
AGU24
Washington, D.C. | 9–13 December 2024
WHAT'S NEXT FOR
SCIENCE


AGU24
WHAT'S NEXT FOR SCIENCE
#AGU24
DO NOT BLOCK INTERSECTION
ONLY


Enabling Technology: DOE's GPU Exascale Systems


Sensitivity of convective precipitation extremes to relative humidity
Robert van der Drift, MIT EAPS
In collaboration with Paul O'Gorman
MIT Climate Grand Challenge on Weather and Climate Extremes


eLightning
AGU24

AGU24

WHAT'S NEXT FOR SCIENCE

#AGU24 is in a different environment. Download the AGU Events mobile app in the Apple Store or Google Play to navigate the meeting, build or view your schedule, and see what sessions, events, activities, and resources are available for online and in-person attendees. You can also explore using your desktop via the online meeting platform here.

- Help / FAQ
- Home
- Search
- Schedule by Day
- Browse Sections
- Programs and Events
- Pod Reservation System
- Suggested Itineraries
- Index Terms
- Meeting Resources
- Conference Format
- Sign out

AGU24 ONLINE PROGRAM

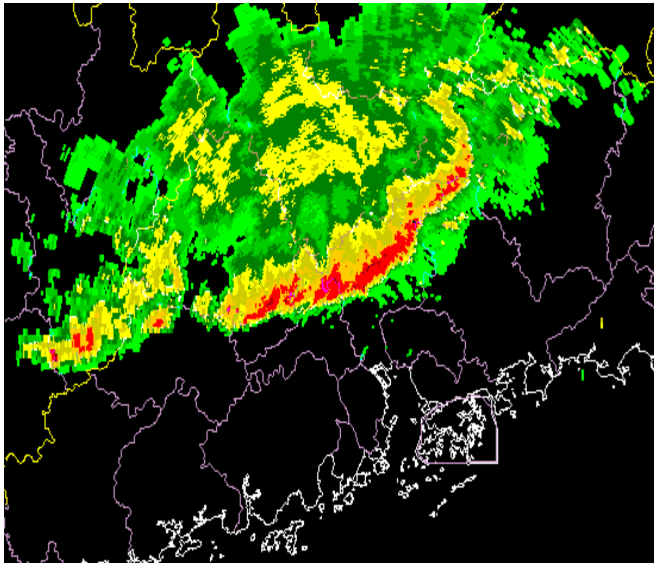
This December, AGU24 returns to Washington, D.C. 9 - 13 December 2024, with the theme "*What's Next for Science.*" We can't wait to see you there.

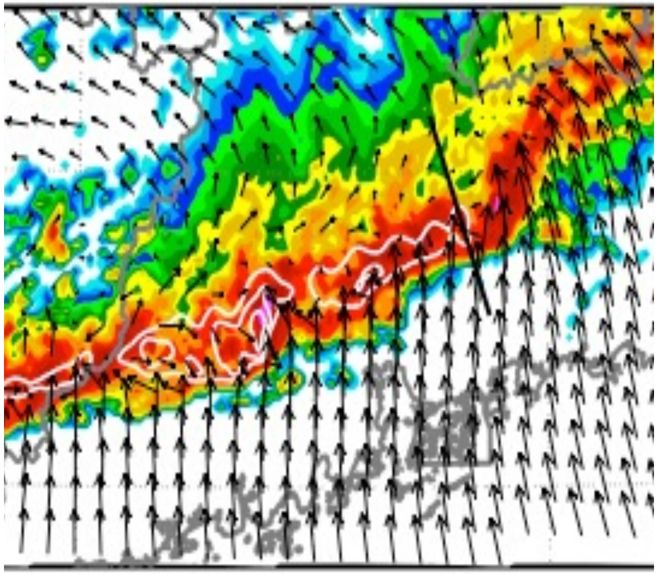
Each year, AGU's annual meeting, the largest gathering of Earth and space scientists, convenes 25,000+ attendees from 100+ countries to share research and connect with friends and colleagues. Scientists, educators, policymakers, journalists and communicators attend AGU24 to better understand our planet and environment, opening pathways to discovery, opening greater awareness to address climate change, opening greater collaborations to lead to solutions and opening the fields and professions of science to a whole new age of justice equity, diversity, inclusion and belonging.

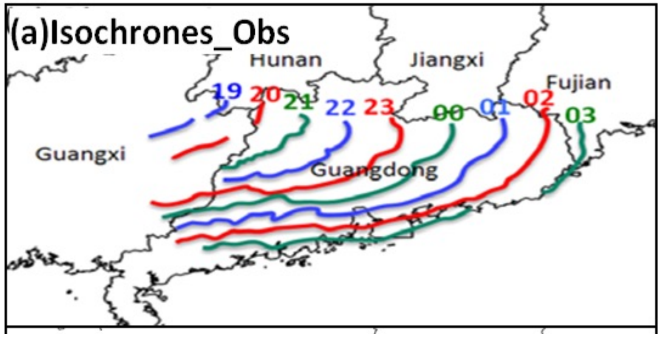
AGU 2024 will be held at the Walter E. Washington Convention Center.
Visit the AGU24 website for the latest updates and information.

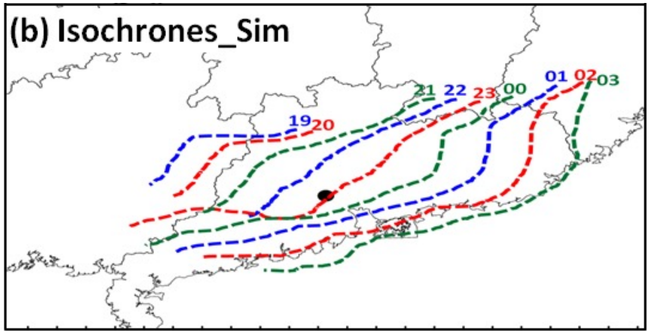
https://agu.confex.com/agu/agu24/meetingapp.cgi/Home/0

Numerical Modeling of convective storm









观测

模拟

本节课提纲

- Basic issue
- Configuration
- Modeling of convective storm- KW model
- Current trends in cloud model

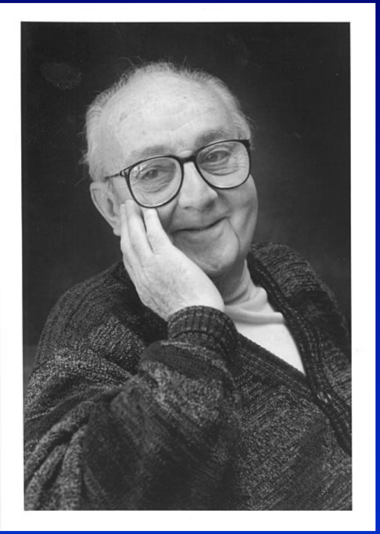
为什么我们要用数值模式研究对流？

- 对流控制方程大多不能解析求解
- 无法直接观测四维空间的热力学变量

- 模式涵盖了描述大气运动基本定律的合理描述
- 模式结果有很高的时空分辨率
- 模式为大气对流的研究提供了作真正控制试验的唯一机会

“All models are wrong. Some models are useful.”

-George Box



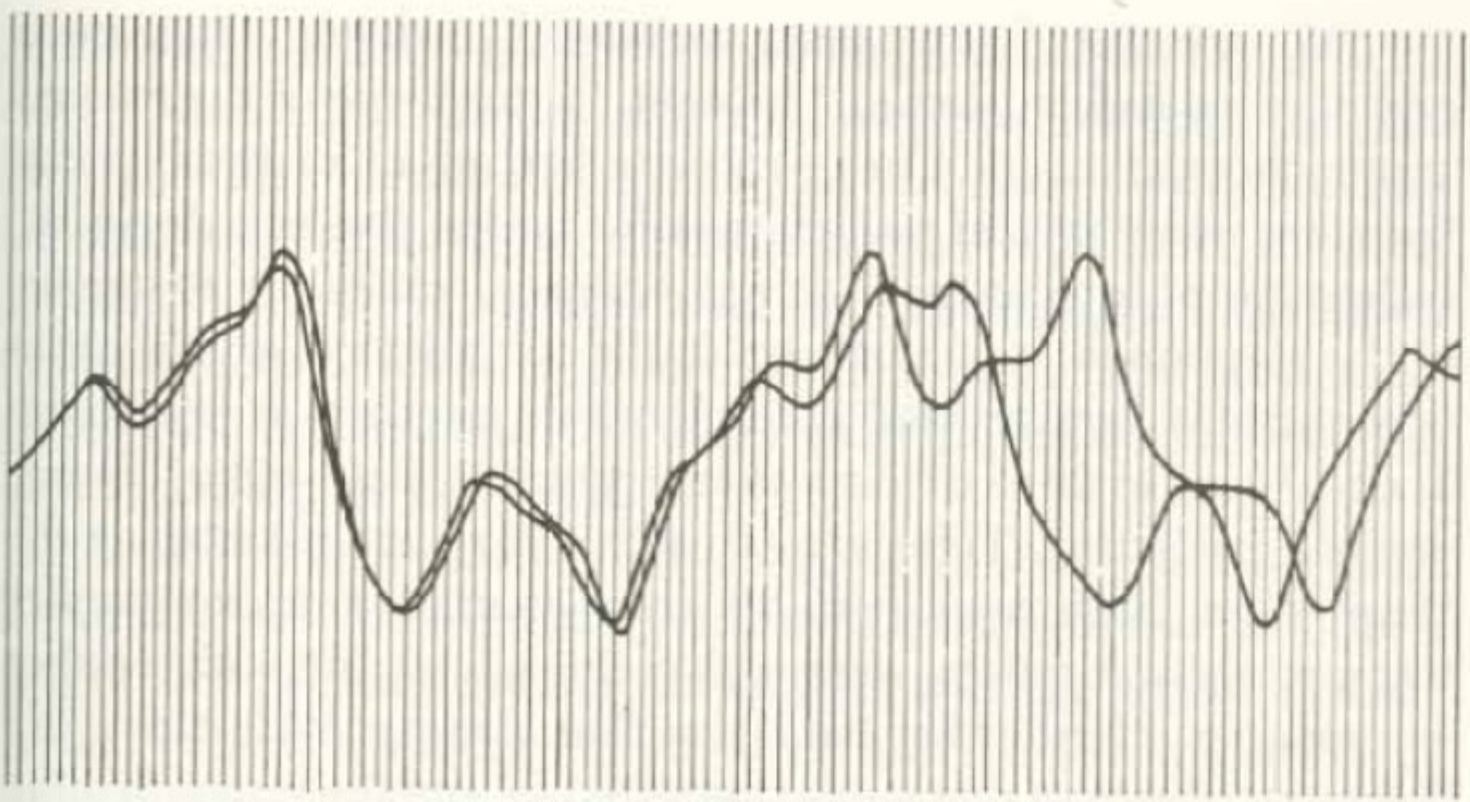
为什么怀疑模式的结果？

- 模式的结果有可能看上去有物理上的真实性，但有可能却是错的
  - 很多假设，用户要做很多的方案选择，有一定的盲目性。导致的误差很难把握
  - 模式中对对流比较重要的一些特征大多被参数化了
    - 一些方案的设计可能不能描述某些过程

模式结果的释用

- 一次模拟本身可能不是特别有用，要考虑其可能的变化
- 模式结果中所分析变量的趋势或敏感性可能比数值本身更有用
- 错误地选择模式方案会误入歧途
  - 不同物理模块之间可能会有很大的误差抵消现象
- 模式结果对初始条件的敏感性

模式结果对初始条件的敏感性



How two weather patterns diverge. From nearly the same starting point, Edward Lorenz saw his computer weather produce patterns that grew farther and farther apart until all resemblance disappeared. (From Lorenz's 1961 printouts.)

- there is a sensitive dependence on initial conditions

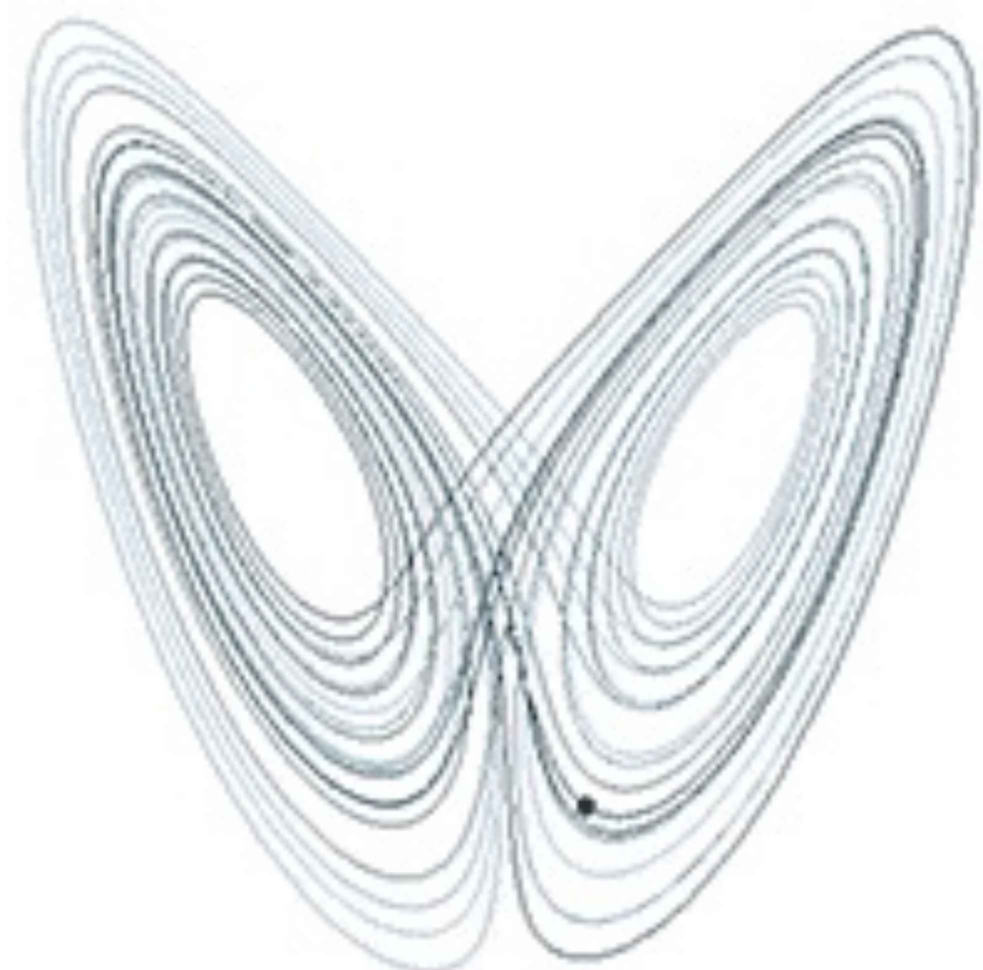
Lorenz caotic system: butterfly effect

$$\frac{\mathrm{d}x}{\mathrm{d}t} = \sigma(y - x),$$

$$\frac{\mathrm{d}y}{\mathrm{d}t} = x(\rho - z) - y,$$

$$\frac{\mathrm{d}z}{\mathrm{d}t} = xy - \beta z.$$

Lorenz (1963)



模式结果对初始条件的敏感性

Source: Dr. David Randall, CSU

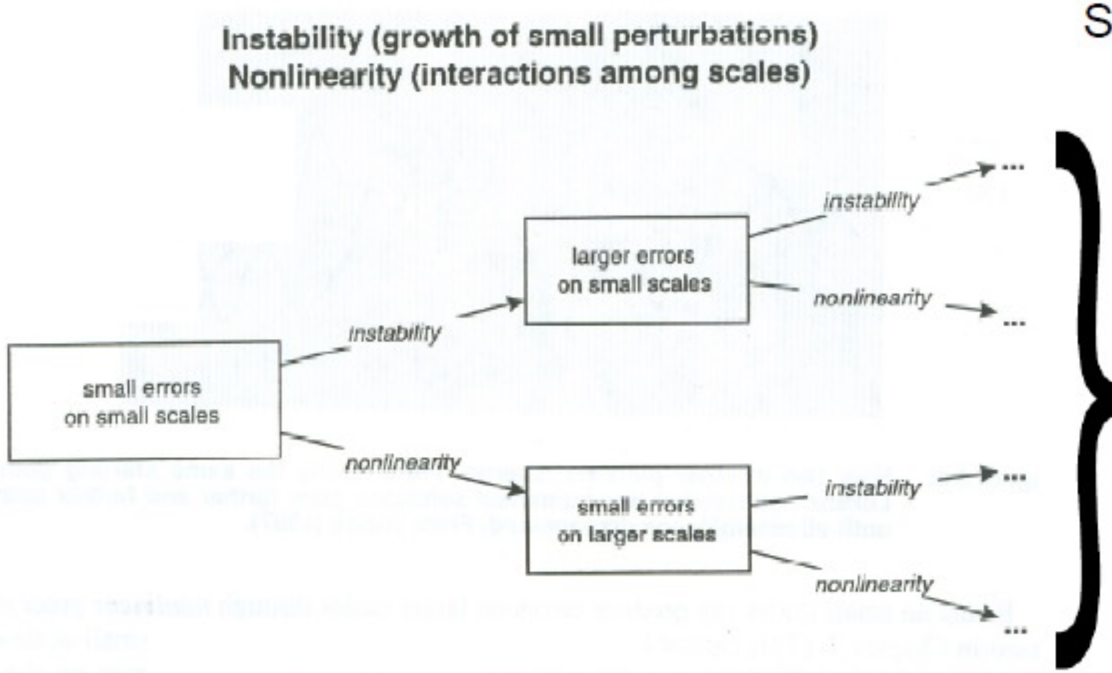


Figure 8.9: Sketch illustrating the role of instability in leading to error growth, and of nonlinearity in leading to the movement of error from small scales to larger scales.

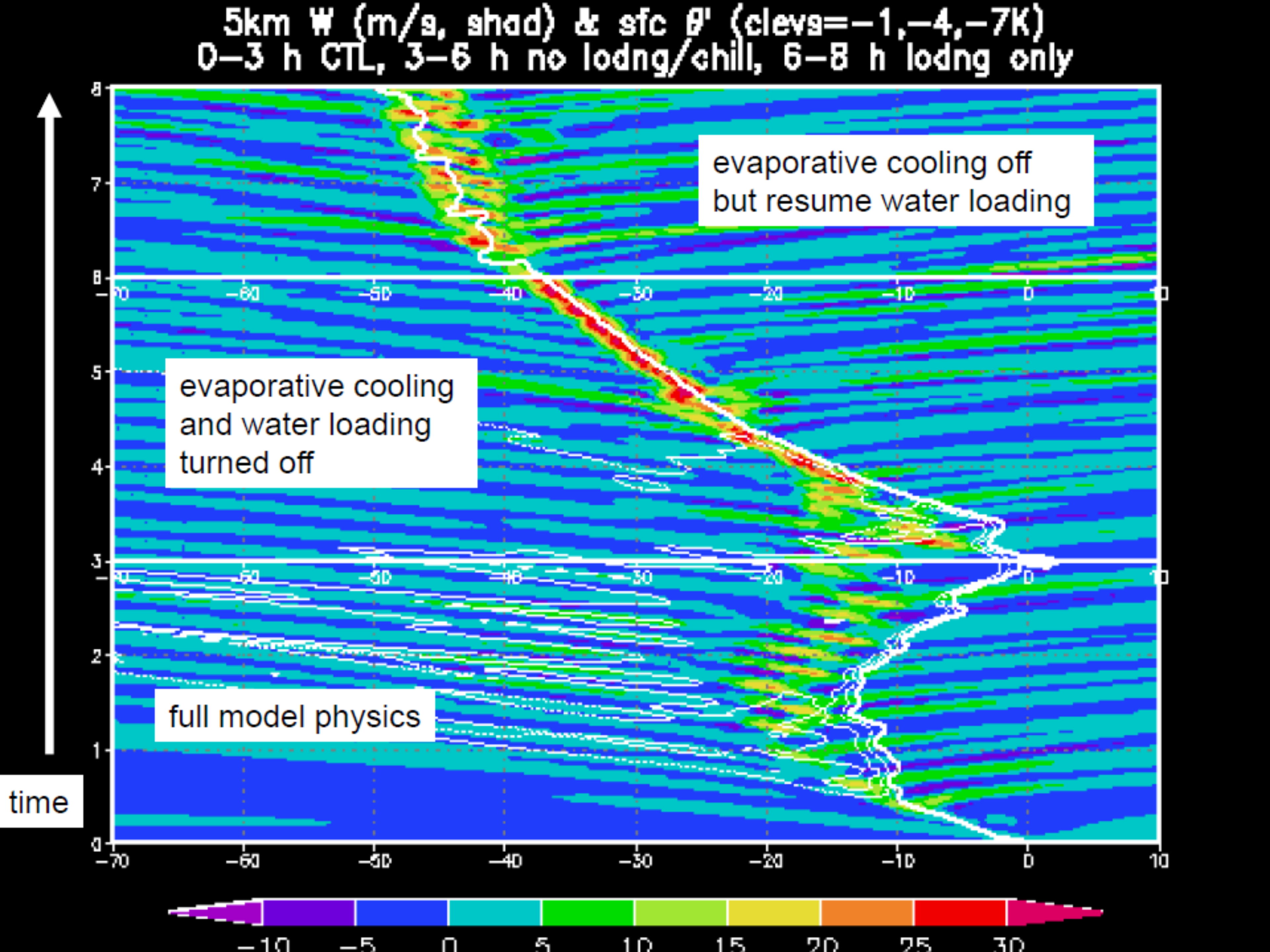
Eventually, after time has passed, it is inevitable that even the very largest scales in a model will be dominated by great uncertainty.

Any forecasting method is subject to this (not just numerical prediction) because the behavior of the system is heavily dependent on the initial conditions!

- there is a sensitive dependence on initial conditions

模拟种类

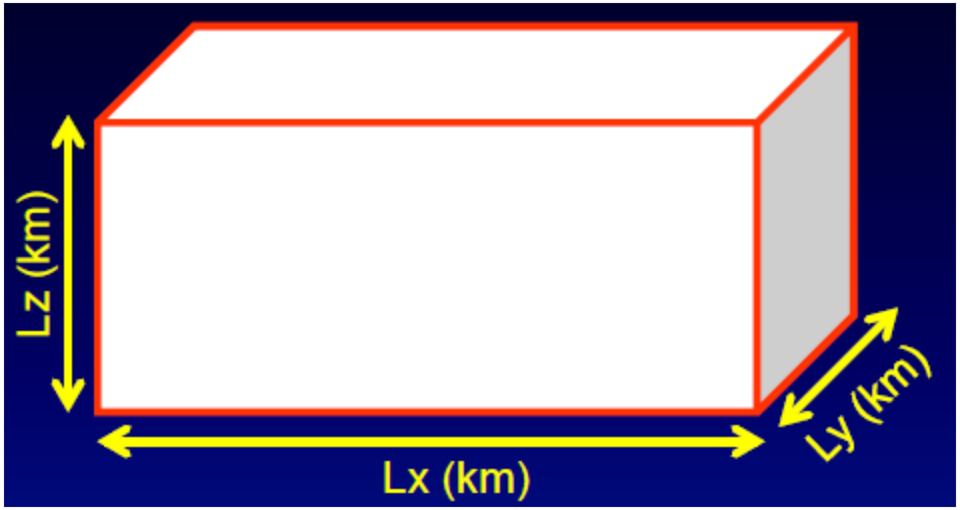
实际资料模拟	理想模拟
初始场：分析场	初始场：高度简化或均一场
可以做一些敏感性研究，但是环境本身受大尺度平衡约束	可以做多种敏感性研究，包括对环境风和热力学廓线的改变
环境强迫	预先设定的人工强迫
陷阱：用户有时会把模式向观测调整 有时会把模式结果当作真实值	模式结果常被质疑实际代表性，但一般也不要求与实际的例子完全符合


5km W (m/s, shad) & sfc θ' (clevs=-1,-4,-7K)
0-3 h CTL, 3-6 h no lodng/chill, 6-8 h lodng only
evaporative cooling off
but resume water loading
evaporative cooling
and water loading
turned off
full model physics
time
-70 -60 -50 -40 -30 -20 -10 0 10
0 1 2 3 4 5 6 7 8
-10 -5 0 5 10 15 20 25 30

- Basic issue
- Configuration
- Modeling of convective storm- KW model
- Current trends in cloud model

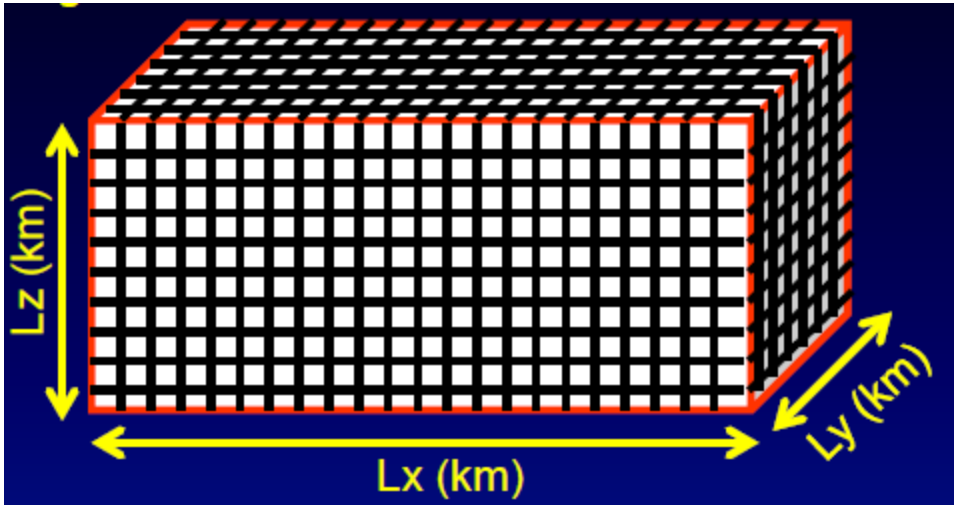
Domain Size

- 模式的边界需要人为给定变界值，所关心区域要离边界尽量远
- 最佳设置：区域足够大，以至于进一步增大积分区域不改变模式结果。



Grid Spacing

- 格距的选择要基于所研究过程的尺度



Large grid spacing

Reynolds-averaged (filtered) simulation

Net effects of turbulence are entirely “sub-grid scale” and are crudely parameterized (e.g. “K theory”)

dx ~ O(100 m)

Large eddy simulation (“LES”)

Largest (most energetic) eddies are resolved and treated explicitly… the limit of model resolution falls in the inertial subrange, and only small eddies are parameterized

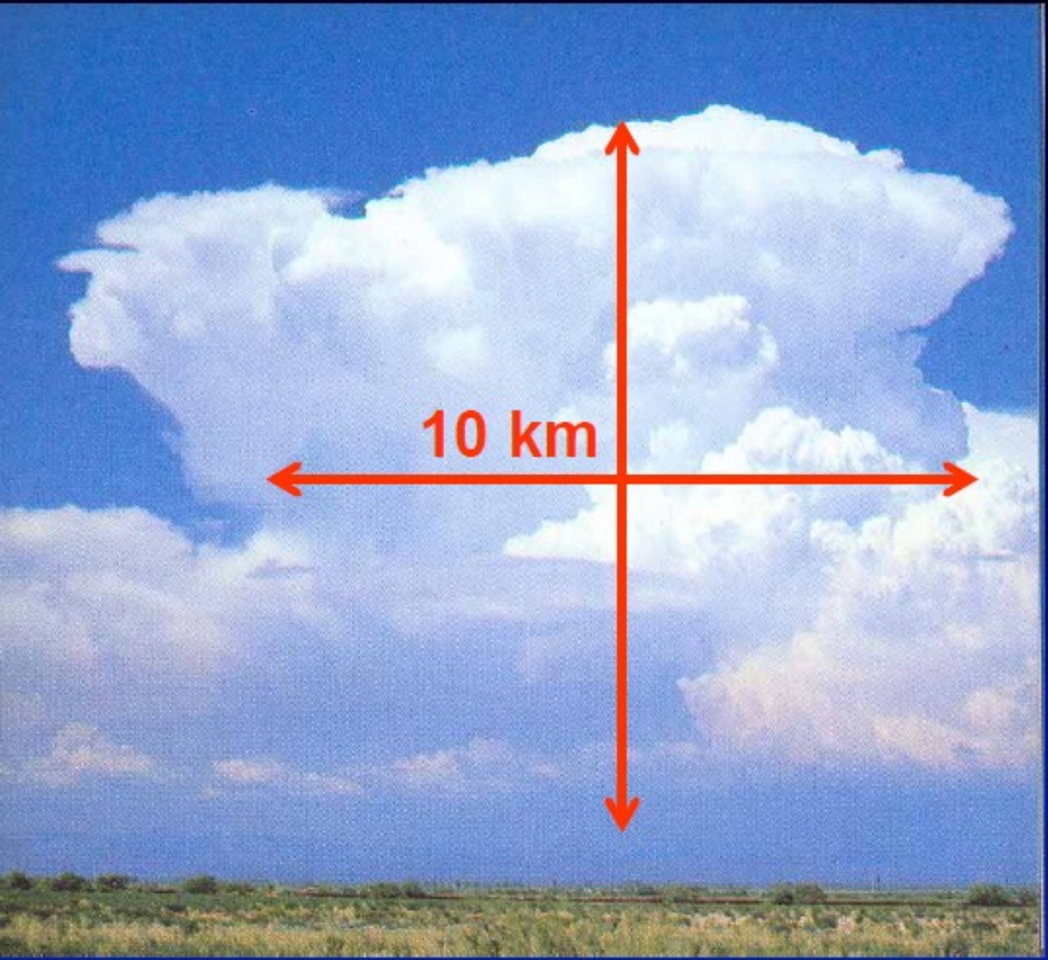
dx ~ O(0.1 mm)

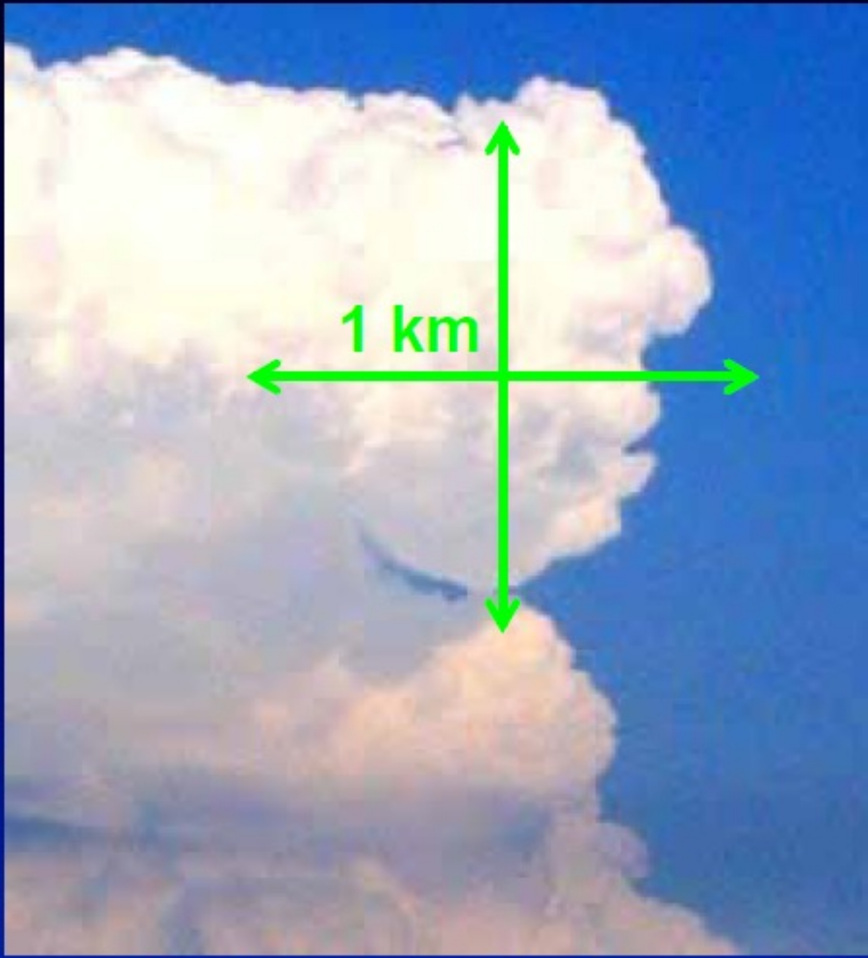
Direct numerical simulation (“DNS”)

All eddy motions are explicitly simulated… the only thing that is parameterized is molecular viscosity. This is not currently practical for any conventional meteorological problem.

Small grid spacing

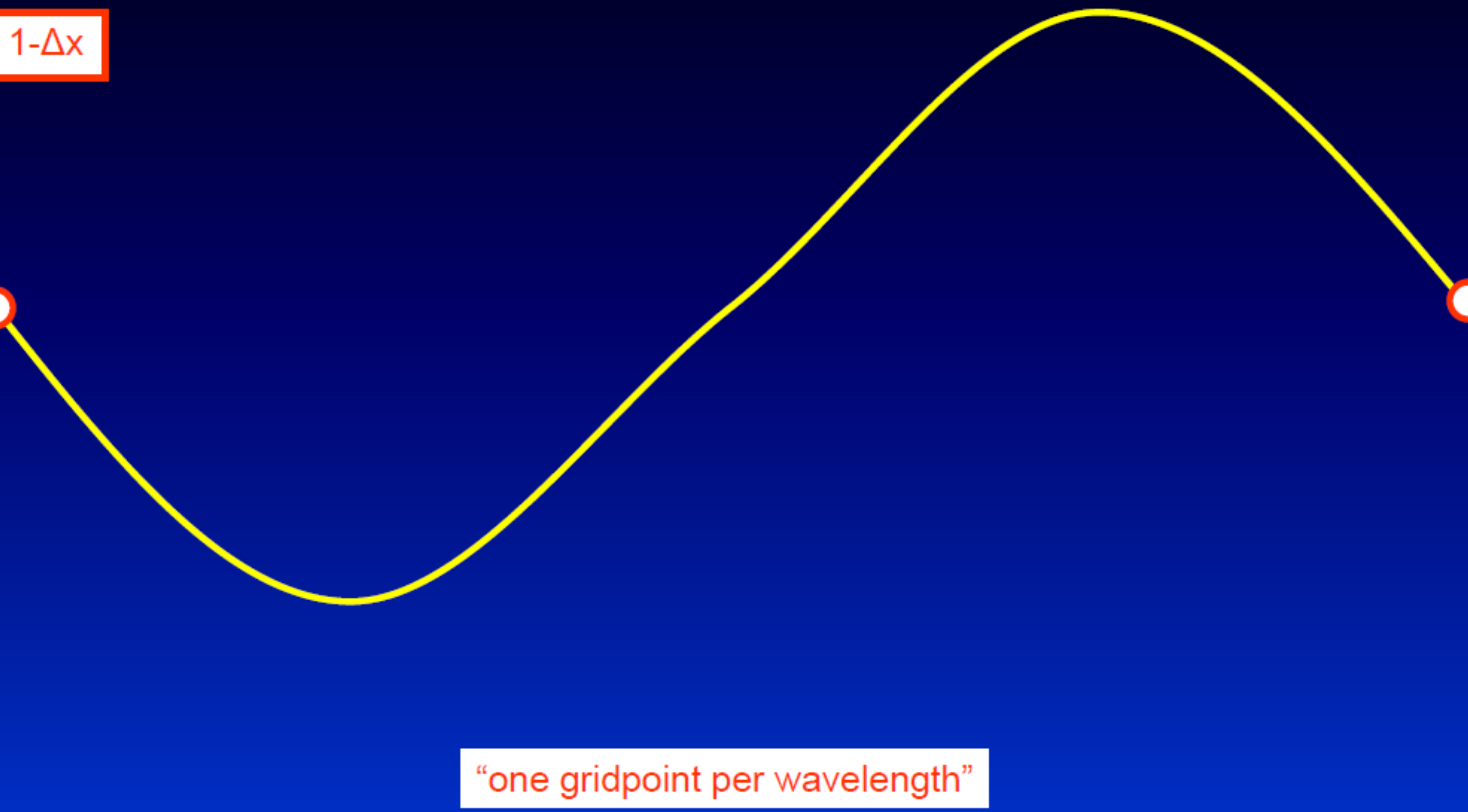
What grid spacing do we need for the thunderstorm scale?

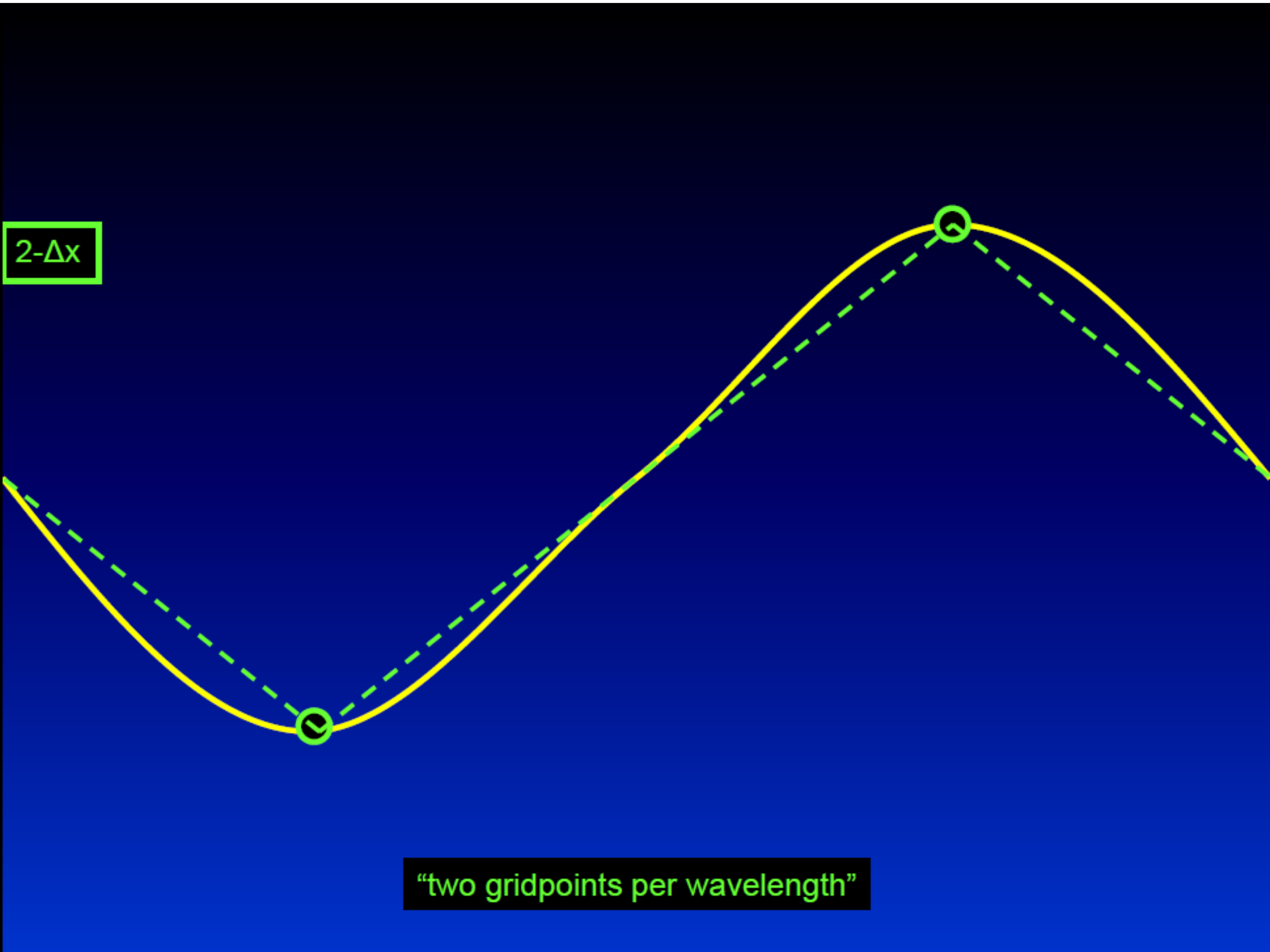


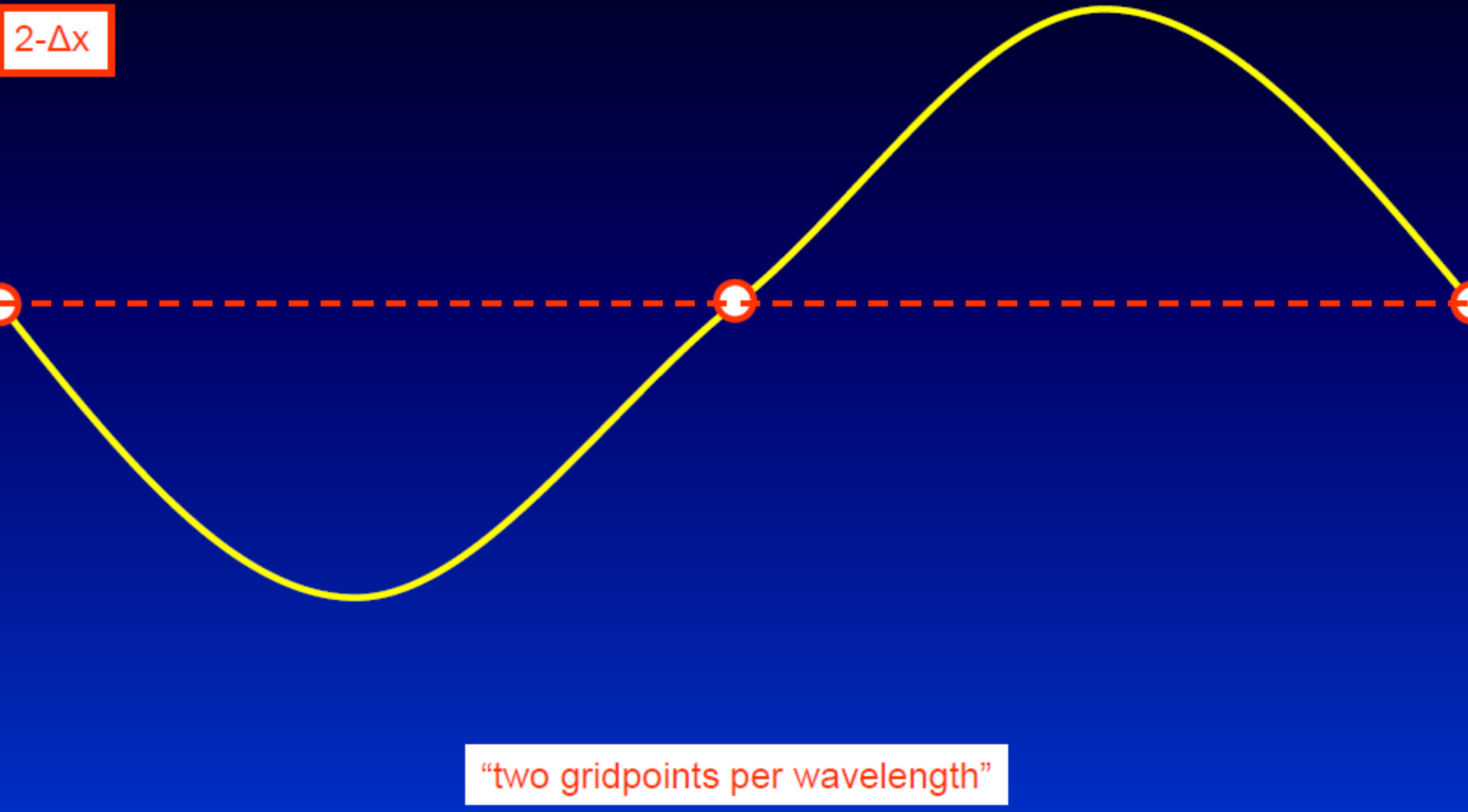


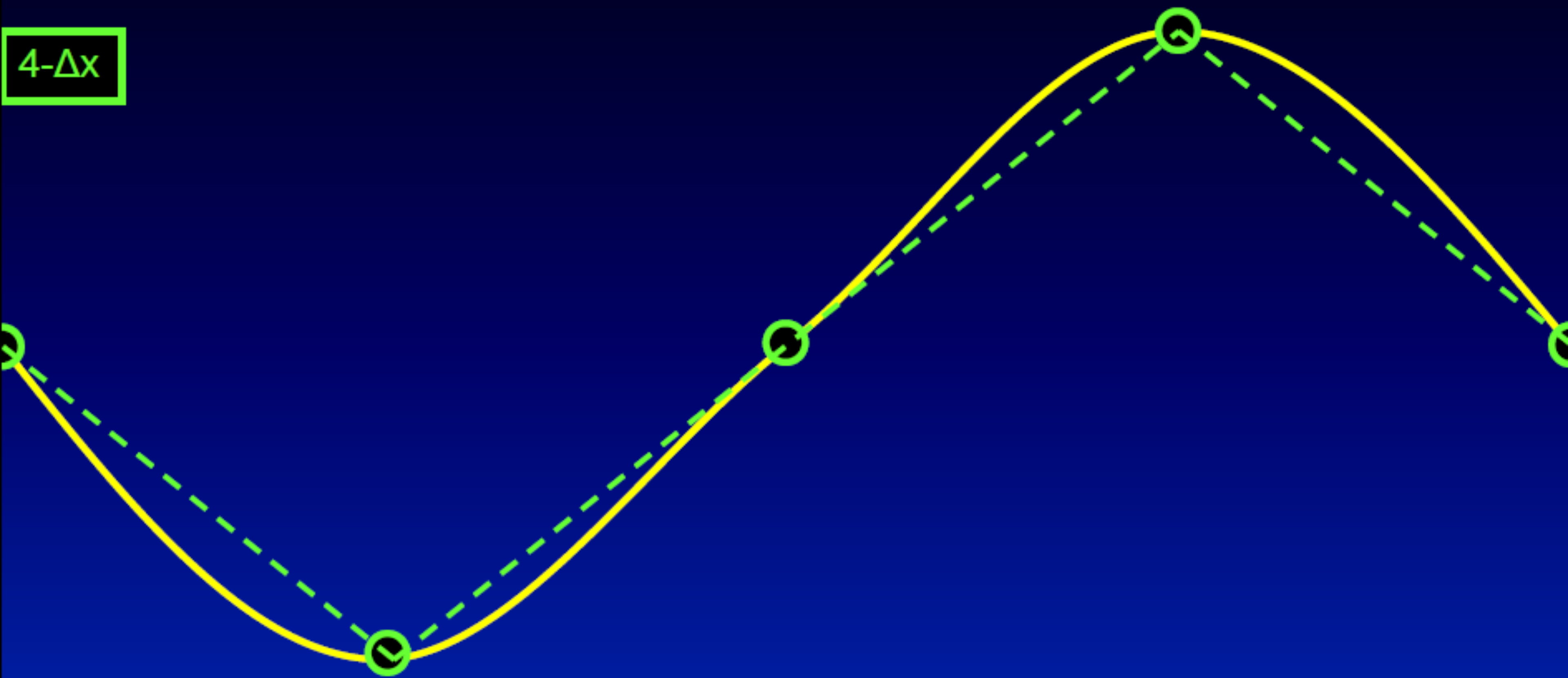
What grid spacing do we need for the major eddies in a storm?

One approach to resolution:
consider a simple signal of interest with some wavelength

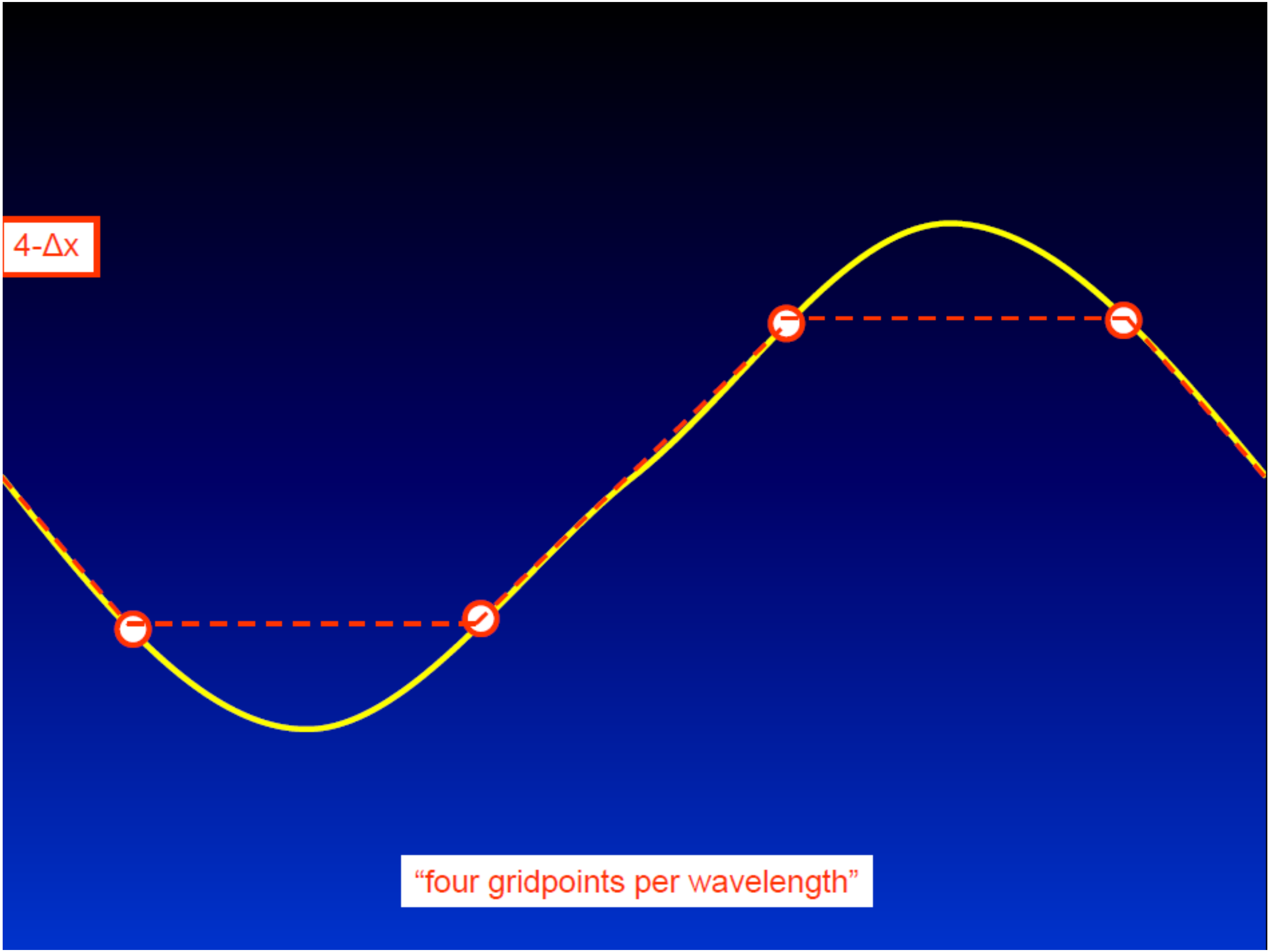



2-Δx
“two gridpoints per wavelength”

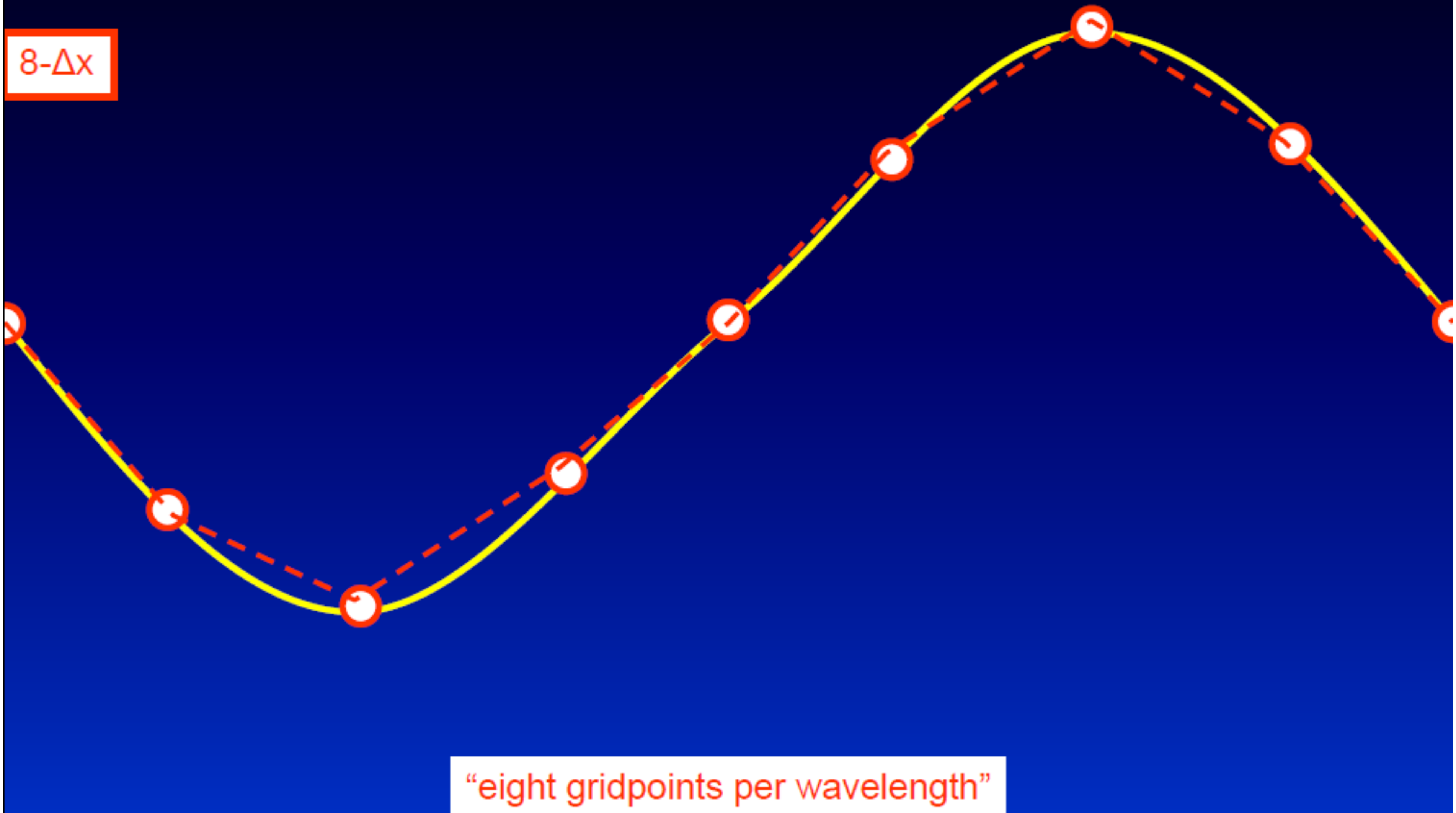

2-Δx
“two gridpoints per wavelength”



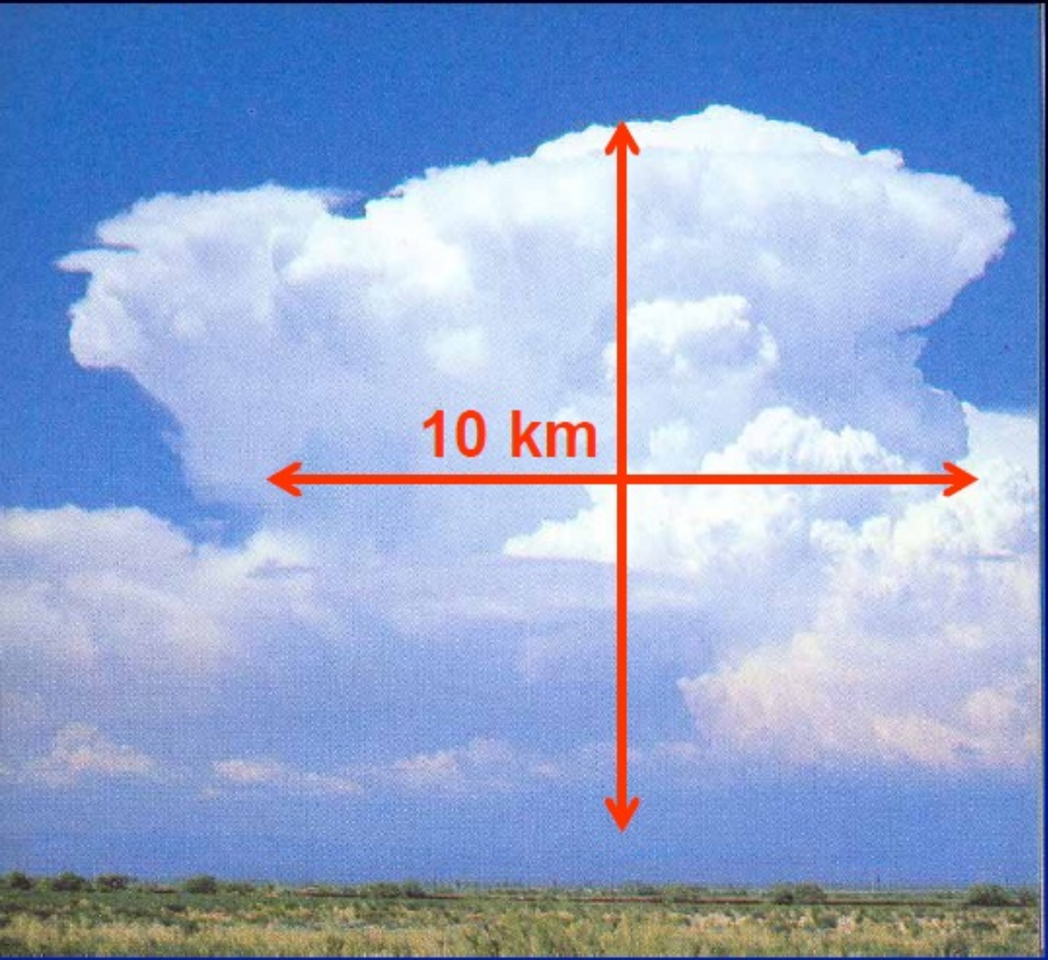
“four gridpoints per wavelength”

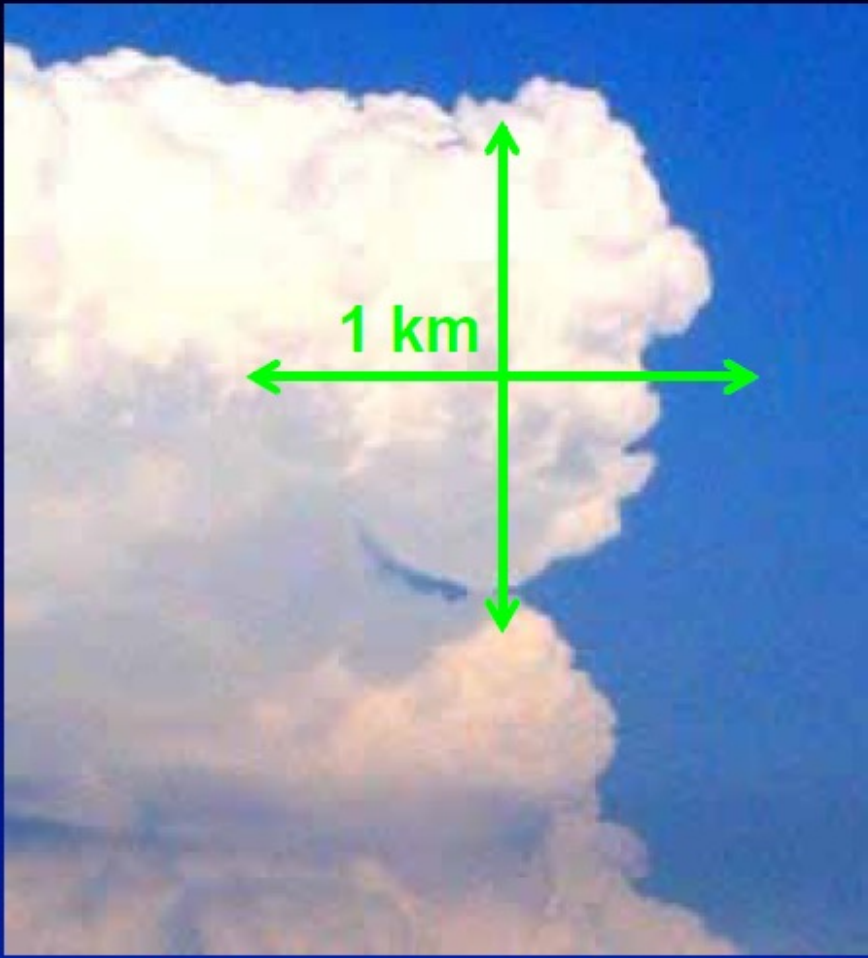

4-Δx
“four gridpoints per wavelength”

Things are probably reasonably represented around 8-Δx



What grid spacing do we need for the thunderstorm scale?





What grid spacing do we need for the major eddies in a storm?

For some time it's been thought that…

- if the characteristic scale of a cumulonimbus is ~10 km, and
- 8-Δx is required to resolve a feature, then
- ~1 km is the appropriate grid spacing for "convection resolving" simulations
    - such simulations are realistic looking
    - if the sub-cloud scale is turbulent, that's okay! This just represents a drain of energy and scalar mixing, which the sub-grid turbulent mixing scheme is meant to emulate.

For some time it's been thought that…

- ~~if the characteristic scale of a cumulonimbus is ~10 km, and~~

on

- The highest-resolution simulations reveal that deep moist convection may be 1–2 km in scale in some conditions. Therefore, the "rule of thumb" that 1 km is sufficient to resolve deep moist convection can be inappropriate in some environments.

- ~~If the sub-cloud scale is turbulent, that's okay! This just represents a drain of energy and scalar mixing, which the sub-grid turbulent mixing scheme is meant to emulate.~~

- With grid spacing of order 1 km, overturning occurs in a relatively *laminar* manner. Using grid spacing of order 100 m, the simulated fields are *turbulent,* with resolved entrainment and overturning within clouds.

Bryan et al (2003)

This is still a reach for many current studies!

Is there no hope?

It all depends on what you want to simulate!

a) if the mesoscale structure of the system is of prime interest, the basic requirements are probably satisfied by grid spacing of 1 km… the sub-cloud eddies are of less dramatic importance

b) “old” (i.e. before mid 2000s) simulations of convection are still useful in terms of their explanations of sensitivities to gross environmental conditions, and the gross dynamics controlled by the cloud-scale pressure fields

c) BUT… the cloud-scale fluxes *are* wrong (or right for the wrong reason), and any science that hinges on them must be interpreted with care

模式参数设定

格距 .vs. 时间步长

$$\frac{\partial A}{\partial t} = -c\frac{\partial A}{\partial x}$$

Upstream scheme:

$$\frac{A(x,t+1) - A(x,t) =}{\Delta t} - c\,\frac{A(x,t) - A(x-1,t)}{\Delta x}$$

$$A(x,t+1) = A(x,t) - c\frac{\Delta t}{\Delta x}[A(x,t) - A(x-1,t)]$$

Courant Number $c\dfrac{\Delta t}{\Delta x}$

Criteria of stability $\left|c\dfrac{\Delta t}{\Delta x}\right| \le 1$

In practice,

$$\left| c \frac{\Delta t}{\Delta x} \right| \leq 1$$

is a criterion that must be met by the fastest current speed or wave speed in the model.

•For a basic anelastic model, perhaps this would be the speed of gravity waves, the fastest of which have c~50 m s^{-1} or so
•For an anelastic model of a tornado or strong upper level jet, we might need to be more conservative and use c~100 m s^{-1}

•For a fully compressible model, we have to worry about the acoustic waves, which have c~300-400 m s^{-1}

a. Smaller grid spacings become expensive because they demand shorter timesteps (so the model takes longer to run)
b. Acoustic waves impose a huge computational burden unless we find a “work around”

“Work around”

Some historical solutions (still in practice today):

•Use a numerical scheme that can tolerate a higher Courant Number

•Use “time-splitting”, whereby the acoustic waves are treated separately from the rest of the dynamics

•Only grid stretching and grid nesting, so that high resolution is only used where it is needed most (this saves on computer memory too!)

"Time-splitting": acoustic waves are treated separately from the rest of the dynamics

Consider dx=1000m…

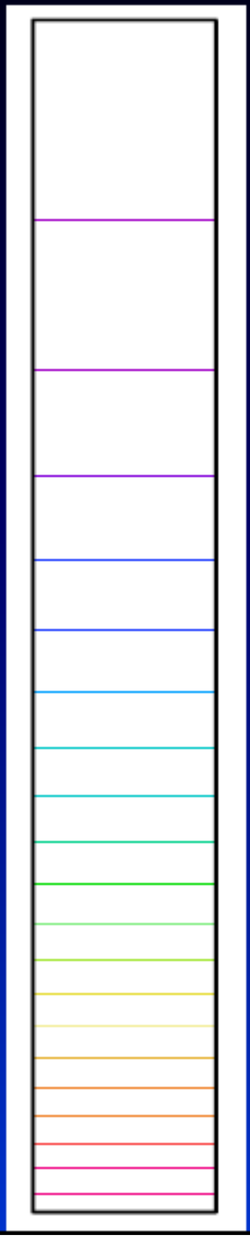
c = 50 m/s requires a time step of ≤ 20 s
c = 300 m/s requires a time step of ≤ 3.333 s

So, we save on calculations by only using the shorter timestep on the terms that require it

Higher vertical resolution is often obtained in the lower troposphere via grid stretching

模式参数设定

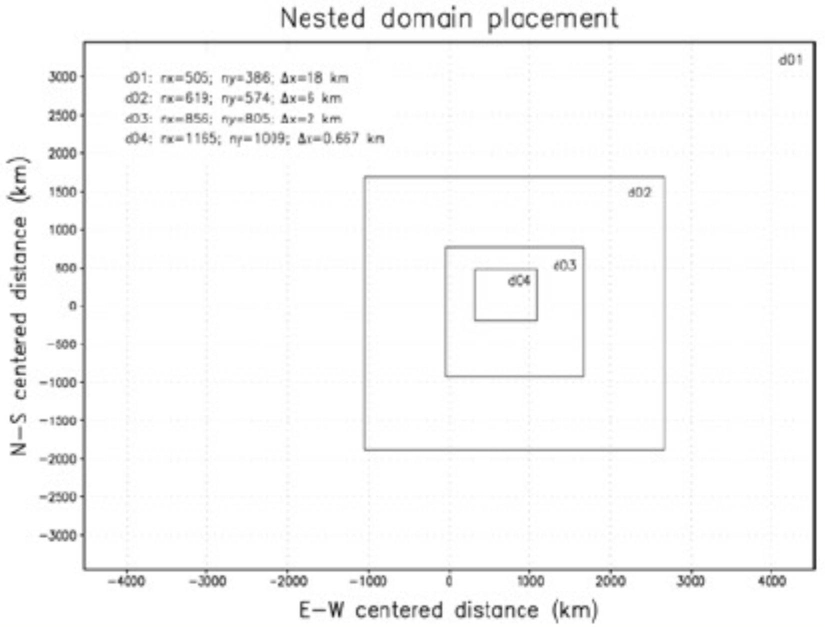
less resolution in the stratosphere

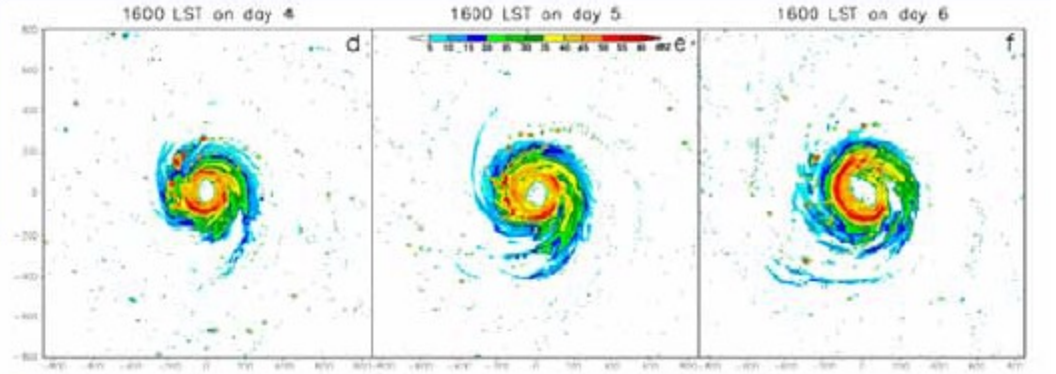


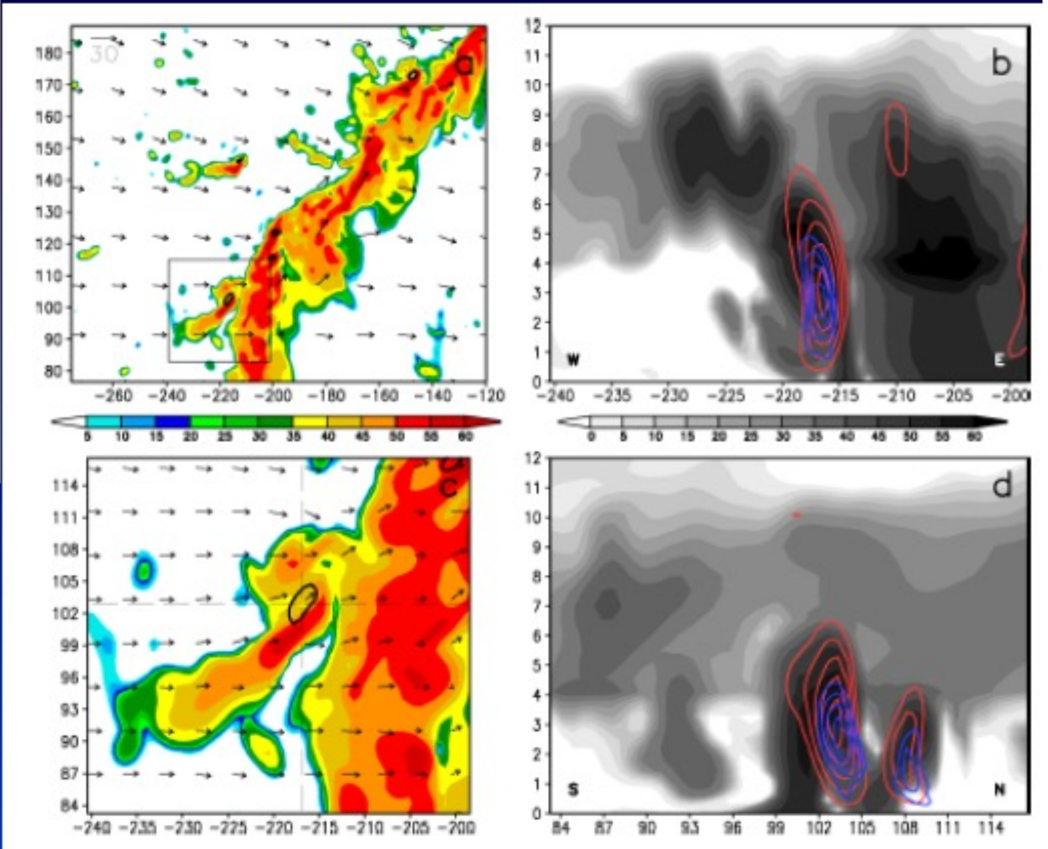
more resolution in the boundary layer

Higher horizontal resolution is often locally obtained via grid nesting

模式参数设定







Matt Morin M.S. thesis (2011)

- Basic issue
- Configuration
- Modeling of convective storm- KW model
- Current trends in cloud model

Modeling studies of convective storms

- First true cloud models emerged in early 70s, and at the time they mostly 2D

As mentioned earlier, many fundamental results in the field of convective dynamics arose from idealized numerical simulations…

- dynamics of supercells
- sensitivity of storm type to environmental wind profile
- dynamics of long-lived squall lines
- dynamics governing the multicell process

Many of these results (esp. those of Klemp, Rotunno, Weisman, and Wilhelmson), at least into the early 90s, came from one cloud model: the Klemp-Wilhelmson (KW) model.

The "Weisman-Klemp" experiments

- Maybe the first detailed, systematic attempt to study convective dynamics and sensitivities using a model

- Papers studying the sensitivity of convective storms to the sounding and wind profile: Weisman and Klemp (1982); Weisman and Klemp (1984); Weisman and Klemp (1986); Rotunno, Klemp, and Weisman (1988); Weisman, Klemp, and Rotunno (1988); Weisman (1992); Weisman (1993)

- The general formulation of these experiments included:
  - An idealized sounding in which the lapse rates and low-level humidity could be easily changed to modify instability
  - A simple wind profile whose amount of shear and shape could be easily changed
  - Initiation of storms with simple warm thermals
  - Kessler warm rain microphysics parameterization

The “Weisman Klemp” sounding (WK82)

Potential temperature profile:

$$\bar{\theta}(z) = \begin{cases} \theta_0 + (\theta_{tr} - \theta_0)\left(\dfrac{z}{z_{tr}}\right)^{5/4}, & z \leqslant z_{tr} \\ \theta_{tr} \exp\left[\dfrac{g}{c_p T_{tr}}(z - z_{tr})\right], & z > z_{tr} \end{cases} \quad (1)$$

Relative humidity profile:

$$H(z) = \begin{cases} 1 - \dfrac{3}{4}\left(\dfrac{z}{z_{tr}}\right)^{5/4}, & z \leqslant z_{tr} \\ 0.25, & z > z_{tr} \end{cases} \quad (2)$$

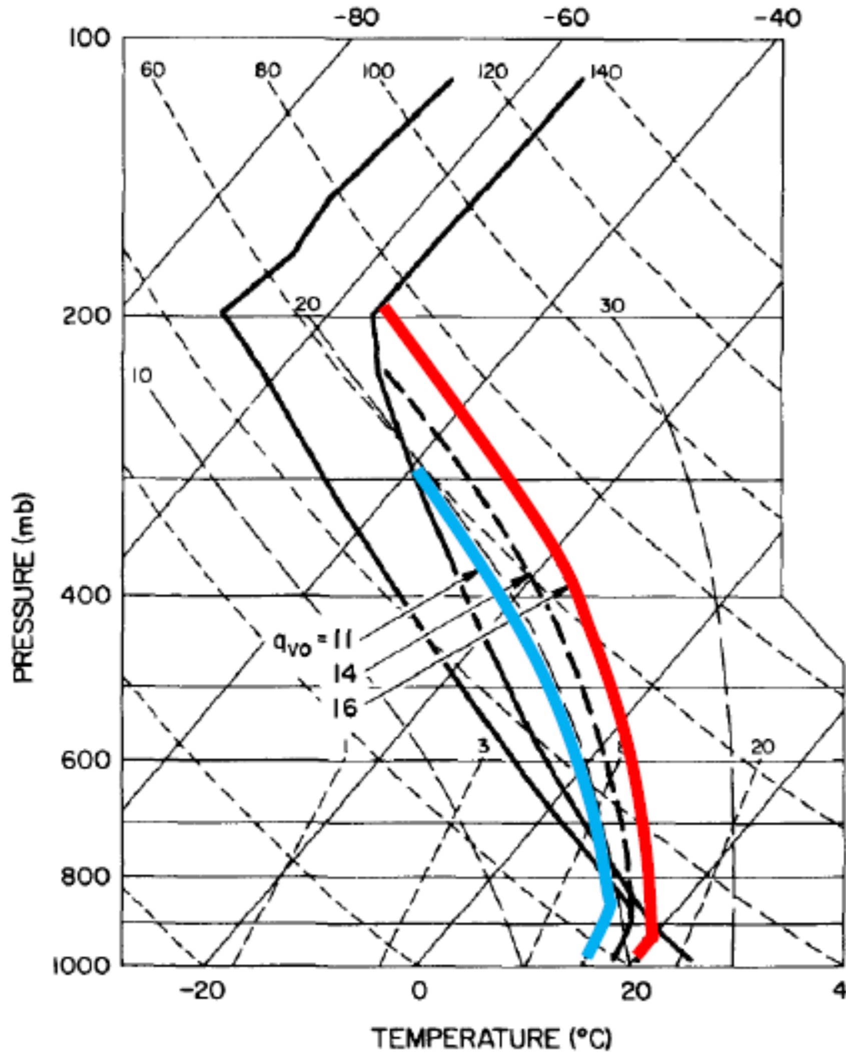


FIG. 1. Skew T diagram depicting temperature and moisture profiles used in model experiments (heavy solid lines). Heavy dashed line represents a parcel ascent from the surface based on a surface mixing ratio q_{v0} = 14 g kg^{-1}. Heavy dotted lines represent similar parcel ascents for q_{v0} = 11 g kg^{-1} and 16 g kg^{-1}. Tilted solid lines are isotherms, short dashed lines are dry adiabats, and long dashed lines are moist adiabats.

For qvsfc=11 g/kg, CAPE~1000 J/kg

For qvsfc=16 g/kg, CAPE~3500 J/kg

The "Weisman Klemp" wind profiles (WK82, WK84)

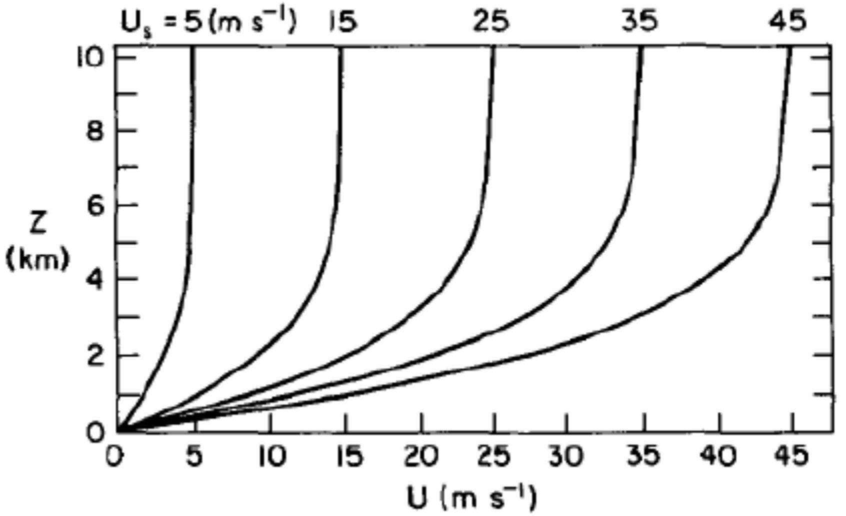


FIG. 2. Wind profiles as defined by Eq. (4).

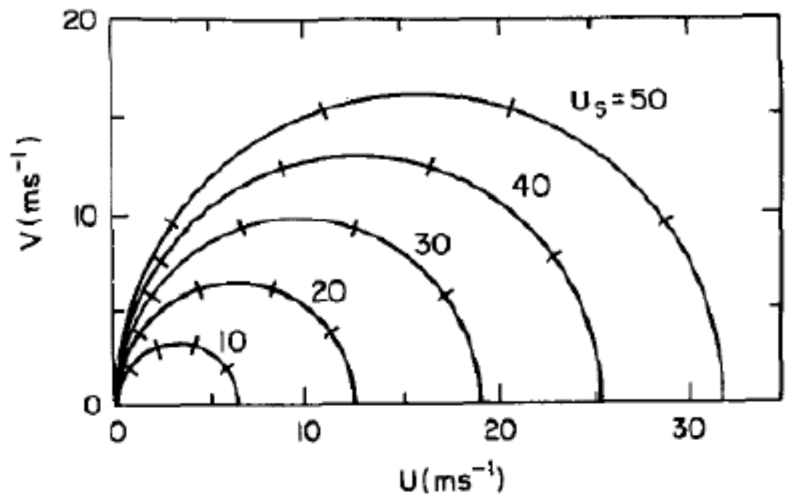
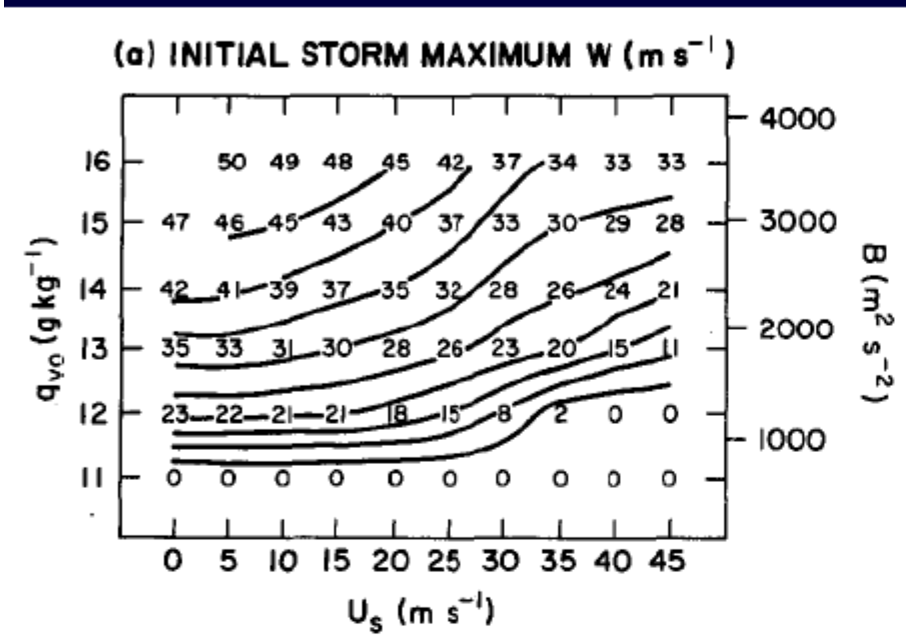


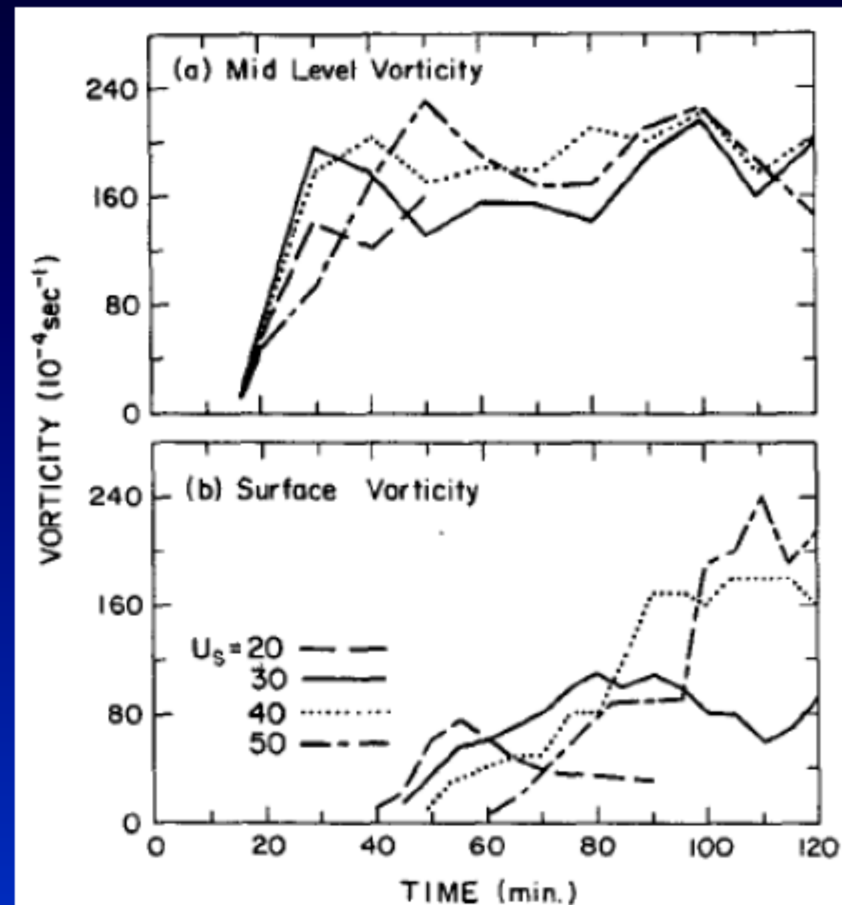
FIG. 2. Wind hodographs used in model simulations. Tick marks are placed at 1 km intervals in height up to 5 km. Winds are kept constant above 5 km.

Sensitivity tests

WK82 example: updraft strength as a function of CAPE and shear

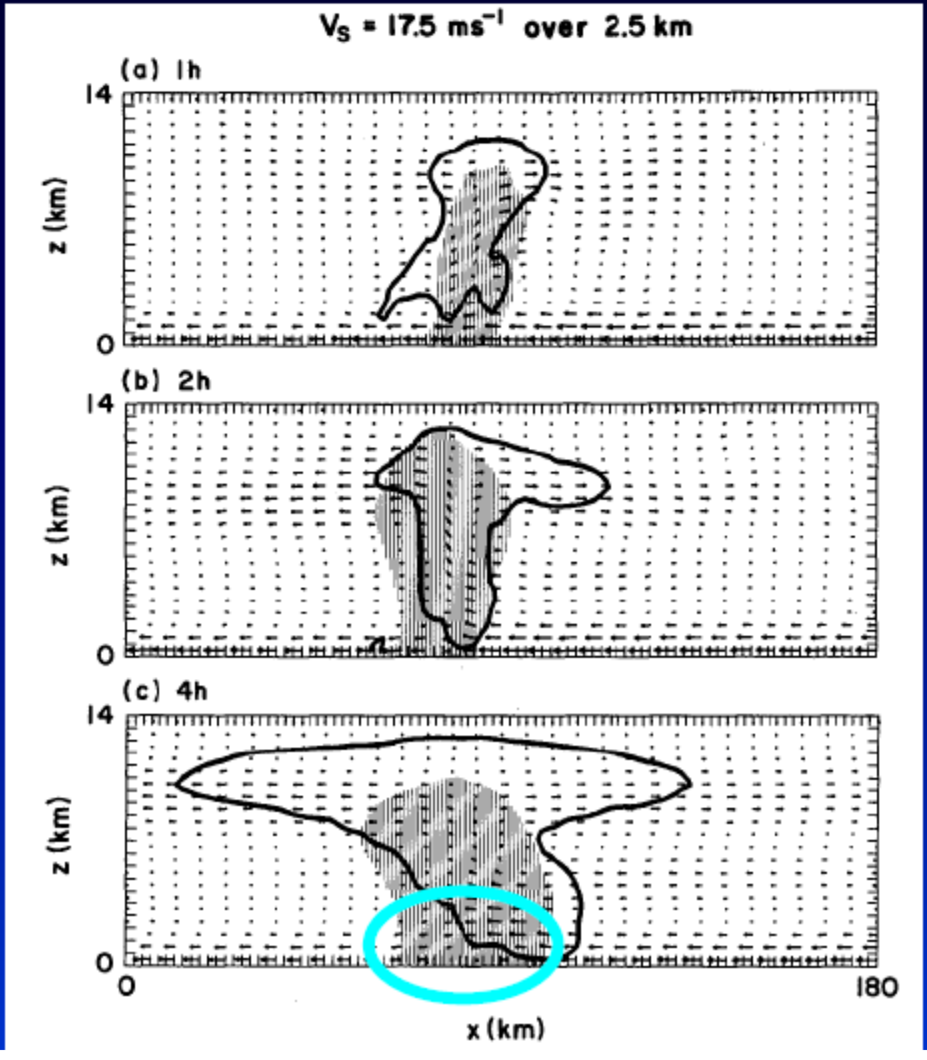


WK84 example: middle and low-level vorticity as a function of shear



Some problems with the KW model studies…

- the model did not include the ice phase: only Kessler microphysics… very bad for studying anvils and stratiform regions!

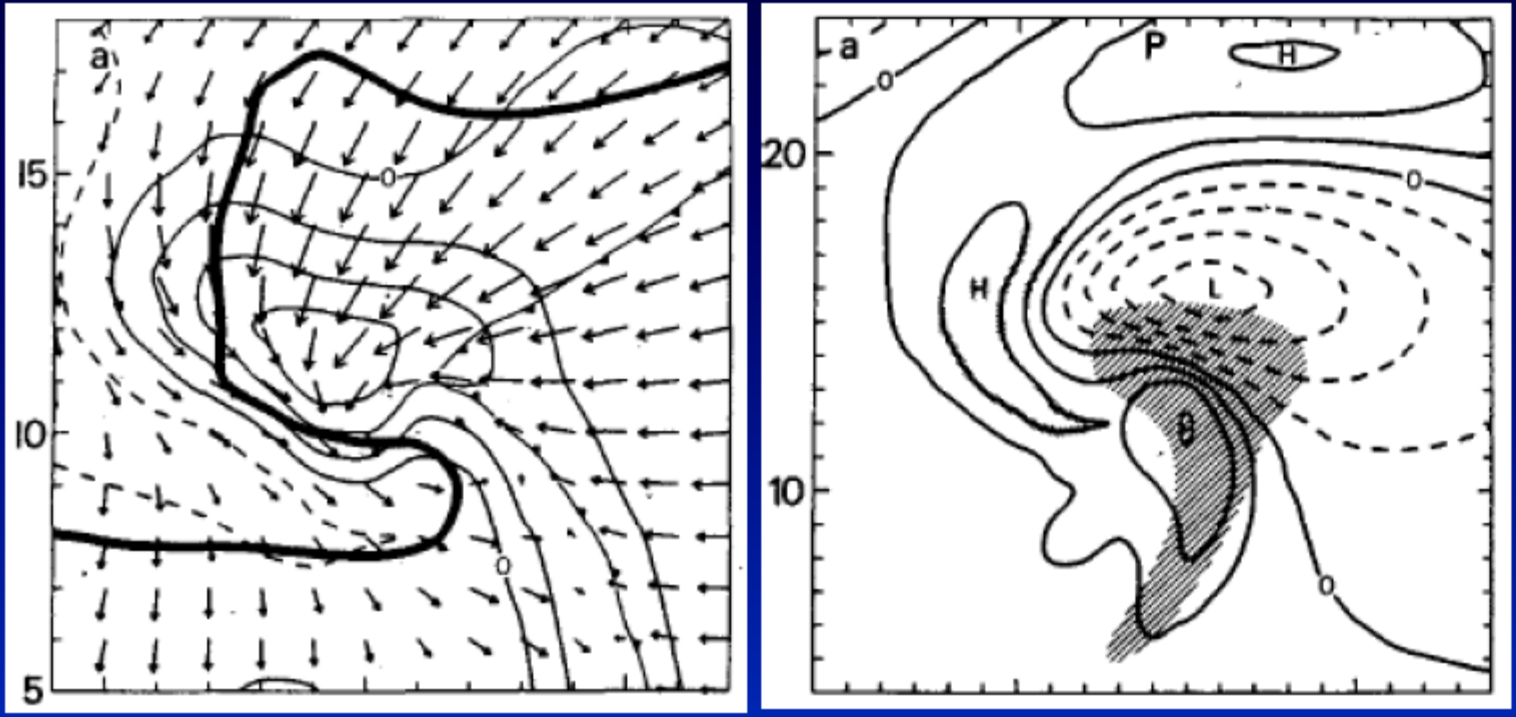


Weisman et al (1988)

The entire rain region of this squall line is only ~40 km wide! (~100-200 km is what we observe)

Some problems with the KW model studies…

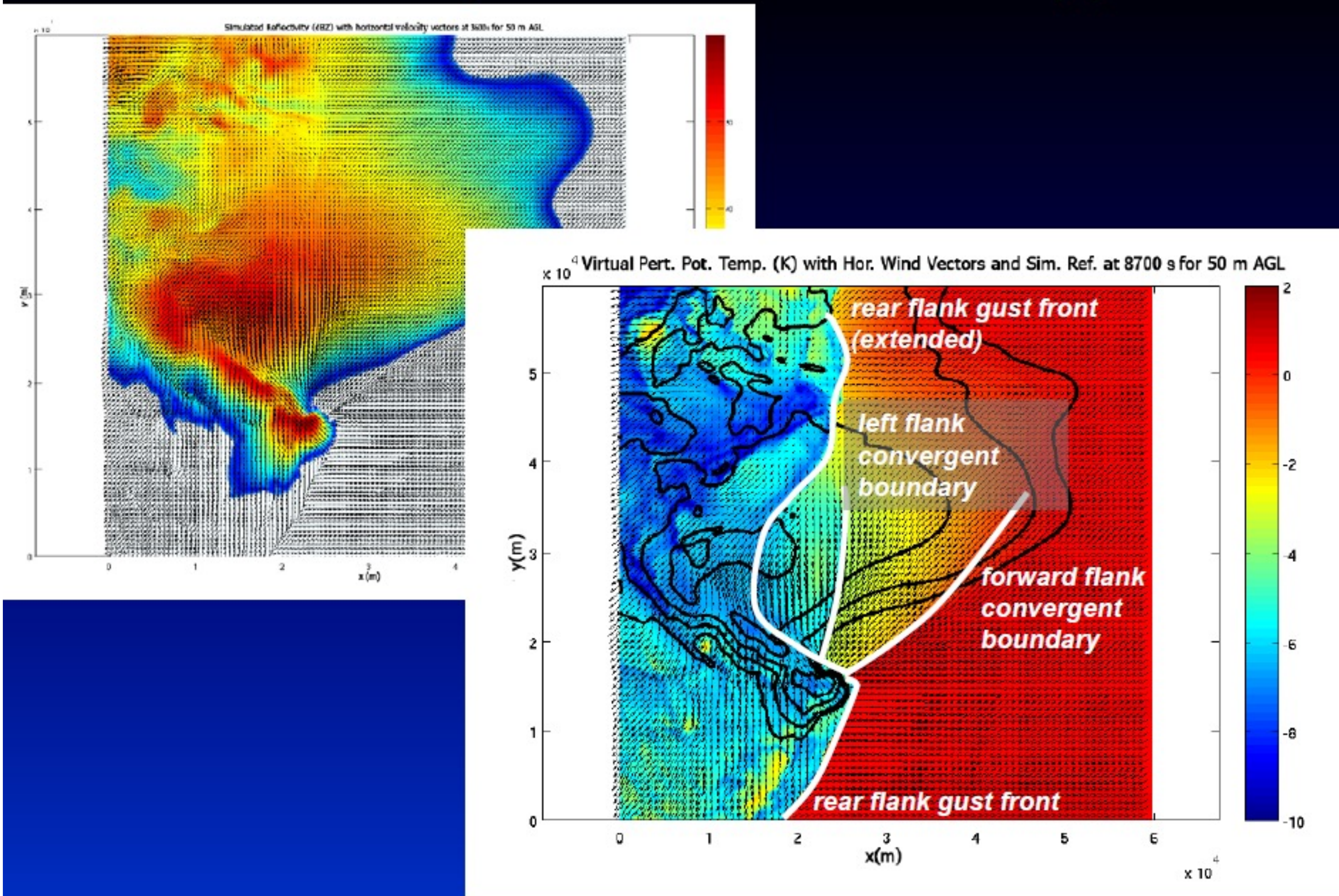
- the numerics were somewhat primitive and the grids were coarse (the finite differences had large truncation errors)
- as a result of the above, the model applied a large (by today's standards) amount of artificial diffusion…



These supercell fields look much too smooth and pretty

Klemp and Rotunno (1983)

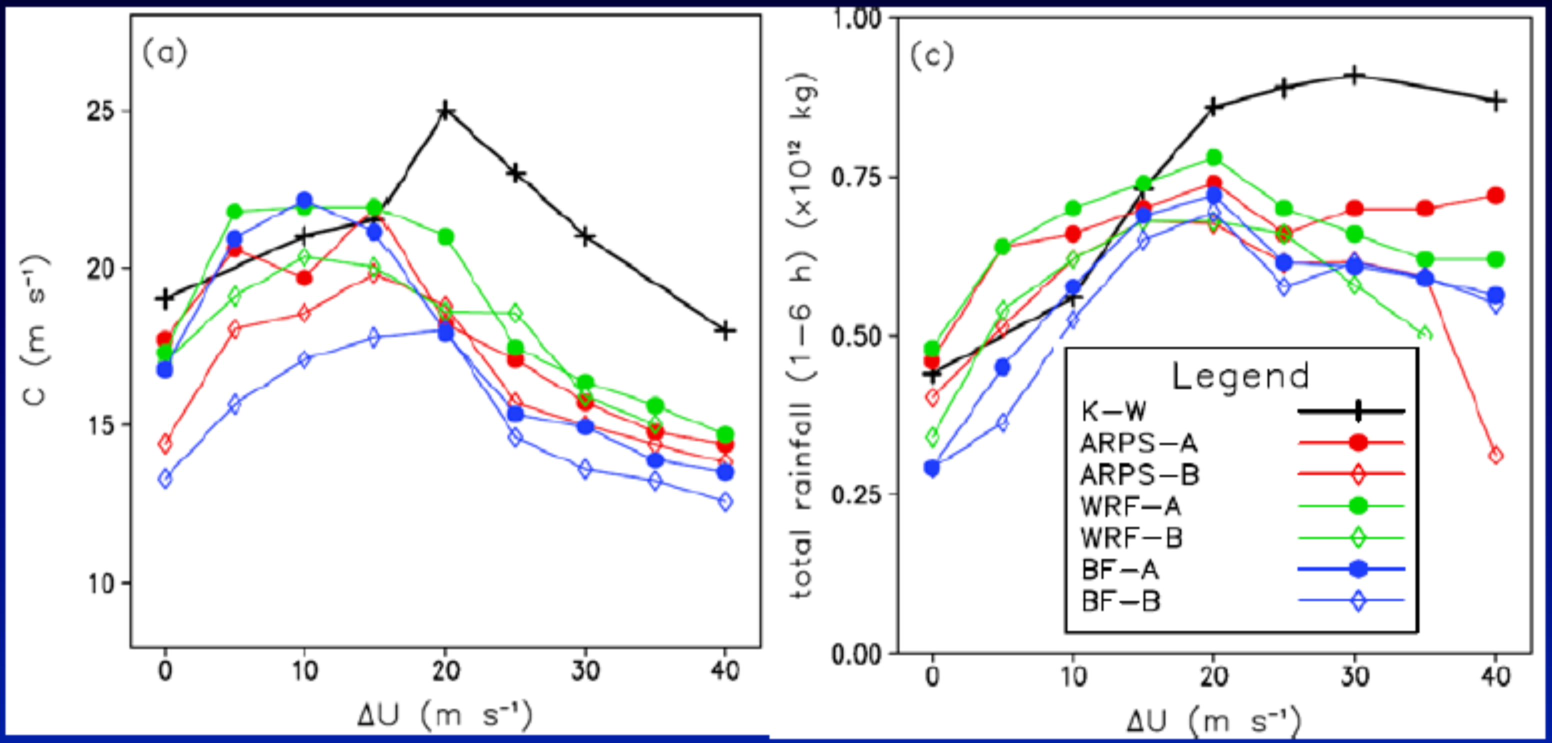
Simulations with higher resolution and more realistic microphysics



Beck (2009)

Some problems with the KW model…

- the model had a poor bottom boundary condition (when coupled with the vertical diffusion scheme) that caused cold surface outflows artificially to keep getting colder with time!



Bryan et al (2006)

Other, more modern models are generally superior (ARPS, Bryan-Fritsch/CM1 model, RAMS, WRF, etc.)

Does this mean that the results from the K-W model studies are invalid?

- Model results must be interpreted in the context of the model that was used. Scientists must try to identify the model artifacts and extricate them from the physically meaningful signals.

- Trends and sensitivites among runs should be emphasized over specific output values

- Straightforward processes such as advection, PGF generally warrant more confidence than results that rely heavily on complex parameterizations

- Much of what we know about storm dynamics today derived from these original experiments, and almost all of those results still stand the test of time!

- Basic issue
- Configuration
- Modeling of convective storm- KW model
- Current trends in cloud model

Current trends in cloud models:

- Higher and higher resolution

- Studies include more simulations (no longer in the era of "one production run")

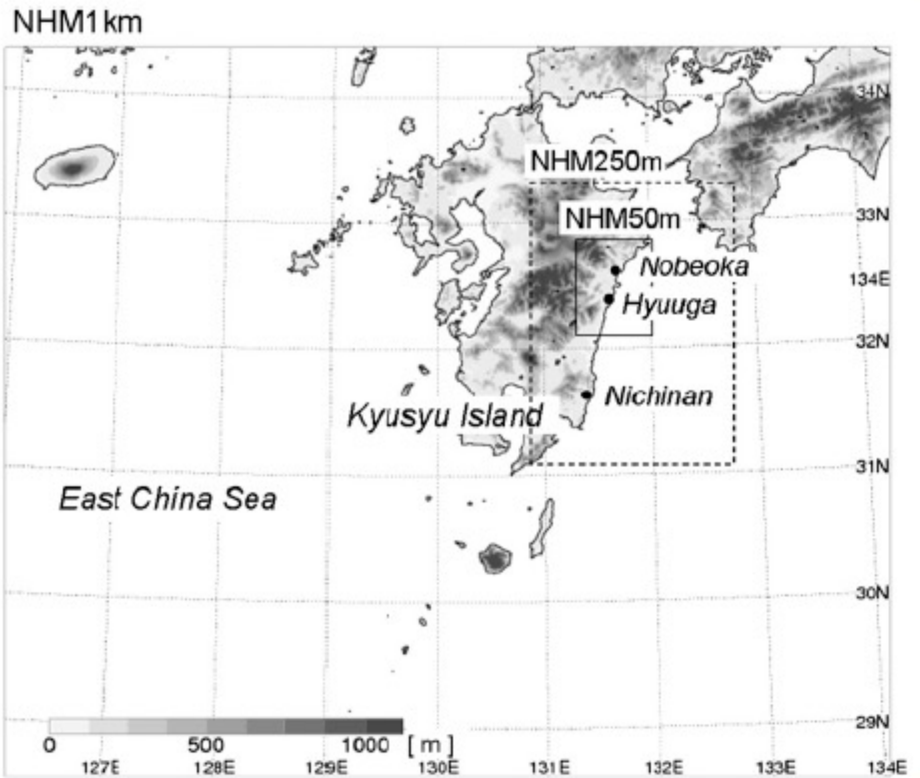
- Ever increasing sophistication of microphysical parameterizations

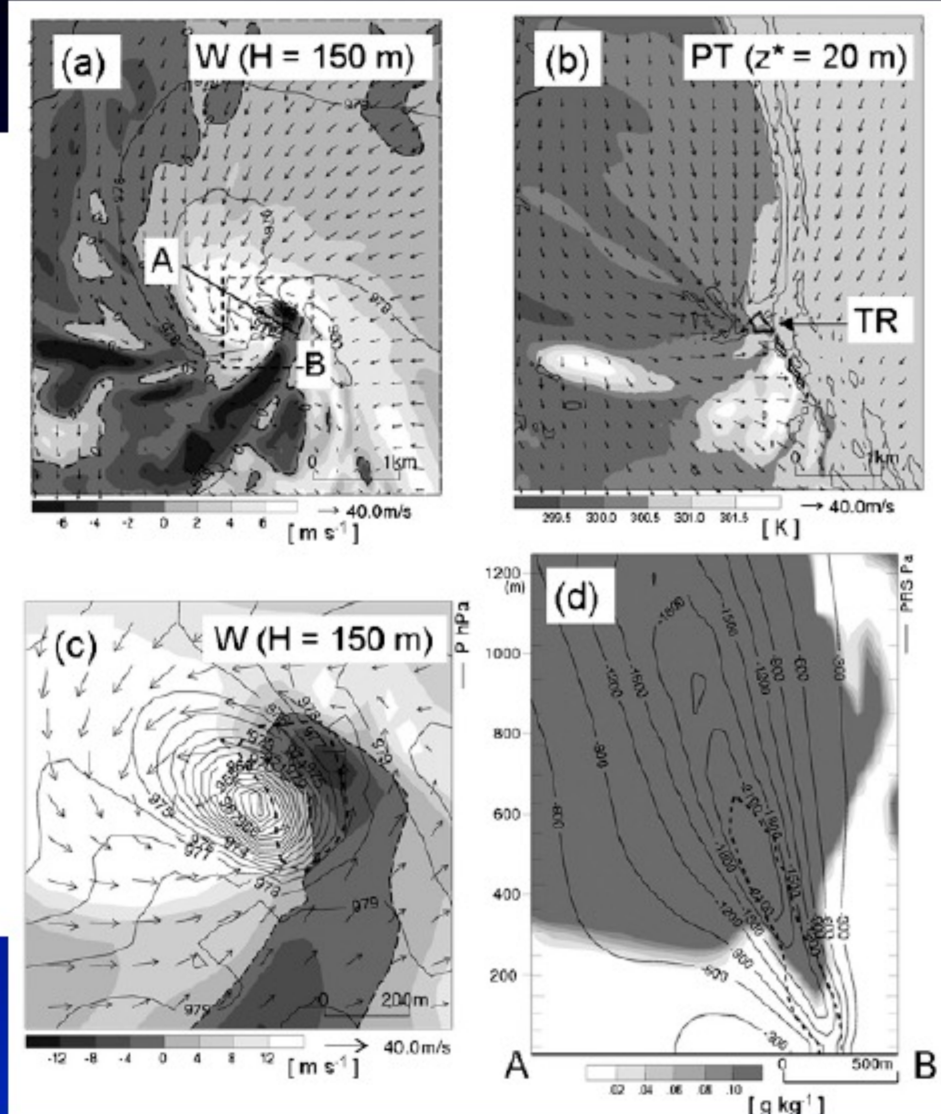
- Increasing use of ensembles

- Increasing use of dynamical data assimilation techniques

- Operationally useful NWP that resolves smaller scale convective processes

Trends: Higher and higher resolution



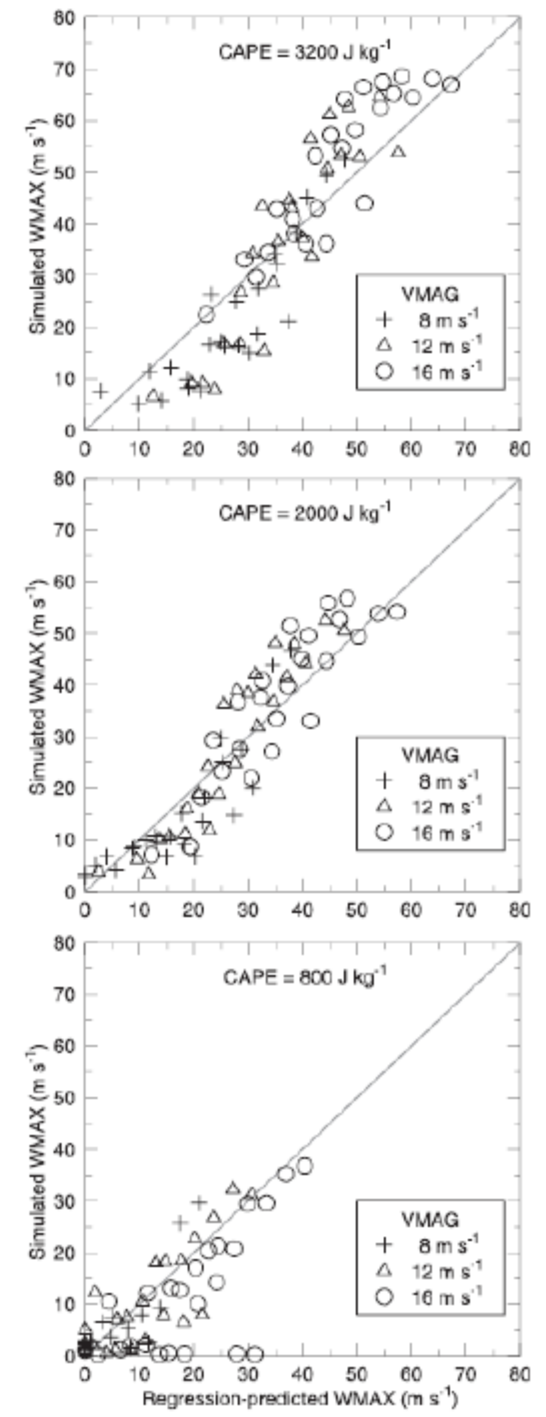


Nesting down to 50 m grid spacing!

Mashiko et al (2009)

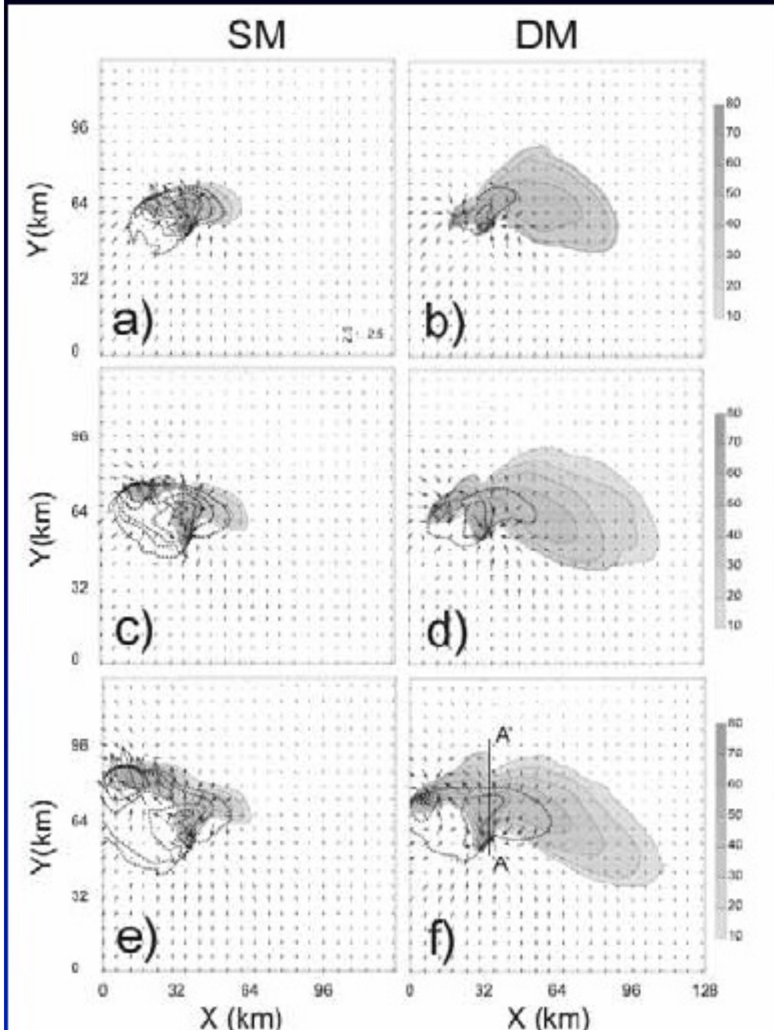
<u>Trends:</u> Studies include more simulations

Statistics on updraft properties from a suite of more than 200 simulations!



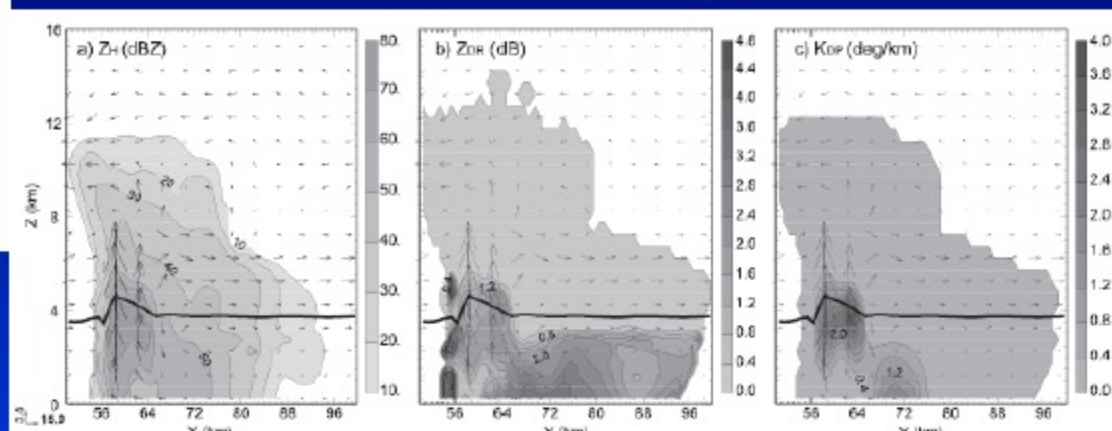
Kirkpatrick et al (2009)

Trends: Increasing sophistication of microphysics



Dual-moment (DM) schemes often produce more realistic sizes and shapes for storms precipitation areas

More sophisticated treatments of dual-polarization radar variables are possible, enabling more thorough model validation



Jung et al (2010)

Trends: Increasing sophistication of microphysics

TABLE 1. List of microphysics schemes and their descriptions.

Microphysics scheme/configuration	Description
LINA	Based on Lin et al. (1983) and Tao and Simpson (1993)
LINB	LIN scheme with N_{0r} reduced from default value of 8.0×10^6 m^{-4} to 4.0×10^5 m^{-4}
MY1	Single-moment version of the MY scheme (q predicted)
MY2	Double-moment version of the MY scheme (q and N_t predicted)
MY2DA	As in MY2 but with diagnostic relations for shape parameter α
MY3	Triple-moment version of the MY scheme (q, N_t, and Z predicted)

Even triple moment schemes are now in use! (this involves predicting a shape to the distribution as well)

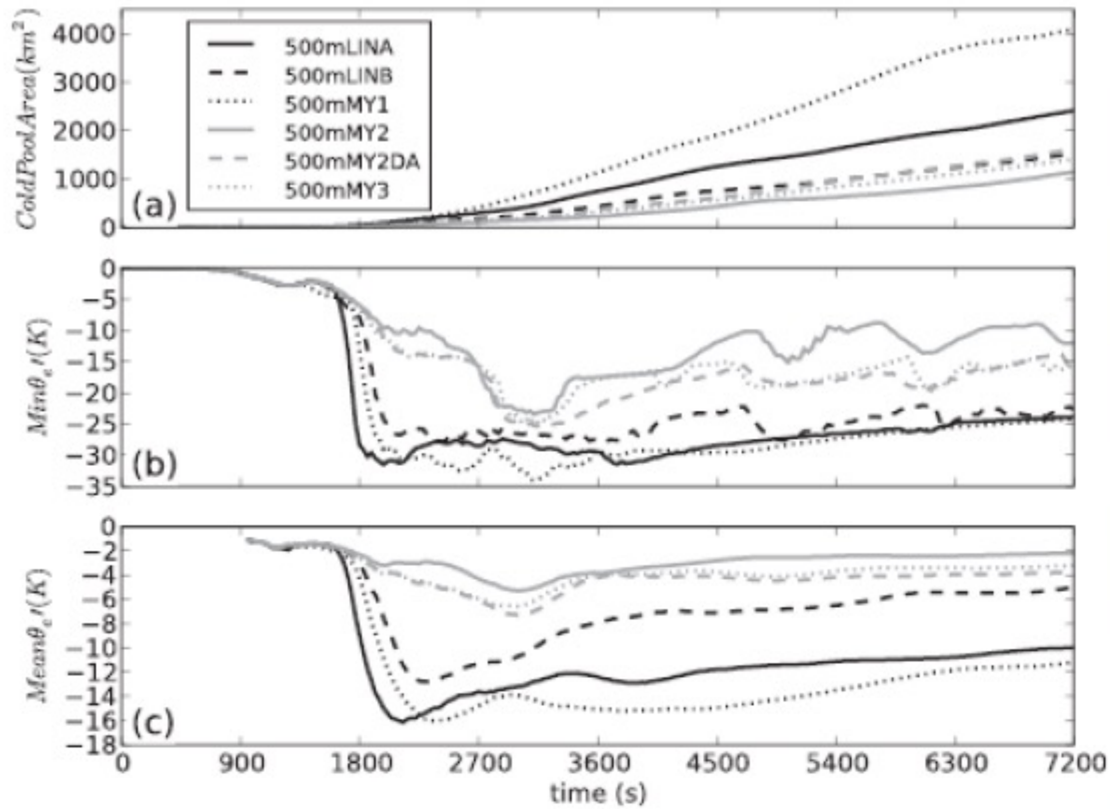
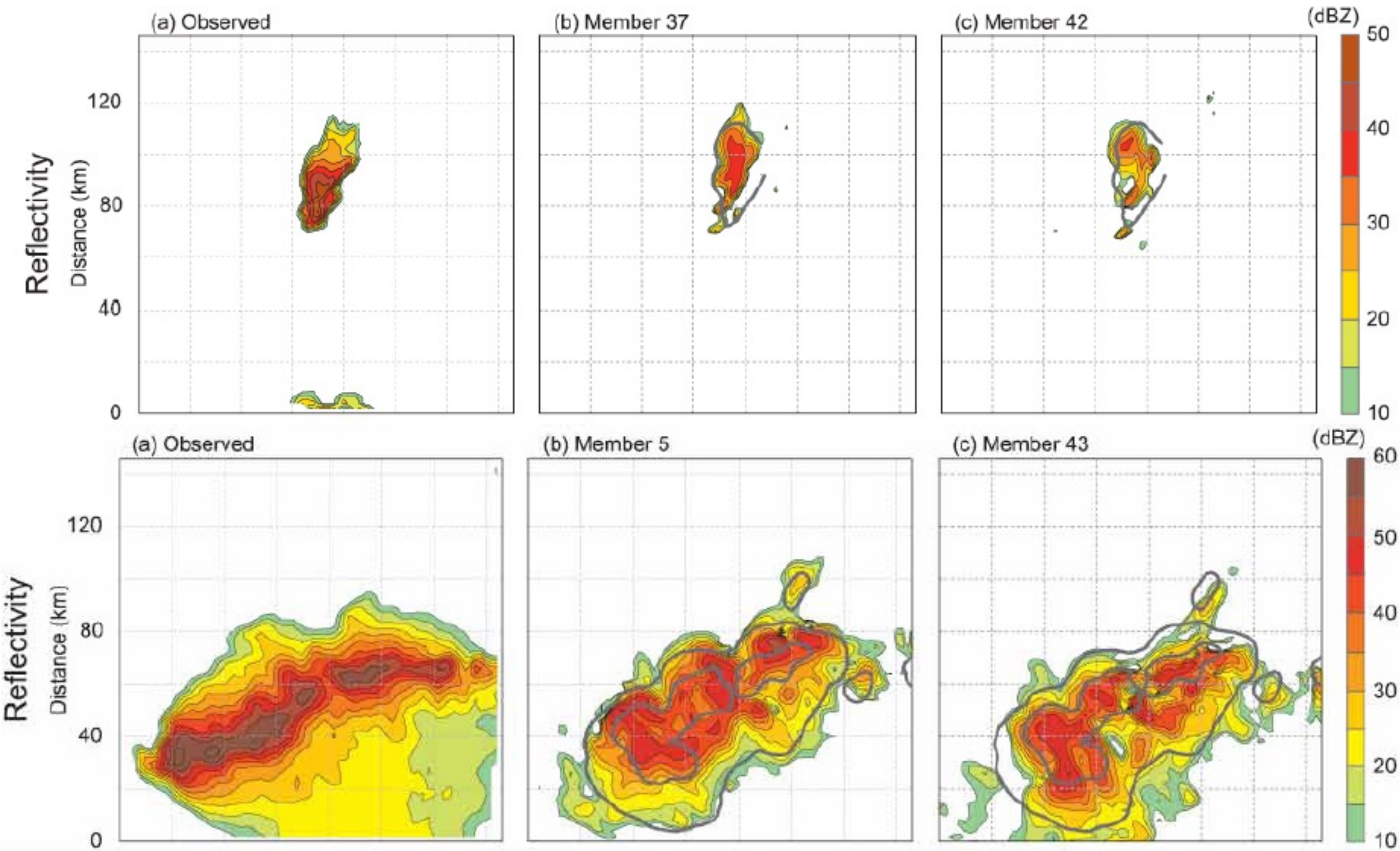


FIG. 5. Time series of (a) total surface cold pool area as defined as the sum of the area of all grid squares with $\theta_e' < -1$ K, (b) minimum θ_e' at the surface, and (c) mean θ_e' within the cold pool as defined above, for each of the 500-m experiments.

Cold pool intensity and size are very sensitive to the choice of microphysics parameterization!

Dawson et al (2010)

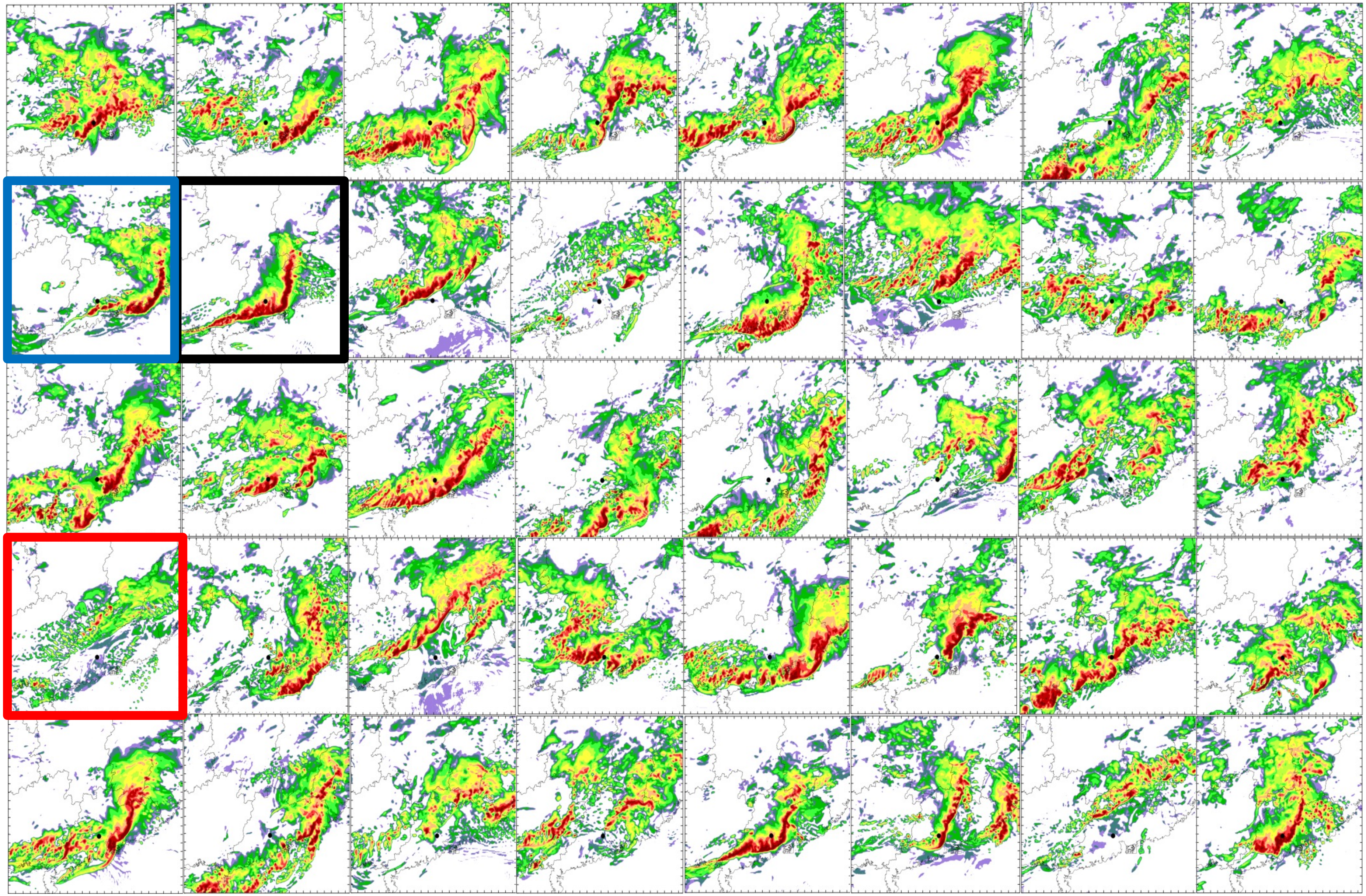
Trends in cloud models: Increasing use of ensembles



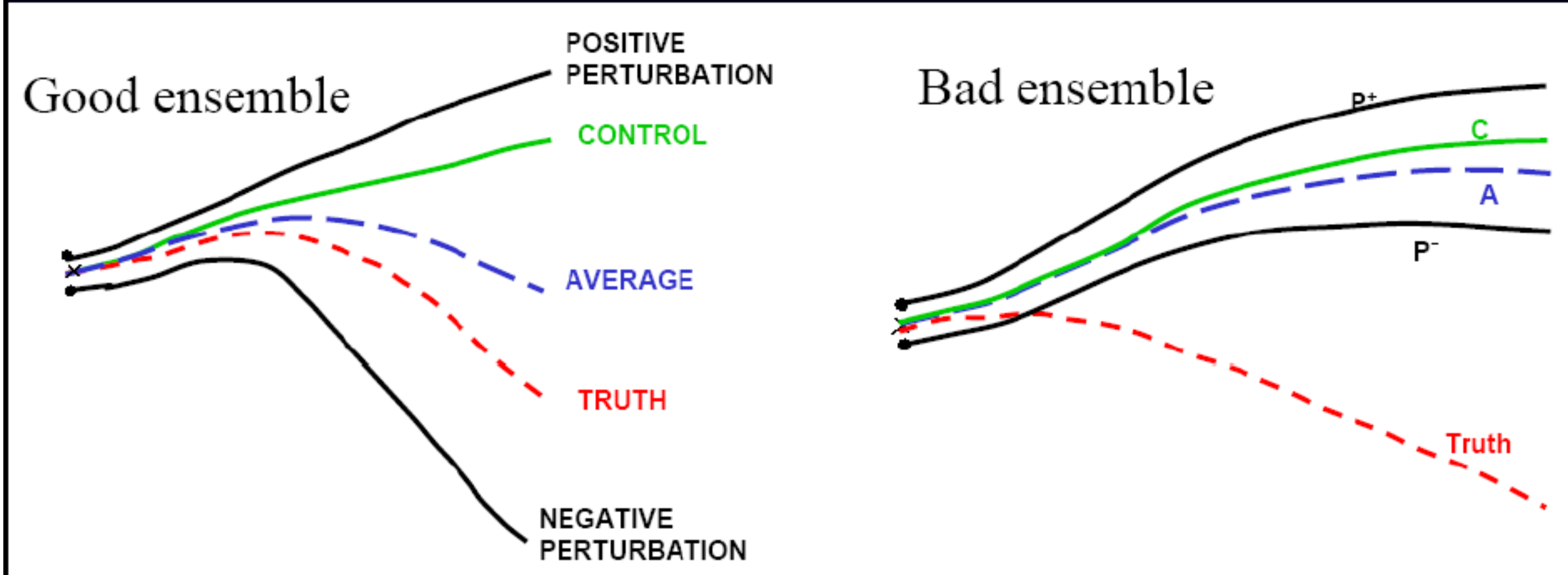
Exploit the best forecasts (here in a 50-member ensemble)!

Aksoy et al (2010)

The CNTL ensemble, reflectivity valid at 24/00z



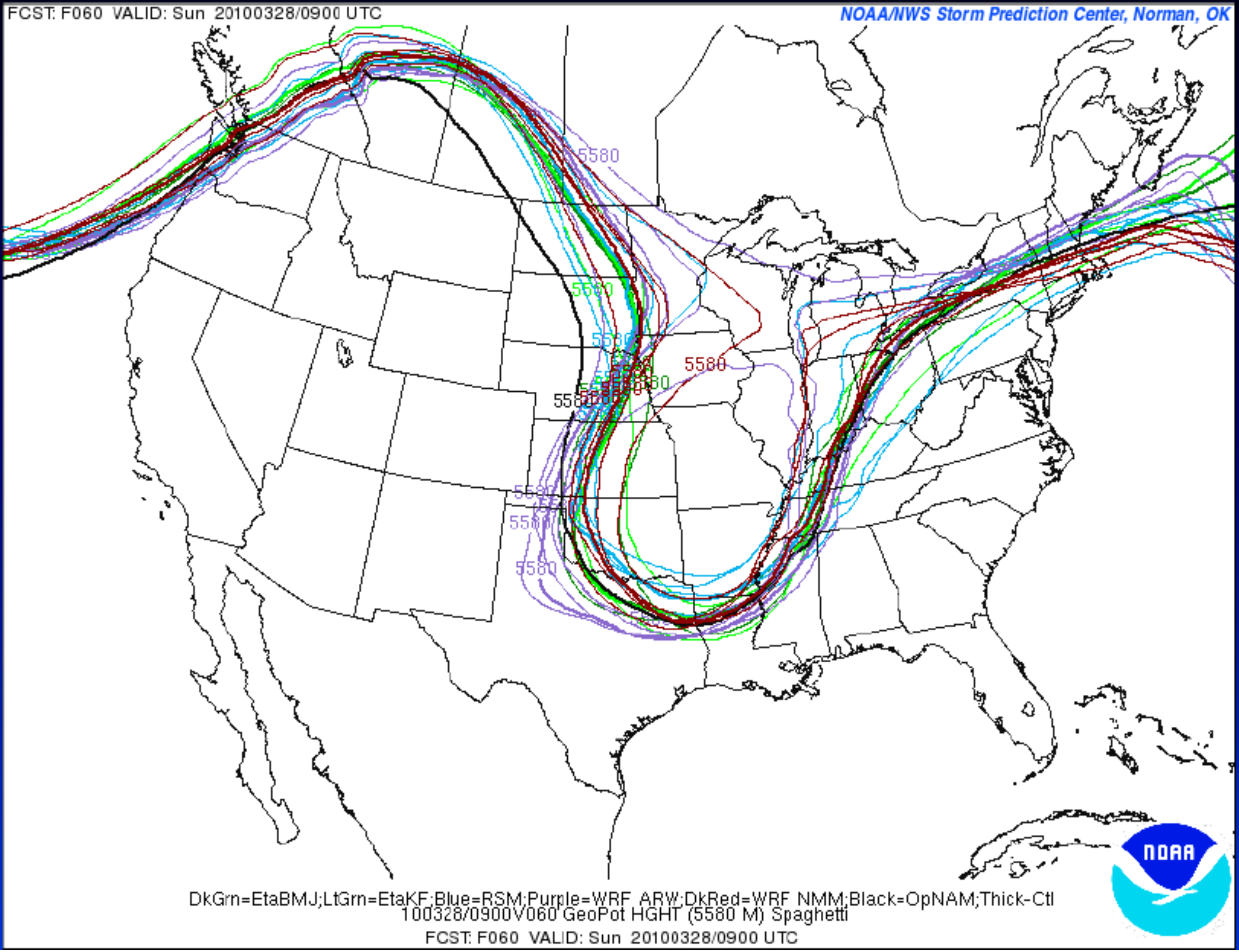
Model ensembles



- The ensemble mean tends to outperform any individual deterministic model over the long haul (even though any one ensemble member may be better than the mean on any given day)
- The differences among the ensemble members provide information about the uncertainty, provide some bounds (best and worse cases), and lead directly into probabilities (e.g. probability of precipitation)

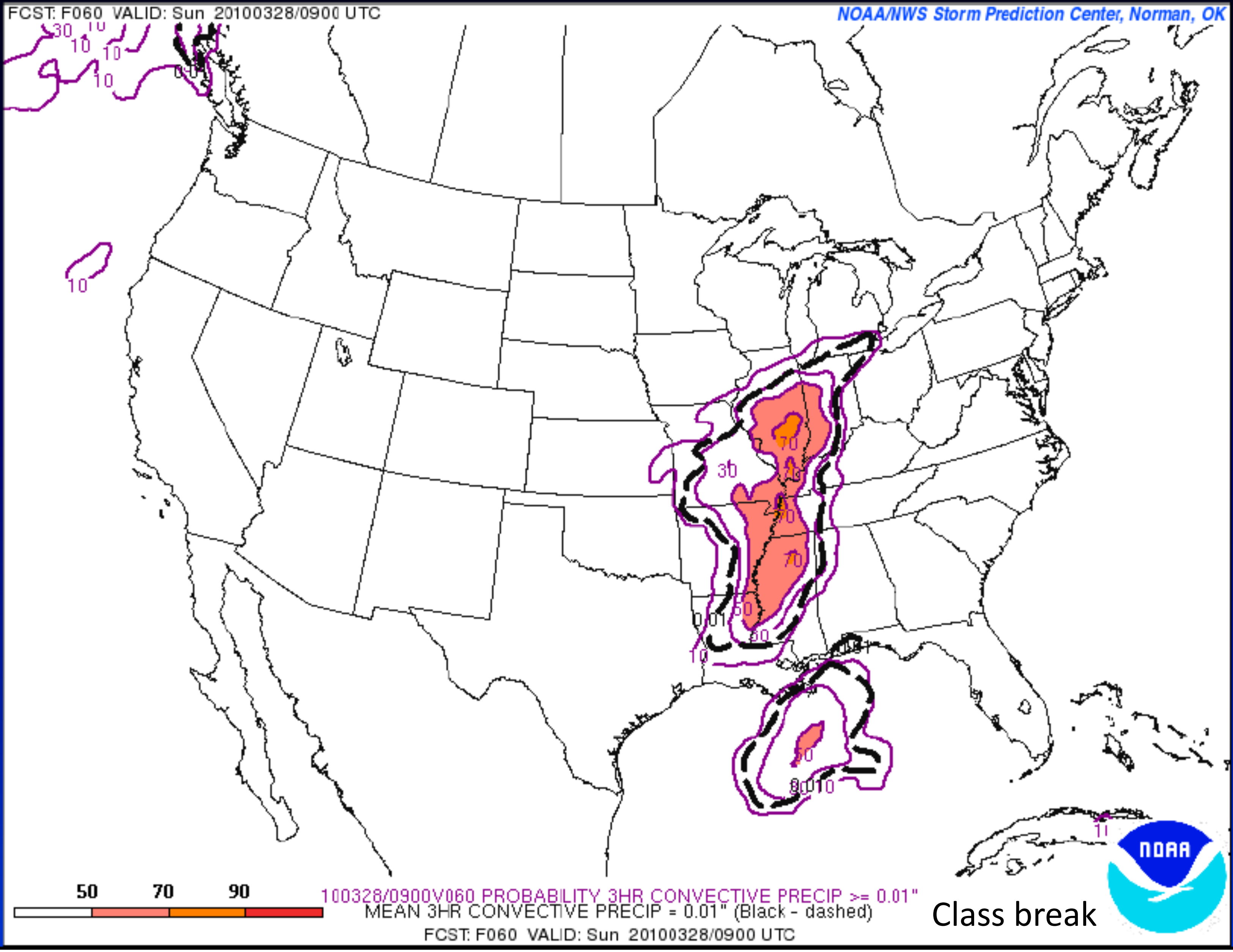
Examples: SPC's short range ensemble forecast (SREF) model output

Precip: *5580 m 500 mb height contour for each ensemble member*



Examples: SPC's short range ensemble forecast (SREF) model output

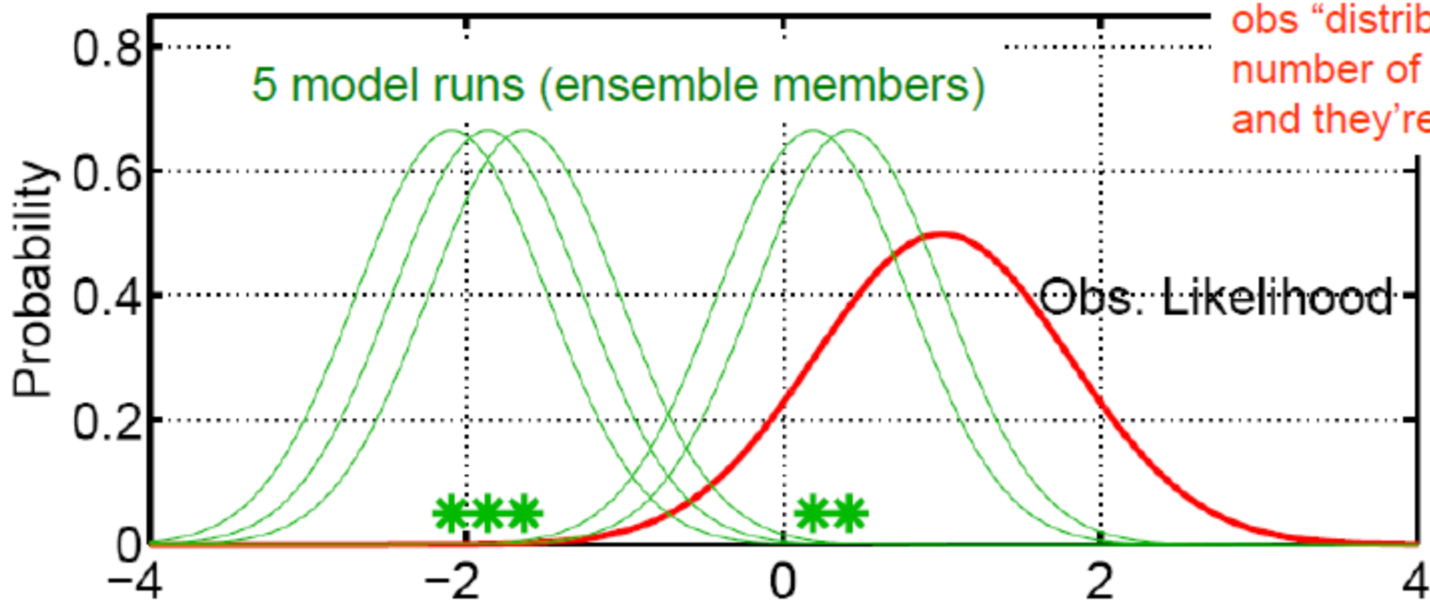
Precip: *percentage of members producing precip at each grid cell*



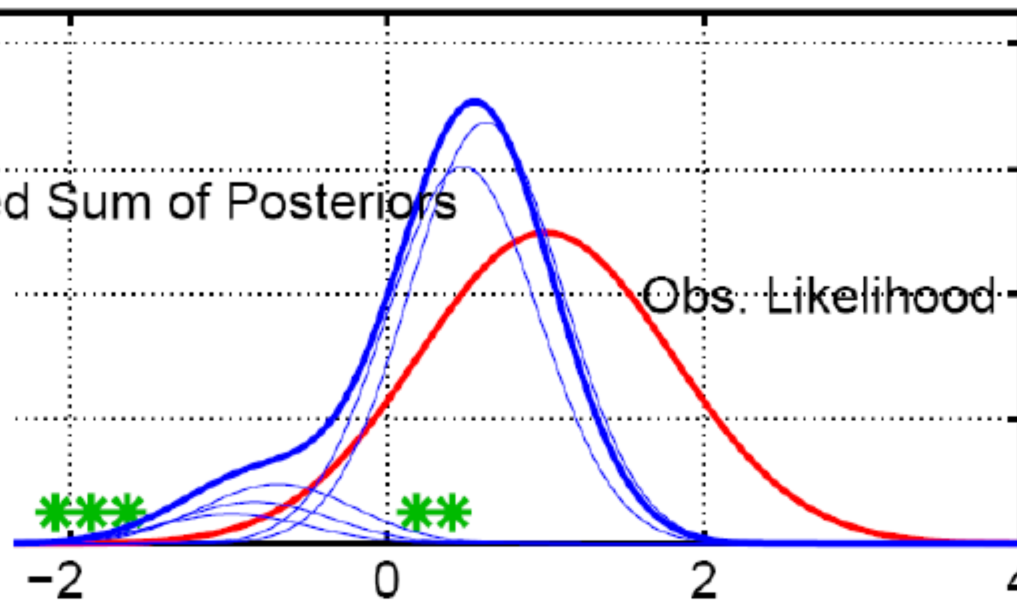
Class break

Trends: Increasing use of data assimilation (especially Ensemble Kalman filter)

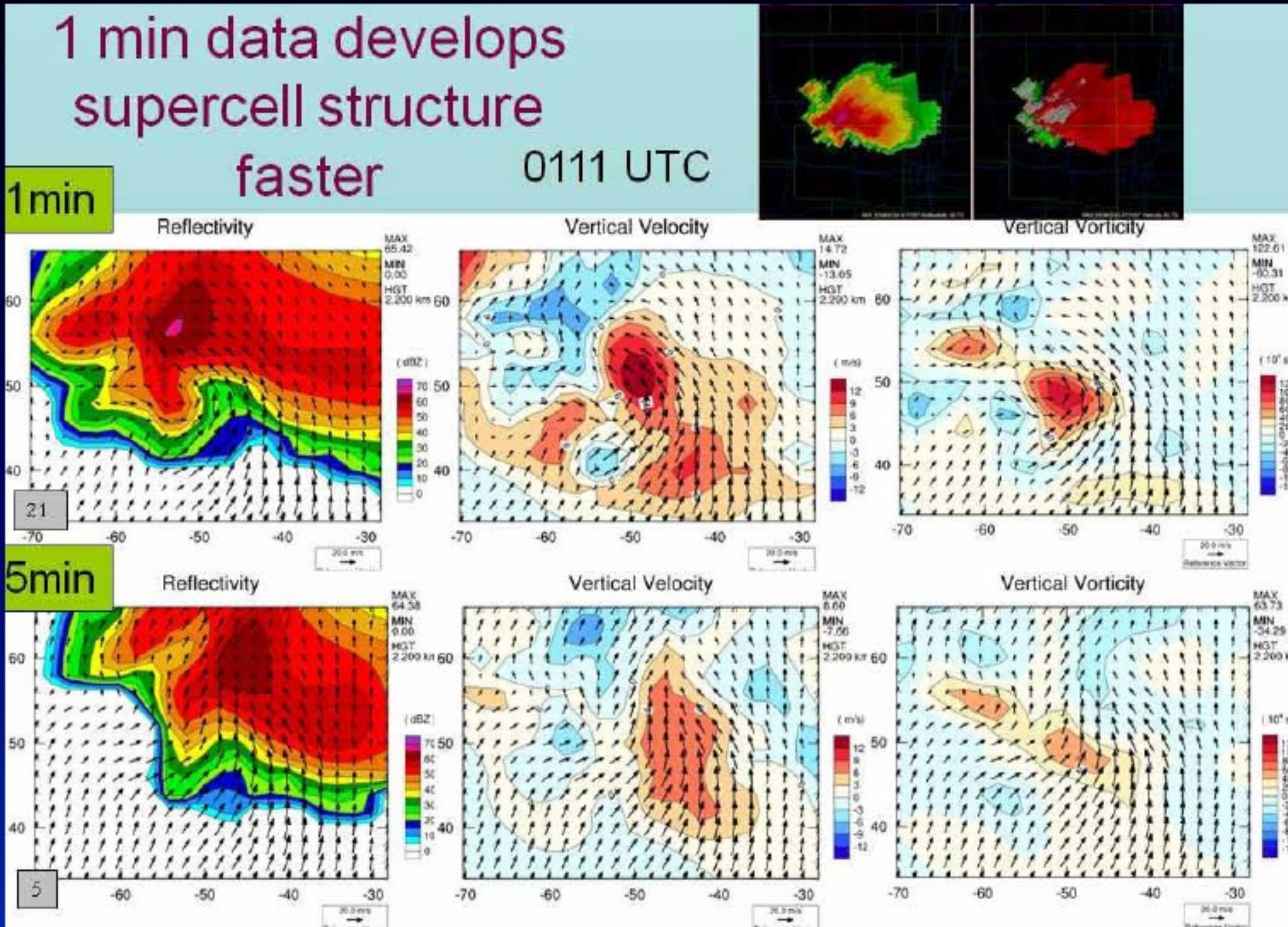
obs “distribution”: a large number of obs are available, and they’re assumed to be noisy



Each member’s values are updated to new posterior distributions, which are proportional to the product of the ensemble member’s PDF and the observed PDF; the ensemble’s new overall “best analysis” field then has the distribution of the normalized sum of the posteriors.



Trends in cloud models: Increasing use of data assimilation

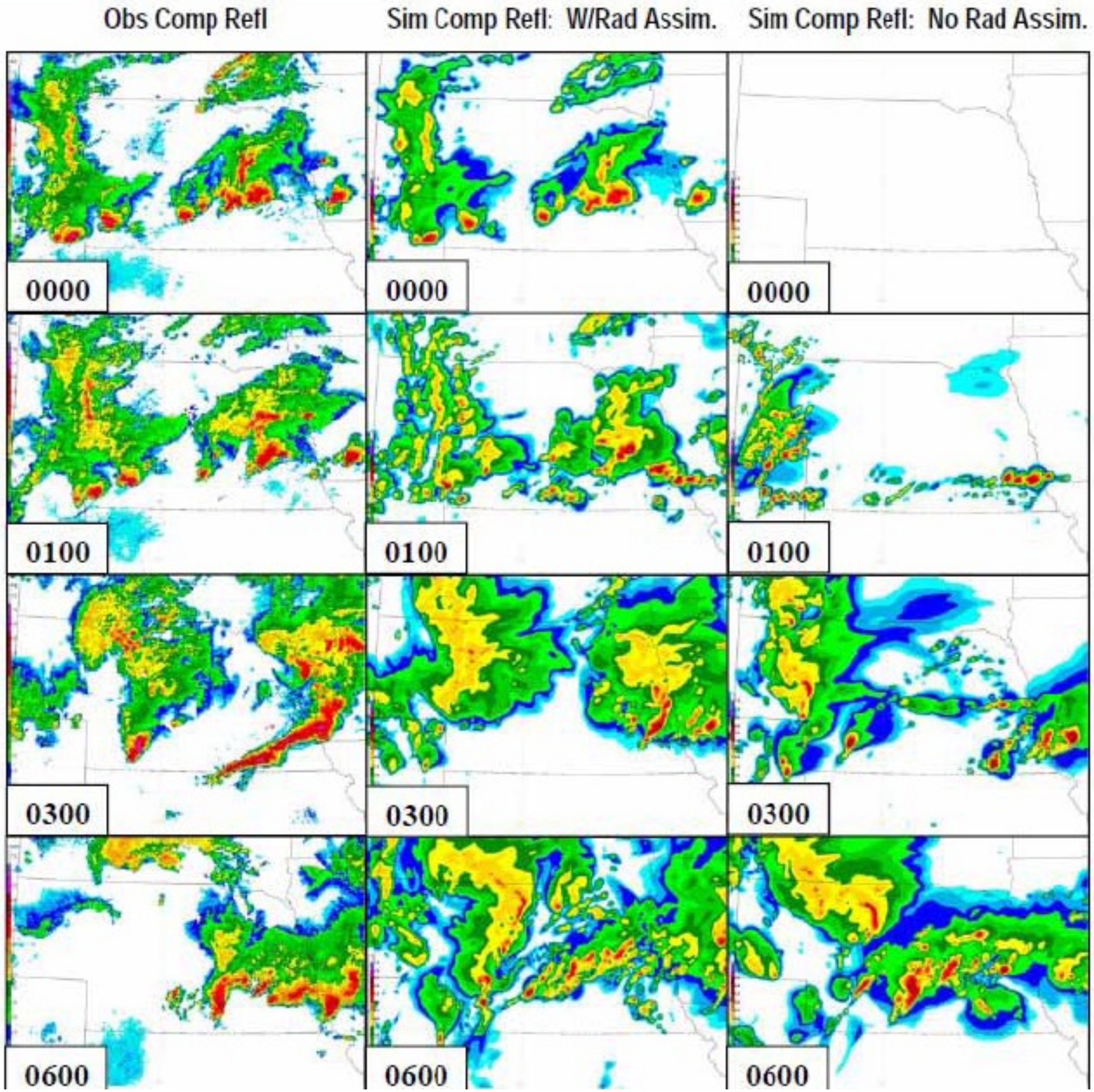


Assimilating 1 min radar data improves representation of supercell compared to assimilating 5 min radar data!

Thompson et al (2010)

Trends in cloud models: NWP that resolves convection

Models for this domain are being run with grid spacings of 1-4 km every day now!



Kain et al (2008)

小结

- 大气对流的数值模拟一般来讲是可信的
- 模式可用于敏感性试验，对某些假设的检验
- 对模式结果的阐释

  模式结果≠观测

  – 如果矛盾，倾向于高质量的观测结果
- 随着计算机和观测手段尤其是云和边界层观测能力的提高，模式模拟的能力将快速发展

WRF USERS PAGE

Home | Model System | User Support | Download | Doc / Pub | Physics | Support Forum | WRF Forecast

Search

WRF General Information

Public Domain Notice

WRF User Support

Download WRF

WRF Version 4 User's Guide

How to Cite WRF

WRF Model Users' Page

Welcome to the users' page for the Weather Research and Forecasting Model (here "WRF", for short). WRF is a state-of-the-art atmospheric modeling system designed for both meteorological research and numerical weather prediction. It offers a host of options for atmospheric processes and can run on a variety of computing platforms. WRF excels in a broad range of applications across scales ranging from tens of meters to thousands of kilometers, including the following.

– Meteorological studies
– Real-time NWP
– Idealized simulations
– Data assimilation
– Earth system model coupling
– Model training and educational support

The Mesoscale and Microscale Meteorology Laboratory (MMM) of NCAR supports the WRF system to the user community, and maintains the WRF code on GitHub. MMM provides user assistance via an online Support Forum. MMM also issues WRF releases, conducts WRF tutorials, and hosts the annual WRF and MPAS Users' Workshop.

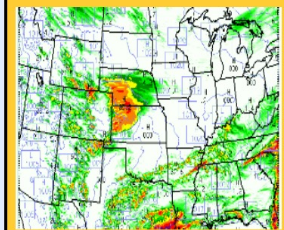
The WRF system is available via free download through these pages. In addition to providing the code and documentation for WRF system, this site provides information and links on WRF code contributions, releases, and events.

Related Systems and Information

There are a number of WRF-related systems and specialty capabilities with separate pages. Key ones are listed below, and users are directed to these for the system details.

– WRF Data Assimilation System: WRFDA
– WRF-Chem (WRF atmospheric chemistry model): WRF-Chem
– WRF-Hydro (WRF hydrological modeling system): WRF-Hydro

WRF Forecast



WRF Real-Time Forecasting

Announcements

Register now for the Winter 2025 WRF Tutorial.

Presentations from the Joint WRF & MPAS-A Users' Workshop, June 2024.

Latest WRF Release: **WRF Version 4.6.1** is now available for download.

WRF Releases - Known Problems

General Information

User Support Statement

General Notes on Compiling and Running on Derecho.

Frequently Asked Questions

WRF Code Repository and Release Administration

Information for Code Contributors

WRF Physics Review Process and Panel

https://www2.mmm.ucar.edu/wrf/users/

An Introduction to the WRF Modeling System

Wei Wang

January 2021

Mesoscale and Microscale Meteorology Laboratory, NCAR

NCAR

This material is based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977.

https://www.youtube.com/watch?v=wzSu-343b-0