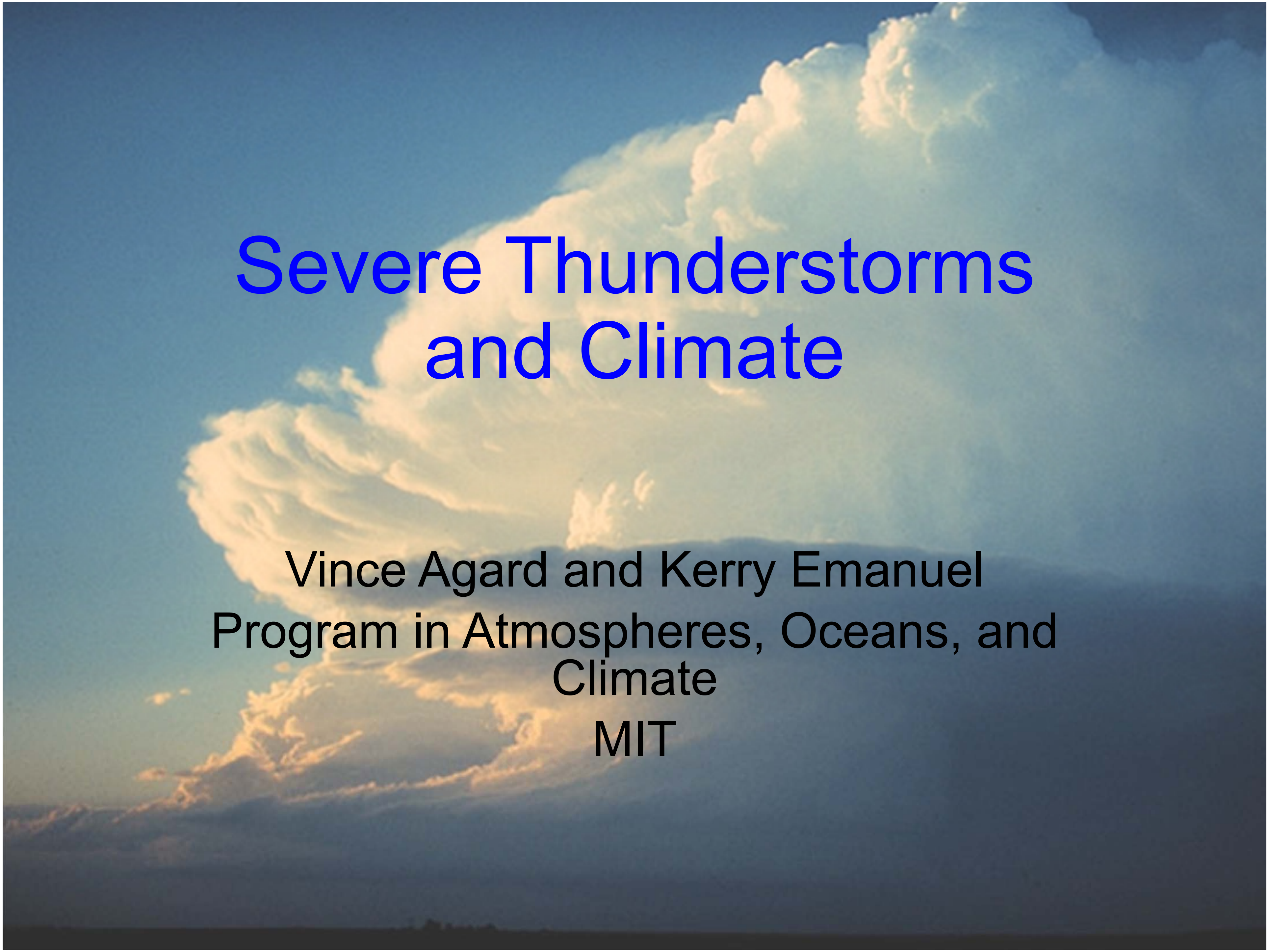


Severe Thunderstorms and Climate

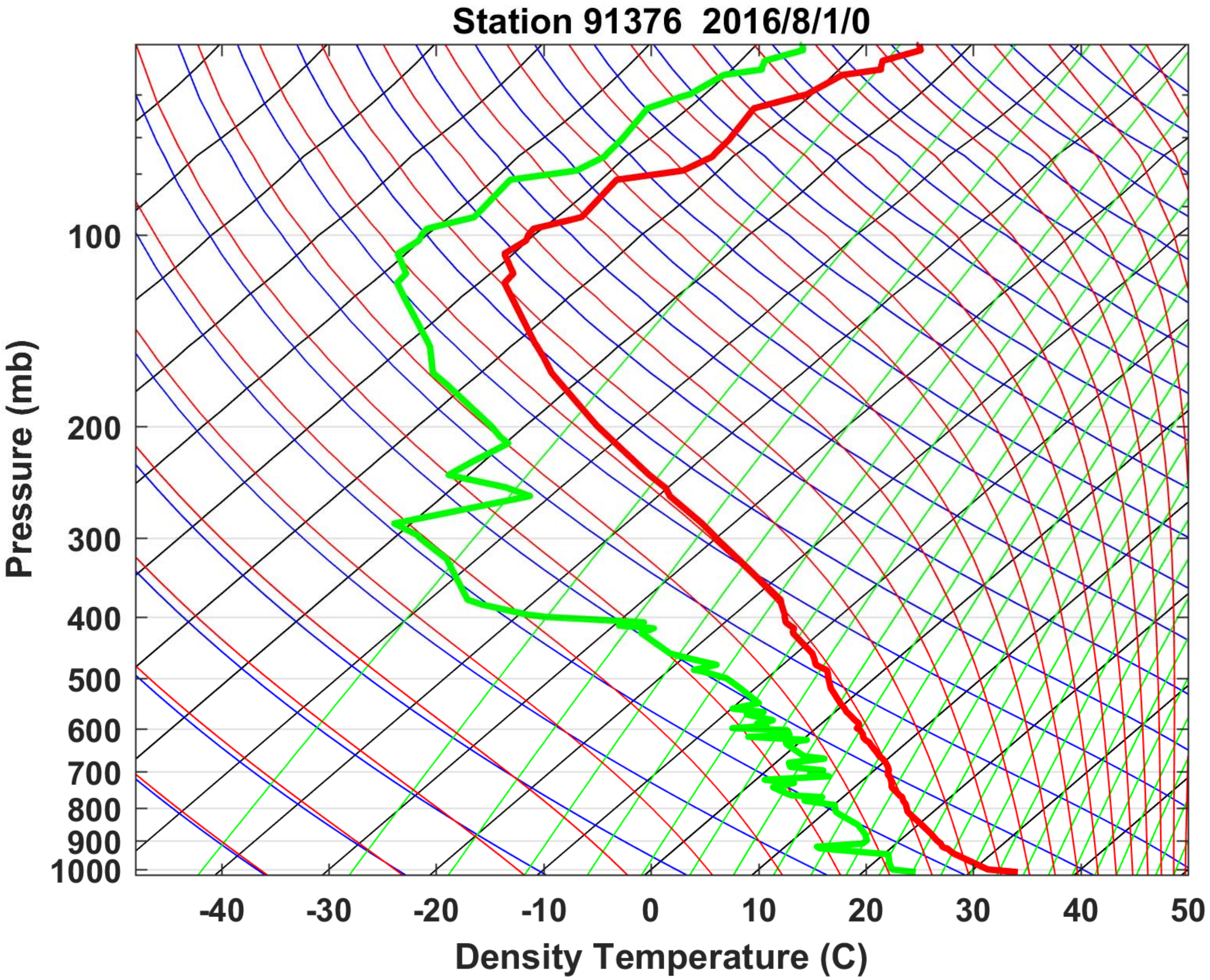
Vince Agard and Kerry Emanuel
Program in Atmospheres, Oceans, and Climate
MIT

Two Broad Categories of Convection:

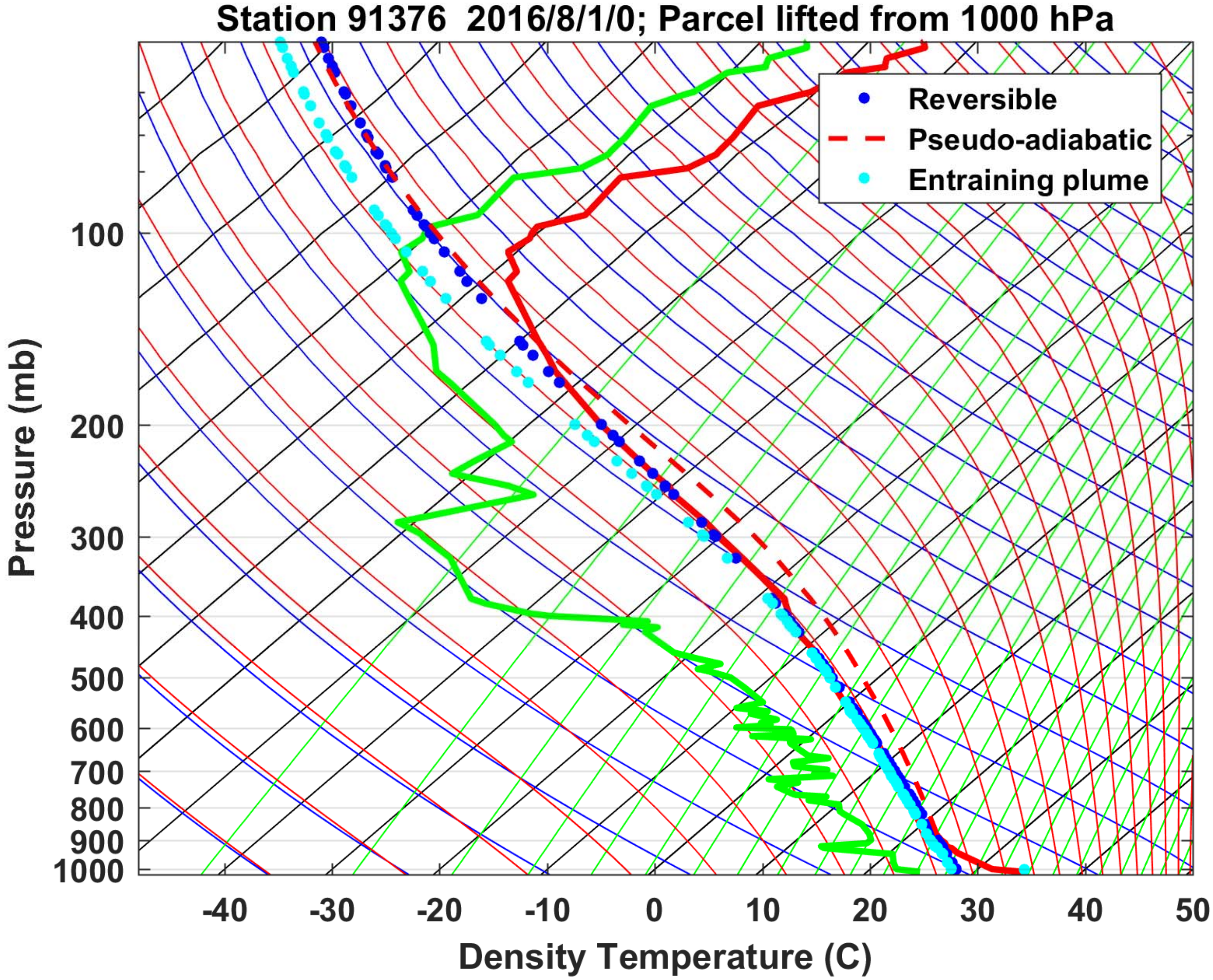
- Quasi-equilibrium convection
  - Convection consumes available energy at about the rate that large-scale processes generate it
  - Most tropical convection and middle-latitude summer convection is of this type
  - Generally benign
  - Responsible for significant fraction of global mean, annual mean rainfall
- Stored-energy convection
  - Convective available energy builds up over time and is then suddenly released
  - Comparatively rare
  - Responsible for most convection-related problems: tornadoes, hailstorms, flash-floods, and straight-line wind storms

Quasi-Equilibrium Convection

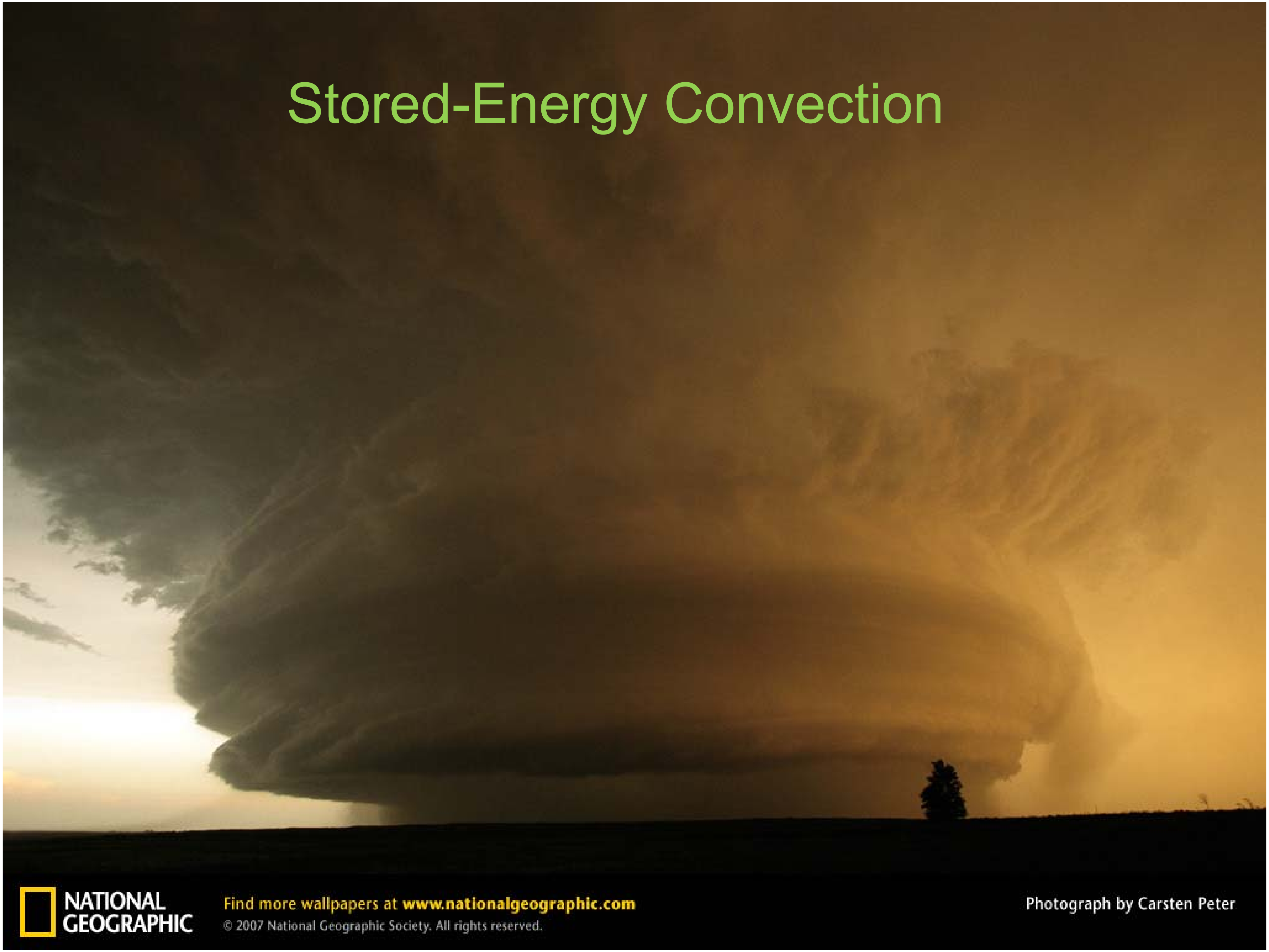
Sounding at Majuro, August 1 2016 0 GMT



Sounding at Majuro, August 1 2016 0 GMT



Stored-Energy Convection



Photograph by Carsten Peter

© Marko Korosec/Solent News

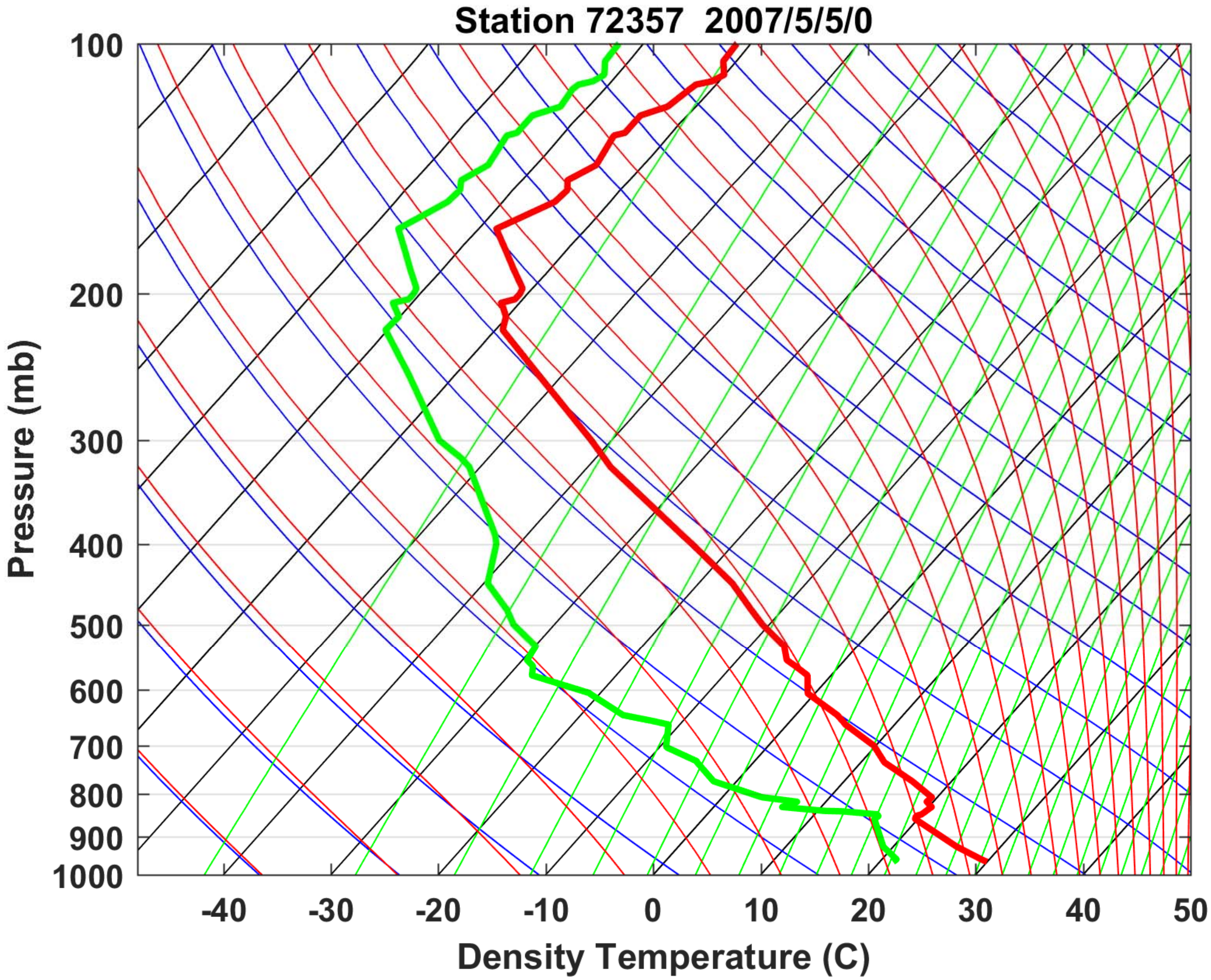
Each year in the U.S., 1,200 **tornadoes** on average kill 60 people, injure 1,500, and cause roughly $400 million in damages

Hail causes about $1 billion dollars in damage to crops and property each year, according to the National Oceanic Atmospheric Administration (NOAA)

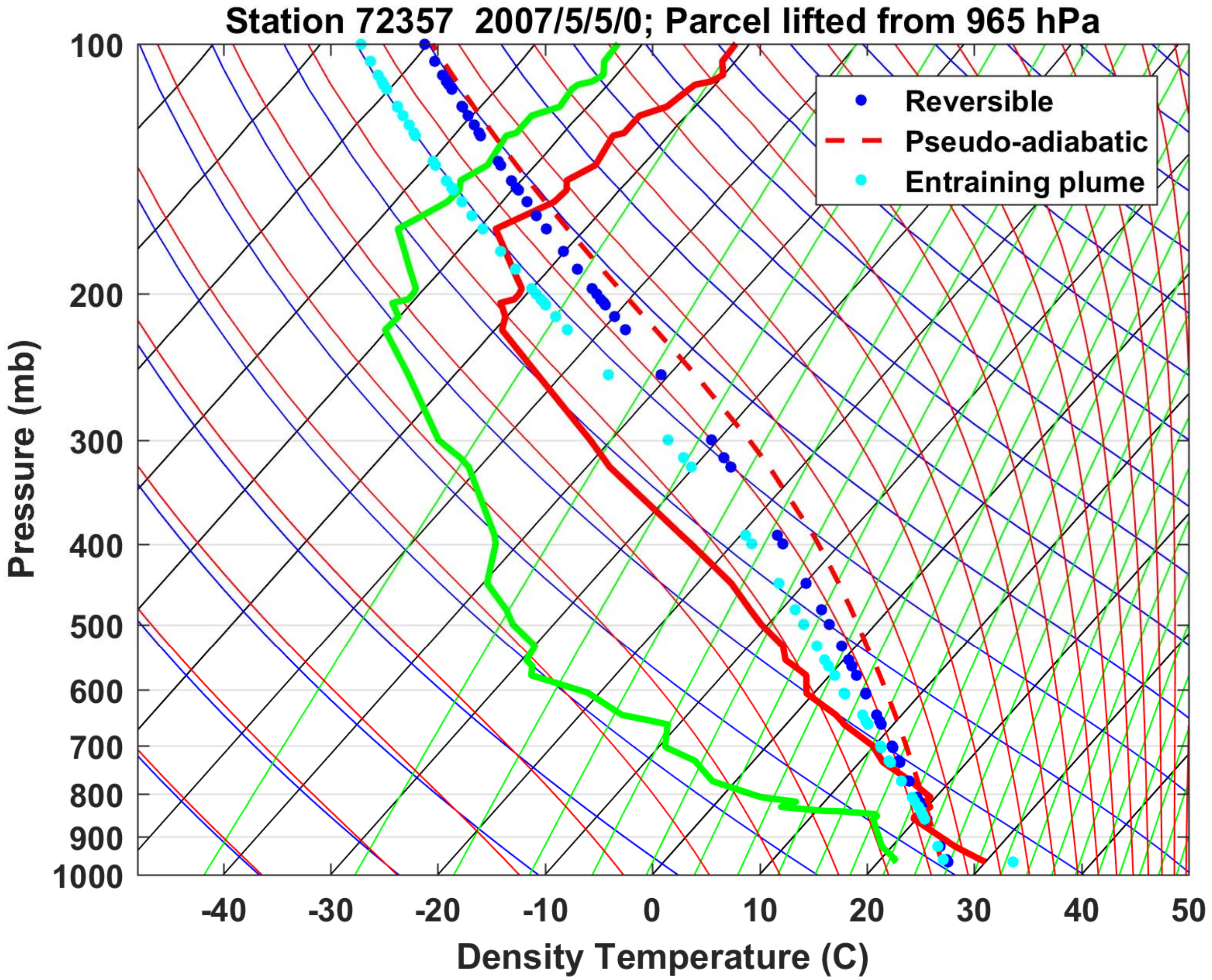
Even worse…..

Eight million bottles' worth of Champagne grapes wiped out by freak hailstorms

Sounding at Norman, Oklahoma, May 5th 2007



Sounding at Norman, Oklahoma, May 5th 2007

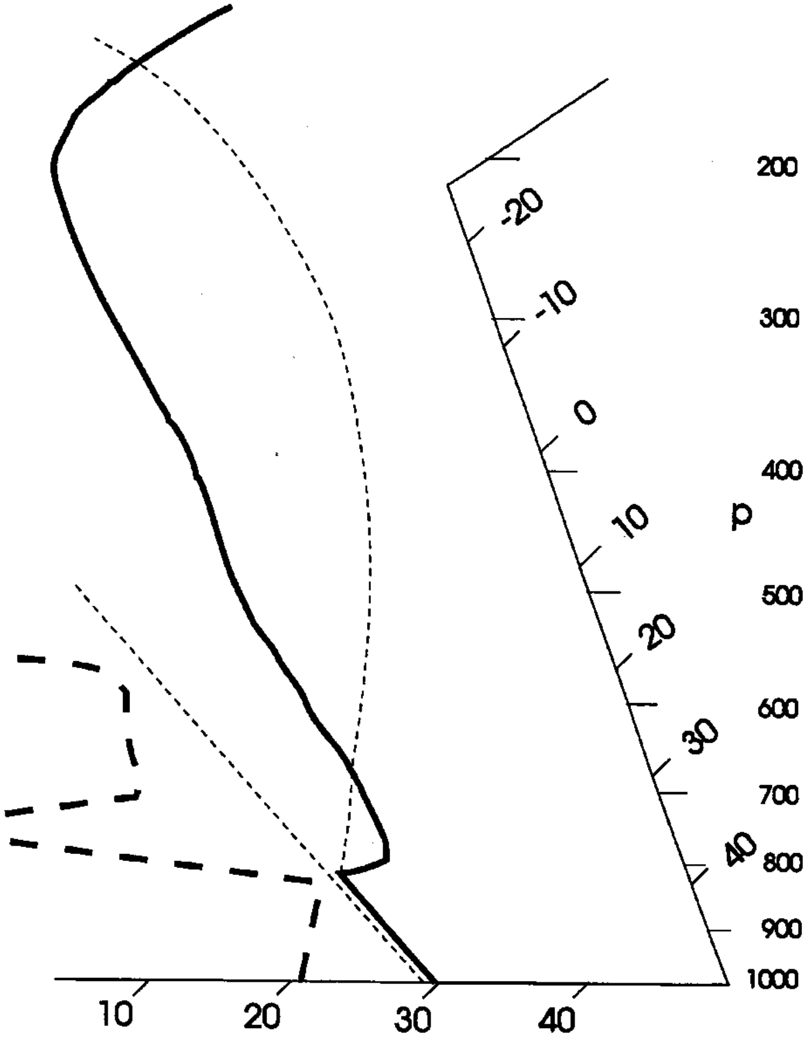


Stability Assessment using Tephigrams:

Convective Available Potential Energy
(CAPE):

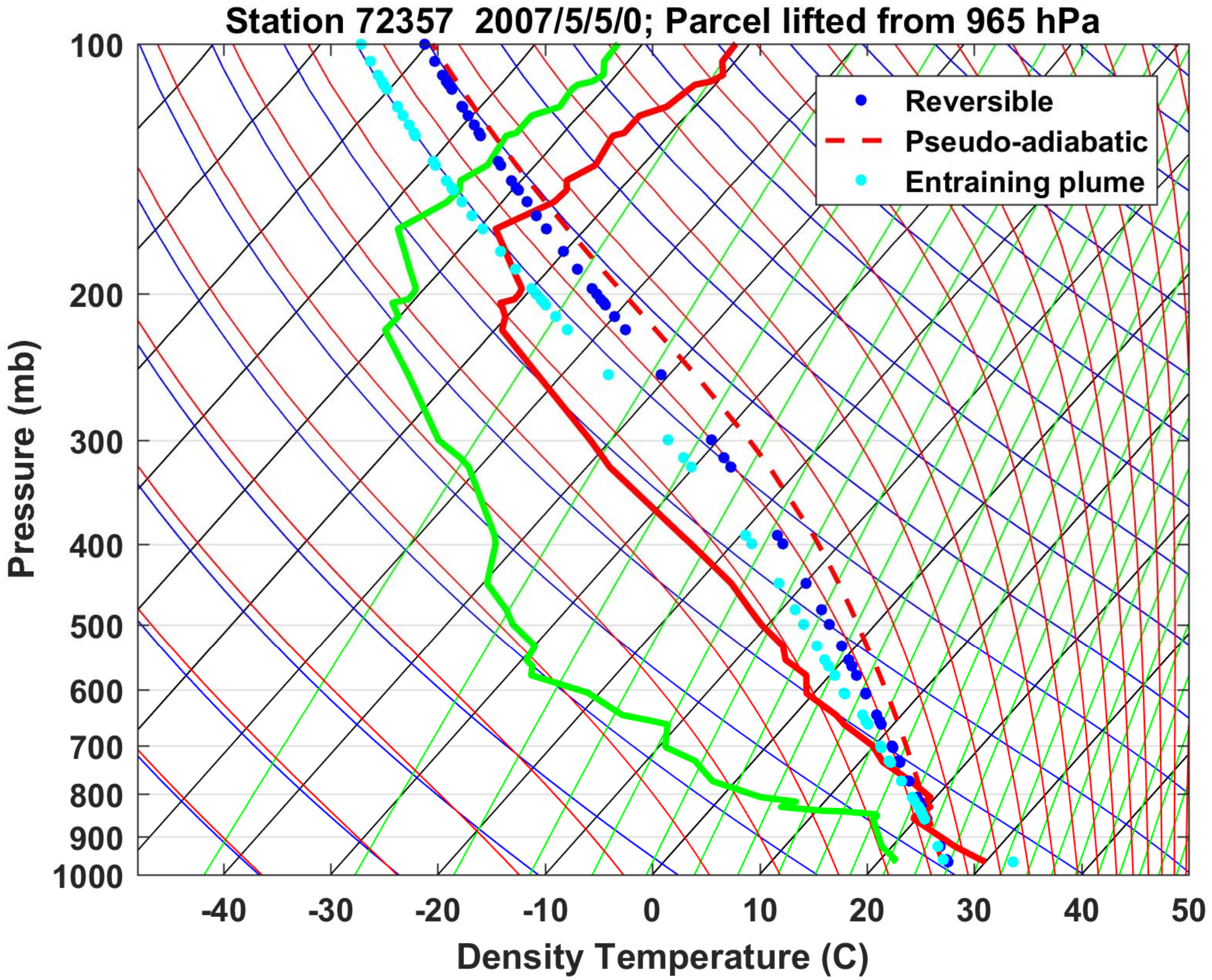
$$CAPE_i \equiv \int_{p_n}^{p_i} \left(\alpha_p - \alpha_e\right) dp$$

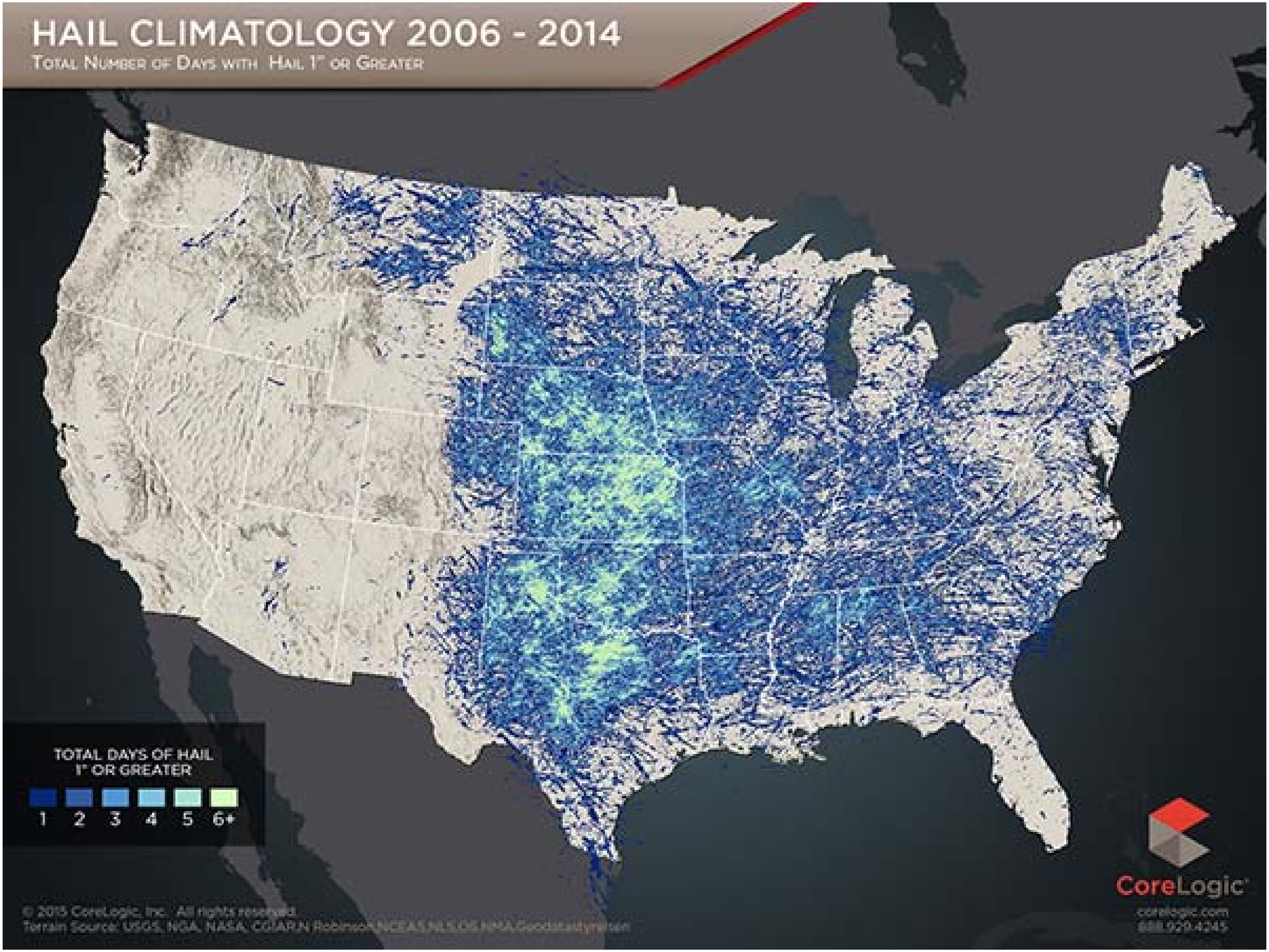
$$= \int_{p}^{p_i} R_d \left(T_{\rho_p} - T_{\rho_e}\right) d\ln\left(p\right)$$



Sounding at Norman, Oklahoma, May 5th 2007

CAPE = 6900 J/Kg → w = 110 m/s



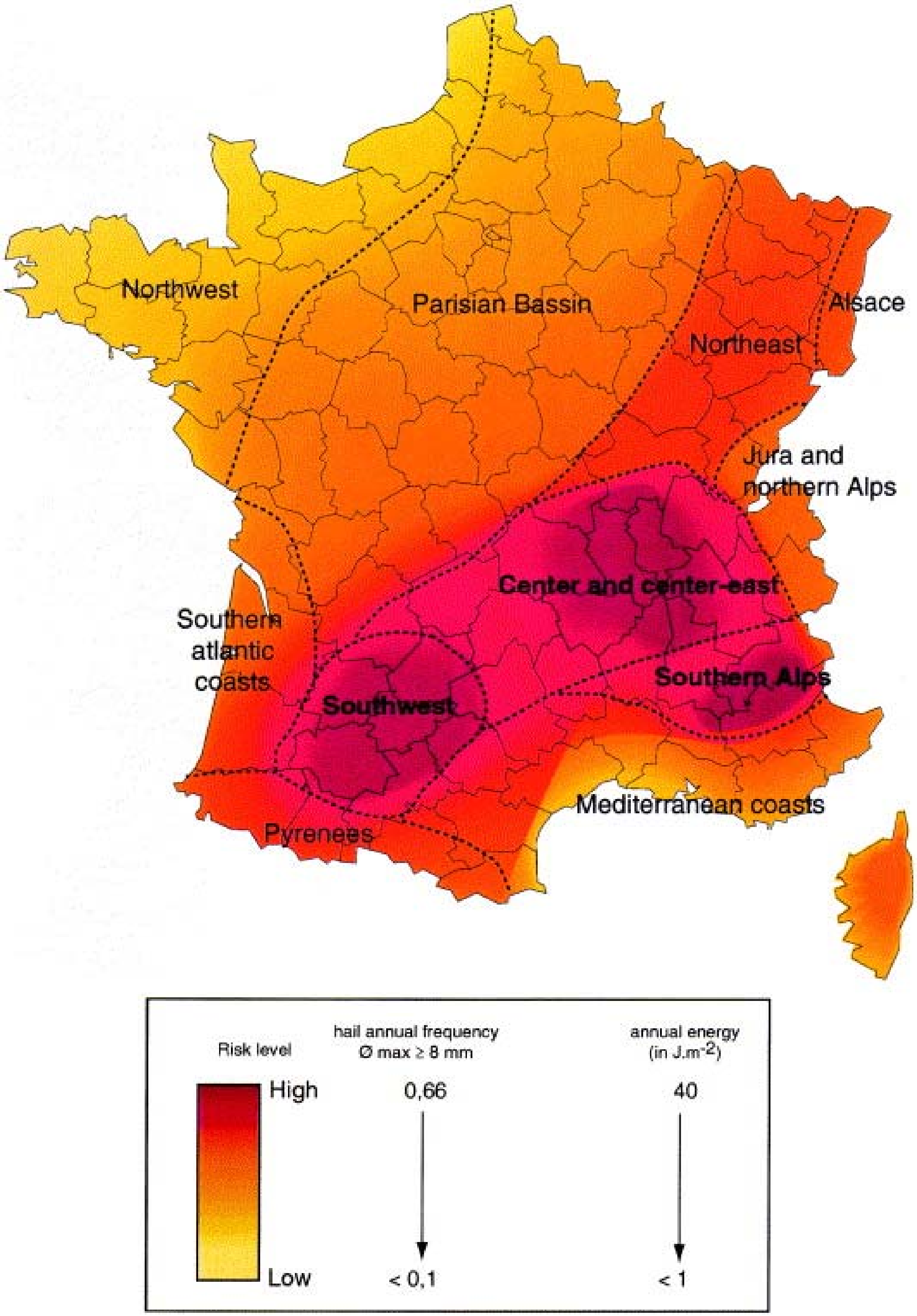


HAIL CLIMATOLOGY 2006 - 2014

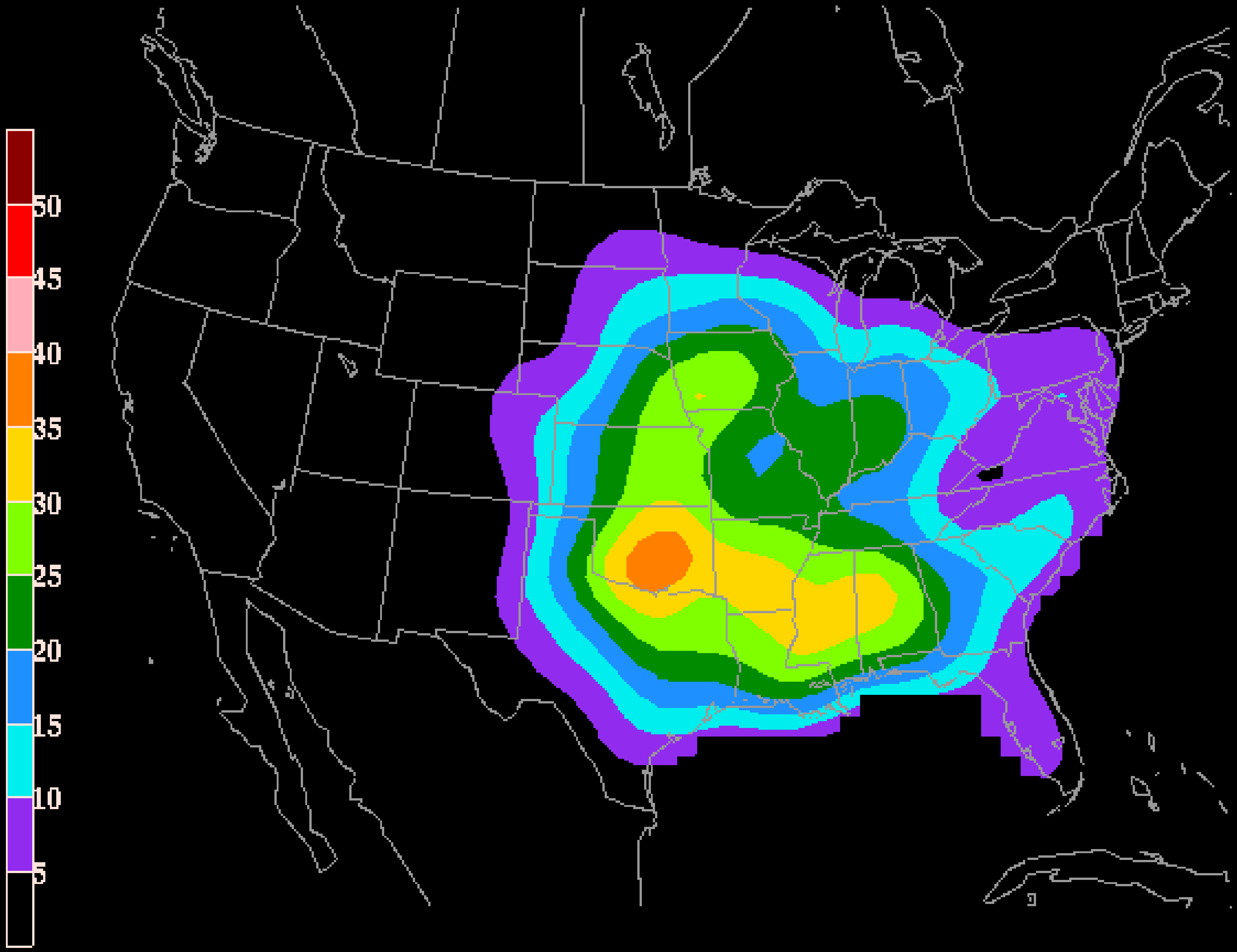
TOTAL NUMBER OF DAYS WITH HAIL 1" OR GREATER

Terrain Source: USGS, NGA, NASA, CGIAR,N Robinson,NCEAS,NLS,OS,NMA,Geodatastyrelsen

Hail climatology of France



Number of Significant (>= F2) Tornadoes per Century

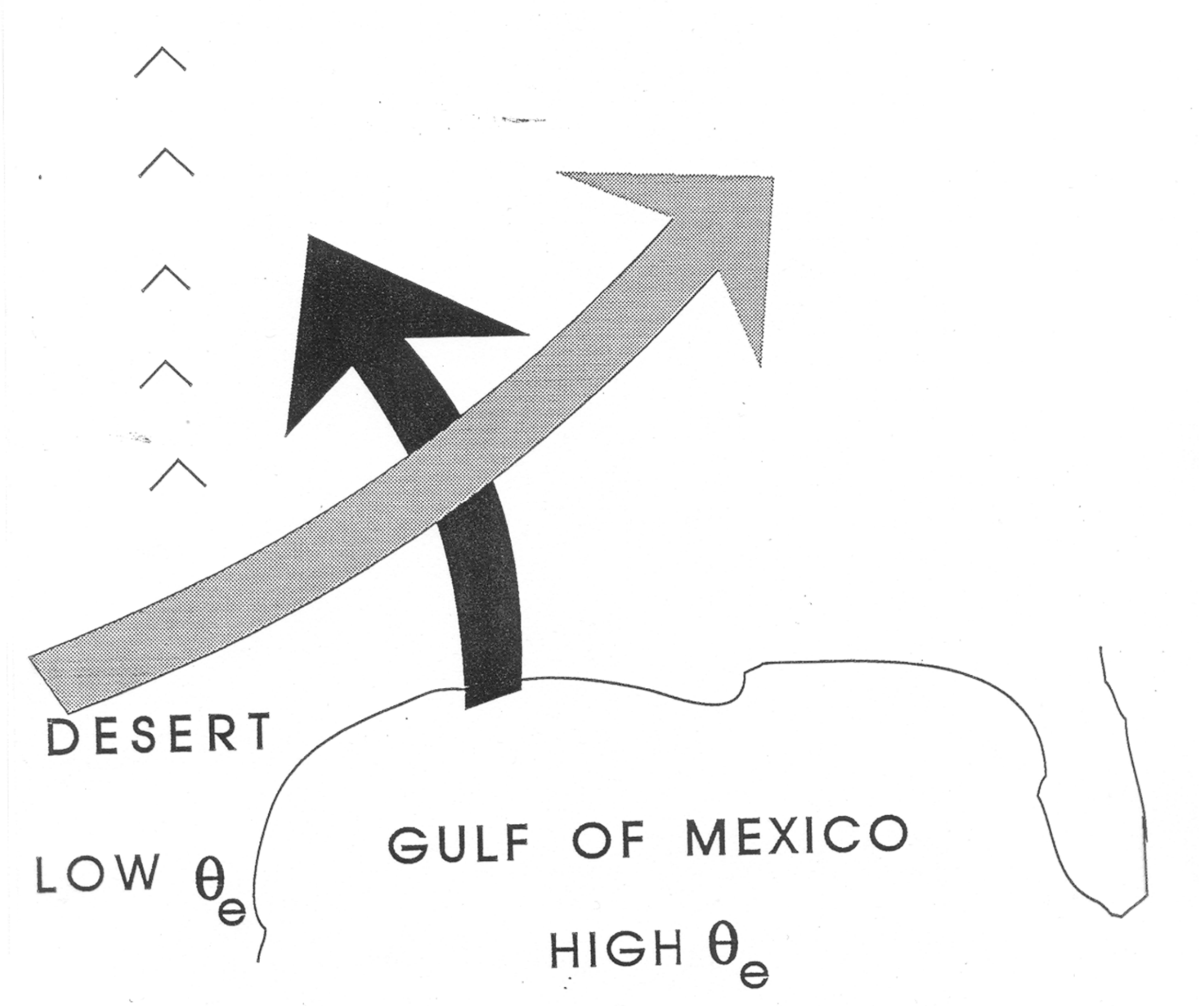


Significant (F2 or greater) Tornado Days Per Century (1921-1995)

Necessary Conditions for Severe Thunderstorms:

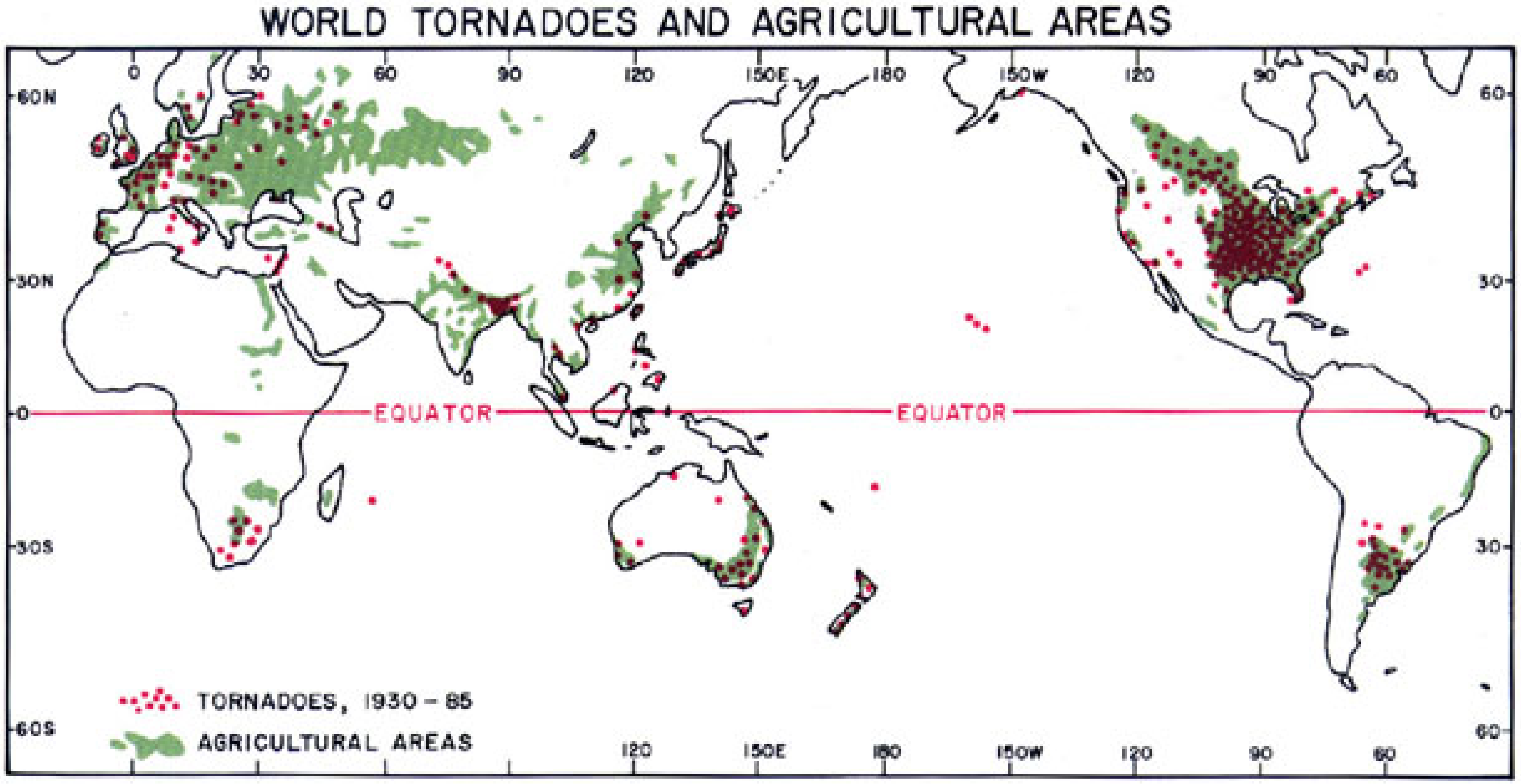
- High values of CAPE
- Large vertical shear of horizontal wind, particularly at low levels

Conventional View: Differential Advection

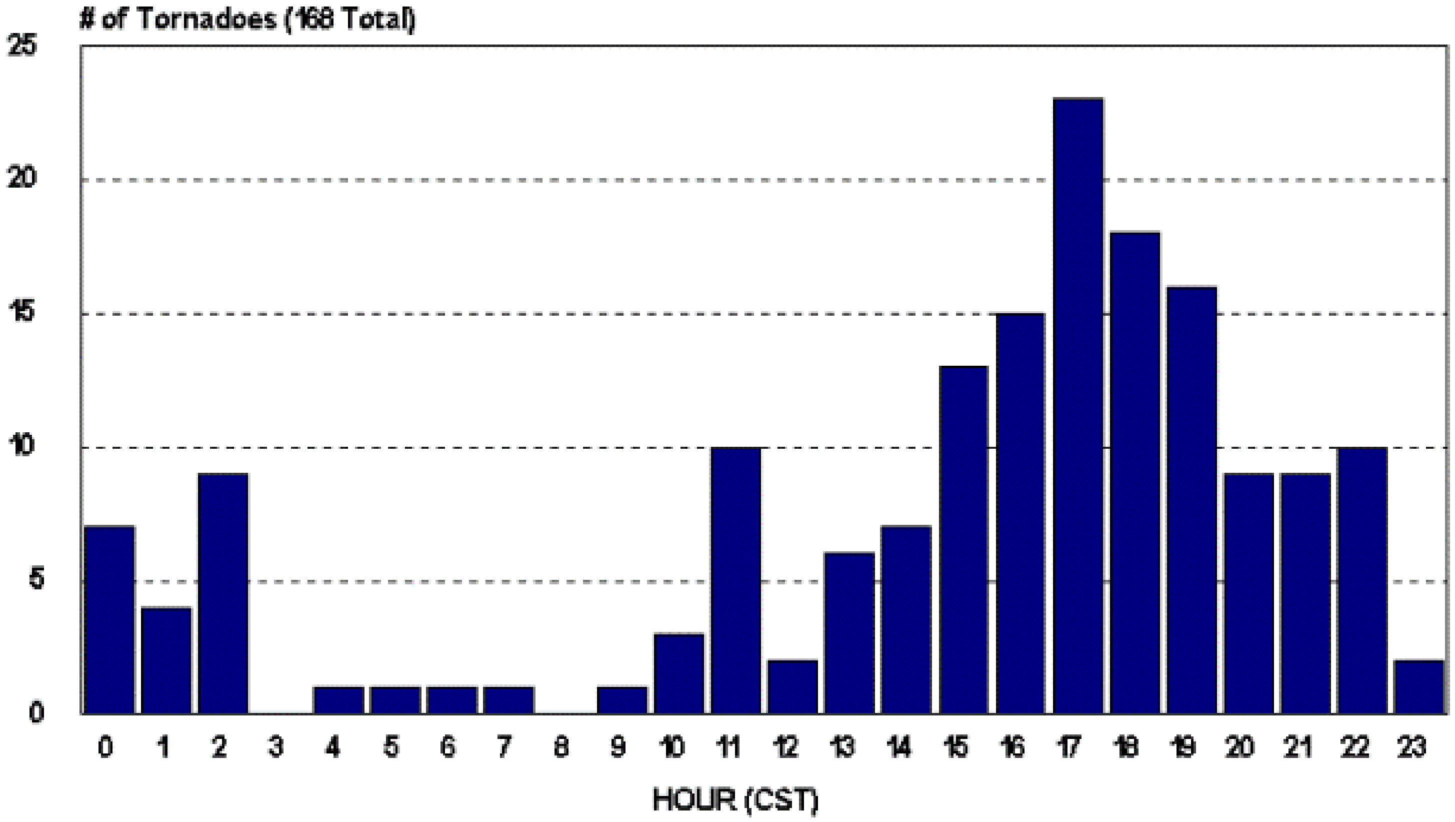


Emanuel, *Atmospheric Convection*, 1994

Global Distribution of Tornadoes



Diurnal Variation of Tornadoes



Key Questions:

- What determines geographical distribution of stored-energy storms?
- Why do tornadoes and hailstorms peak in late-afternoon to early evening?
- Why are peak CAPE values around 3000-6000 J/Kg?
- How might these values change with climate?

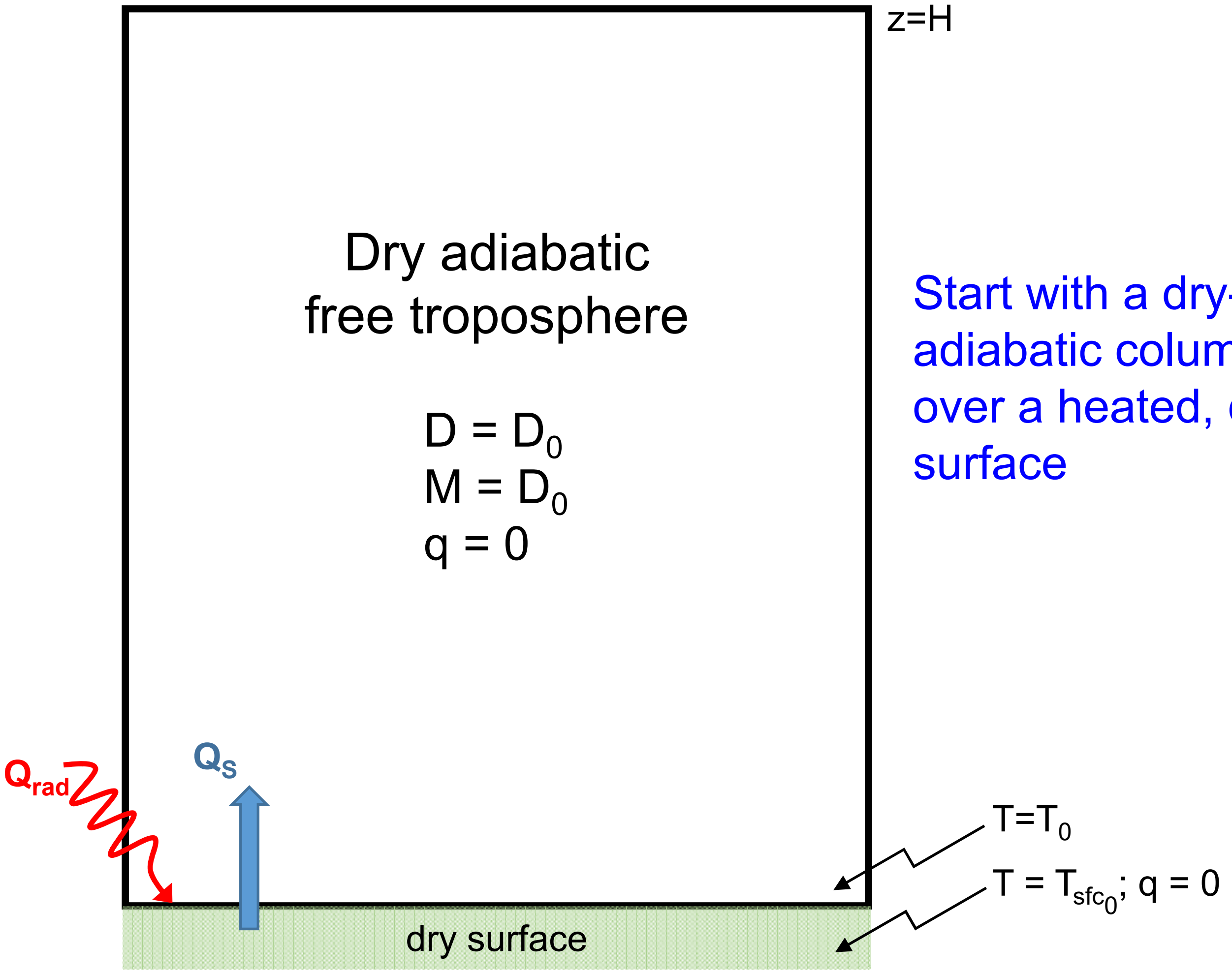
Hypothesis:

- Large CAPE is produced when a deep, dry-adiabatic layer is advected over moist soil which is then subjected to solar heating.

We can model these circumstances with an idealized initial value problem

Dry Static Energy:
$D = c_pT + gz$

Moist Static Energy:
$M = c_pT + L_vq + gz$



z=H

Dry adiabatic
free troposphere

$D = D_0$
$M = D_0$
$q = 0$

Q_{rad}

Q_S

$T=T_0$

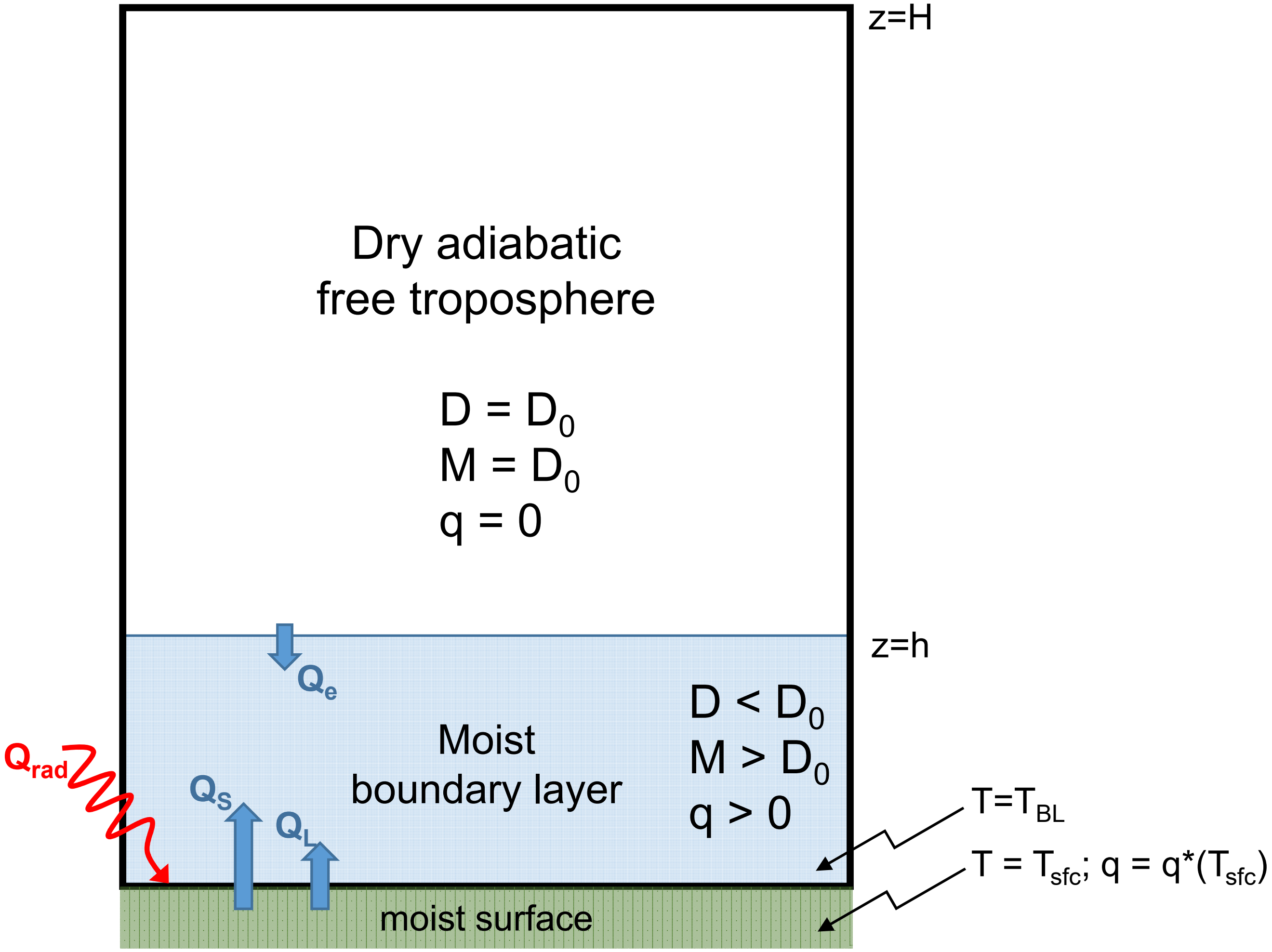
$T = T_{sfc_0}$; $q = 0$

dry surface

Start with a dry-adiabatic column over a heated, dry surface

Replace lower boundary by a moist soil surface and create an initially thin, moist boundary layer. Then heat surface with solar radiation and allow new boundary layer to develop.

$$D = c_pT + gz$$
$$M = c_pT + L_vq + gz$$



$z=H$

Dry adiabatic
free troposphere

$D = D_0$
$M = D_0$
$q = 0$

$z=h$

Moist
boundary layer

$D < D_0$
$M > D_0$
$q > 0$

$T=T_{BL}$

$T = T_{sfc}$; $q = q^*(T_{sfc})$

moist surface

Boundary Layer Equations

$$\rho h \frac{dD}{dt} = F_s + \rho w_e \left(D_0 - D \right)$$

Dry static energy

$$\rho h \frac{dM}{dt} = F_{net} + \rho w_e \left(D_0 - M \right)$$

Moist static energy

$$\rho w_e \left(D_0 - D \right) = A F_s$$

Lilly’s entrainment formulation

$$F_s = \rho C_k \left| \mathbf{V} \right| \left(D_s - D \right)$$

Surface sensible heat flux

$$F_L = \alpha \rho C_k \left| \mathbf{V} \right| \left(M_s - M - D_s + D \right)$$

Surface latent heat flux

$$F_s + F_L = F_{net}$$

Net surface flux

$$w_e = \frac{dh}{dt}$$

Boundary layer mass

Note: M_s is related to D_s by Clausius-Clapeyron Equation

Initial conditions:

$M\ (t=0) = D_0$

$D\ (t=0)$ determined so that air is just saturated at boundary layer top

$h=h_0$

Nondimensionalize:

$$\left[D, M\right] \rightarrow D_0 \left[D, M\right]$$

$$h \rightarrow h_0 h$$

$$t \rightarrow \frac{h_0}{C_k \mid \mathbf{V} \mid} t$$

$$F \equiv \frac{F_{net}}{\rho C_k \mid \mathbf{V} \mid D_0}$$

Equations are normalized and recombined to arrive at

$$\frac{dh}{dt} = A\frac{D_s - D}{1 - D}$$

$$M = 1 + \frac{Ft}{h}$$

$$D = 1 - \left(1 - D_{init}\right)h^{-\frac{1+A}{A}}$$

$$(1-\alpha)(D_s - D) + \alpha(M_s - M) = F$$

$$M_s = D_s + \frac{L_v q_s^*(D_s)}{D_0}$$

$At\ t = 0:$

$h = 1$

$M = 1$

$D = D_{init}$

Determined so that air is initially just saturated at boundary layer top

Long-time Asymptotic Behavior

$$\text{If } F > \frac{\alpha L_v q_s^*(T_s)}{D_0}$$

CAPE reaches a maximum at a particular time and then falls to zero at a later time, while the boundary layer depth goes to infinity at the later time and D, D_s, and M approach unity. T_s is the surface air temperature of the initial dry state.

$$\text{If } F < \frac{\alpha L_v q_s^*(T_s)}{D_0}$$

CAPE still reaches a peak at a particular time and then falls off to or asymptotes to a positive long-time asymptotic value. The asymptotic limits are given by

$$D \rightarrow 1 \qquad D_s \rightarrow 1$$

$$M \rightarrow 1 + \frac{L_v q_s^*(T_s)}{D_0} - \frac{F}{\alpha} \qquad h \rightarrow \frac{Ft}{\frac{L_v q_s^*(T_s)}{D_0} - \frac{F}{\alpha}}$$

Note: When $\alpha = 1$, these criteria are equivalent to $T_s > T_0$ and $T_s < T_0$, respectively

Convective Available Potential Energy (CAPE)

$$CAPE = \left(M - D_0\right)\ln\left(\frac{T_{PBL}}{T_{top}}\right)$$

T_{top} determined by fixed anvil temperature hypothesis

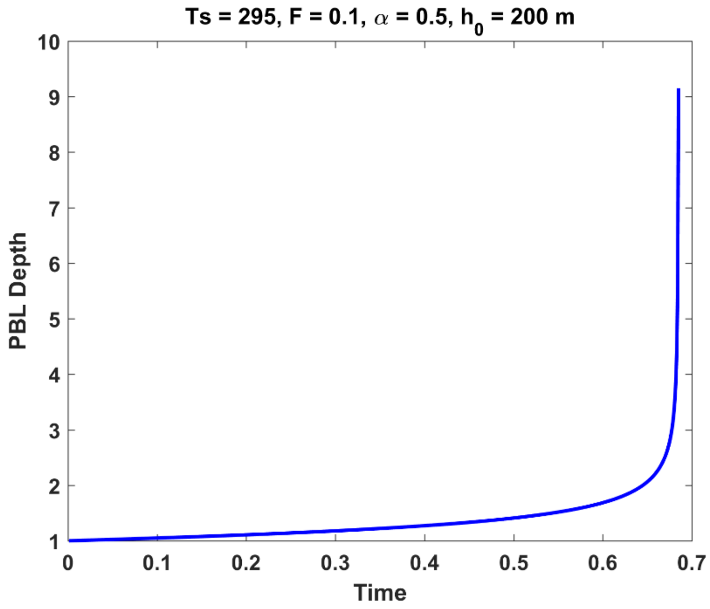
Asymptotic Cape Scaling in ‘Warm’ Regime, Applicable at Time when PBL Growth Becomes Linear

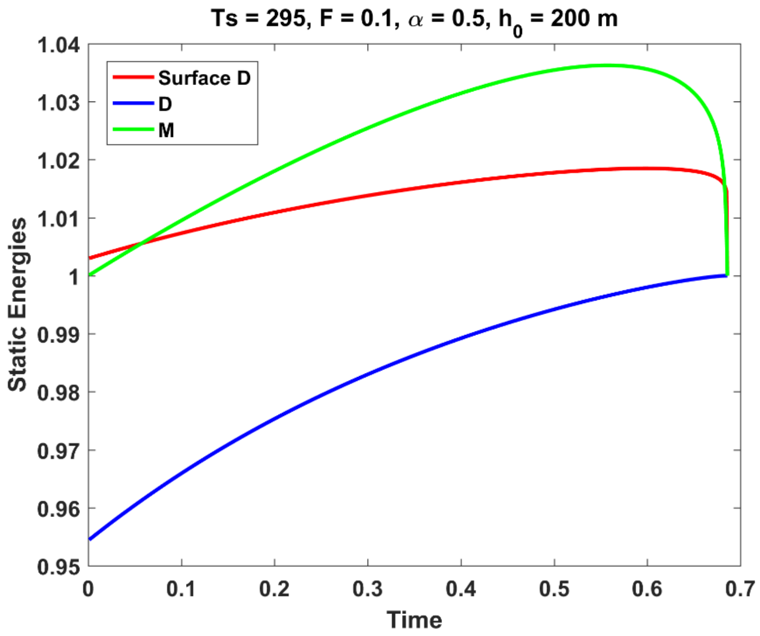
$$\text{If } F < \frac{\alpha L_v q_s^*(T_s)}{D_0}$$

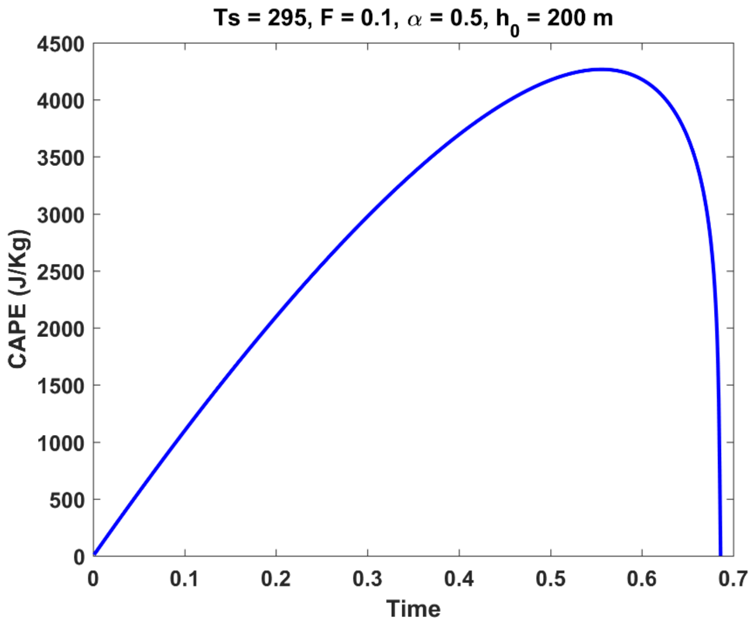
$$CAPE(t > t_c) = \left[L_v q_s^*(T_s) - \frac{F_{net}}{\alpha \rho C_k |\mathbf{V}|} \right] \ln\left(\frac{T_{PBL}}{T_{anvil}} \right)$$

Results

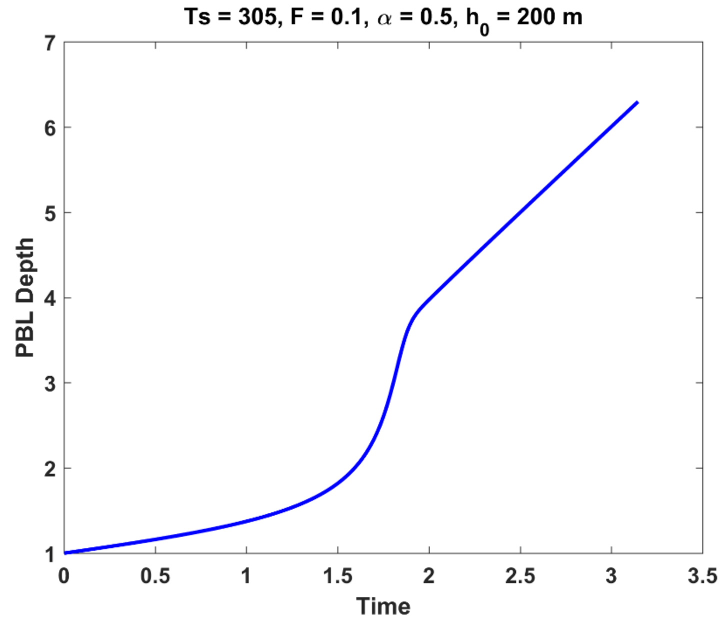
Cold Regime

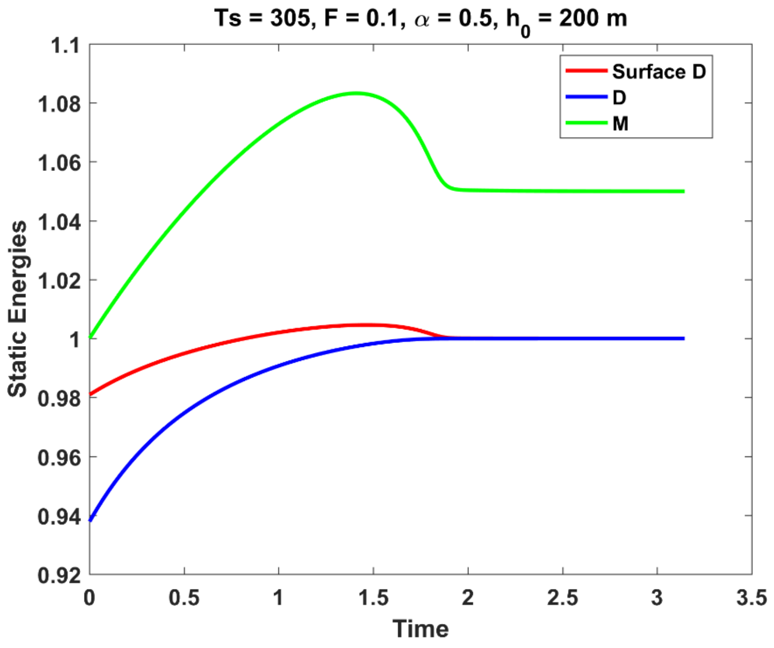

Ts = 295, F = 0.1, α = 0.5, h_0 = 200 m

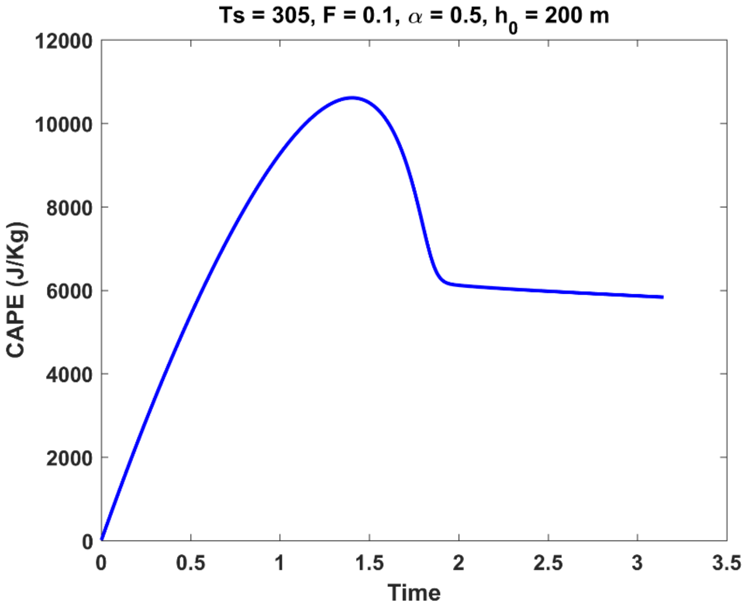

Ts = 295, F = 0.1, α = 0.5, h_0 = 200 m


Ts = 295, F = 0.1, α = 0.5, h_0 = 200 m

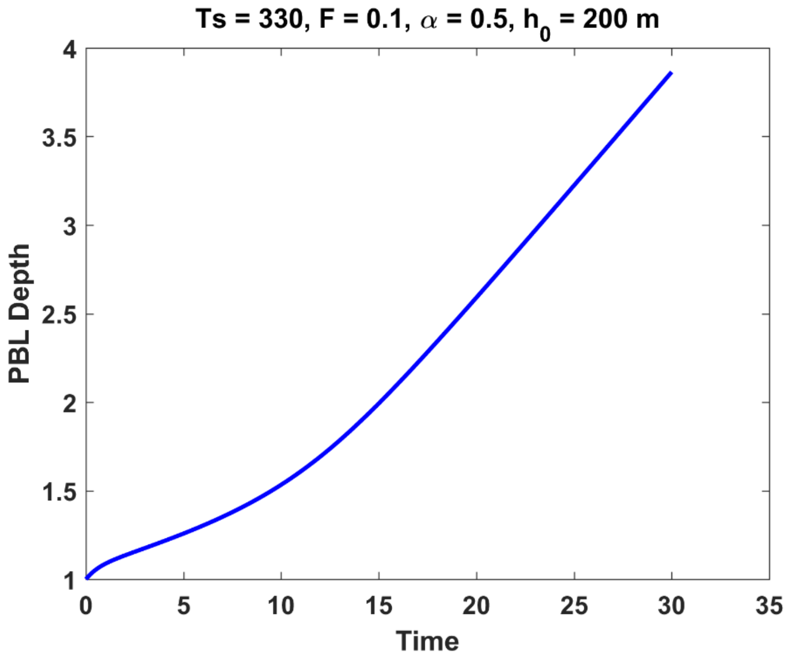
Warm Regime

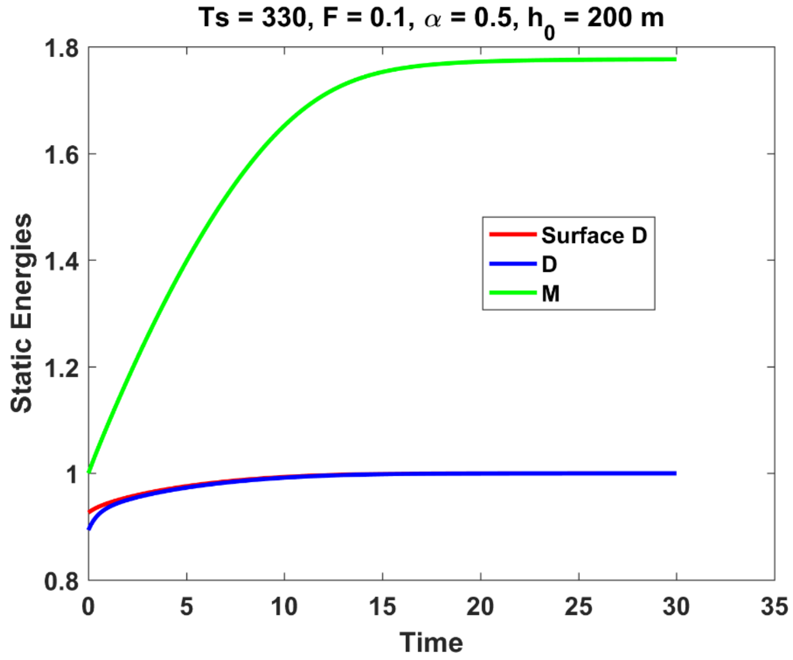

Ts = 305, F = 0.1, α = 0.5, h_0 = 200 m

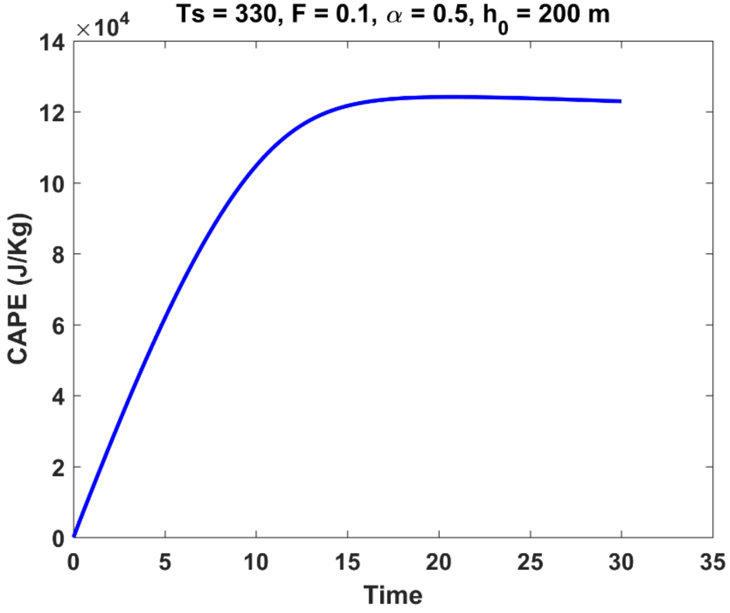

Ts = 305, F = 0.1, α = 0.5, h_0 = 200 m


Ts = 305, F = 0.1, α = 0.5, h_0 = 200 m

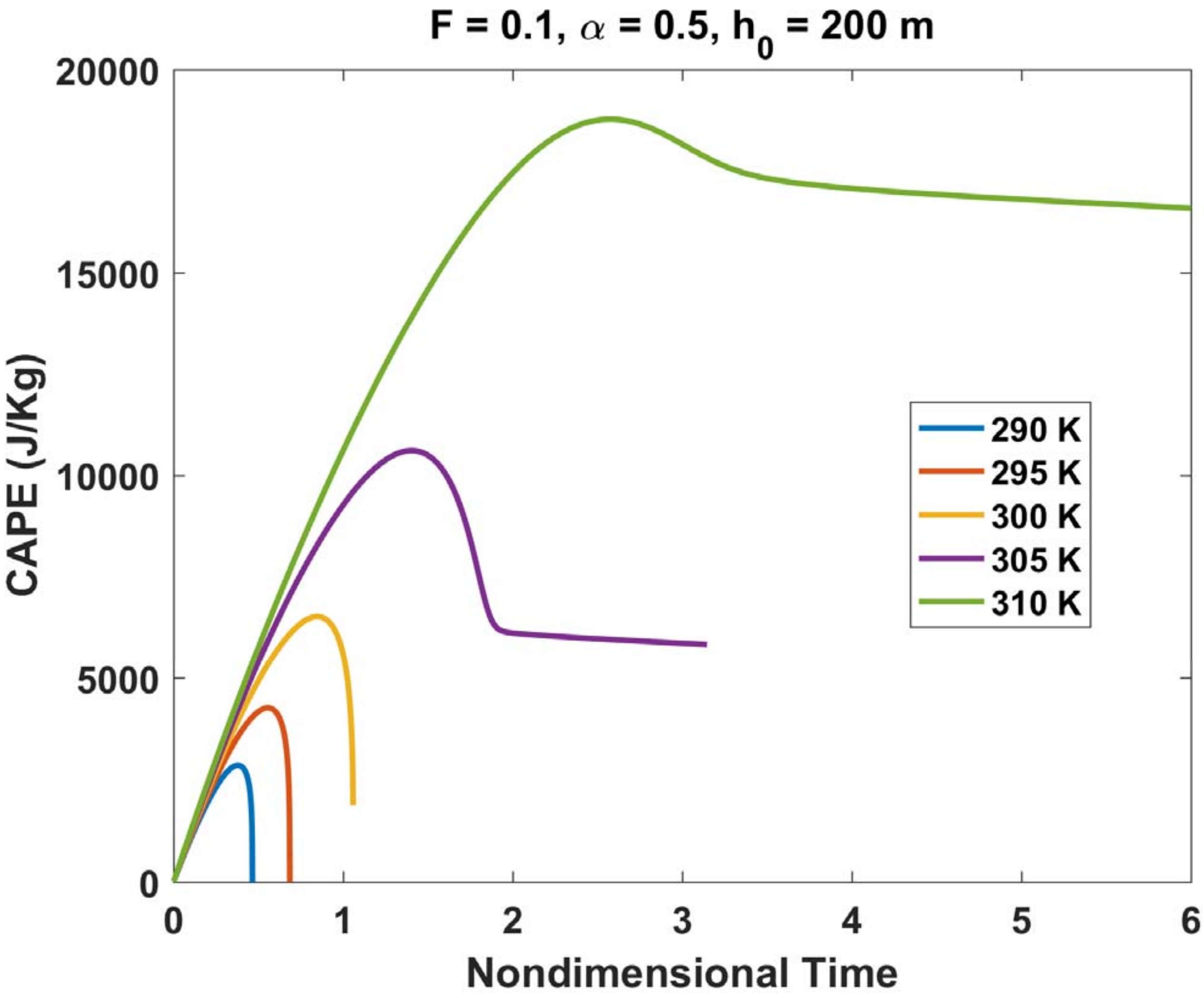
Very Warm Regime


Ts = 330, F = 0.1, α = 0.5, h_0 = 200 m


Ts = 330, F = 0.1, α = 0.5, h_0 = 200 m

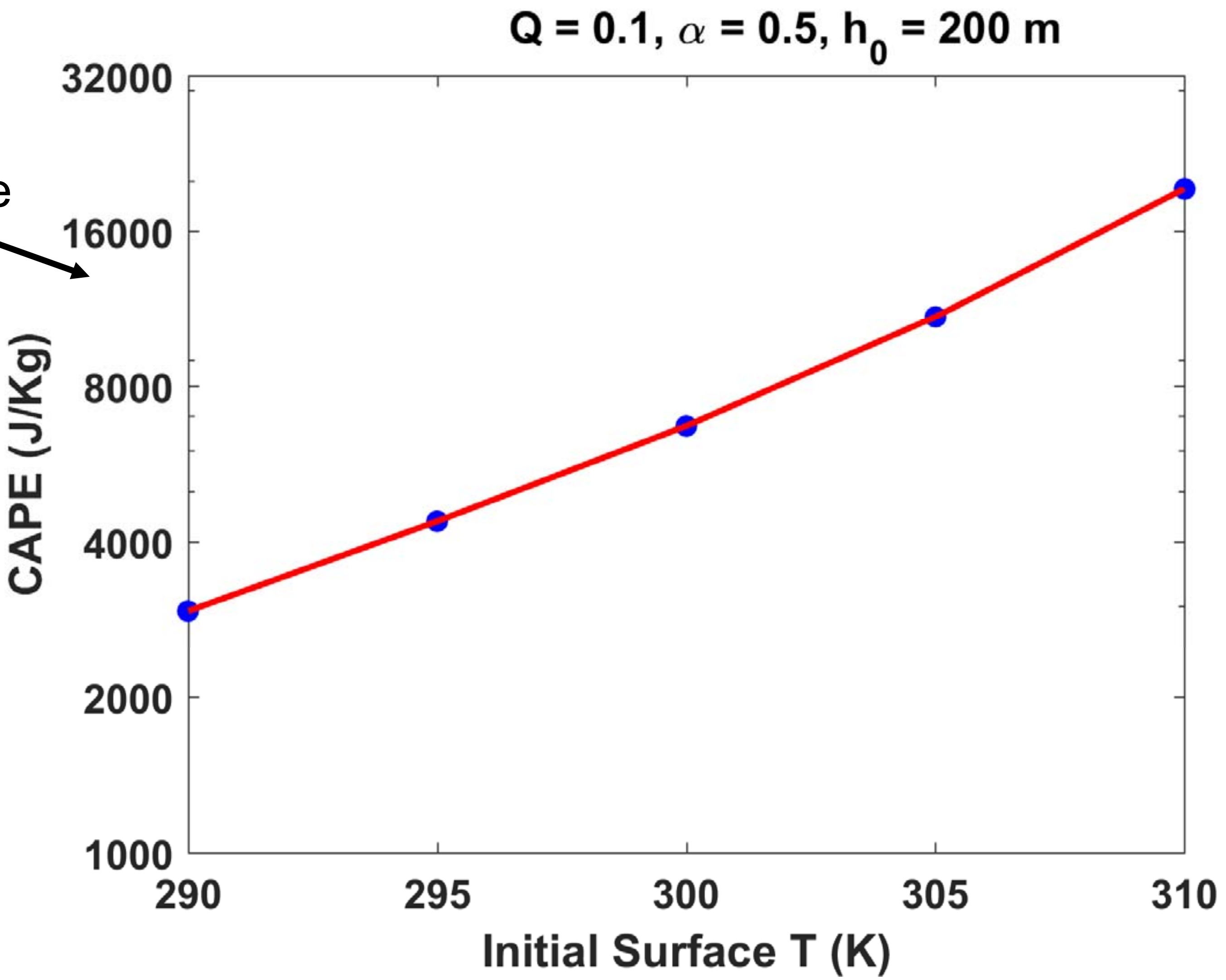

Ts = 330, F = 0.1, α = 0.5, h_0 = 200 m

Peak CAPE increases with increasing temperature

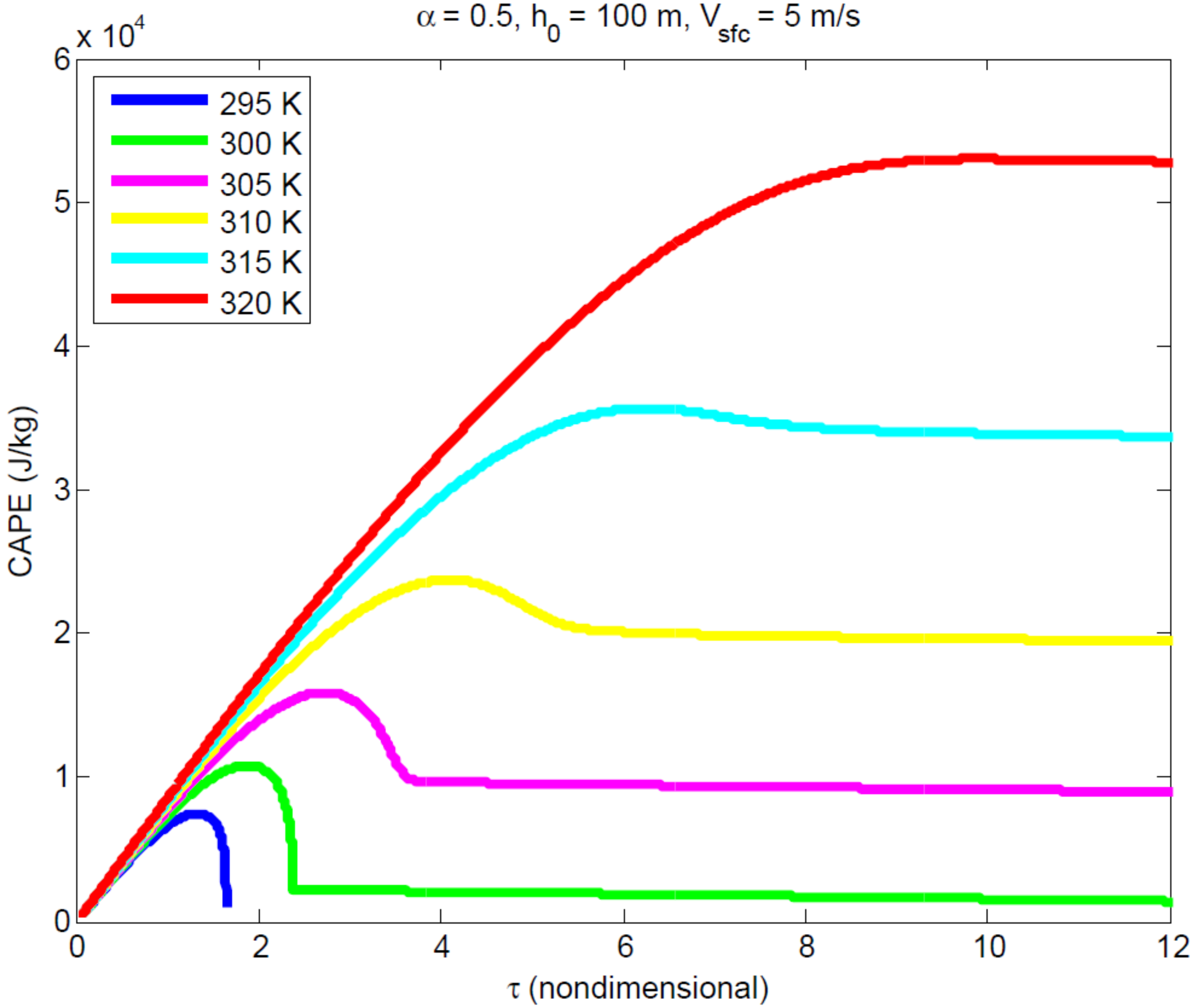


The relation between initial surface temperature and peak CAPE is slightly faster than exponential

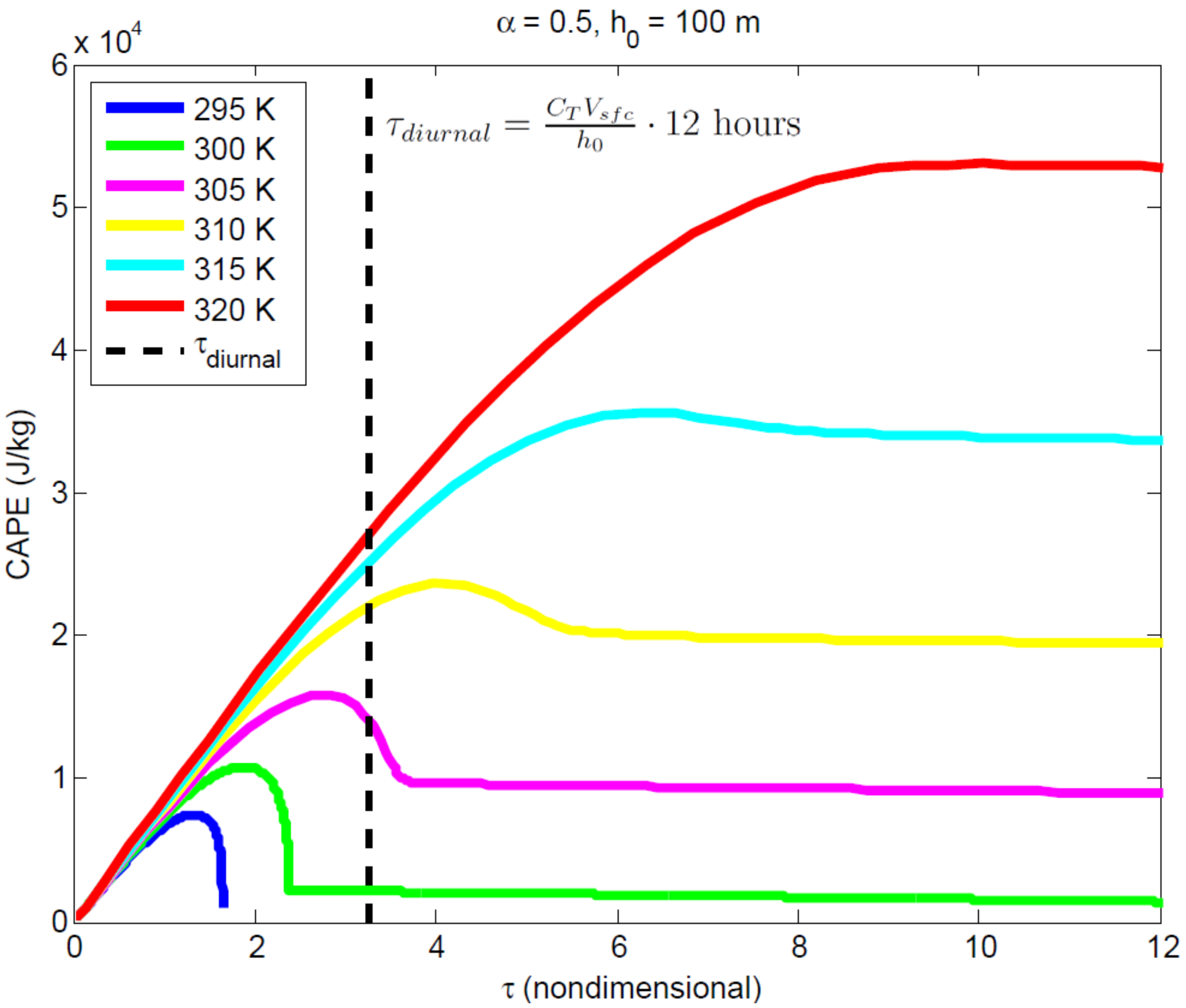
Log scale



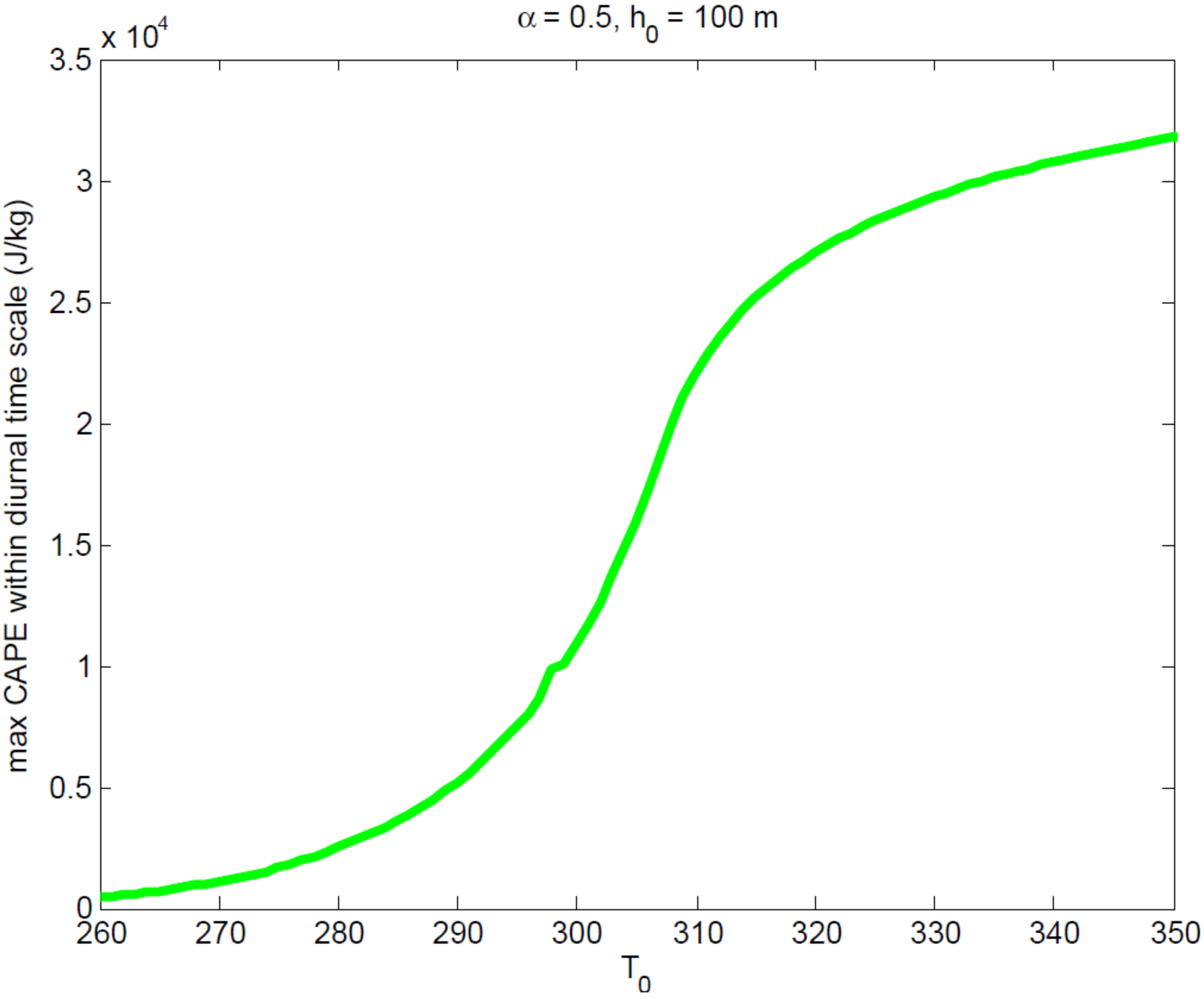
What happens when we impose a limiting time scale?



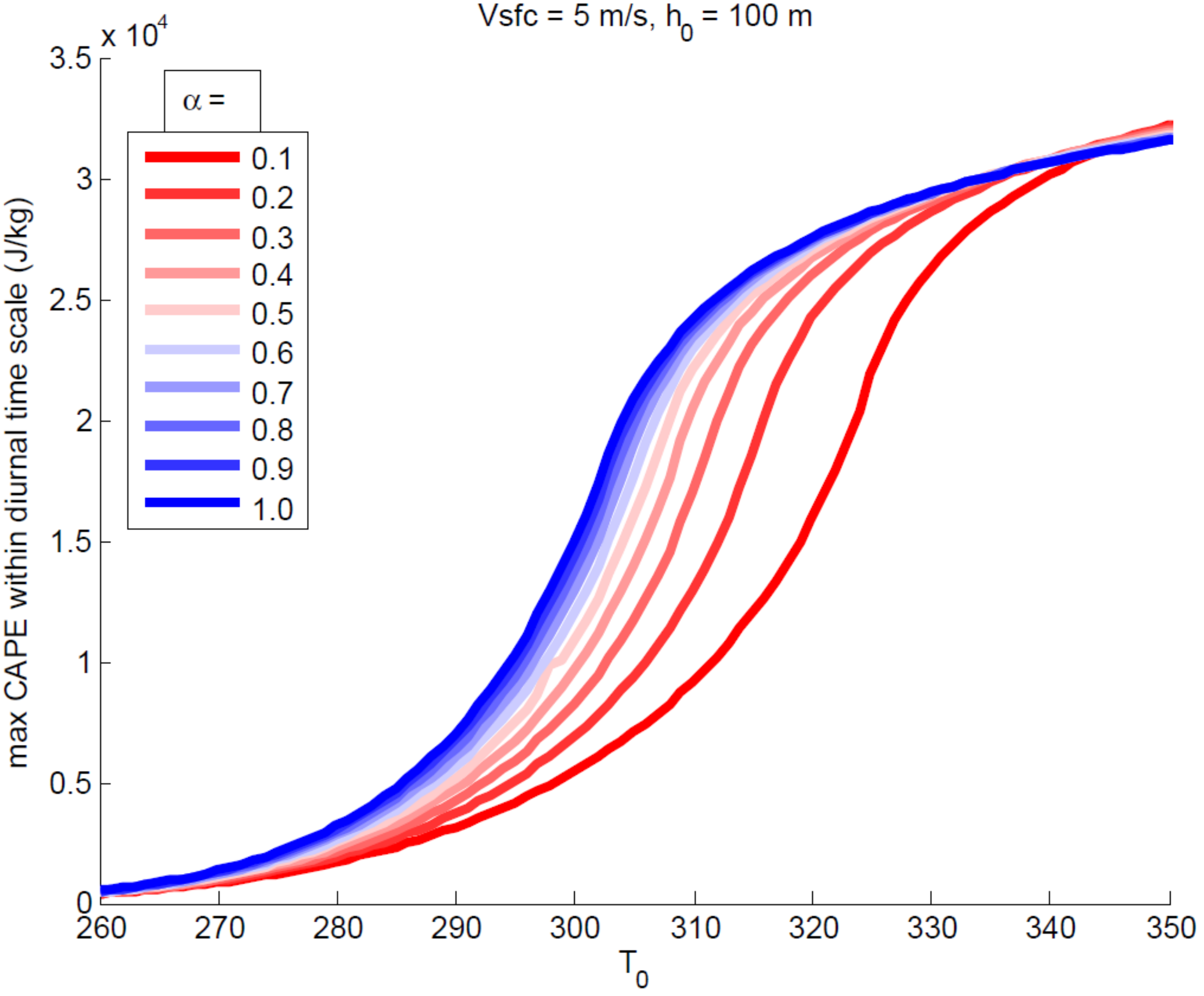
What happens when we impose a limiting time scale?



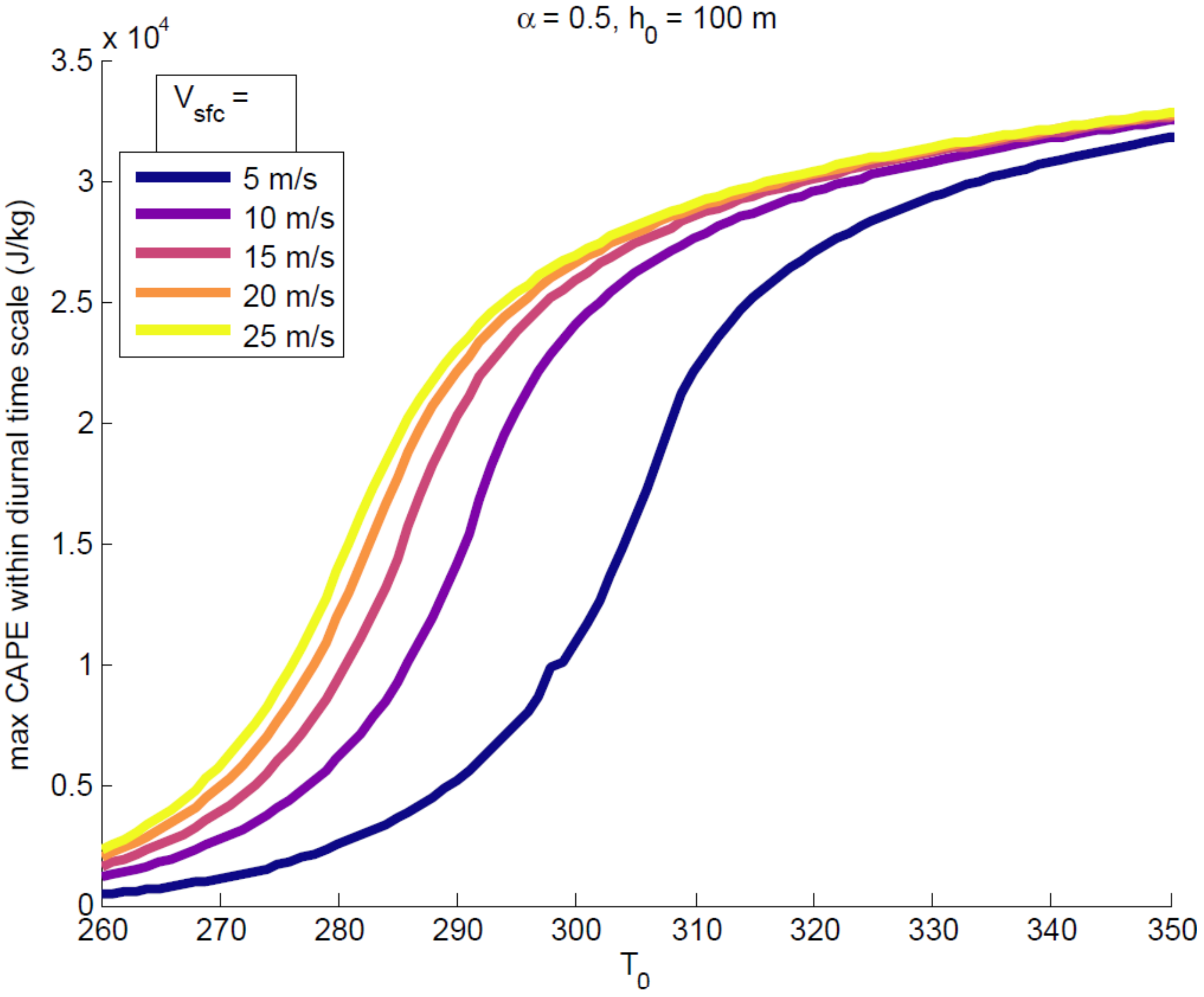
What happens when we impose a limiting time scale?

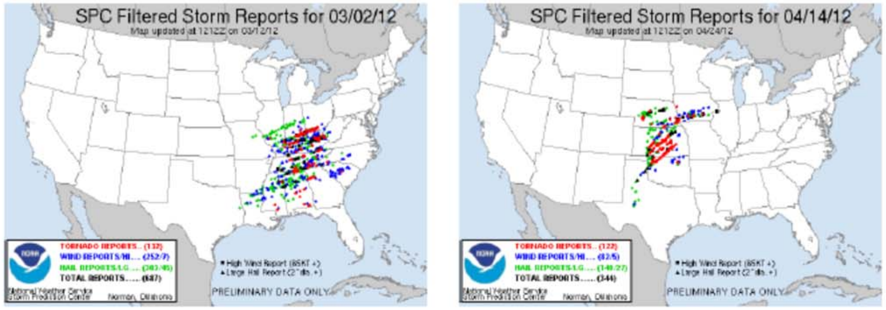


A moister land surface means higher CAPE at lower temperatures

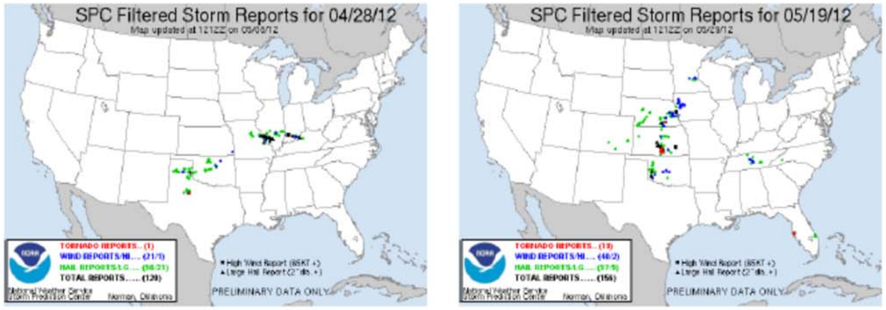


Higher surface wind speed also translates to higher CAPE

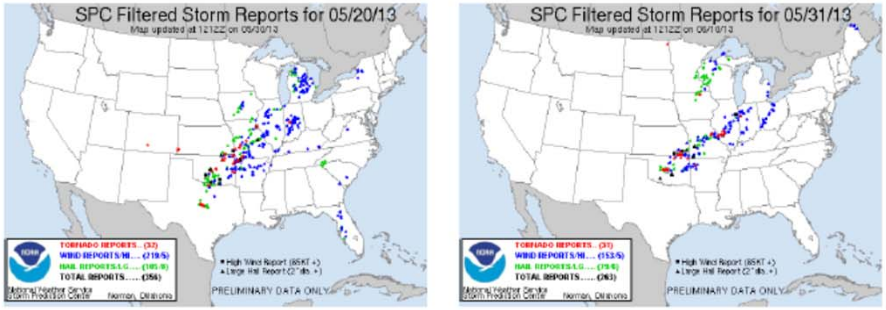




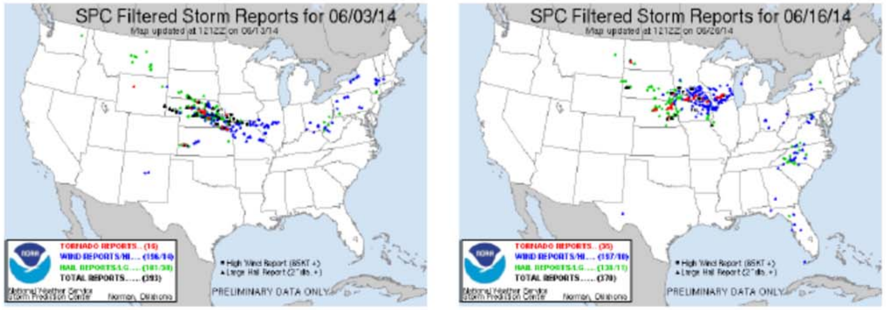
(a) March 2, 2012 (b) April 14, 2012



(c) April 28, 2012 (d) May 19, 2012

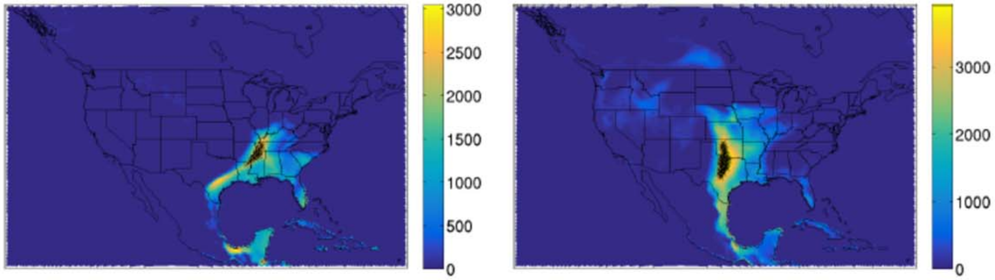


(e) May 20, 2013 (f) May 31, 2013

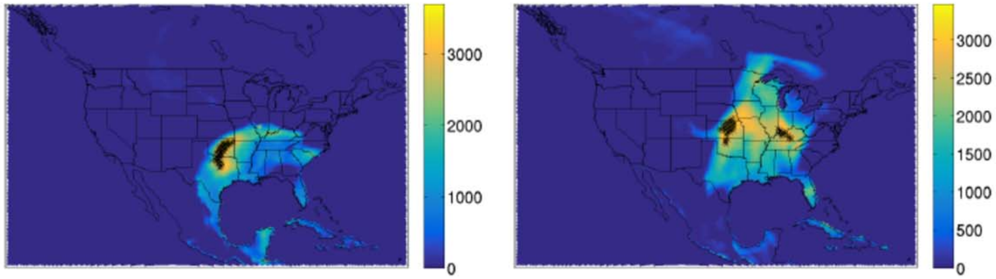


(g) June 3, 2014 (h) June 16, 2014

CAPE



(a) March 2, 2012 18Z (b) April 14, 2012 21Z



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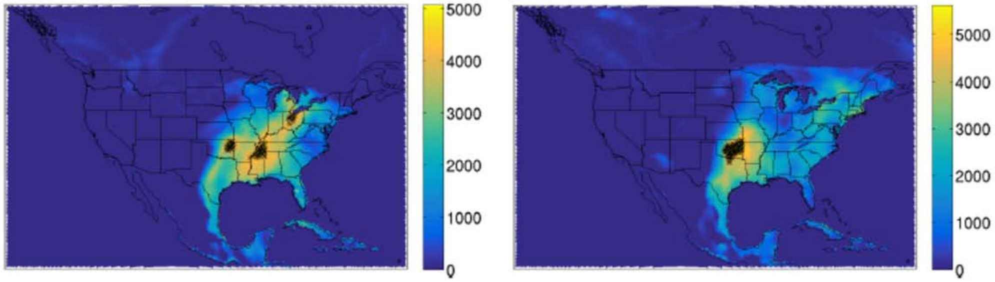

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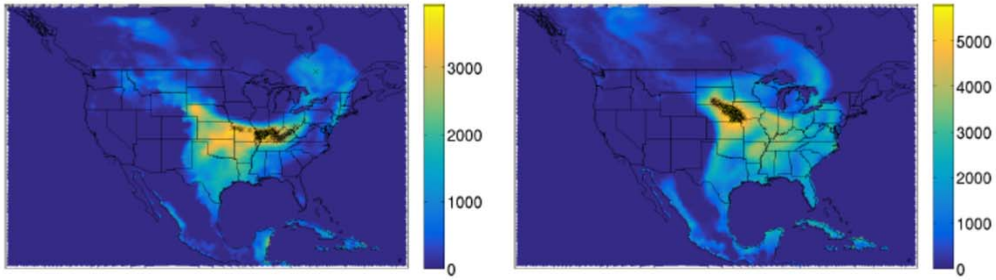

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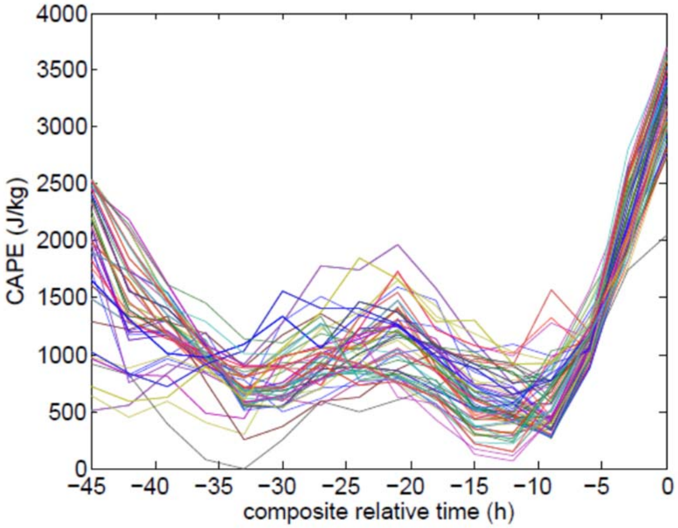
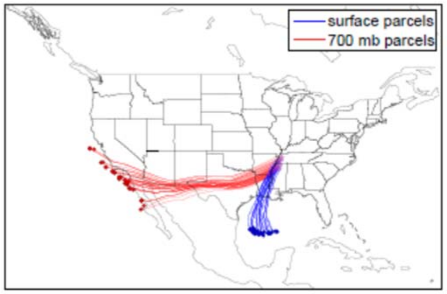
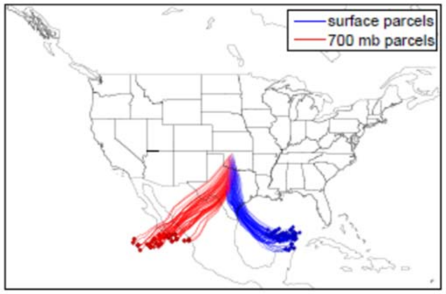




(a) March 2, 2012 18Z



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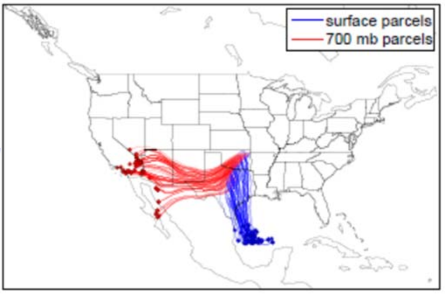

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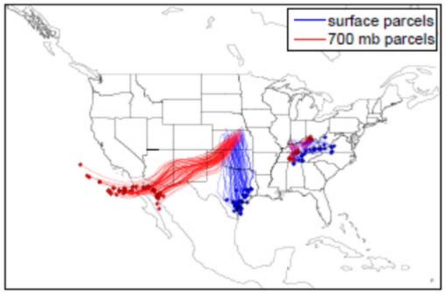

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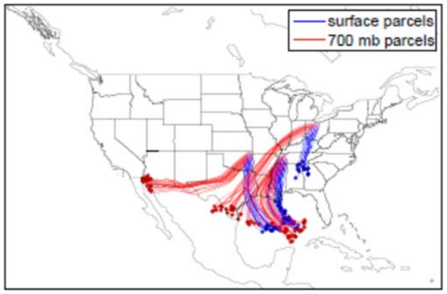
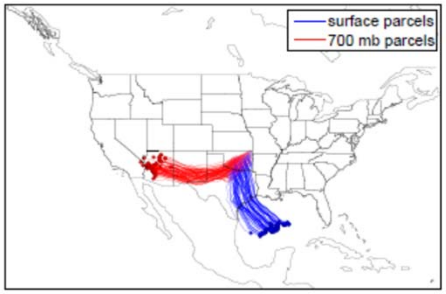
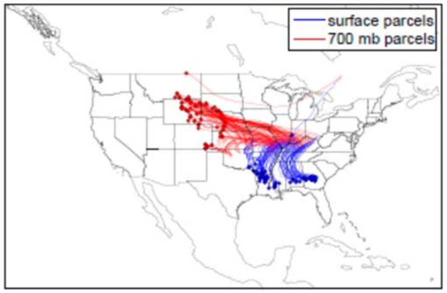


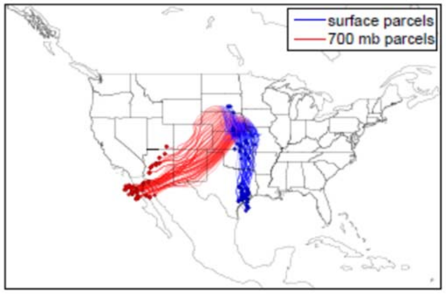
(e) May 20, 2013 21Z



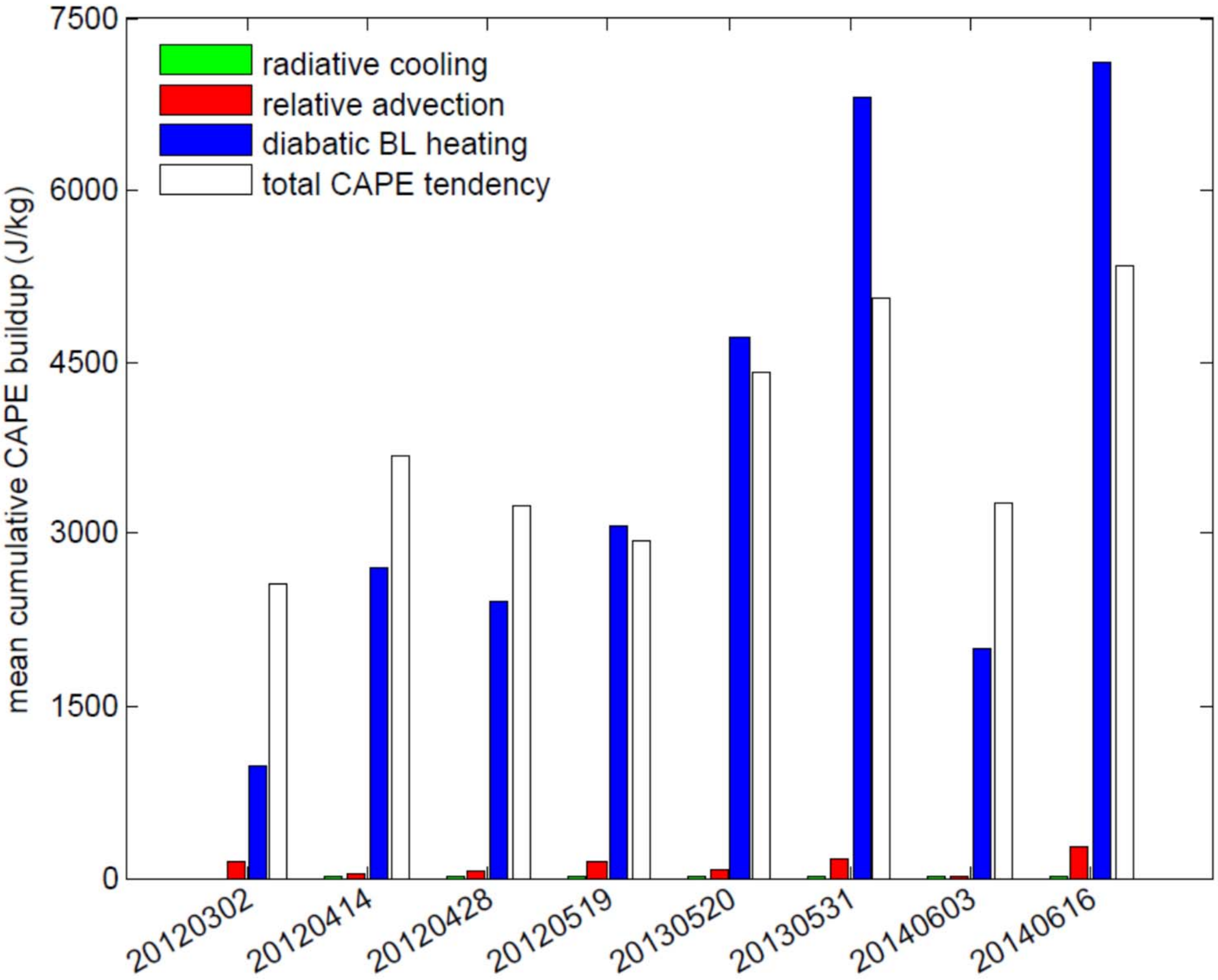
(f) May 31, 2013 21Z



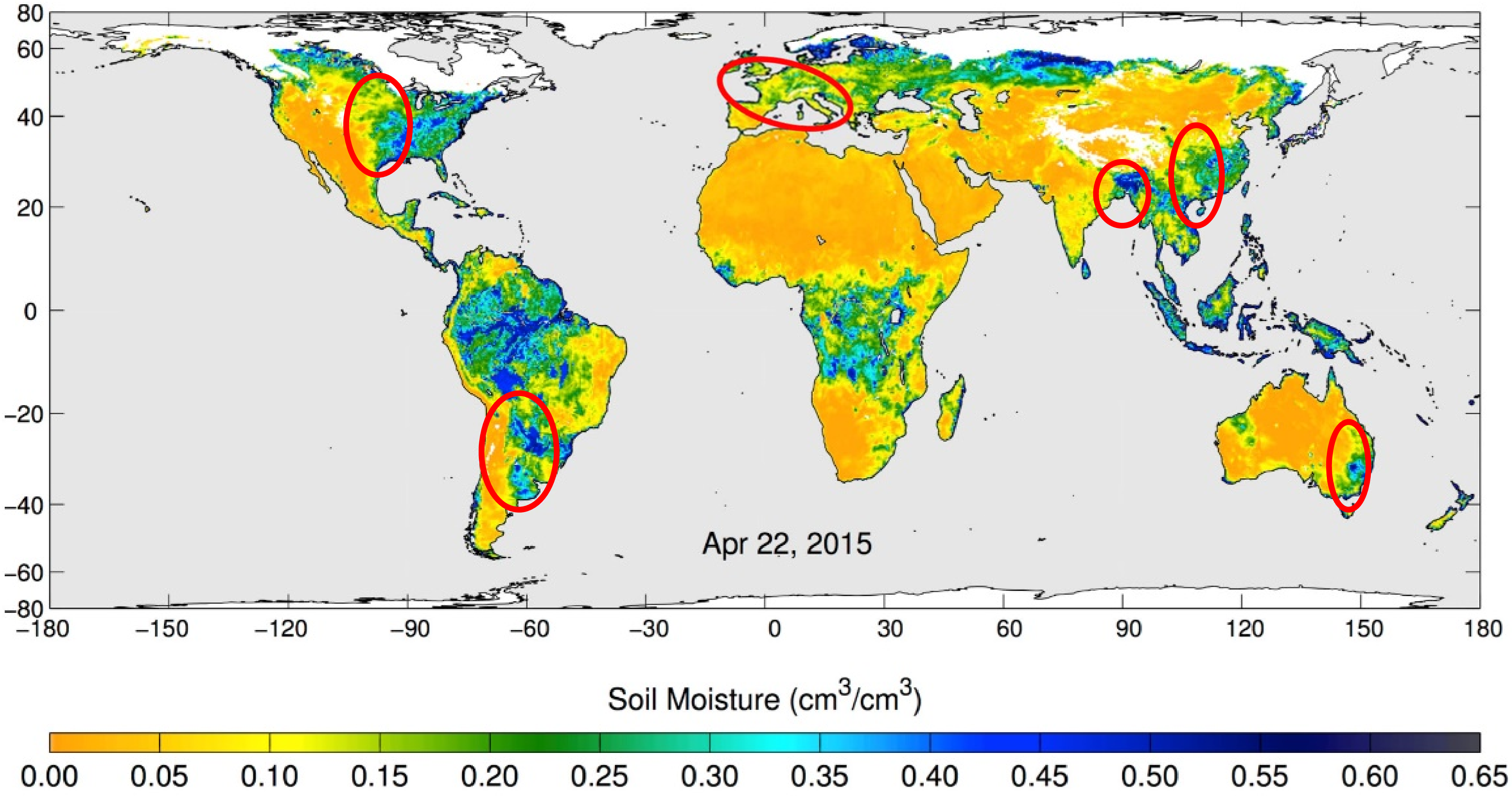
(g) June 3, 2014 18Z



(h) June 16, 2014 21Z

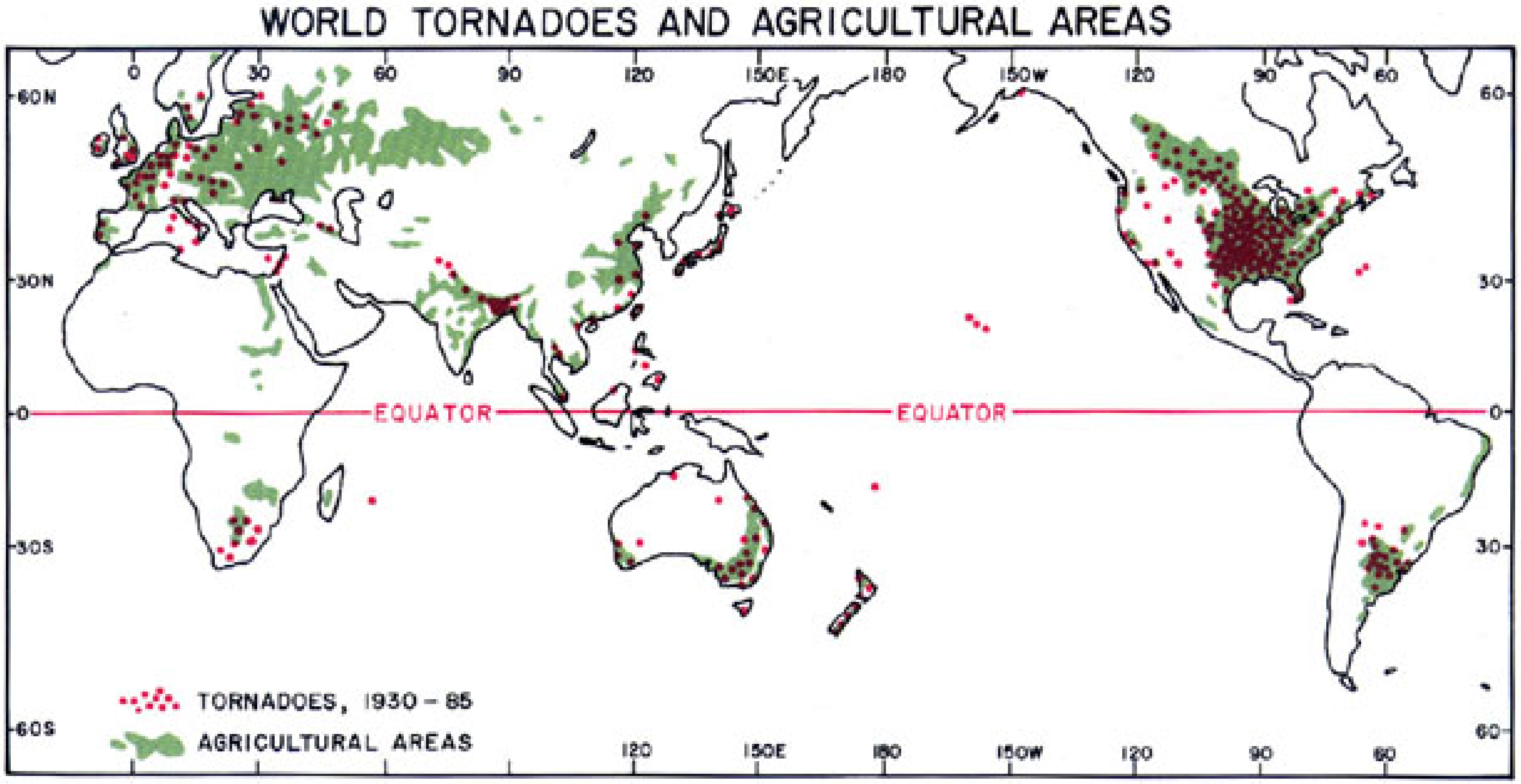


Mean total accumulated CAPE (white), and contributions to CAPE accumulation from diabatic heating (blue), relative advection (red), and radiative cooling (green) in columns of interest for each case.



Volumetric water content in the top 5 centimeters of soil, from NASA's Soil Moisture Active Passive (SMAP) observatory, 22 April 2015

Global Distribution of Tornadoes



Summary

- Large CAPE occurs when deep dry-adiabatic layers are advected over moist soils (connection to agriculture?)
- Peak values of CAPE scale approximately with the difference between wet- and dry-bulb temperature, which increases exponentially with surface temperature
- Imposing a diurnal cycle limits the growth of peak CAPE with surface temperature
- Peak CAPE increases with surface wind speed and soil moisture
- Dependence on soil moisture may offer a degree of seasonal predictability of CAPE
- Dependence on soil moisture may also yield multiple equilibria