THE NAVAL OCEANIC VERTICAL AEROSOL MODEL: PROGRESS REPORT

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SUMMARY

The Naval Oceanic Vertical Aerosol Model (NOVAM) has been formulated to estimate the vertical structure of the optical and infrared extinction coefficients in the marine atmospheric boundary layer (MABL). NOVAM was designed to predict the non-uniform and non-logarithmic extinction profiles which are often observed. It is based on a combination of empirical and physical models which describe the aerosol dynamical behaviour. The extinction properties are calculated from the aerosol profiles using Mie theory. For the initial evaluation of NOVAM, data from the July 1987 FIRE experiment (conducted off the coast of southern California) was used. Aerosol particle size distributions, aerosol scattering and required meteorological parameters throughout the MABL were obtained from both airborne and surface based platforms (aircraft, ship and balloon instrumentation packages). The aerosol-derived extinction properties throughout the MABL are compared with the NOVAM estimates.

1. INTRODUCTION

NOVAM, the Naval Oceanic Vertical Aerosol Model,[1,2,3] is being formulated to estimate the vertical structure of the extinction coefficients in the marine atmospheric boundary layer (MABL) for wavelengths between 0.2 and 40 µm. Its development is based on a combination of empirical and physical models[4,5,6,7] which describe the aerosol dynamical behavior. The input to the empirical-dynamical model to calculate the profiles of the optical and infrared (IR) extinction coefficients is a given set of atmospheric parameters.[1,2,3]

NOVAM was designed to describe the non-uniform but also non-logarithmic extinction profiles which are observed to exist throughout the MABL. It is mainly based on physical models for the processes that determine the aerosol vertical structure. The model is restricted to the marine atmosphere, hence the designation "Oceanic" in its title. The differences between this model and land-based models are the marine type of scaling used for the turbulent controlled processes near the sea surface, and the determination of the surface concentrations with the Navy Aerosol Model (NAM).[4] The structure is a function of turbulent controlled processes and of particle growth due to height varying relative humidities. The turbulent processes produce, deposit and mix the aerosol and also determine the depth of the mixed layer itself.

NOVAM is a combination of models developed at the authors' institutes,[4,5,6,7] which were merged by Gathman.[3] In this paper the model is briefly summarized. A complete description of the model has been presented elsewhere.[1,2,3] The NOVAM flow chart is shown in Figure 1. The kernel for NOVAM is NAM[4] which has been extensively updated from the original. NAM produces a particle size distribution at a height of 10 m above the surface from the input data of wind speed (both current and the 24-hour average), visibility and relative humidity. This NAM-generated surface-layer particle size distribution is mixed throughout the MABL by turbulent-controlled processes, further modified by relative-humidity effects. The physics describing these processes are determined by the MABL vertical structure. Various models describing the atmospheric vertical structure are included in NOVAM, such as a simple mixed-layer model[6] and a shallow convection case.[5] Provision has been made to include other models such as for deep convection. The selection of the model is based on the input parameters describing the vertical stratification (thermal stability, the presence of an inversion and the inversion height), cloud cover, cloud type, wind speed, and the requested wavelength for the extinction calculation.

NOVAM will perform best when all of the above parameters, and those listed in section 2.1, are available. Thus the input files need to contain surface observations and the MABL vertical structure. The latter information can be obtained from a rawinsonde observation. If the information on the vertical structure is not available a default relative humidity profile, based on the surface observations,[8] is generated. This default profile is also used when the required input parameters do not satisfy the presently supported models (mixed-layer, shallow convection or stratus). The stratus model is an empirical model that applies only to the marine stratus clouds for wind speeds less than 5 m/s and a desired extinction calculation for wavelengths between 1 and 11 µm.[7]

A preliminary NOVAM-estimated profile comparison with one set of experimental data yielded favourable results.[1] This paper presents a more comprehensive initial evaluation of NOVAM utilizing an extended aerosol and extinction data base obtained during the project FIRE (First ISCCP Regional Experiment),[9] see section 2. Results are compared with NOVAM predictions in section 3. Conclusions follow in section 4.

2. THE FIRE/EOMET EXPERIMENTS

2.1 APPROACH TO EVALUATION OF NOVAM

During June and July, 1987, the Marine Stratocumulus Intensive Field Observation Experiment of FIRE was conducted in the Southern Californian offshore area. FIRE is a cloud research program to validate/update the ISCCP (International Satellite Cloud Climatology Project) data base and cloud radiation parameterizations used in the general circulation models. Coordinated surface, aircraft, and satellite observations of marine stratocumulus clouds within and just above the marine boundary layer were made by a myriad of participants. A general overview of the FIRE project and the participants involved are outlined in reference 9. The Navy's EOMET (Electro-Optics METeorology program) participation in FIRE was both to be supportive of FIRE and to build a quality data base from which NOVAM could be evaluated.

The meteorological parameters required for the NOVAM evaluation are the mean surface-layer wind, temperature, humidity, aerosol size distributions, and visibility, Radon count or air mass parameter (AMP), the boundary layer profiles of temperature, humidity and either aerosol size distributions or optical/IR extinctions. Measurements were made from both airborne and surface based platforms (aircraft, ship, and balloon instrumentation packages). Rawinsonde launches were made from the ship.

2.2 MEASUREMENTS

Measurements were made from several platforms at different geographic locations during FIRE to characterize the stratocumulus topped MABL over spatial distances appropriate for satellite imagery (10 to 100 km). This scale corresponds to the meso-scale which is inherently three dimensional and has important temporal variations at intervals of hours. The measurements from San Nicolas Island (SNI), from aircraft and from the R/V Point Sur were designed to characterize meso-scale features. The measurements from the different platforms and locations were coordinated within intensive periods to describe the three dimensional nature of such features.

SNI is situated 102 km south-southwest of Point Mugu, California. The island is 14.5 km long and 5 km wide. It is an ideal location to make oceanic measurements.

2.2.1 R/V POINT SUR MEASUREMENTS

The R/V Point Sur, operated for the National Science Foundation by the California State University System for the Naval Postgraduate School (NPS), was an important platform because of its over water location and continuous (24 hour/day) measurement schedule for the period 7-16 July. The R/V Point Sur was generally located 30-40 km upwind (Northwest) of San Nicolas Island.

Several meteorological measurement systems were on board the R/V Point Sur to characterize surface layer stability and aerosol properties, and the mixed layer depth and turbulence. The quantities measured and the sensors are listed in Table 1.

2.2.2 AIRCRAFT MEASUREMENTS

The Naval Ocean Systems Center (NOSC) airborne platform was utilized to characterize the low level structure of the marine boundary layer. Flights were made in the vicinity of SNI and were coordinated with the R/V Point Sur, and the Naval Research Laboratories (NRL) Tethered Balloon Facility at SNI. NOSC evaluated one flight during the low stratus conditions on 15 July, and one during the clear sky conditions on 19 July. The former was the only flight when the R/V Point Sur was on station. The prescribed flight pattern for the NOSC aircraft consisted of spiral profiles taken near the NRL ground facility at SNI and upwind of SNI near the R/V Point Sur. Meteorological parameters recorded by the NOSC aircraft are shown in Table 1. Spiral climb rates were at 152 meters/minute. Meteorological data were recorded every 5 seconds and aerosol data every 4 to 8 seconds (depending on meteorological conditions). Each flight was scheduled to occur simultaneously with the NOAA-9 satellite overpass.

In making such a comparison, one must consider the measurement accuracy of the input meteorological parameters required by NOVAM and the accuracy of the independently obtained optical/IR extinction data. Both of these are subject to instrumentation accuracies and errors introduced by statistical sampling of time and spaciously varying fields. Although all precautions were taken to eliminate measurement and sampling errors, these types of errors still exist and must be considered when comparing data from different instruments. Therefore, in this evaluation, data envelopes were defined to show the most probable range of the extinction profiles.

Because of the significance of the meteorology to NOVAM, a description of the synoptic situation around SNI is given first. The R/V Point Sur measurements are used for comparison with the NAM. The simultaneous NOSC airborne and NRL Aerostat profile measurements provide the basis for the extinction comparisons with NOVAM.[1-3] Both stratus and clear-sky conditions are considered. Finally, a qualitative summary of the initial evaluation of NOVAM is presented.

3.1 SYNOPTIC SITUATION AND SURFACE MEASUREMENTS ON THE R/V POINT SUR, 14-16 JULY

The meteorological synoptic scale situation during the 14-16 July period was controlled by two pressure systems,[11] Figure 2. A stationary 1032-1036 mb closed surface high pressure system was located west of Washington State and British Columbia, Canada. A well-defined thermal low was located over Southern California. These two systems caused west to northwest winds in the vicinity of SNI due to the outflow from the high located to the northwest.

The time series of surface layer parameters and representative rawinsonde profiles obtained from the R/V Point Sur for 14-16 July are presented in Figures 3 and 4. Features of interest in the 3-day time series, Figure 3, are the steadily decreasing wind speeds and the diurnal variation of both the wind speed and direction. Steadily decreasing wind speeds are important to the production of marine aerosols. The diurnal variations in the MABL parameters due to the vicinity of the US Mainland, could imply a local circulation influenced by the land-sea proximity. Thus continental aerosol can be carried to the area, which influences the extinction.

The steady decrease in wind speed was associated with the thermal low which was moving northeast (more inland) from the Baja of California on 14 July to the California-Nevada border on 16 July (Figures 2a through f). The eastern Pacific surface high pressure systems remained nearly stationary during this period. The variations in wind speed and direction, during the 24-hour periods, were concluded to be due to the intensification of the thermal low, east of the area, during the local afternoon (1200 PDT is 1900 UT in Figures 2 and 3).

Evidence that there was a land-sea influence associated with the diurnal variation appears in the diurnal variation of the Radon concentration. Whether the Radon was advected horizontally or arrived in the mixed layer due to entrainment is unknown. The increase in temperature and decrease in humidity on the diurnal scale could be associated with entrainment of warm dry air from above the inversion. The entrainment of overlying air with continental aerosol is as important to NOVAM's performance as the horizontal advection of continental air.

The continental influence is obvious in the afternoon of 15 July. The increased Radon concentrations, a clear indication of continental influences, are followed by an increase in the extinction coefficients. The increase in the extinction coefficients is observed at all wavelengths from the visible to the far IR.

The vertical structure of the MABL is of crucial importance to the evaluation of NOVAM. The R/V Point Sur obtained this information from the rawinsonde launches. Profiles for 14, 15 and 16 July, around 2200-2300 UT, are shown in Figure 4. They exhibit differences as well as similarities. The differences are only in the depth of the mixed layer, which increases from the 14th to the 16th. The similarities are in the cloud cover, in the gradients within the mixed layer and in the features at the inversion.

Because of the importance to the stratus case presented in section 3.3.2, features in the rawinsonde profile for 15 July, 2253 UT, Figure 4b, are discussed. A stratus deck existed between 250 m and 650 m. Gradients are observed in the potential temperature and specific humidity throughout the boundary layer. This is not the case for the well-mixed boundary layers observed on 19 July (cf. Figure 6b). The large jumps in the potential temperature above the cloud tops are characteristic for the area. They are an effective lid on the boundary layer, preventing strong mixing of air between the boundary layer and the overlying free atmosphere. Moist layers due to advection are observed in the upper air. The vector winds are seen to be quite variable between the various layers. Changes in wind direction of 180 degrees over distances of less than 100 m are observed.

3.2 TIME SERIES OF SURFACE EXTINCTION

Figures 3d and 3e show the 3-day time series of surface extinction coefficients at 1.06 µm and 10.6 µm, calculated from the particle size distributions measured on the R/V Point Sur. The diurnal variation in the extinction coefficients follows the diurnal variations in the meteorological parameters, i.e. wind speed, Radon concentration and

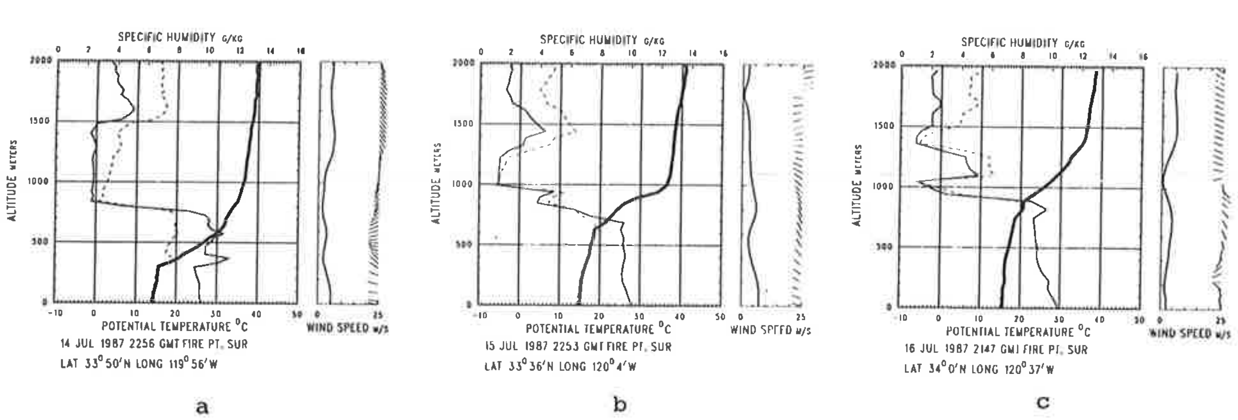

Figure 4. Rawinsonde profiles from the R/V Point Sur for 14, 15 and 16 July, for 2200-2300 UT.

relative humidity. Some of this variation is caused by the continental aerosol being advected from the US Mainland as seen in the afternoon of 15 July when the Radon concentrations peaked to 60 pCi/m^3. In the far infra-red, the diurnal variation is caused in part by the variation in the sea-salt production in response to the wind speed. Overall, a slight decrease in the extinction coefficients is observed.

The extinction coefficients obtained from near-simultaneous (both in time and geographically) aerosol measurements by the NOSC airborne platform and the R/V Point Sur on 15 July are indicated. The airborne data are for an altitude of 120 m. The data are compared with NOVAM surface predictions, calculated every 3 hours from the observed meteorological parameters. Good agreement exists between the measured and NOVAM-estimated values.

3.3 SIMULTANEOUS AIRCRAFT AND BALLOON FLIGHTS

3.3.1 GENERAL COMMENTS ON EVALUATION

Simultaneous aircraft and balloon flights were considered under two different meteorological conditions, stratus and clear skies. The vertical structures of the meteorological and the optical/IR properties of the marine boundary layer were compared.

The purpose of having simultaneous flights is two fold. First, to see the variations between island-based and upwind measurements,[12] and second, to compare the two instrumentation packages in situ for data validation considering different system performance accuracies. This applies to both the meteorological instruments and the devices used to determine the optical/IR properties. These instrument accuracies influence both the NOVAM estimates and the data to which they are compared.

3.3.2 STRATUS CASE: 15 JULY 1987

Evaluation of the NOVAM stratus model utilized the aircraft- and balloon-derived meteorological profiles and surface-based observations for the stratus conditions of 15 July 1987, 1500-1700 (PDT). A uniform stratus layer (100% cover) existed at and upwind of SNI with a base around 400 m and tops at 700 m. Winds were northwesterly at 5 m/s. Cloud base at SNI was determined at 320 m from the balloon liquid-water measurements. Drizzle was observed at the ground. Extinction coefficients fluctuated from 80 km^{-1} in the cloud, to low values (0.01 km^{-1}) above the cloud layer. The balloon RH instrument was pegged at 100% throughout the whole boundary layer. Upwind, however, the relative humidity below the clouds varied in the vertical between 95% and 100%, as determined from the aircraft data. The surface relative humidity at the R/V Point Sur, approximately 30 NM upwind from SNI, was 92% (Figure 3). This is a classic case of a stratus deck in which warm dry conditions existed above the moist marine stratus layer.

In Figures 5a through c we show the extinction profiles for wavelengths of 0.55, 1.06 and 10.6 µm from all available sources, including the NOVAM estimates below the cloud base. NOVAM presently incorporates two models for the stratus condition, the selection of which is determined by the desired wavelength. For wavelengths less than 1 µm or greater than 11 µm a mixed-layer model is used (Figure 5a). For wavelengths between 1 and 11 µm the sub-stratus model is used (Figures 5b and c). NOVAM does not support conditions of 100% relative humidity, nor does it support situations in which precipitation occurs. The NOVAM comparison of Figures 5a through c utilized the NOSC aircraft data because the NRL instrumentation at SNI recorded relative humidities of 100% and precipitation was observed.

Figure 5a shows the AMP sensitivity of NOVAM for the visible wavelengths. Note that NOVAM selected the mixed-layer model for these calculations because the sub-stratus model does not apply to wavelengths smaller than 1 µm. The fluctuations in the extinction coefficients determined from all sources are generally contained within the AMP limits. In the regions around 120 m and those above 320 m, where the extinction coefficients are outside the NOVAM bounds, the aircraft-observed relative humidities approached 100% - a region where NOVAM is not applicable. The problem here is that the hygroscopic aerosol (like sea salt droplets in the MABL) can be activated when relative humidities go slightly over 100%. The activated aerosols grow in size very fast and behave as cloud droplets[13] and cannot be described by equations that apply to subsaturated aerosol. This puts them into the arena of fog or cloud physics, and outside of the realm of aerosol modeling - including the capabilities of NOVAM. Figure 5d shows the liquid water concentration profile and Figure 5e the measured size distributions associated with this supersaturation phenomenon.

Figures 5b and c show the extinction profiles for 15 July for the sub-stratus model. The sub-stratus model is not as sensitive to the AMP as the mixed-layer model. Differences between the measured extinction coefficients and NOVAM estimates are in the high-humidity regions just described. The peak in the size distributions shown in Figure 5e affects the far IR more than the near IR.

The dilemma for model verification studies is how to avoid cases where activation is taking place but yet test the model at relative humidity values just below 100%. This dilemma arises because of the uncertainties in both measurement accuracies and horizontal variations of relative humidity. The activation problem can be avoided by excluding all cases where the apparent relative humidity is greater than some trigger value.

3.3.3 CLEAR SKY CONDITIONS: 19 JULY 1987

On 19 July 1987 the sky was clear and the visibility was essentially unrestricted. The winds were northwesterly at 6.5 m/s. The base of the inversion was at 400 meters and the top at 575 m. For clear sky conditions, NOVAM uses the mixed-layer model. Figure 6a shows, for the visible wavelength (0.55 µm), the NOVAM-estimated and aerosol calculated extinction profile. An excellent agreement between the NOVAM predicted and aerosol calculated extinction profiles could be obtained for an AMP between 1 and 10. The curves shown are for an AMP of 2.

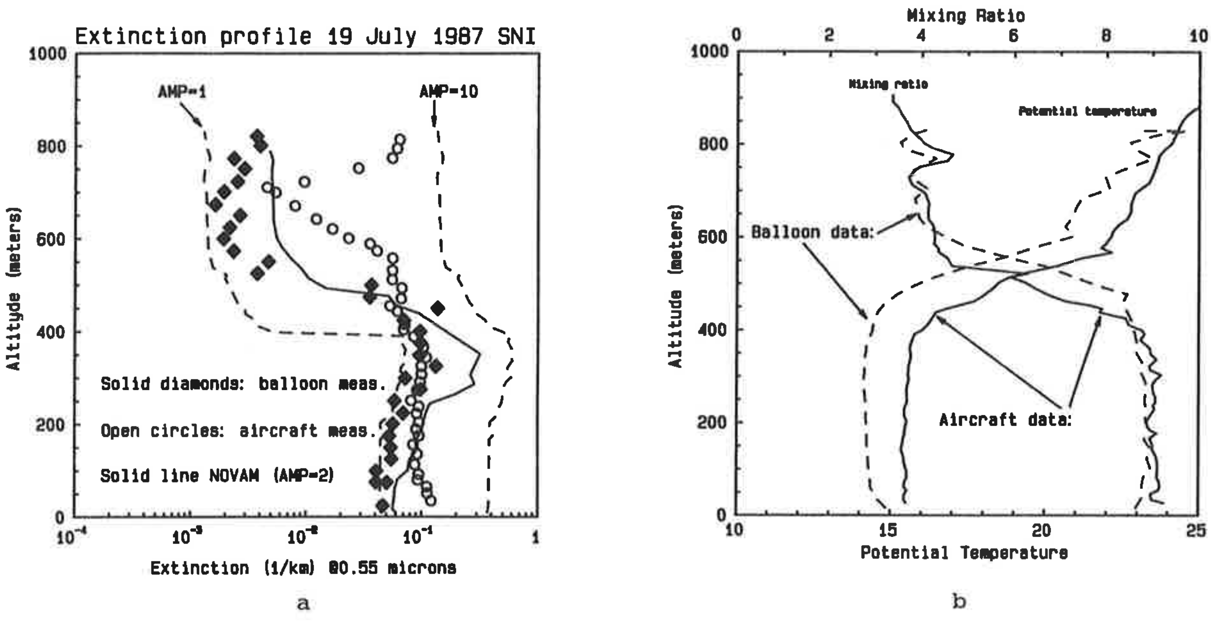

Figure 6. Profiles for clear air case of 19 July:
a. extinction profiles at 0.55 µm, derived from the aerosol measurements with the balloon (◆) and with the aircraft (o). The line is the NOVAM-estimated extinction profile for AMP=2, the broken lines are for AMP's of 1 and 10. The NOVAM-estimated extinction profile is within the envelope of the experimental data for 90% of the time. This profile would thus be graded "A" (see section 3.4).
b. potential temperature and mixing ratio profiles.

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7. ACKNOWLEDGEMENTS

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ATMOSPHERIC PROPAGATION IN THE UV, VISIBLE, IR AND MM-WAVE REGION AND RELATED SYSTEMS ASPECTS

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