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Emissivity of Clear Skies

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EMISSIVITY OF CLEAR SKIES*

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In a recent article Berdahl and Fromberg [1] discussed the thermal radiance of clear skies and presented measured data from three U.S. cities in the form of a correlation of sky emissivity versus surface dewpoint temperature. In this note we present additional data and the corresponding improved formula for the sky emissivity.

In the prior article, the clear sky emissivity at night was found to be given by

$$\varepsilon = 0.741 + 0.0062\, T_{dp} , \qquad \text{(old)} \qquad (1)$$

where T_{dp} (°C) is the dewpoint temperature near the ground. (The sky emissivity ε is defined as the ratio of the total thermal sky radiance to σT_a^4, where is the Stefan-Boltzmann constant and T_a is the absolute air temperature near the ground.) The average difference between nighttime and daytime observations was found to be 0.016, with the larger values observed at night. The day/night difference was independent of dewpoint temperature, within experimental accuracy.

The larger "new" data set consists of 57 months of data obtained at 6 sites as compared to the "old" data set of 11 months of data at 3 sites. The final result, to be derived below, gives a value for the 24-hour average of the total sky emissivity for clear skies:

$$\varepsilon = 0.711 + 0.56\left(\frac{T_{dp}}{100}\right) + 0.73\left(\frac{T_{dp}}{100}\right)^2 \quad . \qquad (2)$$

The range of monthly average values of T_{dp} was [-13, 24] °C; Eq. (2) probably has useful predictive capability over the range [-20, 30] °C. for applications in which estimates of ε are required for a

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particular time of day, a diurnal correction is suggested:

$$\Delta\varepsilon = 0.013 \cos\left(2\pi \frac{t}{24}\right) , \tag{3}$$

where t is the solar time in hours. The coefficient 0.013 was chosen to produce the observed average day/night difference of 0.016 [1]. The cosine function was chosen as the simplest analytic function which produces an appropriate day/night difference.

The extension of the analysis to the new data set would seem to be straightforward. However, in order to use the largest possible set of data and to maintain the highest possible accuracy, an indirect analysis of the data is required. One problem is that valid pyrgeometer measurements of total sky emissivity are not always present in the data set to coincide with the spectral radiometer measurements. This reduces the size of the data set available. Another problem is that in the original study the pyrgeometer was calibrated each month with the more accurate spectral radiometer. This calibration procedure is rather complex, and furthermore, does not work unless there are several cloudy days in the month in question.* To avoid these experimental difficulties, the following procedure was adopted.

The systematic difference between the old and new data sets was evaluated as a function of dewpoint temperature, using the pseudo-pyrgeometer measurement (to be described below). This small difference can be used to estimate the required adjustment in the old ε vs. T_{dp} correlation. Thus the technique relies on the accurate calibration of the old data set. Since the correction of the ε vs. T_{dp} correlation is small, 10% relative accuracy in its evaluation is satisfactory.

The pseudo-pyrgeometer measurement is performed with the "no-filter" channel of the spectral radiometer. The spectral response of the instrument is determined by a coated germanium lens and is given in [1]. The radiance measurements made in this channel at zenith angles of 0, 20, 40, 60, and 80 degrees are summed with appropriate weights to yield the hemispherical average value called the pseudo-pyrgeometer measurement. This measurement has the correct angular response, but the spectral response is not identical to that of a real pyrgeometer.

The pseudo-pyrgeometer emissivity ε_{ps} for clear sky conditions is shown as a function of dewpoint temperature in Fig. 1. Each point represents the average clear sky emissivity for the month and

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*Data from September 1979 at Tucson was reported but not used in [1] because the calibration procedure did not work.

the corresponding average dewpoint during clear conditions. The 57 values were obtained in 6 U.S. cities in the southern portion of the country (Tucson, AZ; San Antonio, TX; Gaithersburg, MD; St. Louis, MO; West Palm Beach, FL; and Boulder City, NV). The actual number of clear sky observations at half-hour intervals is 30,835. The curve through the data in Fig. 1 is a least squares fit to a quadratic function of T_{dp}, weighted by the actual number of observations comprising each point. The root mean square deviation of the monthly values from the fit is 0.018. Figure 2 shows the same sort of plot and fit with the data restricted to the original months of data used in [1]. For reference the quadratic curve of Fig. 1 is repeated. The difference between the two curves in Fig. 2 is

$$\delta\varepsilon_{ps} = -0.0232 - 0.066\left(\frac{T_{dp}}{100}\right) + 0.66\left(\frac{T_{dp}}{100}\right)^2 \quad . \tag{4}$$

This equation expresses the systematic difference between the two data sets. The new, larger data set has average emissivities which are slightly smaller at most values of the dewpoint temperature. The greatest downward adjustment in ε_{ps} is 0.025 at T_{dp} = 5°C.

Now, a relation between $\delta\varepsilon_{ps}$ and $\delta\varepsilon$ is required. These quantities should be closely related since the pyrgeometer and pseudo-pyrgeometer emissivities are very similar physical quantities. A linear relationship will prove adequate for the current purposes. For a small change in dewpoint temperature the corresponding changes in ε and ε_{ps} are given by

$$\delta\varepsilon = \left(\frac{d\varepsilon}{dT_{dp}}\right)\delta T_{dp}$$

and

$$\delta\varepsilon_{ps} = \left(\frac{d\varepsilon_{ps}}{dT_{dp}}\right)\delta T_{dp} \quad .$$

Eliminating δT_{dp} between these equations and evaluating the derivatives with respect to T_{dp} using Eq. (1) and Fig. 1, one obtains

$$\delta\varepsilon = (0.8 \pm 0.1)\ \delta\varepsilon_{ps} \ , \tag{5}$$

an approximate linear relation between $\delta\varepsilon_{ps}$ and $\delta\varepsilon$. This equation relates changes in ε_{ps} to changes in ε caused by changes in T_{dp}. We do not know the reason for the systematic difference in ε's between our old and new data sets. Nevertheless, we assume that the approximate proportionality, Eq. (5), holds. Thus with Eqs. (4) and (5), one has

$$\delta\varepsilon = -0.019 - 0.053\left(\frac{T_{dp}}{100}\right) + 0.53\left(\frac{T_{dp}}{100}\right)^2 , \qquad (6)$$

which can be added to Eq. (1) to produce the new ε vs T_{dp} relationship. Since this new relationship is quadratic, it is desirable to reconsider the original 11-month data set and fit it to a quadratic function. This procedure yields

$$\varepsilon = 0.738 + 0.61\left(\frac{T_{dp}}{100}\right) + 0.20\left(\frac{T_{dp}}{100}\right)^2 . \qquad \text{(old)} \qquad (1a)$$

This equation was not given in [1], because, as stated there, the data is equally well fit by the linear equation, Eq. (1). Adding Eqs. (1a) and (6), and subtracting half of the day/night difference, we obtain Eq. (2), our best estimate for the 24-hour average value of the total sky emissivity for clear skies.

One conclusion reached using the original data analysis [1] was that no observable site-to-site difference could be detected. It appears that, with the full data set, such a difference may have been observed: Gaithersburg, Maryland has consistently higher sky emissivity values at a given dewpoint temperature than the average for the data from all six cities. Figure 1 shows each Gaithersburg measurement to be above the fitted line. The average difference is 0.024 in ε_{ps}, which with Eq. (3) translates into 0.019 in ε. We are not certain whether this deviation is due to a real climatic difference between Gaithersburg and the other sites or whether it may be due to one or more systematic measurement errors. For most of the months of record we expect systematic errors to be less than the observed 0.024 in ε_{ps}.

Using this data it can be concluded that there exists a "universal" curve for monthly average clear-sky emissivity as a function of dewpoint temperature; that this universal curve is approximately given by Eq. (2); and that systematic deviations from the universal curve are less than or equal to (the Gaithersburg value of) 0.02 at midlatitude sites below an elevation of 1 km.

Finally, we note that our current best estimate of the emissivity of clear skies is now a quadratic function of dewpoint temperature, requiring three fitted parameters. It is interesting that a two- parameter fit of the type introduced by Brunt [2,3] fits the data equally well:

$$\varepsilon = 0.564 + 0.059\, e^{\frac{1}{2}} , \qquad (7)$$

where e is the water vapor partial pressure in mb. This relation gives values of ε differing from Eq. (2) by no more than 0.003, a negligible difference.

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Individuals at our laboratory who made important contributions to our measurement program were Gerald Stoker, Peter Fuller, and Brian Smith. Equation (1a) is from unpublished notes by Richard Fromberg.

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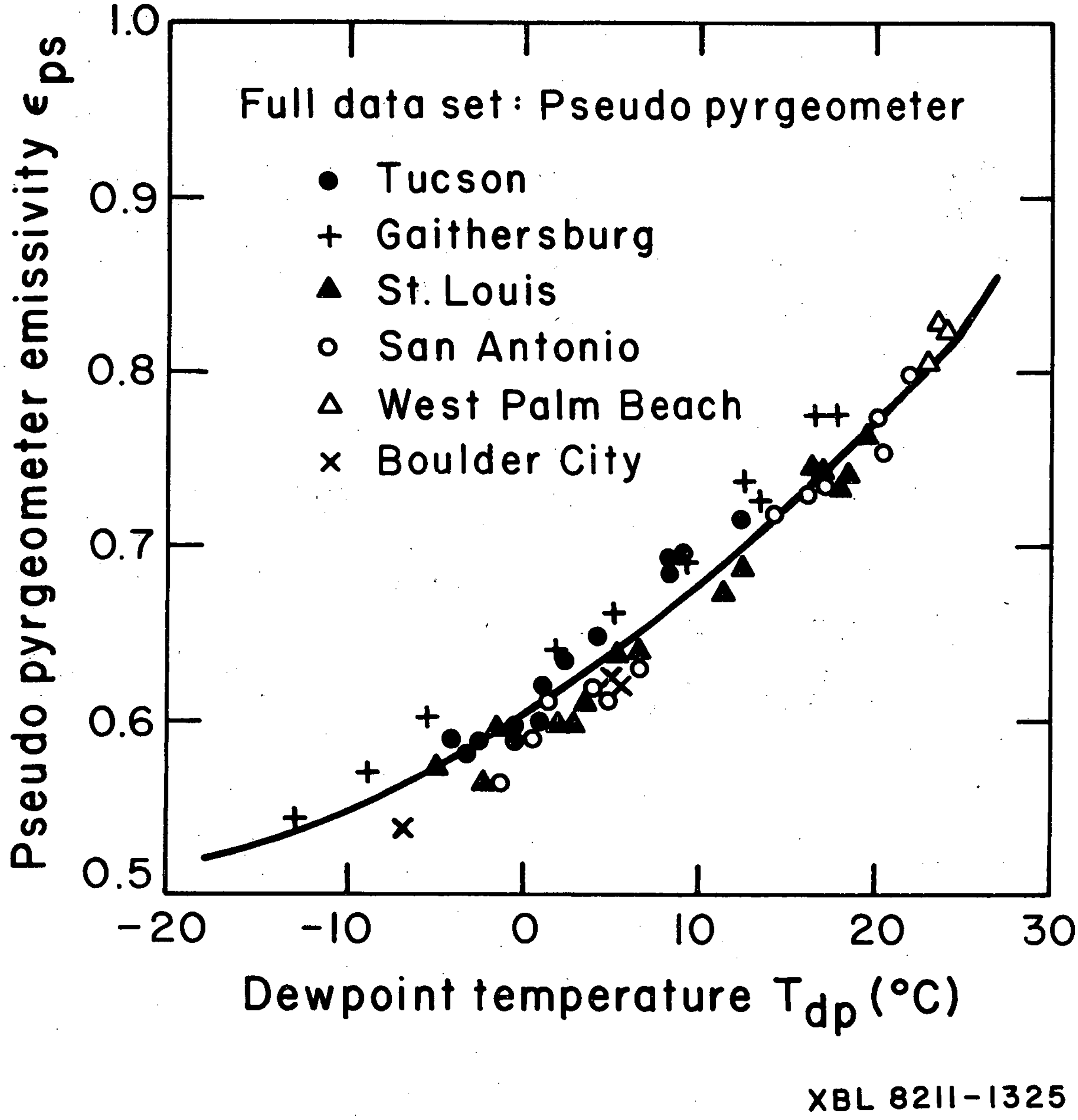

Figure 1. Monthly Pseudo-Pyrgeometer Sky Emissivity for Clear Skies Based on Measurements by the LBL Spectral Sky Radiometer, as a Function of Dewpoint Temperature. The Solid Line is a Least Squares Fit to a Quadratic Function of T_{dp}.

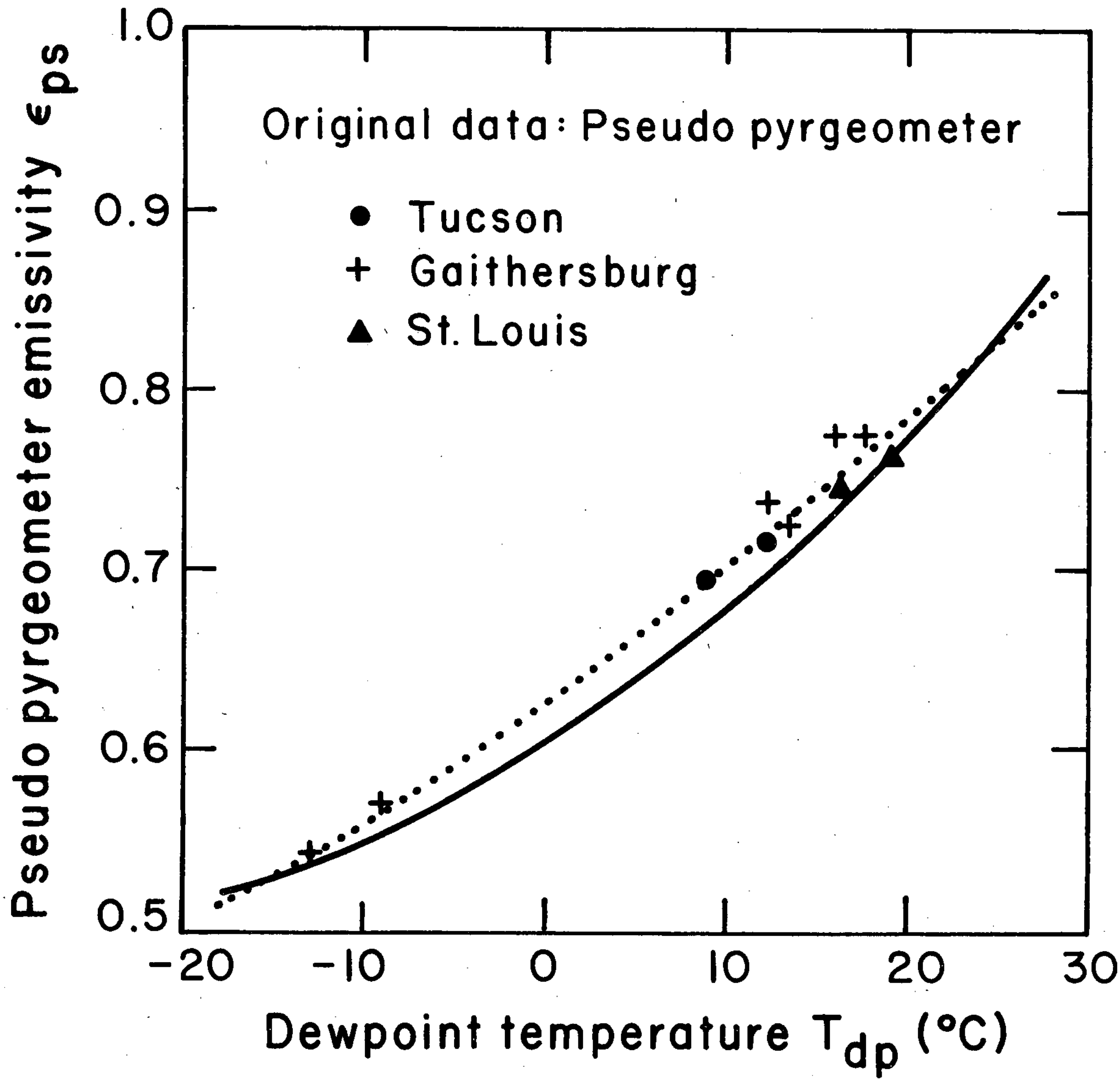

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Figure 2. Monthly Pseudo-Pyrgeometer Sky Emissivity for Clear Skies as Measured by the LBL Spectral Sky Radiometer Showing Only the Original Data Set used in [1]. The dotted line is a Least Squares Fit of this Restricted Data Set to a Quadratic Function of Dewpoint Temperature. The Solid Line is the Same Curve Shown in Fig. 1.

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