Mechanisms Affecting the Transition from Shallow to Deep Convection over Land

Research Highlight

The simulation of the diurnal cycle is an important measure of a climate model's performance. A well known problem is that climate models usually cannot produce the observed afternoon convective rainfall peak over land. Recently, theoretical studies of cloud-resolving models or large-eddy simulations have revealed several mechanisms on the transition from shallow to deep convection focusing on the influence of (1) free-tropospheric humidity, (2) sub-domain variability, such as boundary-layer cold pools driven by precipitation evaporation, and (3) atmospheric instability at the cloud levels. In this study, we use convective-regime-oriented composites from long-term observations over land to make a systematic assessment of these transition mechanisms. Specifically, 11 years of summertime observations at the ARM Southern Great Plains site have been used to categorize the diurnal cycle into different convection regimes (Figure 1). We focus on the comparison of environmental parameters between two regimes, the days with fair-weather shallow cumulus and the days with afternoon deep convection, in order to reveal the mechanisms controlling the transition from shallow to deep convection.

A few hours before rain events begin on afternoon deep convection days, higher relative humidity is found both in and above the boundary layer, especially between the levels of 2 to 4 km above the surface (Figure 2 (a)). The higher moisture content at 2 to 4 km depends on the wind direction being from the south. Relative to days of fair-weather shallow cumulus, greater instability, stronger inhomogeneity in boundary-layer temperature, less wind shear between 600 and 850 hPa, and weaker subsidence are found preceding afternoon rain events. Based on the composite sounding for the two regimes, we also find that the level of free convection is 1.7 km lower on days with afternoon rain events. Furthermore, although the diurnal variation in surface fluxes drives the growth of the boundary layer, the difference between regimes in their magnitude appears to be a response to changed boundary-layer conditions.

We then focused on the relationship between these conditions at 1130 local time and afternoon rain statistics. With greater relative humidity at 2 to 4 km, rain starts earlier and lasts longer (Figure 2(b)). Boundary-layer inhomogeneity, the 600 to 850 hPa westerly wind component, and the 2 to 4 km lapse rate are positively correlated with total rain and maximum rain rate; furthermore, these environmental parameters are correlated with each other. While not manifest in every statistical test, these observations are consistent with a role for lower troposphere (2 to 4 km) humidity and boundary-layer inhomogeneity in the transition from shallow to deep convection.

With respect to boundary-layer variability, we showed that in the early stage of precipitation, boundary- layer temperature and wind variability slightly lag precipitation by up to 1 hour. The creation of cold pools by deep convection may explain this correlation as well as the large increase of boundary-layer inhomogeneity on deep convection days relative to that on shallow cumulus days (Figure 2(c)). In addition, we also showed a connection between moisture and moist static energy inhomogeneity before afternoon precipitation begins and the subsequent precipitation (Figure 2(d)). This last correlation suggests that boundary-layer inhomogeneity promotes as well as results from deep convection. Note, however, that the inhomogeneity which may promote convection is not due to cold pools, as this inhomogeneity is present before precipitation.

A plausible, albeit not exclusive, interpretation is that the observational evidence is consistent with a mechanistic view of the transition from shallow to deep convection that emphasizes the ability of a parcel of boundary layer air to reach the level of

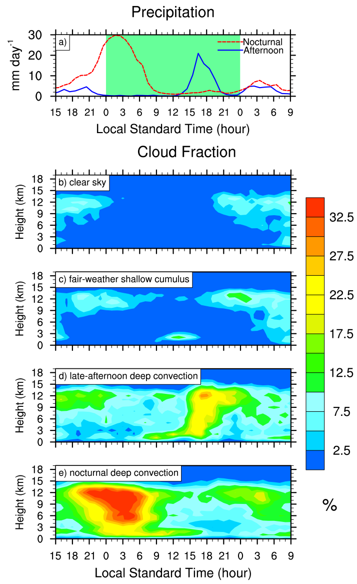

Figure 1: Diurnal composites of surface precipitation (a) and cloud fraction for days with: clear-sky (b), fair-weather shallow cumulus (c), late-afternoon deep convection (d), and nighttime deep convection (e). In (a), the blue line denotes rain rate for late afternoon deep convection days; the red line is for nighttime deep convection days. The green shaded area in (a) signifies the diurnal cycle of interest. The 9-hour period before and after is shown for the purpose of process continuity.

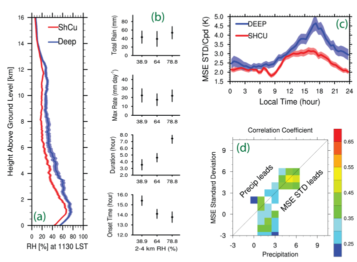

Figure 2: (a) relative humidity (RH) at 1130 local time (LST) for fair-weather shallow cumulus days and late-afternoon deep convection days. (b) Afternoon rain statistics stratified by different 2–4 km RH values at 1130 LST on deep convection days. (c) Diurnal cycle of surface moist static energy (MSE) standard deviation (STD) (d) Correlation between rain rate and MSE STD on afternoon deep convection days. The scale for both the abscissa and ordinate are hours after rain onset time.

free convection. In particular, the parcels that reach the level of free convection are those that have the highest values of moisture in the boundary layer, and they may have more momentum than expected due to mesoscale fluctuations in boundary-layer wind. This ability is also assisted by high relative humidity and a steeper lapse rate in the first few kilometers above the boundary layer. Higher relative humidity in this layer diminishes the buoyancy-reducing effects of entrainment, whereas the steeper lapse rate increases parcel buoyancy directly. Therefore, these observations provide partial support to parameterizations focusing on the ability of boundary-layer air parcels to penetrate the level of free convection, similar to the evolving CIN-based parameterizations of moist convection. Furthermore, the observations are somewhat encouraging for the nascent efforts to parameterize mesoscale boundary-layer inhomogeneity and its role in the transition from shallow to deep convection.

Reference(s)

Zhang Y and SA Klein. 2010. "Mechanisms affecting the transition from shallow to deep convection over land: Inferences from observations of the diurnal cycle collected at the ARM Southern Great Plains site." Journal of the Atmospheric Sciences, 67(9), 2943-2959.

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Working Group(s)

Cloud Life Cycle