Satellite and Ship-based Lidar Estimates of Optical Depth during EOPACE

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SUMMARY

Coastal Marine Atmospheric Boundary Layer (MABL) aerosol optical depth is estimated from satellite data and compared with ship-based aerosol and lidar backscatter measurements, aircraft-measured aerosol, and rawinsonde data during the EO Propagation Assessment in Coastal Environments (EOPACE) Intense Observing Period (IOP) during April 1996. In the examined cases, satellite retrievals of aerosol optical depth and the ship and aircraft measurements were in good qualitative agreement. The ratio of visible and rear-infrared NOAA AVHRR channels successfully depicted regions of maritime aerosol during the beginning and later parts of the IOP and the period of continental aerosol associated with the strong offshore flow of the Santa Ana event.

1. INTRODUCTION

Knowledge of the coastal MABL for the entire battlespace is critical for modern Navy operations. To support modern weapon and sensor systems, quantitative assessment of a number of MABL properties are needed. They include: optical depth, boundary layer depth, sea surface temperature, and surface layer temperature and moisture. These needs are even more critical in the coastal zone with the sparse surface observations away from the coast and the high temporal and spatial variability of littoral circulation systems. Satellite remote sensing is the only data source that can measure MABL properties in the coastal zone with the needed high spatial resolution. However, many of the uses of satellite data are qualitative. Quantitative satellite remote sensing methods need to be tested to provide these needed littoral data.

The EOPACE program focuses on the characterization of aerosol and boundary layer properties in the coastal zone and the determination if air mass parameters in various coastal locations can be derived, to a practical degree, from satellite imagery. In support of this project, several IOPs have been conducted. The combination of satellite data with several in situ surface and aircraft data sets offers an excellent opportunity to monitor significant optical depth and aerosol changes and in the coastal zone. In addition, quantitative comparisons can be made. The objective of this paper is to evaluate satellite-derived aerosol optical depths estimates using aircraft and ship-based aerosol measurements, a ship-based lidar and rawinsonde profiles of the MABL. Results from the April 1996 experiment will be presented in this paper with additional results from the March 1997 experiment expected to be available at the conference.

2. SATELLITE OPTICAL DEPTH RETRIEVALS

Radiative transfer theory provides the basis for methods used to characterize aerosol properties from satellite remote measurements. In a cloud-free, marine environment, the shortwave, solar radiation measured by a satellite radiometer is primarily the result of scattering by both molecular constituents of the atmosphere (Rayleigh scattering) and larger suspended aerosol (Mie scattering). Corrections to solar irradiance of less than 5% for ozone absorption are applied and aerosols are assumed to be non-absorbing. In the absence of sun glint, reflectance from the ocean surface is also small and contributions to the satellite-measured radiance due to surface foam and subsurface reflection are accounted by empirical measurements.

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For atmospheres with small optical depths such as the clear, marine atmosphere, contributions by multiple scattering can be neglected. After accounting for Rayleigh scatter, the satellite-measured radiance can be related to optical depth, as illustrated in Equation 1.

$$L_a = \frac{\omega_o F_o}{4\mu} p(\psi_s)\delta_a \qquad (1)$$

where L_a is the measured radiance at the satellite due to aerosol scattering at a given wavelength, ω_o is the single scattering albedo, F_o is the incoming solar radiance at the top of the atmosphere, P is the scattering phase function, ψ_s is the scattering angle, δ_a is aerosol optical depth, and μ is the cosine of the satellite zenith angle (Ref. 1).

Durkee et al (Ref. 1) and Rouault and Durkee (Ref. 2) proposed a method of parameterizing the scattering phase function, P, based on the ratio of the aerosol radiance measured in channel 1 (visible) and channel 2 (near-IR) of the NOAA AVHRR satellite sensor. Other recent multi-channel aerosol estimates have been presented by Veefkind, et al (Ref. 3). Because the scattering efficiency of an aerosol distribution is wavelength dependent, scattering for a specific aerosol population peaks when the radius of the aerosol is nearly equal to the radiation wavelength. Subsequently, radiance counts measured by the AVHRR visible and near-IR channels will change with aerosol size distribution changes such that the ratio of channel radiances will be larger for smaller size particle distributions and smaller for larger size particle distributions. Durkee et al (Ref. 1) called the ratio of the channel aerosol radiances the particle size parameter, S12. Since S12 varies pixel by pixel over the entire image, the scattering phase functions can be parameterized pixel-by-pixel allowing variations in aerosol distributions to be properly factored into the optical depth retrieval. In addition, the S12 permits characterization of the aerosol size properties for the clear air in the image.

3. EOPACE IOP

This paper will report on the EOPACE IOP that was conducted from 2-12 April 1996 off the Southern California coast. During this IOP the R/V Point Sur traversed the coastal zone with a vertical pointing 1.06 micrometer LIDAR (provided by TNO), frequent rawinsonde temperature and moisture measurements (provided by NPS) and surface layer aerosol measurements. In addition, an instrumented aircraft measured aerosols and basic meteorological parameters in the region. Polar orbiting NOAA satellite data was received and processed at NPS for the period. This IOP was of particular interest in that significant changes in MABL properties and aerosols occurred during the measurement period.

4. RESULTS

After leaving port on 2 April, the R/V Point Sur moved southward along the coast on 3 April. During this day, low and mid tropospheric flow was from the northwest and maritime aerosols spectra dominated the MABL. The MABL was very deep with a thickness of approximately 1100 m. NOAA satellite pass (not shown) from 2227 GMT 3 April showed clear conditions along the coast. The retrieved optical depth in this region was .25 associated with the larger-size marine aerosol size distribution and deep MABL. The S12 ratio for this area shows small values ranging between 1.7 and 1.9. These values indicate the larger, maritime aerosols dominate the MABL. This is consistent with ship-based data and air trajectories for this day.

Significant changes occurred in the low-level flow during the next 24 hours. Strong offshore northeasterly flow developed as illustrated in the 1000 mb streamline analysis for 0000 GMT 5 April in Figure 1. Doppler wind profilers in the region also show the development of a Santa Ana wind regime. The profiler at the Ontario airport measured NE winds in excess of 30 knots during the afternoon of 4 April while the coastal profiler at Los Angeles (LAX) airport measured north and NE winds of 10-20 knots above 700 m.

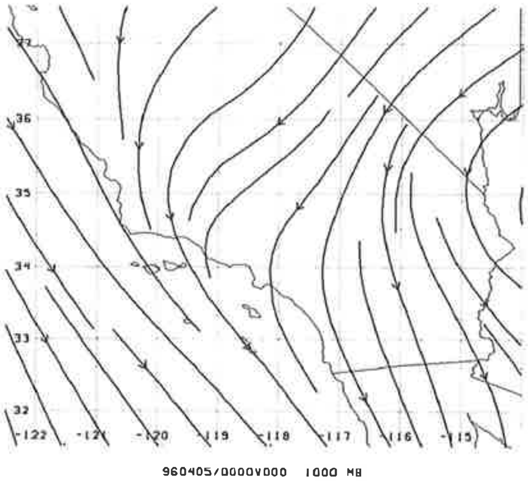

Fig. 1. 1000 mb streamlines for 0000 GMT 5 April 1996. Wind flow in the coastal region of the Southern California bight is offshore, bringing continental aerosols over the water.

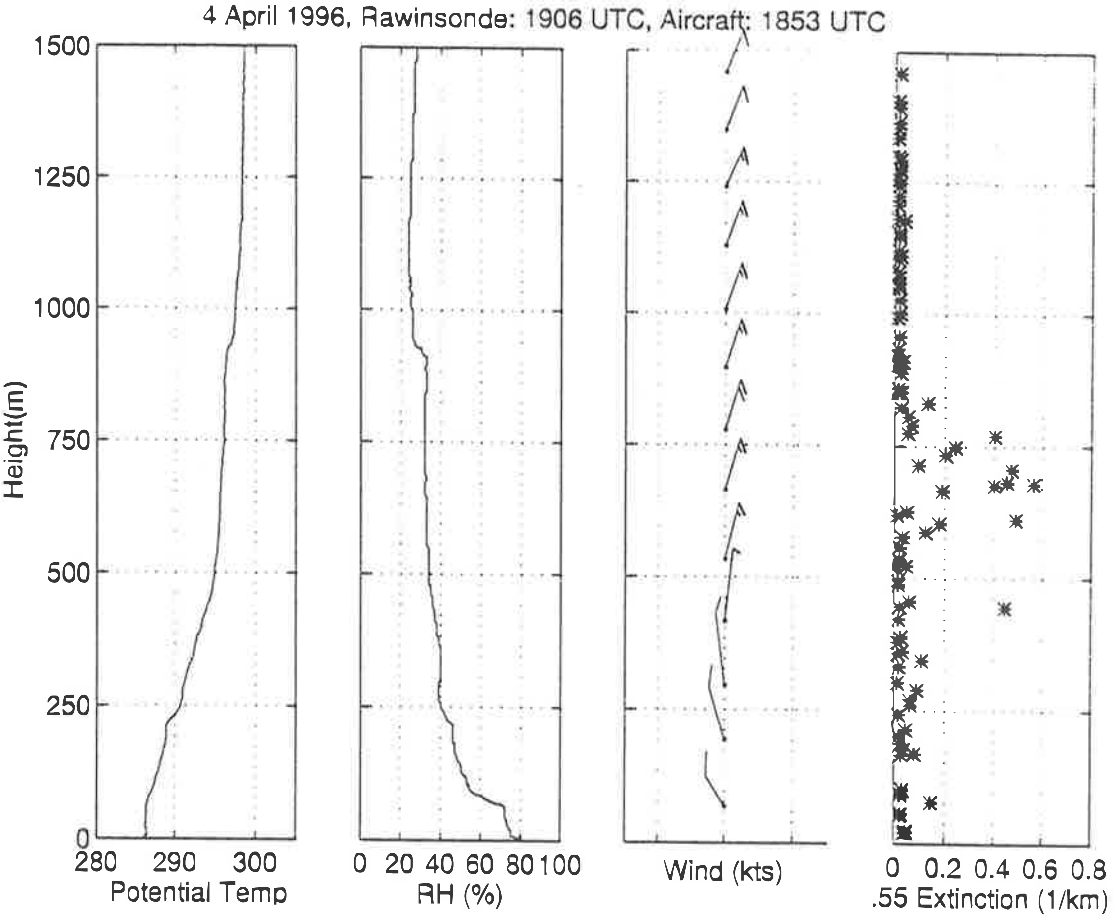

Fig. 2. Rawinsonde for 1906 GMT and aircraft aerosol extinction data for 1853 GMT 4 April 1996. Rawinsonde was launched from the R/V Pt. Sur and the aircraft concurrently flew a spiral vertical profile over the Pt. Sur. Plotted from left to right is rawinsonde measured potential temperature (C), relative humidity (%), winds (kts), and aircraft measured aerosol extinction at 0.55 microns.

Associated with this flow, an elevated layer of continental aerosols was observed by ship, aircraft and satellite sensors. Figure 2 presents an aircraft profile at 1853 GMT 4 April showing a distinct layer of aerosol extinction at 600-800 meters. Rawinsonde temperature, moisture, and wind data, collocated with the aircraft extinction data, are also included in this figure. These winds show NE winds in this layer of 15 to 20 knots. Figure 3 presents a timesection of backscatter from the TNO mini lidar aboard the R/V Point Sur. The emitter is a 60 mJoule Nd/YAG laser and lidar returns are averaged over 10 minute periods. Data from 4 April shows strong backscatter return in a layer from 400 to 700 m. The layer of strong backscatter is in agreement with the high extinction values from the aircraft.

The NOAA satellite data from 2216 GMT 4 April is presented in Figure 4. High values of optical depth are estimated over the entire Southern California coastal area. Values range from .17 to .38. There is a distinct plume of aerosols leaving the coast between Los Angeles and San Diego. The S12 ratio from this pass indicates a much higher ratio than 24 hours earlier. Values range from 2.9 to 3.1 indicating small aerosol sizes, typical of continental sources, are dominating the region. This is consistent with the lidar and aircraft data discussed earlier.

On April 5 the R/V Point Sur moved southeastward toward the plume observed by the NOAA satellite on 4 April. Subsidence associated with the offshore flow was quite intense this day and the MABL depths were very shallow, less than 100 m. Aircraft profiles and ship-based lidar (Fig. 3) continue to show aerosols in the lowest 1000 km. The aircraft data does not show a distinct layer of elevated extinction, but small values of aerosol extinction are present throughout the lowest

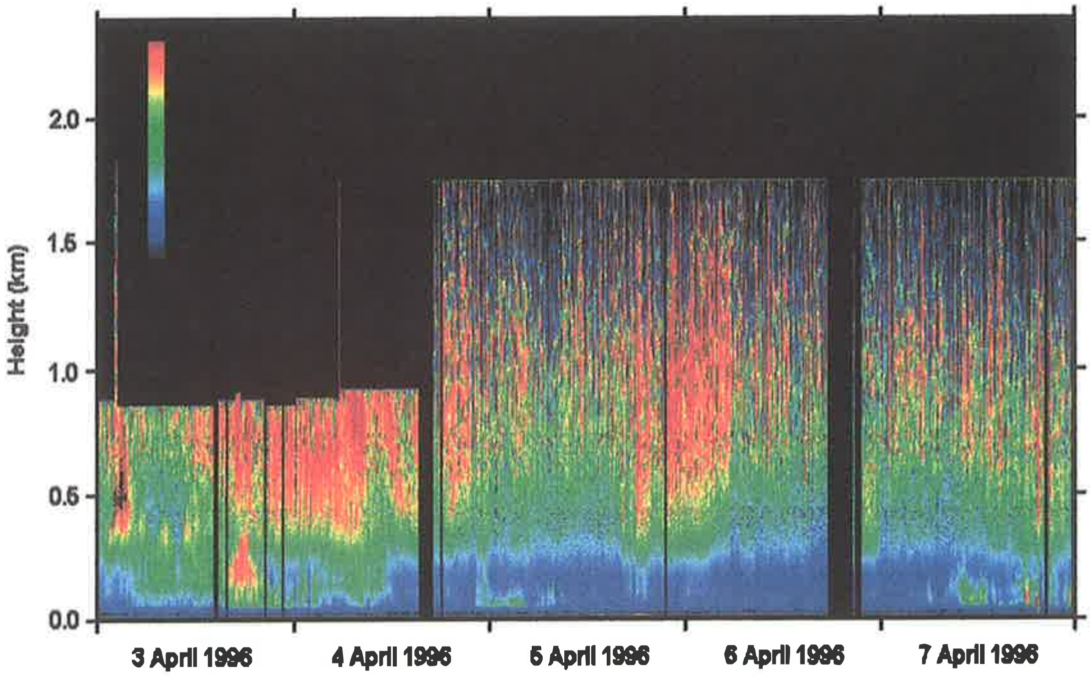

Fig. 3. Backscatter from the TNO mini lidar aboard the R/V Point Sur for 00 GMT 3 April - 00 GMT 8 April 1996. The emitter is a 60 mJoule Nd/YAG laser and returns are averaged over 10 min periods.

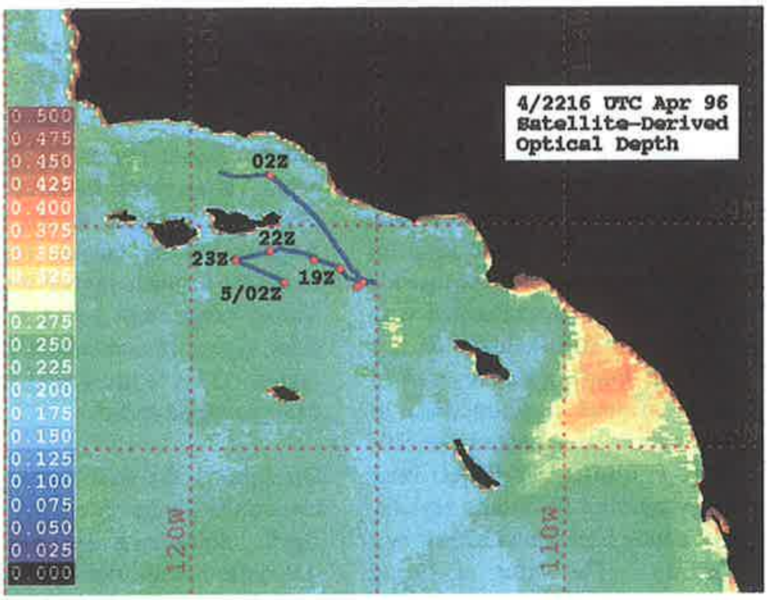

Fig. 4. Optical depth estimated from NOAA AVHRR data for 2216 GMT 4 April 1996. The R/V Point Sur ship track is indicated by the blue line. Rawinsonde launch locations are denoted by the red dots.

1 km. Satellite data for 2205 GMT 5 April (not shown) indicated lower values of optical depth (.15 to .25) but the remnant of the plume is still detectable.

The ship steamed though the plume location between 15 and 24 GMT 5 April. The stronger lidar backscatter values at that time (Fig. 3) are consistent with the satellite data. The S12 ratio continues to be high indicating smaller, continental aerosols over the coastal zone. In addition, Doppler wind profilers in the region also show the strengthening of this Santa Ana regime. The profiler at Ontario airport showed NE winds between 25 and 40 knots in the lowest 500 m during the afternoon of the 5 April while the coastal profiler at LAX airport showed N wind of 20 knots below 700 m.

On 6 April, the Point Sur traversed along the coast, 20 miles offshore, between Oceanside and Long Beach, which was the area of the plume on 4-5 April. The MABL continued to be quite shallow, less than 100m, due to subsidence and strong offshore flow. By 2100 GMT, rawinsonde data indicates that 10-15 knot westerly flow was reestablished below 1200m, and the strong NE winds continued above that level. The lidar (Fig. 3) for 6 April measured strong backscatter off the aerosol early in the day, but the significant decrease in backscatter at the end of the day is consistent with the return of westerly flow and a marine air mass.

On 7-8 April, the Point Sur traversed around San Clemente and Santa Catalina Islands and then returned near the coast, south of Long Beach, on its way to San Diego. During this period the offshore flow ceased, the MABL deepened to 300 m, with NW low-level winds. This was accompanied by more low-level cloudiness in the MABL. In the clear areas, optical depth values decreased to .10 to .15 and the S12 ratio decreased indicating the return of maritime aerosols in the MABL. This was confirmed by in situ measurements aboard the R/V Point Sur.

5. CONCLUSIONS

During this IOP satellite retrievals of aerosol optical depth and the ship and aircraft measurements were in good qualitative agreement. The NOAA satellite S12 ratio successfully depicted regions of maritime aerosol during the beginning and later parts of the IOP and the period of continental aerosol associated with the strong offshore flow of the Santa Ana event. At this time, quantitative data from the lidar of aerosol extinction are not available. Therefore, a more quantitative assessment of satellite versus in situ data is not available. This will be a major priority in future studies with this and other IOP data sets.

The new generation of geostationary satellite, GOES-9, was operating over the West Coast at this time. The higher radiometric resolution from GOES-9 sensors provide the opportunity to retrieve aerosol depth. GOES-9 data from this period will be used to add to the temporal resolution of the satellite data for this period. In particular, GOES data should be able to monitor the development of the aerosol plume on 4 April.

6. ACKNOWLEDGMENTS

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