4.4 DRIZZLE-INDUCED MESOSCALE VARIABILITY OF BOUNDARY LAYER CLOUDS IN A REGIONAL FORECAST MODEL

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1. INTRODUCTION†

Subtropical marine stratocumulus clouds have a pronounced impact on the global shortwave radiation budget and may be an important feedback process in the topic of global climate change. Large eddy simulation (LES) models have supplied insight into these cloud-topped boundary layers (CTBLs) and show that cloud macroscopic properties such as cloud base, height, and fraction result from a delicate balance between surface fluxes, cloud radiative fluxes, large scale subsidence, and when present, precipitation in the form of drizzle.

Broken fields of boundary layer cloud may be organized on the mesoscale. Previous studies have attempted to explain the characteristic aspect ratios of open and closed mesoscale convective cells, for example. Observational and modeling studies suggest that drizzle is one mechanism that can lead to the breakup of a stratocumulus cloud field. Drizzle evaporating below the cloud deck can stably stratify the subcloud layer, reducing the vertical fluxes and allowing heat and moisture to accumulate in the shallow surface layer. This accumulation leads to potential instability, which is realized in the from of a field of boundary layer cumulus. Studies suggest that this breakup might lead to an emergence of mesoscale organization in the form of cellular or banded structures.

It is becoming possible to run operationally mesoscale models with horizontal grid spacings on the order of an LES domain size (2-3 km), and it is important to know whether the mesoscale model is correctly representing the CTBL dynamics. Unbroken stratocumulus are largely forced by cloud-top radiative cooling, which drives eddies that span the depth of the well mixed boundary layer. These eddies are resolved in LES simulations but fall in the subgrid range of a mesoscale grid and must be parameterized.

In this study the US Navy Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS™††; Hodur 1997) has been applied to a case of coastal California summer season stratocumulus. Using a two-moment microphysical scheme (Khairoutdinov and Kogan 2000; hereafter “KK”), we show that a regional model can mimic the diurnal cycle in cloud thickness and produce a cloud pattern organized on the mesoscale and accompanied by a drizzle-induced transition from unbroken stratocumulus to boundary layer cumulus that occurs over the period of a few hours. The presence of drizzle seems to be crucial in producing mesoscale organization on a short timescale and has a complicated nonlinear effect on cloud cover, since it depletes cloud water while also damping mean boundary layer energetic quantities, reducing drying of the PBL via entrainment. Analysis is concentrated on the fine 2 km mesh and analyzed in the context of consistency with conclusions derived from LES-based studies.

2. MODEL CONFIGURATION

COAMPS is run for 24 h in a one-way nested grid configuration, with domains of 18, 6, and 2 km in horizontal grid spacing located over the California costal region. The 6 km and 2 km domains are overlaid on Figure 1. Vertical grid spacing ranges from 10 m near the surface to 800 m at the model top, and from 25-75 m at the inversion. Two 12 h simulations are performed to serve as a preforecast in order to obtain a reasonable boundary layer thermodynamic and cloud field structure. The preforecast begins at 00 UTC 24 July 1997 and undergoes two update cycles, one at 12 UTC and the second after the preforecast completes at 00 UTC 25 July 1997. The 24 h simulation begins at this time.

The KK scheme is used to parameterize microphysical processes. KK is a bulk parameterization based on the partial moments of the drop size distribution. Like other bulk schemes, it segments liquid water into a precipitating part (drizzle water) and a nonprecipitating part (cloud water). Equations for number concentration of cloud droplet, drizzle drop, and cloud condensation nuclei (CCN) are also solved to total five prognostic variables (q_c, q_r, N_c, N_r, N_{CCN}). Initial CCN concentration is assumed to be 45 cm^{-3}, a value representative of a clean air mass and consistent with the north-northwesterly flow pattern on 25 July. CCN boundary conditions are fixed at the initial value, and in situ sources are neglected.

In addition to the control simulation that uses the KK parameterization (“KK”), reference will be made to a sensitivity experiment (“ND” — no drizzle) that uses the operational Kessler microphysical parameterization.

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††COAMPS™ is a trademark of the Naval Research Laboratory.

Since the autoconversion threshold of 1 g kg^{-1} is never reached, the Kessler cloud physics scheme becomes essentially simple saturation adjustment.

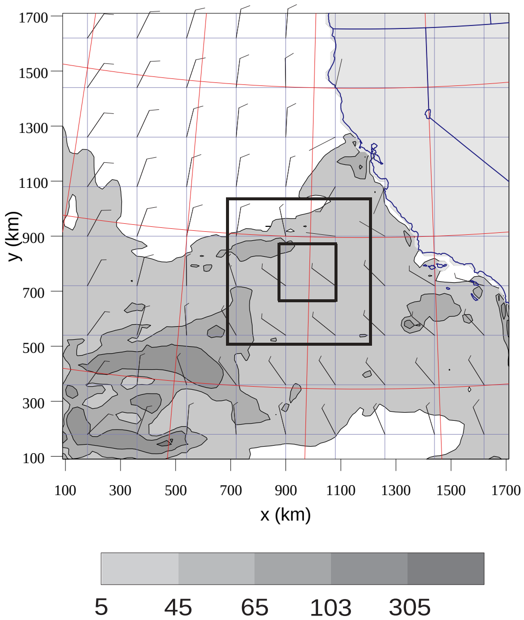

Figure 1. 18 UTC liquid water path [g m^{-2}] for the 18 km KK simulation. Boxed regions denote the 6 km and 2 km domains.

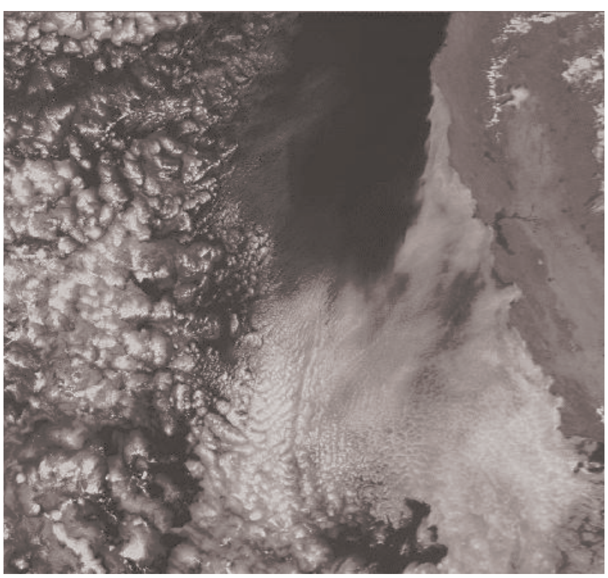

Figure 2. Multi-band AVHRR (Advance Very High Resolution Radiometer) composite of visible and infrared bands for 1743 UTC on 25 July 1997.

3. MESO-α SCALE CLOUD SYSTEM GEOMETRY

Figure 1 shows that the simulation produces a wedge-shaped cloud system and a decrease in cloud fraction west of the Baja California peninsula. This is generally consistent with AVHRR imagery in Figure 2. A hint of cellular boundary layer convection is visible over the southwest side of the domain, where local maxima in liquid water path (LWP) indicate deep regions of liquid water characteristic of cellular convection.

4. REPRESENTATION OF BOUNDARY LAYER CLOUD PROCESSES ON THE FINE (2 KM) MESH

By scrutinizing the 2 km mesh, understanding obtained from LES studies can be brought to bear, since the scale difference between a typical LES grid spacing and 2 km is only one order of magnitude, while that between the LES and typical current NWP meshes may be two orders or more. Interpretation is made difficult by the fact the in the mesoscale model much of the PBL dynamics is parameterized.

4.1 Diurnal cycle and statistics

The evolution of mean quantities over the 2 km mesh is shown in Figure 3. The cloud-top inversion slopes upward away from the shore, so we normalized columns of cloud water, potential temperature, and mixing ratio by mean cloud top height to ensure the sharp gradients associated with the inversion are maintained.

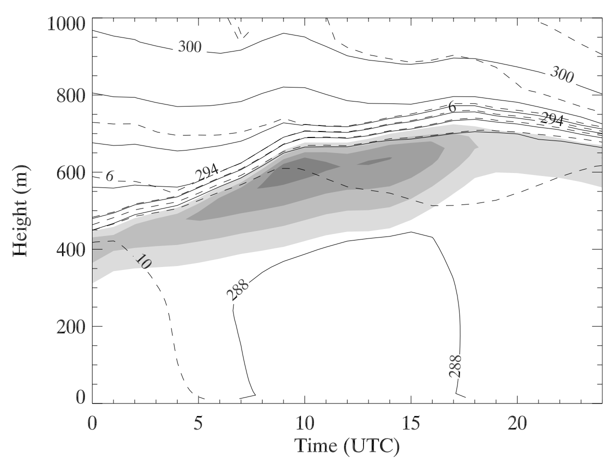

Figure 3. Evolution of potential temperature (solid) [K], mixing ratio (dashed) [g kg^{-1}], and cloud water (shaded, 0.1 g kg^{-1} interval) averaged over the 2 km mesh.

Local sunrise and sunset are 1330 UTC and 0327 UTC, respectively, and the rising cloud top and inversion between 00 UTC and 17 UTC indicate a diurnal cycle produced by the model. After 17 UTC, cloud top descends and mean liquid water content quickly diminishes. The ascent of the inversion and cloud top before

08 UTC is a result of boundary condition forcing, while drying of the cloud layer indicated by the descent of the 9 g kg^{-1} contour is indicative of the entrainment process. Moisture rather than temperature is a better indicator of entrainment in this COAMPS simulation, but it is apparent that the PBL grows more slowly after entrainment has brought about a slightly stratified moisture structure, indicating either that entrainment is somewhat self-regulating (as suggested by Stevens et al. 1999) or that because of the relatively small size of the domain, the residence time of cloudy air over the 2 km mesh places an upper bound of the amount of entrainment a cloudy column experiences prior to exiting the domain.

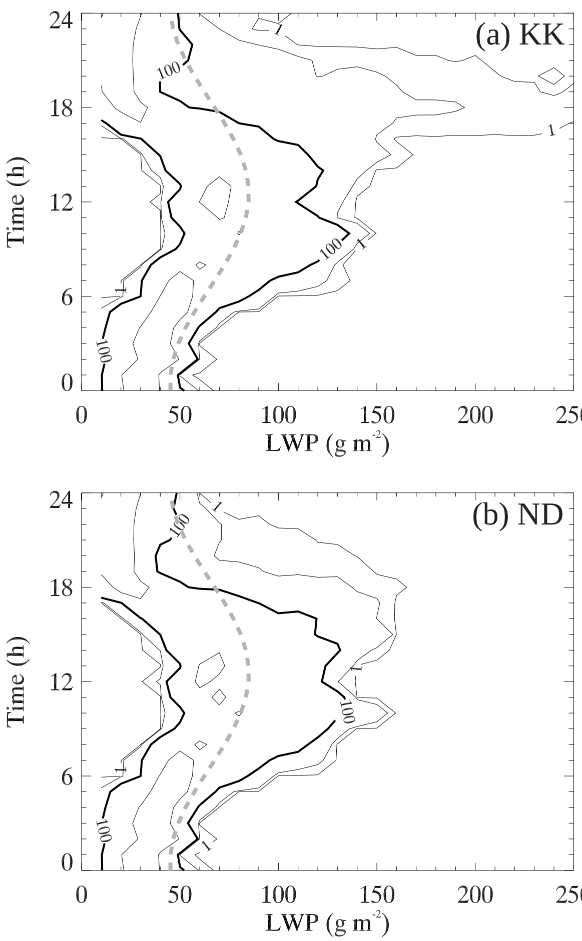

Figure 4. Evolution of hourly LWP PDFs, composited and contoured on a logarithmic scale. Contour units are [10^{-6} h^{-1} (g m^{-2})$^{-1}$]. Light grey dashed line represents the TMI-derived JJA satellite climatology supplied by R. Wood (see Wood et al. 2002 for methodology).

Figure 4 shows the evolution of the probability distribution function (PDF) of LWP over the 2 km domain for the KK (control) and ND (no drizzle) simulations. These figures are composed by making PDFs of LWP at hourly intervals, then stacking them to make three dimensional fields of probabilities, which are then contoured (similar to the CFAD diagram of Yuter and Houze 1995). Results for both cases show an increase in modal LWP from 00 UTC until approximately 12 UTC, roughly corresponding to nocturnal conditions. After sunrise (1330 UTC), LWP begins to decrease until 00 UTC of the following day. This sinusoidal-like pattern in modal LWP for this case resembles the JJA diurnal climatology calculated by Wood et al. (2002) from two years of TMI (Tropical Rainfall Measuring Mission Microwave Imager) data and represented by the dashed light grey lines. These particular simulations resemble the climatological behavior in phase and maximum diurnal value, while somewhat underestimating the diurnal minimum LWP.

The pronounced tail of the distribution from 17 UTC to 20 UTC in Figure 4a hints at an organized mesoscale variability and corresponds to the development of linear PBL convective features characterized by large values of LWP. *In the KK simulation, these convective features represent a drizzle-induced mesoscale organization and the transition from unbroken stratocumulus to a boundary layer cumulus regime, a process that does not occur in the ND case.* The tail in the KK distribution decreases after 20 UTC as the convective clouds leave the domain and absorption of shortwave radiation thins the cloud deck, suppressing the further formation of drizzle-induced cumuli.

4.2 Physical interpretation of the cloud structures

The KK simulation develops mesoscale organization in the form of cloud bands 5-20 km wide and corresponding regions of resolved-scale vertical velocities visible in Figure 5. The spatial scale of the COAMPS vertical velocities is an order of magnitude larger than those in an LES, while the magnitudes are an order less. If vertical velocities in an LES model correspond to actual boundary layer eddies that are parameterized in a mesoscale model, how should the dynamic fields in the mesoscale model being interpreted? Results of observational studies of mesoscale convective cells imply that the most logical approach is to consider the resolved updraft regions in the numerical experiments a *mesoscale* vertical velocity, representative of the mean upward motion from an ensemble of cloud elements.

LES and mesoscale models represent drizzle production processes differently. In COAMPS, drizzle formation is greatest in regions of high LWC, which is itself proportional to resolved updraft intensity. LES results demonstrate a more complicated relationship between drizzle production and vertical velocity on a scale much smaller than that captured by a mesoscale model. The mesoscale model updrafts are a *mesocale* representation of the PBL cloud processes and are taken to correspond to an ensemble mean of the actual eddy structure resolved by an LES model.

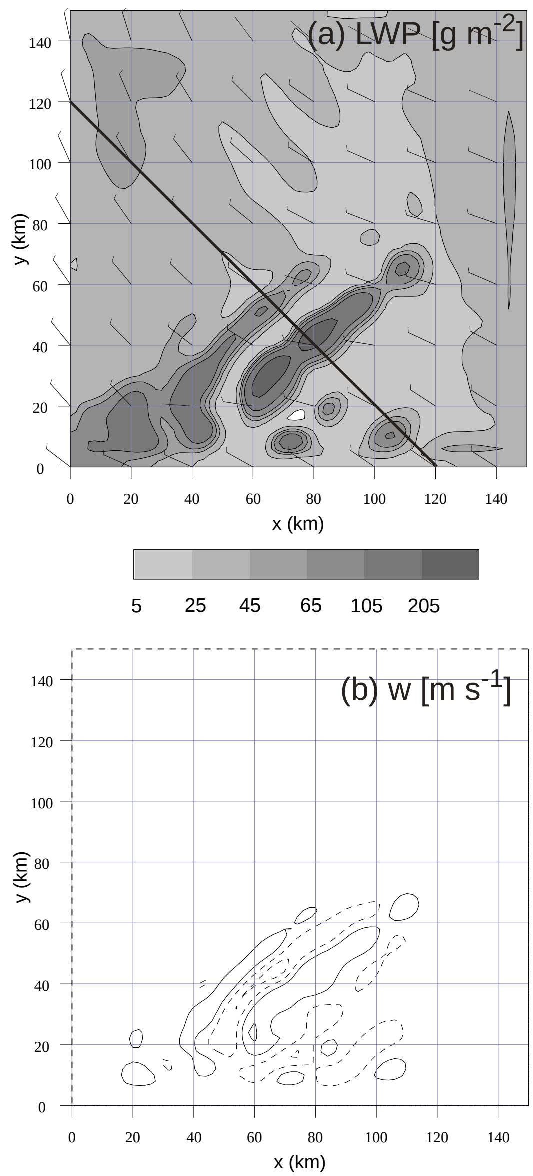

Figure 5. 18 UTC boundary layer quantities. (a) LWP [g m^{-2}]. (b) Vertical velocity (contour intervals of 0.1 m s^{-1}). Dark line in (a) oriented northwest-to-southeast represents vertical cross sections shown in Figure 6.

4.3 Emergence of mesoscale organization

The vertical cross sections in Figure 6, indicated by the dark line in Figure 5a, shed light on how an organized mesoscale pattern emerges from unbroken stratocumulus. The wind field is predominantly northwesterly and contains little vertical shear, so a vertical cross section from northwest to southeast may be thought to represent a Lagrangian of cloudy columns of air through the domain. Because of the boundary conditions imposed from the 6 km mesh, the cross sections do not represent the evolution of similar columns of air but rather of columns with different initial properties.

The cross sections are not perfect substitutes for a thorough trajectory analysis, but they show development of significant structure in the thermodynamic fields as columns of PBL air traverse the domain. Bolded contours of 290 K and 8 g kg^{-1} in Figures 6a and 6b denote the base of the inversion. The potential temperature structure of the subcloud layer is rather well mixed from the domain boundary to the strong drizzle core at 115 km (Figure 6a), while these strong regions of drizzle are associated with greater moisture stratification and an increase in surface water vapor (Figure 6b). The strongest regions of drizzle correspond to low cloud bases and resolved upward vertical motion, as illustrated in Figure 6d. The cooling and moistening in these convective regions arises from evaporation of falling drizzle, since the low level moisture increase in Figure 6b is accompanied by cooling in 6a.

Equivalent potential temperature (Figure 6c) is rather stratified, decreasing nearly 2 K over the 350 m cloud layer. θ_e decreasing with height satisfies the condition for potential (convective) instability such that a finite displacement of the layer will lead to buoyant free ascent. θ_e is used frequently as a parameter in deep convective circulations and would seem to be appropriate for a stratified boundary layer with moisture pooling in the surface layer. θ_e should be invariant under conditions of evaporating drizzle, implying that it can only evolve through advection, turbulence, or diabatic processes. In this simulation, weak horizontal gradients predominate, but resolved and parameterized vertical mixing, as well as diabatic processes of radiation and surface fluxes, can significantly modify θ_e. The θ_e stratification here can be thought of as an analog to the deep convective situation of a moisture-rich PBL underlying a capping inversion. Figure 6c shows a steady increase in surface θ_e near 75 km in a region outside any strongly drizzling core. This increase is accompanied by a positive trend in surface q_v but no significant signal in temperature, indicating that moisture form the surface flux is not at this point being efficiently mixed throughout the depth of the PBL. The thermodynamic structure, with low level θ_e increasing over time, leads to the resolved buoyant motions in Figure 6d, weak ensemble updrafts and downdrafts. Updrafts are associated with thicker convective towers and promote drizzle growth, while downdrafts are conducive to drizzle-free regions and cloud thinning.

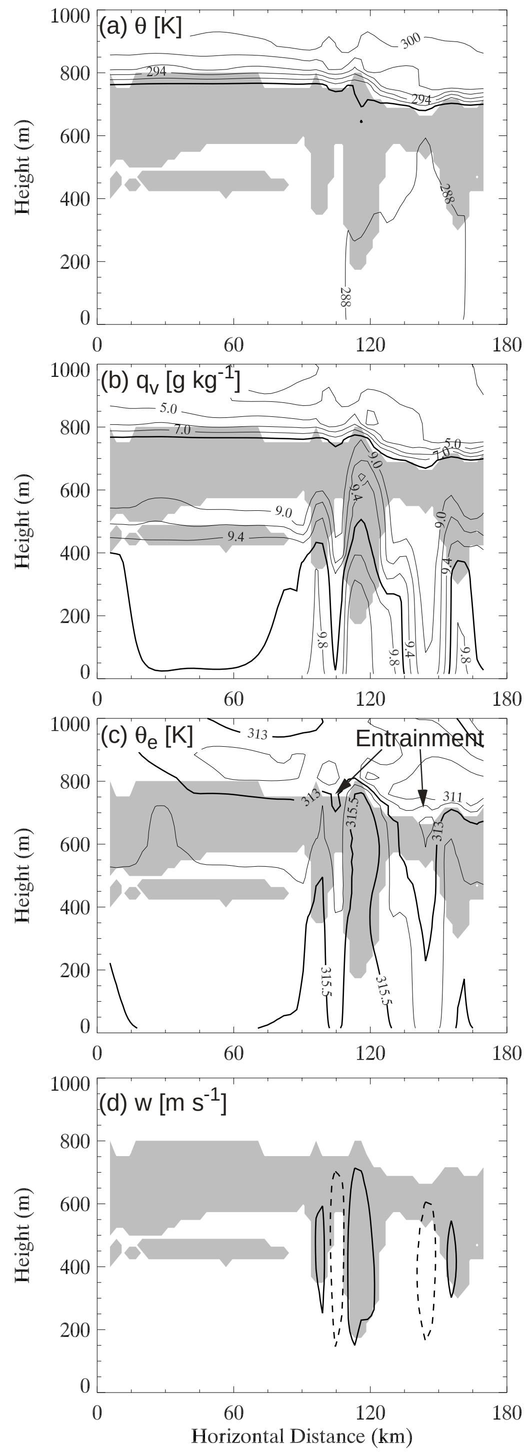

Figure 6. 18 UTC vertical cross sections of model thermodynamic and dynamic quantities taken along the northwest-southeast cross section in Figure 5a.

The emergence of mesoscale organization is enhanced by another aspect of this simulation — a kind of explicitly resolved entrainment, though different from that brought about by the turbulent eddies in LES results. Figure 6c shows entrainment events associated with the resolved downdrafts in Figure 6d, where free tropospheric air of low θ_e is drawn into the boundary layer from above, while air of larger θ_e in the boundary layer itself is displaced upward. The cloud depths reflect the entrainment process, with a thinning cloud deck accompanying the entrainment of free-tropospheric air. This *mesoscale* entrainment in our results appears to amplify or exaggerate further the banded structure of the cloud field.

The relationship that exists between cloud base and updraft and downdraft elements is an aspect of the organized mesoscale circulation exhibited in the simulation. In the LES study of Stevens et al. (1998), the presence of drizzle leads to downdraft bases being located higher than updraft bases. Drizzle reduces the LWC of updraft parcels, and after being detrained into surrounding downdraft regions, they descend and become subsaturated at a level higher than the original updraft parcels. The COAMPS simulation produces low cloud bases associated with the strongest drizzle in the updraft regions and thinner cloud in the downdraft areas. The cause of the thinning appears to be related to the mesoscale effect of free tropospheric dry air being entrained into the cloud layer rather than the asymmetry mechanism of the LES results. The resolved updraft and downdraft elements in the mesoscale model are not analogous to the eddy structures in the LES, so it is not surprising that the asymmetry behavior is not produced.

5. CONCLUSIONS

In the ND simulation, cloudy columns of air pass completely through the domain, with thermodynamic quantities remaining nearly well mixed. In the drizzling experiment, on the other hand, drizzle evaporating in the subcloud layer changes the character of the boundary layer sufficiently to allow a slight pooling of high θ_e air just above the surface. The instability associated with this slight CAPE is subsequently realized through resolved updrafts, which are associated with the strongest drizzle production. Previous modeling studies have produced a transition that occurs over a period of days by steadily increasing SSTs, while for the rapid transition (~6 h) occurring in our model, the presence of drizzle is vital.

Previous observational and modeling studies have hinted that the effect of drizzle on boundary layer cloud might produce some degree of mesoscale organization. We have used a mesoscale forecast model to show that, when drizzle processes are included, an organized mesoscale pattern in the form of cloud bands emerges. The cloud bands come about when drizzle stably stratifies the subcloud layer, which leads to conditions of potential (convective) instability. A form of explicitly resolved entrainment seems to amplify the organized aspect of the dynamics.

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