A satellite image showing the top of a severe storm. The cloud deck is a dense, textured layer of white and grey clouds. Above this, a large, dark, and somewhat featureless area represents the storm's anvil or a region of deep convection. The background is a clear, deep blue sky.

Physics of Satellite-observed features on top of severe storms

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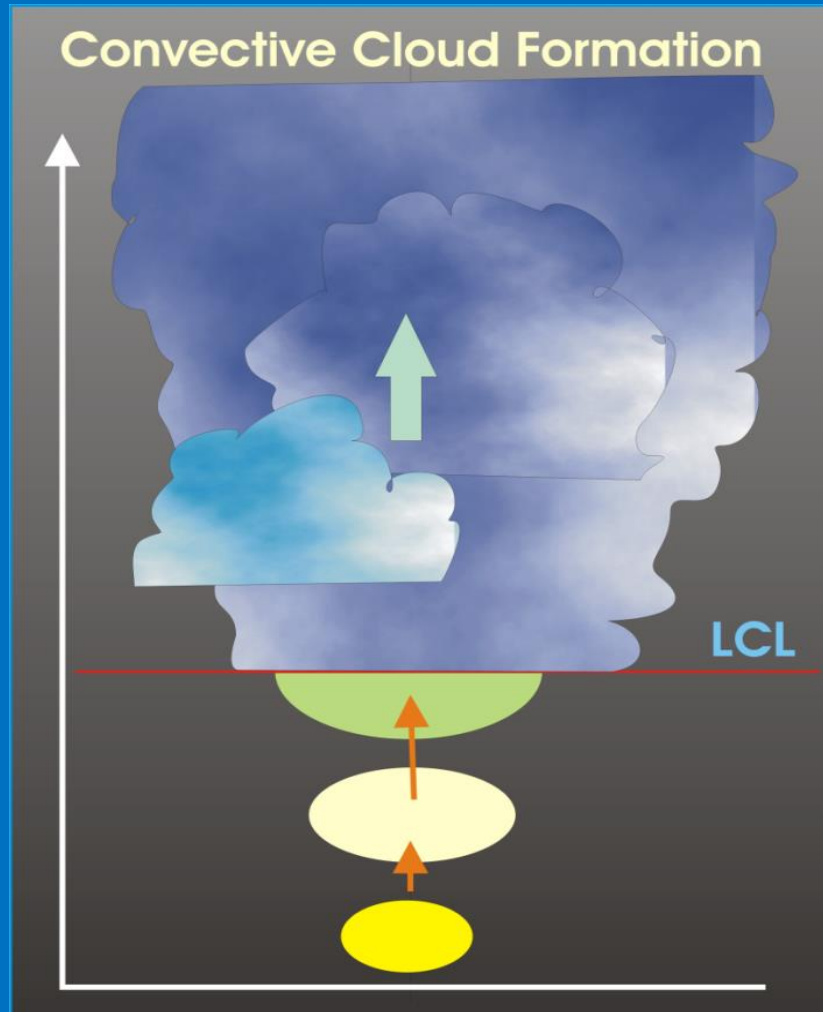
University of Wisconsin-Madison

Madison, Wisconsin, USA

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.

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



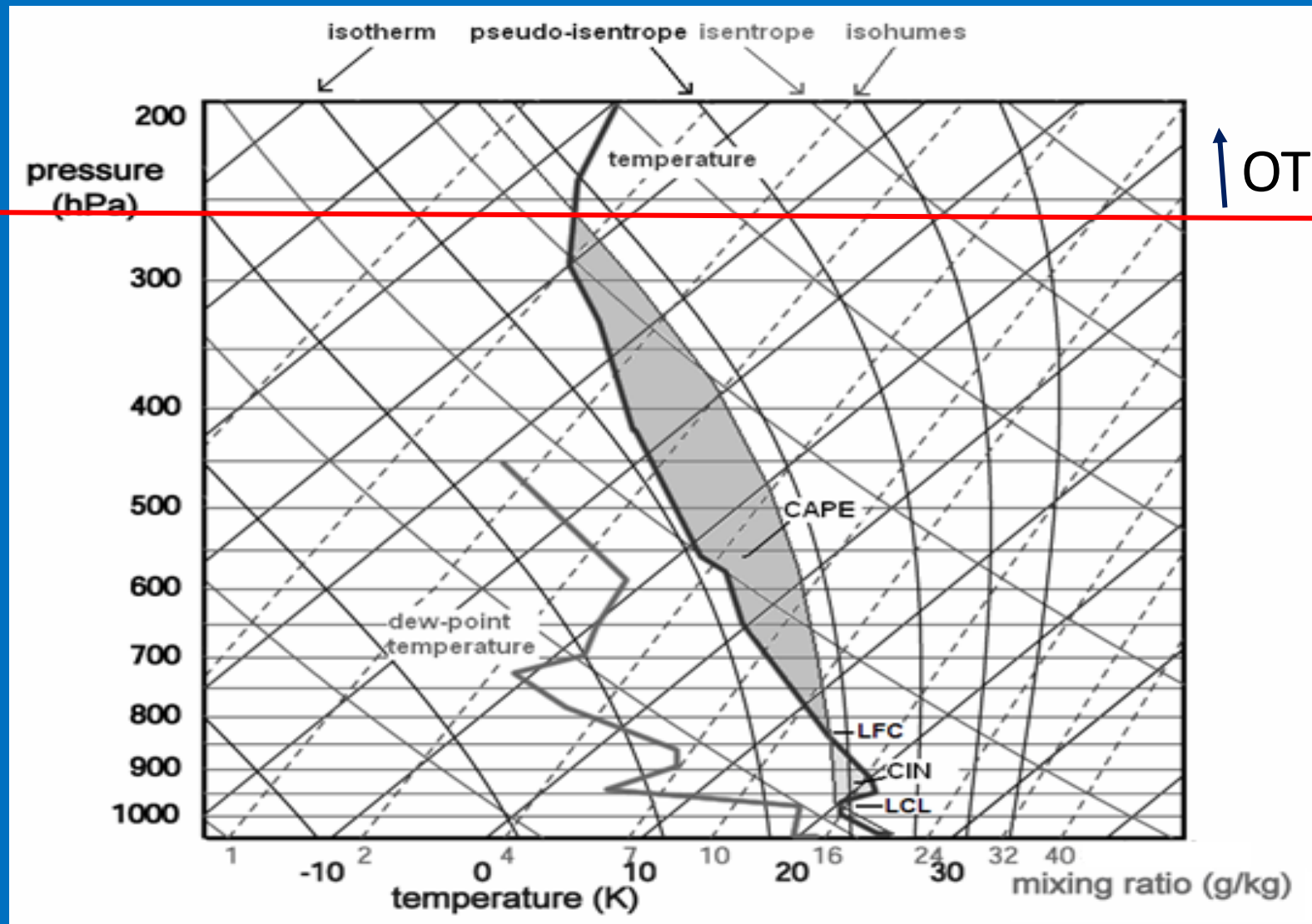
$$c_{p,m}dT + L_e dq_{v,sat} - \alpha_m dp = 0$$

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

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

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

Typical severe storm sounding in US Midwest



Buoyancy and Static Stability

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

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

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

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

$$\begin{aligned} \frac{1}{\theta} \frac{d\theta}{dz} &= \frac{1}{T} \frac{dT}{dz} - \frac{\kappa}{p} \frac{dp}{dz} = \frac{1}{T} \frac{dT}{dz} + \frac{(R_d / c_p)}{\rho_a R_d T} (\rho_a g) \\ &= \frac{1}{T} \left(\frac{g}{c_p} + \frac{dT}{dz} \right) = \frac{1}{T} (\Gamma_d - \Gamma) \end{aligned}$$

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

$$\left\{ \begin{array}{ll} \frac{d\theta}{dz} > 0 & \text{stable} \\ \frac{d\theta}{dz} = 0 & \text{neutral} \\ \frac{d\theta}{dz} < 0 & \text{unstable} \end{array} \right\} \text{ (unsaturated), or } \left\{ \begin{array}{ll} \frac{d\theta_e}{dz} > 0 & \text{stable} \\ \frac{d\theta_e}{dz} = 0 & \text{neutral} \\ \frac{d\theta_e}{dz} < 0 & \text{unstable} \end{array} \right\} \text{ (saturated)}$$

Brunt-Väisällä frequency

Brunt-Väisällä frequency (Wang, 2013)

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

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

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

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

where

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

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

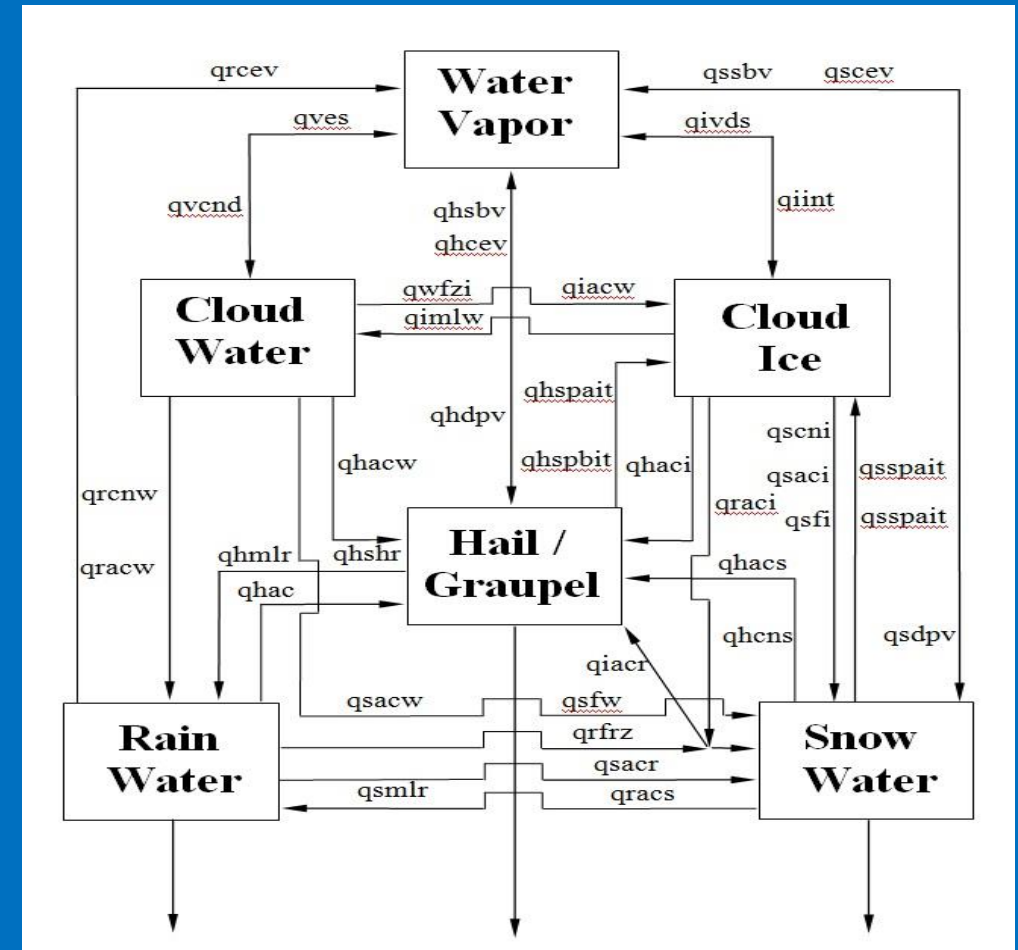
Overshooting (OT)

- 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.



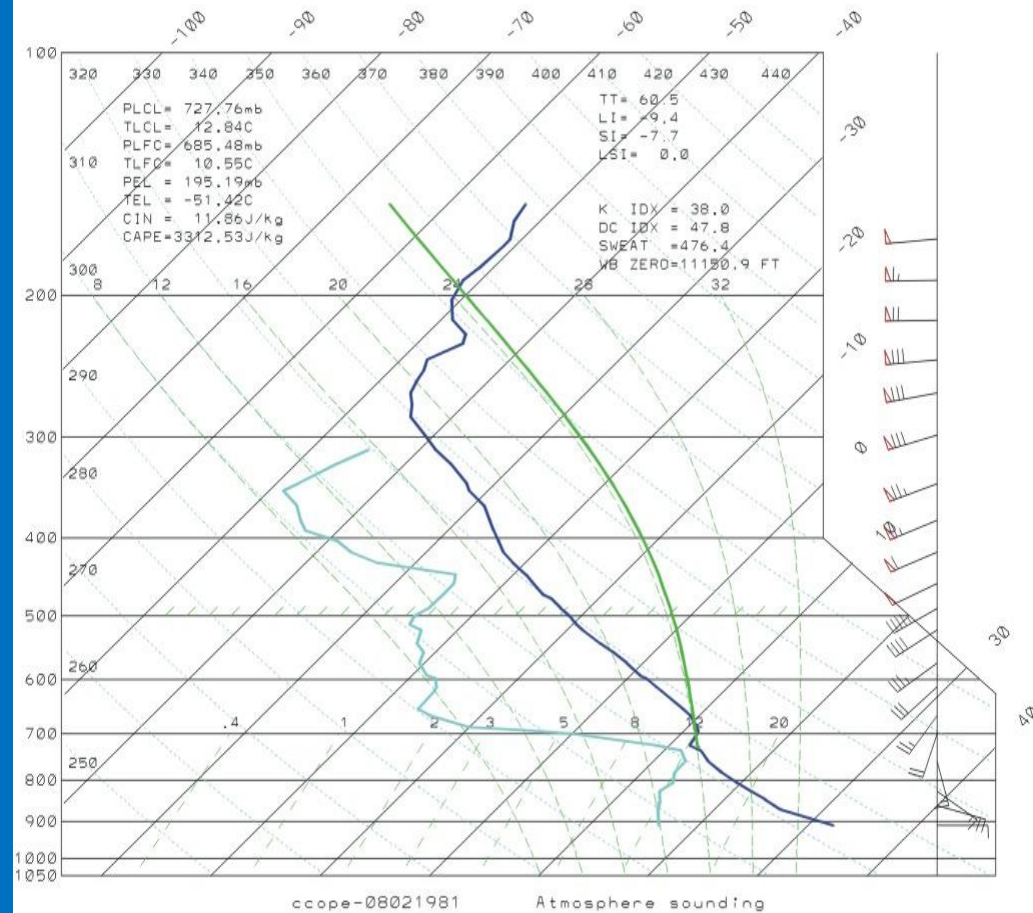
WISCDYMM-I and WISCDYMM-II

- 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)

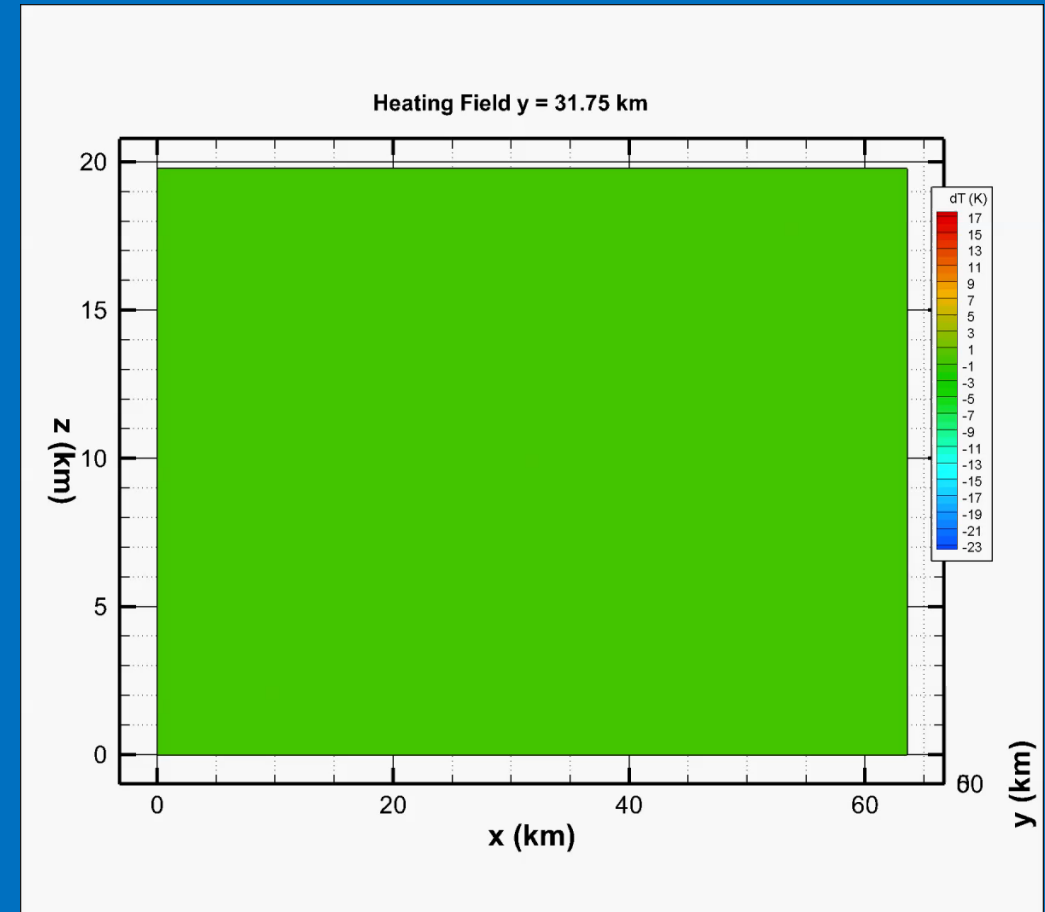
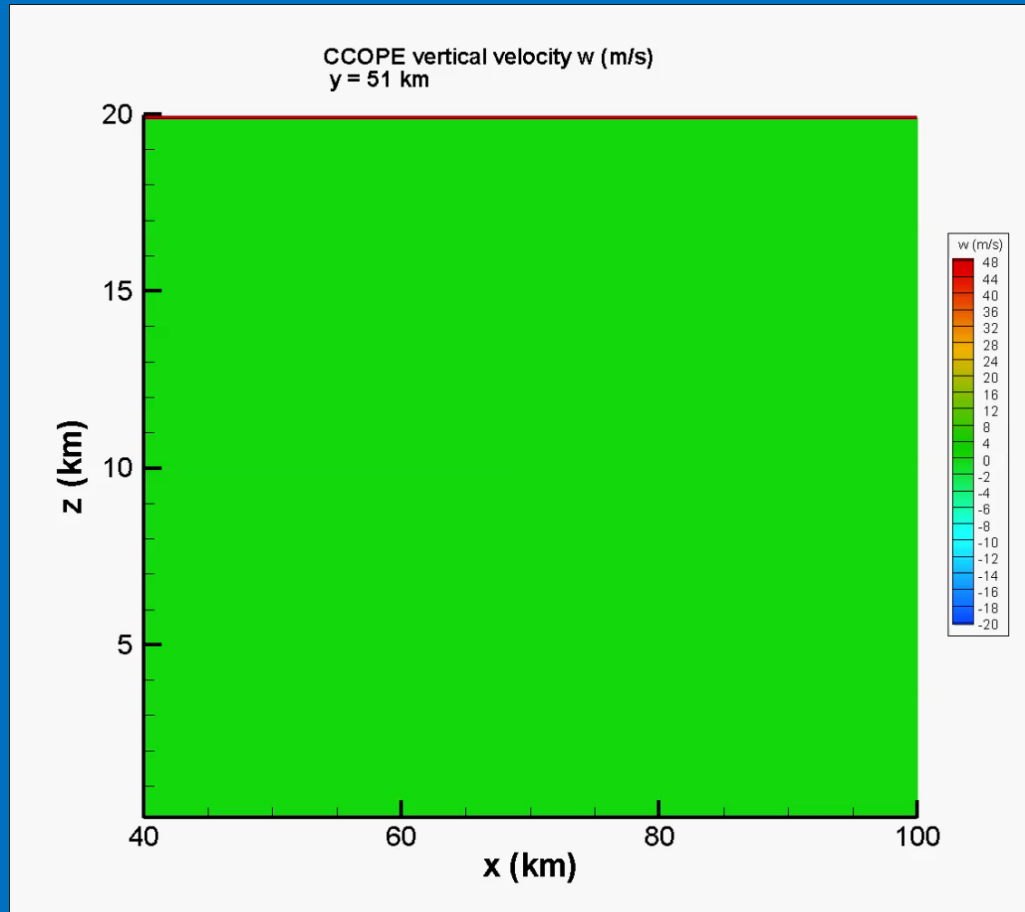


Initial conditions and initiation of convection

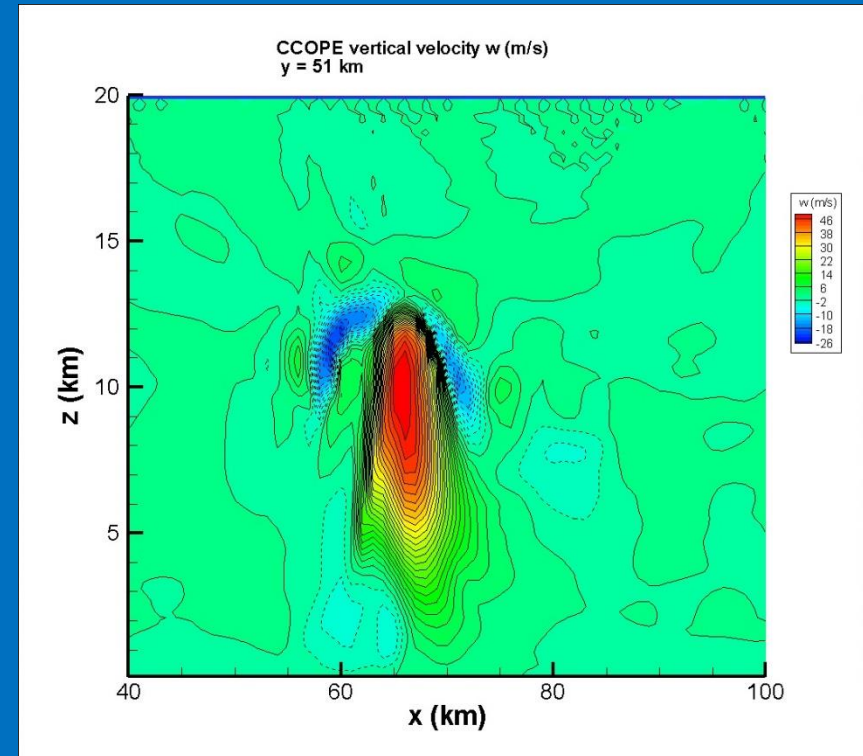
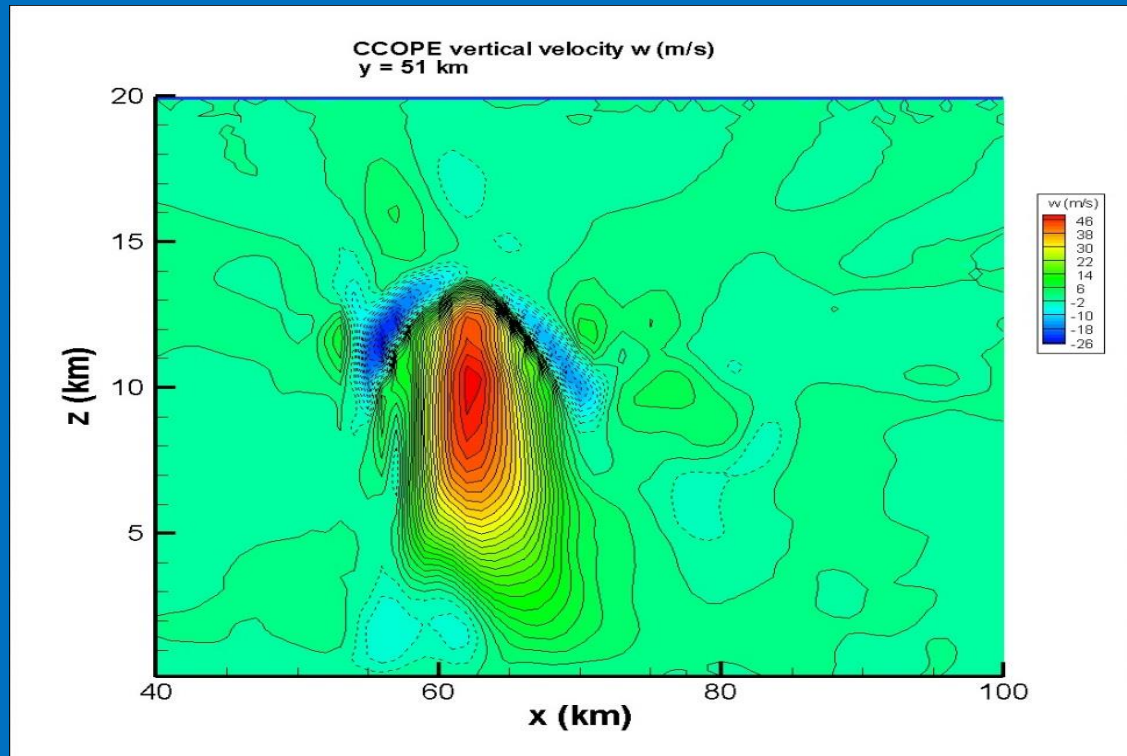
Initial sounding of the CCOPE Supercell 2 AUG 1981, Knowlton, Montana



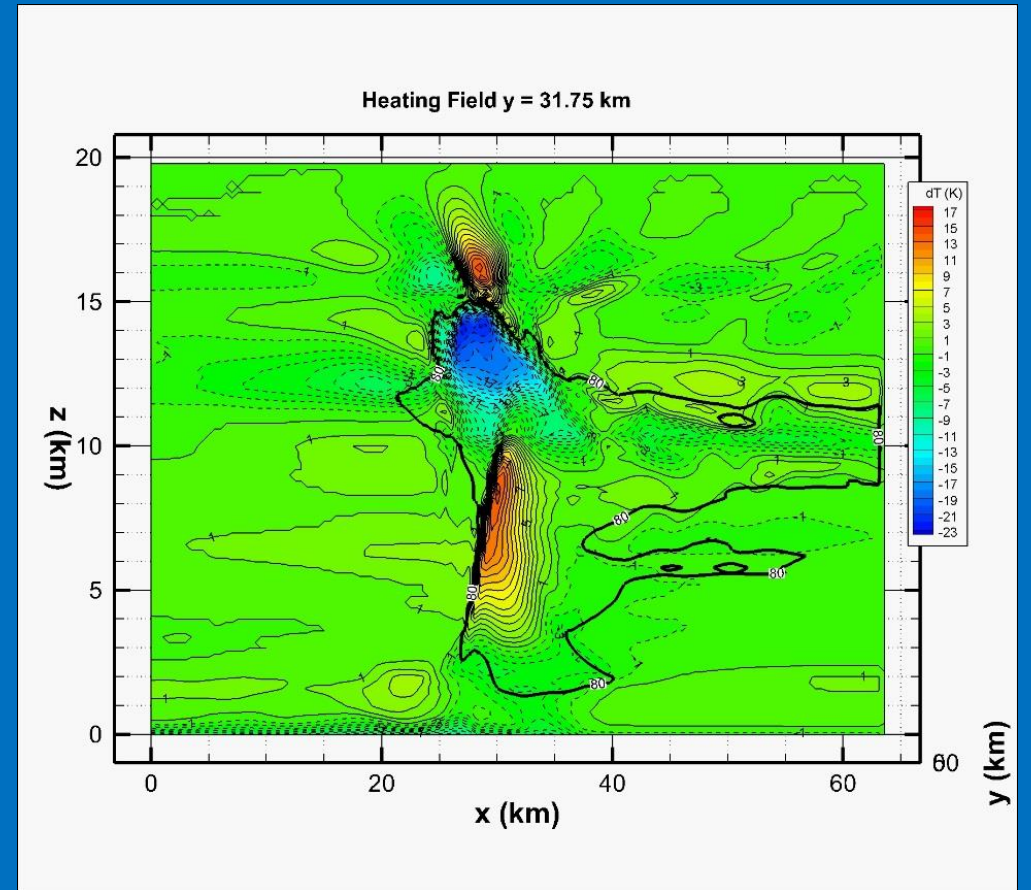
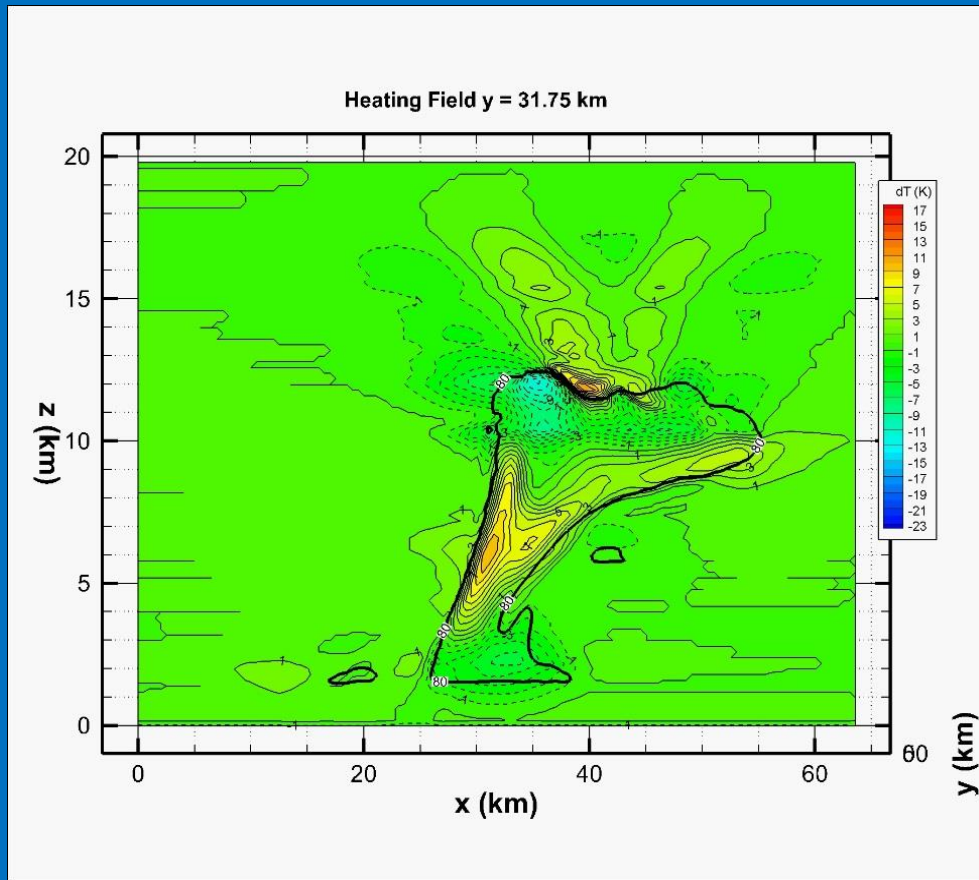
Vertical velocity and heating fields



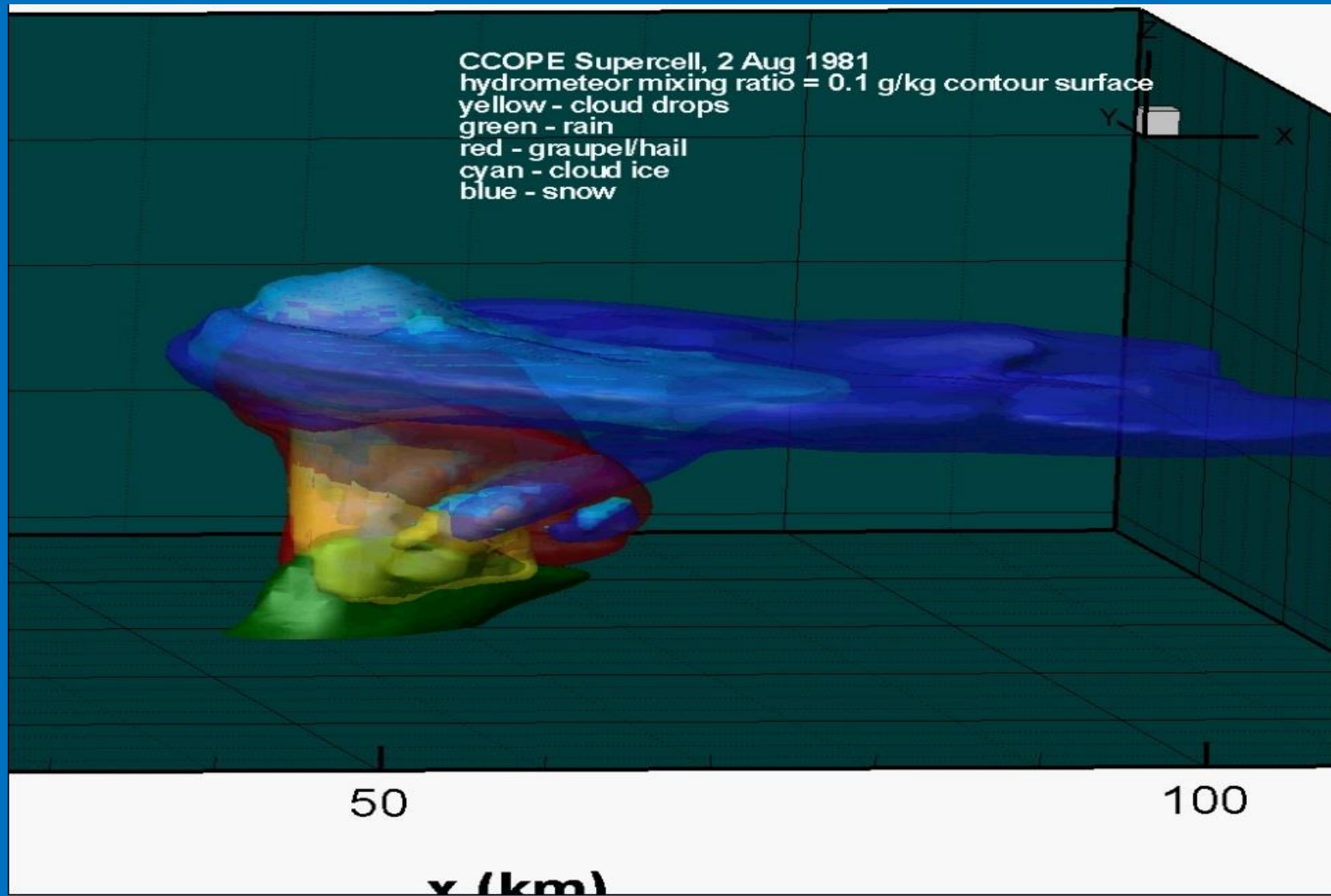
Vertical velocity field



Thermal structure



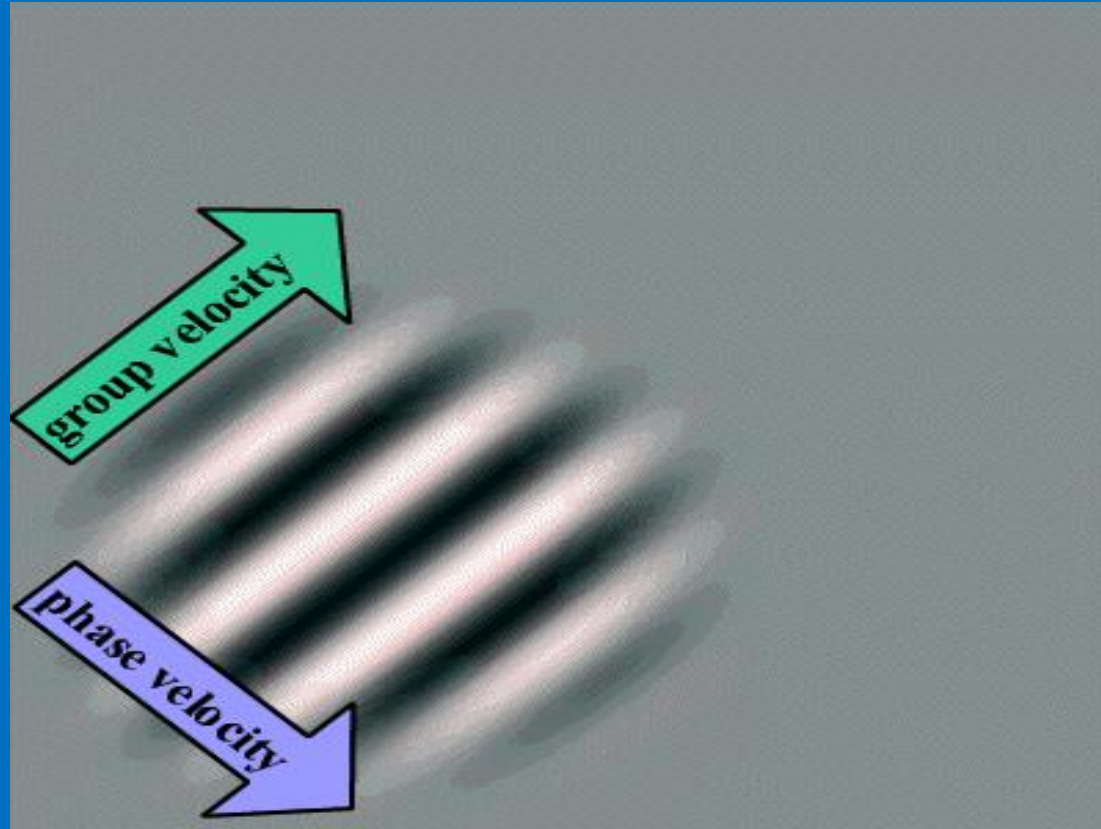
Distribution of hydrometeors



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

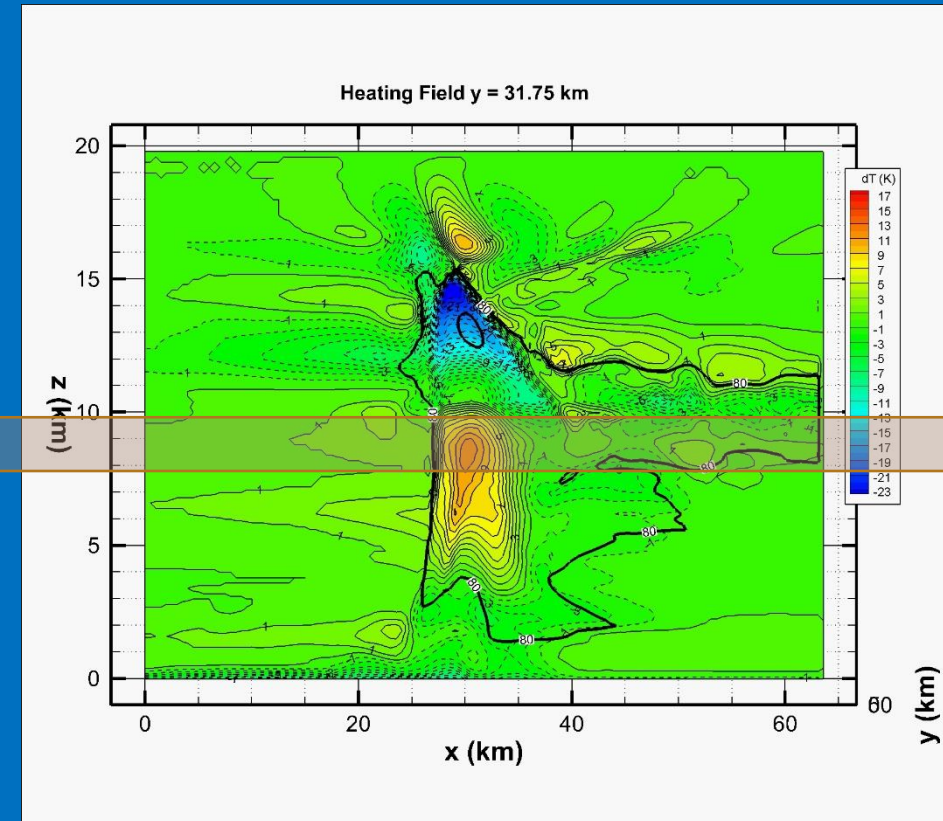
Overshooting top (OT), Cold -U or V, close-in warm area (CWA), distant warm area (DWA), above anvil cirrus plumes, jumping cirrus (JC), ship waves, radial cirrus, gullwing cirrus (GC), etc.



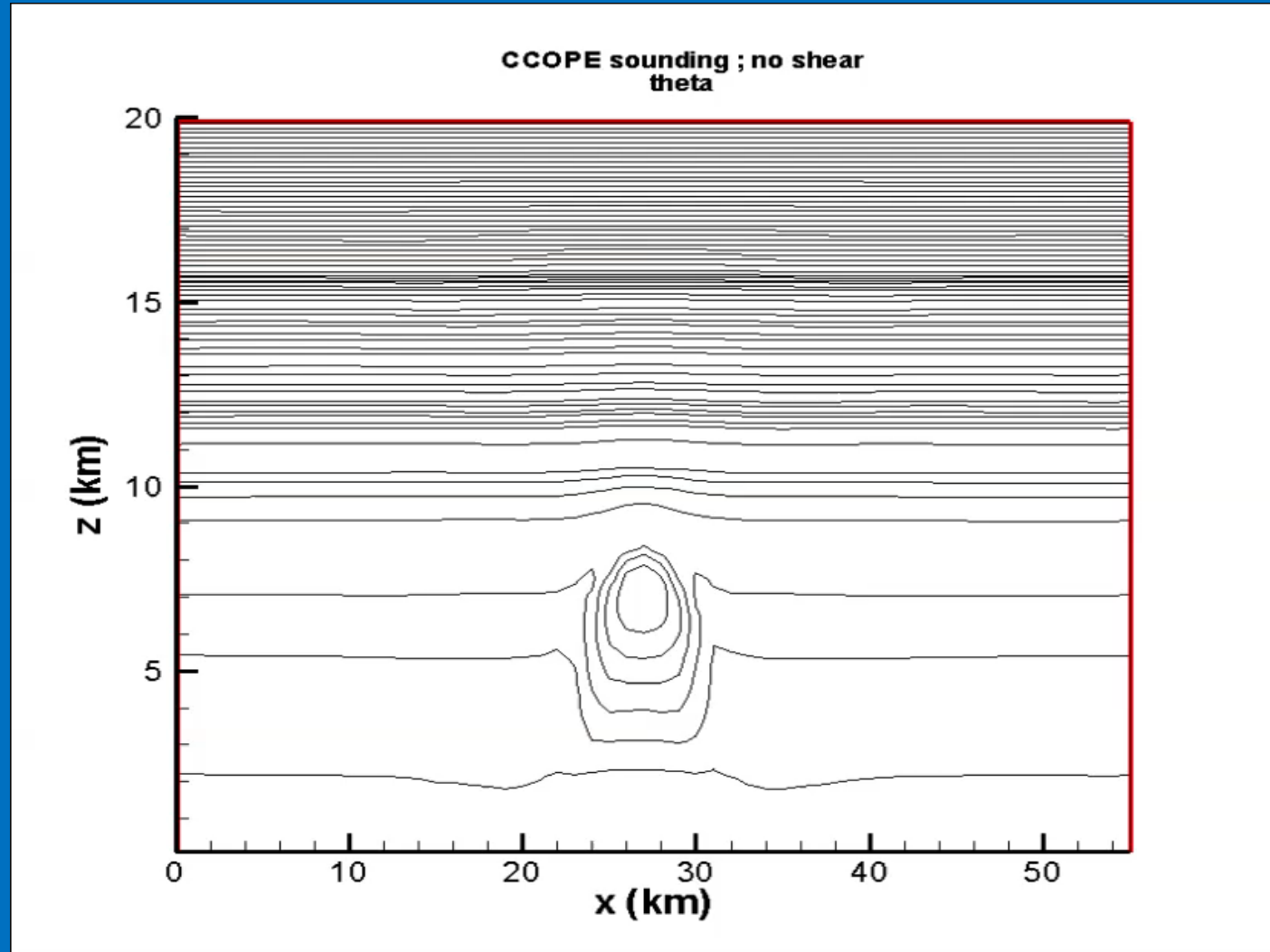
Transition layer ~ 8-10 km

Instability physics dominated

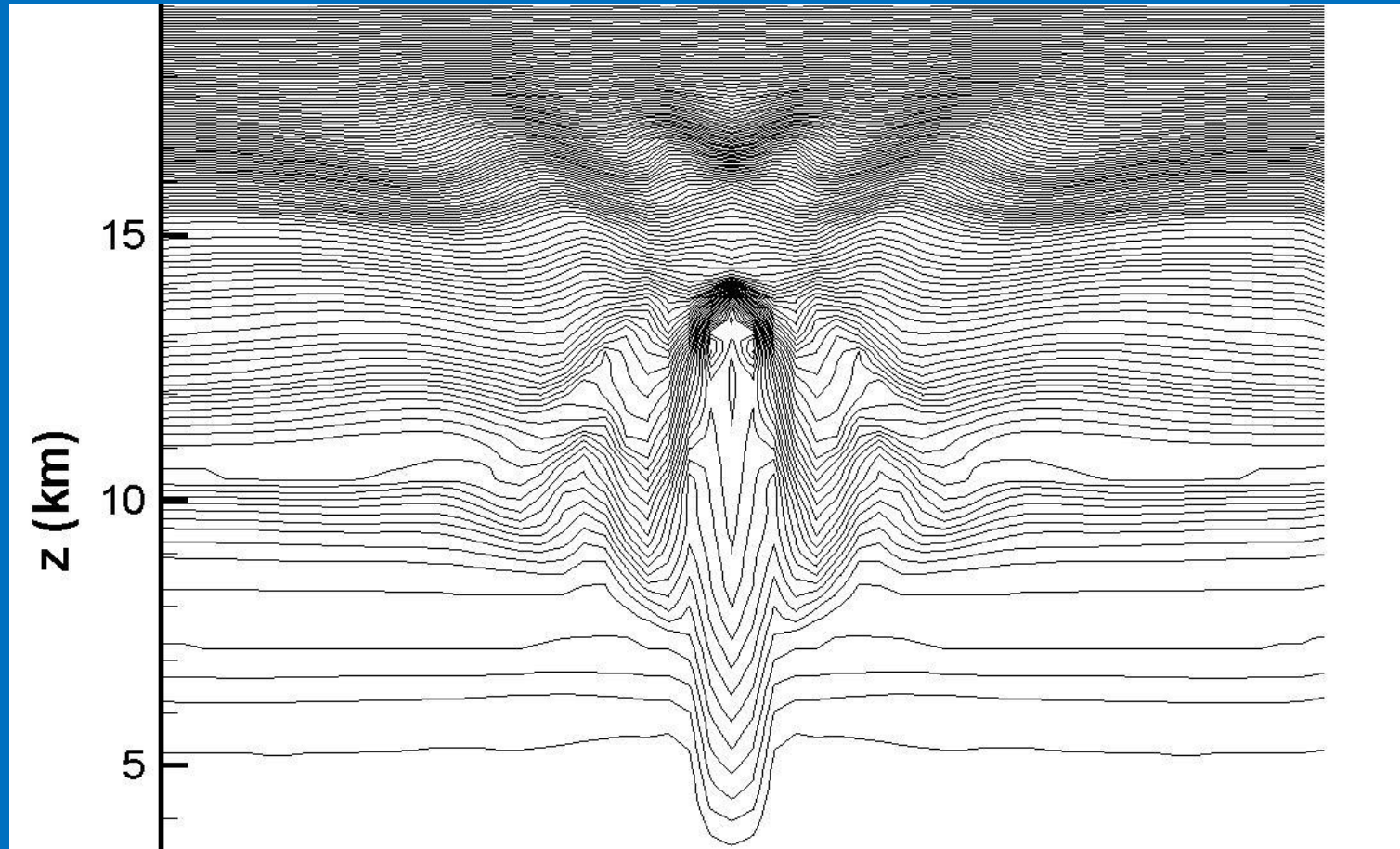
Intense updraft, heavy precipitation, strong wind, large hail, hook echo, gust front, cold pool, thunder and lightning, tornado, etc.



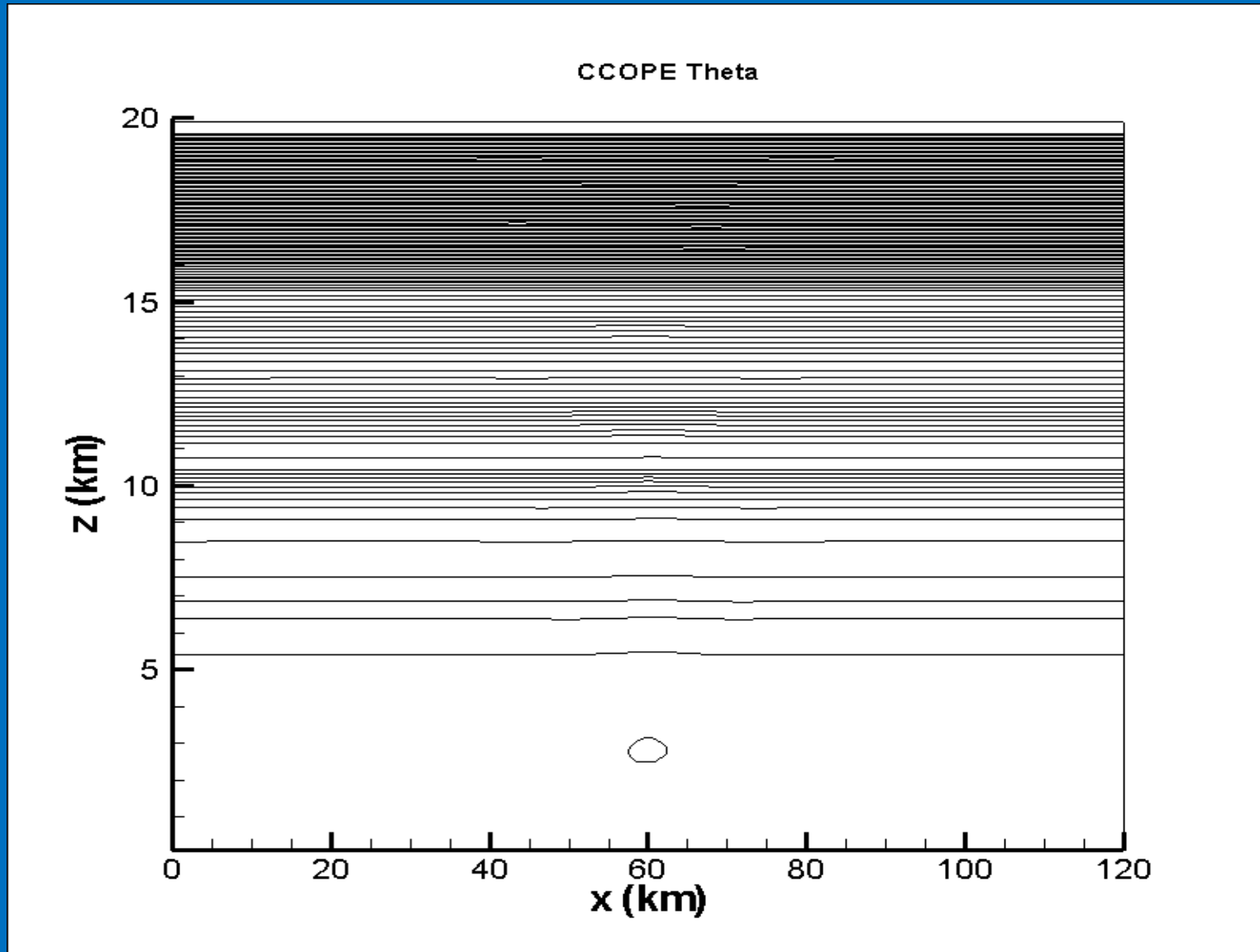
CCOPE without wind shear



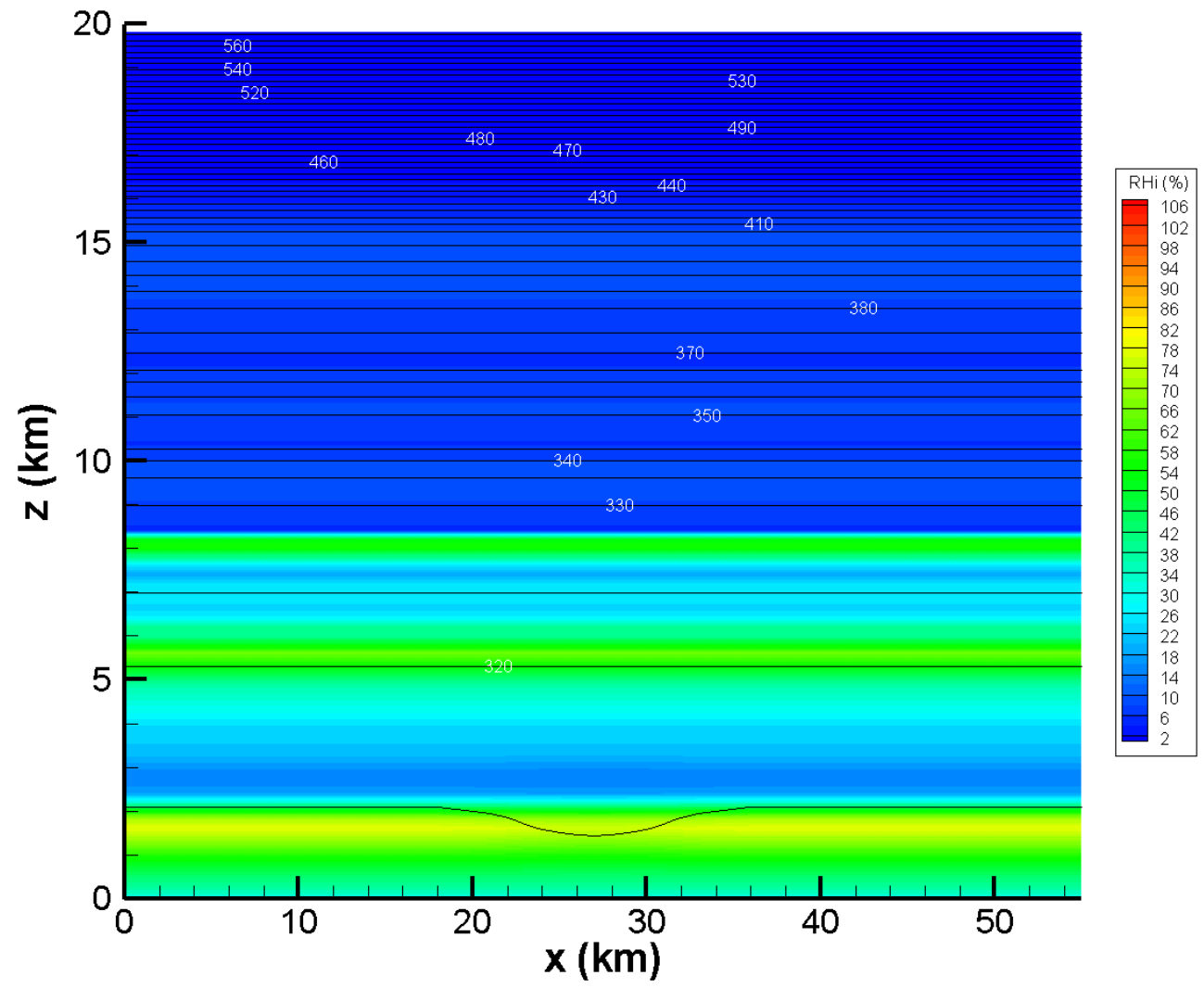
CCOPE with no wind shear



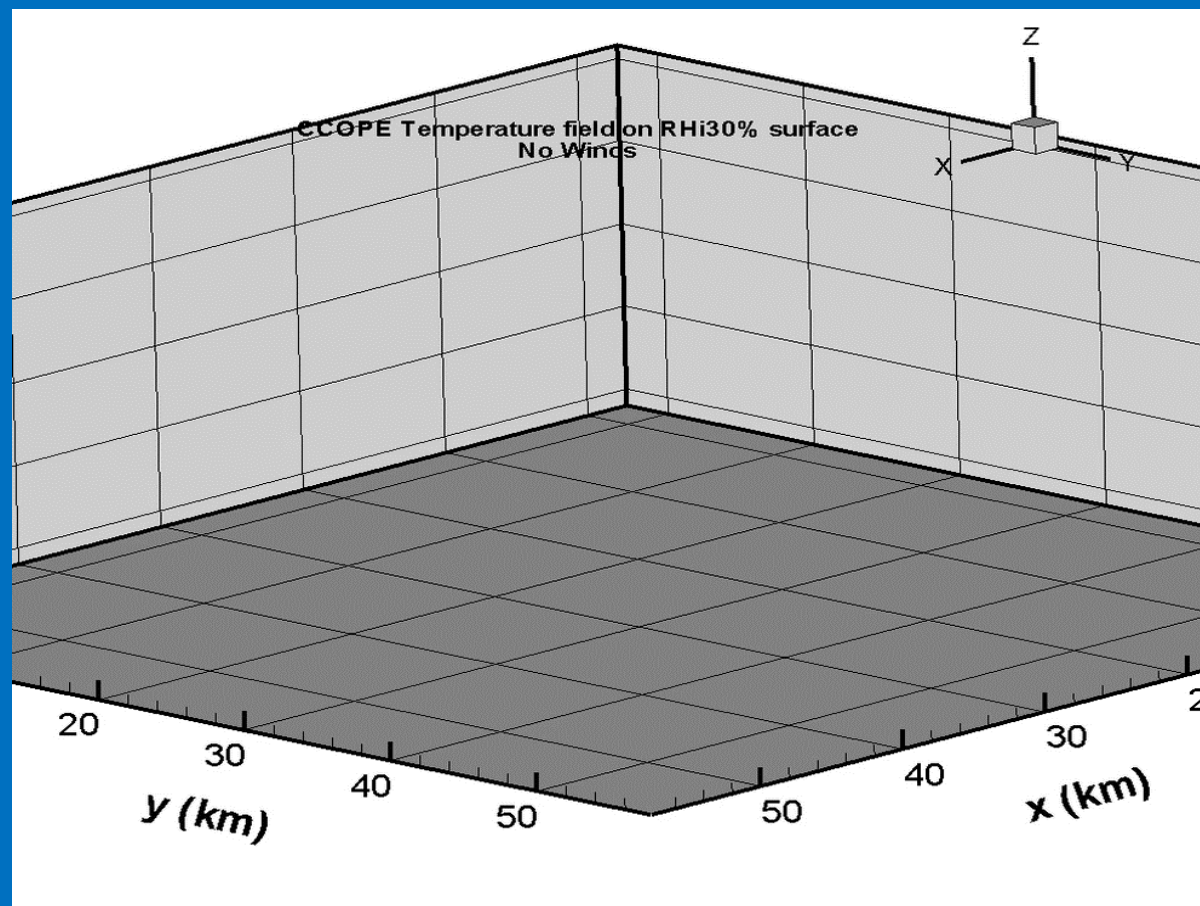
Now add the wind shear



- 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!**)



Pancake cloud



Pancake cloud (courtesy of Po-Hsiung Lin)

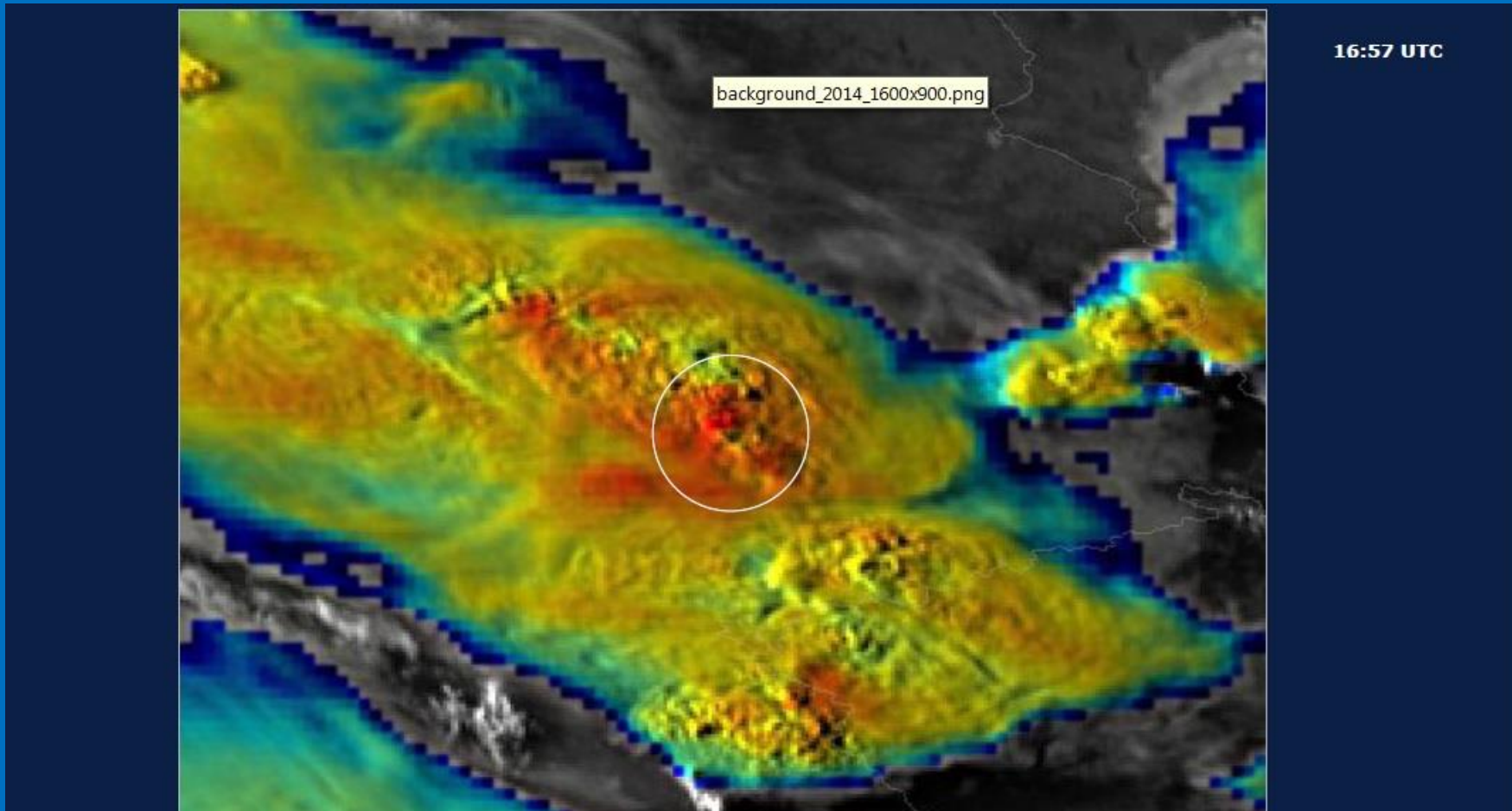


Storm cloud over Laos – pancake cloud?

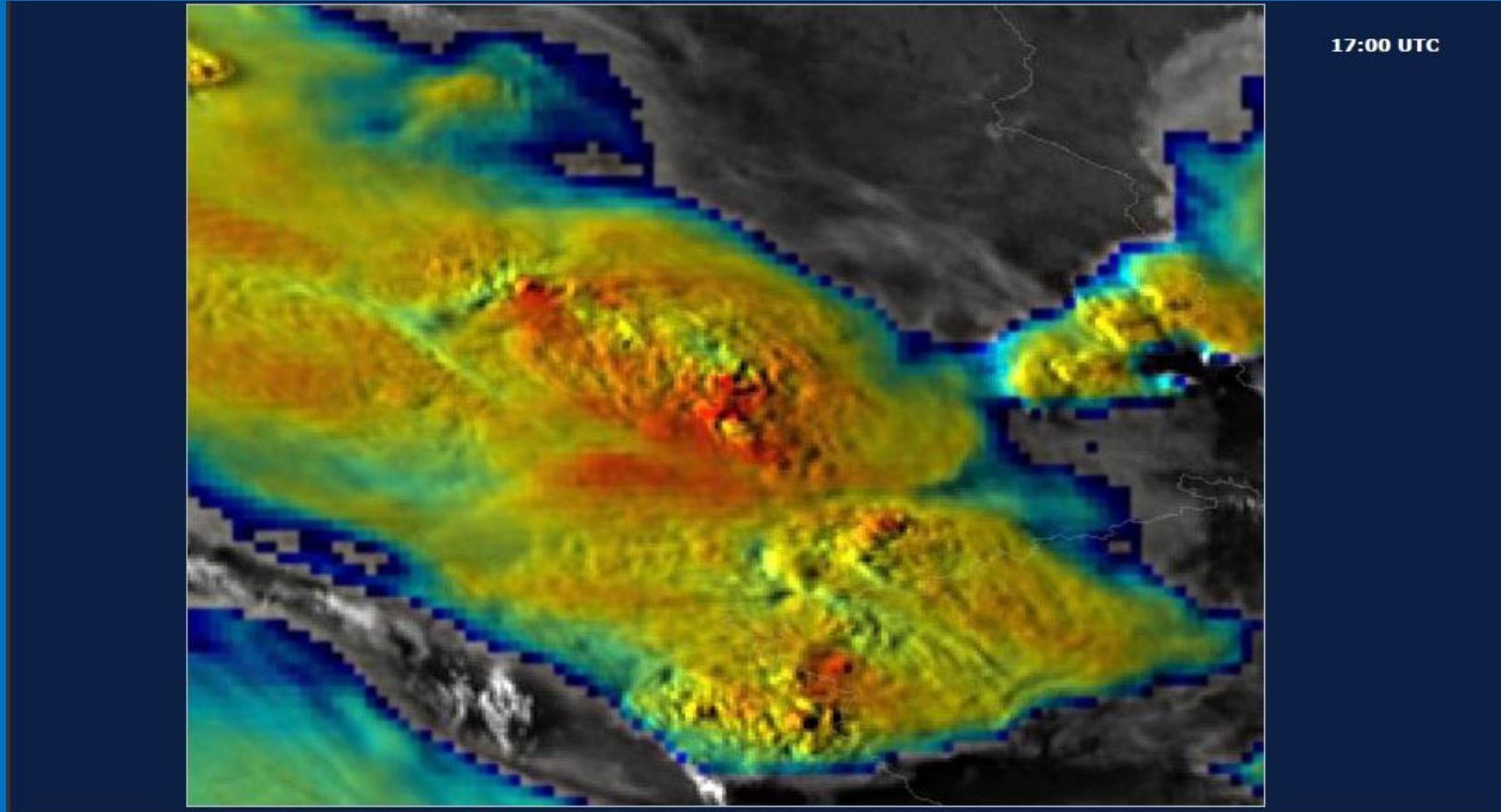


From: <http://montanaron.com/wordpress/tag/weather>

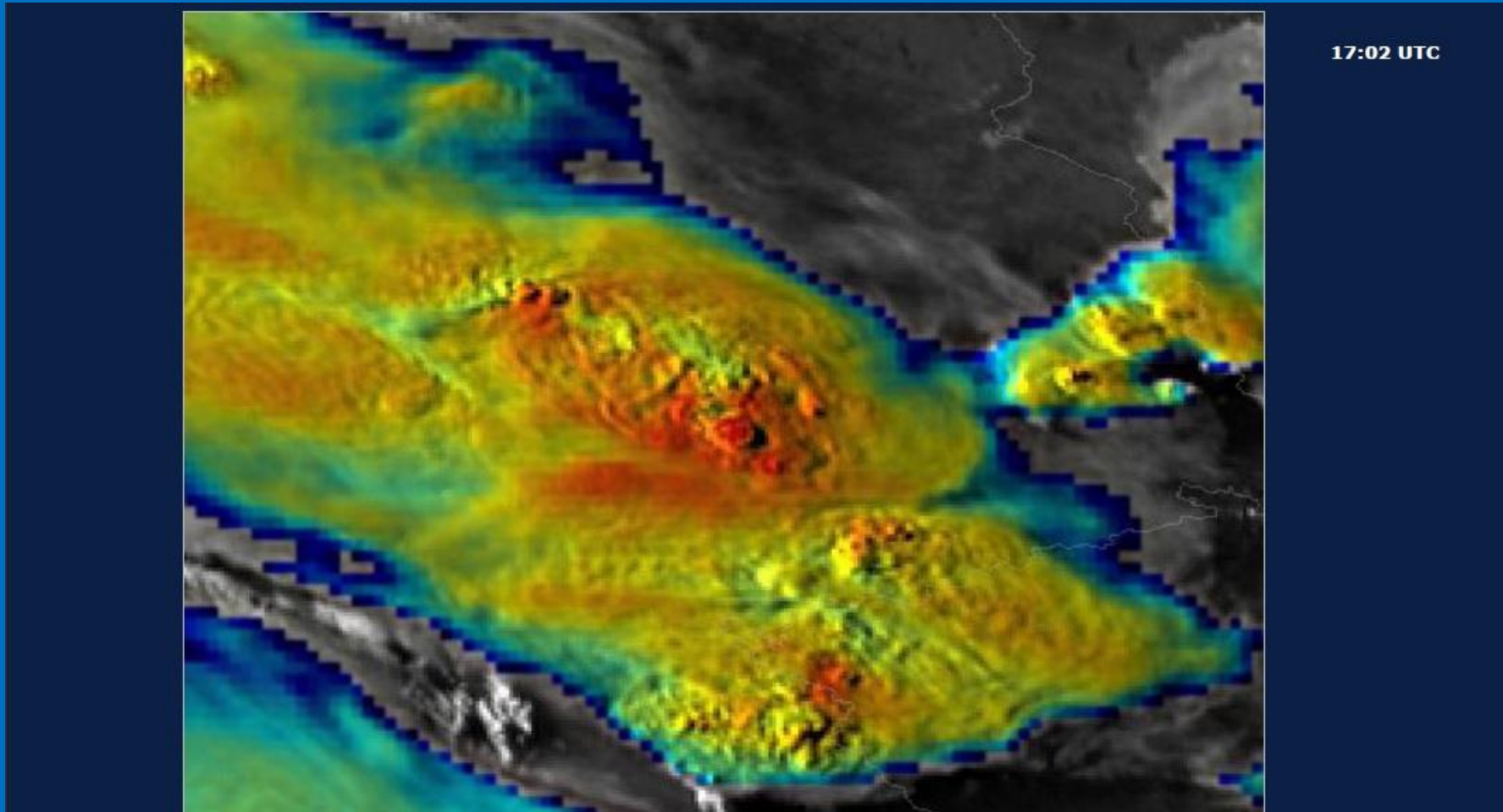
Low wind shear –cold-V not obvious



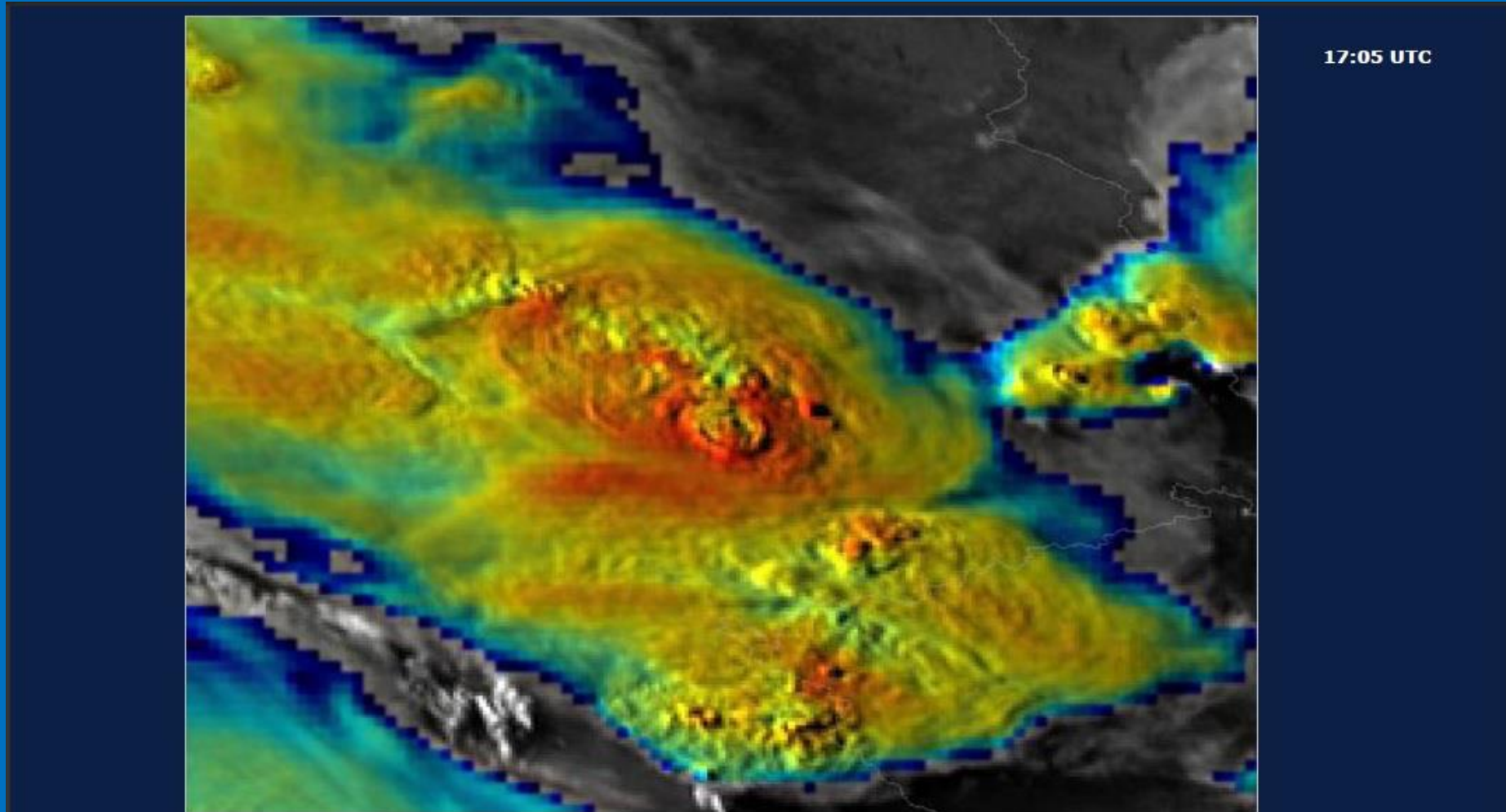
Courtesy of Martin Setvak



Courtesy of Martin Setvak

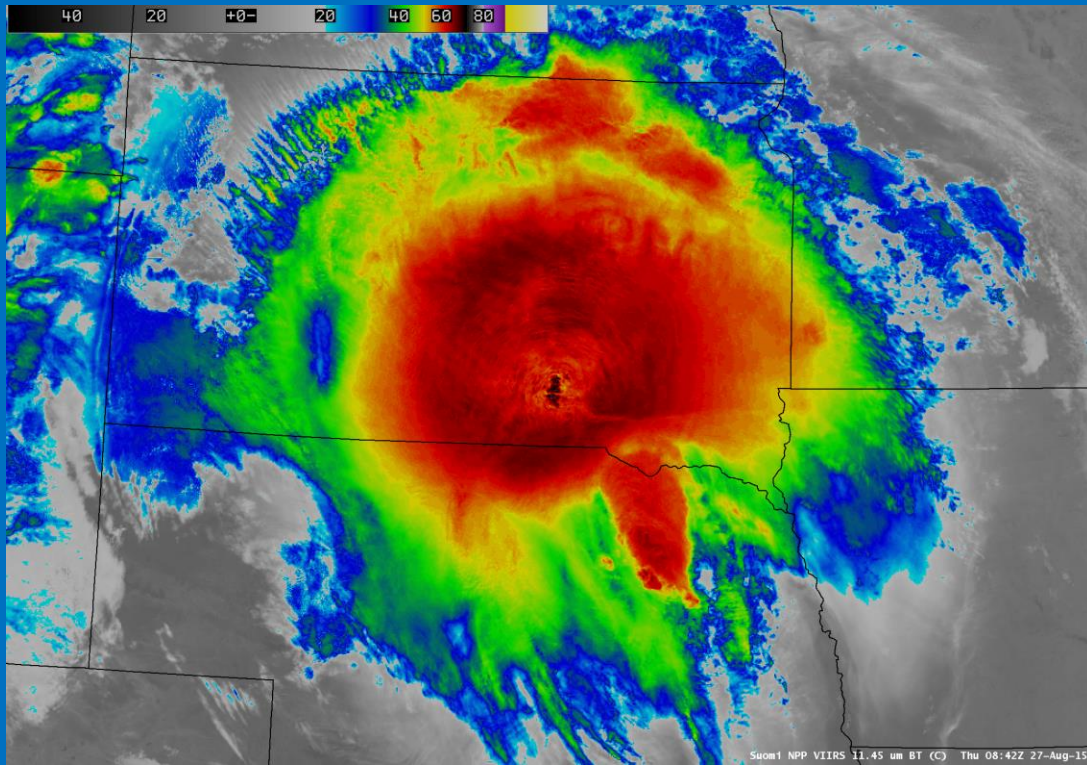


Courtesy of Martin Setvak

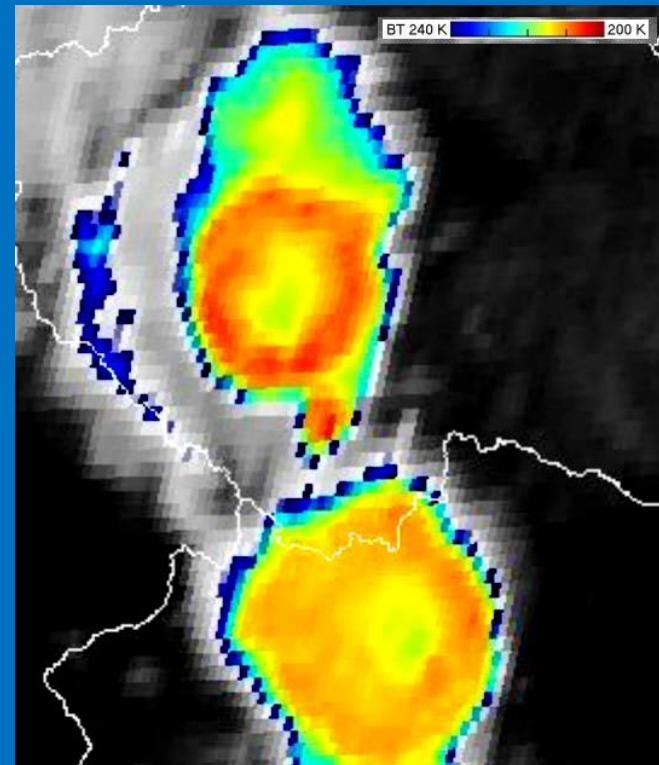


Courtesy of Martin Setvak

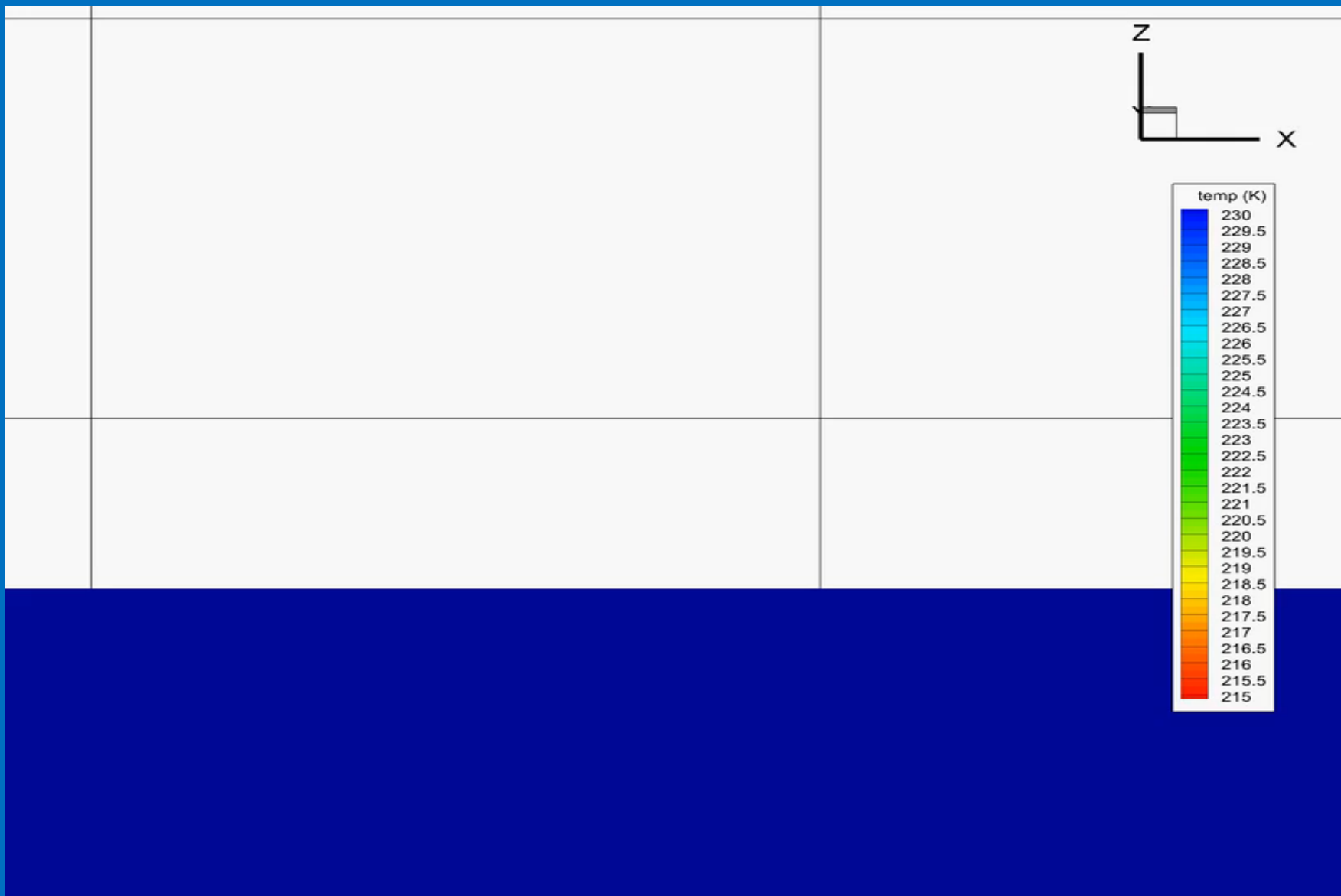
Cold Ring



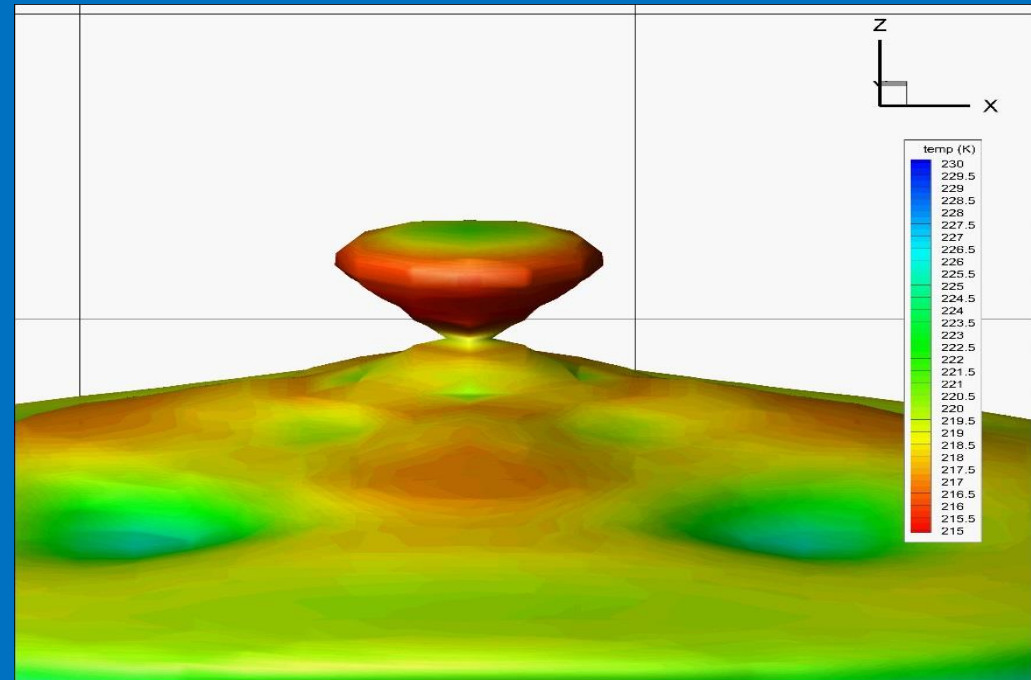
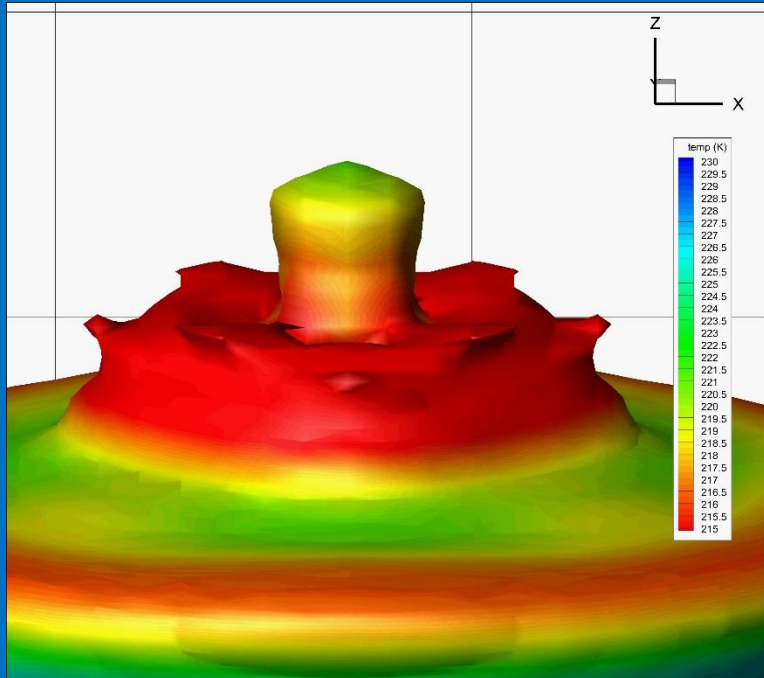
Courtesy of Scott Bachmeier/CIMSS/SSEC/UW-Madison



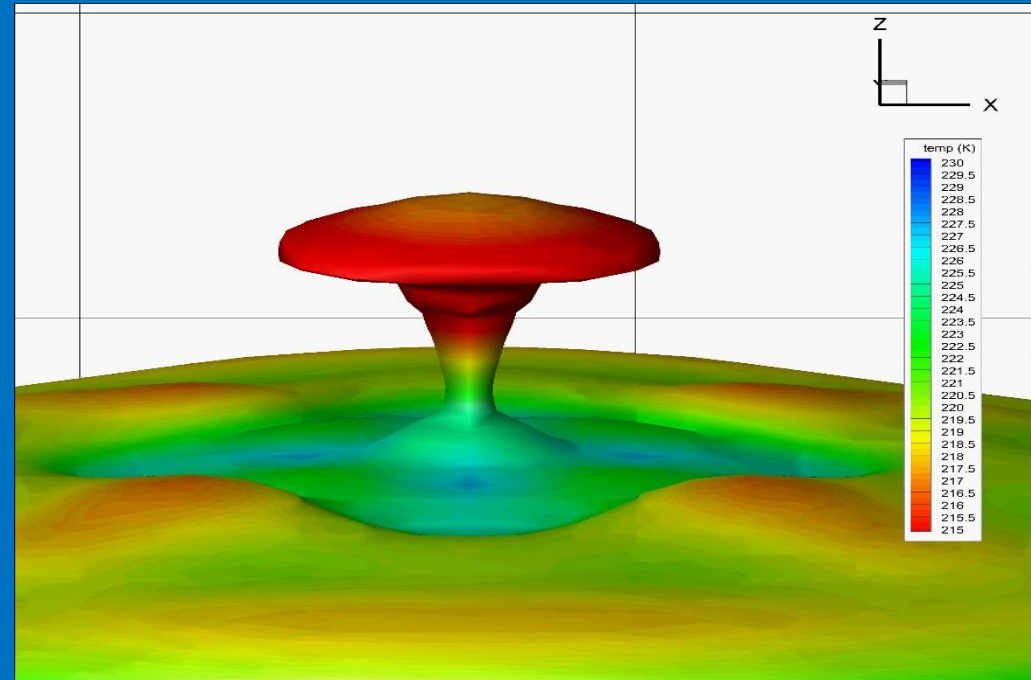
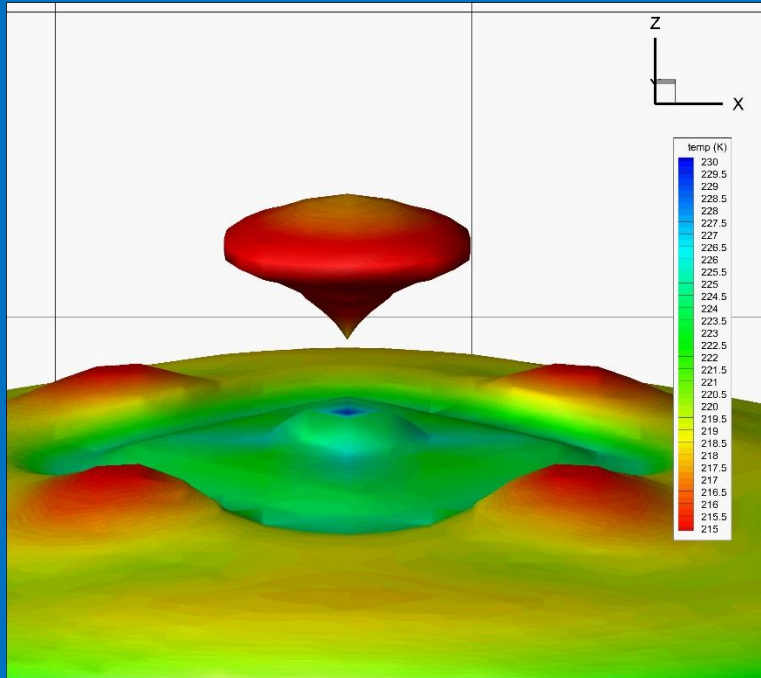
Courtesy of Martin Setvak



Pancake formation due to mixing instability

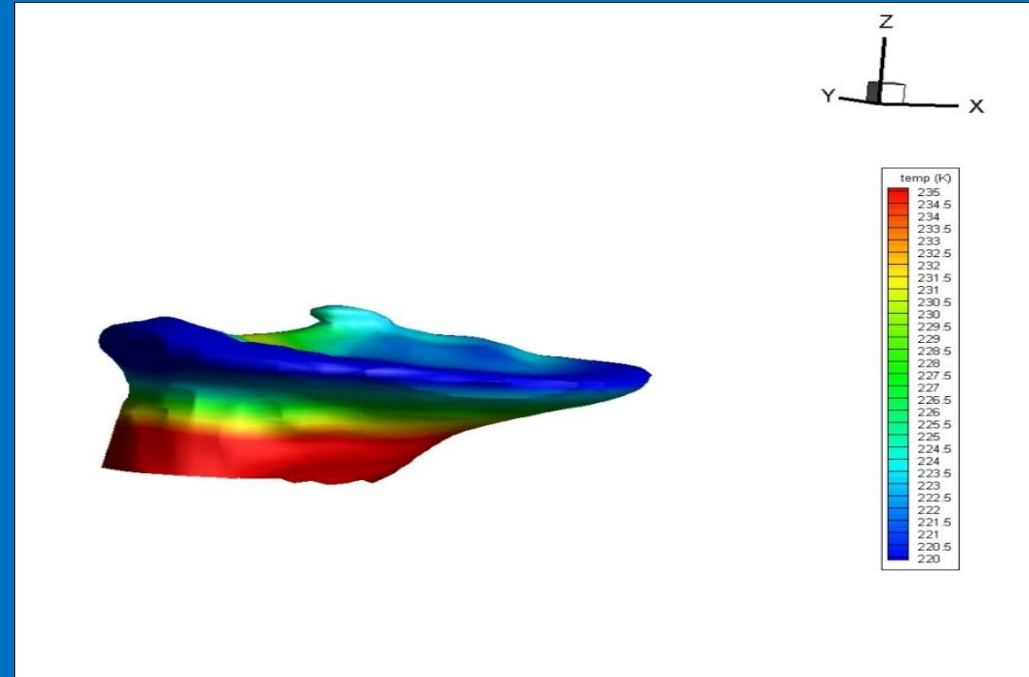
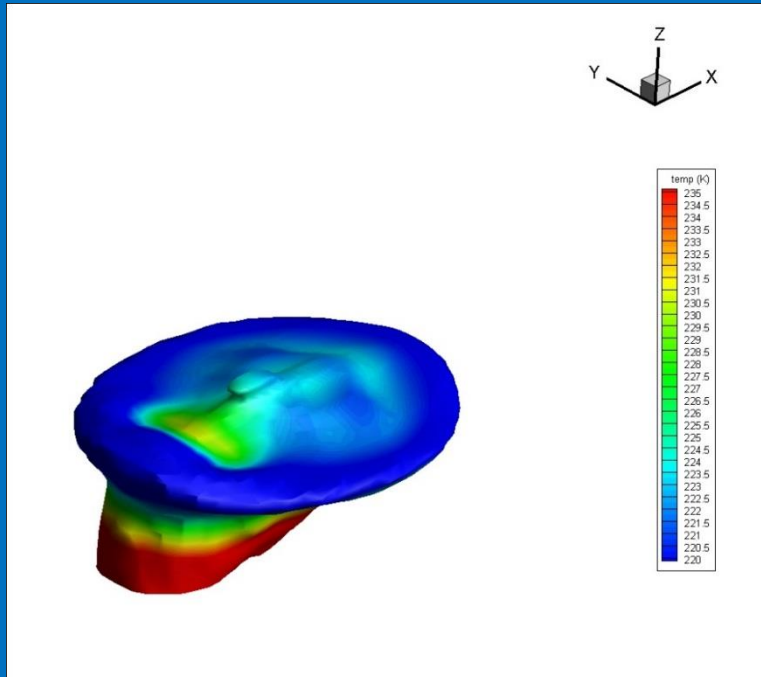


This feature may appear more often in rapid or super-rapid scan images



HIGHER BUT WARMER ?!

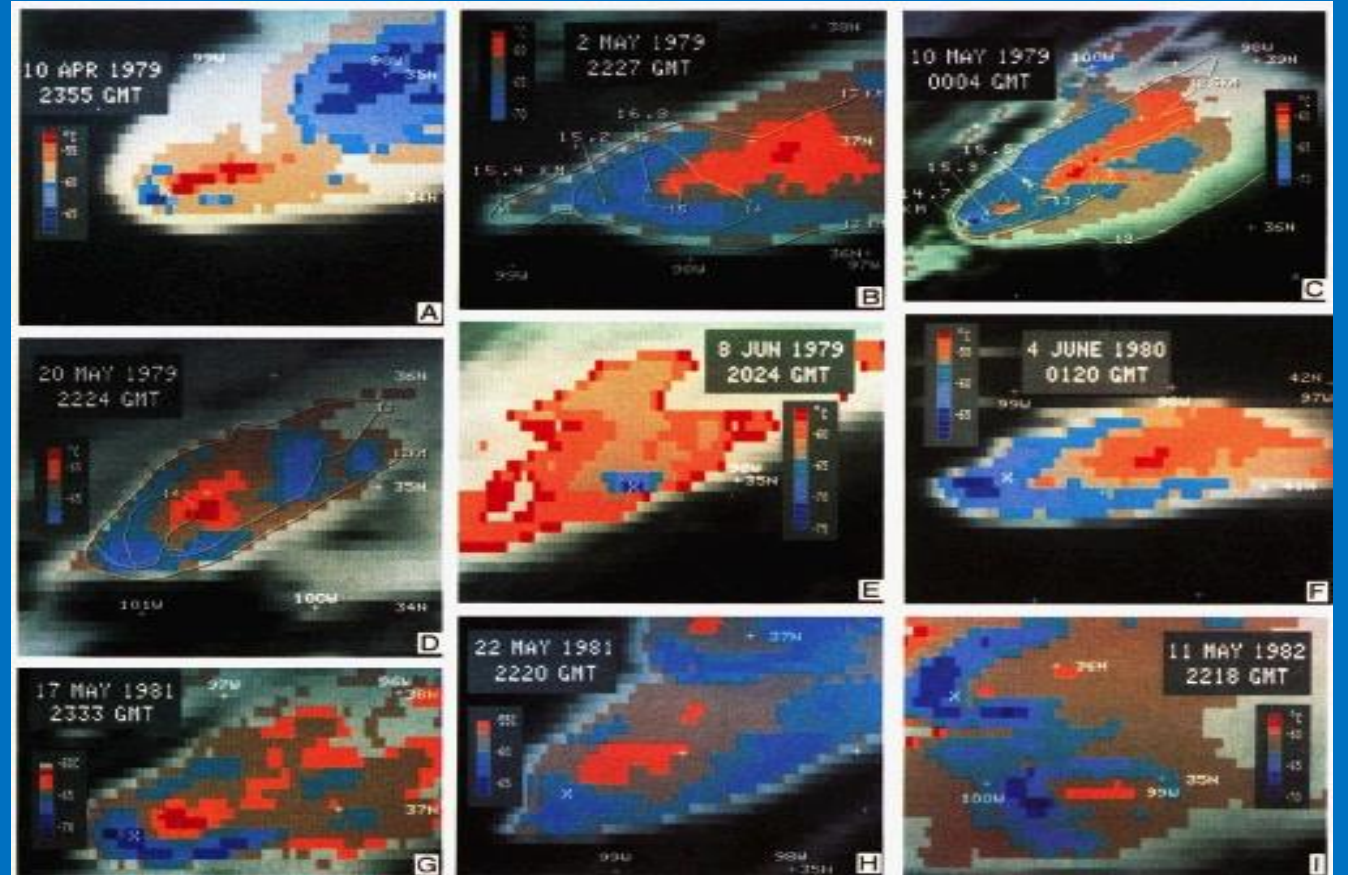
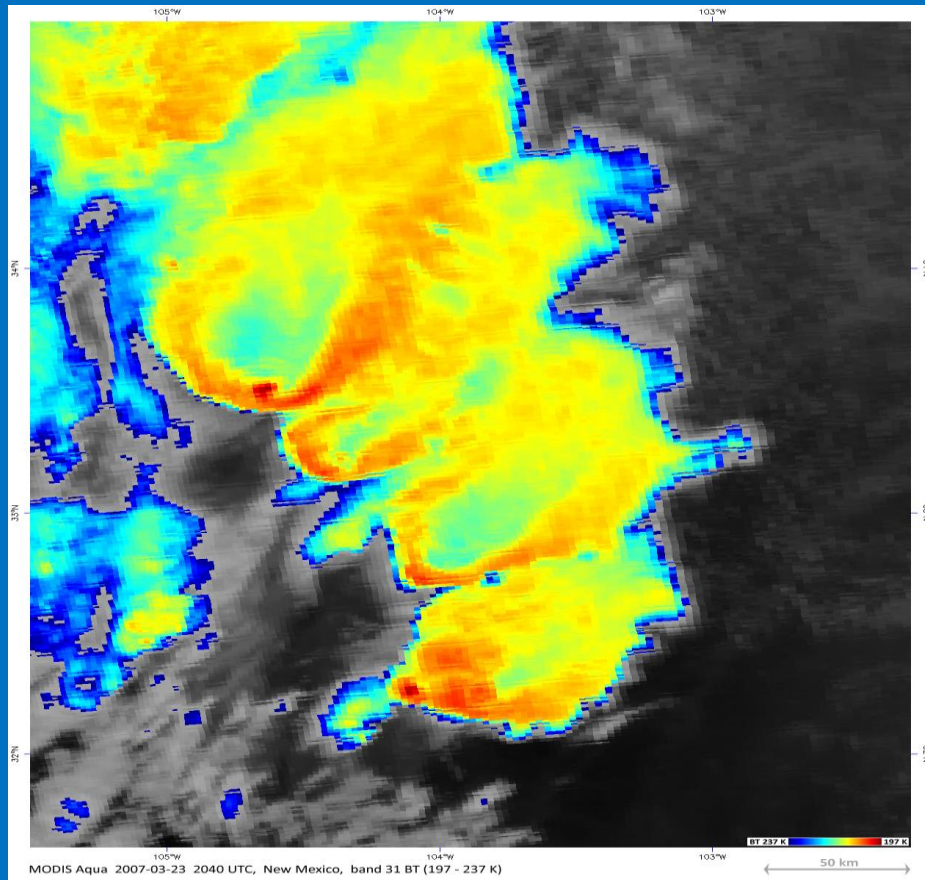
Wave breaking and mixing

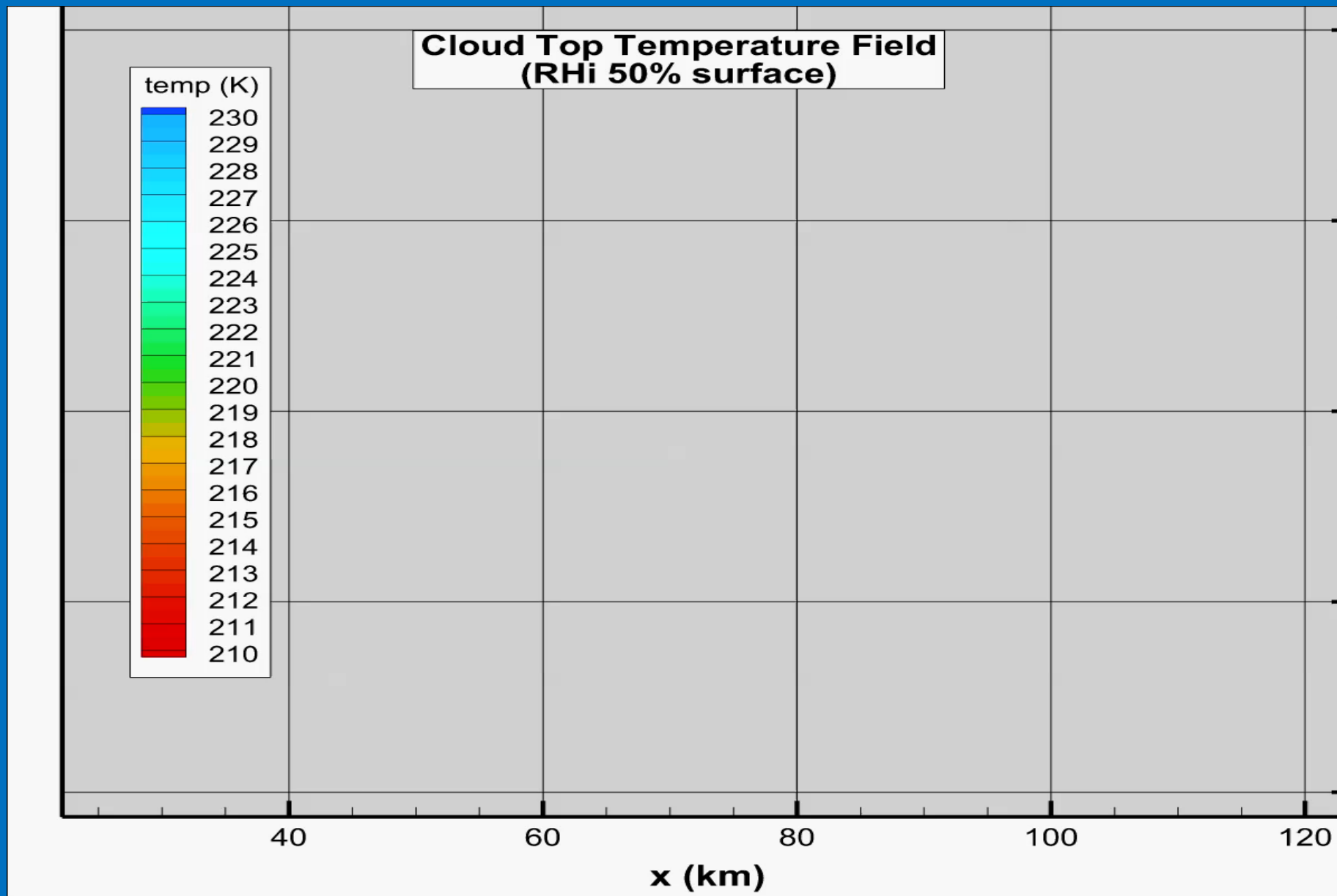


When wind shear is present

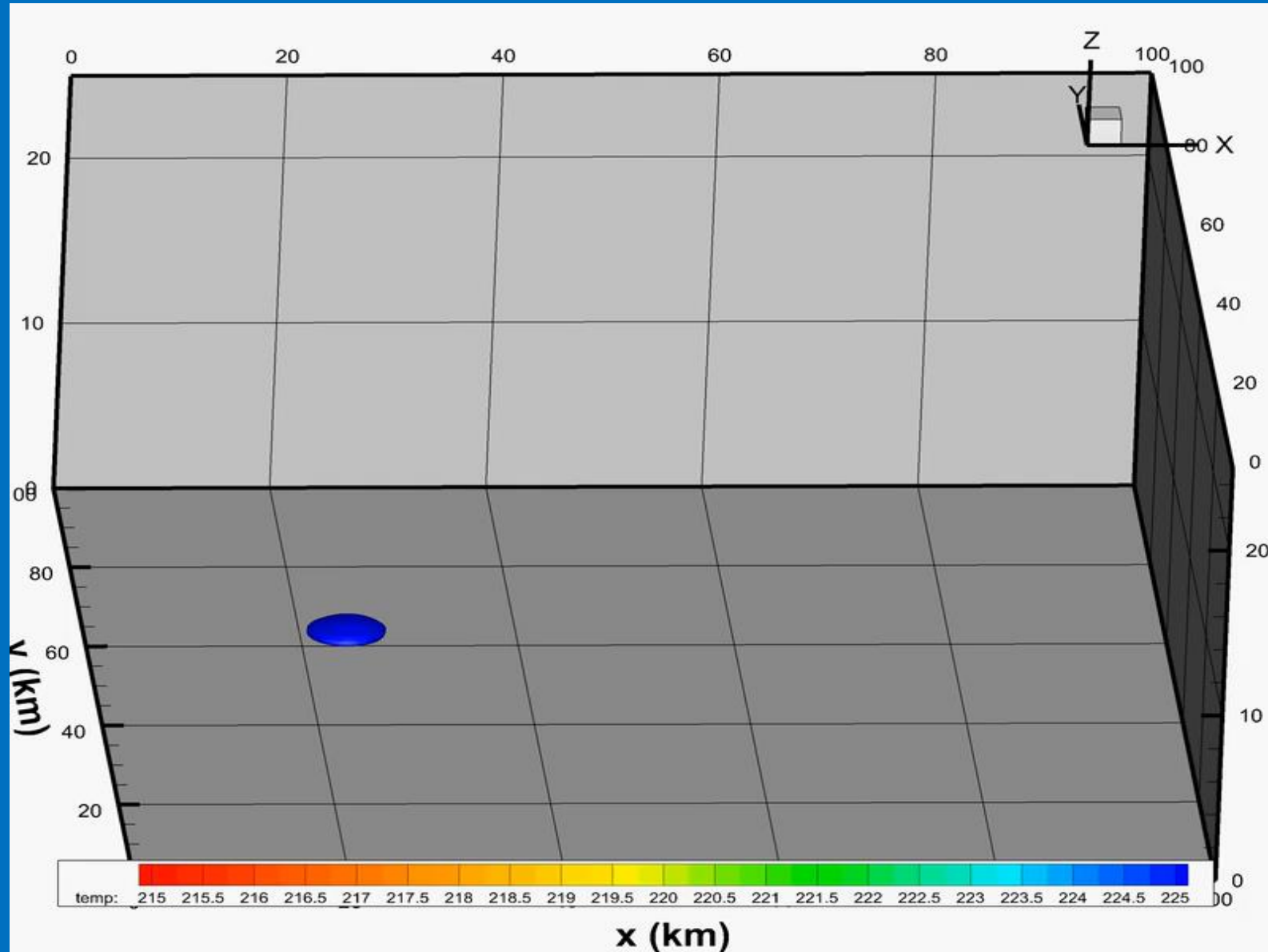
- Interaction between ambient wind and updraft
- Updraft behaves like an obstacle—moving mountain-- to the ambient wind, causing
 - Cold-U (V) upstream of OT
 - Mountain wave → close in warm area (CWA)
 - Above anvil cirrus plumes, jumping cirrus and gullwing cirrus due to gravity wave breaking
 - Storm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

Cold-U or V, CWA, DWA

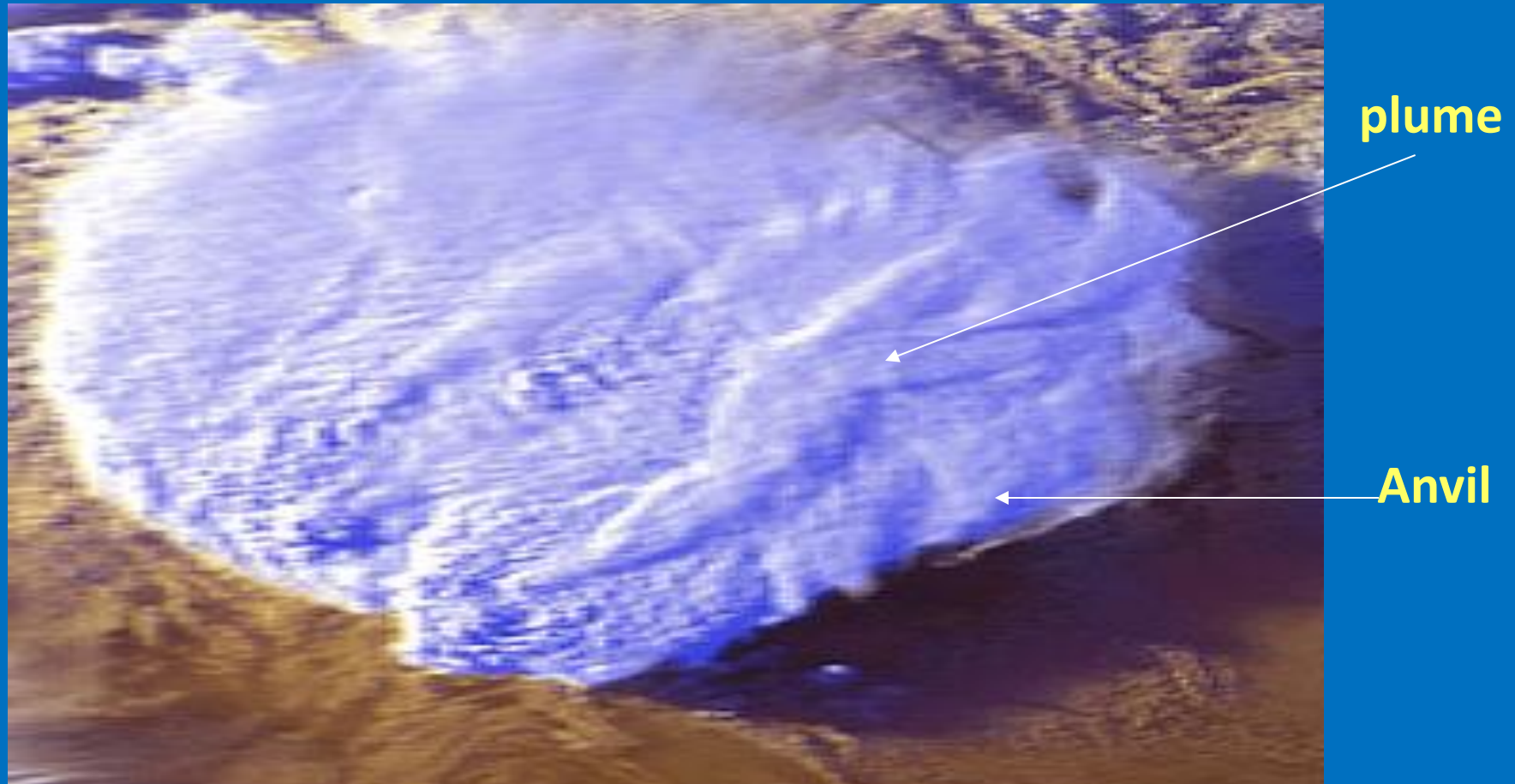




OT can be warm some times



Above anvil cirrus plumes

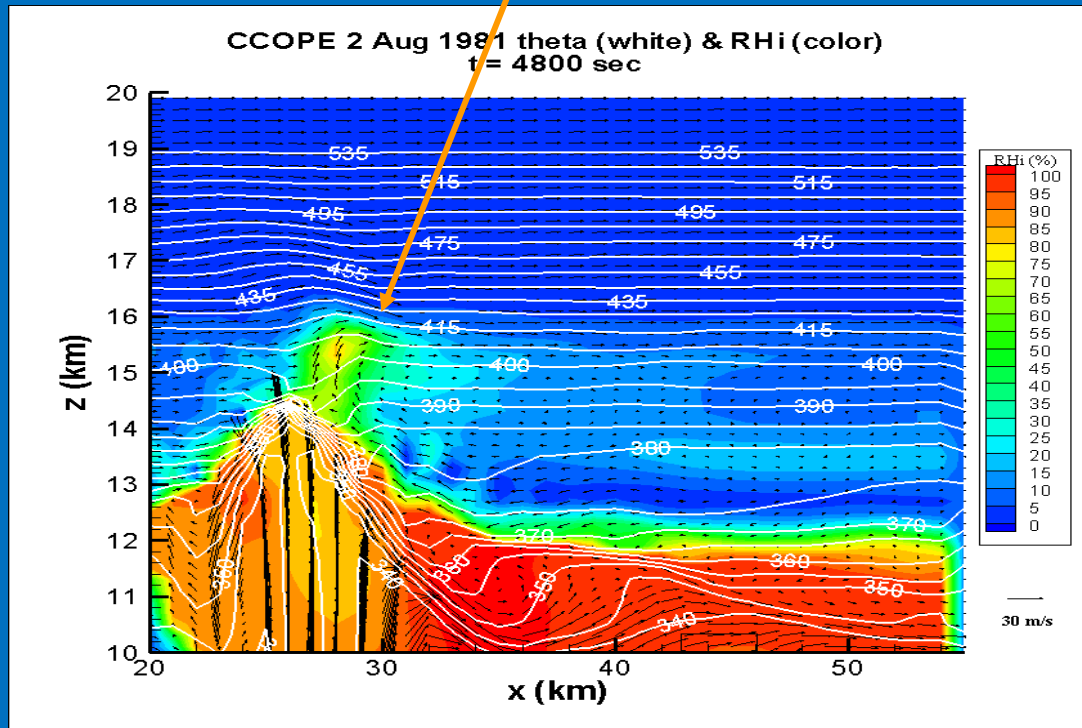


Storms over Balearic Islands (Martin Setvak)

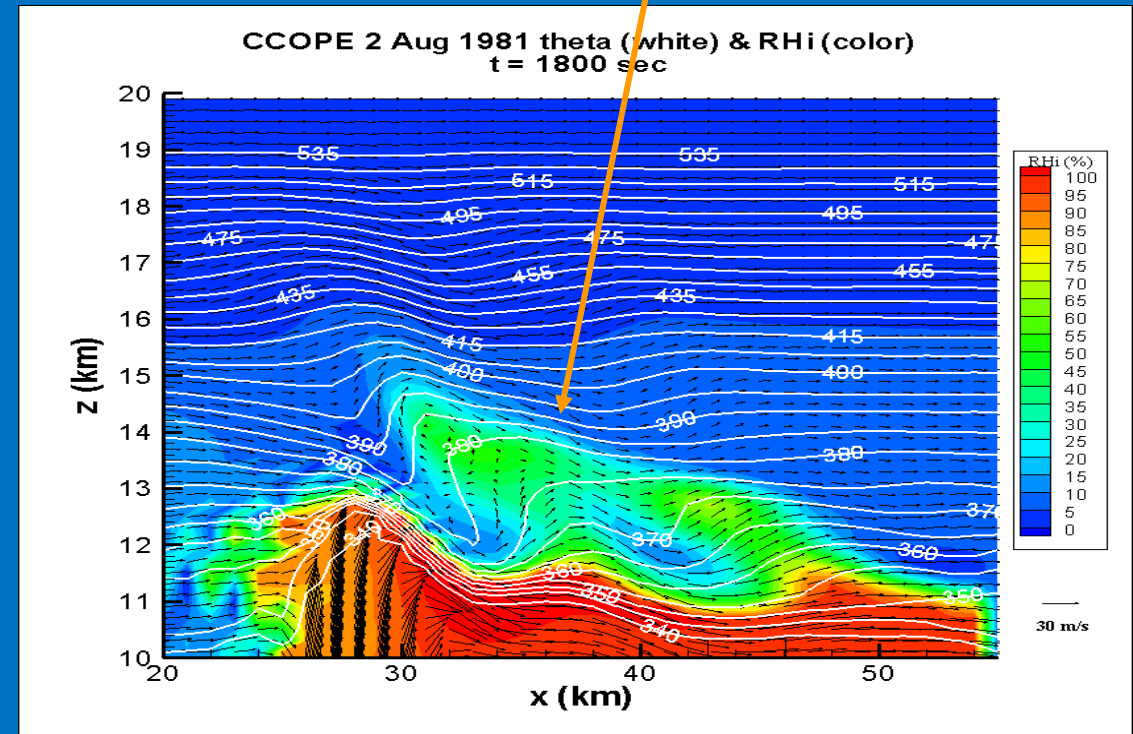
Instability and Wave Breaking

- 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



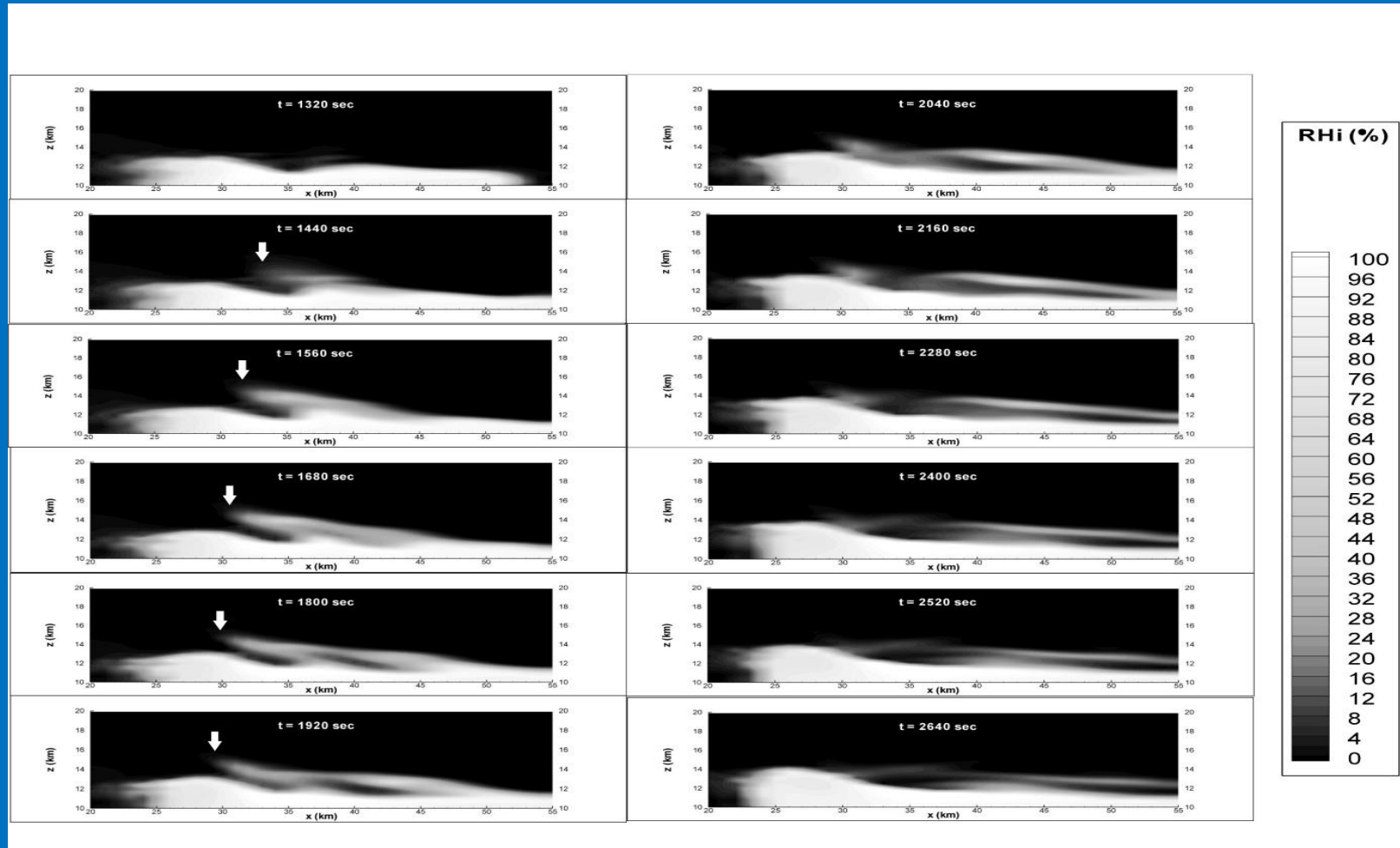
Fujita's jumping cirrus

“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:

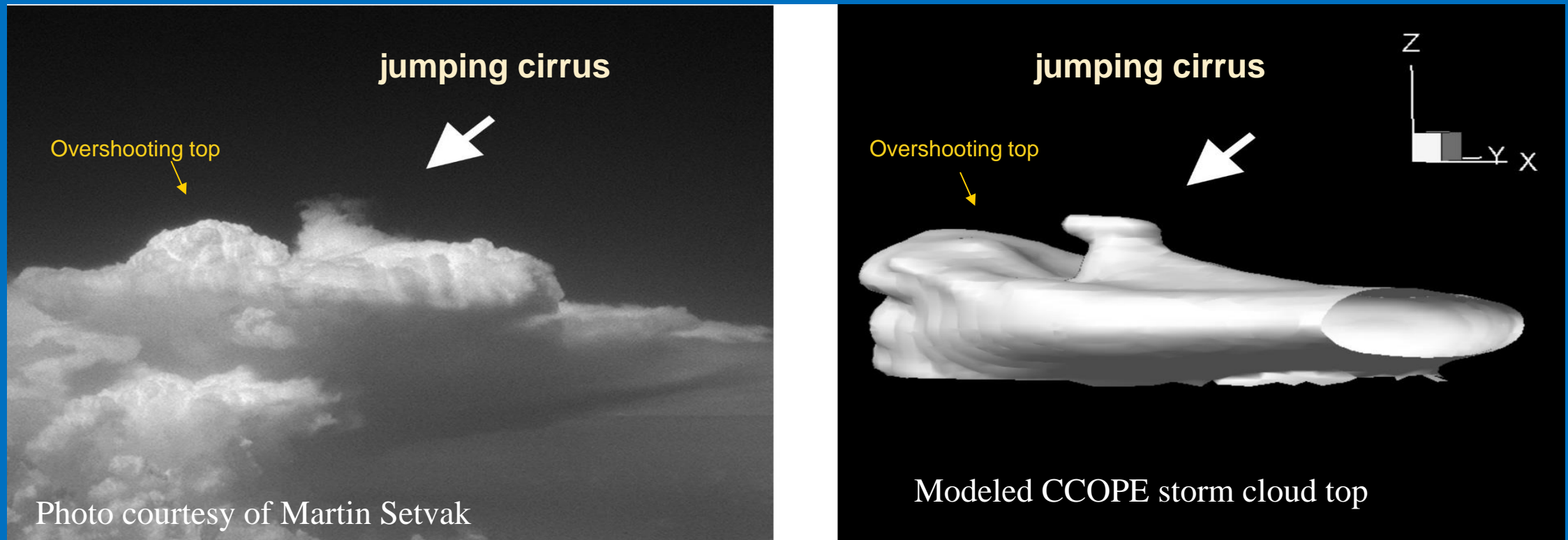
- (1) Clean overshooting domes
- (2) Curly-hair cirrus
- (3) **Fountain cirrus** – cirrus, which splashes up like a fountain, 1 to 2 min after an overshooting dome collapses into an anvil. This appears to be what mentioned in the quotation above.
- (4) **Flare cirrus** – cirrus that jumps 1 to 3 km above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

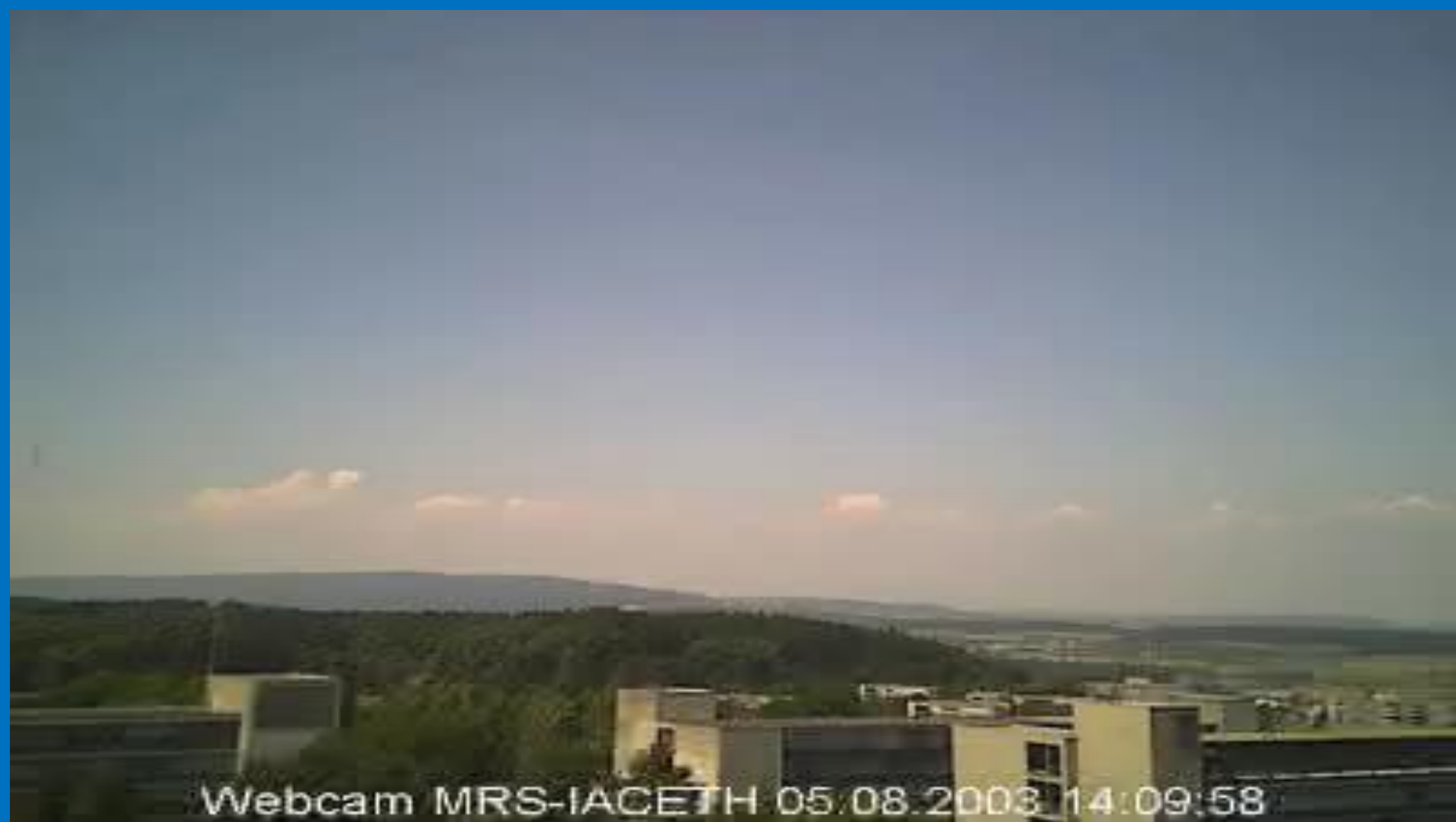


Fujita (1982, 1989) observed jumping cirrus above severe storms – they are also due to wave breaking

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



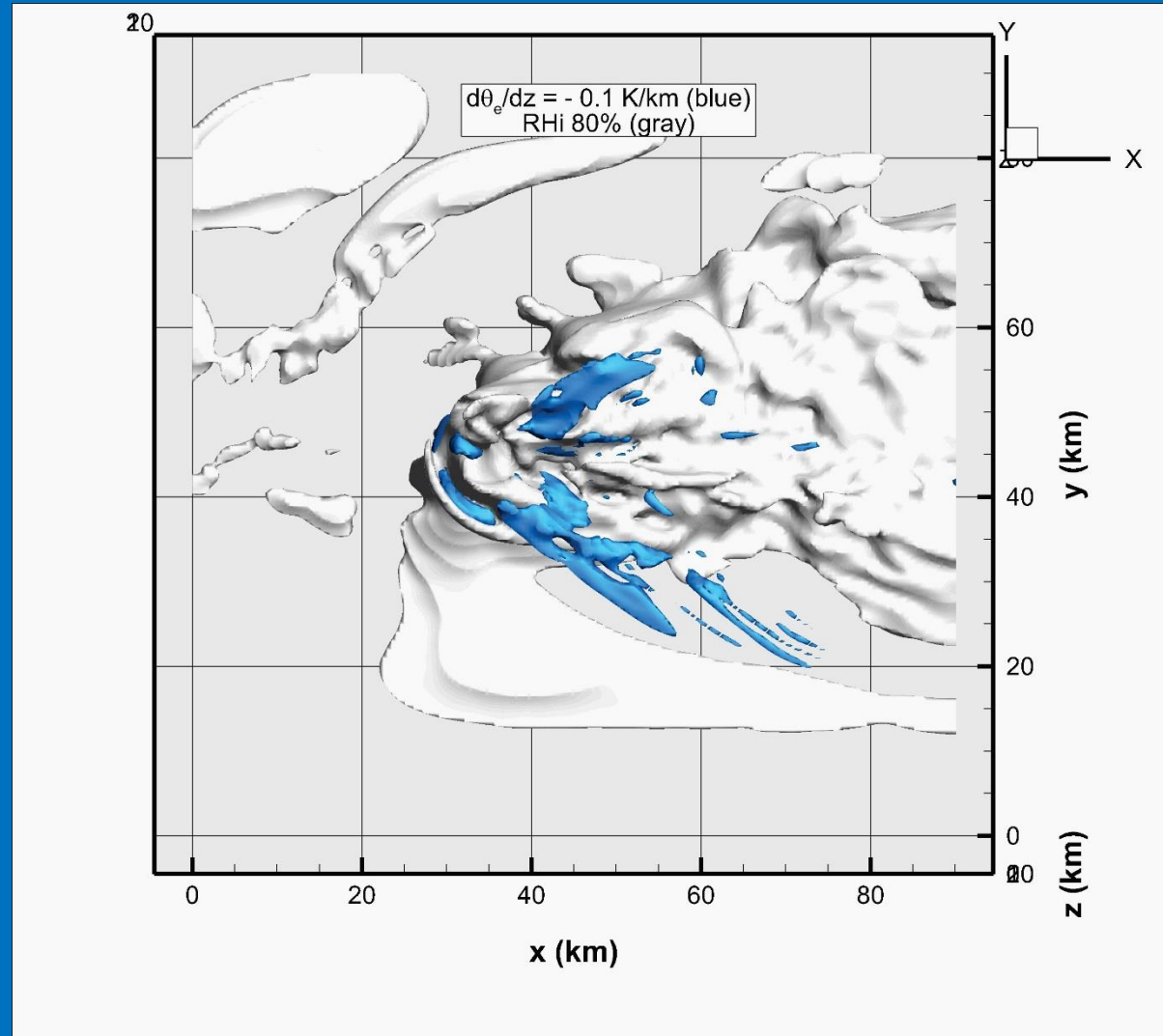
From: Wang (2004, GRL)



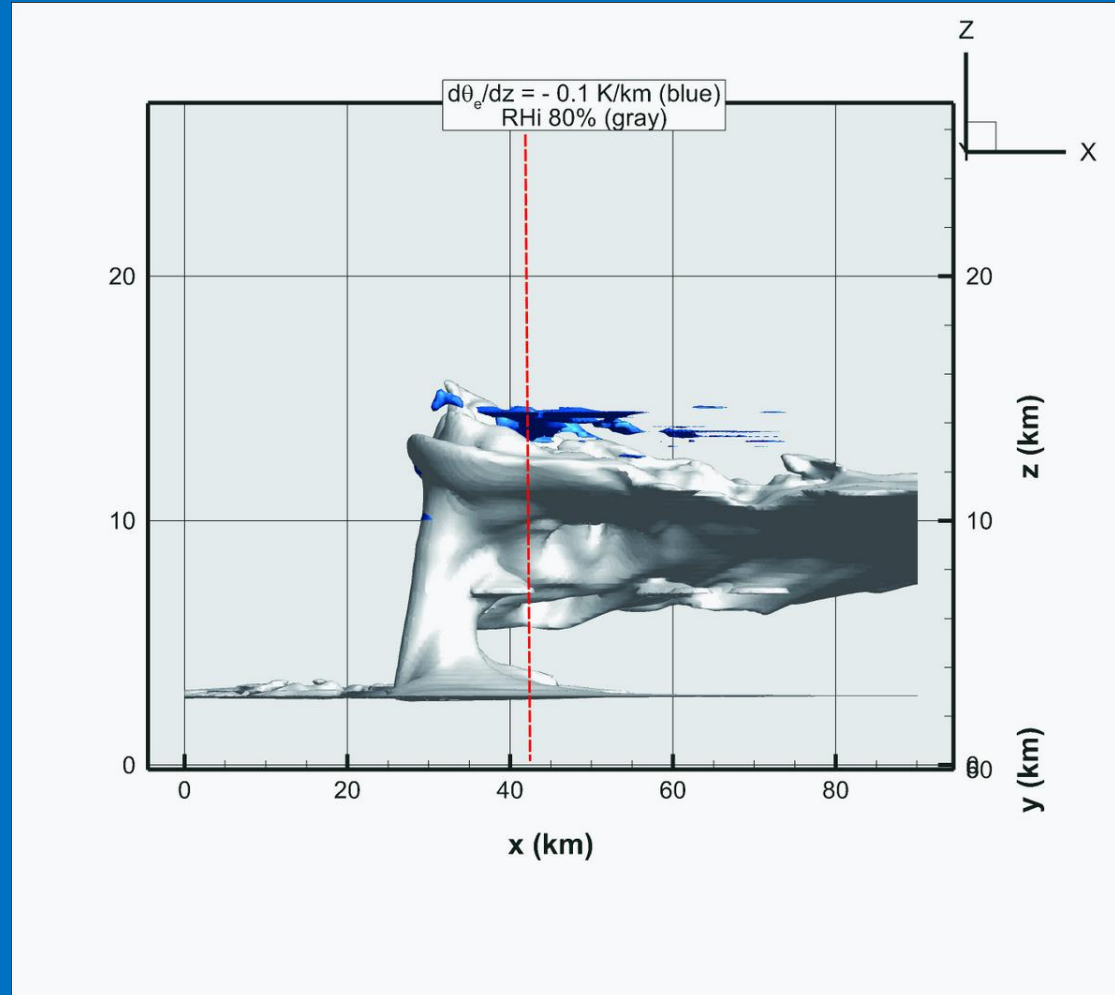
Webcam MRS-IACETH 05.08.2003 14:09:58



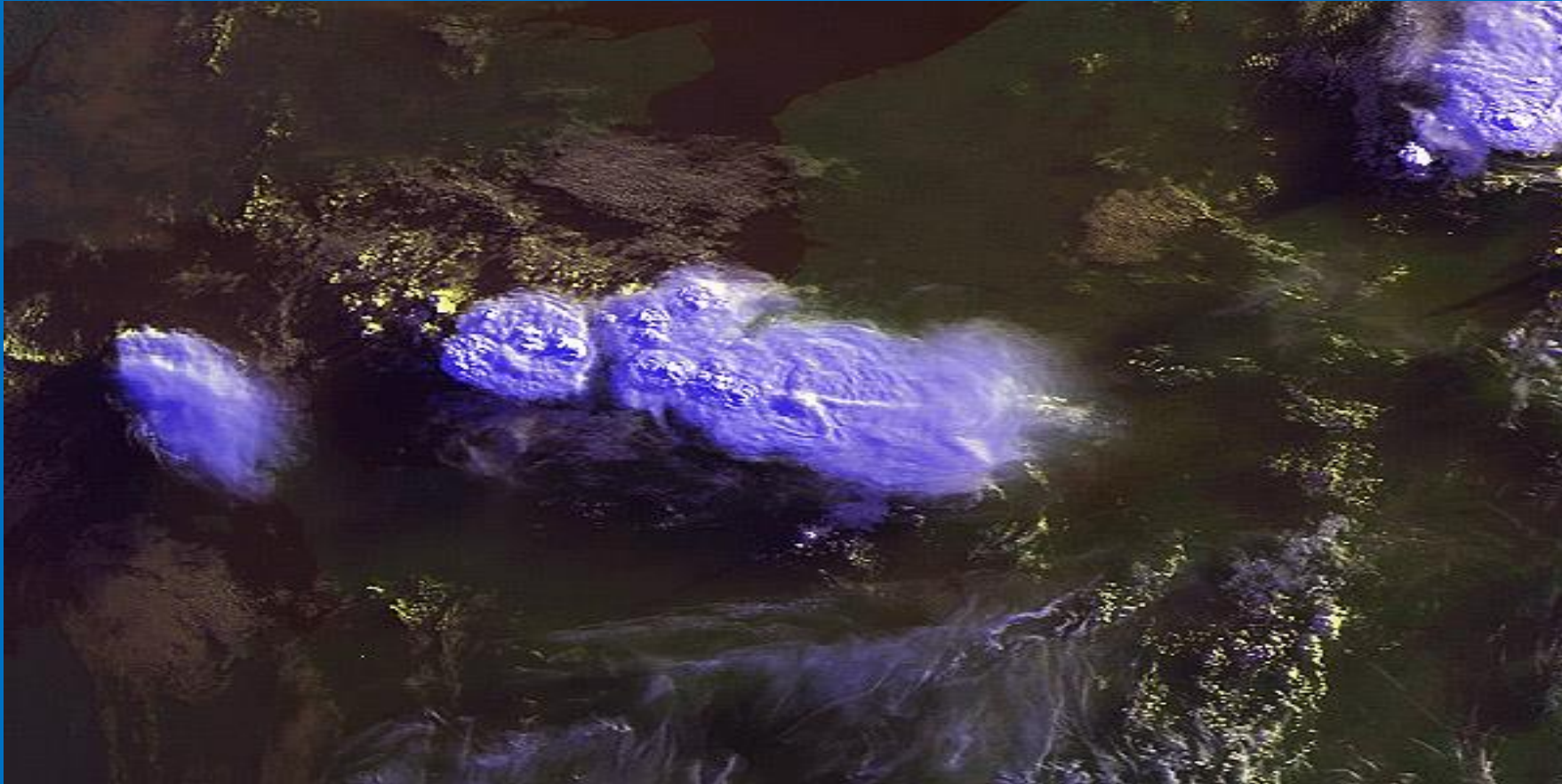
Where wave breaking occurs ($\partial\theta/\partial z \leq 0$)



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



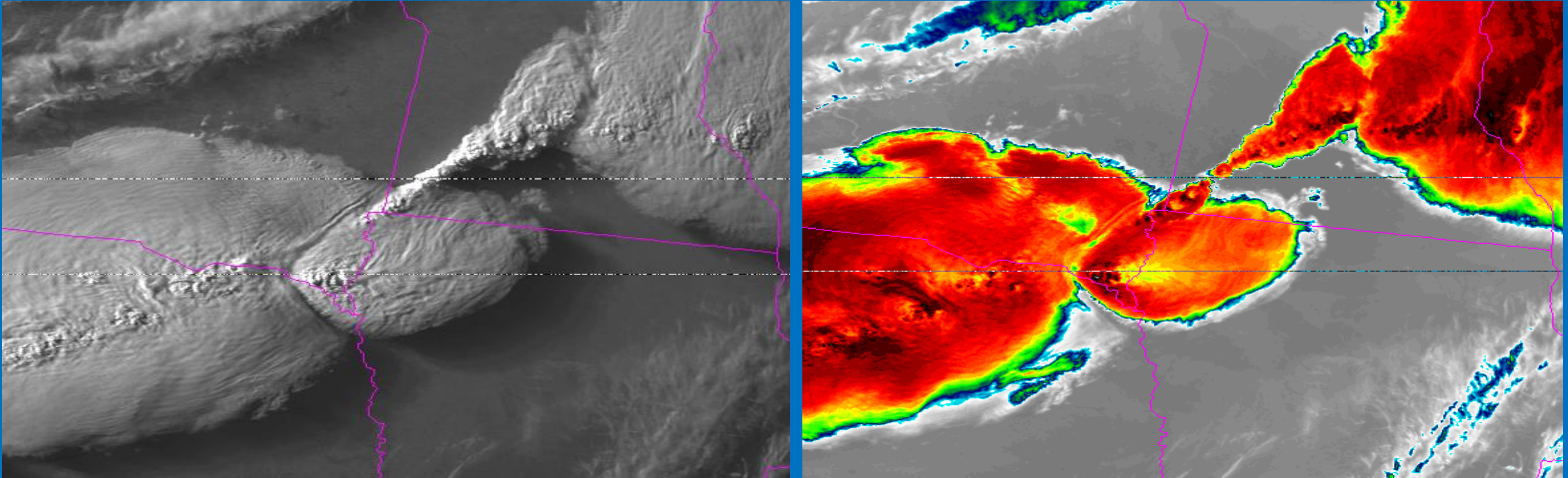
Storm top ship waves



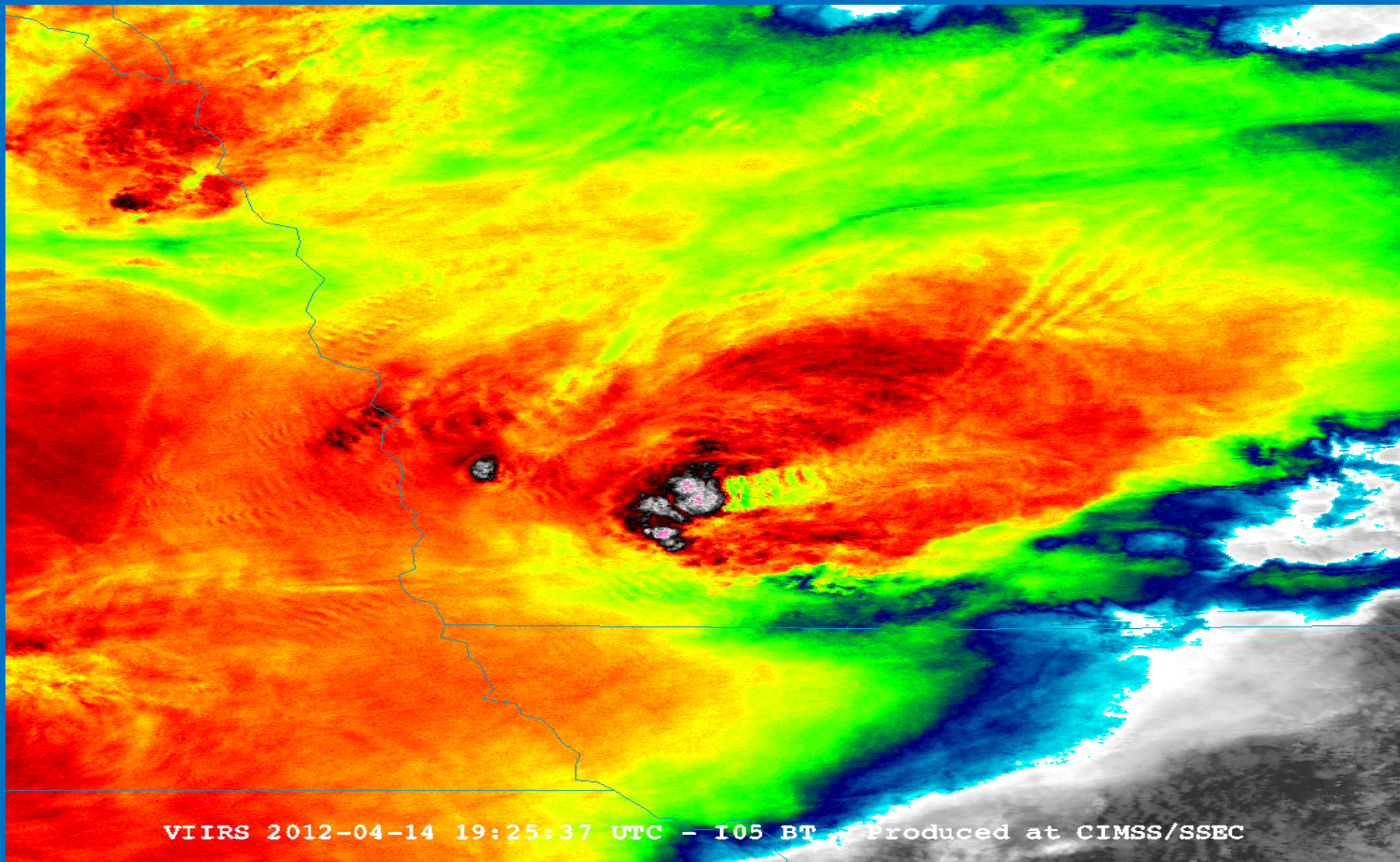
Levizzani and Setvak (1996)



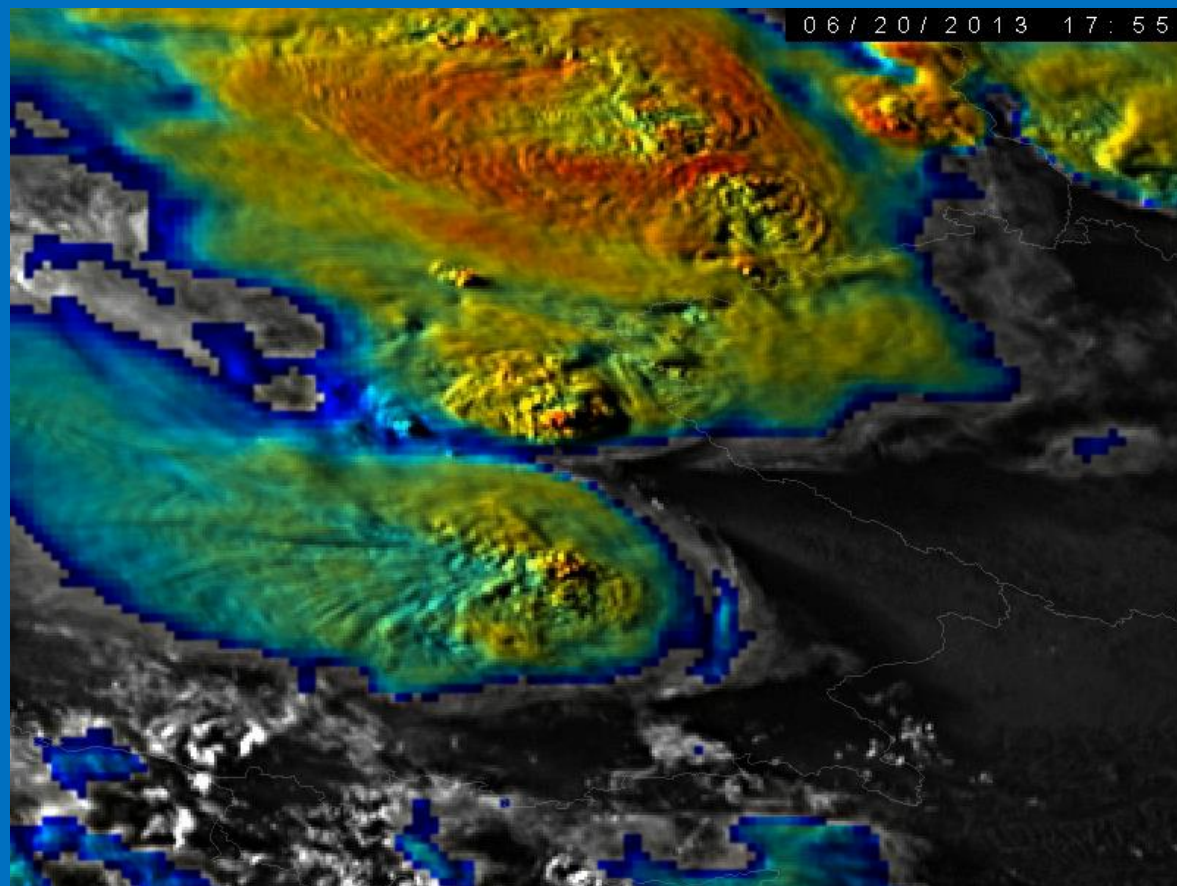
Storm top ship waves



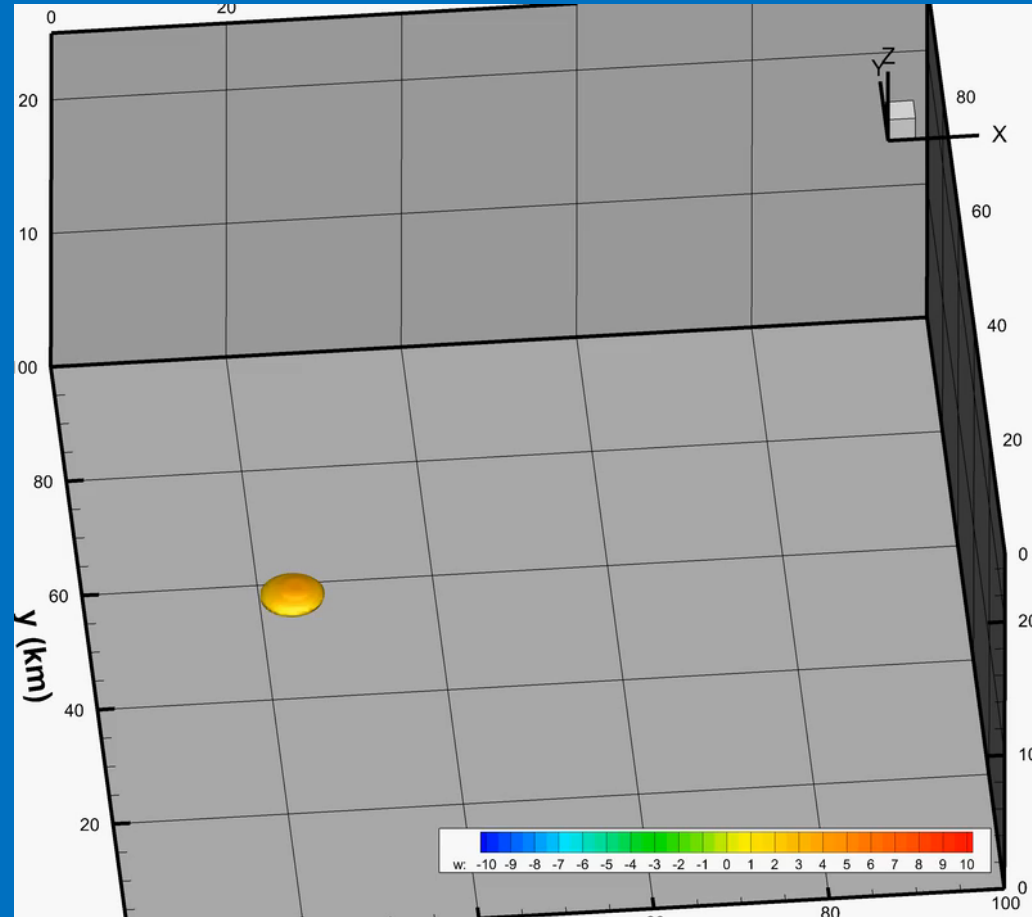
Courtesy of CIMMS/Scott Bachmeier



Courtesy of Kris Bedka



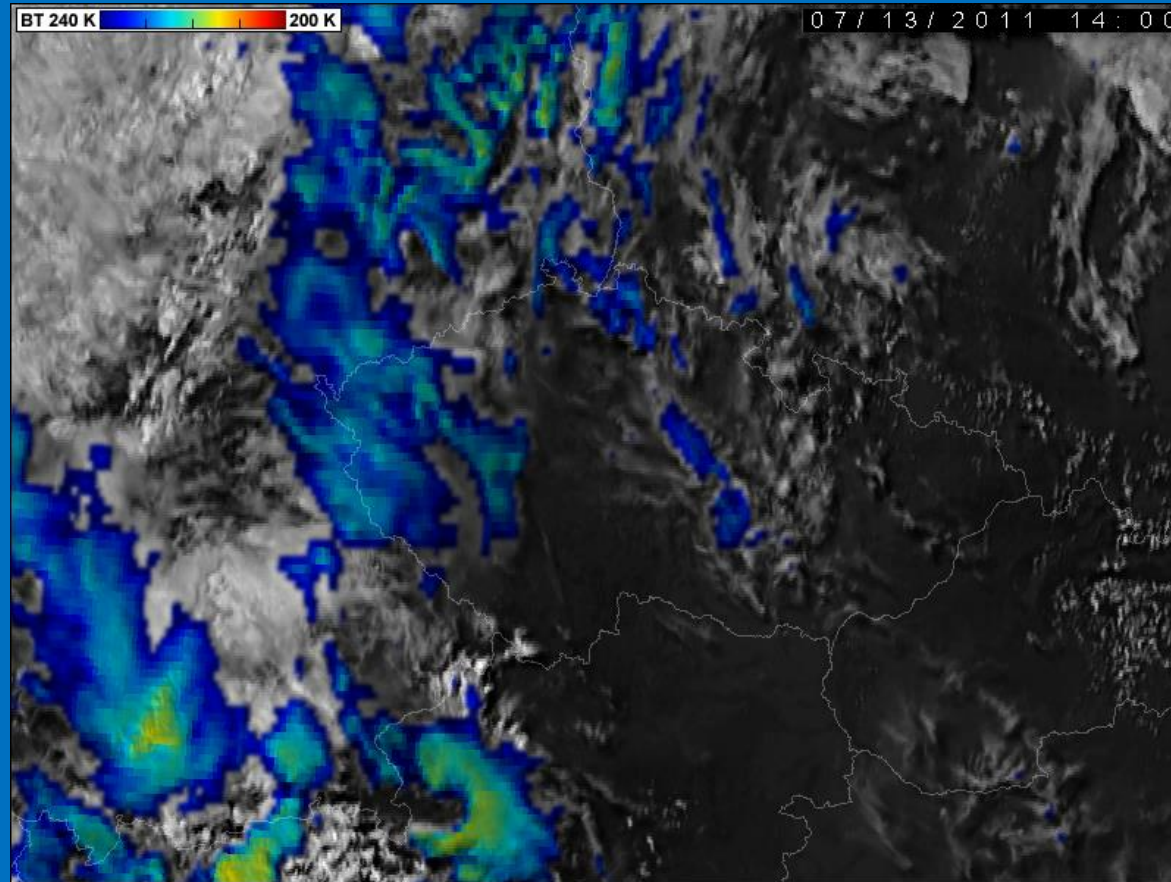
Courtesy of Martin Setvak



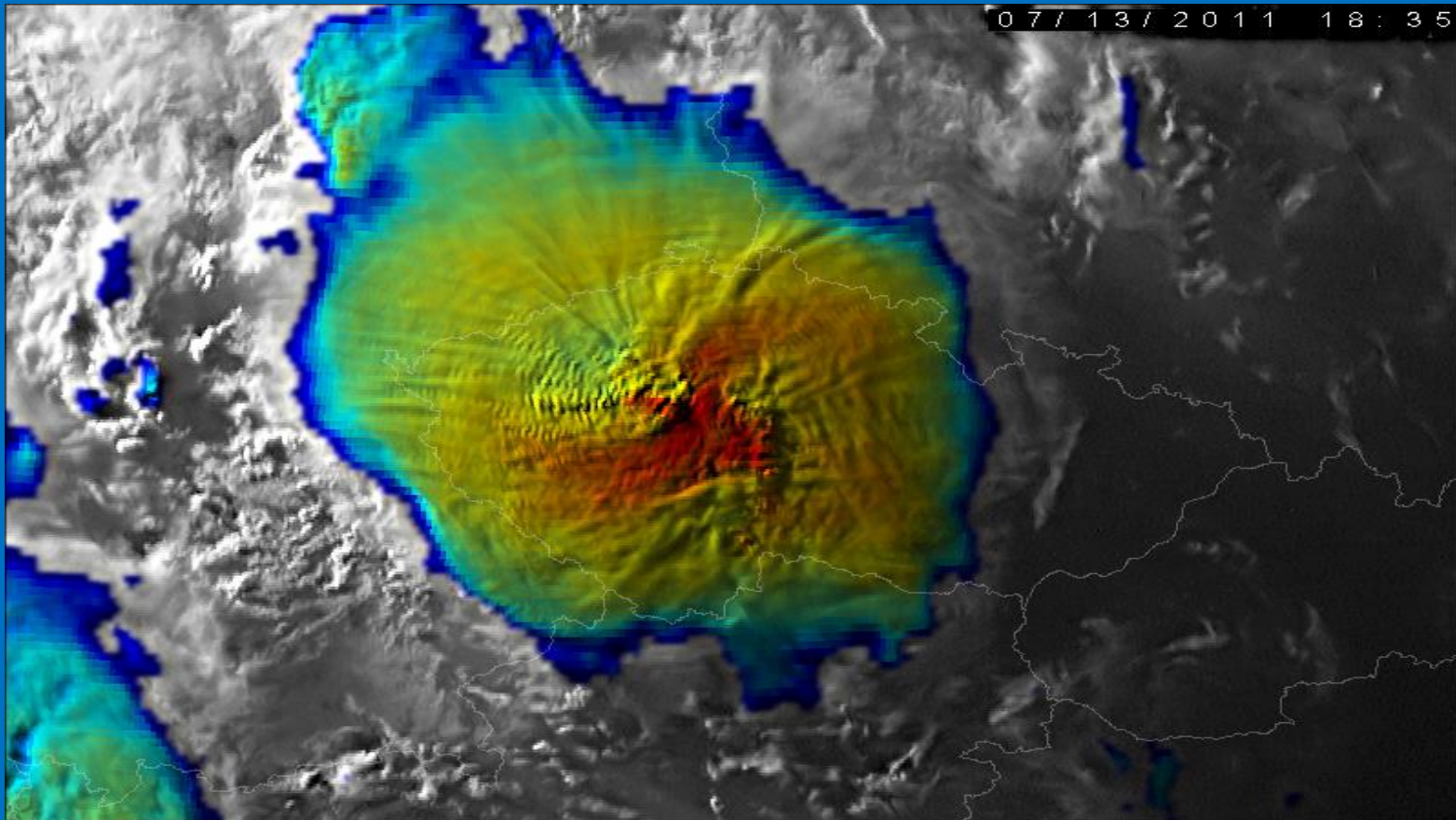
When multiple OTs are present

- Interference of IGW can happen
- Interference pattern in a moving fluid
- Curvature of some above anvil cirrus
- Storm top radial cirrus

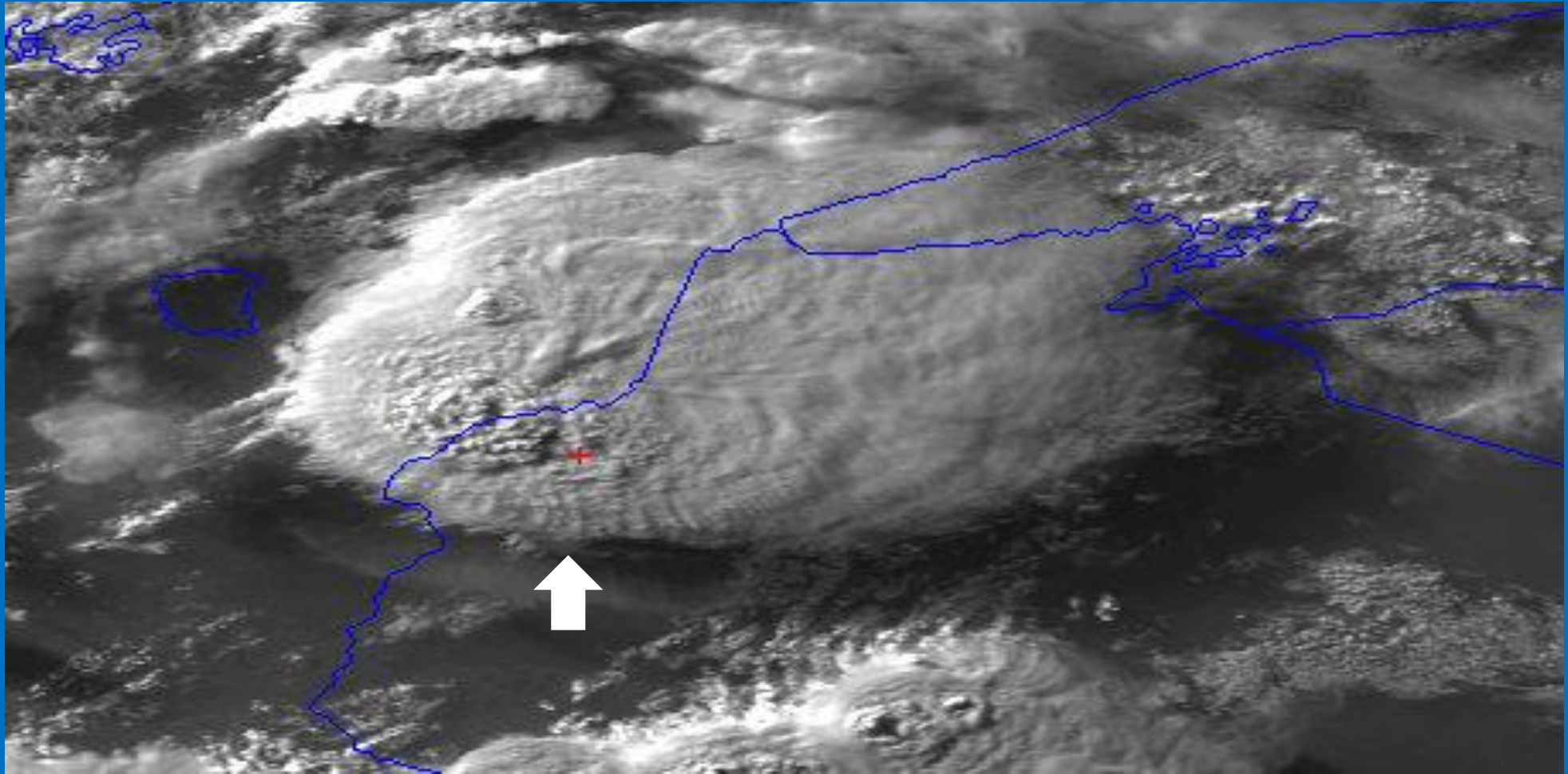
Storm top radial cirrus



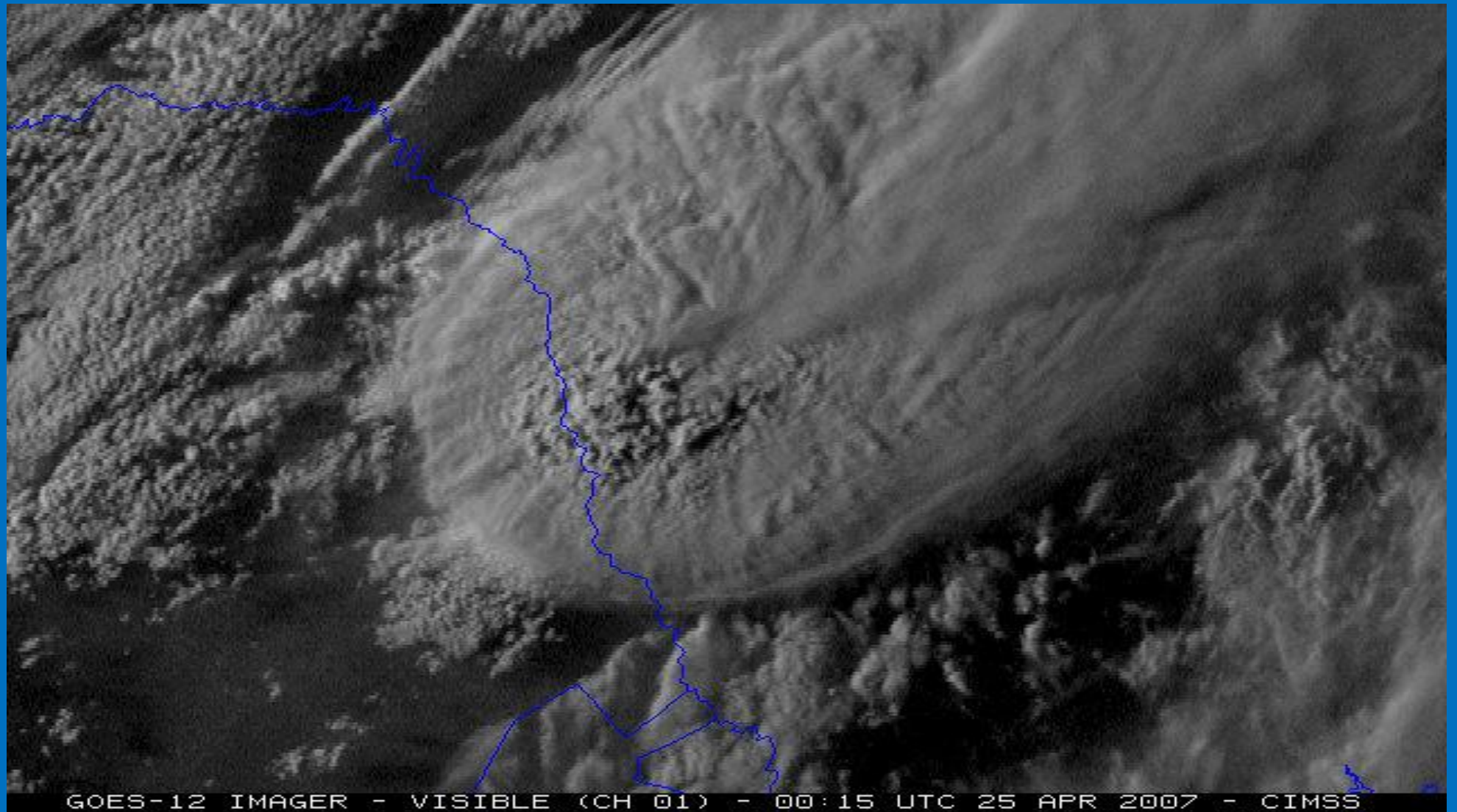
Courtesy of Martin Setvak



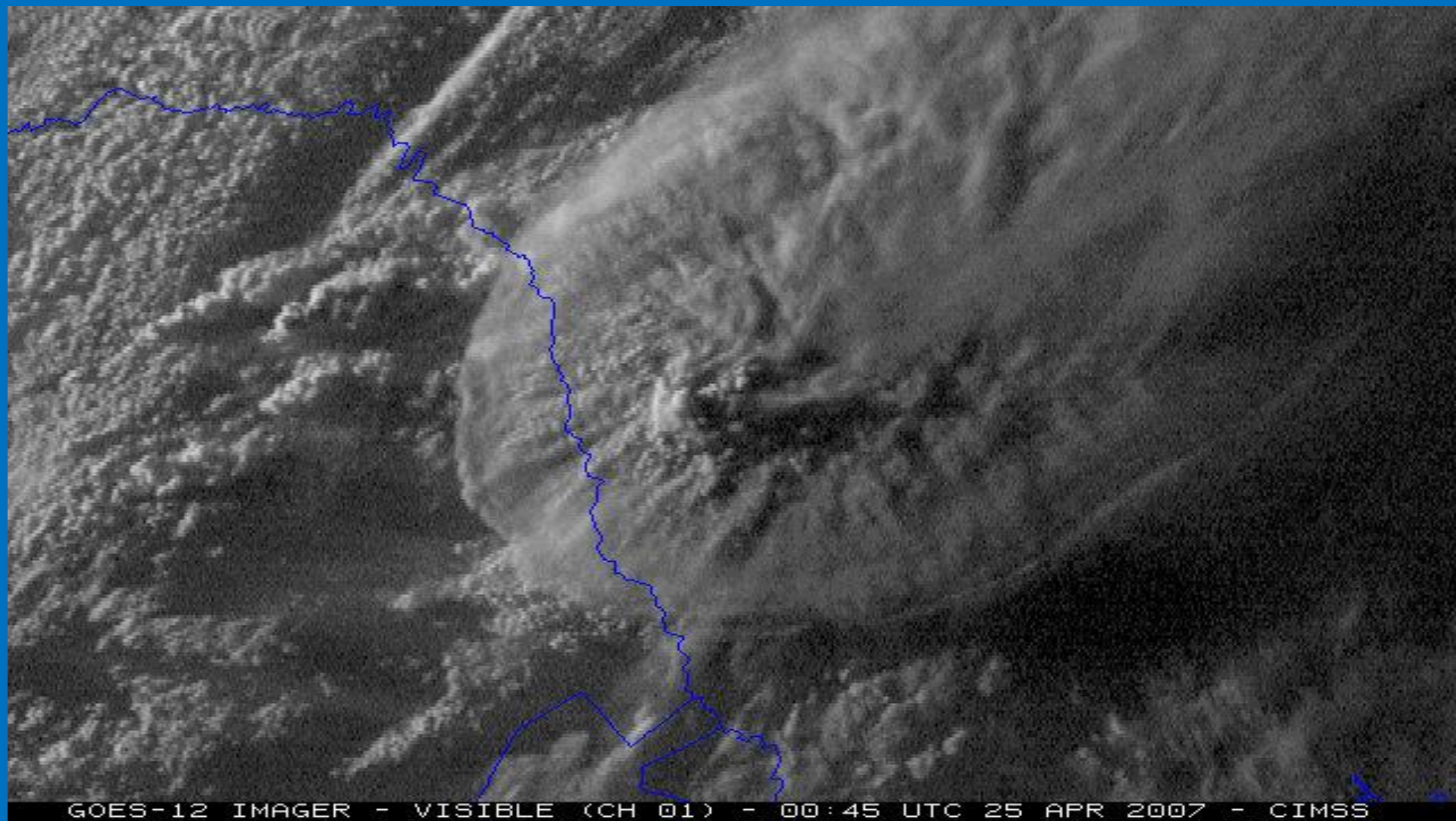
Courtesy of Martin Setvak



Courtesy of CIMMS/Scott Bachmeier



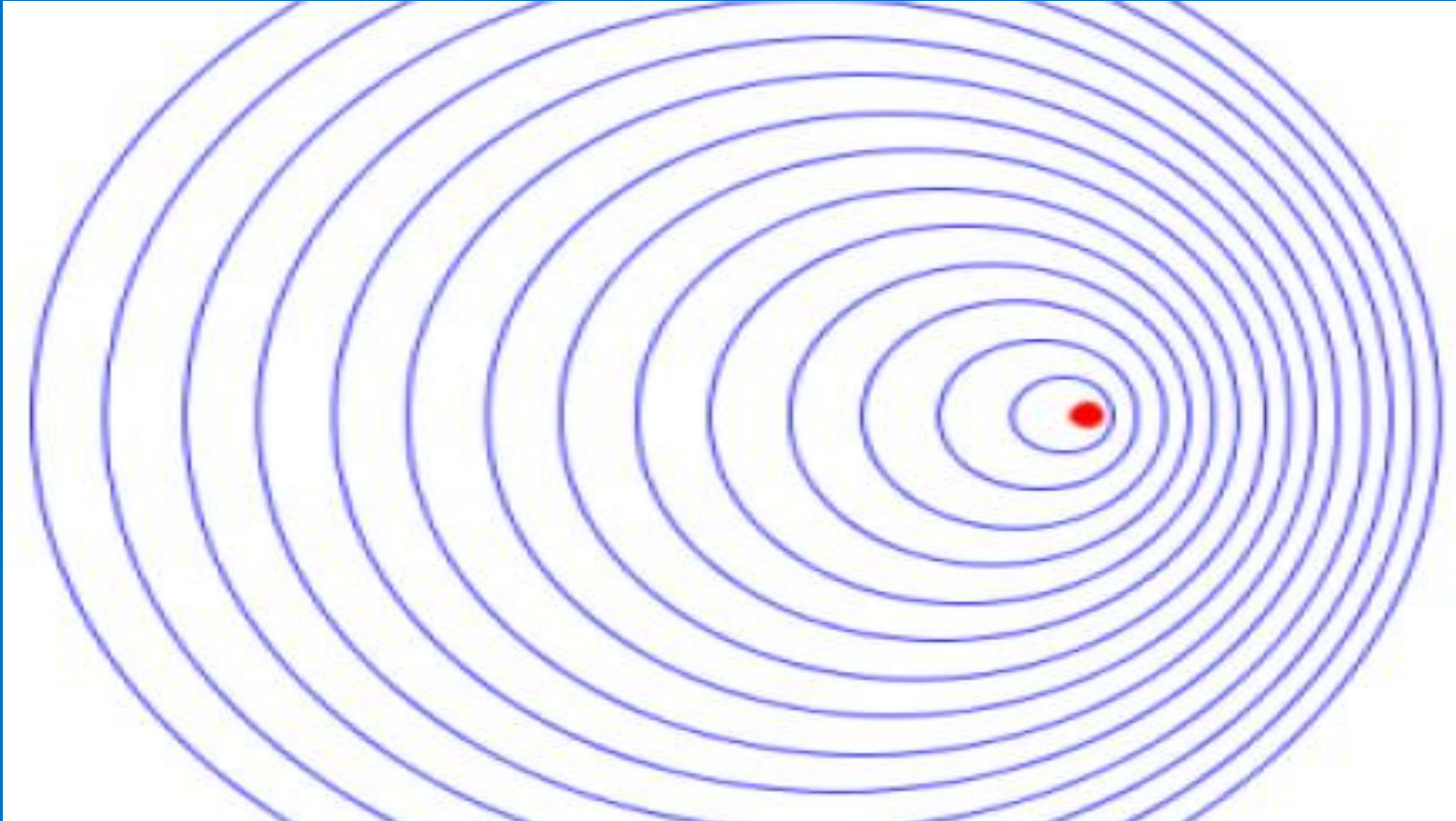
Courtesy of CIMSS/Scott Bachmeier

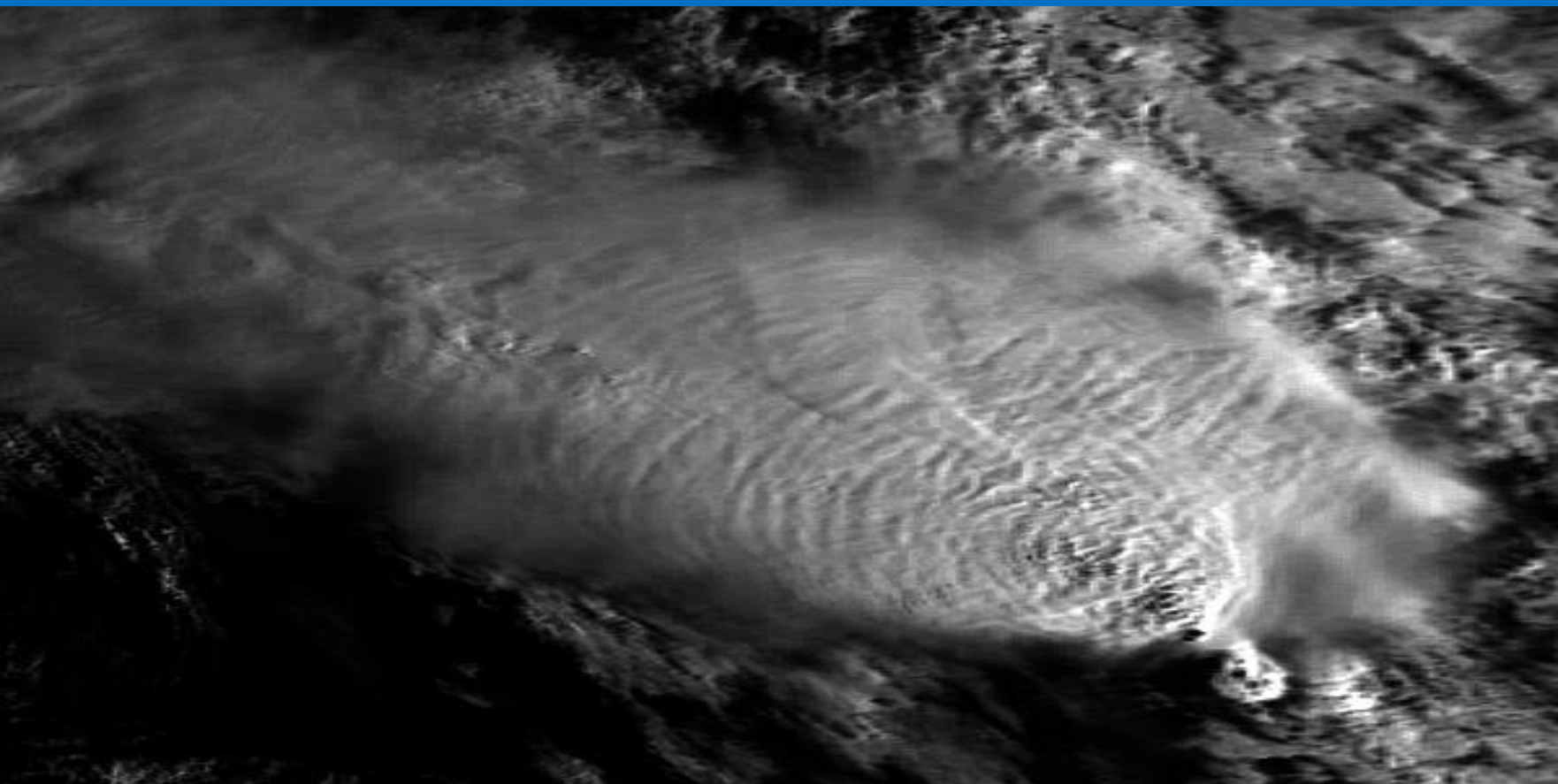


Courtesy of CIMSS/Scott Bachmeier

Wave in a moving fluid

← wind

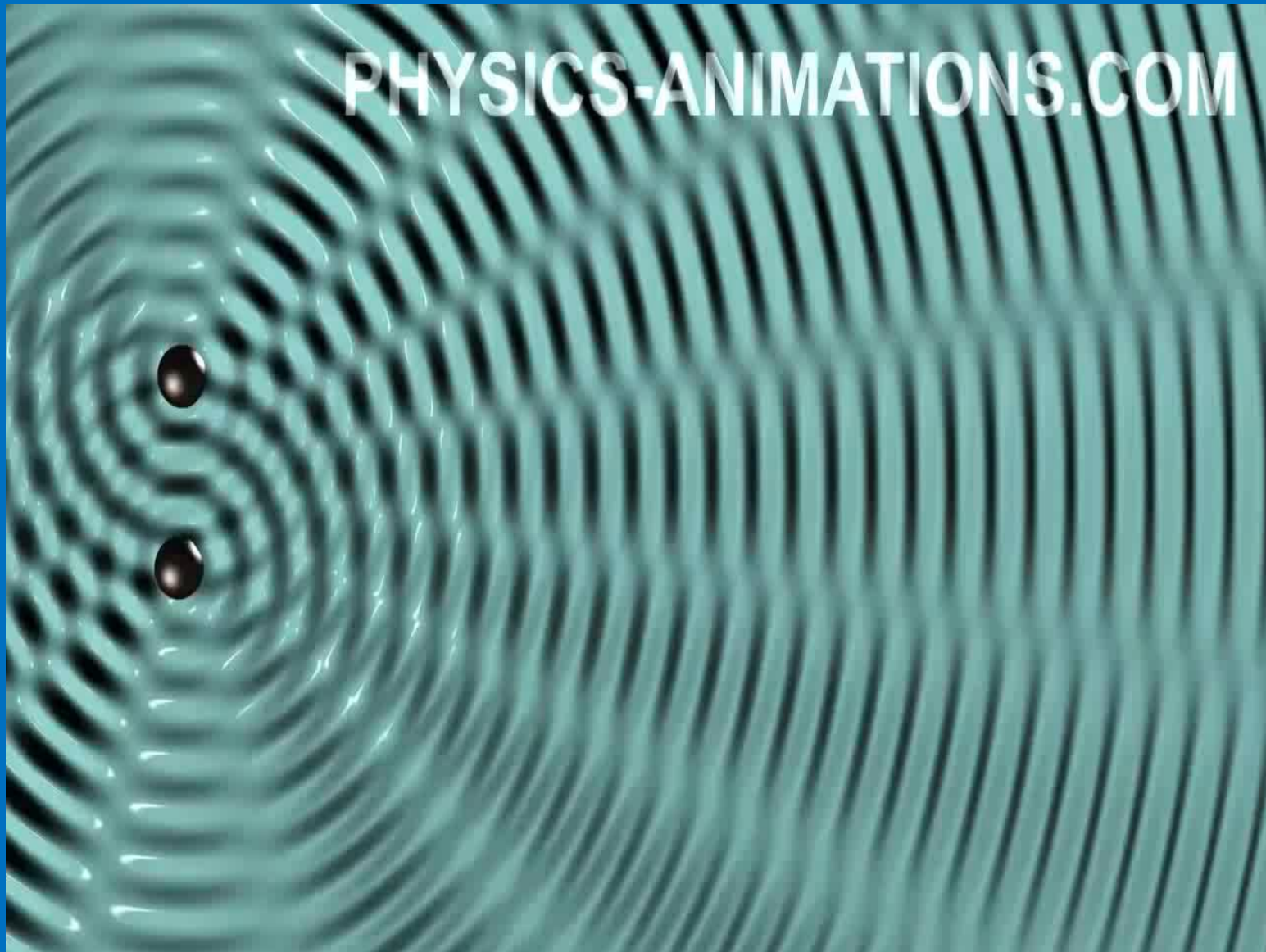




Courtesy of Martin Setvak

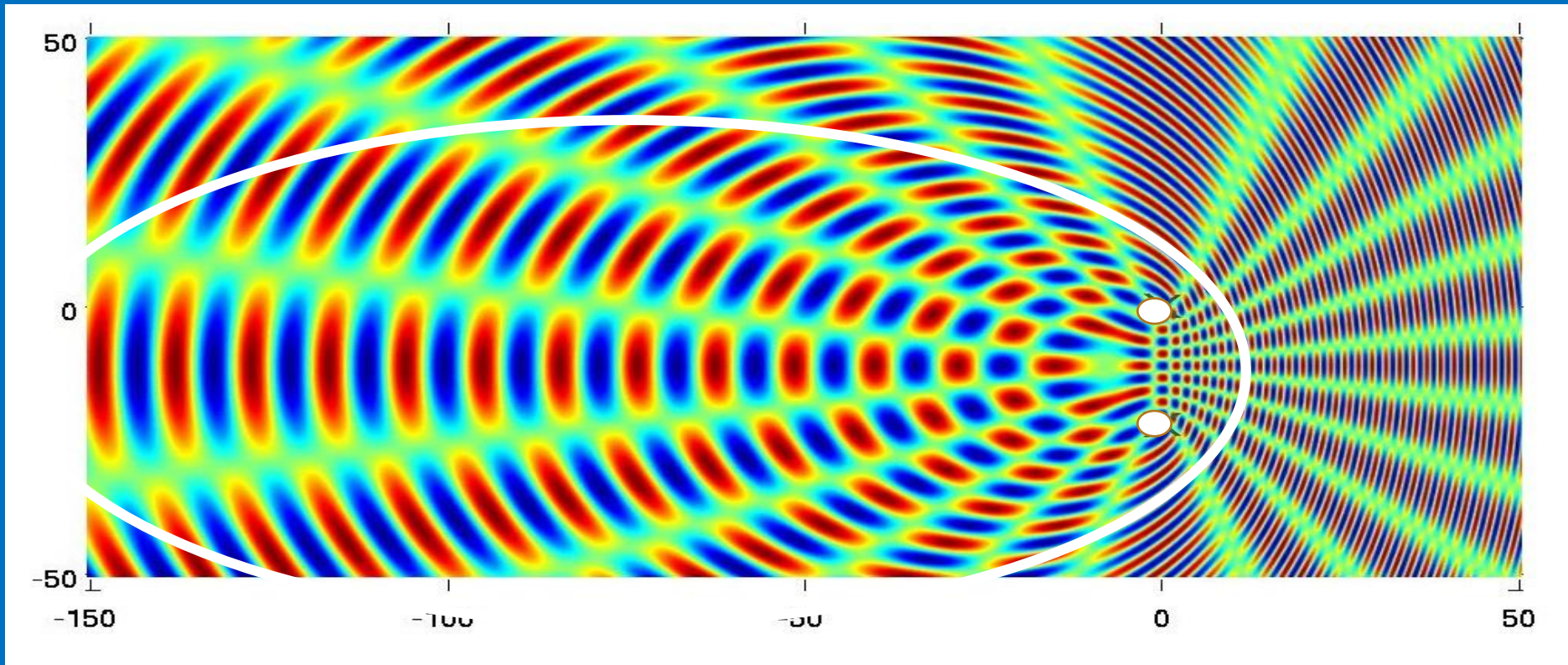
Interference of waves

same phase, frequency, amplitude, no wind

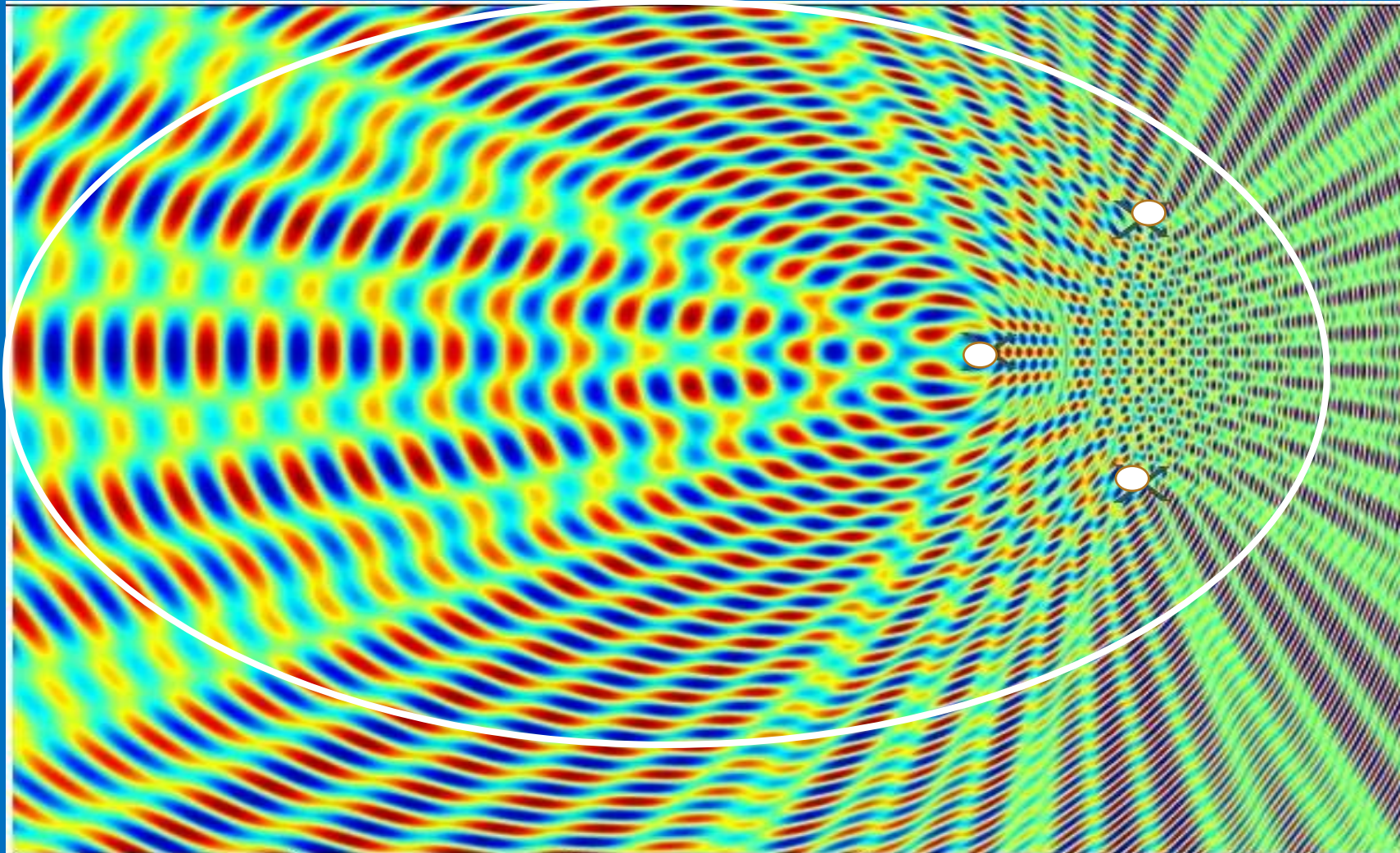


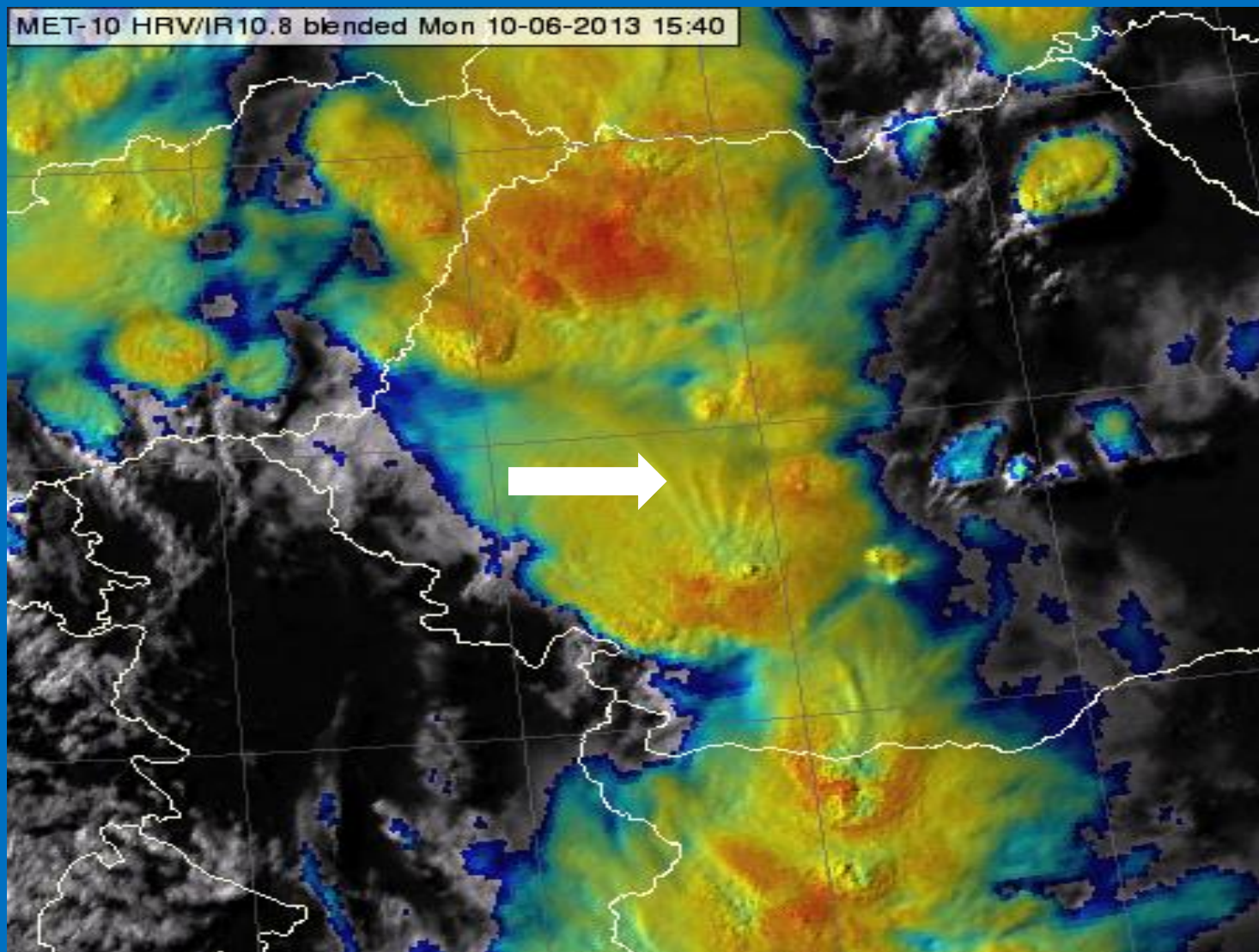
Now add fluid motion

Same phase, frequency, amplitude, constant wind
2 point sources. $D = 3.5 \lambda$

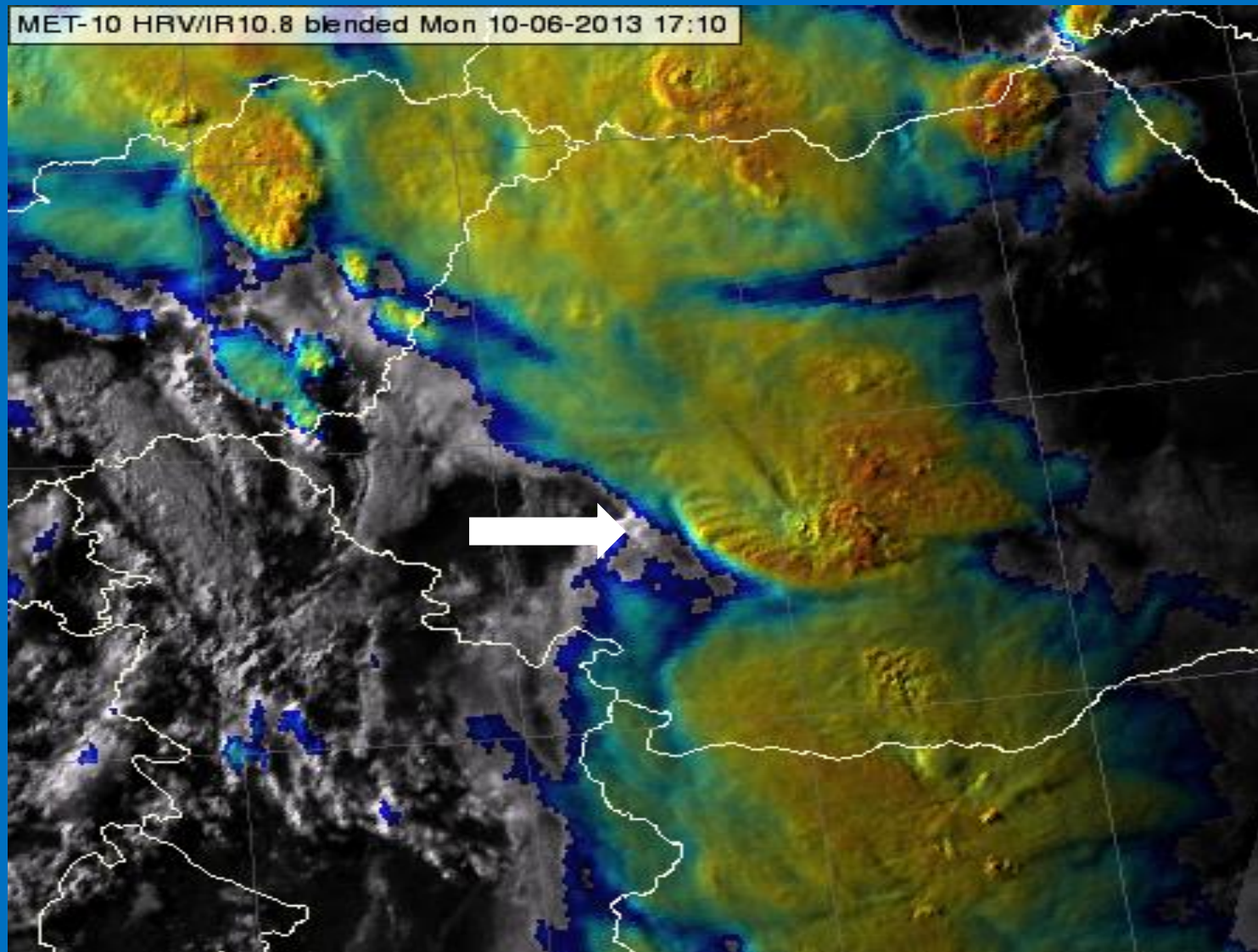


3 sources (i.e., 3 OTs)



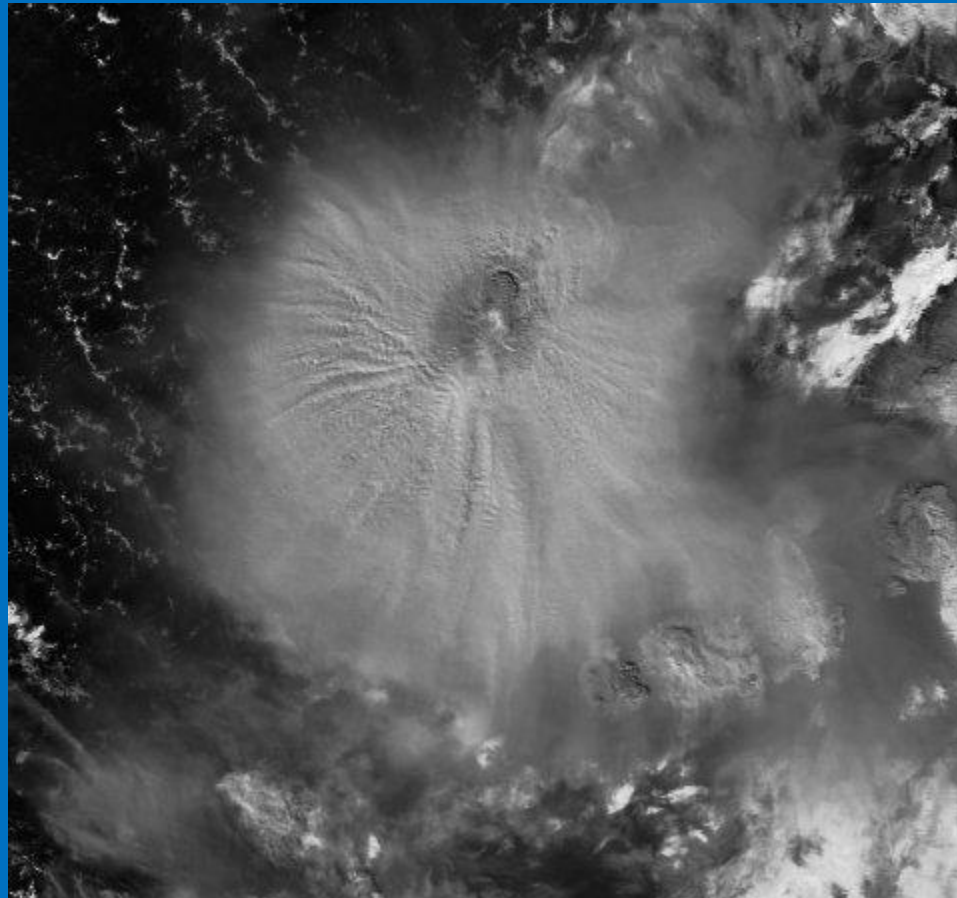


Courtesy of Maria Putsay



Courtesy of Maria Putsay

When wind shear is weak
interference pattern is more symmetric



Courtesy of Martin Setvak