Update of Radiance Calibrations for ISCCP

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ABSTRACT

Since July 1983 ISCCP has collected, normalized, and calibrated radiance data (visible and thermal infrared) from the imaging radiometers on the National Oceanic and Atmospheric Administration polar orbiters and from the geostationary satellites GOES, Meteosat, and GMS. Although analyzed by the International Satellite Cloud Climatology Project (ISCCP) to obtain information about clouds, this global radiance dataset also represents a valuable resource for other remote sensing studies. Examination of the 8-yr cloud climatology produced with the first version of the ISCCP calibration revealed artifacts in the global means that coincided with the changes in the afternoon polar orbiters (used as a reference standard), as well as some localized anomalies related to occasional errors in the geostationary normalizations. This paper reports the changes to the ISCCP normalization and calibration procedures (originally reported in Brest and Rossow) that have been made to reduce these artifacts and errors and to produce a revised calibration. The key assumption, made after examining more than 10 years of global data, is that the mean properties of the earth are more nearly constant over this timescale than are the calibration of these radiometers. The authors conclude that the relative calibrations of the radiances used by ISCCP are now uncertain on average by no more than ±0.01–0.02 absolute, ±3%–5% relative, for visible (VIS) radiances and ±l–2 K absolute, ±0.3%–1.0% relative, for infrared (IR) radiances. The absolute calibration uncertainty is estimated to be about 10% for VIS and 2% for IR. The history of efforts to calibrate the Advanced Very High Resolution Radiometer (AVHRR) points to some lessons important to future spacecraft observations of climate change: Real decadal-scale changes of the earth are much smaller in magnitude than uncertainties in calibration changes and cannot be reliably detected without significant improvements of instrument calibration; infrequent aircraft calibration results for AVHRR with their attendant uncertainties make it difficult to distinguish real interannual variability from short-term calibration changes and suggest that something more will be required to obtain the needed accuracy; and finally, even calibrations based on onboard targets may not be sufficient, given that the authors still find differences in IR calibrations of more than 1 K. These results suggest, in particular, that reliance on one method of calibration for future spacecraft missions is unlikely to reduce calibration uncertainties enough for climate change monitoring. Even with improvements in all of these areas, the relative accuracy attained will only be apparent in the context of a long data record.

1. Introduction

One of the objectives of the International Satellite Cloud Climatology Project (ISCCP) of the World Climate Research Program is to take advantage of current and planned operational weather satellites, both geostationary and polar orbiting, to produce a global, reduced-resolution, calibrated, and normalized *radiance* dataset that can be used to derive cloud properties (Schiffer and Rossow 1983). Since July 1983 radiance data have been collected from the imaging radiometers on the National Oceanic and Atmospheric Administration (NOAA) polar orbiters (*NOAA-7, -8, -9, -10, -11*, *-12*, and *-14*) and from the geostationary satellites, such as GOES (*GOES-5, -6, -7, -8,* and *-9*), Meteosat (*MET-2, -3, -4,* and *-5*), and GMS (*GMS-1, -2, -3, -4,* and *-5*). The spatial resolution of the ISCCP radiance data is reduced by sampling the original satellite data at intervals of about 30 km. For example, the ISCCP Stage B3 version of Advanced Very High Resolution Radiometer (AVHRR) data is identical to the global area coverage (GAC) form, which has a nominal resolution of 4 km, except that the radiance count values have been truncated from 10 to

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TABLE 1. ISCCP data products.

- Reduced resolution radiance data (stage B3)
  - Resolution: 30-km pixel, 3 h, individual satellites
  - Contents: Radiances with calibration and navigation appended. Uniform format for all satellites
- Calibration table dataset (stage BT)
  - Resolution: 3 h, individual satellites
  - Contents: Updates of calibration tables for B3 dataset
- Pixel-level cloud product (stage CX—not available publicly)
  - Resolution: 30-km mapped pixel, 3 h, individual satellites
  - Contents: Calibrated radiances, cloud detection results, cloud and surface properties from radiative analysis
- Pixel-level cloud product—revised algorithm (stage DX)
  - Resolution: 30-km mapped pixel, 3 h, individual satellites
  - Contents: Calibrated radiances, cloud detection results, cloud and surface properties from radiative analysis
- Gridded cloud product (stage CS—not available publicly)
  - Resolution: 280-km equal-area grid, 3 h, individual satellites
  - Contents: Spatial averages of DX quantities and statistical summaries
- Gridded cloud product (stage DS—not available publicly)
  - Resolution: 280-km equal-area grid, 3 h, individual satellites
  - Contents: Spatial averages of DX quantities and statistical summaries
- Gridded cloud product (stage C1)
  - Resolution: 280-km equal-area grid, 3h, global
  - Contents: Spatial averages of CX quantities and statistical summaries. Satellites are merged into a global grid. Atmosphere and surface properties from TOVS appended
- Gridded cloud product—revised algorithm (stage D1)
  - Resolution: 280-km equal-area grid, 3 h, global
  - Contents: Spatial averages of DX quantities and statistical summaries, including properties of cloud types. Satellites are merged into a global grid. Atmosphere and surface properties from TOVS appended
- Climatological summary product (stage C2)
  - Resolution: 280-km equal-area grid, monthly, global
  - Contents: Monthly average of C1 quantities including mean diurnal cycle. Distribution and properties of total cloudiness and cloud types
- Climatological summary product—revised algorithm (stage D2)
  - Resolution: 280-km equal-area grid, monthly, global
  - Contents: Monthly average of D1 quantities including mean diurnal cycle. Distribution and properties of total cloudiness and cloud types

8 bits and the pixels sampled at intervals of about 30 km. Since the ISCCP cloud analysis uses only radiances from the spectral channels common to all radiometers, namely ''visible'' (wavelength approximately 0.6 μm, called VIS) and ''window'' infrared (wavelength approximately 11 μm, called IR), only these radiances have been calibrated and normalized by ISCCP (Brest and Rossow 1992; Rossow et al. 1992; Desormeaux et al. 1993; Rossow et al. 1996a).

Although analyzed by ISCCP to obtain information about clouds, this global radiance dataset also represents a valuable resource for other remote sensing studies (Schiffer and Rossow 1985). Thus, ISCCP has made available the original reduced-resolution radiance dataset (stage B3) and a pixel-level analysis product (stage DX) that also contains the radiances classified as cloudy or clear (see Table 1 for descriptions of all the ISCCP data products). Both of these datasets are multiyear, multisatellite, global products with VIS and IR radiances calibrated to a common documented standard and are archived in common documented formats (Rossow et al. 1996b; Rossow et al. 1996c) with READ programs supplied. For imaging radiometers that obtain radiances at other wavelengths that are not used in the ISCCP cloud analysis, the extra radiances are also retained in both ISCCP pixel-level products (stages B3 and DX). However, they are not calibrated by ISCCP. The calibration coefficients for these extra radiances are those provided by the satellite operators. The VIS and IR calibrations discussed here are applicable to any radiances from these same satellites, not just the ISCCP version, and are useful to any researcher using data obtained from NOAA AVHRR, GOES, GMS, and Meteosat in the period from July 1983 through the present (currently through 1994, calibrations for 1995–1996 available in 1997, eventually through 2000).

To produce a globally uniform radiance dataset, the calibrations of all the imaging radiometers have to be normalized to a common standard (Schiffer and Rossow 1985). Because the NOAA polar-orbiting satellites underfly all the geostationary satellites, the ''afternoon'' polar orbiters are used as the normalization standard. The geostationary-to-polar orbiter normalization (Desormeaux et al. 1993) is performed at the ISCCP Satellite Calibration Center (Centre de Meterologie Spatiale, Lannion, France). Since the NOAA polar orbiters are replaced after 3–4 years and the calibrations of their radiometers (AVHRR) drift with time, the calibration of the AVHRRs must be monitored and succeeding AVHRRs (as well as those on the ''morning'' orbiters) normalized to the reference one. This analysis (Brest and Rossow 1992) is done at the ISCCP Global Processing Center (NASA Goddard Institute for Space Studies, New York, USA). Finally, the absolute calibration of the AVHRRs must be tied to an absolute reference standard.

The original reference AVHRR was on *NOAA-7*; however, the absolute calibration has been best determined for the AVHRR on *NOAA-9* (cf. Whitlock et al. 1990; Rao et al. 1993a; Rao et al. 1993b). Examination of the first 8-yr cloud climatology produced with the first version of the normalization and calibration revealed two artifacts in the global means that coincided with the changes from *NOAA-7* to *NOAA-9* and from *NOAA-9* to *NOAA-11*, as well as some localized anomalies related to occasional errors in the geostationary normalizations. This paper reports the changes to the ISCCP normalization and calibration procedures that have been made to reduce these artifacts and errors and to produce a revised calibration for the whole ISCCP VIS and IR radiance dataset. Section 2 reviews the problems found in the first polar-orbiter calibrations, describes the changes in the methodology, and summarizes the new calibration by showing how the artifacts have been reduced. Section 3 does the same for the geostationary normalization procedure. Section 4 describes the available calibration information and datasets: The calibration coefficients are not presented here but can be obtained from the ISCCP Web site[1] or from a technical document published by the World Meteorological Organization (Rossow et al. 1996a), which can also be downloaded from the ISCCP Web site. Finally, section 5 summarizes the new calibration uncertainties and discusses some implications of these results for research uses of satellite-measured radiances.

2. Polar-orbiter calibration

The NOAA polar-orbiter AVHRR data serve as the radiometric calibration standard for all the satellites. Although a thorough prelaunch calibration of all AVHRR channels is performed (see Kidwell 1995; Rossow et al. 1996c), only the IR channels are monitored after launch using an onboard calibration target. To maintain a constant calibration over the whole radiance dataset requires monitoring of the calibrations of the AVHRR over long periods. Since the polar orbiters are replaced episodically, the calibration standard must also be transferred from one satellite in the series to the next.

Because the procedures used to calibrate and monitor the VIS and IR channels differ significantly, they will be presented separately. After briefly describing the original methodology used to produce the first version of the ISCCP radiance calibration, we assess its accuracy and describe and illustrate the changes made to reduce errors.

a. Visible channel

1) ORIGINAL METHODOLOGY

(i) Relative calibration

The ISCCP calibration procedure differs from most in that instead of using one small selected site (e.g., a desert target), we use a wide variety of targets and the entire globe itself as a target. All of the B3 data are processed, representing approximately 20 million daytime image pixels per month per satellite. Data are corrected for Rayleigh scattering and daily variations of solar irradiance and ozone absorption as a function of illumination and viewing geometry.

Reflectance frequency histograms are collected for nine surface–vegetation classes (grassland, shrubland, tundra, deciduous, evergreen, rain forest, desert, snow/ice, and water), subdivided into 28 geographic ''targets,'' representing distinct regional and hemispheric occurrences of each surface class. Each target consists of the occurrence of the appropriate land cover type within a predefined latitude–longitude window. These targets are well distributed geographically and comprise the bulk of the earth's land areas.

Because clear-sky radiances vary little in time, frequency peaks in the histograms can be used to define clear-sky filters for each surface type and/or vegetation class, and each geographic target or region (see details in and Rossow 1992). The filtered data are sorted into four global maps with a latitude–longitude grid of ½° resolution: monthly mean surface reflectance, two biweekly surface reflectance maps representing the first and second half of the month, and a mean ''total'' (surface and clouds) reflectance map that represents an average of all the data available for the month. The monthly mean surface maps are used in a variety of comparisons to check the consistency of the results.

Because of the global nature of the ISCCP project, we chose global statistics as the best way to monitor calibration. The time series of global monthly means over the lifetime of a given satellite are fit with a straight line to determine the long-term monotonic drift rate of the AVHRR calibration (see discussion in section 5). To normalize calibration to a standard, the global statistics from a particular AVHRR, after removal of any trend, are adjusted to match those of the standard AVHRR. This method was used to monitor the calibration of each polar orbiter and, in a slightly modified form, using data from several weeks of overlapping satellite data collection, to normalize succeeding polar orbiters to the ISCCP relative calibration standard (Brest and Rossow 1992).

(ii) Absolute calibration

At the beginning of the project in July 1983 there was little absolute calibration information available, so a comparison was made between the retrieved surface reflectances from *NOAA-7* and published values of surface VIS reflectances. There was sufficient agreement between the *NOAA-7* and published VIS reflectances to adopt the performance of the AVHRR channel 1 on *NOAA-7* in July 1983 as the absolute calibration standard for VIS radiance measurements in the entire ISCCP dataset (Brest and Rossow 1992).

The results of an intercomparison of several absolute and relative calibration methods for *NOAA-9,* combined with the absolute measurements obtained from simultaneous and coincident aircraft measurements (from the NASA *ER-2* collected in October 1986), provided a much better documented and more accurate absolute calibration for AVHRR channel 1 (Whitlock et al. 1990). The new calibration required correction to the original VIS calibration recorded in the original ISCCP (B3) radiance data by multiplying all VIS radiance values by 1.2. Final results were reported for *NOAA-7, NOAA-8,* and *NOAA-9* in Brest and Rossow (1992), but the first method was also employed to normalize and trend-correct *NOAA-10* and *NOAA-11* data during the first ISCCP data production period (July 1983–June 1991). Com-

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[1] Available on-line at http://isccp.giss.nasa.gov

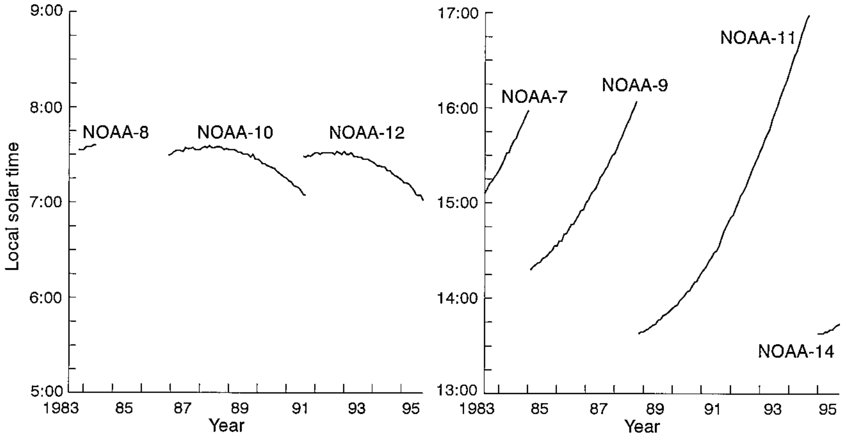


FIG. 1. History of monthly mean polar orbiter daytime equator crossing times for the morning satellites (left) showing little orbital drift, and the afternoon satellites (right) showing significant drift over the lifetime of each satellite.

parisons with other available results were excellent (Brest and Rossow 1992; Che and Price 1992; Rao et al. 1993b; Rao and Chen 1995).

2) ASSESSMENT

Examination of the complete 8-yr record of cloud and surface properties obtained with the first calibration reveals some problems. Most notable is a systematic ‘‘step-down’’ in monthly global mean VIS reflectances at each transition of polar orbiters, from *NOAA-7* to *NOAA-9* between January and February 1985, and from *NOAA-9* to *NOAA-11* between October and November 1988 (Klein and Hartmann 1993; Rossow and Cairns 1995). This effect was noticed at the time, but it was impossible to determine if this resulted from problems with the method, the inherent variability in the datasets, or the result of angular reflectance effects due to the differences in the solar geometry at the time of the satellite transitions (Brest and Rossow 1992).

The AVHRR polar orbiters are not sun synchronous and undergo significant orbital drift, particularly the afternoon satellites. Daytime equator crossing times for all of the NOAA polar orbiters are shown in Fig. 1. Note the difference in behavior between the morning and afternoon satellites. The effect of the change in orbit on solar geometry is shown in Fig. 2, which displays the time history of monthly modal values of μ_0 (cosine of solar zenith angle) for all of the orbiters.

Using the *NOAA-9* to *NOAA-7* normalization as an example, we see that the difference in equator crossing time is significant: the 1 h 40-min difference in equatorial crossing times created a significant difference in solar geometry ($\Delta\mu_0 = 0.34$, equivalent to a difference of almost 30° in solar zenith angle) between the two satellites during the 3-week overlap period in January–February 1985.

To mitigate the effects of such differences in μ_0 in the retrieved surface reflectance, we developed empirical corrections for varying solar zenith angles from one year of *NOAA-7* data (July 1983–84) for eight targets representing the major vegetation and surface types (Brest and Rossow 1992). This relatively crude approach probably accounted for some but not all of the bidirectional effects. However, because this was an experimental technique, we only used it to normalize one AVHRR to the next but did not apply it to the data to determine long-term calibration trends. Therefore, one would expect to see some difference in surface reflectance values obtained from the two satellites, one at the end of its life and the other at the beginning. We had no way to determine how much of this difference was real (due to differing solar geometry) and how much was due to limitations in our normalization.

At the time that the ISCCP procedures were completed, there was only one available case that provided validation of our normalization results. These results, shown as the last aircraft point in the *NOAA-9* plot and the first aircraft point in the *NOAA-11* plot in Fig. 3, confirmed our result for these two AVHRRs to within a few percent (Brest and Rossow 1992). However, now that we can examine the whole *NOAA-9* and *NOAA-11* calibration record in Fig. 3, together with many other results, we see that both the last aircraft calibration point for *NOAA-9* and the first aircraft point for *NOAA-11* are not on the linear trends defined by a fit of all the aircraft data and by several trend estimates (some not shown in the figure), including ours. However, the separations of these two aircraft points from these linear trend lines are consistent with the estimated uncertainty of the individual aircraft results: ±9%. Thus, we conclude post facto that the noticeable step-down in the 8-yr ISCCP record is due to residual errors in normalizations of the *NOAA-9* and *NOAA-11* VIS radiance calibrations to *NOAA-7*.

The other notable problems with the original calibration, namely, residual spurious trends in the calibra-

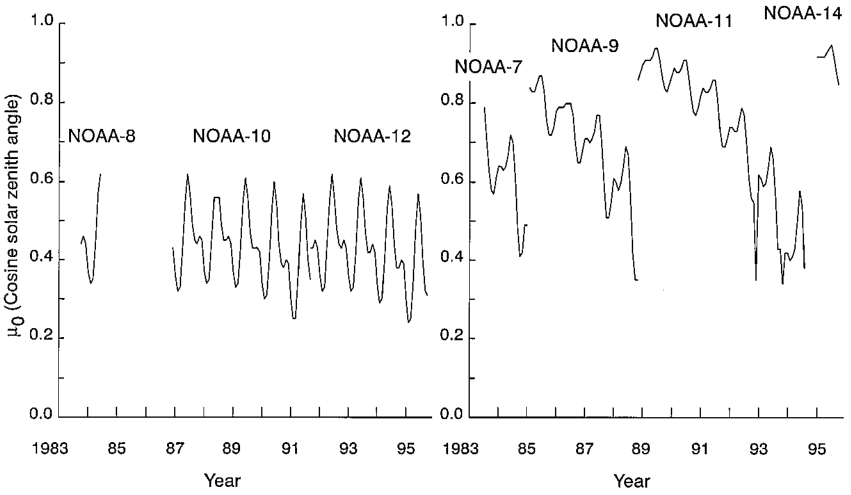


FIG. 2. History of monthly modal μ_0 (cosine of solar zenith angle) values for daytime orbits from the polar orbiters for the morning satellites (left) and the afternoon satellites (right).

tions of *NOAA-7* and *NOAA-11,* only became noticeable when the *NOAA-7* data record was lengthened from 19 months (available at the beginning of ISCCP) to 40 months, and the *NOAA-11* data record was lengthened from 32 months to 68 months. There are enough aircraft calibrations (processed by a single procedure) available to determine a calibration trend only for *NOAA-9* and *NOAA-11.* In addition, a number of authors have employed other vicarious methods to monitor trends for these two AVHRRs, most of which were compared as part of the NASA–NOAA Pathfinder project: Staylor (1990), Che and Price (1992), Teillet et al. (1990), Kaufman and Holben (1993), Rao and Chen (1995), and Frouin and Simpson (1995). Figure 3 compares a collection of these results published by Whitlock et al. (1990): the calibration drift rates obtained from these different analyses differ from the first ISCCP estimates by as much as 30%, relative. The linear trends determined by Staylor (1990) and Brest and Rossow (1992) for *NOAA-9* are nearly the same as given by a least squares linear fit to the aircraft data. These results suggest, on the one hand, that the accuracy of a trend determination depends on the length of the data record and, on the other hand, raise a question as to whether there are shorter-term deviations of the AVHRR calibration from a linear trend.

3) REVISED METHODOLOGY AND NEW RESULTS

The removal of the discontinuity between satellite calibrations was the prime motivation for revising the calibration procedure. A second, but also important motivation, was to detect instrument drift more quickly. Given the old method's reliance on monthly mean surface reflectances with their annual cycle, it was necessary to wait as long as two full annual cycles before the drift in the calibration could be determined with some degree of confidence. The revisions to the calibration procedure include switching from *NOAA-7* to *NOAA-9* as the absolute calibration standard, and revising the normalization and monitoring procedures to use monthly mean deviations of surface reflectance from a *NOAA-9* climatology.

The switch from *NOAA-7* to *NOAA-9* as the standard was motivated by two factors—our improved knowledge of our calibration procedure and the extensive effort that went into deriving the calibration of *NOAA-9* by several groups of researchers (cf. Fig. 3 and Whitlock et al. 1990).

The studies of AVHRR calibration conducted by ISCCP (Brest and Rossow 1992; Desormeaux et al. 1993), by the Surface Radiation Budget project of the World Climate Research Program (Whitlock et al. 1990), and by the NASA–NOAA Pathfinder program (Rao et al. 1993b; Rao and Chen 1995) provide the most detailed and best documented information for the *NOAA-9* and *NOAA-11* AVHRRs. Because a number of aircraft campaigns were conducted during the lifetime of *NOAA-9* (February 1985 to October 1988 for our purpose), and because of the significant effort spent in understanding and correcting the sensor degradation of *NOAA-9,* we feel that it is probably the best-calibrated instrument of the AVHRRs used in ISCCP. Since there are still some small discrepancies in the results of these studies, in the aircraft calibrations and in other information concerning the *NOAA-11* instrument, the *NOAA-9* instrument was chosen to be the calibration reference standard for the AVHRR Pathfinder program and for the new version of the ISCCP radiance calibration: *NOAA-7, NOAA-8, NOAA-10, NOAA-11, NOAA-12,* and soon, *NOAA-14,* are all normalized to the *NOAA-9* standard. Note that this calibration standard is now an absolute standard because it includes the calibration derived from the aircraft measurements. The previous standard was a relative one, which was tied to an absolute standard post facto.

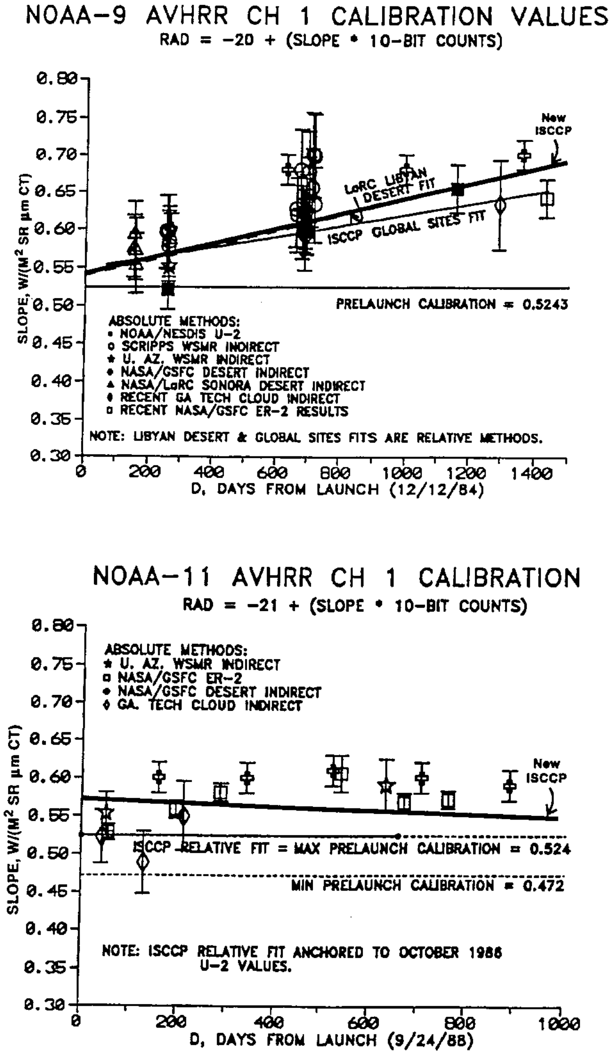


FIG. 3. Various calibration results for AVHRR channel 1 on *NOAA-9* (top) and *NOAA-11* (bottom) (after Whitlock et al. 1990). The thin solid line shows the first ISCCP calibration, and the thick solid line shows the new calibration.

The new trend-correction and normalization procedures use a climatology of monthly mean surface VIS reflectance derived from 45 months of *NOAA-9* data. Instead of normalizing each new satellite to the prior one by using 3–4 weeks of overlapping observations, we now normalize the global distribution of surface VIS reflectances observed by each AVHRR each month to the monthly climatology derived from *NOAA-9.* The *NOAA-9* climatology is created by calculating the monthly mean surface reflectances from the ½° maps and then averaging these into a mean monthly reflectance for each of the 12 months. The original *NOAA-9* dataset was compared to its own climatology to detect any residual trends not corrected by the original analysis. A slight darkening still present in the data was corrected, and then the climatology was recalculated using the slightly revised monthly values. The change in mean monthly reflectance was slight, less than 0.1% (absolute), but the new trend is in even closer agreement to that derived by Staylor (1990) (and Rao et al. 1996) and by a linear least squares fit to the aircraft data. This 12-month climatology serves as the ISCCP calibration standard.

In the revised method, the same analysis as before is used to produce global maps for each month. Each monthly mean map point is differenced with the *NOAA-9* climatology for the corresponding month. The mean global differences are plotted as a time series for each satellite. This procedure has a significant advantage over working with the monthly means themselves (as was originally done) in that the removal of the annual cycle allows us to use any length time record to determine calibration trend. Each satellite is corrected for instrument drift until a least squares linear regression fit to its whole time series of monthly differences has a slope as close as practical to zero given the precision of the radiances. The trend correction factor is determined by an iterative procedure by applying a monthly correction factor to the data and recomputing the regression fit until the slope is as close as practical to zero.

By using this approach we are explicitly assuming that the only change in AVHRR calibration after launch appears as a *linear* trend. Although we use the *NOAA-9* climatology to remove seasonal variations, this approach avoids imposing the *NOAA-9* seasonal cycle on the observations by other AVHRRs in other years because we only use the systematic (i.e., mean) long-term variations of the deviations from this climatology, not the values for individual months, to correct the calibration. If we made corrections using individual monthly means (or infrequent determinations, as have other authors), we might confuse real interannual variations of the surface for calibration changes. In other words, based on the behavior of the *NOAA-7, NOAA-9,* and *NOAA-10* AVHRRs, we interpret all the small variations on timescales less than about 4 yr to be real variations of the earth, not changes of the AVHRR calibration. As we will see, the *NOAA-11* AVHRR may have exhibited more complicated changes, but the available independent information, particularly as it is confused by Pinatubo volcanic aerosol effects, is not sufficient to resolve this ambiguity.

Once each satellite is individually detrended, its calibration is then normalized to the *NOAA-9* standard by requiring that a linear regression fit to a time series of that satellite and the *NOAA-9* time series show no trend. Again, an iterative procedure is used to derive the correction factors. Finally, the fit of the entire time series (e.g., *NOAA-7, NOAA-9,* and *NOAA-11* from 1981 to 1994) is examined for any residual trend. The selected coefficients give the best overall fit for the whole time record composited of *NOAA-7, NOAA-9,* and *NOAA-11.* Note that this last small revision would not have been possible earlier in the data collection period.

The coefficients obtained from this procedure are then applied to the actual radiance data, and the full retrieval

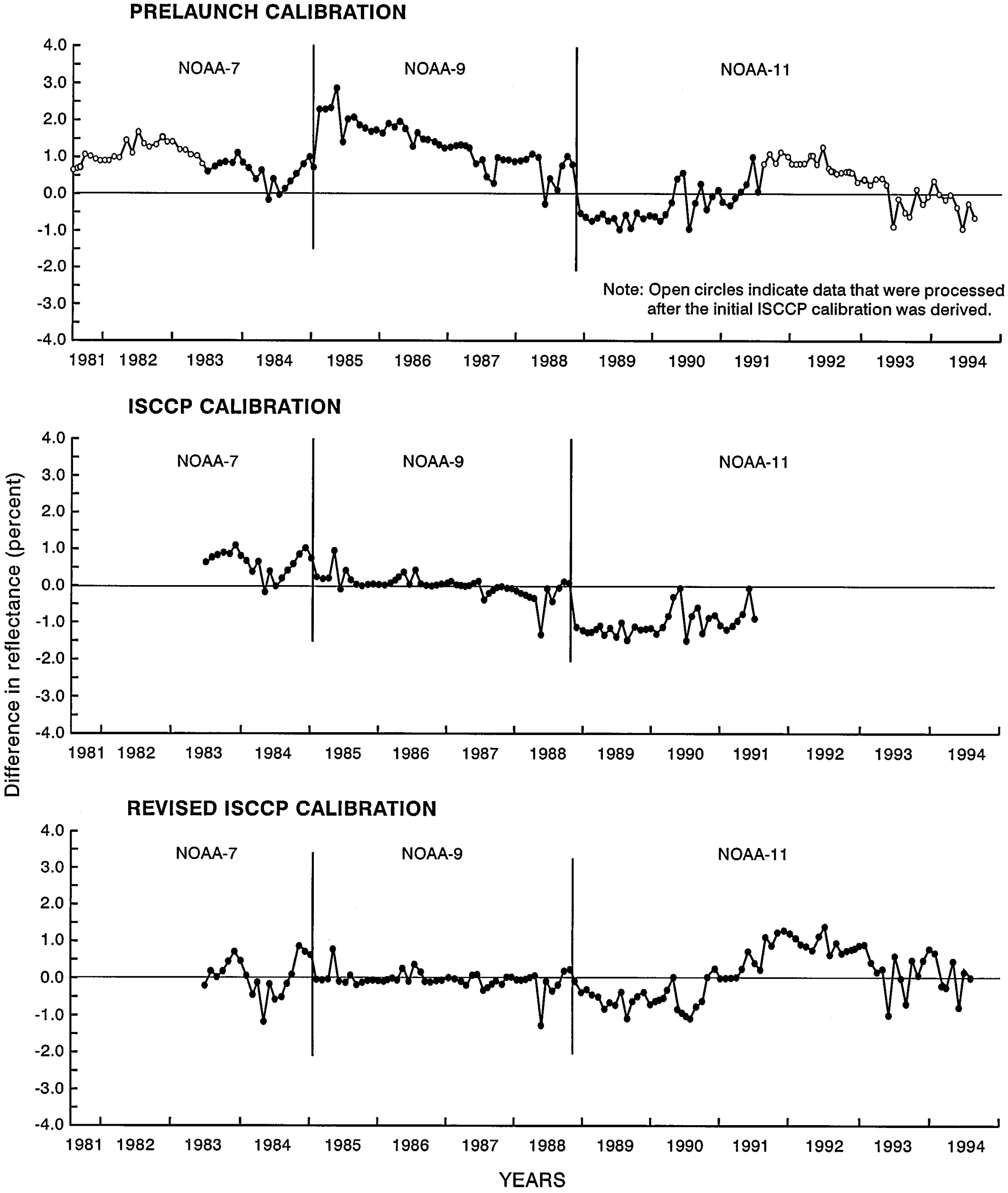


FIG. 4. Global monthly mean anomalies of surface visible reflectance obtained from AVHRR on the indicated polar orbiters with respect to a monthly climatology based on the *NOAA-9* results with the first ISCCP calibration. The upper panel shows results using the original (prelaunch) calibration, the middle panel shows the old (first) ISCCP calibration, and the lower panel shows the new (revised) ISCCP calibration.

and trend analysis are repeated. The entire data record from July 1983 through September 1994 (end of *NOAA-11*) was reprocessed and the results were analyzed. A final adjustment to the normalization coefficients is then made to minimize any residual trend. The result is as close as possible to achieving ''no trend'' given the precision of the radiance data and the calculations. The significant improvement in the calibration is evident in Fig. 4.

The new method was also used to revise the normalizations of the morning satellites, *NOAA-8, NOAA-10,* and *NOAA-12,* and will shortly be employed to normalize and detrend *NOAA-14.* The coefficients used to correct the data to the ISCCP standard are given in Table 2. These coefficients are presented here only to show the relative magnitude of the calibration corrections applied to the various satellites. The actual procedure to apply the ISCCP calibration is explained in section 4.

The revised procedure analyzing the difference between each satellite month of data and the corresponding

TABLE 2. ISCCP normalization and absolute (trend correction) coefficients for AVHRR channel 1 data. In the column of absolute coefficients the value listed for multiplicative coefficient is applied to each month of data consecutively, starting with the second month of data (no trend correction is needed for the first month). The value of m ranges from 1 to the number of months minus 1 in the lifetime of a particular satellite.

	Normalization coefficients		Absolute coefficients	
Satellite	Multiplicative	Additive	Multiplicative	Additive
NOAA-7	0.920	−0.001	$(1.00105)^m$	0.0
NOAA-8	0.996	0.0	$(1.00141)^m$	0.0
NOAA-9	—	—	$(1.00125)^m$	−0.0029
NOAA-10	1.0665	0.0	$(1.00126)^m$	0.0
NOAA-11	1.094	0.0	$(0.99860)^m$	0.0
NOAA-12	0.908	0.0	$(1.00453)^m$	0.0

value from the *NOAA-9* climatology eliminates difficulties caused by the annual cycles of surface reflectances. The first procedure used a linear regression fit to the time series of monthly global mean surface reflectances. Consequently, the results were dependent on the length of the record and where the starting and ending points fell in the annual cycle. Thus, reliable results were obtained only when several full cycles were used. The new approach allows for a quicker detection of instrument drift because fewer data points are needed. Another significant benefit from this procedure is that we no longer need to have several weeks of overlapping data to normalize succeeding polar orbiters. For instance, we would not have been able to normalize *NOAA-14* to *NOAA-11* because of the 5-month gap in coverage produced by the unexpected failure of *NOAA-11.* Normalizing *NOAA-14* to the *NOAA-9* climatology avoids this problem.

The new method also allows us to deal with the difficulties in the original method that are produced by global anomalies of stratospheric aerosols produced by large volcanoes, specifically El Chicon in 1982 and Pinatubo in 1991. The effects of these two volcanoes in the record of global mean reflectance are hard to assess quantitatively (cf. Sato et al. 1993). However, the increased reflectance caused by the volcanoes is easy to detect in the difference plots.

To avoid spurious effects on the determination of calibration drift, we eliminate the months affected by the volcanic aerosols. Figure 5 shows the low-latitude anomalies in the monthly mean surface reflectances for the Pinatubo eruption. We discard 10 months (June 1982–March 1983) of data following El Chicon and 18 months (July 1991–December 1992) during the post-Pinatubo period from the statistical fits to the time series. Note that the effects of volcanic aerosols remain in the data shown in Fig. 4; but we did not use that data to determine the calibration trends.

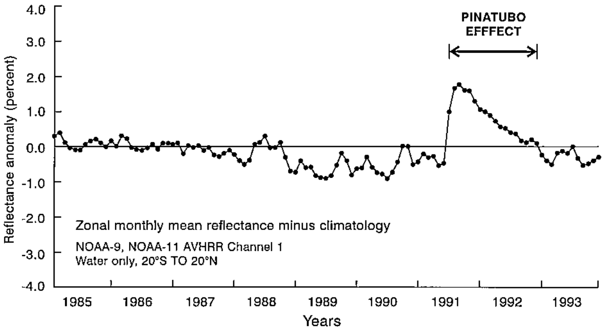


FIG. 5. Anomaly record for the Tropics showing the Pinatubo effect. These results use the old ISCCP calibration. The climatology is derived from *NOAA-9* data.

Results are shown for the 11-yr period July 1983 through June 1994 for the afternoon polar orbiters used in ISCCP (thus far). Figure 4 shows global monthly mean VIS reflectance (as deviations from the *NOAA-9* climatology) from ISCCP data processed using three calibrations. The first is the original nominal calibration (i.e., the prelaunch calibrations obtained from NOAA); the second is the calibration used in the first processing of ISCCP; and finally, the third panel shows results of the revised calibration procedure described here. The significant improvement in each case is evident. Note that we fit a single line to the reflectance from each satellite over its lifetime rather than adjusting each individual monthly data point. This retains the month-to-month and interannual variations within the satellite dataset. Figure 6 shows similar results from all satellites for the Sahara.

b. IR channel

1) ORIGINAL METHODOLOGY

Calibration of the IR channels is done actively on the spacecraft, once per scan, by having the radiometer view space and a standard blackbody with a known temperature (Kidwell 1995; Rossow et al. 1996c; Rao et al. 1993a). Prelaunch measurements of a precision calibration blackbody with the radiometer are used to relate the output counts from four thermistors to the temperature of the reference blackbody with a fourth-order polynomial. This temperature is converted to a radiance by integrating the product of the Planck function and the spectral response functions. None of the calibration standards is more accurate than 1–2 K (e.g., Njoku 1985). But we initially assumed that the IR radiances were already well calibrated.

2) ASSESSMENT

Figure 7 shows the history of IR calibration (channel 4 on AVHRR) for *NOAA-7* and *NOAA-9* as the global and monthly mean value of counts and the AVHRR brightness temperatures inferred from the onboard calibration. Each point represents an average of all the data collected by ISCCP for that month. We assume that the global, annual mean temperature of the earth is also

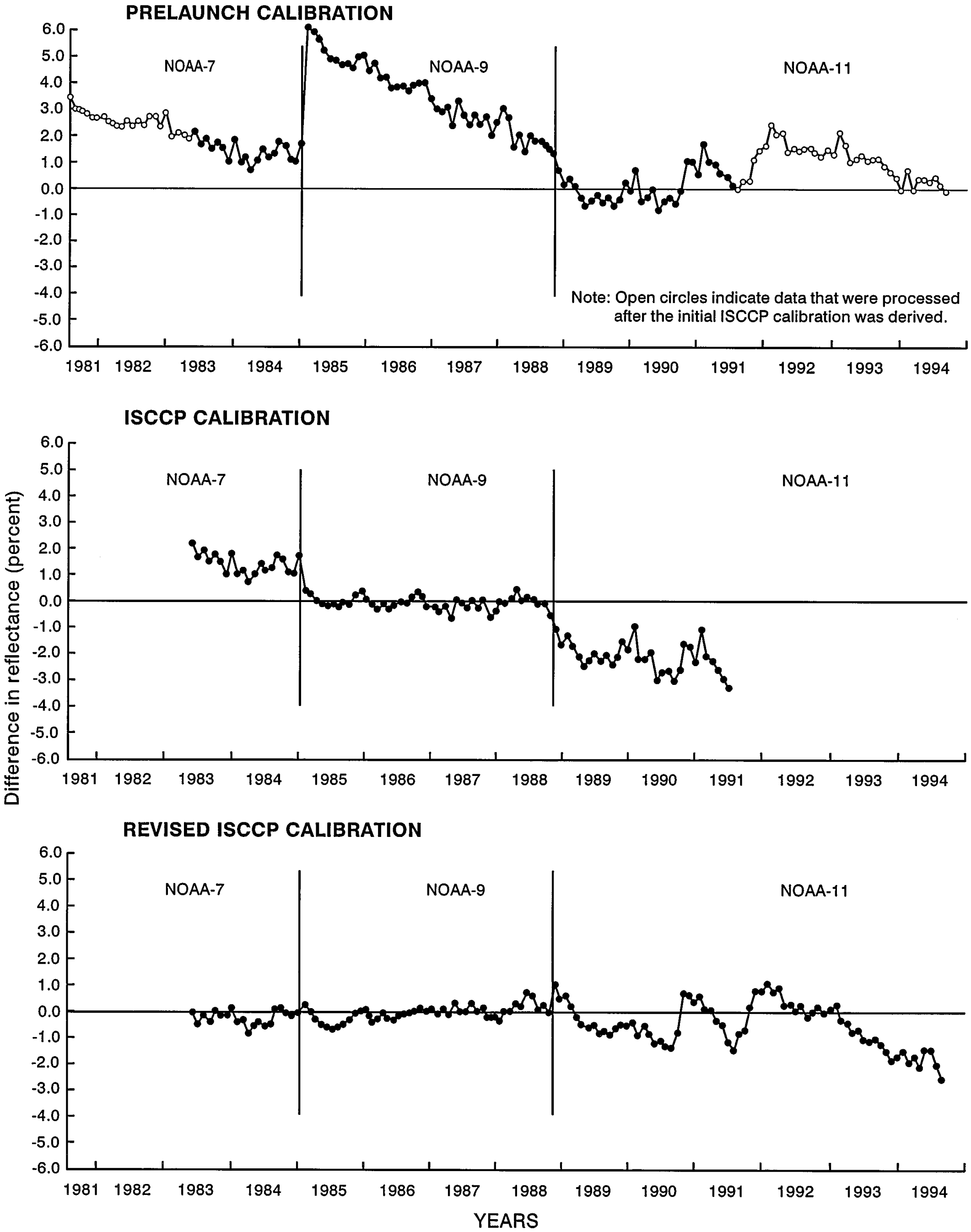


Fig. 6. Time records of reflectances for Sahara. See Fig. 4 for detailed explanation.

constant over time periods of 5–10 years. The evolution of global monthly mean temperatures shown in Fig. 7 exhibits a seasonal variation but no trend over 4.5 years. The average count values suggest that the *NOAA-9* channel sensitivity changed slowly with time and differed significantly from that of the *NOAA-7* channel; however, the operational calibration procedure eliminated these variations. The initial difference in calibration between *NOAA-7* and *NOAA-9* (Fig. 7) is similar in magnitude to differences between coincident observations by *NOAA-7* and *NOAA-8*. We conclude that the calibrations of the IR (channel 4) measurements are generally stable to within about 1 K.

3) Revised methodology and new results

The response of the AVHRR IR channels is slightly nonlinear, but the onboard calibration measurements

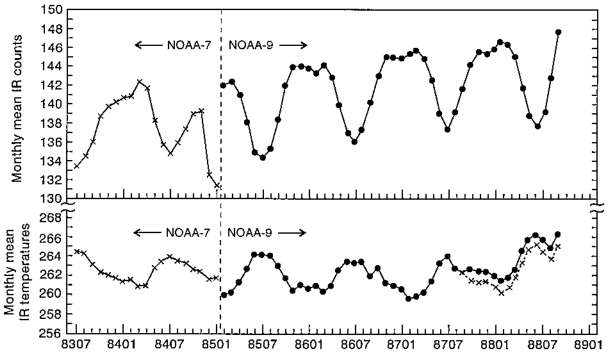


FIG. 7. Time history of AVHRR channel 4 calibration for *NOAA-7* and *NOAA-9*, shown as monthly global mean counts and temperature values. The differences between the two radiometers and the drift of the *NOAA-9* radiometer, as shown by the mean count values, are eliminated in the operational calibration procedure that uses an onboard standard source. The dashed line with ''×'' represents ISCCP's adjustment of calibration when NOAA changed their procedure. See discussion in text.

only monitor instrument response at two temperatures—cold space and a ''hot'' reference target. Hence, the operational calibration procedure effectively assumes a linear response. During the first 4 years of ISCCP, the small nonlinearity was partially accounted for in the NOAA operational calibration procedure by allowing the radiance associated with cold space to be negative, thereby providing a better linear fit to the nonlinear response function. However, beginning in October 1987, this procedure was discontinued in favor of a different approach. To maintain the subsequent consistency of the ISCCP radiance dataset, IR brightness temperatures after this date were normalized to values before this date. Later Pathfinder studies (Rao et al. 1993a) have developed a more accurate procedure to correct for the nonlinear response; however, its application requires use of the time history of the onboard calibration target temperature for best results. Without this detailed history, the correction procedure can be employed using an estimate of the target temperature, but this produces results similar to the original operational method with negative space counts. Moreover, comparisons of retrieved values of sea surface temperatures (Rossow and Garder 1993) and total IR fluxes at the top of the atmosphere calculated from the retrieved cloud-top temperatures (Rossow and Zhang 1995) during the *NOAA-9* period (February 1985–October 1988) suggest that the absolute IR calibration is accurate to better than ±1.5 K. Hence, we have not applied the new Pathfinder correction procedure (because we lack the detailed history information). Instead we normalize all other AVHRR IR radiances to the *NOAA-9* values calibrated by the old NOAA procedure as the reference standard.

Examination of the global monthly distributions of IR radiances over oceans shows some systematic differences among the NOAA satellites, despite the onboard calibration sources. The larger differences are at the cold end of the temperature scale. Biweekly averages of the 10th and 90th percentile IR radiances over global oceans have been observed to be extremely stable, showing little annual variation and no sign of long-term trends. However, small offsets are observed among the satellites, so these statistics are used to normalize the various AVHRRs to *NOAA-9.* Correction factors were derived to adjust the cold end while having minimal impact at the warm end, where there was generally good agreement between satellites (because of the onboard calibration). The normalization coefficients selected and the nominal (before) and normalization (after) mean temperatures for the 10th and 90th percentiles are shown in Table 3. These coefficients are presented here solely to indicate the relative magnitude of the adjustments for each satellite; the actual application of ISCCP calibrations is discussed in section 4. The magnitude of the corrections at various temperatures is shown in Table 4 and illustrated in Fig. 8.

TABLE 3. ISCCP normalization coefficients and percentile means for clear-sky temperatures (K) of water pixels derived from nominal and normalized calibrated channel 4 data.

	Normalization coefficients		10th percentile water pixels mean temperatures		90th percentile water pixels mean temperatures	
	Multiplicative	Additive	Nominal	Normalized	Nominal	Normalized
NOAA-7	1.03	−8.6	287.66	287.69	243.34	242.04
NOAA-8	1.03	−9.0	287.93	287.57	243.81	242.13
NOAA-9	—	—	287.64	—	242.05	—
NOAA-10	1.00	0.0	287.78	—	242.12	—
NOAA-11	1.00	−0.5	288.14	287.64	242.39	241.89
NOAA-12	1.038	−11.0	287.21	287.12	244.48	242.77

3. Geostationary satellite calibration

A similar procedure is used to normalize both VIS and IR radiances from the geostationary satellites to the polar orbiter, so they will be presented together.

TABLE 4. Effect of ISCCP IR normalization on temperatures (K) derived from AVHRR channel 4. Table shows temperature changes (K) at selected temperature levels resulting from normalization of calibration for each polar orbiter.

Temperature (K)	*NOAA-7*	*NOAA-8*	*NOAA-11*	*NOAA-12*
300	0.4	0.0	−0.5	0.4
290	0.1	−0.3	−0.5	0.0
280	−0.2	−0.6	−0.5	−0.4
270	−0.5	−0.9	−0.5	−0.7
260	−0.8	−1.2	−0.5	−1.1
250	−1.1	−1.5	−0.5	−1.5
240	−1.4	−1.8	−0.5	−1.9
230	−1.7	−2.1	−0.5	−2.3

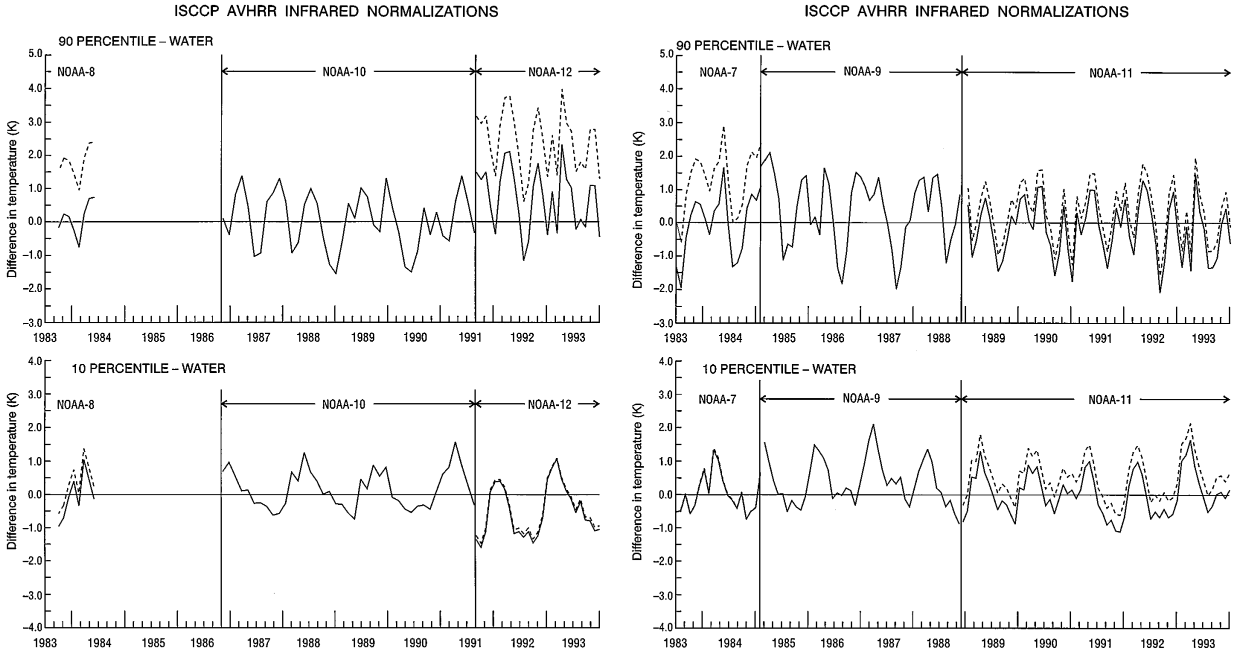


FIG. 8. Monthly anomalies of the 90th (cold) and 10th (warm) percentile brightness temperatures obtained from global ocean distributions of individual measurements from AVHRR on the indicated polar orbiters (a) morning series and (b) afternoon series. The anomalies are calculated relative to a monthly climatology based on *NOAA-9.* The dashed lines indicate the original calibration, and the solid lines indicate the new ISCCP calibration. No corrections were applied to *NOAA-10.* The change in *NOAA-9* calibration in October 1987 has already been removed.

a. Original method

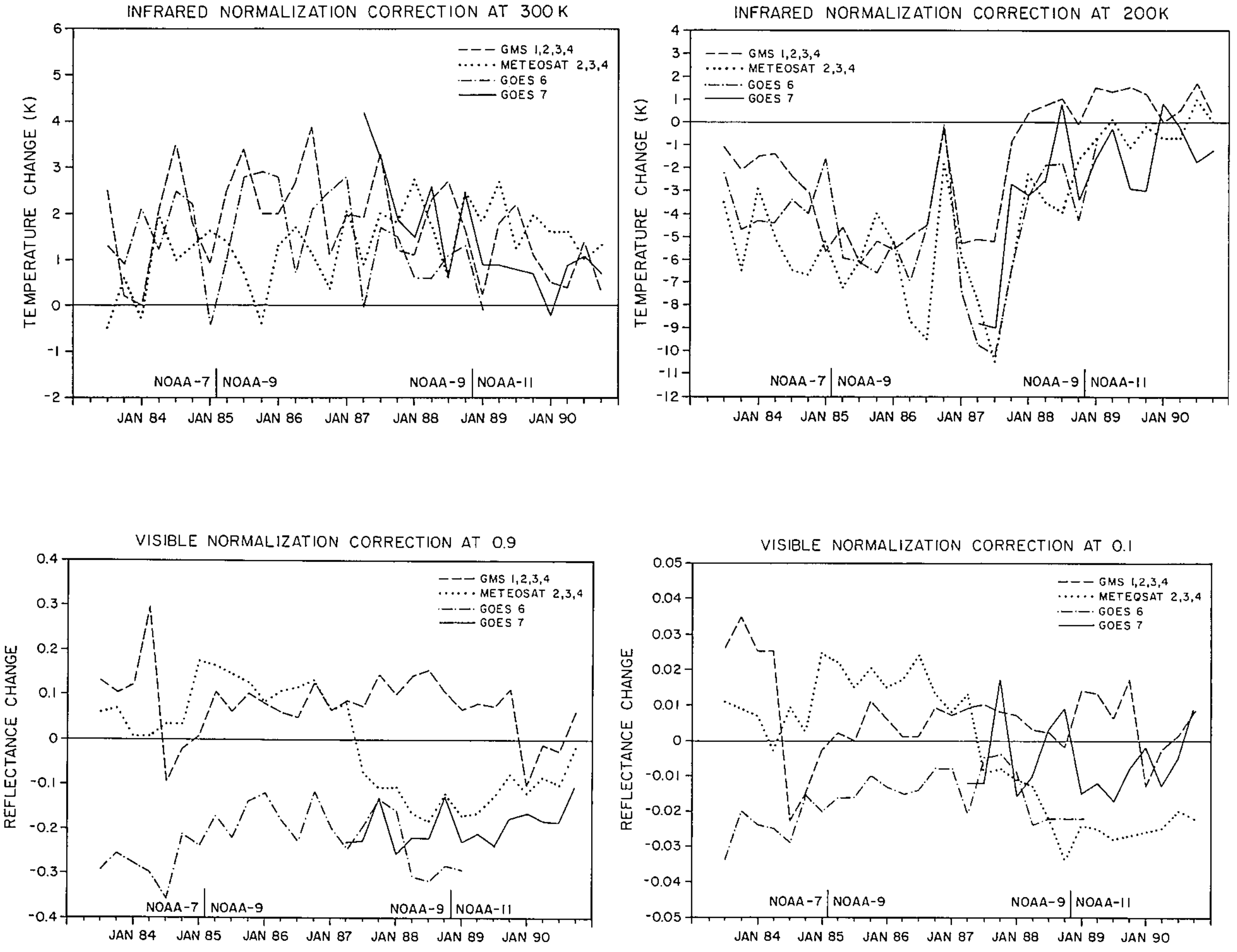
The geostationary to polar-orbiter calibration normalization is a two-part procedure. The first part is accomplished by comparing radiances measured at the same time and location with the same viewing geometry (Desormeaux et al. 1993). Obtaining accurate normalization from this comparison requires careful selection of coincident images and detailed analysis to identify common targets. The second part examines the time record of the radiance distribution for each image for short-term changes in calibration. The most common problem for the geostationary satellites is spurious diurnal variations in IR calibration caused by the diurnal (i.e., orbital) cycle of spacecraft heating and cooling (Desormeaux et al. 1993).

The first part of the procedure is usually performed every third month, although it is occasionally performed monthly when there are indications of calibration changes in the intervening months (Desormeaux et al. 1993). Three to five coincident pairs of full-resolution images are collected from each geostationary and the afternoon polar orbiter, checked for quality, and remapped to a common grid with 3-km resolution. Then 50–150 small targets are selected from areas where the two satellites have the same viewing geometry. Because the spectral responses of the different radiometers vary somewhat, only clear ocean and clouds over the ocean are used as targets to minimize spectral effects. Mode radiances from each satellite–target pair are plotted as 2D scatterplots, and a linear least squares fit is determined. The slope and intercept for the best-fit line are used to normalize the geostationary calibration to that of the reference AVHRR. The magnitude of the corrections for various satellites is illustrated in Fig. 9 for both VIS and IR.

Spurious calibration variations on timescales less than 1 month are identified in time records of the distribution of radiances over the whole image, particularly over oceans (Desormeaux et al. 1993). Three kinds of problems have been identified: individual images with very different radiance distributions, discontinuous changes in the time record, and spurious diurnal variations. These problems are corrected by adjusting the calibration of individual images.

b. Assessment

To monitor the whole normalization and calibration procedure, a number of statistics are collected describing the distributions of cloud and surface properties retrieved in the ISCCP analysis. In particular, as the results from all the satellites are merged into a single product, the results from overlapping satellite observations are compared every 3 h. Frequency histograms of the differences of surface VIS reflectance, surface temperature, cloud VIS reflectance (obtained from the optical thickness), and cloud-top temperature are collected for each month. Mode values of these differences, if significantly


INFRARED NORMALIZATION CORRECTION AT 300 K

INFRARED NORMALIZATION CORRECTION AT 200K

VISIBLE NORMALIZATION CORRECTION AT 0.9

VISIBLE NORMALIZATION CORRECTION AT 0.1

FIG. 9. History of calibration changes for visible and infrared channels on geostationary satellites calculated using results for individual targets from coincident image pairs. Magnitudes are shown for changes at brightness temperatures of 300 and 200 K (top) and for visible reflectance values of 0.9 and 0.1 (bottom).

different from zero, are used to adjust the monthly mean data product (stage C2). Figure 10 shows the 8-yr history of the modal differences between quantities determined from geostationary radiances and those from the afternoon polar orbiter. The rms differences of the temperatures are approximately 1.8 K and of the VIS reflectances approximately 0.03. There are also a number of months with differences that are larger than these rms deviations.

The larger differences in Fig. 10 actually represent systematic normalization errors, as is illustrated in Fig. 11 by one example of an artifact in the geographic distributions of the physical quantities at the boundaries between geostationary satellites. Figure 11 (upper panel) shows a conspicuous boundary in the sea surface temperatures, the north–south discontinuity in the mid–Pacific Ocean, corresponding to the unusually large modal difference in temperatures highlighted in Fig. 10. In Fig. 10 this is evident as a large spike (rising above 2.0 K) in the surface temperature plot for GOW (GOES-West satellite) in September 1987. Direct sensitivity tests were performed, where the calibration was artificially changed by a known amount and the data processed as before, to show that the procedure is very sensitive to calibration differences between satellites. Since most of the larger differences shown in Fig. 10 are for months not directly normalized by the SCC in the original processing, this problem arises because the geostationary satellite radiometers occasionally change calibration more rapidly than on a 3-month timescale, and the routine procedures did not detect all of these changes.

c. *Revised methodology and new results*

The first two steps of the geostationary normalization have not been changed. However, in a new step, the offset corrections determined after the cloud analysis are used to determine additive offsets. If the offsets exceed a threshold, they are applied directly to the stage B3 radiances and the whole cloud analysis is repeated. In the case of old data (before July 1991), the offsets

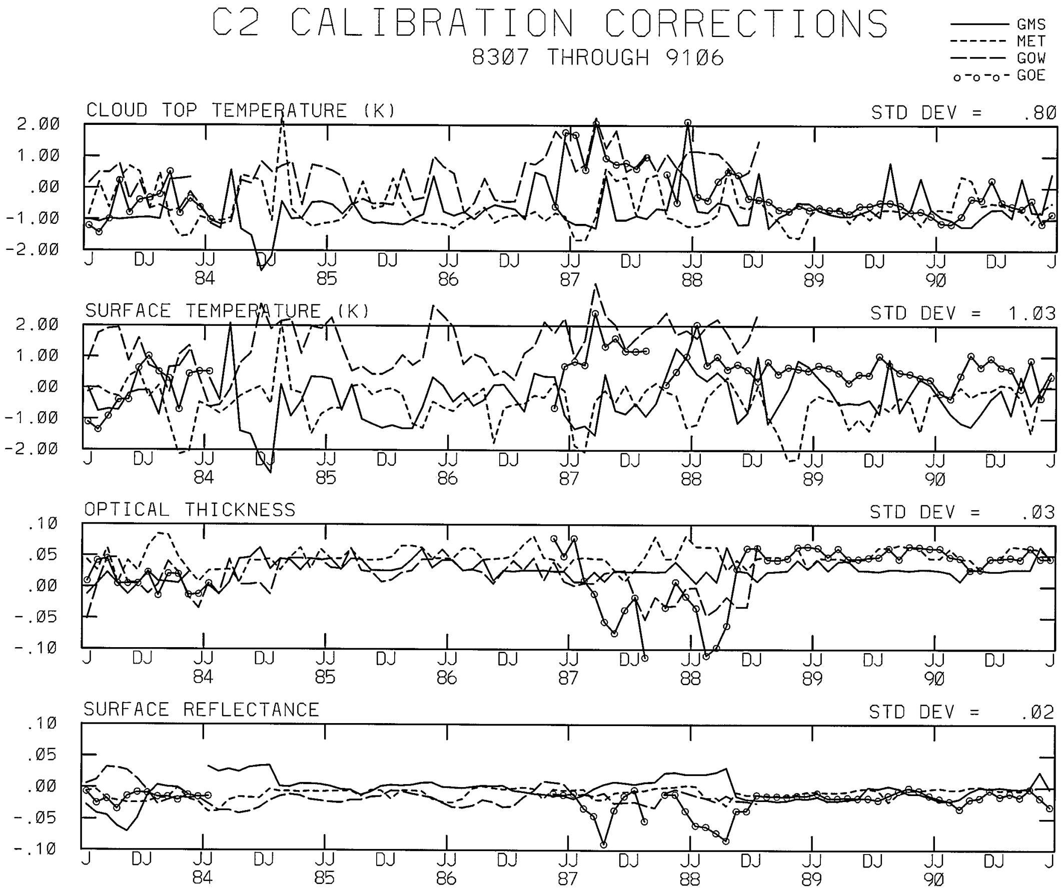


FIG. 10. History (July 1983–June 1991) of modal differences between retrieved cloud-top temperature, surface temperature, cloud optical thickness (in reflectance units), and surface visible reflectances from overlapping geostationary and polar-orbiting satellite observations. Distributions for each month are differences of individual observations at 3 h and 280-km resolution. The polar orbiter is the afternoon NOAA satellite. The geostationary satellites are the Meteosat series (short-dashed line), the GMS series (solid line), and the GOES-East series (long-dashed line), and the GOES-West series (line with circles).

have already been determined, so they are being incorporated into the revised calibration before reprocessing. In the case of new data that have not been previously analyzed (after June 1991), the statistics shown in Fig. 10 are monitored during the first processing: if any case exceeds the offset thresholds, then radiance calibration adjustments are calculated, as described below, and the whole dataset is reprocessed. Thus, the major difference in the new procedure is that the calibration offsets determined *after* cloud analysis are used to modify the B3 radiance calibrations directly, rather than correcting only the monthly mean cloud product (stage C2) as was done previously.

The VIS channel correction is determined by averaging the mode differences for the surface reflectance and cloud optical thickness (expressed as a reflectance). If the absolute value of the average is greater than 0.02 (these quantities are expressed as a fraction of the instrument's response when viewing a surface that reflects all the radiation from an overhead sun at the mean sun–earth distance) and the surface reflectance is greater than 0.02, then an adjustment is determined as the smallest number of 0.01 increments that must be added or subtracted to reduce the difference below the threshold without making the surface reflectance less than 0.0. The IR channel correction is determined by averaging the mode differences for the surface temperature and cloud-top temperature. If the absolute value of the average is greater than 1.0 K, then the adjustment is determined as the smallest number of 0.5-K increments that can be added or subtracted to reduce the difference below the threshold. Experiments were conducted using a variety of combinations of threshold values and adjustment increments; the above values were found to produce the best results as judged by avoiding a high frequency of essentially insignificant corrections and avoiding overcorrection of the difference in mode values.

This procedure was checked in a set of experiments using selected months of data from several satellites where 1) known changes in the radiance calibrations were artificially introduced, 2) the whole month of data

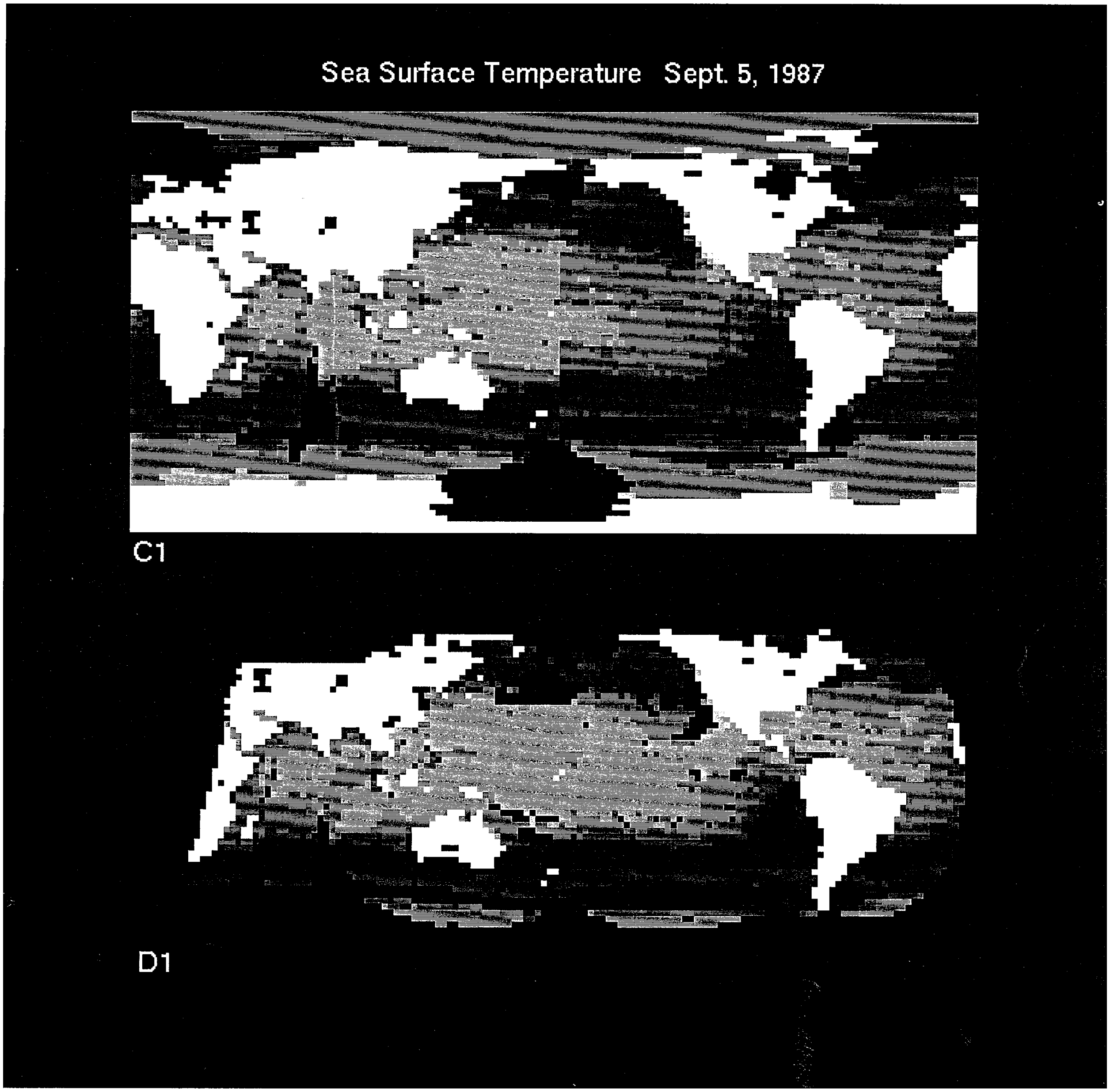


FIG. 11. Global map of retrieved surface temperatures for 5 September 1987 showing in the upper panel a large difference between the domain covered by GMS and GOES-West in the first ISCCP datasets, and in the lower panel the same data after correcting the infrared calibration of both GOES-West and GOES-East based on the monthly modal differences. The data are sea surface temperatures where darker grays represents colder temperatures, and lighter grays represent warmer temperatures. Land areas (white) are shown for orientation.

was processed through the entire ISCCP analysis, 3) calibration offsets were determined as described, 4) the adjustments were applied to the radiances, and 5) the dataset was reprocessed to check the magnitude of the remaining offsets. Figure 12 repeats a part of Fig. 10 to show the effect of the correction procedure by comparing stage C2 (left panel) and stage D2 (right panel). The lower panel in Fig. 11 also shows that the artificial boundary between the two adjacent geostationary fields of surface temperature is much reduced in the corrected version of the data. The procedure is conservative in that we do not eliminate the offsets entirely; rather, we correct the calibration only enough to reduce the magnitude of the offset to below the threshold amounts. Thus, offsets up to 0.02 in VIS and up to 1.0 K in IR can remain. Any remaining offsets are still corrected in producing the monthly mean product (stage D2).

4. ISCCP calibration datasets

There are three sources of calibration information: the WMO technical document (Rossow et al. 1996a),

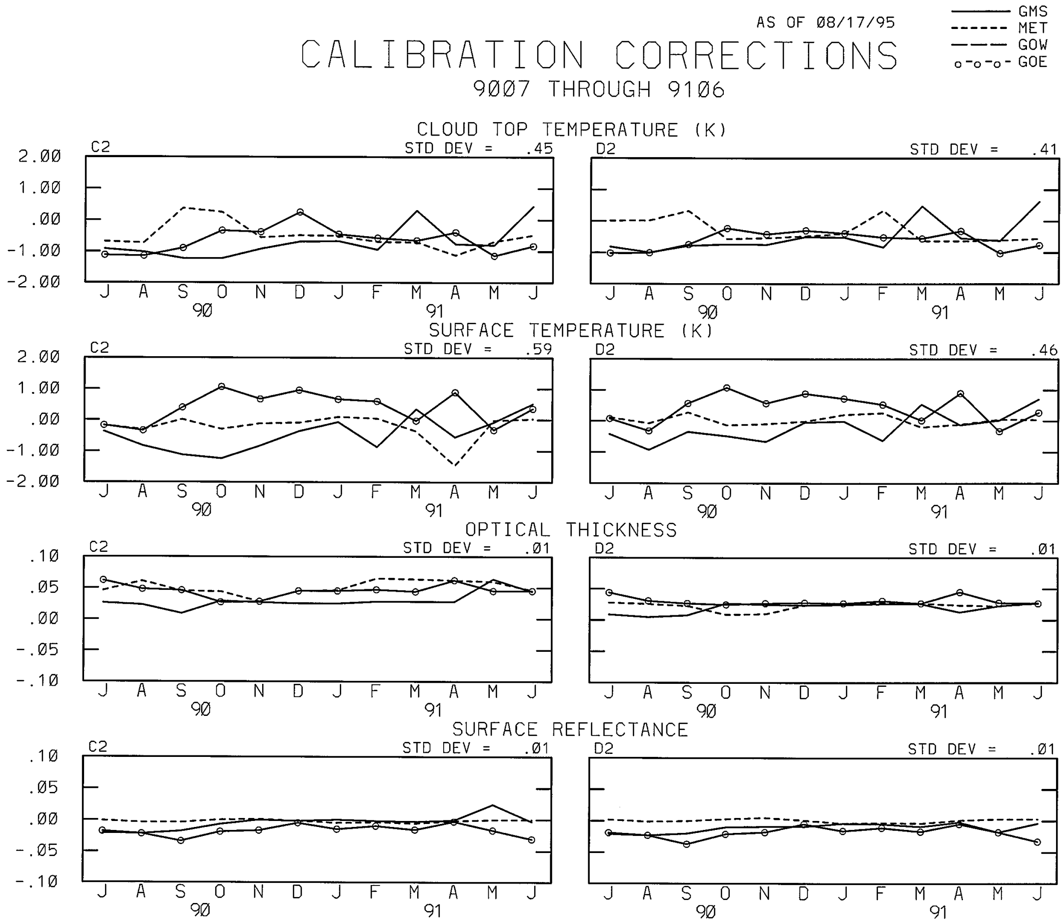


FIG. 12. Repeat of the history of the modal differences shown in Fig. 10 for the period July 1990 through June 1991, together with the same results after applying calibration corrections.

which can be downloaded from the ISCCP Web site; separate calibration summary tables on the Web site; and the ISCCP stage BT dataset, available from the ISCCP archives. The former contains monthly calibration coefficients for all of the satellites, while the latter contains the calibration lookup tables for each individual B3 image produced. The stage BT datasets contain some minor adjustments to individual images that are not contained in the first two sources. Users of ISCCP stage B3 data must use the latest version of the BT datasets, while users of the same satellite data, obtained from other sources, can use the monthly tables found in Rossow et al. (1996a). However, they need to ensure that their data use the identical calibration originally supplied by the satellite operator and the same response function as was used by ISCCP to process the same data. This information can also be obtained from Rossow et al. (1996c), which is also available on the Web site.

a. Calibration document and Web site

A summary of ISCCP calibration for each of the satellites is available on the ISCCP Web site for each month of data processed. The calibration adjustment coefficients found in these tables are meant to be applied either to scaled visible radiances (values from zero to one) or to brightness temperatures (K): for VIS scaled radiances,

$$L_a = S_a L_a + I_a;$$

for IR brightness temperatures,

$$T_a = S_a T_a + I_a,$$

where L_a and L_a are the absolute and nominal scaled visible radiances, T_a and T_a are the absolute and nominal brightness temperatures, and S_a and I_a are the respective slope and intercept values given in the absolute calibration tables (labeled as total correction in the polar-orbiter tables). The values of L_a and T_a are determined from the original telemetry count values (8-bit values representing integers from 0 to 254, 255 is reserved for "no data") using the nominal calibration for each satellite radiometer. (Users of 10-bit data must make the appropriate modification of the slope values.) The absolute calibrations given here are valid *only* when used with the assumed nominal calibration and spectral response functions that are defined in Rossow et al. (1996c).

In Brest and Rossow (1992) it was necessary to show all of the steps in the calibration calculations and lead the readers through the various stages in order for them to be able to apply the ISCCP calibration to data by themselves. Now, all of the information is summarized in the tables described above and the procedure simplified to use the coefficients directly, as described above.

b. Stage BT datasets

To make it possible to change the calibration of the stage B3 radiance dataset without having to reprocess hundreds of data tapes for each year, a new stage BT dataset has been created to report the calibration for every individual satellite image in the stage B3 dataset. This product consists of calibration lookup tables to convert radiance count values to physical radiance units for each image in the same format as the stage B3 dataset. Only images that have actually been processed by ISCCP have calibration tables included. A B3 image may have radiances for up to five spectral channels, depending on the satellite. The number of calibration tables varies accordingly and is indicated in the header record for each time. The calibrations provided in the absolute tables represent the best available calibration.

As a reference, version 0 of this dataset, available only for data prior to July 1991, presents the original stage B3 calibration *without* the final aircraft-derived absolute correction factor of 1.2 applied to vis radiances (i.e., exactly the same lookup tables as are found on B3 data tapes). Version 1, available for data from July 1983 onward, contains the new calibration that resulted from the reanalysis described above, *including* the final aircraft-derived absolute adjustment factor of 1.192 for the VIS radiances. The stage BT datasets are available from the ISCCP Central Archive.[2]

The stage BT dataset reports the results of the ISCCP calibration procedure in the same form as in the stage B3 dataset: Tables are provided for each satellite image that list the physical radiance values for each radiance count value (0–254, 255 is reserved to indicate no data). For the VIS channels, counts are converted either into radiances in units of watts per square meter per steradian, representing the energy intercepted by the instrument, or scaled radiances, normalized to the amount of energy received by the instrument when viewing a surface with unit albedo illuminated by the sun at zenith at the mean sun–earth distance. For IR channels, counts are converted either into radiances or into brightness temperatures, which represent the intercepted energy in terms of the temperature of a blackbody that emits the same amount of energy.

5. Discussion

Based on more than a decade of global observations by the imaging radiometers on the constellation of operational weather satellites, we have reached the following three conclusions that are the basis for the ISCCP calibration procedure.

1) Since there are many time periods exceeding 100 days during which the whole-image radiance distributions obtained from the geostationary radiometers are very stable (rms deviations less than or equal to 5% for VIS and less than or equal to 2% for IR), we interpret systematic, larger, short-term ($<$ 100 days) deviations of the geostationary radiance distributions to indicate changes in the calibration if confirmed by comparisons with other radiometers.
2) Based on the excellent quantitative agreement between two independent long-term monitoring analyses (ours and that of Staylor 1990) of the *NOAA-7* and *NOAA-9* AVHRRs and lacking more frequent and higher accuracy aircraft calibrations, we assume that all AVHRR radiometers have calibrations that are highly stable over the short term and vary only slowly ($<$10% per year) and monotonically over their lifetimes.
3) Based on the sudden occurrence of significant changes in global mean surface and cloud properties at the time of transition between the reference AVHRRs used to calibrate all the other radiometers, we conclude that these changes are caused by differences in the AVHRR calibrations, not differences on the earth.

Overall, these radiometers have performed very well for their intended purpose, weather observations, exhibiting relatively small and generally slow changes in calibration. The most notable exception is the occasional occurrence of spurious diurnal variations in IR calibrations of some geostationary radiometers. None of these instruments was designed for climate change detection, which requires very high accuracy radiometric calibrations determined independently of the earth. From comparisons of all of these radiometers, we find that the geostationary calibrations tend to be less stable than that of AVHRR, presumably because of the larger and more systematic changes in the instrument environment that occur in geostationary orbits.

The analyses of Staylor (1990) and Brest and Rossow (1992) both obtain radiance distribution statistics on a monthly basis: both results show steady, monotonic calibration trends over the lifetimes of the *NOAA-7* and *NOAA-9* AVHRRs with very little month-to-month deviation from the trend (the original analysis of Brest and Rossow has been extended to the full lifetime of *NOAA-7*). However, Fig. 3 (top) shows more scatter of the

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[2] ISCCP Central Archive, Satellite Data Services Division, NOAA/NESDIS, World Weather Building Room 100, Washington, DC 20233.

aircraft calibration determinations about the trend lines for *NOAA-9* than found by either Staylor or Brest and Rossow, which can be interpreted to be caused either by real, shorter-term variations of calibration not detected by the two trend analyses or by the uncertainties of the aircraft results. The estimated uncertainties of the aircraft results are large enough to explain the scatter (Abel 1990); but the best supporting evidence for this interpretation comes from the one occasion (October 1986) when three aircraft determinations of the *NOAA-9* calibration were obtained within a few days. The spread of these three results is about as large as the scatter of the individual aircraft points around the trend lines: a least squares linear fit to the aircraft points agrees with the trend lines to within about 5%.

Figure 3 (bottom) shows a similar situation for *NOAA-11,* except that the aircraft points seem to indicate a change of the sign of the trend of the calibration in mid-1990. Unfortunately, all other results are for the period prior to the Pinatubo eruption: the trend analysis for this period by Rao et al. (1993b, 1995) obtains a very small (about 1% per year) negative trend. Our results are the only ones that cover the whole lifetime of *NOAA-11,* but the Pinatubo aerosol effect eliminates 18 months of the available data to determine calibration changes. The history of the global, monthly mean anomalies of surface reflectance from *NOAA-11* (Fig. 4) shows that the reflectances are distinctly lower in 1990 than in 1989 and the second half of 1993 and 1994. Note, however, that there appears to be a brightening trend in our results that begins in mid-1990 until the beginning of the Pinatubo-affected time period (about October 1991). The stratospheric aerosol optical thickness falls back below 0.05 in mid-1993 (based on an extension of the SAGE (Stratospheric Aerosol and Gas Experiment) II analysis by Sato et al. 1993), so that little effect on our surface reflectance value should remain (cf. Fig. 5). Thus, we could interpret the *NOAA-11* record as a slow decline of instrument sensitivity from late 1988 through mid-1990, followed by an increase of instrument sensitivity until the end of its life in fall 1994. However, since we cannot confirm this change of behavior, given the scatter caused by the uncertainties of the aircraft measurements and other vicarious results, which all occur pre-Pinatubo, and the lack of any results during the Pinatubo event, we assume that the *NOAA-11* AVHRR is the same as all others, exhibiting only steady, monotonic calibration trends. Thus, our final result for *NOAA-11* is obtained from a linear fit to the surface reflectance anomaly record over the whole lifetime of the instrument (including the Pinatubo period), implying that the decrease of reflectances in 1990 is real. There is not enough information to choose between these two interpretations.

Our use of the whole (clear sky) earth as a calibration reference places constraints on the use of these radiance data. Based on the fact that the only significant changes in the global annual mean cloud and surface properties retrieved by the ISCCP analysis occur when the reference AVHRR is changed, and that such changes are inconsistent with observations of the planetary radiation budget by ERBE, we assume that the earth as a whole does not systematically change over this decade. Instead, the changes are interpreted to be AVHRR calibration changes. In other words, we conclude that the earth is more stable as a radiometric target than the calibrations of these radiometers; despite the significant effort expended, the calibration uncertainty is still much larger than any climate change signal apparent in the data record. Use of such an assumption to calibrate the radiances precludes the use of these data for long-term climate change detection; however, it does not preclude detection of regional variations, which are probably larger in magnitude. Moreover, since we only remove a single linear calibration trend over the lifetime of each radiometer, we have not arbitrarily removed interannual variability (although the *NOAA-11* case remains in doubt). Finally, because we use only the surface radiances, we have not removed any long-term changes in the cloud properties that might appear in the ISCCP analysis results.

By adjusting the AVHRR calibrations to produce global annual mean VIS and IR radiances that are constant over more than a decade, the uncertainty in the relative calibration is caused by the limited precision of the radiance measurements; by the statistical uncertainties of the trend analysis; by any uncorrected, short-term calibration changes; and by any real global mean, long-term variations of the earth. The 8-bit radiance precision (equivalent to about 0.4%) of the ISCCP version of the radiances limits the magnitude of the corrections that can be applied. Depending on the length of record used to determine the trend, the monthly corrections may be more precise than this limit. This effect limits the accuracy of VIS calibration trends of no better than about 1% (absolute reflectance units) over the typical 4-yr lifetime of individual radiometers: for the trends actually determined, this represents a relative trend uncertainty ranging from 5% to 25%. No trends in global mean IR radiances were detected in our analysis, but the precision of this result could allow trends in surface temperatures of less than 0.2 K per decade. The statistical uncertainty of our trend determinations is estimated by the scatter of global mean radiances for individual months, which is also a measure of possible uncorrected short-term calibration variations: this scatter implies uncertainties of about 3% in VIS and 1 K in IR. The uncertainty produced by real climate variations over a decade is probably much smaller than other sources of uncertainty. Relative variations of the global mean planetary albedo from year to year are enough to estimate the effect of the Pinatubo aerosol (Minnis et al. 1993): These results imply that real changes in VIS radiances should be less than 5%. Analyses of surface temperature records imply real changes are less than 0.2 K per decade (e.g., Hansen et al. 1993).

Thus, we conclude that the relative calibrations of the radiances used by ISCCP are now uncertain on average by no more than ±0.01–0.02 absolute, ±3%–5% relative for VIS radiances, and ±1–2 K absolute, ±0.3%–1.0% relative for IR radiances. The absolute uncertainties are larger because of the extra difficulty of relating the spaceborne radiometer observations to an absolute standard (at the surface). We estimate the absolute calibration uncertainty to be about 10% for VIS and 2% for IR. The calibration results described are represented by the latest version of the ISCCP calibration dataset (stage BT) and the information now available on the ISCCP Web site. ISCCP calibration monitoring will continue through at least the year 2000.

The history of efforts to calibrate AVHRR points to some lessons important to future spacecraft observations of climate change. The discovery that the largest changes observed in the first 8-yr ISCCP record were apparently caused by instrument calibration changes indicates that real decadal changes of the earth are much smaller in magnitude and cannot be reliably detected without significant improvements of instrument calibration. The difficulties interpreting the aircraft (and other) calibration results for AVHRR suggest that something more will be required to get the needed accuracy. Even calibrations based on onboard targets may not be sufficient, given that we still find differences in IR calibrations of more than 1 K. These results suggest, in particular, that reliance on one method of calibration for future spacecraft missions is unlikely to reduce calibration uncertainties enough. Use of a combination of calibration methods is probably necessary, but support missions (coincident aircraft flights, instrumented ground sites) must be conducted much more frequently and regularly than in the past. Because of the expense of these aircraft and instrumented site approaches, vicarious calibration methods will still be needed to confirm onboard calibrations (Slater et al. 1996). Even with all these changes, the relative accuracy attained will only be apparent in the context of a long data record. This last conclusion also emphasizes the value of overlapping observations by instruments in a series: Our experience suggests that the overlap time period needs to be much longer than 3 weeks, possibly 3–6 months long.

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