Representing Cloud Processing of Aerosol in Numerical Models

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Introduction

The satellite imagery in Figure 1 provides dramatic examples of how aerosol influences the cloud field. Aerosol from ship exhaust can serve as nucleation centers in otherwise cloud-free regions, forming ship tracks (top image), or can enhance the reflectance/albedo in already cloudy regions. This image is a demonstration of the first indirect effect, in which changes in aerosol modulate cloud droplet radius and concentration, which influences albedo.

It is thought that, through the effects it has on precipitation (drizzle), aerosol can also affect the structure and persistence of planetary boundary layer (PBL) clouds. Regions of cellular convection, or open pockets of cloudiness (bottom image) are thought to be remnants of strongly drizzling PBL clouds. Pockets of Open Cloudiness (POCs) (Stevens et al. 2005) or Albrecht's "rifts" are low cloud fraction regions characterized by anomalously low aerosol concentrations, implying they result from precipitation. These features may in fact be a demonstration of the second indirect effect.

To accurately represent these clouds in numerical models, we have to treat the coupled cloud-aerosol system. We present the following series of mesoscale and large eddy simulation (LES) experiments to evaluate the important aspects of treating the coupled cloud-aerosol problem.

1. Drizzling and nondrizzling simulations demonstrate the effect of drizzle on a mesoscale forecast off the California coast.

2. LES experiments with explicit (bin) microphysics gauge the relative importance of the shape of the aerosol spectrum on the 3D dynamics and cloud structure.

3. Idealized mesoscale model simulations evaluate the relative roles of various processes, sources, and sinks.

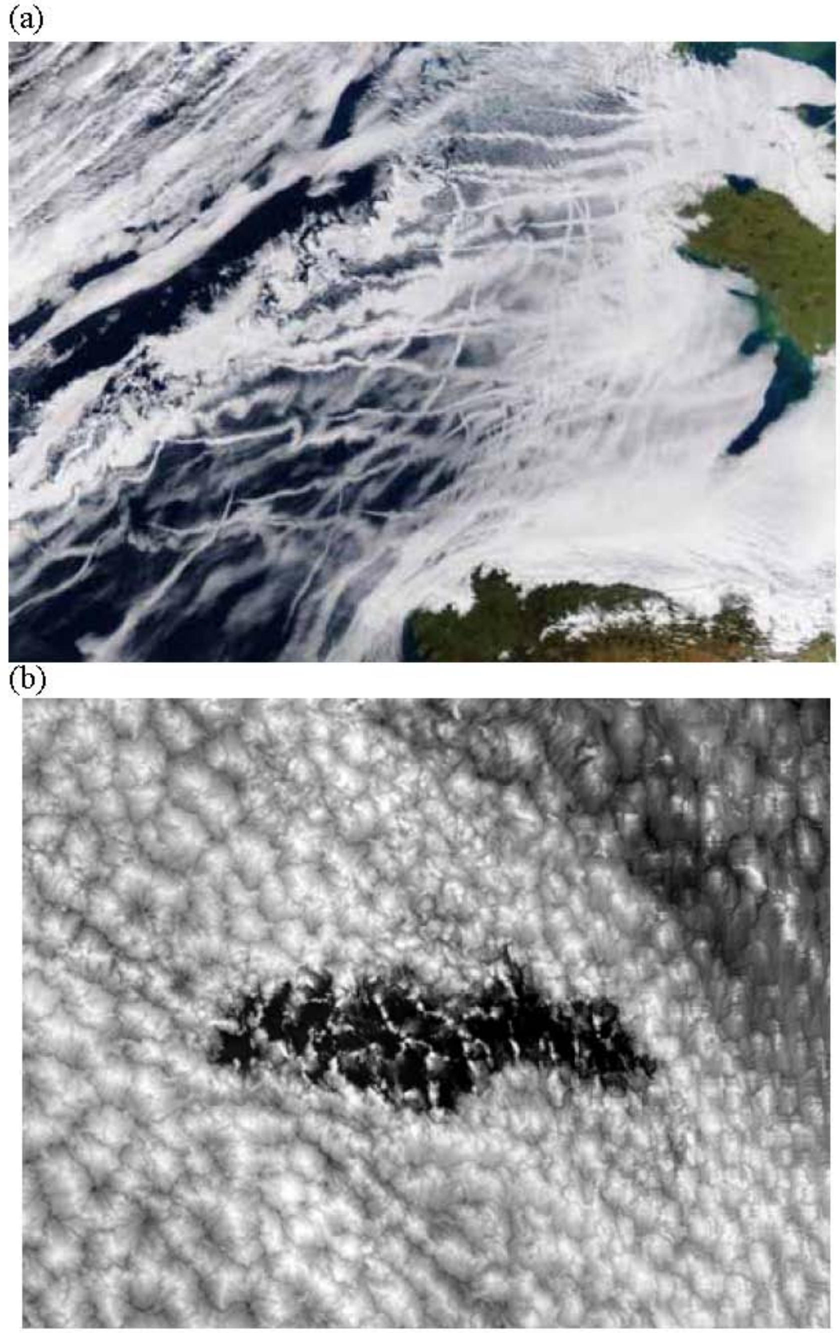

Figure 1. MODIS (Moderate Resolution Imaging Spectroradiometer) imagery of boundary layer cloud systems. (a) Ship tracks over the Bay of Biscay, north and west of Spain and France. (b) POCs over the subtropical Pacific. Imagery is courtesy of Robert Wood.

Importance of Dizzle in a Mesoscale Forecast

Simulations conducted with the Naval Research Laboratory Coupled Ocean/Atmosphere Mesoscale Prediction System (NRL COAMPS; Hodur 1997) demonstrate significant improvements when the cloud system is represented as a coupled aerosol-cloud-drizzle problem (Mechem and Kogan 2003). Figure 2a and b show the liquid water path (LWP) field for simulations both with and without drizzle on a coarse 18 km grid mesh. Three improvements are realized, relative to satellite imagery in Figure 2c. First, reduced entrainment from drizzle induced stabilization leads to a further northern extent of the cloud wedge. Second, including drizzle results in a reduction in LWP and cloud coverage south and east of Point Conception. Finally, the open oceanic LWP in the drizzle simulation is a better match with climatology. Figure 3 shows the evolution of the surface aerosol concentration over the course of 12 hours. The underlying aerosol behavior at the surface is a combination of cloud processing and transport (both resolved and subgrid).

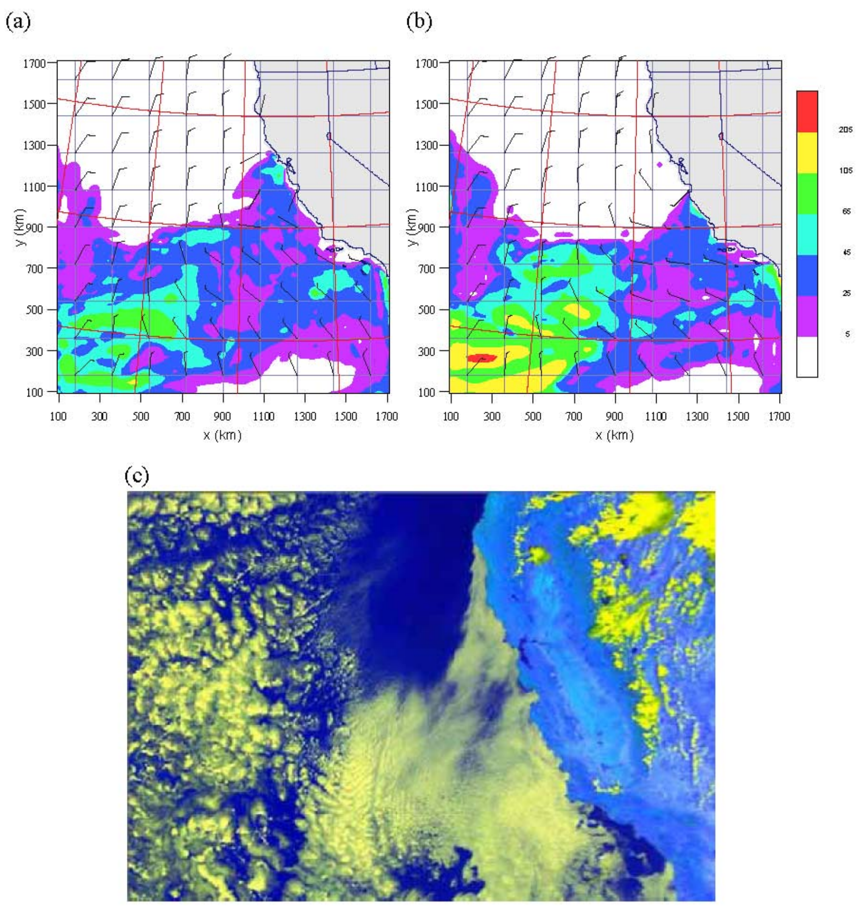

Figure 2. Comparison of COAMPS simulation and satellite imagery for 1800 UTC 25 July 1997. (a) LWP (g, m^{-2}) on the 18 km mesh, using the 5-moment micro-physical scheme that includes drizzle and aerosol processing. (b) LWP, using the operational (Kessler) microphysics without drizzle. (c) AVHRR (Advanced Very High Resolution Radiometer) visual imagery for 1743 UTC. See Mechem and Kogan (2003) for more details.

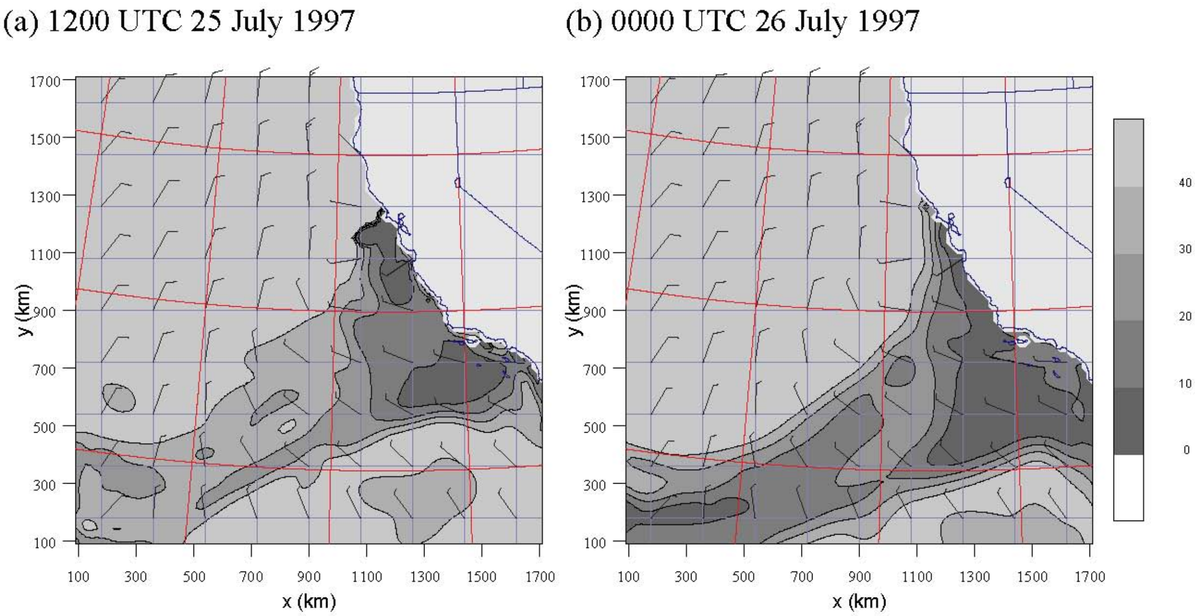

Figure 3. Surface aerosol concentration (cm^{-3}) at two simulated times twelve hours apart.

Including drizzle over the fine (2 km) mesh results in the emergence of mesoscale variability in the form of cloud bands that are deeper than the unbroken stratocumulus (not shown). We take these thick cloud bands to be representative of an ensemble of cumulus clouds associated with the transition from unbroken boundary layer stratocumulus to boundary layer cumulus. Accounting for the aerosol-cloud-drizzle link improves the treatment of clouds through a wide range of grid sizes, over the regimes of both resolved and parameterized boundary layer processes.

Influence of Aerosol Spectrum Shape on 3D Cloud Dynamics and Structure

The mesoscale model results in Section 2 represent atmospheric aerosol using a single number concentration parameter. LES results demonstrate that trying to represent aerosol properties by a single parameter may be problematic. Figure 4 shows two LES simulations, one with the background sulfate mode in the free troposphere, and the other with the sulfate mode plus giant aerosol. When pollution above the inversion is predominantly fine-mode (sulfate), drizzle production is suppressed. When giant aerosol in the free troposphere is entrained into the cloud system, the cloud experiences enhanced drizzle production, PBL turbulence is attenuated, and cloud breakup is accelerated. These results demonstrate that a single parameter representing aerosol is inadequate to represent all aspects of aerosol-cloud-drizzle interaction.

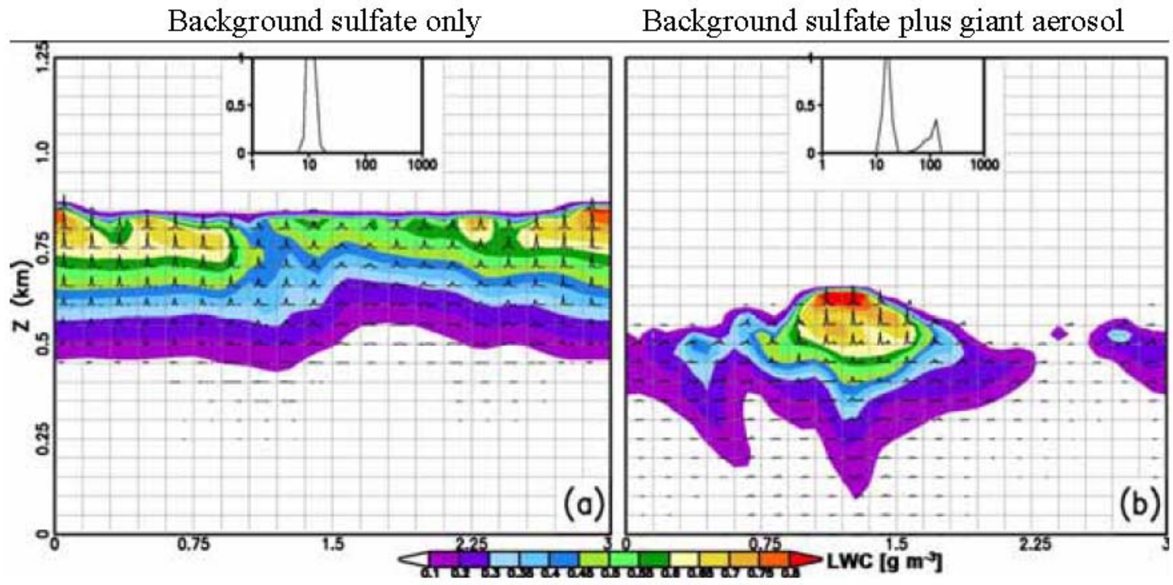

Figure 4. Vertical cross sections from two LES simulations of liquid water content (g m^{-3}) and droplet spectra at each point. (a) Background sulfate aerosol only. (b) Background sulfate plus free tropospheric giant aerosol, which seed the boundary layer as it entrains.

LES simulations also evaluate the effect of sea salt for various background sulfate and Aitken mode concentrations. The sea salt effect depends on the sulfate aerosol concentration, N. When N is low, the effect of sea-salt is to significantly increase cloud droplet concentration. When N is high, the addition of sea salt tends to suppress the supersaturation such that fewer of the sulfate nuclei are activated, resulting in smaller concentration of cloud droplets. This latter effect, however, depends on the concentration of Aitken nuclei.

LES results indicate that prediction of aerosol-cloud-drizzle feedbacks should include three main bulk aerosol parameters: Aitken nuclei, background (fine mode) sulfate, and coarse mode (giant) aerosols.

Relative roles of boundary layer processes and aerosol source and sinks

We run a mesoscale model in an idealized configuration to evaluate the relative role and importance of various process, sources, and sinks for atmospheric aerosol. Using a budget approach, we isolate cloud processing rate relative to imposed sources, other sinks, and entrainment. Figure 5 shows total concentration (aerosol + cloud droplets), relative to their initial values, for two initial concentrations. Entrainment, whether dilution in this case or a source of aerosol from an elevated polluted layer, plays a major role in modulating the PBL aerosol concentration. Representing this source of aerosol requires accurate entrainment rates and knowledge of the free tropospheric aerosol.

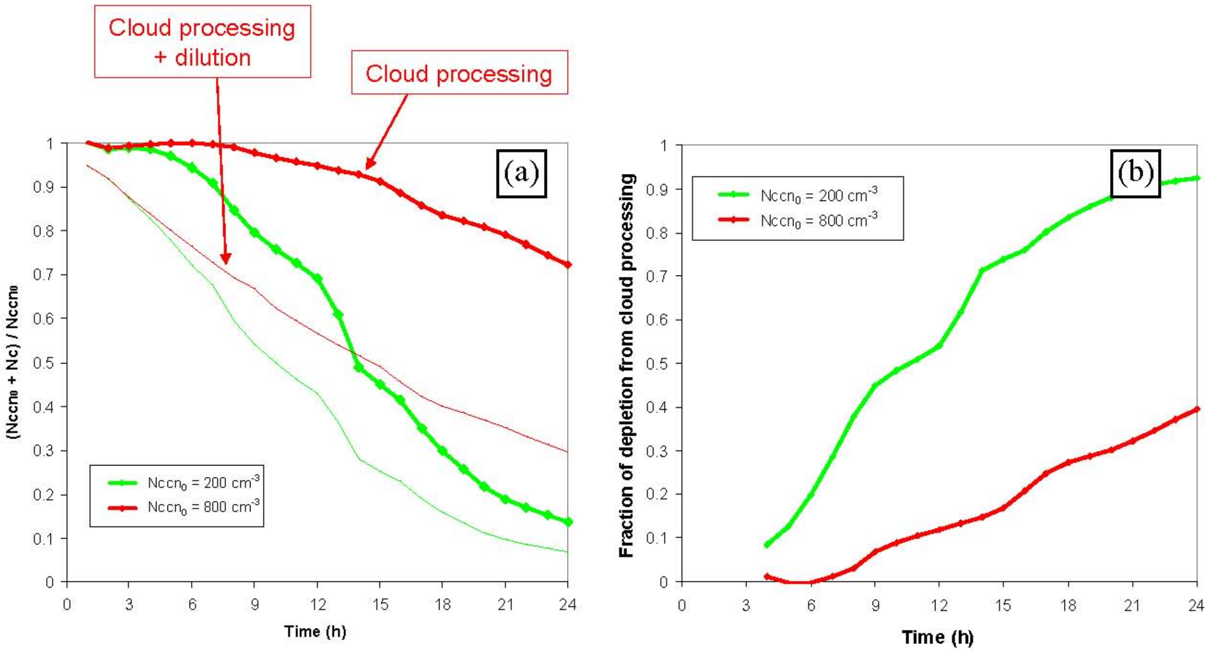

Figure 5. (a) Evolution of mean boundary layer total particle concentration (aerosol + cloud droplets), relative to their initial values, for two values of initial aerosol concentration. Thicker lines represent the cloud processing components. (b) Fraction of the total particle depletion from cloud processing for the two aerosol initial conditions.

Cloud processing (depletion) is correlated to drizzle rates by simple power laws and largely independent of initial conditions. Depletion can also be related to other model parameters, which might serve as a nexus of aerosol-cloud interactions in large-scale models.

Components Required to Accurately Represent Aerosol-Cloud-Drizzle Interactions

- Specification of aerosol field (initial and [sometimes] boundary conditions)
  Size characteristics
  Spatial distribution
  Observations and data assimilation necessary for three aerosol parameters; possibly more important for mesoscale and numerical weather prediction (NWP) models than GCMs

- Specification of sources and sinks
  Urban sources
  Sea salt
  Heterogeneous chemistry
  Transformation rates (fine↔coarse mode)
  Sea salt source parameterizations exist; parameterizations for aerosol transformation rates have yet to be developed.

- Transport
  Advection
  Sedimentation
  Turbulent mixing (entrainment)
  Depends largely on model numerics and how well the SGS represents entrainment

- Cloud processing
  Activation
  Coagulation, rainout, diffusiophoresis
  Regeneration
  Processing via coagulation represented in some cloud physics schemes; recent activation parameterizations not yet linked to SGS energetics

Conclusions

- Accurately representing PBL cloud processes in mesoscale, NWP, or GCMs requires including the aerosol part of the problem and is vital for any physically-based representation of the first and second indirect effects.

- The general requirements of how to treat aerosol-cloud-drizzle interactions are becoming clearer

- Absolute magnitudes of sources/sinks are at present poorly constrained

- A major effort is required to estimate these quantities and develop parameterizations of the sources and sinks, either from observations or process models (LES, cloud-resolving model). Some of the aerosol components will be easier than others to evaluate/estimate. Easier (relatively): Entrainment, sea salt, coagulation, activation. Harder: Heterogeneous chemistry, aerosol transformation rates, aerosol regeneration.

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