

NASA PREDICTION OF WORLDWIDE ENERGY RESOURCE HIGH RESOLUTION METEOROLOGY DATA FOR SUSTAINABLE BUILDING DESIGN

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ABSTRACT

A primary objective of NASA's Prediction of Worldwide Energy Resource (POWER) project is to adapt and infuse NASA's solar and meteorological data into the energy, agricultural, and architectural industries. Improvements are continuously incorporated when higher resolution and longer-term data inputs become available. Climatological data previously provided via POWER web applications were three-hourly and 1x1 degree latitude/longitude. The NASA Modern Era Retrospective-analysis for Research and Applications (MERRA) data set provides higher resolution data products (hourly and 1/2x1/2 degree) covering the entire globe. Currently POWER solar and meteorological data are available for more than 30 years on hourly (meteorological only), daily, monthly and annual time scales. These data may be useful to several renewable energy sectors: solar and wind power generation, agricultural crop modeling, and sustainable buildings. A recent focus has been working with ASHRAE to assess complementing weather station data with MERRA data. ASHRAE building design parameters being investigated include heating/cooling degree days and climate zones.

1. INTRODUCTION

The Prediction of Worldwide Energy Resource (POWER) home page at <http://power.larc.nasa.gov> is the central web portal providing user-friendly access to solar radiation and meteorology data useful for renewable energy technologies. The POWER project team is developing the potential of NASA's cloud, radiation, and meteorology data by working closely with partners from government, commercial industry, educational, and non-profit

organizations. To this end, POWER is developing and improving the web based data archive as well as web based portals that provides access to this information. Currently the POWER data ports are focused on industry and research sectors with parameters and formats specifically targeted to needs within the energy, buildings, and agriculture industries. The POWER data archive includes solar insolation on a global 1-degree grid and meteorological data on a global 1/2-degree grid. The solar data is based upon satellite observations, while the meteorological data is from global assimilation models. Satellite-based solar products have been shown to be accurate enough to provide reliable solar resource data over regions where surface measurements are sparse or nonexistent. The meteorological parameters include air pressure, average/minimum/maximum air temperature, relative humidity, dew point temperature, earth skin temperature, and wind speed.

The POWER project, in collaboration with ASHRAE (formally the American Society of Heating, Refrigerating and Air-Conditioning Engineers), have explored a potential and important application of meteorological data products from NASA's Modern Era Retrospective-analysis for Research and Applications (MERRA) assimilation model. ASHRAE is a professional organization with over 50,000 worldwide members. A major emphasis of ASHRAE is in the development of standards for the design of residential and commercial buildings in the United States. Building codes developed by local and state enforcement entities typically based their respective building codes on guidelines developed by ASHRAE. These building codes are typically tied to the dominant climate within the enforcement jurisdiction, where the dominant climate is based upon a 30-year average of local to regional surface observations. Based

upon surface observations ASHRAE, in partnership with the Department of Energy, have developed climate zone maps such as illustrated in figure 1.

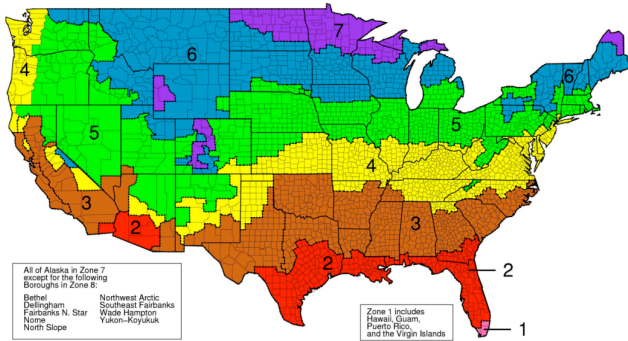


Fig. 1: Briggs *et al.* Climate Zones for the United States

TABLE 1: Characteristics of Briggs buildings climate zones

Zone	Name and Type	Zone	Name and Type
1A	Very Hot – Humid	5A	Cool – Humid
1B	Very Hot – Dry	5B	Cool – Dry
2A	Hot – Humid	5C	Cool – Marine
2B	Hot – Dry	6A	Cold – Humid
3A	Warm – Humid	6B	Cold – Dry
3B	Warm – Dry	7	Very Cold
3C	Warm – Marine	8	Subarctic
4A	Mixed – Humid		
4B	Mixed – Dry		
4C	Mixed – Marine		

A significant shortcoming of the methodology used in constructing such maps is the use of surface observations that may be far removed from the construction site of interest and from the fact that most surface observation sites are located at airports that may not reflect the environment of the construction site. Moreover surface observations can frequently have periods of missing data that need to be filled by various approximation schemes. The MERRA meteorological data offers the potential for supplementing surface observations and/or serving as a primary data source when surface data is unavailable. In this paper we describe results from a study that uses the MERRA meteorological data to construct US and worldwide climate zones such as illustrated in figure 1.

2. MERRA

As part of making data sets available for societal benefit, the POWER project focuses upon providing data quality information. In this case, we are making available data sets from NASA’s Modern Era Retrospective-analysis for Research and Applications (MERRA) data products [1] [2]. MERRA is an atmospheric data assimilation system that produces long-term estimates of key atmospheric meteorological variables at the surface and throughout the atmosphere. In this paper, we focus upon the hourly near surface (i.e. 2m elevation) meteorological quantities with the native resolution remapped to 1/2x1/2 degree horizontal resolution.

The NASA Global Modeling and Assimilation Office Modern Era Retrospective-analysis for Research and Applications (MERRA) assimilation model provides a temporally continuous and global meteorological data set spanning the time period from 1981 through near-present time. Briefly, the MERRA assimilation model is a general circulation model that provides estimates of various parameters via “An atmospheric analysis performed within a data assimilation context [that] seeks to combine in some ‘optimal’ fashion the information from irregularly distributed atmospheric observations with a model state obtained from a forecast initialized from a previous analysis.” The model seeks to assimilate and optimize observational data and model estimates of atmospheric variables. Types of observations used in the analysis include (1) land surface observations of surface pressure; (2) ocean surface observations of sea level pressure and winds; (3) sea level winds inferred from backscatter returns from space-borne radars; (4) conventional upper-air data from rawinsondes (e.g., height, temperature, wind and moisture); (5) additional sources of upper-air data including drop sondes, pilot balloons, and aircraft winds; and (6) remotely sensed information from satellites (e.g. height and moisture profiles, total precipitable water, and single level cloud motion vector winds obtained from geostationary satellite images).

The initial output from MERRA provides hourly surface and vertically resolved meteorological parameters at a global resolution of 0.5° latitude by 0.67° longitude from 1981 to near-present time. For this analysis, a bilinear interpolation was used to regrid the MERRA data to a resolution of 0.5° latitude by 0.5° longitude. We note in particular that the MERRA temperatures represent values averaged over the half-degree grid at an elevation of 2m. In complex terrain the average elevation of the MERRA half-degree grid box is likely to be different from a surface site contained within the borders of the box.

Analysis has been tested to incorporate a lapse rate adjustment of the MERRA temperatures based upon the elevation difference between the MERRA grid and the surface site. Developments in lapse rate adjustment techniques are still being investigated.

3. CLIMATE ZONES

The climate zone classifications illustrated in Figure 1 are based largely upon a multi-step process developed by Briggs *et al.* (2002) using temperature and precipitation values for individual locations. The first step involves a determination of the climate type characterized as: (1) Marine, (2) Dry, or (3) Humid. These climate types and their definitions are described in Table A-1 of Appendix A. The three types are based upon criteria defined using the monthly and annual temperature and precipitation values for a given region. Once the climate type is determined, the final climate zone designation is based upon the local heating degree days (HDD) and cooling degree days (CDD).

The HDD and CDD is defined by ASHARE as:

$$\text{HDD} = \text{SUM}(T_{\text{base}} - \langle T_i \rangle)^+ \quad (1)$$

$$\text{CDD} = \text{SUM}(\langle T_i \rangle - T_{\text{base}})^+ \quad (2)$$

where, T_{base} is the reference temperature to which the degree days are calculated, and $\langle T_i \rangle$ is the mean daily temperature calculated as the sum of T_{max} and T_{min} for the day divided by 2, or $(T_{\text{max}} + T_{\text{min}})/2$. The “+” superscript indicates that only the positive values of the bracketed quantity are taken into account in the sum. For yearly values of HDD and CDD, the sum is taken from $i = 1$ to N , where N is number of days in the particular year. The climatologically averaged HDD or CDD is then the average of the annual values over the desired time period.

For the Briggs *et al.* (2002) climate zones, T_{base} for HDD = 18.3° C (65° F) resulting in the number of HDD for daily averaged temperatures below 18.3° C (65° F); T_{base} for CDD = 10° C (50° F) giving the number of CDD for daily averaged temperatures above 10° C (50° F).

4. VALIDATION

4.1 Temperatures

From the preceding discussion it is clear that the daily averaged (or daily T_{max} and T_{min}) temperature is the dominant parameters used to define a climate zone.

Accordingly, a first step in assessing the applicability of the MERRA data to developing climate zone maps is the validation of near surface temperatures. The evaluation of the MERRA temperatures was based on comparison of the MERRA 2-meter daily average (T_{ave}), and daily minimum and maximum temperatures (T_{min} , T_{max}) with the corresponding 2-meter surface observations obtained from the National Climatic Data Center (NCDC) Global Summary of the Day (GSOD) files. The MERRA T_{ave} , T_{min} , and T_{max} values are based upon the MERRA hourly values. The observational data reported in the NCDC GSOD files are hourly observations from globally distributed surface stations with observations typically beginning at 0000 Universal Time Coordinate (UTC). The NCDC daily T_{ave} , T_{min} , and T_{max} reported in the GSOD were derived from the available hourly observations. For the MERRA versus NCDC comparison reported below, the NCDC daily T_{ave} , T_{min} and T_{max} values were filtered by an “85%” selection criteria applied to the observations reported for each station. Namely, only values from NCDC stations reporting 85% or greater out of the possible 1-hourly observations per day and 85% or greater out of the possible days per month were used. This selection criteria results in a balance of having enough global NCDC stations reporting daily data while also having enough 1-hourly observations to capture the daily temperature cycle.

The MERRA versus NCDC comparison metrics included parameters associated linear least squares fit to scatter plots of MERRA versus NCDC (*i.e.* slope, intercept, and the coefficient of determination, R^2), the root mean square error (RMSE), mean bias error (MBE), and the absolute mean bias error (AMBE) of the MERRA based values relative to the NCDC values. The MBE, AMBE, and RMSE are given as:

$$\text{MBE} = \left(\frac{1}{N} \right) \sum_j \left\{ \sum_i [(T_{ij})_{\text{MERRA}} - (T_{ij})_{\text{NCDC}}] \right\} \quad (3)$$

$$\text{AMBE} = \left(\frac{1}{N} \right) \sum_j \left\{ \sum_i \text{ABS}[(T_{ij})_{\text{MERRA}} - (T_{ij})_{\text{NCDC}}] \right\} \quad (4)$$

$$\text{RMSE} = \left\{ \sum_j \left\{ \sum_i \left(\frac{1}{N} \right) [(T_{ij})_{\text{MERRA}} - (T_{ij})_{\text{NCDC}}]^2 \right\} \right\}^{1/2} \quad (5)$$

where, \sum_i is summation over all days meeting the 85% selection criteria described above, \sum_j indicates the sum over all stations, $(T_{ij})_{\text{NCDC}}$ is the temperature on day i for station j , and $(T_{ij})_{\text{MERRA}}$ is the MERRA temperature for day i and station j , and N is the number of matching pairs of NCDC and MERRA values. The temperature evaluation was performed using observations from

surface sites within a CONTinental United States (CONUS) study region of rectangular shape defined by 23°N 125°W and 50°N 65°W.

Figure 2 show the scatter plots of daily Tave, Tmin, and Tmax based upon MERRA hourly temperatures versus corresponding values from 1,116 surface sites reporting observations meeting the 85% selection criteria within the CONUS region defined above. In the upper left corner of each figure are the parameters for the linear least squares regression fit to these data, along with the MBE and RMSE between the MERRA and surface site observations, and the color bar gives the number/percentage of observations within each color. Overall the MERRA data exhibits a very high degree of correlation with the surface observations (R=0.94), and perhaps equally significant is the fact that well over 80% of the MERRA versus surface data falls along a central core (i.e. non-blue values) of the scatter plot.

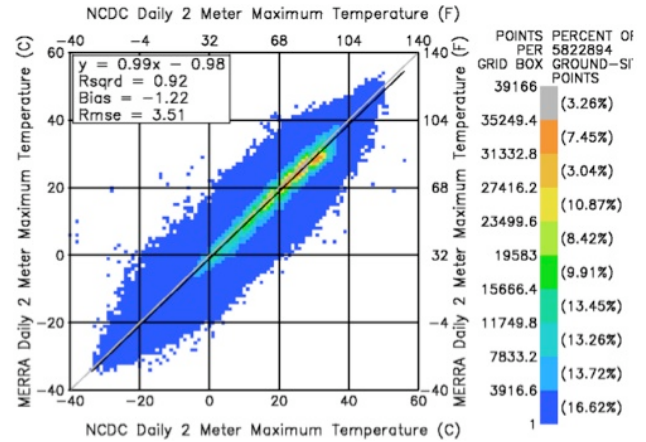
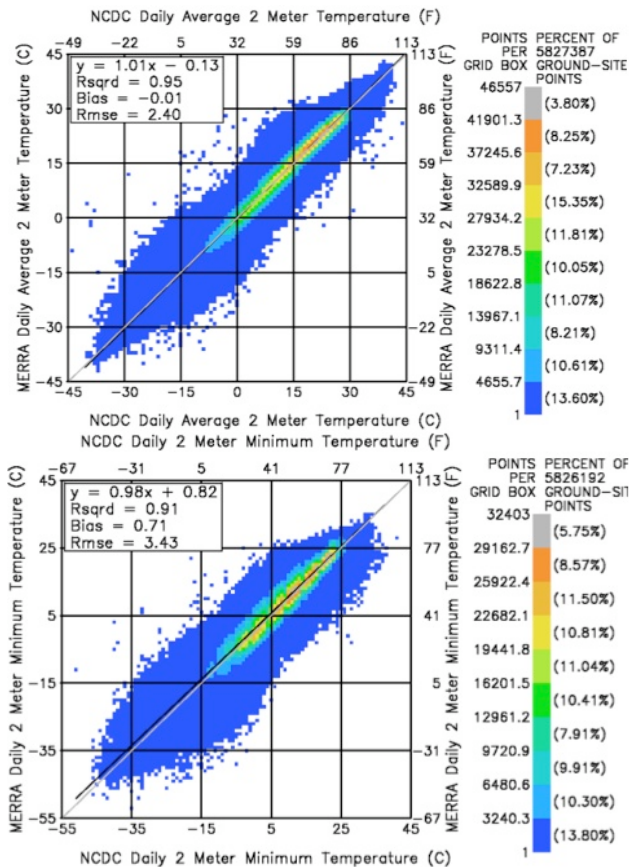
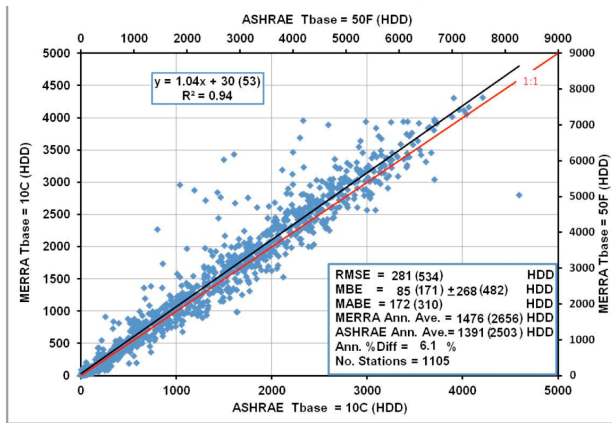


Fig. 2: Scatter plots of the MERRA temperatures (Tave, Tmin, and Tmax) for 1/2x1/2 degree grid boxes versus observations from surface stations contained within those MERRA grid boxes. The comparison covers 1,116 surface stations in the CONUS study region meeting our 85% selection criteria. The color bar is indicative of the number and percentage of observations represented by each color.

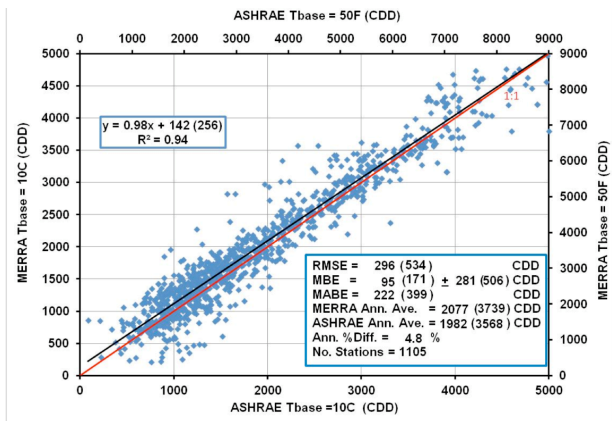


4.2 Heating and Cooling Degree Days

Since HDDs and CDDs are a core component of the development of climate zones, an important element in this analysis is the comparison of the HDD and CDD based upon MERRA and to the equivalent values based upon surface temperatures. The surface based HDD and CDD values were taken from the ASHRAE Weather Data Viewer (WDV) CD-version 4 which provided the annual averaged values at surface sites over the years 1982 – 2006. Accordingly, only MERRA temperatures for these years were used. HDD and CDD were calculated using Eqs. (1) and (2). Figures 4 and 5 show scatter plots of the annual averaged heating and cooling degree days based upon MERRA hourly temperatures for MERRA cell overlapping the respective surface sites and values extracted from the ASHRAE WDV-4 for 1,105 surface stations in the CONUS study region. The HDD and CDD are averaged over the years 1982 – 2006. For both the annual HDD and CDD the MERRA based values are greater than the ASHRAE values based upon surface site observations by 85 °C days (Figure 4) and 95 °C days (Figure 5) respectively. However, both of these biases are well within the value of their respective standard deviations (HDD ± 268 °C days; CDD ± 281 °C days), given in the lower left box on each figure.



(a)



(b)

Fig. 4: Comparison of the MERRA based HDDs (a) and CDDs (b) versus the respective values taken from the ASHRAE WDV-4 Standard deviations are provided for the MBE. Numbers in parentheses are based on degrees Fahrenheit.

4.3 Climate Zones

As a final point of assessment, climate zones based upon surface observations were taken from the ASHRAE Addendum b to ANSI/ASHRAE Standard 169-2006 (Public Review Draft of the Proposed Addendum b to Standard, Climate Data for Building Design Standards) and compared to climate zone values based upon MERRA meteorological data for overlapping grid cells. The time period for the ASHRAE and MERRA data was nominally 1982 – 2006. The MERRA data was continuous and complete over this time. The ASHRAE characterization of climate zones was based upon observations from ground sites having a minimum of 8 years. In the comparison of the climate zones based upon the MERRA and surface site observations, the MERRA years of data

were matched with the surface observations, however no attempt was made to match the monthly data. For example, the MERRA data for a given year is temporally continuous while the surface observation could be missing data from one or more months.

Figure 5 shows the comparison of climate zone designation for 889 surface sites and the corresponding values for the overlapping MERRA grid.

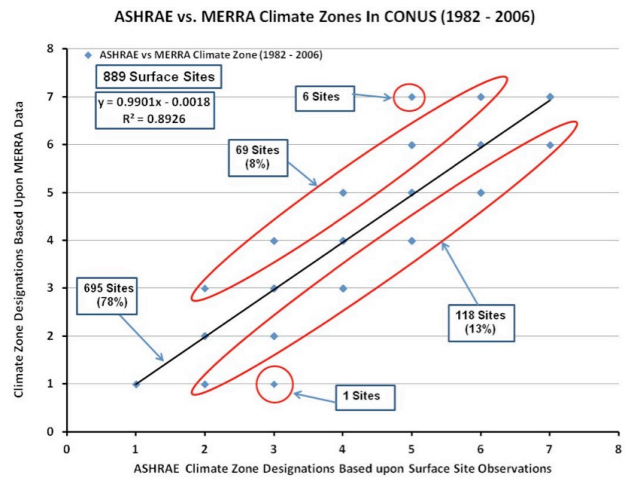


Fig. 5: Comparison of the ASHRAE climate zones based upon surface observations to those based upon MERRA meteorological values. The ASHRAE and MERRA values are yearly values averaged over the 1982 – 2006 time period.

For 695 sites (*i.e.* 78% of the sites) there was a 1:1 correspondence between the MERRA and Surface based climate zones. For about 13% of the sites (118 sites) the MERRA classification underestimated the climate zone by 1 and for about 8% of the sites MERRA overestimated the zone value, and for 6 sites, all in ASHRAE zone 5, the MERRA classification was zone 7.

5. MERRA CLIMATE ZONE MAPS

From the preceding sections it is clear that the MERRA ½-degree data can serve as a supplement to surface observations and as a credible primary data source in the absence of surface observations. As already noted the MERRA data set is currently continuous from 1981 to within several months of real time. Equally noteworthy is that MERRA is spatially contiguous on a global scale albeit with a ½-degree resolution. Combined these attributes lend themselves to construction of regional to global maps such as illustrated in Figures 6-8. Figure 6 shows the CONUS map of MERRA temperatures at 2m

above the surface and Figure 7 shows, respectively, the HDD (a) and CDD (b) maps for the CONUS region.

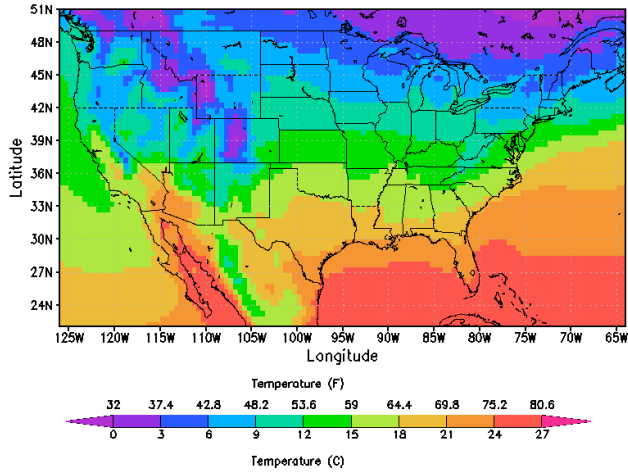
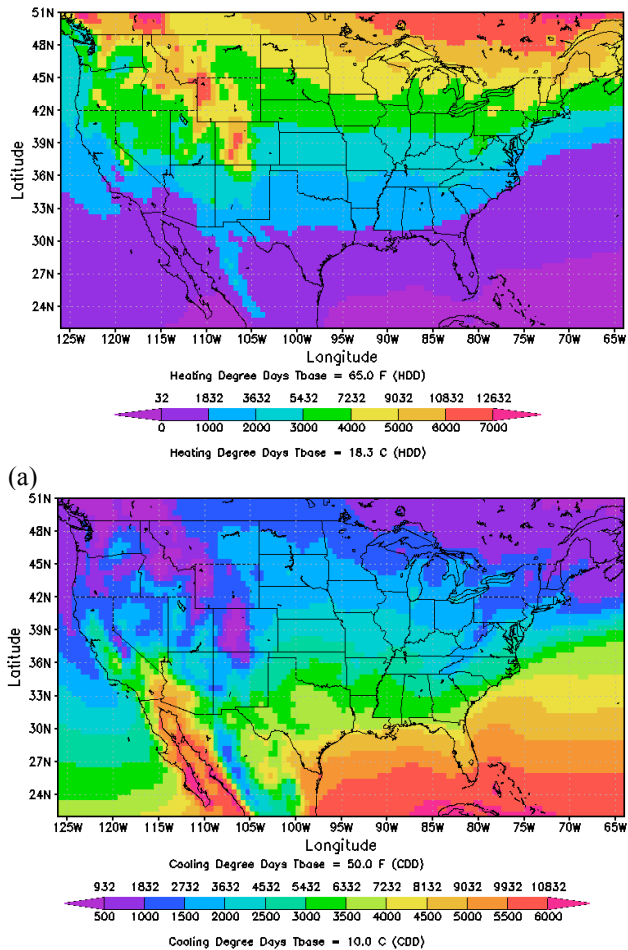


Fig. 6: Near surface temperature map constructed using MERRA temperatures at 2m above surface.



(b)
Fig. 7: HDD (a) and CDD (b) map constructed using MERRA near surface temperatures.

Fig. 8: is the CONUS climate zone map and Figure 9 is a World climate zone map both based upon MERRA temperatures. Note also that we have included a new climate designated as zone 0 in these maps which is under review by the Climate Committee within ASHRAE. Climate zone 0 is characterized as being extremely hot (i.e. $CDD_{50^{\circ}F} > 10,800$, $CDD_{10^{\circ}C} > 6000$) either in a dry or humid environment.

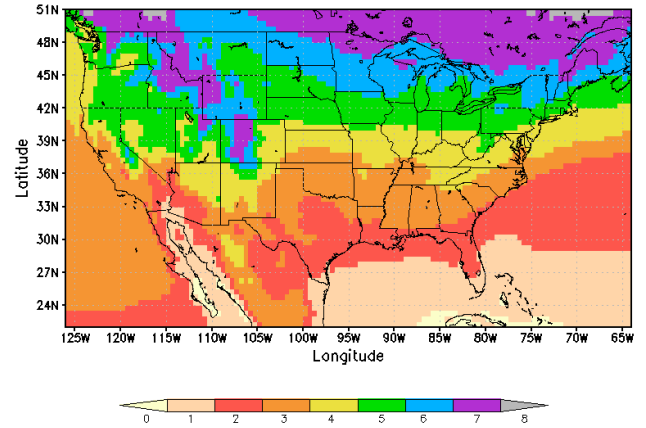


Fig. 8a: CONUS climate zone map. Note the addition of climate zone 0.

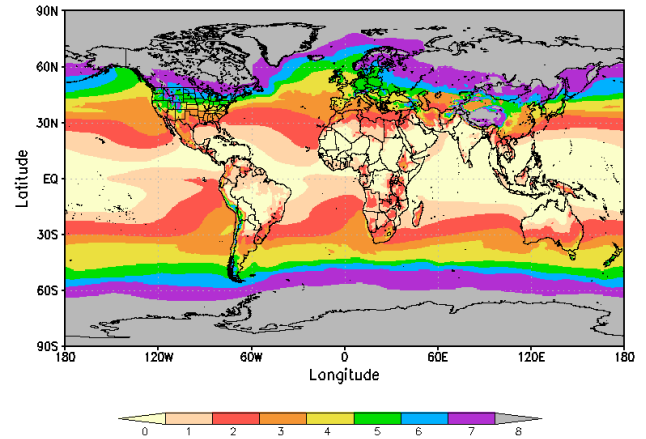


Fig. 9: Climate zone of the world based on MERRA temperatures.

6. LONG-TERM SURFACE METEOROLOGICAL PRODUCTS FROM MERRA

The POWER project has provided near real-time daily averaged radiation and meteorological time series data via the Internet for several years on a 1x1 degree scale. The time series data has a begin date of January 1, 1983 for meteorology and July 1, 1983 for radiation. The data stream is appended to as soon as the data become available. Typically, the meteorology is current to within

three days before present and the radiation is current to within 7-10 days before present. There have been changes in the input data (2 changes for meteorology and 1 change for radiation) in the course of the past 30 years.

Currently, the MERRA input data sets from the NASA Goddard Global Modeling and Assimilation Office (GMAO) are produced with a lag of 2-3 months. Meteorological daily averaged time series data is now available from January 1, 1981 through November 30, 2012 on the POWER web site.

ASHRAE in partnership with the Department of Energy develop the climate zone maps which are used by state and local governments to define building code specifications for heating, cooling, and window systems, etc., that are appropriate and energy efficient for their typical environment. Currently, ASHRAE is working towards improving on the method provided by Briggs [3]. ASHRAE has put out a draft "Proposed Addendum b to Standard 169, Climate Data for Building Design Standards: July 2012" for public review. The POWER project is evaluating the use of MERRA data to produce global climate zone maps using the proposed improvements to the method. Most of the data analysis has been centered on the contiguous United States (CONUS), but can be applied globally.

7. SUMMARY

Satellite based products have been shown to be accurate enough to provide reliable solar resource data over regions where surface measurements are sparse or nonexistent. Insolation and many other environmental parameters (e.g. cloud amount, air pressure, average/minimum/maximum air temperature, relative humidity, dew point temperature, earth skin temperature, wind speed) of interest to the above-mentioned industries are made available on a worldwide basis through the POWER web portal. The NASA MERRA data set is now providing a path to produce higher resolution data products, improving on past POWER data products.

Currently useful in a variety of applications, future versions of these data have the potential to significantly advance the global adoption of renewable energy technologies, facilitate the design of sustainable buildings, and the development of more efficient agricultural practices. An important finding is that MERRA is useful for climate zone determination and will be useful to evaluate changes in zones as the time series is extended into the future.

8. ACKNOWLEDGEMENTS

Support for this work was provided through the NASA Earth Applied Science program under the direction of Lawrence Friedl and through a grant under a NASA program to contribute to the National Climate Assessment under the direction of Dr. Jack Kaye and Lawrence Friedl. The authors would like to thank members of ASHRAE TC-4.2 for their useful comments and suggestions in this work.

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