Energy and Buildings 54 (2012) 418–425

Contents lists available at SciVerse ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Relationship between annual mean temperature and degree-days

Monjur Mourshed*

Building Energy Research Group (BERG), School of Civil and Building Engineering, Loughborough University, Loughborough, Leicestershire, LE11 3TU, United Kingdom

ARTICLE INFO

Article history:
Received 15 February 2012
Received in revised form 22 May 2012
Accepted 21 July 2012

Keywords:
Annual mean temperature
Global relationship
Heating degree-days
Cooling degree-days

ABSTRACT

Degree-days are a versatile climatic indicator and used for many applications in the design and operation of energy efficient buildings – from the estimation of energy consumption and carbon emissions due to space heating and cooling to the energy and environmental monitoring of buildings. This research is aimed at developing an equation for calculating degree-days from low-resolution temperature data by exploring the relationship between degree-days and annual mean temperature of 5511 locations around the world, using multiple non-linear regression. Results suggest a very strong relationship between annual mean temperature and degree-days. Incorporating standard deviation (SD) of monthly mean temperature and latitude increases the accuracy of prediction ($R^2 > .99$), demonstrating the strength of the location-agnostic relationship in predicting degree-days from two temperature parameters: annual mean and SD of monthly mean. Research findings can be used to calculate degree-days of locations, for which daily temperature data may not be available. The equation can also be used to calculate degree-days from low-resolution global circulation model (GCM) projections of increasing temperature, for investigating the impact of climate change on building heating and cooling energy demand at global scale without the need to create synthetic weather series through morphing or downscaling.

1. Introduction

Degree-days are an important climatic design indicator that captures the extremity and duration of ambient temperature [1]. They are essentially the summation of temperature differences between the ambient or outdoor air temperature and a reference temperature, which is also known as the base or balance point temperature. The base temperature, T_b, is referred to as the outdoor air temperature at which the heating or cooling systems do not need to run in order to maintain comfort conditions [1]. In other words, for the specified value of the indoor air temperature; i.e., set point temperature, the total heat loss from the space is equal to the heat gain from sun, occupants, lights, and equipment [2]. When outdoor air temperature is below the base temperature, the heating system needs to provide heat. As heat loss from a building is directly proportional to the differences between indoor and outdoor air temperatures, the energy consumption of a heated building over a period of time relates to the sum of these temperature differences over this period. On the other hand, cooling systems need to operate if outdoor air temperature is above the base temperature. The summed temperature differences or the cooling degree-days also have a relationship with cooling energy consumptions.

Degree-days and their uses depend on two distinct but essentially unrelated issues: the way degree-days are calculated and the way they are applied to building energy [1]. Calculation techniques for degree-days vary depending on the temporal resolution of temperature data. Hourly temperature (outdoor air) data produces better estimates of degree-days than daily or monthly methods. On the other hand, the application of degree-days varies depending on whether it is for heating or cooling season. Thermal response of the building; i.e., the overall heat transfer coefficient is an important factor for the application of heating degree-days as it influences the base temperature, specific to the building. Another factor affecting the use of heating degree-days is whether the building is continuously or intermittently heated. For the application of cooling degree-days, the type of cooling systems affects its use. This paper is concerned with the calculation of degree-days from a low resolution temperature dataset and, therefore, the reader is directed to the associated references for detailed discussions on: general overview [1,2]; the use and identification of base temperature [3]; estimates of chiller energy consumption using degree-days [4]; use in energy management [5] and uncertainties in energy estimates using degree-days [6].

Apart from their use in estimating energy demand and associated carbon emissions, degree-days are widely used as a climatic indicator for the assessment of the impact of climate change, in particular the increasing temperature. Degree-days are particularly suited for the analysis of extremity and duration of increased outdoor temperature [7–9] due to the simplicity of its concept and its

* Tel.: +44 01509 228792; fax: +44 01509 223981.
E-mail address: m.m.mourshed@lboro.ac.uk
URL: http://monjur.mourshed.org/.

0378-7788/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.enbuild.2012.07.024

Symbols and units

T	annual mean outdoor air temperature (°C)
T_d	daily mean outdoor air temperature (°C)
T_m	monthly mean outdoor air temperature (°C)
T_i	outdoor air temperature at the ith hour of the day (°C)
T_{max}	daily maximum outdoor air temperature (°C)
T_{min}	daily minimum outdoor air temperature (°C)
S_d	standard deviation of daily mean temperature in a month (°C)
S_m	standard deviation of monthly mean temperature (°C)
T_b	base temperature (°C)
DD	degree-days (°C-day)
HDD	annual heating degree-days (°C-day)
HDD_d	daily heating degree-days (°C-day)
HDD_m	monthly heating degree-days (°C-day)
CDD	annual cooling degree-days (°C-day)
CDD_d	daily cooling degree-days (°C-day)
CDD_m	monthly cooling degree-days (°C-day)

extensibility in investigating the inherent uncertainties in climate projection from global circulation models (GCM). The uncertainties in GCM projection primarily originate from the use of various emissions scenarios[1], which result in a range of temperature projections instead of a single figure [10]. Other forms of uncertainties originate from the ocean-atmosphere coupling in the underlying model; i.e., the way atmospheric interactions are modeled in a particular GCM. Multi-model ensembles are, therefore, used to quantify uncertainties and to generate projections of future climate [11] for wider applications such as risk and vulnerability assessments.

On the other hand, GCM projections of surface air temperature are typically reported as anomalies at monthly scale. Only a few models, 8 out of 23 in the IPCC fourth assessment report (FAR), give air temperature outputs at daily scale and only for a few selected marker scenarios. These outputs are not readily suitable for building applications. GCM outputs need to be temporally downscaled to finer resolutions; e.g., hourly, if detailed-based building simulation tools are to be used. Such downscaling techniques introduce uncertainties in the synthetic future weather series, mainly because of the assumption that the variability and distribution of weather pattern is similar in present-day and future climates [12], which may not necessarily be the case. The alternative is to develop a technique that uses coarse resolution (e.g., monthly or annual) GCM outputs of surface air temperature to determine changes in degree-days. This would eliminate uncertainties associated with downscaling and enable the reconciliation of multiple marker scenarios for improved reliability of projections.

Considering the importance of calculating degree-days from a low temporal resolution temperature series, this paper explores the relationship between annual mean temperature and degree-days of 5511 locations around the world. The aim is to develop an equation to predict heating and cooling degree-days from annual mean temperature and site-specific geographical parameters such as latitude. The rest of the paper is organized as follows. Commonly used methods for calculating degree-days are discussed next, followed by a discussion on the methods adopted in this research and sources of data. The results and directions of future research are deliberated, with an emphasis on the accuracy of the developed equation. The paper ends with concluding remarks.

2. Calculation of degree-days

Depending on the availability of outdoor air temperature data, different methods are used for calculating heating and cooling degree-days. The hourly or *ideal* method produces the most accurate estimate. However, the hourly method is not suitable for all applications due to the unavailability of hourly temperature series for many locations. Therefore, several attempts have been made in the past to develop methods for calculating degree-days from reduced datasets. Of note are the works by Thom [13], Erbs et al. [14], Hitchin [15] and Schoenau and Kehrig [16]. Of available techniques using reduced datasets, the following are commonly used and, therefore, are discussed in this article: the American Society of Heating, Refrigerating and Air-Conditioning (ASHRAE) daily mean temperature method [2]; UK Meteorological Office (UKMO) daily maximum and minimum temperature method [1] and Schoenau and Kehrig's monthly mean temperature method [16].

2.1. Hourly method

Hourly temperature data for a location are used in this method to sum differences between the base temperature and hourly temperature measurements; i.e., degree-hours. The cumulative degree-hours of a day is divided by 24 to get the mean degree-hours or degree-days. Daily heating degree-days, HDD_d and daily cooling degree-days, CDD_d are given by Eqs. (1) and (2) respectively.

$$HDD_d = \frac{\sum_{i=1}^{24}(T_b - T_i)^+}{24} \quad (1)$$

$$CDD_d = \frac{\sum_{i=1}^{24}(T_i - T_b)^+}{24} \quad (2)$$

where T_b is base temperature and T_i is outdoor air temperature at the ith hour of the day. The plus symbol ($^+$) means that only positive differences between T_b and T_i are taken into account.

Monthly degree-days, DD_m is calculated by summing up the daily degree-days, DD_d in a month:

$$DD_m = \sum_{j=1}^{P}(DD_{d,j}) \quad (3)$$

where P is number of days in a month and $DD_{d,j}$ is daily degree-days on the jth day of the month.

Annual degree days, DD_a is calculated by summing up monthly degree-days, DD_m:

$$DD_a = \sum_{k=1}^{12}(DD_{m,k}) \quad (4)$$

where $DD_{m,k}$ is monthly degree-days of the kth month of the year.

2.2. ASHRAE formula

According to the ASHRAE daily mean temperature method, the daily degree-days is the difference between the daily mean

[1] Climate change projections depend on future human activities: economic, environmental and technological. Future climate projections are, therefore, based on several scenarios, each making different assumptions for future technological and economic development, affecting the concentration of greenhouse gas in the atmosphere. There are six families of scenarios adopted in the assessment reports by the Intergovernmental Panel on Climate Change (IPCC) [10]. The six illustrative marker scenarios are B1, A1T, B2, A1B, A2, and A1FI, representing an approximate CO_2-eq concentrations in 2100 of about 600, 700, 800, 850, 1250 and 1550 ppm, respectively. The use of different scenarios results in uncertainties in climate projection; e.g., the best estimate of temperature change at 2090–2099 is 1.8 °C and 4.0 °C for B1 and A1F1 scenarios, respectively.