Downward Longwave Surface Radiation from Sun-Synchronous Satellite Data: Validation of Methodology

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ABSTRACT

An extensive study has been carried out to validate a satellite technique for estimating downward longwave radiation at the surface. The technique, mostly developed earlier, uses operational sun-synchronous satellite data and a radiative transfer model to provide the surface flux estimates. The satellite-derived fluxes were compared directly with corresponding ground-measured fluxes at four different sites in the United States for a common one-year data period. This provided a study of seasonal variations as well as a diversity of meteorological conditions. Dome heating errors in the ground-measured fluxes were also investigated and were corrected prior to the comparisons. Comparison of the monthly averaged fluxes from the satellite and ground sources for all four sites for the entire year showed a correlation coefficient of 0.98 and a standard error of estimate of 10 W m^{-2}. A brief description of the technique is provided, and the results validating the technique are presented.

1. Introduction

The surface radiation budget (SRB) and its spatial and temporal variations are important to all aspects of the study of weather and climate phenomena. This budget plays a major role in determining radiative heating as well as sensible and latent heat fluxes at land and ocean surfaces. As a result, SRB affects surface temperature fields, atmospheric and oceanic circulations, and even the hydrologic cycle (WMO, 1983). Satellite techniques are attractive for SRB measurement because of the regional to global coverage available. Because of the intervening atmosphere, SRB proves difficult to measure by satellite, whereas top-of-the-atmosphere (TOA) radiation balance can be measured directly. Consequently, over the past two decades, considerable effort has been expended in the global measurement of TOA radiation budget (Vonder Haar and Soumi, 1971; Raschke et al., 1973; Smith et al., 1977; Jacobowitz et al., 1979; Ellingson and Ferraro, 1983). Presently, the Earth Radiation Budget Experiment (ERBE), a multisatellite TOA program, is being conducted and is expected to continue through the mid-1980s (Barkstrom, 1984). Progress in SRB measurement by satellite has been much slower, beginning with insolation estimates (Ellis and Vonder Haar, 1978; Raschke and Preuss, 1979; Tarpley, 1979; Gautier et al., 1980). Only recently, techniques for estimating the downward longwave component of surface flux have emerged. Darnell et al. (1983; hereafter DGS-1) were the first to develop a technique using only satellite data. Smith and Woolf (1984) have described a geosynchronous satellite approach, and recently, Pinker and Corio (1984) and Pinker et al. (1985) have provided a correlation between net radiation at the surface and the satellite-measured net radiation and outgoing IR at the top of the atmosphere.

One of the most difficult problems associated with satellite measurement techniques is validation of the satellite-derived flux results by direct comparison with ground-measured flux data. Darnell et al. provided a limited validation of their technique by comparing flux results obtained from Tiros-N satellite data with corresponding ground-measured fluxes taken at a mid-latitude land site for a one-month period. In the present investigation, year-long ground-measured flux datasets from four widely distributed sites in the eastern United States have been used to validate the satellite technique. These datasets provided a test of the technique under a broad range of meteorological conditions including the variations produced by seasonal changes. Operational global satellite datasets from NOAA's (National Oceanic and Atmospheric Administration) sun-synchronous satellite series have been used with this technique, permitting the approach to be expanded to regional or global applications.

2. Radiative transfer model

A radiative transfer model (Gupta, 1983) was used with the NOAA satellite data to compute individual flux values for each satellite pass over a site. Most of the features of the radiative transfer model used in the present study are unchanged from those used in DGS-1, but for convenience the radiative transfer model used in the present study is summarized here.

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Downward radiance at the surface from a plane-parallel clear atmosphere can be expressed as

$$N_\nu^c(\theta) = \int_{\tau_{\nu h}}^{1} B_\nu(T_z)d\tau_{\nu z}(\theta), \qquad (1)$$

where $B_\nu(T_z)$ is the Planck function at the altitude z, $\tau_{\nu z}$ the atmospheric transmittance between the surface and altitude z, h represents the top of the atmosphere, and θ the viewing zenith angle. For an overcast atmosphere, the downward radiance is given by

$$N_\nu^0(\theta) = B_\nu(T_c)\tau_{\nu c}(\theta) + \int_{\tau_{\nu c}}^{1} B_\nu(T_z)d\tau_{\nu z}(\theta), \qquad (2)$$

where the first term on the right side represents radiation from the cloud base and the second term is the radiation from the atmosphere below the cloud. Assuming that the cloud surface is plane-parallel and radiates as a blackbody in the infrared, the downward radiance is obtained as

$$N_\nu(\theta) = (1 - C)N_\nu^c(\theta) + CN_\nu^0(\theta), \qquad (3)$$

where C is the fractional cloud cover.

Features of the radiative transfer model that are changed from those of the earlier work (Gupta, 1983; DGS-1) are the following: The 50–200 μm (200–50 cm^{-1}) region, treated as a single interval in the earlier model, was broken into 10 cm^{-1} intervals. The region from 5–50 μ (2000–200 cm^{-1}) continues to be treated in 10 cm^{-1} intervals. Flux density was obtained by numerically integrating total radiance $N_\nu(\theta)$ over the viewing zenith angle from 0° to 90° (assuming azimuthal symmetry) instead of using the diffusivity approximation. Spectral parameters for absorption bands of all atmospheric constituents are taken from the latest available AFGL line parameter compilation (Rothman et al., 1983).

3. Satellite and ground data

Satellite data consisted of Tiros Operational Vertical Sounder (TOVS) meteorological data obtained from the NOAA National Climatic Center, Washington, DC. These data were obtained from NOAA-6 and -7 satellites, which operated in near-polar, sun-synchronous orbits of about 850 km with nominal equatorial crossing times of 0730/1930 LST and 0230/1430 LST, respectively. The TOVS system, which has been onboard all the Tiros-N series of NOAA satellites, is a combination of three instruments: High Resolution Infrared Sounder–Version 2 (HIRS-2), Microwave Sounding Unit (MSU), and Stratospheric Sounding Unit (SSU). These instruments provide combined atmospheric soundings from the surface to the stratosphere, with a nominal ground resolution of about 300 × 300 km, referred to as a TOVS box. In the present work, only the lower tropospheric portion of the soundings, provided by the HIRS-2 and MSU, are of interest. The HIRS-2, using 19 IR and 1 visible channel, provides temperature and water vapor soundings, but only under clear and partly cloudy sky conditions. The MSU, with four microwave channels, provides temperature soundings under all sky conditions except rain, although the soundings are generally of lower quality than those of HIRS-2.

Retrieval of the meteorological data from the multichannel soundings of HIRS-2 and MSU is accomplished by NOAA using algorithms developed by Smith and Woolf (1976) and later modified by McMillin and Dean (1982). The operational TOVS data product is composed of sets of meteorological parameters, one set for each TOVS box. Each data set contains surface temperature and pressure, a 15-layer temperature profile, a 3-layer tropospheric precipitable water-vapor profile, fractional cloud cover, cloud-top pressure, and total ozone burden. A complete description of the TOVS data products and instrumentation is given by Smith et al. (1979). TOVS data products have been compared with radiosonde measurements in limited investigations (Scoggins et al., 1981; Brodrick et al., 1981; Smith et al., 1979) to determine the accuracy of TOVS data. Efforts have also been made in the present work to compare the satellite-derived parameters with corresponding ground data. For users of TOVS products, NOAA has published target accuracy values (Kidwell, 1983), which are presented in Table 1.

Ground data consisted of surface-measured radiation flux data for all sites and some climatological variables for two sites. The flux data were provided by four solar research centers operating throughout the data period (July 1981 through June 1982) at the following universities: Georgia Institute of Technology (Ga.), Hampton University (Va.), University of Michigan (Mich.), and State University of New York at Albany (N.Y.). All solar research centers used calibrated Eppley PIR (Precision Infrared Radiometer) pyrgeometers in automated networks to measure downward longwave flux at one-minute intervals. Diffuse, direct, and global components of downward solar flux were also measured at one-minute intervals by adjacent Eppley PSPs (Precision Spectral Pyranometer). Hourly averages of all flux data were then computed and recorded on tapes.

Surface air temperature and dew-point readings were

TABLE 1. Target accuracies for TOVS data products by NOAA (Kidwell, 1983).

TOVS data product	Anticipated maximum error
Layer mean temperature	
(a) surface to 850 mb	±2.5 K
(b) 850 mb to tropopause	±2.25 K
Layer precipitable water	±30%
Cloud cover	±20%
Total ozone	
(a) tropical	±15%
(b) polar	±50%

recorded at the Georgia and New York sites using high quality thermister-type sensors. Ground-measured surface temperatures from these sites were compared with corresponding TOVS-derived surface temperatures. Tiros Operational Vertical Sounder surface temperatures were consistently biased 1–3 K low. Similar differences also were observed for several ocean locations selected from our one-year TOVS dataset when compared with the sea surface temperature climatology of Alexander and Mobley (1976). Personal communication with L. McMillin, NOAA (1985), revealed that TOVS surface temperatures are only partially corrected for the effects of water vapor absorption; therefore, our TOVS surface temperatures were corrected for water vapor effects before being used in flux calculations. The correction ΔT was obtained using a simple parameterization (Cogan and Willand, 1976):

$$\Delta T = 0.66\,M + 0.086\,M^2, \qquad (4)$$

where M is the atmospheric water vapor burden in precipitable-centimeters (pr-cm). A comparison of the water-vapor-corrected, daily-averaged TOVS surface temperatures and ground-measured temperatures for the New York site is shown in Fig. 1. The bias in the TOVS data has been reduced from -1–3 K to -0.75 K, indicating reasonable comparison between satellite and ground measurements. The standard error for these data is ±2.7 K, which is slightly greater than the NOAA estimate of accuracy for TOVS-derived surface temperature (Table 1). A very similar comparison was obtained for the Georgia site, where ground-measured temperature data were also available.

Comparisons were also made between TOVS-derived and surface-calculated water vapor data. Surface values for water vapor burden were computed using the local dew-point temperature, T_d, available from two sites. First, water vapor density at the surface, ρ, was computed using the following expression (Selby and McClatchey, 1975):

$$\rho = A\exp(18.9766 - 14.9595\,A - 2.4388\,A^2), \qquad (5)$$

where $A = 273.15/T_d$. Water vapor burden of the atmosphere, U (pr-cm), was then computed from the equation (Smith, 1966):

$$U = (p_0\omega_0)/[g(\lambda + 1)], \qquad (6)$$

where p_0 is the surface pressure, $\omega_0 = (\rho/d)$ is the water vapor mixing ratio at the surface (d = atmospheric density), g the acceleration due to gravity, and λ is related to the water vapor scale height (an average value of $\lambda = 3$ was used). A comparison of the surface-calculated water vapor and the TOVS-derived water vapor values using daily averaged data is shown for the Georgia site in Fig. 2. The water-vapor burden is overestimated by the satellite in the lower range in the wintertime, which may be attributed to the presence of

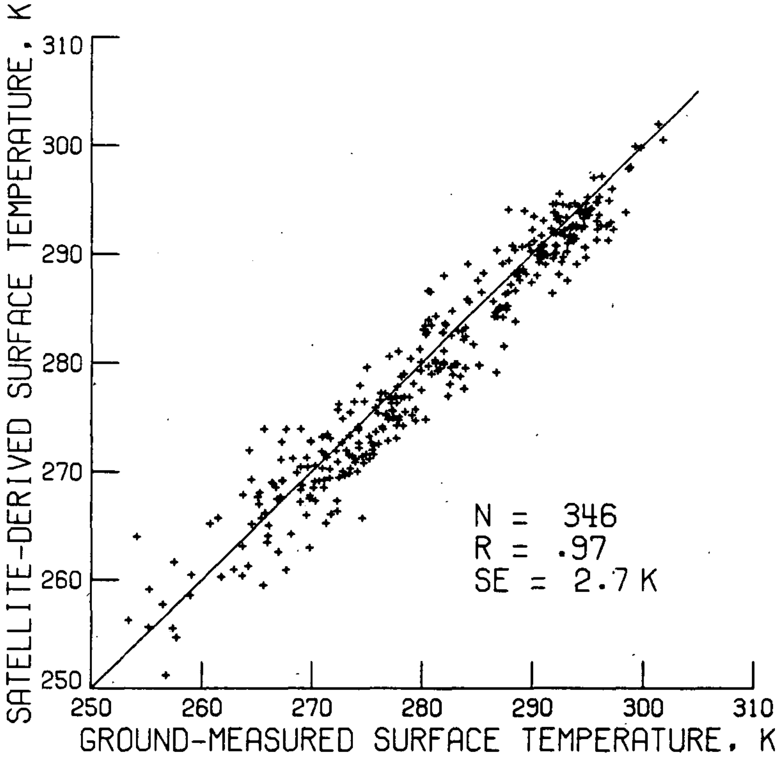

FIG. 1. Comparison of satellite-derived and ground-measured surface temperature at the New York site. Solid line is the ideal one-to-one relation for the points.

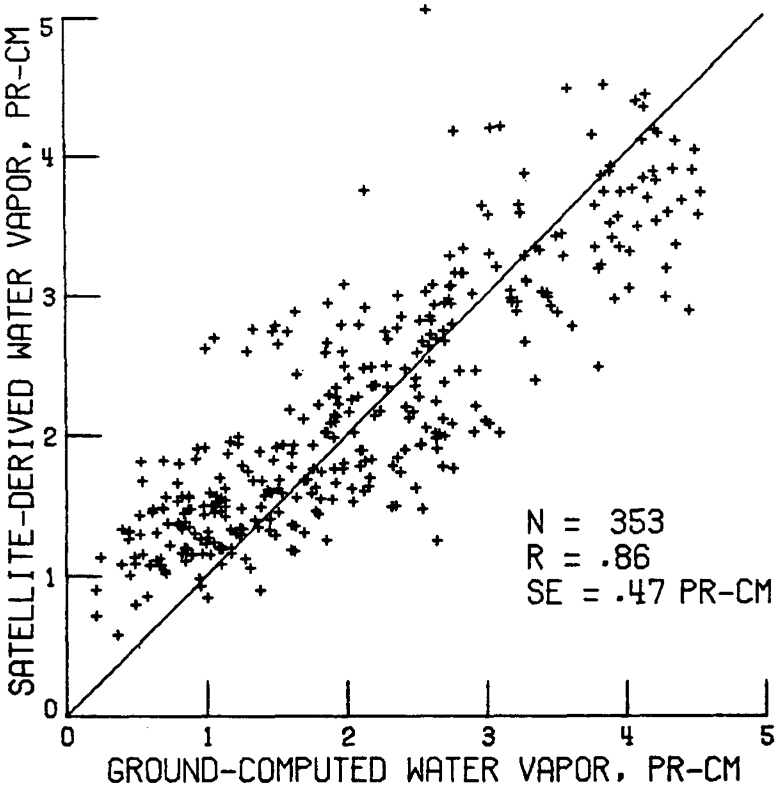

FIG. 2. As in Fig. 1 but for water vapor at the GA site.

temperature inversions and also partly to the difference in the spatial scales for the satellite and ground measurements. Surface inversions accompanied by low dew-point temperatures can be expected to produce low water-vapor burden in the ground measurements. The standard error of the data of Fig. 2 about a regression line is 0.47 pr-cm, which is about 21% of the mean annual value and within the NOAA target accuracy value given in Table 1.

Comparison of the satellite- and ground fluxes from each site required careful matching in space and time. This was accomplished by 1) limiting the ground area for satellite coverage to ±2.5° in lat and long about each site and 2) using time-interpolated ground flux values to match the satellite overpass times.

Water vapor and cloud data were missing occasionally from a dataset, such as when sky conditions were too cloudy to allow soundings by HIRS-2. In such cases, averages from neighboring box values were used, if available, otherwise, climatological models were used to fill in the missing data. For missing cloud percents, however, a value of 100 was used, based on the assumption that cloudy conditions prevailed.

Completed sets of TOVS data were processed further, as outlined in DGS-1, to make them compatible with the radiative transfer model. It should also be noted that the assumption of a nominal cloud thickness, equivalent to a 50-mb pressure difference from top to base, was used herein as described in DGS-1. This allowed cloud-base height and cloud-base temperature to be computed for each dataset.

4. Pyrgeometer correction

A comparison of satellite-derived and ground-measured flux values for individual overpasses of the New York site is shown in Fig. 3. Comparison of monthly averages of these same data is shown in Fig. 4. Figure 4 indicates that there is good comparison between the satellite and ground data in the lower flux range (wintertime values), but ground-measured fluxes in the higher flux range (summertime values) are significantly higher than the corresponding satellite fluxes. This characteristic is typical of the data from each of the four sites and is attributed mainly to the effects of dome heating on the Eppley pyrgeometers used to provide the ground data at each site. Absorption of solar energy in the silicon dome causes an internal, uncompensated IR radiation input to the detector. The result is an artificial excess in pyrgeometer output that varies with solar input, wind speed, and ambient temperature, and under most sky conditions produces significant error during daylight hours.

Several investigators have studied the Eppley dome-heating problem, but the results have been highly variable. Enz et al. (1975) noted errors as great as 11 to

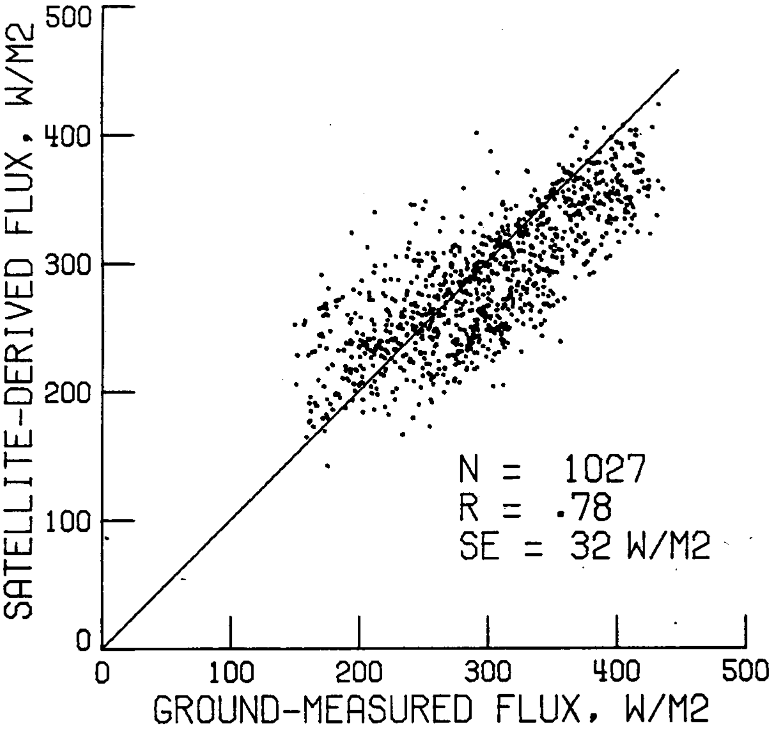

FIG. 3. Comparison of individual satellite-derived and uncorrected ground-measured fluxes at the New York site. Solid line is the ideal one-to-one relation for the points.

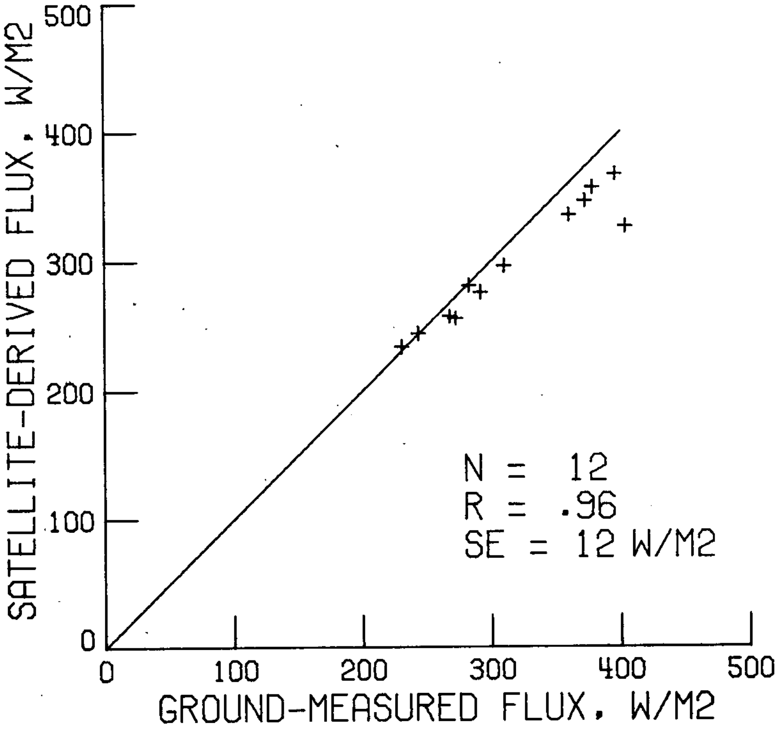

FIG. 4. Comparison of satellite-derived and uncorrected ground-measured monthly averaged flux values at the New York site. Solid line is the ideal one-to-one relation for the points.

20% for winter to summer, low-wind, clear-sky conditions. These findings, however, were based on an Eppley PIR using an earlier KRS-5 dome design. Weiss (1981), who investigated the current silicon dome model, found that extreme summer heating conditions in southeast Nebraska produced an error of 98 W m^{-2} on one occasion. Berdahl and Fromberg (1982) found errors of 30 W m^{-2}, and Ryznar and Weber (1982) also agreed on an error of about 30 W m^{-2}. In most of these cases, measurement error was determined by comparisons with other radiometer devices or else by alternately shading and exposing the pyrgeometer to the direct solar beam while measuring the corresponding change in output. A third technique is to observe the pyrgeometer output in the field when minimum haze, broken-cloud sky conditions prevail. Clear and cloudy conditions overhead change abruptly, producing the desired test on the pyrgeometer. The direct component of the solar input should be observed simultaneously to pinpoint the abrupt changes of solar heating by the direct component. We applied the latter technique to our ground datasets to determine the amount of dome heating at our data sites. Figure 5 shows an hour segment of minute-by-minute data taken on 13 June 1982 between 1200 and 1300 LST at the Michigan site. Increases of 40–45 W m^{-2} (10–12%) occurred in the IR radiation output at the cloudy-to-clear change points, and similar fluctuations were observed in other examples studied during summertime conditions. In wintertime cases, fluctuations of 5–10% were observed in the IR. For all these examples, only the heating effect of the direct component of solar radiation has been considered. The diffuse component, which is considerable during cloudy and hazy conditions, must be considered also. Under the broken sky conditions seen in Fig. 5, the diffuse component varied between about 200 and 400 W m^{-2}. Two other factors must also be recognized: 1) when a cloud comes directly overhead, the downward radiation from the cloud base will produce an increase in the IR at the pyrgeometer, offsetting part of the decrease in dome heating that would otherwise be seen; and 2) on bright, cloudless days the dome heating from sustained solar radiation can be expected to be substantially higher than under partly cloudy conditions.

As a result of our investigation, dome heating errors of 20 and 10% were assumed as the maximum values for summertime and wintertime, respectively, under clear-sky noontime conditions. No assumption was made with respect to wind speed. In practice, dome heating corrections were applied to the ground IR data as a function of month of year, average daylight fraction for the month, and satellite-derived monthly averaged cloud fraction at each site. The summer to winter maximum error factors of 0.20 and 0.10 were applied in somewhat arbitrary but reasonable monthly step changes, E, beginning with 0.10 for January, maximizing at 0.20 for June and July, and returning to 0.10 in December. A monthly averaged daylight fraction, D (daylight hours/24), and the monthly averaged cloud cover fraction, C, also were determined. The three quantities were then used in the following formula to

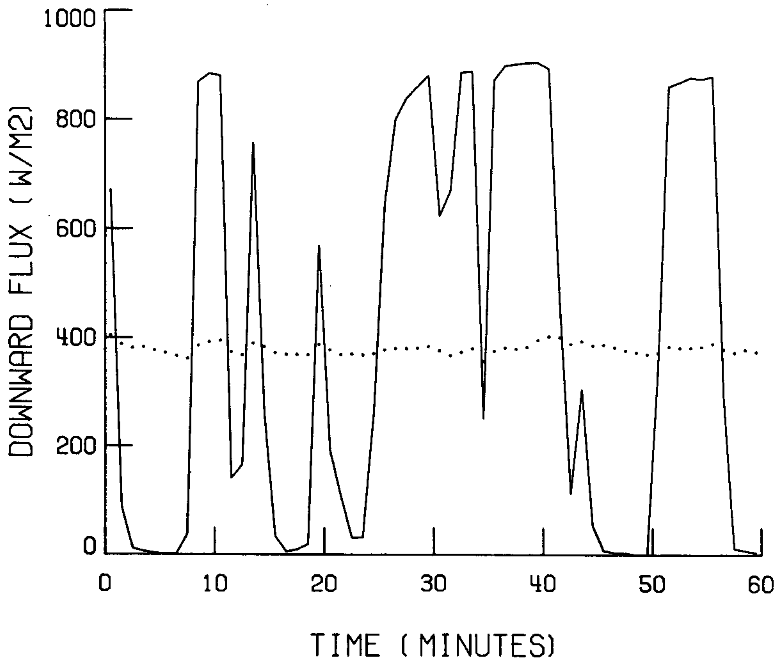

FIG. 5. Minute-by-minute variation of ground-measured direct solar (solid curve) and longwave (dotted curve) fluxes for one hour on 13 June 1982 at the Michigan site.

transform pyrgeometer output (G, W m^{-2}) to corrected fluxes (G', W m^{-2}):

$$G' = G[1 - E \times D \times (1 - C)]. \qquad (7)$$

The assigned monthly values for E, D, and C are given in Table 2. Application of Eq. 7 resulted in reductions of the ground-measured flux values by 4 to 30 W m^{-2} for the monthly averaged values of Fig. 4.

5. Results and discussion

A satellite-derived flux value was calculated for each overpass of the four sites throughout the data period (July 1981 through June 1982). During the month of July and the first two weeks of August, only the NOAA-6 satellite was active, limiting site overpasses to a maximum of two per day. For the remainder of the data year, overpasses averaged about three per day at each site. A summary of the range of meteorological parameters observed by TOVS at each of the four sites during the one-year data period is presented in Table 3.

A scatterplot comparing monthly averaged satellite-derived fluxes and corrected, ground-measured fluxes for the New York site is shown in Fig. 6. This plot, when compared to Fig. 4, where uncorrected data were used, shows the large improvement resulting from the correction for dome heating. A combined scatterplot of monthly averaged fluxes for all the sites is shown in Fig. 7. The correlation coefficient between satellite-derived and corrected ground data is 0.98 with a standard error of estimate of 10 W m^{-2}. Monthly averaged flux comparisons show marked improvement over that of the individual flux comparisons because the large short-term variations of meteorology tend to be averaged out. Monthly averaging also compensates for the error caused by the difference in spatial scales between the ±2.5° region around the site and the highly localized site itself. Theoretical studies by Fung et al. (1984) suggest that temperature determinations in the lower-atmospheric layers must be accurate to within ±2 K, and specific humidity must be accurate to within ±1 gm kg^{-1}, to enable downward flux to be determined to within ±10 W m^{-2} in instantaneous comparisons. TOVS instantaneous meteorological data contain larger errors in both the temperature and water vapor values than these limits, but monthly averaging of the fluxes yields significantly lower error in the results. Development of monthly averaged flux values is the intended use of this technique, which is also in compliance with the WMO temporal requirement (WCP-70).

TABLE 2. Monthly constants used for dome heating (Eq. 7).

Month	Error factor (E)	Daylight factor (D)	Cloud cover factor (C)			
			Ga.	Va.	Mich.	N.Y.
July	0.20	0.60	0.29	0.31	0.26	0.34
August	0.18	0.56	0.37	0.35	0.31	0.35
September	0.16	0.52	0.21	0.25	0.38	0.40
October	0.14	0.48	0.31	0.35	0.37	0.42
November	0.12	0.44	0.32	0.43	0.41	0.44
December	0.10	0.40	0.39	0.56	0.56	0.60
January	0.10	0.40	0.37	0.55	0.53	0.55
February	0.12	0.44	0.51	0.52	0.44	0.51
March	0.14	0.48	0.45	0.49	0.46	0.46
April	0.16	0.52	0.46	0.49	0.49	0.47
May	0.18	0.56	0.39	0.47	0.54	0.48
June	0.20	0.60	0.35	0.43	0.45	0.51

TABLE 3. Summary of ranges of TOVS-derived meteorology.

Site	Water vapor (pr-cm)[†]	Surface temperature (K)	Surface pressure* (mb)
Ga.	0.5–5.5	260–308	974.4
Va.	0.7–4.9	270–304	1010.3
Mich.	0.2–3.8	249–304	978.5
N.Y.	0.1–3.8	251–302	1003.7

[†] Precipitable-centimeters.

* Surface pressure values were taken from the U.S. Standard Atmosphere tables using the local site elevation; TOVS surface pressure data were not used.

The ability of the technique to respond to seasonal variations in meteorology was an important concern. Month-by-month comparison, showing seasonal variability between the satellite and ground data at the New York site, is seen in Fig. 8. Agreement is good for all months except May, when ground data were available only for the last five days of the month, producing a biased monthly averaged ground-flux value. Our data show that the technique has responded well to the seasonal variations offered by the four midlatitude sites. The ability to provide similar results at other locations will depend somewhat on the consistency with which TOVS can produce good meteorological data over the globe.

The major error in comparisons between satellite-derived and ground-measured longwave downward flux was the pyrgeometer dome-heating error in the ground data, but this could be characterized and was corrected as discussed earlier. Another pyrgeometer-related error, though much smaller in magnitude, arises due to a small amount of solar radiation getting through the filter dome. Berdahl and Fromberg (1982) discussed this error in detail and put a theoretical upper limit of 7 W m^{-2} on this leakage, though less than 4 W m^{-2} was expected to apply in most situations. On the side of the satellite measurements, numerous small error sources can be anticipated in the use of the technique. In site-by-site comparisons, the large field of view of TOVS will frequently produce somewhat different meteorology than would be found directly over the site. This nonrepresentative meteorology used by TOVS can cause significant error for individual flux results but very acceptable results for monthly data since the short term fluctuations of the meteorological data average out. Examples of other conditions that may produce

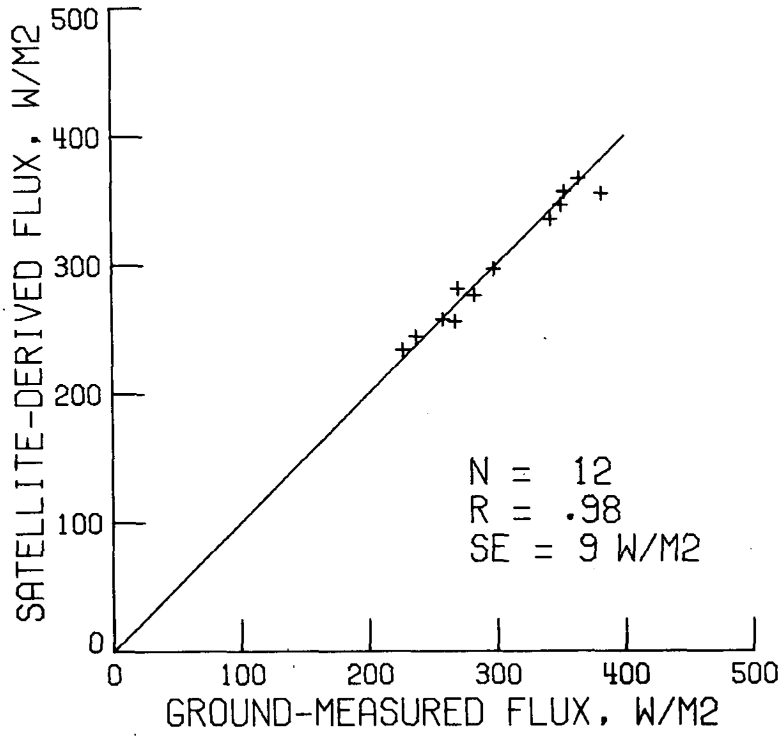

FIG. 6. Comparison of satellite-derived and ground-measured monthly averaged flux values at New York site after applying dome heating correction to the ground data. Solid line is the ideal one-to-one relation for the points.

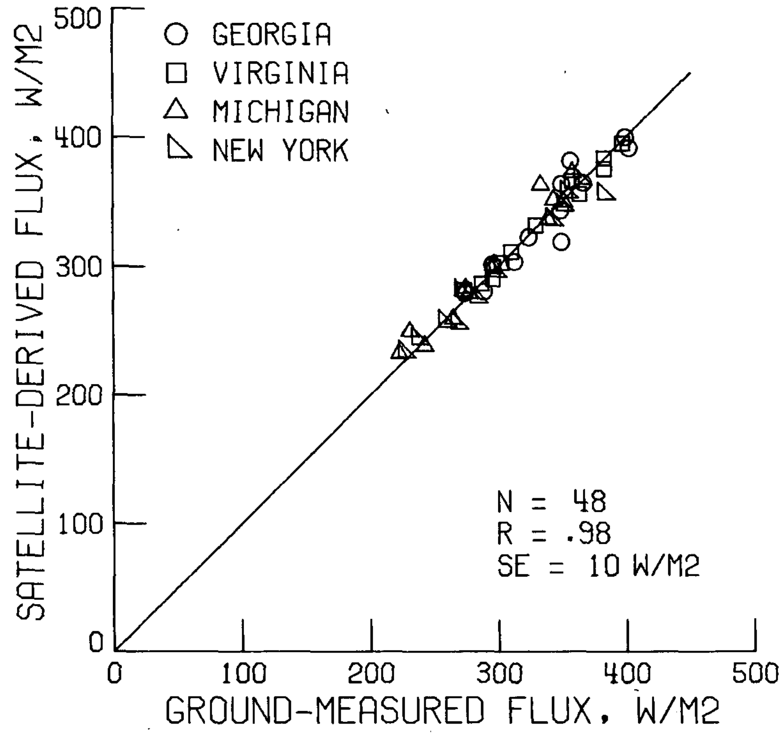

FIG. 7. Comparison of satellite-derived and ground-measured monthly averaged flux values for all sites. Solid line is the ideal one-to-one relation for the points.

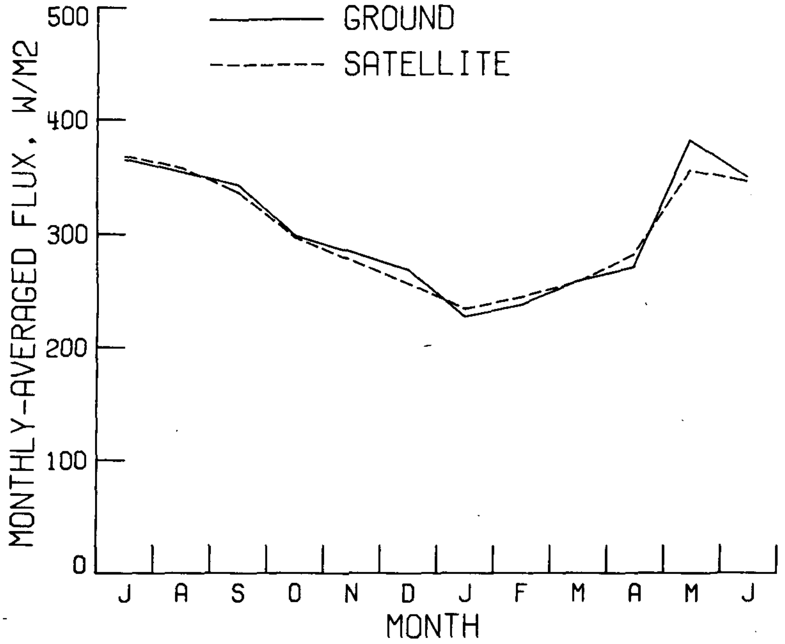

FIG. 8. Variation of monthly averaged flux with month of year for ground-measured and satellite-derived data at the New York site.

errors in TOVS data are ground hazes and fogs which will appear only as cool ground areas and will result in satellite fluxes which are too low. Also, TOVS ability to produce accurate cloud height data is limited, but this information is critical only for very low clouds, as was shown in DGS-1.

Potential errors in the modeling and preprocessing portion of the technique include the assumptions of plane-parallel clouds, 50-mb equivalent cloud thickness, and cloud-covered sky conditions when HIRS-2 cloud data are missing.

6. Concluding remarks

This work was an extensive effort to validate a technique for estimating downward longwave radiation from operational, sun-synchronous satellite meteorological data. Validation was accomplished by direct comparisons of satellite-derived flux with ground-measured flux at four sites within the United States for a one-year period. Because this technique is based on the use of sun-synchronous satellite data which cover the entire globe, it can be used for developing downward longwave radiation on a global basis. A standard error of about 10 W m^{-2} was achieved when comparing monthly, satellite-derived flux with corresponding monthly ground-measured flux for the four sites over the one-year period. These results included corrections for the dome heating errors experienced with the Eppley PIR pyrgeometers used at all sites. Higher accuracies should be achievable when site-by-site data are not required and grid sizes greater than 250 km are used. Over oceans, where the variability of meteorological parameters is smaller than over land surfaces, higher accuracies should also be achievable.

The validation of the technique has been limited here to midlatitude land sites because of the lack of long-term ground datasets from other regions of the globe. Because the technique is physical rather than statistical, it should be well suited to the estimation of downward longwave flux in tropical or polar latitudes, including ocean environments. An important factor which also must be considered is the consistency with which TOVS can supply good data results over all regions of the globe.

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