Development and Application of Remote Sensing of Longwave Cooling from the NOAA Polar Orbiting Satellites

Robert Ellingson, David Yanuk, Arnold Gruber, and A.J. Miller

Abstract
Satellite data have provided considerable information on the radiation budget at the top of the Earth-atmosphere system. However, in order to maximize the usefulness of these observations, it is necessary to know how the radiative heating and cooling are distributed within the atmosphere and between the Earth's surface and the atmosphere. A technique has been developed to use radiance data from the High Resolution Infrared Sounder (HIRS) instrument flown on NOAA operational satellites to obtain estimates of the profile of longwave atmospheric cooling (LC) and the atmospheric emission to the Earth's surface (downward longwave radiation, DLR). Briefly, the DLR and LC are estimated from HIRS radiance observations using regression techniques on radiative transfer calculations. The technique requires the spectral radiance data from HIRS and the vertical distribution of cloud amount and cloud-base and cloud-top heights. Cloud information is not generally available concomitantly with the HIRS radiances, and the initial effort has focused on the development of clear sky models. Radiative cooling is calculated for four layers: surface to 700 mb, 700 to 500 mb, 500 to 240 mb, and 240 to 10 mb.

Initially, a month-long data set was produced — 15 December 1990 through 15 January 1991 — for study and technique evaluation. Calculations were global on a 2.5° by 2.5° latitude-longitude grid. Monthly averages and five-day running means were produced. Comparisons were made to the National Meteorological Center (NMC) medium range forecast (MRF) model fields of LC and DLR. The agreement was generally within values expected from comparisons of calculations from the different models, especially for zonally averaged quantities. There were, however, significant differences over specific geographical areas (e.g., Africa and Australia). Analysis of these differences indicated where improvements were needed in the HIRS and the MRF techniques, resulting in an improved HIRS model for estimating clear sky DLR and LC.

The clear-sky algorithms for the LC and outgoing longwave radiation at the top of the atmosphere have been implemented as an experimental quasi-operational system for further evaluation. Twelve months of data (June 1992 through May 1993) have been processed to date, and the availability of the data were announced to the international climate community for use and evaluation beginning in January 1993.

Introduction
Radiative processes in the Earth-atmosphere system are essential for maintenance of the atmospheric general circulation. Absorbed solar radiation is the principal source of energy, whereas energy lost to space through terrestrial radiative processes is the ultimate energy sink. Most of our information on the time varying geographical distributions of the radiation source and sink at the top of the Earth-atmosphere system has come from Earth orbiting satellites. The better known experiments that measured the planetary short- and longwave radiation budget were Nimbus 6 and 7 ERB and the Earth Radiation Budget Experiment (ERBE) (Barkstrom *et al.*, 1989). Operational estimates of the top of the atmosphere radiation budget are provided by NOAA from the polar orbiting satellite data (e.g., Gruber and Winston, 1978).

These data sets have limited utility because they only yield an estimate of the radiative cooling for the entire Earth-atmosphere system. In order to gain maximum utility from these data in forecasting and climate diagnostics, it is necessary to know how the radiative cooling is distributed between the atmosphere and the surface. This has been clearly demonstrated by Slingo and Slingo (1988; 1991) and Ellingson and Campana (1987). Such information is of interest as well to all "three streams" of the World Climate Research Programme (WCRP) (WCP-115, 1986): extended range forecasting, time scale of 1 to 2 months; interannual variation, time scale of several years; and time scales of several years to several decades. Because the atmosphere is mostly transparent to shortwave radiation, the major portion of the atmospheric radiative heating (cooling) is accomplished by longwave radiation. (The terms longwave and shortwave are used herein to denote radiation of wavelengths greater than or less than 3 micrometres, respectively.)

At the start of this project there was no operational product available to scientists with which to study the relationship of this cooling with climate and long-range weather forecasts, although the need for knowledge of the distribution of radiative cooling had been established. In 1987 we

R. Ellingson and D. Yanuk are with the Department of Meteorology, University of Maryland, College Park, MD 20742.

A. Gruber and A.J. Miller are with NOAA/NESDIS, Washington, DC 20233.

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proposed to NASA to rectify this gap by developing an operational methodology for providing estimates of longwave cooling on a global scale from satellite observations. The objective of the proposed project were to (1) develop and evaluate the methodology for determining the vertical distribution of longwave cooling from the NOAA High Resolution Infrared Sounder (HIRS) onboard the NOAA operational satellites, and (2) implement the developed procedure into a pilot operation for test and evaluation as input into an operational forecasting model and for use as a climate diagnostic tool. This paper summarizes our activities to meet those objectives.

Structure of the Project Team

The project consists of teams at the University of Maryland (UMD), headed by Ellingson; NOAA/NESDIS, headed by Gruber; and NOAA/NMC, headed by Miller. The idea for the project arose from discussions between Ellingson and Gruber at the NOAA Cooperative Institute for Climate Studies (CICS) at UMD about using or extending the NOAA operational radiation budget product to estimate vertical profiles of longwave radiative cooling rates. Similar discussions had produced a technique for estimating the outgoing longwave radiation at the top of the atmosphere (OLR) from the operational sounders (HIRS) (Ellingson *et al.*, 1989a), and Ellingson's experience with radiative transfer theory led him to believe that such a technique was possible with the HIRS data. Furthermore, both Gruber and Miller had extensive experience in the development and analysis of data from NOAA's operational programs and in the dissemination of data to the international meteorological community.

The team at UMD had the primary responsibilities for developing the inference techniques, developing the technology for displaying the data, interpreting the differences between estimated and calculated fields, and distributing the data in a quasi-operational mode. This activity was supported by the full-time assistance of a faculty research assistant, two full-time graduate students, and one-fifth of Ellingson's time. The computer resources included a dedicated Apollo workstation, unlimited access to the UMD Meteorology Departments local area network of DEC and Apollo workstations, access to UMD's computational facilities, and access to the Internet.

The NOAA/NESDIS activity provided access to the operational satellite data stream, provided assistance with the interpretation of the observed and inferred satellite data, and provided guidance with streamlining the technique to operational status. This activity was assisted for one year by a UMD faculty research assistant along with about 10 percent of Gruber's time. The project provided a workstation which was connected with the NOAA operational network. The workstation received the HIRS data, performed initial data reduction, and forwarded the data to UMD for further processing.

The NOAA/NMC participants provided operational NMC products for use in testing the inference schemes, provided guidance on the interpretation of the NMC and inference products, and provided guidance on the structuring of the data products for the potential user community. This activity was accomplished by input from several NMC scientists which amounted to about 10 percent of a man year per year.

Cooling Rate And Surface Flux Estimation Techniques

The vertical distribution of temperature, water vapor, and cloudiness are the primary modulators of the thermal radiation emitted to space and to the surface. As such, measurements of radiance emitted by the Earth-atmosphere system to space have been used to estimate profiles of the atmospheric temperature and humidity since the advent of man-made, Earth-orbiting satellites. In principle, the temperature and water vapor profiles inferred from routine satellite observations, when combined with cloud estimates, could be used in radiative transfer models to calculate radiation energy budget quantities such as vertical profiles of upward and downward longwave fluxes and cooling rates. This type of approach has been done routinely since the mid 1980s at the major medium range (3 to 5 day) weather forecast centers in Europe (the European Center for Medium Range Weather Forecasts, ECMWF) and the U.S. (the National Meteorological Center, NMC) at the start and during the daily forecast cycles using radiative transfer theory and the initial and forecast variables. Such calculations require extensive amounts of computer time, and errors in the forecast model assimilation and satellite inferred temperature and humidity fields may lead to undesirable errors in the calculated flux and cooling rate fields.

An alternative approach is to use the radiance observations to directly infer the fluxes and cooling rates without performing the intervening radiative transfer model calculations. This approach is physically reasonable because the outgoing longwave radiance measured in space is part of the total outgoing radiation flux at the top of the atmosphere (OLR), and it is an integral measure of the atmospheric cooling to space for a given spectral interval. Rodgers and Walshaw (1966) showed that "cooling to space" is the major contributor to the total longwave cooling (LC) at any level in the atmosphere. Theoretical studies by Liou and Xue (1986) have shown that it should be possible to estimate vertical profiles of LC from radiance observations. More recently, Ellingson *et al.* (1989a; 1993) have shown that a linear combination of radiance observations from the HIRS on the NOAA operational satellites may be combined to produce estimates of the OLR at the top of the atmosphere that rival the accuracy of those observed by ERBE, and Lee and Ellingson (1990) showed that similar procedures could be used to obtain an accurate estimate of the downward radiation flux at the Earth's surface (DLR). Because the Ellingson *et al.* (1989a) technique offered the possibility of rapid, and potentially accurate, estimates for global scale analyses, we decided to pursue its extension to the derivation of vertical profiles of longwave cooling (LC).

Briefly, the vertical profile of LC is estimated from HIRS radiance observations using regression techniques based on radiative transfer model calculations. The cooling rate for the k-th layer is estimated in a manner similar to the way it would be calculated in a radiative transfer model, namely

$$LC_k = \Sigma\, a_{ki}\, N_{oi} + A_j\, \Sigma\, b_{kji}\, N_{oi} \tag{1}$$

where the a's and b's are coefficients determined from regression analysis of model calculations, the N_{oi}'s are *cloud-cleared* radiances obtained from the operational analysis of the measured radiances, and A is the effective cloud fraction at level j (multiple, randomly overlapped, cloud layers are allowed in the analysis). The first term on the right hand side of Equation 1 is the clear-sky cooling rate and the second term is the difference between the completely overcast and the completely clear terms. Note that the cloud-cleared radiances contain information on the vertical distribution of atmospheric variables other than clouds.

The spectral intervals and the regression coefficients for Equation 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, cooling rate, and radiance data were calculated with a version of the radiation model described by Ellingson and Serafino (1984). Briefly, the model uses the Malkmus (1967) band model fitted to the 1986 AFGL spectral line data for H_2O, CO_2, O_3, CH_4, and N_2O in the spectral region between 0 and 3000 cm-1 (i.e., all wavelengths less than 3.3 mm). The water vapor continuum is included using a modification of the parameterization given by Roberts *et al.* (1976) so that it more nearly reproduces the data of Burch and Alt (1984). 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 axi-symmetric, 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 four-point Gaussian quadratures, respectively. The application to the 19 HIRS channels was done using NOAA supplied, laboratory measured values of the instrument response functions.

Cooling rates were computed in each of four layers (1000 to 700, 700 to 500, 500 to 240, and 240 to 10 mb). The effects of clouds were included by computing cooling rates in the individual layers with complete (black) cloud cover below, within or above the given layer with cloud thicknesses ranging upwards from 1 mb. For a given layer and cloud base pressure, regression coefficients were calculated as a function of cloud layer top. Cloud bases and tops were aligned with model levels to span the range of possible cloud locations and thicknesses. It should be noted that the atmospheric water vapor profiles were not modified to yield 100 percent relative humidity in the regions of assumed cloudiness. Actual cloud emissivities may included by multiplying the cloud fraction by the appropriate emissivity. In operational use, the precalculated regression coefficients may be interpolated to match the observed cloud locations.

The 1600 soundings used in the radiative transfer calculations were compiled by Phillips *et al.* (1988). Briefly, each sounding includes 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 to 30°N) and midlatitude (summer and winter) conditions. The O_3 data were chosen 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.

The regression analyses used to develop the OLR, LC, and DLR estimation techniques were performed with a least-squares, stepwise, backward glance technique of the type described by Efroymson (1960). A variety of subroutines from the S+ (see SPLUS, 1992) and IMSL libraries (see IMSL, 1984) were used in the analysis, 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 determination of the form and coefficients of the regression equation consumed a large fraction of our research efforts during the first 24 months of the project. Our analysis shows that linear combinations of HIRS radiances yield uncertainties in individual estimates of LC on the order of 10 to 15 percent relative to the mean (about 0.3°C/day RMS), respectively, for homogeneous clear or (black) cloudy scenes. The largest errors occur in the two lowest layers where the technique tends to underestimate the actual cooling for large column water vapor amounts (i.e., tropical regions). The spectral intervals chosen for the clear-sky LC analysis are listed in Table 1 along with information concerning the HIRS channels and the RMS estimation errors. The coefficients may be obtained from Ellingson (Internet email-bobe@atmos.umd.edu).

Table 1. Summary Information Concerning the Results of the Regression Analysis for Obtaining Longwave Cooling Rates from HIRS Radiance Observations

Atmospheric Layer (mb)	HIRS Channel Number and Central Wavelength	Principal Absorbing Constituents	Level of Peak Energy Contribution	RMS cooling rate error (°C/day)
1000-700	6 (13.70μm) 8 (11.10μm) 11 (7.30μm)	CO_2/H_2O Window H_2O	800 Surface 700	0.31
700-500	12 (6.70μm)	H_2O	500	0.28
500-240	9 (9.90μm) 11 (7.30μm)	O_3/H_2O H_2O	25/Surface 700	0.28
240-10	2 (14.70μm)	CO_2	60	0.12

It is often difficult to attribute physical significance to predictors selected in regression analysis of geophysical data because of the intercorrelations between the variables. However, the spectral intervals chosen by the regression analysis coincide quite closely with our knowledge of the physics governing the cooling in the various layers. For example, cooling in the 1000 to 700 mb layer occurs mainly in the portion of the spectrum from 8 to 12 μm and is controlled largely by the surface temperature and the total amount of water within and above the layer. Likewise, the variables chosen for the 700- to 500- and 240- to 10-mb layers reflect the dominance of "cooling to space" by these layers. Cooling in the 700- to 500-mb layer is controlled primarily by water vapor emission in the 20- to 25-μm region, and this is highly correlated with emission in the 6.7-μm region. In the stratosphere, cooling to space by the 15-fm CO_2 band dominates the exchange process. Cooling in the layer from 500 to 240 mb is controlled by water vapor emission in the 20- to 50-μm region, but the HIRS channels are not very sensitive to this emission. Nevertheless, the channels chosen by the regression analysis reflect the intervals that best explain the variance in this region.

The cooling rate errors are sufficient for many climatological studies, particularly because uncertainties in measured or inferred temperature and water vapor profiles can lead to errors of this magnitude in radiation model calculations (Ellingson and Gille, 1978). Therefore, we decided to use this formulation for all of our LC analyses. Nevertheless, it is quite likely that the instantaneous errors might be reduced by a more detailed analysis to account for the insensitivity to high concentrations of water vapor (see below).

It should be noted, however, that due to the non-random nature of atmospheric profiles, this type of technique may lead to systematic errors. In mid-latitude regions, where the atmospheric temperature and moisture profiles change frequently, the uncertainties over a months time period largely cancel. However, systematic errors will likely persist in tropical regions (see Ellingson *et al.*, 1989b). Nevertheless, the large scale horizontal patterns should be largely correct. We have not looked closely at the magnitude of the signs of the errors in successive layers, which is related to the change in the stability of the atmosphere. The technique could be improved in this regard by only choosing combinations of spectral intervals that confine the uncertainty of the first derivative to within particular limits. Modifications to reduce the magnitude of the estimation errors may require a different approach to the regression analysis, which is left for future research.

Model Calibration and Validation

Flux and radiance calculations from the radiation model used to develop the OLR, DLR, and LC estimation techniques have been compared with observations from a variety of sources (satellite radiance data, Ellingson and Gille (1978); aircraft pyrgeometer data, Ellingson and Serafino (1984); ERBE OLR data, Ellingson *et al.* (1994)), and the calculations have been found to agree to within the rather large uncertainties of the observations. Furthermore, the longwave radiative transfer model was tested in the framework of the Intercomparison of Radiation Codes in Climate Models (ICRCCM) (Ellingson *et al.*, 1991). As such, it is calibrated against international standards. The study by Ellingson *et al.* (1994) shows individual OLR estimates to agree with ERBE data to within 5 W/m^2 RMS for all cloud and surface types. However, the LC and DLR estimation techniques have not been calibrated with observations directly, although that is being done as part of our participation in the NASA sponsored surface radiation budget algorithm intercomparison study, the FIRE Cirrus II Experiment (Cox *et al.*, 1987), and the DOE sponsored Atmospheric Radiation Measurements Program (DOE, 1990).

The application of any model-based inference scheme to observed radiance data requires consistency between the observed and model-calculated radiances. That is, although the fluxes calculated by the model may be in excellent agreement with observations, the radiances in some narrow spectral intervals may show large differences with observed data. Such disagreements will lead to large errors in the inferred quantities when the model-based coefficients are applied to the observations.

To guard against this possibility, we used clear-sky radiosonde observations collocated with NOAA-10 HIRS overflights in an attempt to determine the magnitude of the errors in the radiance calculations. On the basis of 2667 calculations, we found the model to have mainly spectrally varying systematic differences with the observations in HIRS channels 1 to 7 (i.e., the 15 mm CO_2 band). Furthermore, the analysis showed that some of the regression estimates were particularly sensitive to small variations in some spectral intervals. Therefore, weve modified the regression analysis to eliminate spectral intervals which appeared to yield gross errors in the LC fields. The systematic differences are subtracted from the observed radiances when the estimation equations are applied to observed data. Although this is tantamount to tuning the analysis procedure, this step is necessary in order to insure the stability of the retrieval technique. Such modifications will become less important as radiation models are improved. Overall, on the basis of our comparisons with ERBE, our limited comparisons with aircraft and surface flux data, our intercomparisons with line-by-line calculations, and from the regression analysis, we estimate the RMS accuracy of individual clear-sky OLR, DLR, and LC estimates to be about 5 W/m^2, 15 W/m^2, and 0.35°C/day (outside of tropical regions), respectively.

As noted above, the DLR and LC estimation techniques require spectral radiance data from the HIRS and the vertical distribution of cloud amount and cloud-base and cloud-top heights, the latter of which are not available on an operational basis. Furthermore, the radiation model and the inference schemes have not been calibrated adequately for cloudy conditions. Nevertheless, we have determined the coefficients necessary for the inference techniques for cloudy conditions and we are testing them for potential operational implementation using cloud distributions from U.S. Air Force RTNEPH analyses and climatological cloud locations and joint probability information. The uncertainties in DLR calculations due to uncertainties in the cloud base altitude are estimated by Frouin *et al.* (1988) to fall between 4 and 9 $W/m^2 \cdot km^{-1}$ for tropical and subarctic winter conditions, respectively, for 100 percent cloud cover. These estimates are linear in cloud fraction. The uncertainties for cooling rates are not as easily quantified as they depend upon the positions of the clouds relative to the layer boundaries. Errors of several degrees per day are possible in individual LC estimates by misplacing the position of the cloud top.

Although we have developed the technique to account for all types of cloud conditions, the results shown in the remainder of the paper are restricted to clear-sky conditions due to the lack of a detailed cloud analyses at the time of the radiance observations. Effects of clouds will be covered in subsequent publications.

Preliminary Operational Testing

A month long operations study was carried out for the period from 15 December 1990 through 15 January 1991 for the purpose of testing the throughput of the technique in an operational setting and for providing a data set for initial application by NMC. In particular, the initial application consists of a determination of the agreement between NMC calculated and satellite determined fields of clear-sky OLR, DLR, and LC. Clear-sky conditions were chosen because of the lack of an operational cloud product for each procedure. Therefore, comparisons of the global fields of radiation budget quantities produced by our technique with the numerical models yield estimates of deficiencies in the initialized fields as well as in the inference technique.

During this time the cloud-cleared radiances from each NOAA-10 orbit were obtained from the NESDIS operational data stream along with clear-sky OLR, DLR, and LC calculations from the initializations of the NMC Medium Range Forecast (MRF) model. The data from each source were interpolated to a common 2.5° latitude by 2.5° longitude grid to produce the daily and monthly averaged clear-sky radiance, OLR, DLR, and LC fields.

Certain characteristics of the data stream are important to the interpretation of the results. First, the NOAA-10 satellite is a sun-synchronous polar orbiter with an equator crossing time of approximately 0730 and 1930 local time. The initializations of the MRF are performed globally at 00, 06, 12, and 18 UTC with observations obtained at or interpolated to those times. The initialization data include satellite inferred temperatures, but the water vapor distribution is based upon the model spin-up parameterizations. Thus, the MRF radiation fields include the effects of a more highly resolved diurnal cycle as compared to the HIRS estimates. Furthermore, the global inferred fields are not synoptic (i.e., not determined everywhere at the same time).

Second, the individual HIRS cloud-cleared radiances are representative of approximately a 250 km² area on Earth, but these are not spatially continuous, because cloud-cleared radiances are not determined by NOAA in overcast regions. However, over the course of the month, about 97 percent of the gridded boxes had observations. We approximated the missing data on a daily basis by interpolating either linearly in longitude or bi-linearly in latitude and longitude, depending upon the density of clear-sky radiance field.

It should also be noted that the NMC MRF radiation model does not include the same parameterizations of the absorption properties of atmospheric gases used to develop the inference schemes. The longwave radiation model used in the MRF follows the work of Fels and Schwarzkopf (1975) with modifications as described by Schwarzkopf and Fels (1991). The model has been compared extensively with line-by-line (LBL) calculations and with our model as part of ICRCCM (Ellingson *et al.*, 1991). It should be remembered that there is no absolute standard for comparisons, but LBL calculations most accurately account for the known physics. The published ICRCCM results show the Fels-Schwarzkopf model and LBL calculations to agree to the order of 1 and 3 W/m² for the OLR and DLR, respectively, and to about 0.1°C/day for one kilometre average LCs in the troposphere. However, the ICRCCM calculations did not include the effects of CH_4 and N_2O. The results from ICRCCM combined with the MRF-missing effects of CH_4 and N_2O indicate that the MRF model yields higher (lower) OLR (DLR) values relative to our model of about 6 (12) W/m² when it is applied to the same temperature and water vapor profile. We estimate the model cooling rates to agree to within about ±10 percent for the layers used in this study.

Because the data used for the MRF come from the model initialization rather than from the satellite observations, one can not rely solely on the above numbers to estimate the accuracies and magnitudes of the expected agreement between the MRF and satellite inferred values of OLR, DLR, and LCs. For the DLR, the review by Schmetz (1989) gives differences between monthly averaged DLR observations and calculations using data from the TIROS Operational Vertical Sounder (TOVS) on the order of 10 W/m². Using LOWTRAN7 (Kneizys *et al.*, 1988), we have calculated the effects of uncertainties in the TOVS retrieval to be on the order of 10 and 20 W/m² for temperature and water vapor, respectively, for individual clear soundings. For the OLR, these effects are of the order of 5 W/m².

We suspect the errors in the MRF temperature initializations to yield similar DLR and OLR uncertainties as noted above over oceanic regions, and somewhat larger errors than our calculations due to improper specification of the water vapor field in data sparse regions (the tropical oceans and Africa). Because the temperature of the Earth's surface is calculated by the MRF over the continents from energy balance considerations as part of the models initialization, we anticipated potentially larger discrepancies in these regions, particularly at times of maximum heating or cooling. For cooling rates, we estimate the uncertainties in the MRF cooling rates on individual profiles to be at least on the order of 10 percent (see Ellingson and Gille, 1978) because the uncertainties in the MRF products are as large as or larger than the errors in radiosonde data. The random and/or systematic nature of these differences follows our previous discussion.

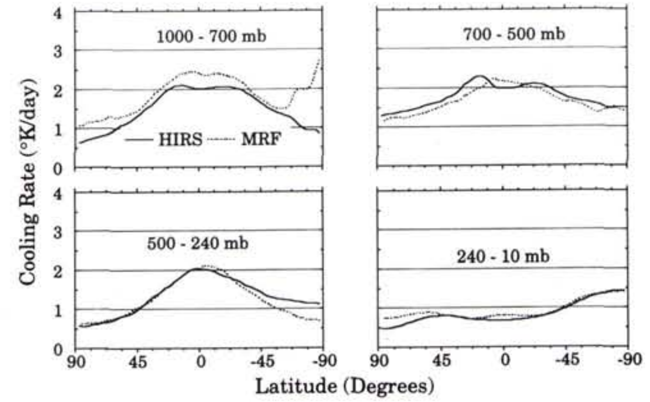

Figure 1. Comparison of zonally averaged clear-sky cooling rates from the HIRS and the MRF for the period from 15 December 1990 through 15 January 1991.

Overall, for monthly averaged data, we expect the zonally averaged differences to be similar to the differences between model calculations using the same profiles, because we will have averaged over effects of both systematic and random errors in the regression estimates as well as the initialized meteorological fields (assuming both positive and negative systematic errors are uniformly distributed around a latitude circle). However, there are likely to be large differences at any given location due to persistent systematic errors in both the MRF and satellite inferred analyses.

Plates 1 and 2 show the inferred monthly averaged, clear-sky global distributions of the OLR, DLR, and the 700- to 500-mb and 500- to 240-mb LCs and their differences relative to the MRF results for the study period, respectively. Zonally averaged inferred and MRF calculated values of the LC and OLR/DLR are displayed in Figures 1 and 2, respectively. In general, the clear-sky global fields are zonal in nature (i.e., the major changes are in the north-south direction) due to the zonal nature of the large-scale distributions of temperature and water vapor. The larger diurnal variation of temperature near the surface over continental regions is responsible for most of the east-west variation of the DLR and OLR, whereas east-west water vapor variations are the largest modulators of the zonal character of the layer cooling rates.

Overall, the comparisons of the zonal averaged HIRS inferred with MRF calculated quantities show relatively good agreement with the OLR and DLR agreeing to within the expected differences at most latitudes. Similarly, the large-scale patterns of the clear-sky global distributions of all of the quantities are in generally good agreement. These features add further credibility to the inference techniques. However, there are large differences in the fields of all inferred quantities in some geographical locations, particularly over Africa and Australia and some tropical oceanic regions, that cannot be explained by differences in the parameterizations of the radiation physics.

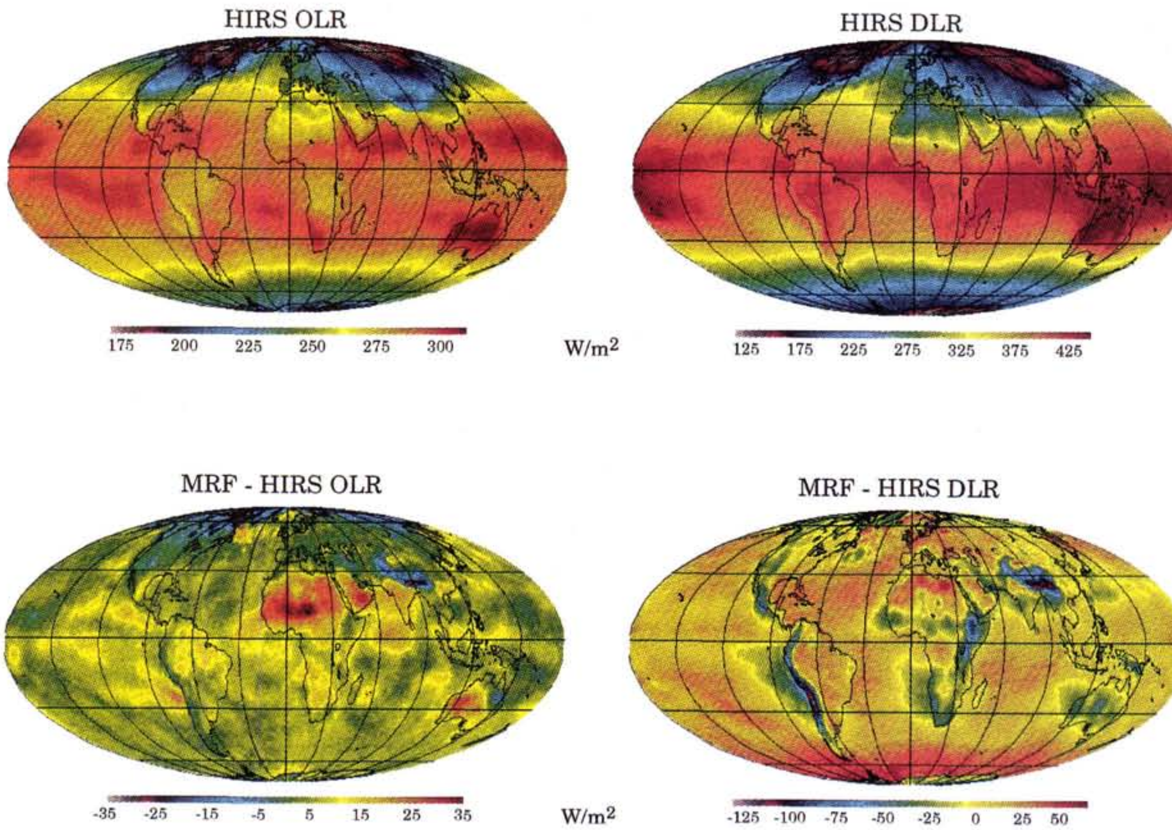

Plate 1. Global distributions of the HIRS estimated OLR, DLR, MRF - HIRS OLR and MRF - HIRS DLR for the period from 15 December 1990 through 15 January 1991. Flux units are W/m².

It is the analyses of the differences that will lead to improvements in the MRF initialization and the HIRS inference techniques. For example, we were particularly concerned with the OLR differences over the dessert regions, because many of the differences were almost an order of magnitude greater than the rms differences seen in previous comparisons with the ERBE. We were concerned that they might be do to a combination of regression errors, the asynoptic nature of the satellite data, or perhaps to large temperature gradients near the surface. These differences might also be responsible for some of the differences seen in the LC and DLR fields.

To test for these possibilities, the MRF initialization fields for one day were used as input to our detailed radiation model to calculate the global fields of OLR, DLR, LC, and the HIRS radiances at each of the synoptic times. The calculated radiances were then used as input to the inference schemes to provide regression estimates of the same fields at the synoptic times. A variety of comparative studies were then performed to test the inference schemes. The results of those comparisons show that only about 25 percent of the OLR and LC differences seen over the continental regions may be explained by the asynoptic sampling and/or the large near-surface temperature gradients. We now suspect that the differences are due to errors in the MRF initialization in these regions. These results have been shared with NMC, and they are examining the problem to see if it continues during the operations test discussed below. Additional studies of the differences in the LC fields are underway.

As seen from Plate 1, there are differences in the DLR fields that amount to as much as 100 W/m². The largest differences occur in regions of high terrain which were not taken into account in the results shown. Nevertheless, aside from the orographic effects, there are many regions where the differences are substantially greater than the purporte 15W/m² RMS accuracy of the DLR technique. Our analysis of the detailed model calculations discussed above found that the DLR model which is linear in radiance has serious shortcomings when there is either high or low column water vapor amounts. This led one of our students, Hai-Tien Lee, to completely reanalyze the DLR technique and the radiation model calculations.

In a recently completed dissertation, Lee (1993) has shown that the clear or overcast DLR may be accurately inferred from the HIRS radiances with an equation of the form

$$\mathrm{DLR} = \sigma T^4 (N_{o10})\, \epsilon(N_{o7}, N_{o8}, N_{o10}, N_{o13}) \qquad (2)$$

where σ is the Stefan-Boltzmann constant, T is brightness temperature corresponding to N_{o10}, and the emissivity function ϵ is fitted to non-linear functions of the indicated clear-column HIRS radiances. The functional form of ϵ and the

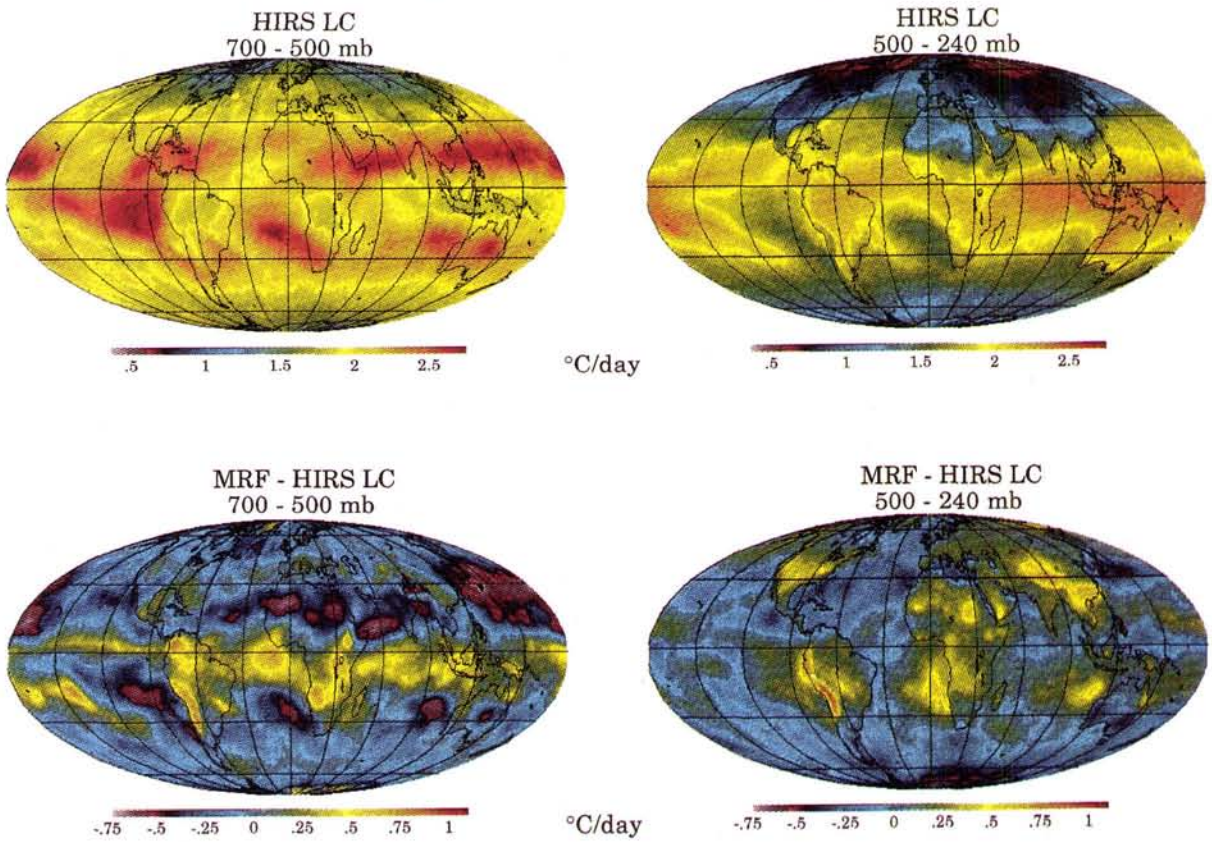

Plate 2. As in Plate 1 but for the LC in the 700- to 500- and the 500- to 240- mb layers. Heating rate units are °C/day.

choice of particular HIRS channels depend upon the altitude of the surface and the cloud layer in question. This form of the equation led to RMS errors of less than 10 W/m² for clear and overcast conditions using the Phillips *et al.* (1988) data as well as for the global, one-day, clear-sky data set noted above. The Lee technique is in the process of being recoded for use in the operational technique, and the details concerning this technique will be submitted for publication in the near future. A similar analysis is underway for the clear-sky LC to account for the underestimation at high water vapor amounts.

Quasi-Operational Data Collection, Analysis, and Distribution

The clear-sky algorithms for the LC and OLR were implemented as an experimental quasi-operational system for further evaluation in May 1992, and the availability of the data for use and evaluation by the international community was announced by letter and OMNET bulletin board in January 1993. The operations proceed as follows.

The daily radiance observations by the TOVS HIRS/2 instruments onboard the NOAA-11 and NOAA-12 polar orbiting satellites are operationally processed by NOAA to produce their five-day rotating sounding product archive (DSD3). A subset of the DSD3 is extracted by NOAA/NESDIS and modified with our equations to include the clear-sky OLR and LC for four atmospheric layers. Each observation is considered representative of the quantity associated with an area covered by a 3 by 3 array of individual HIRS scan spots (an area of about 250 km² at nadir). This high resolution data set is produced at NESDIS and then transferred to UMD via the Internet for analysis and further processing.

At UMD/CICS, 2.5° latitude by 2.5° longitude gridded fields are produced for each satellite and the four orbit daily means are used to enhance quality control and analysis of the data. Global images and bulk statistics are produced to quickly assess data integrity and to aid in analysis utilizing data visualization products.

The data sets currently available include the high resolution fields (as they are obtained directly from NESDIS) and the 2.5° by 2.5° gridded fields for both satellites. The daily average, obtained from both satellites, is also included at the 2.5° by 2.5° resolution. As the data are collected, special temporally averaged data are produced, including five-day and monthly mean 2.5° by 2.5° gridded fields. The monthly mean data are also available as contoured images and can be viewed as a time series loop. The current archive includes daily observations from June 1992 to the present.

In order to facilitate the transfer of data from the University of Maryland to the site of an interested user, an X-Window based, menu-driven, interactive database facility is

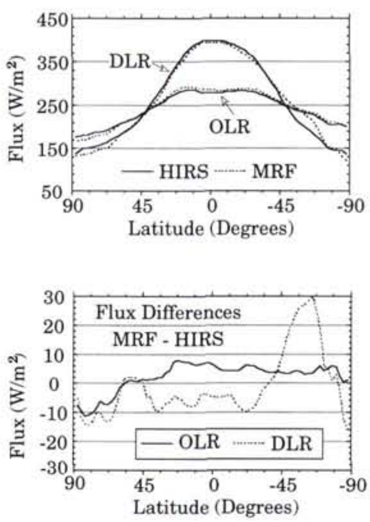

Figure 2. As in Figure 1 but for the OLR and DLR.

available via a standard TCP/IP telnet session. A complete description of the data, including naming conventions and field formats, is available via on-line documentation. Interested users may obtain the necessary login information through e-mail contact with dave@atmos.umd.edu.

A list of the organizations which have successfully transferred data include

- Bureau of Meteorology Research Center, Melbourne, Australia;
- Department of Oceanography, Dalhousie University;
- Institute for Physics, GKSS Forschungszenstrum, Geestchacht, Germany;
- Jet Propulsion Laboratory, Pasadena California; and
- NOAA/NMFS, Narragansett, Rhode Island.

It should be noted that the DLR fields will be added and analyzed from the beginning of our archival period when the coefficients for the Lee (1993) model are derived for the NOAA-11 and NOAA-12 HIRS instruments. It should also be noted that cloud effects may be added easily when cloud analyses for the period become available from either the ISCCP or the NESDIS procedure now under development. Furthermore, we plan to add analyses of the total OLR from the HIRS observed (raw) radiances during 1993. This will allow an operational determination of the top of the atmosphere "cloud forcing" being studied by a variety of climate groups.

Product/Technique Evaluation within NOAA

The LC, OLR, and DLR estimation techniques are experimental, and their adaptation for operational implementation must undergo a thorough review. The process for introducing a new product into operational production within NESDIS involves interactions with several standing NESDIS groups, and the LC and DLR inference techniques are still in the evaluation process. The groups and their functions are described below along with the status of the inference schemes relative to them.

Research and Development Council (RDC)

The Research and Development Council is a forum for the review and evaluation of research and development projects in NESDIS. Typically, new research ideas are surfaced at the R&D Council plenary sessions. Plenary sessions are open to all personnel within and outside of NESDIS, so that discussion of research activities benefit from diverse points of view, generally resulting in improved research plans. Reviews of the research during various developmental and testing phases may also be presented at an R&D Council plenary session. The concept of the LC inference scheme was discussed with the RDC before the start of the project, and the results of our preliminary results were described to them in the fall of 1991.

Satellite Product Review Board (SPRB)

The Satellite Product Review Board (SPRB) reviews all new product efforts at the times they are ready to move from development phase to the operational test phase and from the operational test phase to the operations phase. Development phase is a design of the procedure to generate a data product from satellite radiances; it includes initial testing by the developer. Operational test phase insures that the product will meet efficiency and resource constraints in an operational environment. It is also the time when the product is produced on an experimental basis, for a limited time, and assessments of usefulness and expected reliability as an operational product are made. The operational phase represents the long-term routine production and distribution of the data product by NESDIS. New products must be approved by the SPRB before they can become operational.

This project has had an informal review at the SPRB before the beginning of our current operations test. The project will be reviewed again early in 1994 after the users have had at least 12 months to use the data in an operational setting.

Product Oversight Panels (POP)

Product Oversight Panels were established at NESDIS to provide end-to-end scientific and technical oversight and recommendations to the SPRB regarding proposed new products, and improvements, modifications, and deletions of existing products. The POPs are composed of scientists from the NESDIS Office of Research and Applications, and Office of Satellite Data Processing and Distribution. Outside scientists may be invited to participate in the POP. The POP recommended the project for continued development in the fall of 1991.

Summary, Conclusions, and Suggestions for Future Activities

Radiative transfer theory and regression analysis have been used to develop a technique to infer vertical profiles of longwave radiative cooling in the atmosphere from radiance data observed by the HIRS instrument flown on NOAA operational satellites. The analysis shows that cooling rates in the layers from the surface to 700 mb, 700 to 500 mb, 500 to 240 mb, and 240 to 10 mb may be estimated to within about ± 15 percent RMS for individual radiance observation sets. These errors should decrease as the length of the averaging period increases.

An initial test of the technique in an operational framework was performed by collecting data from the NOAA-10 satellite during a one-month period between 15 December 1990 and 15 January 1991. Clear-sky global fields of OLR, DLR, and LC were obtained on a 2.5° by 2.5° latitude-longitude grid, and monthly averages were produced and compared with calculations made by the NMC MRF. The agreement was generally good, especially for zonally averaged quantities. There were, however, significant differences over many continental areas, particularly Africa and Australia. A detailed analysis of these differences led to an improved technique for estimating the DLR, and it provided insights to NMC concerning needed improvements in the MRF techniques.

The clear-sky algorithms for the LC and OLR were implemented as an experimental quasi-operational system for further evaluation in May 1992, and the availability of the data was announced to the international climate community in January 1993. The data from the technique are currently being used by several climate and medium range weather forecast groups. Most groups have only had access to the data for a few months, and this is too short a time to assess its usefulness in their operations.

However, from the perspective of utilizing a precisely determined longwave cooling rate from space observation within the operational analysis/forecast system, two positive arguments arise. The first is as an evaluation mechanism for the current within-model procedures. The second is that, if successful, the determinations can be input into the model as a type of forcing function. In two recent studies, Kahn *et al.* (1994) utilized one year of NMC data (1985-86) to investigate the meridional energy transports determined from the operational analyses, and Yang *et al.* (1994), in a prognostic study, examined the column cooling distribution in medium range forecasts from the NMC global model. Both studies demonstrated that the NMC forecast system in effect at that time generated excessive longwave radiative cooling in the tropics. As a consequence, the Hadley cell and walker circulations were weakened, and the energy divergence in the tropics was over 35 W/m^2 less than derived from net radiation measurements by ERBE. It is possible, then, that successful, operationally derived data from the HIRS instruments could have an impact in improving the operational analyses and forecasts.

There are additional applications of the data that we are aware of or that are under study. For example, NOAA/NMC has archived the global distributions of clear-sky radiation model calculations using MRF initialized fields for about half of our archival period, and they plan to compare many of their fields to ours, thereby providing an evaluation of the radiation physics in the MRF as well as testing the initialization schemes. As the NEDSIS operational cloud products become available, these comparisons and our data will gain added significance as they will lead to the initialization of the forecast models with a better estimate of the vertical distribution of radiative cooling. Similarly, information on the monthly and seasonal changes in the large-scale surface energy budget and atmospheric cooling fields will likely replace indirect inferences now made from the OLR alone and used in climate diagnostics and forecasts by the NOAA Climate Analysis Center. Furthermore, the improved DLR radiation scheme developed as an outgrowth of this project, and the experimental operational data collection now underway, will lead to a more complete description of the global surface energy budget, a term poorly understood, and one under extensive study by the World Climate Research Program.

This project has proceeded relatively smoothly and has accomplished most of its goals, but some of the problems that arose might have been alleviated by better information at the time of the initial planning stage. The major problem areas concern a determination of the necessary computer resources, ease of access of data from federal agencies, interagency agreements concerning continuation of funding during budget crises, and obtaining feedback from users of the new product. A determination of the required computer resources is difficult unless one limits the analyses at the outset. However, as there tends to be a natural growth in curiosity and computer power as projects proceed, it is perhaps best to extend ones initial estimate of needs or to allow expansion of the computer resources as the project proceeds.

Our access to data from NOAA was exceptionally good. However, it was sometimes impaired by operational constraints or prior commitments. It is quite likely that this occurs with every agency, and investigators should attempt to make arrangements for data access well in advance of when the data are actually required.

One of the major factors decreasing the pace of the project was the aperiodic funding of the program. Although full funding of the program was anticipated from the outset, vagaries in the political budgetary process often delayed the receipt of funds beyond the anticipated date. In the absence of special agreements or financing, such activities require one to simultaneously maintain more than one project in order to insure the continued funding of required personnel. This is not always possible or desirable, particularly in a university setting where much of the research is being done by degree seeking students.

Perhaps our biggest disappointment to date concerns feedback from users of the product. However, it should be kept in mind that there are many new projects underway in the international climate community, and most investigators have precious little time to use new data that may be outside of the immediate scope of their projects or which may be entirely new. Our experience with other projects suggests that published results are the best drawing card. This, however, takes a considerable amount of lead time. Alternatively, workshops to examine special problems are usually very stimulating. Such activities require planning at the beginning of the project as well as agency support.

Although it is too early to evaluate the usefulness of these data to the various institutions, our experiences with NOAA lead us to believe that the continued use of these data will lead to better climate analyses and data assimilation techniques of the radiation fields for use in forecast models. The technique is under continuing evaluation by NOAA for possible operational implementation. In the interim, it is continuing under the sponsorship of NOAA's Climate and Global Change Program in the Operational Measurements section, and we will report on the data and its use in future publications

Finally, the estimation technique would likely be improved and be more easily extended to future satellite instruments if the radiation calculations were performed with a line-by-line model so as to more accurately account for all of the physics. Such detailed calculations were a monumental task at the start of this project because of the large amount of computer time required for the calculations. Furthermore, it was difficult to justify such calculations on the basis of the ICRCCM results and the uncertainties associated with estimating cloud effects. Nevertheless, such calculations are more easily accomplished now and they will be necessary if the technique is to be applied to higher spectral resolution instruments, such as the Advanced Infrared Sounder (AIRS), planned for implementation in the late 1990s.

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