The Advanced Very High Resolution Radiometer (AVHRR) Pathfinder Atmosphere (PATMOS) Climate Dataset: Initial Analyses and Evaluations

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ABSTRACT

As part of the joint National Oceanic and Atmospheric Administration—National Aeronautics and Space Administration (NOAA—NASA) Pathfinder program, the NOAA/National Environmental Satellite, Data and Information Service (NESDIS) has created a research-quality atmospheric, climate-scale dataset through the reprocessing of archived Advanced Very High Resolution Radiometer (AVHRR) observations from four afternoon satellites, in orbit since 1981. The raw observations were recalibrated using a vicarious calibration technique for the AVHRR reflectance channels and an improved treatment of the nonlinearity of the three infrared emittance channels. State-of-the-art algorithms are used in the Pathfinder Atmosphere (PATMOS) project to process global AVHRR datasets into statistics of channel radiances, total cloud amount, components of the earth’s radiation budget, and aerosol optical thickness over oceans. The radiances and earth radiation budget components are determined for clear-sky and all-sky conditions. The output products are generated on a quasi-equal-area grid with a spatial resolution of approximately 110 km, with twice-a-day temporal resolution, and averaged over 5-day (pentad) and monthly time periods. The quality of the products is assessed relative to independent surface or satellite observations of these parameters. This analysis shows that the PATMOS data are sufficiently accurate for studies of the interaction of clouds and aerosol with solar and terrestrial radiation, and of climatic phenomena with large signals, for example, the annual cycle, monsoons, and the four ENSOs and two major volcanic eruptions that occurred during the 19-yr PATMOS period. Analysis also indicates that smaller climate signals, such as those associated with longer-term trends in surface temperature, may be difficult to detect due to the presence of artifacts in the time series that result from the drift of each satellite’s observation time over its mission. However, a simple statistical method is employed to remove much of the effect caused by orbital drift. The uncorrected PATMOS dataset is accessible electronically.

1. Introduction

The general objective of the National Oceanic and Atmospheric Administration—National Aeronautics and Space Administration (NOAA—NASA) Pathfinder program is to generate consistent, well-calibrated, long-term datasets from archived operational environmental satellite data and make them easily accessible for climate research. The program has produced datasets from the following polar and geosynchronous satellite instruments: Advanced Very High Resolution Radiometer (AVHRR), Television Infrared Observational Satellite (TIROS) Operational Vertical sounder (TOVS), Special Sensor Microwave Imager (SSM/I), and Vertical Atmospheric Sounder (VAS). Responsibility for producing the AVHRR Pathfinder data was distributed among three processing centers (University Corporation for Atmospheric Research 1994): land products at NASA Goddard Space Flight Center (GSFC), ocean products at NASA Jet Propulsion Laboratory (JPL), and atmospheric products at NOAA/National Environmental Satellite Data and Information Service (NESDIS). An AVHRR Pathfinder Calibration Working Group (CWG) developed a calibration history for the visible and near-infrared channels, which have no onboard calibration and tend to degrade with time in orbit. A stable reflecting target—the Libyan desert—was used as a vicarious calibration source to determine the degradation rate of these channels (Rao and Chen 1995). The CWG also developed an improved calibration that accounts for the nonlinearity of the IR channels (Walton et al. 1998). These calibration histories are used at all three processing centers. The AVHRR Pathfinder Atmosphere (PATMOS) Project at NOAA was guided by a Science Working Group (SWG) chaired by James Coakley (appendix A contains a complete SWG membership list).

The PATMOS project has reprocessed five-channel AVHRR data from the NOAA-7, -9, -11, and -14 after-
noon Polar Orbiting Environmental Satellites (POES), forming a nearly continuous record of atmospheric products spanning over 19 years from September 1981 to December 1999 (see appendix B for notes on the extent of this dataset). The principal dataset parameters are the channel reflectances (%) and infrared radiances [mW (m² cm⁻¹ sr⁻¹)], total cloud amount (%), components of the earth’s radiation budget (ERB, W m⁻²)] at the top of the atmosphere (TOA); outgoing longwave radiation (OLR), and absorbed solar radiation by the earth-atmosphere system (ASR), and aerosol optical thickness (AOT) over the oceans (dimensionless). The radiances and ERB components are determined for both clear-sky and all-sky conditions. All parameters are provided on an approximately equal-area grid with a resolution of ~110 km [1° in latitude by variable degrees in longitude (given by 1° times the secant of the latitude)]. They are generated twice daily, once for orbits ascending south to north (mostly during the daytime) and again for orbits descending north to south (mostly during the nighttime). They are further averaged over 5-day (pentad) and monthly time periods. A number of other auxiliary parameters (e.g., land fraction, and viewing and solar illumination angles) are also gridded and processed in this manner.

The AVHRR is an imaging radiometer that measures the radiation reflected and emitted by the earth in five spectral channels (Cracknell 1987). Channels 1 and 2 measure reflected solar radiation, channels 4 and 5 measure infrared radiation, and channel 3 is sensitive to both sources. The response of all five channels is within spectral “window” regions in which the atmosphere is quasi transparent. Table 1 lists the engineering specifications of the spectral channels (Kidwell 1995).

The instantaneous field of views (FOV) of the instrument [termed local area coverage (LAC) pixels] is nominally 1.1 km × 1.1 km at nadir. These pixels are contiguous along the orbital track but overlap somewhat across the orbital track. The global LAC data are too voluminous to be stored on the satellite tape recorders. Thus, to achieve global coverage, the LAC pixels are averaged and sampled on board the satellite. Four consecutive FOVs on a given scan line are averaged for each channel and the fifth FOV is omitted. The next two scan lines are omitted. These newly formed pixels constitute what is termed global area coverage (GAC) data. A GAC pixel has a 1.1 km × 4.0 km FOV at nadir and represents a 3 scan line × 5 FOV array of LAC pixels, corresponding to an area at nadir of approximately 16 km². The swath width covered by scanning perpendicular to the orbital track is about 2700 km. The nominal local times of observations are not the same for all afternoon satellites. The NOAA-7 and -9 satellites initially had local standard time (LST) equator crossing times of approximately 0230 (descending) and 1430 LST (ascending), while the NOAA-11 and -14 crossed the equator about 0130 (descending) and 1330 LST (ascending).

The methods used in PATMOS to generate the products from the recalibrated AVHRR data are discussed in section 2. Samples of the products and comparisons with other datasets are shown in section 3. A summary is presented in section 4 and future plans for a more comprehensive reprocessing, which would include land and oceanic surface and other atmospheric parameters, are described in section 5. Appendix B provides more details about the PATMOS dataset, and describes methods of electronically accessing it.

### Table 1. Specifications of the NOAA/AVHRR spectral channels

<table>
<thead>
<tr>
<th>Channel</th>
<th>Bandwidth (μm)</th>
<th>NEdT</th>
<th>S/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.58–0.68</td>
<td>3:1 @ 0.5% albedo</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.725–1.10</td>
<td>3:1 @ 0.5% albedo</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3.55–3.93</td>
<td>0.12 K @ 300 K</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>10.3–11.3</td>
<td>0.12 K @ 300 K</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>11.5–12.5</td>
<td>0.12 K @ 300 K</td>
<td></td>
</tr>
</tbody>
</table>
The following sections describe the three major climate-related parameters contained in the PATMOS-2...
dataset: cloud amount, Earth radiation budget, and aerosol optical thickness. Each section gives examples of the parameters and evaluates them by comparison with other published satellite-derived datasets. The period covered by PATMOS includes four major El Niño events (1982/83, 1987/88, 1992/93, 1997/98) and two stratospheric aerosol events from the major volcanic eruptions of El Chichón (1982–84) and Mt. Pinatubo (1991–93). July 1986 was selected for evaluation of all PATMOS parameters as it allows comparison with the following: 1) cloud cover obtained from the latest version of the International Satellite Cloud Climatology Project monthly mean dataset (ISCCP-D2; Rossow and Schiffer 1999); 2) aerosol optical depth derived from ISCCP radiance data (Mishchenko et al. 1999); and 3) radiation budget from Earth Radiation Budget Experiment (ERBE; Wielicki et al. 2000). The 20°N–20°S zone is chosen for all time series analyses in this paper because of the following considerations:

1) This zone is fully illuminated by sunlight for the entire period of record, thereby eliminating concern for temporal differences in spatial sampling of reflected radiation parameters or in the cloud masking (CLAVR-1) algorithm. Because of drift in satellite equator-crossing times, this is not true of other zones;

2) recent studies with broadband earth radiation budget datasets (Wielicki et al. 2000) have shown this zone to be highly variable both interannually (e.g., El Niño and volcanic eruptions, long-term drift) and intra-annually (seasonal changes).

A simple technique for removing much of the affect due to orbital drift is described and adjusted time series are compared with the other published datasets.

A. Cloud amount

A quantitative evaluation of the two cloud amount computational methods (FFS) and (SESC) in the PATMOS dataset was conducted in Stowe et al. (1999). It used an image processor to display contrast-enhanced scenes derived from the pixel level-1b data (Stowe et al. 1999). Human analysts used these enhanced images to independently estimate the amount of cloud on a fixed geographical area, and then compared it with the results from CLAVR-1. A previous study indicated that an analyst could estimate the cloud fraction from such imagery to an accuracy of 0.05–0.10 in daytime and 0.10–0.15 at night (Stowe 1984). This current analysis indicates that the fractional cloud amount derived by CLAVR-1 is within 0.05–0.10 of the values estimated by the image analysis, the smaller value representing the performance of the SESC method (cf. Stowe et al. 1999). The CLAVR-1 algorithm has difficulty in discriminating between cloud and the surface; over land at high latitudes in winter, over high-latitude oceans, over some desert and mountainous regions, and when viewing regions of ocean specular reflection.

Figure 1 is a map of PATMOS global mean cloud cover (SESC), averaged from all ascending (mostly daytime) orbits for the month of July 1986. Relatively large percentages of cloud cover are seen in the tropical regions due to cloudiness associated with the intertropical convergence zone (ITCZ) and off the west coasts of continents at low- and midlatitudes, from stratus clouds associated with cold upwelling ocean water. Small percentages occur over the subsidence zones in the low latitudes of the three major oceans and over desert areas. Although the cloud amount at higher latitudes are less accurate, note the highest cloud percentages occur over the Arctic and Antarctic, poleward of the polar fronts, along which major storm systems and their associated clouds form (although a prominent region of reduced cloud cover is apparent over the eastern half of Antarctica). Only over Australia, are the latitude–longitude boundaries of the region defined to be desert in CLAVR-1 apparent. This indicates that there are problems with the algorithm’s ability to detect cloud over that surface type. Obviously, such boundaries are artificial. Future versions of CLAVR should provide for a better treatment of desert scenes.

A zonal plot of day/night average PATMOS and ISCCP-D2 cloud amounts for July 1986 is shown in Fig. 2. The ISCCP-D2 data are an average of eight 3-hourly observations provided primarily by global geosynchronous satellite imager data, but supplemented by NOAA polar orbiter AVHRR data poleward of 60° latitude, while the PATMOS is an average from two 12-hourly observations. Note that the zonal distribution of ISCCP cloud amount from about 60°N to 50°S generally tends to follow the pattern from that derived from PATMOS, but its value is approximately 10–15 percentage units greater (the mean global bias is 12.34%, with standard deviation of 10.35%). This bias is likely due to differences in the way the two algorithms classify those pixels considered mixed (partially cloud-filled or overcast pixels with variable cloud heights and thicknesses) in CLAVR-1, as indicated by several case studies conducted by Luo et al. 1998. ISCCP tends to classify the partially cloud-filled pixels as cloud to preserve accuracy in its clear-sky radiances (W. B. Rossow 1999, personal communication). PATMOS more correctly assigns a value between 0% and 100% to these pixels. However, the variably overcast pixels, erroneously are given a partial cloud amount in CLAVR, while ISCCP classifies these pixels correctly as cloudy. Consequently, the true cloud amount is expected to be somewhere between these two estimates.

Poleward of 50° in the Southern Hemisphere, ISCCP values decrease while PATMOS continues to increase to about 70°S, then decrease to about 80°S, and then increase to 100% at the Pole. Also, between 60° and 90°N, ISCCP values decrease toward the Pole, while PATMOS values increase. The cause of differences in
the polar region is not yet understood. It is very difficult to use AVHRR visible and infrared radiances to separate clouds from the underlying surface when it is as cold and as bright as most clouds. CLAVR-1 and ISCCP-D2 use the difference between the 0.63- and 3.7-μm albedos to separate water clouds from snow/ice, but with different test thresholds, which may be one cause of the differences in the North Polar region.

Time series analysis of cloud amount is potentially useful for investigating the effects of natural and anthropogenic changes in the earth’s radiation balance and hence, its climate. However, the PATMOS series is derived from observations where the equator-crossing times (ECT) for all 4 satellites gradually drifted toward later times by as much as 3 h (Fig. 3a) during the duration of each satellite’s mission (Gutman 1999). Unfortunately, this introduces temporal trends that vary with the ECT and cause discontinuities between the four satellite records of all climate-related parameters in the PATMOS data, complicating the detection of long-term trends. As an example, Fig. 3b shows the affect of the orbital drift for PATMOS monthly mean cloud amount (day/night average) from September 1981 to December 1999 (restricted to the latitude zone 20°N–20°S as explained earlier). For comparison purposes, the 1985–93 time series of the ISCCP-D2 dataset is also shown for the same zone. Clearly seen are the increases in PATMOS cloud amount with increasing ECT and the large discontinuities between satellites. Cloud amount is relatively low at the beginning of each satellite’s record and progressively increases throughout its duration by between 2 and 3 percentage units, depending on the satellite. This pattern could be the result of a “real” change in cloud cover, if cloud amount increased as the observation time of each satellite drifted to later in the afternoon (or morning). To test this hypothesis, the diurnal trends in tropical total cloud amount were derived from the seasonal mean diurnal variations of low and high cloud from the ISCCP-D2 data, as reported in Ros sow and Schiffer (1999). This analysis indicated that
the daytime values do increase, but by no more than 1 percentage unit as observation time drifted from 1400 to 1700 LST, while nighttime cloud amount decreased by about 0.6 percentage units over the corresponding 3-h period. The net effect on the day/night average is an increase of less than 0.4 percentage units over this 3-h period. Thus, it is concluded from this analysis that diurnal changes in cloud amount could only be responsible for a small part of the increase seen in each satellite’s PATMOS record.

It is therefore likely that most of these upward trends in PATMOS cloud amount within each satellite’s lifetime are due to some unaccounted for dependency of the cloud detection algorithm on solar zenith angle increases (albedos used in daytime cloud detection algorithm) or surface temperature decreases (infrared radiances used in nighttime cloud detection, although the trends in day/night average are mostly coming from daytime observations) resulting from satellite drift to later equator-crossing times. There may also be an effect due to residual errors in the time-dependent correction for calibration drift of channels 1 and 2. Further research is required to determine which of these physical, instrumental, or algorithmic time-dependent processes are responsible for the observed pattern in the long-term record of PATMOS cloud amount. The long-term average cloud amount for this tropical band is 50.4%, while that for the ISCCP dataset is 62.7%. The high bias of the ISCCP data relative to PATMOS exists for all months in the time series. A graph of the PATMOS cloud amount simultaneously plotted for all four satellites versus ECT shows a strong linear trend, which can be removed. The best-fit line is obtained through regression analysis, which can then be used to remove the linear trend (this process is generally referred to as detrending). Detrending should have only a small effect on interannual trends because it is based only on the variation of cloud amount with variation in the ECT of all four satellites taken together and not on its variation with time for each satellite. The result of this detrending is shown in Fig. 3c along with the ISCCP time series. The datasets show a remarkable correlation in variations within any particular year, given the large bias between them, and the obvious differences in long-term trends. They essentially have the same annual cycle in tropical cloud cover, with maxima in the July–December period, and minima in the January–June period (note the relatively higher peak in 1991 only in the ISCCP-D2 data, the year of the Mt. Pinatubo eruption).

With respect to their longer-term trends, the ISCCP-D2 cloud amount is steadily decreasing by about 3 percentage units over its 9-yr record, as evident from the linear regression line drawn through it, while the adjusted PATMOS cloud amount due to detrending increases very slightly.

b. Aerosols

The retrieval algorithm for aerosol optical thickness used by PATMOS is identical to the one running operationally at NOAA/NESDIS, that is, the second-generation algorithm described in Stowe et al. (1997). It uses AVHRR channel-1 reflectance to retrieve total-column optical thickness at an effective wavelength of 0.63 μm. The algorithm is based on physical principles, starting from the observation that the top of the atmosphere clear-sky reflectance over oceans is generally very low in regions removed from sun glint. The presence of aerosols can be detected as an increase in the reflectivity against this dark background through their backscattering of solar radiation. The greater the reflectivity, the greater the aerosol optical depth. The retrieval algorithm uses a radiative transfer model with an assumed marine aerosol described by a monomodal, lognormal size distribution, to compute lookup tables relating reflectance to viewing and solar illumination geometry and aerosol optical thickness. It further assumes that the particles are spherical and nonabsorbing.

The performance of this idealized retrieval algorithm is surprisingly good. When pixel-level operational retrievals of AOT from AVHRR were compared with shipboard sun-photometer observations from the western North Atlantic Ocean, using methods described in Ignatov et al. (1995), this second-generation algorithm had a systematic error less than 10% relative to the surface observations, and a random error in the optical depth less than 0.04 (Stowe et al. 1997). In PATMOS-2, this same algorithm is applied to gridcell mean clear-sky reflectances, rather than pixel-level reflectances used in the operational processing. There is no significant change in performance if any given set of illumination and viewing geometries, provided AOT < 1. The gridcell-averaged geometry departs typically by less than 6° in satellite zenith, and by even less for solar and relative azimuth angles, when compared to pixel-level values within the grid cell.
Thus, the linearity of the retrieval algorithm should be maintained in the PATMOS application.

To test these expectations, PATMOS-2 AOT values have been statistically compared with Aerosol Robotic Network (AERONET) level-2 sun-photometer observations (Holben et al. 1998) at 22 island and coastal sites from 1993 to 1999. A total of 1015 matchup days result from applying the following criteria to individual PATMOS-2 gridcell observations and AERONET measurements: (i) the PATMOS-2 grid cell must be an all ocean cell (i.e., land cover = 0%) for which an AOT value has been computed, (ii) the center of the grid cell must be within 125 km of an AERONET site, having at least one sun-photometer AOT observation, and (iii) the observation at the site must be within ±1 h of the PATMOS-2 observation time. The multispectral AOT observations from AERONET at each observation time are interpolated to the AVHRR observation wavelength and then averaged. Figure 4a shows the scatterplot from this matchup analysis. The correlation coefficient is 0.87 and the regression line has a slope of 0.68, an intercept of 0.05 and a standard error of estimate of 0.07. These results imply that the PATMOS-2 global retrievals are biased low by 20%–30% relative to the surface obser-
Fig. 4. PATMOS-2 AOT vs 1993±99 level-2 AERONET observations for (a) all sites within 125 km and ±1 h of PATMOS gridcell center and observation time, and (b) three oceanic sites in the North Atlantic (i.e., Bermuda, Andros Island, and Barbados). Horizontal and vertical hash marks represent temporal standard deviation of the AERONET observation and spatial standard deviation within the PATMOS gridcell, respectively. For both plots, the solid and dashed lines represent the 1–1 relationship and linear regression result, respectively.

AOT values in Fig. 4a in excess of 0.6 are from two sites near the western coast of tropical Africa: Dakar and Cape Verde, where the aerosol is likely to be dominated by Saharan dust. Thus, the low bias observed for the global matchups is most likely due to dust, where the particles are typically nonspherical (Mishchenko et al. 1995; they scatter radiation less effectively in the backscatter direction than spherical particles assumed in retrieval model) and absorbing (Sokolik et al. 1993; assumed nonabsorbing in the retrieval model). Thus, the operational and PATMOS aerosol datasets can be shown to be of very comparable quality.

A third-generation algorithm is under development that will use multiple-channel observations from AVHRR to infer aerosol particle size information, similar to the methods developed by Higurashi and Nakajima (1999), Mishchenko et al. (1999), and Tanre et al. (1997). It should partially reduce the error associated with aerosol regional variability, and thereby make the quality of the retrievals less dependent on aerosol type.

The global distribution of AOT available in PATMOS is shown in Fig. 5 for July 1986. Relatively high AOTs are noted off the western coast of Africa and the southern coasts of Saudi Arabia due to wind-blown desert dust. A tongue of this dust extends across the Atlantic into the Caribbean. Elevated values associated with smoke from agricultural burning practices in tropical Africa are also noticeable off the west coast of southern tropical Africa. Plumes of aerosol generated by fossil fuel burning can be observed off the east coasts of the United States and Asia (cf. Husar et al. 1997). The typical background values of AOT over the oceans, away from continental influences, is generally less than 0.15. The black area south of about 35°S is caused by a solar zenith angle cutoff of 70° in the algorithm where plane-parallel assumptions become less valid and low levels of illumination occur.

The latitudinal variability of AOT is shown in Fig. 6, again for July 1986. An independent retrieval (interpolated to 0.63 μm) using two AVHRR reflectance channels is also shown from the work of Mishchenko et al. (1999), at NASA Goddard Institute for Space Studies (GISS) in support of the Global Aerosol Climatology Project. Both datasets exhibit essentially the same latitudinal dependence, although there are differences in the latitudinal gradients in the Tropics, and at a few isolated zones in the northern extratropics, possibly associated with cloud-masking difficulties (cf. Fig. 2). Both exhibit a double peak in tropical AOT, associated with smoke from biomass burning near the equator and with dust near 15°N. PATMOS shows the dust peak to
be larger, perhaps indicating either that the GISS cloud mask is considering some of this dust as cloud, or that the single-channel algorithm used in PATMOS is underestimating the optical thickness of the smoke. The GISS values extend about 10° farther south, due to differences in solar zenith angle cutoffs.

There is an overall high bias of the GISS values relative to PATMOS, the area-weighted mean difference being −0.04, with a standard deviation of 0.02. This can be caused by differences in cloud masking (already noted), instrument calibration, or retrieval algorithm assumptions. GISS uses a linear calibration slope (% reflectance/count) for channel 1, which is 0.8% higher than PATMOS, and an offset (% reflectance), which is 4% lower than PATMOS (I. Geogdzhayev 2001, personal communication), which could by themselves account for most of the GISS high bias. There are also known differences in Rayleigh optical thickness [PATMOS (solar and response function weighted value of 0.0607) is incorrectly higher than GISS by about 0.004, which could also explain as much as 0.03 of the GISS high bias], ocean surface reflectance [e.g., PATMOS assumes a flat Lambertian surface with a diffuse glint correction, while GISS treats the ocean as a specular,
wavy (wind driven) surface, which would typically cause GISS to be biased low relative to PATMOS, and aerosol microphysical properties (e.g., GISS assumes absorbing aerosols, which could explain some of their high bias relative to PATMOS) in the two retrieval algorithms. Some if not all of these differences are probably contributing to the overall bias observed in Fig. 6. Which of these two algorithms is more correct ultimately depends on each being validated against an independent measure of AOT in regions of differing aerosol type, such as provided by AERONET. An initial PATMOS validation analysis is reported in this paper. The GISS and PATMOS monthly mean retrievals were qualitatively compared against AERONET monthly mean data by Kinne et al. (2001), but their systematic and random errors relative to AERONET were not computed.

Not only can tropospheric aerosols be detected with AVHRR observations, but also stratospheric aerosols resulting from major volcanic eruptions. Figure 7a shows the time series of the PATMOS monthly mean AOT averaged for the Tropics between 20°N and 20°S and detrended from September 1981 to December 1999, and for GISS, from February 1985 to October 1988. An adjusted PATMOS time series was not derived in the manner that was done for the cloud amount, because of the large increases in the AOT due to major volcanic eruptions. Instead, the AOT for each satellite was first
detrended excluding the two years following each major eruption. The entire series was then adjusted to have a long-term mean equal to that observed over the 1981–99 time period minus the excluded years (0.110). The most striking features in the figure are the two broad peaks in PATMOS AOT associated with stratospheric aerosols from the eruption of El Chichón in April 1982 and Mt. Pinatubo in June 1991 (cf. Stowe et al. 1992; Strong and Stowe 1993; Long and Stowe 1994). The smaller-scale intra-annual variations are due to seasonal changes in general circulation patterns that lift and transport tropospheric aerosol from land to ocean downwind of deserts, fires, and industrial regions. Some of this variability may also originate from seasonal changes in ocean biological activity (Husan et al. 1997).

As observed in Fig. 6 for July 1986, the GISS values are also higher than PATMOS over the entire NOAA-9 record, having a mean value of 0.161. They also exhibit a much less pronounced downward trend than the original PATMOS data, shown as a dashed line on the NOAA-9 record of Fig. 7a. This implies that the GISS calibration and/or algorithm is less sensitive to the three factors possibly affecting this time series: 1) a residual uncorrected time-dependent drift in the calibration of channel 1; 2) response of the algorithm to a diurnal change in AOT; or 3) an unaccounted dependence of the retrieval algorithm on solar zenith angle changes as the satellite drifts to later equator-crossing times.

The independent calibration drift correction equations used by the PATMOS and GISS processing systems yield calibration slopes for channel 1 that are within 1% of each other over the entire NOAA-9 mission. Thus, differences in calibration drift correction is probably not the cause of the observed differences in their time series. With respect to differences in response to diurnal variability in AOT, the mean AOT at 0.63 μm from all AERONET level-2 data between 1993 and 1999 has been computed within ±30 min of 1330 and 1630 LST, a time range typical of the NOAA satellite time drift. From the 5591 days with data at both times, the average difference in AOT at 1330 LST (0.1517) and 1630 LST (0.1594) is +0.007. Thus, it is very unlikely that the strong downward trend in the adjusted PATMOS data (maximum of 0.6 for NOAA-9) is due to a real diurnal change. Therefore, an unaccounted dependence of the PATMOS algorithm on solar zenith angle is the most likely explanation for the downward trend in the original PATMOS time series for each satellite. Similar trends occur for the other three satellite records.

The GISS algorithm appears to have better accounted for the variation in solar zenith angle with drift in satellite equator-crossing time. This is most likely related to its more correct treatment of the ocean surface reflectance, as discussed earlier. The third-generation retrieval algorithm, under development at NOAA, will include many of the features present in the GISS algorithm, including the specular, wavy ocean surface. Until such time as this algorithm is included in the PATMOS processing, statistical detrending of the PATMOS AOT data will be the only way these long-term drifts and discontinuities in the time series can be removed.

c. Earth radiation budget

The earth’s radiation budget (ERB) operational product at NOAA/NESDIS has a long history since its initial development in 1974. The ERB consists of two components: the total (broadband) longwave radiation emitted to space at the top of the atmosphere by the earth–atmosphere system, that is, the outgoing longwave radiation (OLR), and the total solar radiation absorbed by the earth–atmosphere system, that is, the absorbed solar radiation (ASR). The ASR is also referred to as the net solar radiation at the top of the atmosphere. Improvements in the algorithms have been documented in numerous journal articles and NESDIS scientific reports (e.g., Wydick et al. 1987; Ruff and Gruber 1988; Taylor 1990).

The OLR is estimated from the spectral radiance in channel 5 (in an atmospheric window centered approximately at 12 μm), using models of decreasing brightness temperature with increasing satellite zenith angle to account for limb-darkening, as well as a model relating the narrowband to the broadband brightness temperature (Ohring et al. 1984). The ASR is computed from the visible and near-infrared narrowband channels 1 and 2 using models of the angular distribution of reflected solar radiation to adjust for the anisotropy and the diurnal solar zenith angle variation of the top of the atmosphere reflectance (Jacobowitz 1991).

Monthly mean maps of the OLR and ASR for both all-sky and clear-sky conditions for July 1986 are shown in Figs. 8–11. In the map for all-sky OLR (Fig. 8), maxima are located over desert regions of North Africa and Saudi Arabia. Minima in the tropical regions are due to cloudiness associated with the intertropical convergence zone (ITCZ) and the Indian monsoon circulation. Extreme minima occur in the cold South Polar regions, as expected for this month (no solar heating). A comparison of this map with that for cloud amount (Fig. 1) shows a high correspondence between areas of small cloud amount and high values of the OLR. The map for the clear-sky OLR (Fig. 9), shows how the effects of clouds have been removed from Fig. 8, particularly noticeable in the ITCZ and Indian monsoon regions. The desert regions are still prominent as before. The clear-sky map is considerably more zonal in nature than the all-sky map. Black areas (grid cells) indicate that clear-sky conditions were not observed there during any day in the month (i.e., were missing). As discussed earlier, the CLAVR-1 algorithm cannot unambiguously separate cloud from sea ice poleward of 50°, so any grid cell reporting sea ice is considered missing for all clear-sky parameters.

In the map for the all-sky ASR (Fig. 10), high values are apparent in oceanic and vegetated land regions with
little cloud cover (for example, in the tropical oceans and the Mediterranean Sea and Great Plains of the United States). Minima in ASR are in regions of maxima in cloud cover (e.g., the ITCZ) and over sparsely vegetated regions of continents (where solar reflectance is higher). At high latitudes, ASR decreases due to a combination of increasing cloud cover and decreasing amounts of available solar energy [ASE, i.e., the daily average amount of solar radiant energy flux (W m\(^{-2}\)) incident at a given latitude, a parameter in the PATMOS dataset]. Poleward of about 60\(^\circ\)S, no solar radiation is available (black area). This latitudinal dependence of the ASE tends to make the all-sky ASR more zonal in nature than the OLR. Unphysical negative values occur in a few high-latitude regions due to the strong forward scattering from highly reflective surfaces at low solar elevation. Mean angular models that are applied to correct for anisotropy can cause the albedo to exceed 100% and hence the negative values of the ASR. They were not removed so as not to bias the mean. There must be regions where the ASR is overestimated and there is no way to remove these since they are in the physical range.

The clear-sky ASR (Fig. 11) is highly zonal in character over oceans due to the spatial uniformity of ocean albedo. ASR has its maximum in the Northern Hemisphere (NH) and minimum in the Southern Hemisphere (SH) in July because of solar declination, making solar incidence angles smallest (ASE greatest) in the NH. This map shows the stark contrast between the high ASR values over the darker ocean and the generally lower values over the brighter land. The variable albedo of the land surface is evident, ranging from bright (deserts and snow in Greenland) to dark vegetation. As with the clear-sky OLR, all grid cells containing any fraction of sea ice have been treated as missing in the clear-sky ASR dataset. Antarctica is black because there is no ASE, again due to the solar declination in July. Also, some negative values are observed.

Figure 12 shows a zonal plot of the OLR for July 1986 derived from PATMOS compared with that from
the ERBE instrument (Wielicki et al. 2000) on the same NOAA-9 satellite (average of ascending and descending orbits). In general, the two estimates are in good agreement, with a globally averaged zonal mean difference between ERBE and PATMOS of 0.7 W m$^{-2}$, with a standard deviation of 4.7 W m$^{-2}$. The ITCZ can be seen as the minima in the curves at about 10°N, while the maxima correspond with the relatively cloud-free regions in the subsidence zones of the Hadley circulation on either side of it.

A similar zonal plot is shown for the ASR in Fig. 13. The comparison with ERBE is not quite as good as it was with OLR, with a global-average difference (only includes values where there is sunlight) between ERBE and PATMOS of 2 W m$^{-2}$, with a standard deviation of about 11 W m$^{-2}$. The region with the largest differences in ASR is in the extratropical Northern Hemisphere, while with the OLR, it is in the Southern Hemisphere. As with the OLR, the effects of clouds within the ITCZ can again be seen as a local minima at 10°N. The maxima on either side are not as pronounced as in

Fig. 13 possibly for two reasons: 1) because the ITCZ is composed mainly of thin cirrus clouds, which are not as effective at reflecting as they are at emitting radiation; and 2) the ASE is lower on the south of the ITCZ, which reduces the impact of the reduction in cloud cover on ASR on this side of it.

A time series of zonal mean day/night averages of the OLR from PATMOS for the Tropics (20°N–20°S) is shown in Fig. 7b. They were adjusted (detrended) in the same manner as for the cloud amount. Also shown for 1985 to mid-1999 is the OLR derived from the ERBE broadband nonscanning (i.e., a fixed FOV covering the earth’s disk) instrument on the Earth Radiation Budget Satellite (ERBS). It is in a 57°, inclined, precessing orbit, covering all equator-crossing local times in a 36-day period. This greatly reduces the impact of diurnal variability on the monthly mean and makes it more representative of a true monthly mean. The magnitude of these nonscanner observations have been shown to be consistent with periodic measurements of OLR by other broadband scanning radiation budget instruments.
[ERBE, the Scanner for Radiation Budget (ScaRaB) and the Clouds and Earth’s Radiant Energy System (CERES); Wielicki et al. 2000]. Both time series show similar intra-annual changes, with maxima occurring in the NH spring/summer seasons and minima in the NH fall/winter seasons, consistent and negatively correlated with intra-annual cloud-cover variability (cf. Fig. 3c).

However, the longer-term trends are very different between the two datasets. There is a uniform long-term increase of about 4–5 W m$^{-2}$ in the OLR record from ERBE, about a mean value of 253.4 W m$^{-2}$. The figure shows that the detrended PATMOS values do not exhibit the same increasing long-term trend observed in ERBE. In fact, it decreases about 2 W m$^{-2}$ over the same time period of ERBE data, varying about a long-term mean of 246.3 W m$^{-2}$, 7.1 W m$^{-2}$ lower than the ERBE value. Wielicki et al. (2000) have argued that this increase in OLR from ERBE is consistent with the decrease in cloud amount observed with ISCCP (cf. Fig. 3c). Similarly, it appears that the small long-term downward trend in PATMOS OLR is consistent with the small long-term upward trend in PATMOS cloud cover.

A time series comparison of another ERBE and PATMOS radiation budget parameter is shown in Fig. 7c, reflected solar radiation (RSR, where $RSR = ASE - ASR$). Again, the ERBE and detrended PATMOS observations have very similar intra-annual patterns, with maxima occurring in the NH fall/winter seasons and minima in the NH spring/summer seasons. These intra-annual variations are generally out of phase with OLR, but in phase with cloud cover (cf. Fig. 3c). As these features are in all datasets presented, it strongly suggests that the intra-annual variability in the PATMOS datasets are correct, being primarily driven by intra-annual changes in cloud cover (cloud cover is more variable, and usually more reflective and colder, than the surface). Changes in aerosol concentration can also have a measurable effect on the earth’s radiation budget, as illustrated by the increase in RSR within the year following the Mt. Pinatubo eruption (Minnis et al. 1993) caused
by the stratospheric aerosol resulting from it (cf. Fig. 4a). This is noticeable in both datasets, although it is stronger in the ERBE data, between 5 and 10 W m\(^{-2}\) for over a year following the eruption in June 1991.

The ERBE broadband RSR values systematically decreased by about 3 W m\(^{-2}\) over the 14-yr record mean of 93.4 W m\(^{-2}\), as indicated by the linear regression line. This mean is only 0.3 W m\(^{-2}\) higher than the adjusted PATMOS long-term mean (note that in Fig. 7c ERBE is offset by 20 W m\(^{-2}\)). Notice that the long-term trends are very different. The ERBE and adjusted PATMOS trends are physically consistent with the long-term trends in their respective OLR and cloud amount datasets. The ERBE observations, however, come from wide field-of-view, nonscanning instruments, on a processing satellite, making them less dependent on the accuracy of angular models used to adjust for changing solar zenith angles, which for PATMOS, are slowly changing with time due to ECT drift of the NOAA satellites.

4. Summary

In this paper, the AVHRR Pathfinder Atmosphere (PATMOS) processing system has been described and samples of its atmospheric parameters, covering the period from September 1981 to December 1999, have been presented. These parameters are observed twice daily and include total cloud amount, aerosol optical thickness over oceans, outgoing longwave radiation, and absorbed (or reflected) solar radiation at the top of the atmosphere. They are geographically referenced to a quasi-equal-area grid with resolution of approximately 110 km, and temporally averaged into pentad (5-day averages) and monthly periods. The accuracies of these parameters have been inferred either from comparisons to ground truth data or to independent satellite retrievals of the same parameters. These comparisons indicate that the unadjusted data are of sufficient accuracy for studies of climate phenomena with large signals, such as the annual cycle, ENSO, major volcanic eruptions, and mon-
soons, and for exploring relationships among various atmospheric and radiation parameters (e.g., Wetzel and Stowe 1999; Nalli and Stowe 2001, manuscript submitted to J. Geophys. Res., hereafter NS01; Knapp and Stowe 2002). Systematic differences in long-term averages and trends exist between the unadjusted PATMOS and the independent datasets. These differences are most likely related to errors introduced in the PATMOS retrieval algorithms as a result of progressive increases in solar zenith angle as the NOAA polar-orbiting satellites drift in equator-crossing time during their respective missions. There is also a possibility that residual errors in calibration drift corrections for the reflectance channels, at least for some of the NOAA satellites, may be affecting the longer-term variations of the PATMOS parameters. Detrending the PATMOS data removes many of the artifacts. Removal of these satellite-dependent trends in the PATMOS data makes the derived parameters more useful for studying the smaller signals associated with longer-term climate change. The unadjusted PATMOS datasets are electronically accessible (see appendix B).

5. Future AVHRR data processing plans

Although the Advanced Very High Resolution Radiometer is only expected to be in operation in NOAA for another 10 yr, being replaced by the Visible Infrared Imaging Radiometer Suite of the National Polar-orbiting Operational Environmental Satellite System (NPOESS), there is still a need to optimize its real-time processing system, and to provide for continued periodic reprocessing of the entire AVHRR time series. The former is important to economize on the cost of producing these products, and the latter is needed to assure the climate community that when new understanding of the performance of the AVHRR becomes available, or the science of converting its measurements into geophysical parameters advances, its long-term record will be retrieved to allow for these potential enhancements in the detection of climate change.

NOAA has been processing the AVHRR data continuously, in real time for over 20 yr, producing a variety of atmospheric and surface products over land and ocean. While there have been many upgrades to the products and a number of additional products have been added during this time, the structure of the data processing system has not changed. Each data product system is currently configured to include all the processes required, from ingesting the raw data to producing the final products. This includes calibration, navigation, and if necessary, the determination of the presence or absence of clouds.

The successful development of CLAVR (Stowe et al. 1999), which has provided calibrated and navigated radiances, as well as logic for determining whether a given pixel is cloudy or clear for the PATMOS processing system, has led to the concept that it could also be utilized in the AVHRR real-time processing system to perform these functions for all derived products. Termed the Modernized AVHRR Processing System (MAPS), it essentially involves implementing the PATMOS processing system into the NOAA real-time system, and appending additional parameter algorithms to it. MAPS running retrospectively would replace the function of PATMOS for the generation of long-term atmospheric, as well as possible oceanic and land parameters. Although the basic design of the system is not yet completed, some progress toward its realization is being made.

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APPENDIX A

The Pathfinder Atmosphere Science Working Group

Following is a list of AVHRR Pathfinder Atmosphere Science Working Group members. The group met several times in the early 1990s to formulate the approaches that eventually became PATMOS.

- Kenneth Campana, NOAA/National Weather Service
- Robert Cess, State University of New York, Stoney Brook
- James Coakley, Oregon State University (Chair)
- Leo Donner, NOAA/Geophysical Fluid Dynamics Laboratory
- Herbert Jacobowitz, NOAA/National Environmental Satellite, Data, and Information Service
- Yoram Kaufman, NASA Goddard Space Flight Center
- Rachel Pinker, University of Maryland
- William Rossow, NASA Goddard Institute for Space Studies
- Larry Stowe, NOAA/National Environmental Satellite, Data, and Information Service
- Bruce Wielicki, NASA Langley Research Center

APPENDIX B

Other Information About the PATMOS Dataset

a. Extent of the PATMOS dataset

Production has continued up to June 2001. However, there are no current plans to continue production with NOAA-16 data in 2001. Some months of AVHRR data are missing from the PATMOS record: there are AVHRR data for July and August, 1981, but the infrared radiances are not reliable due to an uncorrectable error in calibration; there are also AVHRR data for November 1988, but only for part of the month (start of NOAA-11 operation); finally, there is a gap from September 1994 to February 1995, due to failure of the NOAA-11 AVHRR in September and the time needed to stabilize its replacement, NOAA-14, after its launch in late December.

d. Access to the unadjusted PATMOS datasets

Selected unadjusted PATMOS-2 monthly mean parameters can be visualized and electronically accessed at the Satellite Active Archive’s Web site (http://www.saa.noaa.gov/). These data can be located by clicking Product Data, followed by AVHRR Pathfinder, the particular product of interest, and finally the form that is desired. (e.g., maps, spreadsheet, generic ASCII text, etc.). Global maps permit interactive zooming to select various regions of the earth. The PATMOS-1 datasets are accessible after reaching the AVHRR Pathfinder por-
tion of the Web site by clicking on Pathfinder Products next to Related Web Site. Further instructions are given in the readme.wpd, distribution.tar, and userguide.tar files.

c. Infrared radiance precision loss

The infrared radiance gridcell statistics contained in the daily PATMOS-1 dataset were computed from pixel-level AVHRR brightness temperatures (level-1c data precision 0.1°C) that were inadvertently rounded to the nearest 1.0°C. For applications where scenes are typically horizontally homogeneous (e.g., in retrievals of SST), this lost precision will introduce an additional source of random error. Research by NS01 have indicated that this loss in precision increases the random error in PATMOS daytime SST estimates by approximately 0.2°C, but does not introduce any systematic bias error. The rms error (uncertainty) of the monthly mean SST is given approximately by rms(daily)/√n, where n is the number of retrievals in a particular grid cell over the course of a month. Assuming that retrievals are possible from half the days, the increase in monthly mean scatter is approximately given by 0.2/√15 ~ 0.05°C. Although small, this increased error represents 25% of the accuracy required of monthly mean SSTs for climate studies (<0.2°C). Thus, it would be desirable to reprocess the PATMOS data with the full 0.1°C precision to remove this unnecessary source of error. However, for most other infrared applications, where the scenes have thermal variations in excess of 1.0°C (e.g., land and cloud temperature remote sensing), the effects of this lost precision will fall within the errors of the retrieved algorithms, and thereby be negligible.

REFERENCES


