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Physical processes in present and future large-scale models

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Summary

PBL: Cloud/convection interaction - Chris Bretherton

The Challenge of Simulating Cloudy Boundary Layers

Cloud-topped boundary layers (CTBLs) are important for weather and climate simulation. Weather forecasts must simulate the diurnal evolution of CTBL thermodynamic and cloud structure to predict surface temperature, fog and visibility, deep convective onset, etc. In climate models, boundary-layer clouds have a major impact on the global and regional albedo, and CTBL vertical mixing processes affect air-mass transformation, the Hadley circulation, air-sea fluxes, cloud feedbacks on climate change, and cloud-aerosol interactions.

This talk focuses on marine clouds, which are particularly important for global climate on a mostly water-covered earth. Low clouds over land and their interaction with complexities of the underlying surface are also an important simulation challenge. Diverse types of marine low clouds are seen in different locations and synoptic regimes [1,2,3]. Over cooler ocean regions, stratus and stratocumulus (Sc) cloud layers prevail. Over warmer low-latitude oceans and in air masses formed during cold air outbreaks, shallow cumulus (Cu) are common. ‘Decoupled’ boundary layers commonly form as cold advection deepens a Sc-capped boundary layer, and are often characterized by surface-driven Cu rising into an elevated radiatively-driven Sc layer [4]. Warm advection can generate fog or shear-driven stratus layers. In addition to diverse vertical structure, CTBLs have rich mesoscale structure that is simulated by high-resolution global models or even large-eddy models (LEMs) models with domains 50 km or larger [5]. The release of latent heat due to condensation and precipitation is localized to thicker cloud patches and may reinforce mesoscale variability in CTBLs [6].

Boundary layer clouds are maintained by and strongly feed back on small-scale turbulent circulations. LEMs, which resolve these circulations, can produce quite realistic simulations of CTBLs and their transitions between different regimes, e. g. the subtropical Sc-Cu transition [7], although uncertainties remain involving microphysical parameterizations [8] and the role of numerical and subgrid turbulent diffusion in sharp inversions [9]. In global models, the cloud-turbulence interaction is not resolved, hence the subgrid covariability of vertical motion and cloud properties must be parameterized. This involves the interaction of what are typically separate modules for turbulence, shallow cumulus convection, subgrid cloud variability, cloud microphysics, surface fluxes and radiation. Add to this that boundary-layer Sc are often no more than 1-2 grid layers thick and may underlie a sharp inversion poorly resolved by the global model, and it is no surprise that CTBLs challenge global models.

Two key design objectives of a CTBL parameterization system are smooth simulations of regime transitions (e. g. Sc decoupling and breakup into Cu) as well as smooth response to the mesoscale variability that global models are trying to produce. This requires attention to parameterization interactions and a lot of testing and refinement both using idealized cases and global forecasts. One modern development is ‘unified’ parameterizations that better handle Sc-Cu transitions and associated cloud structure by combining the parameterizations of turbulence, cumulus and subgrid cloud distributions into a single coherent unit.

Three recent approaches are discussed in the talk. The first, CLUBB [10], is a simplified higher-order turbulence closure scheme that assumes vertical motion, temperature and humidity can be represented within each grid cell as mutually correlated double-Gaussian PDFs. 10 prognostic equations for turbulent moments are used to predict the subgrid vertical transports and cloud properties. Given sufficient vertical and time resolution, this approach can nicely simulate Sc to Cu transitions; it will be adopted for the next version of a leading US climate model, the Community Atmosphere Model. The second, ED(MF)^n [10] is an 'Eddy Diffusivity Mass Flux' approach in which small-scale turbulence is modeled as a diffusivity and eddies spanning several grid layers are treated using a mass-flux approach. Multiple starting updrafts are initiated near the surface with different entrainment rates, and shows that competition between the updrafts naturally generates the correct vertical structure of a trade cumulus layer with no cumulus mass flux closure (replacing it by an assumption that each updraft class has equal fractional area within the subcloud layer). The third, UNICON [11], adds to Neggers' MF approach a sophisticated downdraft treatment including cold pool variability in the subcloud layer of parameterized precipitating convection. It is very comprehensive and internally consistent but builds in a host of modeling assumptions that might make it hard for a modeling group to further refine.

The next part of the talk shows that stratocumulus cloud-aerosol interaction can create 'regimes' with disparate cloud albedo separated by sharp transitions, even though low cloud properties respond smoothly to a smooth change in cloud-condensation nucleus (CCN)-forming aerosol concentration [13]. 'Pockets of open cells' (POCs), mesoscale regions of broken cumuliform cloud, are commonly embedded in subtropical and midlatitude Sc decks where liquid water contents have become high enough and CCN concentrations low enough to initiate heavy drizzle [14]. The drizzle locally cleanses the CTBL and favors decoupling, leading to an aerosol-poor cumuliform region within an aerosol-rich Sc region with less drizzle. LES shows that these regions are mutually supporting [15], so the POC structure can last for days until the airmass drifts into a different large-scale environment. In contrast, shallow Cu cloud regimes may exhibit a 'buffered' (insensitive) response to aerosol changes [5]. This raises issues about what kinds of global models need to include interactive prognostic aerosols.

The last slides point out that for CTBLs with tops below O C, the parameterization of mixed-phase microphysics is a major source of uncertainty. Most weather and climate models predict too little cloud in the cold sector of midlatitude cyclones [16]. In climate models this bias leads to warming of the Southern Ocean and may lead to a spurious southward shift in tropical oceanic rainfall [17]. It can be largely eliminated by inhibiting the freezing of supercooled liquid water [18.19], but more in-situ observations and process modeling are needed to guide this process and understand whether CCN and ice nucleus concentrations may also play a role.

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