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CLOUD RESOLVING MODEL SIMULATIONS OF WATER AND ENERGY BUDGETS FOR THE INDIAN OCEAN REGION: EFFECTS OF AEROSOLS ON TRADE WIND CUMULI

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1. INTRODUCTION

The Indian Ocean Experiment (INDOEX) was held in 1999 to investigate the regional and global climate forcing associated with the anthropogenic haze that spreads over the North Indian Ocean during the winter monsoon. Consistent with other regions, both direct and indirect aerosol effects arise in this region, where indirect effects are associated with reductions in cloud droplet size that cause enhanced reflection of solar radiation and increases in cloud lifetime. In addition, recent studies (Ackerman et al. 2000; Ramanathan et al. 2001) have shown that a semi-direct effect might also be acting, where carbonaceous aerosols in polluted air absorb solar radiation, resulting in the warming and desiccation of cloud layers. There is considerable uncertainty in estimates of indirect and semi-direct effects, which severely limits the ability to represent these processes in large-scale models.

The purpose of this study is to better characterize the nature of semi-direct and indirect effects by conducting three-dimensional limited domain simulations of trade wind cumuli in the Indian Ocean region, where processes such as the effect of soot absorption can be represented in finer detail than possible in large-scale models. Because semi-direct effects should decrease cloud coverage and indirect effects increase the optical depths of existing cloud layers, the premise of the modeling simulations can be tested against observations of these quantities obtained during INDOEX. These observations come from a combination of in-situ and remote sensing observations.

2. INDOEX OBSERVATIONS

The National Center for Atmospheric Research (NCAR) C-130 aircraft flew 5 so-called gradient missions during INDOEX, where it departed Male, Republic of Maldives, and flew south as far as possible, sampling clouds and aerosols in the boundary layer. This allowed sampling of both polluted conditions typically prevalent near Male and pristine conditions present for the furthest south penetrations near 7^{o}S. The NCAR TSI-3760 condensation nucleus (CN) counter gave estimates of aerosol concentrations, and the air masses were identified as pristine, polluted or intermediate following the classification of Heymsfield and McFarquhar (2001).

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Observations of cloud coverage were needed for determining whether or not clouds were less common in polluted environments due to soot absorption. The simplest measure of cloud coverage comes from analysis of data collected using the in-situ spectrometers installed on the NCAR C-130. Liquid water contents (LWCs) were calculated from analysis of data from a composite of probes (Heymsfield and McFarquhar 2001), and clouds were identified as all points with LWCs greater than 0.01 g m^{-3}. Following this definition, there were not significant trends in how cloud coverage varied with the degree of pollution. For example, cloud coverage in pristine conditions was 3.4% on average, compared with cloud coverage of 5.1% and 3.6% for the transition and polluted conditions respectively.

No significant trends might exist in cloud coverage because in-situ microphysical data offer a very limited data set. Further, only one location within the boundary layer is sampled, and if clouds exist above or below the flight level of the aircraft, the location is recorded as cloud free. Hence, remote sensing data are required in order to accurately represent cloud statistics in the boundary layer. Statistics of cloud coverage from the multi-channel radiometer (MCR) as a function of CN number will be presented at the conference. These data show a marked dependence of cloud coverage on CN number, suggesting a dominance of the semi-direct effect.

Analysis of in-situ data was informative, though, in that it showed that cloud coverage statistics could vary significantly for the five different days during which these gradient flights were flown. For example, in polluted air masses clouds were present at flight level only 1.1% of the time, whereas they were present 4.1% of the time for the flight made on February 20. This shows that each day has to be treated separately in order to determine how semi-direct and indirect effects feedback on both cloud macrophysical (i.e., cloud fraction) and microphysical (i.e., optical depth and typical cloud particle sizes) properties. Further, numerical simulations are required to investigate the processes that are associated with the observed variations in cloud cover.

3. CRM SIMULATIONS OF TRADE WIND CUMULI

A cloud-resolving, anelastic, nonhydrostatic Eulerian/ semi-Lagrangian (EULAG) model (Smolarkiewicz and Margolin 1997) was used to simulate the evolution of the trade-wind cumuli field. This model is unique in its use of unified semi-Lagrangian/Eulerian, non-oscillatory forward-in-time numerical algorithms, which are second order accurate in time and space. The EULAG model currently includes the moist precipitation thermodynamics described by Grabowski and Smolarkiewicz (1996) and Grabowski (1999).

Simulations are performed using a high horizontal resolution of 100 m on a doubly-periodic domain covering an area of 6.4 by 6.4 km and a vertical height of 3 km. The use of fine resolutions and fine time steps is required because of the small horizontal dimensions of trade wind cumuli. The simulations are performed in three dimensions because the use of a two-dimensional version of the model gave non realistic oscillations in the cloud field associated with a heating of the domain, which caused subsequent large-scale subsidence that suppressed cloud development. The height of the domain was systematically decreased to the lowest possible value that exhibited no influence on the resulting cloud cover and modeled liquid water paths. The horizontal resolution was set to the lowest possible value for which the available computational resources would give results in a reasonable time; sensitivities to further increases in horizontal resolution are not known.

Simulations were initialized with temperature and humidity profiles measured by dropsondes released by the C-130 during its high altitude transect back to Male. Figure 1 shows an example of one. Prominent features include a layer beneath approximately 1 km where the temperature decreases and the relative humidity increases with height. A temperature inversion, or at least a large decrease in the atmospheric lapse rate occurs between approximately 1 and 1.5 km that acts to cap the heights to which the small cumuli rise. Small-scale fluctuations in the temperature and humidity fields that are observed may be due to gravity waves or radiative destabilization effects. The model profiles were smoothed out in order to assess if such small-scale features could be produced from the model.

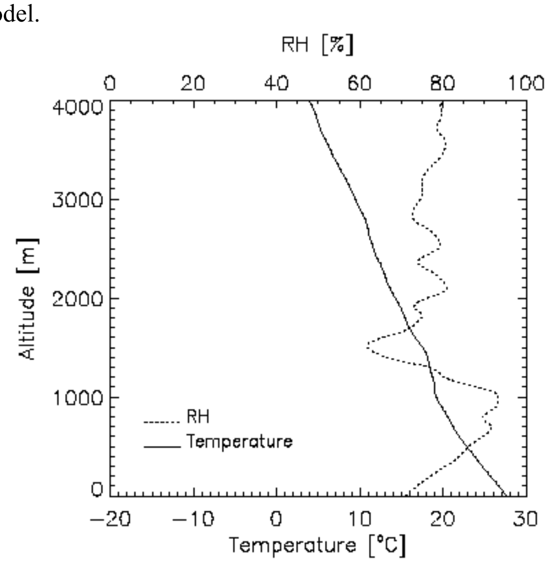

Figure 1: Temperature and relative humidity as function of height from dropsonde released from NCAR C-130 on February 24, 1999 at 7:26 during gradient leg.

Figure 2 shows an example of the temporal evolution of liquid water path predicted by the model for simulations with varying locations and thickness of the aerosol layer. It can be seen that the model simulations are sensitive not only to the total amounts of aerosol, but also to the location of the aerosols above or within the boundary layer. Other figures to be presented at the conference show the sensitivity of the predicted cloud fraction and the profiles of shortwave and longwave heating to these assumptions.

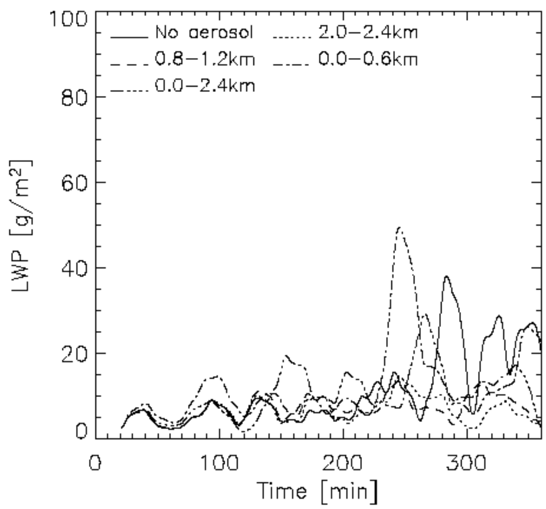

Figure 2: Temporal evolution of simulated LWP for three-dimensional model simulation of limited-area INDOEX domain. Different line colors correspond to varying locations and thickness of aerosol layer.

Other sensitivity studies will be presented at the conference to show the effect of different processes on simulated cloud fields and heating profiles. The processes to be examined include effects of the composition and single-scattering properties of aerosols (e.g., inclusion of soot core in aerosol particles), effects of varying number concentrations of cloud droplets, effects of varying the fluxes of heat and moisture from the ocean surface, effects of varying thermodynamic profiles by simulating different days from the INDOEX project, and the effects of using different relaxation schemes to force the simulations back to the observed temperature and moisture profiles. A simulation representing the diurnal evolution of trade wind cumuli will also be presented.

4. SUMMARY

Analysis of data collected during INDOEX suggest that semi-direct effects have a major impact on the cloud properties observed, and hence, on the water and energy budgets of the Indian Ocean region. Because the relative importance of the semi-direct effect and aerosol indirect effects are not well known but important for an overall understanding of climate, limited-area cloud-resolving model simulations are conducted of the effects of aerosols on cloud properties and heating rate profiles. Observations obtained during INDOEX can be used to evaluate whether the model processes are adequately predicting cloud fields, and hence the model results can be used to assess the impact of aerosols on the local water and energy budgets. This information should proof valuable for application of these effects in large-scale climate models.

5. ACKNOWLEDGEMENTS

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