LOCAL INFRA-RED CLEAR SKY TEMPERATURES

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Summary

The surface of the Earth, and bodies on it such as buildings and agricultural properties, radiate energy into the sky at a rate which depends on a number of factors. One of these factors, which is particularly significant, is the equivalent temperature of the sky. Here, we wish to discuss a pilot study of the magnitude of changes in the equivalent temperature of the clear sky as the observation location is changed on a local, neighbourhood, scale. In this study, measurements were made mainly in the southern suburbs of the Adelaide metropolitan area.

KEY WORDS: clear sky, long wave infra-red

Introduction

Bodies on the surface of the Earth radiate (thermal) energy into space through our atmosphere. To the extent that this radiation process obeys thermal radiation laws, terrestrial temperatures of about 300 K result in the bulk of the radiation being carried by a broad range of wavelengths centred on 10 µm, sometimes referred to as long-wave infra-red. This radiating process is fundamental to determining the long-term equilibrium temperature of the surface of the Earth, when considered with the properties of the incoming solar radiation. On a large-scale, the process is known as the greenhouse effect.

From a local point of view, the ways in which our bodies, houses, vehicles etc. cool by infra-red emission into the sky are determined by their temperatures (the emitted power of thermal energy emission is proportional to the fourth power of the absolute temperature), their surface properties (emissivities as functions of wavelength), and the downward radiative properties of the local environment. Such local environmental considerations can be of great practical importance, for instance, in determining the need for, and cost of, air conditioning in buildings, the cost of heating for buildings, and the temperatures of crops.

For some years, we have studied the radiative properties of clear and cloudy skies at a number of fixed sites world-wide as part of our program to develop efficient night-time cloud detectors for astronomical sites (Clay et al. 1998, Riordan et al. 2005). In that field of study, it is conventional practice to assign an equivalent temperature in the field of view of a radiometer (which measures the total received power from the sky in a defined wavelength range), away from the solar direction, based on an artificially assumed sky emissivity of one. One assumes the Stefan-Boltzmann law, which states that the power emitted per square metre of a black-body (meaning that the emissivity is equal to one) depends on the fourth power of the absolute temperature, multiplied by the well known ‘Stefan-Boltzmann’ constant

\[(5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4})\].

This is somewhat unphysical, but it is also rather practical as it allows one to picture the local environment which surrounds a location on the ground as having a temperature. The environment then emits incoming infra-red radiation, based on that temperature, which bathes the ground. The warm ground cools by radiating into the sky and so the overall thermal process is simply understood by assigning an appropriate temperature to the sky and calculating the radiation balance between outward energy from the ground and incoming energy from the (cooler) sky. Our students are taught this, but various undergraduate authorities assign different versions of the clear sky temperature such as “–23 °C (Halliday, Resnick and Walker 2005)” or, in other literature, one finds values such as 10 °C below the ground temperature (e.g. http://www.astecpaints.com.au/energystar/about_energystar.htm accessed 2 June 2006). These are
not necessarily very helpful statements, although they may have some usefulness as first approximations. The literature of this field is substantial. It provides detailed predictions for the clear sky temperature under a range of meteorological conditions and for a variety of geographical areas. The details of those predictions are still not without controversy. We will see below that the appropriate values for the clear sky temperature can vary substantially with small changes in location.

The clear sky temperature has been the subject of study for close to a century and continues to be of interest due to its practical consequences in relation to our understanding of local cooling and of large scale climate effects. Milestones in the field over the past fifty years are discussed and their major results listed by Duarte, Dias and Maggiotto (2006) who also provide a good selection of key references. The main factors affecting the clear sky temperature are known to be the screen (air) temperature and the water vapour content of the atmosphere. However, one of the early, influential, studies (Swinbank 1963) showed that a good approximate formula for predicting the clear sky temperature could be found with only the use of the screen temperature. We note that this result emphasises the dominance of the screen temperature as a factor. Duarte, Dias and Maggiotto list many proposed, and approximately equivalent, related formulae which use the screen temperature plus some measure of the atmospheric water vapour content. Those formulae were developed based on data from differing geographic sites. They all tell the same broad story but do not provide identical clear sky temperature predictions. We will see below that one reason for this is that detailed local conditions can be significant.

We have studied the clear sky temperature for the past ten years as part of a program to develop automatic systems for locating night-time cloud at astronomical observatories (Clay et al. 1998). We were concerned when we found small but significant discrepancies in our results between two metropolitan Adelaide sites, the central business district and the outer Edinburgh air base. We have developed our own parameterisations for the clear sky temperature using the screen temperature and various water vapour parameters. For instance:

$$T_{\text{ClearSky}} \ (°\text{C}) = -39.2 \ °\text{C} + 0.80T_{\text{Screen}} \ (°\text{C}) + 3.45 \ (\text{Vapour Pressure} \ (\text{mbar}))^{\frac{1}{5}}$$

applies to the central Adelaide metropolitan area. Our two sites under study seemed to differ in terms of their constant offsets in this formula.

The work reported here was intended to be a pilot investigation of the degree of dependence on location of the infra-red radiometric sky temperature over small distances, such as between suburbs in a metropolitan area. We use radiometers which we build and which are designed to directly measure this sky temperature. Thus, at an exposed site with well understood local conditions, our in situ measurement of this sky temperature can provide valuable information on local terrestrial cooling, and can also contribute to an understanding of the greenhouse effect.

We will show here that the effective sky temperature is actually a very local parameter, changing appreciably with local conditions, and over quite short distances even when allowance is made for changes in screen temperature and atmospheric water vapour pressure. The purpose of this paper is to report on our pilot investigation of this variability with location, and to draw some conclusions about the source of the variability in the context of measurements in some parts of the southern Adelaide metropolitan area. We will show that these local variations are greater than expected based on conventional ground-level parameters such as those used by ourselves and many others. This means that calculations of the net radiant flux require a knowledge of local conditions and that there is not a simple relationship between that flux and local temperatures.

**A Brief Introduction to Thermal Properties of the Clear Sky**

The clear sky is a thermal interface between the surface of the Earth and the very cold Universe. It is not opaque at thermal wavelengths (greater than a few microns) and its opacity (and so its emissivity) is wavelength dependent with a minimum in the vicinity of a wavelength of 10 µm
which, coincidently, is close to the peak of terrestrial thermal emission. The opacity is determined by the atmospheric greenhouse gases. The most important of these is water vapour which is concentrated in the lowest 1-2 km of the atmosphere. Since the sky is semi-transparent, it cannot radiate as a black body but it does have an emissivity and can be assigned an equivalent radiative temperature. In predicting that temperature, the most useful parameter has proved to be the local ground-level air temperature. Next in order of usefulness is the atmospheric water vapour content. We have found that this is best measured by the total precipitable water vapour above the local site. This parameter can be measured using radio-sonde or GPS data but these are often not available and cannot be used to specify a particular locality since balloons drift and GPS satellites move over the sky. We have shown that a useful proxy may be the local vapour pressure, or relative humidity plus the air temperature, which may be readily measured, but this applies only to water vapour at the measurement level and does not give information on the thickness of the water vapour layer.

Since the clear sky is semi-transparent, it is 'thinnest' and coldest when viewed vertically. It progressively thickens as the viewing angle increases from the zenith, until its temperature is close to ground temperature at low elevations. Thus, the most extreme (coolest) equivalent sky temperatures are to be found at the zenith. We have confirmed data in the literature which show that this change of sky temperature (relative to the ground temperature) varies with zenith angle ($\theta$) as:

$$(\text{Sky temperature at zenith angle } \theta - \text{ground temperature}) = (\text{sky zenith temperature-ground temperature}) \times (-\ln(\sec(\theta)))$$

Figure 1 illustrates what is happening physically in this case. The atmospheric black body spectrum, which is approximated by the emission from the semi-transparent atmosphere, progressively fills as greater atmospheric thicknesses are viewed with increasing zenith angle.

Integration of this equation over the solid angle of the sky results in an equivalent all-sky temperature (radiating to a horizontal surface). It turns out that this is the same as the temperature at a zenith angle of about $53^0$. This temperature could reasonably be regarded as appropriate for understanding the thermal equilibrium of flat, horizontal, roofs.
The Radiometer

The University of Adelaide has developed radiometers with a variety of characteristics, based on an EG&G Heimann TPS 534 thermopile element. The principles behind the radiometers as cloud detectors are described by Clay et al. (1998). This radiometer accepts thermal radiation (in a wavelength range from 5.5 microns to above 15 microns) which heats a sensing element. The device then produces an output voltage dependent on the temperature difference between that element and an internal thermistor. When calibrated, the device responds to the temperature of a test black body, filling its field of view, with an uncertainty of better than 1K. The element itself has a 90° field of view but, for this work, we use an infra-red Fresnel lens to limit the field of view to 3°. The radiometer was mounted above a car, viewing vertically with no line of sight to the vehicle itself, along with electronic temperature and relative humidity sensors exposed to the free-flowing air passing over the moving vehicle. The latter sensors have proved to be accurate and reliable over long term comparisons with other such sensors and with data from the Australian Bureau of Meteorology.

Figure 2: Data taken on 24 March 2006. The lines (from the top) correspond to relative humidity (%), external temperature (°C), detector internal temperature (°C) which tracks the external temperature but is smoothed somewhat by the thermal mass of the detector electronics box, vapour pressure (mbar), compensated (true) sky temperature (°C), and predicted sky temperature (°C) based on the measured air temperature and the vapour pressure using a parameterisation in the text found over many years to apply to Adelaide City conditions. The route was via Coromandel Valley (19:13), Crafers (19:28), Mt Lofty Summit (19:30), Brownhill Creek/Fullarton Road (20:01), Aberfoyle Park (20:22). The many vertical lines are due to various thicknesses of tree canopy above the clear-sky baseline. The discussion in this paper relates to data from sensors monitoring the relative humidity, the external temperature, and the compensated sky temperature.

The Observations

The purpose of these observations was to determine the extent of variations of the clear sky temperature over local distances within Adelaide metropolitan suburbs. In order to achieve this, data from the radiometer, the external and internal temperature sensors and the humidity sensor were logged at 20 s intervals on a large number of suburban, and near-suburban, routes in cloud-free early evenings (to avoid the possibility of direct solar radiation affecting the infra-red optics) through the
summer and autumn of 2005/6. Typical observing periods were of duration 1-2 hours through a variety of environments. Figure 2 shows typical graphical representation of such data. We have included in this figure data on the vapour pressure which was derived from the relative humidity measurements. We have also included clear sky temperature predictions based on our parameterisations using vapour pressure and the screen temperature (see the formula above).

The radiometer measurements are in terms of equivalent temperatures, which are generally well below the local air temperature. The clear exceptions are when data are recorded below trees which, naturally, exhibit apparent temperatures (averaged over the field of view) close to the ground (air) temperature. That simple observation emphasises the effect of a local tree canopy on reducing the ability of the local sub-canopy environment to cool radiatively.

Results

Apart from sky temperature variations associated with the serendipitous passage below a tree or tunnel canopy, we have clearly observed substantial variations in the local clear sky equivalent temperature over distances as small as hundreds of metres. A careful examination of our routes and the logged data shows a strong dependence on local altitude. Measurements have been made over the full range of altitudes accessible in the Adelaide metropolitan area, from the coast to the summit of Mount Lofty at an altitude of approximately 700 m. It is well known that the air temperature decreases with altitude at a rate known as the lapse rate. This is generally well-followed by our recorded local air temperature which has a lapse rate with altitude of 8.5 K km\(^{-1}\) when measured in the region of the Adelaide plains to Mount Lofty. This is rather higher than the conventional environmental lapse rate of 6.5 K km\(^{-1}\), but well below the dry adiabatic lapse rate of 9.8 K km\(^{-1}\). The clear sky temperature exhibits the same sense of variation but at a much greater rate, 25 K km\(^{-1}\). That is, the sky temperature varies with altitude at close to three times the rate of the simple air temperature.

Whilst a decrease in temperature with increasing altitude was the general rule, some sites violated that rule. The suburb of Aberfoyle Park as a whole violated the rule on most (but not all) occasions, as did Coromandel Valley. On a number of occasions, the lower levels of Coromandel Valley proved to be the coldest regions on a route, colder even than the summit of Mount Lofty, the highest altitude investigated. Again, sky temperatures were related to air temperatures but the sky temperature varied much more strongly. That is, these sites exhibited both air and sky temperatures below those of neighbouring regions. Coromandel Valley is rather steep sided (with a depth of the order of 150 m) and commonly showed a sky temperature which was at least 6 K below that expected on the basis of its altitude. Aberfoyle Park was carefully studied on a number of occasions. It is a suburb roughly fitting into a bowl-shaped valley (the basin is approximately 100m lower than the edges), with the lowest sky temperatures (typically reduced by 5 K) often being at the lowest levels of the valley, its south western corner, contrary to expectations based on a temperature decrease with increasing altitude.

The 'downtown' central region of Adelaide city was expected to exhibit a 'heat dome' with unexpectedly high temperatures compared with suburban regions. This effect was not found in this investigation, although it would not necessarily have been noticeable until the early hours of the morning when the thermodynamic heat retention of that central city area should be most prominent (Erell 2005).

Temperature variations up hills and in valleys may be anticipated, but an unexplained observation was that the temperatures over the Adelaide metropolitan plains (south of the city centre) were generally quite constant. The land in that region slopes (rather gently) towards the sea in the west. The altitude decreases, so some change in the sky temperature might have been expected, but none was consistently found. Indeed, on a number of occasions, the warmest region for the measured skies was in suburbs two to three kilometres east of the city centre at appreciably higher altitudes.
Discussion

A knowledge and understanding of sky temperatures is a serious matter for many, but it has presently not been well studied in a small-scale context. It is important because it is a major factor in determining the temperatures of buildings, particularly their cooling after hot, clear, summer days, and the temperatures of agricultural land, particularly in frosty periods. This investigation represents a pilot study to identify some of the major issues. As a simple illustration, the rate of energy radiation of a typical 150 m² Australian house roof changes by about 1 kW for every 1 K change in sky temperature if it acts as a black body (as most roofing surfaces approximate to in the long-wave infra-red). Since a variation of at least 12 K is found in this study between different metropolitan locations, summer cooling requirements for similar housing in different locations may differ significantly even for the same air temperature.

It has been interesting to find that the sky temperature is, as expected, related to the local air temperature, but that it has a stronger variation (typically 2-3 times the rate of change, as can be seen when comparing the amplitude of variations of the measured and predicted sky temperatures in figure 2). This is different to our results for temperature variations at a fixed location, such as those used to develop formulae for the predicted clear sky temperatures as in figure 2. At a fixed location, the sky temperature varies more slowly than the air temperature (typically varying at 50-80% of the rate) as one would expect for a radiating medium which is only partially opaque. The observed changes of the air and sky temperatures with altitude are clearly more complex. Our air temperature lapse rate is not out of line with expectation for clear nights. However, the much greater value of the sky temperature lapse rate must be associated with the air temperature lapse as a function of altitude, plus a further factor which is altitude dependent. This further factor must represent a local change in the character of the atmosphere and we speculate that it is associated with the thickness and temperature of the atmospheric layer with water vapour content. This is known to have a scale height much less than the atmosphere itself, typically hundreds rather than thousands of metres. Our measurements of relative humidity relate to ground-level water vapour and do not show much variation with altitude. However, they may not be a good proxy for the total precipitable water vapour above a given level. Even though that ground humidity parameter varies little, one can picture that a rise (say) to the top of Mount Lofty of 700 m could well be associated with passing through much of the horizontally stratified water vapour layer (which has a typical scale thickness of 1-2 km), leaving a thinner, and colder, water vapour layer above a thin boundary layer. Dilley and O’Brien (1998) give a particularly clear discussion of the complexity of the relationship between the sky temperature, the screen temperature, the screen vapour pressure and the precipitable water vapour along the line of sight.

It is well known that cold air drains into valleys where it accumulates. This must be related to our observations in valleys of particularly cold skies. Our humidity measurements show that is common for this accumulating cold air to have a higher water vapour content than air immediately outside the valleys. This observation may then be related to the enhancement of the effect of any clear sky temperature changes since the cold, local, air will have a particularly strong long-wave infra-red emissivity with its additional water vapour content.

Conclusions

The infra-red temperature of clear skies is an important parameter in understanding the cooling of terrestrial bodies. In this pilot study, we have found that this clear sky temperature at the zenith varies significantly with location over quite small distances (< 1 km) in a metropolitan area. The reasons for such variations seem to be associated with altitude, and with identifiable geographic structures, but the magnitude of the effect is appreciably greater than has usually been assumed when calculating local cooling.
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