9.3 PARAMETERIZATION OF NET-ALL WAVE RADIATION FOR URBAN AREAS

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1. Introduction*

Direct measurements of net all-wave radiation (Q*) are uncommon particularly for urban areas. Existing parameterizations for Q* have not been widely evaluated over a range of seasonal, climatological, and surface conditions in urban areas; recent efforts primarily have used summertime and daytime observations at a single site (Sozzi *et al.* 1999, Newton 2000). Here a simple parameterization of Q* that relies on a minimum of measured inputs (meteorological & surface characteristics) is evaluated with data from three contrasting urban areas (Łódź, Poland; Chicago & Los Angeles).

2. Framework

The radiation budget for a horizontal surface is: $Q^* = K^* + L^* = K_\downarrow - K_\uparrow + L_\downarrow - L_\uparrow$ where, K and L represent the short- and long-wave components, respectively; the arrows the direction of the flux; and * the net flux. Although it would be nice to minimize data requirements to commonly available meteorological fields, we find that observations of incoming solar radiation are almost mandatory. There are many simple relations for $K_\downarrow$ based on latitude and average cloud cover (see Sozzi *et al.* 1999); however, the errors for hourly estimates tend to be large, given the temporal variability of cloud cover. Measured $K_\downarrow$ also can be used to estimate cloud fraction. For the model here, screen-level air temperature (T_a), relative humidity (RH), and $K_\downarrow$ are required to estimate Q*.

Table 1: Equations referenced in text

1	$K^* = K_\downarrow (1-\alpha_0)$
2	$L_\downarrow = \varepsilon_{sky}\, \sigma\, T_{sky}^4$
3	$\varepsilon_{clear} = 1 - (1 + w) \exp\{-(1.2 + 3.0\, w)^{0.5}\}$; $w = 46.5\, e_a/T_a$
4	$K_{\downarrow,\, clear} = I_{Ex} \cos(Z)\, \tau_R \tau_{pg} \tau_w \tau_{aer}$
5	$FCLD = 1 - K_\downarrow / K_{\downarrow,\, clear}$
6	$\varepsilon_{sky} = FCLD + (1-FCLD)\, \varepsilon_{clear}$
7	$L_\uparrow = \varepsilon_0\, \sigma\, T_0^4 + (1 - \varepsilon_0)\, L\downarrow$
8	$\varepsilon_0\, \sigma\, T_0^4 \approx \varepsilon_0 \sigma T_a^4 + 4\, \varepsilon_0\, \sigma T_a^3 (T_0 - T_a)$
9	$4\, \varepsilon_0\, \sigma\, T_a^3 (T_0 - T_a) = c\, K\downarrow (1-\alpha_0)$

2.1 Net shortwave radiation

The K* term is a function of $K_\downarrow$ and the bulk surface albedo, α_0 (eq. 1, see Table 1 for all equations referenced in text), with no distinction made between direct and diffuse radiation. Measured values of α_0 for urban areas typically range from 0.10 – 0.27 with a mean near 0.15 (Oke, 1987). $K_\downarrow$ dominates the daytime radiation budget (Q*) during summertime, at low latitudes, and if there is no significant cloud cover. Simple linear regression models of Q*, based on measured $K_\downarrow$, can then generate impressive results, with root-mean-squared errors (RMSE) < 30 W m^{-2} (Kaminsky & Dubayah 1997).

2.2 Incoming longwave

One could make an argument similar to that for K↓ to include measurements of $L_\downarrow$ in a relation for Q*, because the variability of cloud cover makes estimation of $L_\downarrow$ difficult. As $L_\downarrow$ is less commonly observed than $K_\downarrow$, estimation approaches are needed. Here a single-layer atmosphere model is used (eq. 2), where T_{sky} is the bulk atmospheric temperature (K) estimated by T_a, σ is Stefan's constant, and ε_{sky} is an estimated broadband atmospheric emissivity. Surface-level schemes for clear-sky emissivity have been reviewed in detail elsewhere (Prata 1996, Crawford & Duchon 1999 [CD99], Niemelä *et al.* 2001). The Prata (1996) formulation (eq. 3) has been found to perform best (Newton 2000, Niemelä *et al.* 2001). In eq. 3, w is the precipitable water content (g cm^{-2}) approximated to mean atmospheric values based on screen-level vapor pressure (e_a) and T_a.

Cloud effects are harder to generalize based on simple cloud fraction, but physically cloudiness should increase ε_{sky} towards its maximum of 1 as total cloud cover is approached. The ratio of measured $K_\downarrow$ to that predicted under clear-sky conditions ($K_{\downarrow,\, clear}$) can give an estimate of daytime cloud cover (CD99). $K_{\downarrow,\, clear}$ is estimated by eq. 4 (CD99), where I_{Ex} is extra-terrestrial solar insolation, Z is the solar zenith angle and $\tau_r\tau_{pg}\tau_w\tau_{aer}$ is the product of transmissivities for Rayleigh scattering (R), absorption by permanent gases (pg) and water vapor (w), and absorption and scattering by aerosols (aer). The transmissivities are a function of time of year, zenith angle, latitude and surface dewpoint, which is computed from T_a and RH. Since urban areas are likely to be more polluted than the base state, $K_{\downarrow,\, clear}$ is multiplied by a site-specific transmissivity. Jacovides *et al.* (2000) found an average urban-rural difference for Athens of 15% in the visible wavelengths, although this could be an extreme case. The daytime cloud fraction (FCLD) is given by eq. 5 (CD99). For nighttime, the last daytime value for FCLD is used. Clear sky ε_{sky} is then adjusted for the effects of cloud cover (eq. 6, CD99). The performance of this or other parameterizations of lonq-wave cloud effects will depend on site cloud climatology.

2.3 Outgoing longwave

$L_\uparrow$ is primarily driven by surface temperature T_0, only a small fraction being due to reflection of $L_\downarrow$ from the surface (eq. 7). T_0 is difficult to determine directly and it is almost never available on a routine basis. This makes it necessary to substitute the approximation of T_0 by T_a in eq 7. However, this tends to bias the estimate particularly during the daytime when the surface heats up more quickly than the atmosphere due to absorbed solar radiation. Holtslag & van Ulden (1983) proposed a

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correction for unstable conditions based on either Q* or $K_\downarrow$ (eq. 8). We use $K_\downarrow$ since Q* is the unknown here and $K_\downarrow$ is an observed quantity in the parameterization. The magnitude of this correction is estimated by eq. 9, which is a modification of the original formulation that did not incorporate α_0. With $\alpha_0 = 0.15$, $K_\downarrow = 1000$ W m^{-2}, T_a = 300 K, the correction is equivalent to $T_0 - T_a = 9$ K which seems appropriate for a dry surface. However, this approach does not account for any hysteresis. At night it results in no correction at all. In practice T_0 should peak after $K_\downarrow$, approach T_a near sunset, and T_0 may become cooler than T_a at night under stable conditions. However, these differences are likely to be small relative to the overall correction. Including a nighttime ($T_0 - T_a$) correction is likely to have little impact relative to the errors associated with cloud cover and ε_{sky} determinations and it is difficult to apply without some knowledge of stability.

3. Site and measurement characteristics

Evaluation of the parameterization scheme is made using observations from sites in: Chicago, USA (1992-93), Los Angeles, USA (1993-94) and Łódź, Poland (2001). In Chicago and LA, REBS Q*6 net radiometers measured Q* and Li-cor pyranometers (Li-200) monitored $K_\downarrow$. In Łódź, a KZ CNR1 measured the 4 component fluxes of the radiation budget.

The Q*6 stated accuracy is ±5% during daytime. The nighttime accuracy is poorer with the error biased toward zero. The expected CNR1 accuracy for daily totals of Q* is ±10%. Longwave measurements for both instruments are known to be affected by dome or window heating by direct solar radiation, particularly at times of low wind speed. The CNR1 $L_{\downarrow,\uparrow}$ fluxes may be biased by the instrument reference T. To avoid condensation on the domes and windows of the CNR1 the instrument was heated, but only at night. Heating typically affects shortwave more strongly than longwave readings, hence restricting it to the night should reduce the potential for errors. The T_a and RH sensors were located close to the net radiometers.

In Chicago the tower was in an area of low commercial structures and mixed vegetation (trees & grass). The LA tower was located in a residential area with mixed vegetation (trees, shrubs & sandy soil). At the Łódź site, near the urban core, building roofs and walls dominated the net radiometer's field of view. The effective α_0 and ε_0 used were from Arnfield (1982), except in Łódź where the α_0 was measured.

4. Results

Results of the scheme, run for 15 min intervals for each site, are promising considering differences between the sites (Table 2). Daytime errors are sensitive to α_0, leading to bias if mean α_0 is incorrect. When the mean midday α_0 was measured RMSE tends to be less in the daytime, due to the dominance of $K_\downarrow$ in the budget (Fig. 1, Łódź). The availability of cloud estimates for the daytime further improves performance. The larger daytime errors (Table 2) in Chicago and LA compared to Łódź relate to the bias associated with the albedo. In the results here, α_0 and ε_0 were held constant, even though they actually vary seasonally with vegetation and the presence of snow cover. This is apparent for both LA (dry period in early summer) and Chicago (snow around YD 72).

Table 2: RMSE (W m^{-2}), mean values in brackets

Site	N	Day	Night	All
Łódź	35039	18.9 (150)	29.4 (-42)	24.9 (50)
LA	30240	23.4 (236)	24.3 (-47)	23.9 (94)
Chicago	29556	28.6 (150)	22.1 (-33)	25.4 (54)

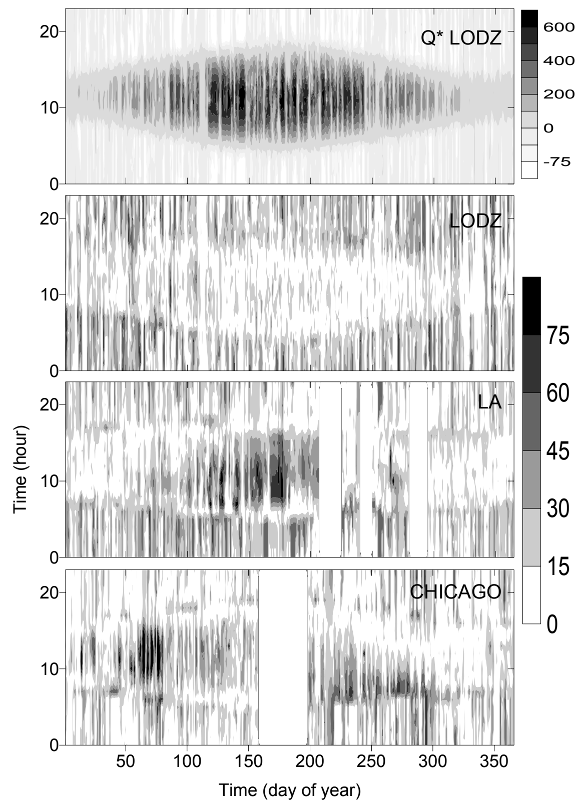

Figure 1: Calculated annual hourly Q* for Łódź, and RMSE (W m^{-2}) between measured and calculated Q* for Łódź, LA & Chicago. N.B. missing data in LA and CHI

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