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MONITORING THE MT. PINATUBO AEROSOL LAYER WITH NOAA/11 AVHRR DATA

L. L. Stowe, R. M. Carey, and P. P. Pellegrino

NOAA/NESDIS

Abstract: The NOAA/NESDIS operational aerosol optical thickness product has provided an exceptional view of the development of the Mt. Pinatubo stratospheric aerosol layer. The product is derived from reflected solar radiation measurements of the Advanced Very High Resolution Radiometer onboard the NOAA/11 polar orbiting environmental satellite. The greater the optical thickness, the greater the amount of reflected solar radiation. Daily and weekly composites of aerosol optical thickness (AOT) at a wavelength of 0.5 micrometers have been analyzed to monitor the spatial and temporal variability of the aerosol layer and its optical thickness since the major eruption of Mt. Pinatubo on June 15, 1991. These analyses show that: the volcanic aerosol layer circled the Earth in 21 days; there are inhomogeneities in the layer that seem to remain after over two months of circling the Earth; using an AOT of 0.1 to define the layer, it covered about 42% of the Earth's surface area after two months, over twice the area covered by the El Chichon aerosol layer two months after its eruption; the layer is confined to the latitude zone 20S to 30N, with occasional patches seen at somewhat higher latitudes; the largest mean optical thickness of the layer was 0.31, occurring on August 23rd; the mass of SO_2 required to produce this aerosol optical thickness is 13.6 megatons; and, the globally averaged net radiation at the top of the atmosphere may be reduced by about 2.5 Wm^{-2} (cooling effect of at least $0.5^{\circ}C$) once the aerosol is distributed globally over the next two to four years.

Introduction

In July of 1987, NOAA/NESDIS began producing aerosol optical thickness (AOT) charts globally over the Earth's oceans from the Advanced Very High Resolution Radiometer (AVHRR). Prior to the eruption of Mt. Pinatubo on June 15, 1991, this aerosol product was being used to monitor the spatial and temporal distribution of tropospheric aerosols, such as dust from the Saharan and Saudi Arabian deserts, haze from industrialized urban areas, smoke from forest fires and agricultural burning. However, all of these events pale by comparison to the massive aerosol layer that has been produced by this eruption. Ash, dust, and sulfur dioxide gas were injected 20-30 km into the atmosphere, well into the stratosphere (Bluth, et al., 1992). Easterly stratospheric winds of 20-30 ms^{-1} carried this material westward. The larger (heavier) material fell out rather quickly, but the sulfuric acid particles created from the sulfur dioxide will linger for years. These particles reflect sunlight which is measured by the AVHRR onboard the NOAA/11 polar orbiting environmental satellite. Computer analyses convert the intensity of this reflected radiation into an aerosol optical thickness estimate (Griggs, 1983, Rao, et al., 1989). The more particles in the atmosphere, the greater the reflected intensity and the larger the AOT value.

Other scientists have also shown that aerosol optical properties can be derived from AVHRR reflectance data, e.g., Durkee, et al., 1986, Kaufman, et al., 1990. This capability is being developed because, besides affecting the quality of the air we breath, aerosol particles are very effective scatterers of solar radiation, and hence can alter the radiation budget of the planet, causing changes to its climate. For example, Hansen, et al., 1981, Charlson, et al., 1987, have hypothesized that atmospheric aerosol increases concomitant with increases of greenhouse gases, may be responsible for the more gradual increase observed in surface temperature compared with the increase predicted from climate models, which do not include the effects of aerosol variability. This realization has made aerosol remote sensing a major requirement of future climate monitoring systems, such as NASA's Earth Observing System.

In this paper, the remote sensing method will be briefly described. Then the observations of the Mt. Pinatubo aerosol layer will be presented, both in a sequence of weekly composite global images over a 12 week period, and as daily time/longitude and latitudinal average/time series plots for the Pacific ocean, where the east to west progression of the aerosol layer is clearly detected. A discussion of other measurements of Mt. Pinatubo and an estimate of the magnitude of this eruption compared with the El Chichon eruption of 1982 will be made, with inference to possible environmental consequences.

Remote Sensing Technique

The remote sensing of aerosol optical thickness is based on the theoretical and observed linear relationship between reflected solar radiation and aerosol optical thickness. Griggs, 1983, demonstrated that reflectance measurements from AVHRR could be used to extract aerosol optical thickness with a random error of about 0.03 - 0.05. This work was used as the basis for the NOAA/NESDIS operational algorithm.

The algorithm consists of the following steps:

1) generation of look-up tables using the Dave, 1972, scalar radiative transfer code, where the model parameters, adjusted to give best comparisons to simultaneous sun-photometer measurements are: Junge size distribution with radius exponent (nu) of 3.5; size range 0.03 to 10 micrometers; index of refraction 1.5-0.0i; Elterman 1964 vertical distribution; Lambertian surface albedo 0.015; these tables are computed in 6 degree increments over all possible ranges of solar and satellite zenith angles, and 10 degree increments in relative solar azimuth angle.

2) 2x2 arrays of AVHRR/GAC (1 x 4 km) pixels are selected from the anti-solar side of the orbit to avoid specular reflection from the ocean surface; these arrays are further selected as being cloud-free using multi-spectral sequential threshold algorithms developed for sea surface temperature measurements, (McClain, et al., 1985), and modified to include an important discriminator between aerosol and cloud, the reflected radiation at 3.7 micrometers (channel 3); a solar zenith angle dependent offset is applied to the radiance at 0.63 microns (channel 1) for each cloud-free pixel for consistency with the Dave model (i.e., minimum observed radiance matches that from Rayleigh scattering in the model).

3) Each 2x2 array average radiance is used to interpolate in the look-up tables to find the aerosol optical thickness that matches the observed radiance for each specific viewing and illumination condition; the derived optical thickness is adjusted to a wavelength of 0.5 microns in a manner consistent with the Junge particle model; the AOT values are composited over a seven day period and computer analyzed on a 1 degree latitude/longitude grid; the grid values are stored on computer tape and contour analyzed for display in chart form; tapes and charts are archived at the National Climate Data Center, in Asheville, NC.

Mt. Pinatubo Aerosol Layer Observations

To describe the development of the Mt. Pinatubo aerosol layer, a sequence of four computer enhanced images of the 1 degree weekly analysis data are shown in figure 1. The images are three weeks apart, beginning with week 6/15-6/19/91, the week of the major Mt. Pinatubo eruption, and ending with week 8/15-8/21/91. The AOT value is indicated with yellow shading, the larger the value the brighter the shade of yellow, until values in excess of 0.6 are shown

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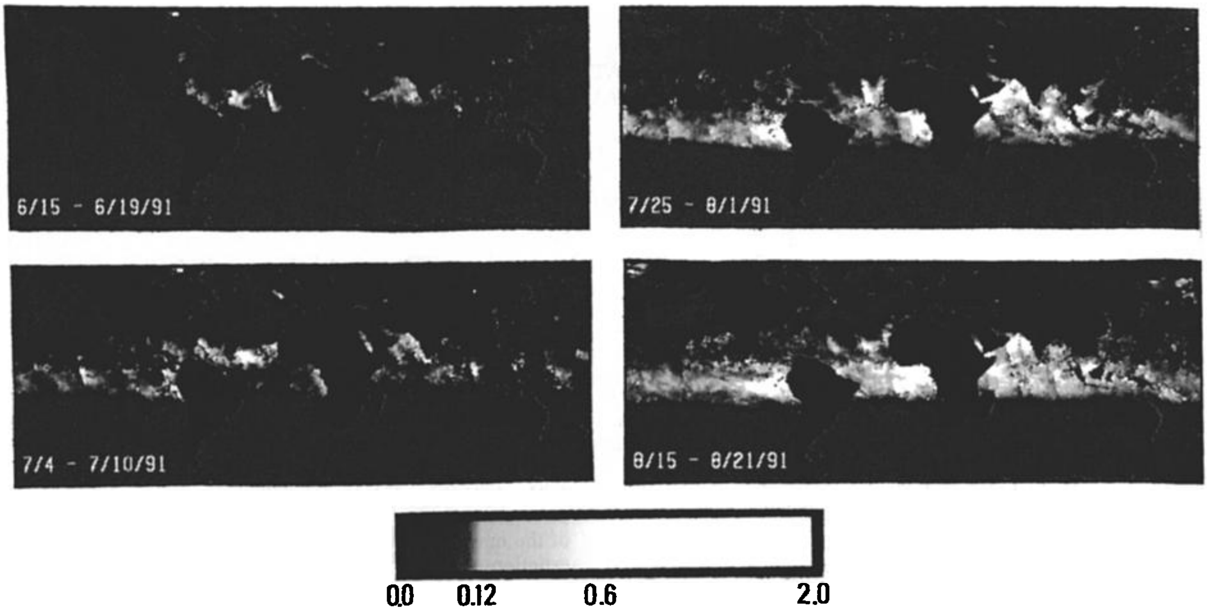

Fig. 1. Each image shows a color rendition of aerosol optical thickness (AOT) at 0.5 micrometer wavelength derived from AVHRR channel 1 reflectance data. The dull-yellow to bright-yellow/white shades show AOT values increasing between 0.12 and 0.6. The four images cover the time period from 6/15, the day of the major Mt. Pinatubo eruption, to 8/21, nine weeks after the eruption.

in white (the retrieval algorithm is capable of detecting AOTs as large as 2.0). Since random errors in the AOT measurement can be as large as 0.05, and to clearly delineate excessive amounts of aerosol back scattering from background levels, the yellow shades start at the 0.12 level of optical thickness. This is about a factor of 2 above normal oceanic background levels in the troposphere, and about 30 times larger than stratospheric background levels.

The earliest image shows extreme values of AOT east, north, and west of Africa, associated with dust being blown off the deserts, and possibly some haze in the Arabian Sea generated by the smoke coming from oil fires in Kuwait. Also evident are patches of elevated AOT values associated with haze coming off the East coasts of the United States and Asia. The Mt. Pinatubo aerosol layer has just begun to form as apparant from the elevated AOT values around Indonesia.

Three weeks later, the stratospheric aerosol layer has been transported westward by the stratospheric winds, completely encircling the tropics back to the Philippines, their origin. At this time the layer appears to be spanning about 40 degrees of latitude, from 15S to 25N. The longitudinal bands apparent in this and subsequent images are caused by the satellite sampling on only one side of an orbit.

The next image shows that the layer has slowly expanded north and south, as well as becoming thicker during this three week period. The AOT values are increasing as indicated by increasing areas of white and bright yellow in the images (also see fig. 3). In the last image, the southern boundary is between 18-20S, and the northern boundary between 25 and 30N, covering as much as 42% of the Earth. Also evident in this image is smoke from forest fires in Siberia, first noticeable off the Kamchatka Peninsula and in the Bering Sea a week earlier.

Small patches appear to break off from the tropical layer and move to higher latitudes, particularly in the northern hemisphere. It is probably these patches that have caused some brilliant sunrises and sunsets at latitudes outside of the main band of aerosol.

As the seasons change, the stratospheric wind circulation will also change, eventually causing this tropical aerosol layer to be distributed over the entire globe. The SAGE instrument (McCormick and Veiga, 1992) has already detected Mt. Pinatubo aerosols globally, but at AOT levels below the AVHRR detectability of about 0.02 - one digital count. Progressively, these particles will fall out of the stratosphere, but this could take five to ten years.

The remainder of the analyses will be confined to the tropical Pacific Ocean, since this ocean is least affected by tropospheric aerosols. Shown in figure 2 is a time/longitude contour analysis of

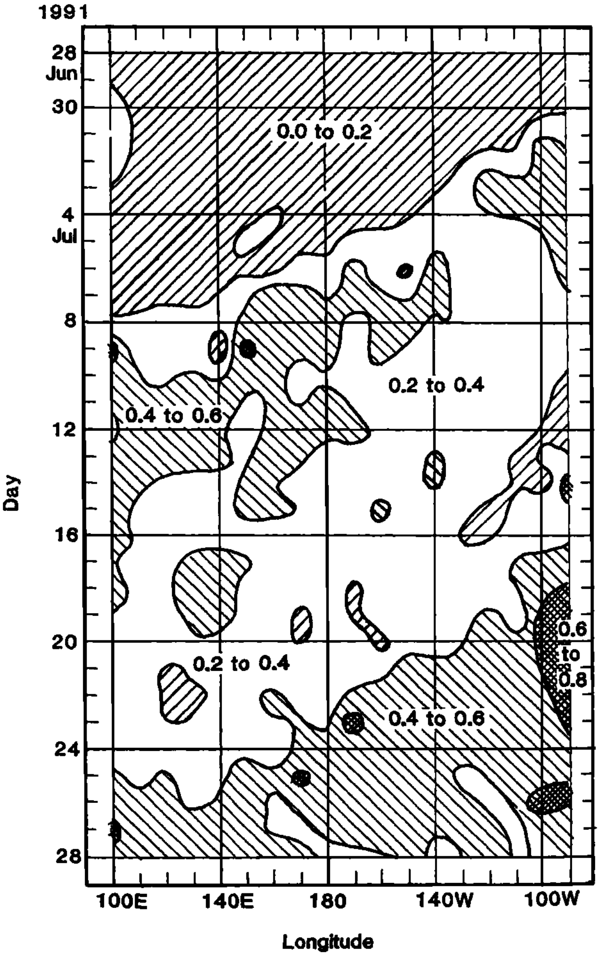

Fig. 2. The east to west progression of the stratospheric aerosol layer and the increase in AOT with time is evident from the slope of the 0.2 and 0.4 contour lines on this plot of AOT for the zone from 0-10S at ten degree longitude increments from 80W to 100E, over the period of time from 6/28 to 7/28/91.

the mean AOT in ten degree latitude/longitude bins centered at 5S and ranging in time from the 28th of June, to the 28th of July, and 100 spanning 80W to 100E longitudes. The slope of the 0.2 contour line indicates that from July 1 to July 8, the aerosol layer was moving westward at about 28 ms^{-1}. Some 16 to 18 days later, another band of increased AOT passed from east to west, this time appearing slightly thicker, and having a slope consistent with eesterly winds of about 22 ms^{-1}. Although not shown, similar analyses for the month of August, show that this 16-18 day wave is maintained, suggesting that inhomogeneities in the aerosol layer are not mixing longitudinally, but are being transported around the equator.

Another way of displaying this wave behavior, as well as estimating the average optical depth for the layer, is shown in figure 3, where the zonal average AOT value between 100E and 80W is shown for five ten degree wide latitude bands between 20S and 30N. The latitudinal averages of AOT were all clustered between 0.04 an 0.1 prior to July 1st. After that date, each latitude zone appears to begin to increase its optical thickness, most rapidly from 0-10N, reaching a peak of 0.4 on July 6th. The slowest to rise is the band from 20-30N. As the aerosol layer continued its circulation around the tropics, the band averages cycle with time, with a period of about 18-22 days, as also shown in figure 2. After July 7th, except for a few days near the end of July, the 0-10S band appears to have the largest AOT values, peaking at 0.57 on August 23rd. The latitudinal gradient in AOT is consistent with the color shading seen in figure 1.

The area weighted average AOT on August 23rd between 20S and 30N was 0.38. After this date, the AOT in all layers began to decrease, until on November 30th, the mean layer AOT was 0.24. By contrast, the average value on June 28th, prior to any volcanic aerosol in this area, was 0.07, the result of background tropospheric aerosol scattering. This analysis suggests that the largest mean AOT for the Mt. Pinatubo stratospheric aerosol layer between 20S and 30N observed thus far is 0.31, and occurred on August 23rd.

Discussion and Possible Environmental Impacts

The analyses of McCormick and Veiga, 1992, indicate that the aerosol particles are concentrated between 16 and 25 km above sea level and that patches of the layer have broken off and been observed periodically at high latitudes. Compared with sulfur dioxide measurements following the 1982 eruption of El Chichon, the Mt. Pinatubo eruption is at least twice as large according to Bluth et al., 1992. They estimate that 18.5 megatons of SO$_2$ were emitted into the atmosphere, compared with 7 megatons for El Chichon.

The maximum daily mean AOT value of 0.31 for the Mt. Pinatubo layer observed by AVHRR corresponds to a mass of 13.6 megatons of SO$_2$ for the assumed Junge size distribution. This is quite close to that reported by Bluth, et al., considering the large number of assumptions that enter into such calculations. The total mass of a 75% by weight solution of sulfuric acid aerosol particles is 1.8 times the mass of sulfur dioxide needed to form it.

Computer models of the climate, e.g., Hansen et al., 1981, indicate that stratospheric aerosol layers covering the entire globe for years can decrease surface temperatures by about 2°C for every 0.2 increase in AOT. These particles reflect solar radiation more effectively than they trap the Earth's heat radiation, so the net effect is to cool the Earth's surface.

The effect of the Mt. Pinatubo aerosol layer on the radiation budget at the top of the Earth's atmosphere has been estimated using the theoretical calculations of King, et al., 1984, together with the AOT measurements from AVHRR. Assuming that the maximum AOT observed for the 20S to 30N layer (42% of globe) is spread uniformly over the globe, the mean global AOT value would be 0.13 (i.e., 0.31 x 0.42). Using this value, the King, et al. sensitivity estimates indicate that: 1) the planetary albedo would be increased by 1.3%; 2) the shortwave reflected flux would be increased by 4.3 Wm^{-2}; 3) the longwave emitted flux would be decreased by 1.8 Wm^{-2}; and 4) the net radiation flux would be reduced by 2.5 Wm^{-2}. This change in net flux could cause a net global cooling of about 1°C according to Hansen's model results. For comparison purposes, this change in net radiation is about half the change resulting from a doubling of carbon dioxide, the radiative forcing used to compute a global warming of between 2°C and 4°C, depending on feedback processes in the models.

Experience from El Chichon, which provided AOT values in excess of 0.2, but only in a latitude band between 5N and 25N (17% of globe, Strong, 1984), was that, after the aerosol was dispersed

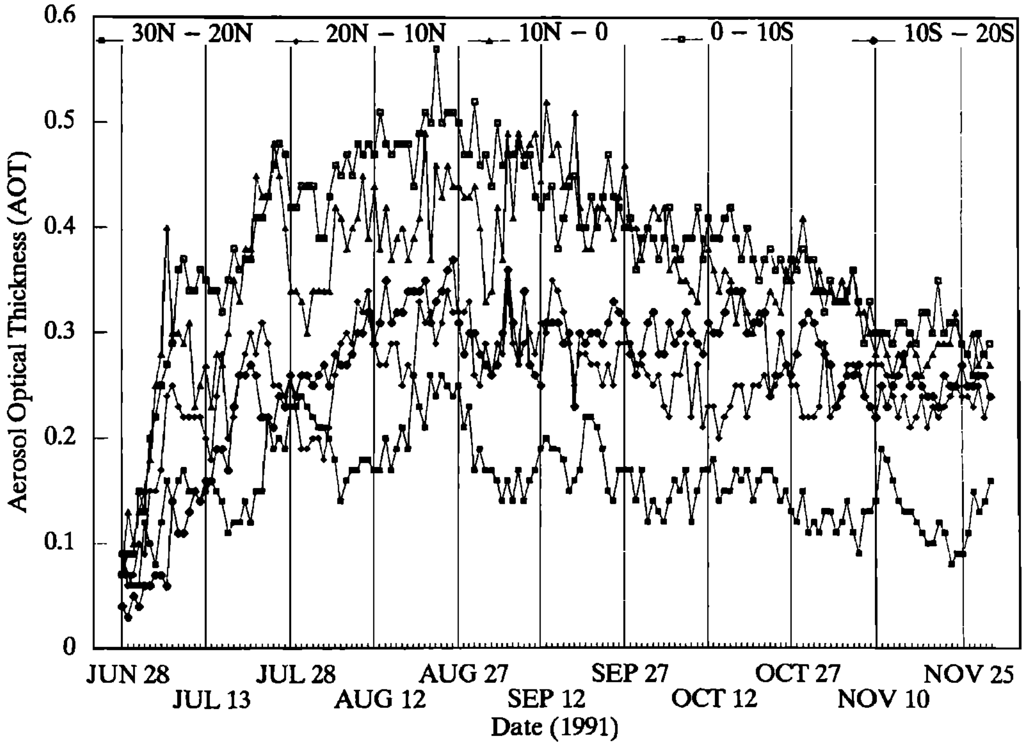

Fig. 3. Plot of mean AOT for ten degree latitude zones from 20S to 30N, covering the longitude range of 80W to 100E in the Pacific Ocean, over the period from 6/28 to 11/30/91.

over the globe, the AOT was substantially reduced and so was the cooling effect. The cooling has been estimated to be about 0.2 to 0.3°C (850-300 mb average) within three years of the eruption (Angell, 1990). However, because of the occurrence of a major El Nino (warming of the eastern tropical Pacific ocean) at the same time, much of this surface cooling was absent from the temperature record.

Since Mt. Pinatubo appears to be similar in many respects to El Chichon, except that it is at least twice its size, it seems reasonable to expect the Earth to temporarily cool by at least 0.5°C within the next two to four years. Climate models indicate that it is reasonable to expect that this cooling will be most pronounced over high latitude land masses (Hansen, et al., 1992). Having a higher heat capacity than land, the ocean cooling will be less than over land, with the largest changes probably occurring in the tropics, since the aerosol will have resided there longer. However, the cooling expected from Mt. Pinatubo may be reduced if the current El Nino (warming of the eastern tropical Pacific ocean) continues or becomes stronger.

The aerosol in the stratosphere may also, as was observed with El Chichon, deplete the ozone in the stratosphere via heterogenous chemical reactions (Hofmann and Solomon, 1989). This would increase the risk of skin cancer over the next few years.

Beautifully colored sunrises and sunsets may be expected at higher latitudes as the aerosol layer disperses globally.

It is even possible that as the sulfuric acid particles eventually descend through the troposphere, they may lead to small increases in the acidity of rain.

Much remains to be learned about the effects of the Mt. Pinatubo aerosol layer on our climate and lives. Through continued monitoring and analysis of this NOAA operational product, never before available following a major volcanic eruption, this knowledge should be more readily obtained.

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L.L. Stowe, R.M. Carey, and P.P. Pellegrino
NOAA/NESDIS, E/RA11, Room 711, WWB, Washington, D.C. 20233.

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