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Developing MEPDG Climate Data Input Files for Mississippi

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16. Abstract

Prior to this effort, Mississippi's MEPDG climate files were limited to 12 weather stations in only 10 counties and only seven weather stations had over 8 years (100 months) of data. Hence, building MEPDG climate input datasets improves modeling accuracy and geographic coverage. The new historic climate files created by this project use hourly data from 23 Automated Surface Observation System (ASOS) and Automated Weather Observation System (AWOS) and daily data from over 100 Cooperative Observer Program (COOP) sources combined to generate a more accurate 40-year historic climate input data file for the 82 counties in Mississippi. This represents over 30 times more climate input data for MEPDG analyses in the state.

The study then built virtual (future) climate files by applying global and regional climate models to the 40-year historic data. These virtual files were limited to nine climate zones across Mississippi due to the nature of long-range climate prediction. The temperature and precipitation data were adjusted in the virtual files and the 82 historic and nine virtual climate data files were checked for logical errors and using the MEPDG program as part of the development process.

The sensitivity analysis examined how the improved climate data input files impacted the pavement performance prediction. The analysis measured the impact of the three different climate input files (MEPDG, Historic, and Virtual) on three common types of pavements (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. The sensitivity study determined that the resources used to build the improved climate files were an appropriate effort with a measureable long-term benefit.

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LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
ASOS	Automated Surface Observation System
AWOS	Automated Weather Observation System
COOP	Cooperative Observer Program
DOT	Department of Transportation
ENSO	El Niño/La Niña-Southern Oscillation
HadCM2	Hadley Centre Coupled Model, version 2; a coupled atmosphere-ocean general circulation model (AOGCM)
HMA	Hot mixed asphalt
HMA1	Thick hot mixed asphalt
HMA2	Thin hot mixed asphalt
IEM	Iowa Environmental Mesonet, Department of Agronomy, Iowa State University
JPCP	Jointed plain concrete pavement
MDOT	Mississippi Department of Transportation
MEPDG	Mechanistic-Empirical Pavement Design Guide
NCAT	National Center for Asphalt Technology
NCDC	National Climatic Data Center
NWS	National Weather Service
PCC	Portland cement concrete
PMS	Pavement Management Services
QC	Quality control
QA	Quality assurance
RegCM2	Regional Climate Model, version 2; developed at the National Center for Atmospheric Research (NCAR)

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Developing MEPDG Climate Data Input Files for Mississippi

Abstract

The effort to build historic climate data files expands the time and improves geographic coverage of the input data for the MEPDG. The current MEPDG climate files for Mississippi are limited to 12 weather stations in only ten of 82 counties. Only seven of the weather stations have more than eight years (100 months) of climate data. The new historic climate files use the hourly data from the 23 Automated Surface Observation System and the Automated Weather Observation System (ASOS and AWOS, respectively) and the daily data from over 100 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 thirty times more climate input data.

The study then built virtual (future) climate files by applying global and regional climate models to the 40-year historic data. Due to the long-range nature of predicting climate over multiple decades, the virtual files were limited to nine general climate zones across Mississippi. Only the temperature and precipitation data were adjusted in the virtual files. The 82 historic and nine virtual climate input data files were checked for logical errors in the files as part of the climate file development process. An example of a logical error would be a database field showing negative precipitation value. The final check of the climate data using the MEPDG program did not find any outlier data.

The sensitivity analysis examined how the improved climate data input files impacted the pavement performance prediction. The analysis measured the impact of the three different climate input files (MEPDG, Historic, and Virtual) on three common types of pavements (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 twenty to forty year analysis period resulted in significantly higher predicted distress in some cases. The sensitivity study determined that the resources used to build the improved climate files were an appropriate effort with a measureable long-term benefit.

Introduction

The mechanistic-empirical pavement design guide (MEPDG) software package includes climate files that are limited in geographic density and limited in length of time. In Mississippi, there are only climate input files from 12 weather stations and only seven of the 12 have more than eight years of climate record. There are only three weather stations in the northern half of the State. This limits the ability of the MEPDG to reasonably predict pavement performance. The climate data must be repeated multiple times to accomplish a 20-year or 40-year pavement design prediction.

This study applies climate science to build more accurate historic climate files and build future climate files (called virtual climate files) applying accepted models of long-term changes in global climate. The study examines how the improved climate data input files impact the pavement performance prediction. The improved climate data input files use a longer period of climate history and information from significantly more weather stations. A sensitivity study will determine if the resources used to build the improved climate files were an appropriate effort with a measureable long-term benefit.

Developing Historic Files

The overall goal of this phase of the project was to generate historical climate files for each county in Mississippi and store this data in electronic files having a format suitable for input into MEPDG model. The period of record for these data would be from 1970 through 2009. Since not every county has a site with an observational record for that period, an interpolation method in space and time was used to fill in data gaps. A summary of the procedural steps taken during this phase of the effort follows and is illustrated as a flow chart in Figure 1:

Step-1. Collect and check the quality of an archive of daily and hourly observations.

Step-2. Produce an hourly gridded analysis using an interpolation method of available data.

Step-3. Grid-point sample the hourly analysis to produce an ".hcd" file for MEPDG.

Step-4. Check the quality of the ".hcd" file to ensure no processing errors occurred.

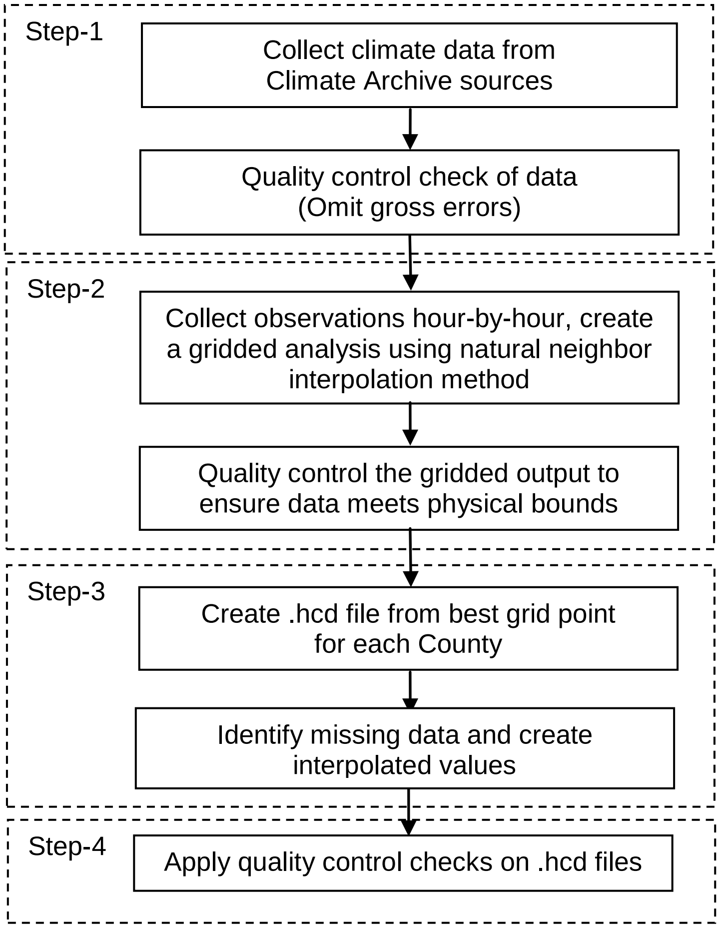


Figure 1. Process for Generating Historical Climate Files

Additional information about each of the above steps is summarized below to better illustrate the scope of the activities undertaken:

Step 1: Acquire and quality control archived data

The most difficult part about assembling climatic data files for MEPDG is the requirement of hourly data. The variables needed for each hour are:

- *Air Temperature* (units: degrees Fahrenheit), the measured air temperature at approximately 2 meters above the ground surface. The value is typically measured at the top of the hour and valid for the minute interval prior to measurement.
- *Wind Speed* (units: miles per hour), the measured speed of the air at approximately 10 meters above the ground surface. This value is typically an averaged wind speed over a two-minute period instead of an instantaneous value.
- *Percent Sunshine* (0% is cloudy and 100% is clear), while the MEPDG labels this as “sunshine”, it can be thought of as the opposite of percent cloud cover. The technique used to measure cloud cover with the automated ASOS/AWOS sensors changed during the 40 year time interval of this study. The legacy technique, used prior to the late 1980s, was to divide the sky into octants and then count the sections covered by clouds. The present-day sensors attempt to estimate a bulk value of sky coverage producing four distinct categories of sky coverage at three altitudes. For this study, the altitude level with the most dense cloud coverage was used to produce the analysis.
- *Precipitation* (units: inches), the accumulated precipitation amount for the previous hour. For example, the value at 6 AM would represent the period of time between 5 and 6 AM.
- *Relative Humidity* (units: percent), the measured concentration of water vapor in the atmosphere versus potential capacity at the measured air temperature. This measurement is valid at the same 2 meter height of the air temperature and for the same one minute period prior to observation time. A representative physical bound of 12 to 100 percent were chosen for quality control purposes.

Some of these variables are more problematic than others considering the possible data sources available. For the time period and domain of interest for this study, there are only two types of data archives available. These are:

- Automated Surface Observation System (ASOS): The observation platforms in this archive are primarily automated equipment located at airports. Prior to modernization efforts in the 1980s and 1990s, these observations were reported by airport personal on an hourly basis, but perhaps not during the night time hours at all locations. The larger airports had overnight manual weather observations. Since 1996, a similar type of observation system called Automated Weather Observation System (AWOS) is also used. Typically, the ASOS system is maintained by United States government entities, while the AWOS system is operated by the local state. While AWOS sites are technically different than ASOS sites, the ASOS term is broadly applied to both systems. The ASOS data source was used to create the MEPDG climate data files.

- Cooperative Observer Program (COOP): The COOP observations are once daily climate observations administered by the National Weather Service (NWS). These observations are the backbone of climate monitoring in the United States. Reliable and relatively (compared with ASOS/AWOS) dense daily observations of high and low temperature and also rainfall exist for our period of interest. Observations are quality controlled by such places as National Climatic Data Center (NCDC) and the NWS.

The Iowa Environmental Mesonet (IEM) is a data collection project within the Department of Agronomy at Iowa State University at Ames, Iowa. The IEM maintains archives of the aforementioned observation datasets. These local archives were expanded in space and time to support the domain of interest for this work by downloading data from available archives found on the Internet. The primary source of these archived datasets was the NCDC. Of course, with any observation dataset, issues of data quality and quantity are of concern.

While the COOP dataset provides a very high quality observation record, the daily time interval presents a challenge for use on hourly time steps. The COOP network also does not record percent sunshine, relative humidity, and wind speed. While the ASOS dataset provides all of the variables needed, it contains errors and gaps of missing observation. Table 1 presents a summary of what the climate data sources contain and how they contribute to variable formulation to build the required MEPDG climate data sets. The ASOS air temperature data give values at the reporting times, but daily extremes may occur between reporting times and hence may be better captured by the COOP data.

Table 1. Variables required and their data sources

Parameter	**ASOS/AWOS**	**COOP**
Reporting Interval	Hourly	Daily
Air Temperature	Value at reporting time	Daily high/low observed
Wind Speed	Value at reporting time	N/A
Relative Humidity	Value at reporting time	N/A
Percent Sunshine	Value at reporting time	N/A
Precipitation	Amount accumulated since last report	Amount accumulated daily

While not exhaustive, some general data quality checks were made to remove any data outside of reasonable physical bounds for Mississippi (i.e. temperature of 150^{o} Fahrenheit, wind speed of 150 mph, or a precipitation amount over 200 millimeters). Since they are percent values, relative humidity and percent sunshine were bounded by values of 0 and 100.

Since the COOP network data are relatively free of data gaps and high spatial density, only observations for Mississippi were acquired. On the other hand, observations from neighboring state's ASOS/AWOS stations were acquired to help with the analysis routine. Figures 2 and 3 present a map of sites in the ASOS and COOP observation networks.

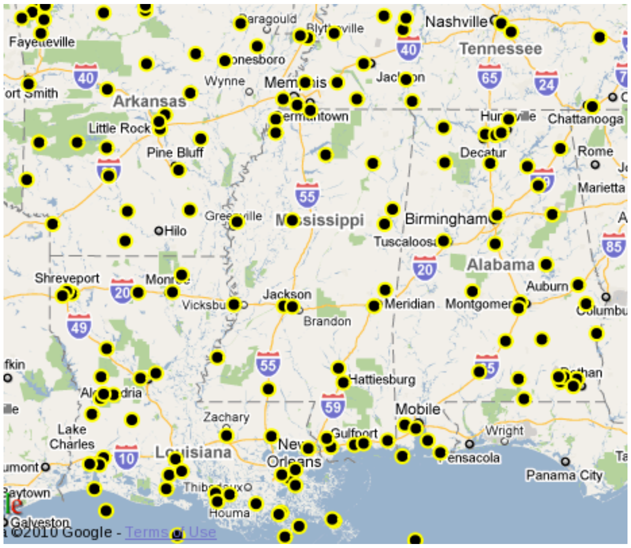


Figure 2. Present day ASOS/AWOS sites for Mississippi and surrounding states

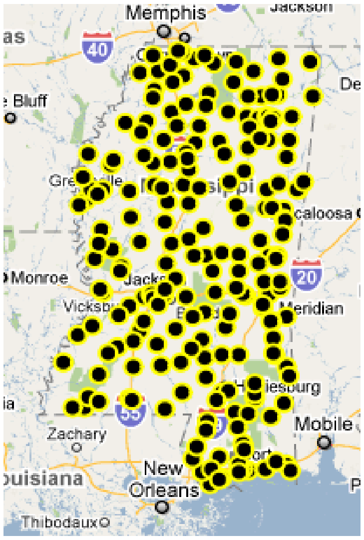


Figure 3. NWS COOP sites with data; 1970-2009

Step 2: Produce an hourly and daily analysis

Since not all counties of interest have both an ASOS and COOP observation point within them, a gridding technique was utilized to interpolate values spatially. A rectangular grid was constructed covering Mississippi with a grid point spacing of approximately 25 km and an exterior buffer of around 25 km. Such a grid has roughly one to two grid points per county in the state and is shown in Figure 4.

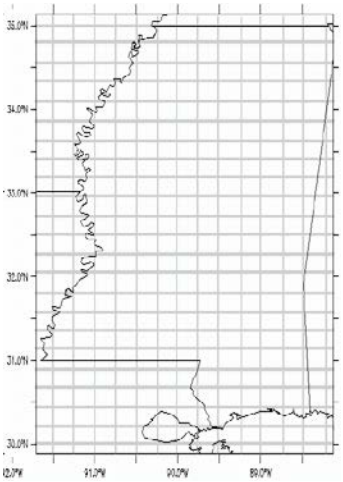


Figure 4. Depiction of analysis grid

The gridding procedure employed a natural neighbor interpolation method (Watson 1994) which is commonly used in meteorological applications of producing a grid analysis. An illustration of this interpolation technique can be found in the Figure 5. Each intersection of the grid lines represents a point in space where interpolation was done. The routine works by considering the relative contribution (based on distance and directional density) of observation sites on a prescribed analysis point (or can be thought of as a cell) of interest.

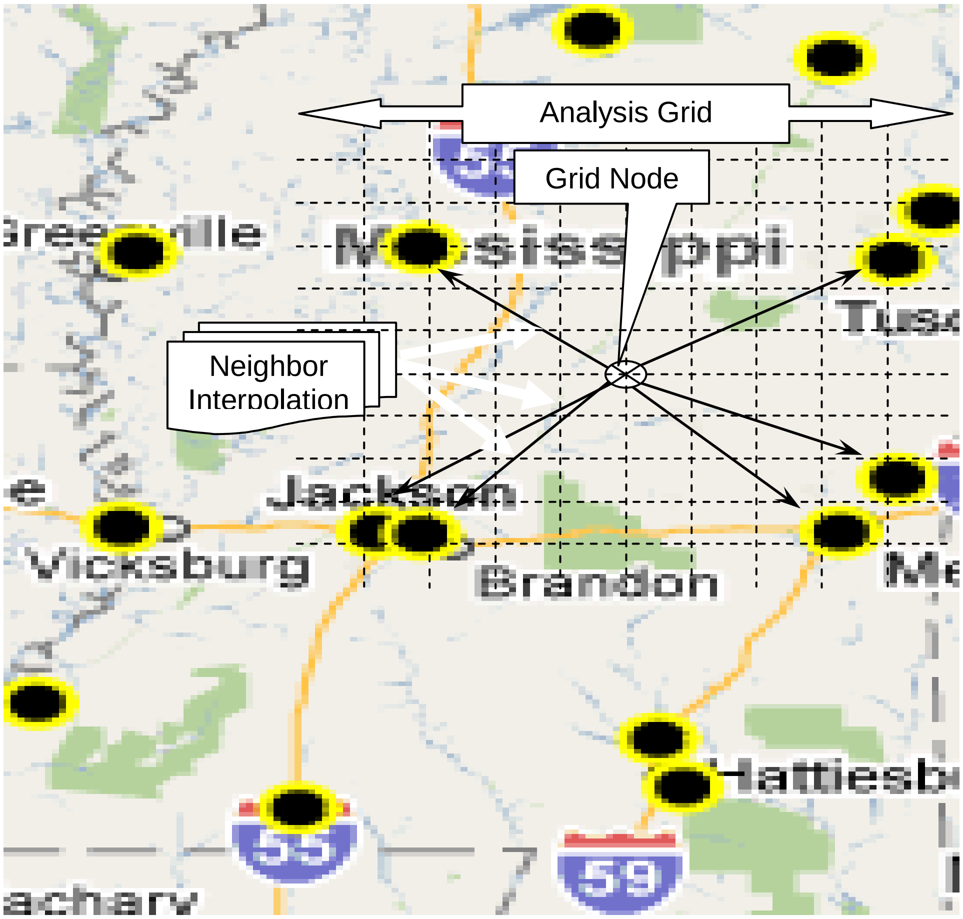


Figure 5. Illustration of Interpolation Technique

For the purposes of this study, code was developed to step through the temporal domain hour by hour and produce an analysis using the natural nearest neighbor interpolation method for the variables of interest. The code required at least four observations valid for the hour for the routine to work. For grid nodes along the border of the State, ASOS/AWOS data from the adjoining State would be used, as needed, in the interpolation process. If four observations were not found, the analysis was marked as missing (more on this later in the text). With the current archive available to the IEM, this error condition was met approximately 25 times (25 missing hours out of 350,640 hours). During these missing hours, all variables were typically missing.

The COOP data were gridded as well on daily time steps. The observation record of COOP sites was of very high quality and little work was necessary to account for incorrect data. The same technique as the ASOS data was used to grid the daily high and low temperature along with precipitation onto the common data grid. There were no days with less than 4 observations, so the gridding technique did not produce any missing values. In fact, each day had over 120 observations available.

Step 3: Extract time series from gridded analysis

With the hourly and daily gridded analysis complete, code was written to extract the values from the grid for the grid point nearest to the centroid of the county of interest. While a more sophisticated areal weighting could be done, for the purposes of this study it would not provide more accurate data due to the coarseness of the data supplied and the analysis technique's tendency to smooth out fine-scale details.

As shown in Table 1, certain variables were constructed based on a combination of data from the ASOS and COOP archives. Since the COOP data are of much better quality than the ASOS and while the ASOS provides hourly values, an approach was utilized to take advantage of this situation. For air temperature and precipitation, the higher quality COOP data were used to adjust the lesser quality hourly ASOS data while maintaining the hourly variability. Figure 6 illustrates an example result of this adjustment. The observed temperature curve is stretched and compressed to match the provided daily high and low temperature.

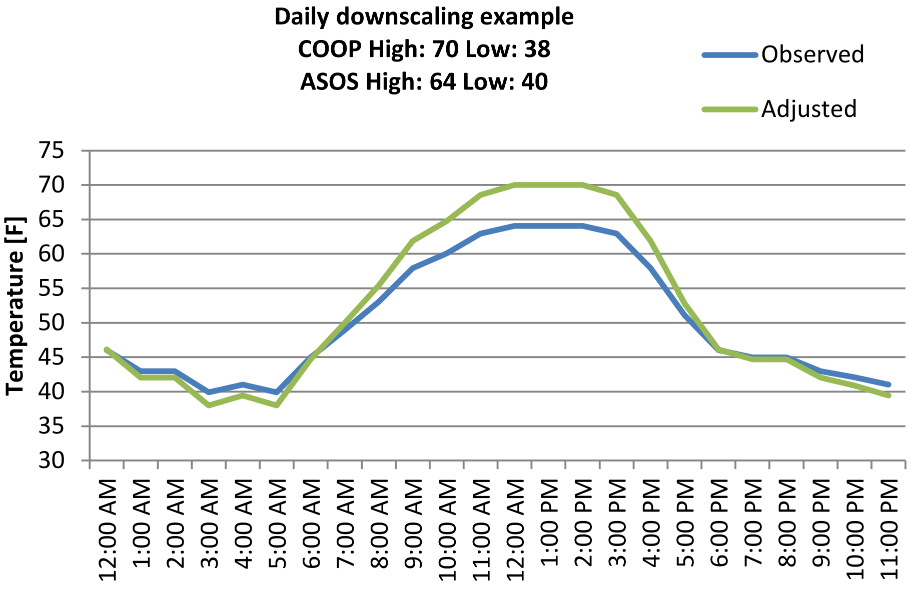


Figure 6. An example of downscaling daily values of high and low temperature to hourly values

The gridding procedure detailed in step 2 was not able to produce an analysis for each hour for the period of interest. Since the hours without data were not persistent in time and sparse in nature, a simple linear temporal interpolation was done between the hour before and the hour after to accomplish a valid analysis. More sophisticated things could have been done in place of this linear interpolator, but the suspected accuracy gain is probably not worth the effort at this time.

The result of this extraction step is an intermediate file that can be processed by the MEPDG's climate data processor. This file has an ".hcd" suffix and also requires an associated entry in the station.dat file distributed with the MEPDG.

Step 4: Quality control the" .hcd" file

The ".hcd" file resulting from step 3 was processed through a final script to ensure the data file was well formed and did not contain invalid values. The following checks were performed on the file:

- A set of values was present for each hourly time step between 1970 and 2009. The files were inspected to verify 350,640 lines in the file.
- The values in the file were checked for any out of bounds values.
    - No percentage values above 100 or below 0.
    - No negative wind speeds or precipitation.
- For each variable, the maximum and minimum values were reported. These numbers were visually inspected for reasonableness. Values outside the ranges described below were further examined for possible errors.
    - Maximum air temperature should be around 100^{o}F and minimum around 0^{o}F.
    - Peak wind speeds shouldn't be much higher than 50-70 mph (typical value of a severe thunderstorm). Some sites may have hurricane data included in them, so locally higher values may happen.
    - Maximum precipitation values should be around 2-3 inches.
- Monthly summaries were generated and visually inspected for any suspicious values.

If errors were found, the data were investigated and the procedure re-started with step 2 to correct any errors. The production of one .hcd file per county and the station.dat file the MEPDG software uses to reference the .hcd files are the products of the data processing covered in this Historic file process.

Developing Virtual Files

Future scenarios of climate are needed for assessing impact of climate change on pavement performance. Developing a future climate scenario for assessing impacts of climate change requires use of a global climate model to create the climate conditions that are consistent with the rising levels of greenhouse gas concentrations in the earth's atmosphere. Since global climate models provide only coarse-resolution results (e.g., one grid point for every 35,000 square miles), a method for refining the spatial distribution of the global climate model results to specific locations within the state was required. Two methods for spatial distribution are typically used: statistical downscaling and dynamical downscaling. Dynamical downscaling is performed by a regional climate model imbedded into a global model.

The second method, dynamical downscaling, is widely recognized as being able to provide results that are physically consistent with the results produced by the global model, although it is more computationally intense to create the results. This second method has been used for assessing the impact of climate change on wind speed (Segal et al., 2001), solar radiation (Pan et al., 2004a), streamflow in the Upper Mississippi River Basin (Jha et al., 2004; Takle et al., 2010), summertime daily maximum temperatures (Pan et al., 2004b), crop production (Takle and Pan, 2005), flow and water quality in the Upper Mississippi River Basin (Takle et al., 2006), precipitation intensity (Gutowski et al., 2007), extreme cold season synoptic precipitation events (Gutowski et al., 2008), subsurface tile drainage in Iowa (Singh et al., 2009), and pavement performance (Breakah et al., 2010). To assess the impact of pavement performance, the results of the global climate model of the Hadley Centre in the UK (known as the HadCM2 model) and the dynamical downscaling method that uses the regional climate model RegCM2 are applied. This global/regional model combination is the same as was used in the above nine studies. The RegCM2 domain regional climate model used for this study is shown in Figure 7, with detail for the state of Mississippi shown in Figure 8.

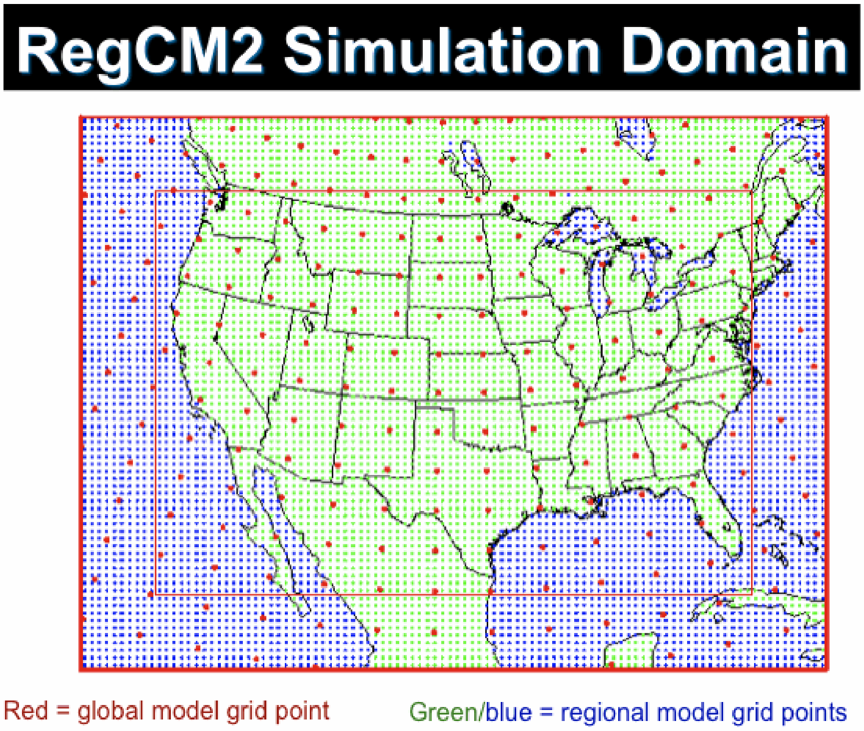


Figure 7. Regional climate model domain grid point locations for global (red) and regional (green) models

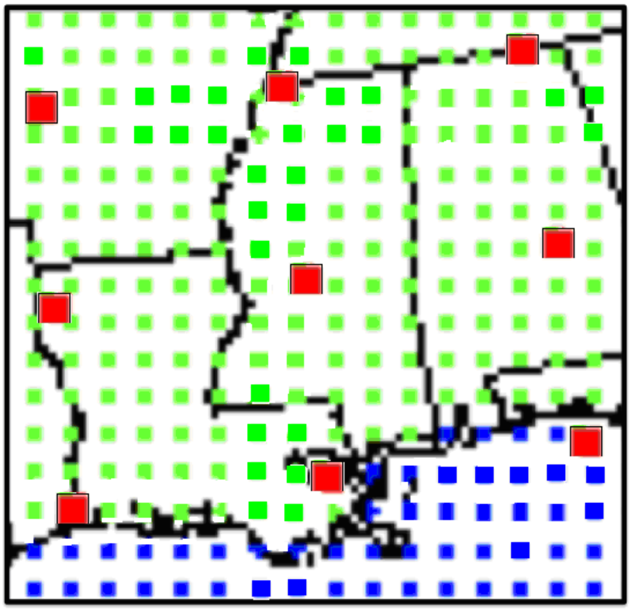


Figure 8. Mississippi's climate model domain grid point locations for global (red) and regional models (green)

The basic weather input to the MEPDG pavement model is a multi-year time sequence of hourly weather variables for a particular location. When the pavement model is run using past climate as input for this location, the meteorological file used as input contains hourly temperatures, precipitation, etc., that are influenced by occurrences of El Niños, La Niñas, and hurricanes. These irregular but important regional climate influences exist and evolve in response to changes in sea-surface temperatures that also slowly change in time. At a given location, say Tupelo, Mississippi, the hourly progression of temperatures is strongly influenced by these "remote" conditions.

Global climate models simulating future climates do not simulate future year-to-year changes in sea-surface temperatures and therefore do not produce plausible future El Niños and La Niñas (ENSO conditions). Large-scale conditions leading to hurricanes are simulated with global climate models, but the hurricanes themselves are not produced by such models. Therefore simply using global climate model output to represent future weather sequences would miss important and known influences on climate variability. There are a couple of ways to address this dilemma. The simplest method is to start by using a global model to create two proxy climates: a "contemporary climate" (e.g., representing the 1990s) and the "future scenario climate" (e.g., representing the 2040s). The global / regional models for building the contemporary and future climate are shown in Figure 9. The global /regional climate model used to generate these is a "first principles" model based on real, physical processes. This global model of the atmosphere is given an accurate amount of solar radiation at the "top" of the atmosphere and green-house gas concentration in the atmosphere representing each 3-minute time step for the 10-year period. As a result, the region simulated (i.e., continental US) has the basic seasonal and daily cycles of weather variables for each longitude, latitude, and altitude point within the model.

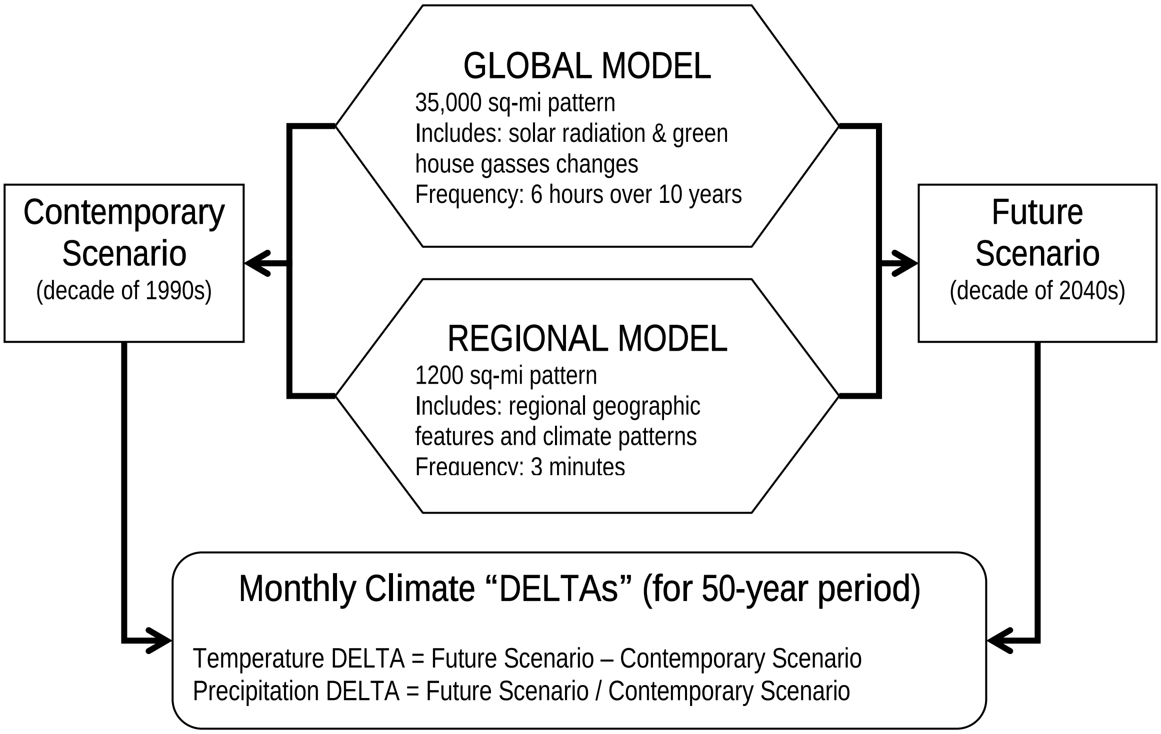


Figure 9. Process of developing temperature and precipitation deltas from contemporary and future scenario climates built from a global/regional climate model

The "contemporary" climate of the 1990s developed by the combined global/regional model will differ somewhat from the actual historical records for the 1990s for several reasons. First, the land surface in the regional climate model *does* include major topographical features such as mountains and major water bodies, but *does not* specify conditions smaller than about one fourth the size of a typical county. So it might not include the influence of a small lake or city. Also vegetation does not "green up" naturally in the model but is changed abruptly in the spring. Furthermore, effects of clouds are not represented accurately because they can occur on many spatial scales and have physical properties that are too small to be fully represented in the regional model. As a result of the approximations used to account for these deficiencies, the regional model produces a "contemporary climate" that has realistic seasonal and daily cycles but may have a systematic "bias"; that is, the regional model may always be a 1-2 degrees Celsius too cool or too warm for a particular location in a particular month when compared with the recorded historical climate.

The "future scenario climate" uses the exact same global model with the exact same land surface (e.g., cities of same size, same agricultural regions, etc.) and same solar radiation at the model top that was used for the "contemporary climate." The only difference is that the global model used to create the boundary conditions for the regional model had a different amount of greenhouse gas (carbon dioxide and methane) in the atmosphere than was used for the contemporary climate. The result was generally there were slightly higher temperatures in the lower atmosphere with subsequent changes in evaporation, cloudiness, etc. The future scenario climate produced by this procedure will also have "biases" as were described for the contemporary climate. However, since the same global climate model was used for both, the assumption was made that their biases would be similar, and when the contemporary climate values were subtracted from future scenario climate values (for the same month and time of day) the biases were eliminated or at least much reduced. The difference (future climate minus contemporary climate) for each grid point and each month produced the "climate deltas."

The climate deltas represent the expected change in future climate due only to the impact of changes in the influence of solar radiation due to the changes in greenhouse gas concentrations between the future period (2040s) and the contemporary period (1990s). They do not represent changes in frequency or intensity of El Niño or La Niña events. To simulate the influence of such events, the monthly climate deltas were added to the observed historical record of the period 1970-2009. In this way, extreme events of the historical record were represented in the virtual climate constructed for the MEPDG pavement performance analysis. The climate deltas were created separately for each regional grid point in the state and for each month of the year. A diagram of the process for creating the climate deltas is given in Figure 9. The 50-year deltas were reduced to an annual rate so they could be applied to the 40-year historic climate data.

For temperature, use the difference (future climate 10-year average value minus contemporary climate 10-year average value) to define the delta T. See Figure 10 for the monthly temperature comparison. For precipitation the customary procedure is to use the ratio (future scenario climate value divided by contemporary climate value) to define the delta P. Use of a ratio for precipitation ensures that there will be no negative precipitation in the final virtual climate. See Figure 11 for monthly precipitation comparison. This produces the future scenario 50-year (2040 minus 1990) "monthly climate deltas" due to climate change, as shown in Table 2.

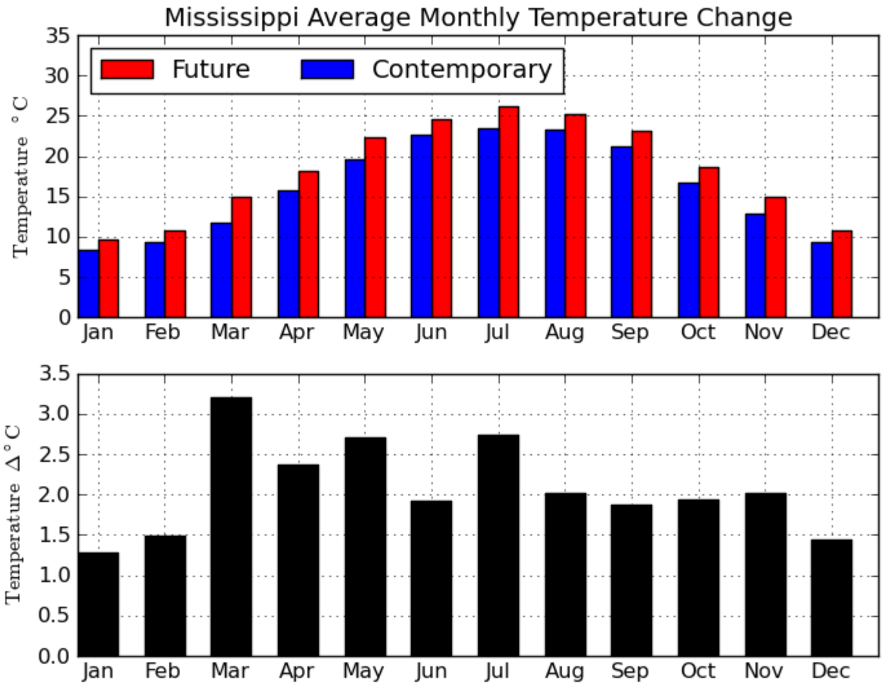


Figure 10. Monthly average temperatures, future and contemporary climate simulations
(The bottom figure presents the change,50-year delta T, from contemporary to future climate.)

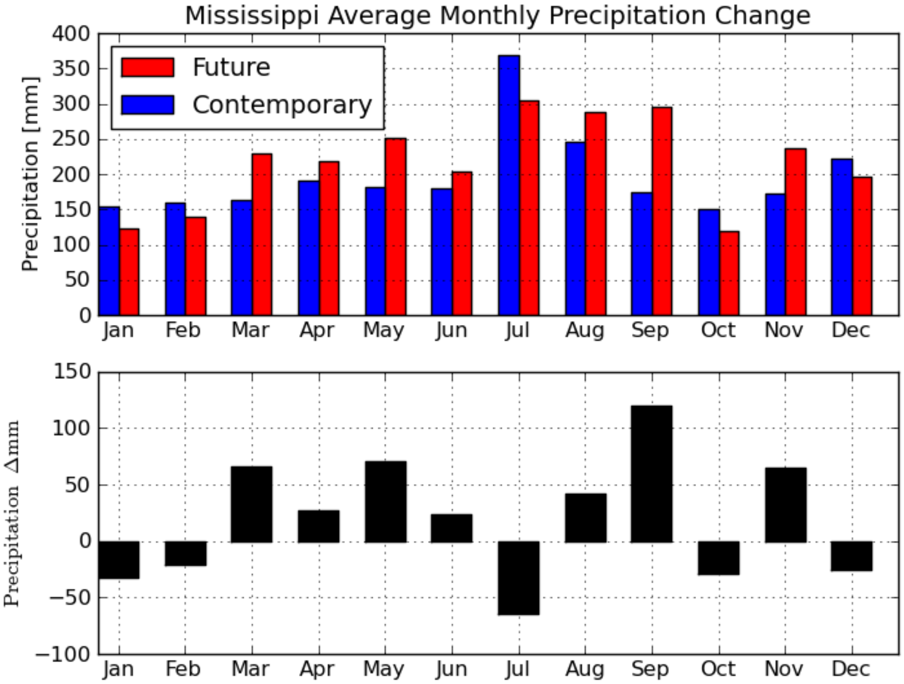


Figure 11. Monthly average precipitation, future and contemporary climate simulations
(The bottom figure presents the change, 50-year delta P. from contemporary to future climate.)

Table 2. Monthly climate "50-year deltas" to be applied to historical data

Data	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T [C]	1.3	1.5	3.2	2.4	2.7	1.9	2.8	2.0	1.7	1.9	2.0	1.4
P [%]	-21	-13	40	14	39	13	-17	17	68	-20	37	-11

The sequence of building virtual climate data for input in the MEPDG pavement analysis was done in a three-step process illustrated in Figure 12. The first step determined the 40-year linear trend of the historic climate (temperature or precipitation) from the 1970 to 2009 data, as shown in hypothetical example in Figure 12a. Because this is a hypothetical example, the values of the y-axis are generic and do not represent a specific climate feature. The significant differences of the historic climate from this linear trend are the "interannual variability" due to conditions like El Nino, which were quantified by subtracting the trend line values from the historic values for each year. The second step determined the new trend for the next 40 years by applying the climate deltas that were previously discussed to the trend of the historic climate. The trend line for 2010-2050 was then tied to the end of the trend from 1970-2009 at year 2010. Finally, the third step added the interannual variability, obtained from the difference between the historic trend line and historic climate, back in to the period from 2010-2050. Note that the historic climate pattern (the interannual variability) from the period 1970-2009 was reproduced in the 2010-2050 period, but departing from a slightly different (increased) slope created from the climate delta.

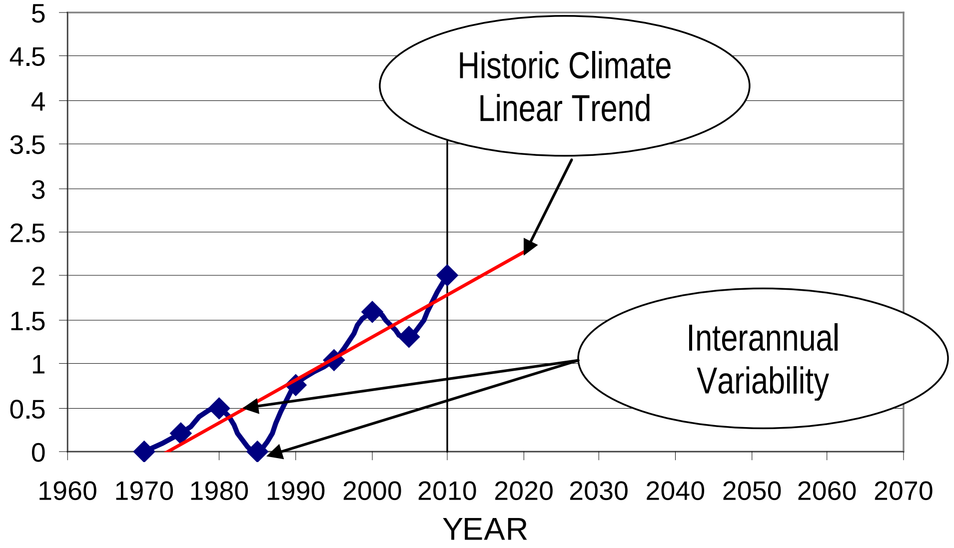


Figure 12(a) Hypothetical historic 40-year climate record and trend line

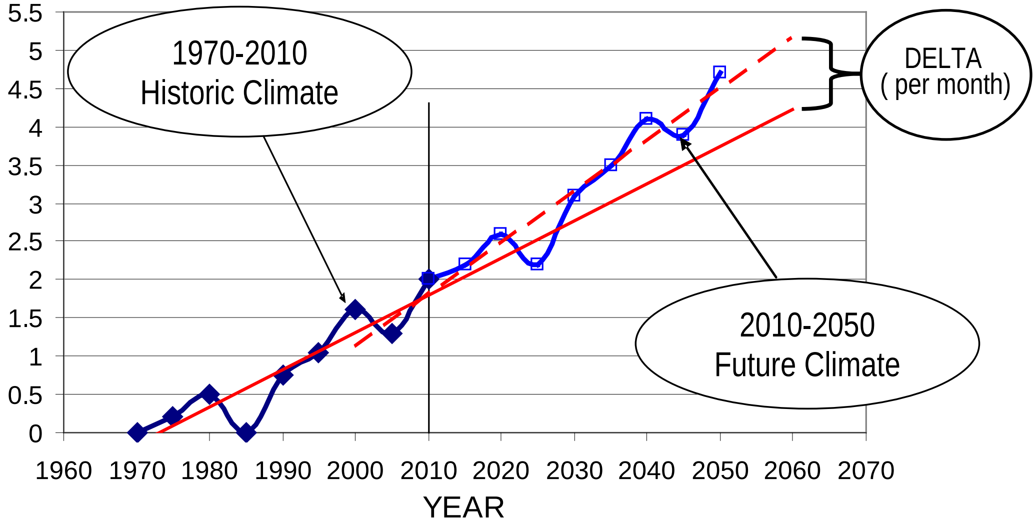


Figure 12(b) Future climate record built from extended historical climate trends adjusted by a global/regional delta

Figure 12. Illustration of building a virtual climate record

The linear application of monthly deltas appears to be a valid approach given the supporting data shown in Figure 13. Each curve displays the distribution 29,200 data points of

3-hour average temperatures for the 10 years of the model. The change in the distribution of temperatures from the model's contemporary scenario climate to the model's future scenario climate appears to be primarily a simple shift to the right (warming). This makes intuitive sense as the future climate scenario run is unable to create dramatically new atmospheric circulation patterns that would cause more irregular shifts in the temperature distribution.

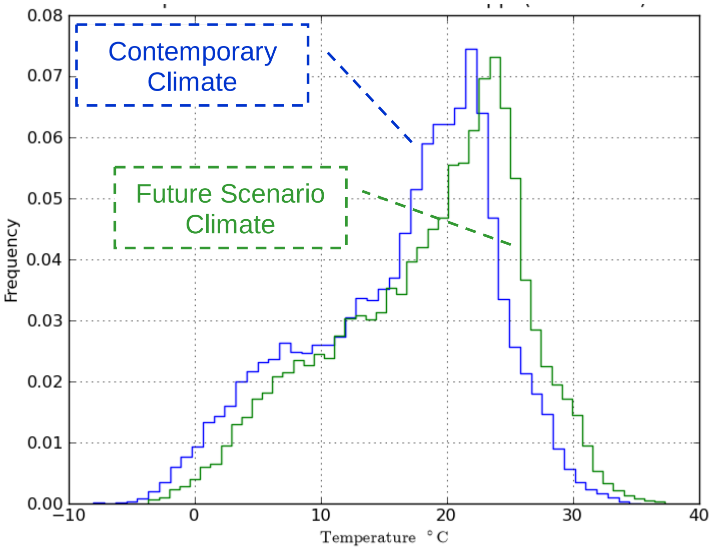


Figure 13. Distribution of near surface air temperature in the climate model
(Contemporary Climate in blue; Future Scenario Climate in green)

A more sophisticated method is to do a statistical analysis of past ENSO conditions and redistribute these according to a trend and/or frequency of occurrence model. However, no rigorous method has been proposed to make this modification. The impact of this method on the results of MEPDG pavement analysis is uncertain.

A discussion, similar to modeling ENSO conditions, could be given for other regional influences on climate such as the effects of sea-breezes. Without any modifications, the delta method assumes that sea-breeze influences will occur essentially the same in the future (virtual) climate as in the past (historic) climate. However, a modest change in sea-breeze influence will be represented in the virtual climate model because of a likely stronger land-sea temperature difference. However, no rigorous method exists to make this modification.

As previously mentioned, creation of future precipitation conditions is done slightly differently from those for temperature. The precipitation climate delta is a ratio of the monthly future scenario climate value to the contemporary climate value. This monthly value is applied linearly on a daily basis to "move" the observed data into the future.

A consequence of this procedure is that the distribution of wet and dry days remains the same in the future as was observed in the historic record (1970-2009). In short, when it rains it simply rains more (or less) as dictated by whether the precipitation delta is greater than or less than 1.0. A statistical analysis of precipitation events in the future scenario and contemporary scenario might provide an alternative method, but no rigorous studies have been conducted to develop such a method.

Virtual climate files were developed for nine regions across Mississippi. The nine virtual climate regions are bound by the distribution of climate data generated by the global/regional model. Similar to development of the historic files, the virtual climate regions extend into adjoining states, like the coastal counties of Louisiana, to acquire data for developing the climate files. The nine regions for the virtual climate files do not match the ten standard climate regions. Each state in the United States is divided into standard climate regions as shown in Figure 14. Mississippi is divided into ten standard climate regions that are fixed by political boundaries (State and county). In general, nine of the standard climate regions equally divided the body of the state and the tenth region represents the six coastal counties, as shown in Figure 15. There are six to nine counties in each standard climate region. The nine virtual climate regions are also shown in Figure 15.

The method used to build the virtual climate files for Mississippi is only one of several approaches that could be selected by a particular state. The approach used in Mississippi determines the changes projected by the global/regional climate model and applies the changes to the 40-year historic file. Descriptions of possible processes for developing the virtual file are listed in Table 3.

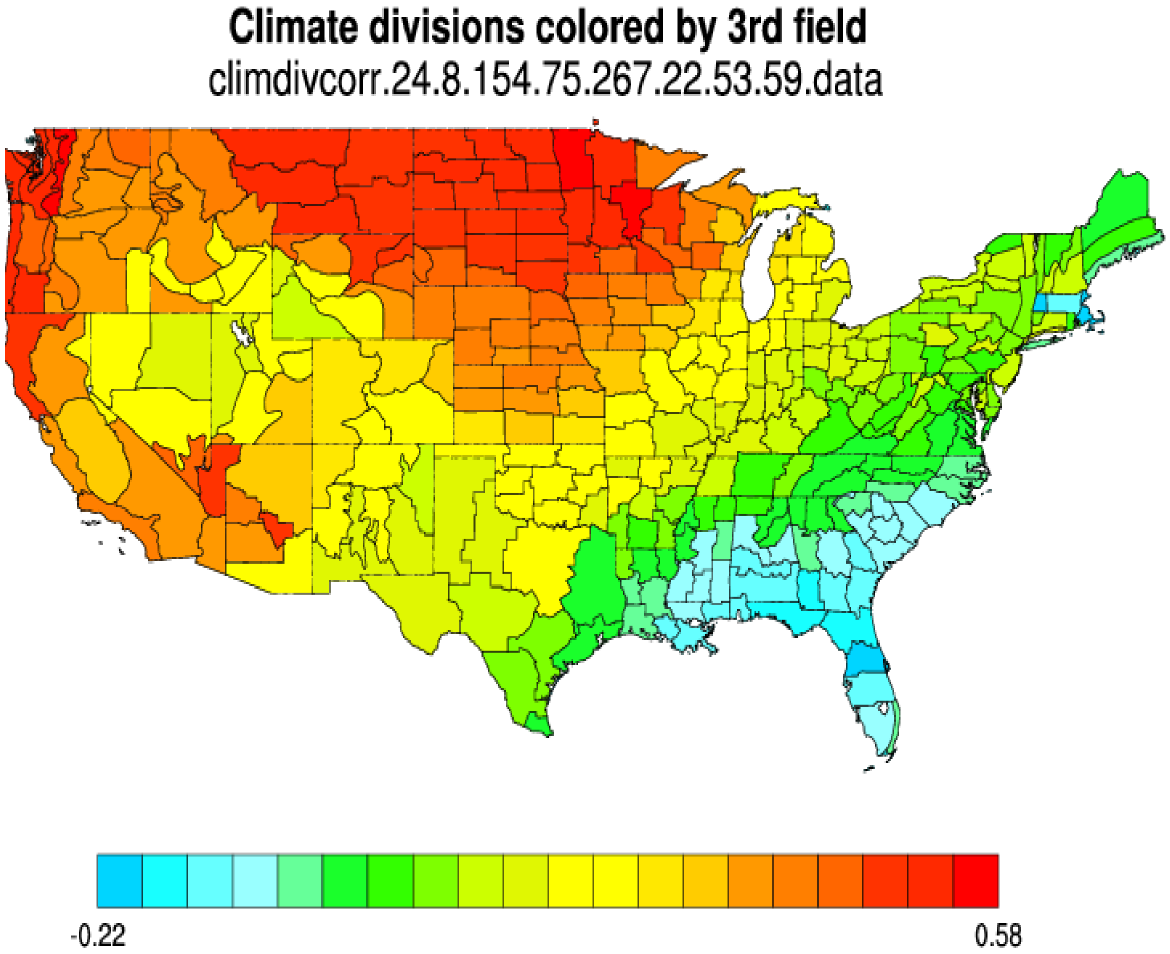


Figure 14. United States Standard Climate Regions

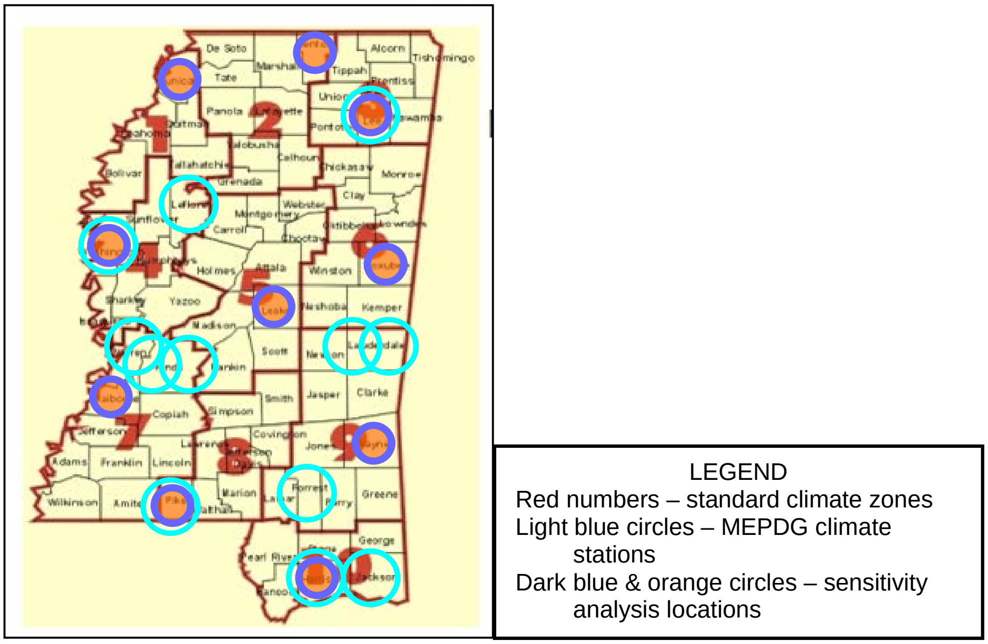


Figure 15a. Standard Climate Zones and Location of MEPDG Weather Stations and Counties Used in the Sensitivity Analysis.

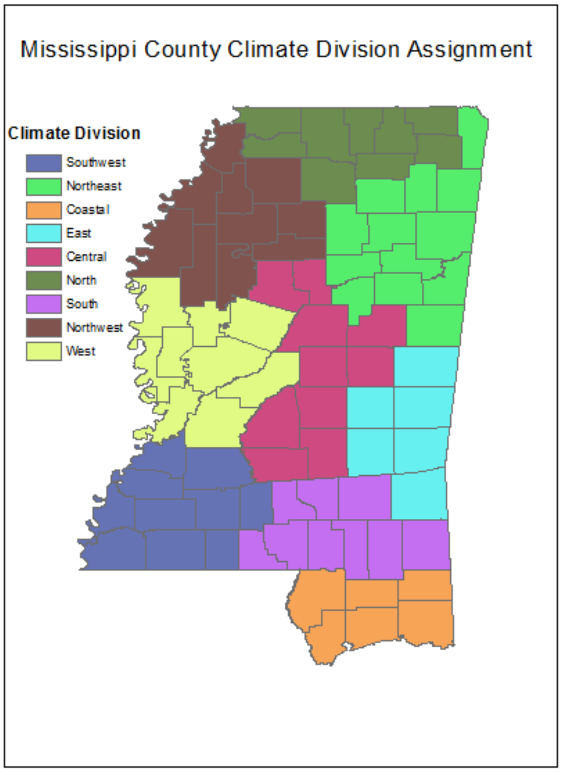


Figure 15b. Virtual Climate Regions

Figure 15. Climate Zones and Weather Stations

Table 3. Methods to Build Virtual Climate Files

Process Name	Description	Discussion
No Change	Used 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 this 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 is 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-bias series of trends.
Biased Adjusted Climate	The 40-year historic data is 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 an 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.

Sensitivity Analysis

This portion of the study examines how the improved climate data input files impact the pavement performance prediction. The improved climate data input files use a longer period of climate history and information from significantly more weather stations. The sensitivity study will determine if the resources used to build the improved climate files were an appropriate effort with a measureable long-term benefit.

The sensitivity analysis measured the impact of the three different climate input files (MEPDG, Historic, and Virtual) on the predicted performance of three common types of pavements used in Mississippi. The first pavement is a conventional 9-inch jointed plain concrete pavement on a lime stabilized base. The second pavement is a 12.5-inch thick HMA pavement directly on subgrade. The third pavement is a 4.5-inch thin HMA pavement placed on a permeable asphalt base and granular base. As shown in Figure 16, these are significantly different pavement sections and should have different predicted pavement performance.

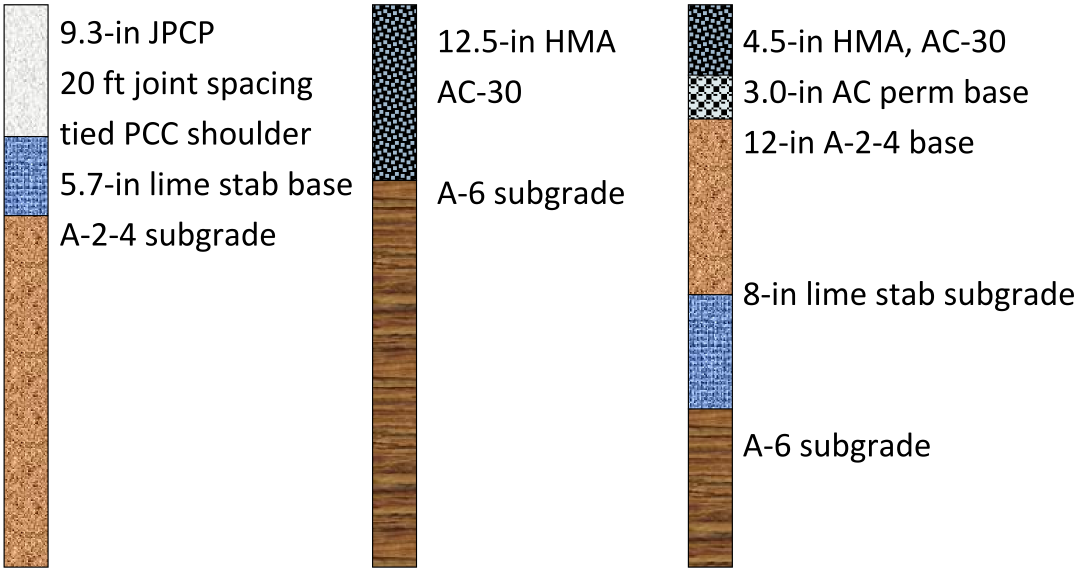


Figure 16. Pavement Structures Used for Sensitivity Analysis

The predicted performance for each of the three pavement types was examined for each of the climate regions defined for Mississippi. For the purpose of this sensitivity analysis, the nine virtual climate regions were logically paired with the first nine standard climate regions. For example, standard climate zone 1 was compared to virtual climate region north-west. The boundaries of the virtual climate zones were refined after the sensitivity analysis was completed. There was no comparison made for standard climate zone 10, but it would have been paired with virtual climate region south-east (coastal).

The sensitivity analysis compared the predicted pavement performance of each of the three pavements, for each of the three climate input data files, in each of the climate regions. The analysis examined the 40-year response of the PCC pavement and the 20-year response of the two HMA pavements. To keep the level of analysis manageable, the predicted pavement faulting and ride for the PCC pavement and the predicted pavement performance rutting and ride for the HMA pavements were examined.

To match the climate files for this analysis, one county historic climate database was selected from each of the ten standard climate regions. In three of the climate regions (Regions 3, 4 and 10), the county was selected to directly match a MEPDG climate station. In the other climate regions, the county historic climate data file was randomly selected, generally away from the MEPDG climate file locations. This selection created another step in the MEPDG software to merge adjoining MEPDG climate stations. Table 4 and Figure 15 give the locations used in this sensitivity analysis. The light blue rings identify MEPDG climate file locations. The blue rings with orange fill are the locations used for this analysis. Minor differences in Table 4 between the selected locations listed and the virtual climate boundaries exist due to the refinement of the boundaries discussed earlier.

As an example, the sensitivity analysis for standard climate zone 5 is based on Leake County. Three existing MEPDG climate stations were merged to develop the MEPDG climate file for Leake County. The specific Historic climate file for Leak County was used for the Historic performance prediction. The Central Virtual Climate File was used to predict the Virtual performance prediction.

Table 4. Climate Files Used for the Sensitivity Analysis

State Climate Zone	MEPDG Station(s)	Historic File	Virtual File Zone
1	West Memphis, AR Memphis, TN Jonesboro, AR	Tunica Co	Northwest
2	West Memphis, AR Memphis, TN Jackson, TN	Benton Co	North
3	Lee Co	Lee Co	Northeast
4	Monticello, AR	Washington Co	West
5	Leflore Co Hinds, Co (1) Hinds, Co (2)	Leake Co	Central
6	Lauderdale Co (1) Lauderdale Co (2) Leflore Co	Noxubee Co	East
7	Warren Co Hinds Co (1) Hinds Co (2)	Claiborne Co	Southwest
8	Pike Co Baton Rouge, LA Warren Co	Pike Co	South
9	Lauderdale Co (1) Lauderdale Co (2) Forrest Co	Wayne Co	Southeast (Coastal)
10	Harrison Co	Harrison Co	no analysis

After the locations were determined, the MEPDG software (version 1.1) was run to generate predicted pavement performance output files for each combination of pavement type (3), climate input (3) and climate zone location (9 or 10). There were 30 sets of pavement performance output files with MEPDG climate, 30 output files for Historic climate, and 27 output files (only 9 virtual climate zones) for Virtual climate.

The analysis of the pavement performance predictions focused on two distress types for each pavement type. For the PCC pavement, the analysis examined the differences in the faulting and ride predictions over 40 years. For the two HMA pavements, the analysis examined the differences in the rutting and ride predictions over 20 years. An analysis of variance (ANOVA) comparison was done for each pavement distress type and generally found significant statistical difference between the predicted performances for the climate input types. However, this analysis examined the predicted performance based on a statewide database. When the data were divided into each climate zone, the analysis using Tukey Confidence Intervals for pair-wise comparisons found significant differences in the predicted performance for only some combinations of climate. Table 5 identifies which combinations of pavement type, climate input and climate zone showed significant statistical difference. Each table cell with an “S” indicates the difference in predicted performance was significant. Based on this analysis, it can be stated that the asphalt pavements were impacted by differences in the climate input files. The concrete pavement performance was not statistically impacted by the different climate input files. From the examination of the results for the two asphalt pavements, it is also noted that there was no statistical difference in predicted pavement performance when comparing the historical and virtual climate input.

It is important to recognize the difference between a statistically significant difference and a practical significant difference. It is possible to have a statistical significant difference that does not have a practical meaning. For example, the predicted rutting could show a 100% increase in the amount of rutting (statistically significant), but the comparison is based on 0.05 inches and 0.10 inches of rutting (not a practical significance).

A set of bar charts was prepared to examine the practical degree of difference between the predicted performances. The bar charts display the difference in pavement performance using the following three sets of climate input comparisons:

1) Compare MEPDG climate to Historic climate (M-H). This comparison determined the impact of the climate files on the state’s MEPDG calibration. Will higher quality climate files improve the accuracy of the local calibration?
2) Compare MEPDG climate to Virtual climate (M-V). This comparison will determine if the Virtual files will have an impact on the design of future pavements. While the virtual climate files have more data, does this amount of data impact the predicted performance?
3) Compare Historic climate to Virtual climate (H-V). This comparison will determine if the added effort to predict changes in future climate will impact the pavement performance predictions. Will changes in the predicted future climate impact the predicted pavement performance?

Table 5. Summary of Significant Pavement Performance Differences* by Tukey Confidence Intervals

Pavement Type	Pavement Performance	Climate Comparison	Mississippi Standard Climate Zone									
			1	2	3	4	5	6	7	8	9	10
PCC	FAULT	MEDPG-Historic										
		MEPDG-Virtual										
		Historic-Virtual										
PCC	RIDE	MEDPG-Historic										
		MEPDG-Virtual										
		Historic-Virtual										
Thick HMA	RUTTING	MEDPG-Historic			S	S	S		S		S	
		MEPDG-Virtual				S	S		S		S	
		Historic-Virtual										
Thick HMA	RIDE	MEDPG-Historic				S						
		MEPDG-Virtual				S						
		Historic-Virtual										
Thin HMA	RUTTING	MEDPG-Historic			S	S	S	S	S	S	S	
		MEPDG-Virtual			S	S	S		S		S	
		Historic-Virtual										
Thin HMA	RIDE	MEDPG-Historic			S	S	S		S		S	
		MEPDG-Virtual			S	S	S		S		S	
		Historic-Virtual										

*S - the predicted performance difference was significant

Figure 17 displays the differences in predicted pavement performance for the PCC pavement. The largest differences in predicted performance for the PCC in this analysis are in climate zones 3, 4, 8, 9 and10. In these zones the results indicate that the MEPDG climate input data would predict more pavement distress than the higher quality historic and virtual climate input files. There are some differences between the predicted performance between the historic and virtual climates in zones 8 and 9. While there are differences in predicted performance between types of climate input files, these differences are relatively small. The difference in faulting is less than 0.02 inches, while the Mississippi maintenance activity threshold for faulting is 0.13 inches. The difference in ride is less than 8 inches per mile and the Mississippi maintenance activity threshold for acceptable ride performance is 127 inches per mile (2.00 mm/m). There is a direct correlation between the changes in faulting and ride. This is expected because the input for ride performance is created by the other pavement performance characteristics. In this case, a change in faulting creates a similar change in ride.

Figure 18 displays the differences in predicted pavement performance for the thick HMA pavement. The largest differences in predicted performance for the thick HMA in this analysis is in climate zone 4. In this zone the results indicate that the MEPDG climate input data would predict more pavement distress than the higher quality historic and virtual climate input files.

There is very little difference between the predicted performance between the historic and virtual climates. While there are differences in predicted performance between types of climate input files, these differences are relatively small. The difference in rutting is less than 0.07 inches, while the Mississippi maintenance activity threshold for rutting is 0.13 inches. The difference in ride is less than 3 inches per mile and the Mississippi maintenance activity threshold for acceptable ride performance is 174 inches per mile (2.75 mm/m).

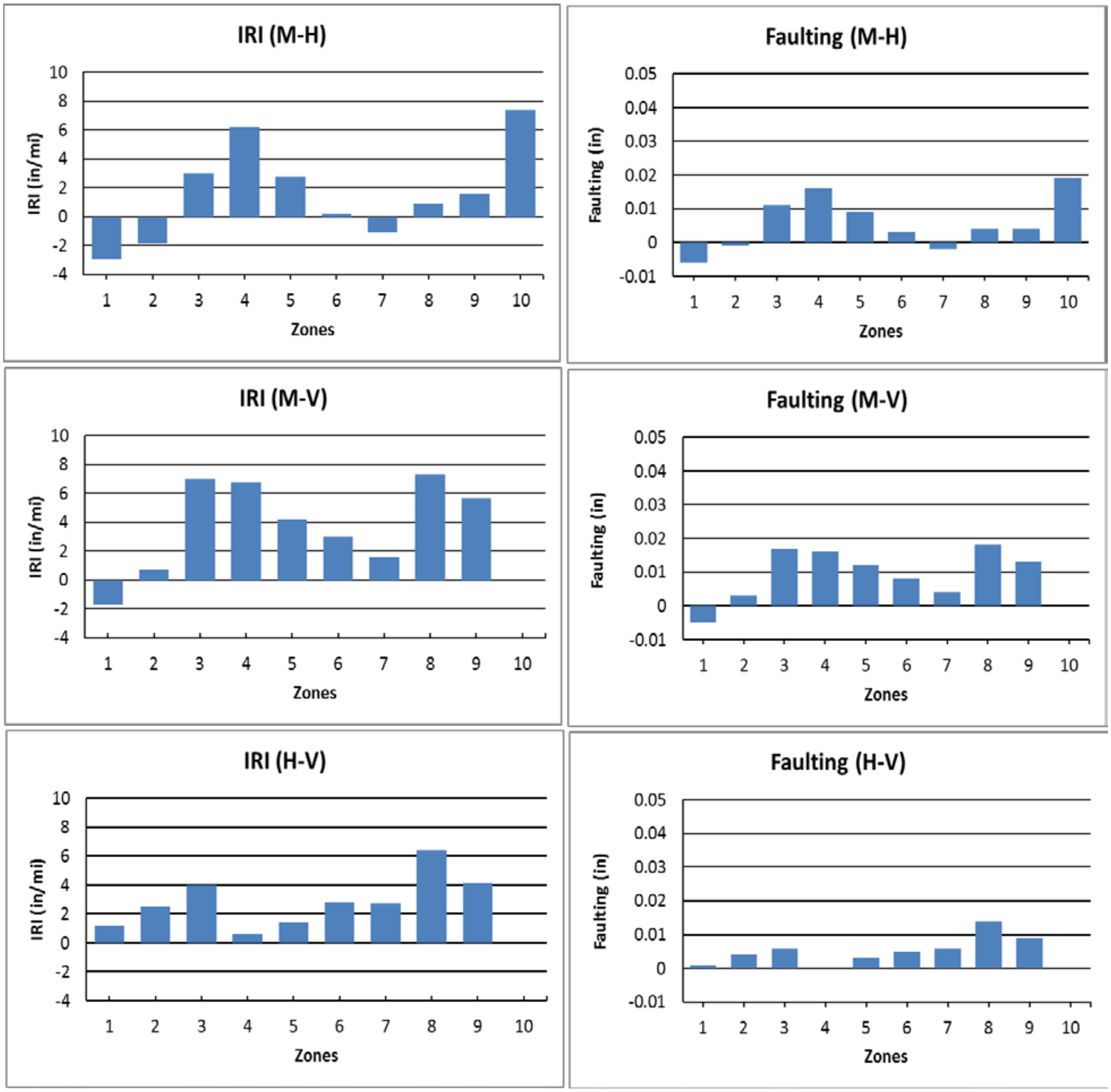


Figure 17. Predicted 40-yr Performance Comparisons for PCC Faulting and Ride

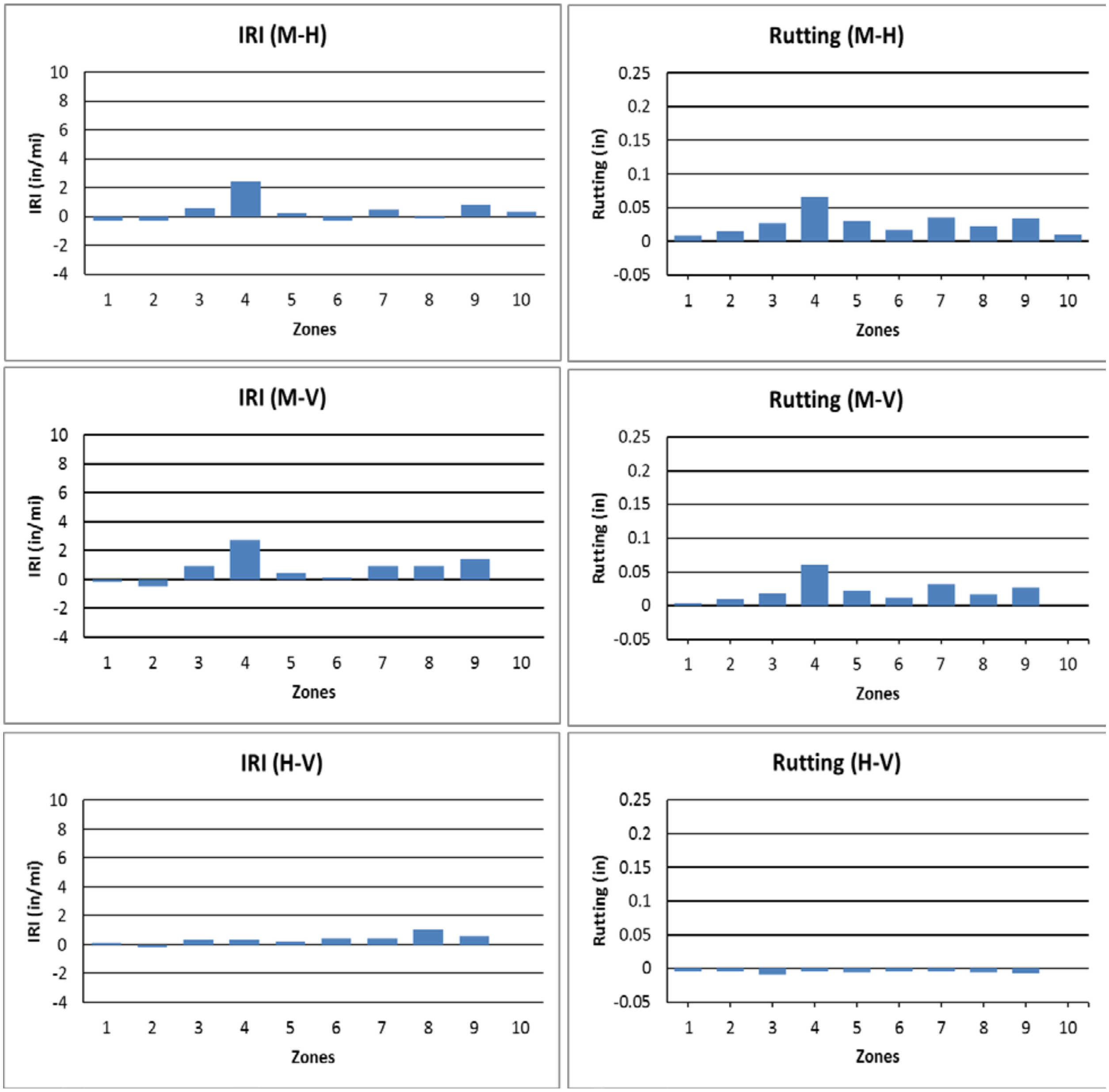
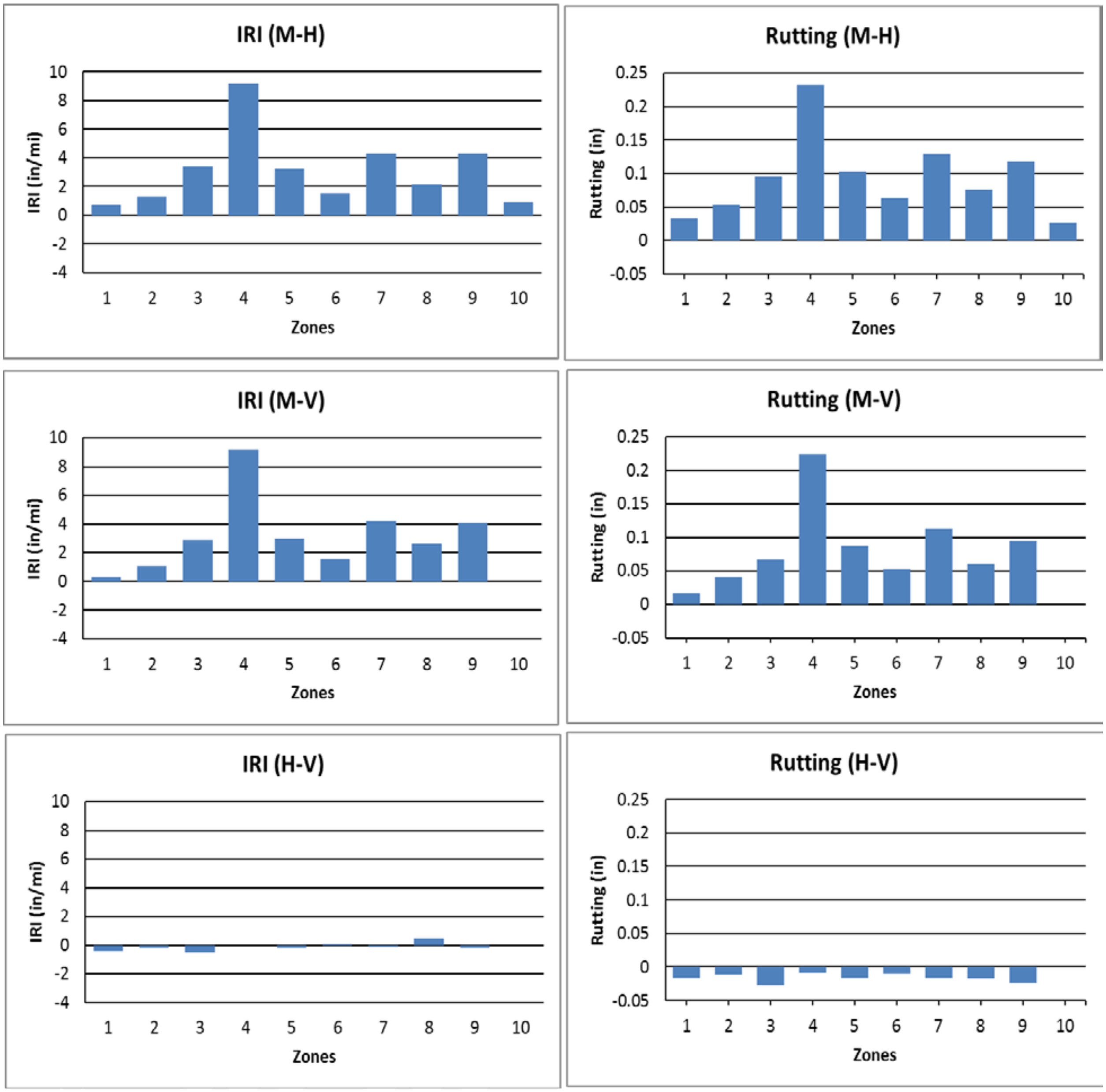


Figure 18. Predicted 20-yr Performance Comparisons for Thick HMA Rutting and Ride

Figure 19 displays the differences in predicted pavement performance for the thin HMA pavement. The largest differences in predicted performance for the thin HMA in this analysis are in climate zones 3, 4, 5, 7 and 9. In these zones the results indicate that the MEPDG climate input data would predict more pavement distress than the higher quality historic and virtual climate input files. The difference in predicted rutting performance in zone 4 is over 0.20 inches, which is significant. There is a consistent small difference between the predicted performance between the historic and virtual climates. This reflects the increase in temperatures built into the virtual climate input files. Except for zone 4, the larger differences in predicted rutting performance between types of climate input files are 0.09 to 0.12 inches. The Mississippi maintenance activity threshold for rutting is 0.13 inches. The difference in ride is less than 10 inches per mile and the Mississippi maintenance activity threshold for acceptable ride performance is 174 inches per mile (2.75 mm/m).


IRI (M-H)

Rutting (M-H)

IRI (M-V)

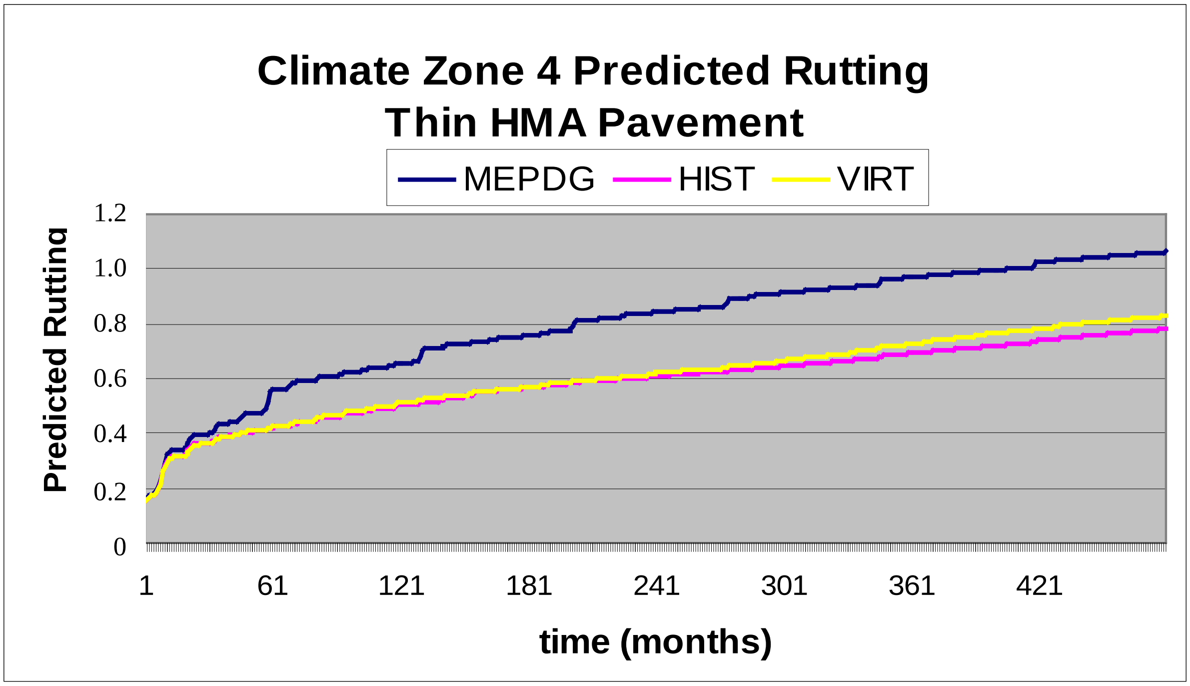
Rutting (M-V)

IRI (H-V)

Rutting (H-V)

Figure 19. Predicted 20-yr Performance Comparisons for Thin HMA Rutting and Ride

For all three pavement types, the MEPDG pavement performance prediction in climate zone 4 shows more distress. Is it possible to determine the climate factor impacting the predicted performance in zone 4? The most significant difference in performance is for the thin HMA pavement. Figure 20 shows the plot of predicted performance for rutting and ride for each of the three climate input files. The predicted performance using the historic and virtual files was very similar. There is an increase in ride distress for the MEPDG climate, but the difference is not significant. The predicted rutting performance for the MEPDG climate clearly shows a significant difference. Of particular note is the step progression in rutting every 67 months.



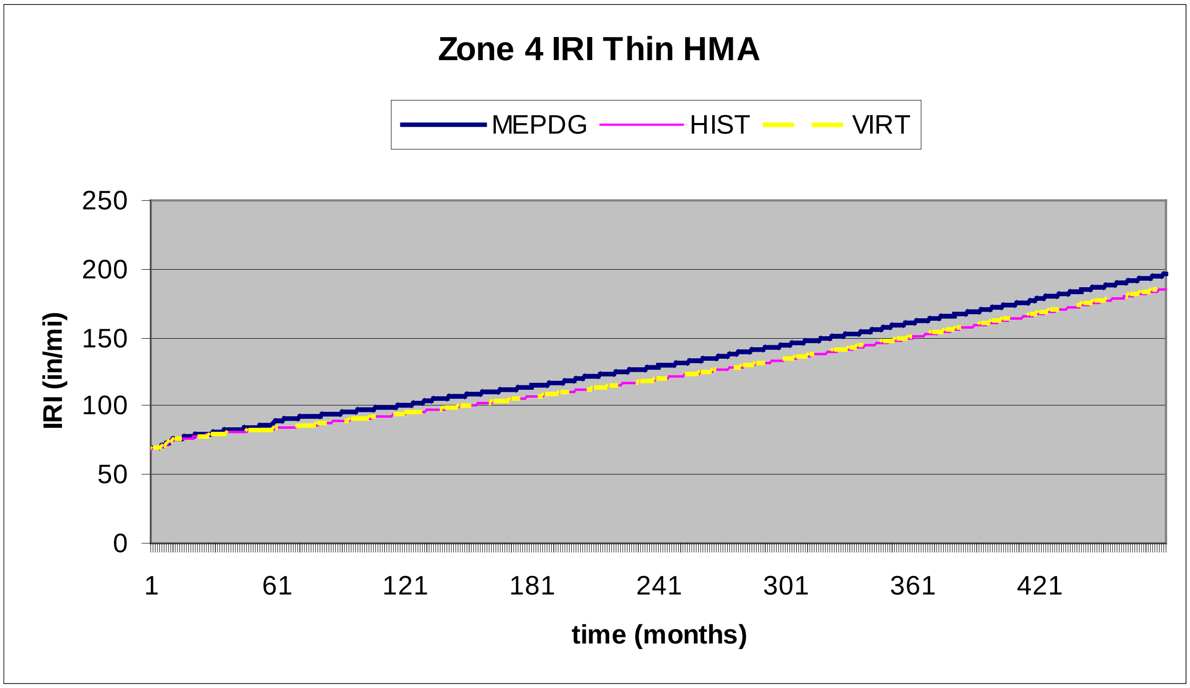


Figure 20. Predicted 20-yr Pavement Performance (Zone 4, Thin HMA)

The pavement surface temperatures were compared to better understand the difference in rutting performance using the three climate input files. This analysis was performed to examine if the pavement surface temperatures corresponded with the predicted performance, specifically for the HMA rutting in climate zone 4. Based on the predicted rutting performance, it would be reasonable to expect the pavement surface temperatures using the MEPDG climate files to be higher than the historic and virtual pavement surface temperatures. Further, the model for the virtual climate temperature did slightly increase over time and the MEPDG output pavement surface temperatures should show a slight increase from the historic to the virtual climate. Figure 21 shows MEPDG computed the pavement surface temperature comparison for all three climate input files in zone 4. Each group of three bars gives the Historic, MEPDG, and Virtual surface temperature (respectively). Each group of nine bars gives the average of the lowest 20% of the hourly surface temperatures for that month (1st quintile), the average surface temperature for the month, and the average of the highest 20% of the hourly surface temperatures for the month (5th quintile). It is easy to observe the higher MEPDG climate data averages for the 5th quintile. In July and August, the MEPDG 5th Quintile average pavement surface temperature is more then 10°F higher than the pavement temperature using the historic and virtual climate data. The 5th quintile temperatures would have the most severe impact on predicted pavement rutting.

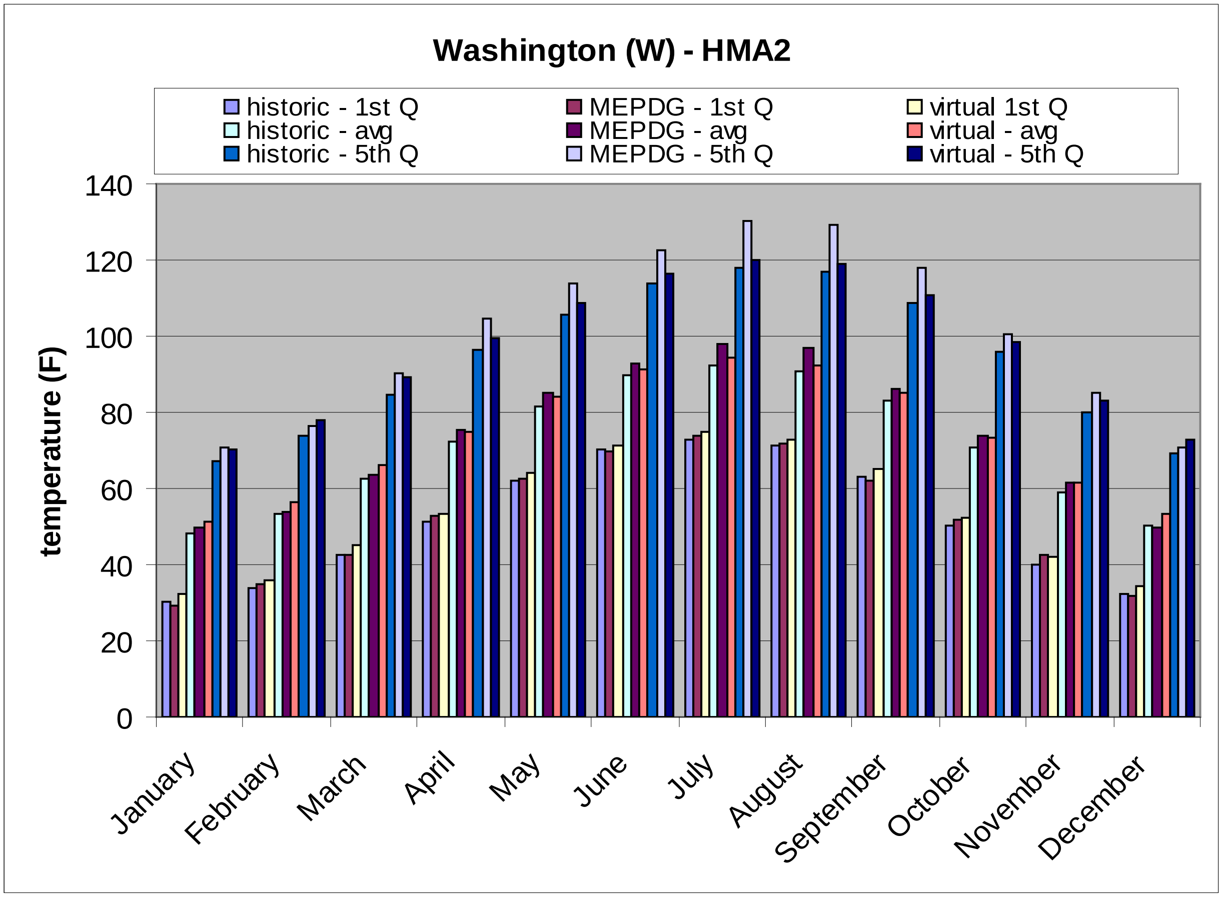


Figure 21. Comparison of Historic and Predicted Pavement Surface Temperatures; Thin HMA in Washington County
(1st Quintile, Average, 5th Quintile)

In a similar analysis, Figure 22 shows the impact of pavement type. As expected, the reflectivity of the PCC resulted in lower 5th quintile average high temperatures compared to the HMA surfaces. Likewise, the thin HMA pavement section (HMA 2) is predicted to be slightly hotter than the thick HMA pavement (HMA 1) due to the pavement's smaller mass (thickness) which does not have the same ability to store and dissipate the heat.

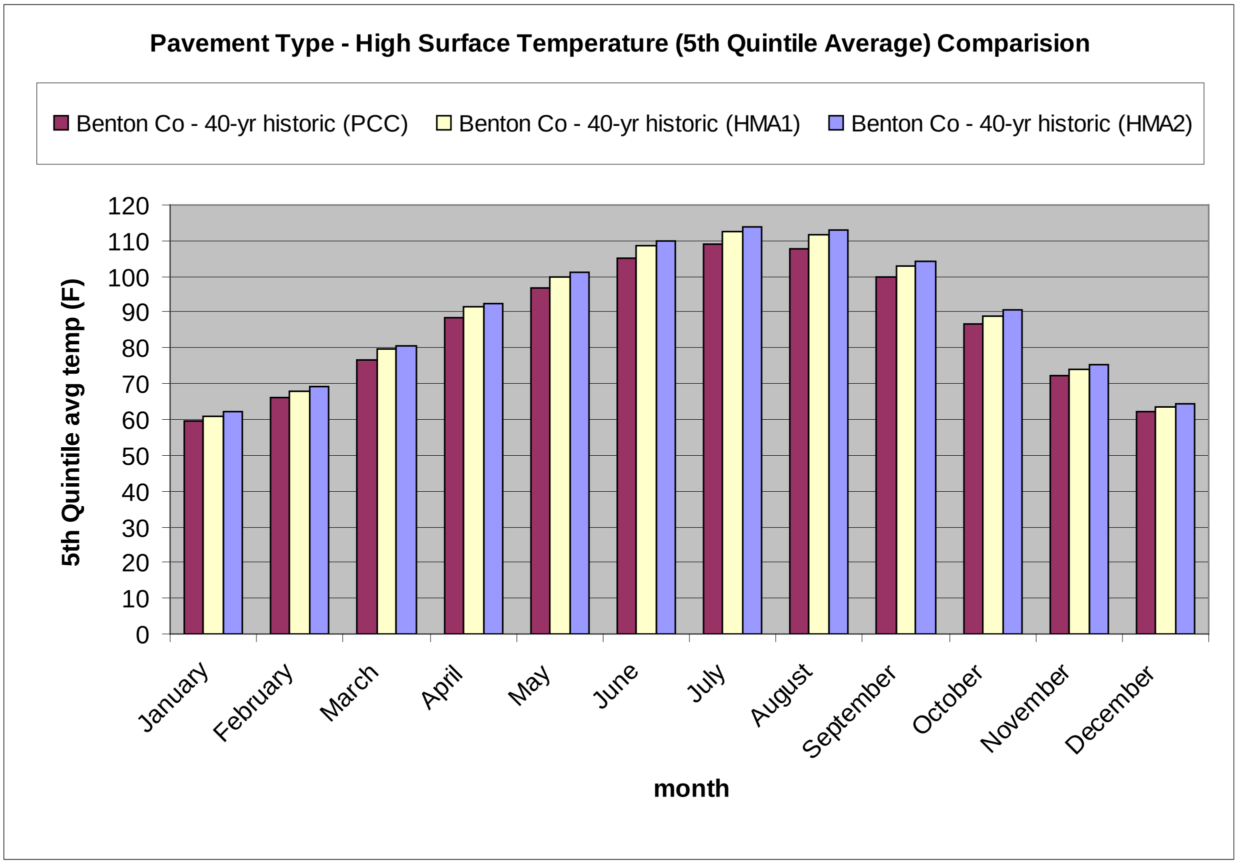


Figure 22. Pavement Type Surface Temperature Comparison

The analysis of the pavement surface temperatures predicted in the MEPDG program provides a degree of confidence that the temperatures used to predict pavement performance (distress) are reasonable. Therefore the analysis of pavement performance can move forward with the knowledge that the climate data input is acceptable.

The 5th quintile averages clearly show the MEPDG climate input file is generating higher temperatures than the Historic and Virtual input files. The next step in the analysis examined the specific climate input data files for climate zone 4 to isolate the differences. The first observation is the MEPDG climate file for zone 4 only contains 88 months of climate data and the Historic file contains 434 months of data. Figure 23 shows the cumulative distribution of the monthly high temperatures for both sets of climate input data. The cumulative distribution curves are very similar and the upper 20% of the curves (80% to 100%) are almost identical. This comparison does not agree with the comparison of quintile averages. Figure 24 is a bar chart of the actual distribution of the monthly high temperatures. Both the Historic and MEPDG climate data distributions are skewed left and the percent of maximum high temperatures for 95°F and 100°F are higher for the 40-year Historic file. Again, this analysis does not support the monthly quintile observations.

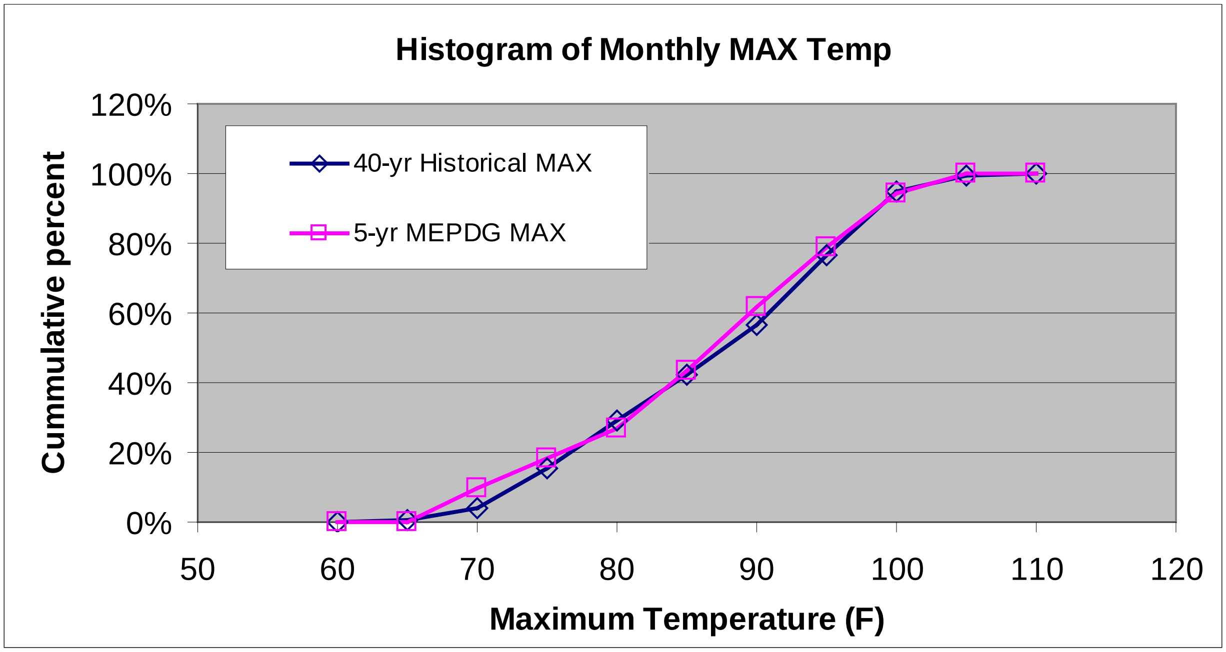


Figure 23. 5-yr MEPDG and 40-yr Historic Maximum Monthly Temperature Cumulative Distribution

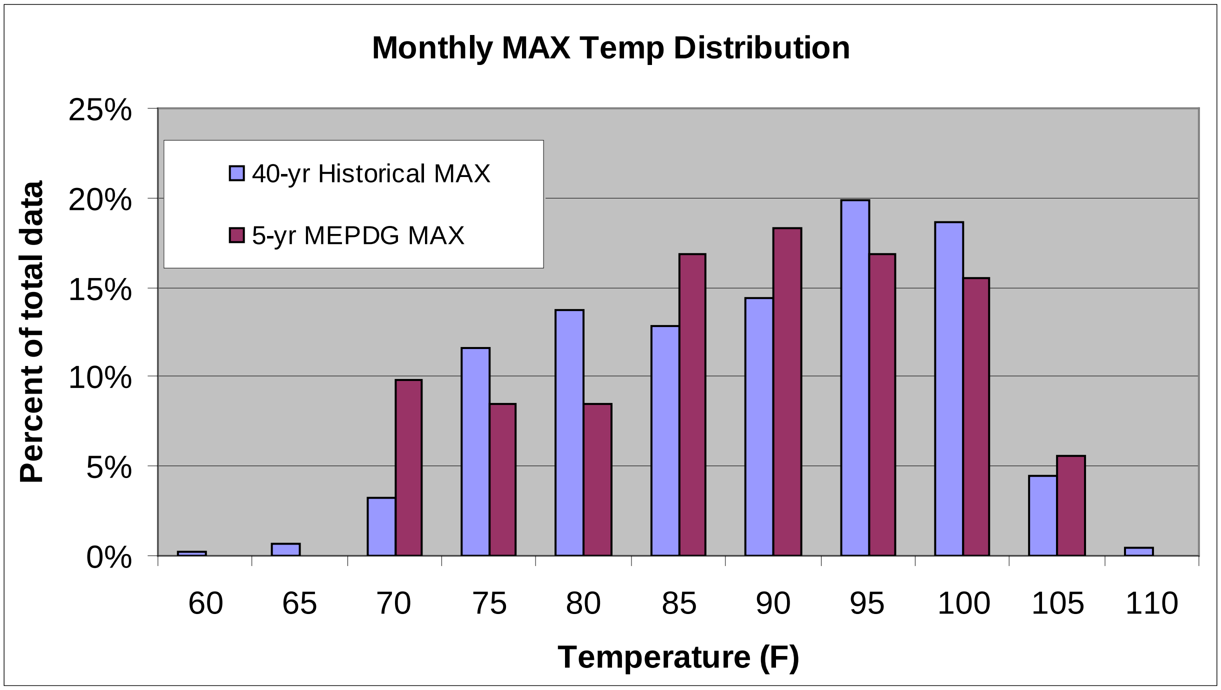


Figure 24. 5-yr MEPDG and 40-yr Historic 5th Quintile Maximum Monthly Temperature Distribution

Examining the climate input data on a combined basis did not identify information to support the higher 5th quintile averages shown in the MEPDG output file. The next step is to look more directly at the climate data. One step in developing the Historic climate input files was to start with daily temperature highs and lows from the COOP database that have been checked for quality and merged the highs and lows with automated hourly distributions to create better quality hourly distributions. Were there significant changes when the hourly temperatures were upgraded? Figure 25 compares the monthly average and maximum temperatures for the MEPDG and Historic climate input files during identical chronologic times, August 1999 through June 2005. There are some minor deviations between the curves, but the differences do not support the differences in monthly 5th quintile average.

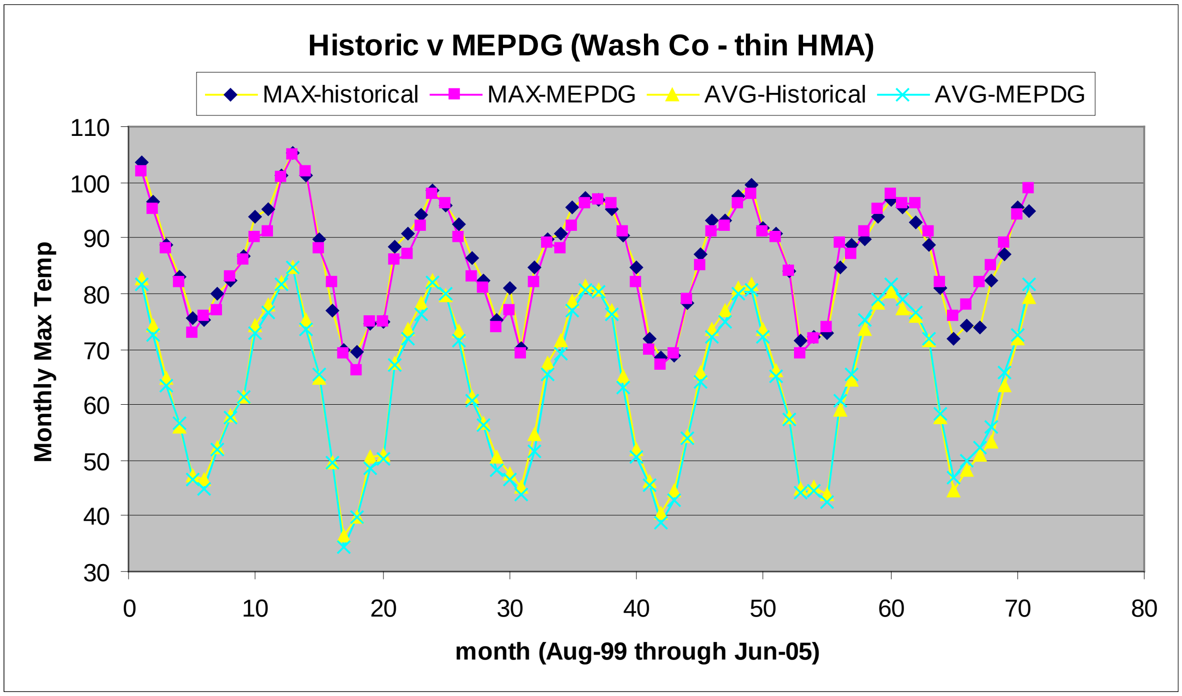


Figure 25. MEPDG and Historic Temperature Comparison, Same Time Period

The procedure used in MEPDG to apply the climate data is not bound by the year of the climate file or the year of construction. The MEPDG initiates the climate on the month of construction. For this analysis, the MEPDG climate file was initiated in August 1999 and the Historic climate file was initiated in August 1970. From the perspective of pavement performance comparison, the climate files should be compared based on the month the climate files are applied in the pavement prediction. Figure 26 displays the first six years of climate used in the MEPDG analysis for both the MEPDG climate input file and the Historic climate input file. Most of the data show similar summer and winter maximum temperatures, but there are two consecutive months (month 13 and 14) of high summer maximum temperatures one year after construction when the MEPDG climate input is 10°F higher than the Historic climate input. This is likely a major difference in the two climate files that is creating the significant change in predicted pavement rutting performance.

The fact that the change occurs after the first year is only a part of the explanation. The MEPDG climate input file for zone 4 is only six years of data. For the MEPDG pavement performance prediction software to complete a 20-year performance projection, the MEPDG climate input file is repeated multiple times. Each time the climate file is repeated, the same two-month high temperature event re-occurs as part of the climate input. Re-examining Figure 20, the impact of this event in the stepped rutting prediction is clearly evident. Each step in predicted rutting corresponds with the repetition of the MEPDG climate file.

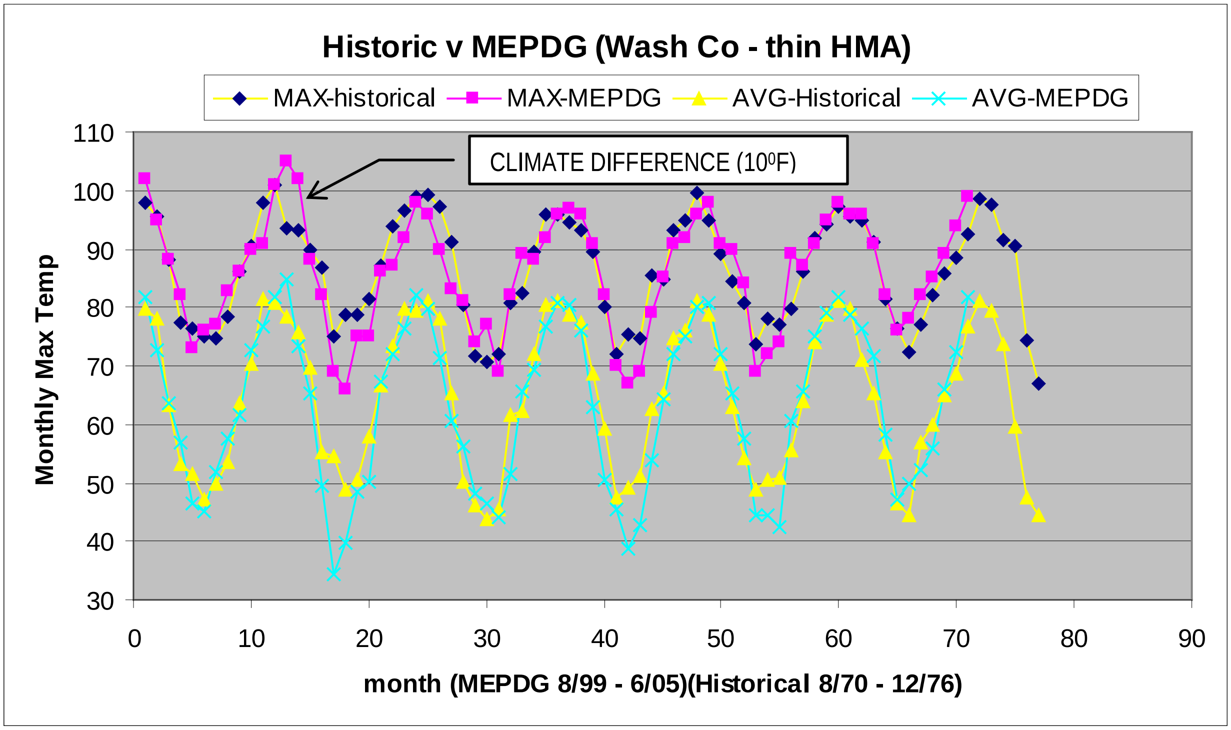


Figure 26. MEPDG and Historic Temperature Comparison by Prediction Start Date

Figure 27 ties this sensitivity analysis back to the calibration, validation and use of the MEPDG for pavement design. The six sets of performance curves compare the actual field performance of the three pavement sections used in this study with the MEPDG prediction using the MEPDG climate file and Historic climate file. The field performance data represents unprocessed DOT PMS data. This comparison gives a clear indication of the importance of good climate input data, but has certain limitations. The key limitation is the need to properly calibrate the MEPDG prediction models for Mississippi pavement performance. Only one of the six predictions (thick HMA rutting) is close to the actual measured performance. For all three pavements, the ride prediction underestimates the increase in roughness. The second limitation is how the MEPDG currently uses climate input data. The current software starts at the beginning of the climate data without regard to the year. For calibration of the MEPDG models, the climate should match the time period of the measured performance. For example, if the pavement section for calibration is constructed and open to traffic in 1985, then the climate file for calibration should also start in 1985. In the case of the actual and predicted performance shown in Figure 27, the starting year for the actual performance and the starting years for the climate files for the predicted performance are given in the legend for each set. The impact of the climate input data is greater for the individual distress than it is for the combined affect on the pavement ride. Using the proper historic climate data for the correct time period will create a more accurate set of calibration factors than using the MEPDG climate files.

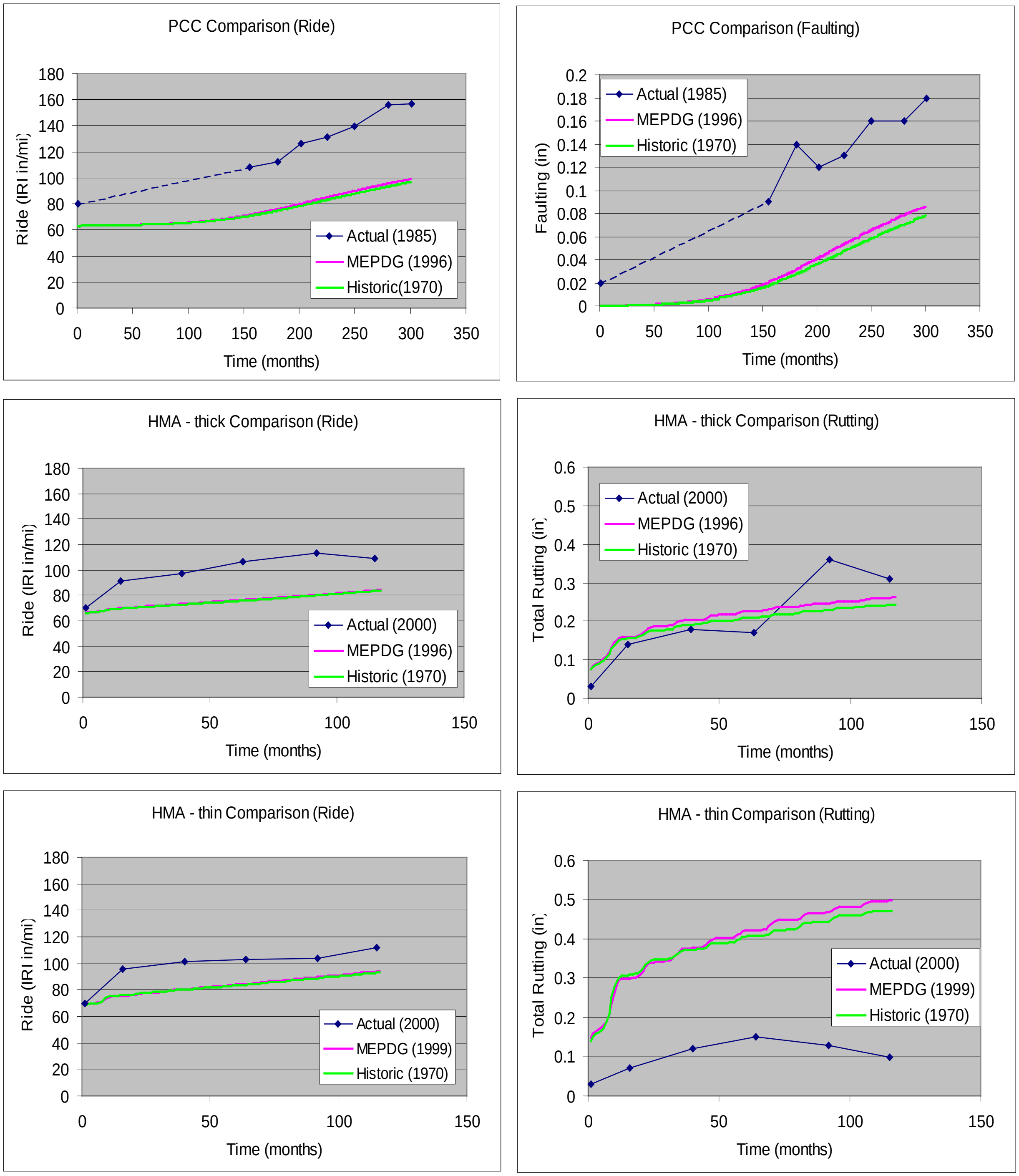


Figure 27. Comparison of actual field performance to MEPDG predicted performance

Conclusions

It was noted at the outset that the climate files for Mississippi which would be used with MEPDG version 1.1 generally include less than ten years of the available climate data. Subsequently, MEPDG climate data files were created using information compiled from ASOS climate databases. It should be noted that the information in these databases are automated data that does not have a system providing rigorous, dedicated quality control checks. It should be further noted that this same ASOS climate database is used for the new DARWin-ME climate files.

Climate scientist have access to different levels of climate data that can be merged together to create high quality hourly data. For this project, several sources of climate data were used to build accurate Historic data files which compiled 40 years of information. Climate input data sets were developed to generate a relatively dense grid of historic climate data. It should be noted that even if some of the climate files for the DARWin-ME™ pavement design software contain more years of data, the number of locations and quality of the data would not be as good as the Historic files created as part of this project.

There are numerous legitimate methods for generating twenty to forty years of future climate data for use in predictive pavement designs. Therefore, each state transportation agency will need to identify the method they determine to be the most appropriate for pavement design within the boundaries of their authority by weighing the advantages and disadvantages of each approach and the data quantity and quality available to support it.

Finally, it must be emphasized that attempting to use small climate data files when conducting MEPDG pavement modeling can be expected to excessively exaggerate pavement distress predictions. This is because otherwise minor anomalies and extreme climate events that are likely to be included in the small database will be replicated several times in the modeling analysis as the system attempts to fill the database for the pavement performance period.

Recommendations

To conclude this project summary, there are several recommendations we would like to advance for those considering pavement performance modeling. These are:

- It is important to build a suitable climate database when the period of record is short. To do this, we suggest one obtain the services of climate scientists to help build an extensive, accurate historic climate dataset. Further, their help in construction acceptable virtual (future) climate files for use with the MEPDG is also important in the success of any subsequent pavement modeling effort.
- Use accurate historic climate data for MEPDG calibration. Pavement performance collected for calibration is influenced by the historic climate for the site. The climate input data file should coincide with the performance period of the calibration. Using climate files that do not match the calibration time period may diminish the accuracy of the calibration.
- Select the method for building future climate files that best fits the agency's pavement design approach.

References

Breakah, T., R. C. Williams, D. E. Herzmann, and E. S. Takle, 2010: The effects of utilizing accurate climatic conditions for mechanistic empirical pavement design, a case study. *Journal of Transportation Engineering.* doi:10.1061/(ASCE)TE.1943-5436.0000195]

Gutowski, W. J., Jr., K. A. Kozak, R. W. Arritt, J. H. Christensen, J. C. Patton, and E. S. Takle, 2007: A possible constraint on regional precipitation intensity changes under global warming. *J. Hydromet.,* 8, 1382-1412.

Gutowski, William J., Jr., Stephanie S. Willis, Jason C. Patton, Benjamin R. J. Schwedler, Raymond W. Arritt, and Eugene S. Takle, 2008: Changes in extreme, cold-season synoptic precipitation events under global warming. *Geophys. Res. Lett.,* **35**, L20710, doi:10.1029/2008GL035516.

Jha, M., Z. Pan, E. S. Takle, R. Gu, 2004: Impact of climate change on stream flow in the Upper Mississippi River Basin: A regional climate model perspective. *J. Geophys. Res. 109,* D09105, doi:10.1029/2003JD003686

National Climatic Data Center, http://www.ncdc.noaa.gov

Pan, Z., R. W. Arritt, E. S. Takle, W. J. Gutowski, Jr., C. J. Anderson, and M. Segal, 2004: Altered hydrologic feedback in a warming climate introduces a “warming hole”. *Geophys. Res. Lett.31,* L17109, doi:10.1029/2004GL020528.

Pan, Z., M. Segal, R. W. Arritt, and E. S. Takle, 2004: On the potential change in solar radiation over the U.S. due to increases of atmospheric greenhouse gases. *Int. J. Renewable Energy* 29, 1923-1928.

Segal, M., Z. Pan, R. W. Arritt, and E. S. Takle, 2001: On the potential change in wind power over the U.S. due to increases of atmospheric greenhouse gases. *Int. J. Renewable Energy* **24**, 235-243.

Singh, Ranvir, Matthew J. Helmers, Amy Kaleita, and Eugene S. Takle, 2009: Potential impact of climate change on subsurface drainage in Iowa's subsurface drained landscapes. *Journal of Irrigation and Drainage Engineering*, July/August 2009, 459-466. DOI**:** 10.1061/ ASCE IR.1943-4774.0000009

Takle, E. S., C. Anderson, M. Jha, and P. W. Gassman, 2006: Upper Mississippi River Basin Modeling Systems Part 4: Climate change impacts on flow and water quality. Pp. 135-142. *In* Singh, V. P., and Y. J. Xu, (eds.), 2006: *Coastal Hydrology and Processes*, Water Resources Publications LLC. Highlands Ranch, CO. 509 pp.

Takle, E. S., M. Jha, E. Lu, R. W. Arritt, W. J. Gutowski, Jr., and the NARCCAP Team, 2010: Streamflow in the Upper Mississippi River Basin as simulated by SWAT driven by 20C results of global climate models and NARCCAP regional climate models. *Meteorologische Zeitschrift, 19,* 341-346. DOI 10.1127/0941-2948/2010/0464.

Takle, E. S., and Z. Pan, 2005: Climate Change and Crop Production: Challenges to Modeling Future Scenarios. In Lal, R., N. Uphoff, B. A. Stewart, and D. O. Hansen, 2005, ed., *Climate Change and Global Food Security*. Taylor & Francis. 383-403.

Watson, Dave, nngridr - An Implementation of Natural Neighbor Interpolation, Dave Watson Publisher, Claremont, Australia, 1994.