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A Lidar Technique for Adjusting Aerosol Model Number Densities Close to the Ocean Surface

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ADMINISTRATIVE INFORMATION

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SUMMARY

A technique is introduced by which the total number density of the LOWTRAN 7 (Kneizys et al., 1988) Navy Aerosol Model (NAM) [the kernel for the Naval Oceanic Vertical Aerosol Model (Gathman et al., 1989)] is adjusted to represent existing conditions close to the ocean surface.

Measurements of bulk meteorological parameters at a reference height above the ocean surface are used to generate stability-dependent logarithmic profiles of temperature and relative humidity. These profiles are used with the aerosol model to determine aerosol extinction and backscatter coefficient variations close to the ocean surface. Using the single-scatter lidar (light detection and ranging) equation, these parameters are then used to calculate a range compensated power, S(R), returned from scattering volumes at different heights in the modeled atmosphere. An iterative method is used by which the calculated S(R) values are adjusted to agree with the corresponding measured values obtained with a lidar operating at 1.06 μm and directed at the ocean over a slant path from an altitude of 10 meters.

Examples are presented of extinction coefficient variations with height above the ocean surface, calculated using the original and adjusted size distributions for different surface wind speed conditions and air-mass characteristics.

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INTRODUCTION

With a Navy interest in using Forward Looking Infrared (FLIR) detectors at submarine periscope heights, it is important to get more detailed information on what the atmospheric characteristics are at these FLIR wavelengths (3 to 5 and 8 to 12 μm) in the first few meters above the surface of the ocean. This information is particularly important for predicting the performance of electro-optical systems operating against skimmer-type missiles approaching a ship or submarine from beyond the horizon.

Computer models have been created to try to predict atmospheric effects on optical systems over a wide range of wavelengths and for various weather conditions. One such model (Gathman, 1983; Gathman et al., 1989) uses relative humidity, current wind speed, 24-hour average wind speed, and visibility as input parameters. In addition, an air-mass factor is entered. This air-mass factor ranges from 1 for pure ocean air to 10 for only continental air in integer increments of 1. One difficulty with this model is there is no good way to determine what this air-mass factor should be for a given situation. Also, determining the true visibility is just about as difficult.

The model is a combination of three aerosol distributions. The size of one of these distributions is controlled by the air-mass factor. The second is controlled by a function of the current wind speed and the third by a function of the 24-hour average wind speed. A current visibility can be included. If current visibility is not, its adjustment factor is set to 1. This is what this factor should be if all other terms are correct.

The preceding model, with some modifications, has been included in a more comprehensive program called LOWTRAN7 (Kneizys et al., 1988).

While this technique is not a stand-alone concept, a single-ended lidar system, when operated in conjunction with measurements of the meteorological parameters, could be used to adjust an aerosol model to existing conditions (Hughes and Paulson, 1989). In this approach, extinction and backscatter coefficients are calculated by the unscaled model using Mie theory. These coefficients are used to calculate the range-compensated power received by the lidar as a function of altitude. The coefficients at each altitude are then sequentially adjusted such that the calculated and the measured lidar return from each altitude agree. This novel method also provides a means of modeling aerosol extinction close to the ocean surface.

The technique, described above, has been used in this study. Although the lidar operates at 1.06 μm, it may be possible to select an air-mass factor that will minimize the aerosol size distribution adjustment. This air-mass factor could then be used with the model to calculate extinction and backscatter in the 3- to 5- and 8- to 12-μm ranges.

EXPERIMENT PROCEDURE

The lidar used was the Visioceilometer Lidar (Lentz, 1982) operating at 1.06 μm. Its characteristics are listed in table 1. Some of these specifications may have changed slightly, however, since the table was made.

Table 1. Visioceilometer characteristics.

Beam Divergence	1.0 mrad
Receiver field of view	3.0 mrad
Laser energy	13 mJ at 1.06 μm
Pulse half-width	6 ns
Receiver aperture	50 mm
Laser exit diameter	16 mm
Optics axis separation	50 mm
Full crossover range	80 m
Log A slope	10 mV/dB
Log A zero	80 μV
Detector noise level	2×10^{-10} W
Laser monitor output	0.75 ± 0.25 V
Sample rate	20 MHz.
A/D converter	10 bits in 2 μs
Sample device	455 sample Dual Channel CCD Fairchild #CCD 321
Operating temperature	-5^0 to 60^0C (Prototype)
Sample range	3.3 km

The lidar was fired from the end of Scripps Pier in La Jolla, CA. This pier is about 10 meters above the ocean surface and extends about a quarter mile out from the shore. The lidar was aimed out to sea and tilted down at an angle such that the range at which it struck the ocean surface was about 330 meters. This provided a height resolution of about 0.23 meter.

The reason for using this site, rather than the bluff at Point Loma, was to have open water, unaffected by the kelp beds. This site also avoided any effects the bluff may have had on the results.

DETERMINATION OF RELATIVE HUMIDITY PROFILES

Temperature, barometric pressure, relative humidity, and wind speed were measured at the lidar location on the pier at the time of the lidar measurements. Ocean water temperature was measured as well. These were used in a program to calculate a relative humidity profile from the ocean surface up to the height of the lidar (Paulus, 1989). This program assumes 100-percent relative humidity at the ocean surface and a logarithmic decrease with altitude to the value measured at the lidar height. Wind speed and temperature difference between the ocean and the air can modify this profile somewhat. Figure 1 shows an example of these profiles.

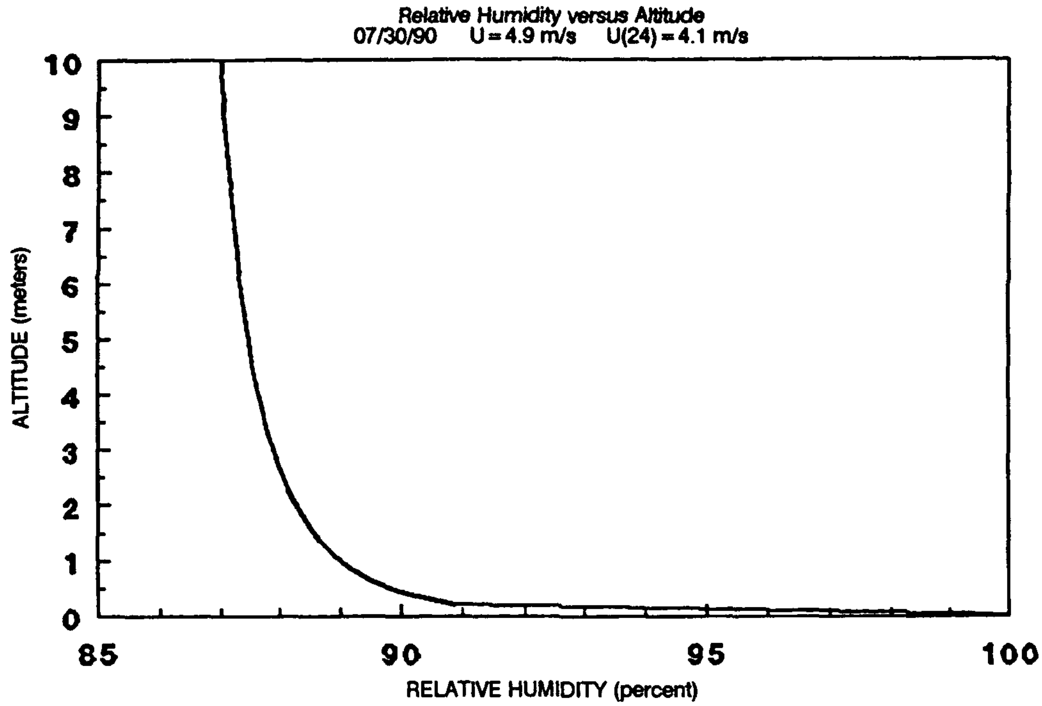


Figure 1. An example of the calculated relative humidity profiles.

DATA ANALYSIS

Five or six lidar shots were taken during each measurement period. Four of these were averaged in each case to minimize the effects of horizontal inhomogeneities.

Current wind speeds and 24-hour average wind speeds were used in the model program along with relative-humidity profiles, as determined above, to calculate extinction and backscatter coefficient profiles over the 10-meter height range. This calculation was usually done for air-mass factors of 1 and 10 to bracket the air-mass factor range. In one case, additional air-mass factors between these were used.

Visibility in most cases was 20 kilometers or better, but was not used in the program.

The calculated extinction and backscatter coefficient profiles were used in the lidar S(R) equation and adjusted by a factor k, for each level, in order to calculate an S(R) profile matching the S(R) profile measured by the lidar.

$$S(R)_{meas} = S(R)_{calc} \tag{1}$$

where $S(R) = \ln\ [P(R)R^2]$ and P(R) is the power received from the scattering volume at range R. The single-scatter lidar equation is then given by

$$S(R)_{calc} = \ln(C) + \ln[k\,\beta\,(R)] - 2\int_0^R k\sigma\ (r)dr \tag{2}$$

where σ and β are the range-dependent volume extinction and backscatter coefficients, respectively, determined from the model using Mie theory. C is the lidar system constant, and k is the multiplying factor of the size distribution allowing equation 1 to be satisfied.

RESULTS

Figure 2 shows the lidar S(R) profile for July 30, 1990. With air-mass factors of 1, 3, 5, 7, and 10 the extinction and backscatter profiles calculated by the model program require corresponding k-factor profiles as shown in figure 3 to match the measured S(R) profile. This profile shows that, for a k-factor close to 1, an air-mass factor of about 8 is required. If we use this air-mass factor in the model program and a wavelength of 10.6 µm, we get an extinction profile as shown in figure 4. The very high value near zero height is caused by the 100-percent relative humidity at the surface as determined by the relative-humidity program. When this profile is adjusted by the k-factor profile, calculated at 1.06 µm for the corresponding air-mass factor, this large extinction coefficient near the surface disappears. This disappearance is also true for the backscatter and extinction coefficient profiles at 1.06 µm. The lidar adjusted profiles do not show the large increase at the surface that the model program predicts based on relative humidity.

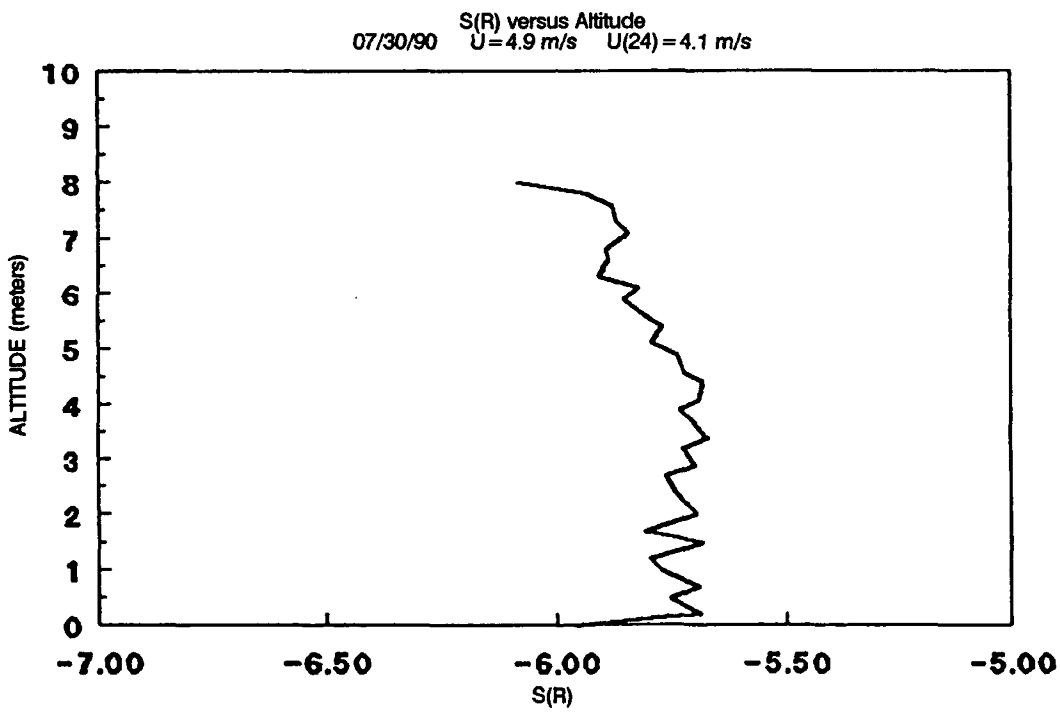


Figure 2. The lidar S(R) profile for July 30, 1990.

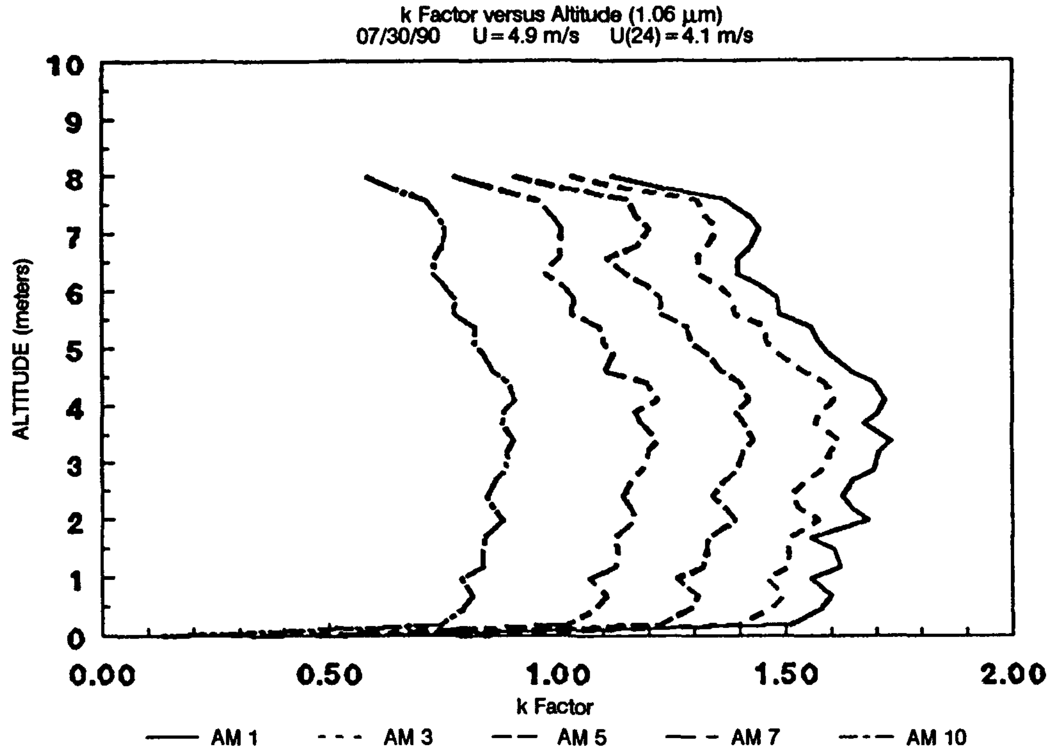


Figure 3. Profiles of k factor needed to match the S(R) profile obtained on July 30, 1990 by the lidar for air-mass factors of 1, 3, 5, 7, and 10.

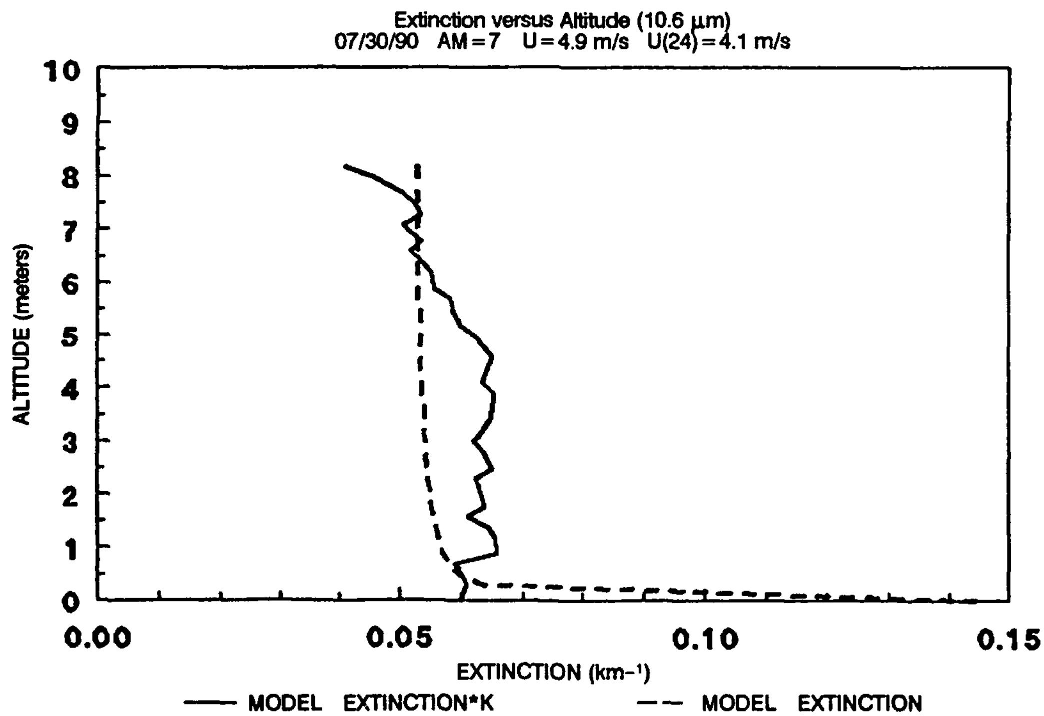


Figure 4. Comparison of a lidar-adjusted extinction coefficient profile at 10.6 μm with that calculated by the model using an air-mass factor of 7 for data taken on July 30, 1990.

The preceding data were for a moderate current wind speed of 4.9 meters/second and a 24-hour average wind speed of 4.1 meters/second. At lower wind speeds the results are quite different. Figure 5 shows the required k-factor profiles for air-mass factors of 1 and 10 for data taken on July 26, 1990. In this case, the current wind speed was 1.8 meters/second and the 24-hour average wind speed was 2.7 meters/second. With an air-mass factor of 1, the k-factor profile is around 35 to 40. Even for an air-mass factor of 10, the k-factor profile required to make the model data fit the lidar data is about 3. To get a k-factor near 1 would require an air-mass factor greater than the 10 allowed by the model.

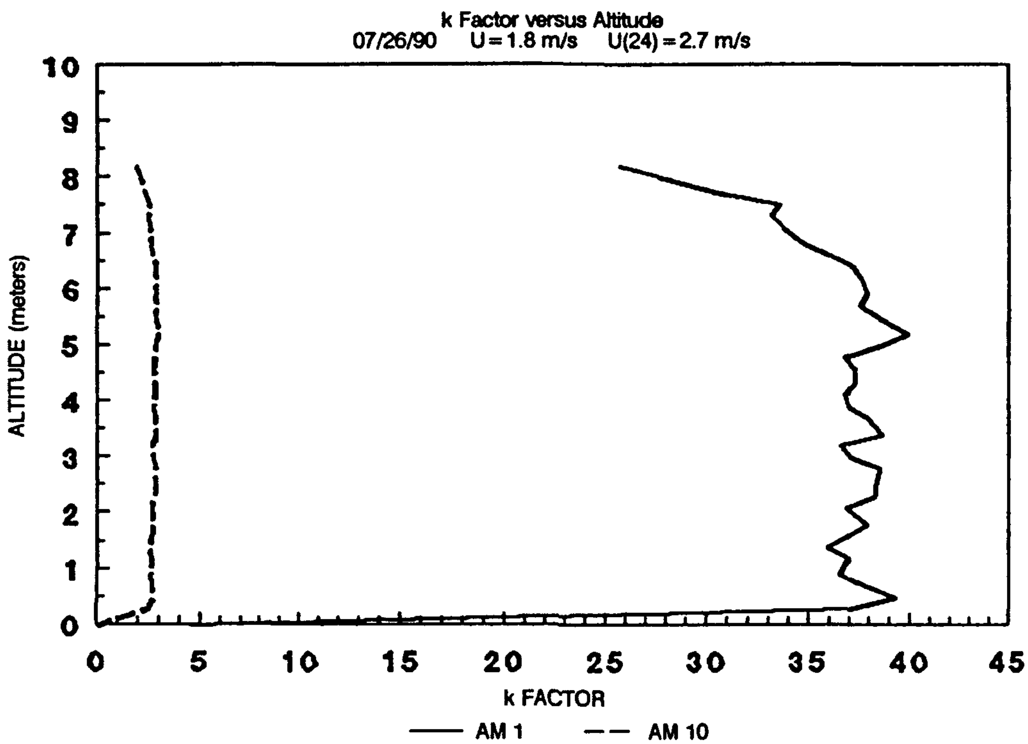


Figure 5. Profiles of the k factor for air-mass factors of 1 and 10 needed to match the lidar S(R) data taken on July 26, 1990.

Even greater differences occurred on September 5, 1990. On this day, the relative humidity was 88 percent, current wind speed was 1.6 meters/second, and 24-hour average wind speed was 1.8 meters/second. Visibility was estimated to be about 5 kilometers. The average k factor here for an air-mass factor of 1 was about 266, with a range of around 225 near the surface to over 375 at 7 or 8 meters. With an air-mass factor of 10, the average k factor was still about 5. The average adjusted extinction coefficient was 0.8 for an air-mass factor of 1, as shown in table 2. For an air-mass factor of 10, the average adjusted extinction coefficient was 0.9. Units of extinction coefficients are per kilometer, and those for the backscatter coefficients are per kilometer per steradian.

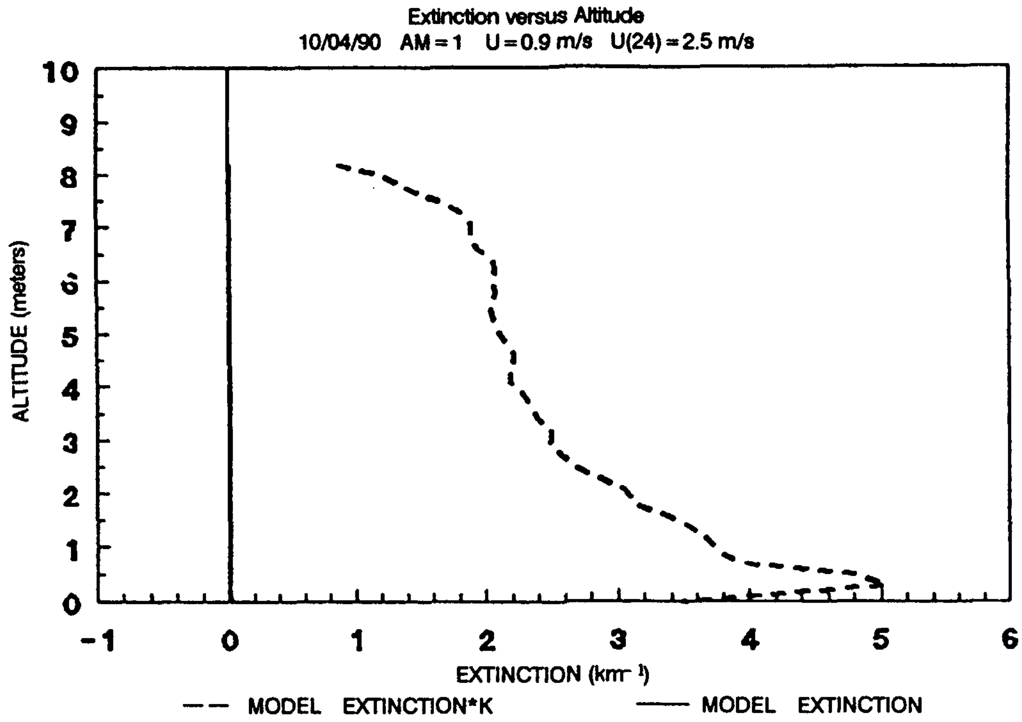
Table 2 shows relative humidity, current wind speed, and 24-hour average wind speed for each of the measurement periods. Table 2 also shows k factors for air-mass factors of 1 and 10, model extinction, model backscatter, the k-adjusted model extinction and model backscatter, and the S(R) value. These measurements have been averaged over the height range from the surface to the height of the lidar.

Table 2. Measurements averaged over the height range from the surface to the height of the lidar.

Date	RH	Wind(m/s)		K	K	EXT.	BSC.	K*EXT.	K*BSC	S(R)
	(%)	Current	24-hr av.	am1	am10	am1	am1	am1	a1	
06/21/90	82	4.3	2.5	5.28		0.0353	0.00182	0.1820	0.0094	-5 30
07/02/90	74	4.0	2.9	4.34	2.24	0.0332	0.00160	0.1810	0.0087	-5.35
07/09/90	79	3.6	2.4	3.44	2.05	0.0296	0.00154	0.0960	0.0050	-5.84
07/17/90	67	3.8	3.4	1.00	0.56	0.0369	0.00166	0.0344	0.0016	-7.00
07/19/90	84	2.7	3.4	3.72	1.05	0.0278	0.00107	0.0988	0.0038	-6.14
07/24/90	84	4.9	3.1	0.80	0.41	0.0590	0.00287	0.0459	0.0022	-6.64
07/26/90	76	1.8	2.7	35.50	2.63	0.0061	0.00016	0.1928	0.0048	-5.94
07/30/90	87	4.9	4.1	1.52	0.79	0.0826	0.00369	0.1173	0.0052	-5.84
08/03/90	80	1.8	2.6	22.34	1.52	0.0064	0.00018	0.1306	0.0036	-6.24
08/16/90	76	6.0	3.0	1.65	1.09	0.0634	0.00322	0.1000	0.0051	-5.84
08/21/90	80	2.7	3.2	5.02	1.32	0.0199	0.00074	0.0953	0.0035	-6.20
08/23/90	76	2.7	2.9	8.88	2.37	0.0157	0.00061	0.1291	0.0050	-5.86
08/28/90	82	1.3	2.2	89.96	1.95	0.0024	0.00006	0.1860	0.0047	-5.97
09/05/90	88	1.6	1.8	266.50	5.04	0.0034	0.00009	0.8125	0.0211	-4.78
09/11/90	84	1.8	3.3	62.20	8.16	0.0200	0.00058	1.1740	0.0336	-4.46
09/17/90	80	4.0	2.9	5.24	2.60	0.0394	0.00187	0.1918	0.0091	-5.33
09/25/90	88	4.0	3.6	5.09	2.23	0.0612	0.00271	0.2984	0.0132	-5.02
10/04/90	78	0.9	2.5	432.97	25.81	0.0062	0.00017	2.542	0.0688	-4.12
10/15/90	76	2.9	1.9	41.10	13.90	0.0118	0.00059	0.4482	0.0227	-4.53
10/24/90	60	0.4	1.7	377.50	10.27	0.0015	0.00004	0.4233	0.0102	-5.34
10/31/90	74	2.7	2.1	17.06	3.67	0.0083	0.00040	0.1297	0.0064	-5.65

On July 24, 1990, the wind speeds were comparable to those of July 30, 4.9 meters/second for current wind speed and 3.1 meters/second for the 24-hour average wind speed. The relative humidity was a bit less, 84 versus 87 percent for July 30. In this case, the average k factor was less than 1 for both air-mass factors of 1 and 10. For an air-mass factor of 1, it was 0.8 and for 10, it was 0.4.

On October 4, 1990, the current wind speed was 0.9 meter/second, and 24-hour average wind speed was 2.5 meters/second. The relative humidity at the 10-meter height of the pier was 78 percent. In this case, the average k factor was 433 for an air-mass factor of 1 and 26 for an air-mass factor of 10. The adjusted extinction coefficient profiles are shown in figure 6 and compared to the model predictions. The upper graph is for an air-mass factor of 1, and the lower graph is for an air-mass factor of 10. In both cases the extinction coefficient profiles show a decreasing extinction with altitude. For an air-mass factor of 1, it decreases from about 5 km^{-1} near the sea surface to about 1 km^{-1} around 8 meters altitude. The corresponding numbers for an air-mass factor of 10 are 11 km^{-1} and 1 km^{-1}.



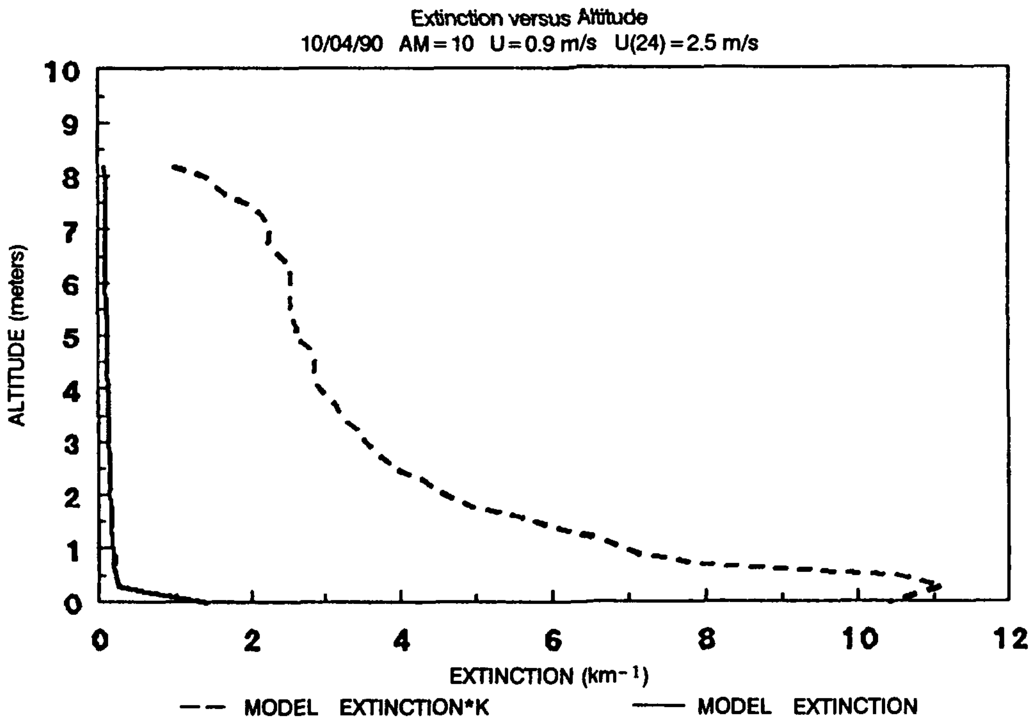
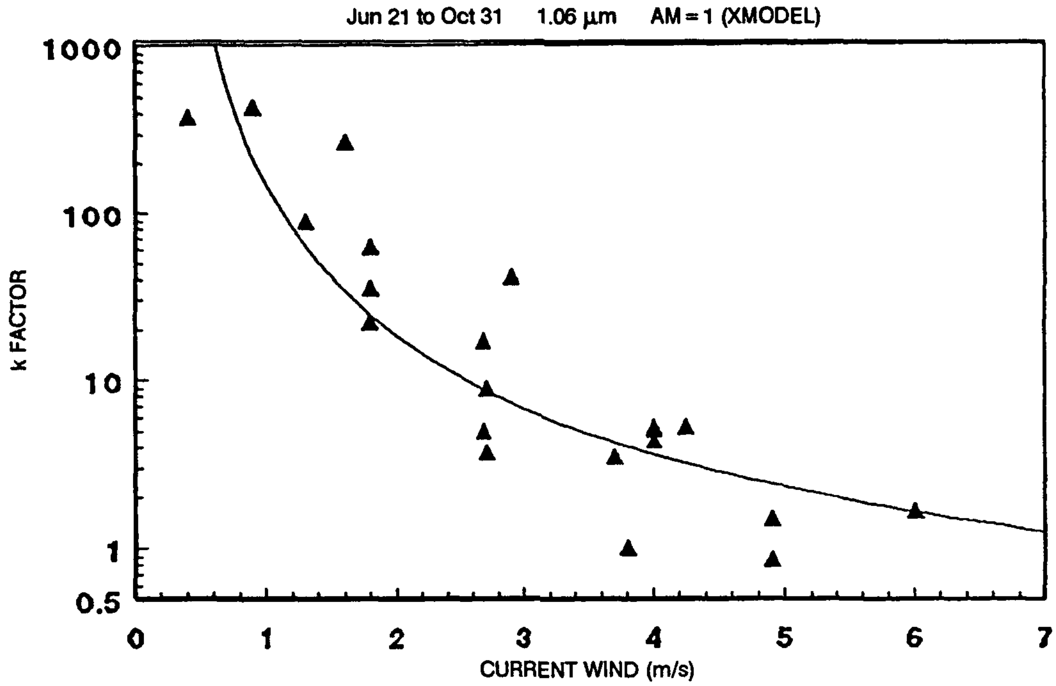


Figure 6. Comparison of lidar adjusted extinction coefficient profiles for October 4, 1990 with those calculated by the model, for air-mass factors of 1 and 10.



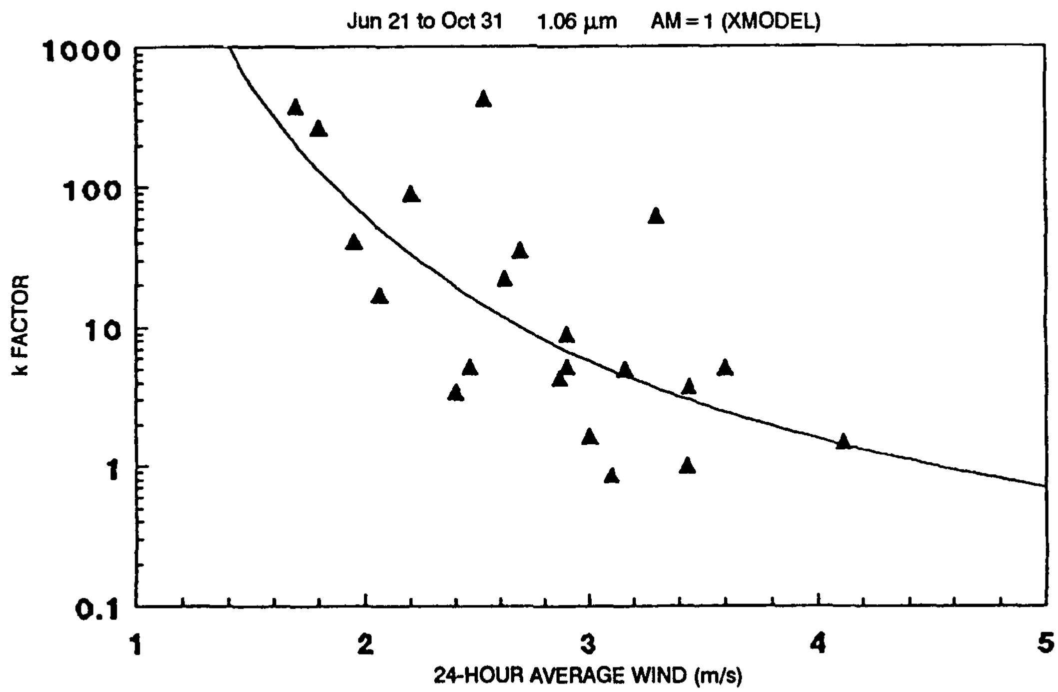
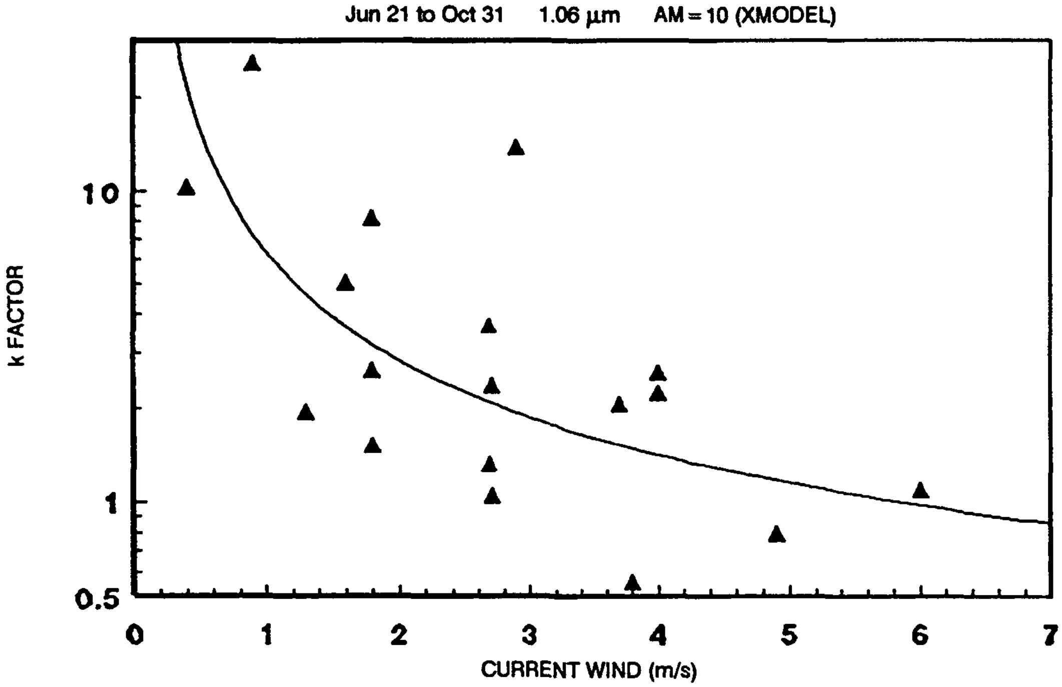


Figure 7. Model adjustment factor, k, as a function of wind speed for an air-mass factor of 1. Upper graph is for current wind speed, and the lower graph is for the 24-hour average wind speed.



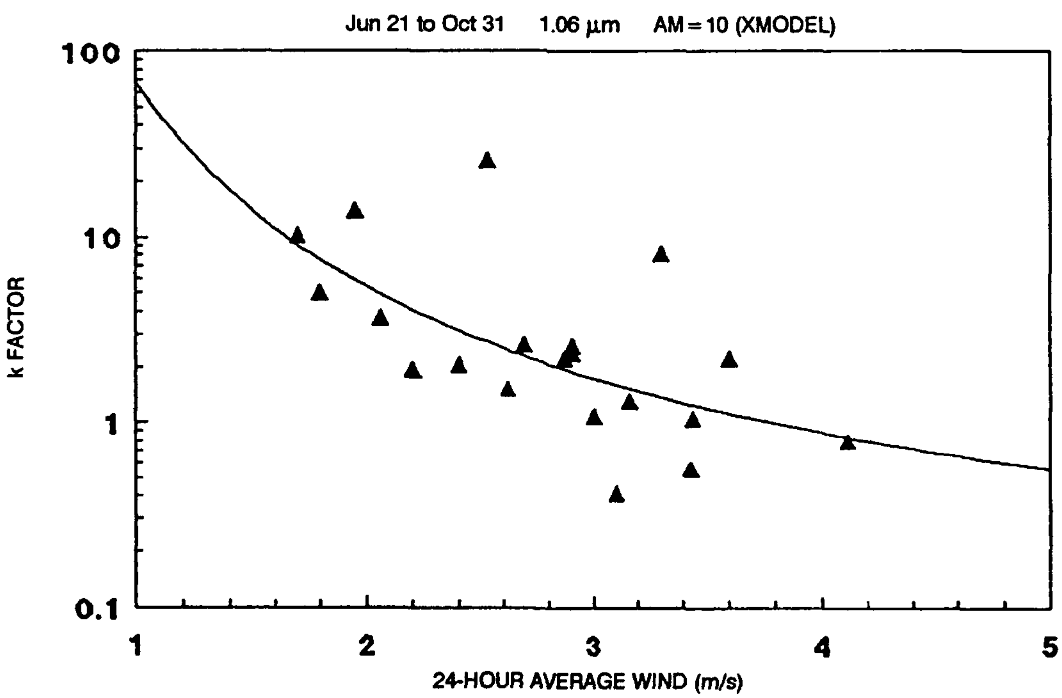
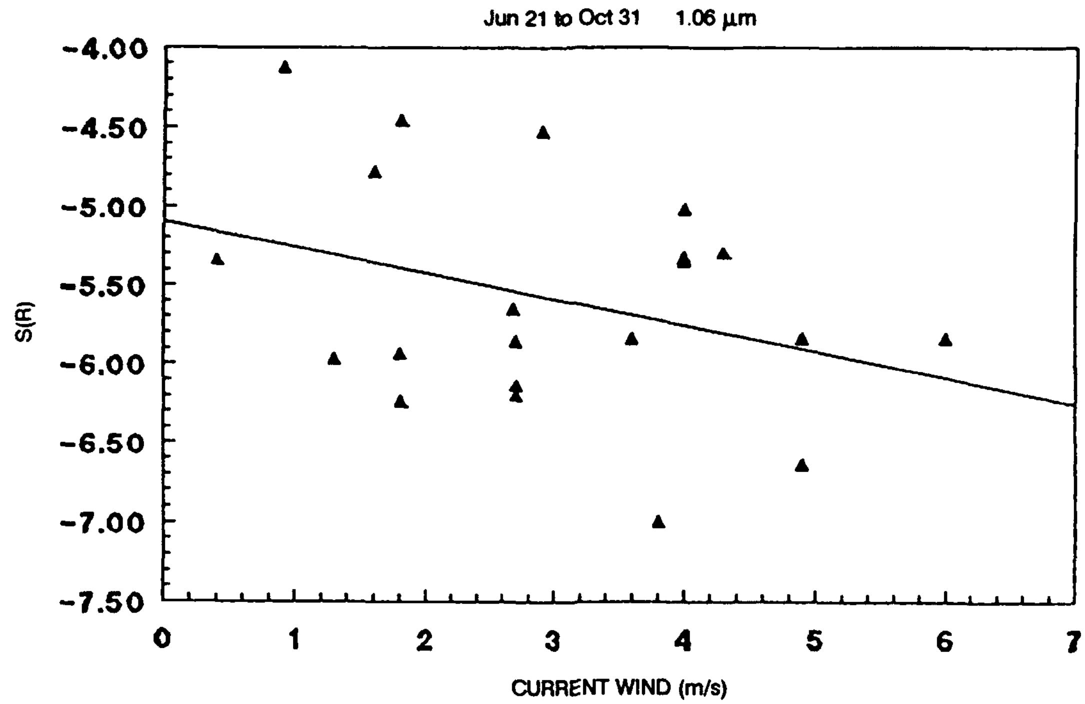


Figure 8. Model adjustment factor, k, as a function of wind speed for an air-mass factor of 10. Upper graph is for current wind speed, and the lower graph is for the 24-hour average wind speed.



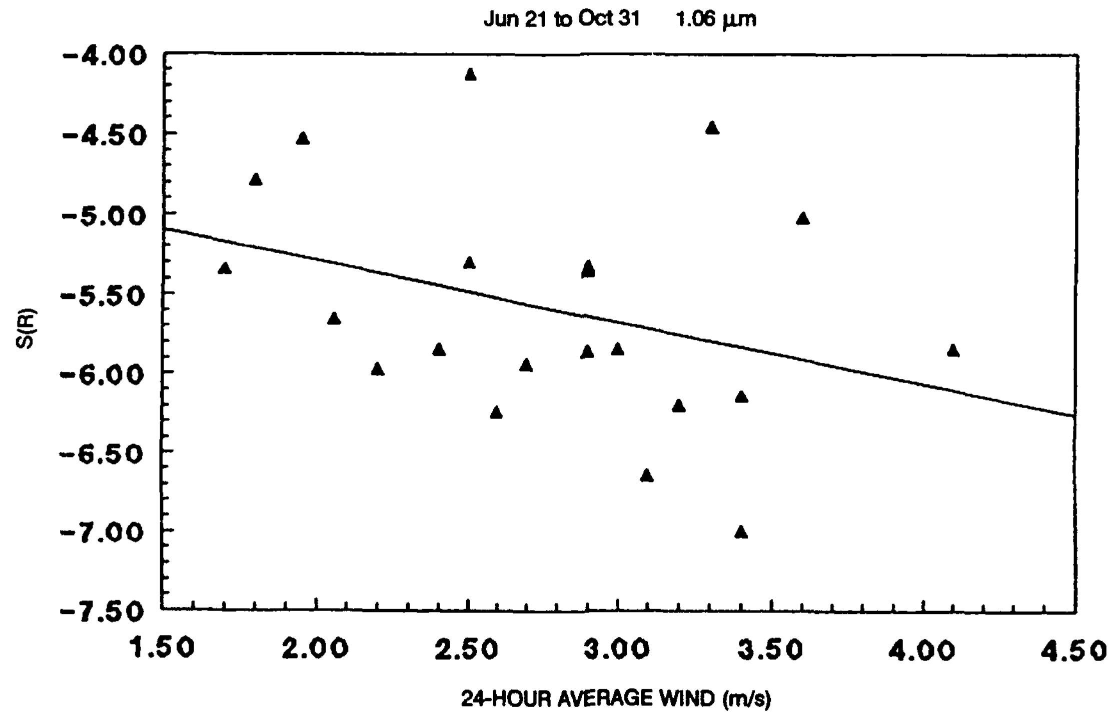


Figure 9. The upper graph is the S(R) averaged over the 10-meter height versus the current wind speed. The lower graph is the same for the 24-hour average wind speed.

The average k factors for the various data samples were plotted as a function of current wind speed and 24-hour average wind speed for an air-mass factor of 1. These samples are shown in figure 7 with the k factor plotted on a logarithmic scale. The same thing was done for an air-mass factor of 10. These samples are shown in figure 8. The k versus current wind speed, plotted in the upper graph of figure 7, shows a curve fit

$$k = 147.25 * U^{(-2.6308)} \tag{3}$$

where U is wind speed in meters per second, and k is the adjustment factor. The correlation fit for these data is -0.891. The fit to the 24-hour average wind speed, plotted in the lower graph of figure 7, shows a best fit to the curve

$$k = 3538.79 * U^{(-5.6841)} \tag{4}$$

In this case, the correlation is -0.703.

The k factors plotted in figure 8 for an air-mass factor of 10, while smaller, still show values greater than unity in most cases. A best fit for current wind speed, plotted in the upper graph, shows a fit to the curve

$$k = 6.645 * U^{(-1.0808)} \tag{5}$$

with a correlation of -0.662. The same thing for the 24-hour average wind speed, plotted in the lower graph, shows a fit to the curve

$$k = 36.0158 * U^{(-2.6808)} \tag{6}$$

The curves fit in this case show lower correlations than those for an air-mass factor of 1. This lower correlation is to be expected since a much smaller part of the model's aerosol distribution is dependent on the wind terms.

A comparison of the 24-hour average wind speeds with the current wind speeds showed a correlation of 0.472. This may account for some of the correlation between the 24-hour average winds and the k factors.

S(R) VERSUS WIND

The S(R) values have averaged over the 10-meter height have been plotted against the corresponding current wind speed and against the corresponding 24-hour average wind speed. These values are shown in figure 9. The upper graph is for the current wind speed. This graph shows a best fit to the linear equation

$$S(R) = -5.093 - 0.1662 * U \tag{7}$$

with a correlation of −0.334. If we use the S(R) values measured at the 5-meter height, only the correlation is slightly better at −0.367. The lower graph is for the 24-hour average wind speed. This graph shows a best fit to the linear equation

$$S(R) = -4.512 - 0.3888 \cdot U \tag{8}$$

with a correlation of −0.335.

While the correlations are not very high, they are negative. This negative correlation is contrary to what one would expect from the model predictions. Possibly the winds cause a more even distribution of aerosols with height and thus reduce those aerosols in the first few meters of altitude.

CONCLUSIONS

The model program, in its present form, cannot be used with any realistic degree of accuracy at 1.06 μm in the coastal region near the surface of the ocean. The program greatly underestimates the extinction and backscatter coefficients for low wind speed conditions. Average adjustment factors up to greater than 400 were required for an air-mass factor of 1 and wind speeds around 1 to 2 meters per second. Since it is very difficult, if not impossible, to determine what the air-mass factor should be, an air-mass factor of 10 was used as well. Even when the air-mass factor is set to its maximum value, to try to compensate, the adjustment factor was usually considerably greater than unity.

Weather conditions did not provide the winds necessary to test the model at wind speeds higher than about 6 meters per second.

RECOMMENDATIONS

While adjustment of the model aerosol number densities can match the model S(R) profile to that measured by the lidar, the large adjustment factors required for low wind speeds would suggest the shape of the aerosol size distribution is probably not correct. The model would then give incorrect results if it were used for the longer wavelengths. A better approach would be to use the lidar, along with the wind measurements and aerosol size distribution measurements, to try to adjust the appropriate parameters in the model so the model and the lidar give the same S(R) profiles with adjustment factors close to unity. If there is some way to accurately get an air-mass factor, it could be included; otherwise, an air-mass factor of 1 should be used.

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13. ABSTRACT (Maximum 200 words)

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