衛星所見雷暴雲頂特徵及它們的物理機制

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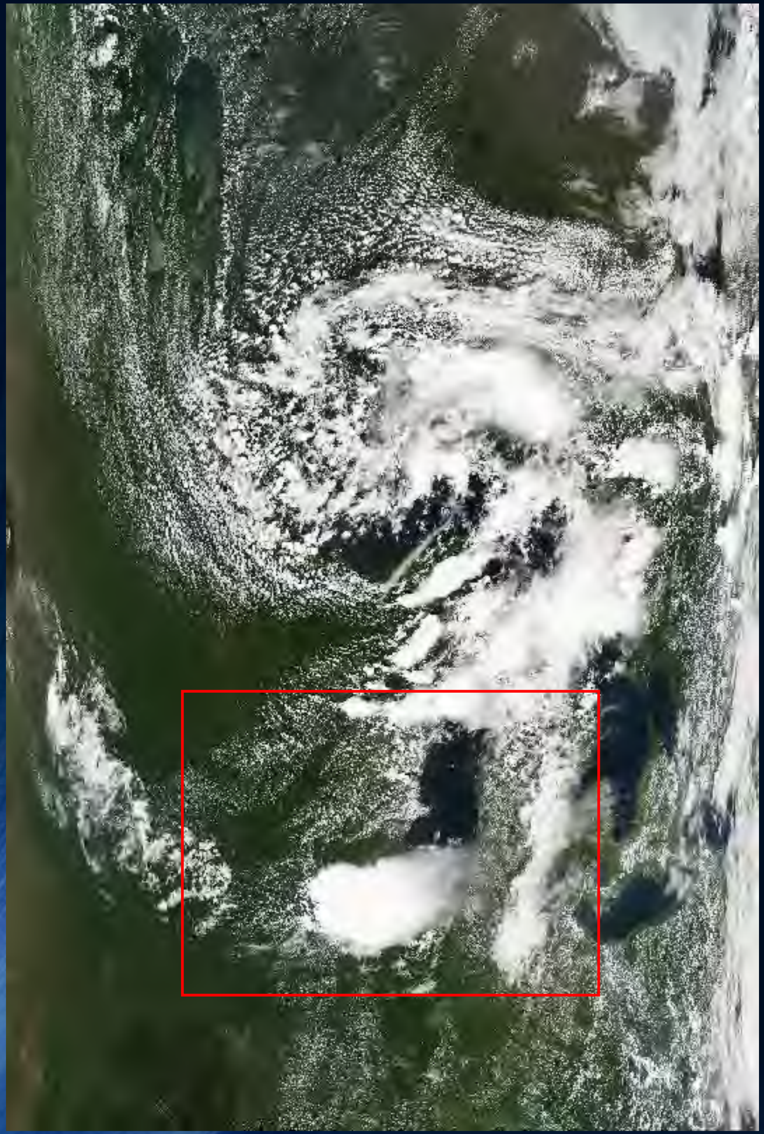
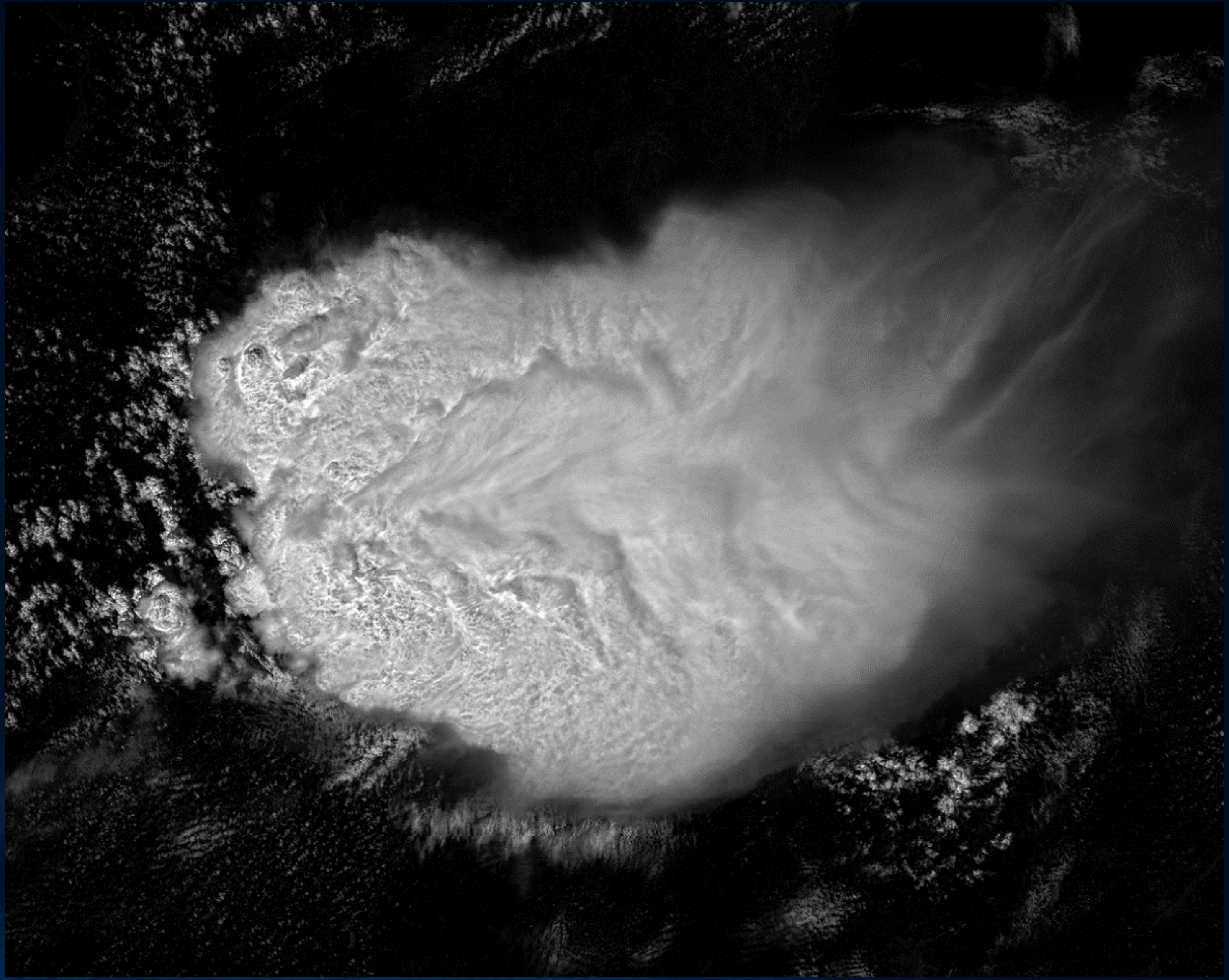
Why study storm top features?

- Satellite images provide storm data that cover large spatial areas (even global if necessary) and can be temporally continuous in the case of geostationary satellites.
- So they provide long lead time for forecasters
- Many storms occur in places where there is no other type of data (conventional or radar) available
- But we only see storm top features. In addition, these are remote sensing data. They need to be interpreted correctly in order to be useful.

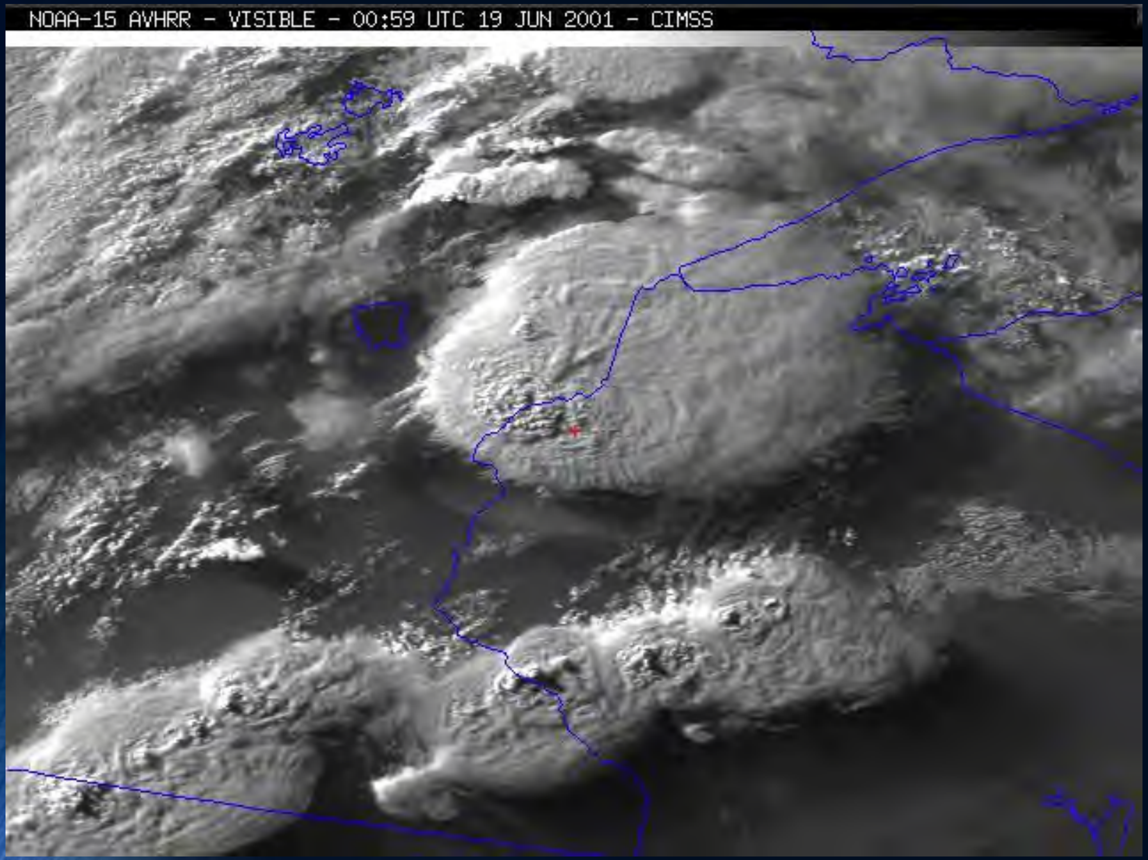
Aqua MODIS 2004/7/13

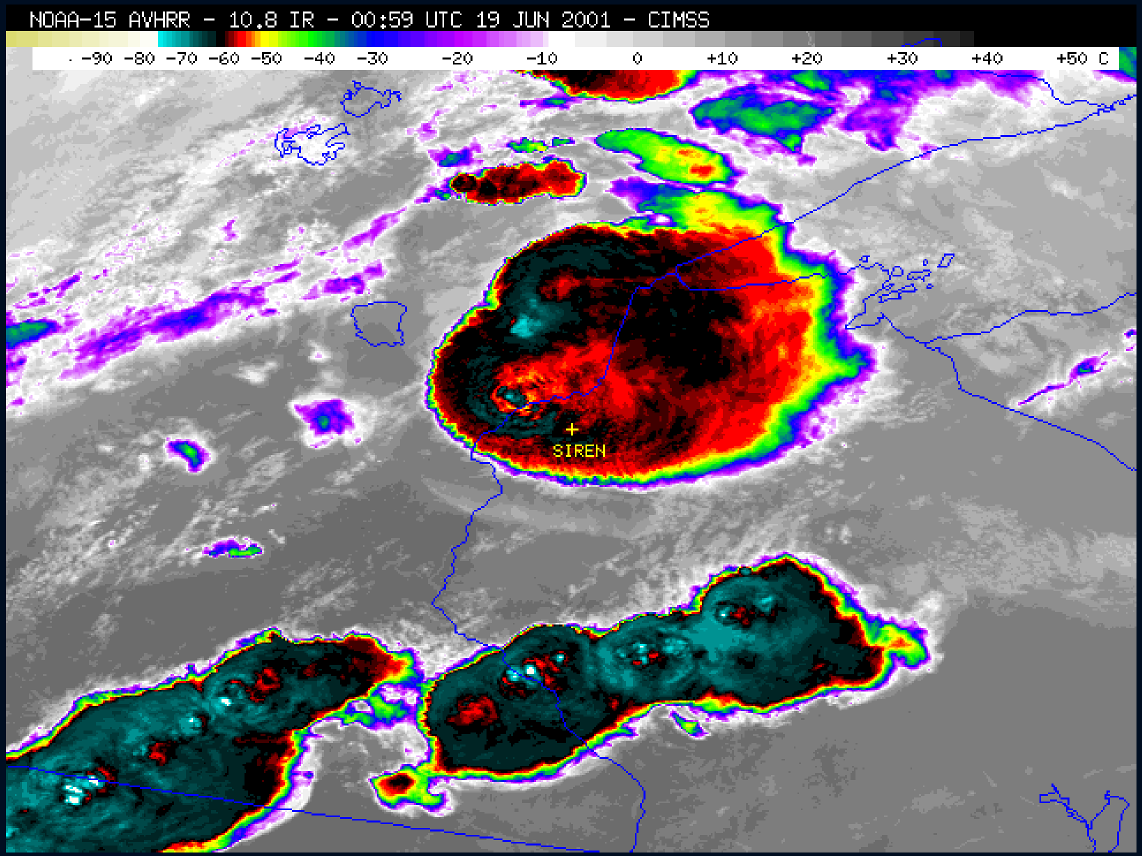


Need enhancement



Visible and IR



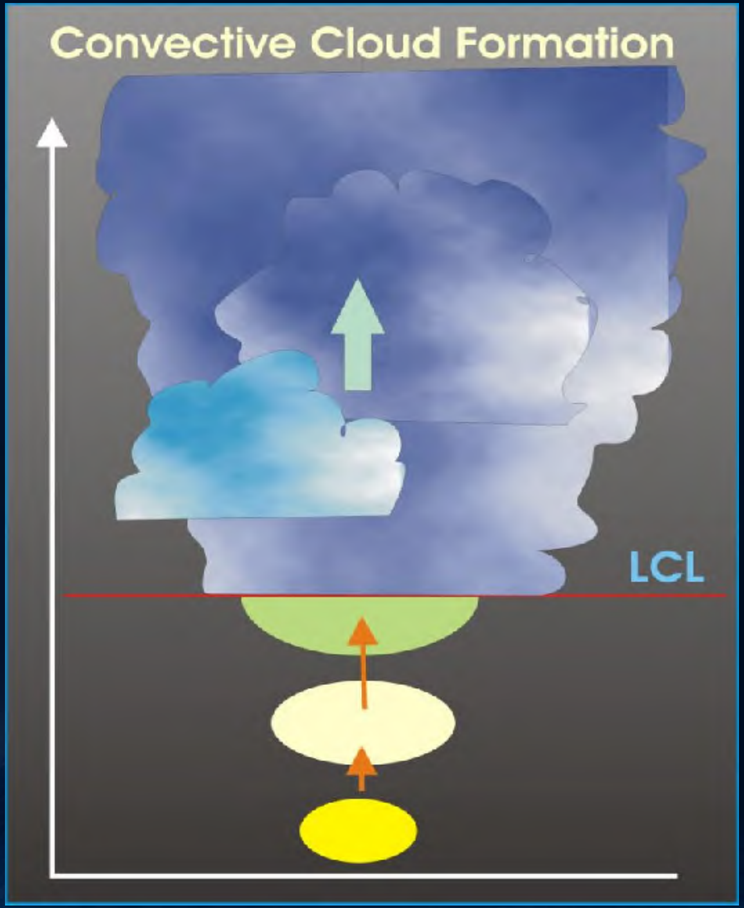


Understand the storm physics

- Several storm top features in both visible and IR will be examined from the point of view of model simulations. The purpose is to understand the physics of the observed phenomena using the physics included in the model.
- Understanding of such physics is useful for forecasters who use these satellite observed features. The forecaster will be able to identify what was happening in the storm at the time the image was taken. Such information will enable the forecaster to project the further development of the storm.

對流雲基礎過程

Below LCL: dry adiabatic process
Above LCL : pseudo-adiabatic process



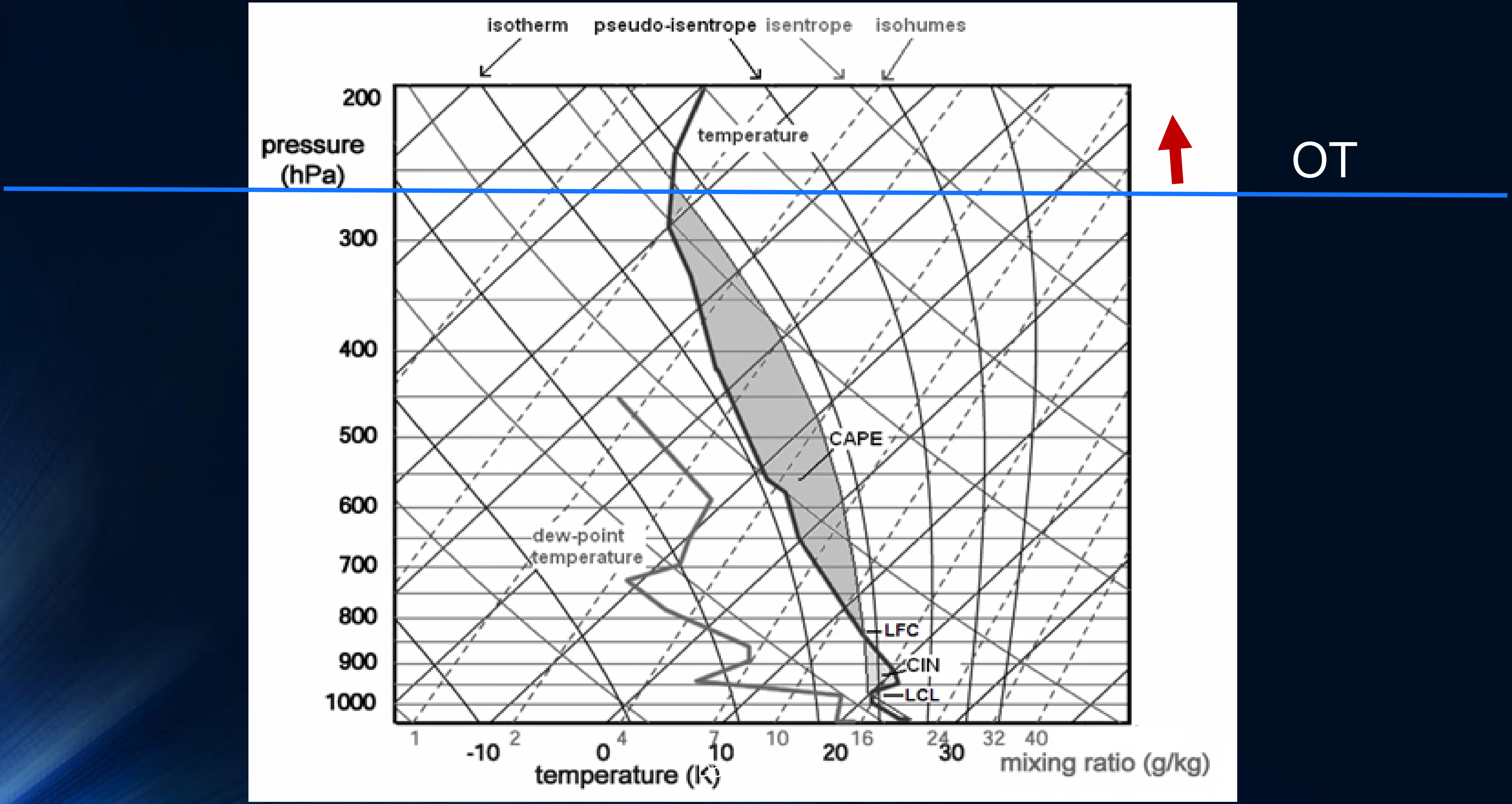
$$c_{p,m}dT + L_e dq_{v,sat} - \alpha_m dp = 0$$

$$\left(c_{p,a} + q_{v,sat}c_{p,v}\right)dT + L_e dq_{v,sat} - (R_a + q_{v,sat}R_v)T\frac{dp}{p} = 0$$

$$c_{p,a}\frac{dT}{T} + L_e\frac{dq_{v,sat}}{T} - R_a\frac{dp}{p} = 0$$

$$\boxed{\Gamma_s = -\frac{dT}{dz} = \frac{g}{c_{p,a} + L_e\left(dq_{v,sat}/dT\right)}}$$

Typical severe storm sounding in US Midwest



Buoyancy and Static Stability

$$F_B = mg\left(\frac{\rho - \rho'}{\rho'}\right) = mg\left(\frac{T - T'}{T'}\right) = mg\left(\frac{\theta - \theta'}{\theta'}\right)$$

$$\begin{cases} \Gamma < \Gamma_d & \text{stable} \\ \Gamma = \Gamma_d & \text{neutral} \\ \Gamma > \Gamma_d & \text{unstable} \end{cases} \text{ (unsaturated), or } \begin{cases} \Gamma < \Gamma_s & \text{stable} \\ \Gamma = \Gamma_s & \text{neutral} \\ \Gamma > \Gamma_s & \text{unstable} \end{cases} \text{ (saturated)}$$

The stability conditions can also be expressed in terms of the potential temperatures:

$$\ln\theta = \ln T + \kappa \ln p_0 - \kappa \ln p$$

$$\frac{1}{\theta}\frac{d\theta}{dz} = \frac{1}{T}\frac{dT}{dz} - \frac{\kappa}{p}\frac{dp}{dz} = \frac{1}{T}\frac{dT}{dz} + \frac{(R_d / c_p)}{\rho_a R_d T}(\rho_a g)$$

$$= \frac{1}{T}\left(\frac{g}{c_p} + \frac{dT}{dz}\right) = \frac{1}{T}(\Gamma_d - \Gamma)$$

$$\frac{d\theta}{dz} = \frac{\theta}{T}(\Gamma_d - \Gamma)$$

$$\begin{cases} \dfrac{d\theta}{dz} > 0 & \text{stable} \\ \dfrac{d\theta}{dz} = 0 & \text{neutral} \\ \dfrac{d\theta}{dz} < 0 & \text{unstable} \end{cases} \text{ (unsaturated), or } \begin{cases} \dfrac{d\theta_e}{dz} > 0 & \text{stable} \\ \dfrac{d\theta_e}{dz} = 0 & \text{neutral} \\ \dfrac{d\theta_e}{dz} < 0 & \text{unstable} \end{cases} \text{ (saturated)}$$

Brunt-Väisällä frequency

Brunt-Väisällä frequency (Wang, 2013)

$$m\left(\frac{d^2z}{dt^2}\right) = mg\left(\frac{\theta-\theta'}{\theta'}\right), \text{ or } \frac{d^2z}{dt^2} = g\left(\frac{\theta-\theta'}{\theta'}\right)$$

$$\left(\frac{\theta-\theta'}{\theta'}\right) = \left(\frac{\theta-\theta'}{\theta'}\right)_0 + \left[\frac{\partial}{\partial z}\left(\frac{\theta-\theta'}{\theta'}\right)\right]_0 z + \ldots$$

$$\left[\frac{\partial}{\partial z}\left(\frac{\theta-\theta'}{\theta'}\right)\right]_0 z = \left[\frac{\partial}{\partial z}\left(\frac{\theta}{\theta'}-1\right)\right]_0 z = -\left(\frac{\theta}{\theta'^2}\frac{\partial\theta'}{\partial z}\right) z \approx -\left(\frac{1}{\theta'}\frac{\partial\theta'}{\partial z}\right) z$$

$$\frac{d^2z}{dt^2} = -\left(\frac{g}{\theta'}\frac{\partial\theta'}{\partial z}\right) z = -N^2 z$$

where

$$N = \sqrt{(g/\theta')(\partial\theta'/\partial z)} \text{ (with unit s}^{-1}\text{)}$$

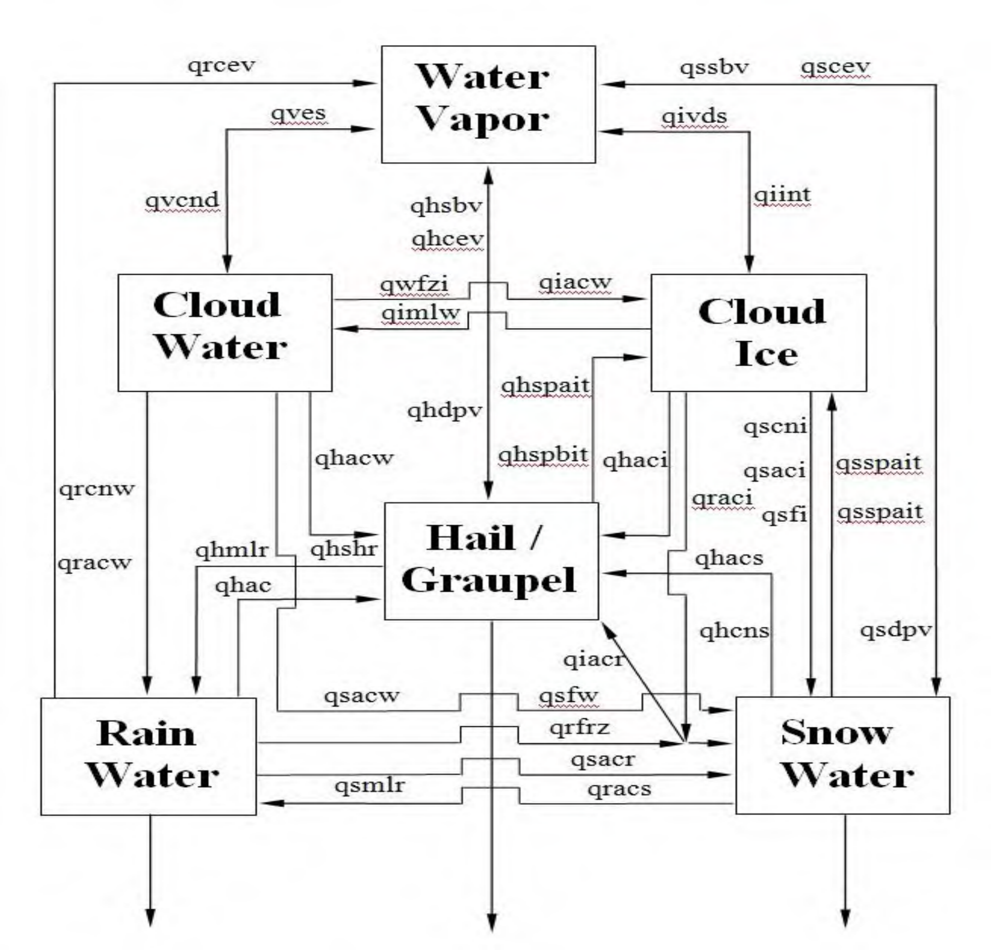
is called the *Brunt-Väisällä frequency* or *buoyant frequency*.

Overshooting (OT)

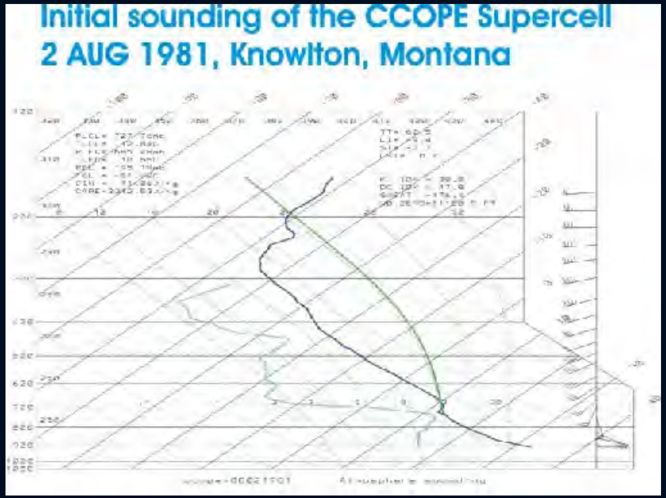
- Note that the overshooting is defined with reference to the equilibrium level (EL) only. Two points need to be clarified:
  - EL is not necessarily the same as the tropopause. In case of a severe storm, however, EL is close to the tropopause.
  - Overshooting does not imply penetration. It may be just simply a distortion of the tropopause. You need other non-adiabatic mechanisms to cause the penetration.
- In general, the OT will oscillate at the local Brunt-Väisällä frequency until its energy is dissipated
- There may be multiple OTs present at a given time but perhaps just a dominant one.

WISCDYMM-I and WISCDYMM-II

- 3-D, time-dependent, non-hydrostatic, prognostic, primitive equations
- 38 cloud microphysical processes
- WISCDYMM—quasi-compressible, 1-moment
- WISCDYMM-II—fully compressible, 2-moment
- Vapor, cloud drops, cloud ice, rain, snow, graupel/hail
- 1.5-order k-theory turbulence closure scheme
- BC: Non-slip (lower), Rayleigh layer (upper), radiation (lateral)
- Use a single sounding as the initial condition
- Convection initiated by thermal and humidity perturbations at the low level (warm bubble)



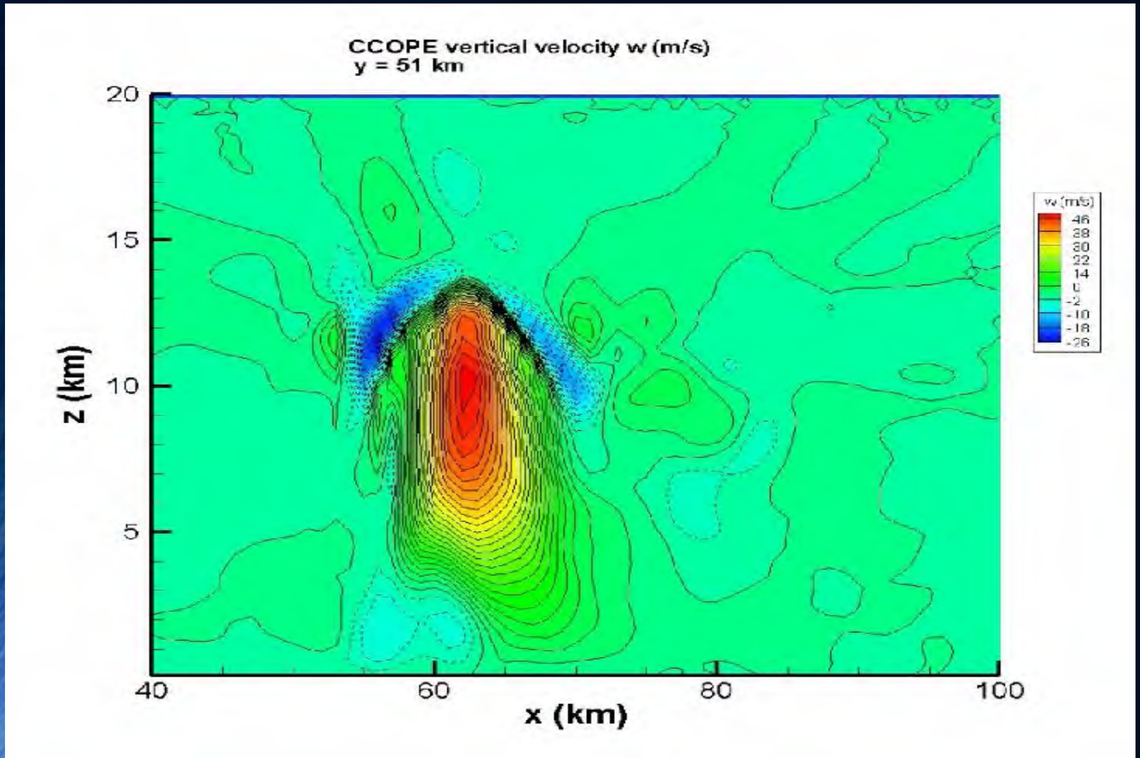
Initial conditions and initiation of convection

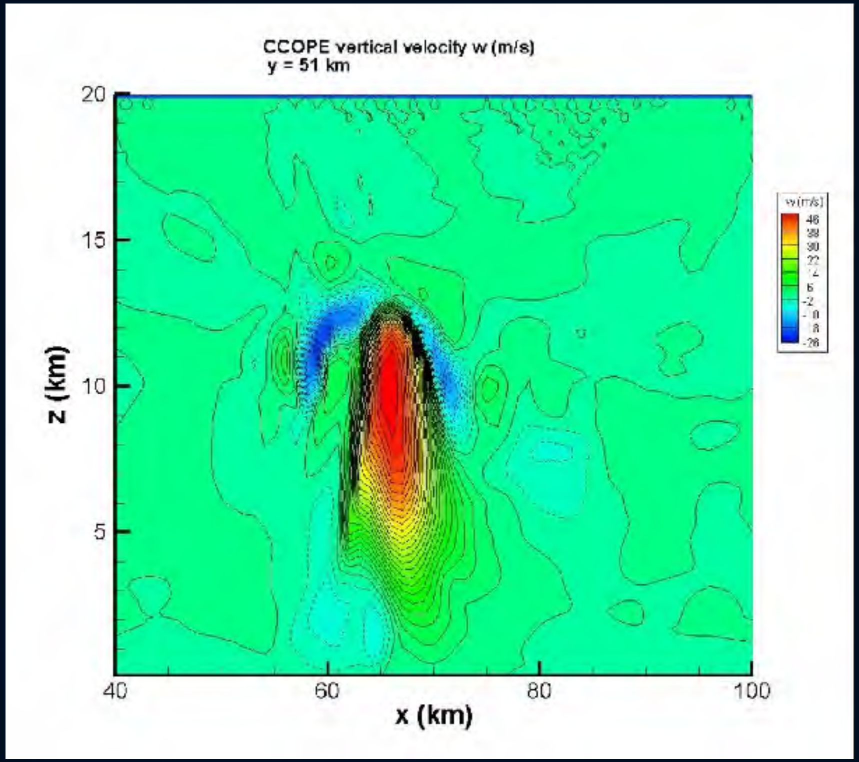


Storm top images

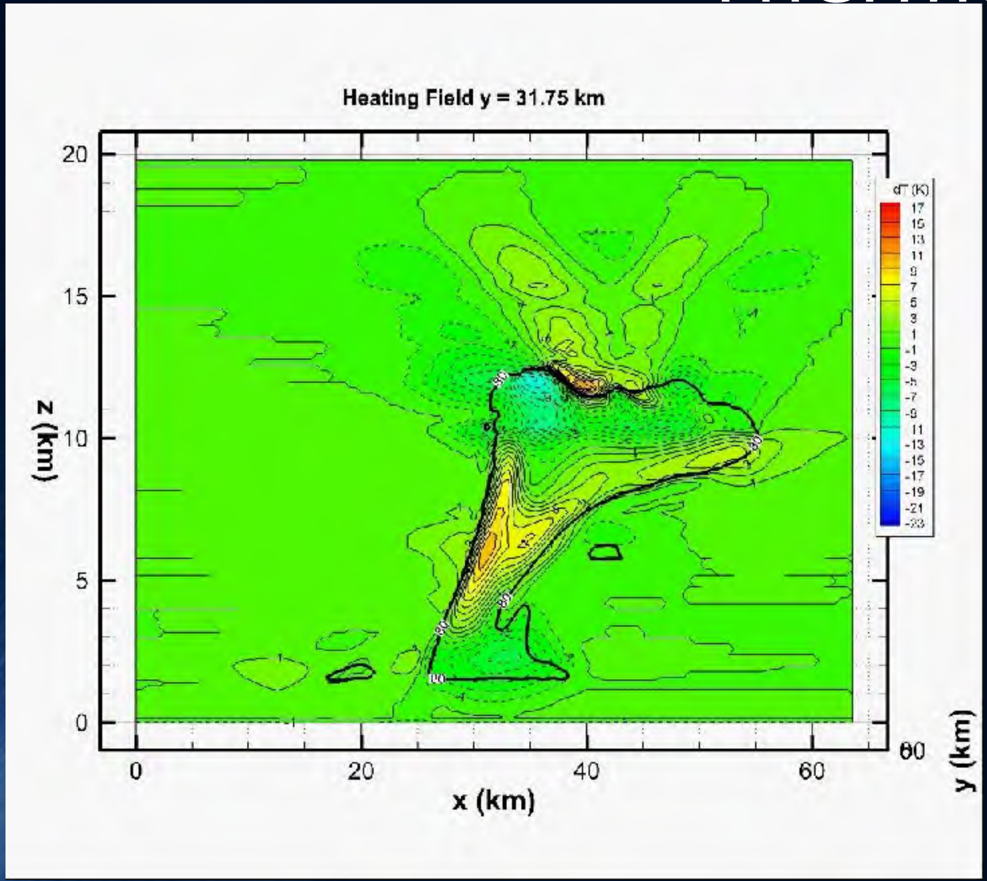
- Mechanical structure
  - Factor influencing the topography
- Thermal structure
  - Factors influencing heating cooling

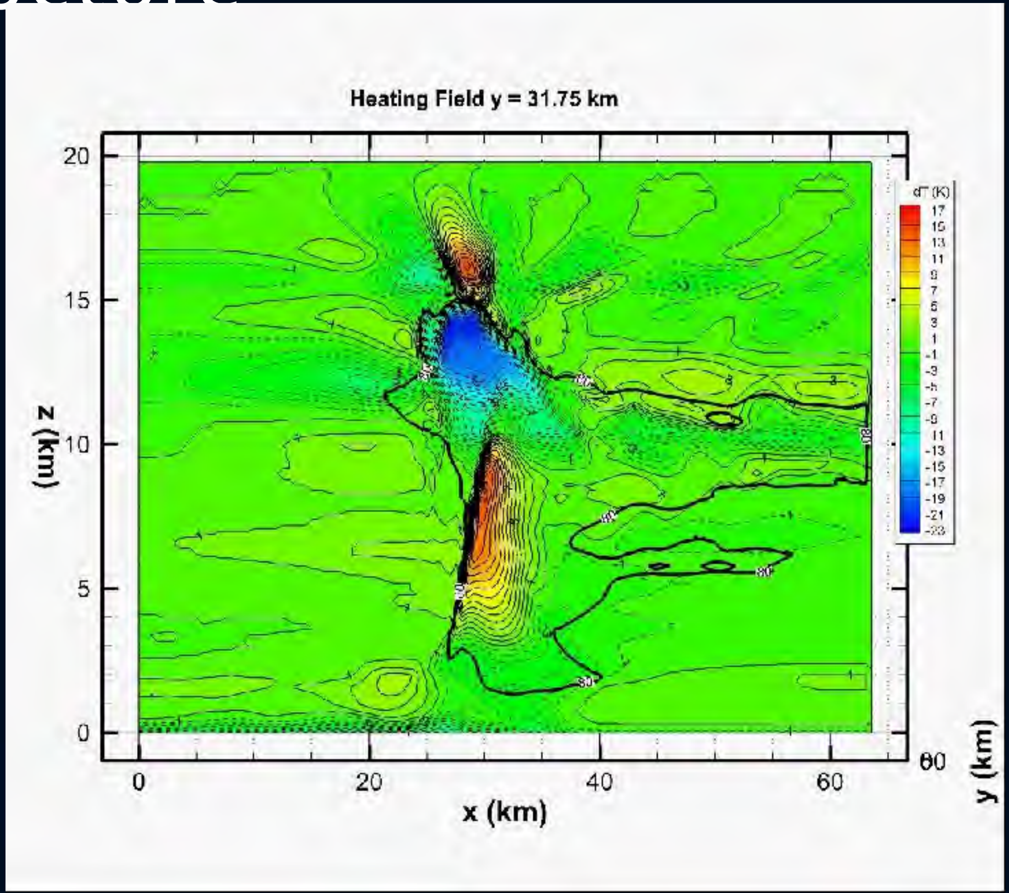
Vertical velocity field



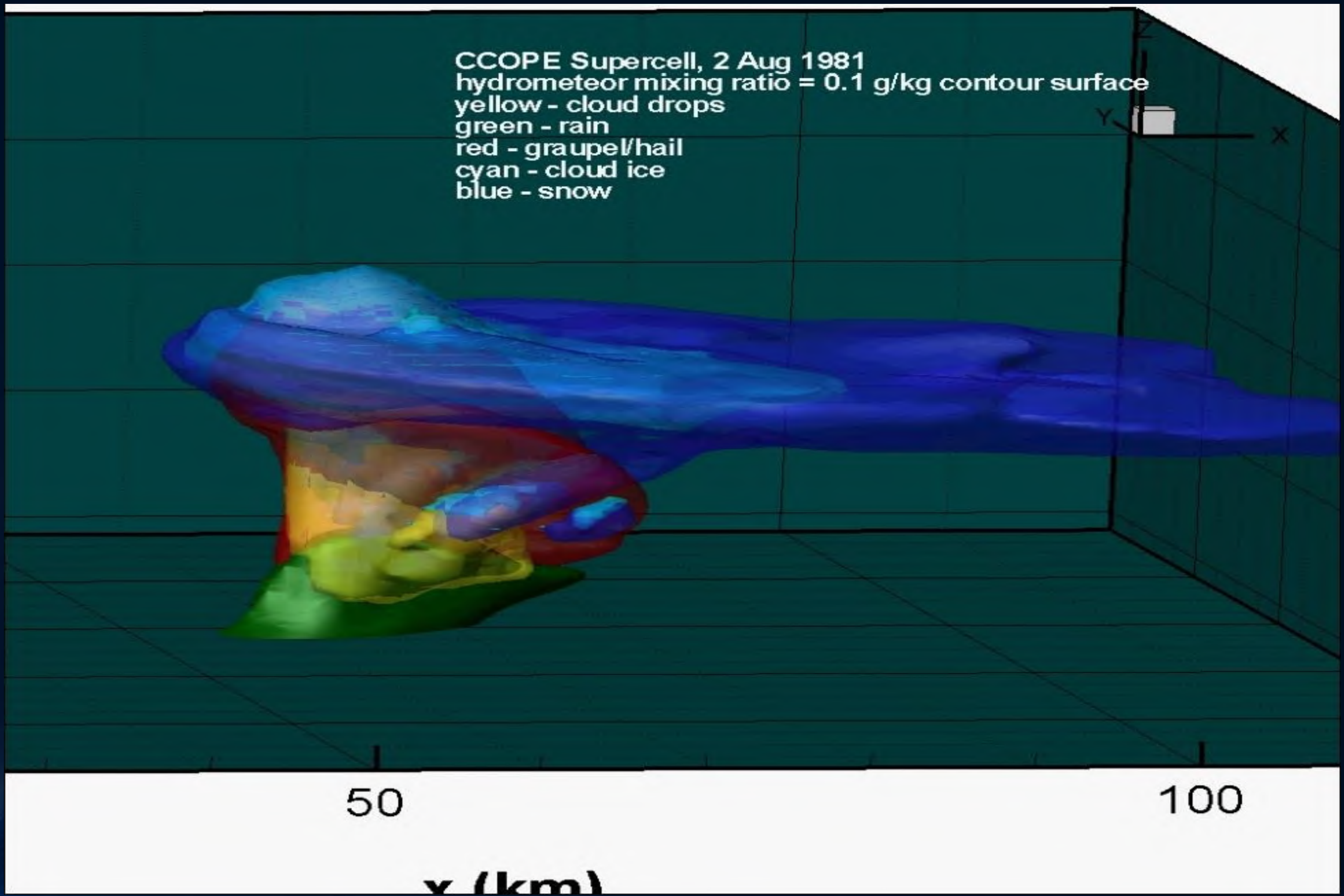


Thermal structure





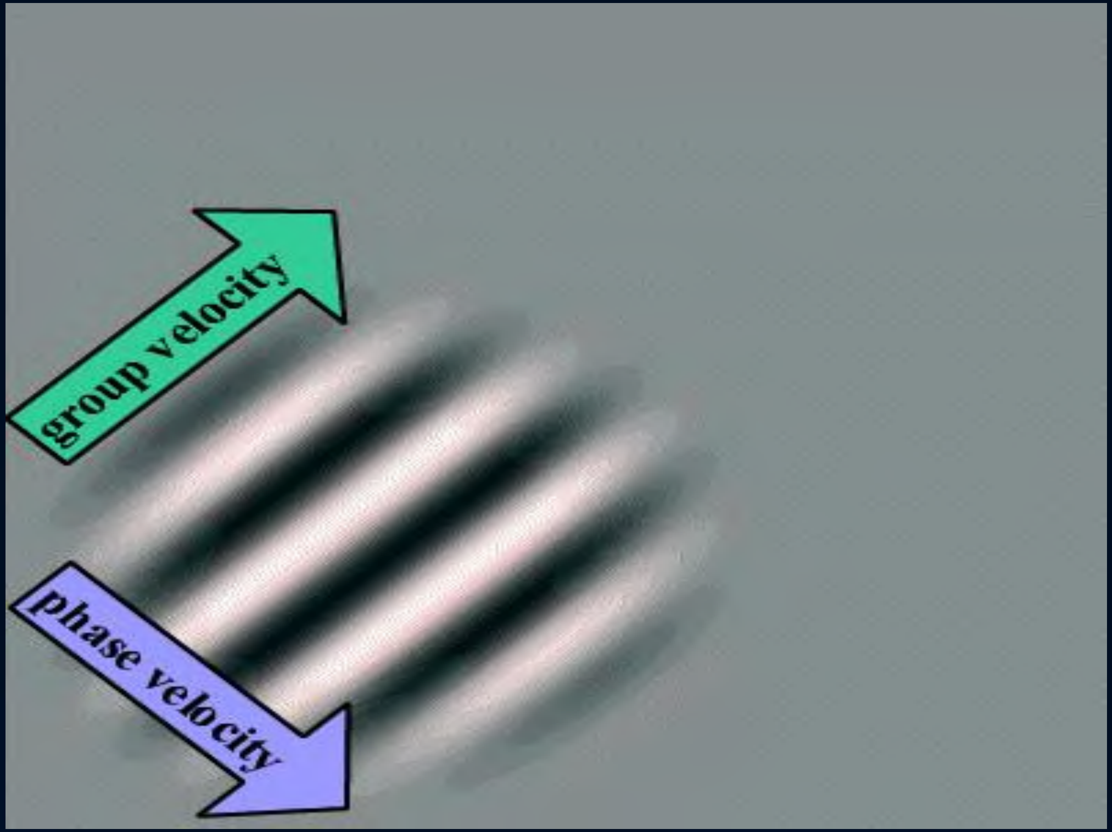
Distribution of hydrometeors



Internal Gravity waves

- Gravity waves are wave motions that utilizing gravity as the restoring force.
- Water wave in lakes or oceans is a kind of gravity waves, but it is a surface gravity wave. The vertical motion is limited to a very shallow layer near the surface, and the phase and group velocities are in the same direction.
- But in the atmosphere, the density is stratified so that the gravity waves can also propagate vertically in addition to propagate horizontally. This wave is called the internal gravity wave (IGW).
- The strange character of IGW is that the phase velocity and group velocity are perpendicular to each other.
- This means that the wave energy propagates along the phase line.

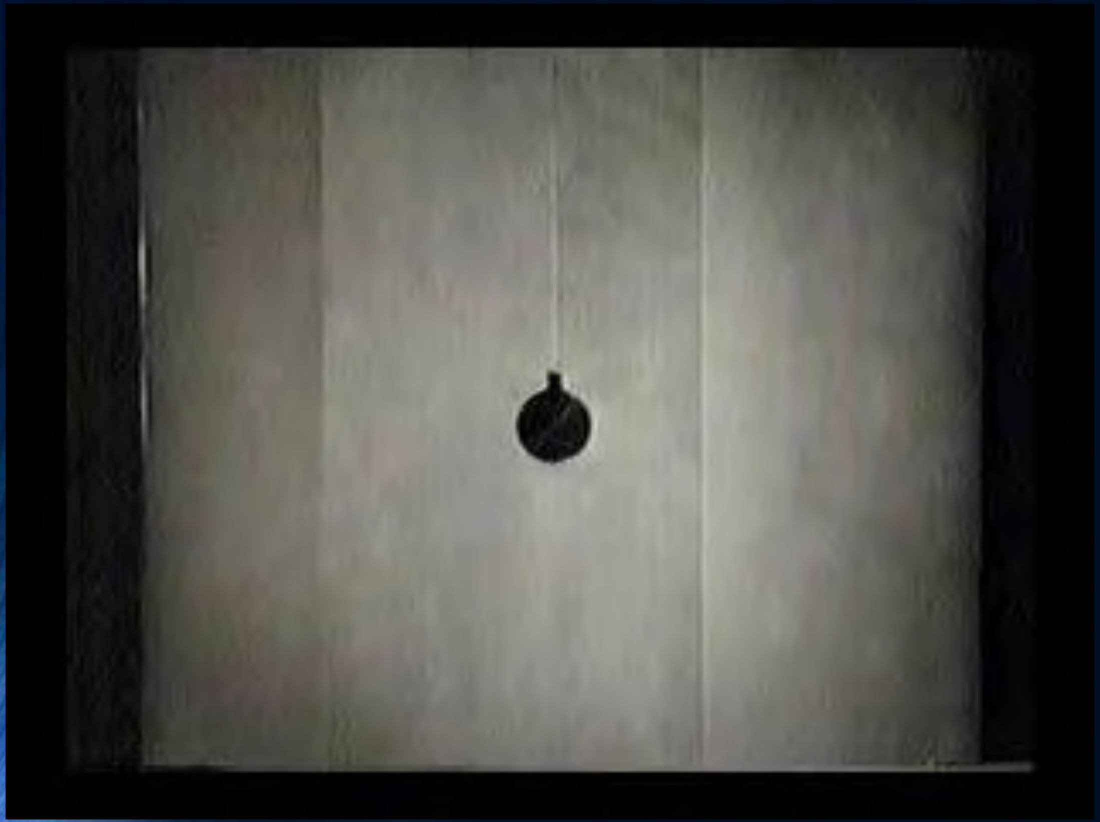
Internal gravity waves



Courtesy of Kyoto University

Internal gravity waves in the lab-1

LOWER FREQUENCY



HIGHER FREQUENCY

Courtesy of Kyoto University

Internal gravity waves in the lab-2

VERY HIGH FREQUENCY – NO PROPAGATION

MOVING WAVE SOURCE (WIND SHEAR)

Courtesy of Kyoto University

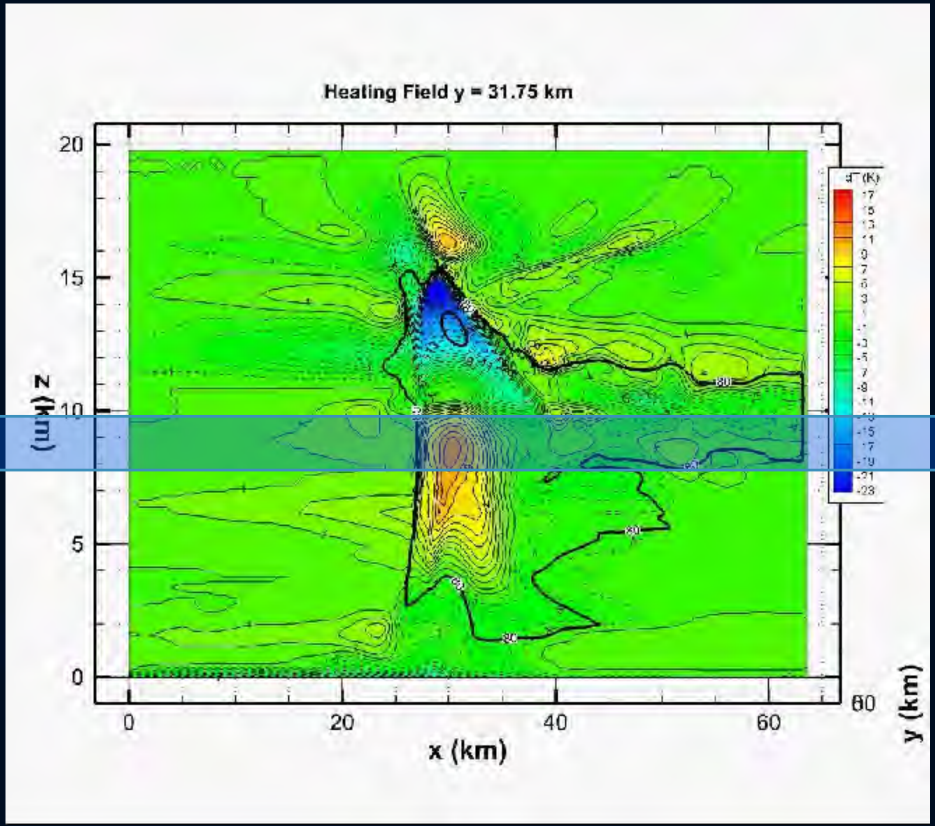
Storm top features

- Atmospheric gravity waves occur in a stable environment. Hence for deep convective storms, the low levels are often quite unstable and it is often impossible to separate IGW from other motions.
- However, the stratification above a severe storm (in the stratosphere) is stable, and therefore the IGW can be more easily observed.
- Many of the storm top features observed by satellites are manifestations of IGW.

Dynamical regimes of deep convective storms

Wave physics dominated

Overshooting top (OT), Cold –U or V, close-in warm area (CWA), distant warm area (DWA), above anvil cirrus plumes, jumping cirrus (JC), ship waves, radial cirrus, gullwing cirrus (GC), etc.

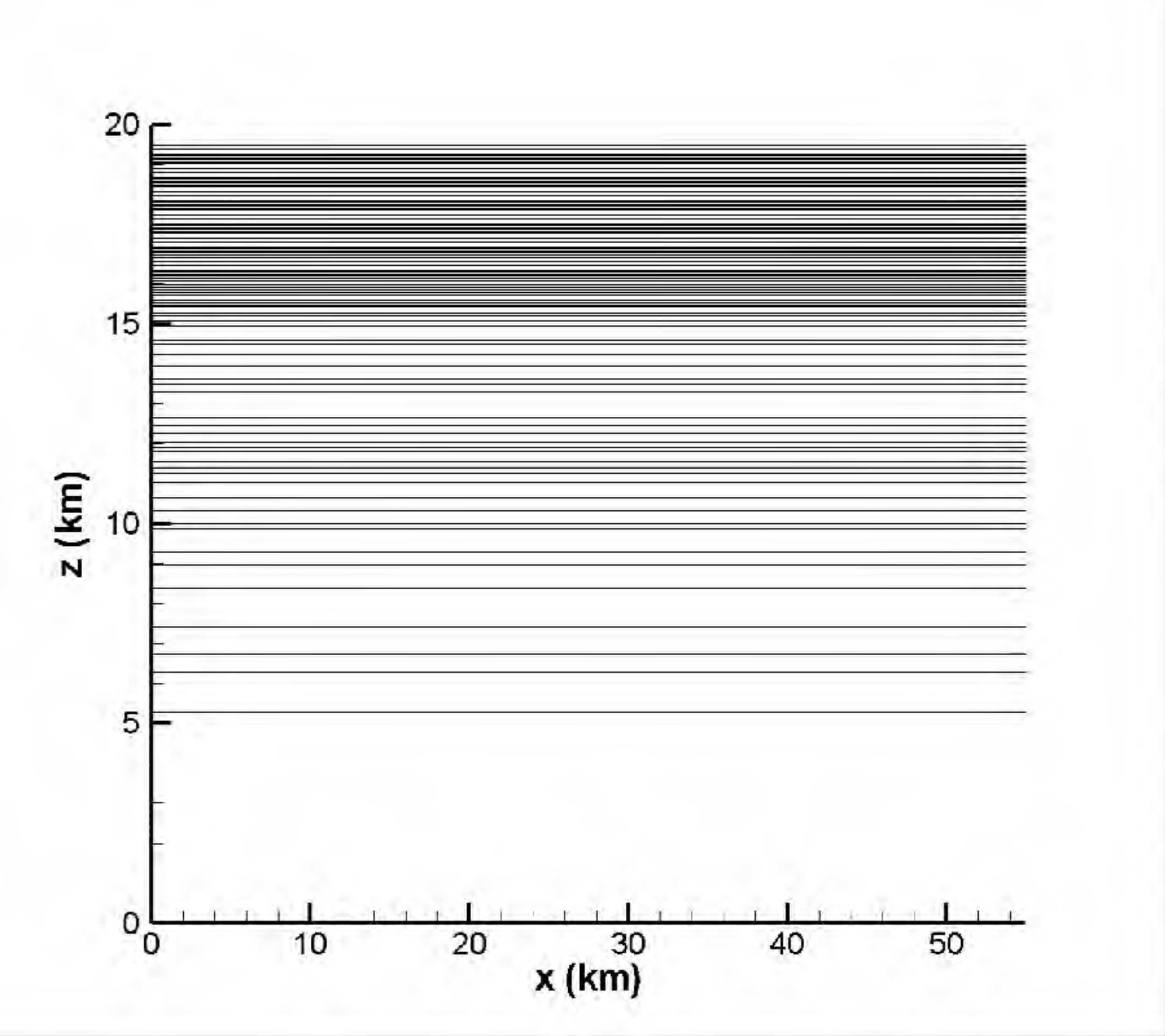


Transition layer ~ 8-10 km

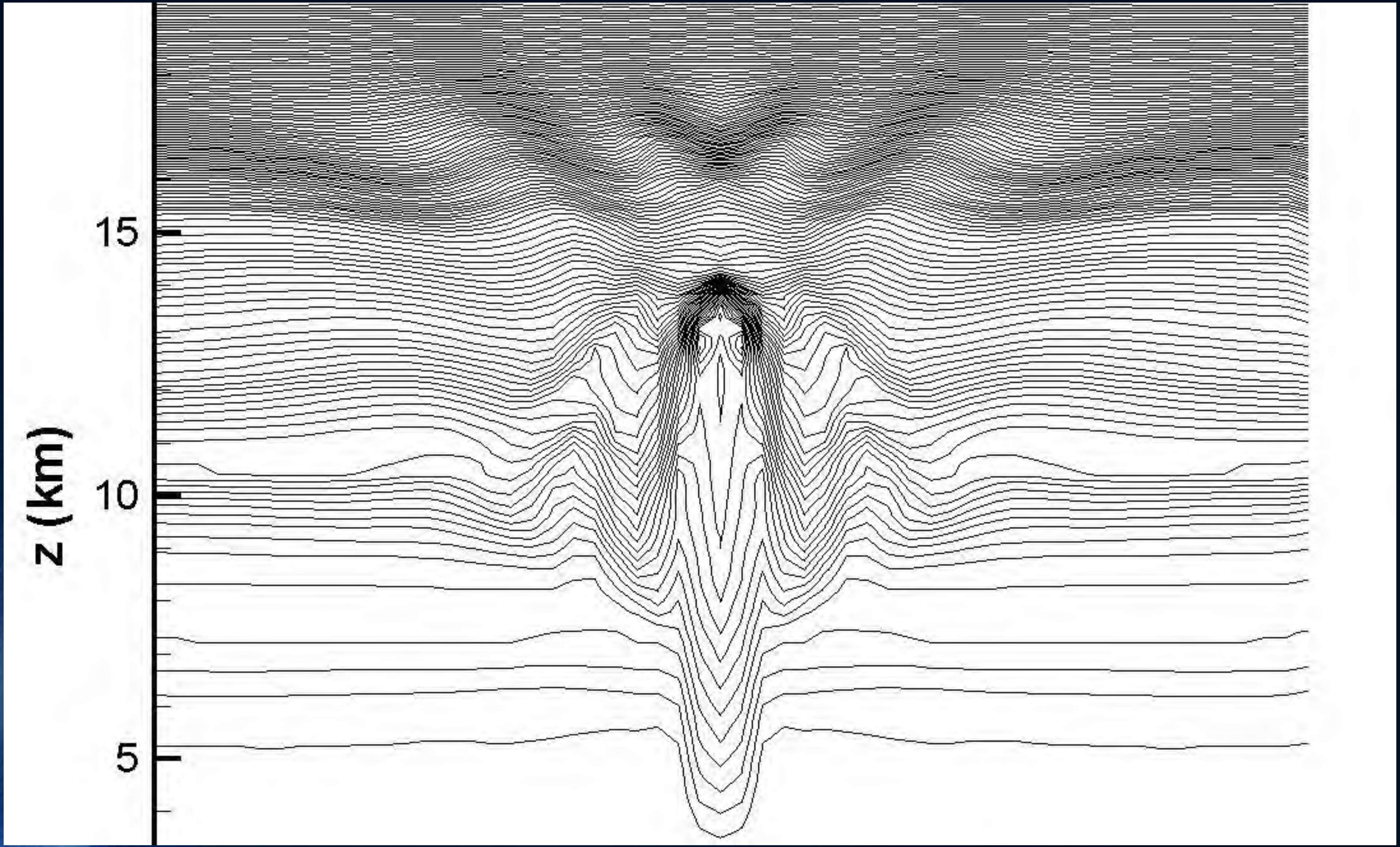
Instability physics dominated

Intense updraft, heavy precipitation, strong wind, large hail, hook echo, gust front, cold pool, thunder and lightning, tornado, etc.

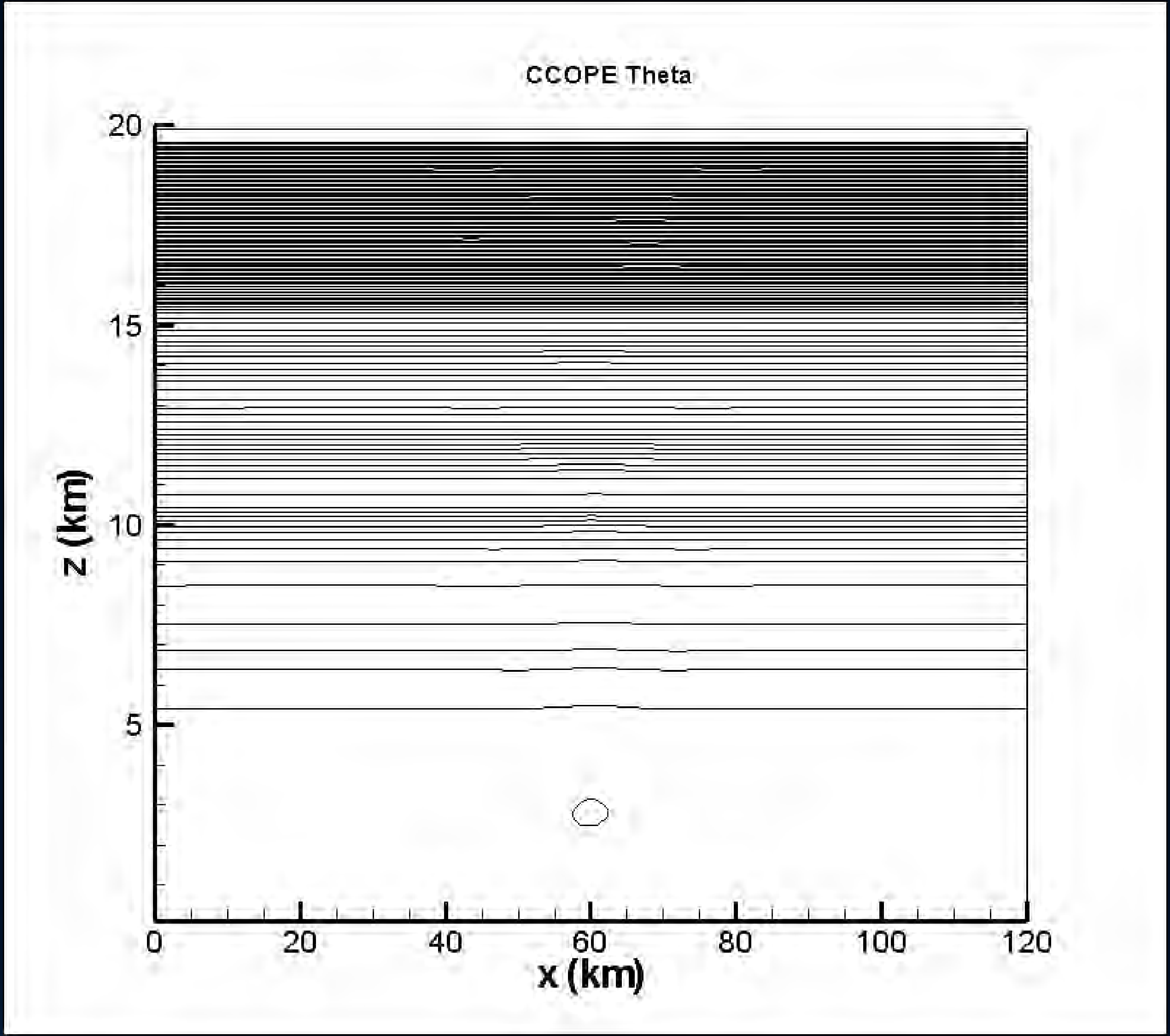
CCOPE without wind shear



CCOPE with no wind shear

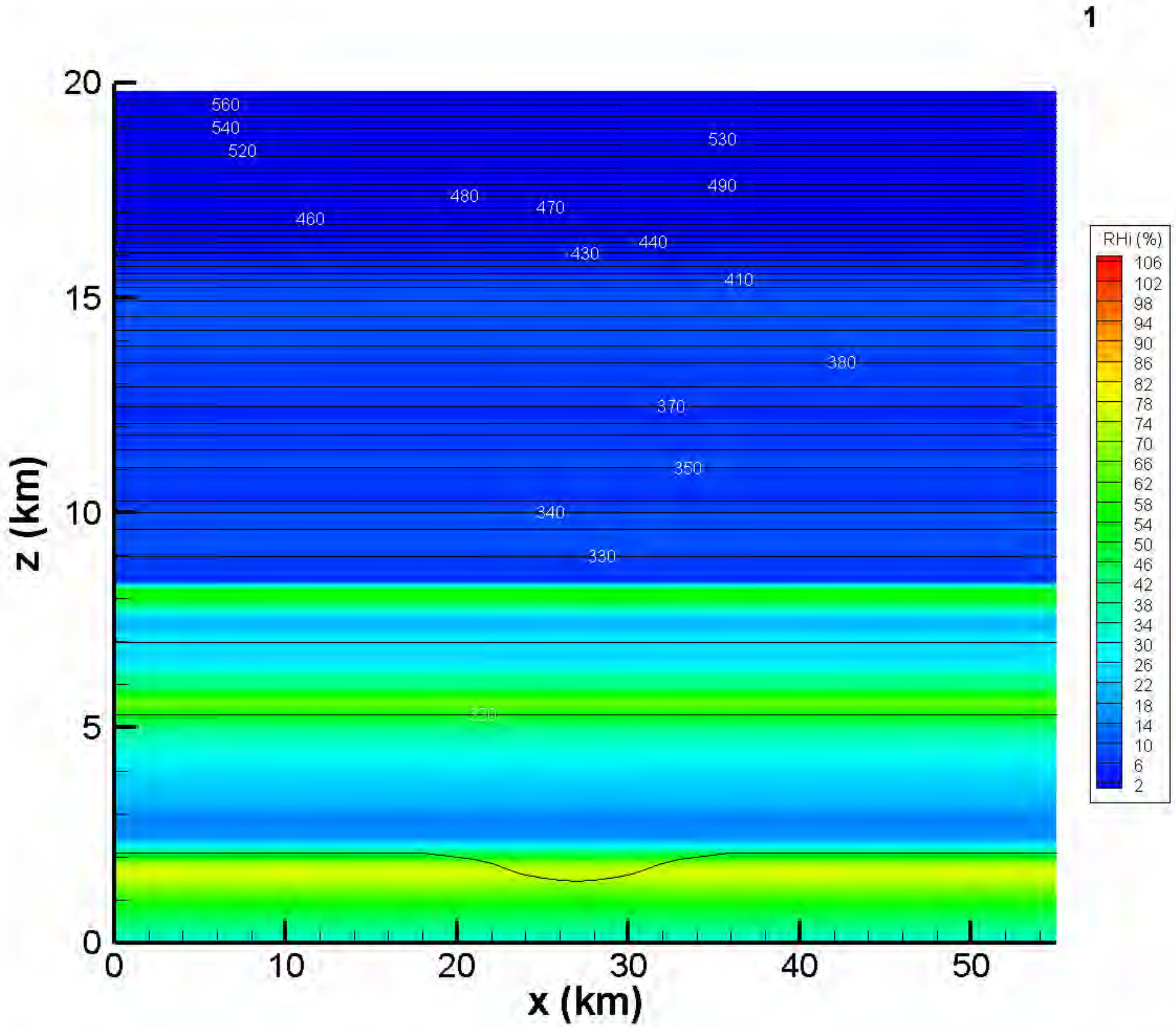


Now add the wind shear

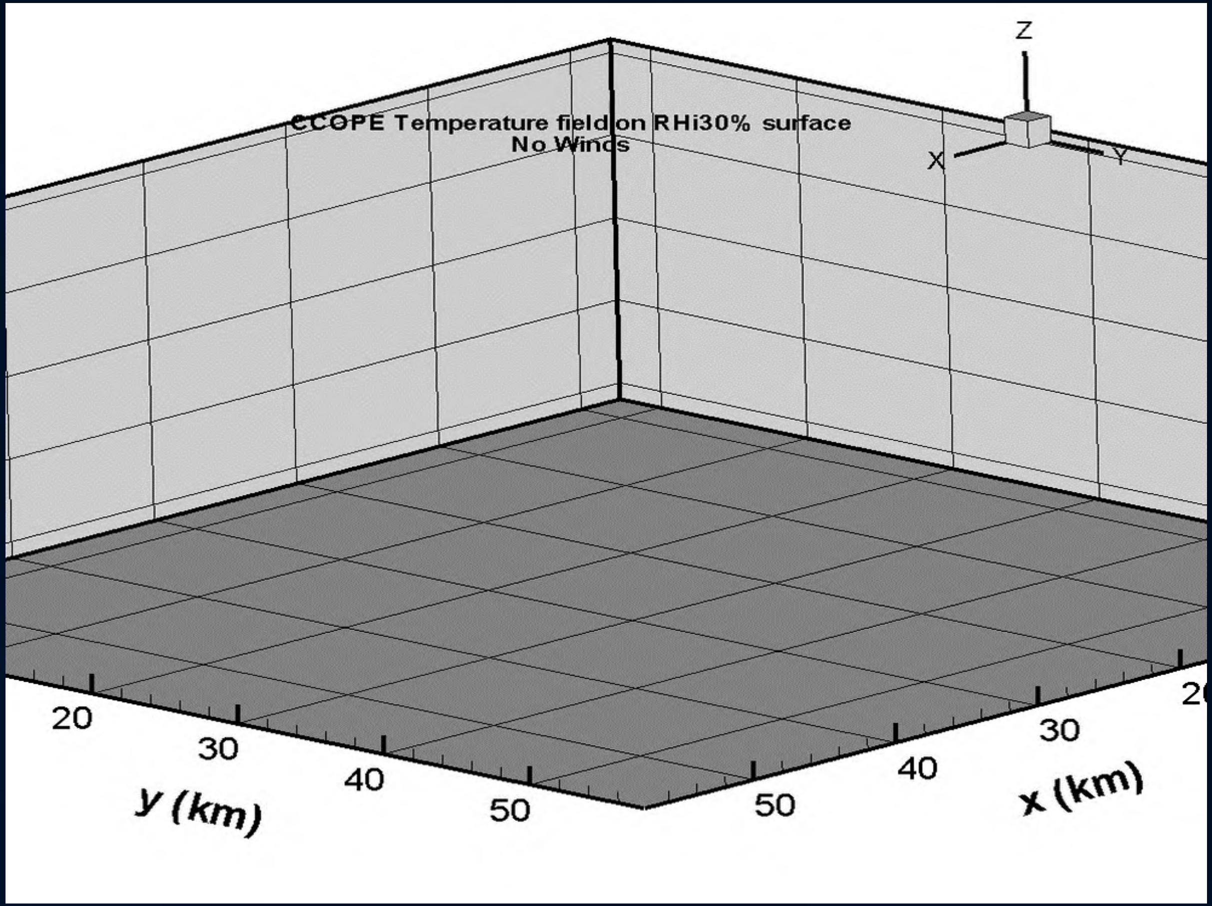


Environmental dynamic processes around a thunderstorm

- Lower troposphere – processes dominated by instability
- Upper troposphere and above – dominated by wave processes
- But the two are connected
- So storm top features are dominated by wave processes–important to satellite observations!
- Can we infer lower tropospheric instability from storm top features? (this is one important mission of satellite storm nowcasting!)


1
z (km)
x (km)
RHi (%)
560
540
520
530
480
490
470
460
440
430
410
380
370
350
340
330
0
5
10
15
20
0
10
20
30
40
50
106
102
98
94
90
86
82
78
74
70
66
62
58
54
50
46
42
38
34
30
26
22
18
14
10
6
2

Pancake cloud

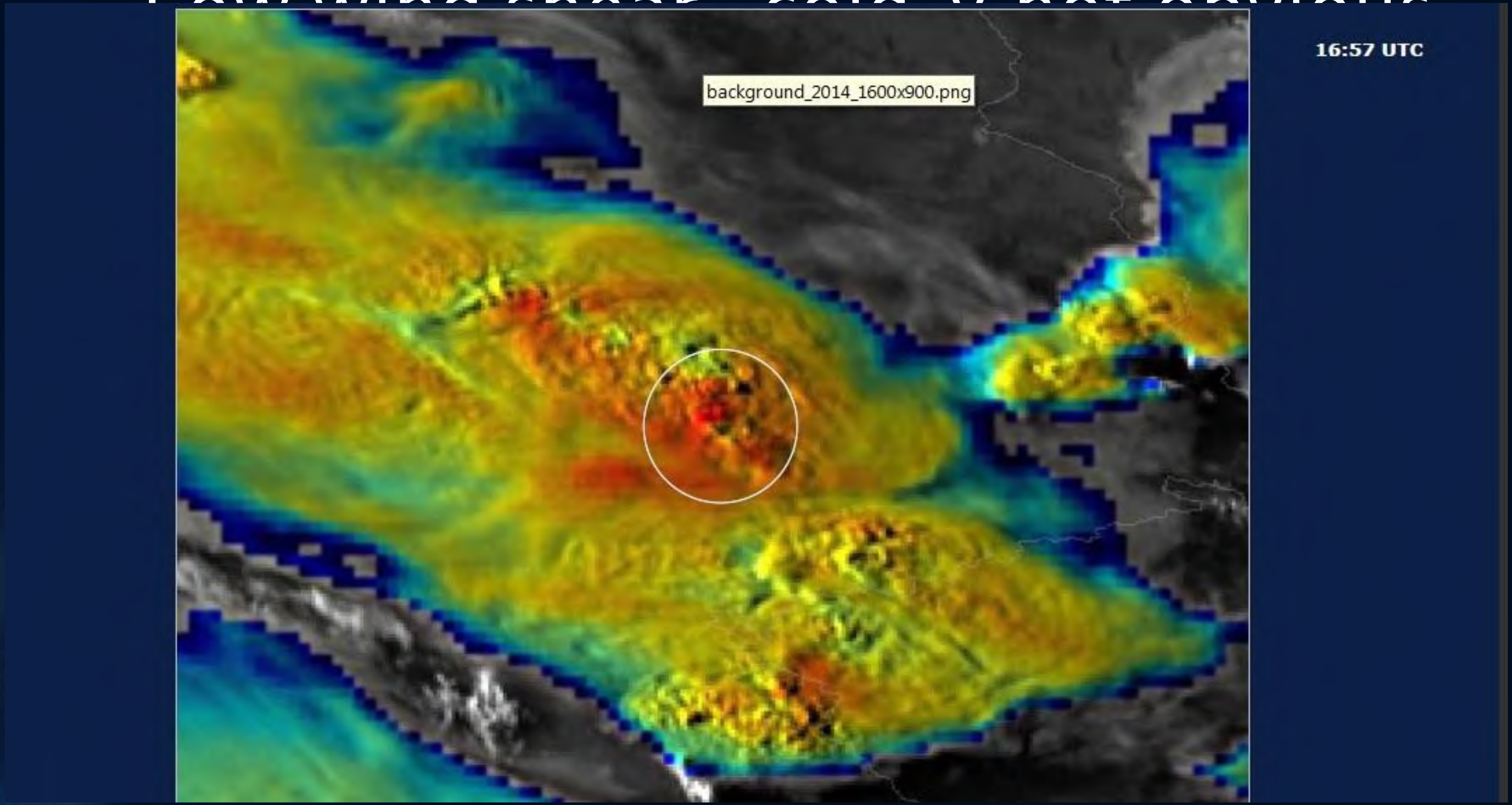


Pancake cloud (courtesy of Po-Hsiung Lin)

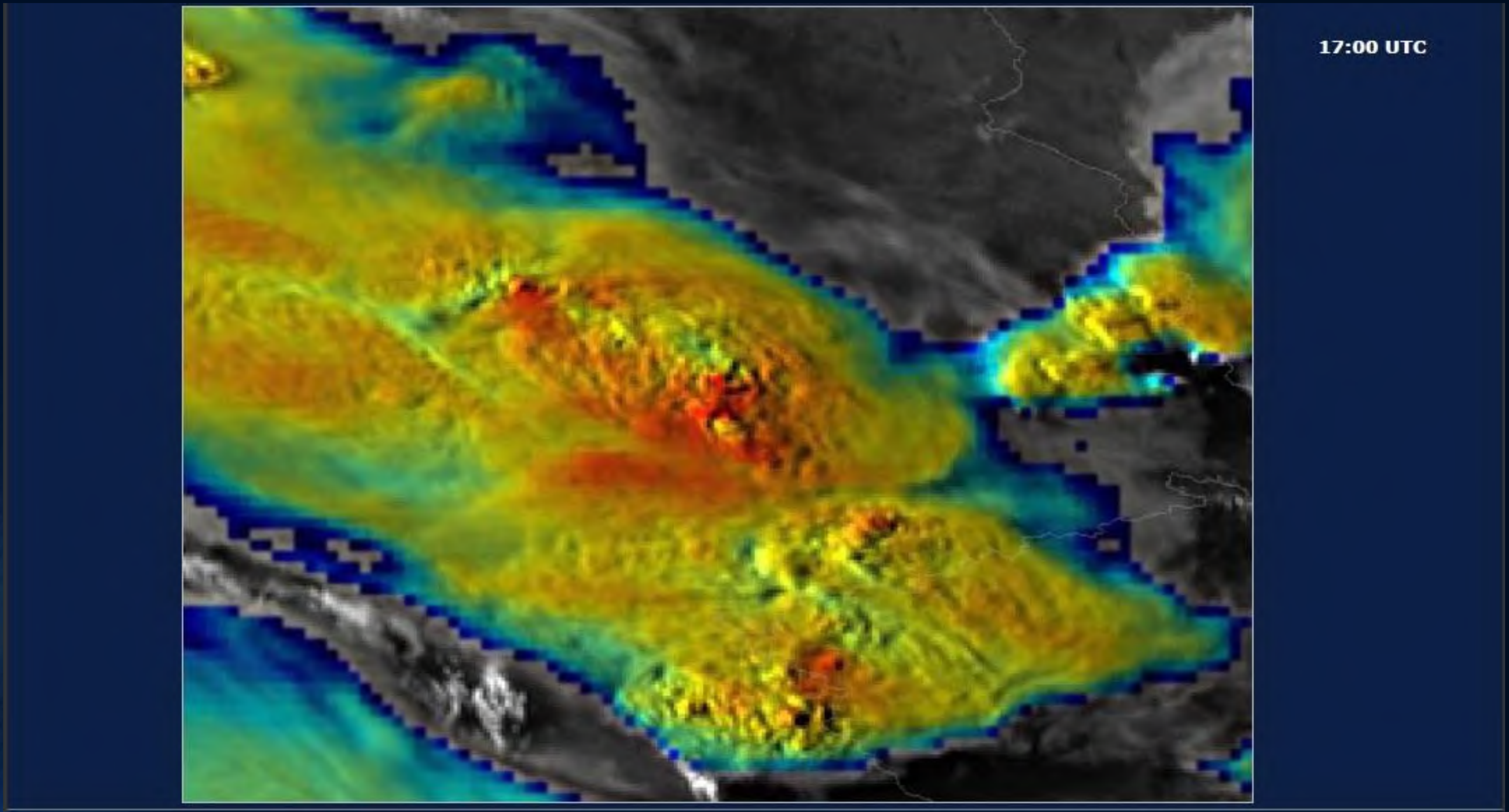
Storm cloud over Laos – pancake cloud?

From: http://montanaron.com/wordpress/tag/weather

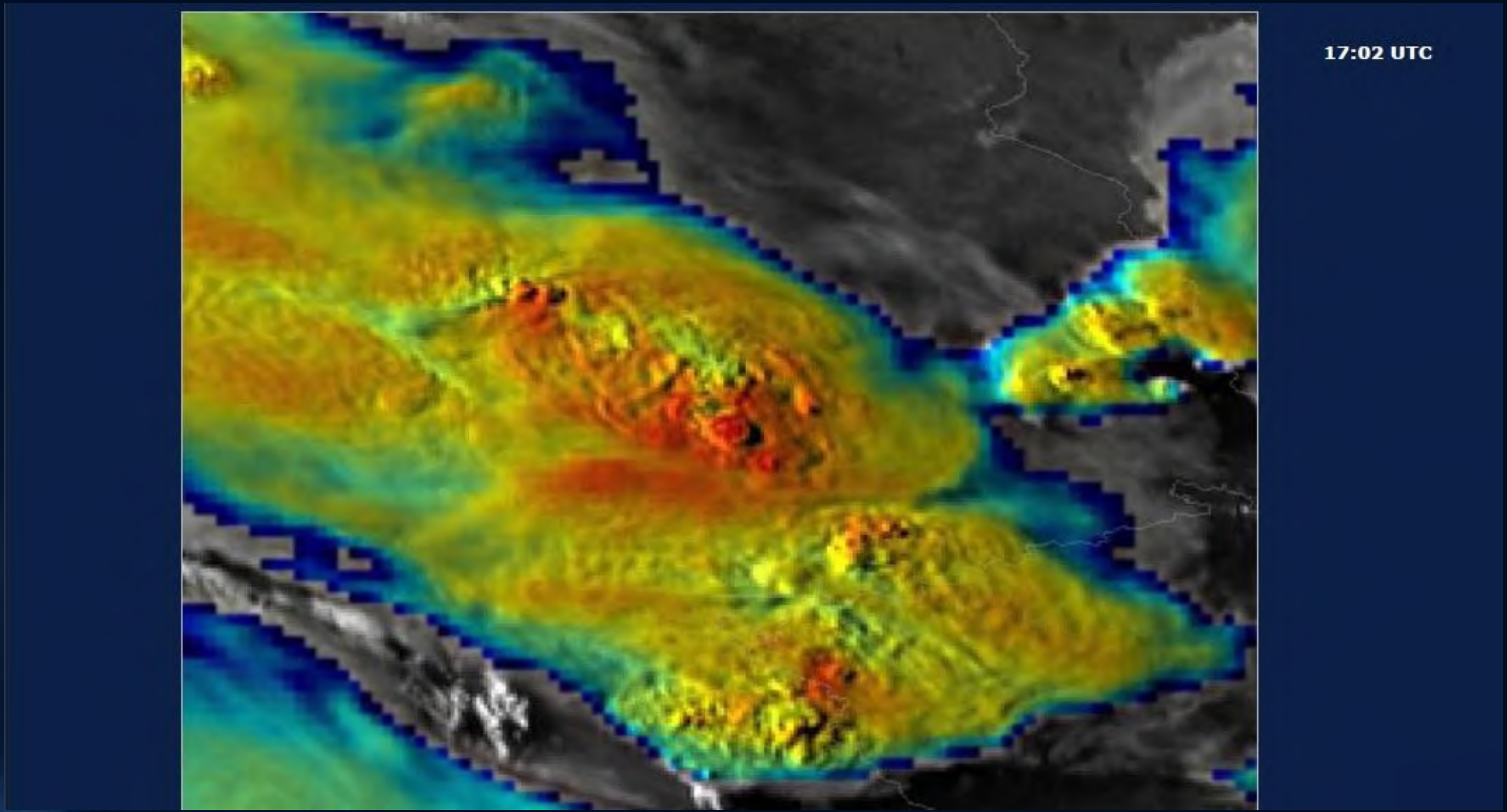
Low wind shear - cold V not obvious



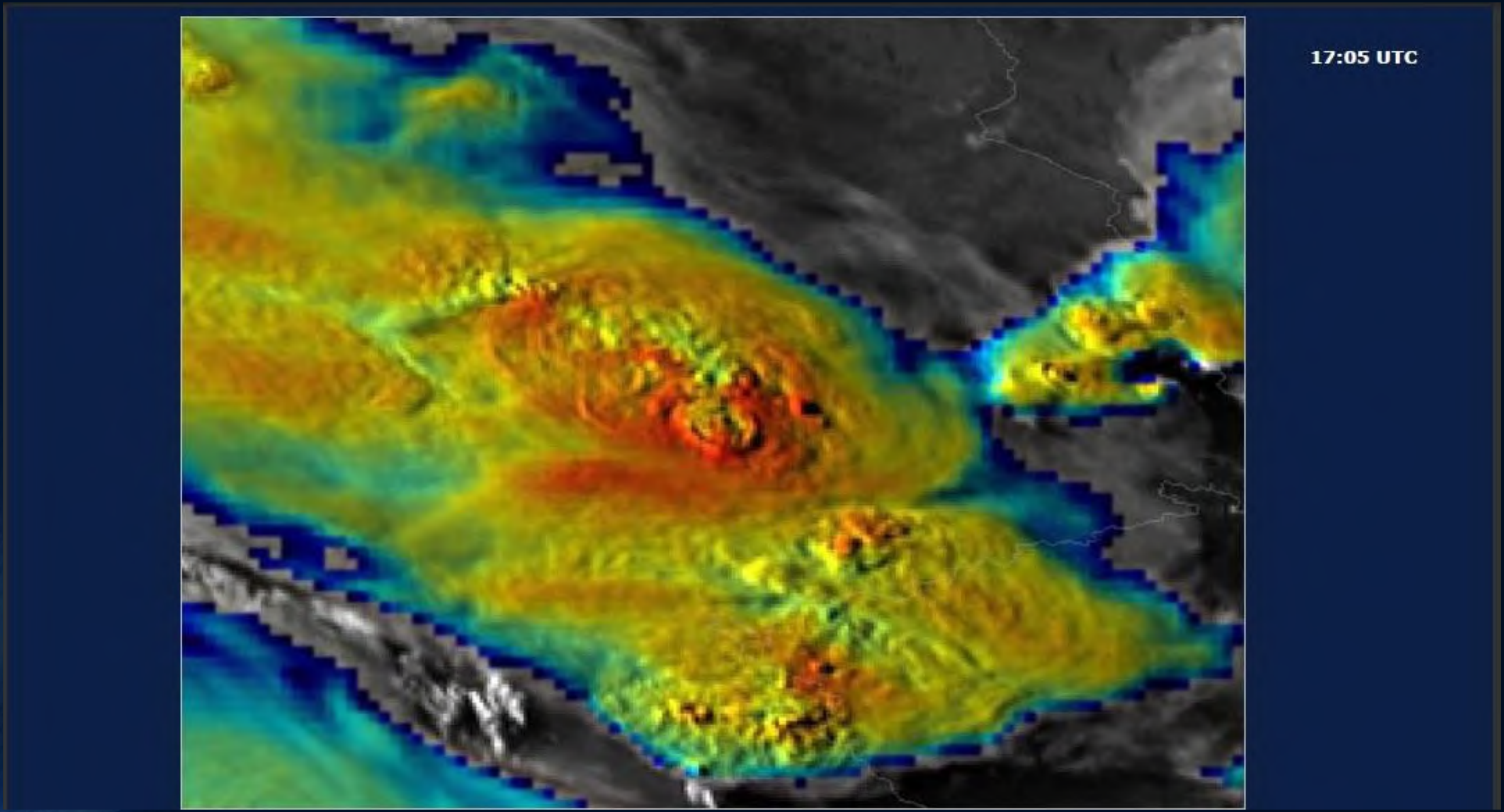
Courtesy of Martin Setvak



Courtesy of Martin Setvak

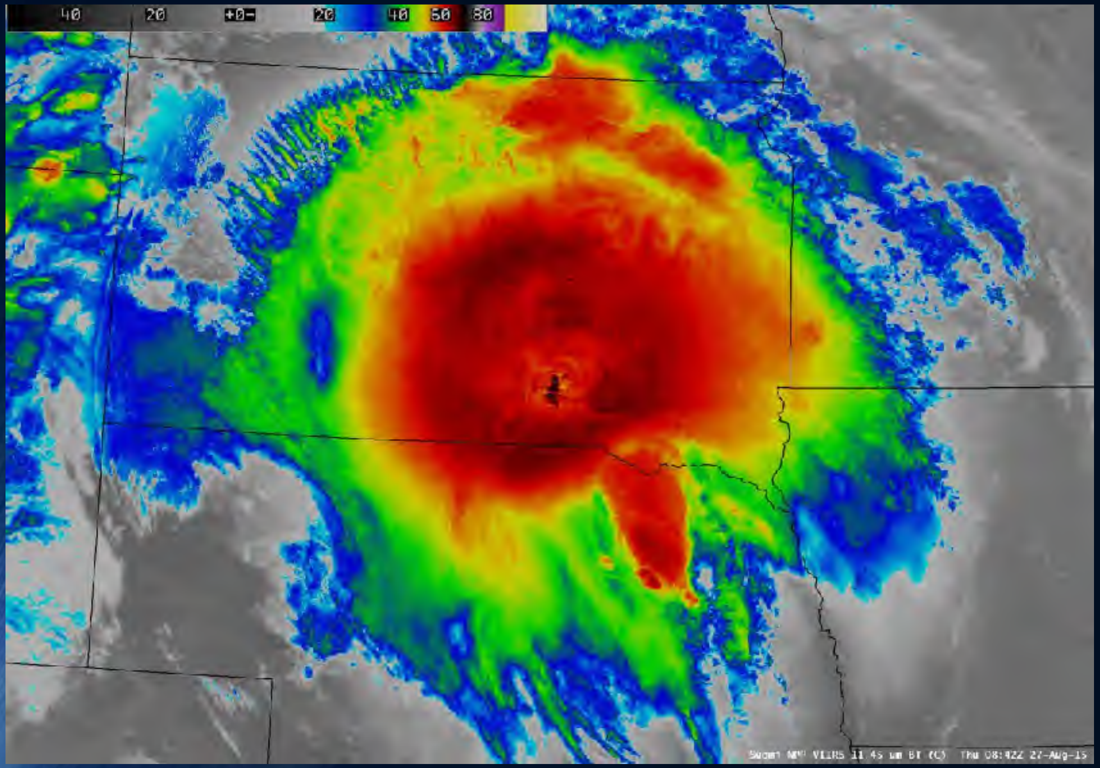


Courtesy of Martin Setvak

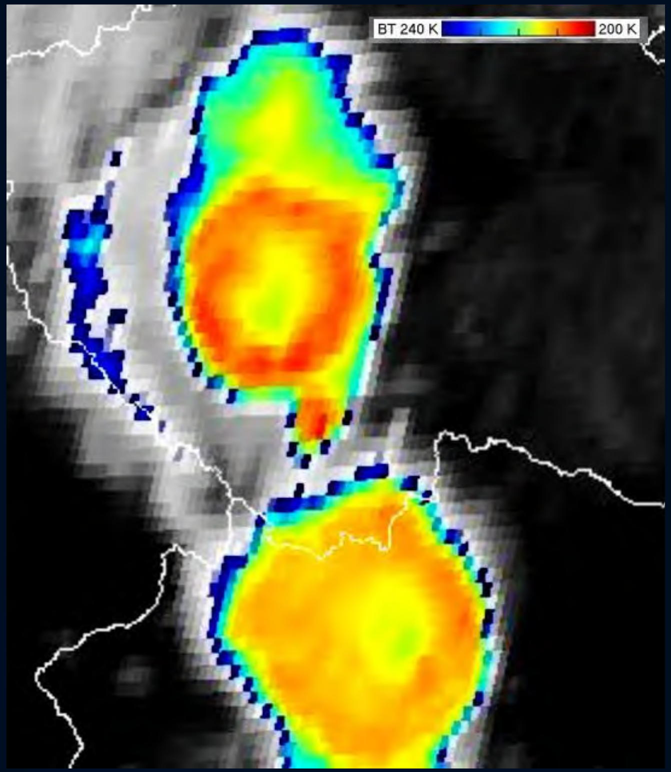


Courtesy of Martin Setvak

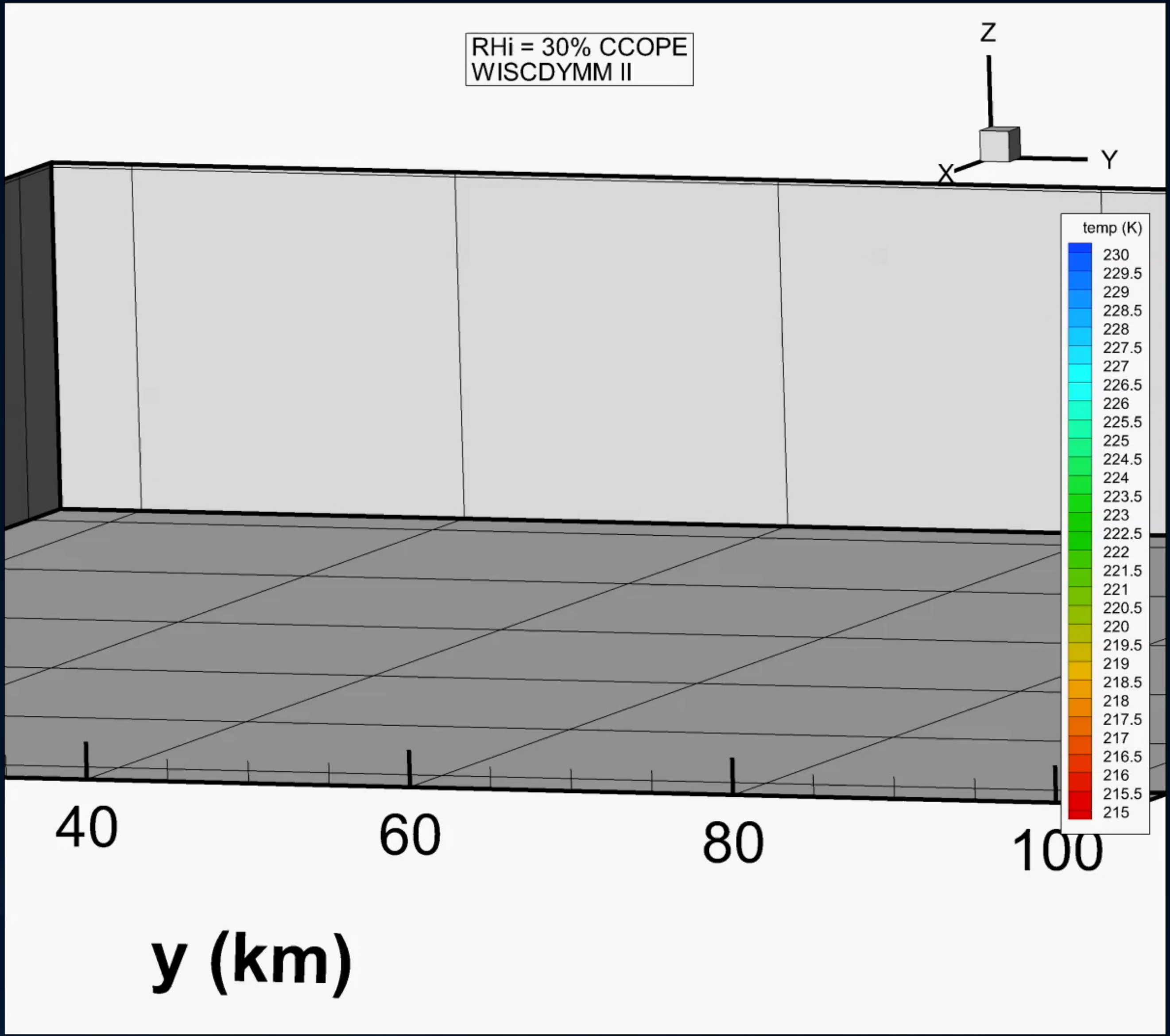
Cold Ring



Courtesy of Scott Bachmeier/CIMSS/SSEC/UW-Madison



Courtesy of Martin Setvak

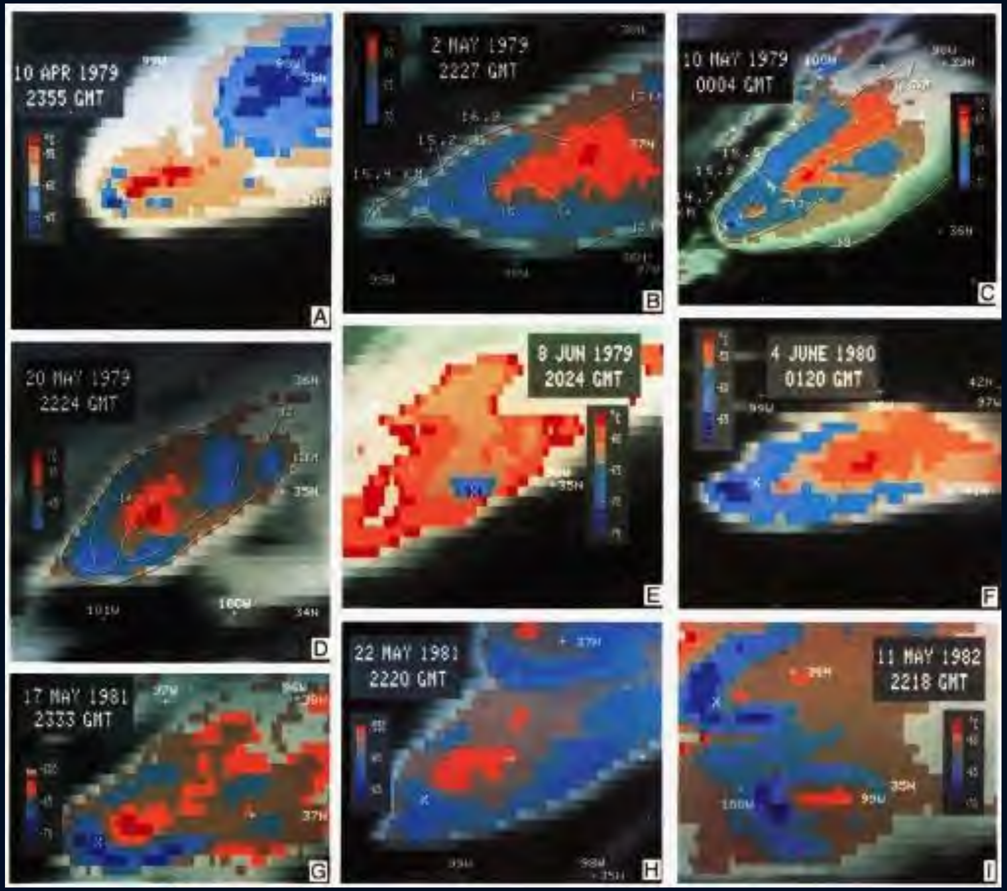

RHi = 30% CCOPE
WISCDYMM II
Z
X
Y
temp (K)
230
229.5
229
228.5
228
227.5
227
226.5
226
225.5
225
224.5
224
223.5
223
222.5
222
221.5
221
220.5
220
219.5
219
218.5
218
217.5
217
216.5
216
215.5
215
40
60
80
100
y (km)

When wind shear is present

- Interaction between ambient wind and updraft
- Updraft behaves like an obstacle—moving mountain-- to the ambient wind, causing
  - Cold-U (V) upstream of OT
  - Mountain wave → close in warm area (CWA)
  - Above anvil cirrus plumes, jumping cirrus and gullwing cirrus due to gravity wave breaking
  - Storm top ship waves

Enhanced-V (or U)
Cold-V (or U)

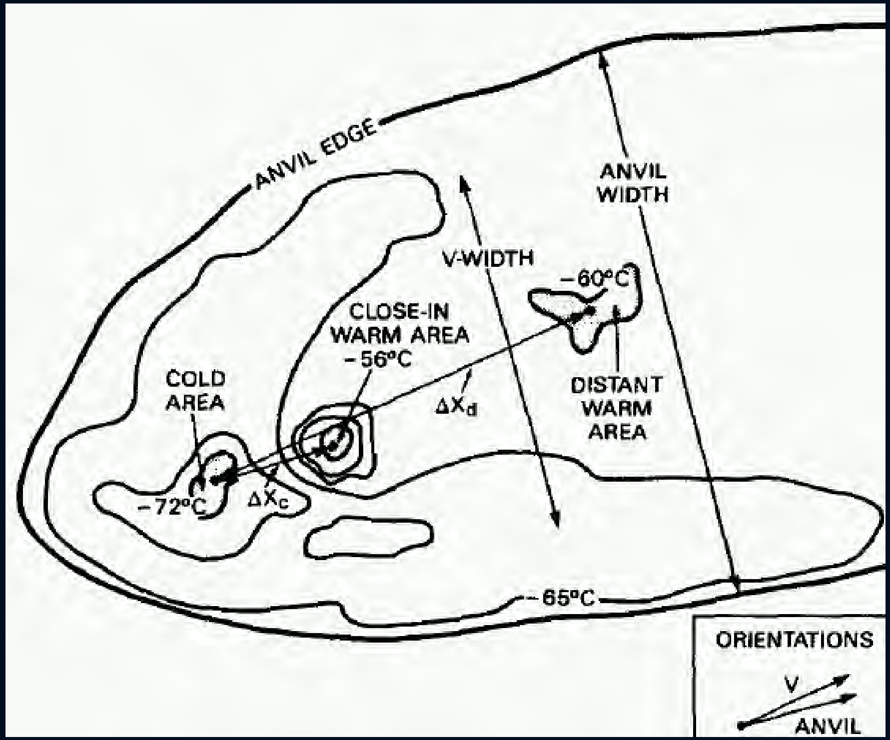
Observed Cloud Top Features
GOES-IR Images



Nine cases analyzed by Heymsfield and Blackmer (1988)

Observed GOES IR features

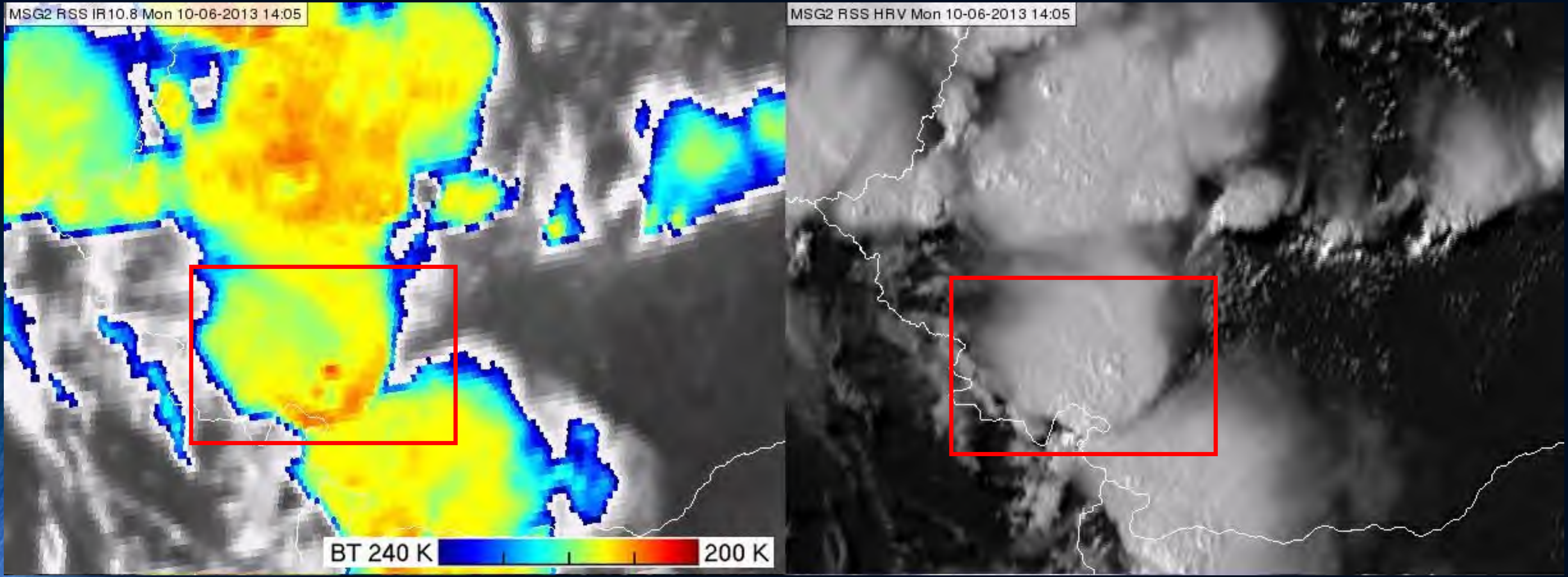
- Enhanced-V
- Cold Area (CA)
- Close-in Warm Area (CWA)
- Warm-cold couplet
- Distant Warm Area (DWA)



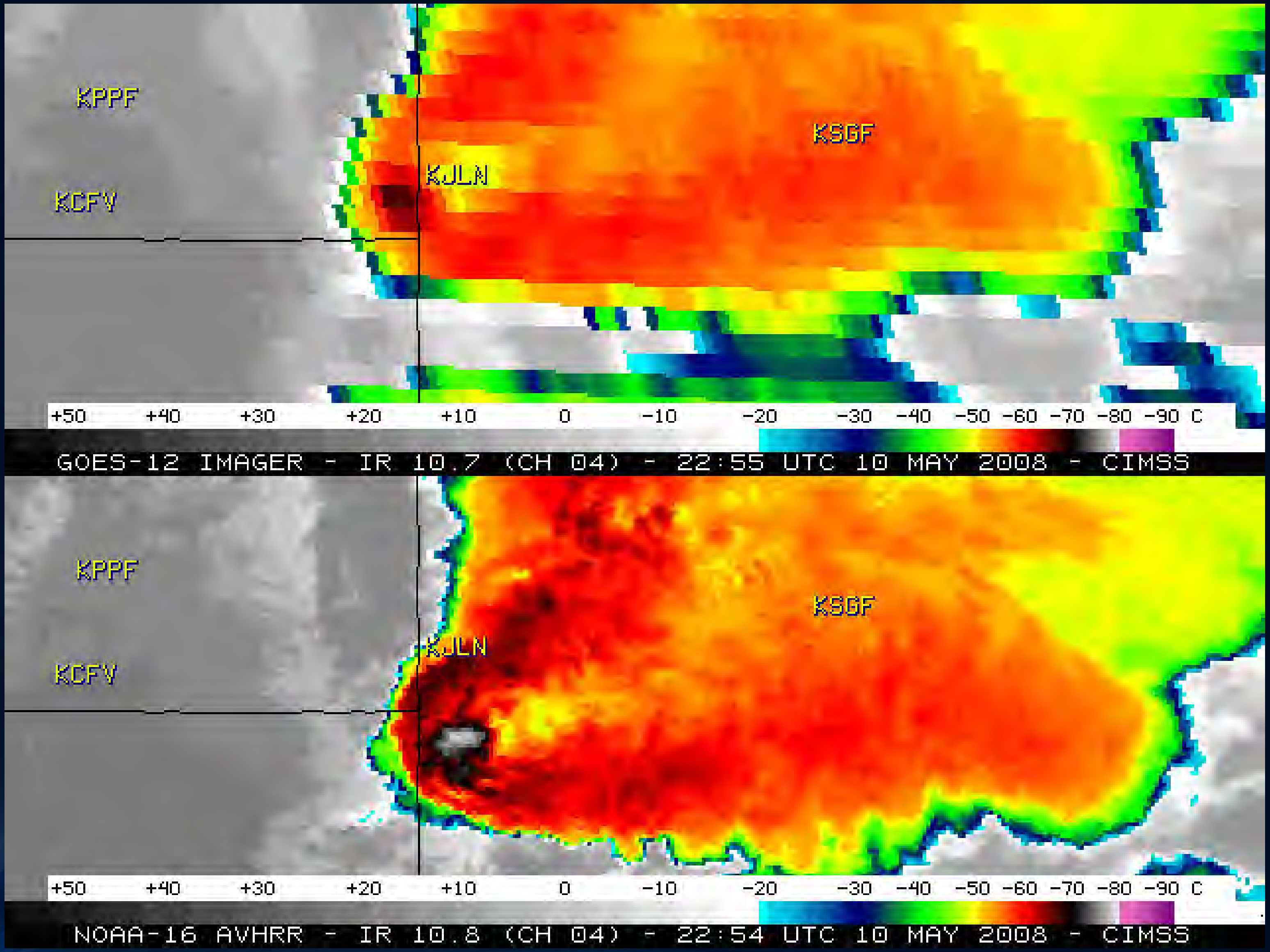
McCann (1983): Storms with enhanced-V have about 70% probability of producing severe weather. Median lead time from the onset of the V to the first severe weather is about 30 minutes.

Adler et al. (1985): 75% of storms with the-V feature have severe weather, but 45% of severe storms don't have this feature

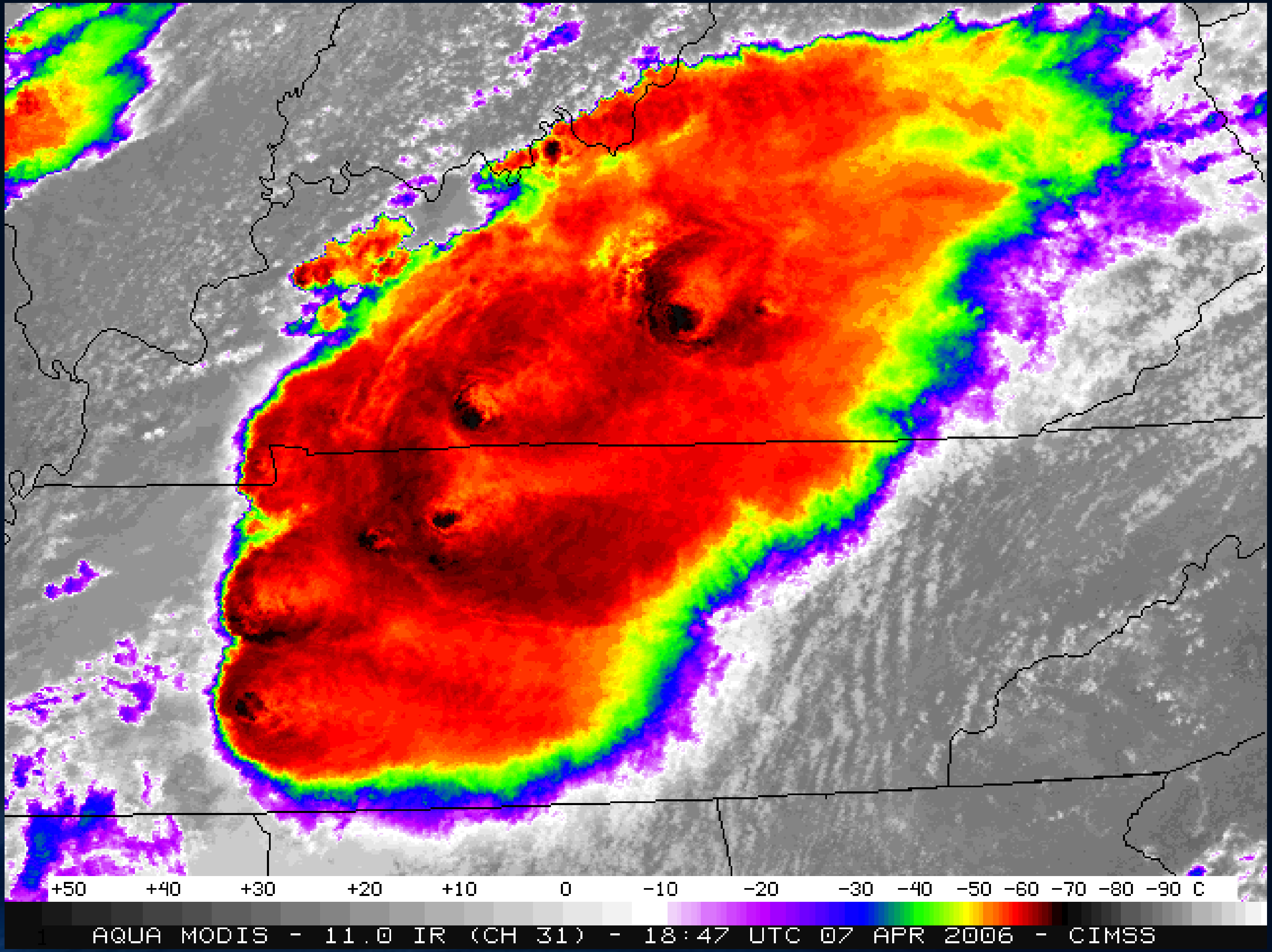
Enhanced-V (cold-V)



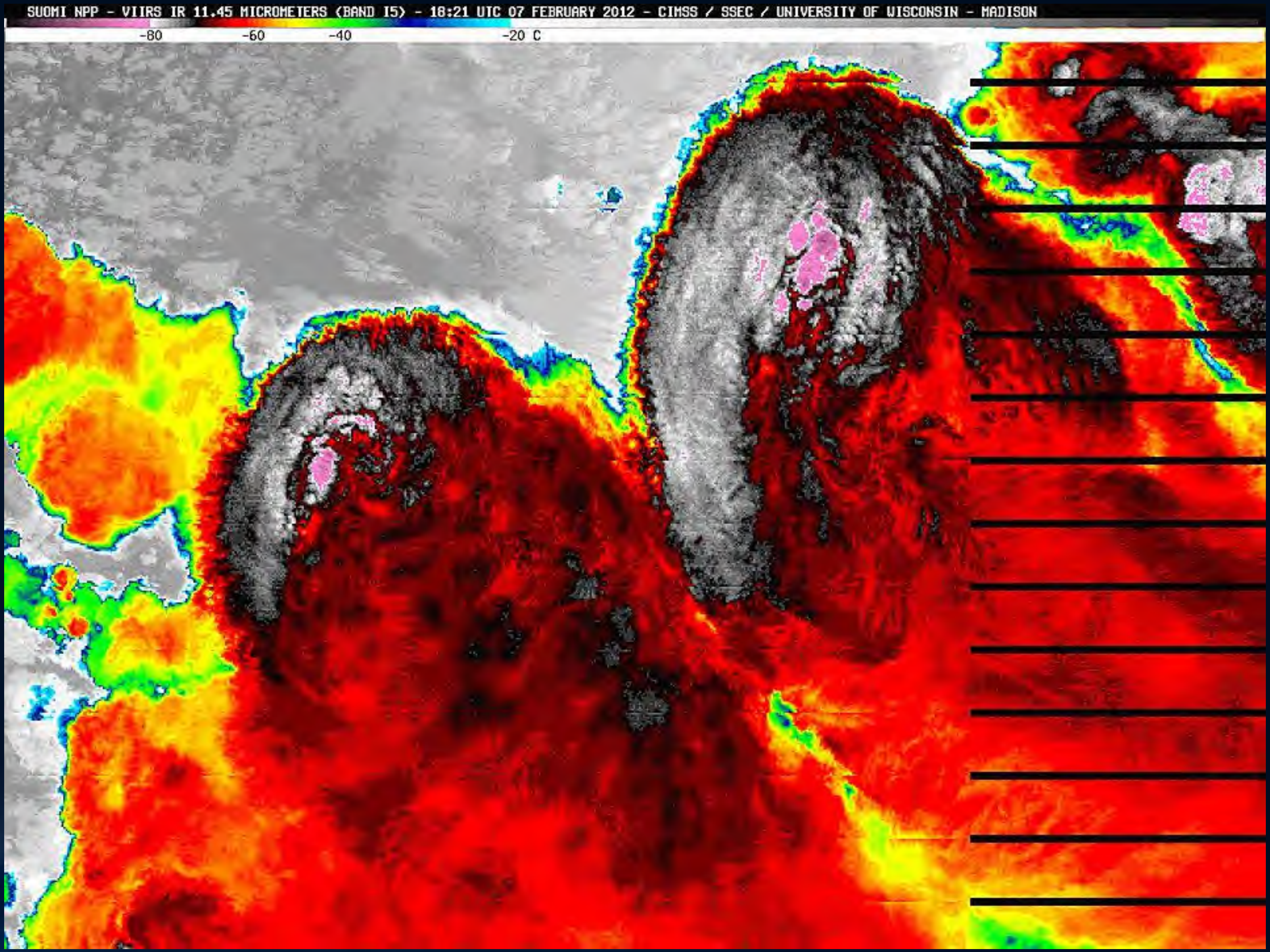
Infrared images (GOES & AVHRR)



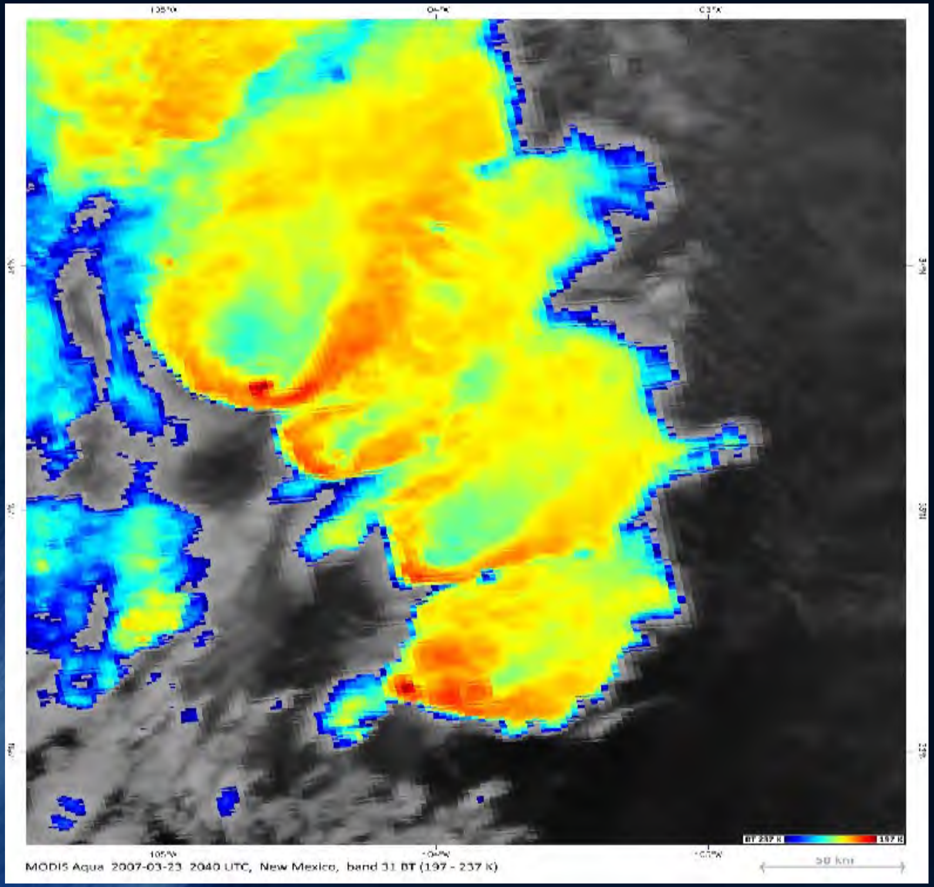
Aqua MODIS

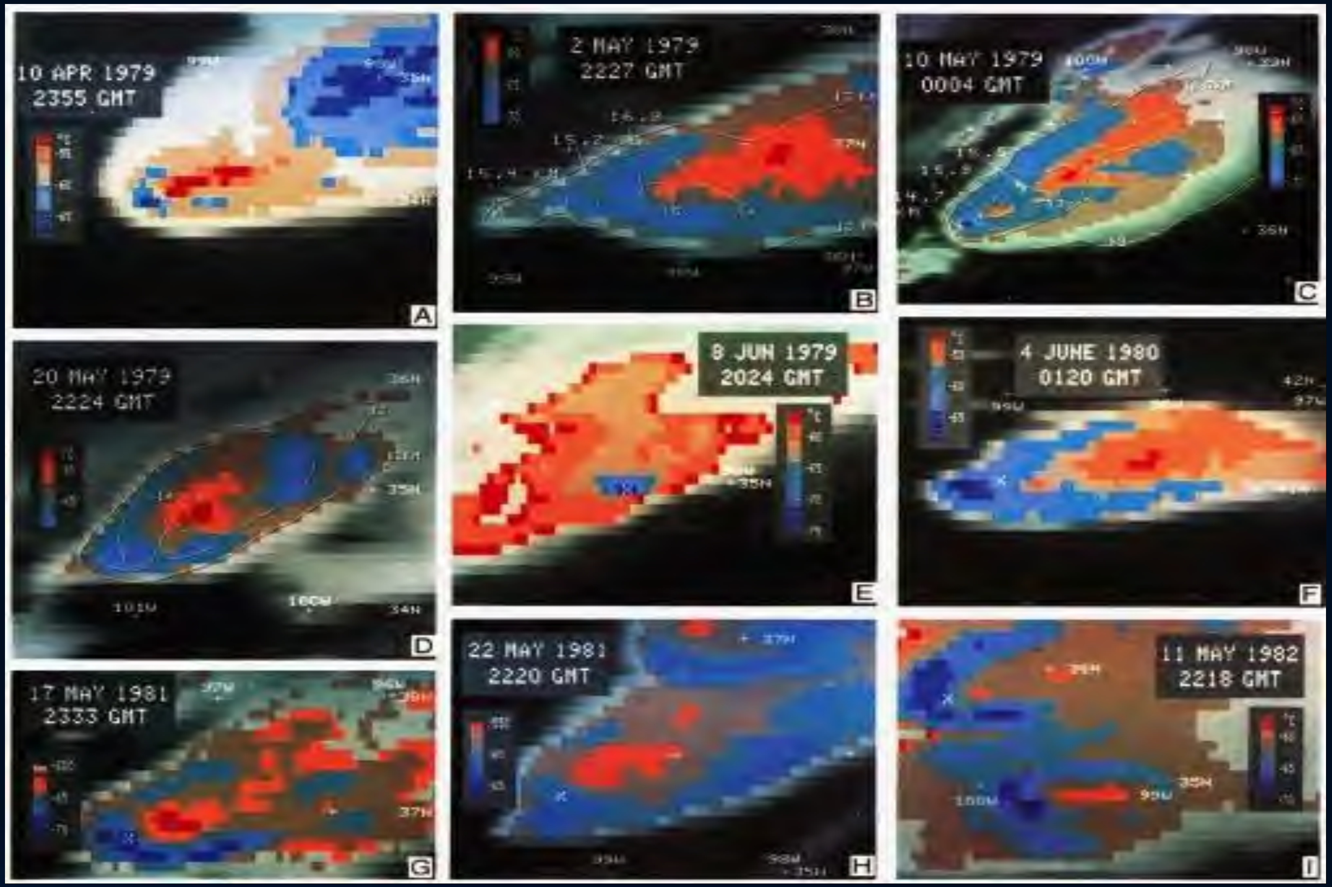

+50 +40 +30 +20 +10 0 -10 -20 -30 -40 -50 -60 -70 -80 -90 C
AQUA MODIS - 11.0 IR (CH 31) - 18:47 UTC 07 APR 2006 - CIMSS

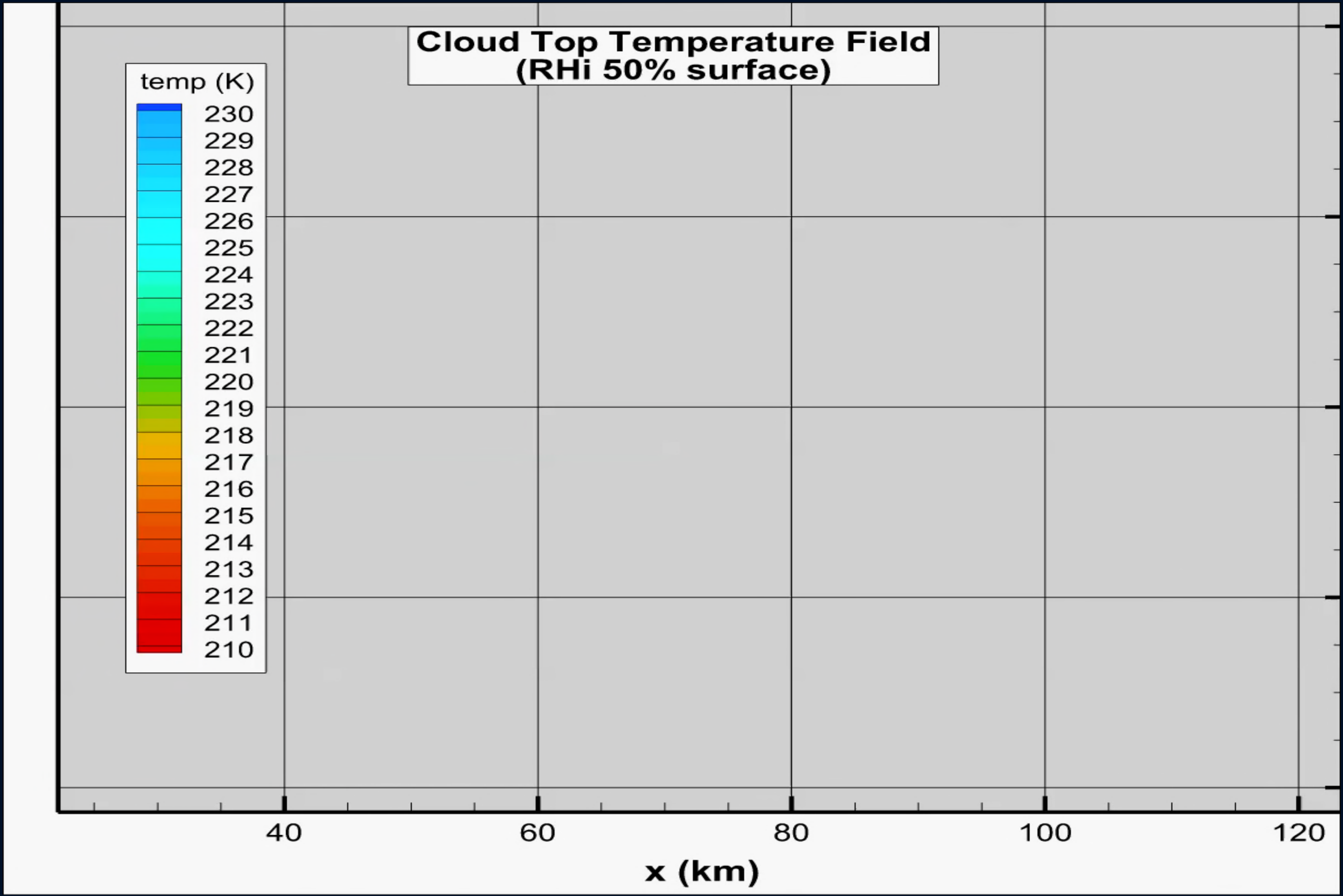
Suomi NPP - VIIRS



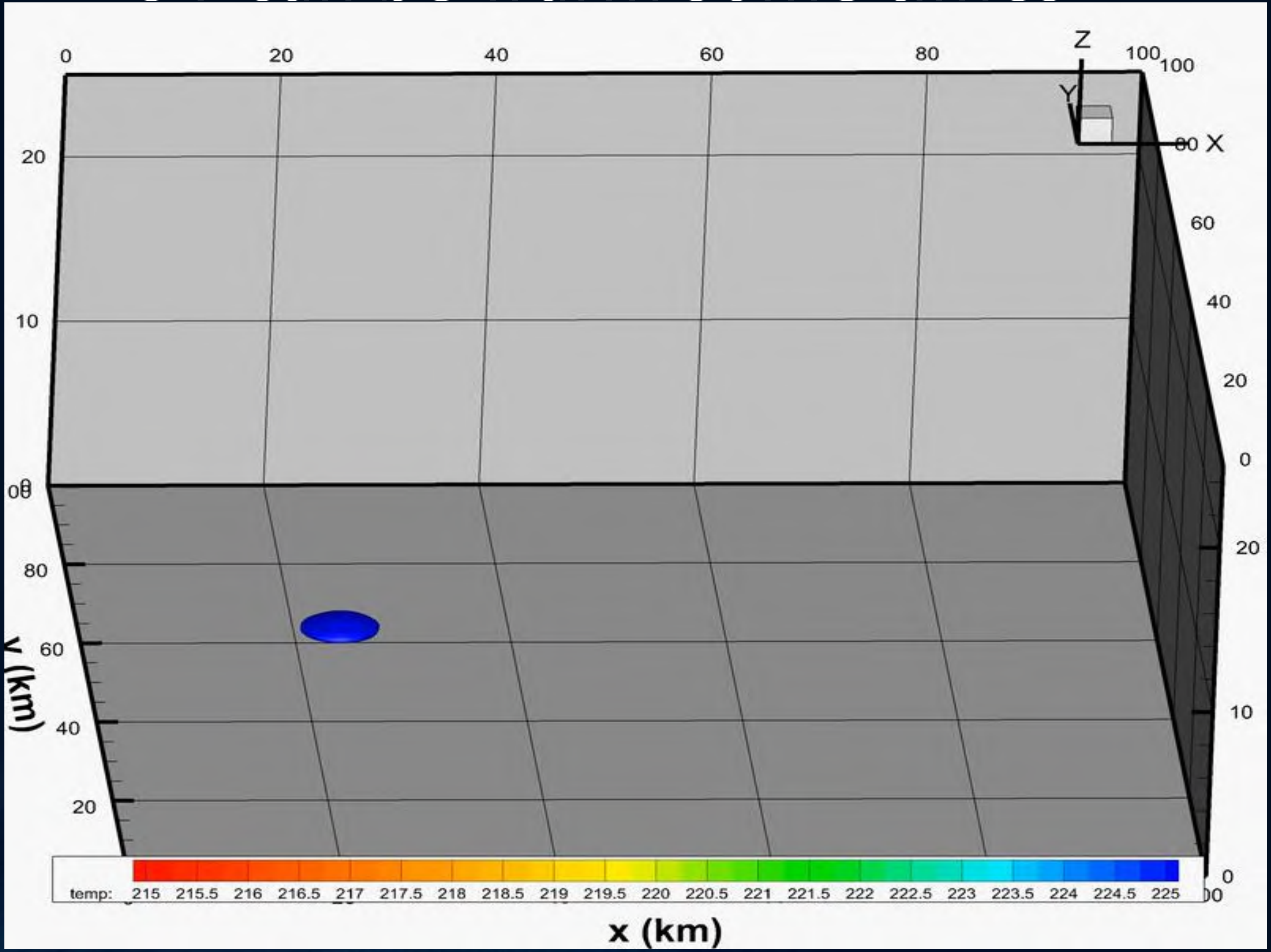
Cold-U or V, CWA, DWA






Cloud Top Temperature Field
(RHi 50% surface)
temp (K)
230
229
228
227
226
225
224
223
222
221
220
219
218
217
216
215
214
213
212
211
210
40
60
80
100
120
x (km)

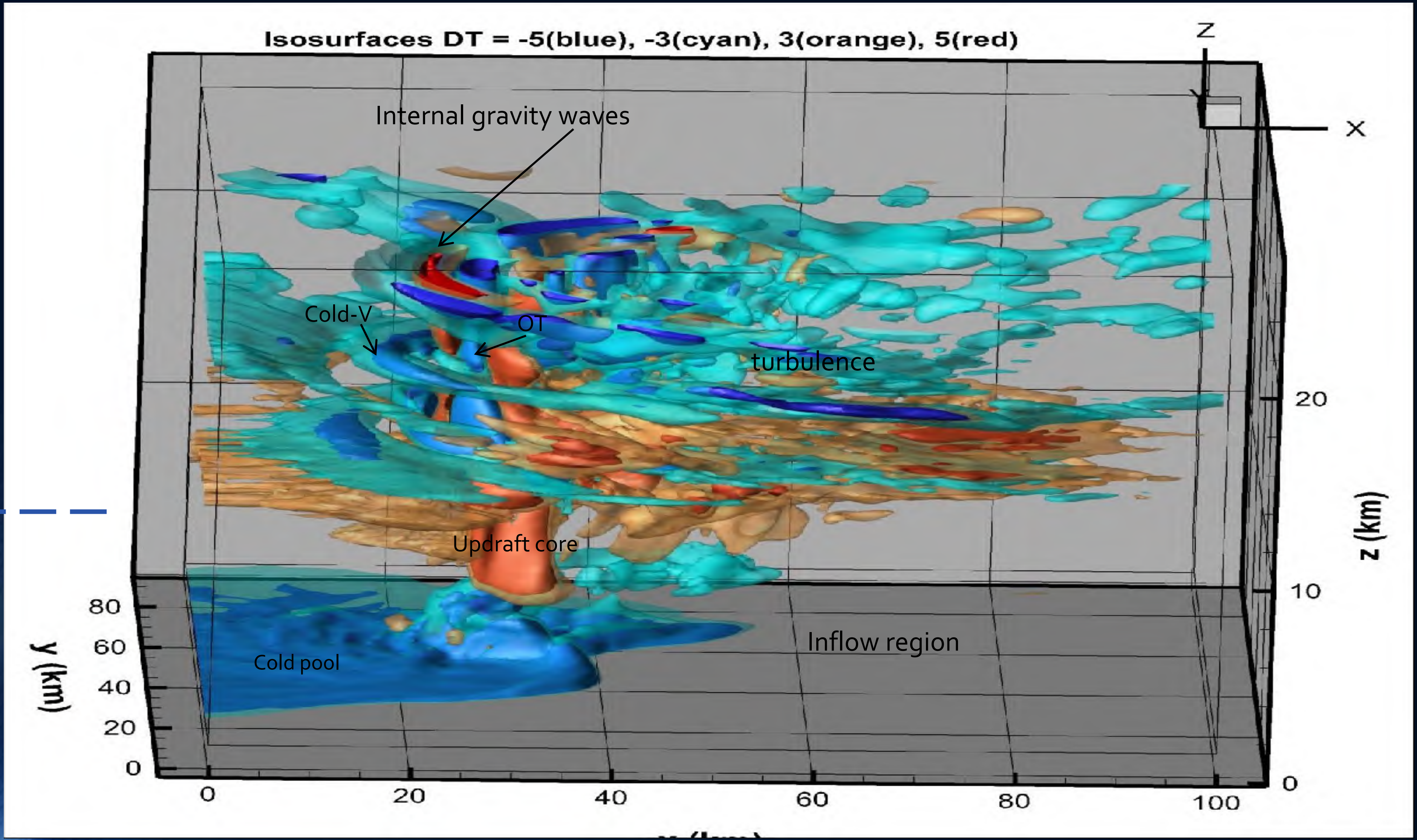
OT can be warm some times



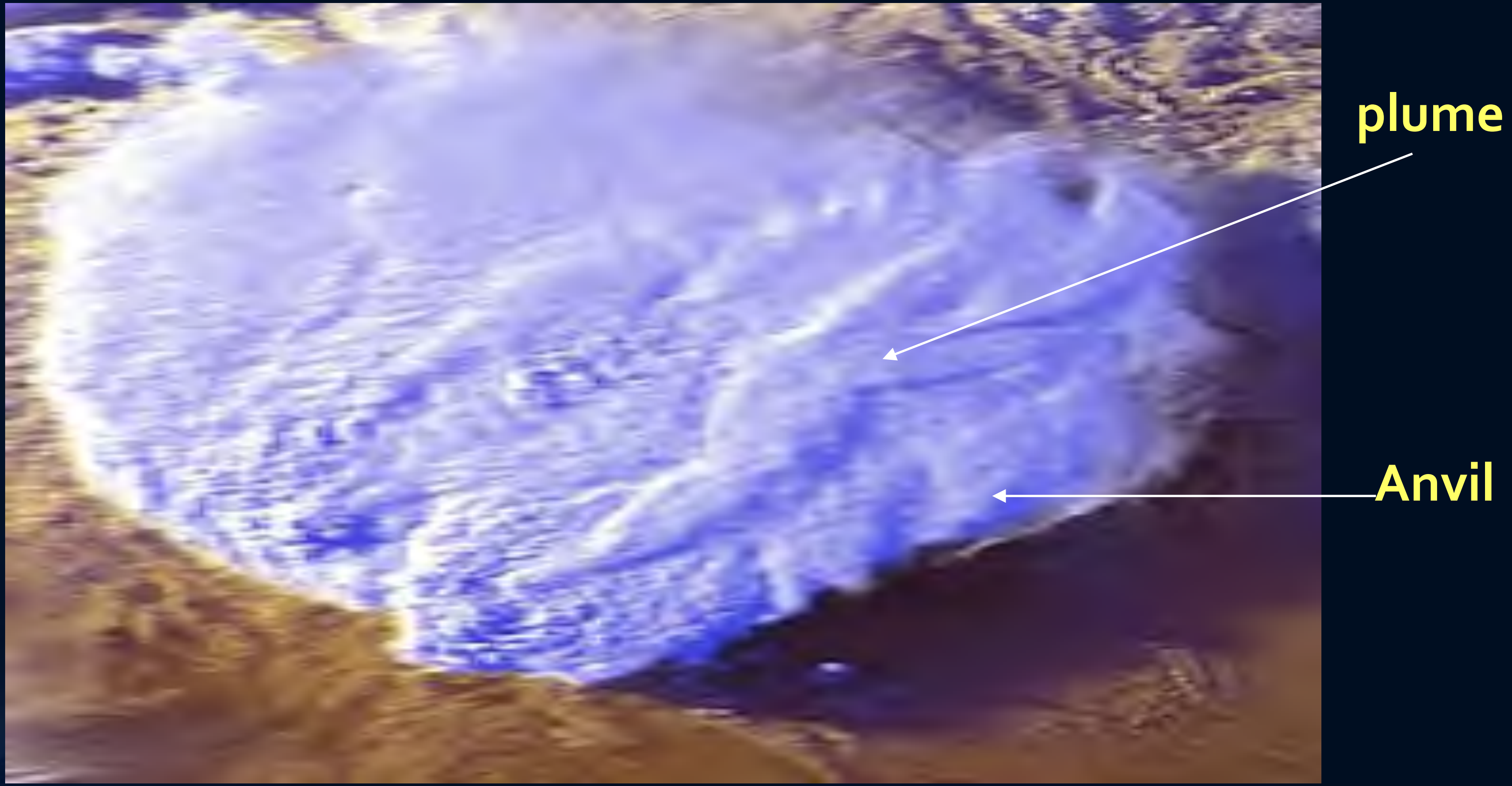
Heating field in CCOPE supercell

Wave-dominated

Instability-dominated



Above anvil cirrus plumes



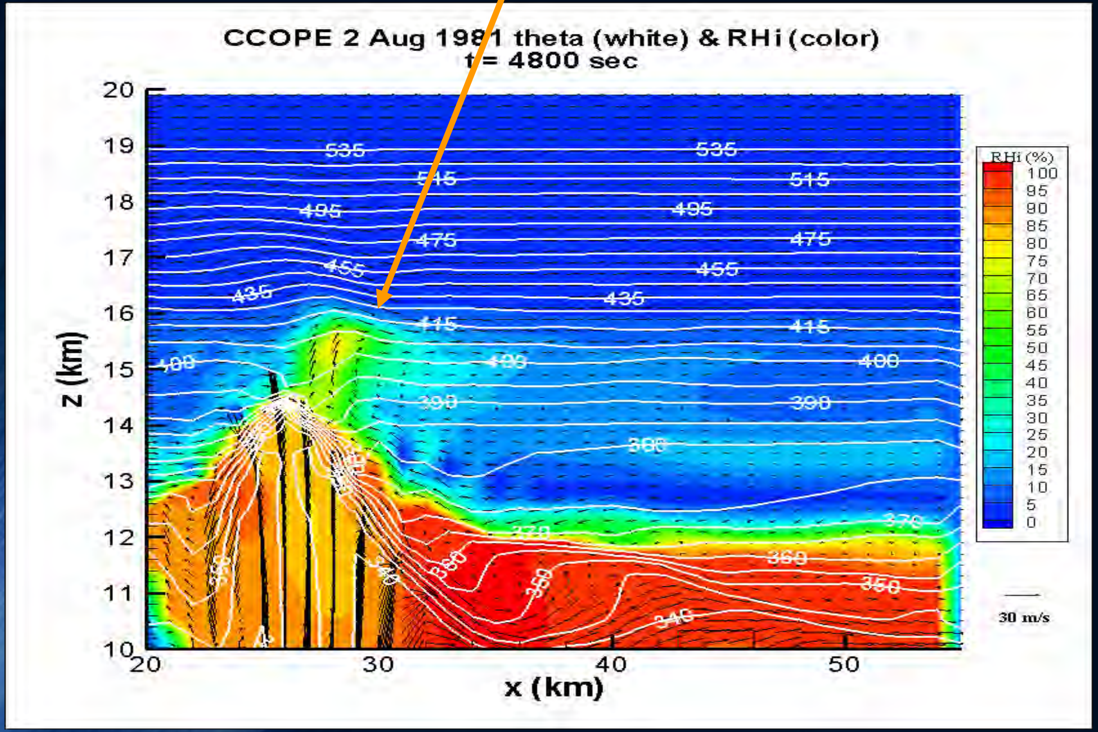
Storms over Balearic Islands (Martin Setvak)

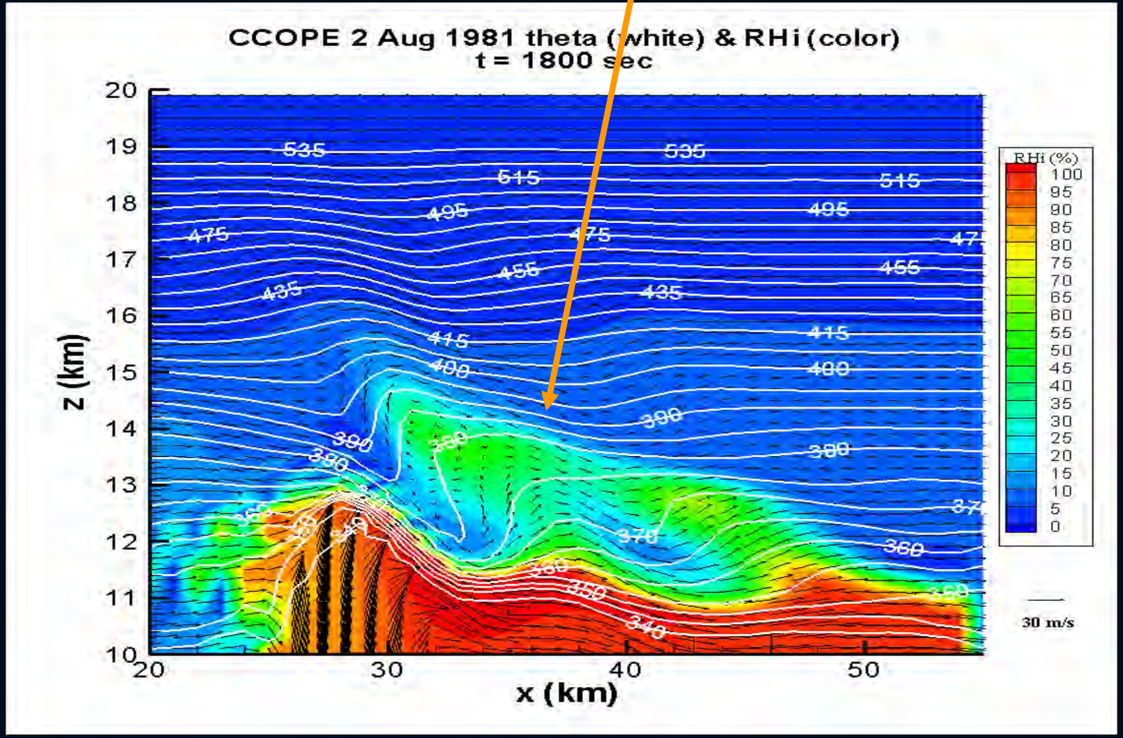
Instability and Wave Breaking

- Convection-induced instability and gravity wave breaking at the storm top send H_2O through the tropopause to enter the stratosphere.

Overshooting top plumes

Anvil wave breaking





Wang (2007)

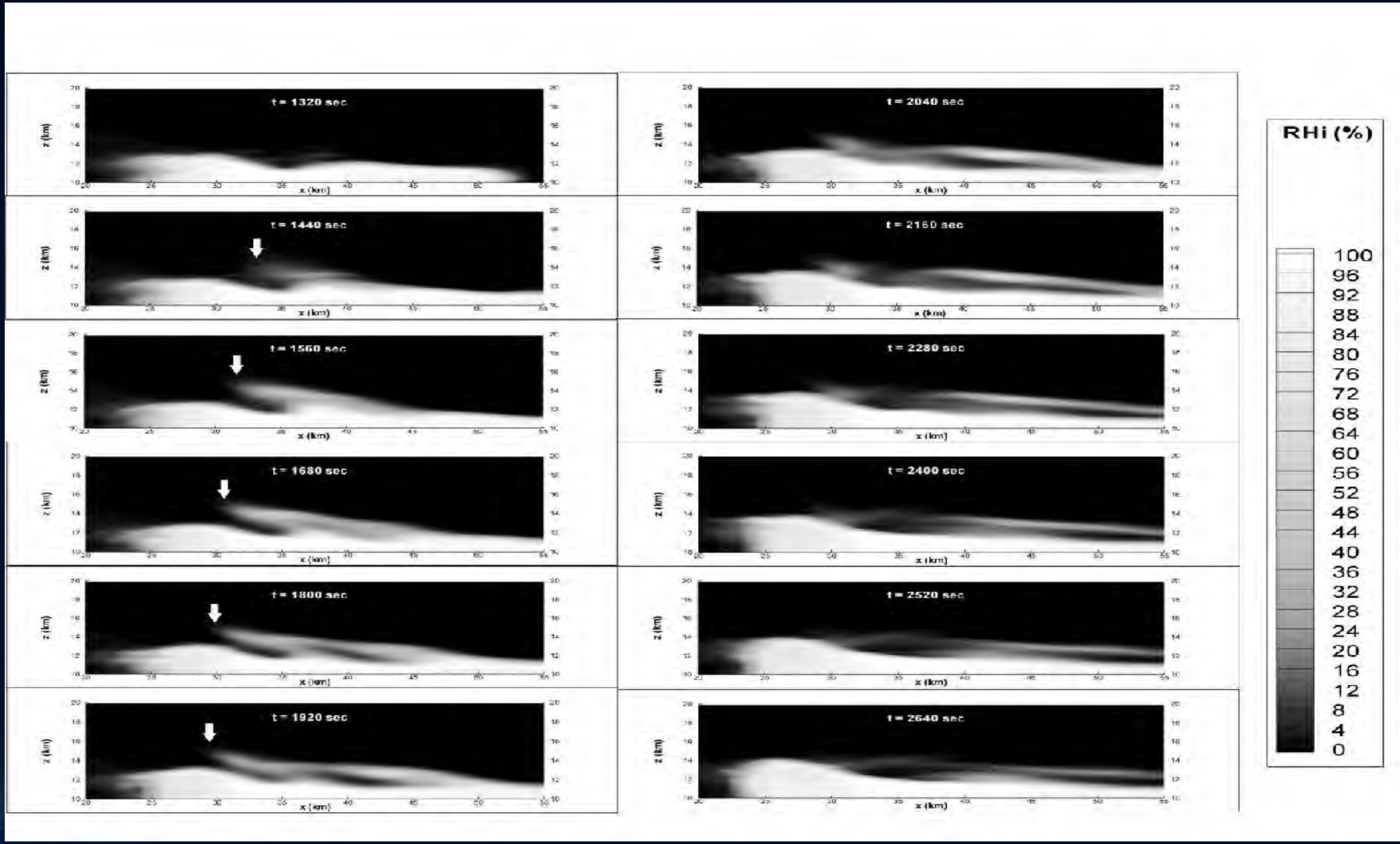
Fujita's jumping cirrus

"One of the most striking features seen repeatedly above the anvil top is the formation of cirrus cloud which jumps upward from behind the overshooting dome as it collapses violently into the anvil cloud". (Fujita, 1982)

Fujita (1989)'s five categories:

- (1) Clean overshooting domes
- (2) Curly-hair cirrus
- (3) Fountain cirrus – cirrus, which splashes up like a fountain, 1 to 2 min after an overshooting dome collapses into an anvil. This appears to be what mentioned in the quotation above.
- (4) Flare cirrus – cirrus that jumps 1 to 3 km above the anvil surface and moves upwind like a flare.
- (5) Geyser cirrus – cirrus that bursts up 3 to 4 km above the anvil surface like a geyser.

WISCDYMM simulation of CCOPE Supercell



Fujita (1982, 1989) observed jumping cirrus above severe storms – they are also due to wave breaking

Similar shape, size, orientation and occur at similar relative location

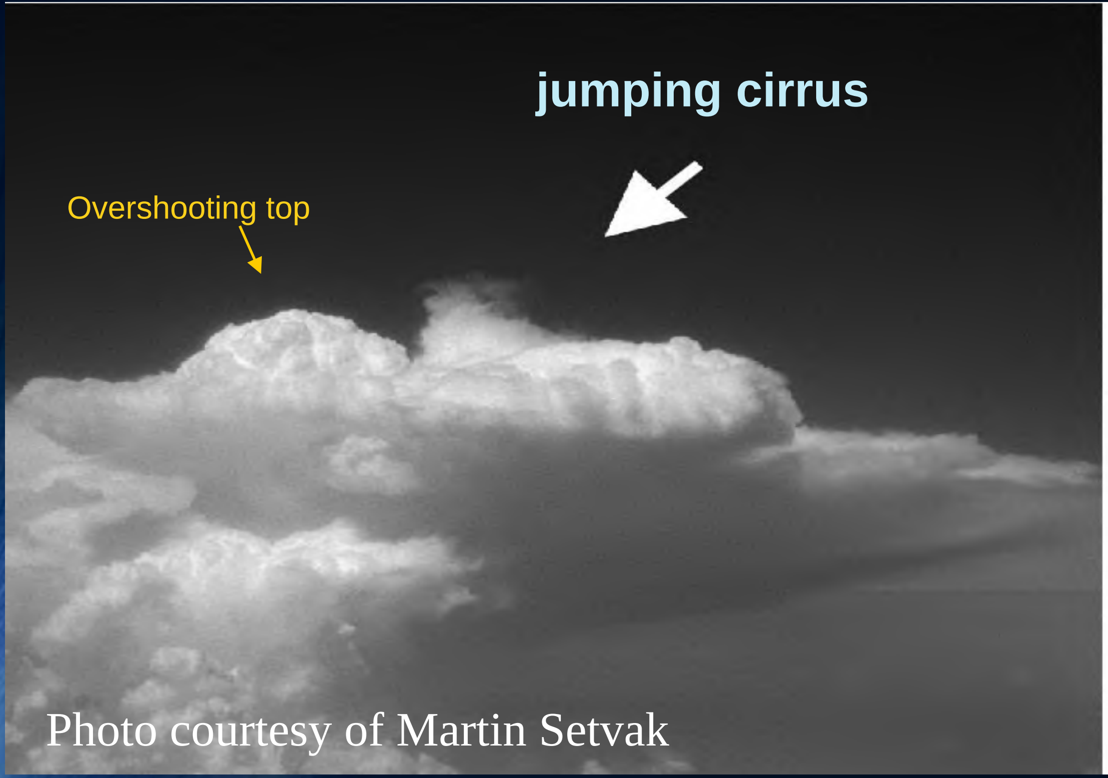
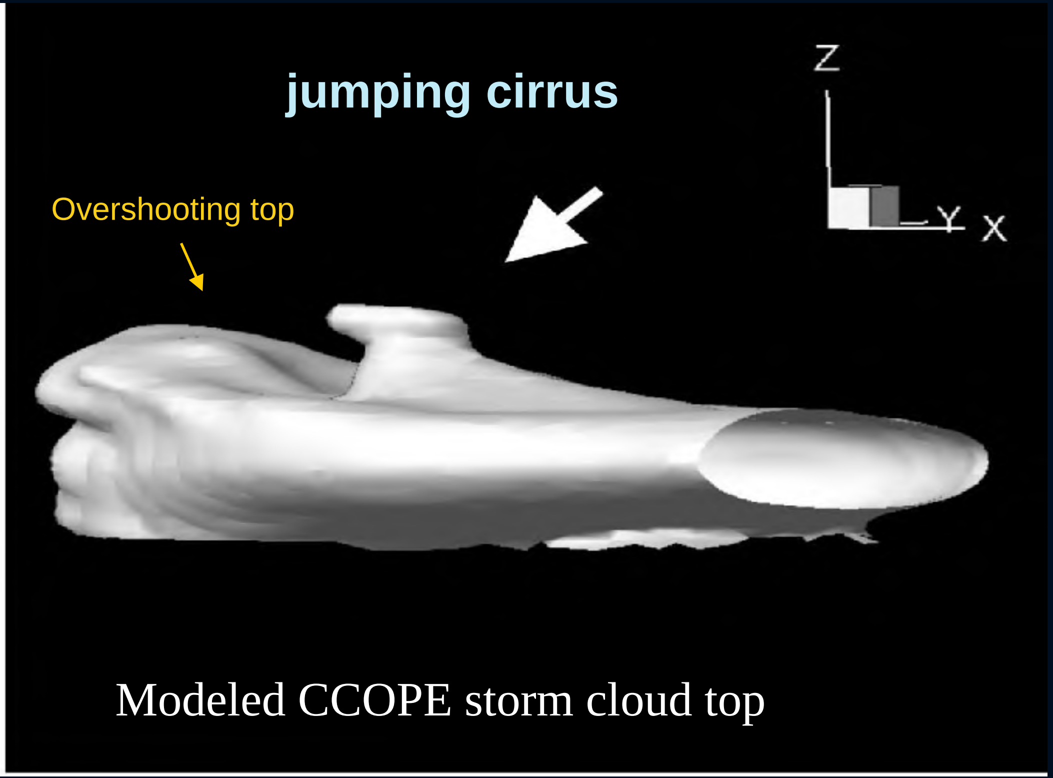
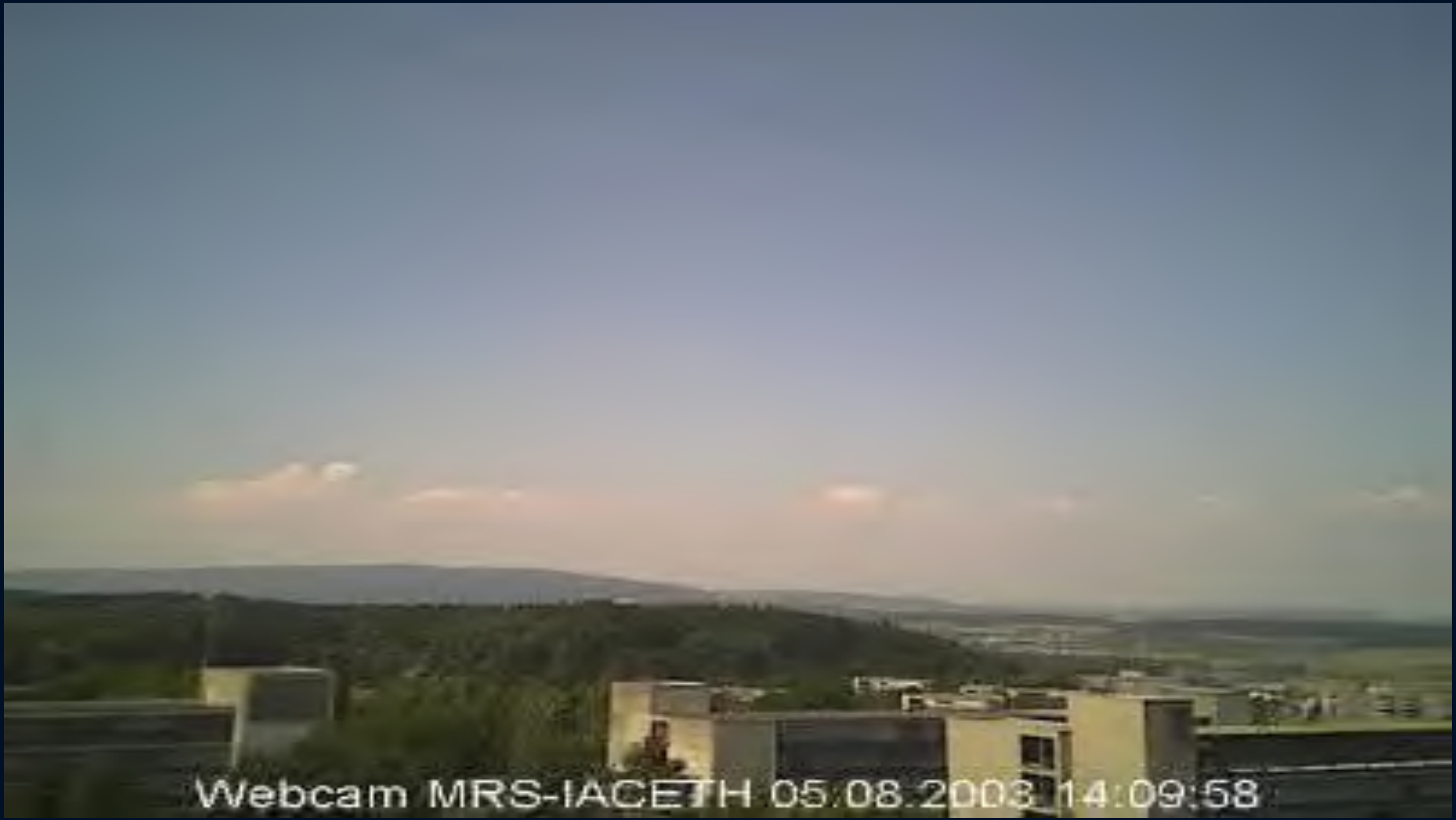


Photo courtesy of Martin Setvak

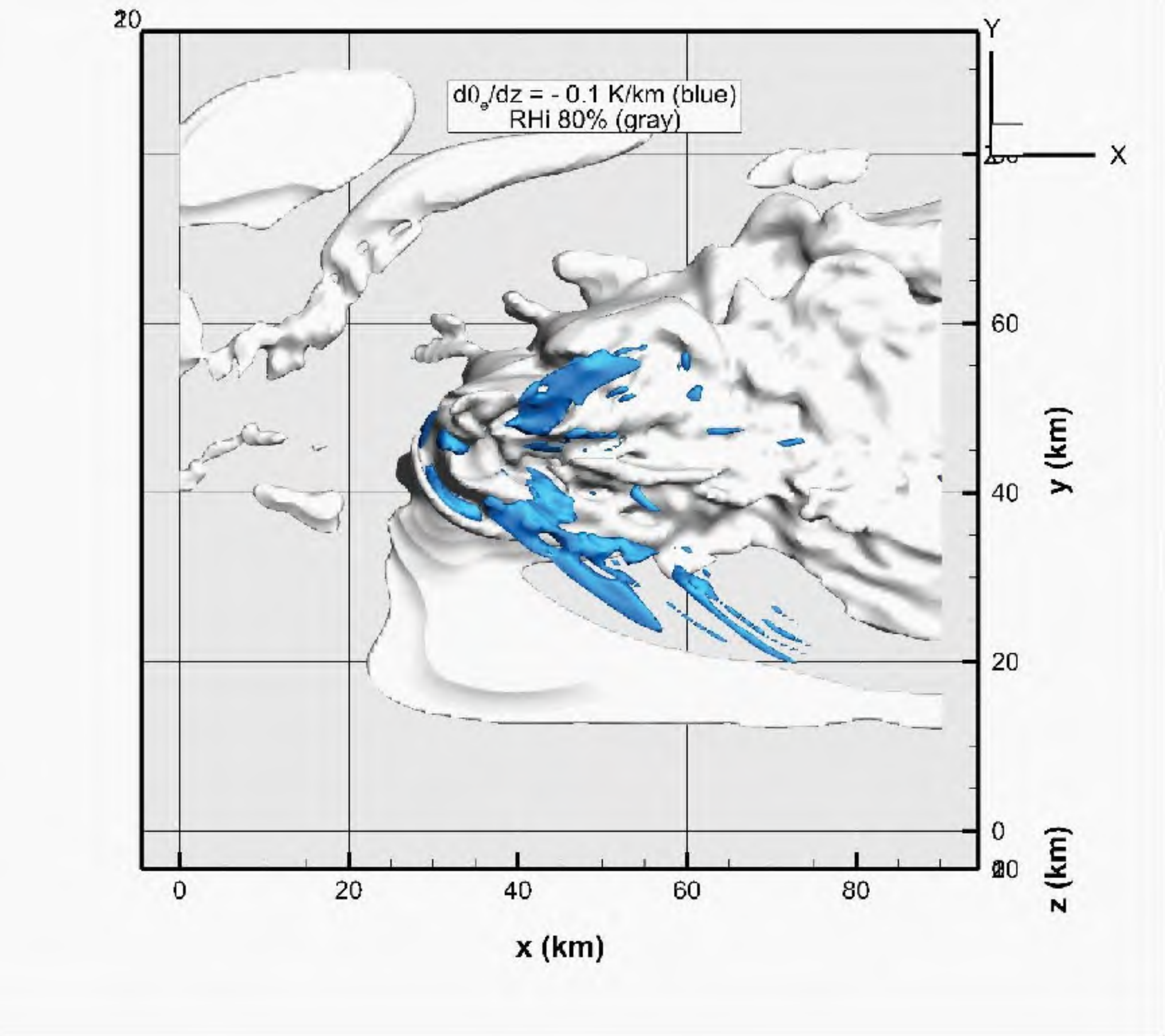


Modeled CCOPE storm cloud top

From: Wang (2004, GRL)


Webcam MRS-IACETH 05.08.2003 14:09:58

Where wave breaking occurs ($\partial\theta/\partial z \leq 0$)



Where wave breaking occurs $(\partial\theta/\partial z \leq 0)$