NOTES AND CORRESPONDENCE

A Technique for Estimating Outgoing Longwave Radiation from HIRS Radiance Observations

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ABSTRACT

A new technique for estimating outgoing longwave radiation from observations on the NOAA operational satellites has been developed from a regression analysis of radiation model calculations. The technique consists of a weighted sum of radiance in but four intervals sensed by the High-resolution InfraRed Sounder (HIRS). The analysis shows that model outgoing flux may be reproduced to within $\pm 2\ \mathrm{W \cdot m^{-2}}$ rms, which is about a factor of 4 smaller than the rms error of the method used by NOAA to estimate flux from the AVHRR. The small errors suggest that the new technique holds the promise of eliminating the large systematic errors possible with the current NOAA technique. Additionally, the new technique offers the possibility of directly relating flux changes to changes in atmospheric parameters.

1. Introduction

The measurement of the planetary radiation budget by earth orbiting satellites has been made from the beginning of the environmental satellite program. Since most of the observations were experimental, however, their duration was limited to the lifetime of the observing system (House et al. 1986). The better known experiments that measured the planetary short- and longwave radiation budget were Nimbus 6 and 7 ERB (Earth Radiation Budget) and the Earth Radiation Budget Experiment (ERBE) which is currently operating. (The term longwave is used herein to denote radiation with wavelengths > 4 μm.)

Within the operational environment, which implies routine and continuous observations and data processing, attempts have been made to obtain the planetary radiation budget from scanning radiometer observations in the visible and the infrared window regions (e.g., Gruber and Winston 1978; Gruber and Krueger 1984). The estimates of the outgoing longwave radiation (OLR), both operational and experimental, have been particularly useful for a variety of problems in climate sensitivity and diagnosis (e.g., Ohring and Gruber 1983; Weickman 1983; Lau and Chen 1983a,b; and Ardanuy and Kyle 1986), numerical weather forecasting, and climate and general circulation models (Ramanathan 1987).

The longest continuous series of OLR data have been obtained from 10 μm window radiance observations on the NOAA operational satellites. Those data have not been universally accepted, however, because they are estimated from the radiance in a narrow spectral region rather than being measured directly, and because of the varied success of comparisons with directly measured data (e.g., Ohring and Gruber 1983). Data from the ERBE will help interpret the data from the operational satellite system, but a major problem exists because a follow-on experiment to ERBE is not planned until the late 1990's. Meanwhile, it will be necessary to provide ERB estimates from the operational satellite system.

Since the radiance measured in space is part of the outgoing flux and since radiance contains information about the major variables influencing the flux, it should

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be possible to estimate the OLR by properly combining radiance observations in several spectral regions. The operational OLR estimation technique used by NOAA (e.g., Ohring et al. 1984) is based on this idea, but it uses data from only one narrow spectral interval on the AVHRR instrument. The amount of information contained in this interval about atmospheric variables is limited. Nevertheless, the technique explains about 94% of the variance of the flux data on which it is based. There are potential problems with this technique, however, one of which is the possibility for large systematic under-or-over OLR estimates in certain geographical regions (see Ellingson et al. 1989).

A multispectral OLR estimation technique was developed and used by Raschke et al. (1973a,b) with data from the Medium Resolution Infrared Radiometer (MRIR) flown on Nimbus 3; but this type of technique has not been exploited for use with data from the HIRS multispectral radiometer used by NOAA for operational temperature and water vapor retrievals (see Susskind et al. 1984). Since the radiance data measured by HIRS contains more information on atmospheric variables than the AVHRR, it is a potentially better instrument for operational estimates of the OLR. The purpose of this paper is to present results from model calculations that show that HIRS data can be used to produce much better flux estimates than the AVHRR.

2. Equations and calculations

If radiance data from many spectral intervals encompassing the entire spectrum were available at a given viewing angle, a first-order estimate of the OLR could be obtained by adding the radiance in each spectral interval. Therefore, the estimation equation for the flux (OLR) was chosen to be a weighted sum of HIRS radiance observations, given as

$$\mathrm{OLR} = a_0 + \sum_i a_i(\theta)N_i(\theta), \qquad (1)$$

where the a's are regression coefficients, θ is the satellite zenith angle, and N is the observed radiance.

The radiance in a particular channel is related to the specific intensity I at wavenumber ν and the instrument responsivity ϕ as

$$N_i(\theta) = \int_{\Delta\nu_i} I(\nu, \theta)\phi_i(\nu)d\nu. \qquad (2)$$

The outgoing flux for an axisymmetric atmosphere is related to the specific intensity as

$$\mathrm{OLR} = 2\pi \int_0^\infty d\nu \int_0^{\pi/2} I(\nu, \theta)\cos\theta \sin\theta d\theta. \qquad (3)$$

The spectral intervals and the regression coefficients for (1) were determined with a stepwise regression analysis of calculations from a theoretical radiation model using 1600 soundings as input data. The necessary intensity, flux and radiance data were calculated with the model described by Ellingson and Gille (1978), Ellingson and Ferraro (1983), Yanuk and Ellingson (1986) and updated by Ellingson et al. (1989). Briefly, the model uses the Goody (1952) random exponential band model fitted to the 1982 AFGL spectral line data for H_2O, CO_2, O_3, N_2O and CH_4 in the spectral region between 0 and 3000 cm^{-1} (i.e., all wavelengths less than 3.3 μm). The water vapor continuum is included using the parameterization given by Roberts et al. (1976). Variations of the band model parameters along the atmospheric path are included using the Curtis–Godson approximation as described by Rodgers and Walshaw (1966). The atmosphere is assumed to be axisymmetric, and plane parallel out to 80°, beyond which spherical symmetry is assumed. Specific intensity is calculated at seven angles in each of 140 spectral intervals ranging in width from 5 to 40 cm^{-1}. The necessary integrations over altitude and zenith angle are performed with trapezoidal and 4-point Gaussian quadratures, respectively.

For this study, the field of view was assumed to be either cloud-free or completely covered by a cloud layer with a specified cloud top pressure. Clouds at pressures greater than 450 mb were assumed to be spectrally black, whereas the high level clouds were assumed to have the spectral properties of cirrus given by Haurwitz and Kuhn (1974). The radiance in the 19 HIRS channels at the seven angles was obtained by trapezoidal integration of (2) using NOAA supplied, laboratory measured values of ϕ.

The 1600 soundings used in the radiative transfer calculations were compiled by Dr. Norman Phillips (see Phillips et al. 1988). Each sounding included temperature values at 65 different pressure levels from 0.1 to 1000 mb and mixing ratios of H_2O and O_3 in the corresponding 64 layers. The soundings were compiled from radiosonde ascents from land and ocean stations between 30°S and 60°N latitude, and the soundings are equally divided between tropical (30°S–30°N) and midlatitude (summer and winter) conditions. The O_3 data were chosen by Phillips to be climatologically consistent with the temperature profiles, and the stratospheric H_2O mixing ratio is assumed to be 3 ppmm. The surface skin and air temperatures were assumed equal. A cloud layer was added randomly in the vertical to each sounding, but the H_2O profile was not altered when the cloud layer was included. In total, the necessary radiation calculations were performed for 3200 different conditions, 1600 clear and 1600 cloudy. The cloudy conditions were nearly uniformly distributed in low (950–850 mb), middle (675–525 mb) and high (400–240 mb) layers.

The regression analysis was done with a least-squares, stepwise, backward glance technique of the type described by Efroymson (1960). The computer subroutine used for the regression is RLSTP on the IMSL library (see IMSL 1984), and 0.05 was specified for the significance level to add or delete variables. The variances of the coefficients were estimated following the techniques illustrated by Anderson and Bancroft (1952).

The regression analysis proceeded in the following fashion. First, the best predictors for $\theta = 0$ were determined for the 3200 sample set using the 19 HIRS channels as candidate predictors. The analysis was then repeated for the remaining 7 angles. There was some angular dependence of the predictors chosen, but the first predictor was always the same (and explained about 95% of the variance). Thereafter, we concentrated on the analysis at $\theta = 0$, and these variables were forced to be chosen at the other angles. Since the explained variance decreases by less than 1% between 0 and 60°, only the $\theta = 0$ results are discussed herein.

3. Results

Shown in Fig. 1 is the rms error of the regression as predictors (channels) were selected through the first eight steps. The first channel chosen explains about 96% of the variance, and the incrementally explained variance becomes small after the addition of the fourth predictor. Although predictors 5 through 8 were judged to be significant by the F test, when the effects of noise were estimated by assuming a noise standard deviation of 1% of the mean radiance in each channel, the increased uncertainty owing to possible noise in these channels is greater than the increased variance explained by their inclusion. Therefore, only the first four predictors were judged to be physically significant. These four channels explain more than 99% of the

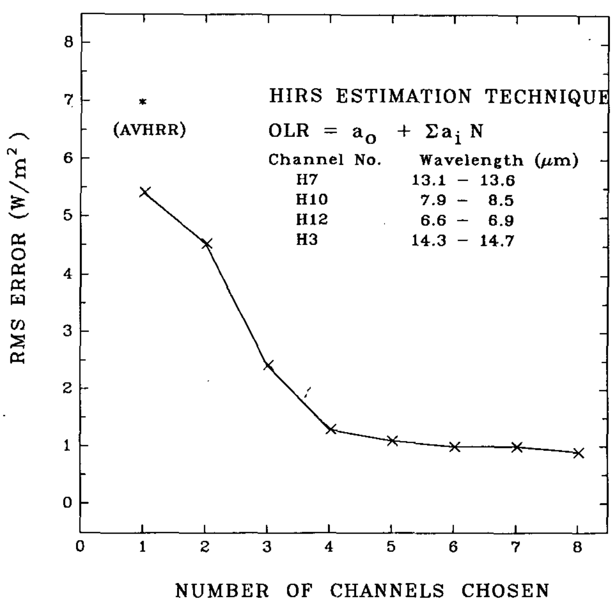

FIG. 1. Rms regression error as a function of the number of channels selected by the analysis technique. The * shows the rms error of the one-channel AVHRR technique.

variance. When noise is included in the error estimate, the rms flux error is slightly larger than 2 W m^{-2}. Table 1 lists the spectral and atmospheric sensitivities of the channels chosen in steps one to four. Table 2 gives the coefficients for the four channels, and their standard deviations, at six different zenith angles that are applicable to NOAA 9 HIRS data.

The first channel selected (H7) is in a window region sensitive to the surface temperature and the total water vapor amount. This channel was selected first because it explained more variance by itself than the others, including H8, located in the cleaner window near 11 μm, that is similar to the interval sensed by the AVHRR. Note that a one-channel estimation scheme linear in H7 radiance explains more variance than does the more complicated method applied to the AVHRR window data (the asterisk in Fig. 1).

It should be noted that Raschke et al. (1973a) found similar explained variance and spectral weighting in their analysis of calculations of spectrally integrated and MRIR radiances. They implied, however, that imperfections in the modeling of the radiative properties of the atmosphere and their use of a small sample of synthetic sounding data limited their technique to estimating the manner to combine radiances to obtain the spectrally integrated radiance. Fluxes were calculated from the radiance estimates and angular models developed from data measured on Nimbus 2. We believe that the more recent spectral data on atmospheric gases and the availability of large samples of measured atmospheric data allow the technique to incorporate the consistency of both the frequency and angular dependences of the calculations.

It is often difficult to attribute physical significance to predictors selected in a regression analysis of geophysical data, but a one predictor technique based on window radiance may be explained on physical grounds for both clear and cloudy conditions. For average conditions, the tropospheric temperature lapse rate remains nearly constant, but the amount and vertical distribution of water vapor changes systematically from tropical to polar regions. Therefore, the average tropospheric absorption and emission should be highly correlated with the surface temperature and, in turn, with the window radiance. Several simple climate model radiation parameterizations are based on this relationship (e.g., Budyko 1969; Sellers 1969). Since liquid water clouds are nearly black, their usual effects are similar to those of colder land or ocean surfaces.

One predictor techniques will lead to errors, however, when the temperature and water vapor distributions are much different from the average distributions associated with the surface temperature because of the nonlinear dependence of the OLR on these quantities. In this analysis the second, third and fourth channels selected (H10, H12 and H3) are sensitive to lower tropospheric water vapor, upper tropospheric water vapor and 100 mb temperatures, respectively.

TABLE 1. HIRS channels selected by the regression analysis and their atmospheric sensitivities (after Susskind et al. 1984). The term IEV denotes the incrementally explained variance as a variable is entered.

Order of selection	HIRS channel	Wavelength range (μm)	IEV (%)	Atmospheric sensitivity
1	H7	13.1–13.6	96.4	surface temperature
2	H10	7.9–8.5	1.1	lower tropospheric water vapor
3	H12	6.6–6.9	1.8	upper tropospheric water vapor
4	H3	14.3–14.7	0.5	air temperature centered at 100 mb

Physically, it is not surprising that H10 and H12 were selected since water vapor variations about average conditions are important to the radiation calculations. Perhaps H3 was selected because it helps to discriminate emission from the stratosphere in mid- and tropical latitude regions (i.e., the effects of temperature and ozone).

Shown in Fig. 2 is the normalized frequency of occurrence of OLR errors (model calculated minus regression estimated) for the 4 channel-HIRS and for the AVHRR techniques. The AVHRR errors range between ± 20 W m^{-2}, and the majority are nearly uniformly distributed in the region between ± 7.5 W m^{-2}. For the HIRS technique, the errors are between ± 5 W m^{-2}, and are primarily confined between ± 2.5 W m^{-2}. Although it is possible for the 4 channel HIRS estimation technique to have large errors, Fig. 2 suggests that the probability of large errors is smaller with HIRS than with the AVHRR technique, at least for this set of atmospheric data.

4. Summary, conclusions and future directions

In summary, the results show that a linear combination of radiance in but four HIRS intervals explains more than 99% of the variance of the 3200 sets of calculations. The rms error of the flux estimates is about 2 W m^{-2}. This represents an increase of about 5% explained variance, or a factor of 4 decrease in the rms error, as compared to the one-channel AVHRR technique.

There are several features of the HIRS technique that suggest the method should be more closely examined for possible operational use, including:

1) The error components are so small that there is little possibility of large systematic errors in any climatic regime, as is possible with the AVHRR technique, unless the radiation model physics are poor.

2) The technique, in its present form, does not require the identification of a scene type or the application of different angular models. As a result, it is computationally fast. Nevertheless, the scheme needs to be tested with calculations from deserts and polar regions.

3) The technique may be used to estimate "cloud forcing" without directly using information on the cloud amount because the operational analysis of the HIRS data estimates the clear column radiance. The estimation of cloud forcing in this manner will depend, however, on the technique by which the clear column radiance is determined in the operational analysis (e.g., Susskind et al. 1984). The sensitivity to errors in the clear column radiance should be tested before this approach is adapted.

4) It may be possible to identify some causes of observed changes in the OLR field because the radiance data have information on variations of temperature, constituents and cloudiness. This is not directly possible with AVHRR or ERBE data, but the development of this idea will require correlation and theoretical analysis that is beyond the scope of the present study.

5) The technique might serve as a suitable surrogate for ERBE between the demise of the ERBE scanners and the beginning of a yet unfunded follow-on project.

On the other hand, there are several major potential problems with the technique, including:

1) There may be changes in the instrument calibration.

TABLE 2. Coefficients for use with Eq. (1) to estimate the outgoing flux in W m^{-2} from NOAA 9 HIRS radiance data in W cm^{-2} sr^{-1}. The numbers in parenthesis are the standard error of the regression coefficients in percent.

Zenith angle (degrees)	Regression coefficients				
	a_0	H3	H7	H10	H12
00.00	67.456 (0.7)	31.147 (1.1)	35.631 (1.8)	35.000 (0.5)	55.790 (0.6)
21.48	67.944 (0.7)	30.086 (1.1)	35.045 (1.8)	36.249 (0.5)	55.710 (0.6)
47.93	70.068 (0.7)	25.391 (1.4)	32.225 (2.2)	42.301 (0.5)	54.578 (0.8)
53.00	70.631 (0.8)	23.897 (1.6)	31.391 (2.4)	44.384 (0.5)	53.867 (0.8)
70.00	72.245 (1.1)	14.256 (3.3)	36.402 (3.3)	54.838 (0.6)	35.786 (2.2)

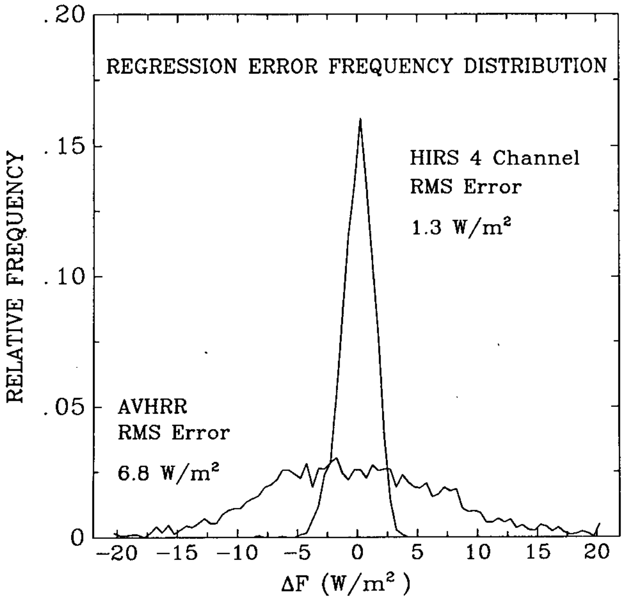

FIG. 2. Frequency distributions of flux estimation errors (model calculated minus regression estimate) for the HIRS (markedly spiked curve) and AVRRR (broad low curve) techniques.

2) The atmospheric constituents, such as O_3, CO_2, chloroflorocarbons, etc., may reach values not included in the regression analysis, or new species may appear in the atmosphere.

3) The model physics may be inadequate, particularly for clouds.

4) The meteorological data used in the analysis may be unrepresentative of the range of atmospheric variability, particularly in high latitudes.

5) The technique does not include the effect of aerosols.

The HIRS instrument does have on-board calibration, but the spectral responses of the various channels may change in-flight and from satellite-to-satellite. The in-flight spectral changes should be detected by relative calibrations with the various channels, and it may be possible to switch to combinations of unchanged channels with similar accuracy. The long-term stability of spectral responses, however, govern this and all other radiation budget experiments. Fortunately, other operational uses of the HIRS data call for replacement of the satellite sensors. Nevertheless, a strategy for long-term use of the HIRS data would have to be developed before the technique was implemented.

Item 2 is a problem for any technique that does not directly measure the flux from the entire spectrum, but changes of trace constituents are generally slow and are usually observed by the various monitoring stations. As a result, the coefficients and the predictors could be modified to account for these variations. Nevertheless, this problem prohibits the use of this technique for some applications.

To check and improve on the radiation model, we have compared model calculations with observations from within the atmosphere (e.g., Ellingson and Serafino 1984) and we have participated in the Intercomparison of Radiation Codes in Climate Models (ICRCCM) (see Luther et al. 1988). For homogeneous clear and cloudy conditions, the results show that the model calculations agree with the observations to within the uncertainty of the observations (about ±5%). Comparisons of our model OLR calculations with ICRCCM line-by-line results for five clear-sky McClatchey et al. (1971) atmospheres show agreement to better than 2%.

The absence of a large set of well calibrated observations, with supporting atmospheric data, limits the range over which the model can be tested. Since the NOAA 9 and 10 satellites are equipped with both the ERBE scanner and the HIRS, it is possible to address items 3 to 5 above by comparing OLR estimates over a large range from collocated homogeneous scenes, as well as from other areas. Such a comparison has begun, and, depending on the results, modifications will be made to the model and perhaps to the channels used for the flux estimation (i.e., the simultaneous sets of data allow the regression analysis to be performed with observed, rather than calculated data). That study will be reported in later publications.

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