The Relationship between the Planetary and Surface Net Radiation

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24 October 1984 and 23 May 1985

ABSTRACT

In this study, an attempt has been made to derive the daily net radiation at the top of the atmosphere using the Geostationary Operational Environmental Satellite (GOES) visible (0.55–0.75 μm) and IR window (10.5–12.5 μm) observations and to correlate it with the net radiation at the surface. The NOAA/NESDIS agency arranged for the collection of GOES-E satellite data for a two year period (1981–82) at selected sites in Canada, where surface net radiation is observed routinely. The derived daily average net radiation at the top of the atmosphere was found to be highly correlated to the daily average net radiation at the surface. Preliminary tests of a statistical approach to estimate the surface daily average net radiation from satellite observations of planetary daily average net radiation yielded encouraging results. It was also demonstrated that when the averaging period for the net radiation was increased from one to ten days, the standard error of estimate was reduced from 20 to 7 W m^{-2}.

1. Introduction

The spatial and temporal variation of the net radiation flux at the earth's surface is responsible for the redistribution of the available energy. Over land, the net radiation controls the input of latent and sensible heat flux into the atmosphere; over the ocean, it controls the oceanic heating which is associated with long term weather and climate variability. Information about radiation fluxes at the surface is essential for climate related studies on all time and spatial scales. It has been recognized that the required accuracy would vary according to the scale. A list of the all the radiation budget components and the required accuracies for their monitoring on different spatial and temporal scales has been prepared during a Committee on Space Research (COSPAR) and the European Space Agency (ESA) sponsored workshop and was reported in COSPAR (1978), known also as the "Alpbach Report." These requirements were later endorsed in World Climate Program—40 (1982), where it is stated that the accuracy requirements on net radiation for climate monitoring are ±20 W m^{-2} with spatial resolution of 200–1000 km for monthly means. In World Climate Program—70 (1984), it is stated that for most purposes, an accuracy of ±10 W m^{-2} for a spatial resolution of 250 km for monthly means is required for surface net radiation observations, and an accuracy of ±20 W m^{-2} would still be useful.

So far, few attempts have been made to estimate the surface radiation budget on a global or regional scale using conventional meteorological data (Budyko, 1956). The available information is not sufficient for obtaining global scale statistics from ground based observations. This has prompted several proposals for projects that will lead to a unified and standard evaluation of procedures for assessing the surface radiation budget using satellite data (Schiffer, 1983). The parameters to be derived before one can determine the surface radiation budget are: the downwelling shortwave (0.2–4.0 μm) and longwave (>4.0 μm) radiation, the surface albedo, and surface temperature and emissivity. At present, algorithms exist only for the derivation of some of these parameters, e.g., downwelling shortwave radiation (Tarpley, 1979; Gautier et al., 1980; Moser and Raschke, 1984; Pinker and Ewing, 1985) and longwave radiation (Darnell et al., 1983). These methods have not been standardized, intercompared, or applied on a global scale. Therefore, indirect methods for deriving the surface net radiation from available space observations would be most beneficial. In that context, the issue of whether planetary and surface radiation budgets are correlated is also of interest.

It has been previously shown that clouds play an important role in the planetary radiation budget. Several studies have been conducted to estimate the compensating effects of clouds on the planetary net radiation (Schneider, 1972; Cess, 1976; Ohring and Clapp,

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1980; Hartmann and Short, 1980). However, no studies have been conducted on the compensating solar and thermal effects of clouds on the surface radiation budget. Stephens and Webster (1984) used a one-dimensional radiative–convective equilibrium model to demonstrate that while the reflected solar flux from cloud layers is independent of their vertical distribution, the downward longwave radiation does depend on the effective cloud base height. They argued that this latter process tends to decouple the radiative budgets at the top of the atmosphere and at the surface. They also state that ". . . the extent to which the planetary and surface budgets are correlated has not been established. The whole issue of whether or not satellite monitoring of changes in the net radiation balance at the top of the atmosphere is indicative of changes in (surface) climate hinges on this correlation."

In a study conducted over the central United States (Pinker and Corio, 1984), it was shown that the net radiation and the outgoing longwave radiation at the top of the atmosphere are correlated with the net radiation at the surface ($r = 0.76$). Several approximations were applied in the process of deriving the daily net surface and planetary radiation fields. The global solar radiation at the ground was computed from hourly observations, while the net longwave radiation was obtained from an empirical model based on average daily screen-level temperature (computed from the daily minimum and maximum), and average daily cloud amount. The solar radiation observing stations and those that observe the necessary meteorological data were not always colocated. The net radiation at the top of the atmosphere was derived from one observation per day in the visible and two observations per day in the infrared (IR) using the NOAA 5 observations (Winston *et al.*, 1979). As such, the diurnal variation at the top of the atmosphere was not well represented. The present study aims to remove some of the above limitations; to re-examine the previously established correlation; and to test the predictive value of the correlations on independent data sets.

2. Data

a. Satellite data

During the spring of 1981, a satellite data collection program over Canada was initiated to facilitate the study of the relationship between planetary net radiation and surface net radiation. The National Environmental Satellite Data and Information Service (NESDIS) arranged for the ongoing collection of GOES-E satellite data from 1981 to the present at the following sites in Canada: Elora, 43°39′N, 80°25′W; Ottawa, 45°27′N, 75°31′W; Sable Island, 43°56′N, 60°00′W; St. Augustin, 46°44′N, 71°30′W; and, Toronto, 43°48′N, 79°33′W. These sites were selected because at these locations surface radiation observations are made. (In 1982, surface observations were moved from St. Augustin to nearby Quebec.)

The satellite data set contained 8 km resolution Visible and Infrared Spin Scan Radiometer (VISSR) pixels from the GOES-E. The VISSR is a scanning radiometer that is stepped from north to south and uses the rotation of the satellite to scan from west to east. It makes measurements in two wavelength regions: an interval in the visible region (0.55–0.75 μm), and one in the thermal IR window region (10.5–12.5 μm). The satellite data were collected as part of an experimental program and are not routinely available. The selected resolution and format were based on experience obtained during an experiment over the Great Plains (Tarpley, 1979). This experiment served as the basis for the development of the present NOAA/NESDIS operational insolation algorithm.

Eleven visible observations and five IR observations were collected each day for each site. The data are in the form of counts which are dimensionless quantities proportional to the square root of the intensity in the associated spectral region. The visible count values are on a scale of 0–63 and were found to lie within a range of 14–57 for the daytime hours studied in the 1982 period for Toronto. Both the mean count values of 5 × 5 arrays of pixels, and the count values for the center pixel of the array were collected. Each array of pixels covers an area on the surface of about 50 km on a side and centered at the latitude and longitude of the surface sites. These two values are generally very similar, differing by no more than 10%.

Provided with every observation is the appropriate time of the observation, an associated solar zenith angle, a satellite azimuth angle, and daily estimates of the atmospheric precipitable water as obtained from the coincident National Meteorological Center (NMC) analysis. A disadvantage of the VISSR is that a calibration procedure is required to convert the counts into radiative fluxes. The calibration procedures are usually based on numerical solutions to the radiative transfer equation (Smith and vonder Haar, 1983; Fraser and Kaufman, 1984) or on comparisons with simultaneous observations from other platforms (Smith *et al.*, 1981; Minnis and Harrison, 1984).

b. Surface data

The surface radiation data consist of hourly totals of net radiation. The data were obtained from the Canadian Climate Center of the Atmospheric Environmental Service and are documented in Phillips and Aston (1980).

3. Procedures

Upward solar fluxes were derived from the GOES visible counts using the calibration procedure developed by Smith *et al.* (1981). The visible counts from the GOES satellite were calibrated in terms of spectrally integrated shortwave fluxes. The calibration is based upon space and time coincident radiation measurements conducted for this purpose from the NASA CV-

TABLE 1. Summary of regression analyses for four locations in Canada, between daily average surface net radiation (GNET) and: daily average planetary net radiation (PNET); daytime outgoing longwave radiation (LWD), using data for August and September 1981. Regression analysis was performed for all locations, and between hourly average of surface net radiation and planetary net radiation for Ottawa.

Location	Variable	Simple R	Multiple R
Toronto	PNET	0.933	0.939
	LWD	0.533	
Ottawa	PNET	0.829	0.879
	LWD	0.712	
Sable Island	PNET	0.601	0.667
	LWD	0.503	
Elora	PNET	0.913	0.944
	LWD	0.701	
All locations	PNET	0.805	0.803
	LWD	0.551	
Ottawa (hourly)	PNET	0.760	0.774
	LWD	0.228	

990 aircraft. The NASA aircraft carried narrowband and broadband narrow-angle directional radiometers and broadband flux radiometers (Ackerman and Cox, 1980). The application of the calibration calls for the transformation of the visible counts into narrowband (0.55–0.75 μm) reflectance; association of a broadband reflectance (0.3–4 μm) with the narrowband reflectance, according to the type of underlying surface; and transformation of the directional broadband reflectance to an angularly integrated albedo. Smith *et al.* (1981) derived independent transformations for several surface types. We used a single transformation derived for an underlying surface of vegetation. Since sensor response varies from satellite to satellite and the response of any single sensor changes with time, the appropriateness of the calibration in each case has to be established first (to be discussed later).

The longwave radiation was computed by using the method of Ohring *et al.* (1984), where the data are first corrected for limb darkening to obtain normalized radiance. The normalized radiance is then converted to a brightness temperature using the Planck function. A flux equivalent temperature is derived from the brightness temperature via a regression formalism. Since the net fluxes are calculated at unequally spaced times, they were weighted consistently with their spacing in order to estimate the daily average planetary net radiation.

4. Results and discussion

Daily totals of planetary net radiation were computed for Toronto, Ottawa, Sable Island and Elora for May–August 1981 using the GOES-E data. Corresponding daily totals of surface net radiation were derived from the surface observations taken by the Canadian Environmental Service.

Linear regression analyses of the form:

$$\text{GNET} = a(\text{PNET}) + b(\text{LWD}) + c \qquad (1)$$

were performed between the daily average net radiation at the ground (GNET), the daily average planetary net radiation (PNET) and the daytime planetary outgoing longwave radiation (LWD). These analyses were performed for all four locations. Computational experiments were conducted with time series of variable length as extracted from the five months of data. A summary of regression analyses for the four locations, using the daily averages for August–September 1981 are presented in Table 1. A regression analysis was performed for the August–September 1981 period after data from all four locations were merged and between hourly values of planetary radiation balance parameters and surface net radiation (for Ottawa only). These results are also presented in Table 1.

The results indicate a high correlation between the two fields of net radiation, and that the addition of the outgoing daytime longwave radiation to the regression

TABLE 2. Linear regression statistics (GNET = m(PNET) + b) between the daily average values of surface (GNET) and planetary (PNET) net radiation as derived for a four-month period between May and August 1982: (a) month by month for Toronto; (b) four months of data merged separately for Toronto, Ottawa and Quebec. All net flux values are in ($W\,\text{m}^{-2}$).

	Mean surface net	Mean satellite net	Number of days	Correlation surface/satellite	Regression equation m	Regression equation b	Standard error (%)
(a) Monthly-Toronto							
May	116.0	37.0	19	0.923	0.6009	93.69	14.7
June	115.0	29.0	9	0.964	0.7693	93.35	15.4
July	156.0	67.0	20	0.916	0.5091	122.00	8.4
August	99.0	−16.0	19	0.933	0.5741	108.00	13.7
(b) Four-month							
Toronto	123.1	29.9	67	0.924	0.614	104.7	14.5
Ottawa	122.2	32.1	67	0.914	0.595	103.1	16.0
Quebec	101.9	10.2	63	0.932	0.530	92.2	15.9

equation as an independent variable only slightly improves the explained variance. This should be expected, since the outgoing daytime longwave radiation is already accounted for in the net radiation term. This was not the case in the study of Pinker and Corio (1984) where adding the daytime longwave radiation as an independent variable in the regression equation explained an additional 13% of the variance. This is consistent with the inherent differences between these two cases. In the Great Plains study, the daily planetary net radiation was estimated from one observation in the visible and two observations in the IR. The daytime and nighttime outgoing IR radiation over the Great Plains is not the same. Since including the daytime outgoing IR radiation to the regression analysis increases the explained variance, it indicates that the daytime situation is dominant in the daily energy budget and should be more heavily weighted. The reason we did not find this additional dependence in the Canadian study is because the planetary net radiation was computed from many observations per day and as such, each component was equally weighted. Also, at the Canadian locations, there was no strong diurnal variation in the outgoing longwave radiation.

When satellite data for 1982 became available, a check for trends in the two years of data was conducted. A displacement between the minimum visible sensor counts during these two periods was found, which would indicate that the same calibration is not appropriate for both periods. To establish which year the Smith *et al.* calibration is more appropriate, use was made of a radiative transfer model described in Pinker and Ewing (1985). With a given surface albedo of 22% (typical for the Toronto site, as measured by the Canadian Environmental Service) and a typical midlatitude summer atmosphere, the planetary albedo was computed for the solar spectrum of 0.3–4 μm. The value obtained was in good agreement with the planetary albedo derived from the 1982 counts over Toronto under clear sky conditions, but was larger than the value obtained with the 1981 counts. This would

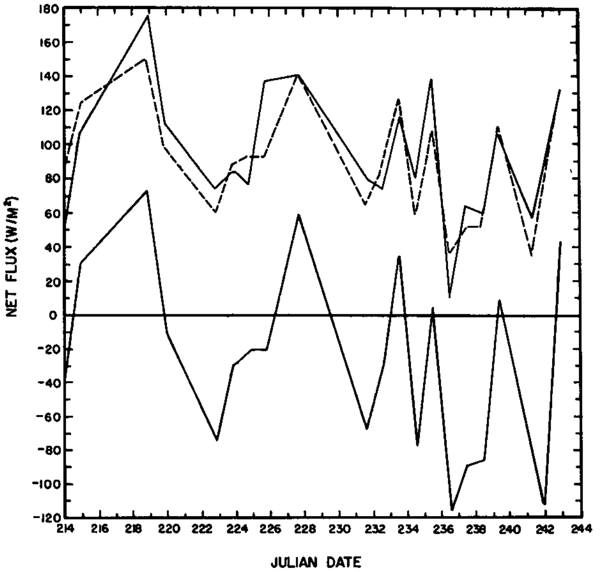

FIG. 1. Daily averaged net radiation fluxes for the month of August 1982 for Ottawa, Canada. Lower solid line: computed planetary net fluxes. Upper solid line: measured surface net fluxes. Upper dashed line: predicted surface net fluxes, generated from a regression equation developed for Toronto for the summer of 1982.

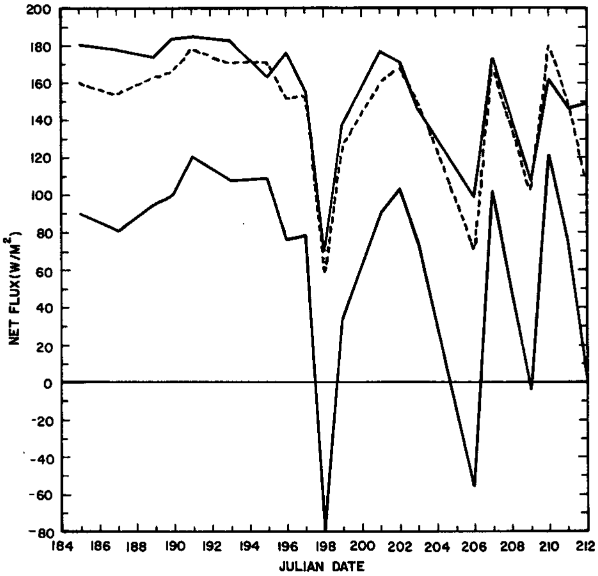

FIG. 2. Daily averaged net radiation fluxes for the month of July, 1982 for Toronto, Canada. Lower solid line: computed planetary net fluxes. Upper solid line: measured surface net fluxes. Upper dashed line: predicted surface net fluxes, generated from a regression equation developed for Toronto for the summer of 1982.

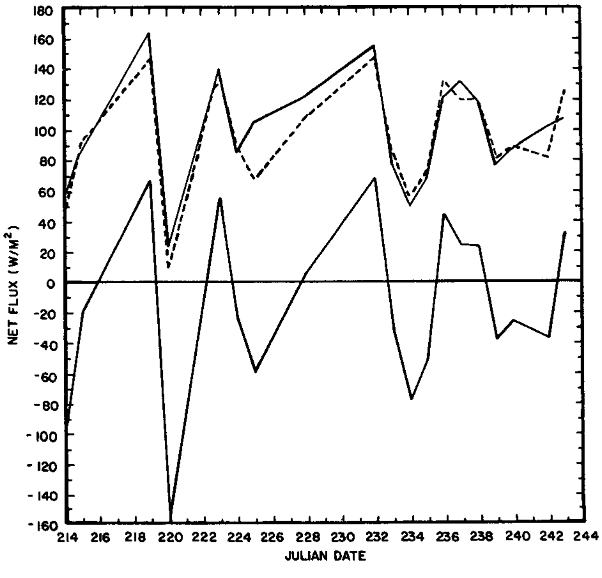

FIG. 3. As in Fig. 2 but for the month of August 1982 for Toronto, Canada.

TABLE 3. Standard error of estimate of predicted surface daily net radiation (GNET) from satellite daily net radiation (PNET) for Toronto, Ottawa and Quebec, using the regression equation derived from Toronto, May–August 1982 (Table 2b). All net flux values are in (W m^{-2}).

Month	Number of days	Mean satellite net	Mean surface net	Mean predicted surface net	Standard error		Average cloud amount
					W m^{-2}	%	
Toronto							
May	19	37	116	127	16	14	6.1
June	9	29	115	123	20	17	7.7
July	20	67	156	146	14	9	5.2
August	19	−16	99	95	13	13	6.4
Ottawa							
May	19	45	123	132	18	15	6.1
June	9	58	128	140	21	16	6.3
July	19	67	149	146	14	10	5.2
August	20	−25	93	89	20	22	6.6
Quebec							
May	18	14	97	113	20	20	7.2
June	8	30	109	123	6	5	6.1
July	18	48	123	134	15	12	6.3
August	19	−11	83	98	17	20	6.7

indicate that the albedos derived for the summer of 1981 are too low and as such, the net radiation is too high. Therefore, the regression equations derived from the 1981 data would not be appropriate for use in a predictive sense. Yet, the results obtained have validity for estimating the correlation between the planetary and surface net radiation. Therefore, new statistical analyses were performed with data obtained during 1982. Linear regression analyses of the form:

$$\mathrm{GNET} = m(\mathrm{PNET}) + b \qquad (2)$$

were performed between the measured surface net radiation (GNET) and the computed planetary net radiation (PNET) for Toronto, for each month separately (Table 2a). As evident, there are missing data for each month, when either satellite or ground observations were not available. For each month and each location, the correlation is very high and the standard error of estimate ranges between 8–15%. Subsequently, the four months of data were merged, separately for each location, and similar linear regressions were performed (Table 2b). The derived regression relationships were tested for their predictive value. The equation developed from the four months of data for Toronto (Table 2b) was used for each location and statistics were derived for each month separately. (For Toronto, each monthly sample is part of a dependent data set used to develop the regression model.) The results are summarized in Table 3. The standard error of estimate ranges between 5–20%. Figures 1–3 show that the daily

TABLE 4. Regression statistics between daily average values of surface (GNET) and planetary net radiation flux (PNET) for Toronto, Ottawa and Quebec for the period May–August 1982, using different averaging periods (from one to ten days). The days grouped were not necessarily consecutive.

	Toronto				Ottawa				Quebec			
Number of days	Number of cases	Correlation	Standard error W m^{-2}	Standard error %	Number of cases	Correlation	Standard error W m^{-2}	Standard error %	Number of cases	Correlation	Standard error W m^{-2}	Standard error %
1	67	0.924	17.8	14.5	67	0.914	19.6	16.0	63	0.932	16.2	15.9
2	33	0.921	13.4	10.8	33	0.937	13.1	10.7	31	0.937	11.9	11.6
3	22	0.926	11.9	9.6	22	0.940	10.8	8.8	21	0.966	8.6	8.4
4	16	0.913	11.8	9.5	16	0.949	9.7	7.9	15	0.921	9.7	9.3
5	13	0.867	12.0	9.7	13	0.955	7.9	6.4	12	0.956	7.3	7.0
6	11	0.922	10.8	8.7	11	0.964	7.2	5.9	10	0.980	4.5	4.4
7	9	0.901	11.6	9.3	9	0.944	9.8	7.9	9	0.981	4.8	4.7
8	8	0.880	11.7	9.4	8	0.965	6.8	5.5	7	0.939	5.9	5.5
9	7	0.865	11.4	9.1	7	0.946	8.3	6.7	7	0.978	5.6	5.5
10	6	0.874	11.3	9.0	6	0.950	6.9	5.5	6	0.978	4.8	4.7

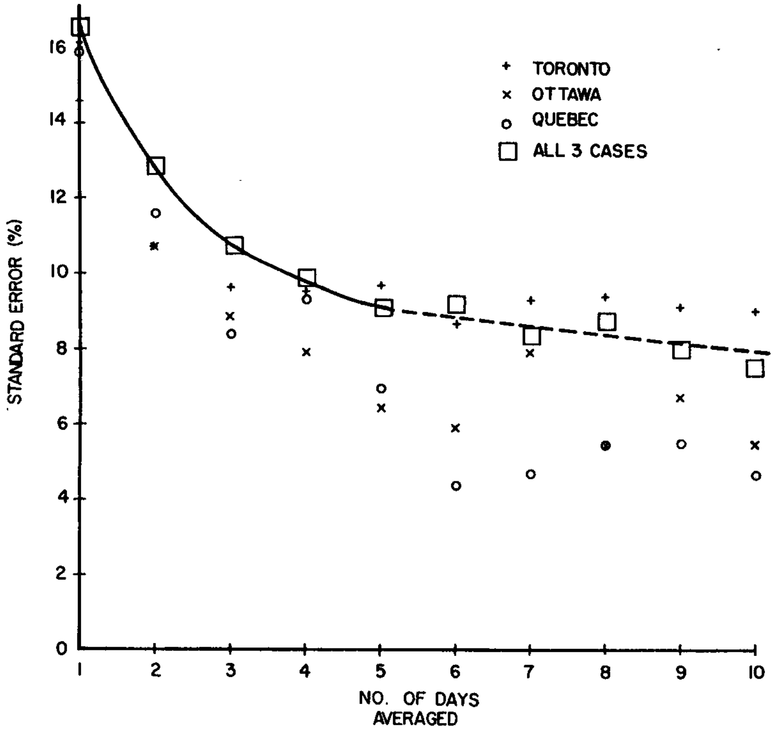

FIG. 4. Standard errors of estimate between daily average values of surface (GNET) and planetary net radiation flux (PNET) for Toronto, Ottawa and Quebec (Table 4) and for all three locations combined for the period May–August, 1982 using different averaging periods (from 1 to 10 days).

planetary net radiation follows very closely the observed daily surface net radiation.

Experiments were conducted where the standard error of estimate was obtained using different averaging periods ranging between 1–10 days (Table 4). (The days grouped were not necessarily consecutive.) When the averaging period increased, the standard error of estimate decreases, ranging between 16–5% for time intervals ranging from one to ten days. One should, however, note that for an averaging period of ten days, the sample was rather small (only six cases). This latter experiment was repeated, using a merged data set from all three locations for the four month period. The results of this experiment are compared in Fig. 4 with the results presented in Table 4. As evident, the standard errors of estimate for the combined data set are higher than the corresponding values derived for each site independently. This would indicate that the regression equations are site dependent. However, even the accuracy obtainable with a regionally derived regression model is still within the bounds of the required accuracy for climate studies.

5. Summary

The usefulness of satellites for deriving planetary radiation budgets has been amply demonstrated. As of now, there is no full agreement among the scientists to whether the planetary radiation budgets alone are directly applicable to climate studies. There is, however, a consensus that the radiative flux divergence in the atmospheric column is a key parameter in atmospheric energetics. As such, the issue of whether satellite monitoring of changes in the net radiation balance at the top of the atmosphere is an indicator of changes in surface radiation budget is of relevance. The present study demonstrates that the daily average planetary net radiation is highly correlated to the daily average surface net radiation and that a statistical approach, based on a correlation formalism, has a potential to predict the surface net radiation.

Acknowledgments. This work was supported by Grant NA80AA-D-0048 from NOAA/NESDIS under project AGRISTARS. The Computer Science Center, University of Maryland provided supplementary computer time.

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