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# Evaluation of the Navy Oceanic Vertical Aerosol Model Using Lidar and PMS Particle-Size Spectrometers

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# SUMMARY

## OBJECTIVE

Evaluate the Navy Oceanic Vertical Aerosol Model (NOVAM) by using the Naval Ocean Systems Center's airborne meteorological platform and the Army's Visioceilometer (lidar).

## APPROACH

Airborne lidar and aerosol-size distribution measurements were made, and the calculated aerosol extinction coefficients were compared with those predicted by NOVAM.

## CONCLUSIONS

NOVAM-predicted extinction coefficient profiles have a similar structure to the aircraft-measured profiles but underestimate the absolute value. When the predicted extinction values are scaled to visibility, good agreement exists between the measured and predicted profiles. Agreement between the predicted and measured extinction coefficients is strongly dependent on air-mass factor.

## RECOMMENDATIONS

The Navy Oceanic Vertical Aerosol Model needs to be scaled to visibility and include an input parameter which better estimates the air-mass factor to provide a more accurate aerosol extinction profile within the marine boundary layer.

# CONTENTS

## FIGURES

# INTRODUCTION

The Navy's development and evaluation of electrooptical systems utilize the LOWTRAN propagation codes.[1,2] These codes incorporate several different atmospheric aerosol models, such as the Navy Maritime Aerosol Model,[3] for calculating aerosol scattering and absorption properties. Another aerosol model being developed that is destined for LOWTRAN is the Navy Oceanic Vertical Aerosol Model (NOVAM).[4] This model is being developed to include the vertical structure of the aerosol extinction coefficients within the marine boundary layer (MBL). It is based on a combination of empirical and physical models[3,5,6,7] which describe the dynamic behavior of aerosols. A summary of NOVAM and its initial evaluation has been given by Gathman, et al.[4] This report extends the initial evaluation by comparing the calculated aerosol extinction profiles from PMS (Particle Measuring Systems, Inc.) particle-size spectrometers (scaled to lidar atmospheric returns) with NOVAM model predictions. Lidar returns cannot be compared directly to the NOVAM predictions because the model aerosol scattering parameters (extinction and backscatter) are not available in the present software configuration. The conclusions are based on a limited data sample taken 30 March 1989.

# MEASUREMENTS

On 30 March 1989, nearly simultaneous measurements of atmospheric structure were made by using the Naval Ocean Systems Center (NOSC) airborne platform (Piper Navajo aircraft)[8] and the Army's Visioceilometer (lidar).[9] The lidar was mounted on the aircraft so as to be pointing vertically downward. Aerosol-size distribution measurements were made with the PMS ASSP-100 aerosol-size spectrometer. The aircraft made a slow ascending spiral over the ocean just south of Pt. Loma, San Diego, CA, from 30 meters to 1525 meters in approximately 8 minutes. Air temperature, pressure, and relative humidity were measured and recorded every 5 seconds (height resolution of 4.5 meters). A complete aerosol spectrum was obtained every 4 seconds (3.6-meter resolution). At 300-meter intervals the aircraft leveled momentarily while the lidar was fired vertically downward. The measured aerosol-size distributions were used to calculate (via MIE theory) the extinction and backscatter profiles. The lidar shots were combined to generate a received backscattered lidar signal profile ($S(R)$) as a function of altitude. The lidar $S(R)$ quantity is given by

$$S(R) = \ln[P(R)R^2] \qquad (1)$$

where $P(R)$ is the power received from the scattering volume at a range $R$. In terms of extinction and backscatter, the lidar single-scatter equation is given by

$$S(R) = \ln(C_1) + \ln[\beta(R)] - 2 \int_0^R \sigma(r)dr \qquad (2)$$

where $\sigma(R)$ and $\beta(R)$ are the range-dependent volumetric extinction and backscatter coefficients, respectively, and $C_1$ is the lidar instrumentation constant. Equation 2 relates the calculated aerosol extinction and backscatter coefficients obtained from PMS aerosol measurements to the lidar back-scattered signal $S(R)$.

# DATA PRESENTATION

Figure 1 shows the vertical sounding of air temperature and relative humidity. Surface visibility was 12–13 km. The inversion base was at 150–200 meters (shallow surface haze layer). Surface winds

were northwesterly at 4.9 m/s. Figure 2 shows the profiles of aerosol extinction and backscatter coefficients. Peak extinction and backscatter occurred just below the inversion at approximately 150 meters. Above 350 meters the coefficients on the average decrease with altitude. Figure 3 shows the $S(R)$ profile taken by the lidar at 600 meters ($S(R)_{lidar}$). By using the aerosol extinction and backscatter coefficients of Fig. 2, an expected $S(R)$ profile can be calculated for the aerosol data ($S(R)_{aerosol}$) from Eq. 2. The $S(R)_{lidar}$ and $S(R)_{aerosol}$ profiles are compared in Fig. 4. Good agreement exists between the two profiles up through the inversion (region of higher aerosol density), but the profiles differ significantly above the inversion (region of lower aerosol density). Above 250 meters the $S(R)_{aerosol}$ data are consistently less than those measured by the lidar (with the exception near 350 and 600 meters). These lower extinction and backscatter-derived $S(R)$ values undoubtedly resulted from:

1. The statistical sampling period required for low aerosol concentration sampling was not sufficient to obtain an adequate data sample.[10]

2. The ASSP-100 was designed and calibrated to size pure spherical water droplets, an unlikely condition above the inversion on a clear day.

3. Particles above the inversion were more likely solid, nonspherical, and inactivated (not growing with relative humidity).[11]

4. The dynamic range of the PMS spectrometer was limited to sample smaller particles (minimum diameter of 0.45 μm).

Above 250 meters the particles most likely did not represent the type of aerosol the PMS ASSP-100 spectrometer was designed and calibrated for.

Following the technique developed by Hughes and Paulson for adjusting aerosol model densities to match lidar $S(R)$ returns,[12] the aerosol-size distribution data, i.e., the aerosol number density and resulting extinction and backscatter coefficients, can be adjusted to allow the calculated $S(R)_{aerosol}$ values from Eq. 2 to match the measured lidar $S(R)$ returns, or

$$S(R)_{aerosol} = S(R)_{lidar} \tag{3}$$

To do this, Eq. 2 is expressed in terms of a scaling quantity, $k$, as

$$S(R)_{aerosol} = \ln(C_1) + \ln[k\beta(R)] - 2\int_0^R k\sigma(R)dr \tag{4}$$

where $k$ is the multiplier of the measured size distribution which allows Eq. 3 to be satisfied. The $k$ value is determined from the measured and calculated data by expressing Eq. 4 in terms of altitude, $h$ (atmosphere assumed to be composed of finite layers at altitude $h_o, h_1, ....h_n$), and solving it by iteration for $k$ at each altitude until Eq. 3 is satisfied.[12] Figure 5 shows the scaling factor, $k$, required to match the aerosol and lidar $S(R)$ data to within 0.1 percent; $k$ varied from 0.7 to 2.25 below the inversion and up to 3.4 above. This result is in agreement with that found by Jensen, et al.[13] They reported that extinction coefficients derived from PMS spectrometer data could vary from ground truth measurements by as much as a factor of three for clear, dry days.

## NOVAM MODEL COMPARISON

NOVAM used the measured surface meteorological data for 30 March 1989 and the corresponding profile of air temperature, relative humidity, and pressure to calculate the predicted vertical profile

of aerosol extinction. Calculations were made for both marine and continental air-mass factors (AMFs) of 1 and 10, respectively. The measured AMF was not available for 30 March 1989. Figure 6 compares the NOVAM extinction predictions for a wavelength of 1.06 µm with those calculated for both the scaled (k multiplier) and unscaled aerosol data. These data show the strong dependency of NOVAM on AMF. When the AMF was varied from 1 to 10, the predicted NOVAM extinction coefficients changed by more than an order of magnitude. The aerosol extinction profiles (both scaled and unscaled) exceeded the predicted NOVAM values for both AMFs. Figures 7 through 9 show similar comparisons for wavelengths of 0.53, 3.5, and 10.6 µm. For all wavelengths, except the visible, NOVAM underestimated the extinction values.

The underestimated extinction values partially resulted from NOVAM not being scaled to surface visibility. Figures 10 and 11 show the 0.53-µm NOVAM calculations for AMFs of 1 and 10, respectively, scaled to the observed surface visibility of 12 km. This scaling forces the lowest level extinction values to be equal. A better agreement now exists between the NOVAM-predicted and the scaled-aerosol extinction profiles. Below the inversion base (150–200 meters), the NOVAM-predicted values did not increase as rapidly as did those obtained from the aerosol data. At the inversion height, an excellent agreement existed, especially for the AMF of 10. Above the inversion (250 meters), the occurrence of a larger variation can be attributed to the aerosol sampling problems previously discussed. Figures 12 and 13 show the NOVAM calculations for the far infrared (10.6 µm) and AMFs of 1 and 10, respectively, scaled to the 0.53-µm surface visibility of 12 km. Even though the structural details below the inversion (150–200 meters) are evident in both profiles, NOVAM still underestimated the extinction magnitude for 10.6 µm. The 10.6-µm-predicted (scaled to visibility) and the measured extinction profiles are in better agreement for an AMF of 1, but not so for an AMF of 10 (refer to the comparison in Fig. 9).

# CONCLUSIONS

The Navy Oceanic Vertical Aerosol Model was evaluated by using nearly simultaneous measurements of atmospheric aerosol structure made with an airborne lidar and a PMS aerosol-size spectrometer. Profiles of measured aerosol-size distributions were scaled to the lidar $S(R)$ returns and compared with the NOVAM predictions. The NOVAM predictions underestimated the extinction values for all AMFs. However, when the predicted extinction values for a given AMF were scaled to surface visibility (scaling not incorporated in NOVAM), better agreement existed between the predicted and the measured vertical profiles of extinction. Atmospheric vertical structural characteristics agreed well with those observed by PMS aerosol spectrometers and lidar returns, especially below the inversion.

The magnitude of the NOVAM extinction predictions is critically dependent upon identifying the air mass as either marine or continental. For AMFs between 1 and 10, the predicted extinction coefficients vary by more than an order of magnitude. Because of this NOVAM dependency on AMF and the difficulty in obtaining a good AMF determination from either radon concentration measurements or an air-mass trajectory analysis, S. G. Gathman* is incorporating into NOVAM a technique whereby AMF is deduced from visibility measurements.

The Navy Oceanic Vertical Aerosol Model shows potential for predicting the vertical aerosol structure within the marine boundary layer. Scaling to visibility and incorporating a technique to better estimate the AMF are expected to improve NOVAM for calculating scattering and the absorption properties of the MBL.
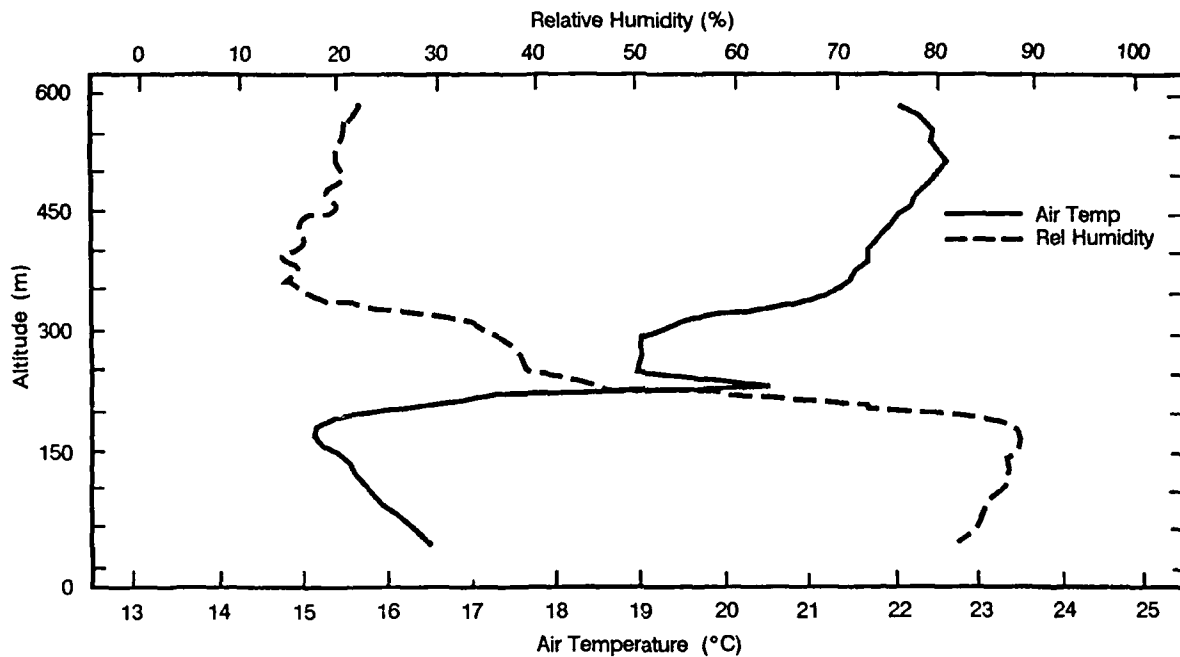
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*Private communication.

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Figure 1. Profiles of air temperature and relative humidity
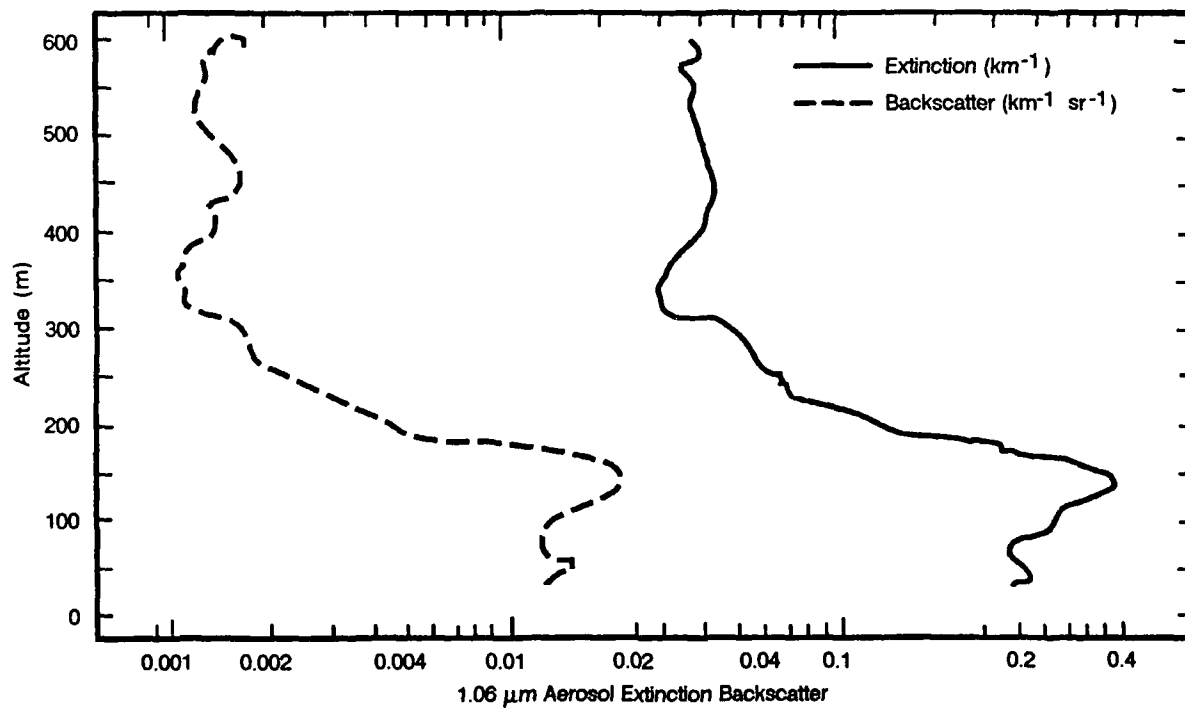for 30 March 1989, 2218:54 GMT.



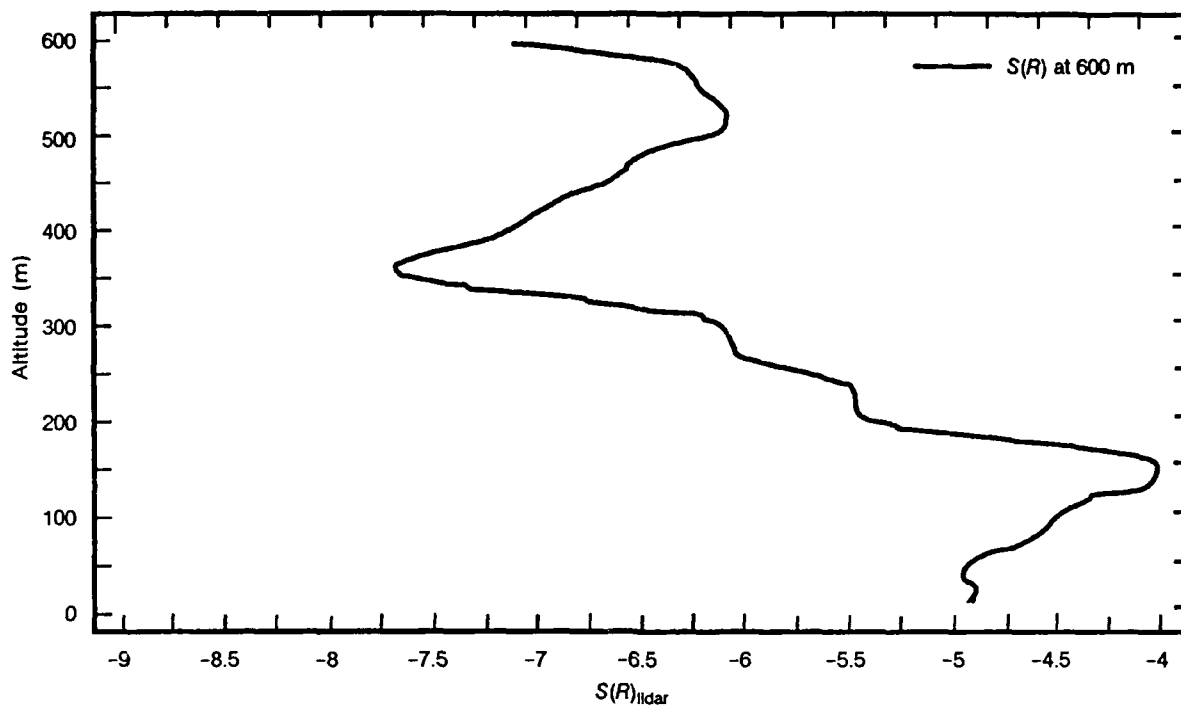Figure 2. Profiles of calculated (1.06 μm) aerosol extinction
and backscatter coefficients.

Figure 3. Profile of airborne lidar $S(R)$ returns from 600 meters.



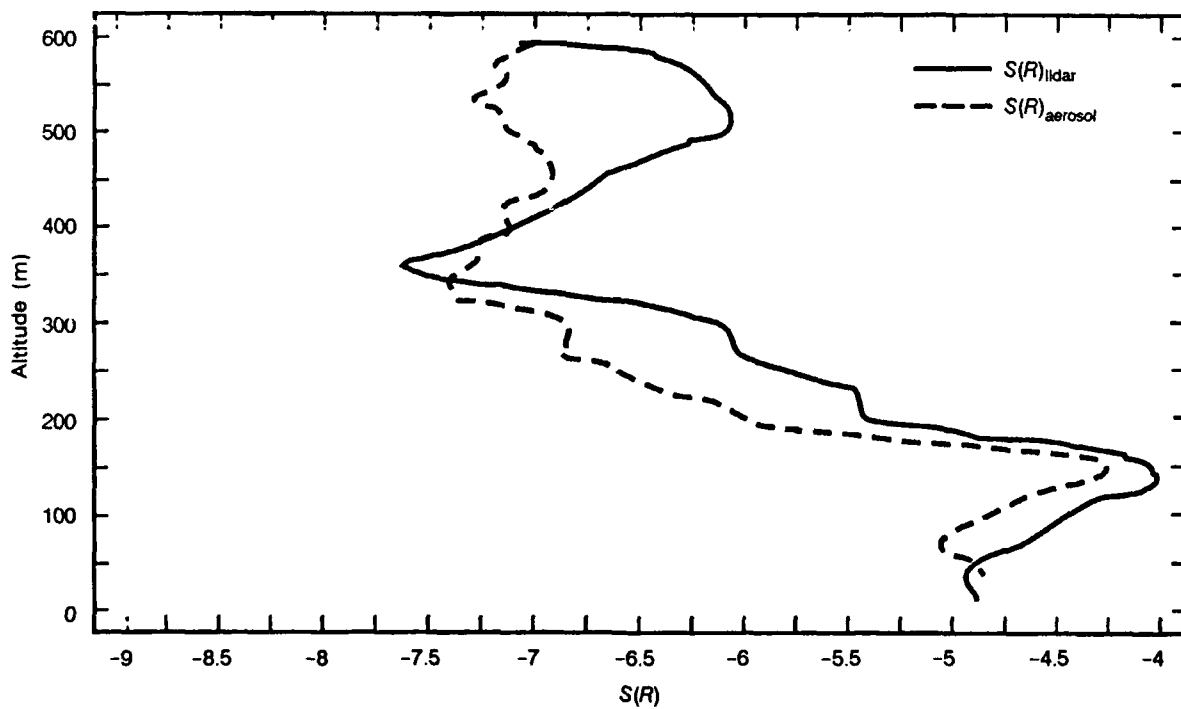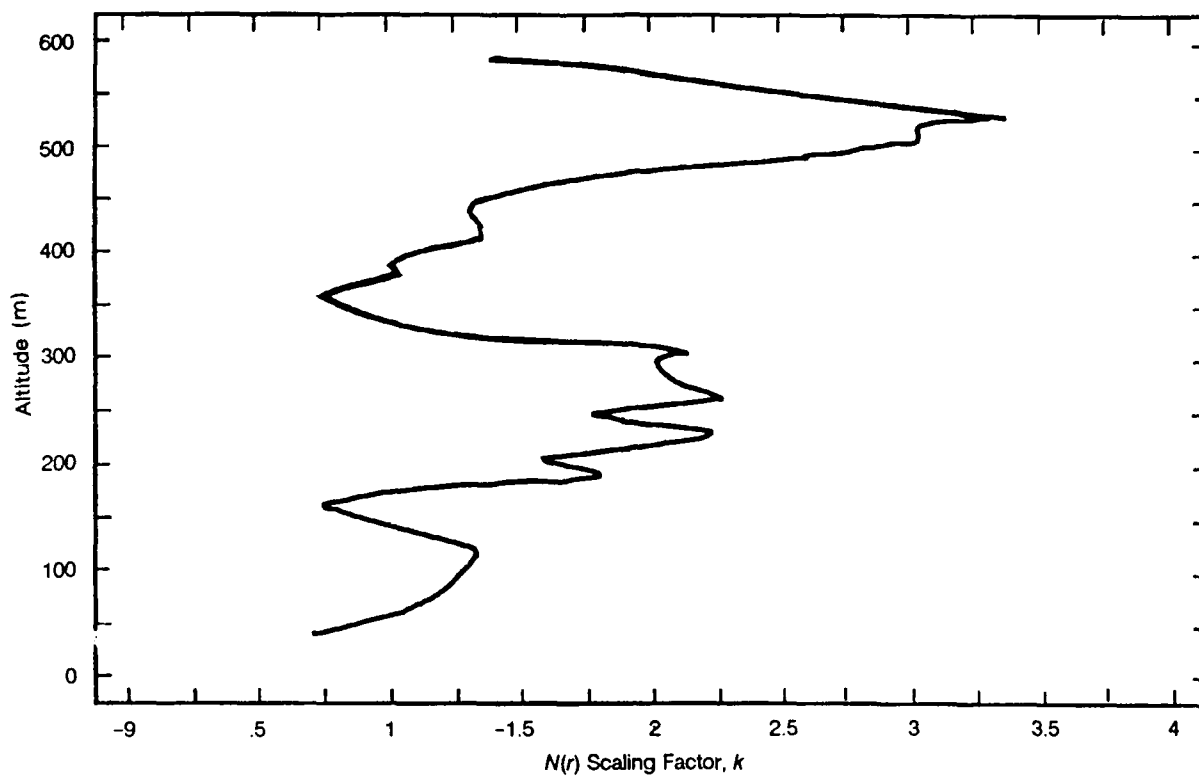Figure 4. Comparison of the lidar $S(R)_{lidar}$ and calculated $S(R)_{aerosol}$ profiles.

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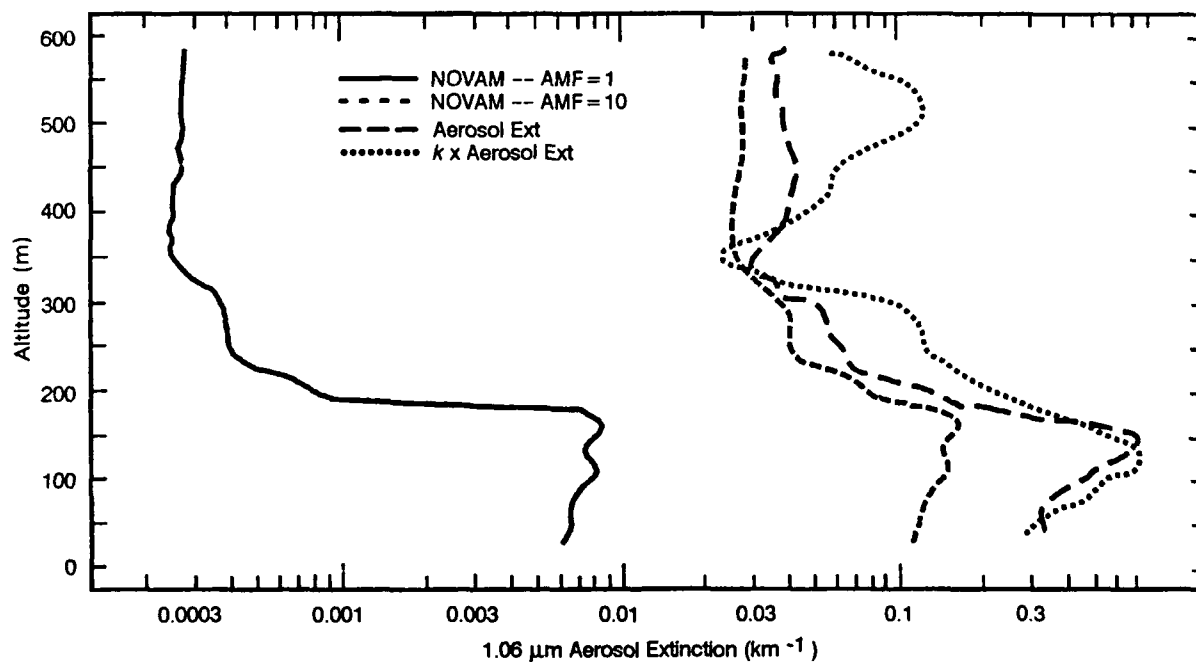Figure 5. Scaling factor $k$ to make the $S(R)_{\text{aerosol}}$ and $S(R)_{\text{lidar}}$ profiles match.



Figure 6. Comparison of NOVAM-predicted 1.06-μm extinction profiles with that calculated using aerosol data (both scaled and unscaled).

Figure 7. Comparison of NOVAM-predicted 0.53-μm extinction profiles with that calculated using aerosol data (both scaled and unscaled).



Figure 8. Comparison of NOVAM-predicted 3.5-μm extinction profiles with that calculated using aerosol data (both scaled and unscaled).
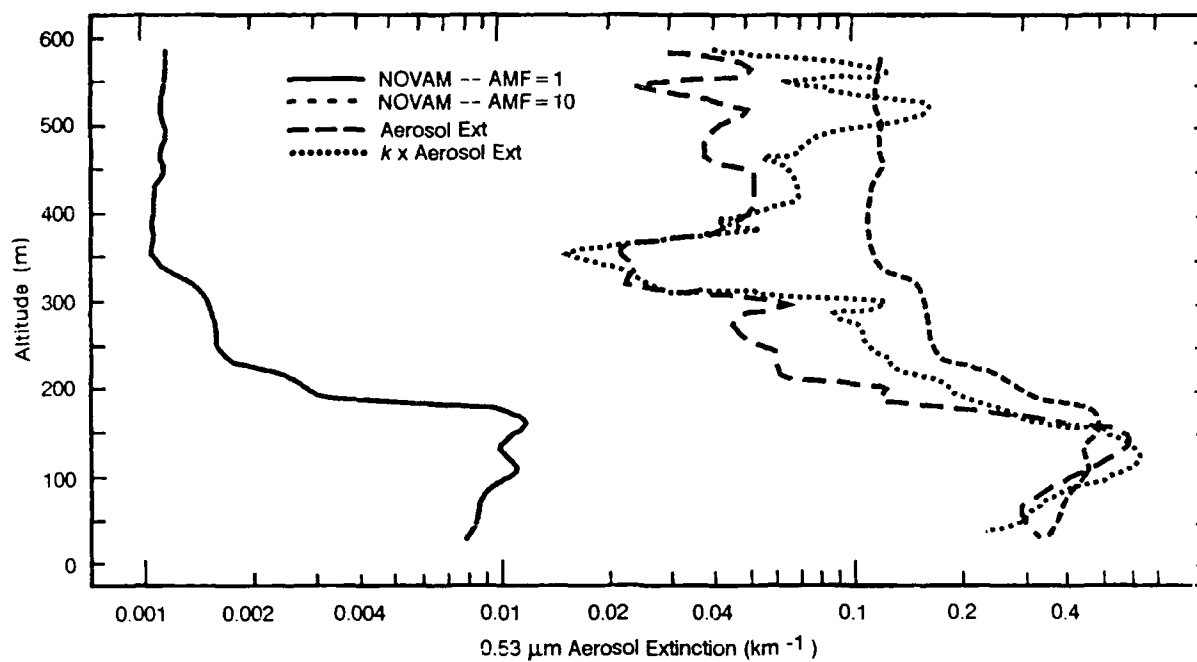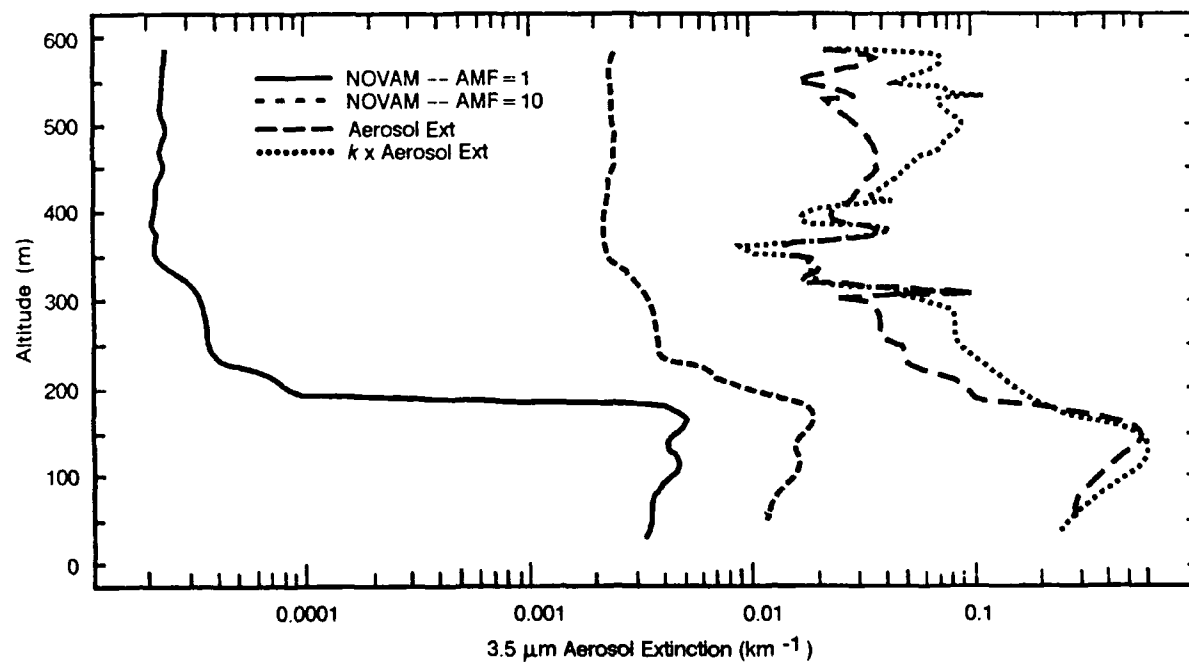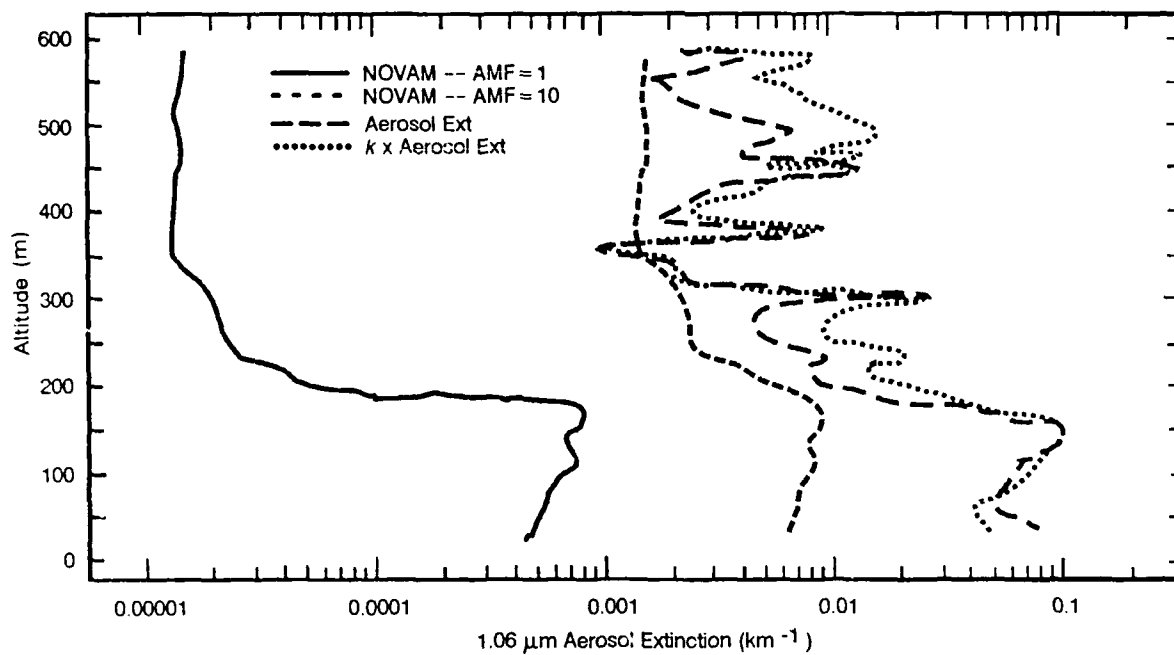
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Figure 9. Comparison of NOVAM-predicted 10.6-µm extinction profiles
with that calculated using aerosol data (both scaled and unscaled).



Figure 10. Comparison of NOVAM-predicted 0.53-µm extinction
profiles scaled to surface visibility with that calculated using aerosol
data. AMF = 1.

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Figure 11. Comparison of NOVAM-predicted 0.53-μm extinction profiles scaled to surface visibility with that calculated using aerosol data. AMF = 10.



Figure 12. Comparison of NOVAM-predicted 10.6-μm extinction profiles scaled to surface visibility with that calculated using aerosol data. AMF = 1.
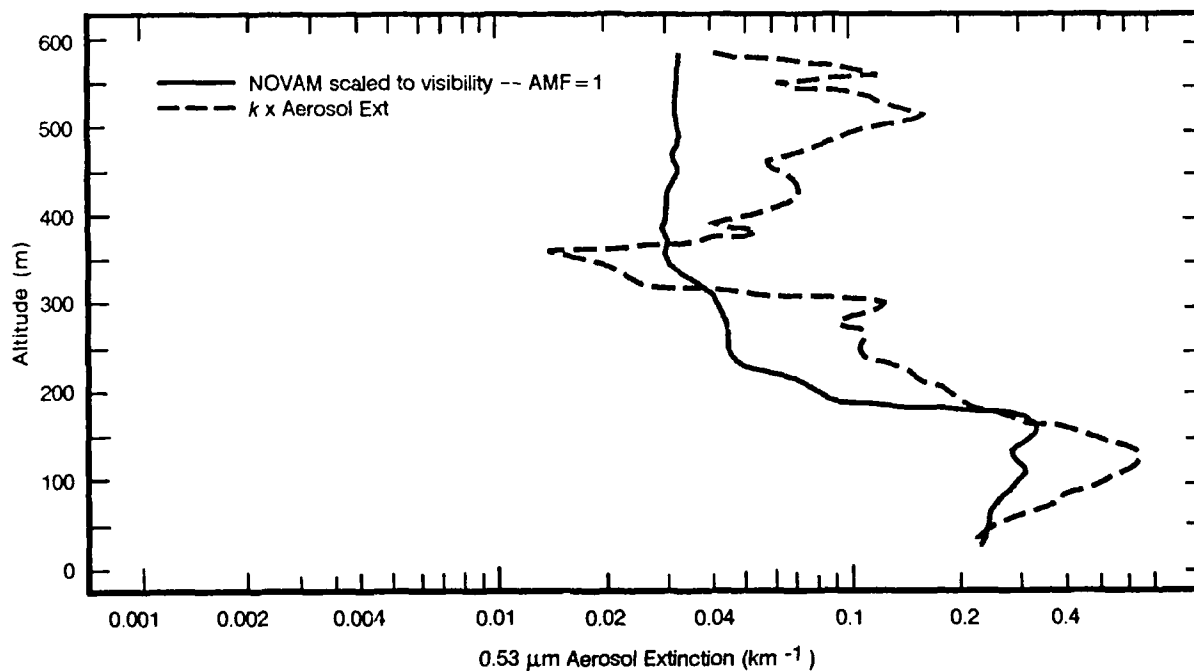
Figure 13. Comparison of NOVAM-predicted 10.6-μm extinction profiles scaled to surface visibility with that calculated using aerosol data. AMF = 10.
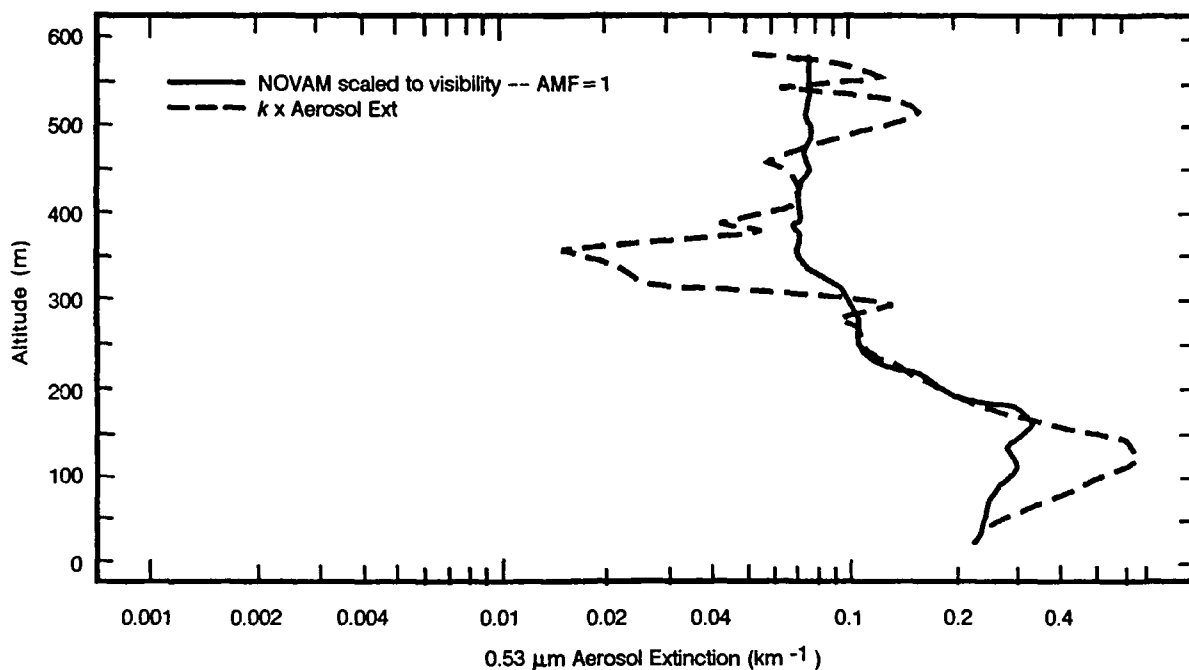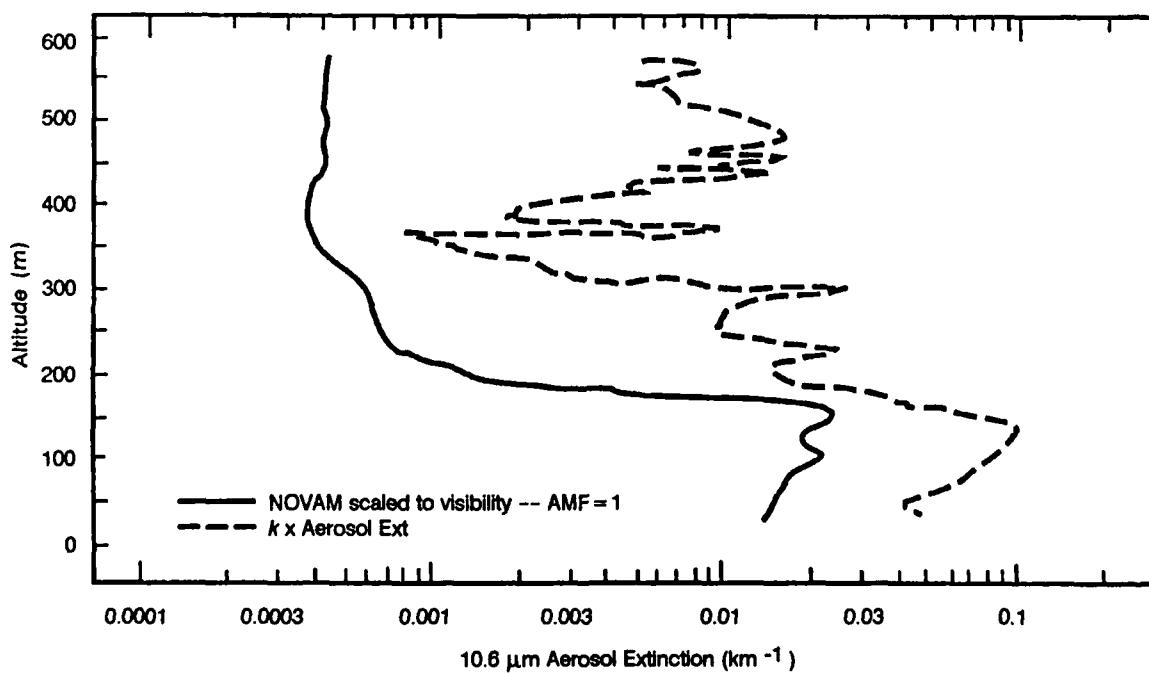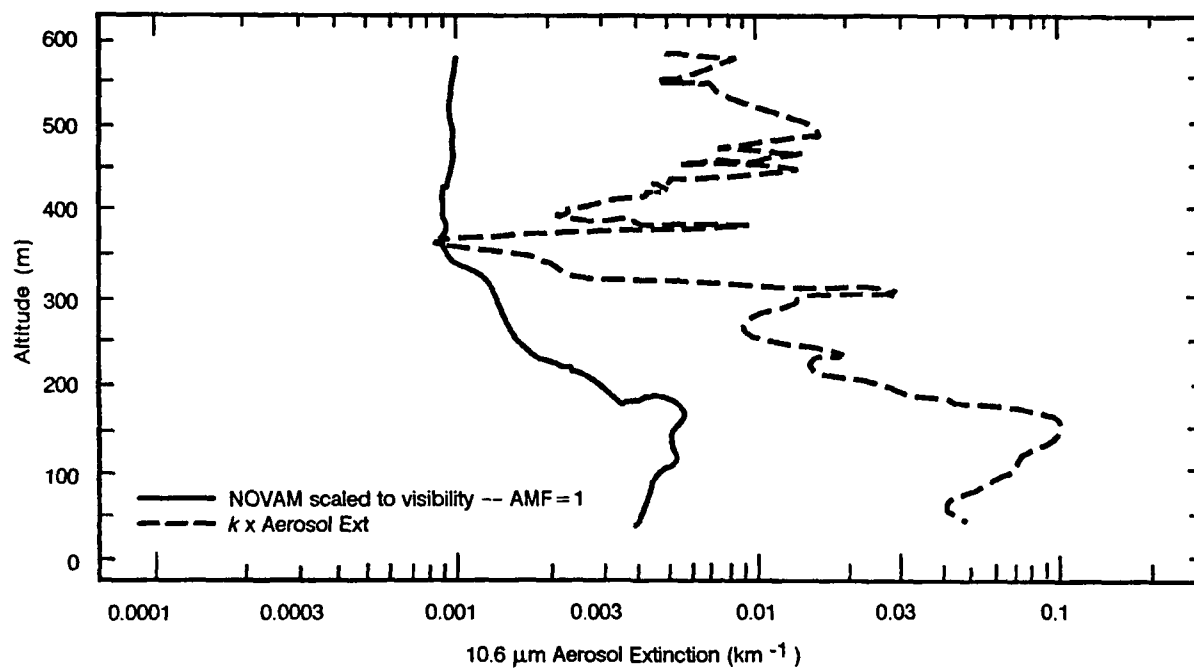
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