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Cloud cover effect of clear-sky index distributions and differences between human and automatic cloud observations

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ABSTRACT

The statistics of clear-sky index can be used to determine solar irradiance when the theoretical clear sky irradiance and the cloud cover are known. In this paper, observations of hourly clear-sky index for the years of 2010–2013 at 63 locations in the UK are analysed for over 1 million data hours. The aggregated distribution of clear-sky index is bimodal, with strong contributions from mostly-cloudy and mostly-clear hours, as well as a lower number of intermediate hours. The clear-sky index exhibits a distribution of values for each cloud cover bin, measured in eighths of the sky covered (oktas), and also depends on solar elevation angle. Cloud cover is measured either by a human observer or automatically with a cloud ceilometer. Irradiation (time-integrated irradiance) values corresponding to human observations of "cloudless" skies (0 oktas) tend to agree better with theoretical clear-sky values, which are calculated with a radiative transfer model, than irradiation values corresponding to automated observations of 0 oktas. It is apparent that the cloud ceilometers incorrectly categorise more non-cloudless hours as cloudless than human observers do. This leads to notable differences in the distributions of clear-sky index for each okta class, and between human and automated observations. Two probability density functions—the Burr (type III) for mostly-clear situations, and generalised gamma for mostly-cloudy situations—are suggested as analytical fits for each cloud coverage, observation type, and solar elevation angle bin. For human observations of overcast skies (8 oktas) where solar elevation angle exceeds 10°, there is no significant difference between the observed clear-sky indices and the generalised gamma distribution fits.

1. Introduction

The most reliable way to determine the solar resource for a particular location, assuming there have been no detectable effects of climatic change, is to set up long-term pyranometer observations. For many sites of interest, pyranometer records are not frequently obtained for a sufficiently long period prior to installation of a solar energy system (Gueymard and Wilcox, 2011). Other meteorological variables such as sunshine hours (Ångström, 1924; Muneer et al., 1998; Prescott, 1940), diurnal temperature range (Bristow and Campbell, 1984; de Jong and Stewart, 1993; Hargreaves et al., 1985; Supit and van Kappel, 1998), precipitation (de Jong and Stewart, 1993), cloud type (Kasten and Czeplak, 1980; Matuszko, 2012) and fractional cloud cover (Brinsfield et al., 1984; Kasten and Czeplak, 1980; Matuszko, 2012; Muneer and Gul, 2000; Nielsen et al., 1981; Supit and van Kappel, 1998; Wörner, 1967) can be used to estimate solar irradiance. Temperature, pressure, cloud cover, cloud type, rainfall and sunshine hours are routinely measured at weather stations globally.

Since clouds are the largest attenuating factors of solar irradiance in large areas of the globe (Wacker et al., 2015), cloud cover is a useful predictor of solar resource (Kasten and Czeplak, 1980). If the sky is cloudless, irradiance can be predicted from the solar geometry, surface albedo, and optical properties of aerosols, ozone and water vapour using a radiative transfer calculation (Müller et al., 2012). Alternatively, several clear-sky models exist in the literature which are empirical relationships between one or more of these atmospheric variables (or of their derived quantities) and clear-sky irradiance (Gueymard, 2012). When clouds are present, the fraction of time clouds obscure the sun, the optical thickness of the clouds, and secondary effects such as reflections from cloud sides and between cloud layers, can all have important effects on the proportion of irradiance that reaches the surface. Cloud transmission is therefore the most uncertain component of surface irradiance in most locations.

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Nomenclature

Acronyms

AERONET	Aerosol Robotic Network
AFGL	Air Force Geophysics Laboratory
BADC	British Atmospheric Data Centre
BSRN	Baseline Surface Radiation Network
CDF	Cumulative Distribution Function
DNI	Direct Normal Irradiance
ECMWF	European Centre for Medium-range Weather Forecasts
GHI	Global Horizontal Irradiance
GLOMAP	Global Model of Aerosol Processes
IGBP	International Geosphere–Biosphere Programme
MIDAS	Met Office Integrated Data Archive System
PDF	Probability Density Function
RMSE	Root Mean Square Error
RO	Global Radiation Observations
UKMO	UK Meteorological Office
UTC	Coordinated Universal Time
WH	UK Hourly Weather Observations

a	probability distribution scale parameter
c	Burr (type III) distribution shape parameter
d	generalised gamma distribution shape parameter
e_i	expected frequency of clear-sky index observations
G	surface global horizontal irradiation (J m^{-2})
G_0	top-of-atmosphere global horizontal irradiation (J m^{-2})
G_{cs}	clear sky surface global horizontal irradiation (J m^{-2})
k	Burr (type III) distribution shape parameter
K_c	clear-sky index
K_T	clearness index
N	cloud cover (oktas)
o_i	observed frequency of clear-sky index observations
p	generalised gamma distribution shape parameter
$\Gamma(\cdot)$	gamma function
θ_e	solar elevation angle (°)
χ^2	goodness-of-fit statistic

Typically, cloud cover is recorded at meteorological stations as an integer number of oktas, here denoted N, which is the number of eighths of the sky obscured by clouds (Met Office, 2010). An additional okta code 9 is used for situations where the sky is obscured by fog, haze or other meteorological phenomena. For human observations, a convention is to reserve 0 oktas for completely cloudless sky and 8 oktas for completely overcast sky, so the limits of 1 okta and 7 oktas are extended to almost clear and almost overcast respectively (Jones, 1992). In some automated algorithms a different convention may be followed, for example recording up to 1/16 cloudiness as 0 oktas and greater than 15/16 cloudiness as 8 oktas (Wacker et al., 2015).

Clear-sky index, $K_c = G/G_{cs}$, estimates atmospheric attenuation due to clouds by measuring the ratio of surface solar irradiance or irradiation G to the corresponding amount that would be received under a clear (cloudless) sky, G_{cs}. It also accounts for the influence of surface albedo. Other cloudless-sky attenuators such as water vapour, ozone and aerosols are retained in the calculation of G_{cs}. The clear-sky index is less dependent on airmass than the commonly used clearness index $K_T = G/G_0$, where G_0 is top-of-atmosphere solar irradiance. Some authors have worked to reduce this dependence by introducing a rescaling of the clearness index, to either map the observed range of clearness indices into the interval 0–1 for each solar elevation angle class (Olseth and Skartveit, 1987) (i.e. a *normalised* clearness index), or to adjust for airmass based on clear-sky Linke turbidity values (Perez et al., 1990).

Previous relationships between N and K_T, K_c, or G, have tended to provide a one-to-one correspondence between N and the variable of interest (Brinsfield et al., 1984; Kasten and Czeplak, 1980; Matuszko, 2012; Muneer and Gul, 2000; Nielsen et al., 1981; Supit and van Kappel, 1998; Wörner, 1967). On the other hand, several authors have described the distributions of clearness or clear-sky index parameterised by its longer-term mean (Bendt et al., 1981; Graham and Hollands, 1990; Graham et al., 1988; Hollands and Suehrcke, 2013; Jurado et al., 1995; Liu and Jordan, 1960; Olseth and Skartveit, 1984, 1987; Suehrcke and McCormick, 1988) or by airmass (Moreno-Tejera et al., 2016; Tovar et al., 1998). We aim to bring these parts together by reporting clear-sky index distributions for each N class, and secondarily binned by solar elevation angle. A simplified distributional approach was provided by the authors in Bright et al. (2015) for clear sky and 6, 7 and 8 oktas to estimate cloud transmission in sun-obscured minutes and clear breaks, but did not group observations into human and automatic cloud retrievals or elevation angle bins, which as will be shown is important.

The hourly statistics of clear-sky index grouped by N and solar elevation angle would be useful in situations where long-term irradiation data were not available, but measurements of hourly N were (assuming the hourly solar elevation angle was known or could be determined). The probability of transitioning from one N state to the next N state can then be simulated with a Markov chain model (e.g. Bright et al., 2015; Ehnberg and Bollen, 2005), and the cloud transmission for each hour selected as a random variable from each K_c distribution for that N class.

2. Determining the clear-sky index

2.1. Relationships between clear-sky index and cloud cover

Kasten and Czeplak (1980) found an empirical relationship between hourly K_c and hourly N using 10 years of data for Hamburg, Germany, for solar elevation angles above 5°:

$$K_c = 1 - 0.75(N/8)^{3.4} \quad (1)$$

where the clear-sky irradiance [W m^{-2}] is modelled as

$$G_{cs} = 910 \sin\theta_e - 30 \quad (2)$$

where θ_e is solar elevation angle in degrees. The attenuation coefficient of 0.75 in Eq. (1) is an overall average over all cloud types, and varies from 0.39 for cirriform clouds to 0.84 for nimbostratus. This relationship was later found to be valid for 5 UK sites by Muneer and Gul (2000), where slightly better fits can be obtained by tuning coefficients for each site. Other, more complex relationships for G as a function of cloud cover were developed by Nielsen et al. (1981) and Brinsfield et al. (1984). Matuszko (2012) tabulated observed 10-minutely irradiance by okta class and solar elevation angle band for Krakow, Poland.

Cloud cover can indicate how likely it is that the sun is obscured by clouds (e.g. Muneer and Gul, 2000). It does not however provide any information as to how opaque the clouds are to solar irradiance. Clear-sky index can take a wide variety of values for each N class. For example, a sky could be overcast ($N = 8$) with thin cirrus clouds or thick nimbostratus clouds. In this case, K_c has been observed to vary from 0.07 for overcast nimbostratus to 1.00 for