33.64	−84.427	304.19	1996-07-01	2006-02-28
13878	Brunswick	31.252	−81.391	5.79	2000-10-01	2006-02-28
53819	Atlanta	33.355	−84.567	243.23	1996-07-01	2006-02-28
53838	Gainesville	34.272	−83.83	385.87	1996-07-01	2006-02-28
53873	Cartersville	34.123	−84.849	229.81	2000-04-01	2006-02-28
93801	Rome	34.348	−85.161	210.922	1997-05-01	2006-02-28
93842	Columbus	32.516	−84.942	119.48	1996-07-01	2006-02-28

TABLE 3
Other Sources of Ground-based Weather Data in Georgia

Data Source	Number of Locations	Comments
Georgia Forestry Commission Weather Station	35	Located at airports; however, the data are provided only for the last 3 days and cloud cover is provided in a different format that cannot be used directly in the MEPDG software.
Georgia Automated Environmental Monitoring Network (GAEMN)	52	Reports daily weather summaries only, not the hourly data required by the MEPDG.
WTVC WeatherNet	9	Covers only the northern portion of Georgia.
GeorgiaWx.net Masonet System	36	Does not provide any data on cloud cover/surface shortwave radiation required by the MEDPG.
Georgia Ambient Air Monitoring Program	Unknown	Not a reliable source. It is not known how many of these stations provide any meteorological measurements.
United States Department of Agriculture (USDA) UV-B Monitoring Network	1	Poor spatial coverage.
Soil Climate Analysis Network (SCAN)	2	Poor spatial coverage.
Ground-based Global Positioning System (GPS) Meteorology Demonstration Network (GPS)-MET	2	Poor spatial coverage.
NOAA/National Centers for Environmental Information	4	Poor spatial coverage. Does not provide solar radiation for all stations.

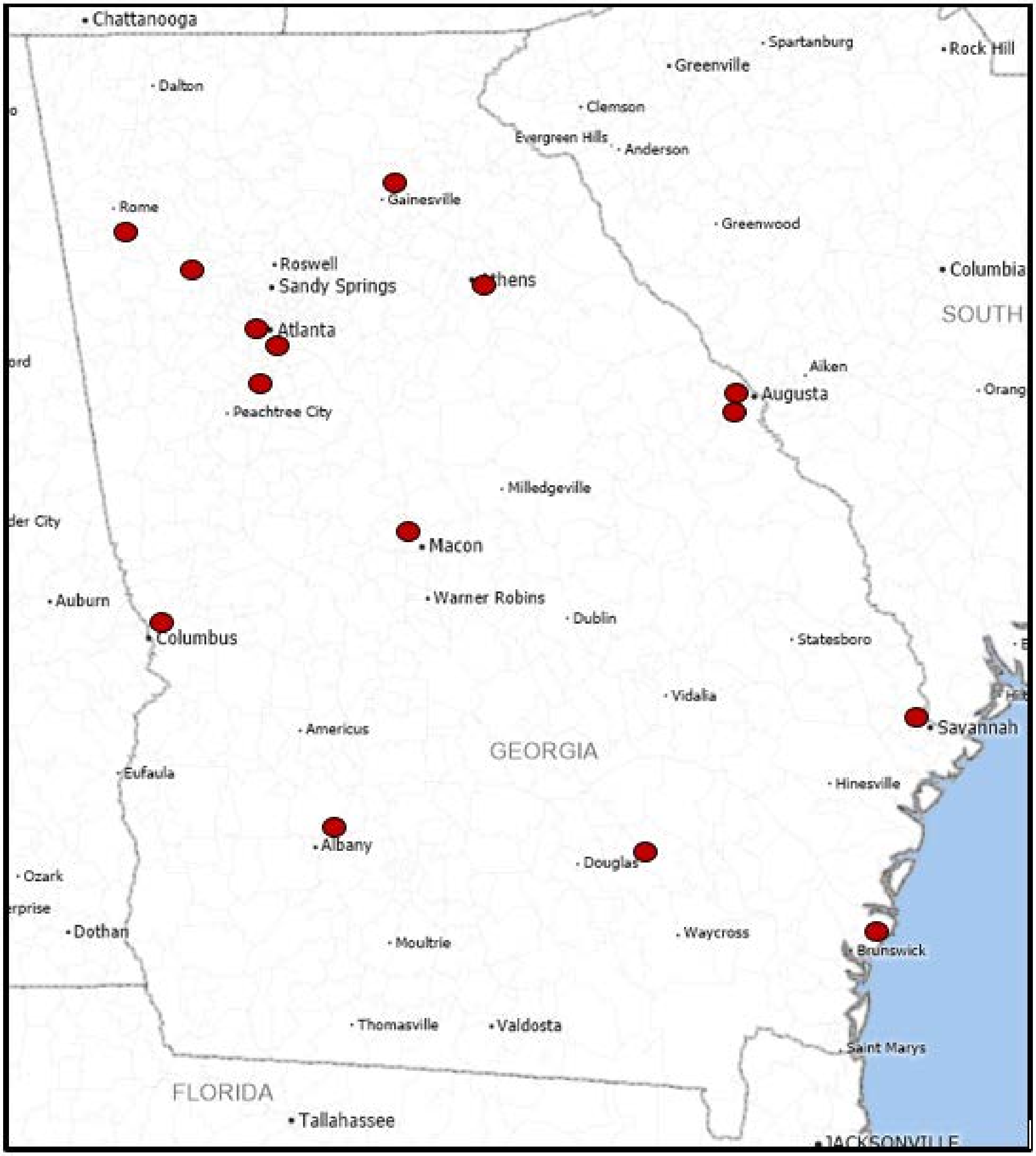


FIGURE 2

Locations of the Current AASHTOWare Pavement ME Design Embedded Weather Stations in Georgia

4. IDENTIFICATION OF ALTERNATIVE CLIMATE DATA SOURCES AND QUALITY ASSESSMENT

4.1. Overview

This study used four different climate data sources for the pavement ME analyses and pavement distress prediction comparisons. Climate data sources used for comparisons are:

- GBWS previously embedded in the AASHTOWare Pavement ME Design software (airport-based weather stations) and referred to as "old MEPDG" in this study;
- NARR currently embedded in the AASHTOWare Pavement ME Design software and produced by NOAA; and
- NASA's MERRA climate data (versions 1 and 2: MERRA-1 and MERRA-2). Each climate data source contains hourly data for air temperature, wind speed, percent sunshine, precipitation, and relative humidity.

Chapter 3 summarized the data from ground-based weather stations embedded in previous versions of the software and the issues identified with it. The following subsections provide an overview of the NARR and MERRA data sources.

4.1.1. North American Regional Reanalysis (the current AASHTOWare Pavement ME Design data)

The North American Regional Reanalysis has been incorporated into the AASHTOWare Pavement ME Design software since 2016, replacing the ground-based weather stations. The NARR is used primarily for atmospheric research requiring historical atmospheric conditions and to study the variability of climate conditions. The NARR was developed by the National Centers for Environmental Prediction (NCEP) to model or assimilate observational data to produce a long-term overview of weather in North America. The model is initialized by using real-world temperature, winds, precipitation, and moisture conditions from surface observations (Brink et al., 2016). Different sources were involved in developing the NARR, some of which were also involved in a global reanalysis. The focus of the NARR was to develop a more accurate reanalysis specific to the North American continent.

The NARR data are available for a 32 × 32 km grid across North America. The data are available in 3-hour, daily, and monthly values from 1979 to present. Since the AASHTOWare Pavement ME Design software requires hourly data, the values were obtained by linearly interpolating between the three hourly values, which is one of the drawbacks for the NARR climate data. However, the 37 years of continuous data are significant compared to the 10 years of data with GBWS. The NARR dataset has already gone through several quality control checks and does not require further data smoothing or quality assurance and control. This is a large advantage given the amount of climate data needed for the AASHTOWare Pavement ME Design climate files. Additionally, a climate file can be generated for any latitude or longitude across North America since the NARR dataset is based on a grid system, which eliminates the use of a physical climate station that may not be close to the actual pavement location.

Many different sources were used to develop the NARR, some of which were also used in a global reanalysis. The focus of the NARR was to develop a more accurate reanalysis specific to North America, so additional sources were used to improve upon the global reanalysis. These sources include:

- U.S. National Centers for Environmental Prediction

- U.S. National Center for Atmospheric Research (NCAR)
- The global reanalysis
- U.S. Climate Prediction Center (CPC)
- NOAA’s National Environmental Satellite, Data, and Information Service (NESDIS)
- NCEP’s Environmental Modeling Center (EMC)
- Center for Ocean–Land–Atmosphere Studies (COLA) at George Mason University
- NOAA’s Great Lakes Environmental Research Laboratory (GLERL)
- Lawrence Livermore National Laboratory (funded by the U.S. Department of Energy)

4.1.2. Modern-Era Retrospective Analysis for Research and Applications (MERRA)

The MERRA product from NASA is an alternative for obtaining high-quality atmospheric and surface weather history data. MERRA is a physics-based reanalysis model that combines computed model fields (e.g., atmospheric temperatures) with ground-, ocean-, atmospheric-, and satellite-based observations that are distributed irregularly in space and time. The result is a uniformly gridded dataset of meteorological data derived from a consistent model and analysis system over the entire data history. MERRA improves on earlier generations of reanalysis models such as those developed by NOAA’s NCEP, the European Centre for Medium-Range Weather Forecasts, and the Japan Meteorological Agency. MERRA data are provided at an hourly temporal resolution and a 0.5-degree by 0.67-degree (latitude/longitude) spatial resolution from 1979 to the present. In addition, MERRA-2, which is the latest version of the series, is considered for comparisons and analysis in this study. MERRA-2 has improved precipitation modeling, enhanced data assimilation, and improved horizontal resolution compared to the previous and inaugural version of MERRA.

The MERRA product utilizes the Gridpoint Statistical Interpolation (GSI) algorithm, which is used to merge observations with a forecast (i.e., GEOS-5) model. In short, GSI computes the difference (or analysis increment) between the model and the observations. An incremental analysis update (IAU) method is then used to gradually apply the analysis increment to the forecast model, which has served to ameliorate precipitation “spin-down” during early stages of the forecast, as well as significantly improved aspects of atmospheric circulation within the forecast model. For the MERRA product, the analysis is performed in 6-hour increments. The first 6-hour run is used to produce an “analysis tendency” called the “corrector” segment. The run is then continued without an analysis tendency for the next 6 hours. This is called the “predictor” segment. This cycle is then repeated. Figure 3 displays this IAU process. The updated model variables from the IAU process make up the variables ultimately provided in the MERRA product.

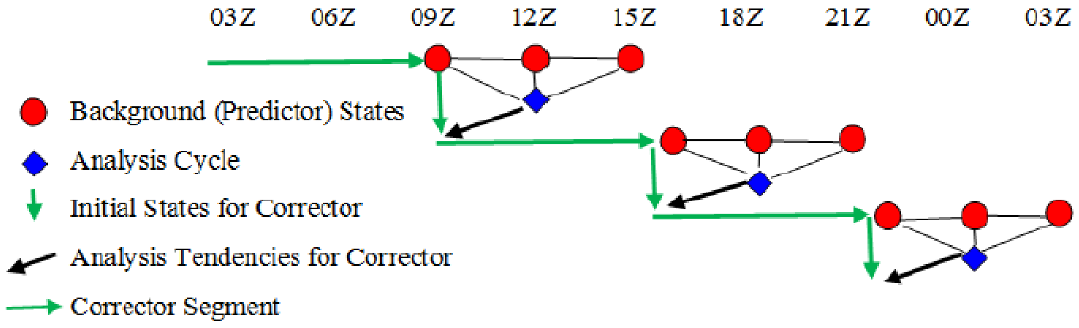


FIGURE 3

Incremental Analysis Update for MERRA

MERRA is capable of providing all of the weather history inputs required by AASHTOWare Pavement ME Design and other current infrastructure applications. Table 4 contains the MERRA data elements used to develop Pavement ME Design weather history inputs. In addition, MERRA contains additional data elements useful for enhancements of current infrastructure applications and/or for support of future applications. Samples of available data elements are provided in Table 5. Figure 4 and Figure 5 shows the Georgia grid points for MERRA-1 and MERRA-2, respectively.

TABLE 4

MERRA Data Elements Available to Develop AASHTOWare Pavement ME Design Weather History Inputs (Schwartz et al., 2015)

Element	Description	Units
CF	Total cloud fraction	fraction
PPT	Precipitation flux incident upon the ground surface	kg H_2O m^2 s^{-1}
PS	Surface pressure at 2 m above ground surface	Pa
Q	Specific humidity at 2 m above ground surface	kg H_2O kg^{-1} air
Rsw	Shortwave radiation incident upon the ground surface	W m^{-2}
Rtoa	Shortwave radiation incident at the top of atmosphere	W m^{-2}
T	Air temperature at 2 m above ground surface	K
U	Eastward wind at 2 m above ground surface	m s^{-1}
V	Northward wind at 2 m above ground surface	m s^{-1}

TABLE 5

Other MERRA Data Elements Available for Transportation Infrastructure Applications (Schwartz et al., 2015)

Element	Description	Units
T	Air temperature at 10 m above ground surface	K
U	Eastward wind at 10 m above ground surface	$m\ s^{-1}$
V	Northward wind at 10 m above ground surface	$m\ s^{-1}$
PRMC	Total profile soil moisture content	$M^3\ m^{-3}$
RZMC	Root zone soil moisture content	$M^3\ m^{-3}$
SFMC	Top soil layer soil moisture content	$M^3\ m^{-3}$
TSURF	Mean land surface temperature (including snow)	K
TSOIL	Soil temperature in layer (available for 6 soil layers)	K
PRECSNO	Surface snowfall	$kg\ m^{-2}\ s^{-1}$
SNOMAS	Snow mass	$kg\ m^{-2}$
SNODP	Snow depth	m
EVPSOIL	Bare soil evaporation	$W\ m^{-2}$
EVPTRNS	Transpiration	$W\ m^{-2}$
EVPSBLN	Sublimation	$W\ m^{-2}$
QINFIL	Soil water infiltration rate	$kg\ m^{-2}\ s^{-1}$
SHLAND	Sensible heat flux from land	$W\ m^{-2}$
LHLAND	Latent heat flux from land	$W\ m^{-2}$
EVLAND	Evaporation from land	$kg\ m^{-2}\ s^{-1}$
LWLAND	Net downward longwave flux over land	$W\ m^{-2}$
SWLAND	Net downward shortwave flux over land	$W\ m^{-2}$
EMIS	Surface emissivity	fraction
ALBEDO	Surface albedo	fraction

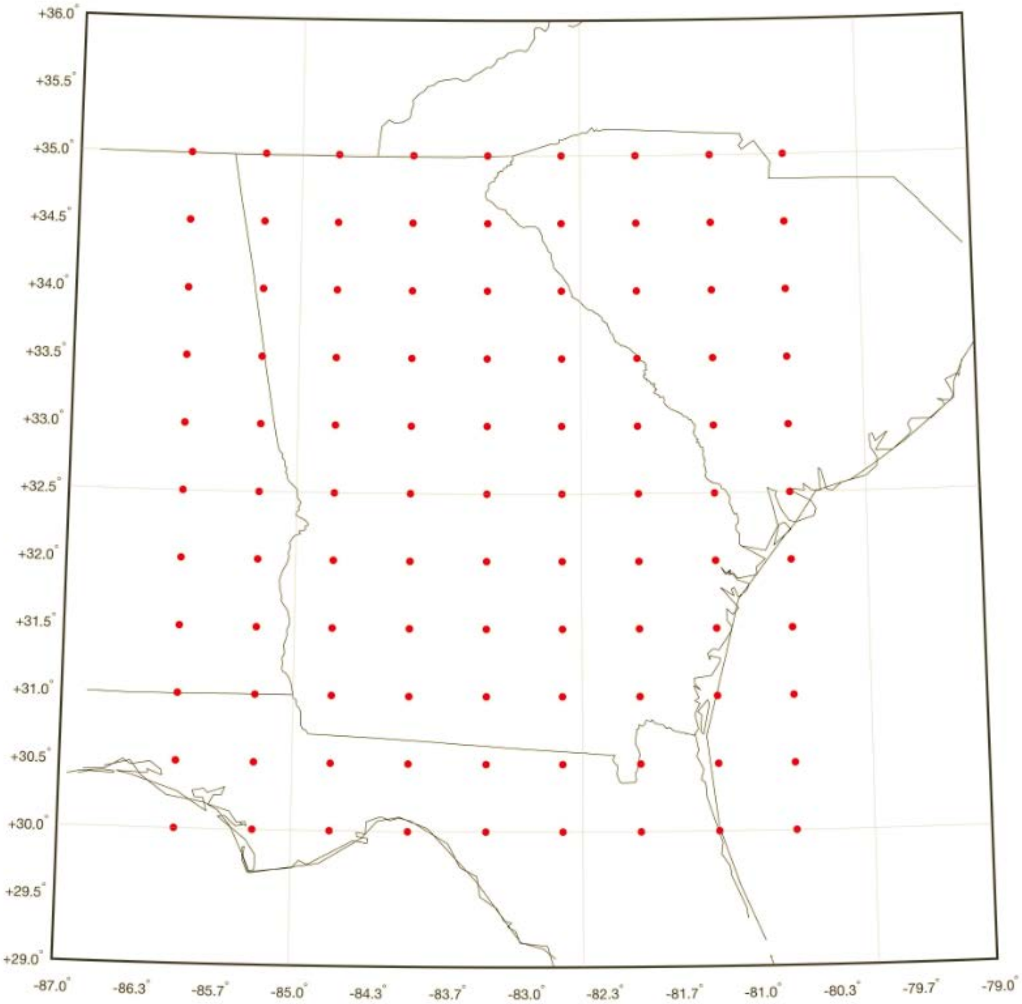


FIGURE 4

Locations of MERRA-1 Grid Cells

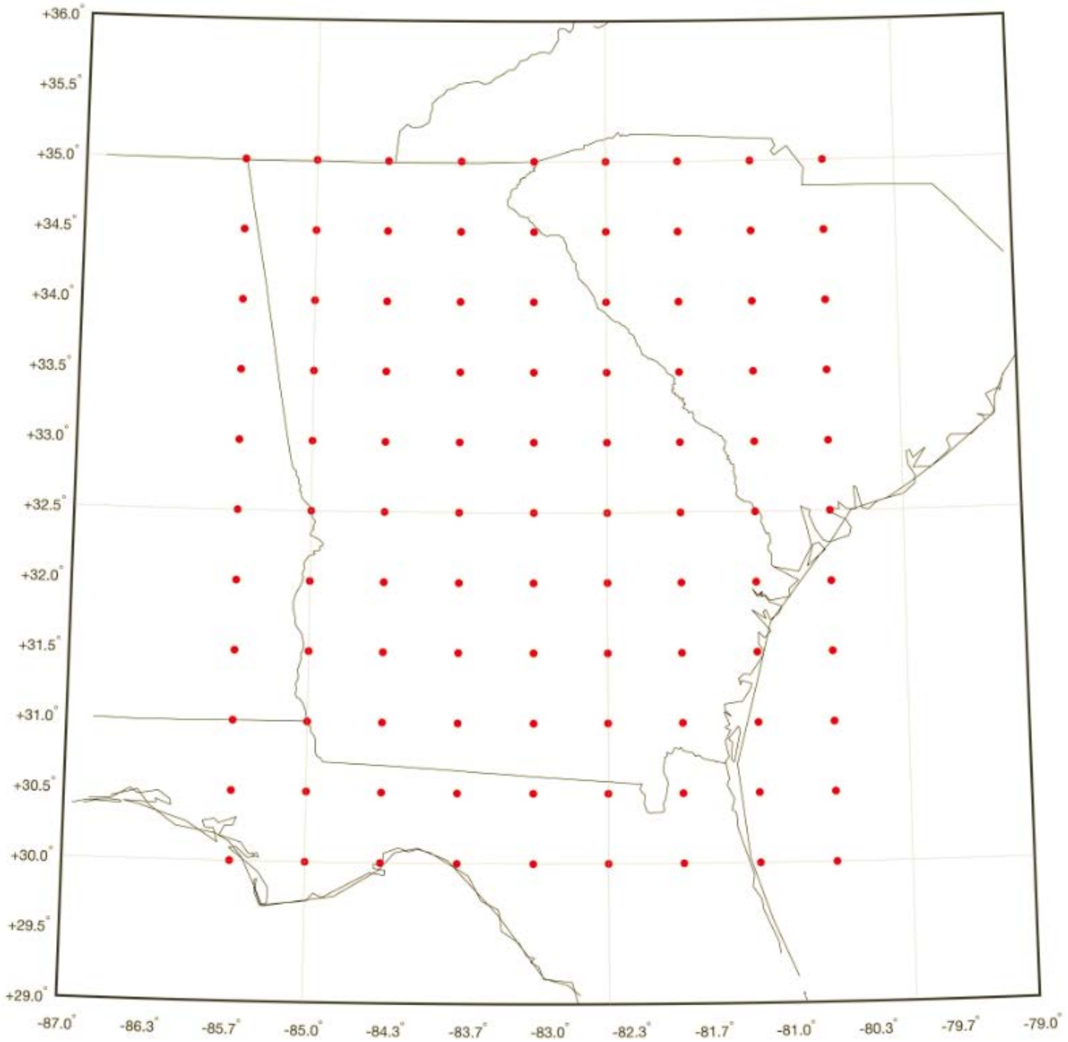


FIGURE 5

Locations of MERRA-2 Grid Cells

4.2. Measurement Product Collocation

For comparisons of measurements from one data source with another, collocation of the previously used AASHTOWare Pavement ME Design GBWS and MERRA grids were necessary prior to synchronizing the measurement sequences in time. The collocation process was conducted relative to the GBWS locations, which means all computed distances treat the given GBWS as located at the center of the search area. Then, for every station, the horizontal distance was computed for every MERRA-1 and MERRA-2 grid cell location in the state of Georgia. The minimum separation distance was specified as 0.5°, which is approximately 50 km at mid-latitudes so that each collocated set of GBWS and MERRA would be representative of the same regional space and, hence, the same topographic and climatic conditions. Based on spatial resolution of MERRA sources, it was guaranteed that at least one MERRA grid cell would correspond to every available ground-based weather station. Typical separation distances between the center of the MERRA grid cell and the collocated GBWS location ranged between 5 and 40 km. Table 6 shows the distances from GBWS to MERRA-1 and GBWS to MERRA-2.

4.3. Results

The traffic levels and major pavement design inputs required by the AASHTOWare Pavement ME Design software for conducting analyses are determined based on standard base cases used by the Georgia Department of Transportation (Von Quintus et al., 2015). Once the inputs were determined for each pavement system, only the climate data source was changed. Table 7 lists the traffic level used in the study, along with the thickness of the pavement layers. Table 8 and Table 9 summarize the values of the major pavement design inputs required by the AASHTOWare Pavement ME Design software.

TABLE 6
Distance between GBWS and MERRA

Distance between MEPDG (GBWS) to MERRA-1 and MERRA-2			
Location ID	**Airport**	**MERRA-1 Distance (mi)**	**MERRA-2 Distance (mi)**
3813	Middle Georgia Regional Airport	22.74	14.1
3820	Augusta Regional Airport	9.2	10.3
3822	Savannah/Hilton Head International Airport	11.2	8.6
3888	Fulton County Airport	17.4	17.4
13837	Daniel Field Airport	3.2	9.7
13869	SW Georgia Regional Airport	11.6	10.9
13870	Bacon County Airport	9.7	2.5
13873	Athens Ben Epps Airport	3.6	12.1
13874	Hartsfield–Jackson International Airport	16.8	10.1
13878	Malcolm Mckinnon Airport	17.4	19
53819	Falcon Field Airport	11.5	14.9
53838	Lee Gilmer Memorial Airport	18.4	16.3
53873	Cartersville Airport	13.4	12.1
93801	Richard B. Russell Airport	14.3	13.9
93842	Columbus Metro Airport	16	3.5

TABLE 7
Traffic and Pavement Layer Thickness for AC and JPCP Pavement Designs (Von Quintus et al., 2015)

Traffic Level		High
Nominal AADTT	AC	4000
	JPCP	4000
Pavement Layer		**(in.)**
Thickness	AC	10
	JPCP	10
Base Thickness	AC	7
	JPCP	6

TABLE 8

AC and JPCP Pavement Design Properties (Von Quintus et al., 2015)

Input Parameter	**Value**
Design Life	20 years for flexible pavements 20 years for rigid pavements
Construction Month	June 2018
Reliability – All Performance Indicators Except AC Total Cracking and Thermal Cracking	95%
Reliability – AC Total Cracking and Thermal Cracking	50%
AADTT Category	Interstate & primary arterials
Number of Lanes in Design Direction	2
Truck Direction Factor	50%
Truck Lane Factor	90%
Default Growth Rate	None
First Layer Material Type	Jointed Plain Concrete Pavement / Asphalt Concrete
Second Layer Material Type	Non Stabilized Base (A-1-b)
Subgrade Material Type	A-4
Base Resilient Modulus	38000 psi
Base Poisson's Ratio	0.35
*Subgrade Resilient Modulus	15000 psi
Subgrade Poisson's Ratio	0.35

TABLE 9

Surface Layer Properties for Base Cases in AC and JPCP Pavement Design

		Value
Asphalt Properties	Surface Shortwave Absorptivity	0.85
	Unit Weight	140 pcf
	Poisson's Ratio	0.35
	Thermal Conductivity	0.67 (BTU/hr-ft-°F)
	Heat Capacity	0.23 (BTU/lb-°F)
	Effective Binder Content	7%
	Air Void	7%
	Binder Type	64-22
	Voids in Mineral Aggregate	7 (%)
Concrete Properties	Design Lane Width	12 ft
	Joint Spacing	15 ft
	Dowel Diameter	1.25 in.
	Dowel Spacing	12 in.
	Erodibility Index	2
	Surface Shortwave Absorption	0.85
	Unit Weight	150 pcf
	Poisson's Ratio	0.2
	Coefficient of Thermal Expansion	5.5 (in./in./°F×10^{-6})
	Thermal Conductivity	0.67 (BTU/hr-ft-°F)
	Cement Content	660 lb/yd^3
	Water to Cement (W/C) Ratio	0.45

4.3.1. Comparisons of Pavement Distress Predictions

The AASHTOWare Pavement ME Design software was used to evaluate the reprocessed MERRA-1 and MERRA-2 data, along with NARR and GBWS, for comparisons of pavement performance predictions. To compare the predicted pavement distresses from different climate sources, it was necessary to collocate the GBWS (i.e., old MEPDG and current MEPDG-NARR) and MERRA as explained previously in Table 6.

4.3.1.1. Asphalt Concrete Predictions

Comparisons of flexible pavement distresses predicted by AASHTOWare Pavement ME Design using old MEPDG (GBWS) vs. current MEPDG (NARR) vs. MERRA-1 vs. MERRA-2 weather data are shown in Figures 6–11 for total rutting, asphalt concrete rutting, alligator fatigue cracking, roughness (IRI), and thermal cracking. In most cases, the pavement distresses predicted via MERRA-2 were relatively higher than those predicted with other climate data sources. Moreover, both MERRA sources resulted in higher pavement distress for flexible pavements, contrary to what was observed with previous studies where MERRA-1 predicted distresses slightly higher than other climate sources (Schwartz et al., 2015; Cetin et al., 2017). While differences in AC layer rutting and total rutting seem to be relatively high, they were very low for the alligator cracking and IRI distresses, with few exceptions. In particular, the use of MERRA-2 almost doubled the AC layer rutting distresses. It was interesting to see that NARR predictions of AC and total rutting were consistently lower compared to GBWS. Four-way comparisons are plotted for reference using the pavement performance predictions shown in Figures 6–11 (refer to Appendix A).

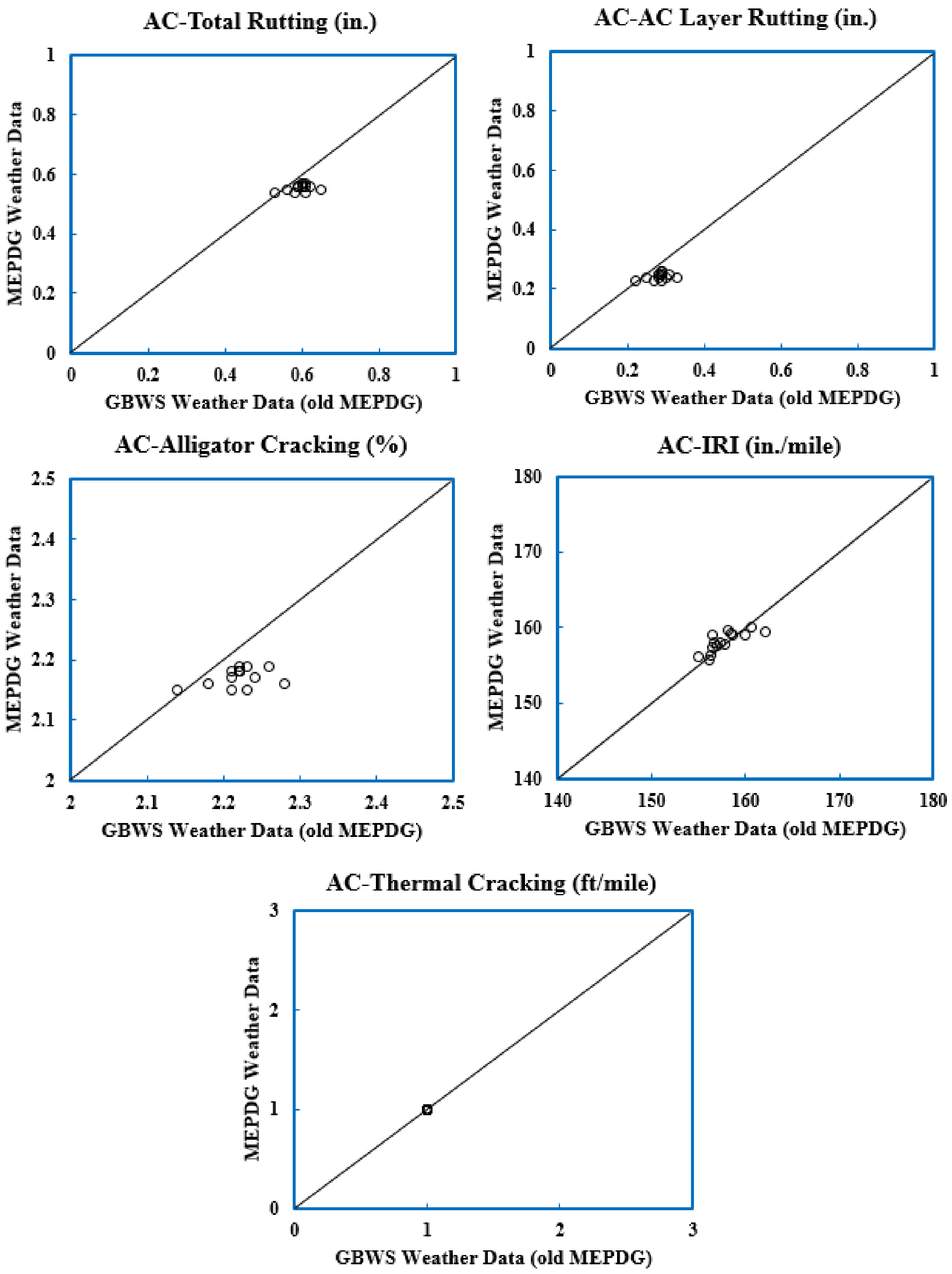


FIGURE 6

Comparison of Asphalt Concrete Predictions Using GBWS (Old MEPDG) vs Current MEPDG (NARR) Weather Data

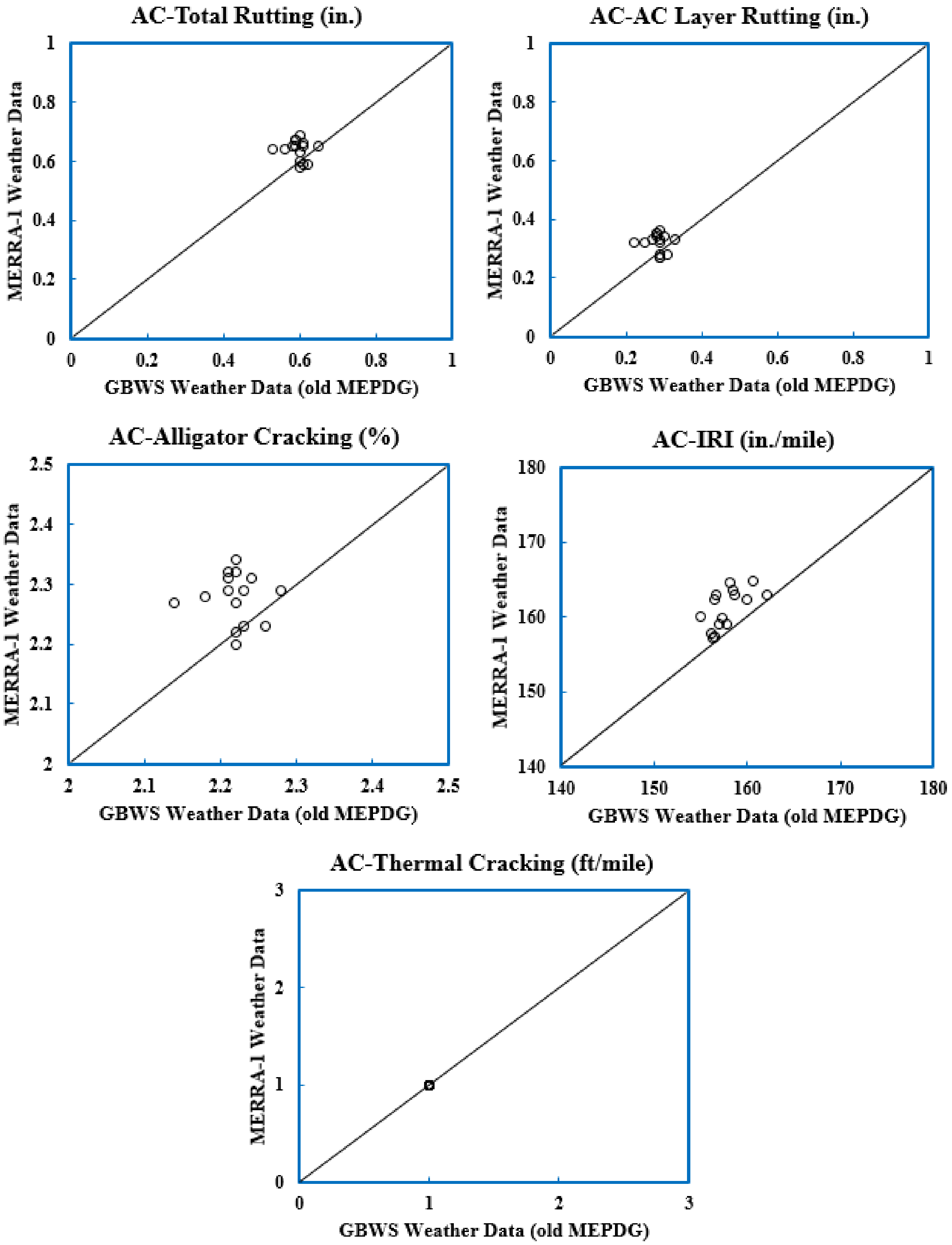


FIGURE 7

Comparison of Asphalt Concrete Predictions Using GBWS (Old MEPDG) vs MERRA-1 Weather Data

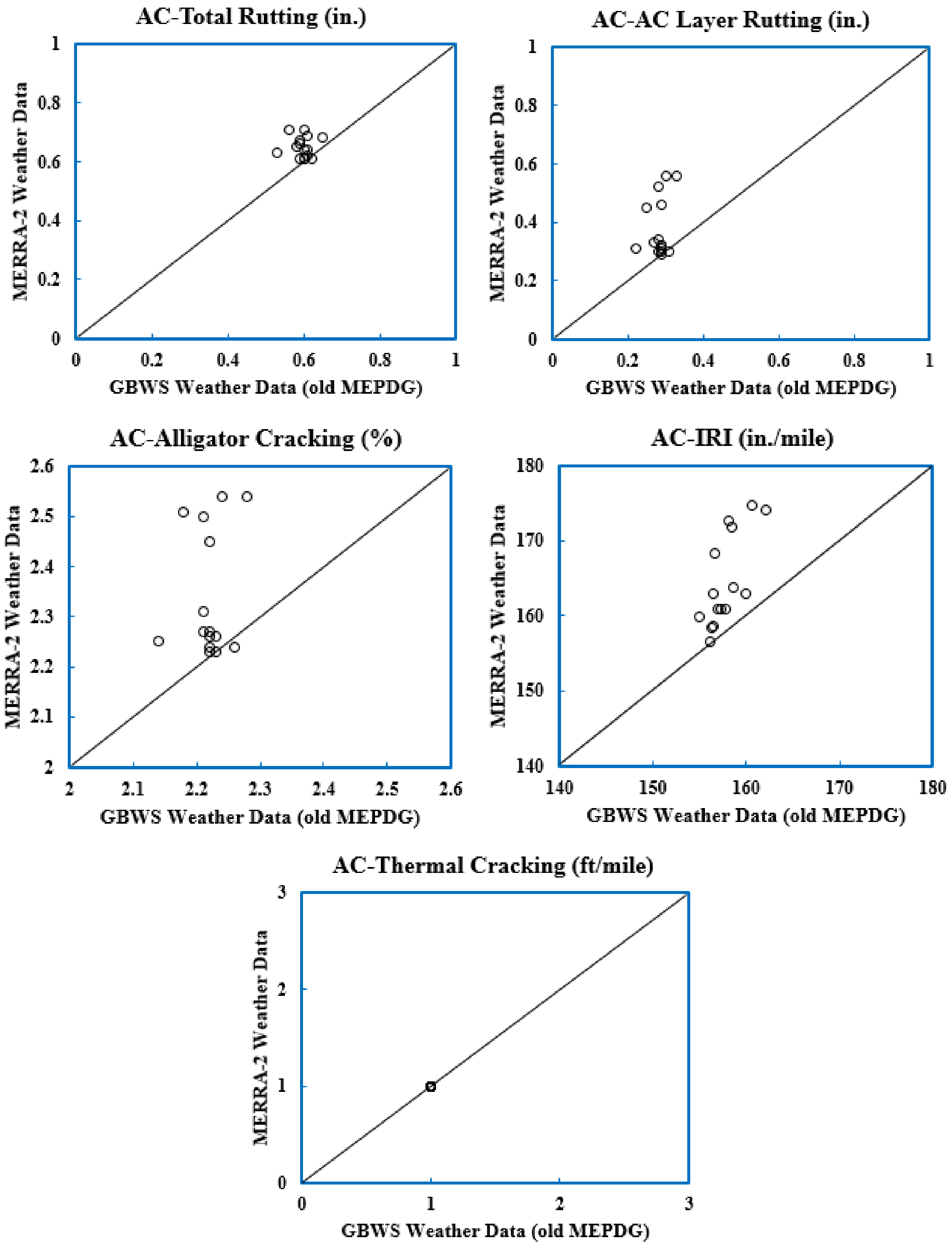


FIGURE 8

Comparison of MEPDG Asphalt Concrete Predictions Using GBWS (Old MEPDG) vs MERRA-2 Weather Data

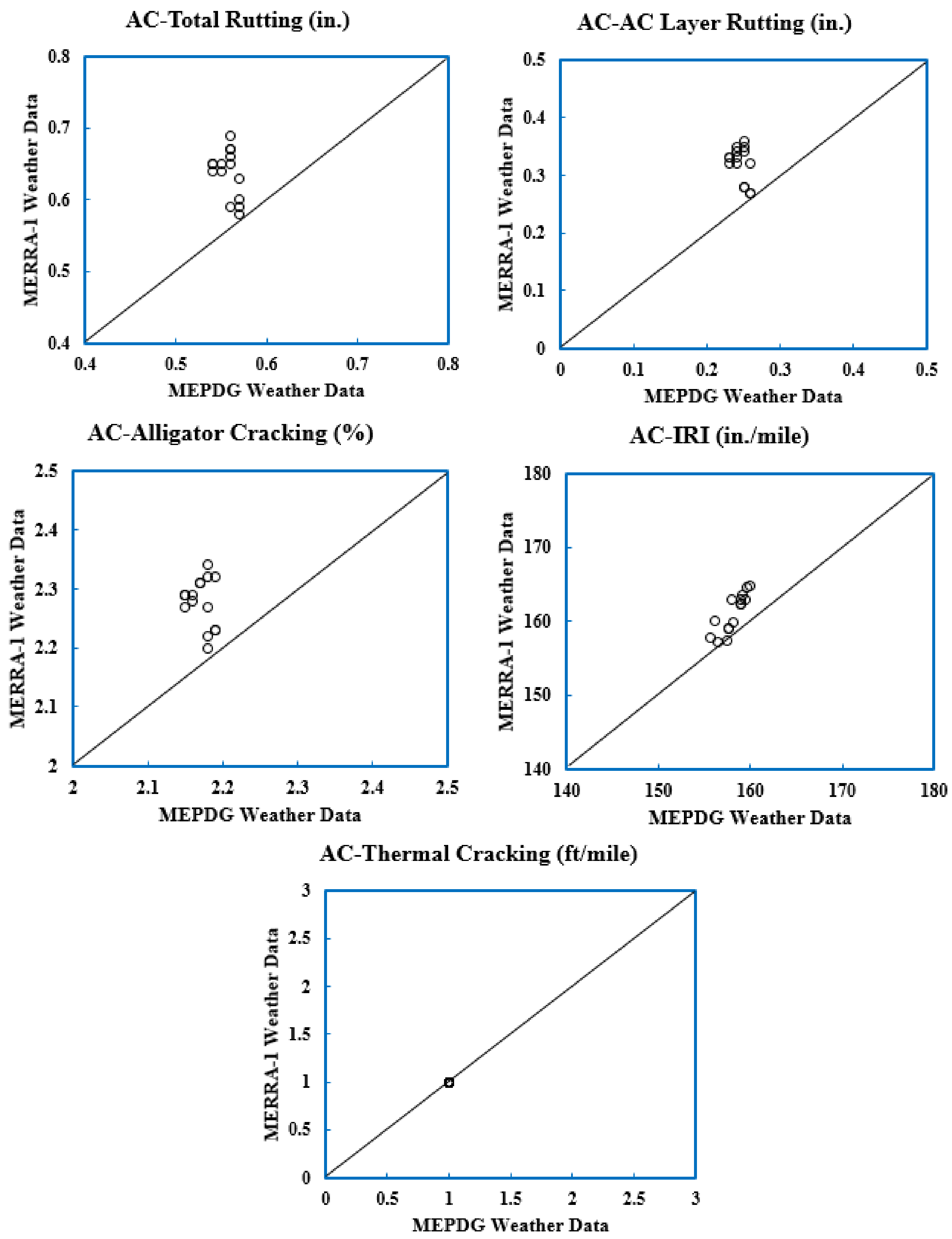


FIGURE 9

Comparison of Asphalt Concrete Predictions Using MERRA-1 vs Current MEPDG (NARR) Weather Data

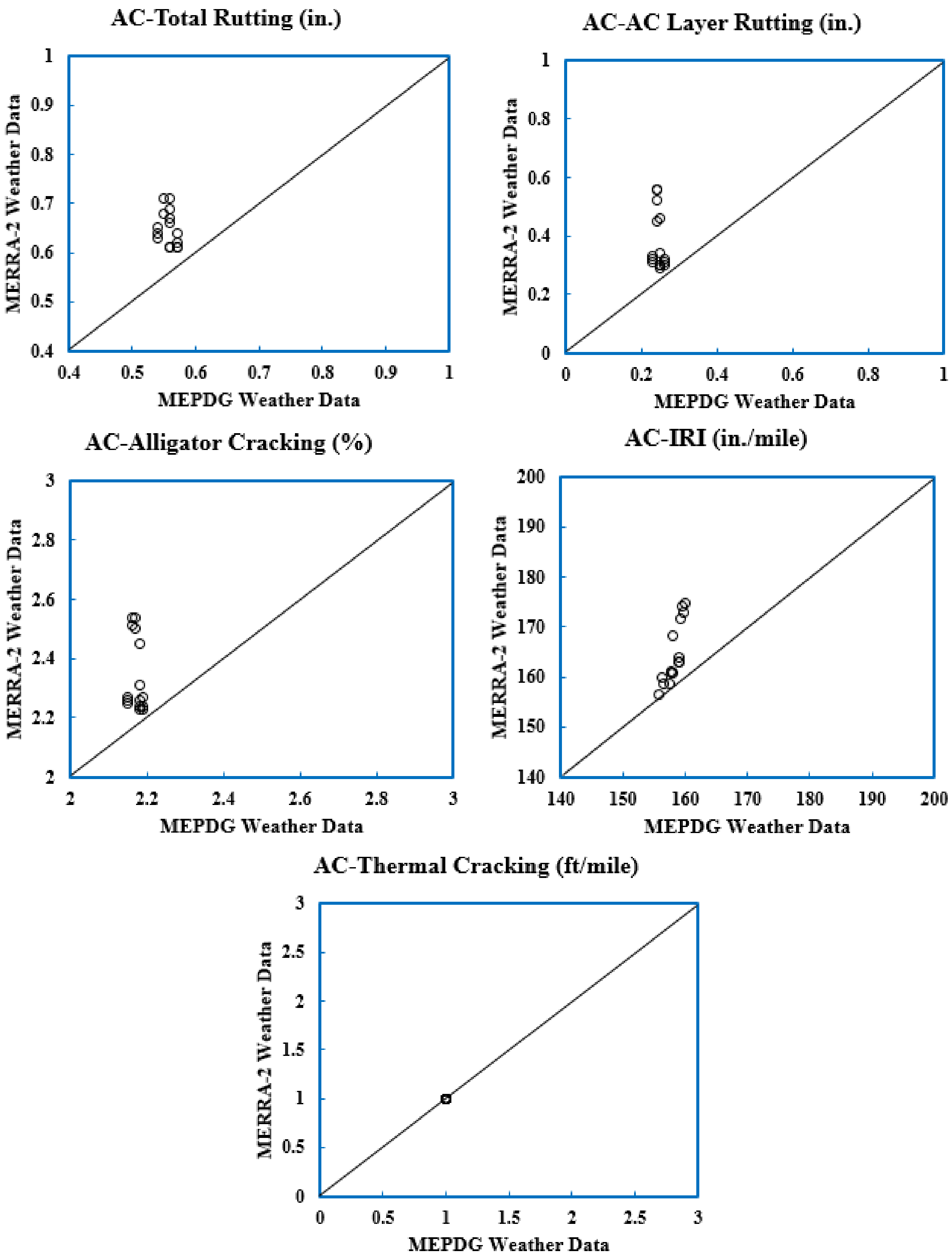


FIGURE 10

Comparison of Asphalt Concrete Predictions Using MERRA-2 vs Current MEPDG (NARR) Weather Data

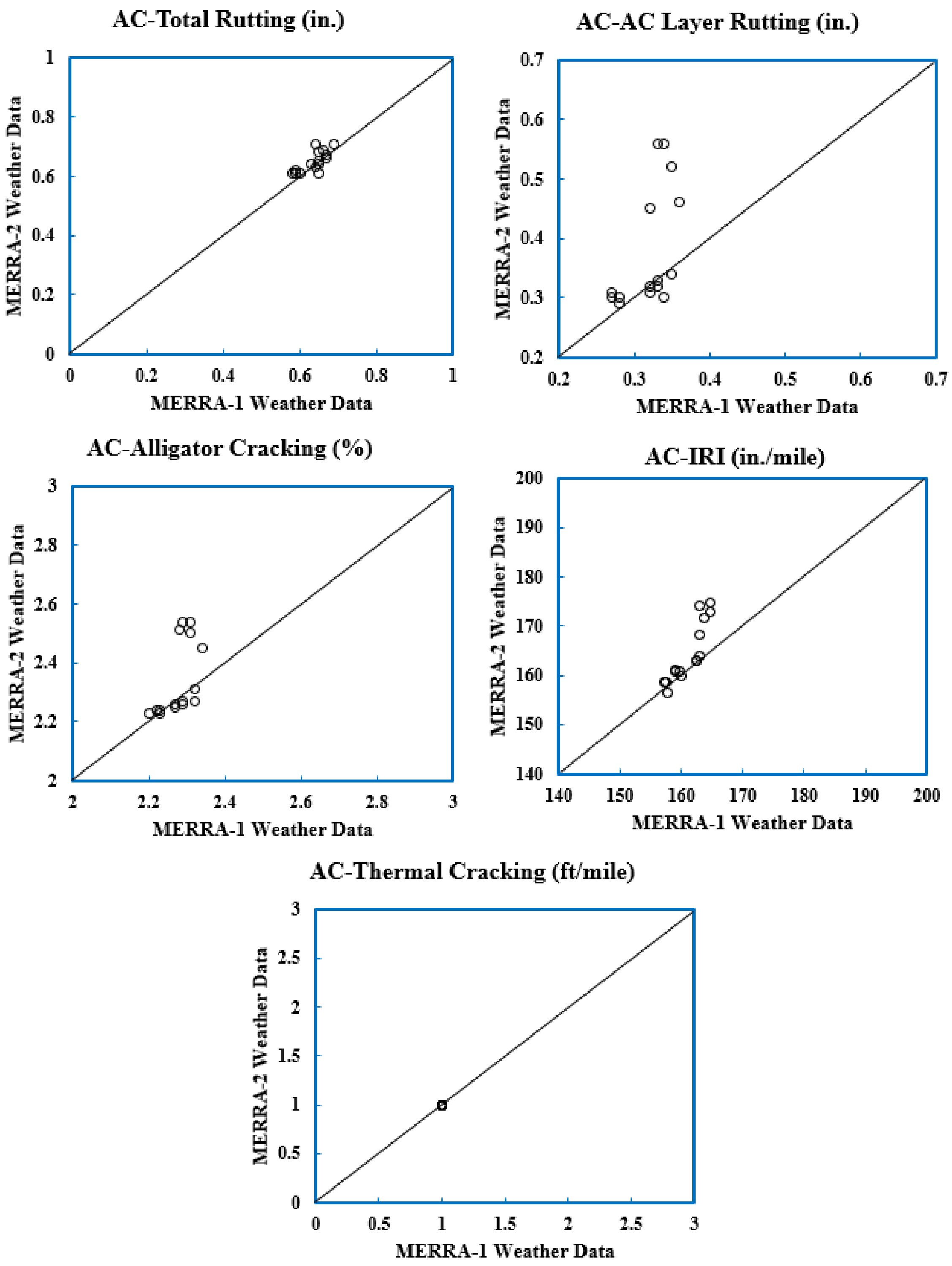


FIGURE 11

Comparison of Asphalt Concrete Predictions Using MERRA-1 vs MERRA-2 Weather Data

4.3.1.2. JPCP Predictions

Comparisons of rigid JPCP pavement performance as predicted by the AASHTOWare Pavement ME Design software using old MEPDG vs. NARR vs. MERRA-1 vs. MERRA-2 weather data are shown in Figures 12–17 for roughness (IRI), joint faulting, and transverse cracking. Similar to the asphalt concrete pavements, MERRA-2–predicted distresses are often relatively higher compared to those predicted via the other climate data sources. The agreement of the distress predictions using the four climate data series is slightly less in rigid pavements compared to asphalt concrete pavements. IRI predictions for rigid pavements were more scattered compared to the asphalt concrete pavements. This was expected because IRIs in JPCPs are slightly more sensitive to slight climate data changes compared to joint faulting and transverse cracking. This is consistent with the findings of Cetin et al. (2017), which also observed that the predicted IRI for rigid pavements with MERRA-1 and GBWS were scattered. In addition, for joint faulting, AASHTOWare Pavement ME Design reports the predictions in 0–0.25 cm precision. This indicates that climate influences in joint faulting predictions are very negligible. Four-way comparisons are plotted for reference using the pavement performance predictions shown in Figures 12–17 (refer to Appendix B).

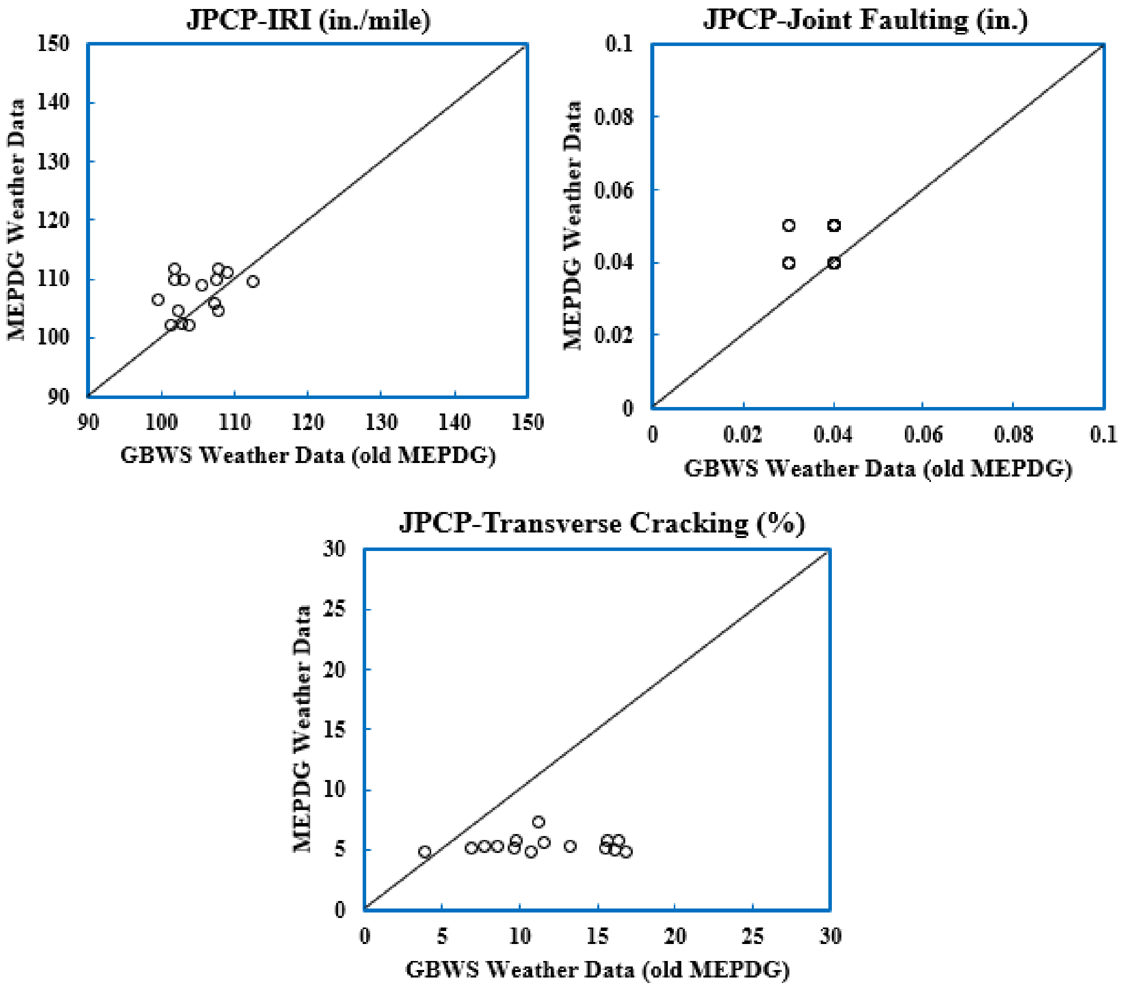


FIGURE 12

Comparison of JPCP Predictions Using GBWS (Old MEPDG) vs Current MEPDG (NARR) Weather Data

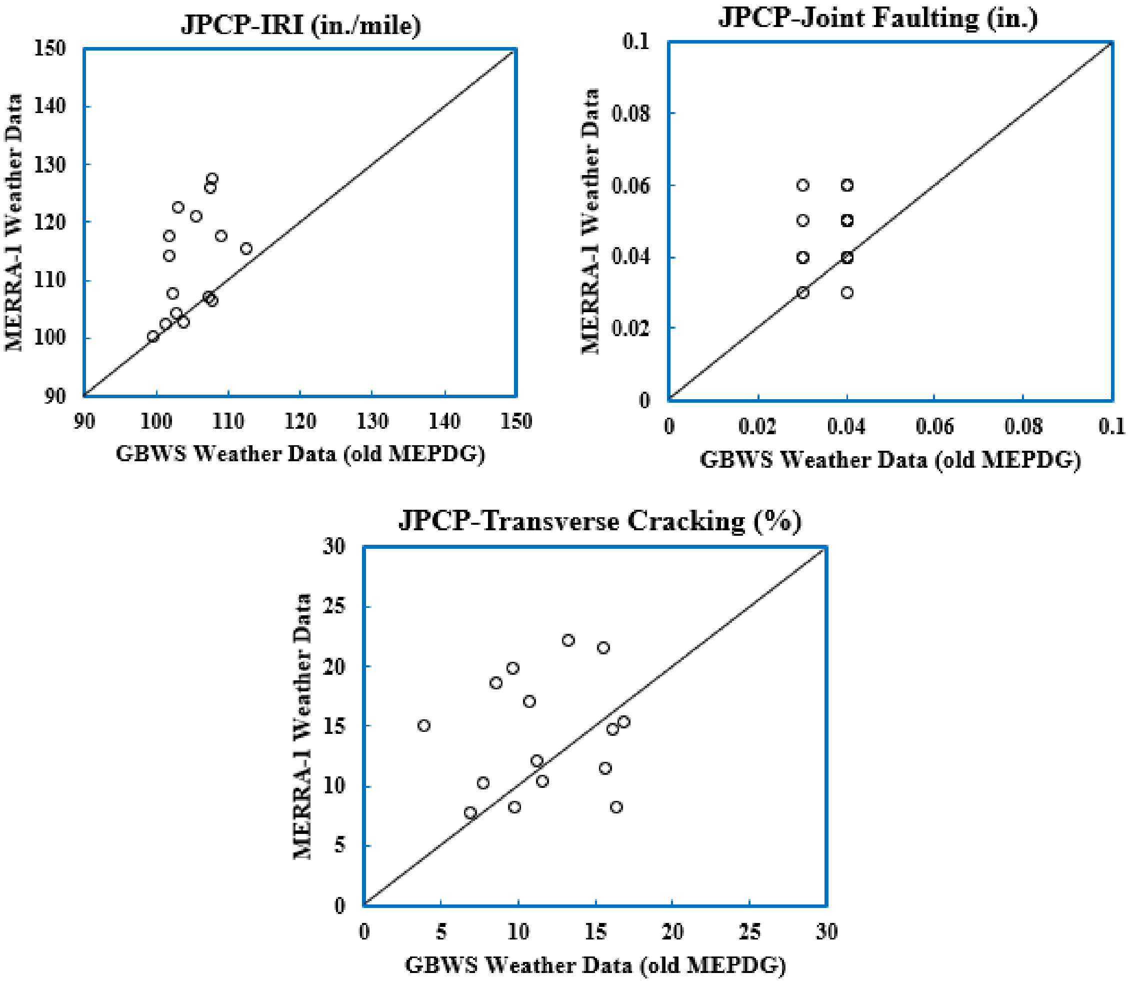


FIGURE 13

Comparison of JPCP Predictions Using GBWS (Old MEPDG)
vs MERRA-1 Weather Data

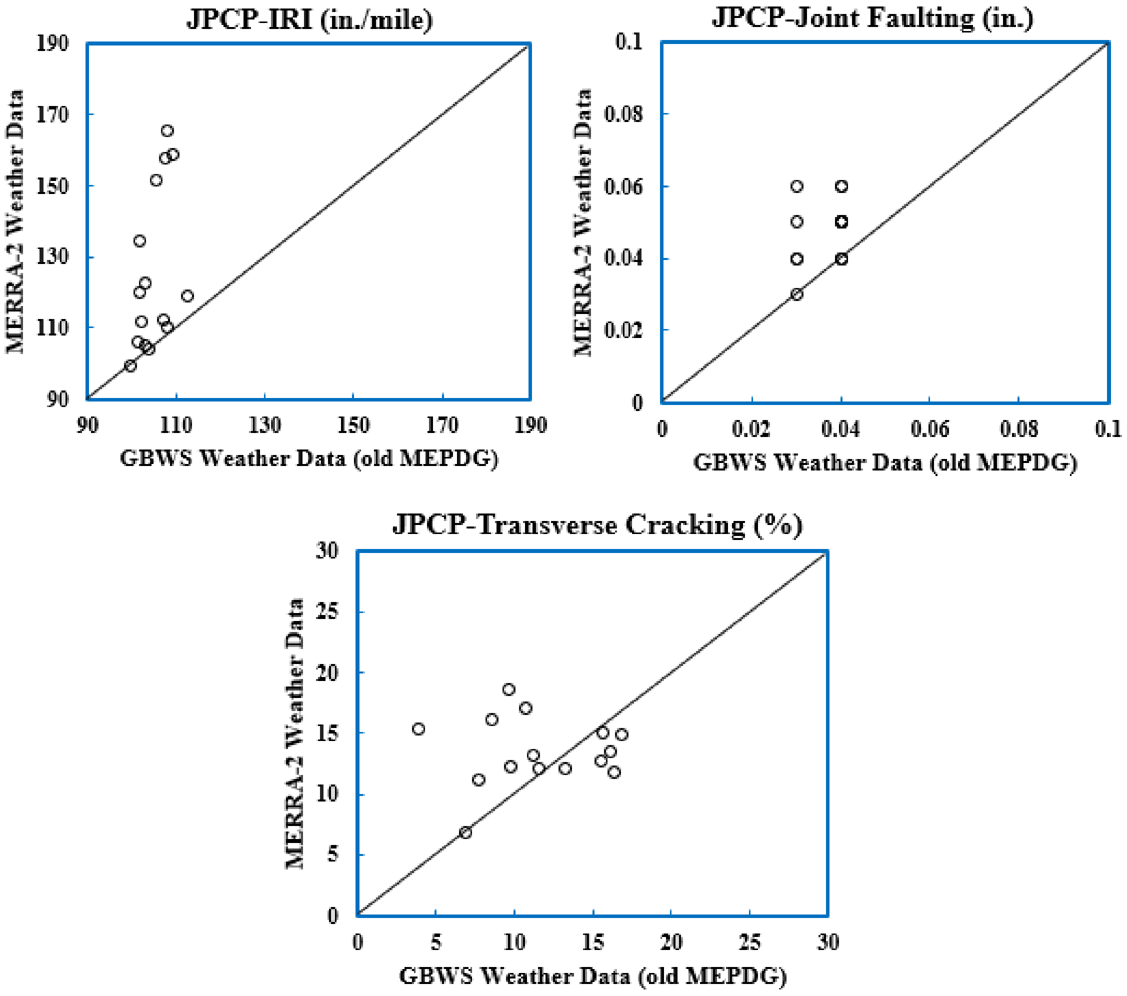


FIGURE 14

Comparison of JPCP Predictions Using GBWS (Old MEPDG) vs MERRA-2 Weather Data

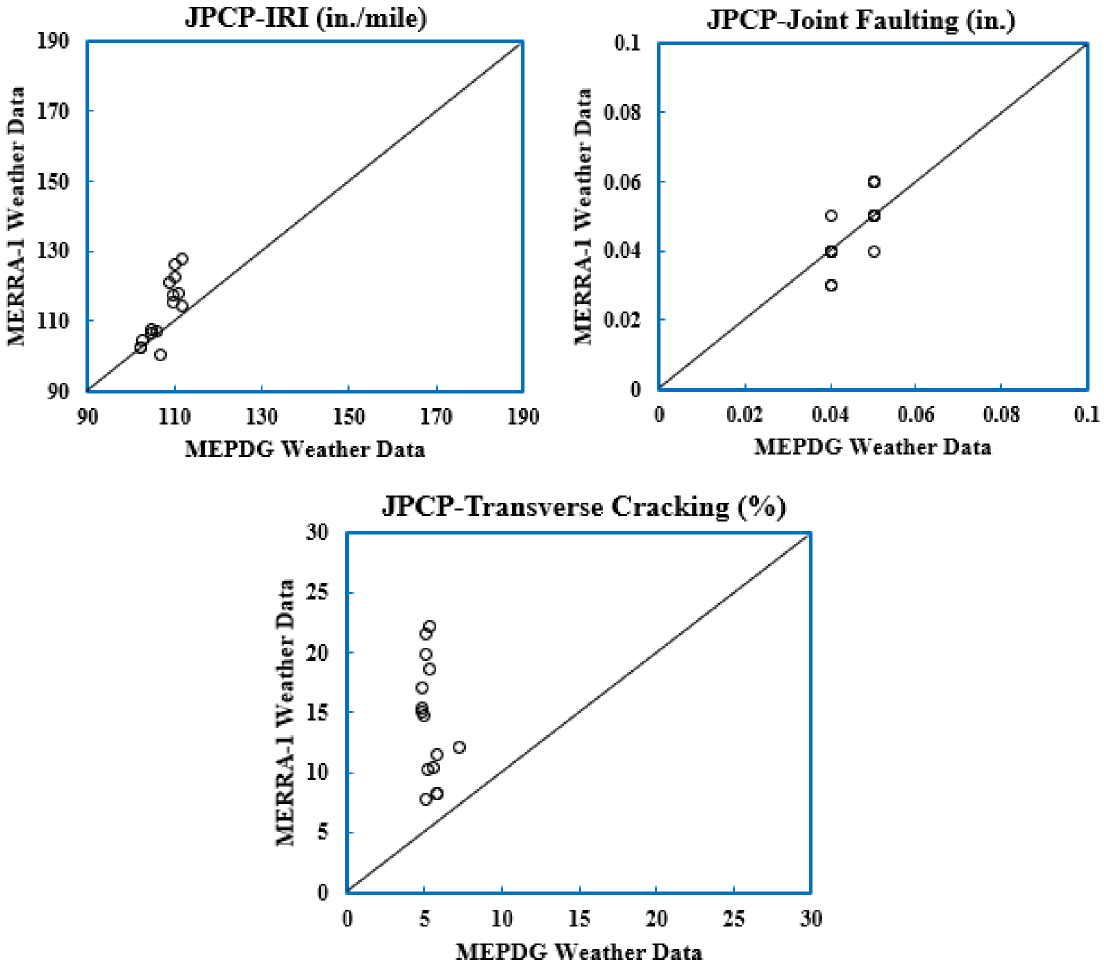


FIGURE 15

Comparison of JPCP Predictions Using Current MEPDG (NARR)
vs MERRA-1 Weather Data

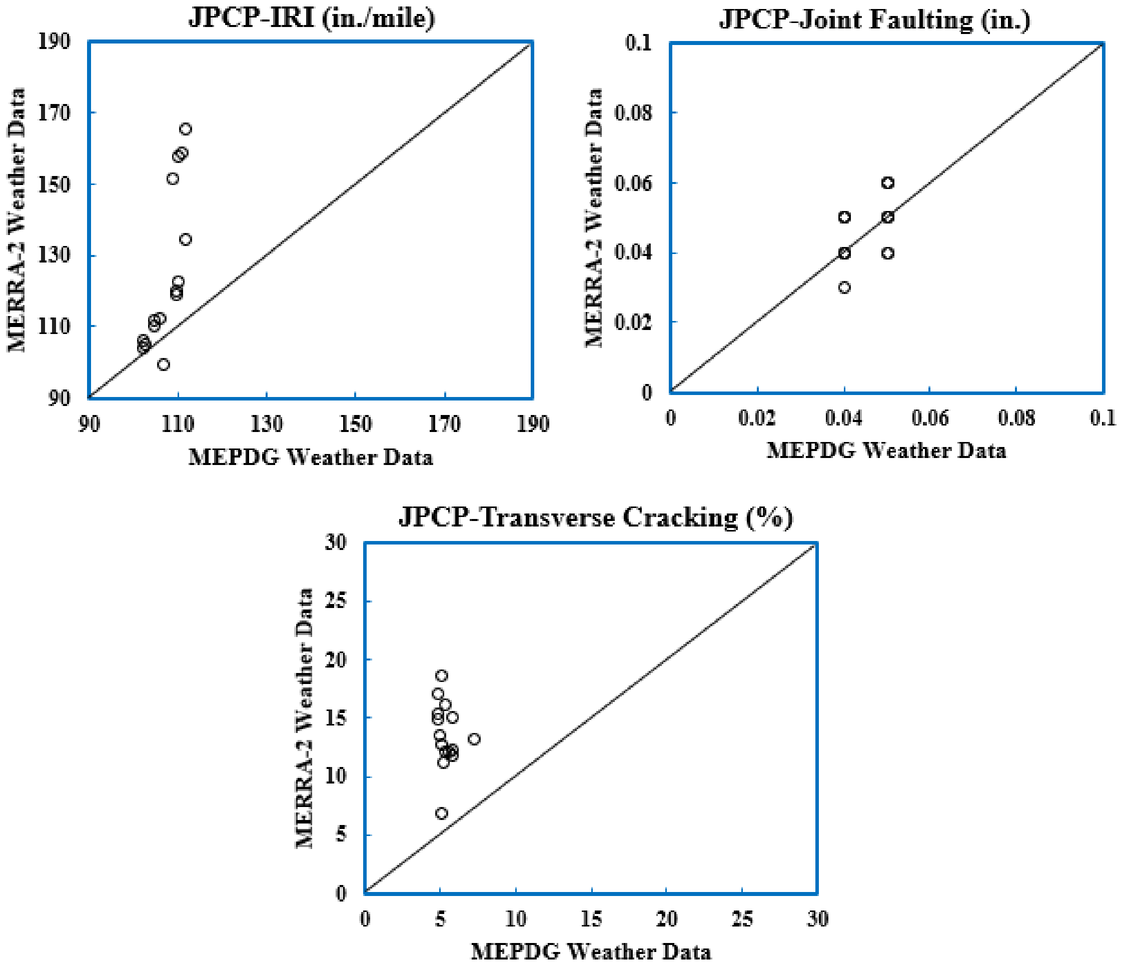


FIGURE 16

Comparison of JPCP Predictions Using Current MEPDG (NARR)
vs MERRA-2 Weather Data

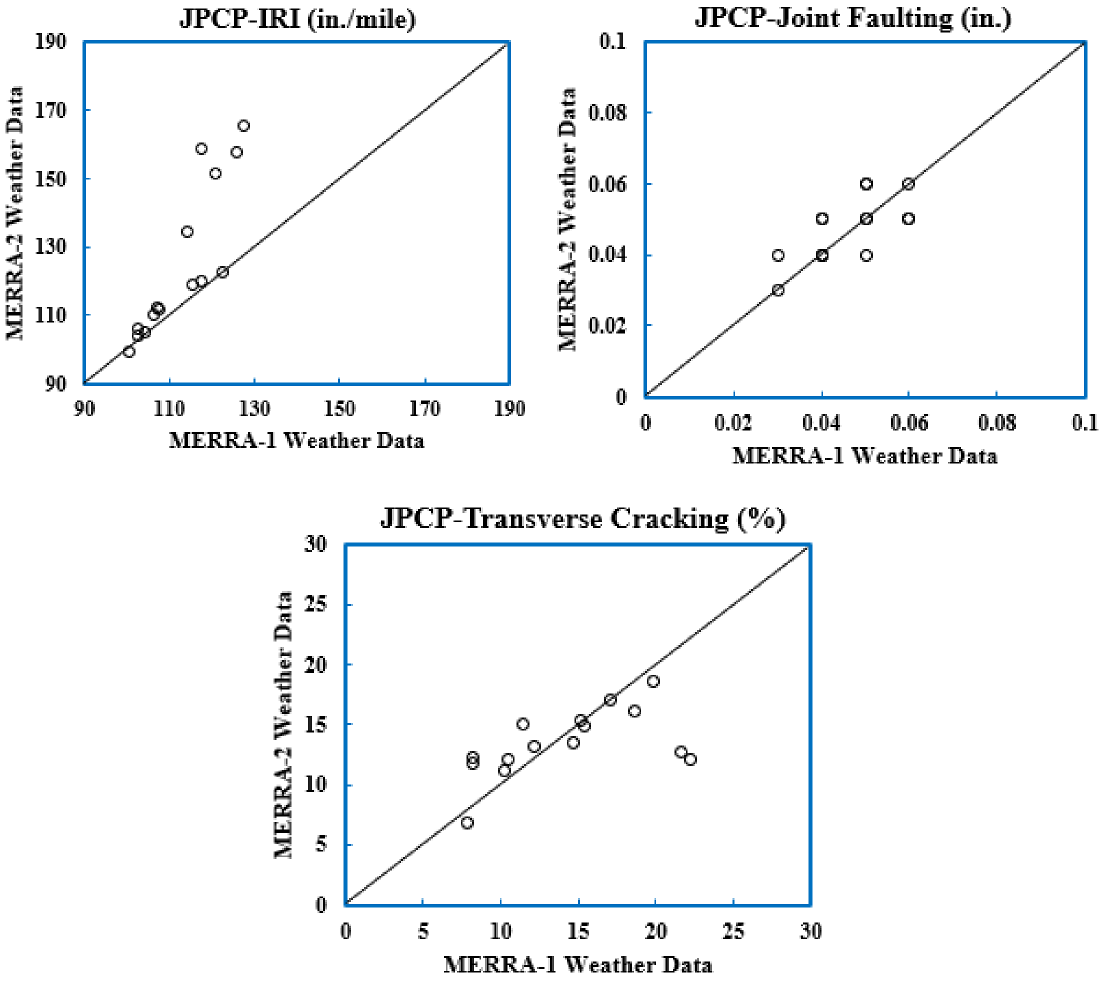


FIGURE 17

Comparison of JPCP Predictions Using MERRA-1 vs MERRA-2 Weather Data

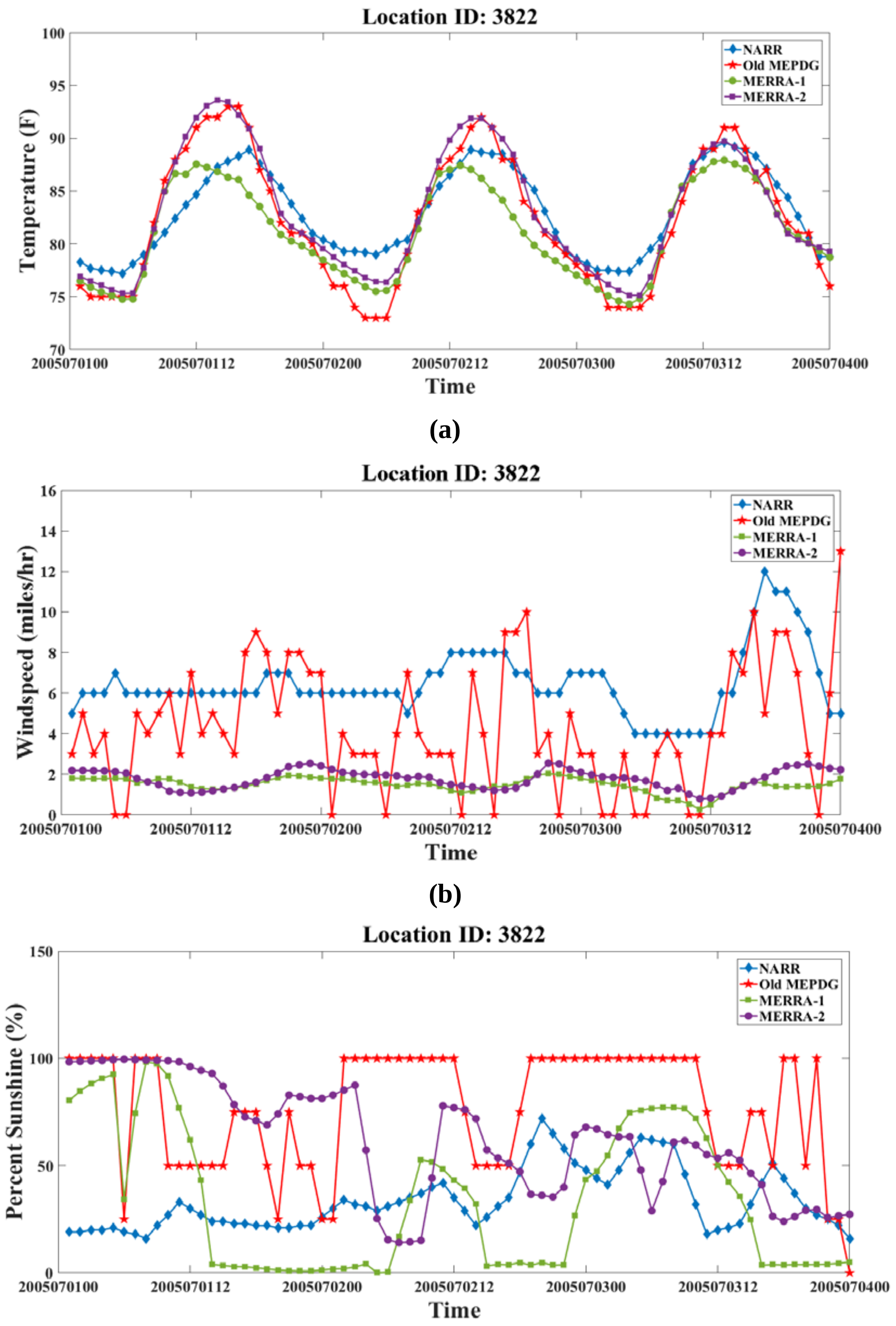
4.4. Reasons for Discrepancies in Comparisons

For flexible pavements, the major reason for variances in predictions among climate data sources is due to considerable differences in percent sunshine values predicted by the climate data sources. Percent sunshine is one of the most sensitive inputs directly related to pavement performance predictions in AC pavements, especially in the case of AC layer rutting and total rutting. Disagreements within the percent sunshine data of different climate sources are discussed in Chapter 5.

For rigid pavements, the reason for differences could be high wind speed values recorded for NARR compared to other sources. Wind speed is the second-most sensitive parameter, especially at high traffic conditions. The example in Figure 18(b) shows higher wind speed compared to other data sources. This result is similar for all the locations across the U.S.

4.4.1. Differences between Climate Data Collected from Different Sources

The variations in pavement performance predictions using the four climate data sources imply that there are differences in the underlying climate data in each source. To investigate these differences, diurnal variations of each climate parameter were analyzed for randomly selected multiday periods. Good agreement was observed for all the parameters except for the percent sunshine data and the wind speed. Figure 18 shows the diurnal variations of temperature, wind speed, and percent sunshine, which were the most sensitive parameters, using all four data source locations in Georgia. Good agreement in diurnal variations was observed for the temperature data, whereas almost no agreement was observed for percent sunshine data. In particular, it was unexpected to observe a poor agreement between the MERRA-1 and the MERRA-2 percent sunshine data since these data sets are generated from the same source. The researchers suspect that this disagreement between the percent sunshine data of the MERRA-1 and MERRA-2 caused significant differences in the pavement distresses.



(a)

(b)

©

FIGURE 18

Diurnal Variations of (a) Temperature, (b) Wind Speed, and (c) Percent Sunshine

4.5. Further Comparisons Using Design Inputs Based on NCHRP 1-37a Base Cases

Based on comparisons shown in Figures 6–17, it was evident that there were differences in climate data from various sources, especially MERRA-2. However, these results are based on design inputs and material properties specific to Georgia DOT calibration factors. To further validate the results, one of the base cases from NCHRP 1-37A was considered. Three-way comparisons using the current MEPDG (NARR) weather data, MERRA-1, and MERRA-2 were performed. The comparisons show almost similar results, which proves the differences in climate data from various sources. Input data of the pavement structure, traffic loads, material properties, and other information are summarized in Tables 10–12.

TABLE 10

Traffic and Pavement Layer Thickness for AC and JPCP Pavement Designs (Schwartz et al., 2015)

Traffic Level		**High**
Nominal AADTT	AC	450
	JPCP	7500
Pavement Layer		**(in.)**
Thickness	AC	6
	JPCP	10
Base Thickness	AC	7
	JPCP	6

TABLE 11

AC and JPCP Pavement Design Properties (Schwartz et al., 2015)

Input Parameter	Value
Design Life	10 years for flexible pavements 20 years for rigid pavements
Construction Month	June 2018
Reliability – All Performance Indicators Except AC Total Cracking and Thermal Cracking	90%
Reliability – AC Total Cracking and Thermal Cracking	50%
AADTT Category	Interstate & primary arterials
Number of Lanes in Design Direction	2
Truck Direction Factor	50%
Truck Lane Factor	55%
Default Growth Rate	None
First Layer Material Type	Jointed Plain Concrete Pavement / Asphalt Concrete
Second Layer Material Type	Non Stabilized Base (A-1-b)
Subgrade Material Type	A-4
Base Resilient Modulus	25000 psi
Base Poisson's Ratio	0.35
*Subgrade Resilient Modulus	15000 psi
Subgrade Poisson's Ratio	0.35

TABLE 12

Surface Layer Properties for Base Cases in AC and JPCP Pavement Design (Schwartz et al., 2015)

		Value
Asphalt Properties	Surface Shortwave Absorptivity	0.85
	Unit Weight	140 pcf
	Poisson's Ratio	0.35
	Thermal Conductivity	0.67 (BTU/hr-ft-°F)
	Heat Capacity	0.23 (BTU/lb-°F)
	Effective Binder Content	7%
	Air Void	7%
	Binder Type	64-34
	Voids in Mineral Aggregate	14 (%)
Concrete Properties	Design Lane Width	12 ft
	Joint Spacing	15 ft
	Dowel Diameter	1.25 in.
	Dowel Spacing	12 in.
	Erodibility Index	5
	Surface Shortwave Absorption	0.85
	Unit Weight	150 pcf
	Poisson's Ratio	0.2
	Coefficient of Thermal Expansion	5.5 (in./in./°F×10^{-6})
	Thermal Conductivity	1.25 (BTU/hr-ft-°F)
	Cement Content	660 lb/yd^3
	W/C Ratio	0.2

Figures 19–21 show the comparisons for AC predictions, and Figures 22–24 show the comparisons for JPCP predictions. The results were consistent with earlier comparisons using GDOT design inputs.

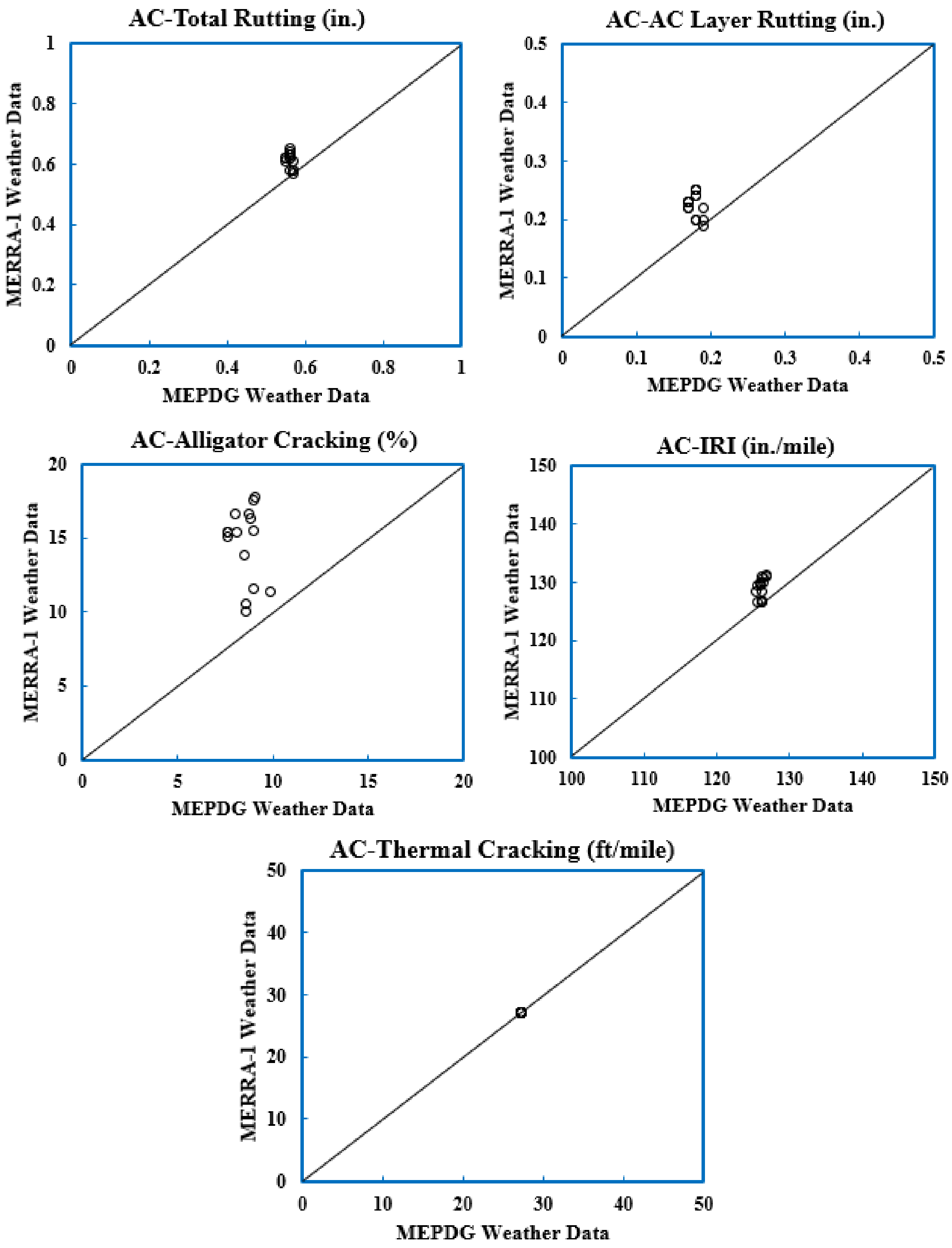


FIGURE 19

Comparison of Asphalt Concrete Predictions Using Current MEPDG (NARR) vs MERRA-1 Weather Data

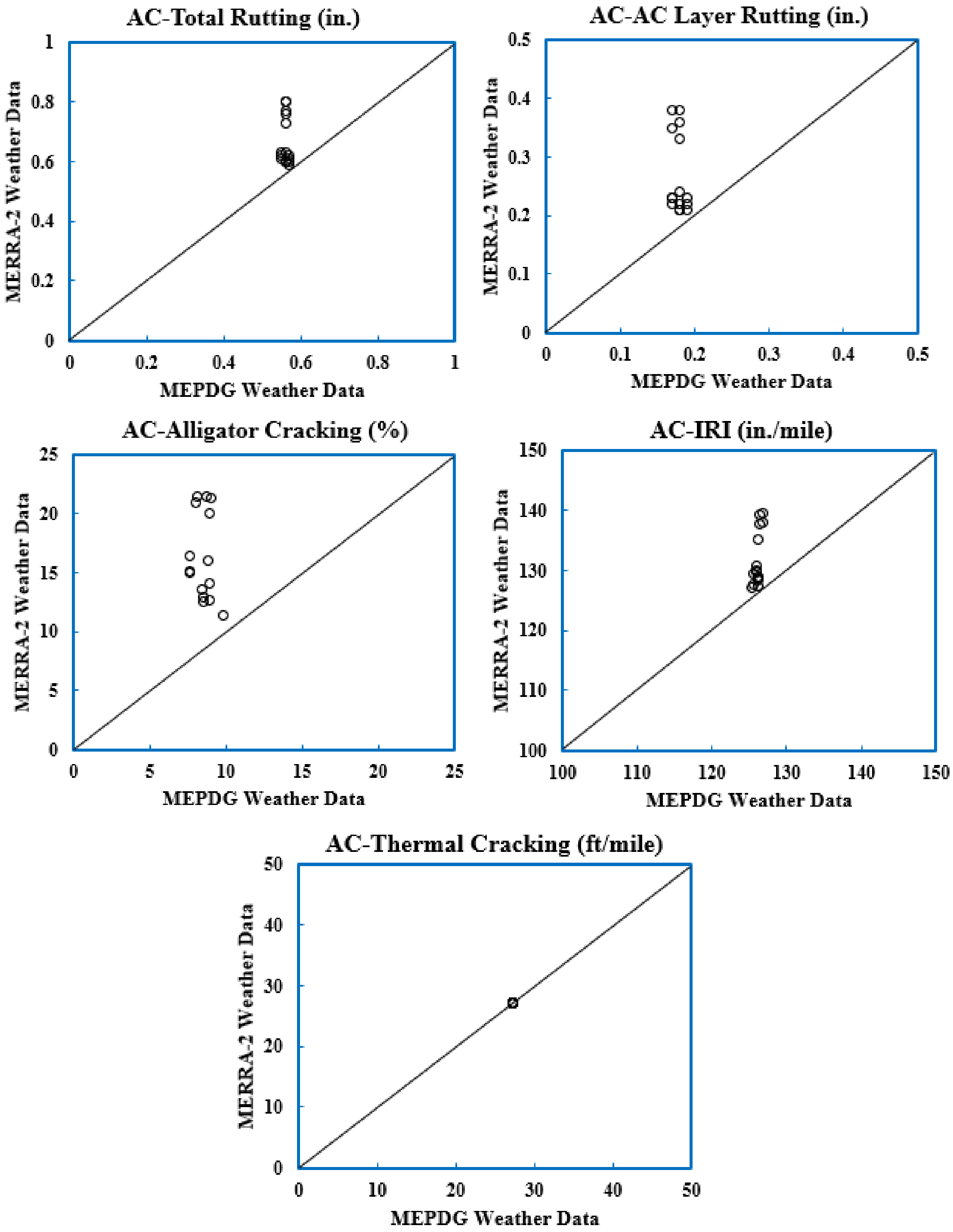


FIGURE 20

Comparison of Asphalt Concrete Predictions Using Current MEPDG (NARR) vs MERRA-2 Weather Data

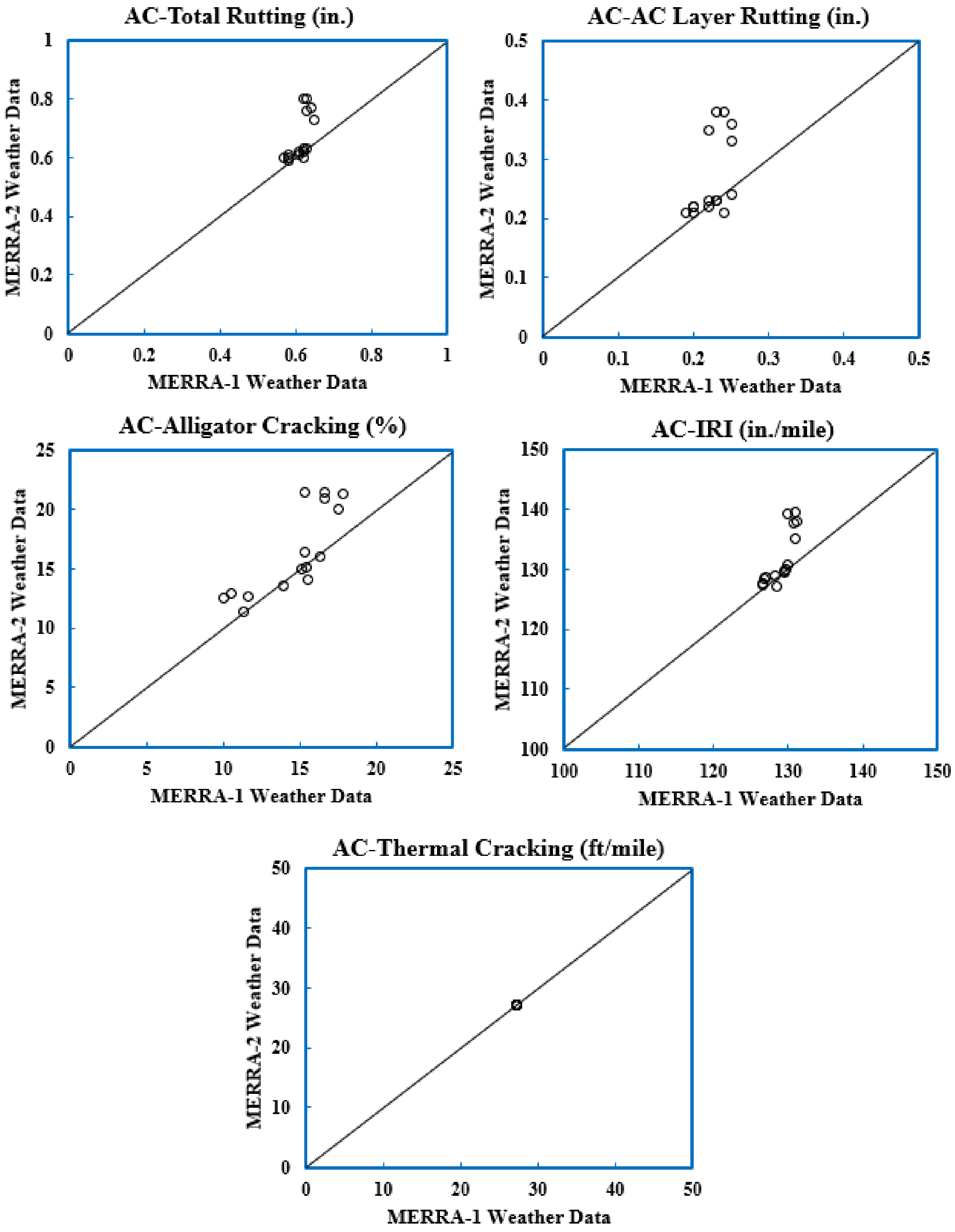
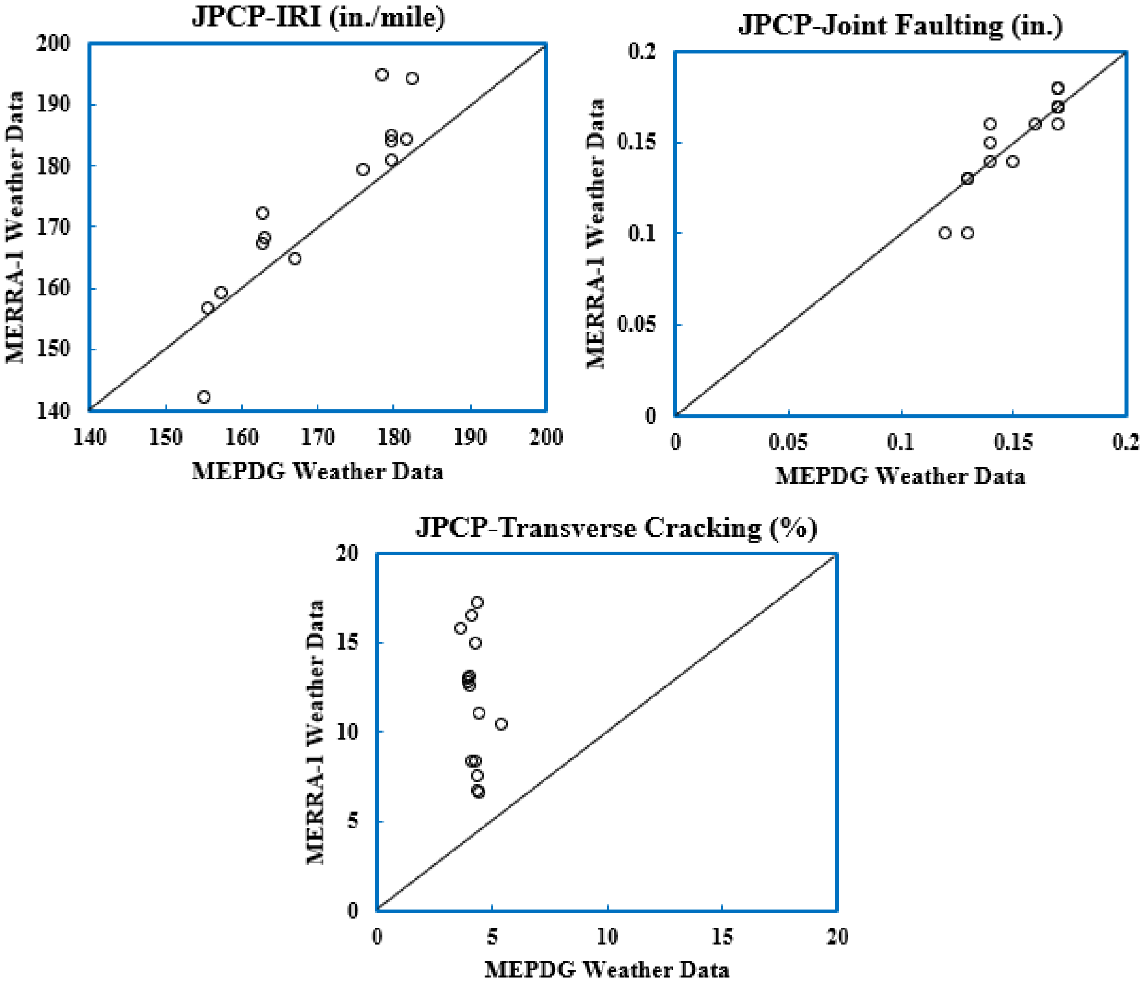


FIGURE 21

Comparison of Asphalt Concrete Predictions Using MERRA-1 vs MERRA-2 Weather Data


JPCP-IRI (in./mile)

JPCP-Joint Faulting (in.)

JPCP-Transverse Cracking (%)

FIGURE 22

*Comparison of JPCP Predictions Using Current MEPDG (NARR)
vs MERRA-1 Weather Data*

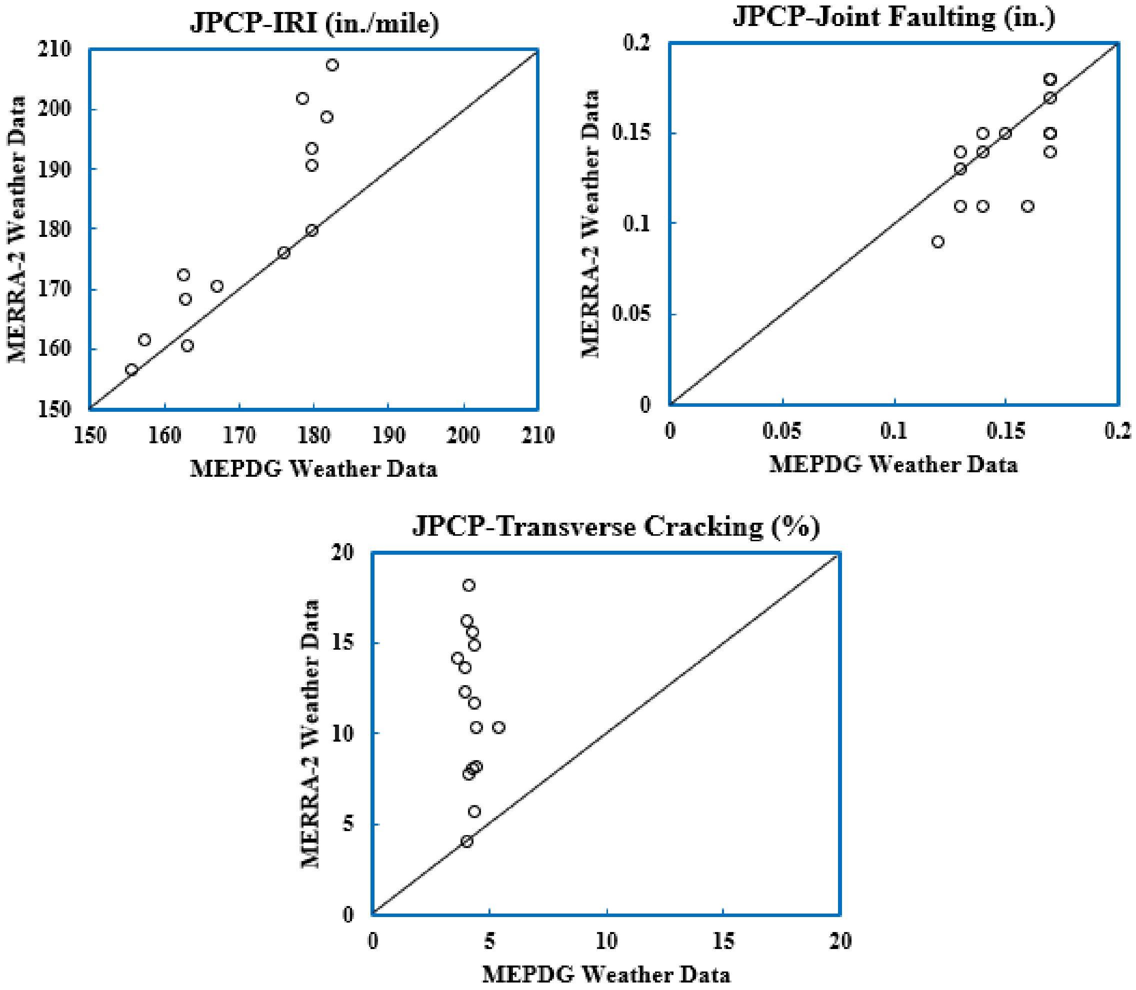


FIGURE 23

Comparison of JPCP Predictions Using Current MEPDG (NARR)
vs MERRA-2 Weather Data

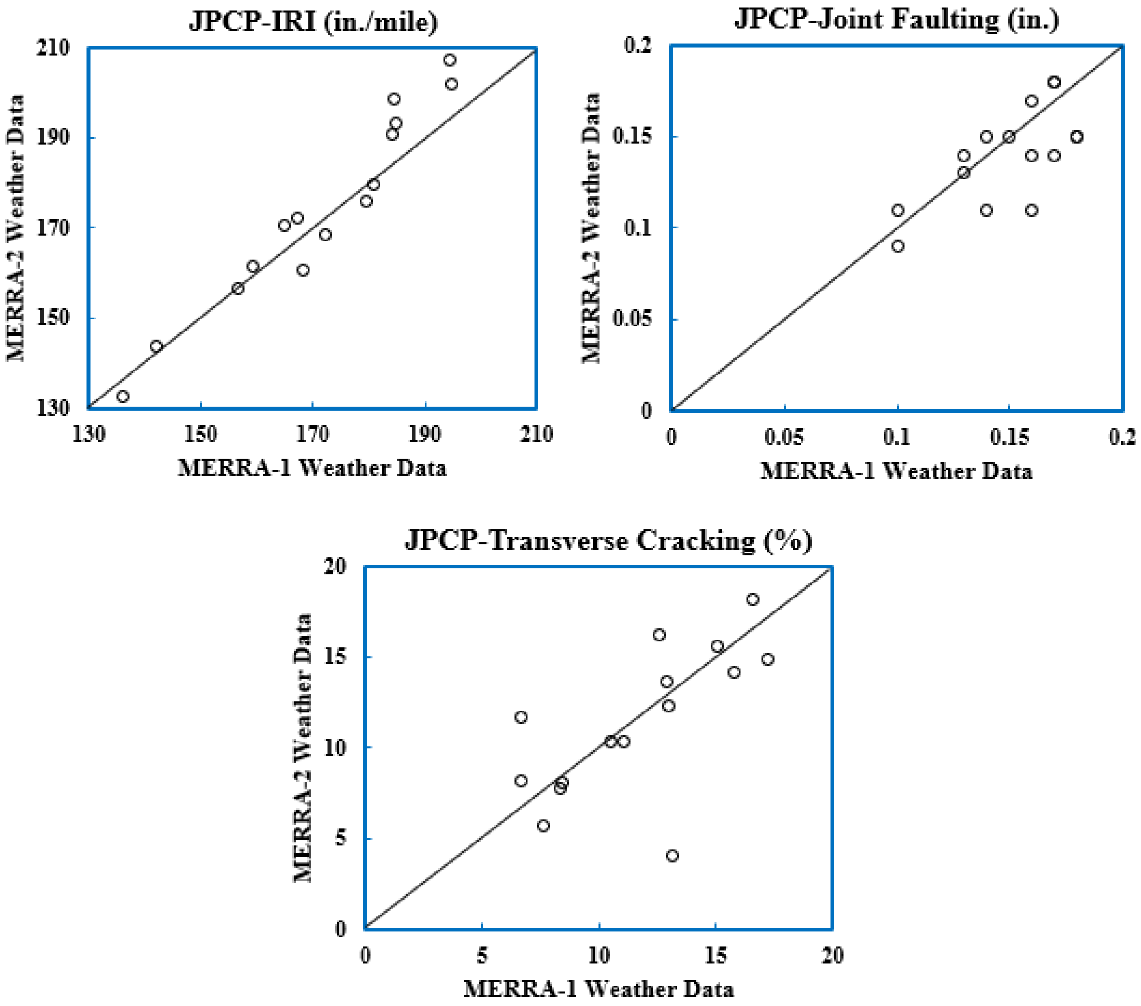


FIGURE 24

Comparison of JPCP Predictions Using Current MERRA-1 vs MERRA-2 Weather Data

5. IMPACT OF SHORTWAVE RADIATION ON PAVEMENT PERFORMANCE

Environmental conditions impact the pavement performance and its service life significantly. Therefore, it is very important to take the effects of environmental conditions into account during pavement design analyses. Previous studies mostly focused on predicting pavement temperature via air temperature, and there are many models developed for this purpose. However, these models did not take shortwave radiation parameters into account while modeling the pavement temperature. Shortwave radiation directly impacts the pavement temperature, in addition to air temperature, and changes the pavement surface reflectivity, which can ultimately alter the shortwave absorptivity of the pavement upper layer and change the temperature of the pavement structure.

The climate model embedded in the AASHTOWare Pavement ME Design software uses percent sunshine as an input. Percent sunshine values collected from NARR are estimated from percent cloud cover, which does not provide the actual shortwave radiation values. On the other hand, MERRA provides direct estimates of surface shortwave radiation instead of using the percent cloud cover in NARR in order to estimate the percent sunshine. Surface shortwave radiation can provide more accurate, physically based, and reliable inputs for use in MEPDG design in the future. Under this task, the research team developed a shortwave radiation model to back calculate the synthetic percent sunshine by incorporating the shortwave radiation values.

5.1. Percent Sunshine as an Input and Incorporation of a Shortwave Radiation Regression Equation

The climate model embedded in all versions of the AASHTOWare Pavement ME Design software has traditionally used percent sunshine input values. The primary function of the percent sunshine inputs in the AASHTOWare Pavement ME Design software is to compute the surface shortwave radiation. Percent sunshine is a function of both percent cloud cover and time of day. Zero percent cloud cover at noon would correspond to 100% sunshine, while 0% cloud cover at midnight in mid-latitudes would correspond to 0% sunshine. There are various reasons for differences in percent sunshine predictions among different data sources. Percent sunshine values collected from the GBWS are estimated from the percent cloud cover and are typically a point estimate. This is determined using a laser ceilometer and generally encompasses only a limited altitude range. Furthermore, the percent cloud cover is categorized in a very approximate manner—i.e., 0%, 25%, 50%, 75%, and 100%. This process does not provide the actual shortwave radiation values. Climate reanalysis products (MERRA and NARR) use model predictions for cloud cover, which are generally the average for an entire grid point cell. Cloud cover prediction, in particular, is still an evolving art for climate analysis models. The cloud prediction models in MERRA-2 are different from those in MERRA-1. Further, clouds are of different types and present at different altitudes. These absorb solar energy differently. However, the Pavement ME Design software does not account for these differences.

To overcome these issues, the research team considered MERRA, as it provides direct estimates of SSR instead of using percent cloud cover in order to estimate the percent sunshine. Surface shortwave radiation provides more accurate, physically based, and reliable inputs for use in the AASHTOWare Pavement ME Design software. In addition, the U.S. Climate Reference Network provides research-grade ground-based SSR measurements at a limited number of sites across the United States and Canada that can be used for ground truth. There are four USCRN sites in Georgia, with locations shown in Table 13.

TABLE 13

Summary of Four Locations in Georgia of USCRN Ground-based Weather Stations

Site ID	Location	Latitude_Deg	Longitude_Deg	Elevation (m)
63850	Watkinsville, GA	33.784	−83.390	225.857
63856	St. Marys, GA	30.808	−81.460	7.620
63828	Newton, GA	31.313	−84.471	53.645
63829	Newton, GA	31.192	−84.447	47.549

Figure 25 shows the diurnal variations of SSR in MERRA-1, MERRA-2, and USCRN data sets. The SSR values from all three data sets are in good agreement, unlike the percent sunshine data as shown previously in Figure 18.

The current study used a pavement heating/shortwave radiation model to generate the synthetic percent sunshine by incorporating the surface shortwave radiation values collected from MERRA-1 and MERRA-2 in order to improve the accuracy of the pavement performance predictions. Surface shortwave radiation is estimated in the AASHTOWare Pavement ME Design software by using the regression model as shown in Equation 1 (Baker and Haines, 1969):

$$\mathbf{Q}_{i} = \mathbf{R}^{*}\left[\mathbf{A} + \mathbf{B}\,\frac{\mathbf{S_C}}{\mathbf{100}}\right] \qquad \textbf{Eq. 1}$$

where:

Q_i = incoming shortwave radiation received at ground level;

$R*$ = shortwave radiation incident on a horizontal surface at the top of the atmosphere (this depends on the solar constant, the latitude of the site, and the seasonally varying solar declination);

A, B = empirical constants that account for diffuse scattering and adsorption by the atmosphere (the values of A and B incorporated in the AASHTOWare Pavement ME Design software, which are based on data for the upper Midwest and Alaska, equal 0.202 and 0.539, respectively); and

Sc = average percent sunshine.

The estimated Q_i is a strong and direct function of the percent sunshine. Large differences in the percent sunshine inputs, as shown in Figure 18, will produce significantly different estimations of Q_i and, as a consequence, different predictions of pavement heating and cooling, affecting the final distress predictions. MERRA directly predicts Q_i separately from the percent sunshine (S_c). This can be used to back calculate the synthetic percent sunshine values that, when used as inputs into the AASHTOWare Pavement ME Design software and run through the regression equation (Eq. 1), would give exactly the same Q_i values predicted by MERRA. The synthetic percent sunshine values computed using this approach (for either MERRA-1 or MERRA-2) can be used to replace the percent sunshine values in the AASHTOWare Pavement ME Design weather data input files. However, while back calculating the synthetic percent sunshine, some of the values were observed to be less than 0% or more than 100%. In order to correct for this and run in the software, these values were truncated to 0 and 100, respectively. These changes do not make a significant difference to the predicted output as these do not happen very often and the excursions are not very large.

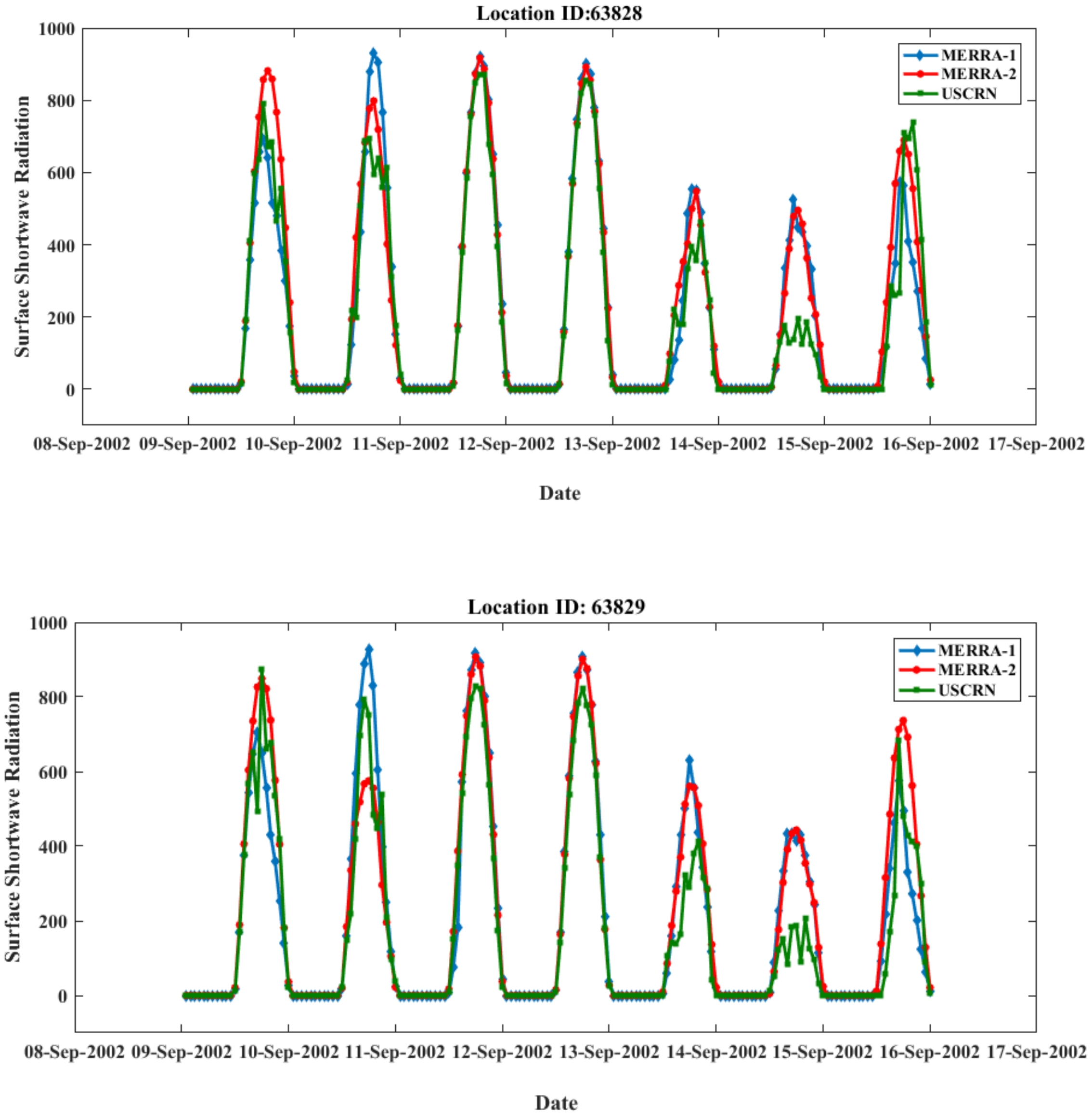


FIGURE 25

Diurnal Variations of SSR Using MERRA-1 vs MERRA-2 vs USCRN (GBWS) in Georgia

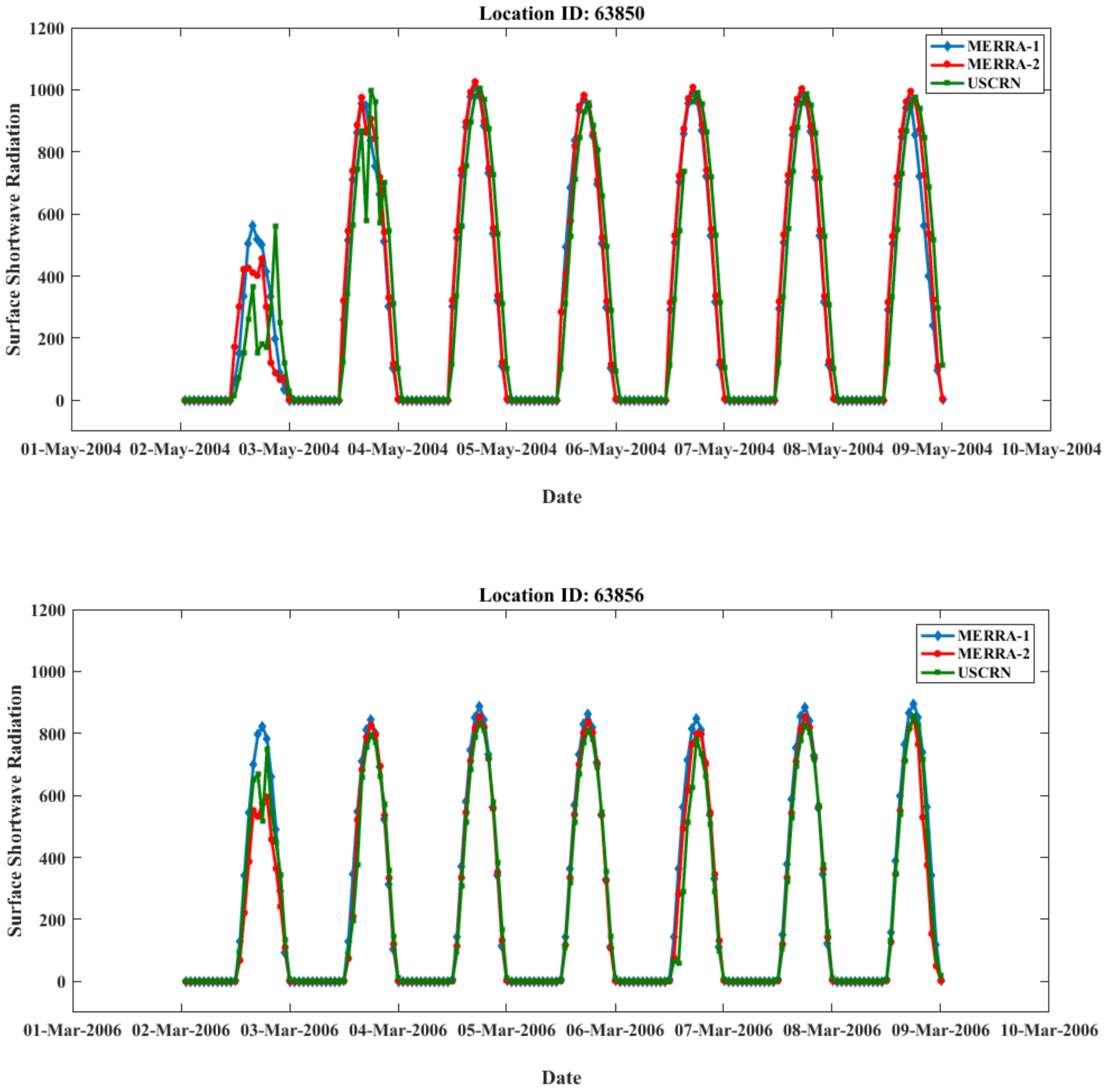


FIGURE 25 Continued

Diurnal Variations of SSR Using MERRA-1 vs MERRA-2 vs USCRN (GBWS) in Georgia

5.2. Sensitivity Analysis of Back-Calculated Percent Sunshine to Pavement Distresses

A sensitivity analysis was conducted to evaluate the impact of pavement performance to back-calculated “synthetic percent sunshine.” A location in Savannah, Georgia, was considered for analysis. Figures 26 and 27 show the design limit normalized sensitivity index (NSI) values for each climate and distress parameter combination determined using the one-at-a-time sensitivity analysis. These figures show the results for AC and JPCP pavements, and are based on results from three different traffic levels. Each subplot in Figures 26 and 27 represents a given level of traffic. In all the cases for both AC and JPCP, the NSI values are positive, which means that an increase in synthetic percent sunshine increases the pavement distresses. However, the NSI values are too low in some cases, indicating very slight impact on distresses.

For flexible pavements, as shown in Figure 26, AC rutting was most sensitive to synthetic percent sunshine, and thermal cracking was the least sensitive. IRI, total rutting, and alligator cracking were moderately sensitive to synthetic percent sunshine.

For JPCP, transverse cracking and IRI were observed as the most sensitive parameters to synthetic percent sunshine. The NSI values below 0.2 in both cases as shown in Figure 27 indicate that the impact is too slight. However, joint faulting is not significantly affected by synthetic percent sunshine.

When using synthetic percent sunshine as inputs in Pavement ME Design software, the MERRA-2 vs. MERRA-1 comparisons of predicted pavement performance for both asphalt concrete and JPCP pavement improved, with the predictions all clustered tightly along the respective lines of equality, as shown in Figures 28 and 29.

The good agreement between the MERRA and the USCRN SSR values shown in Figure 25 supports the use of back-calculated synthetic percent sunshine values as inputs to the AASHTOWare Pavement ME Design software. The synthetic percent sunshine values, when processed through the AASHTOWare Pavement ME Design algorithms, will produce the same SSR values as predicted by MERRA and as confirmed by the USCRN. This provides an interim solution for the improved SSR calculation using the current version of the AASHTOWare Pavement ME Design software. The better long-term solution would be to replace the percent sunshine input with the direct input of the SSR estimates from MERRA-2.

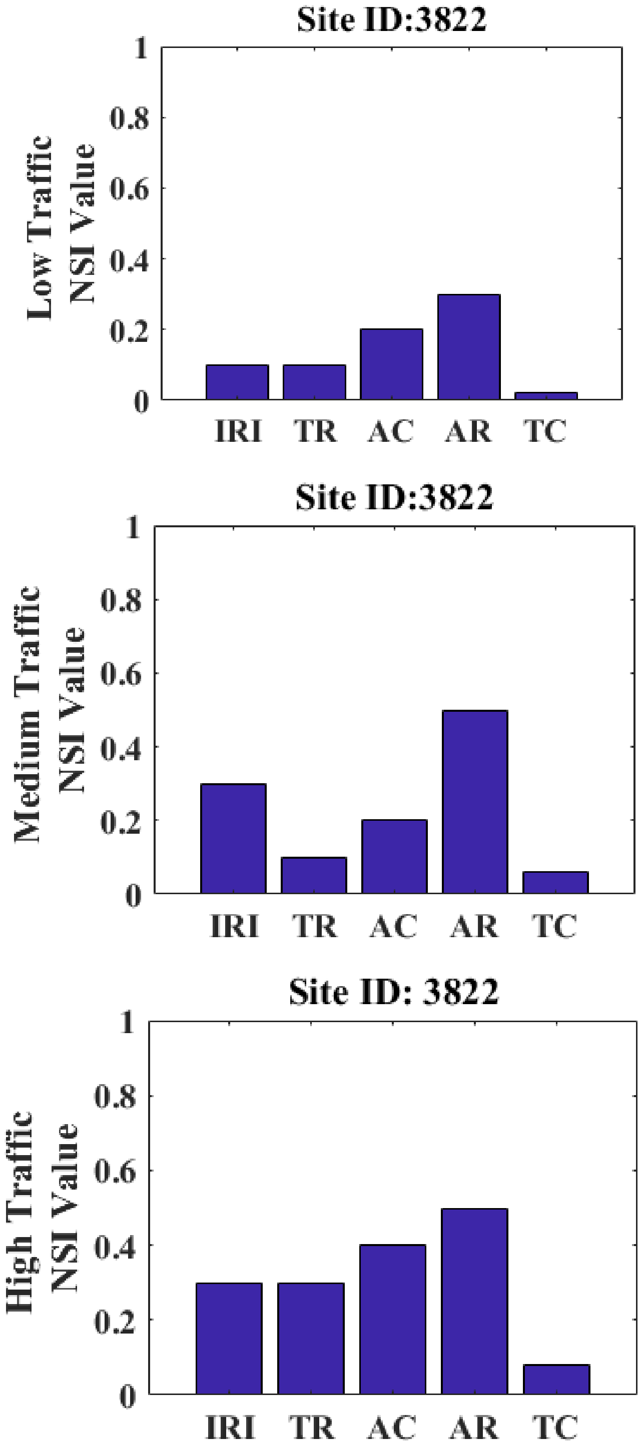


FIGURE 26

Sensitivity Analysis for Flexible Pavements
(IRI: International Roughness Index, TR: Total Rutting,
AC: Alligator Cracking, AR: Asphalt Rutting, TC: Thermal Cracking)

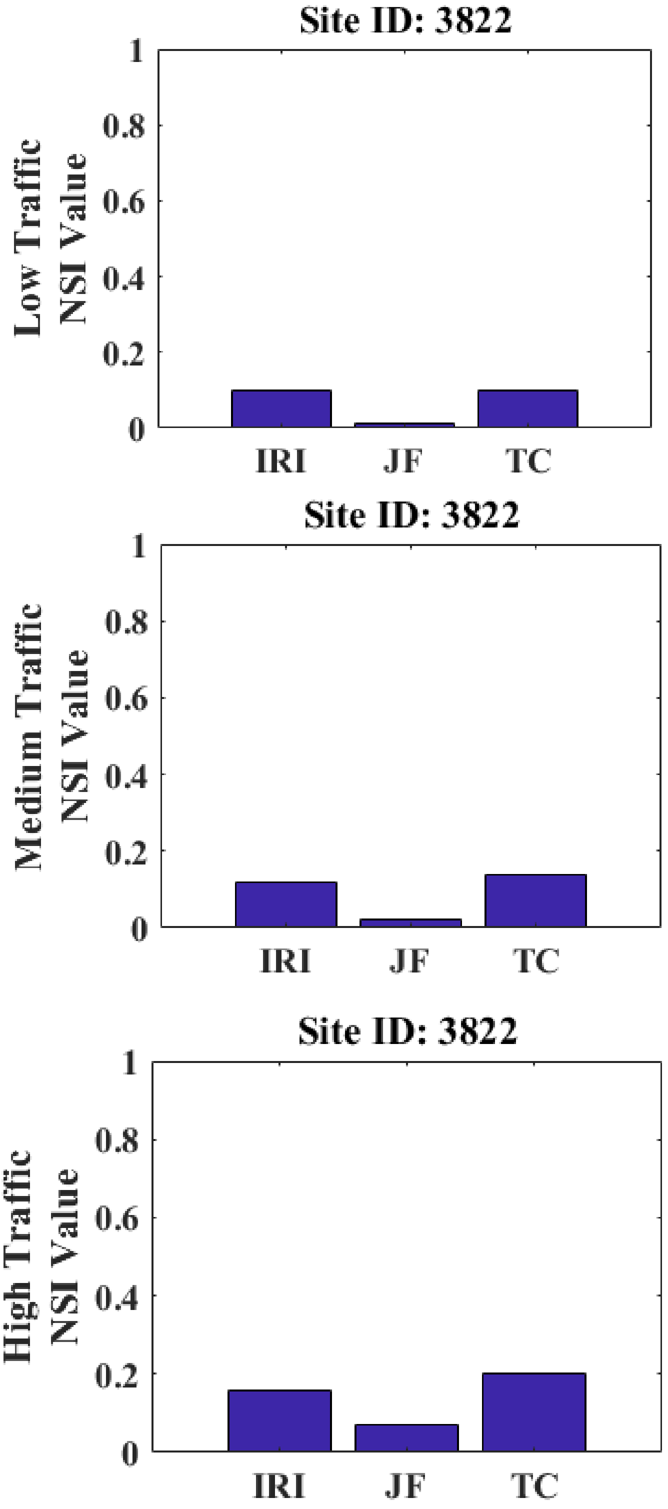


FIGURE 27

Sensitivity Analysis for Rigid Pavements
(IRI: International Roughness Index, JF: Joint Faulting, TC: Transverse Cracking)

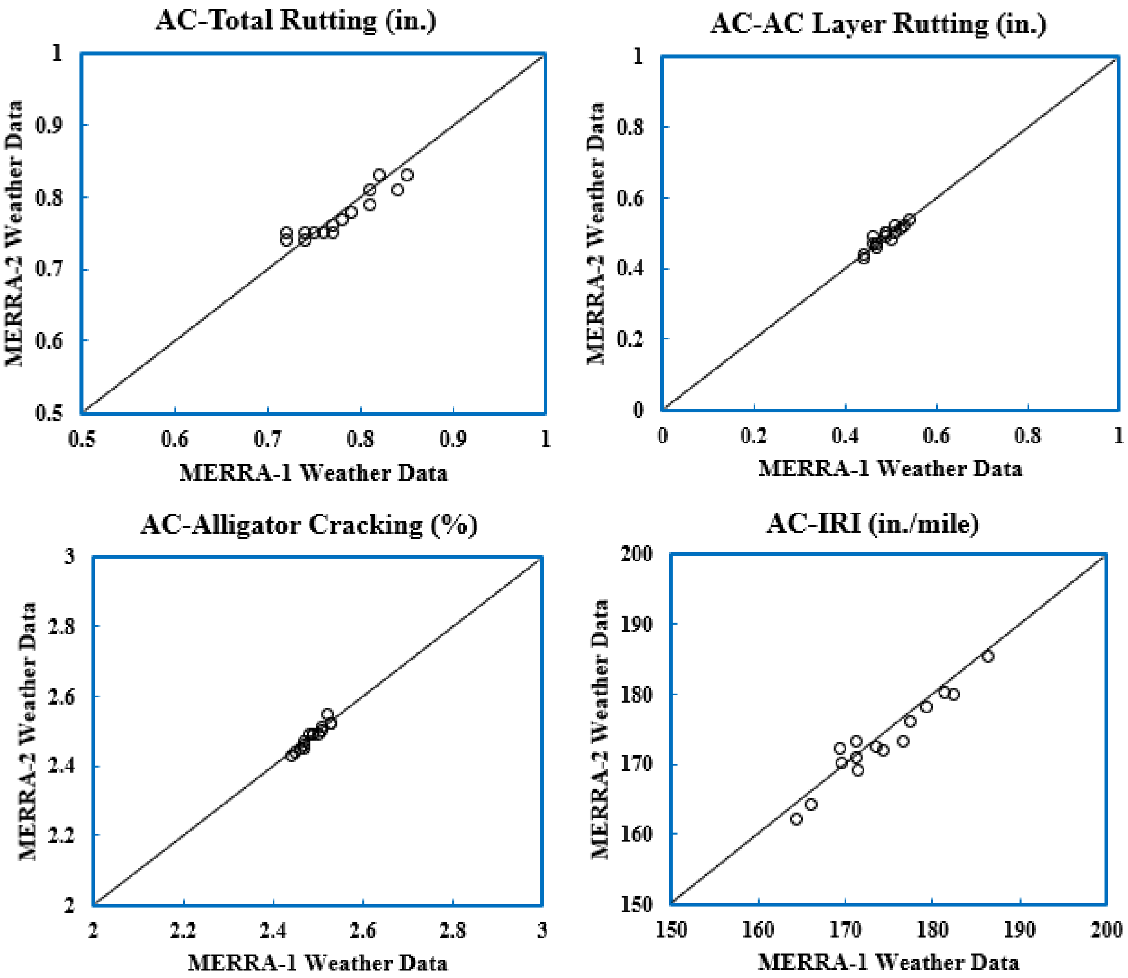


FIGURE 28

Comparisons of Pavement ME Design Asphalt Concrete Predictions for MERRA-1 vs MERRA-2 Weather Data Using Back-calculated Synthetic Percent Sunshine

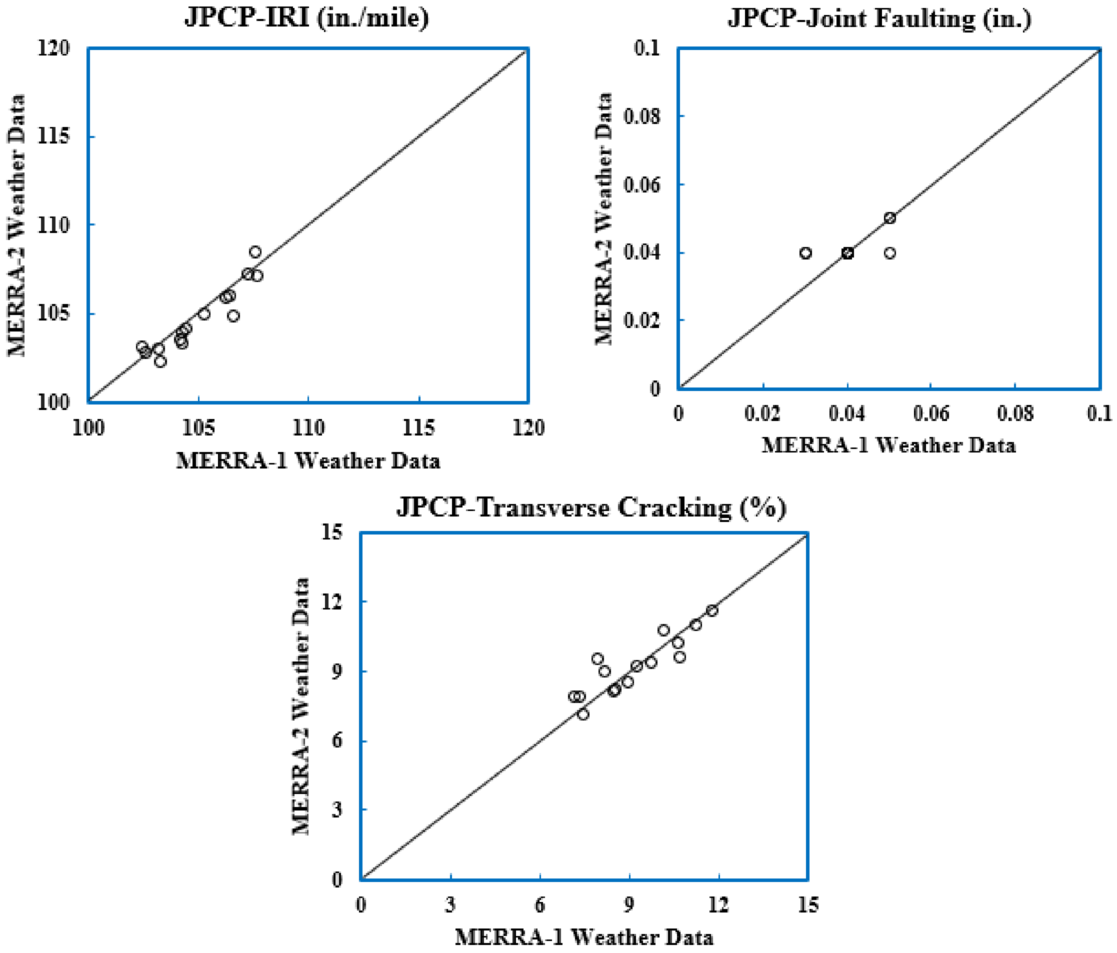


FIGURE 29

Comparisons of Pavement JPCP Predictions for MERRA-1 vs MERRA-2 Weather Data Using Back-calculated Synthetic Percent Sunshine

6. CONCLUSIONS

The main focus of this study was to evaluate various climate data sources that have been identified for use as inputs to the AASHTOWare Pavement ME Design software. Overall, the four-way comparisons of the pavement distresses for both flexible and rigid pavements showed that pavement performance predictions using the MERRA-2 climate data resulted in higher distresses compared to those predicted with other climate data sources.

The diurnal variations of percent sunshine from the four climate data sources showed substantial and non-systematic differences. This is significant, as percent sunshine was found in previous studies to have a significant impact on pavement performance as predicted by Pavement ME Design. The agreement between the MERRA-1 and the MERRA-2 percent sunshine data was particularly poor, which is the likely reason for the differences in predicted pavement performance using these two climate data sources.

The physics-based models for the direct prediction of surface shortwave radiation that the MERRA-1 and MERRA-2 climate reanalysis products incorporate are independent of the predicted cloud cover. Comparisons of the MERRA-1 and MERRA-2 SSR predictions against “ground truth” measurements from the U.S. Climate Reference Network were very good, validating the accuracy of the MERRA-1 and MERRA-2 SSR prediction models.

In order to use the MERRA-1 and MERRA-2 SSR values to drive the environmental calculations, it was necessary to “trick” the Pavement ME Design software. The empirical relationship between SSR and percent sunshine (see Eq. 1) was inverted to back calculate synthetic percent sunshine data that were consistent with the MERRA-1 and MERRA-2 SSR values. These back-calculated synthetic percent sunshine histories were used to replace the percent sunshine values in the climate data files provided with the Pavement ME Design software. Comparisons of predicted pavement performance using MERRA-1 vs. MERRA-2 climate data and their respective synthetic percent sunshine histories showed dramatically improved agreement for both AC and JPCP pavements, with the predictions clustered tightly along their respective lines of equality.

Based on the findings from this study, the authors recommend re-evaluation of the percent sunshine approach currently used in Pavement ME Design. Percent sunshine as obtained from percent cloud cover, whether measured or predicted, is a non-fundamental derived property that is just too imprecise for use in pavement performance modeling. The authors recommend converting to SSR as the direct input to Pavement ME Design for pavement environmental modeling. This recommendation and the need to evaluate the adoption of MERRA as the source for the climate data in the design of both flexible and rigid pavements has been presented to the MEPDG Task Force Group. Further, an analysis should be performed to examine its impact on global calibration factors. The modifications to the Pavement ME Design code necessary to effect this change are trivial.

Percent sunshine is used in the Pavement ME Design environmental modeling for adjusting the net longwave radiation impinging on the pavement. The importance of this longwave radiation and its adjustment for cloud cover was not investigated in this study. The authors recommend future work to examine this topic.

REFERENCES

AASHTO (2015). *Mechanistic-Empirical Pavement Design Guide: A manual of Practice, 2nd Edition.*

Andrey, J., Hambly, D., Mills, B., and Afrin, S. (2013). “Insights into Driver Adaptation to Inclement Weather in Canada.” *Journal of Transport Geography*, 28(0), 192–203.

Ankit, G., Kumar, P., and Rastogi, R. (2011). “Effect of Environmental Factors on Flexible Pavement Peformance Modeling.” *8th International Conference on Managing Pavement Assets*, (3).

Baker, D.G. and Haines, D.A., (1969).Solar radiation and sunshine duration relationships in the north-central region and Alaska. Tech. Bull. 262, MN, 24 pp.

Bell, J. E., Palecki, M. A., Baker, C. B., Collins, W. G., Lawrimore, J. H., Leeper, R. D., Hall, M. E., Kochendorfer, J., Meyers, T. P., Wilson, T., and Diamond, H. J. (2013). “U.S. Climate Reference Network Soil Moisture and Temperature Observations.” *Journal of Hydrometeorology*, 14(3), 977–988.

Breakah, T., Williams, R., Herzmann, D., and Takle, E. S. (2011). “Effects of Using Accurate Climatic Conditions for Mechanistic-Empirical Pavement Design.” *Journal of Transportation Engineering*, 137(1), 84–90.

Brink, W., Von Quintus, H., and Osborne, L. F. (2016). “Updates to the Hourly Climate Data for Use in Pavement ME.” *Transportation Research Rec*, 1–15.

Bulut, R., Muraleetharan, K., Zaman, M., Yue, E., Soltani, H., and Hossain, Z. (2013). “Evaluation of the Enhanced Integrated Climatic Model for Modulus Based Construction Specification for Oklahoma Pavements.” Oklahoma Department of Transportation, 1–46.

Cetin, B., Schwartz, C. W., Forman, B., Roberts, L., and Gribb, M. M. (2015). “Climate and Groundwater Data to Support Mechanistic-Empirical Design in South Dakota.” South Dakota Department of Transportation, 1–120.

Cetin, B., Forman, B., Schwartz, C. W., Ruppelt, B. (2017). “Performance of Different Climate Data Sources in Mechanistic-Empirical Pavement Distress Analyses.” *Journal of Transportation Engineering.,Part B: Pavements*, 2018, 144 (1)

Daniel, J. S., Jacobs, J. M., Douglas, E., Mallick, R. B., and Hayhoe, K. (2014). “Impact of Climate Change on Pavement Performance: Preliminary Lessons Learned Through the Infrastructure and Climate Network (ICNet).” *Climatic Effects on Pavement and Geotechnical Infrastructure – Proceedings of the International Symposium of Climatic Effects on Pavement and Geotechnical Infrastructure 2013*, 1–9.

Gopisetti, L. S. P. (2017). International Roughness Index Prediction of Flexible and Rigid Pavements Using Climate and Traffic Data. Proquest Dissertations Publishing.

Heitzman, M. (2007). “Evaluation of Iowa Climate Data for the Mechanistic-Empirical Pavement Design Guide.” *Proceedings of the 2007 Mid-Continent Transportation Research Symposium*, (August 2007), 1–5.

Heitzman, M., Timm, D., Takle, G., Herzmann, D., and Truax, D. D. (2011). “Developing MEPDG Climate Data Input Files for Mississippi.” Mississippi Department of Transportation, 1–34.

Heitzman, M., and Wei, G. (2017). “Building Accurate Historic and Future Climate MEPDG Input Files for Louisiana DOTD.” Louisiana Transportation Research Center, 1–2.

Hossain, M. I., Gopisetti, L. S. P., and Miah, M. S. (2017). “Prediction of International Roughness Index of Flexible Pavements from Climate and Traffic Data Using Artificial Neural Network Modeling.” *Airfield and Highway Pavements*, 268–278.

Hozayen, H., and Fouad, A. (2015). “Effect of Climate Environmental Conditions on Pavement Overlay Thickness.” *Proceedings of the International Conference on Civil, Structural and Transportation Engineering*, 1–8.

Johanneck, L., and Khazanovich, L. (2010). “Comprehensive Evaluation of Effect of Climate in *Mechanistic-Empirical Pavement Design Guide* Predictions.” *Transportation Research Record: Journal of the Transportation Research Board*, 2170, 45–55.

Li, Q., Mills, L., and McNeil, S. (2011a). “The Implications of Climate Change on Pavement Performance and Design.” Delaware University Transportation Center, 1–123.

Li, Q., Xiao, D. X., Wang, K. C. P., Hall, K. D., and Qiu, Y. (2011b). “*Mechanistic-Empirical Pavement Design Guide* (MEPDG): A Bird’s-eye View.” *Journal of Modern Transportation*, 19(January), 114–133.

Li, R., Schwartz, C. W., and Forman, B. (2013). “Sensitivity of Predicted Pavement Performance to Climate Properties.” *Airfield and Highway Pavement 2013: Sustainable and Efficient Pavements*, 1–12.

Li, R., Schwartz, C. W., Kim, S., and Ceylan, H. (2012). “Local Sensitivity of Mechanistic-Empirical Flexible Pavement Performance Predictions to Unbound Material Property Inputs.” *Geo Congress*, 1495–1504.

Meagher, W., Daniel, J., Jacobs, J., and Linder, E. (2012). “Method for Evaluating Implications of Climate Change for Design and Performance of Flexible Pavements.” *Transportation Research Record: Journal of the Transportation Research Board*, 2305, 111–120.

Mills, B., Tighe, S., Andrey, J., Smith, J., and Huen, K. (2009). “Climate Change Implications for Flexible Pavement Design and Performance in Southern Canada.” *Journal of Transportation Engineering*, 135(10), 773–782.

National Cooperative Highway Research Program. (2004). “Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures.” 1–219.

National Oceanic and Atmospheric Administration. (2000). “Cooperative Observer Program.” *COOP*, http://www.nws.noaa.gov/os/coop/.

Quintero, N. M. (2007). “Validation of the Enhanced Integrated Climatic Model (EICM) for the Ohio SHRP Test Road at U.S. 23.” Proquest Dissertations.

Von Quintus, H., Darter, M., Bhattacharya, B., and Sadasivam, S. (2015). “Implementation of the Mechanistic-Empirical Pavement Design Guide in Georgia.” Georgia Department of Transportation, 1–120.

Rada, G. R., Schwartz, C. W., Witczak, M. W., and Jafroudi, S. (1989). “Analysis of Climate Effects on Performance of Unpaved Roads.” *Journal of Transportation Engineering*, 115(4), 389–410.

Richter, C. A. (2006). “Long-Term Pavement Performance Program Seasonal Variations in the Moduli of Unbound Pavement Layers.” Federal Highway Administration, 1–283.

Schwartz, C. W., Elkens, G. E., Li, R., Visintine, B. A., Forman, B. A., Rada, G. R., and Groeger, J. L. (2015). “Evaluation of LTPP Climatic Data for Use in Mechanistic-Empirical Pavement Design Guide Calibration and Other Pavement Analysis.” Federal Highway Administration, (May), 1–126.

Schwartz, C. W., Li, R., Kim, S., Ceylan, H., and Gopalakrishnan, K. (2011). “Sensitivity Evaluation of MEPDG Performance Prediction.” Transportation Research Board of the National Academies, 1–505.

Tarefder, R., and Rodriguez-Ruiz, J. (2013). “Local Calibration of MEPDG for Flexible Pavements in New Mexico.” *Journal of Transportation Engineering*, 139(October), 981–991.

Walker, C. L., and Anderson, M. R. (2016). “Cloud Impacts on Pavement Temperature and Shortwave Radiation.” *Journal of Applied Meteorology and Climatology*, 55(11), 2329–2347.

Willway, T., Baldachin, L., Reeves, S., and Harding, M. (2008). “The Effects of Climate Change on Highway Pavements and How to Minimise Them: Technical Report.” Department for Transport, Local Transport Strategy and Funding Division, UK, 1–124.

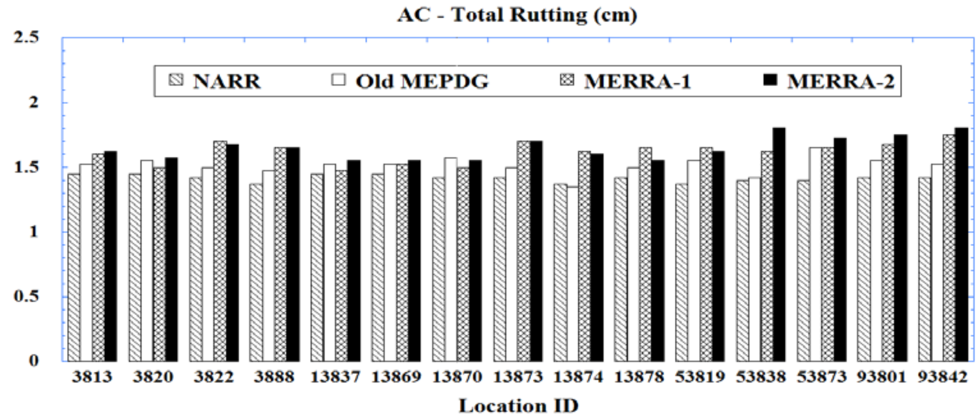
Yang, X., You, Z., Hiller, J., and Watkins, D. W. (2015). “Sensitivity of Flexible Pavement Design to Michigan’s Climatic Inputs Using Pavement ME Design.” *International Journal of Pavement Engineering*, (November), 1–11.

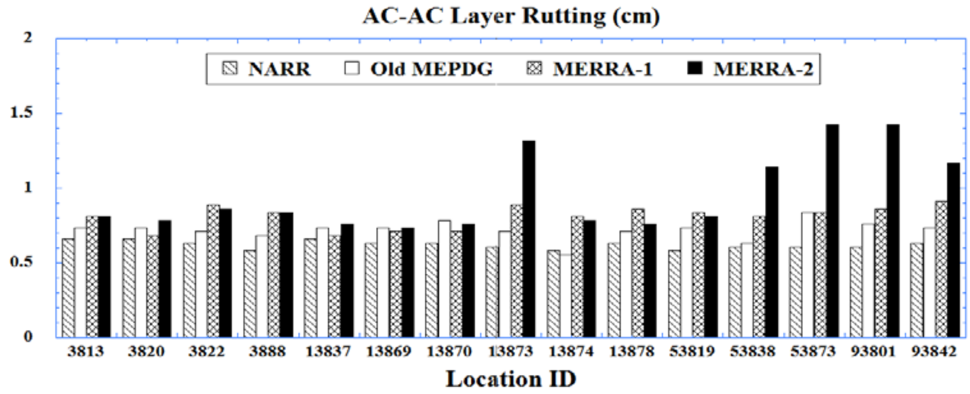
Zaghloul, S., Ayed, A., El Halim, A., Vitillo, N., and Sauber, R. (2006). “Investigations of Environmental and Traffic Impacts on Mechanistic-Empirical Pavement Design Guide Predictions.” *Transportation Research Record: Journal of the Transportation Research Board*, 1967, 148–159.

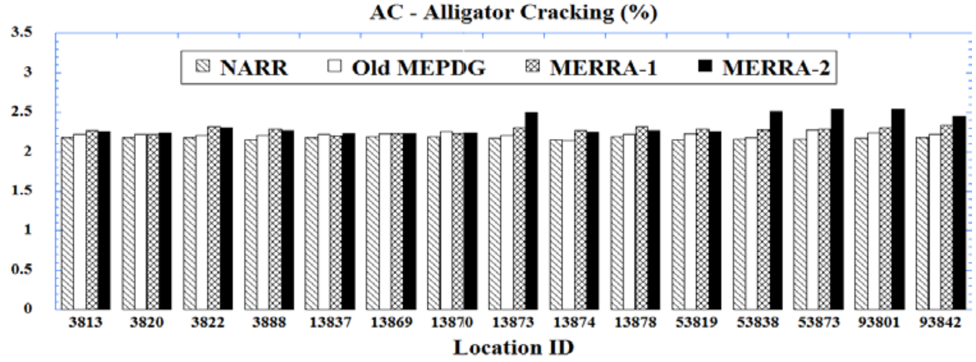
Zapata, C. E., and Houston, W. (2008). “Calibration and Validation of the Enhanced Integrated Climatic Model for Pavement Design.” Transportation Research Board of the National Academies, 1–73.

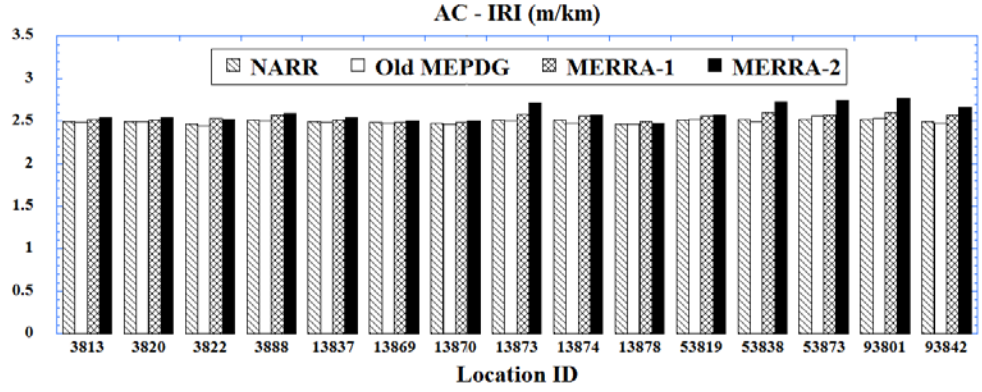
APPENDICES

Appendix A: Comparisons of Pavement ME Asphalt Concrete Predictions Using NARR vs Old MEPDG (GBWS) vs MERRA-1 vs MERRA-2 Weather Data

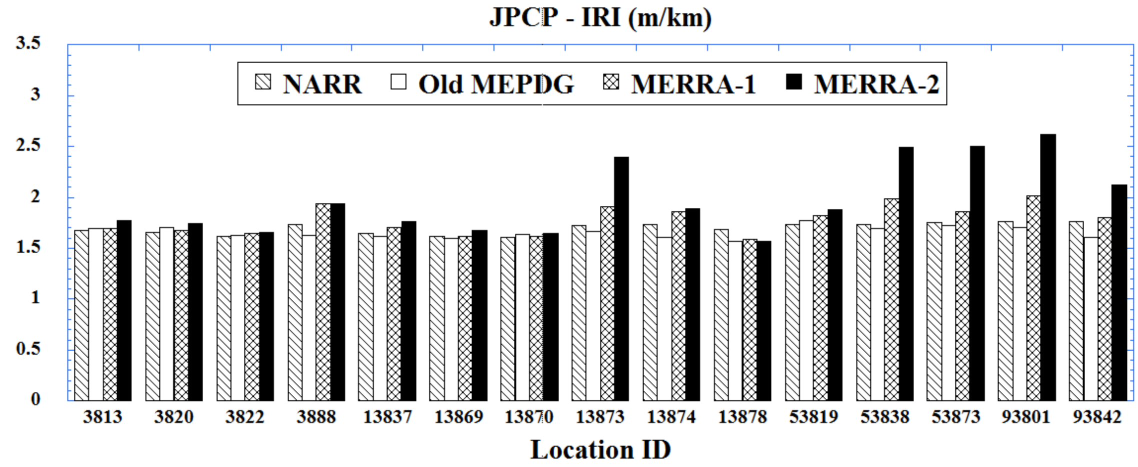


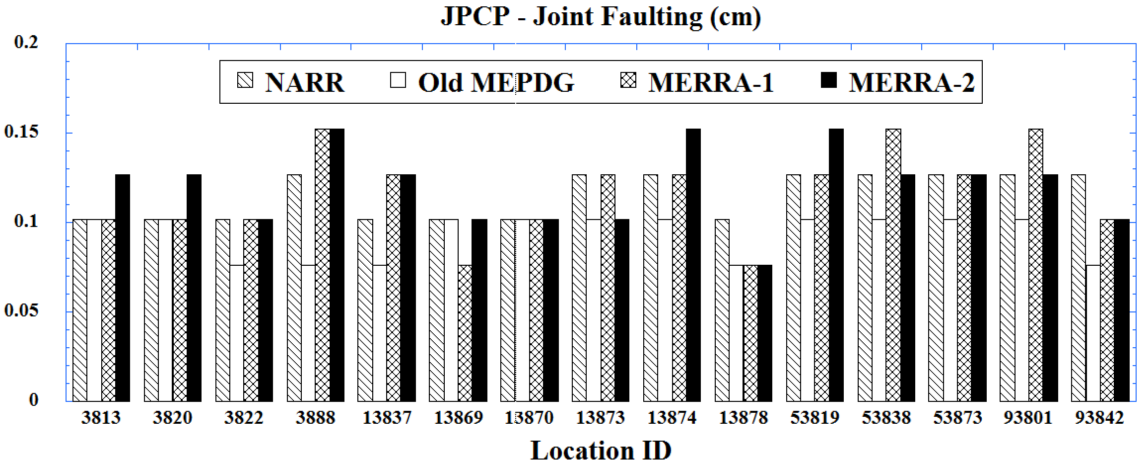


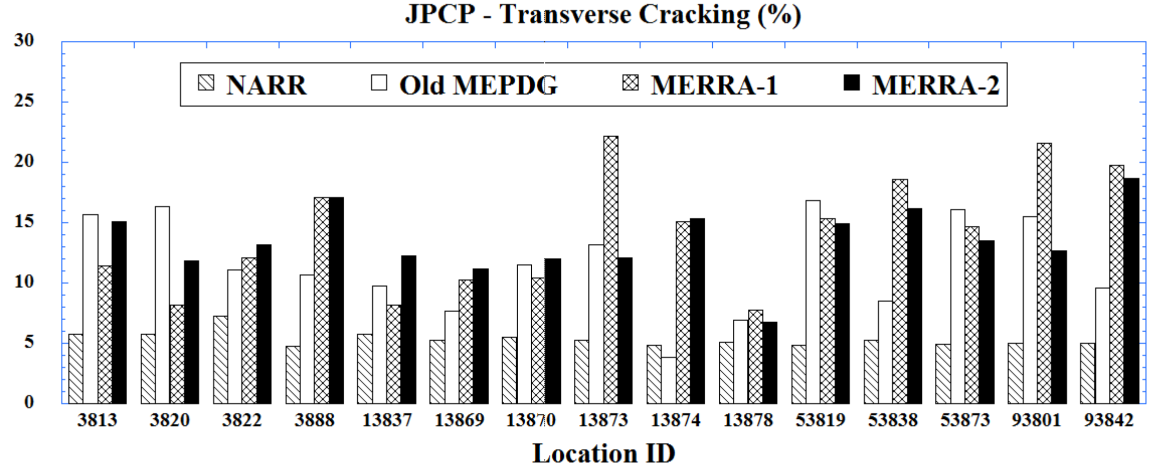




Appendix B: Comparisons of Pavement ME JPCP Predictions Using NARR vs Old MEPDG vs MERRA-1 vs MERRA-2 Weather Data

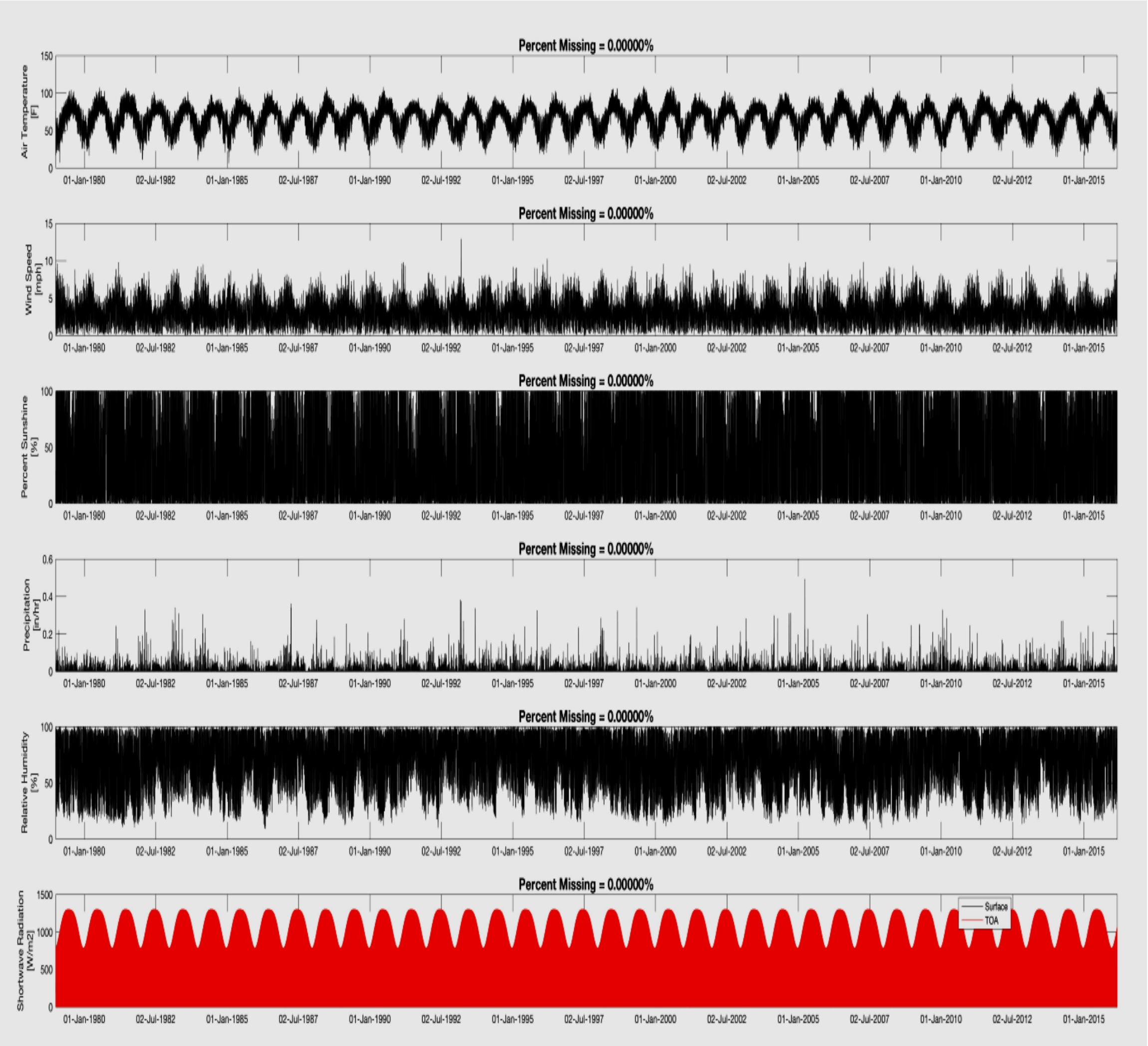




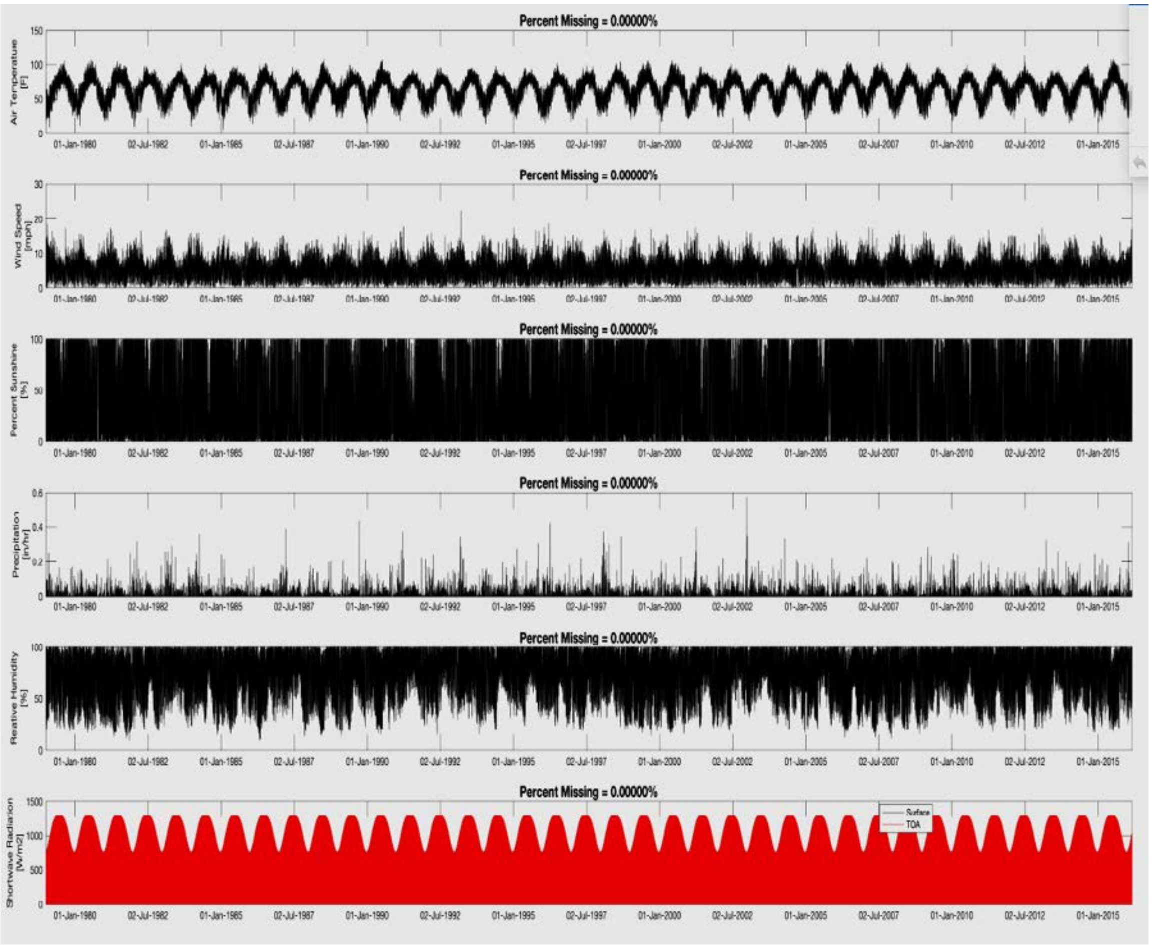


Appendix C: MERRA-1 Climate Data Inputs for All Georgia Locations

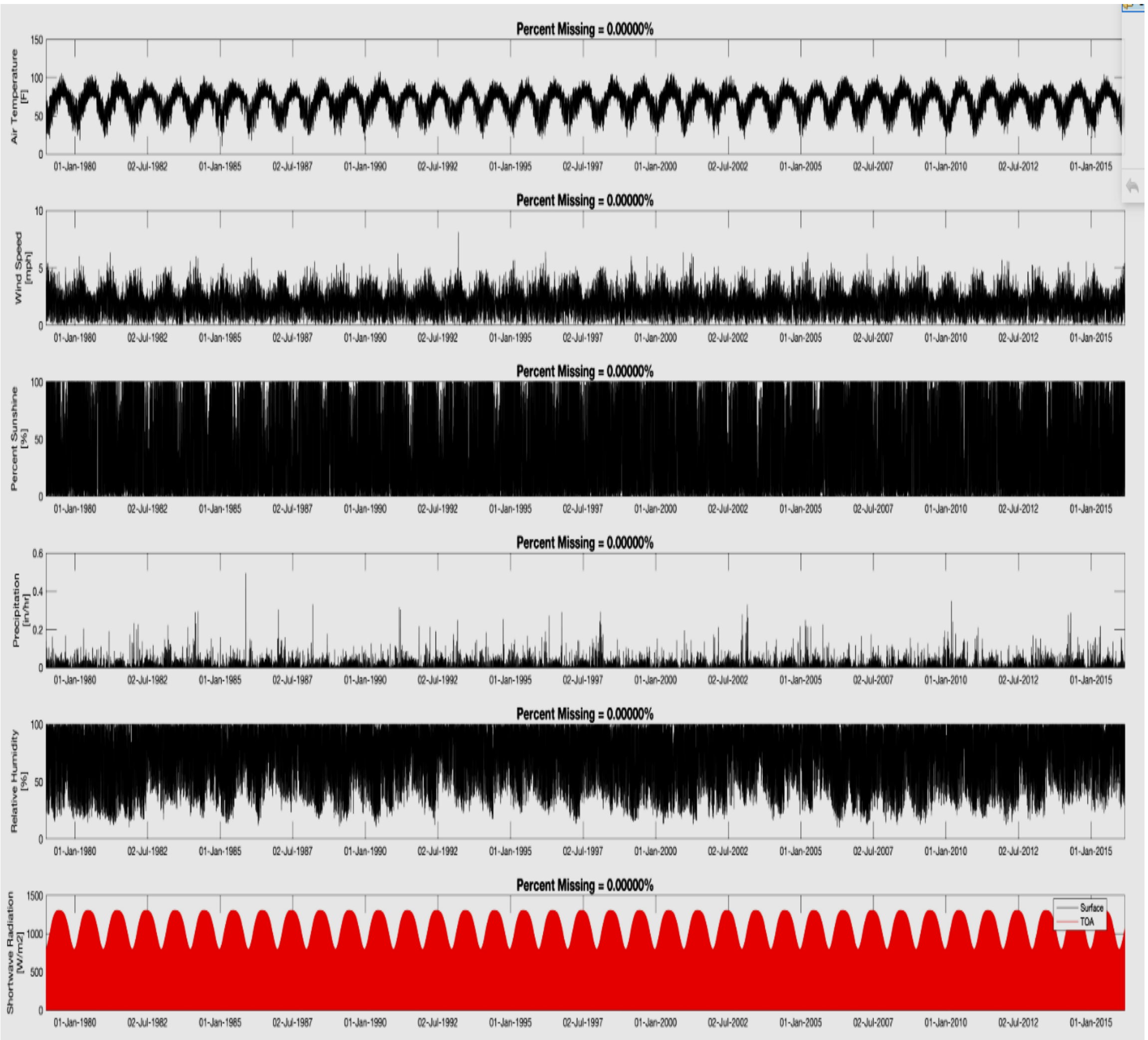
Location ID: 03813



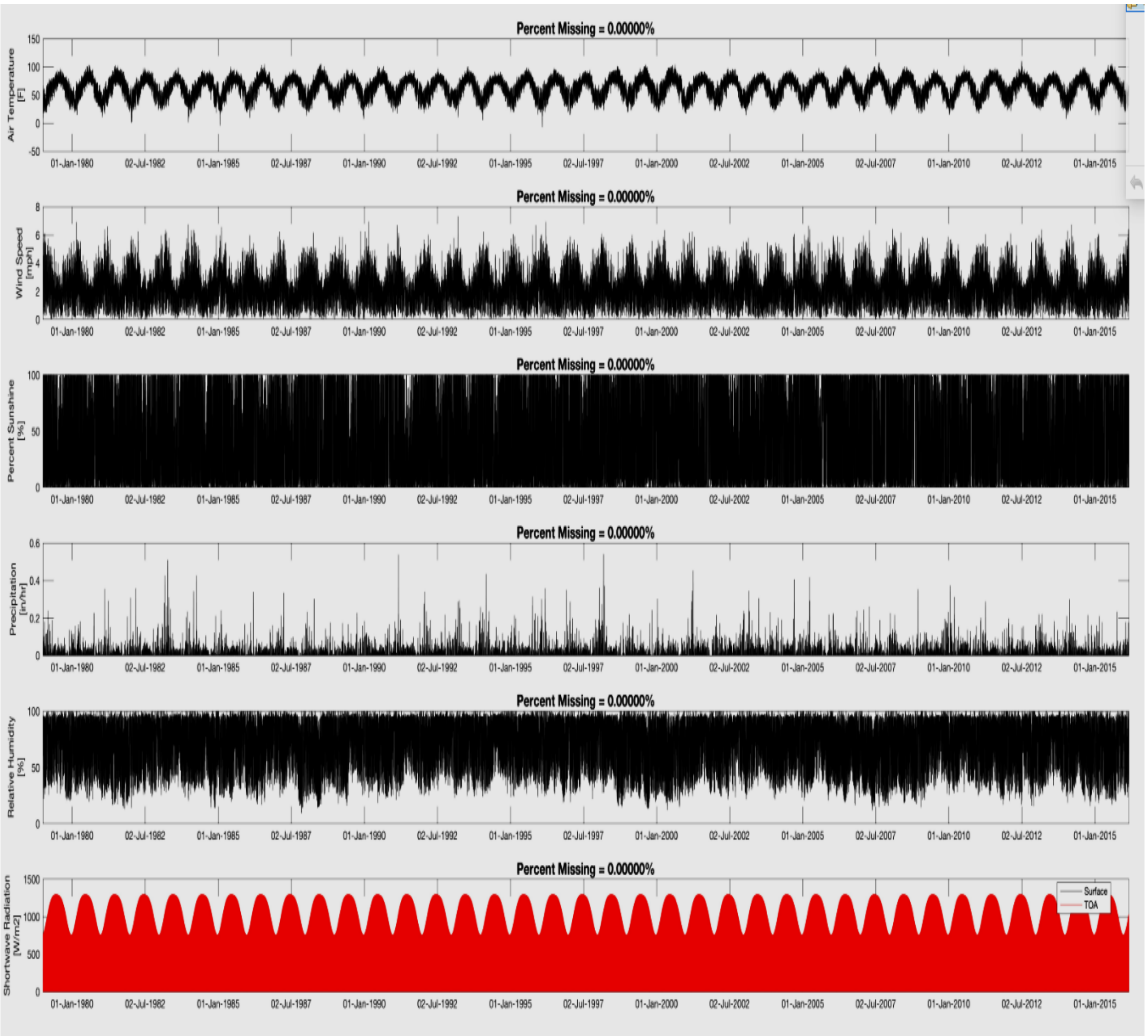
Location ID: 03820



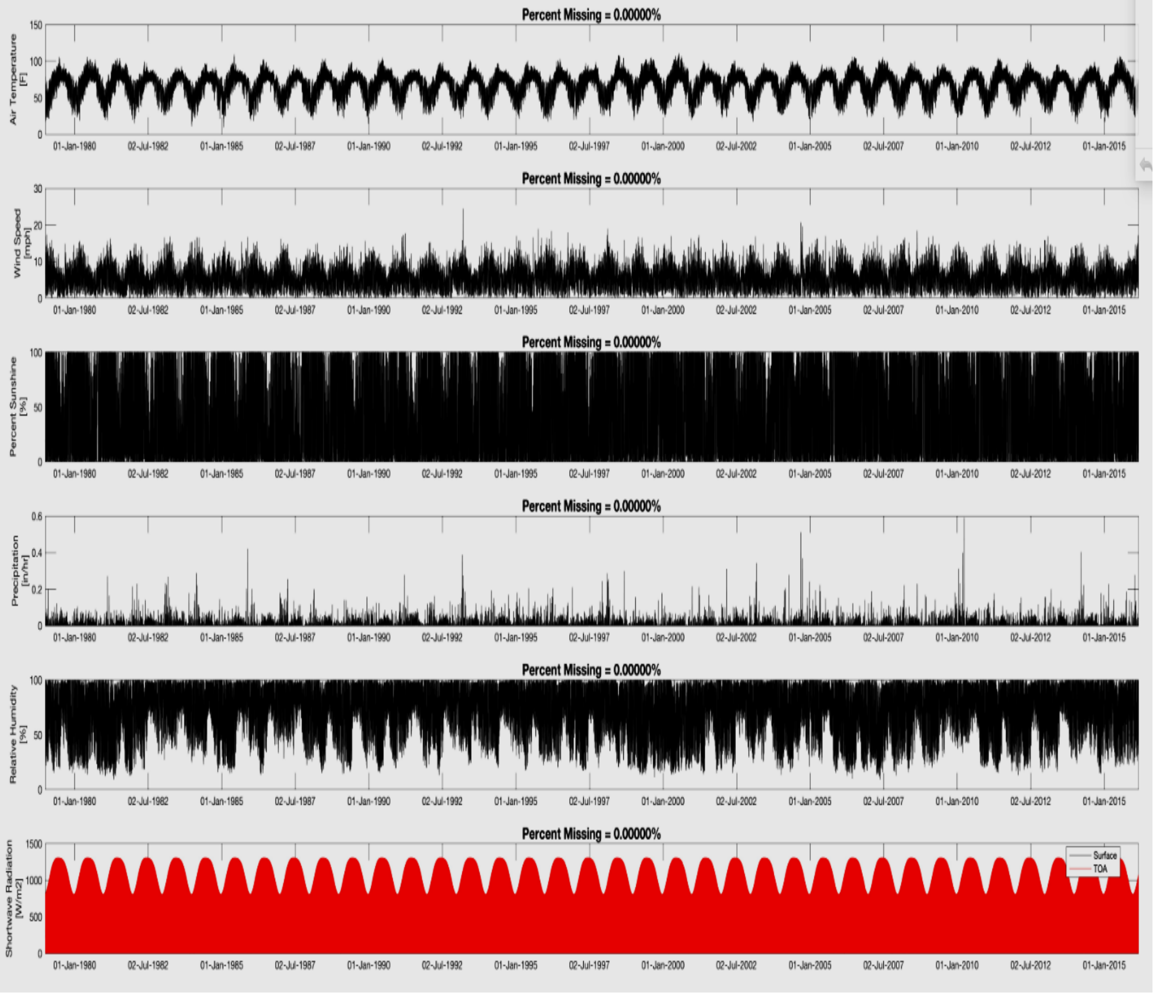
Location ID: 03822



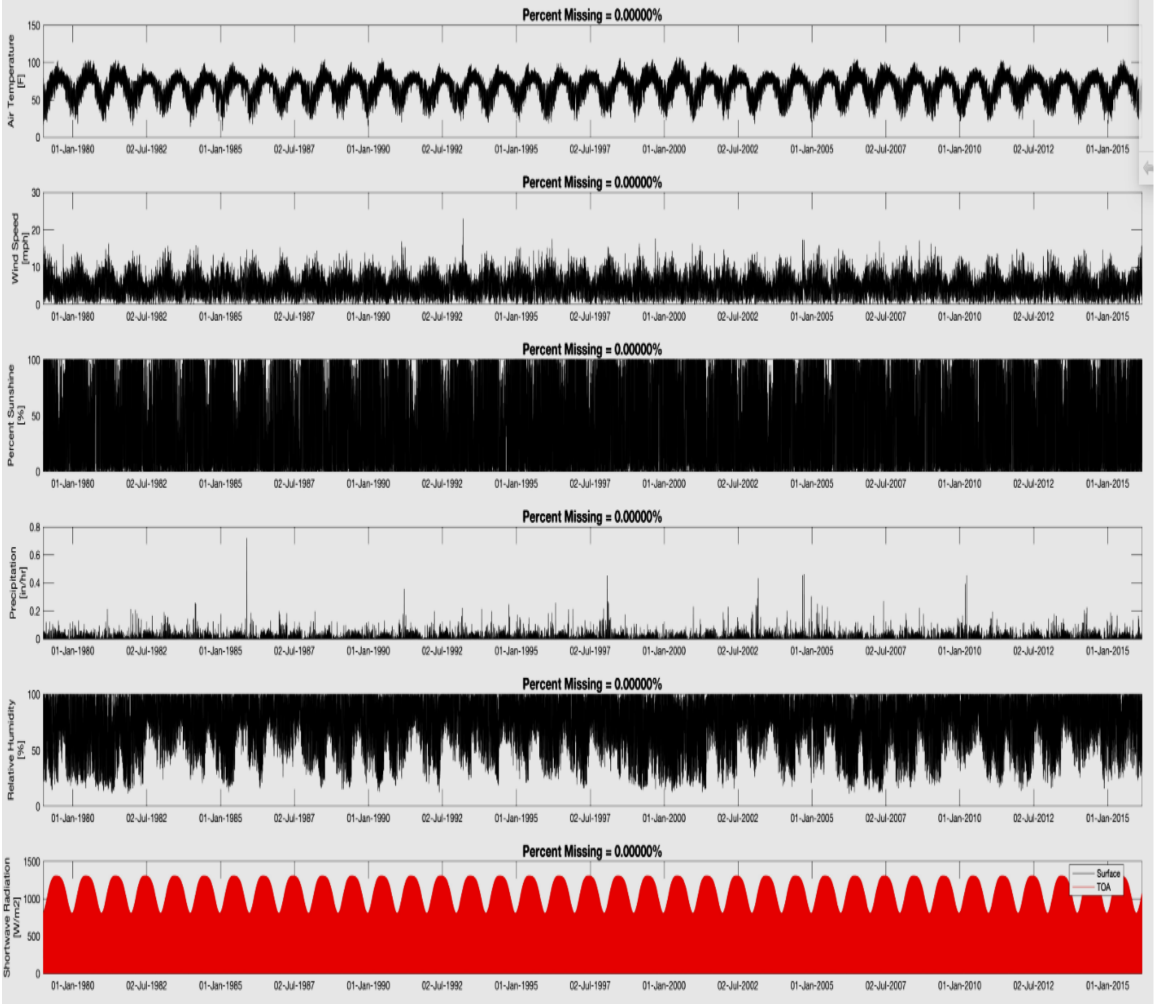
Location ID: 03888



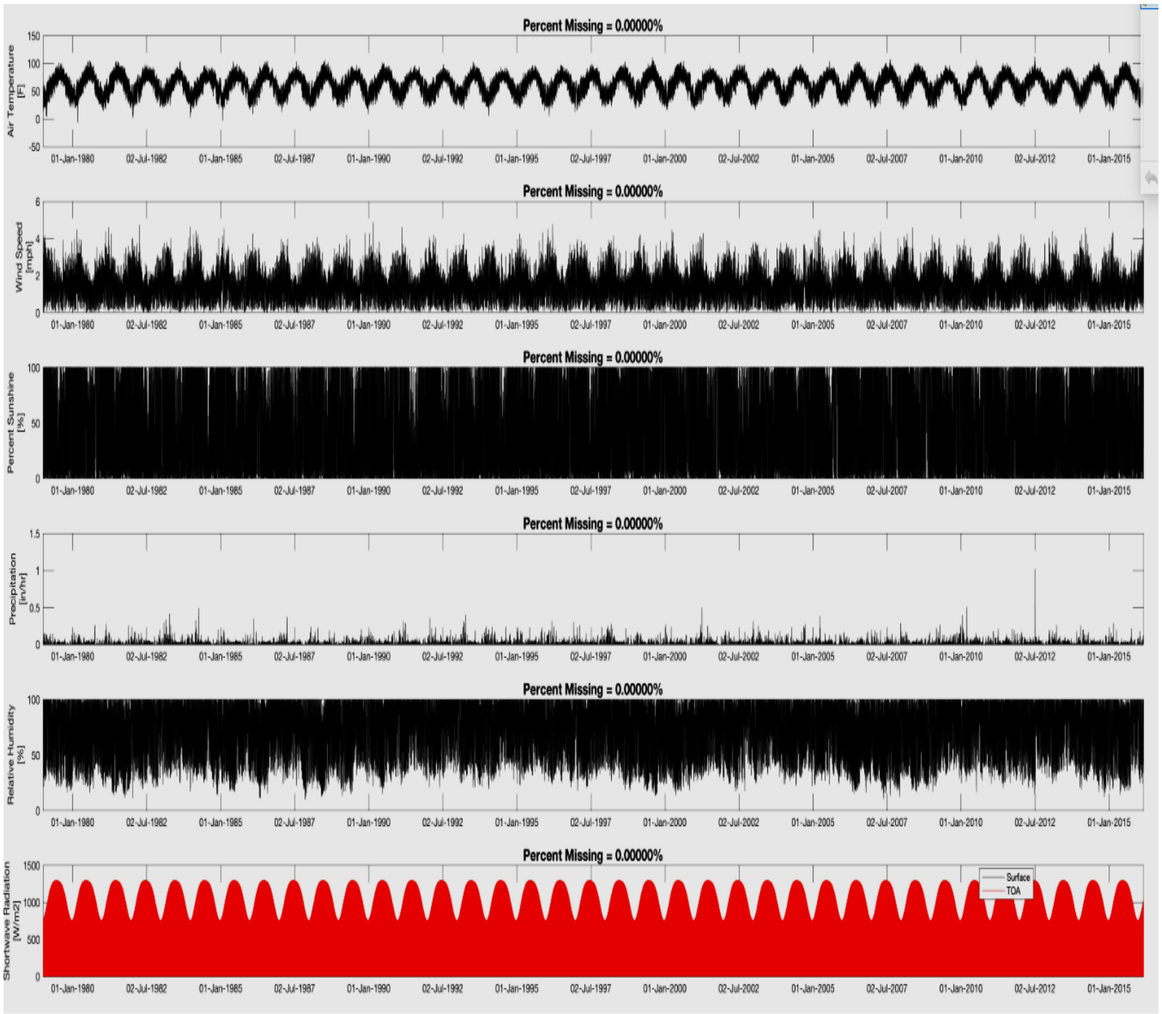
Location ID: 13869



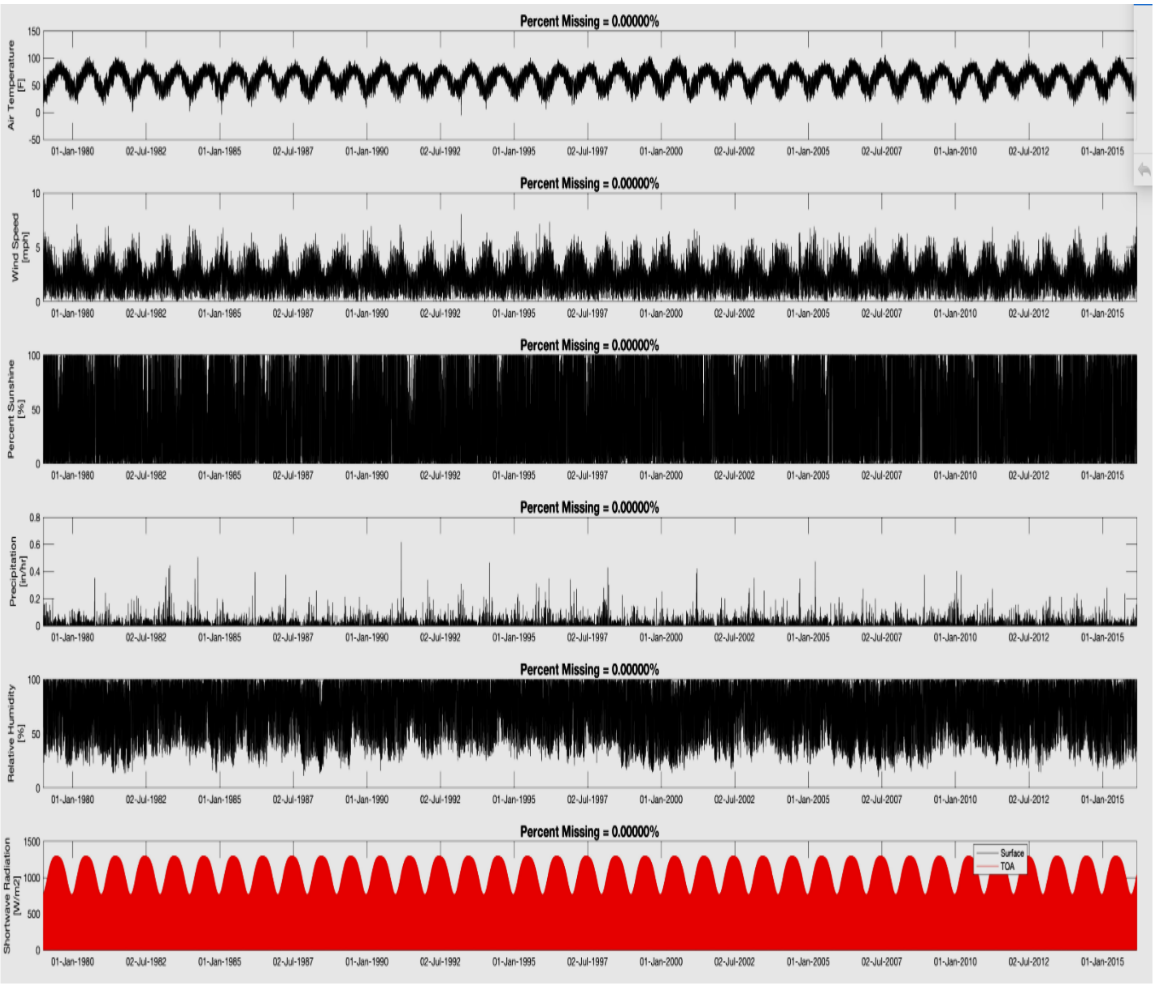
Location ID: 13870



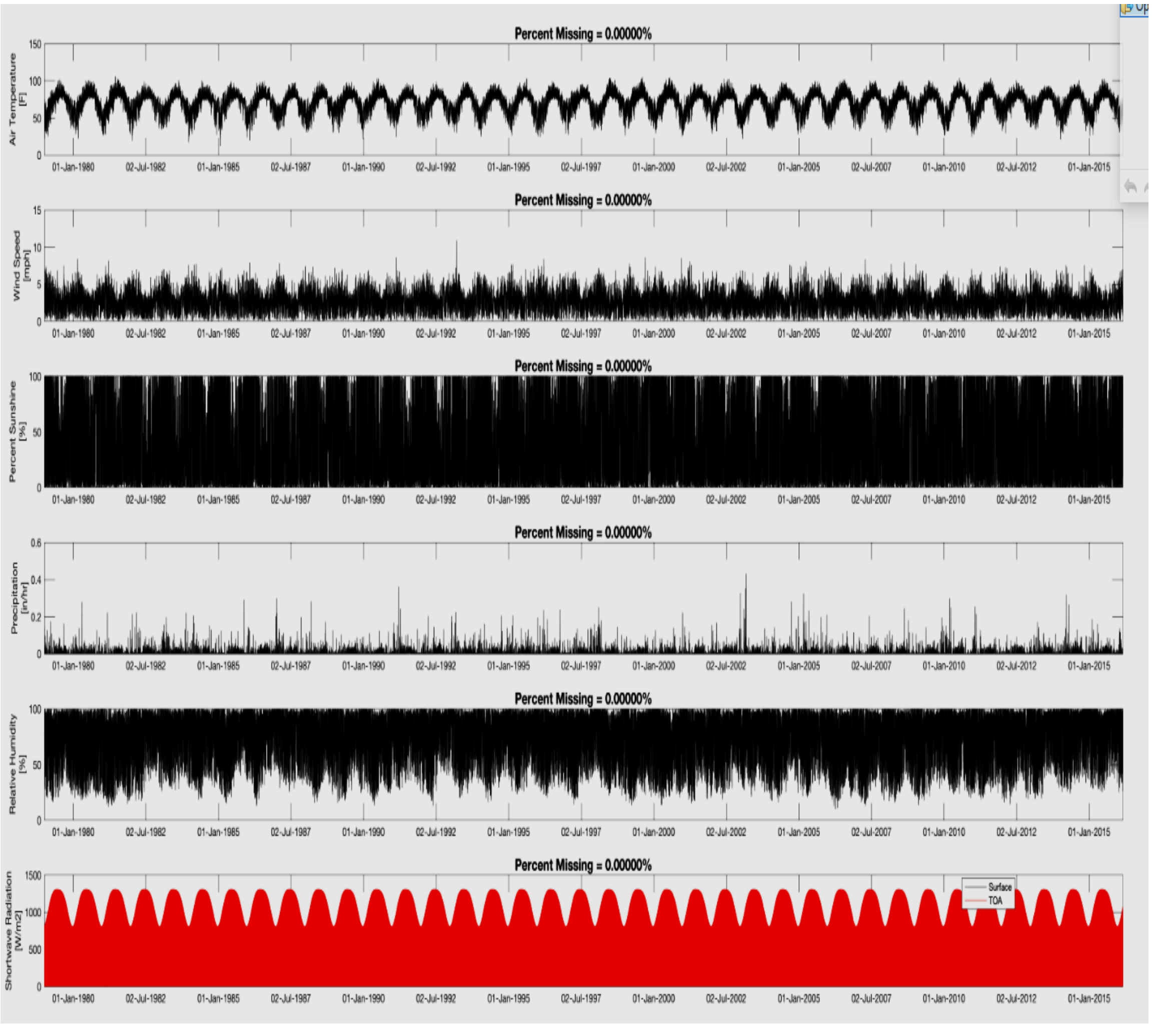
Location ID: 13873



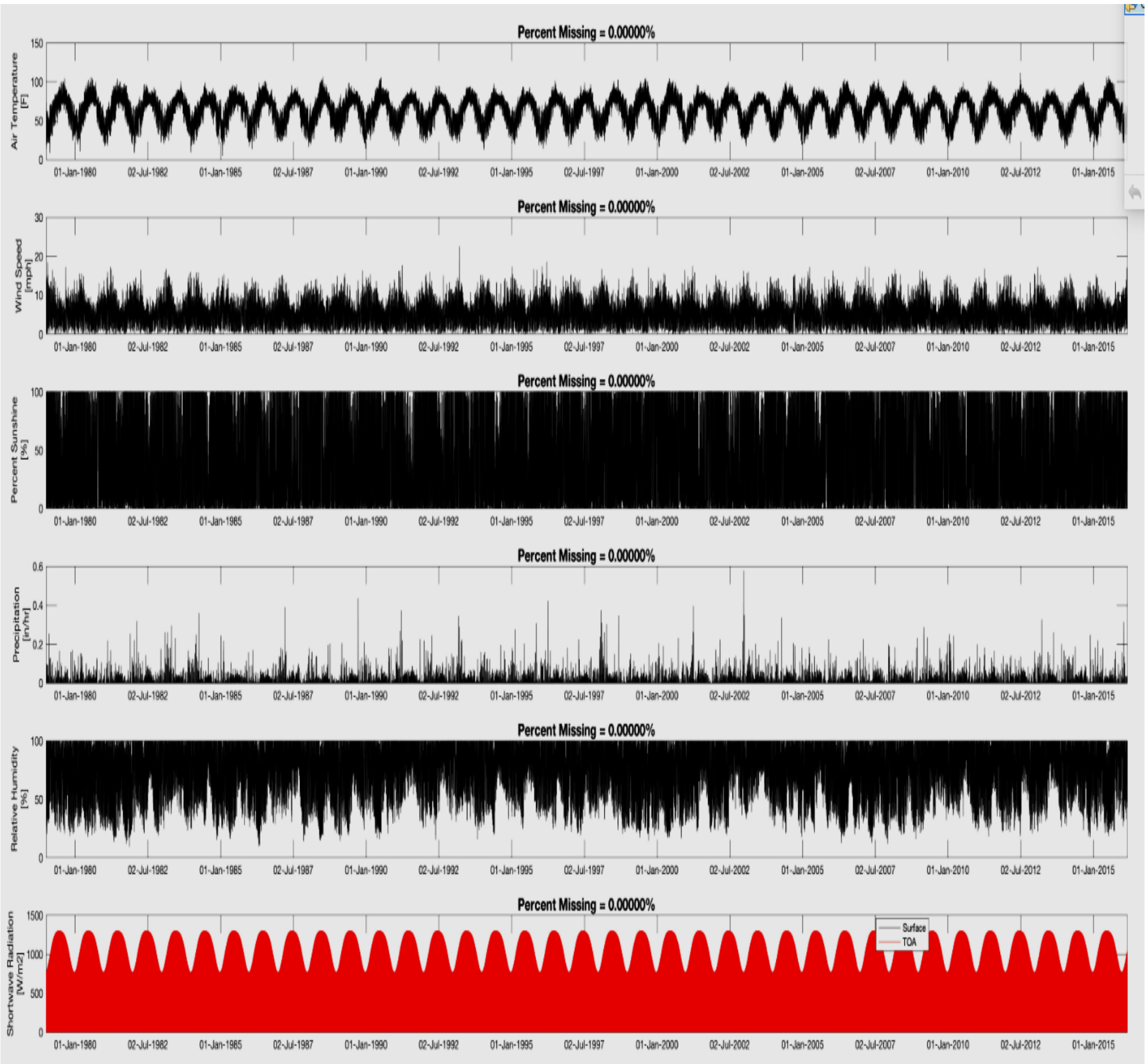
Location ID: 13874



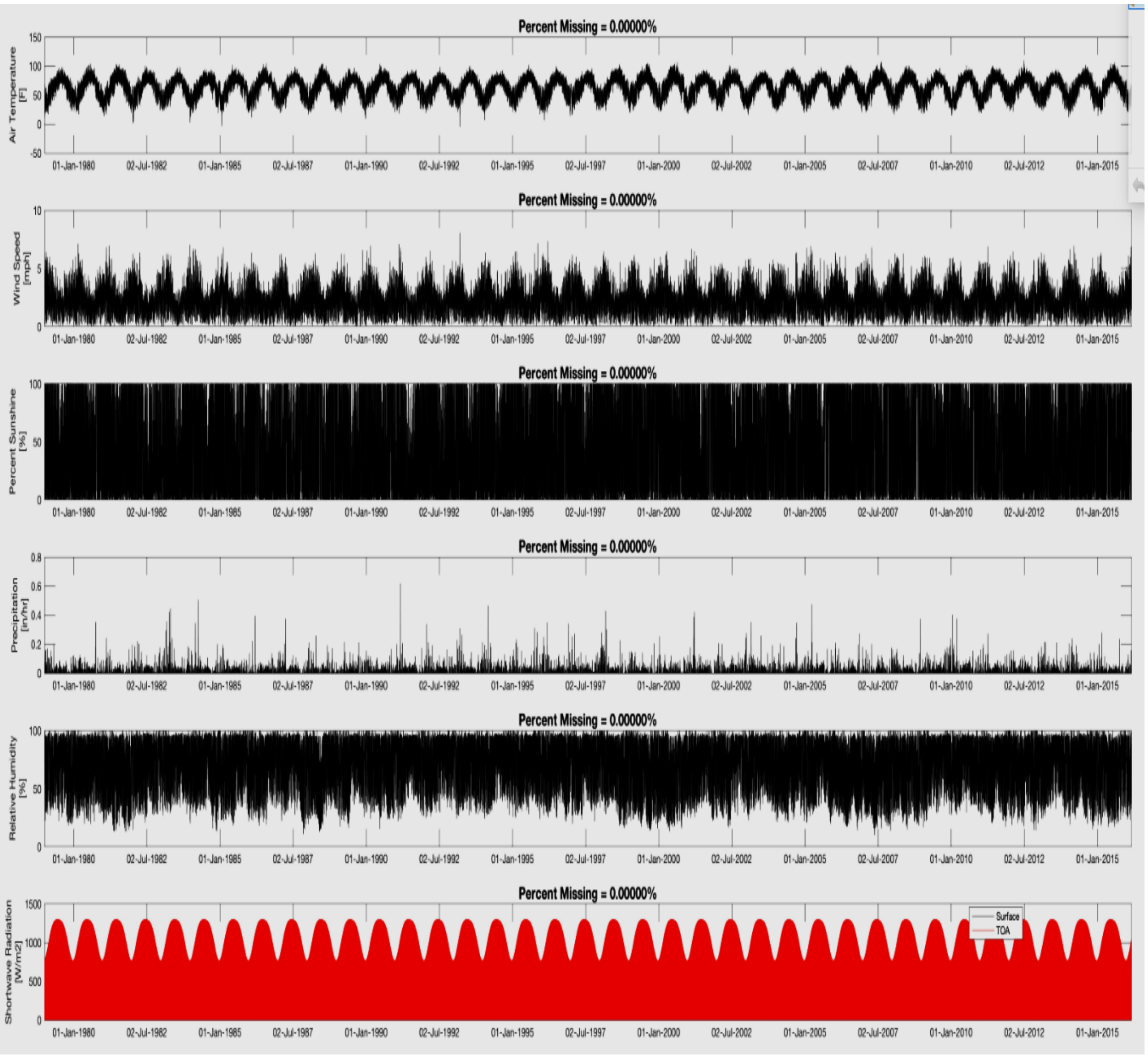
Location ID: 13878



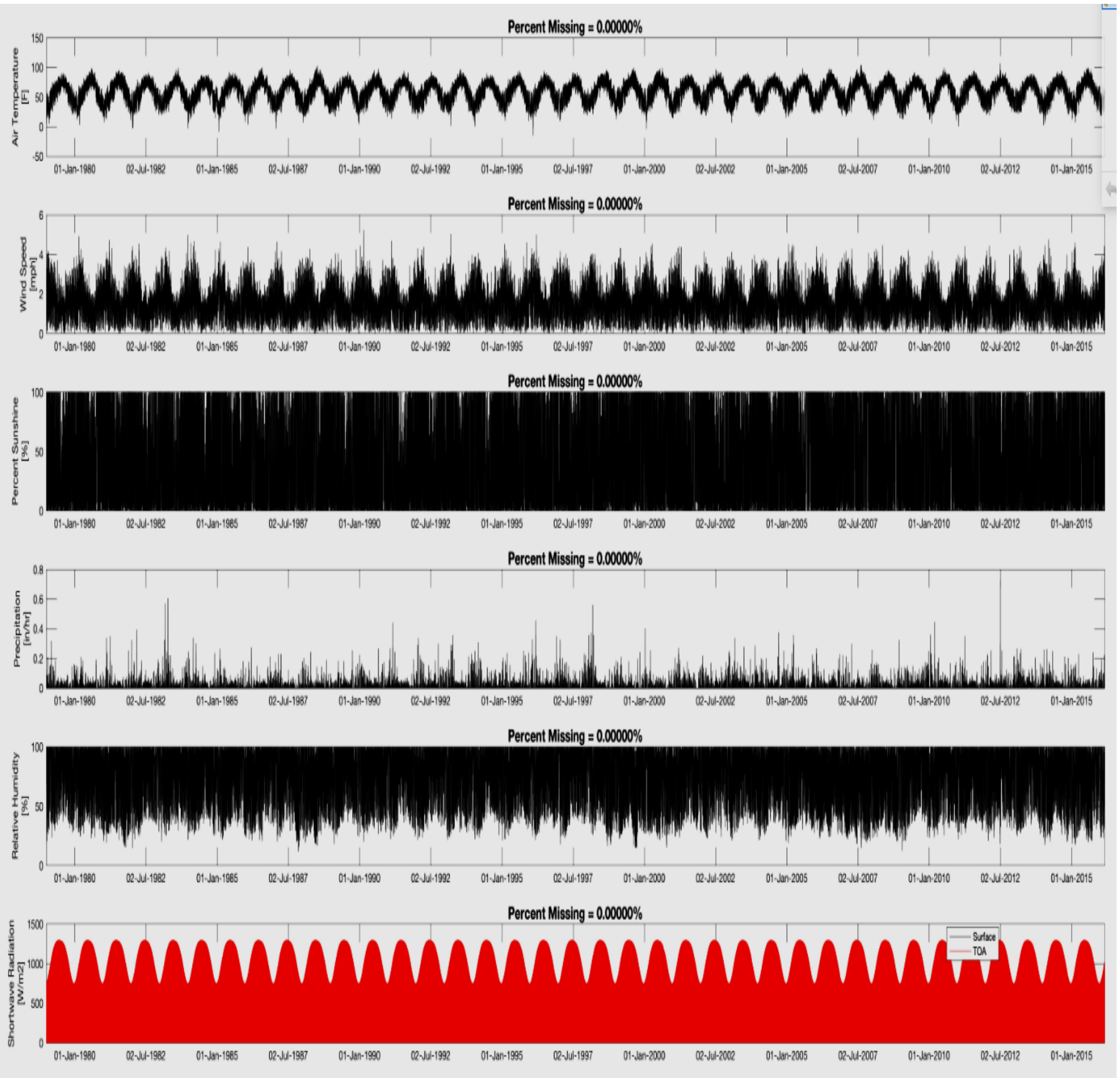
Location ID: 13837



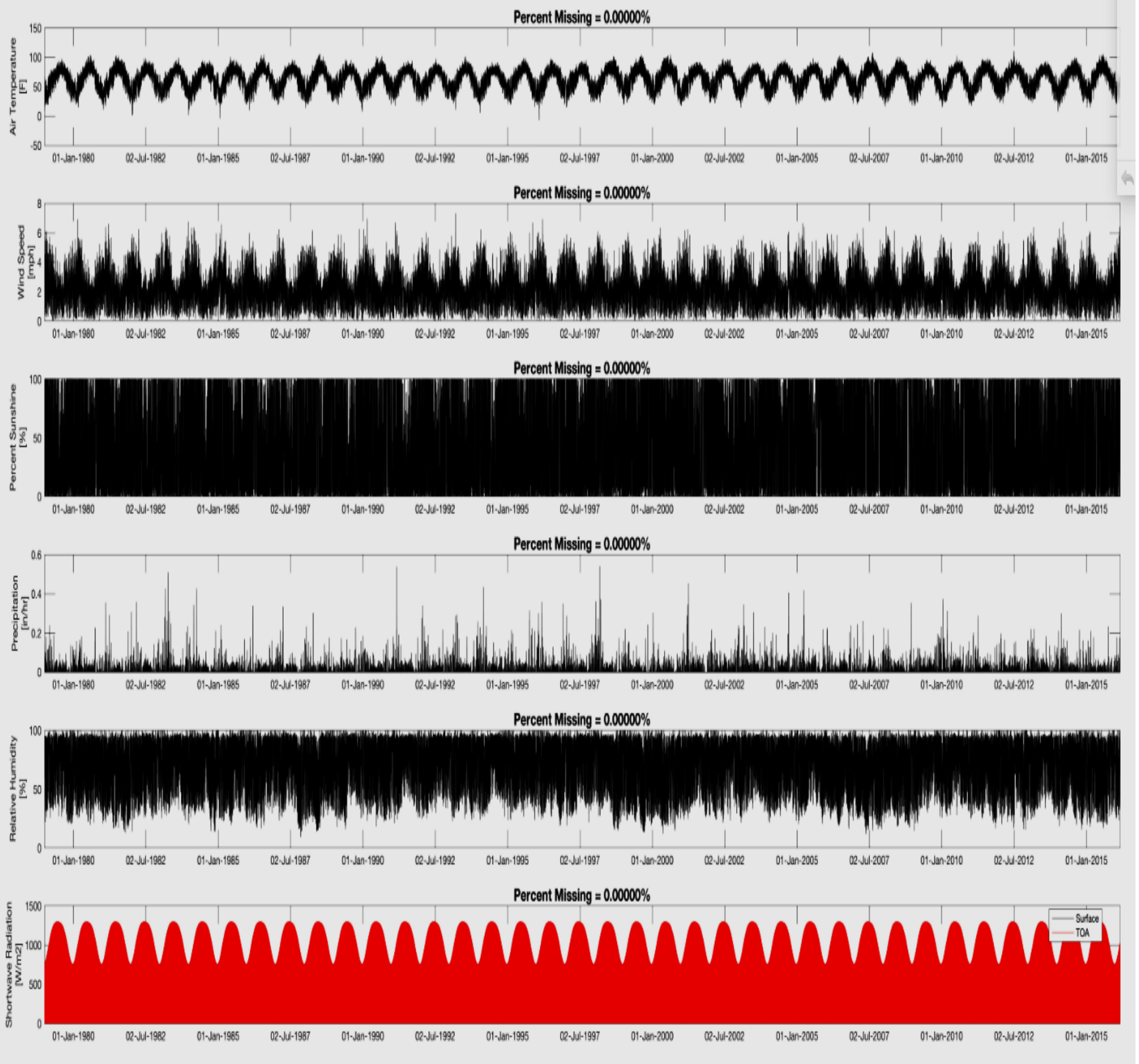
Location ID: 53819



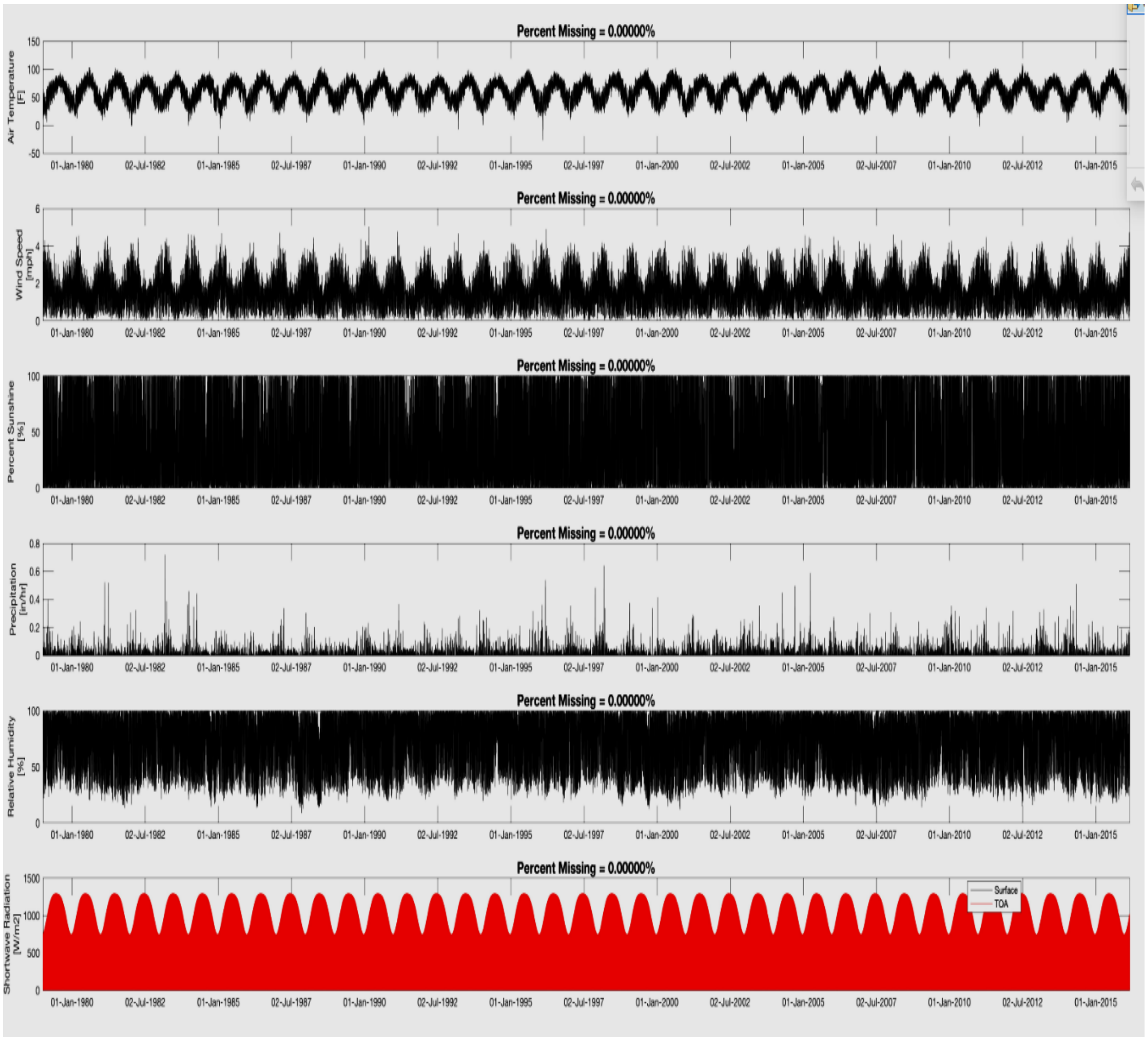
Location ID: 53838



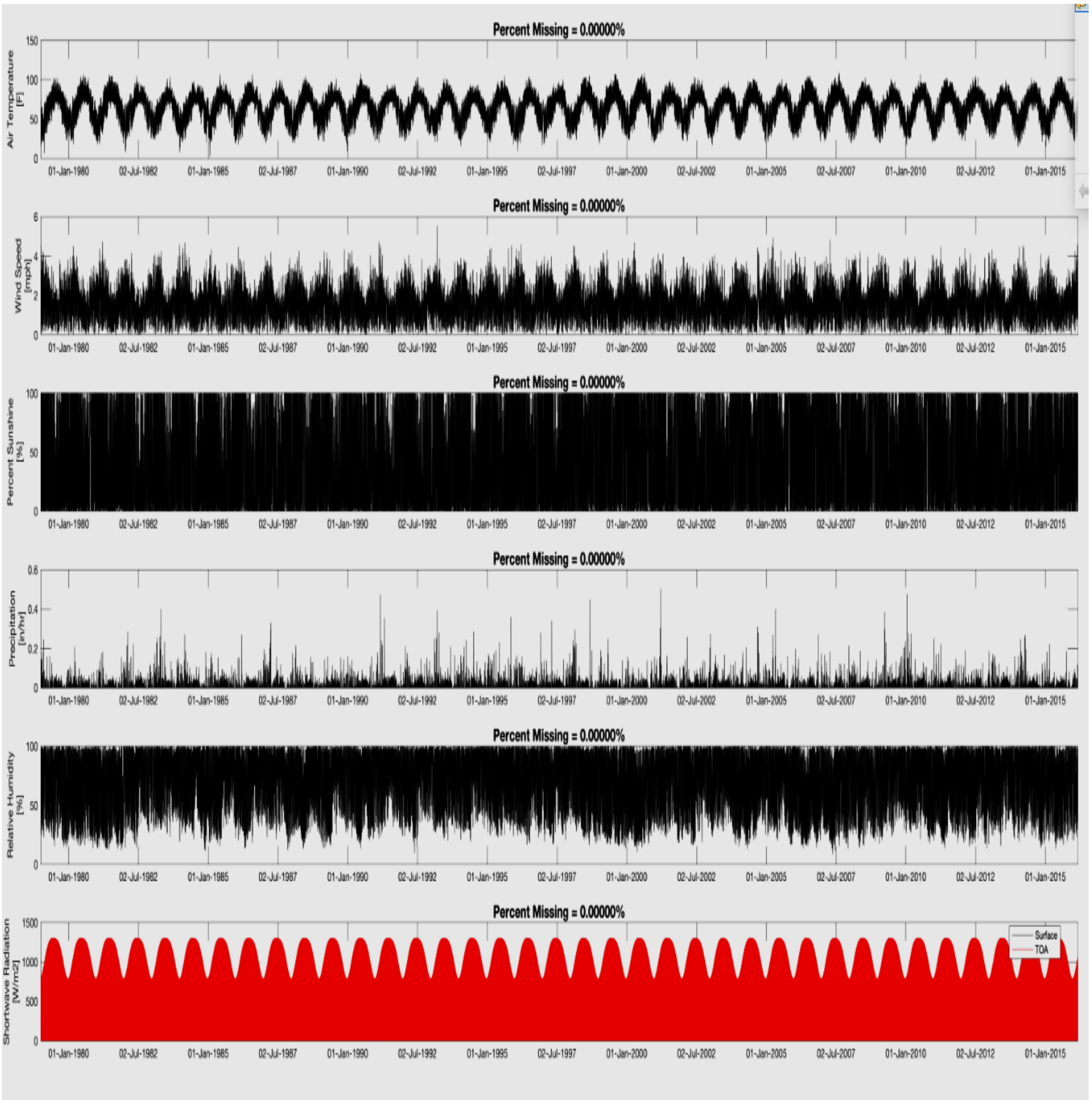
Location ID: 53873



Location ID: 93801

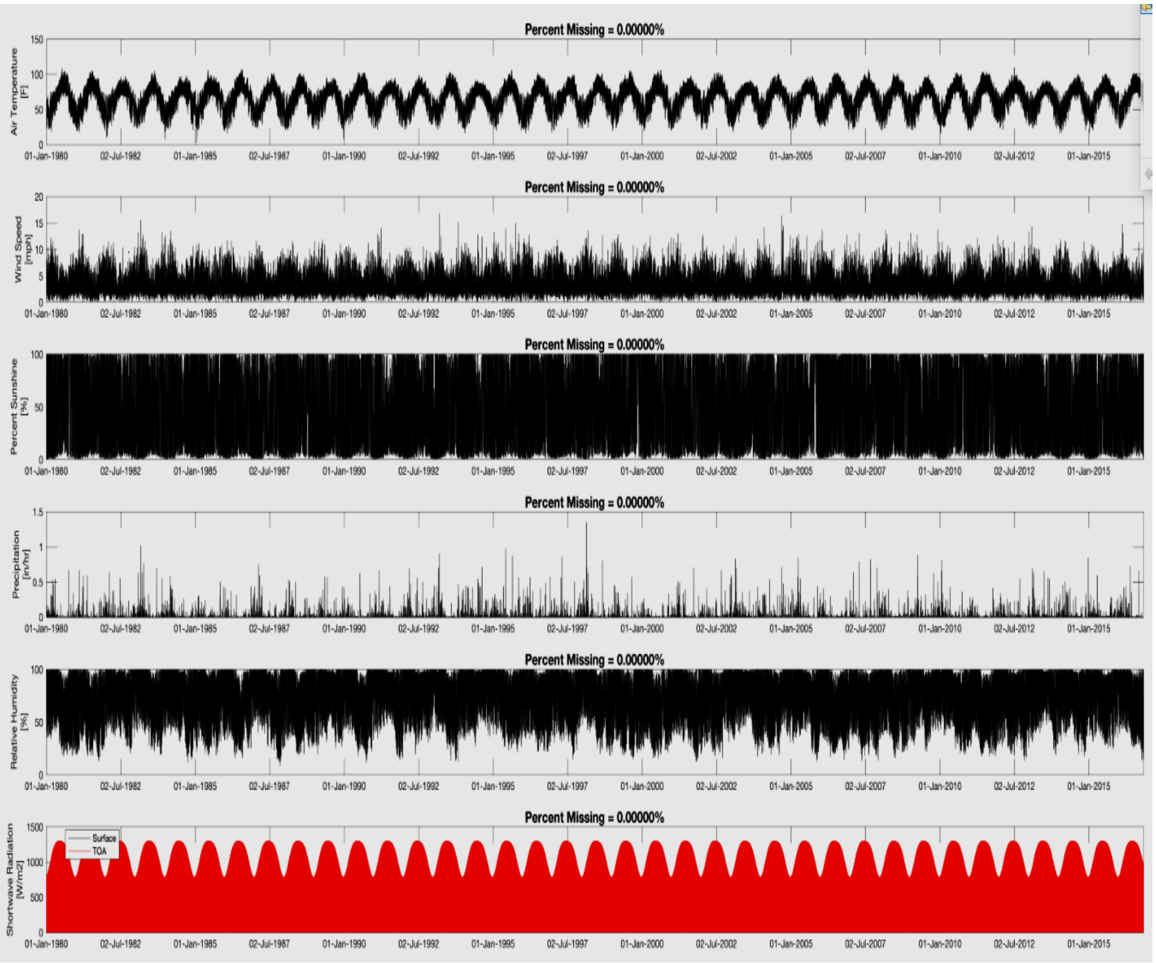


Location ID: 93842

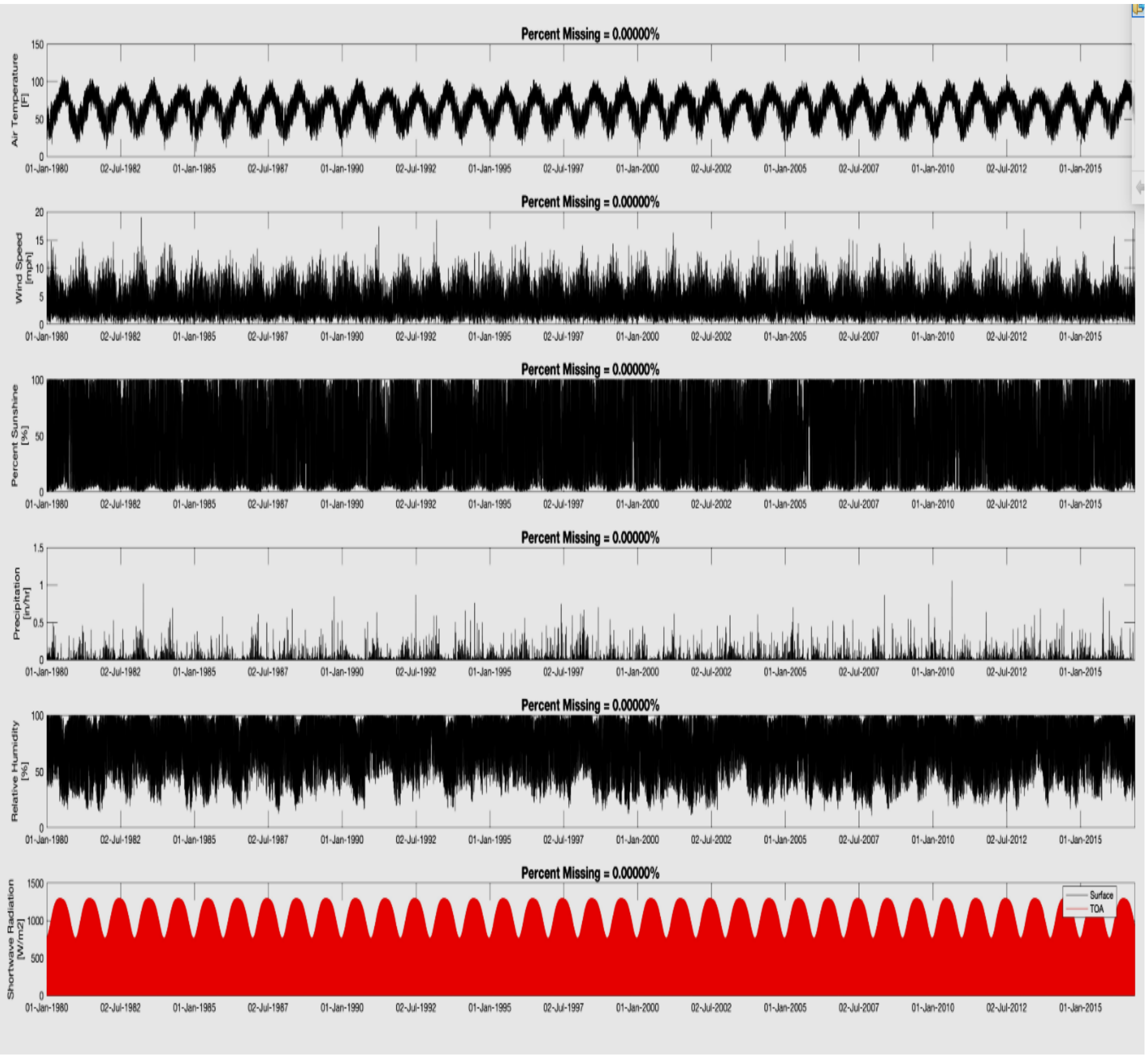


Appendix D: MERRA-2 Climate Data Inputs for All Georgia Locations

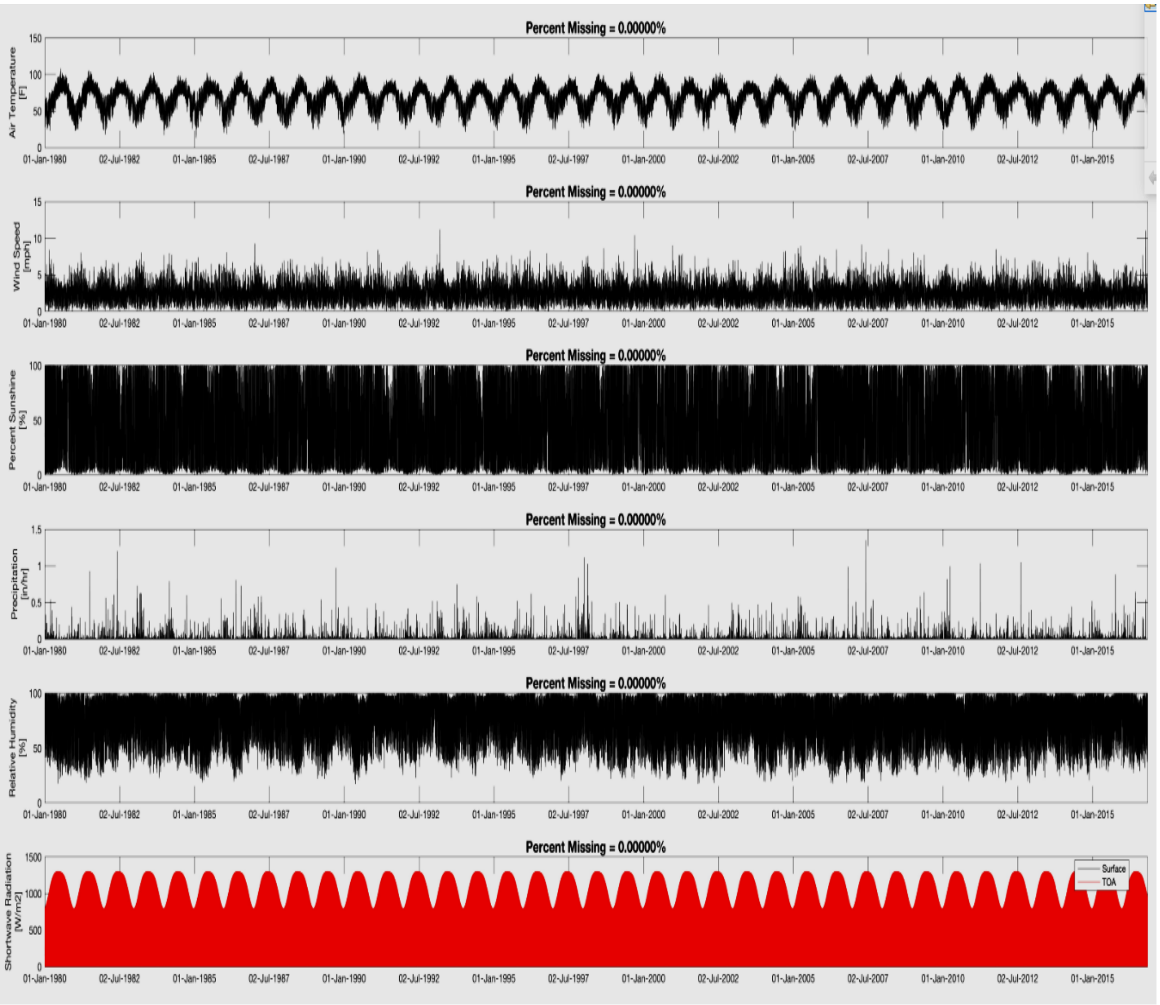
Location ID: 03813



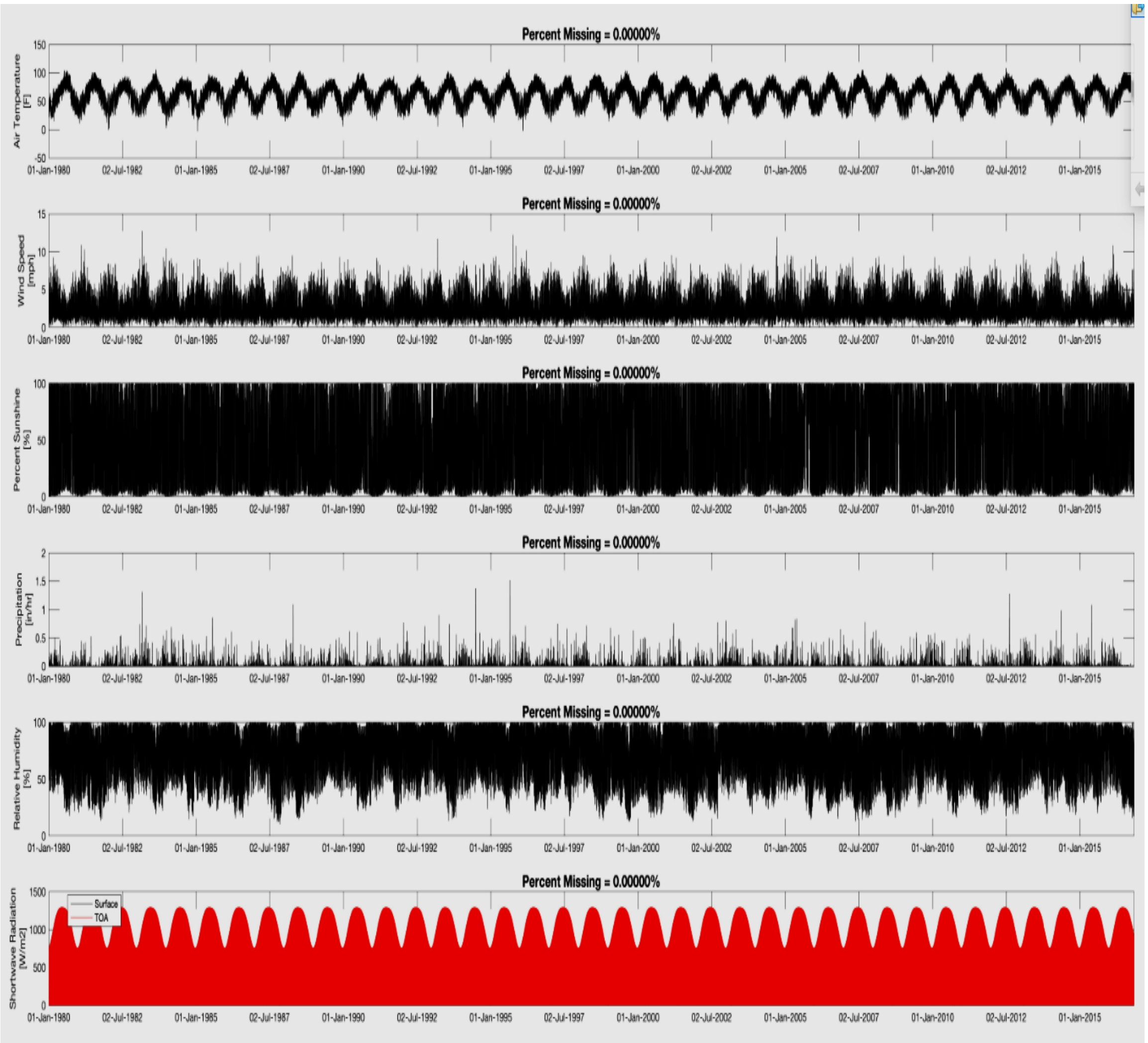
Location ID: 03820



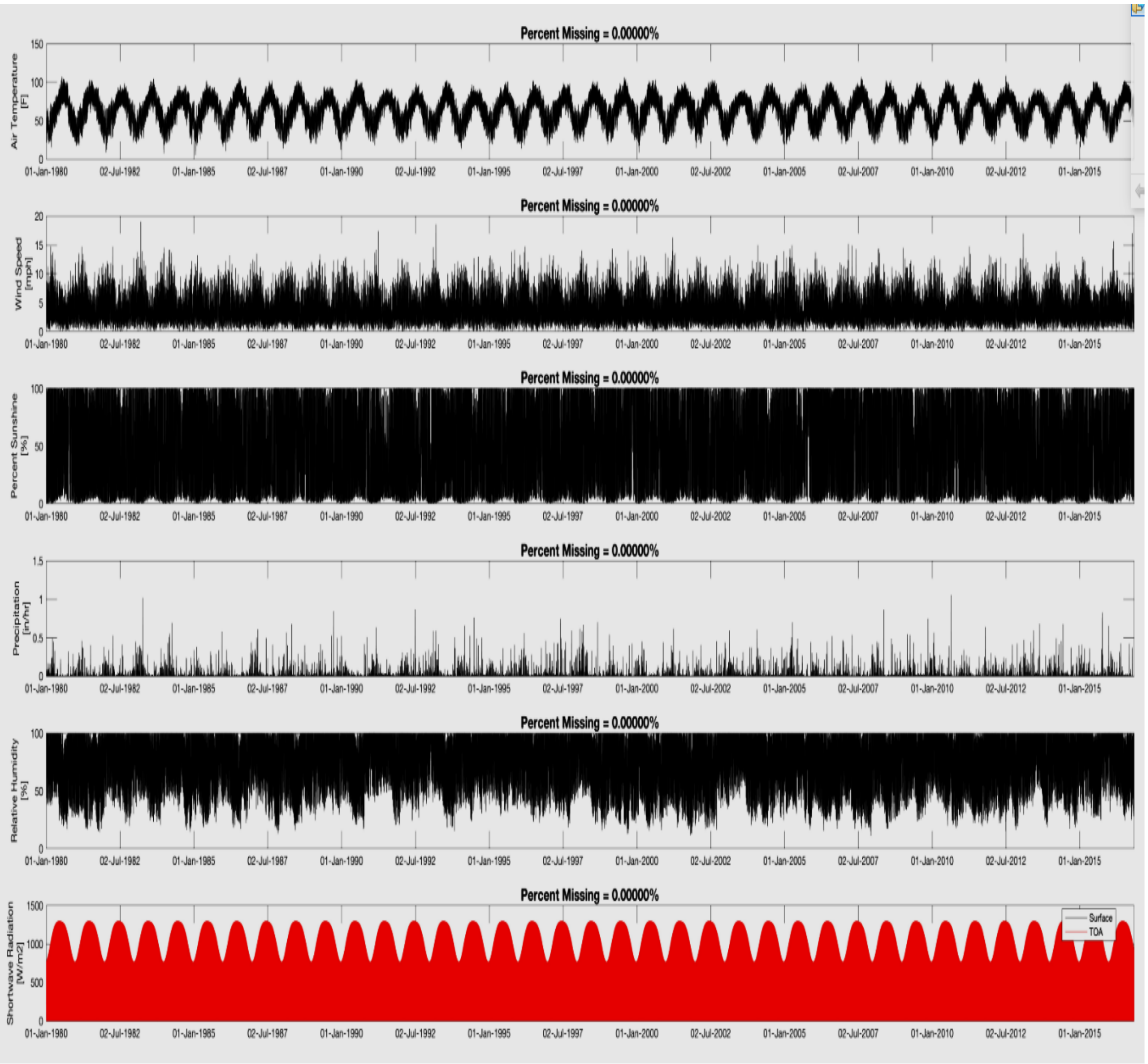
Location ID: 03822



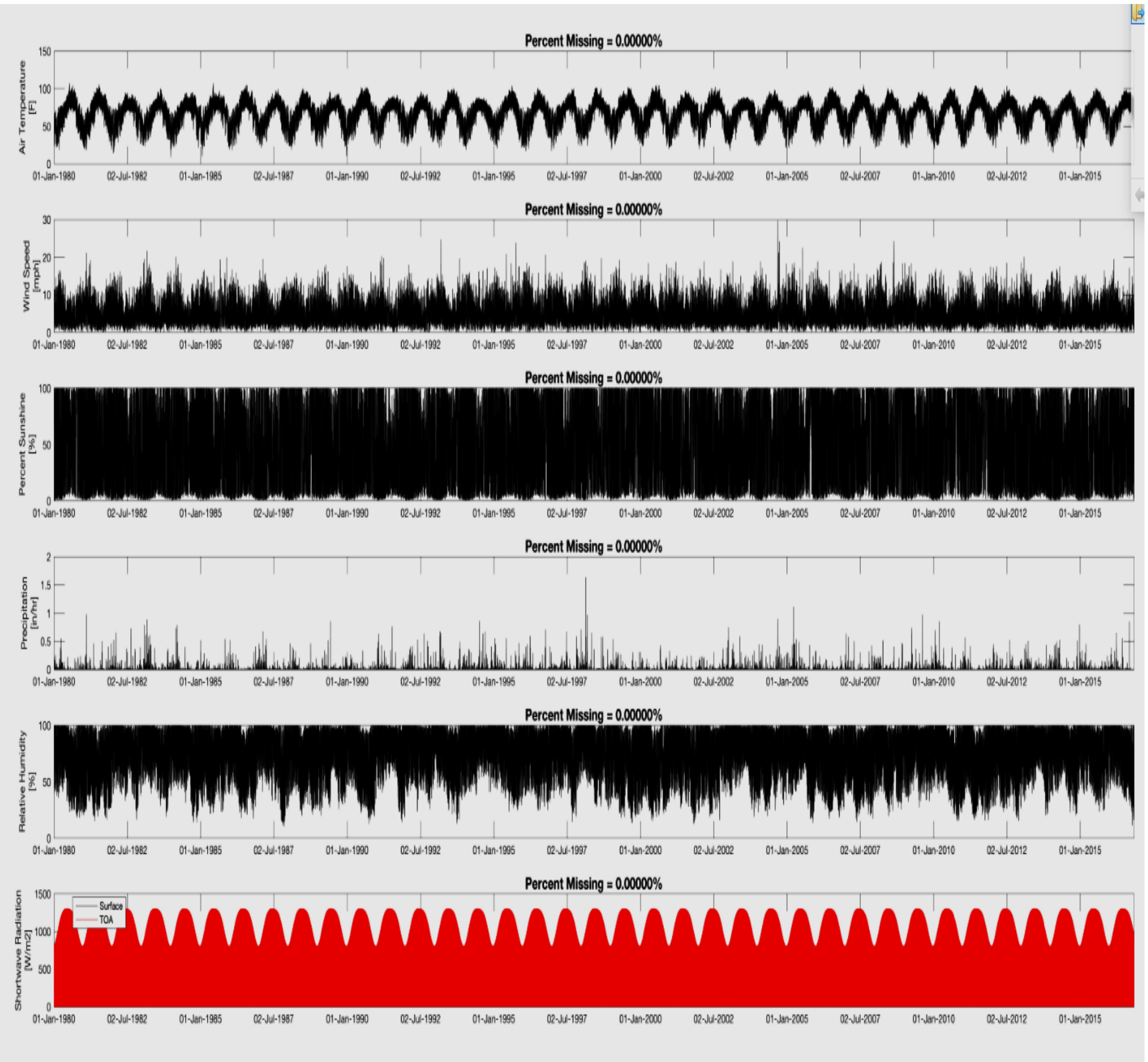
Location ID: 03888



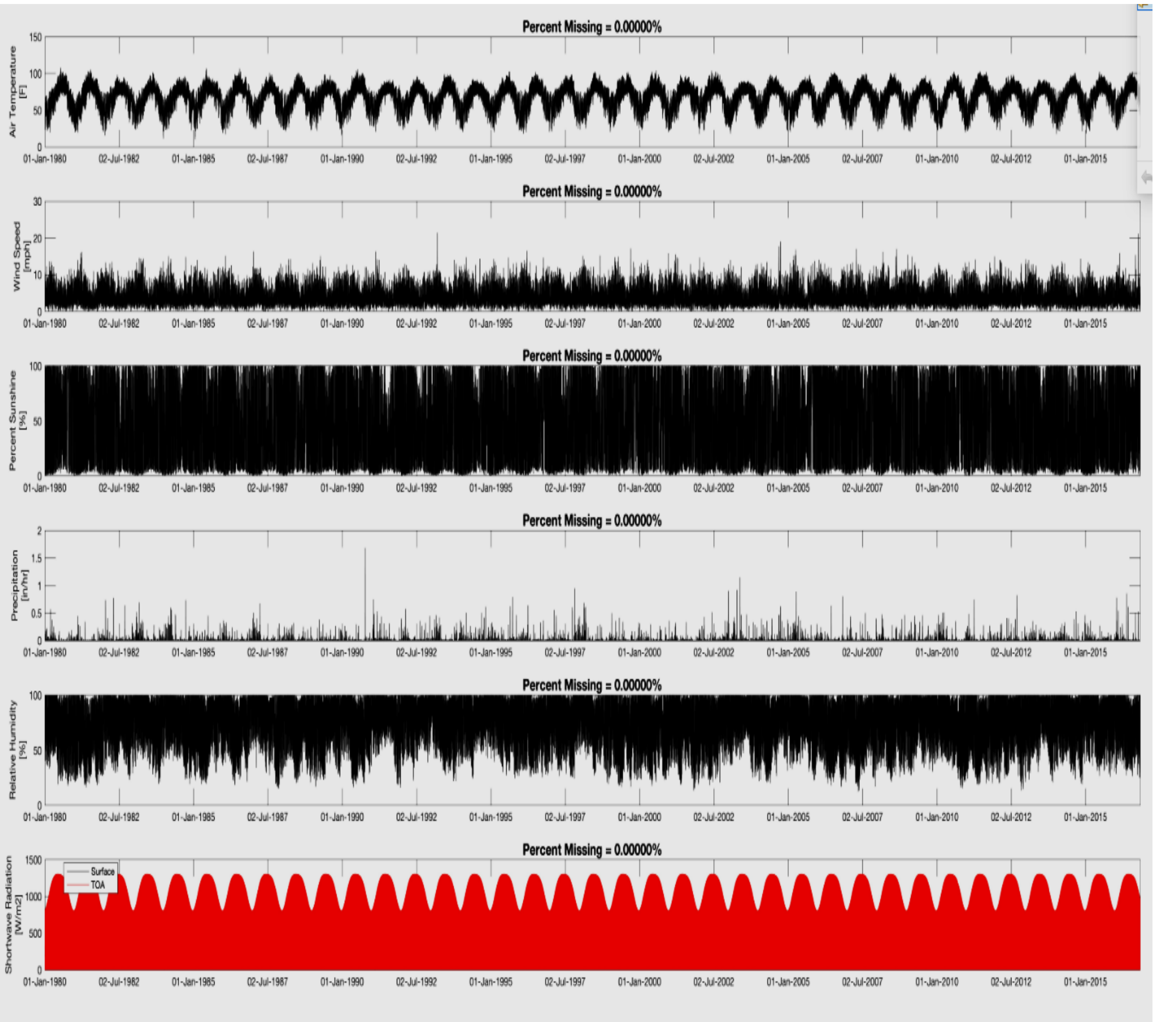
Location ID: 13837



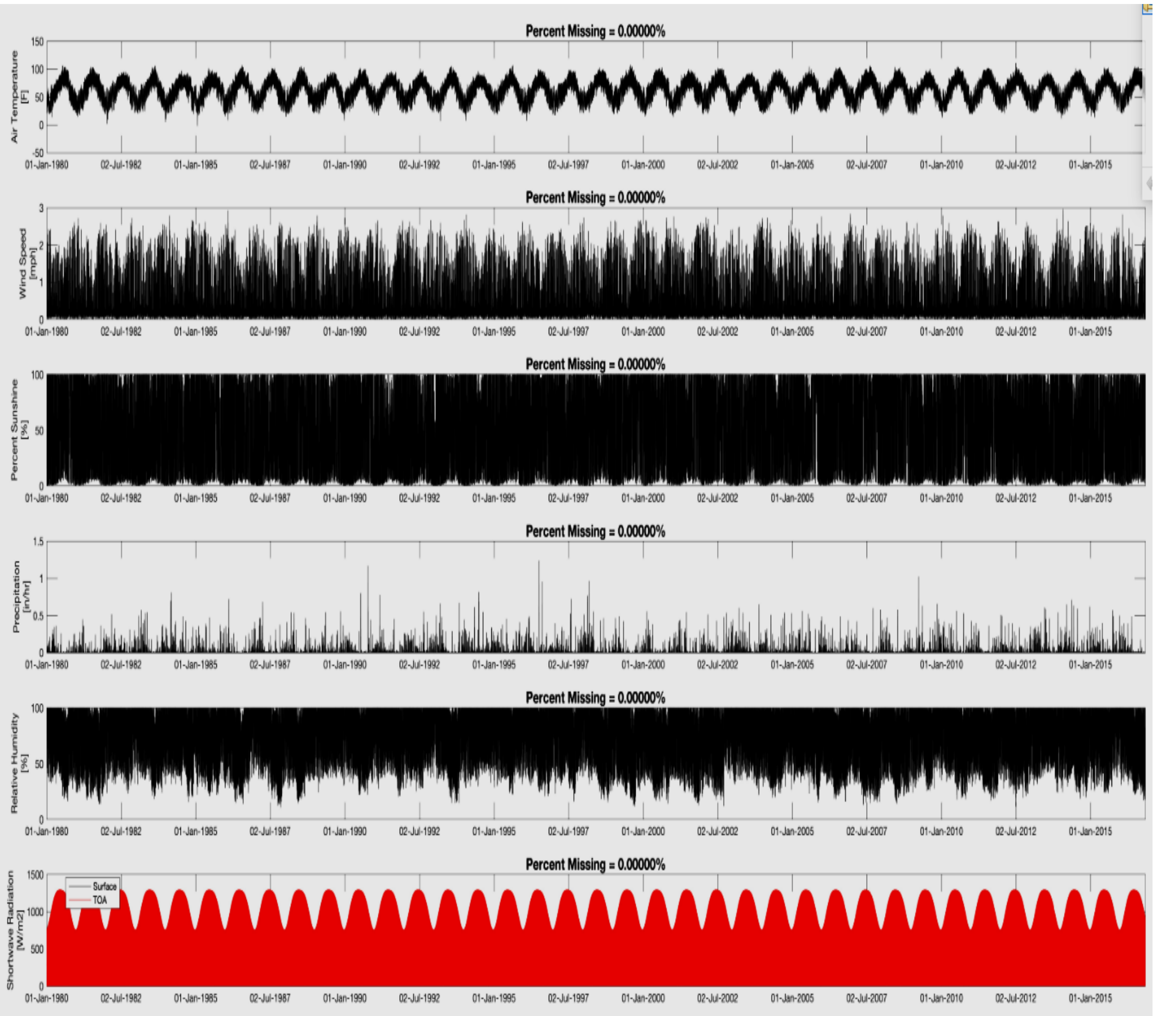
Location ID: 13869



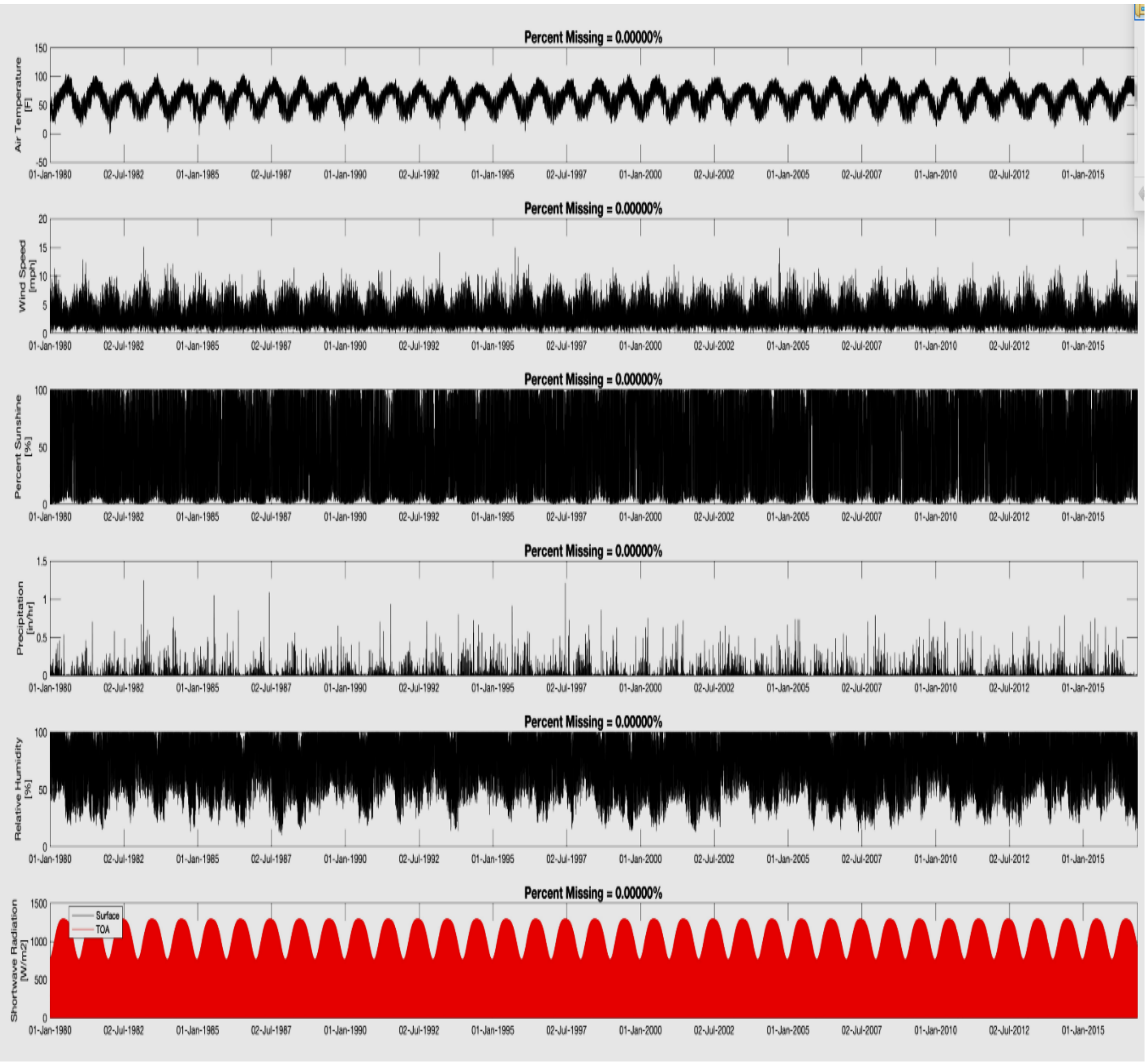
Location ID: 13870



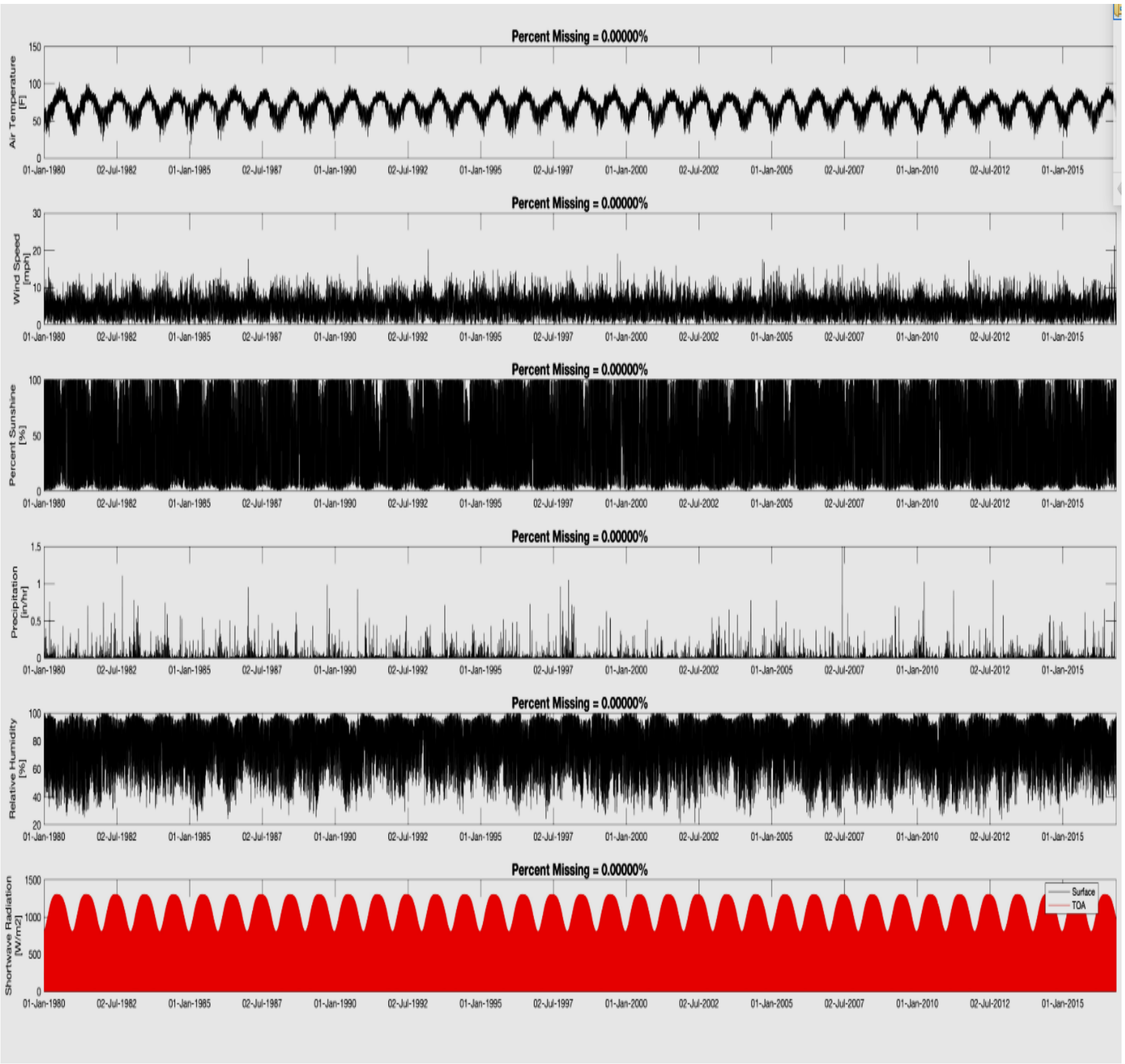
Location ID: 13873



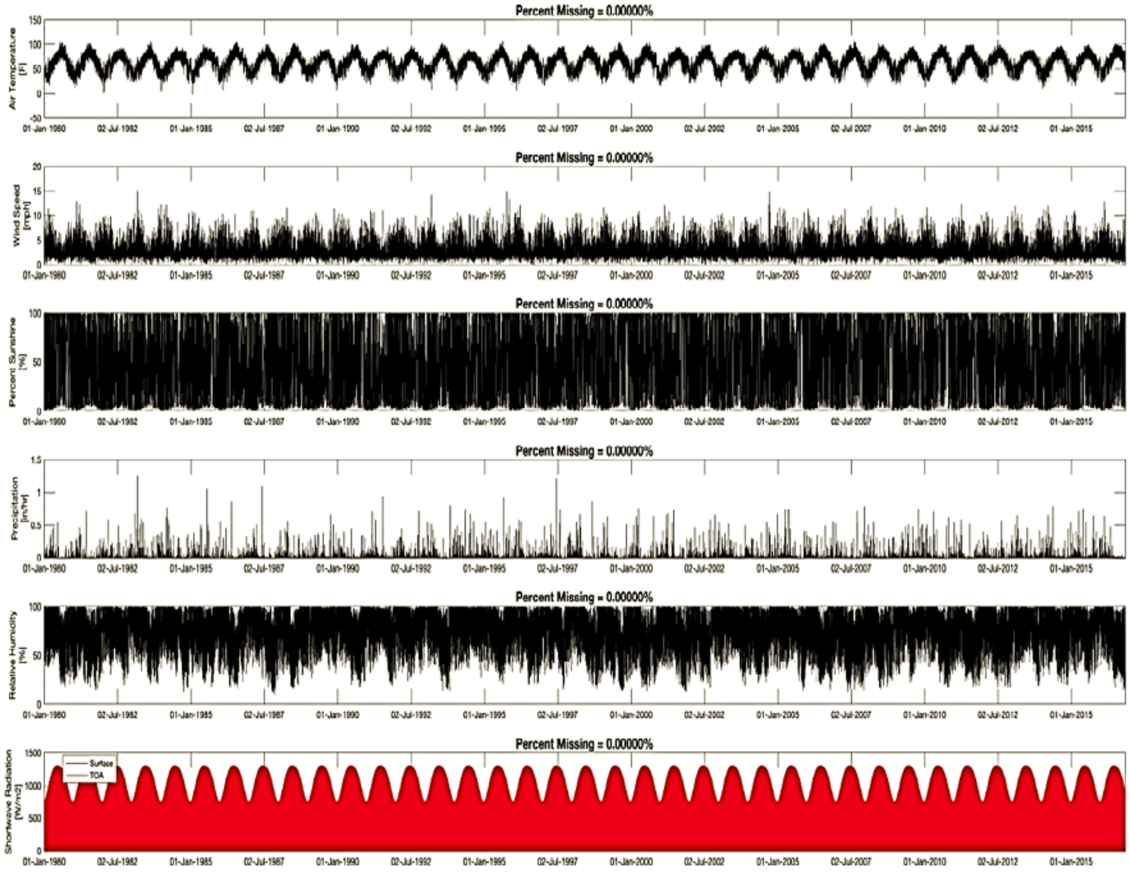
Location ID: 13874



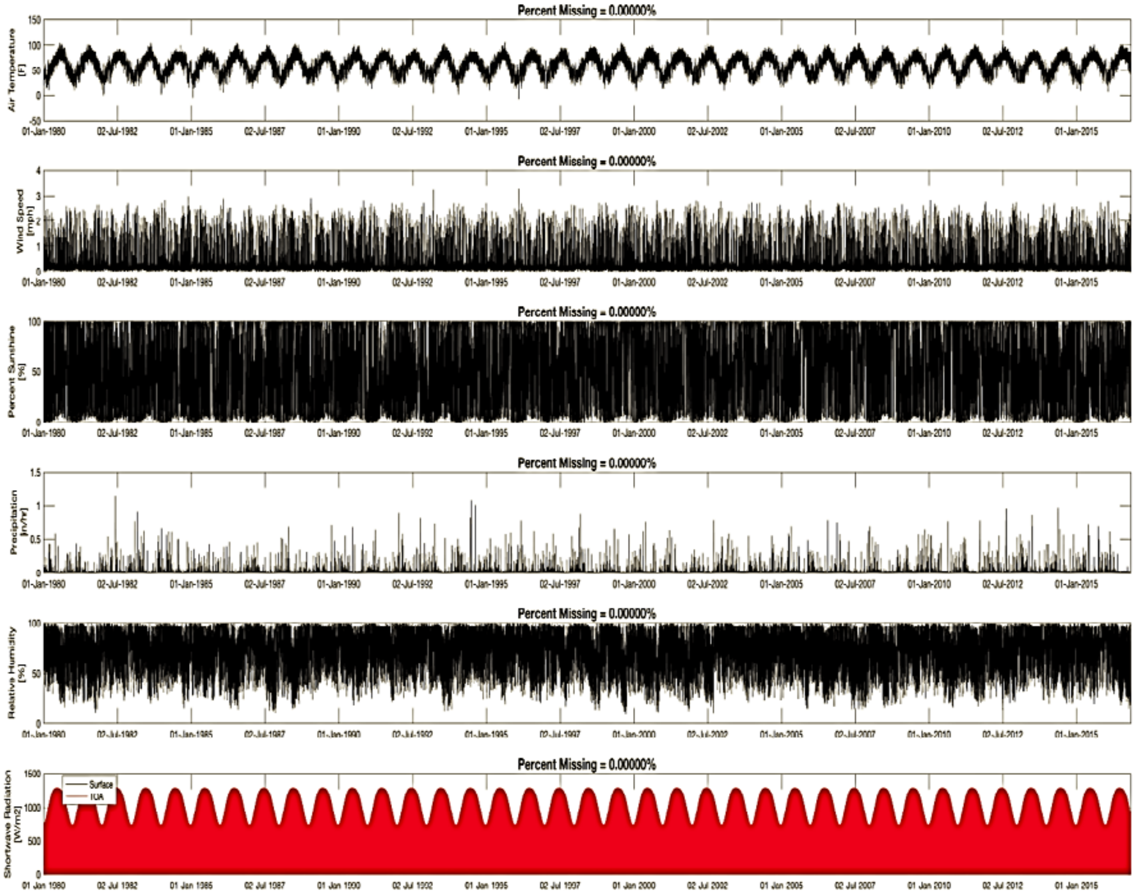
Location ID: 13878



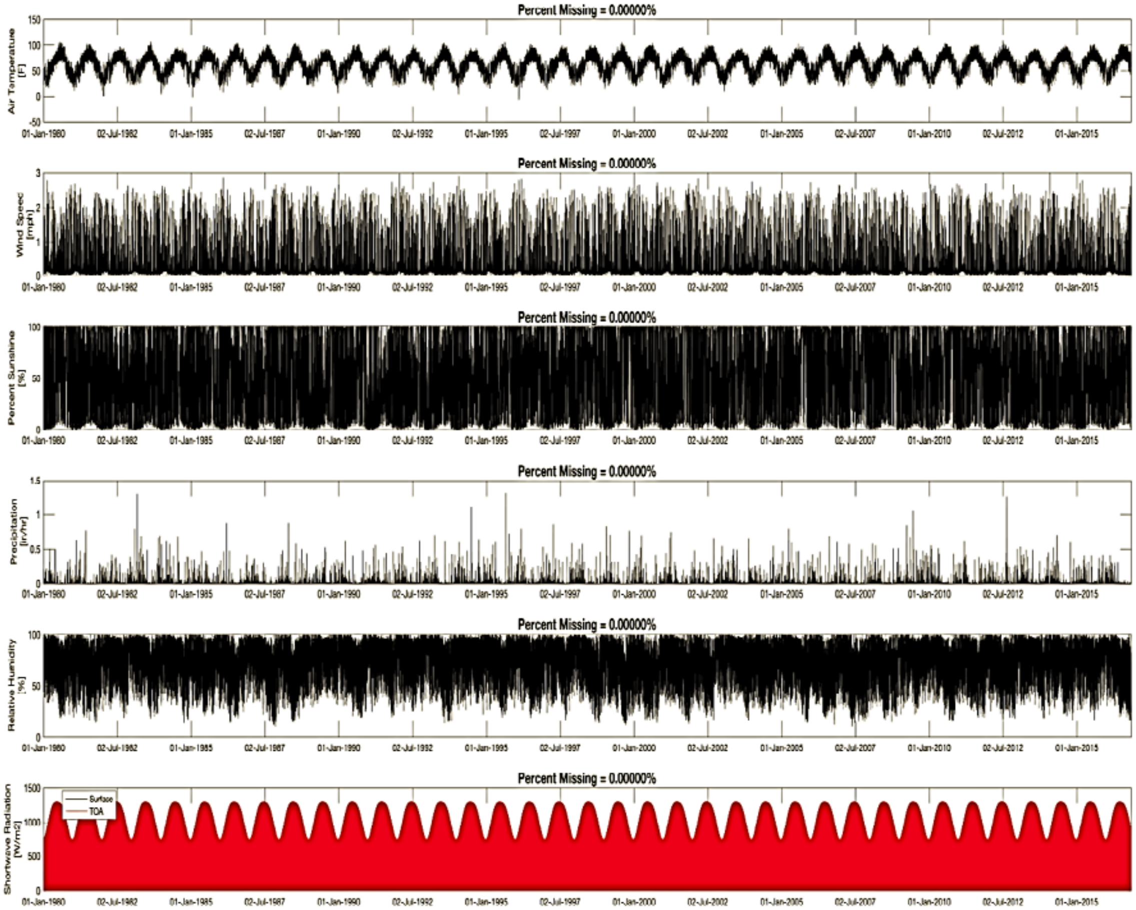
Location ID: 53819



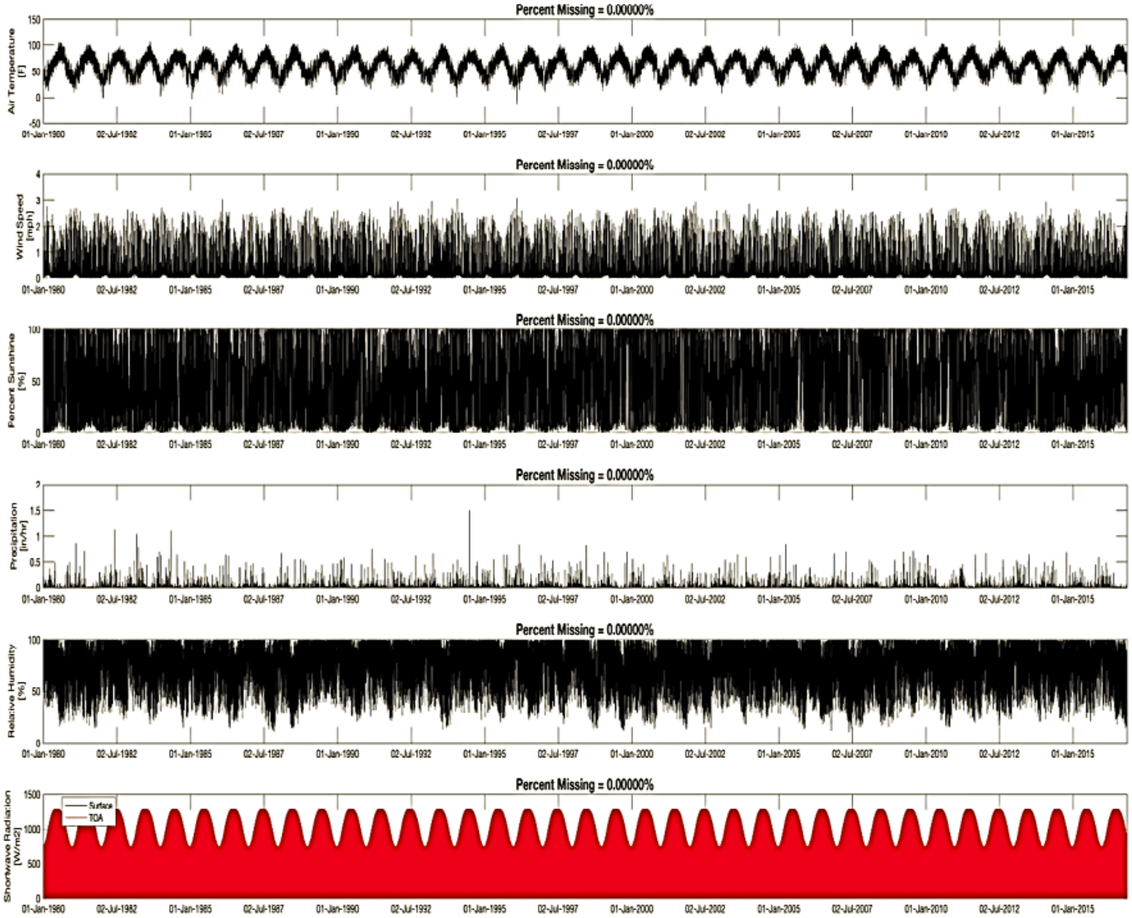
Location ID: 53838



Location ID: 53873



Location ID: 93801



Location ID: 93842