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A method to measure total atmospheric long-wave down-welling radiation using a low cost infrared thermometer tilted to the vertical

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ABSTRACT

Atmospheric long-wave down-welling radiation is a fundamental element of climate change and of input to thermal simulation. Measuring long-wave radiation is needed to calculate locally total energy flows to the earth's surface and night cooling rates in urban precincts. It is an important parameter for the weather files used by energy building simulation software to calculate the thermal performance of buildings and their energy efficiency. Currently, atmospheric down-welling radiation is usually measured by a pyrgeometer, for radiation beyond 3 μm. This is expensive and bulky. A simple methodology for measurement and calculation, with good accuracy, of average atmospheric long-wave down-welling radiation using a tilted, low-cost infrared thermometer is described. Tilt setting, comparison to data gathered by the pyrgeometer, and comparison of simulation studies with both data sets is described. A link of the magnitude of divergence between instant data pairs and radiant intensity is demonstrated and shown to depend on asymmetry in cloud density.

1. Introduction

There is a growing need in various research fields for nearly continuous ground level data on long-wave down-welling thermal radiation, but the scope for such data collection is limited at present by the high cost, and to some extent lack of portability, of state-of-the-art pyrgeometer equipment. As a result many studies requiring such data are forced to use instead either approximate sky radiance models based on cloud cover, or data available from weather stations located many kilometres away. An approach which is: sufficiently accurate; very low cost; easy to monitor and deploy; and with a small footprint; would thus fill an important need. The method proposed here has that goal. It is based upon the link of the output of an infrared thermometer to the average thermal radiance in its field of view. A specially pre-set tilt angle is also required if the reading is to represent the mean sky radiance. The goal in many current climate and related studies is an accuracy with errors less than of 10 W m^{-2} [1] which we shall demonstrate is readily achievable for clear and uniformly overcast skies in our low cost technique. For many partially cloudy conditions accuracy is also in or near this range.

Our own interest grew from a need for accurate down-welling thermal radiation data, primarily from the atmosphere, as input to simulation models of net thermal radiation flows from building roofs and façades, and from the surfaces around these buildings. Energy efficient building design is increasingly reliant on such simulation. Cooling rates at night are particularly sensitive to the differentials between incoming and outgoing thermal radiation flows, and these differences may dominate when local air-flow rates are small. Roofs which view much or all of the sky vault hemisphere can dominate night sky cooling, but façades can also contribute. Thermal comfort within buildings is influenced directly and indirectly by radiative cooling [2]. The storage of absorbed solar energy in façades, roofs, and exterior ground level materials such as roads and paths [3] significantly impacts on building thermal flows. Local air is heated above that of the atmosphere creating in cities an UHI (urban heat island). The four best counter measures to the UHI are to (i) minimise storage of solar heat by maximising average solar reflectance (ii) utilise evapo-transpiration in plants (iii) maximise the ability to cool exterior surfaces and interior mass at night (iv) minimize the need for air conditioning use, and maximise its efficiency when in use, to keep heat pumped to the outside low.

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Cooler air adjacent to a building will both improve COP (coefficient of performance) of HVAC (heating, ventilation and air conditioning) systems, and lower their use by allowing more ventilation cooling [2]. It is thus important to know as accurately as possible the variation of incoming thermal radiation intensity over time for accurate modelling of thermal performance of buildings and their surrounds. Saving more energy, improved thermal comfort, and better understanding of how to plan complete urban structures so as to limit the urban heat island problem, will follow.

Long-wave down-welling radiation is also a critical component of energy balance and global energy flows at the earth's surface [4]. Changes in average atmospheric long-wave down-welling radiation are expected as climate change evolves. The small variation year to year makes long-wave down-welling radiation at the Earth's surface an element for monitoring climate change with respect to global warming as it links on average to atmospheric temperature as well as atmospheric gas content. Radiation from local sources at night is also an important signal of an urban heat island problem but can vary widely as the field of view and position of each measurement changes. The measurement of all such flows in a novel, low cost way is the focus of this report.

A pyrgeometer is the traditional device used, and it is our reference for accuracy. It integrates the total incoming atmospheric infrared radiation with flat spectral response from 3 μm to 50 μm. A coated silicon dome transmits incident radiation of wavelength longer than 3 μm and cuts off the short-wave radiation completely in the daytime [5]. Pyrgeometers also allow cloud detection and are used to separate clear-sky from cloudy-sky situations especially during dark hours [5]. Our IRT (infrared thermometer) based technique is also well suited, and easily modified for studies in urban canyons. A further advantage of the IRT's very light weight and small footprint is an ability to possibly be used on quite small UAVs (unmanned airborne vehicles) in urban situations (if allowed) to measure and map both down-welling and up-welling thermal radiation. Such very small UAVs could not cope with multiple heavy payloads. IRTs are small in area and convert IR photons which are absorbed (net of those emitted thermally) to an electrical signal using semiconductor based thermopiles. Their hot junction is in contact with a black absorber and cold junction at body temperature. IRTs have a narrower field of view to the thermopile sensor in standard pyrgeometers which also sense net absorption of IR photons, but from anywhere in the sky hemisphere. Directional sensitivity has advantages in some urban studies. However if the source of interest is the full atmosphere account must be taken of the changes in its thermal radiance with direction. This varies strongly with angle to the zenith for many wavelengths. A sensor with directional sensitivity is not ruled out but requires its tilt to be set at an angle which takes account of the specifics of the dependence of atmospheric emittance on θ the angle of tilt to the zenith, $E_A(\theta)$. Non uniform cloud cover adds axial or ϕ dependence to atmospheric emittance as $E_A(\theta,\phi)$. This impact on data from one fixed IRT is interesting, and studied to a limited extent here. It is the main error source.

Radiometric instruments which sense over a very limited field of view were first used for studying the dependence of atmospheric radiance on the zenith angle many years ago. Pioneering instruments were built by Dines in 1920 [6]. They yielded mean radiation intensities from different parts of the sky, as reported by Dines and Dines in 1927 [7]. Spherical mirrors with a limited field of view and cone half-angle of 6°, moved and collected radiation at each position from a limited portion of the sky. It was then directed onto a thermopile sensor located near the end of a 65 cm long tube. Today's pyrgeometers and most accurate infrared thermometers still use thermopile sensors. Both hence utilise the thermoelectric voltage sum generated between series of linked multiple hot and cold junctions. The hot junction temperature is determined by the absorption of incident radiation on a black surface with which it is in good thermal contact. The junctions between different thin film, doped semiconductors at the hot and cold junctions allow modern IRTs to be compact.

A well-known improvement to Dine's device is the Link–Feussner system as reported by Robinson [8]. A related tubular device was used by Dalrymple and Unsworth [9], who confirmed the earlier Dines and Dines finding [7] that there is a representative angle θ_R at which detectors with very small acceptance angles can point to provide a measure of the mean sky radiance. For clear skies and completely overcast skies θ_R was found to be 52.5° to the zenith. Our IRT methodology utilises an experimentally predetermined representative angle. We found it experimentally to be 55°. This is close to the theoretical clear sky value of 52.5°. A difference from 52.5° was expected for the IRT used due to its much larger acceptance half-angle of around 40° compared with those of the early tubular devices of around 6°. The issue of field of view sensitivity for θ_R does not appear to have been raised previously. A detailed analysis is beyond the scope of this article and will follow, but the well known rise in atmospheric emittance of the uniform sky (see section 3) as angle to the zenith rises, means θ_R is expected to vary as Ω the solid angle viewed opens up. Other impacts of $\Omega > 6°$, as in IRTs, are worth briefly noting. They include reduced sensitivity of mean sky radiance results to varying tilt direction θ from $\theta_R(\Omega)$, and reduced errors relative to a full sky sensor for inhomogeneous or anisotropic cloud cover.

Another more recent highly directional pyrgeometer [1] reported by Sakai et al. aimed at further simplification of the older approaches. Their fixed tilt data was compared to that from a standard all sky, vertical pointing, Kipp and Zonnen pyrgeometer. Our overall approach uses a similar comparative methodology to evaluate the accuracy of the proposed sensor system. Our major difference from Ref. [1] is the use of a much larger field of view. Other meteorological research groups [10,11] have recently utilised an infrared temperature sensor, for example to establish the water vapour content in the atmosphere.

Our ultimate goal is accurate thermal simulation [12]. Model accuracy requires that explicit account of actual incoming thermal radiation is required. This also means that net radiation loss cannot be treated as part of an approximate combined heat transfer coefficient (with convection). It also means as we have found explicitly that approximate sky models in common use are inaccurate for roof cooling studies at night [13]. Among many simulation models available for studying thermal flows in buildings some have oversimplified the theoretical treatment of radiative flows. In the following results a comparison of models and data on a roof will be used to highlight the need for both accurate down-welling thermal radiation data, and for algorithms which treat radiative fluxes explicitly and correctly. The accuracy of this approach to simulation when IRT data is used to establish atmospheric radiance, is demonstrated in section 5 by modelling also with simultaneous pyrgeometric data.

2. The pyrgeometer and infrared thermometer

Fig. 1 shows the pyrgeometer MS-202 from Eko Instruments [14] used to gather accurate atmospheric infrared radiation. This sensor utilises a silicon dome which transmits radiation of wavelength longer than 3 μm and cuts off any incident solar radiation. The sensor has response time of about 3 s and voltage output is linear in the incident radiation to within ±1%. A separate measure is taken of the body temperature T_B using the most accurate measure available, a four-wire Pt100 probe with accuracy to ±0.15 °C. The outputs of sky temperature in an IRT and down-welling radiant intensity in