Microclimate modelling for prediction of environmental conditions within rock art shelters

Ian D. MacLeod* and Philip Haydock
Department of Materials Conservation
Western Australian Museum
Cliff Street
Fremantle, Western Australia 6160
Fax: +61 8 94318489
E-mail: ian.macleod@museum.wa.gov.au, phaydock@cyllene.uwa.edu.au
Web site: www.museum.wa.gov.au

Abstract

Surface temperatures for calcareous and sandstone rock art shelters have been modelled for the West Kimberley region of Western Australia during both wet and dry seasons. The best correlations between the surface and predicted values were for still air conditions. The model correctly predicts the timing but not the magnitude of dips and bumps in the surface temperatures when drying or moisture bearing winds affect the sites.

Keywords

Aboriginal rock art, microclimate, modelling, Kimberley, Western Australia

Introduction

Conservators working on rock art sites need some way of ensuring that observations made during an inspection, or recorded during treatment, will relate to the long-term conditions that will prevail when their work is done. The first step involves monitoring the microclimate of the shelters, since this provides an understanding of how moisture moves across the painted images and through the rock substrates. Since most of the sites are more than 2300 km from the laboratory, limited budgets are not conducive to regular site inspections, so measurements were done during the characteristic seasons. Microclimate modelling was developed to check that the limited data obtained during seasonal visits was generally applicable. Since poor adhesion and cohesion is a major factor in determining the survival rate of the images, an understanding of the impact of heating, cooling and moisture on the rock substrate was essential. Lyons developed a computer model, based on surface energy balance, that enables prediction of the heating and cooling rates of various surfaces (Lyons 1986). Previous work at the granitic Walga Rock site had shown that the Lyons model needed local climate data to reproduce the temperature profiles (Lyons and Haydock 1987) and this data was obtained from data loggers in a meteorological screen close to the rock art shelters.

The new model was tested for the wet and dry seasons at representative locations in the West Kimberley region of Western Australia. The analysis of the rock painting pigments, bacteria and other biological agents involved in rock weathering was conducted in the presence of, and with the specific approval of, Aboriginal owners (Clarke 1976, Clarke1978, Ford et al. 1994, MacLeod et al. 1995). The region has hot humid summers and heavy periodic rains originating from the monsoon trough to the north and tropical low-pressure systems (Elliot 1991). Winters are generally rainless with a dry southeasterly airflow giving mild to warm and dry conditions. The Bunuba calcareous sites in the southwest (Napier Ranges) are much drier than the Wunambal-Ngarinyin sandstone sites in the north (Mitchell Plateau) because they are much closer to the coast and more subject to the extremes of monsoons and of cyclonic rainfall.

Experimental

Data loggers recorded microclimate data, which were downloaded to a laptop computer. More than eight thermocouple wire sensors provided rock face temperatures. In addition, relative humidity sensors were placed at representative points within the shelters. Each thermocouple sensor was ‘pinned’ to the rock surface by tensioned poles that had been trimmed to a chisel point after being cut from small trees. This supported the four relative humidity sensors, which were taped 3 to 5 cm from the rock face. The local microclimate was logged in a meteorological screen up to 100 m from the site, one metre above ground level. This location was chosen to avoid large rocks and to avoid the effects of long-wave

---

*Author to whom correspondence should be addressed radiation emission. All the loggers were calibrated and programmed to record data at 15-minute intervals over three to seven days.

Equipment

Data in the shelters were recorded using a Datataker DT100F, which had 19 channels for type K thermocouples, with an accuracy of ± 0.1°C, and four channels for the Vaisala HMW 20U relative humidity sensors, with an accuracy of ± 2%. A storage capacity of 30K equated to 7700 data points or 80 days of readings at 15-minute intervals. The internal Ni-Cd batteries, which provided 12 days of power was supplemented by a solar panel that trickle-charged a sealed lead-acid battery. The meteorological screen data were recorded with either A.C.R. XT-102s or an ACR Smart Reader SR-002.

Description of the model

Although the model only produces temperature profiles, it is possible to use the associated relative humidity data to provide an understanding of the differences between the surface and modelled data. The absolute humidity, or water vapour pressure, provides an insight into the overall moisture regime of a rock art shelter and the nearby external environment.

The model was initially developed to predict ground surface temperatures, but has been modified to predict vertical rock face temperatures. This modification used concepts based on surface energy balance involving both daytime heating and night-time cooling, which is controlled by the amount of sky that each point on the rock face can see (Lyons and Edwards 1982, Haydock and MacLeod 1996). This 'sky view factor' is a measure of the effective area that receives the incoming radiation and 'rejects' the outgoing radiation. The original model presented the mathematical bases for the determination of these factors in horizontal direction and was modified to include vertical components (Steyn and Lyons 1985). The model assumes that the site corresponds to an 'infinite canyon', meaning that there are no ends to the shelter. While this is demonstrably not true, it does not void the model's applicability.

Daytime heating

Modelling the sky-global irradiance assumes cloudless conditions and the direct irradiance is dependant on transmissions due to water vapour absorption, ψ_{wa}, aerosol absorption, ψ_{da}, water vapour scattering, ψ_{ws}, Rayleigh scattering, ψ_{rs}, and aerosol scattering, ψ_{ds} and their product, as defined in equation 1,

$$I = I_o \cos z\, \psi_{wa}\psi_{da}\psi_{ws}\psi_{rs}\psi_{ds} \qquad (1)$$

The solar constant is I_o (taken as 1353 Wm^{-2}) and z is the zenith distance. Estimation of the diffuse irradiance (D) assumes that the absorption of the direct beam occurs before scattering and that half of the scattered irradiance, without further absorption, reaches the earth as the diffuse component. The values of the diffuse irradiance are calculated according to the equation 2,

$$D = I_0 \cos z\psi_{wa}\psi_{da} \frac{(1 - \psi_{ws}\psi_{rs}\psi_{ds})}{z} \qquad (2)$$

Clear global sky irradiance can be calculated from equation 3.

$$H_{cs} = I_0 \cos z\psi_{wa}\psi_{da} \frac{(1 + \psi_{ws}\psi_{rs}\psi_{ds})}{z} \qquad (3)$$

Detailed derivation of the equations are found in the original papers by Davies and Lyons (Davies 1975, Lyons and Edwards 1982).

Night-time cooling

The energy flux assesses the loss of energy due to cooling in the night, which, in the absence of advection, gives the surface energy balance as

$$Q^{*} = (Q_{H} + Q_{E} + Q_{R}) \qquad (4)$$

where Q^{*} is the net all-wave radiative flux density, Q_{H} and Q_{E} are the sensible and latent heat flux densities respectively, and Q_{R} is the surface heat flux density due to a net change of heat storage within the underlying rock. Under calm conditions, which prevail in the night, the sensible (Q_{H}) and latent heat fluxes (Q_{E}) may be neglected, and $Q^{\star}$ is reduced to $L^{\star}$, the net long-wave radiative flux density, i.e.,

$$L^{*} = (Q_{R}) \qquad (5)$$

Calculation of the long-wave radiation emitted by the rock surface is given by equation 6,

$$L_{O} = \zeta\sigma T_{g}^{4} \qquad (6)$$

where ζ is the surface emissivity, σ is the Stefan-Boltzmann constant and T_{g} is the rock temperature. Estimation of the incoming long wave radiation for clear skies is made using equation 7,

$$L_{i} = 5.16 \times 10^{-13} T^{6} \qquad (7)$$

where T is the absolute air temperature at some reference height in the shelter. Thus the net long-wave radiative flux density is given by equation 8,

$$L^{*} = (5.16 \times 10^{-13} T^{6} \psi_{s}) - (\zeta\sigma T_{r}^{4}) \qquad (8)$$

and ψ_{s} is the all important sky view factor.

The surface heat flux and its dependence on rock face temperature can be computed by the force restore rate equation 9,

$$\frac{\partial T_{r}}{\partial t} = \frac{2}{c} Q_{r} - \Omega(T_{r} - T_{\alpha}) \qquad (9)$$

where Ω is the earth's angular frequency ($7.27 \times 10^{-5} s^{-1}$), T_{α} is the deep rock temperature and c is given by

$$c = \frac{(2\rho_{\gamma}\ c_{\gamma}\lambda_{\gamma})^{\zeta}}{\Omega} \qquad (10)$$

and ρ_{r} is the rock density, c_{r} is the specific heat for rock and λ_{r} is the rock heat conductivity (Deardorff 1978). The product $(\rho_{r} c_{r} \lambda_{r})^{½}$ represents the thermal inertia of the rock, and maybe considered as the resistance of the rock to a change in temperature. The deep rock temperature would be estimated from an integral formulation based on the penetration depth of the annual thermal-wave,

$$\frac{\partial T_{d}}{\partial t} = \frac{Q_{R}}{c_{d}} \qquad (11)$$

where $c_{d} = (2\pi.365)^{½}c$. The rock surface temperature can be calculated by the substitution of equations 5 and 8 into 9 and solving the two differential equations 9 and 11 numerically. The model does not set out to address the various specific weathering situations along the rock face, but rather moves to assess general trends within the shelter. From the indication of these trends, the patterns and processes of weathering are better understood.

Application of the model to Kimberley rock painting sites

Data from four sites from both wet and dry seasons used the simple surface energy budget to model the rock surface temperature (Lyons and Haydock 1987). The ambient air temperature is not assumed to be constant, and the flux of the incoming long-wave radiation is allowed to vary. The maximum rock surface temperature and mean deep rock temperature recorded the previous day were used to initialize the model, as this gave better results. A typical 24-hour period was chosen to be

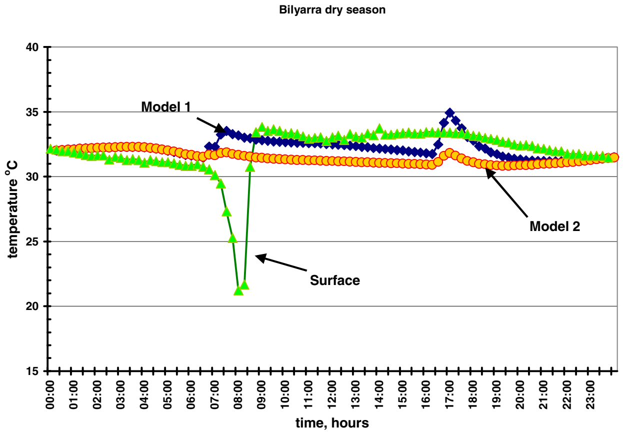

Figure 1. Bilyarra dry season, surface rock and modelled temperatures

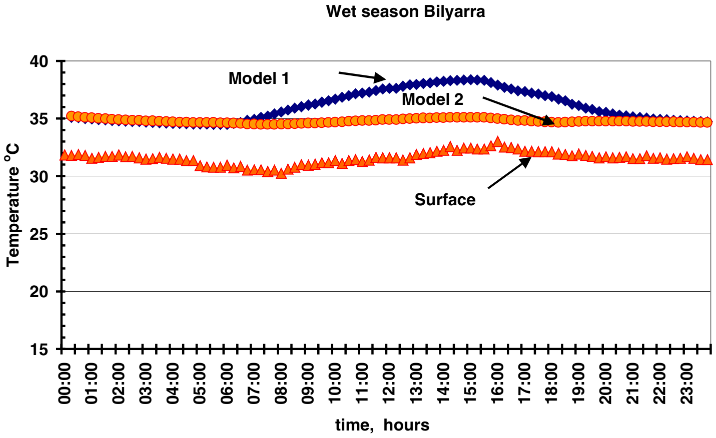

Figure 2. Bilyarra wet season, surface rock and modelled temperatures

representative of the days over which observations were made at the painting sites. The modelling results are presented both with and without consideration of the sensible and latent heat fluxes according to the standard parameterization (Oke et al. 1981).

Calcareous sites in the Napier Range

Bilyarra

The shelter was formed by undercut weathering into a bedding layer of quartzose micaceous calcarenite that had been formed in a high-energy beach or tidal environment, with the substrate coming from weathered granitic sources that have been cemented together with calcite (MacArthur and Wright 1967). The site orientation is 20^0 (almost NNE) and is 120 m long with an overhang width that varies between 5 m and 15 m. The shelter has a complex shape with three separate levels and a variable ceiling height of between 5 m and 7 m. The surface and modelled temperatures for June 24, 1990, (Figure 1) show that while the surface temperature can swing by 13°C in less than an hour, the model does not predict such marked swings. The underlying cause of the rapid changes is probably due to a combination of incident sunlight causing local wind eddies, which causes a rapid loss of water from the surface, and direct incident sunlight. Model 1, which assumes no sensible or latent heat flux, reaches its maximum two hours earlier than the surface. The size of the calculated afternoon sharp rise around 17:00 was greater with Model 1 than Model 2, which were both higher than the surface temperature. The model has correctly predicted the cooling of the rock in the morning and the maximum temperature that it reached with the morning sun. Previous work has shown that changes in the rock surface temperatures can be directly attributable to water adsorption, and evaporation can be detected in the dry season (Haydock and MacLeod 1996).

Because of equipment breakdown during part of the wet-season measurements at this site, the initialization temperatures for the wet season modelling are out by approximately 3°C. Thus it was not possible to directly compare the absolute values of the calculated and observed temperatures for February 13, 1992 (Figure 2). Despite this problem, the temperature-versus-time profile of the surface data lies closest to Model 1, but has some contribution from latent and sensible heat fluxes (Model 2) since the cooling and heating rates lie between the values of both models. The 3°C surface diurnal variation is similar to that predicted by the Model 1 system and the predicted maximum occurs very close to the surface value. Generally, the surface temperature profiles for the first eight hours are more intense than the modelled curves. The absence of the rapid 'evaporative' cooling observed in the dry season is due to the much higher ambient moisture levels prevailing during the wet season.

Barralumma II

This ground level shelter lies within a 25-m long overhang that is 5 m wide and 2.5 m high, on the northern outside edge of the Napier Range. The paintings are

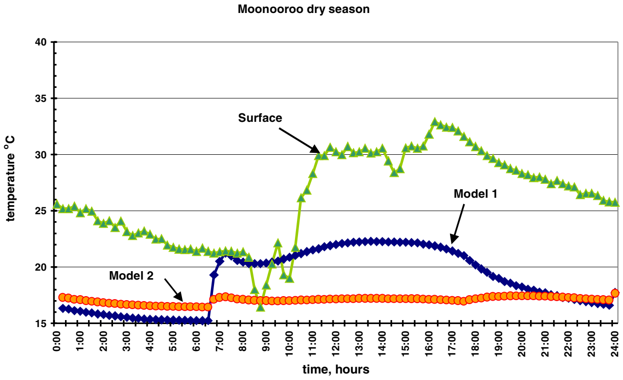

Figure 3. Moonooroo dry season, rock face and modelled rock temperatures

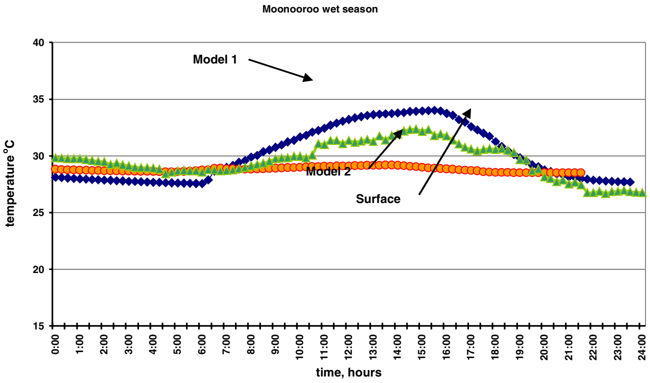

Figure 4. Moonooroo wet season, rock face and modelled rock temperatures

mainly on the ceiling area. The model failed to mirror the observed conditions, with the predicted dry season diurnal temperature range being 8°C less than the observed value. The wet season model agreed with the diurnal range, but did not perform well for the rates of cooling and heating. The failure is probably due to the relatively shallow nature of the rock shelter and the direct impact of the sun on the dry surface.

Modelling for sandstone sites in the Mitchell Plateau

Both sites consist of intensely metamorphosed quartz sandstone where individual sand grains have been deformed and forced together. Void spaces are negligible and some secondary silica overgrowths have additionally bound the grains. Traces of iron normally present in the parent rock display some secondary silicification on the weathered surface. Weathering is generally in the form of granular disintegration on the upward facing surfaces and sheet exfoliation, leading to the leaching of silica.

Moonooroo

Moonooroo consists of an outcrop of low-lying quartzite boulders scattered in piles over about a hectare near the King Edward River. The paintings are scattered in small shelters throughout the outcrops formed by block weathering. The modelled site was on one side of a rock that was 5 m high, 12 m long and 6 m wide, which was oriented 345°, or roughly NNW. The still air model for the dry season data for July 27, 1990 provides the best fit as it predicts the observed sudden rise of rock face temperature in the morning, but two hours too soon, and the long heating cycle over the day and evening cooling gradient mirror much of the rock face behaviour (Figure 3). It fails to depict the direct heating from the sunlight later in the afternoon, which is due to the northwesterly orientation of the shelter. While the minimum for Model 1 and the surface temperatures are coincident at 16°C, the maximum rock temperature at 32° was 10 degrees hotter than predicted by the model. The modelled data provide a much better fit in the wet season on March 14, 1992, which reasonably matches the heating and cooling gradients and the minimum and maximum temperature times, with the surface-cooling rate being faster than the model (Figure 4). The actual diurnal range of more than 6 degrees is essentially identical to the model. Data from succeeding days show a trend to lower night values as the overall temperature cooled down, i.e., the microclimate is dynamic, whereas the model uses data from the preceding day.

Yalgi

The shelter formed by block weathering is oriented 30° or roughly NNE and lies at the base of a rugged outcrop, adjacent to a low sandstone cliff that runs parallel to a large creek. The images cover an area 4 m wide, 7 m long and 1.5 m to 2.5 m high, and the soils within the shelter are generally sandy and stony (MacArthur and Wright 1967). The dry season surface and modelled data for July 31, 1990, show the surface temperature fell 7°C from 03:30 to 09:30 before it rapidly rose to just above the approximate night temperature in less than an hour. This

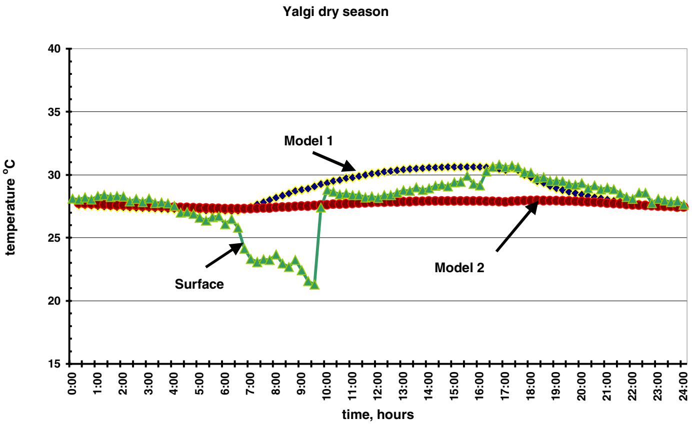

Figure 5. Yalgi dry season rock face and modelled rock temperatures

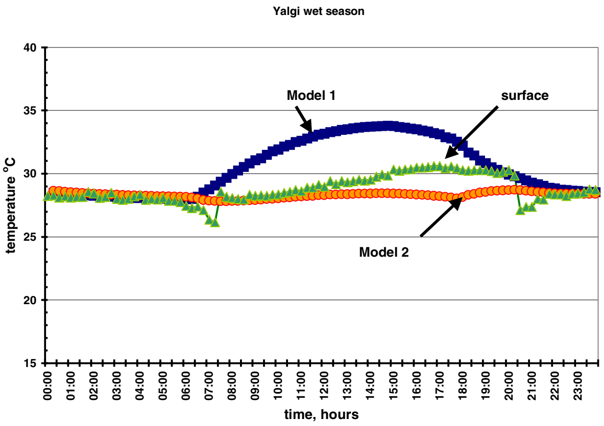

Figure 6. Yalgi wet season, rock face and modelled rock temperatures

temperature drop was due to a cold dry south-easterly wind cooling the rock surface (sensible heat flux).

The surface temperature indicates direct sunlight hitting the rock, but the model indicates the heating should have started as a long generous curve from around sunrise at 06:30 (Figure 5). The calculated and surface maxima are coincident, and there is agreement regarding late afternoon heating around 17:00. The surface temperatures in the wet season, for March 9, 1992, lie between Model 1 and Model 2, and while Model 2 predicts the double dipping of the surface curve there is no synchronization of the times or the magnitude of the dips (Figure 6). Scheme two better represents the heating of the rock face, but it does not predict the sudden heating at 07:30. Scheme one results match the surface data of the cooling rock face prior to 06:00. It is likely that cooling dry winds caused the second temperature drop at 20:00 as the relative humidity also suddenly dipped during this the same period. The temperature recovery results from the thermal mass and deep rock temperature. Only the first six hours of the model provided matching temperature profiles, but the sudden cooling conditions in the evening could not have been predicted.

Conclusion

The normally good correlation between the surface and Model 1 temperatures shows that the shelters generally have little turbulent mixing of the air. The finite size of the caves and their non-ground level bases ensures that the predicted temperature ranges for all caves are smaller than observed values. Lower temperature ranges also result if the rock density is greater than the real value and if they have different heat capacities than standard specimens. However, custodial issues prevented access to suitable weathered host rock for relevant analyses.

Since the model showed the 'sky view factor' is very important for vertical surface elements, significant improvement in the model could be made using photographic techniques to get more accurate values of this factor (Lyons and Haydock 1987, Haydock and MacLeod 1996). The model does not have the ability to predict the temperatures when the microenvironment is highly variable. Rapid rises and dips in the rock temperatures are either due to the impact of direct sunlight on the surface or to localized winds causing evaporation of moisture from rock fissures.

The model successfully predicted the temperature rises of the sun striking the rock face. Allowance for the natural shapes and curves and dipping ceilings would also improve the model. Since the blanketing effects of clouds that impede long-wave cooling and reduce the direct ultraviolet radiation cannot be modelled, the system works best for the clear and open skies that predominate in Western Australia. The combination of recorded and calculated microclimate data, using the modified Lyons model, enables prediction of the microclimate of the shelters over an extended period of time.

Acknowledgements

We wish to thank the Western Australian Heritage Council for funding, the National Gallery of Australia for equipment and assistance from Bruce Ford, members of the Junjuwa Community Incorporated and the Gulingi Nangga Aboriginal Corporation and the Department of Conservation and Land Management rangers from the Windjana Gorge National Park for assistance during our field work. Thanks are due to Tom Lyons and Inge Savage for modelling the data.

References

Clarke, J D, 1976, 'Two Aboriginal rock art pigments from Western Australia: their properties, use and durability', *Studies in Conservation*, 21, 134–142.

Clarke, J D, 1978, 'Deterioration Analysis of Rock Art Sites' in C. Pearson (ed.), *Conservation of Rock Art*, 54–63.

Davies, J A, 1975, 'Estimating Global Solar Radiation', *Boundary Layer Meteorology*. 9, 33–52.

Deardorff, J W, 1978, 'Efficient prediction of ground surface temperature and moisture, with inclusion of a layer of vegetation', *Journal of Geophysical Research* 83, 1889–1903.

Elliot, D, (Bureau of Meteorology), personal communication, April 1991.

Ford, B, MacLeod, I D and Haydock, P, 1994, 'Rock art pigments from the Kimberley region of Western Australia: identification of the minerals and conversion mechanisms', *Studies in Conservation* 39, 57–69.

Haydock, P and MacLeod I D, 1996, 'Microclimate modelling in the West Kimberley: a report on the analysis of microclimate data', unpublished report to the Australian Institute for Aboriginal and Torres Strait Islander Studies, Perth, 1–70.

Lyons, T J, 1986, 'Model: predication of surface temperature', unpublished report, Murdoch University, School of Environmental and Life Sciences, Murdoch, Western Australia, 6150.

Lyons, T J and Edwards, P R, 1982, 'Estimating Global Irradiance for Western Australia, Part I' in *Archives for Meteorology, Geophysics and Bioclimatology*, B30, 357–369.

Lyons, T J and Haydock, P, 1987, 'Surface energy budget model of a cave', *Theoretical and Applied Climatology* 38, 8–14.

MacArthur, W M and Wright, M J, 1967, *Atlas of Australian Soils: Explanatory Data for Sheet 9 – Kimberley Area*, collated by Northcote K.H. C.S.I.R.O. and Melbourne Uni. Press Melbourne (Soil classification Qb34 and soil classification JK14).

MacLeod, I D, Haydock, P, Tulloch, D and Ford, B, 1995, 'Effects of microbiological activity on the conservation of aboriginal rock art', *AICCM Bulletin* 21(1), 3–10.

Oke, T R, Kalanda, B D, Steyn, D G, 1981, 'Parameterization of heat storage in urban areas', *Urban Ecology* 5, 45–54.

Steyn, D G, and Lyons, T J, 1985, 'Comments on "The determination of view factors in urban canyons"', *Climate and Applied Meteorology* 24, 383–385.