CLOUD AND AEROSOL PRODUCTS AT NOAA/NESDIS

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1. ABSTRACT

Global observations of cloud and aerosol properties from satellites are needed to understand the role of these atmospheric constituents in climate change, e.g., their radiative forcing and feedback effects and trends in their optical and physical characteristics. NOAA/NESDIS has developed remote sensing techniques as a means of providing these global measurements. As a by-product of our atmospheric sounding programs, TOVS and VAS infrared window and CO_2 absorption band measurements are used to determine an "effective" cloud amount and cloud top pressure. Cloud liquid water content is being derived from DMSP/SSMT data. And AVHRR data are used to derive total cloud amount. AVHRR data are also used to estimate aerosol optical thickness over the oceans. A brief description of the retrieval methods and their verification will be given, as well as several examples of these products.

2. INTRODUCTION

The role of clouds in offsetting the global warming being predicted as a consequence of increasing concentrations of atmospheric greenhouse gases is unknown at this time. That is, we do not know how clouds are changed as a result of changes in the environment from such warming. An increase of these gases is the only definite thing that is known to be presently occurring. Recent satellite observational studies by Ramanathan et al. 1989, and Ardanuy, et al. 1989, indicate that clouds cool the Earth/atmosphere system, i.e., the amount of radiative energy available for heating the Earth is reduced when the present day distribution of clouds is added to the cloud-free system.

If the Earth is about 50% cloud covered (Stowe, et al., 1989), and if the seasonally and globally averaged cloud radiative effect is to cool the Earth by about 25 W/m^2 (Ardanuy et al., 1989), one can estimate that a 2% change in cloud amount (i.e., to 49% or 51%) would change the radiative effect of the clouds by about 0.5 W/m^2 (this assumes that only cloud amount changes, but not other cloud properties). As the effect of doubling the amount of carbon dioxide gas in the atmosphere is to heat the Earth/atmosphere system by about 4 W/m^2, (Cess et al., 1989), this heating could be compensated by an increase in cloud amount of about 16% (i.e., from 50% to 58%), a negative feedback effect of clouds. On the other hand, and at this time equally plausible, if cloud amount decreased as a consequence of the doubling of CO_2, then the Earth would heat at a faster rate, by the addition of 1W/m^2 for every 4% decrease (e.g., from 50% to 48%) in cloud amount, a positive feedback.

The lack of accurate cloud physical processes in climate models is currently thought to be the major source of uncertainty in the prediction of climate change from the "greenhouse" effect (Cess et al., 1989). Overlooking trends in aerosol concentrations can also effect the accuracy of climate predictions. Hansen and Lacis (1990) provide information that was used to estimate that an increase in tropospheric aerosol scattering optical thickness of 250% (viz., 0.1 to 0.35) would be needed to compensate for a doubling of CO_2. However, smaller increases in aerosol concentrations may be important, as recent studies have hypothesized. Charlson et al. (1987) suggest that biogenically-produced aerosols could act as cloud condensation nuclei, thus affecting cloud albedo, and hence be a possible feedback process in climate change. Their results suggest that it would be hazardous for climate modelers to assume that the microphysics of clouds remains unchanged with a changing climate. Therefore, accurate remote sensing of cloud and aerosol parameters is essential to overcoming these limitations, as well as for monitoring climate change.

3. CURRENT CAPABILITIES

NOAA has demonstrated that cloud properties can be remotely sensed with radiation measurements taken with instruments on-board the NOAA Polar Orbiting Environmental Satellites (POES). As a by-product of the atmospheric sounding program, TIROS Operational Vertical Sounder (TOVS) infrared measurements are used to determine an "effective" cloud amount (product of emissivity and cloud amount) and cloud top pressure (Nappi et al., 1988). The algorithm is illustrated in Figure 1. Plotted on this graph of HIRS channel radiances at 900 cm^{-1} (Ch 8) and at 2515 cm^{-1} (Ch 18) is a curve showing the behavior of these radiances as the temperature of a blackbody is varied over the range expected from clear surface to overcast high cloud. Also shown is a line connecting the derived clear radiance (using microwave measurements from the MSU instrument, McMillin and Dean, 1982) and the observed radiance (the field of view is assumed to be partially filled with a one-layer cloud). If it is further assumed that the cloud emissivity is the same in both channels, then the intersection of the extrapolated line with the curve allows one to compute the cloud top temperature. Given the TOVS derived temperature profile, a cloud-top pressure can be computed. Effective cloud amount is computed as the difference between the clear radiance and the observed radiance (D1), divided by the difference between the clear and overcast radiances (D1+D2).

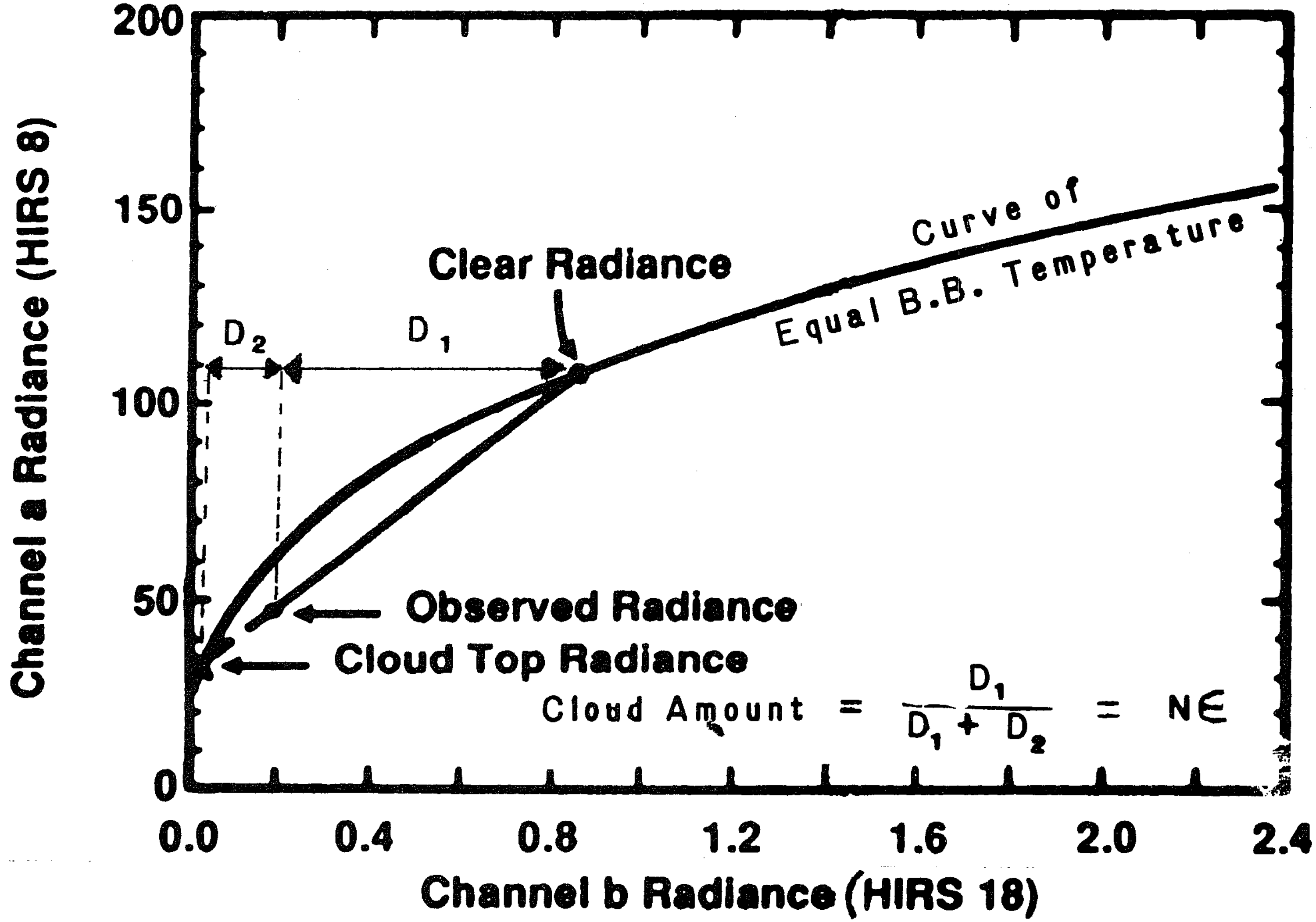

Figure 1. Illustration of the NOAA/TOVS cloud retrieval algorithm using HIRS Channels 8 and 18 radiances.

In the operational product archive, cloud top pressure is assigned to one of nine mandatory layers; then effective amount and pressure are averaged over 3x3 arrays of HIRS fields-of-view (approx. an 80 km region at nadir); and about 20% of these arrays are saved on magnetic tape with an average spacing of about 250 km. It is important to note that the soundings are more densely spaced in regions of large horizontal temperature gradients to maximize the meteorological information. Since these regions are likely to be cloudy, this sampling biases the cloud product. Also, this sparse sampling is insufficient for global analysis on daily time scales. However, monthly mean analyses are possible.

To improve sampling, an experimental archive product has been developed. All 3x3 arrays have been saved on tape since February 1990. Analysis programs have been written to average effective amount and top pressure into 2.5 degree latitude/longitude regions. Currently this is not saved on tape. Figure 2 shows the distribution of monthly mean effective cloud amount for February 1990. The regional differences in cloud amount are clearly similar to other cloud climatologies, e.g., Stowe et al. (1989). However, when compared with other cloud retrieval results for individual days (Susskind et al., 1984; Fye, 1979) it has been concluded that the NOAA/TOVS cloud top pressures (heights) are overestimated (underestimated), and hence, effective amount is also overestimated by as much as 20%. The assumption that emissivity is the same in both channels is the most likely reason for this bias. Methods are being investigated, e.g., the CO_2 ratio technique, Wylie and Menzel (1989), which make that assumption valid. Further difficulties with the interpretation of the NOAA/TOVS cloud products are: cloud emissivity is not separated from cloud amount; no cloud retrievals are made in regions of precipitation (no microwave surface temperatures there); and the 0.7 micron reflectance

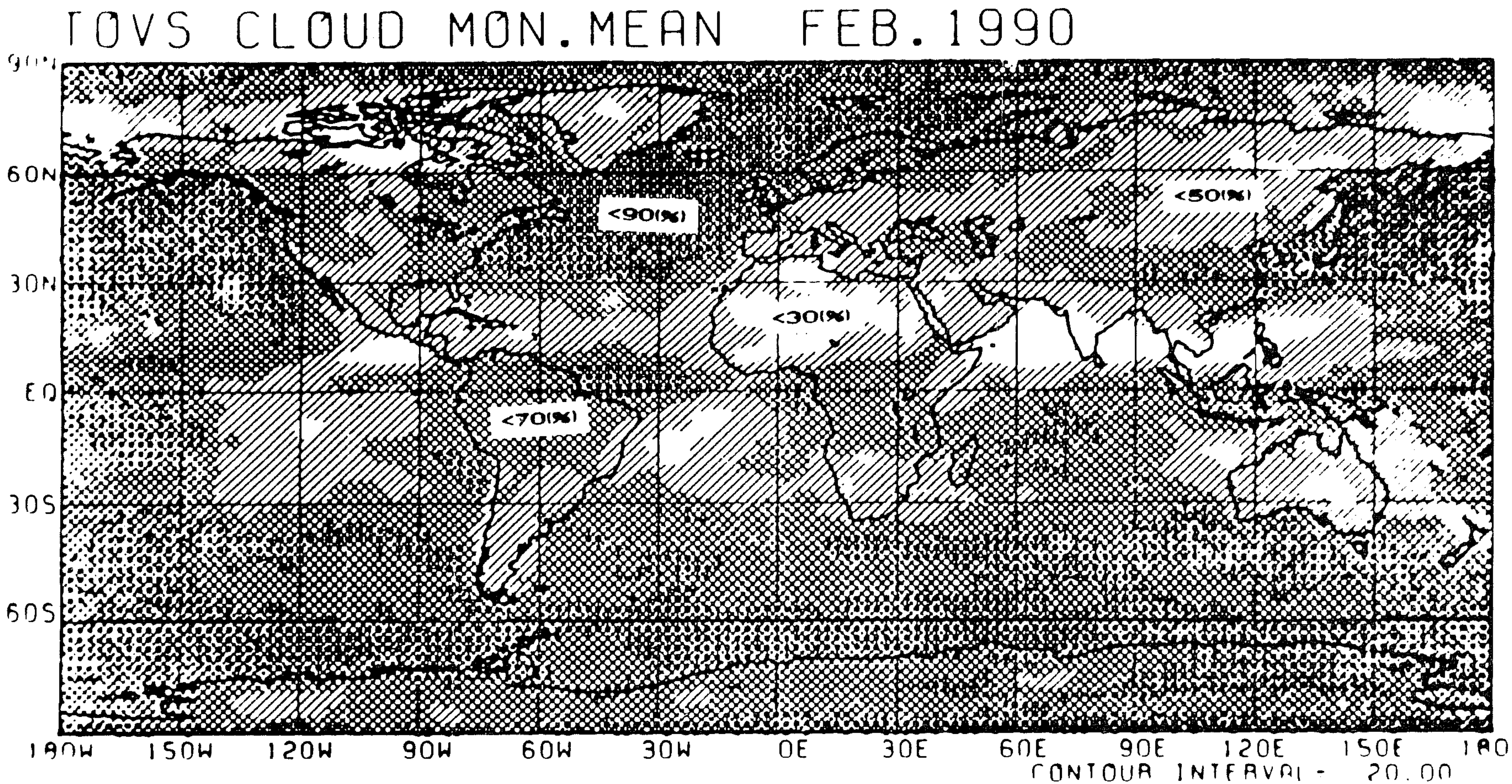

Figure 2. Monthly mean effective cloud amount for February 1990 using the NOAA/TOVS cloud retrieval system.

channel, although used in detecting clear radiances, is not used in the cloud product algorithm. These problems are being addressed, and improvements are planned over the next few years.

NOAA/NESDIS is developing an algorithm for the remote sensing of global cloud cover using multi-spectral radiance measurements from the Advanced Very High Resolution Radiometer (AVHRR) on-board NOAA polar orbiting satellites (Stowe et al., 1991). The technical approach, termed CLAVR (Clouds from AVHRR) Phase I, uses the five-channel AVHRR multi-spectral information in a series of sequential decision-tree type tests (employing established or empirically optimized thresholds) to identify the cloud-free (0% cloud), mixed (variably cloudy, assumed 50% cloud), and cloudy (assumed 100% cloudy) 2x2 GAC pixel arrays. It is based on the following differences between the radiative and physical properties of clouds and the underlying surface: magnitudes of reflected and emitted radiation (contrast); wavelength dependence; and spatial variability. The current Phase I algorithm uses a land/sea auxiliary data base and a globally-invariant (i.e., "universal") set of thresholds.

The sequence of tests and thresholds for Phase I daytime ocean and land scenes are given in Table 1. These universal thresholds have been selected individually for each test in the sequence so that none of the tests is likely to classify cloud contaminated pixels as clear land or ocean. The sequence was ordered to save computer processing time by testing for the most easily detectable characteristics of clouds first. The tests are self explanatory, with the exception of the uniformity tests and the Ch. 3 reflectance test. The uniformity test compares the difference between the maximum and minimum values in the 2x2 array with the threshold. The Channel 3 reflectance test, estimates the albedo in Channel 3

TABLE 1 CLAVR daytime cloud test thresholds.

	LAND SCENE		OCEAN SCENE	
TEST	Channel	Threshold	Channel	Threshold
Reflectance	1	> 44%	2	> 20%
Reflectance Uniformity	1	> 9%	2	> 0.3%
Reflectance Ratio	2/1	0.9<R<1.1	2/1	0.9<R<1.1
Ch. 3 Reflectance	3,4,5	> 6%	3,4,5	> 3%
Thermal Uniformity	4	> 3K	4	> 0.5K
Ch. 4 - Ch. 5	4,5	> fcn T4	4,5	> fcn T4
Thermal	4	< 249K	4	< 271K

by removing the thermal emission in this channel using regression relationships between Channels 3, 4, and 5 established in the MCSST retrieval program (McClain et al., 1985). The use of Channel 3 allows clouds to be discriminated from snow and ice covered surfaces when these surfaces are illuminated by sunlight. The Ch. 4 - Ch. 5 Test compares this difference in blackbody temperature with a threshold that is a function of the Channel 4 temperature. This function is empirically and theoretically derived to account for the increase in water vapor absorption as the surface/atmosphere system warms.

Because some of these tests can erroneously detect cloud when special conditions are present (e.g., deserts, sun-glint, or polar snow and sea-ice), several types of "restoral" tests are used in an effort to recover more cloud-free arrays. For example, to remove the ambiguity caused by sun-glint in the first four reflectance tests, a Thermal Uniformity Restoral (TUR) test is applied only when the satellite is viewing within the expected region of solar specular reflection. The TUR is everywhere identical to the primary TUT for oceans (viz., 0.5K). Those arrays not exceeding the threshold are classified as potentially cloud-free and pass immediately to the last two tests in the sequence. Failure of either a restoral test or a subsequent final test, causes the array to have a final classification of either cloudy or mixed. Deserts present a particularly difficult cloud/clear ambiguity for the Reflectance Ratio and Channel 3 Reflectance Tests, so these tests are excluded over such regions as they are defined by Mathews (1985).

Cloud detection at night cannot utilize Ch1, Ch2, or Ch3 reflectance measurements; so as seen in Table 2, a Thermal Test and a Thermal Uniformity Test are the first two cloud tests. To these is added a Uniform Low Stratus Test (ULST) based on

TABLE 2 CLAVR nighttime cloud test thresholds.

	LAND SCENE		OCEAN SCENE	
TEST	Channel	Threshold	Channel	Threshold
Thermal	4	< 249K	4	< 271K
Thermal Uniformity	4	> 3K	4	> 0.5K
Uniform Low Stratus	3,5	< fcn T4	3,5	< fcn T4
Ch. 4 - Ch. 5	4,5	> fcn T4	4,5	> fcn T4
Ch. 3/Ch. 5 - 1	3,5	> fcn T4	3,5	> fcn T4

the Ch. 3 - Ch. 5 temperature difference. This test, used in the MCSST nighttime algorithm, detects low stratus clouds that frequently escape the first two tests. The ULST used here has a Ch4-dependent threshold, determined from simulation studies, to allow for variable water vapor attenuation between the two channels. The Ch. 4 - Ch. 5 Test, also used in daytime, and a (Ch. 3/Ch. 5 - 1) Test are the final two. The latter test also employs a Ch4-dependent threshold to account for water vapor effects implicitly.

Because of the inability of the Thermal Test to differentiate between snow or sea-ice and cloud at night, all pixels poleward of 50 degrees latitude (60° for land) are subjected to a restoral test. Unless the Ch. 4 - Ch. 5 Test confirms that cloud is present in all four pixels, the pixel array is restored to clear and passes on to the subsequent tests. Also, desert emissivities at 3.7 micrometers are so highly variable that the ULST is excluded from the test sequence for such surface areas.

An example of the application of the CLAVR algorithm is shown in Figure 3, a map of cloud amount for July 9, 1986, from 0E to 110 W, pole to pole, for the ascending part of orbits (mostly sunlit except for the Antarctic). A grey scale is used to represent increasing cloud amount. The cloud amounts are computed for 1/2 degree latitude/longitude regions from the 2x2 pixel array classifications. As with the TOVS analysis, the regional distribution of the clouds looks reasonable. However, quantitative validation with our analyst-interactive image processor system indicates that cloud amount is being systematically overestimated when clear or partly cloudy, and underestimated when mostly cloudy or overcast with the Phase I algorithm. This bias can be significantly reduced by estimating cloud amount within <u>each</u> pixel, i.e. Phase II, where the universal thresholds are to be replaced with space/time

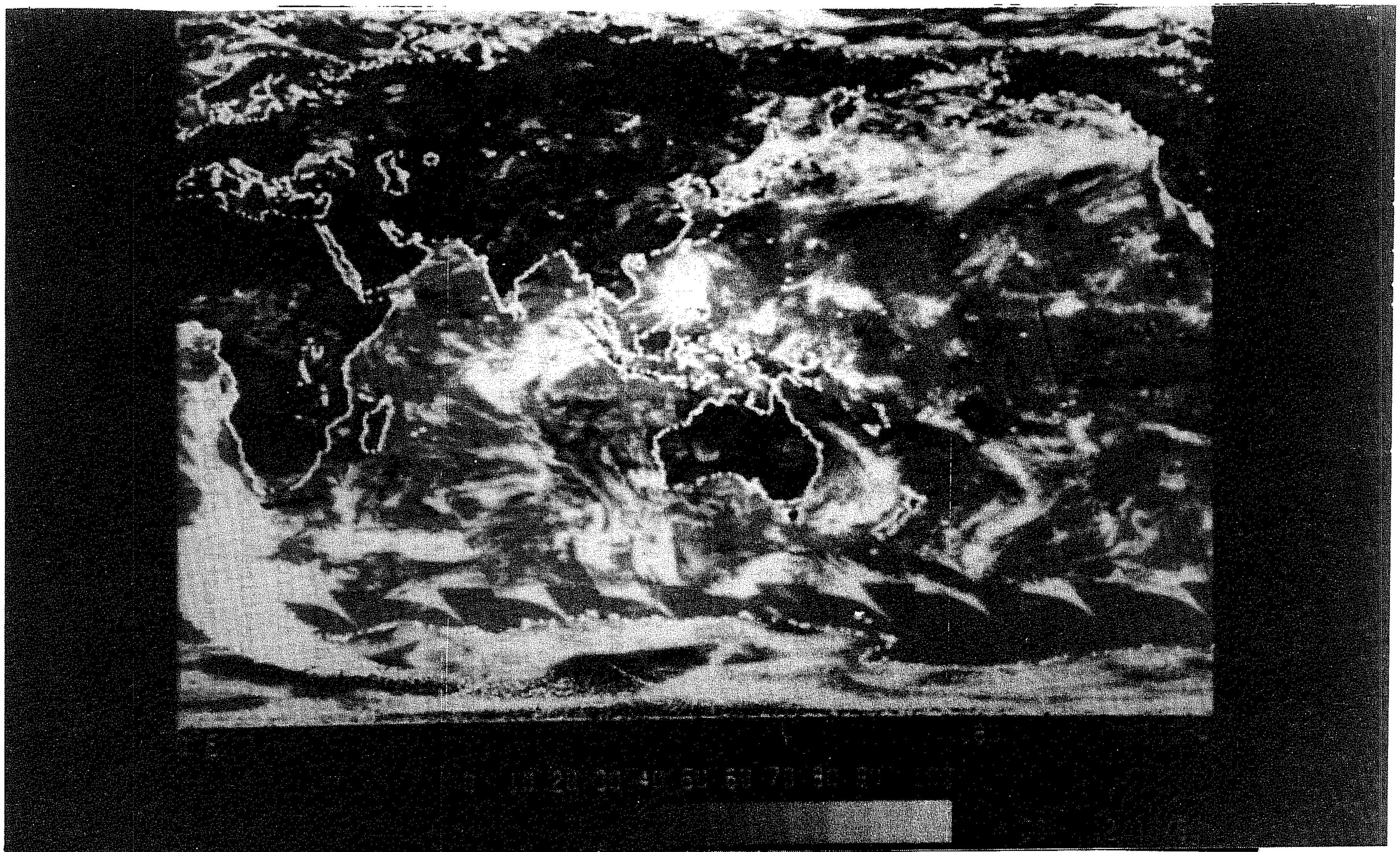

Figure 3. Cloud amount on a half degree grid for July 9, 1990, derived from the CLAVR (Clouds from AVHRR) Phase I Algorithm.

specific ones determined from an analysis of a 9-day series of mapped (1/2 degree grid) clear sky radiation data. Phase II will also incorporate some additional auxiliary information such as terrain height, atmospheric temperature profiles, snow/ice cover, as well as radiative transfer equations to estimate other physical and radiative properties of the clouds.

Surface/cloud "truth" is provided by using contrast-enhanced LAC (Local Area Coverage: 1.1x1.1 km at nadir) or GAC (Global Area Coverage: 1.1x4 km at nadir, sampled every 3rd scan line) scenes displayed on an image processor. An analyst can interact with the processor to independently estimate the amount of cloud in the scene. The image processor has also been used to evaluate the various cloud tests and to find the optimal thresholds for separating the cloudy, mixed, and clear pixel arrays.

In 1991 it is planned to implement Phase I into the operational data stream for real-time evaluation and testing of (1) the use of the CLAVR clear sky pixels as front-end input to the vegetation index, aerosol optical thickness, and sea surface temperature production programs; and (2) an experimental cloud amount product.

Additional cloud research in NESDIS includes the work of Wylie and Menzel (1989), who use sounding channels from the VISSR Atmospheric Sounder (VAS) of the Geosynchronous Operational Environmental Satellite (GOES) to infer cloud top pressure and "effective" cloud amount (see paper by Wylie in this volume). Stowe et al. (1989) have developed a bi-spectral cloud remote sensing algorithm for Nimbus-7 Temperature Humidity Infrared Radiometer (THIR) and Total Ozone Mapping Spectrometer (TOMS) data. They have developed a six year climatology of cloud amount and cloud-top equivalent black-body temperature covering the period April 1979 to March 1985. Also, research at NOAA

(Grody et al., 1980) and elsewhere has shown that cloud liquid water content can be derived from passive microwave instruments, e.g., the Air Force DMSP/SSMI (see Scofield paper in this volume). Research into deriving cloud frozen water content from these instruments has begun.

NOAA has also developed an aerosol parameter retrieval program utilizing AVHRR data over oceans (Rao et al., 1989). This program currently uses Channel 1 to retrieve aerosol optical thickness (AOT) for a wavelength of 0.5 microns. The observed "cloud-free" radiance, screened for clouds by a modified form of the MCSST algorithm, is compared with radiances computed from a radiative transfer model of the atmosphere/ocean system. The observed radiance is matched with a table of computed radiances, and the aerosol optical thickness (AOT) in the model that corresponds to this radiance is determined.

As an example of this product, Figure 4 shows a contour map for the four week period ending July 26, 1990. The dashed contours south of about 40S latitude indicate that no observations were taken within the period because solar zenith angles were greater than 70 degrees. The largest concentrations of aerosols (AOT in excess of 0.2) are from dust being blown off the deserts of Africa and Saudi Arabia, and from haze emanating from the eastern USA and western tropical South America. The air over the oceans of the Southern Hemisphere appears to be much "cleaner" than over the Northern Hemisphere, consistent with more land surface area and industry in the Northern Hemisphere.

In January, 1990, NOAA/NESDIS made its experimental AOT product operational, the experimental production having begun in July, 1987. Contour charts and digital tapes have been archived at the National Climate Data Center since the summer of 1989.

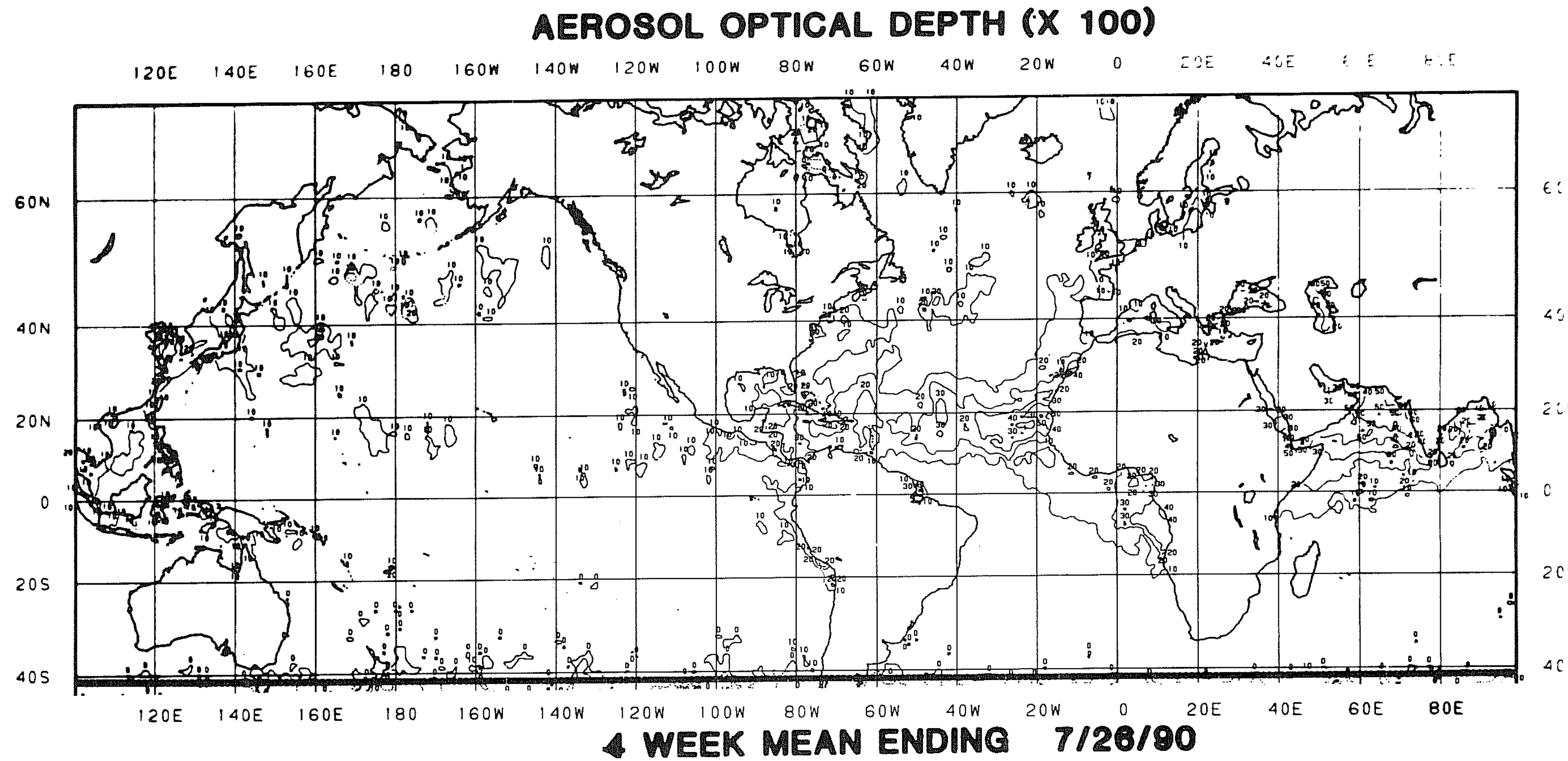

Figure 4. Contours of average aerosol optical thickness are shown for the four week period ending July 26, 1990. The contour interval is 10. Optical thickness is 1/100th the value shown on the contours. Dashed contours indicate that observations are more than four weeks old.

This data set complements the previously described cloud data sets being developed.

Validation of the AOT algorithm consists of intercomparisons with simultaneous surface-based sun-photometer measurements of spectral solar extinction. An off-line form of the algorithm, with manual cloud screening, was validated in 1980 using sun-photometer data from ten island locations in the Atlantic, Pacific, and Indian oceans. From the 132 cloud-free comparisons, the rms error was about 0.03, with a correlation coefficient of 0.95. The establishment of a permanent set of sun-photometer validation locations is greatly needed to continue this work.

Research has been performed that indicates that a more accurate estimate of optical thickness, and some information on size distribution of the particles, could be derived from the use of two and eventually, with AVHRR on the NOAA/KLM, three reflectance channels (Ahmad et al., 1989). The development of algorithms for use over land surfaces is also possible, and these may emerge as more work is done with the clear sky radiation data sets from the CLAVR algorithm. The most easily achievable improvement to the current algorithm would be to use data from the solar side of an orbit that are unaffected by specular reflection. This improvement is planned for implementation in 1991.

4. SUMMARY

The importance of clouds and aerosols for weather and climate prediction and diagnosis has been presented. The operational production of effective cloud amount and cloud top pressure from the TOVS instruments, and of aerosol optical thickness over the oceans from AVHRR data, was described. Improvements to the TOVS cloud retrieval algorithms to better account for the variable emissivity of clouds in the infrared spectrum, and a five channel cloud retrieval algorithm using AVHRR data, are under development. In the next five years, NOAA/NESDIS intends to provide multi-sensor cloud products, as well as AVHRR multi-spectral aerosol products, operationally over both ocean and land surfaces.

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