# Clausius-Clapeyron scaling of peak CAPE in continental severe weather environments

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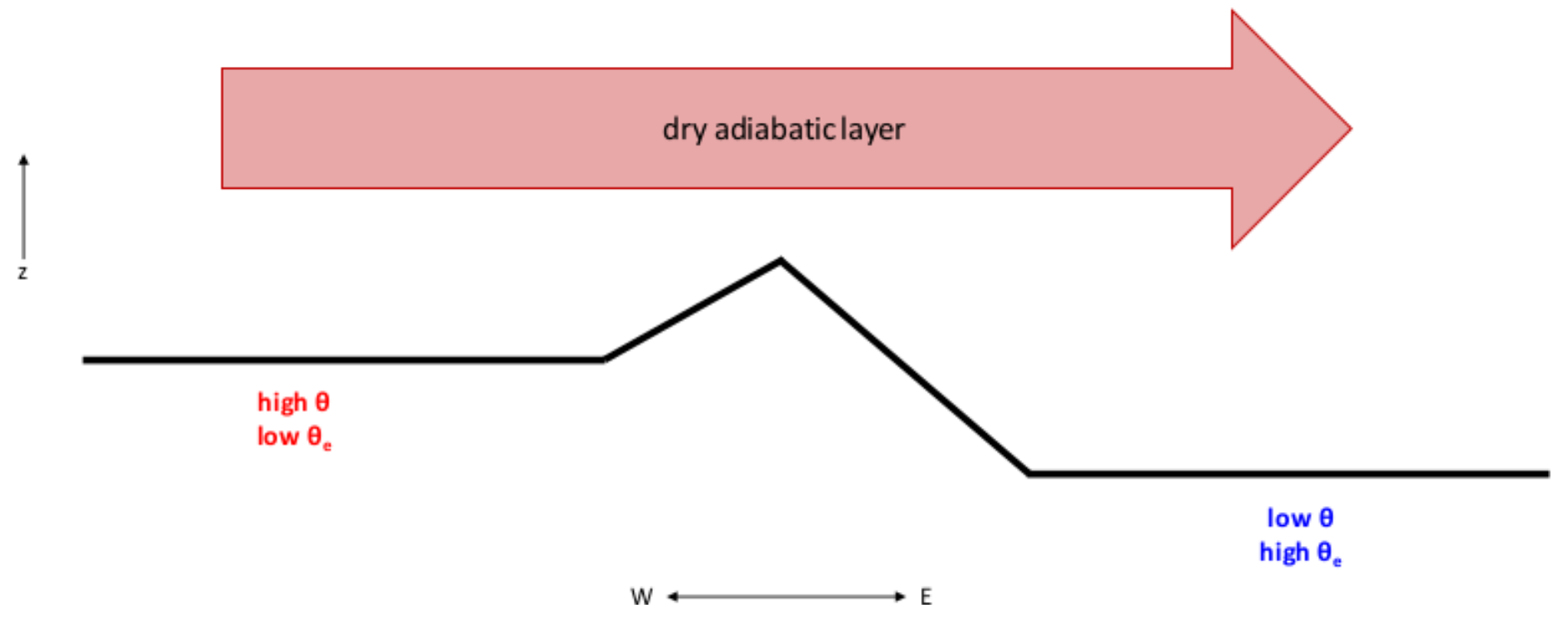
## Motivation

- Continental thunderstorms can be among the most severe on Earth[1]
- Convective available potential energy (CAPE) corresponds to storm severity[2]
- Stored-energy convective paradigm means peak CAPE is transient, as opposed to quasi-equilibrium convection over oceans
- No known theoretical constraint on transient CAPE scales for convection over land
- What sets peak values of CAPE in a given climate?

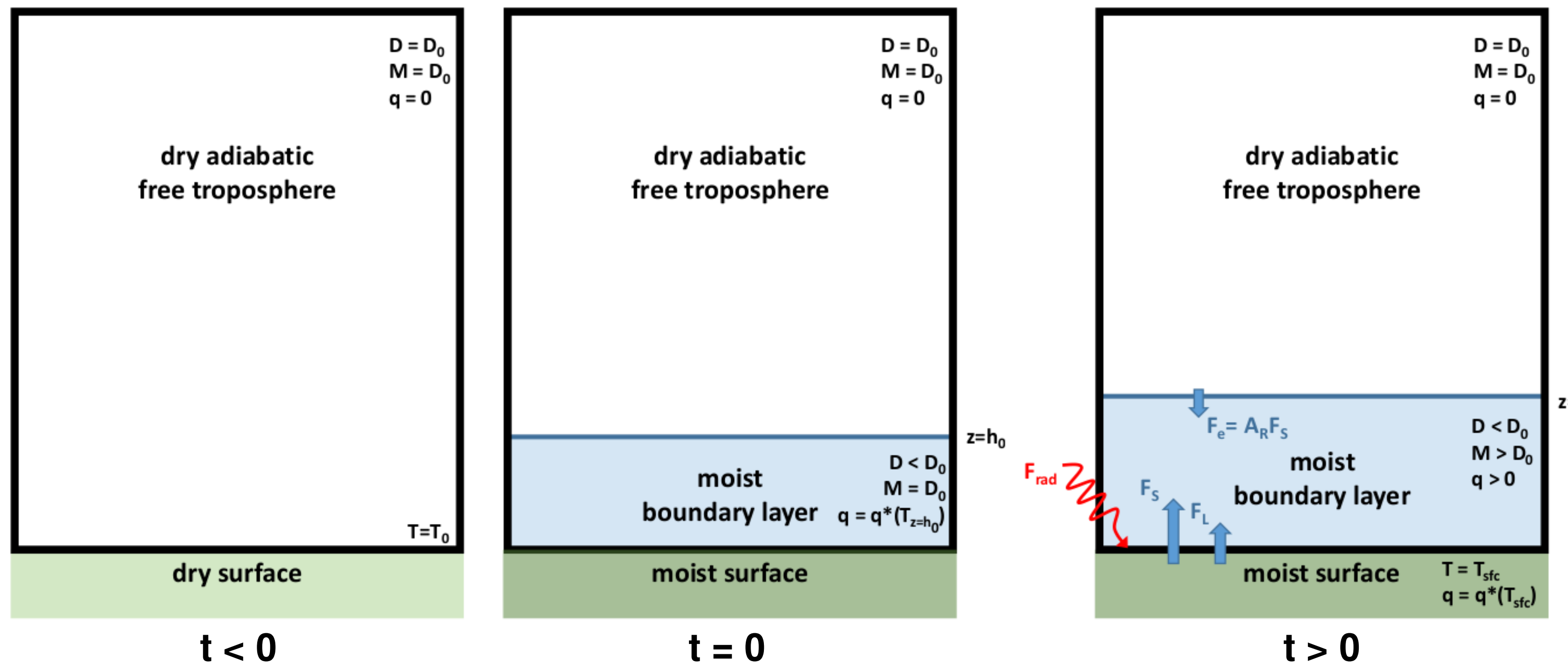
## Stored-energy CAPE buildup in a single column

- In North America, high-CAPE environments often arise when hot, dry desert air mass is superimposed on near-surface moist air mass over Plains, Midwest[3]
- Hot, dry air aloft acts as inhibitive cap, allowing CAPE to build through energy input to near-surface air mass
- Consider a single column of dry adiabatic air being transported from west to east, and instantaneously coming into contact with the cooler, moister downstream surface
- Evolution of the resulting surface boundary layer gives CAPE buildup



## Idealized model

- Single column is pre-initialzed (for t<0) with completely dry adiabatic temperature profile
- At t=0, cooler, moister surface with evaporative fraction α is introduced with accompanying moist boundary layer (BL). The rest of the column (free troposphere) remains dry adiabatic
- At t>0, system is forced with constant net surface radiatve input Frad
- Surface radiative input balanced exactly by sensible ($F_S$) and latent ($F_L$) energy fluxes from surface to boundary layer (assume zero heat capacity surface)
- No raditative cooling or large-scale subsidence in free troposphere
- BL growth is thermodynamically driven: BL height increases at entrainment velocity, defined such that entrainment flux from free troposphere to BL is propotional by a constant ($A_R$) to the surface sensible flux ($F_S$), as in Lilly (1968)[4]
- System of ODEs describes evolution of BL dry static energy (D) and moist static energy (M) and BL height (h), and surface energy balance



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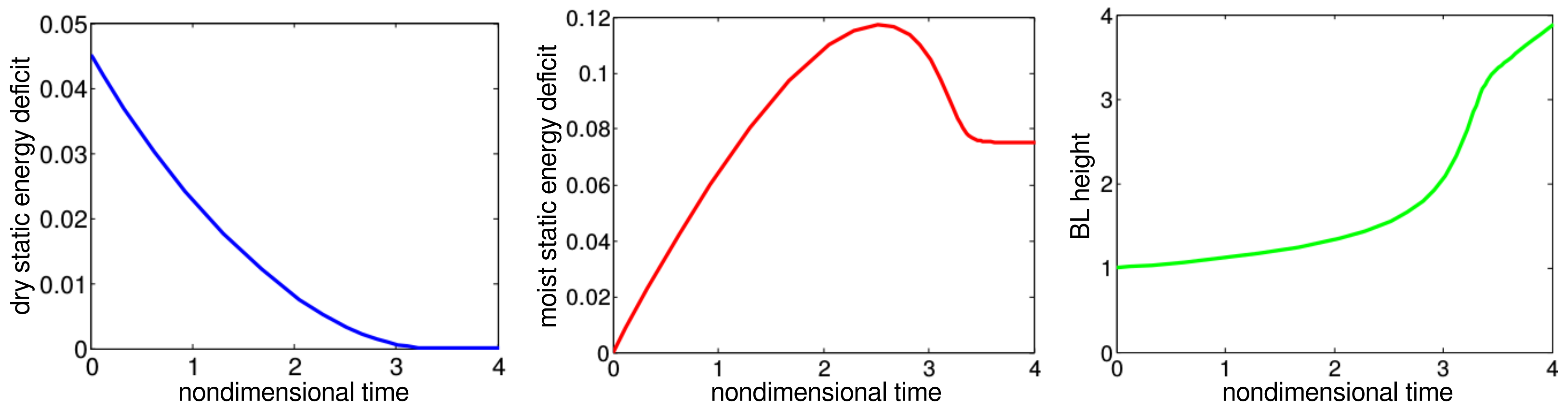
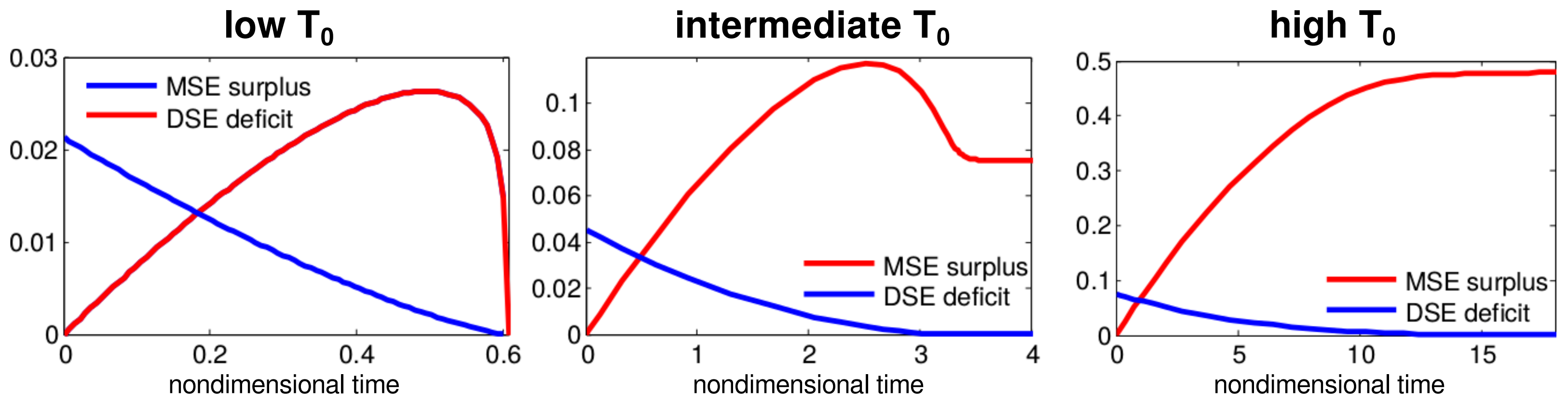
## Numerically integrated model solutions



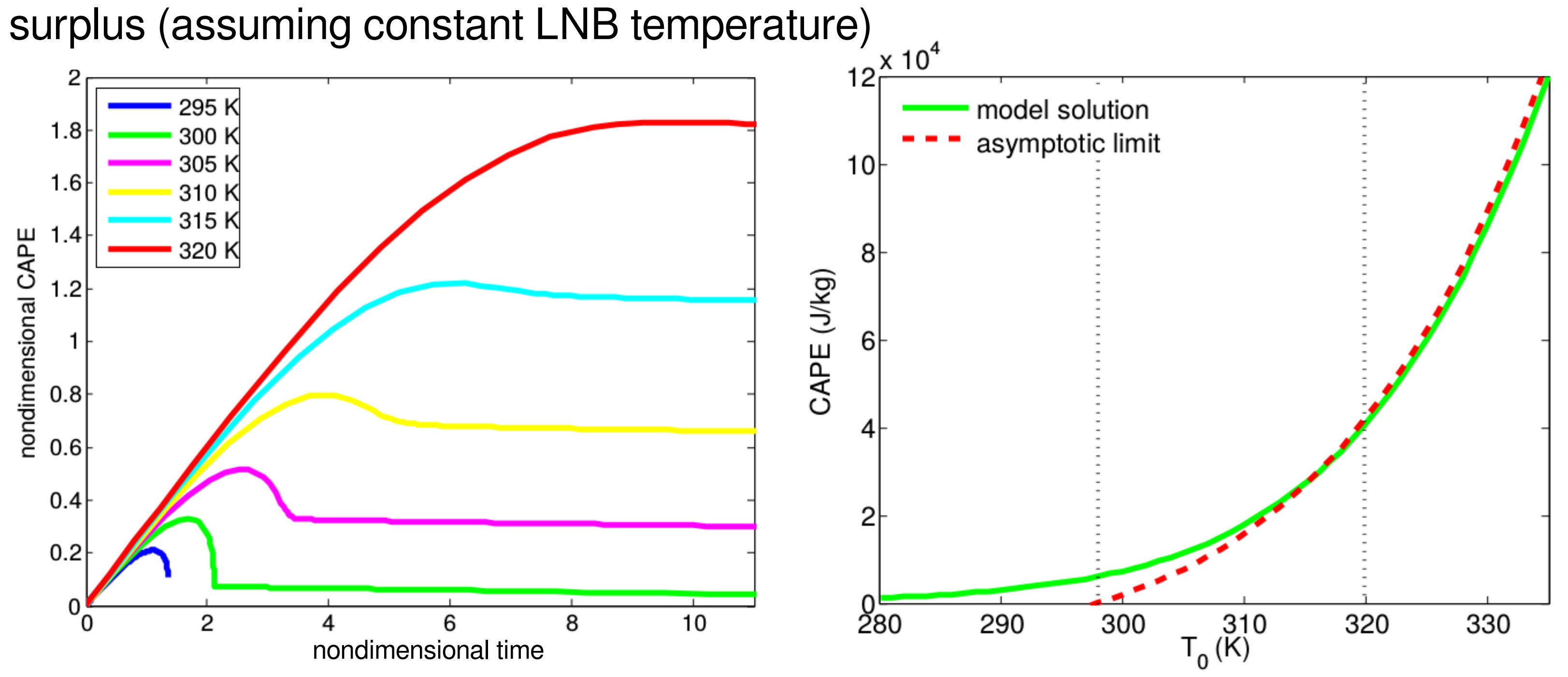
**An example set of solutions for the time evolution of nondimensionalized dry static energy deficit, moist static energy deficit, and boundary layer height.**

- An initial deficit of dry static energy between the BL and free troposphere is eroded monotonically until $D=D_0$, at which point convection is thermodynamically permitted
- A surplus of moist static energy in the BL with respect to the free troposphere is created, and increases until reaching a peak value. This moist static energy surplus can be thought of as a proxy for CAPE
- Boundary layer grows monotonically
- Solutions fall into one of three regimes, depending on the near-surface temperature of the pre-initial column ($T_0$):



## Scaling of peak CAPE

- Approximate dimensional CAPE calculated as function of BL moist static energy surplus (assuming constant LNB temperature)



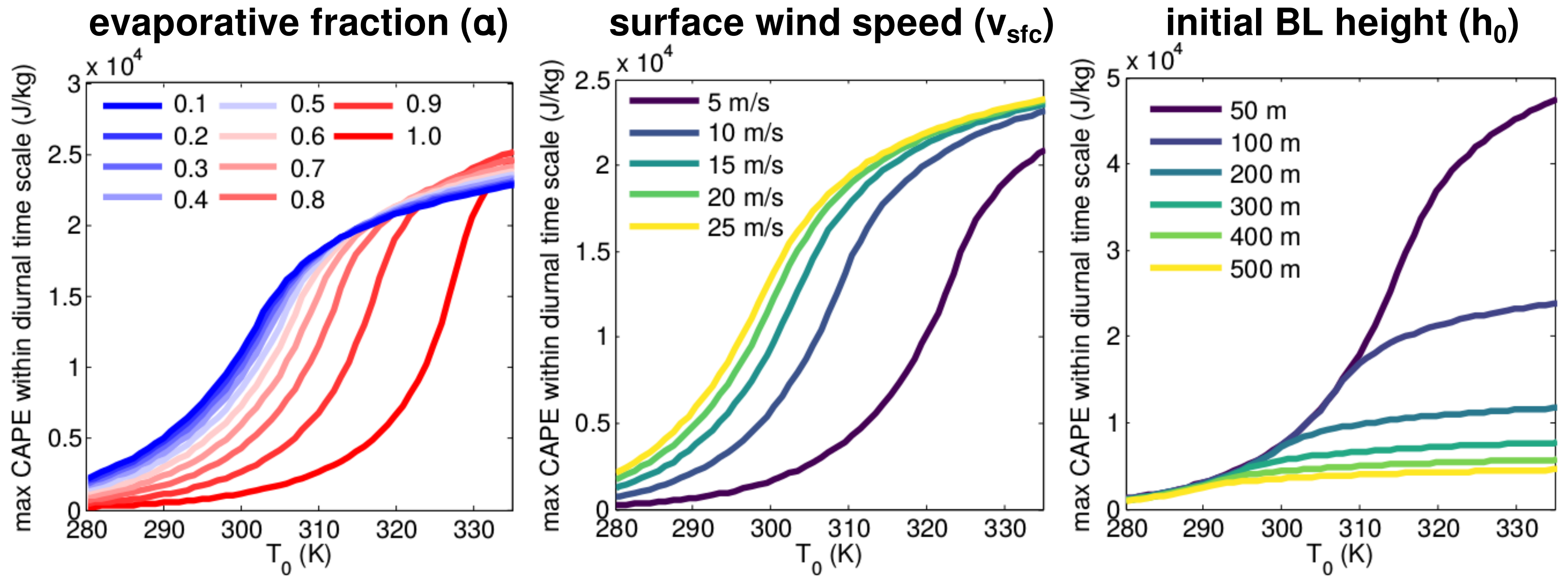
**Left: Evolution of CAPE with time for several different values of $T_0$, given α = 0.5.**
**Right: Dimensional peak CAPE (solid green line) as a function of $T_0$ for $F_{rad}$ = 200 W/m$^2$, α = 0.5, $h_0$ = 100 m, and $v_{sfc}$ = 5 m/s; and a theoretical curve (dashed red line) corresponding to the asymptotic limit of CAPE.**

- Holding other parameters constant, peak CAPE increases with increasing pre-initial near-surface air temperature $T_0$
- At warm temperatures, peak CAPE follows the asymptotic limit that occurs as $t \to \infty$, or $h_0 \to 0$. This limit is an exact solution to the Clausius-Clapeyron equation:

$$\lim_{t\to\infty} M - D_0 = L_v q^*(T_0) - \frac{F_{\mathrm{rad}}}{\alpha \rho C_T v_{\mathrm{sfc}}}$$

## Maximum CAPE within a diurnal time scale

- Increasing $T_0$ also causes peak CAPE to be reached later in the day
- A diurnal cutoff time scale of 12 hours is introduced corresponding to the end of radiative input to the surface at the end of the day
- For sufficiently high temperatures, the diurnal time scale limits the magnitude of peak CAPE that can be achieved

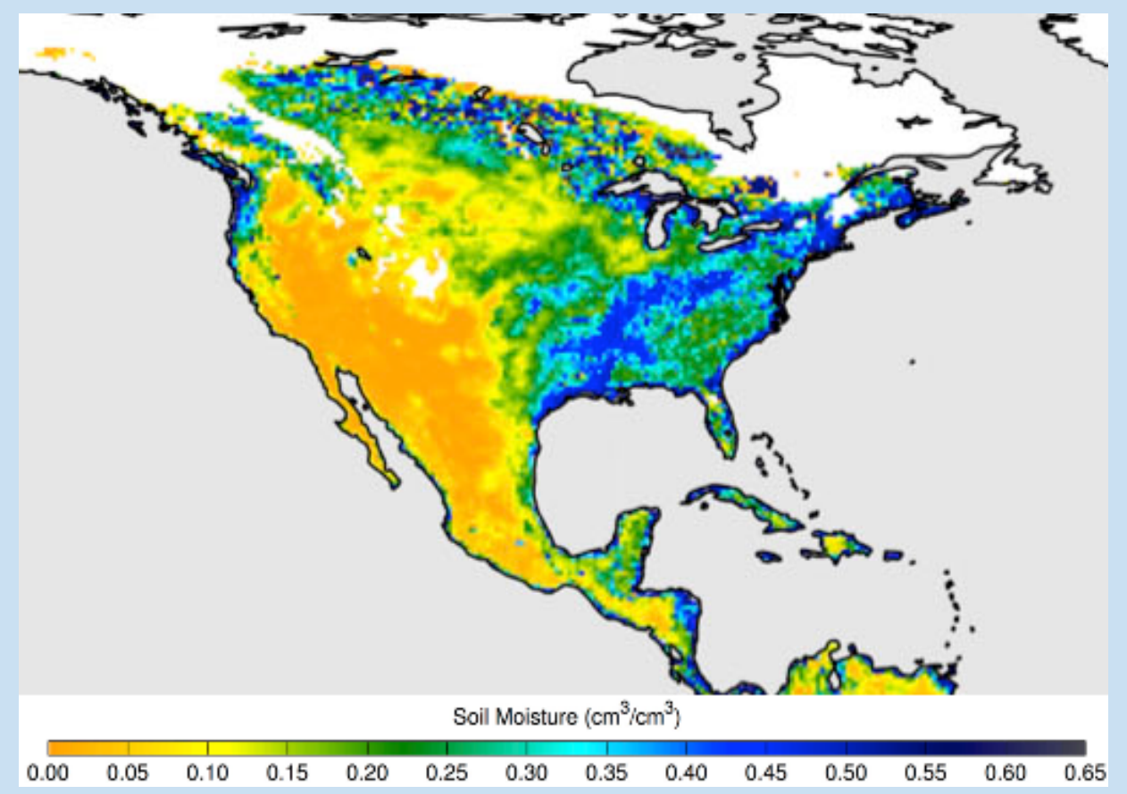


**Maximum dimensional CAPE achieved within diurnal time scale as a function of $T_0$ for varying values of different parameters for $F_{rad}$ = 200 W/m , α = 0.5, h0 =100 m, and $v_{sfc}$ = 5 m/s.**

- Maximum CAPE within the diurnal time scale remains monotonic as a function of T0, but diurnal cutoff gives rise to a maximum in the sensitivity of peak CAPE to temperature
- Increasing the surface evaporative fraction (α) or the surface wind speed (vsfc) also causes an increase in CAPE

### Observations lead the way

- Results suggest surface soil moisture gradients may play a role in determining climatology of peak transient CAPE over continents
- Observational efforts such as Oklahoma Mesonet and NASA SMAP have begun to gather high-resolution and global soil moisture data



**Volumetric soil moisture in North America, as measured by the radiometer on NASA's Soil Moisture Active Passive (SMAP) observatory. This image shows a composite of data from April 14-16, 2015.**

Will these observations prove useful for furthering our understanding of the climatology of severe local storms?

## References

[1] Zipser, E. J., D. J. Cecil, C. Liu, S. W. Nesbitt, and D. P. Yorty (2006), Where are the most intense thunderstorms on Earth?, *Bulletin of the American Meteorological Society, 87* (8).

[2] Holton, J. R. (2004), *An introduction to dynamic meteorology*, Elsevier.

[3] Emanuel, K. A. (1994), *Atmospheric Convection*, Oxford University Press.

[4] Lilly, D. K. (1968), Models of cloud-topped mixed layers under a strong inversion, *Quarterly Journal of the Royal Meteorological Society, 94* (401), 292–309.