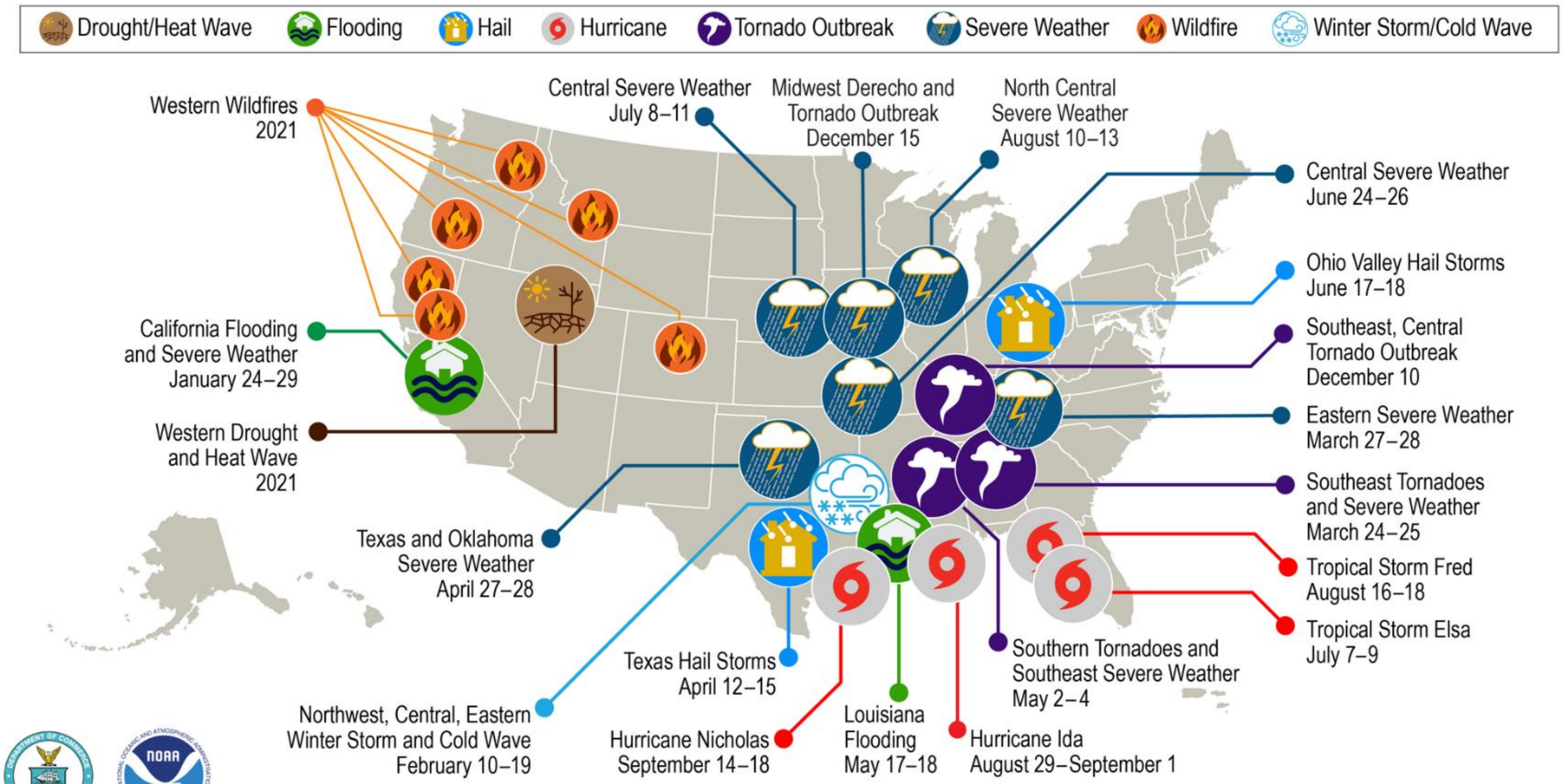
Innovations in the Prediction and Warning of Severe Storms and Tornadoes

Kelvin K. Droegemeier
University of Oklahoma

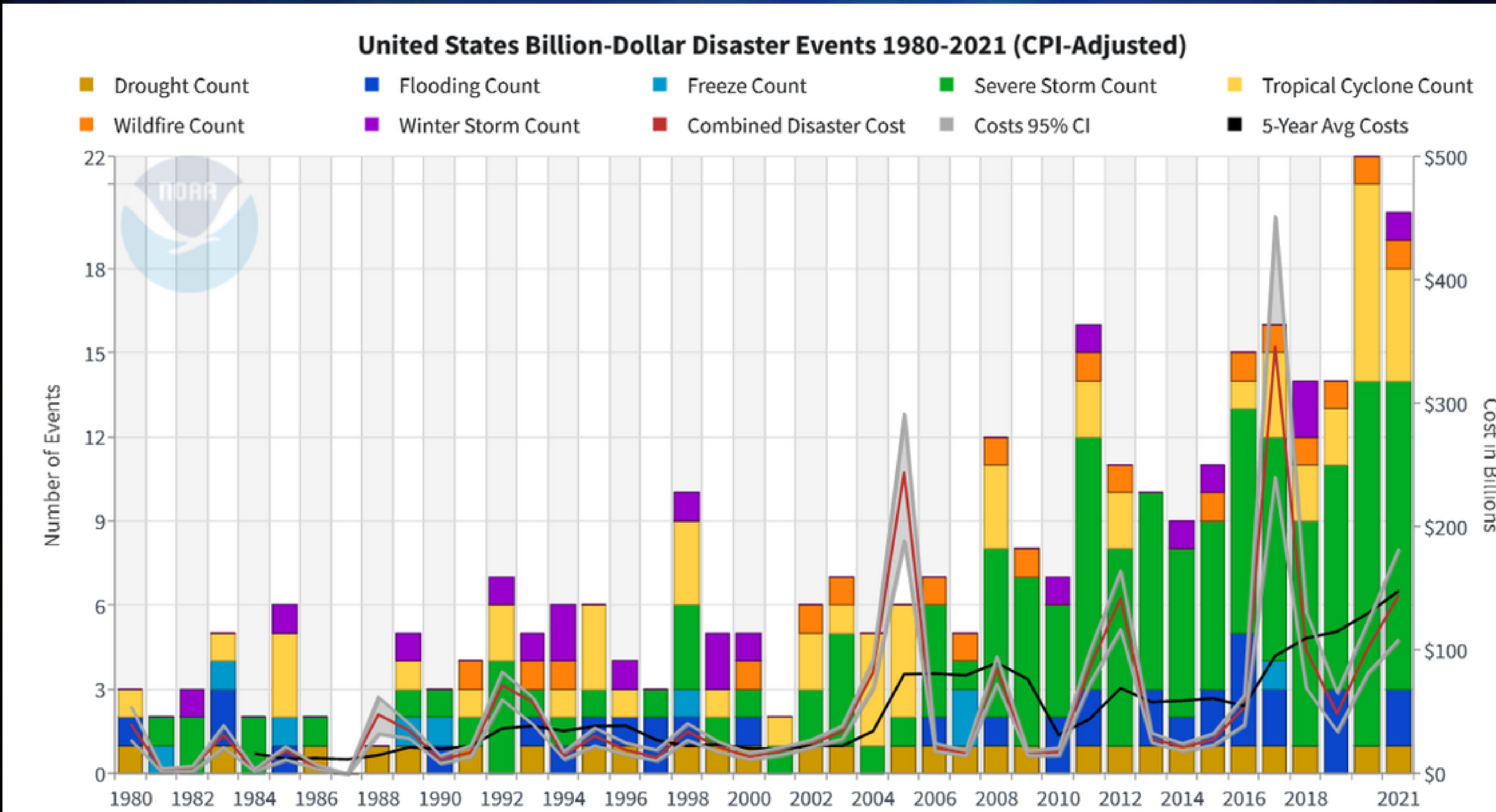
TAMEST Summit on Natural Hazards: Responding to and Mitigating Impacts
16 May 2022

Beautifully Powerful but Deadly

U.S. 2021 Billion-Dollar Weather and Climate Disasters



*This map denotes the approximate location for each of the **20 separate billion-dollar weather and climate disasters that impacted the United States in 2021***



United States Billion-Dollar Disaster Events 1980-2021 (CPI-Adjusted)
Drought Count
Flooding Count
Freeze Count
Severe Storm Count
Tropical Cyclone Count
Wildfire Count
Winter Storm Count
Combined Disaster Cost
Costs 95% CI
5-Year Avg Costs
Number of Events
Cost in Billions
0
3
6
9
12
15
18
22
$0
$100
$200
$300
$400
$500
1980
1982
1984
1986
1988
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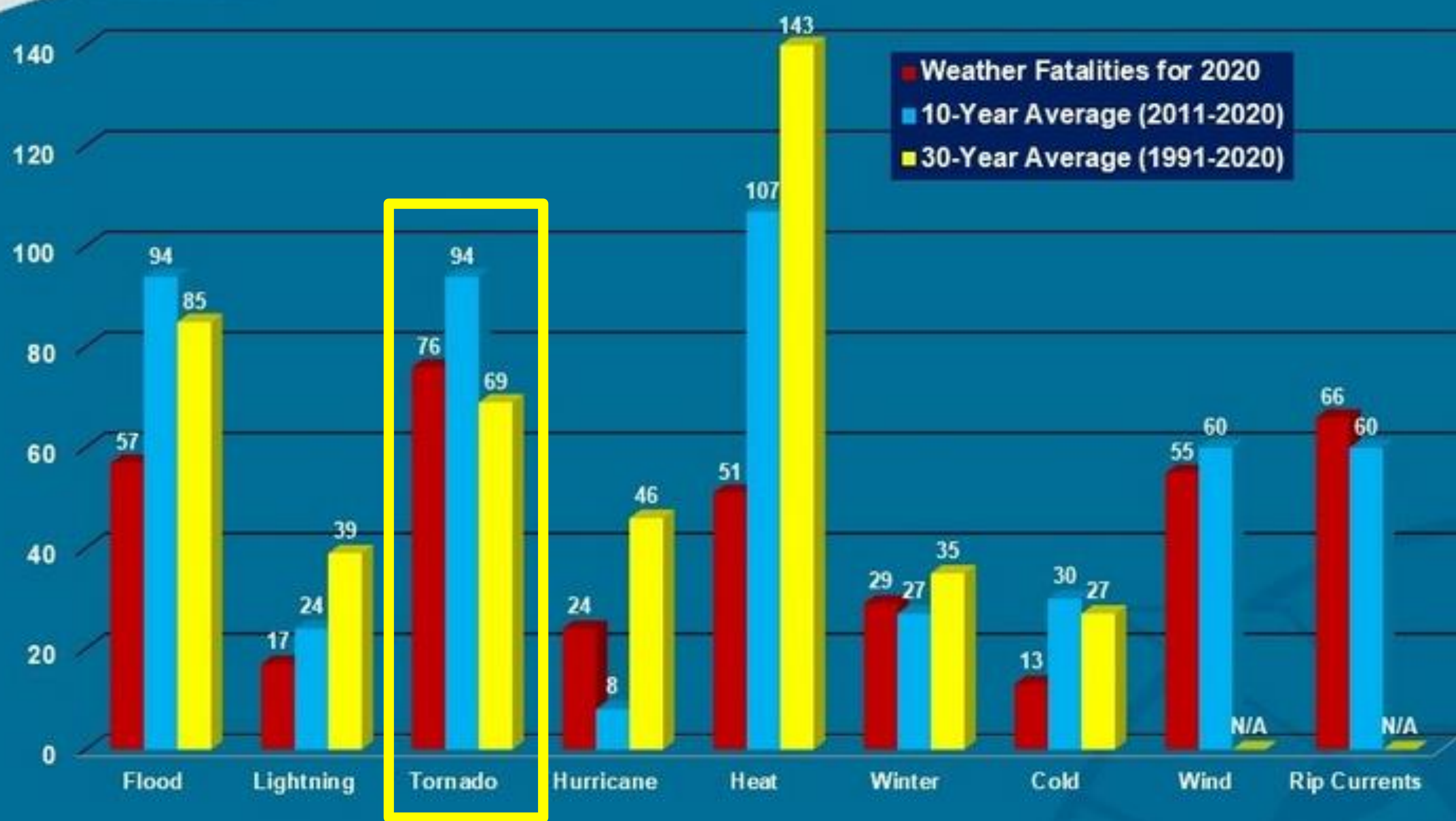
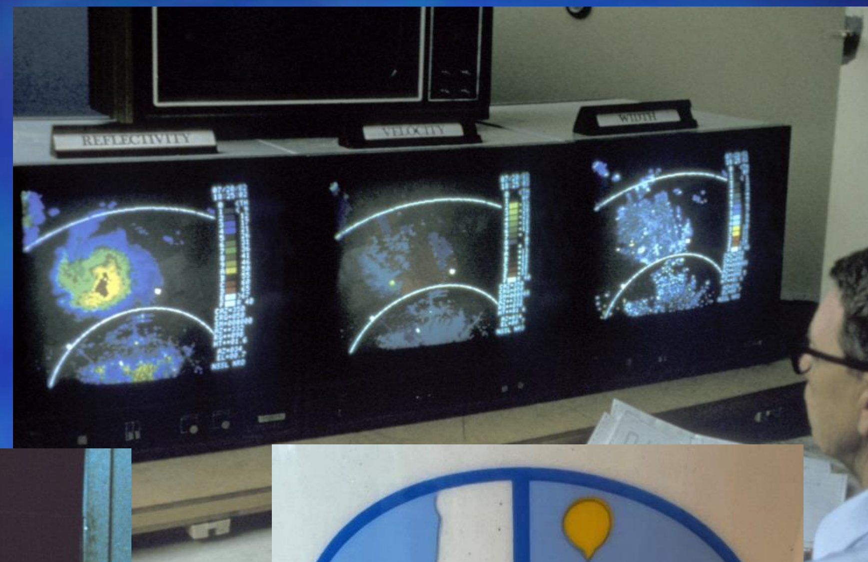
2021

Weather Fatalities 2020

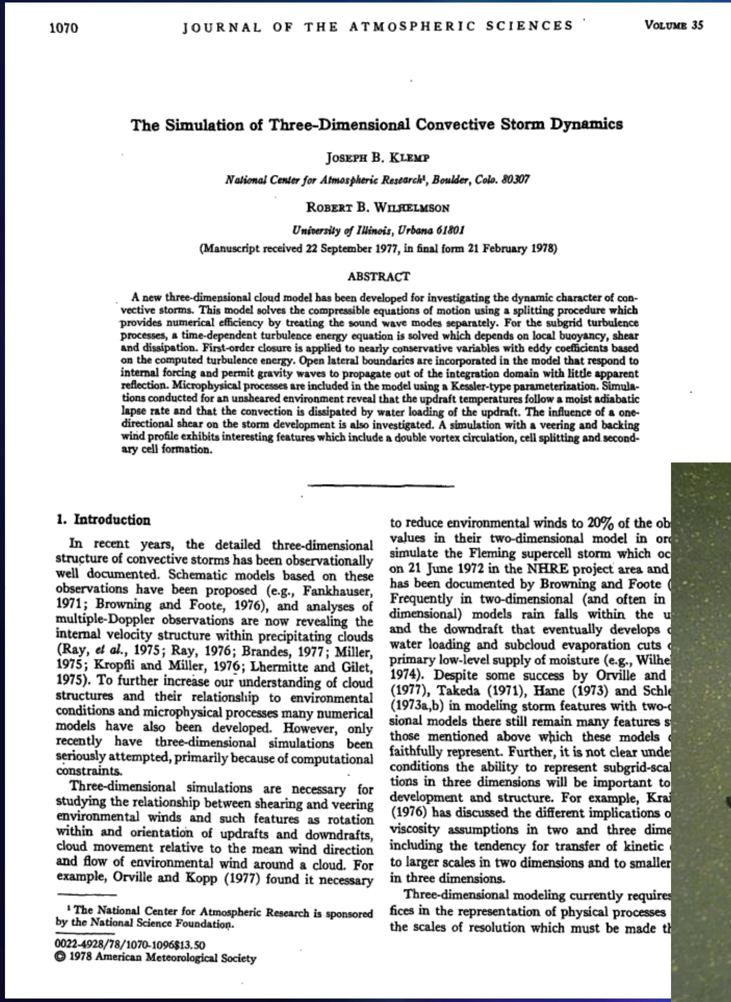


Where We Were in the Late 1970s/Early 1980s



Courtesy NSSL

Where We Were in the Late 1970s/Early 1980s



The Simulation of Three-Dimensional Convective Storm Dynamics

JOSEPH B. KLEMP
National Center for Atmospheric Research[1]*, Boulder, Colo. 80307*

ROBERT B. WILHELMSON
University of Illinois, Urbana 61801

(Manuscript received 22 September 1977, in final form 21 February 1978)

ABSTRACT

A new three-dimensional cloud model has been developed for investigating the dynamic character of convective storms. This model solves the compressible equations of motion using a splitting procedure which provides numerical efficiency by treating the sound wave modes separately. For the subgrid turbulence processes, a time-dependent turbulence energy equation is solved which depends on local buoyancy, shear and dissipation. First-order closure is applied to nearly conservative variables with eddy coefficients based on the computed turbulence energy. Open lateral boundaries are incorporated in the model that respond to internal forcing and permit gravity waves to propagate out of the integration domain with little apparent reflection. Microphysical processes are included in the model using a Kessler-type parameterization. Simulations conducted for an unsheared environment reveal that the updraft temperatures follow a moist adiabatic lapse rate and that the convection is dissipated by water loading of the updraft. The influence of a one-directional shear on the storm development is also investigated. A simulation with a veering and backing wind profile exhibits interesting features which include a double vortex circulation, cell splitting and secondary cell formation.

1. Introduction

In recent years, the detailed three-dimensional structure of convective storms has been observationally well documented. Schematic models based on these observations have been proposed (e.g., Fankhauser, 1971; Browning and Foote, 1976), and analyses of multiple-Doppler observations are now revealing the internal velocity structure within precipitating clouds (Ray, *et al.*, 1975; Ray, 1976; Brandes, 1977; Miller, 1975; Kropfli and Miller, 1976; Lhermitte and Gilet, 1975). To further increase our understanding of cloud structures and their relationship to environmental conditions and microphysical processes many numerical models have also been developed. However, only recently have three-dimensional simulations been seriously attempted, primarily because of computational constraints.

Three-dimensional simulations are necessary for studying the relationship between shearing and veering environmental winds and such features as rotation within and orientation of updrafts and downdrafts, cloud movement relative to the mean wind direction and flow of environmental wind around a cloud. For example, Orville and Kopp (1977) found it necessary

to reduce environmental winds to 20% of the ob
values in their two-dimensional model in or
simulate the Fleming supercell storm which oc
on 21 June 1972 in the NHRE project area and
has been documented by Browning and Foote (
Frequently in two-dimensional (and often in
dimensional) models rain falls within the u
and the downdraft that eventually develops
water loading and subcloud evaporation cuts
primary low-level supply of moisture (e.g., Wilhe
1974). Despite some success by Orville and
(1977), Takeda (1971), Hane (1973) and Schl
(1973a,b) in modeling storm features with two-
sional models there still remain many features s
those mentioned above which these models
faithfully represent. Further, it is not clear unde
conditions the ability to represent subgrid-scal
tions in three dimensions will be important to
development and structure. For example, Krai
(1976) has discussed the different implications o
viscosity assumptions in two and three dime
including the tendency for transfer of kinetic
to larger scales in two dimensions and to smaller
in three dimensions.

Three-dimensional modeling currently require
fices in the representation of physical processes
the scales of resolution which must be made th

[1] The National Center for Atmospheric Research is sponsored by the National Science Foundation.

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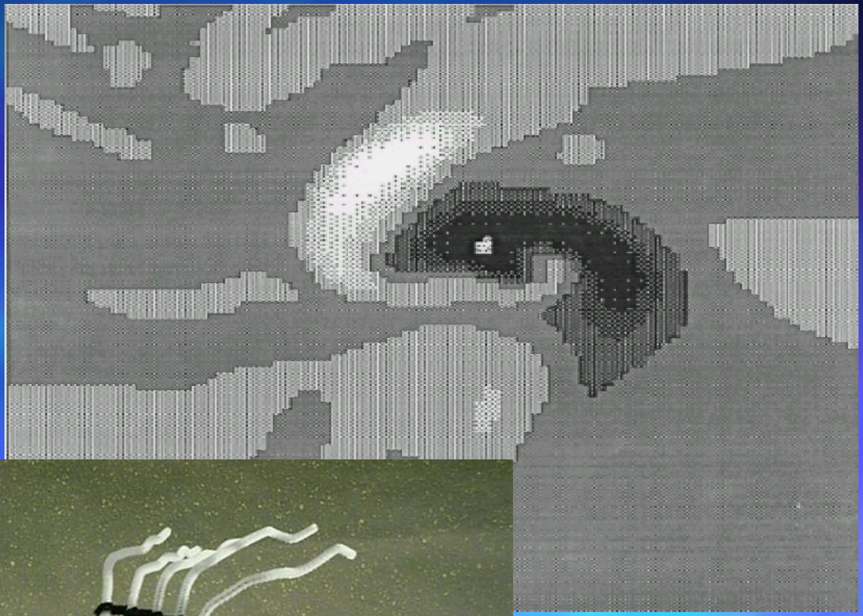
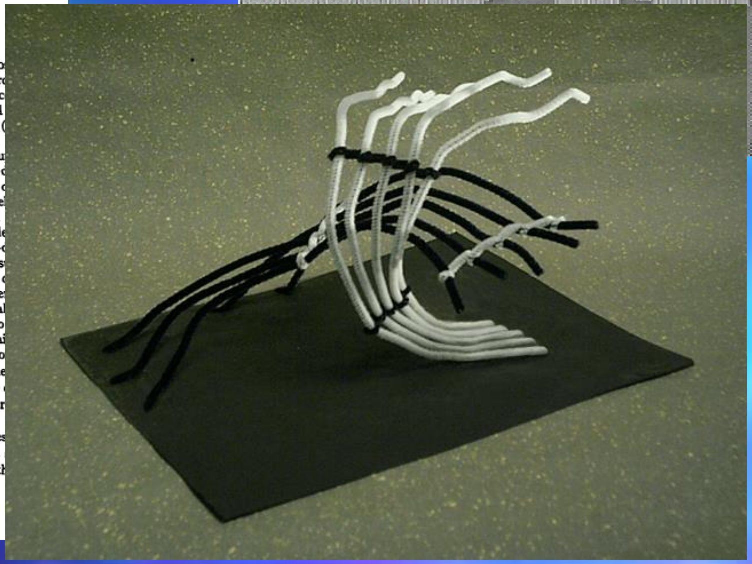




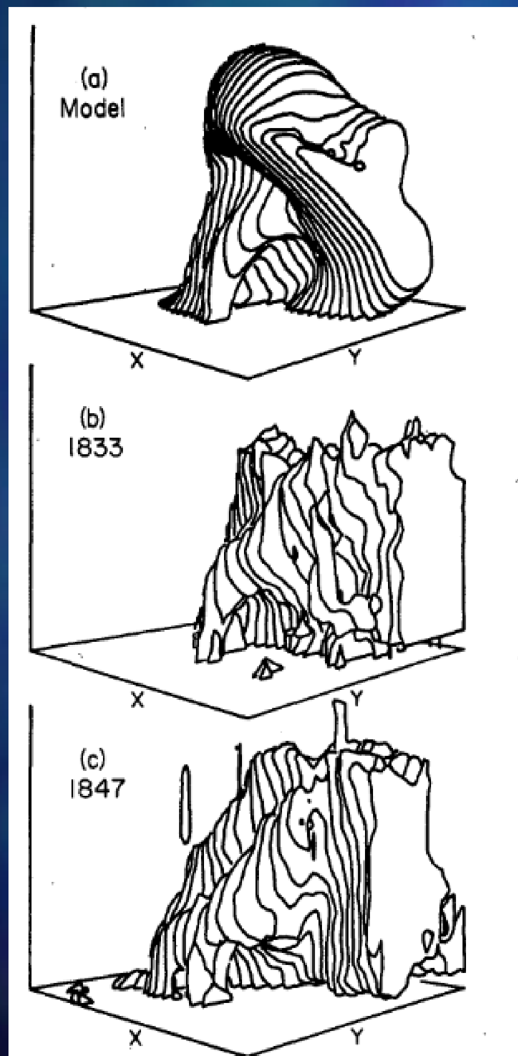
Courtesy R. Wilhelmson, University of Illinois

Where We Were in the Late 1970s/Early 1980s

Numerical Simulation

Radar Observations

Radar Observations



Observed and Numerically Simulated Structure of a Mature Supercell Thunderstorm

J. B. KLEMP

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University of Illinois, Urbana, IL 61801

P. S. RAY

National Severe Storms Laboratory, Norman, OK 73069

(Manuscript received 15 December 1980, in final form 31 March 1981)

ABSTRACT

Through the interactive use of Doppler-radar analyses and a three-dimensional numerical storm simulation the detailed structure of a supercell, tornadic storm is analyzed. This storm, named the Del City storm, occurred in central Oklahoma on 20 May 1977. The storm exhibits certain important features which are essential to maintaining its longevity and which promote the storm's transition to its tornadic phase. These features are strongly influenced by the rotational character of the storm separates the precipitation from the updraft and which orients the resulting downdrafts to which reinforce low-level convergence along the gust front and sustain the storm. Analyses of air parcel and rain trajectories within the storm provide a detailed visualization of this internal structure. These trajectories reveal that air parcels rising through the cyclonically rotating updraft actually turn anticyclonically with height owing to the influence of the storm relative environmental wind field. Downdraft trajectories suggest that the cold outflow air behind the gust front originates in the environment at heights below 2 km. The distribution of vorticity is also investigated within the mature storm. At low levels the strong cyclonic vorticity is found to be located downwind of the convergence line, along the strong gradient between the updraft and downdraft. The similarities in structure between the observed and simulated storm suggest that the larger scale environment plays a dominant role in structuring many of the detailed features of the storm.

1. Introduction

Over the past few years significant advancements in understanding the behavior of convective storms have been achieved through analyses of multi-Doppler radar observations and of three-dimensional cloud model simulations. However, both approaches require complicated numerical procedures in conjunction with a variety of simplifying approximations and thus results are typically generated with a considerable degree of uncertainty. In an effort to enhance investigative capabilities, these two powerful tools are being jointly applied to selected cases as part of a Cooperative Observational and Modeling Project for the Analysis of Severe Storms (COMPASS).

In our initial effort we are investigating the severe storms which occurred in central Oklahoma on 20 May during the 1977 National Severe Storms Laboratory (NSSL) spring data collection period. The morning soundings on this day revealed a very unstable air mass (lifted index of −6) and strong vertical wind shear throughout the region. In the afternoon a major short wave moving into the area combined with moist southeasterly low-level flow to produce a number of severe storms. These storms spawned 16 tornadoes in the state during the afternoon of 20 May and through the early morning hours of the following day. Several storms passed within the NSSL radar network and were observed simultaneously with up to four Doppler radars. Specifics of the NSSL Doppler-radar network are provided by Ray *et al.* (1977).[2] Concurrent observations were also available from a surface network, rawinsondes, instrumented aircraft and satellites. The observations on 20 May provide an excellent and unique opportunity to analyze several tornadic storms over much of their lifetimes.

A detailed discussion of the late afternoon storm activity in the vicinity of the radar network is

[1] The National Center for Atmospheric Research is sponsored by the National Science Foundation.

[2] Ray, P. S., J. Weaver and NSSL staff, 1977: 1977 Spring Program Summary. NOAA Tech Memo ERL-NSSL=84, 173 pp.

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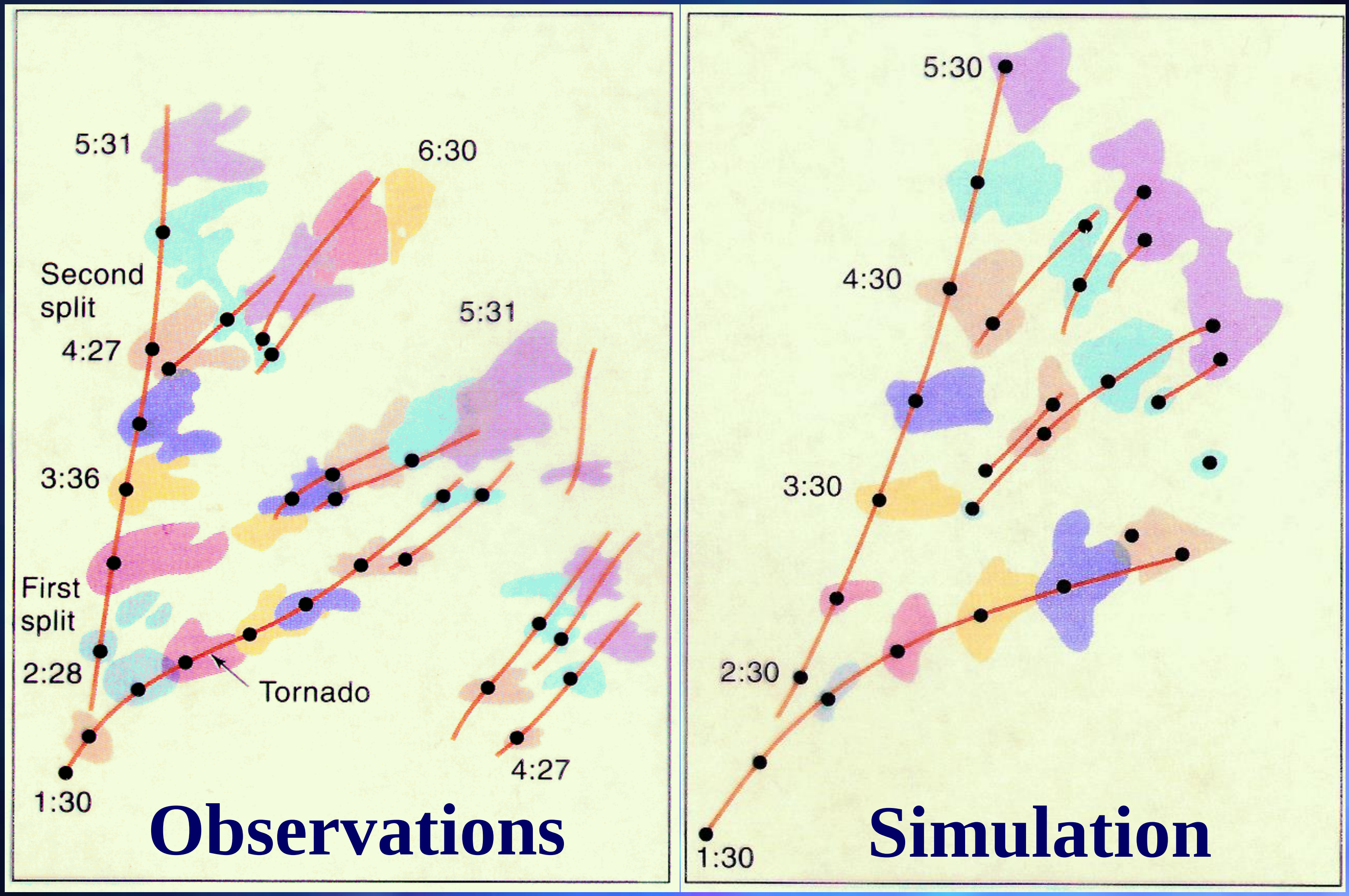
An Intriguing Notion and an Inspiration



"The Atmosphere Finally Did What the Model Had Been Doing for a Long Time!"
– R. Wilhelmson

Wilhelmson and Klemp (1981)

Enter Doug Lilly at OU

Theoretical Predictability of Small-Scale Motions. **1985**

D. K. Lilly
University of Oklahoma - Norman, OK

1. – Summary.

Recently summarized data on the kinetic-energy in the small and mesoscale domains allow extension mates of predictability due to Lorenz [1] and I Several factors limit the validity of these estimates, tant of which may be the highly intermittent na events. Some evaluations of this intermittency are of the effects of intermittency on predictability, a sisting of widely spaced Rankine vortices is analy velocity predictability is found to be greater than itself. Aspects of the strategy of observation and pr tent flows are discussed.

2. – Introduction and scope.

Consideration of the problem pheric activity suggests existence not exist or are less important fo net. I will first outline the straigh scale approach to the smaller scale the validity of that approach. Mo non-Gaussian probability distribu

3. – Conventional estimates of sm

The problem of predictability principle, all the complexities of diction is classically the true test

VOL. 43, NO. 2 JOURNAL OF THE ATMOSPHERIC SCIENCES 15 JANUARY 1986

1986

The Structure, Energetics and Propagation of Rotating Convective Storms. Part I: Energy Exchange with the Mean Flow

Douglas K. Lilly
School of Meteorology, University of Oklahoma, Norman, OK 73019

(Manuscript received 10 October 1984, in final form 21 August 1985)

ABSTRACT

A three-dimensional buoyant convective element responds to the existence of mean vertical shear by rotation about a vertical axis, with the rotational kinetic energy abstracted from that of the mean process is illustrated with the aid of linear analysis. From consideration of nonlinear processes it is that a portion of the rotational energy is transformed into that of the overturning velocity field, thus further buoyant energy release. The storm structure which is optimal for energy transfer from the to rotational disturbances is a single updraft propagating with the mean flow and with counter-rotat on both sides. The transfer of energy from rotational to overturning modes is, however, optimized propagating updrafts with coincident vortices.

1. Introduction and scope

This is the first of two articles displaying results of namics of rotating convective "supercells" by Browning ng convective storms" refers ut a vertical axis observed in ot imply a net storm angular es extend the arguments ear- (Lilly, 1982, 1983). In them, he development of rotation abilizes storm structure. The , the principal subject of this by the storm of a substantial gy from the mean shear, with k into enhancing the buoyant 985; hereafter II) I show that ing storms exhibit high flow lity apparently reduces tur- ereby increases the efficiency s. The storm structure and maximize the buoyancy and the disturbance differ signif- produce maximum updraft I propose that the observed mise between two limits. reviews the current under- sm by which rotation and ed in supercell storms, much eing based on the results merical simulation models. m is extended to determine tant energy transformations.

In section 3, I present a linear a three-dimensional convection in technique proposed by Phillips (1 shows more clearly than previous dimensionality forbids but three-d flow of kinetic energy from the m vective disturbance. Section 4 sum An Appendix contains an outline energy analysis of real and simula

2. Structure and motion of rotati

The discovery that certain thu portions of them associated with significant rotation about a verti to Brooks (1949). In seemingly un and Katz (1958), from analysis of a network, found that many large direction significantly different fr flow in which they were embedde accumulating evidence that the often developed in regions of stron partially rationalized by Brown model of rotating storms. Browni storms supercells, in distinction to accepted) model of ordinary thun of individual cells in various stag Browning's model, shown schema appears as a kidney-shaped raincl low-level inflow and updraft occu region and the cold downdrafts an area. Looking down the mean she vector of the storm is shown to t

1986

The Structure, Energetics and Propagation of Rotating Convective Storms. Part II: Helicity and Storm Stabilization

Douglas K. Lilly
University of Oklahoma, Norman, OK 73019

(Manuscript received 10 October 1984, in final form 21 August 1985)

ABSTRACT

Rotating "supercell" thunderstorms are shown to be characterized by high helicity, the vector inner product of velocity and vorticity, which is obtained both from the mean flow in which they are embedded and from buoyancy enrichment. Some unique properties of supercell helical flow are described, including a tendency for trajectory rotation to be reversed from parcel vorticity. A simple helical (Beltrami) flow model resembles gross supercell structure and also provides a prediction of storm motion. Since theory, closure model calculations and numerical simulations indicate that helicity suppresses turbulent dissipation, it is suggested that supercells owe their noted stability and long life to this effect. Enhanced predictability of such storms is then expected and is apparently seen in some results of Wilhelmson and Klemp. It is concluded that rotating storm structure and propagation must involve a compromise between the energetic effects discussed by Lilly in Part I of this study and those considered here, but that the helicity effects seem to be dominant in long-lived storms.

1. Introduction and scope

This article continues the analysis, begun in Part I (Lilly, 1986; hereafter referred to as Part I) of the evolution, structure and energetics of rotating convective storms, or "supercells." The aspect pursued here is a hypothesis that these storms owe their long life, stability, and apparent predictability to the helical nature of their circulation. In section 2 it is shown, from model and observational results, that helicity, the vector inner product of vorticity and velocity, is typically large in both the storms and their environment, and can be exchanged between them. In section 3 it is shown that the gross structure and movement of supercell storms can be modeled as a purely helical (Beltrami) flow. Section 4 presents a review of the evidence from turbulence theory that helicity suppresses the inertial-range energy cascade and tends to isolate the large energy- and helicity-containing scales from the inertial range and dissipation scales. The implication is that rotating thunderstorms, which contain and produce helicity, are less susceptible to nonlinear stirring and dissipation than are nonhelical turbulent flow fields, such as ordinary thunderstorms. In section 5, additional interpretations are made from the results of Part I and this article.

Since completing this work I have become aware of a series of papers by Levich, Tsinober and colleagues which strongly support and elaborate on the importance of helicity within the general framework of turbulent flow. The energy preservative aspect of helicity, discussed further in section 4, is invoked as an explanation for the high intermittency of turbulent energy dissipation by Levich and Tsinober (1983a,b), Tsinober and Levich (1983) and Levich et al. (1984). It is proposed that, since helical eddies resist dissipation, they will survive longer than other turbulent eddies and will tend to dominate the flow statistics. Thus most large eddies will be characterized by high helicity and low dissipation, while most dissipation will occur in the transitional and short-lived regions of low helicity. This hypothesis has now been tested against results of a numerical simulation of the Navier-Stokes equations (Pelz et al., 1985) with favorable results, as described in section 4.

The possible effects of helicity on atmospheric motions have been considered by Levich and Tzvetkov (1984, 1985), where the term "helical cyclogenesis" is introduced. It is hypothesized that the mean square of helicity is subject to an upscale "cascade", somewhat similar to that of two-dimensional turbulent energy. Following this approach the authors suggest that several kinds of mesoscale disturbances, including tropical cloud clusters, mesoscale convective complexes and squall lines, develop from convective-scale energy sources which organize themselves into large scales through the previously discussed upscale transfer process. It is also noted that supercell storms show helical flow structure.

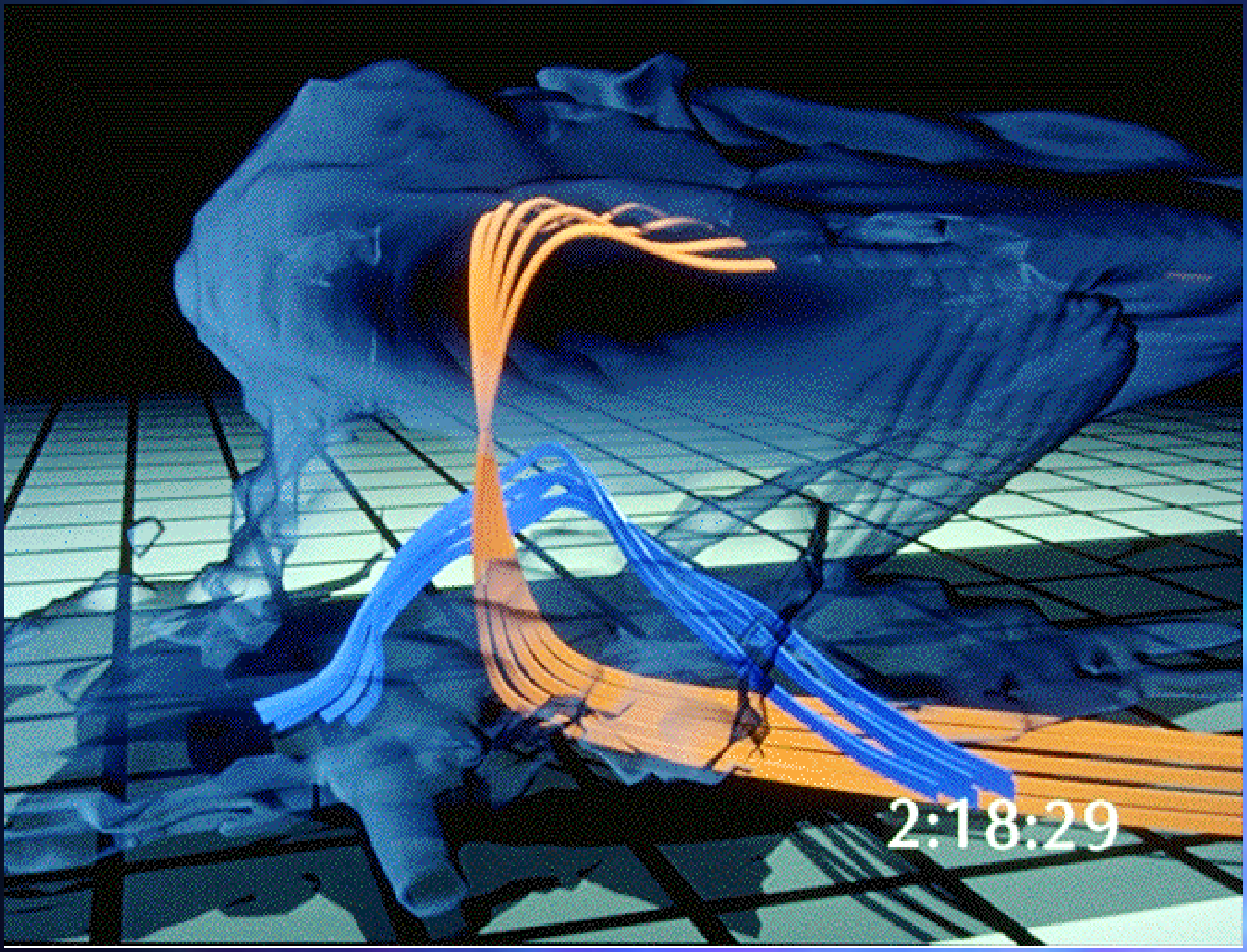
2. Helicity and its relevance to rotating storms

Helicity, here denoted by H, is defined as

$$H = \mathbf{V}\cdot\omega, \quad \omega = \nabla \times \mathbf{V}. \tag{1}$$

As a covariance of the velocity and vorticity vectors,

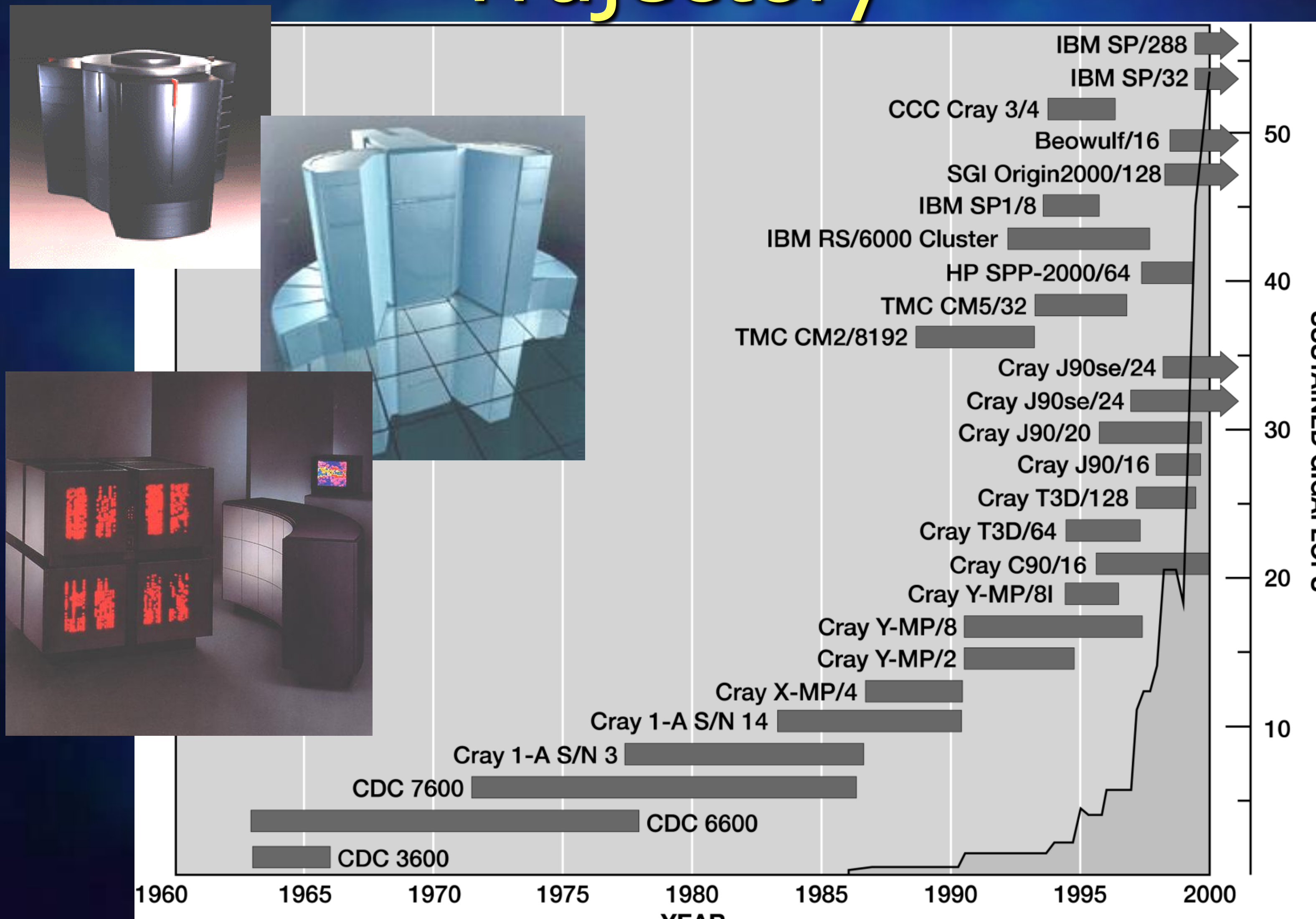
We had 3D Storm Models



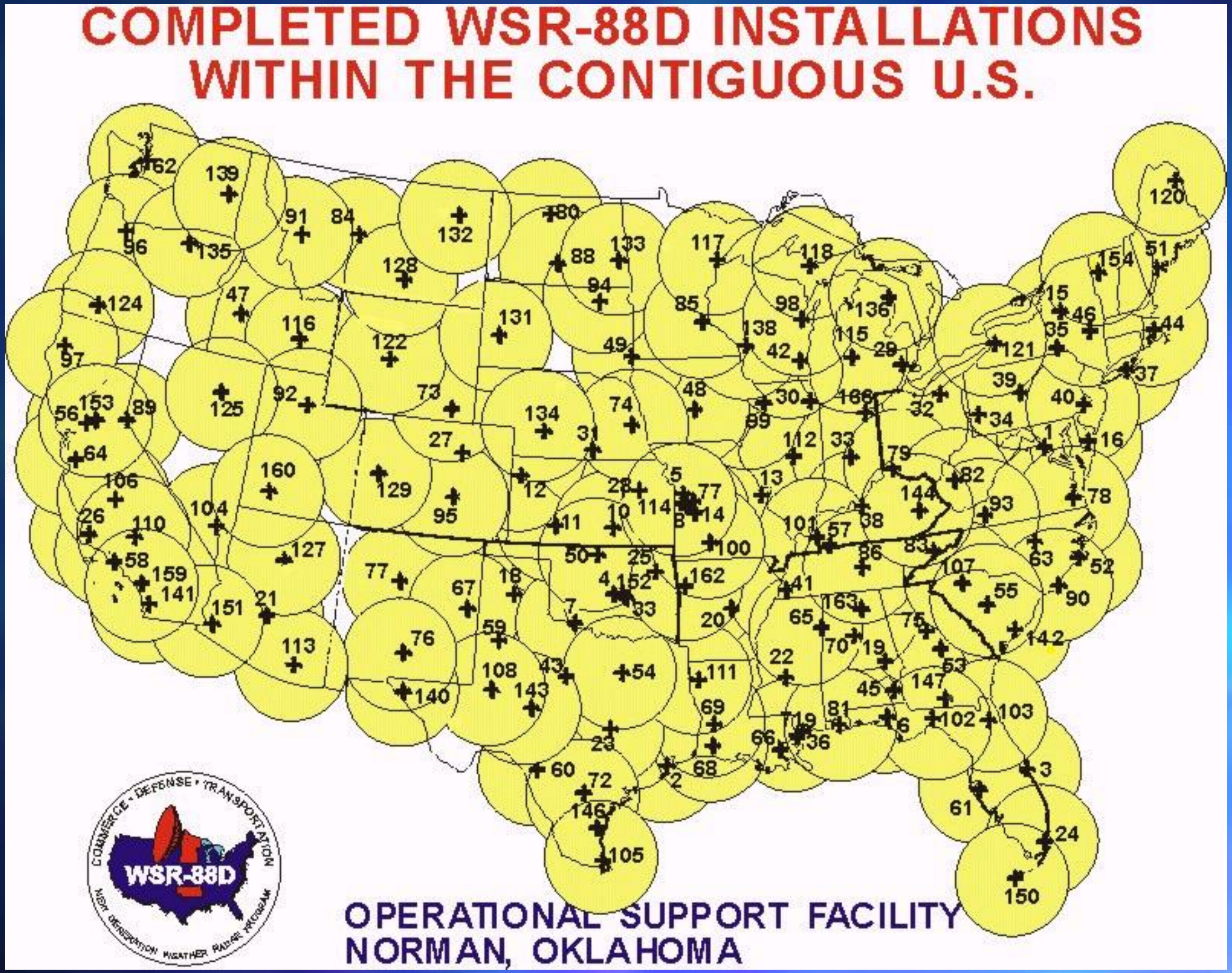
Courtesy R. Wilhelmson, University of Illinois

Klemp et al. (1981)

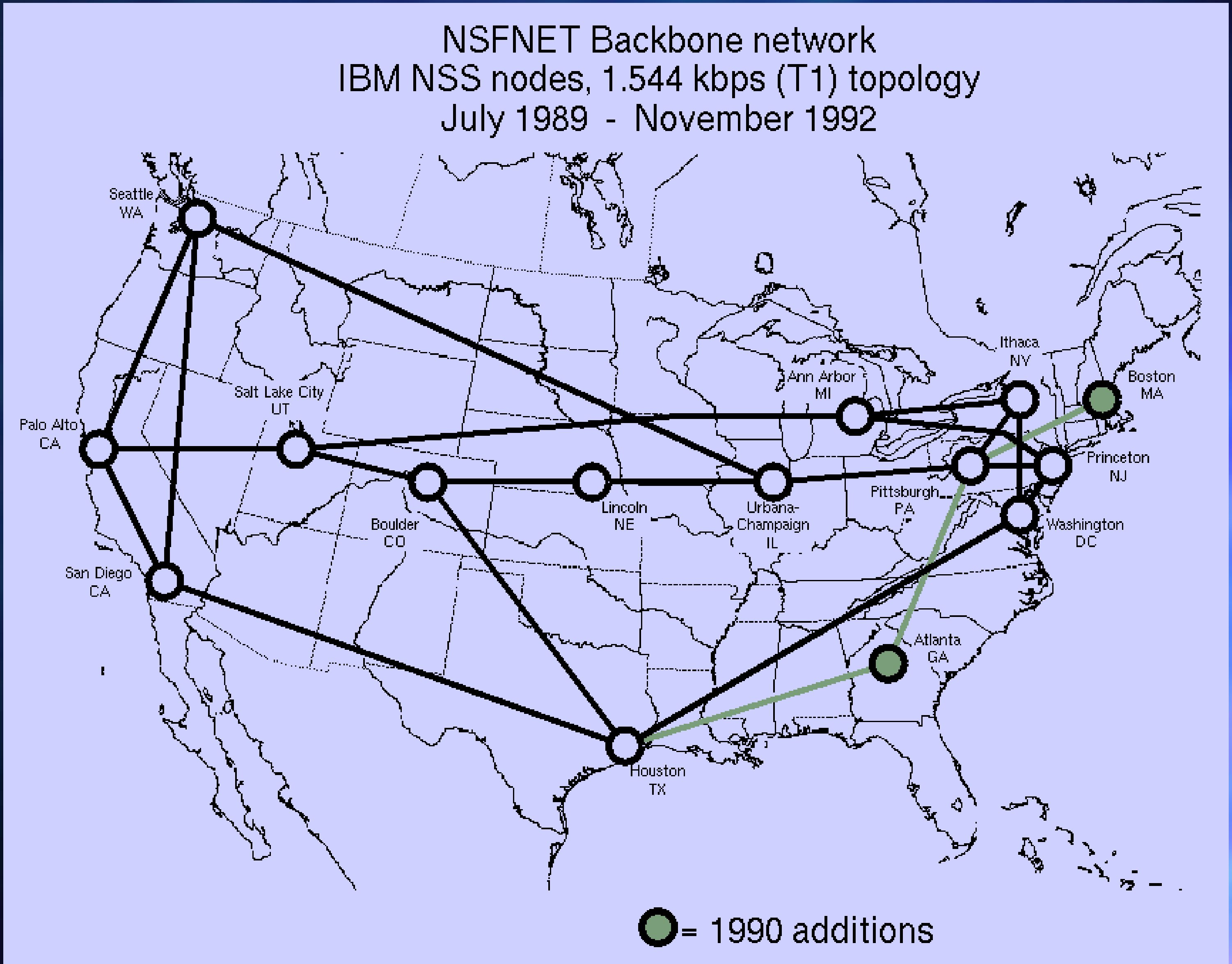
Computing Was on the Right Trajectory



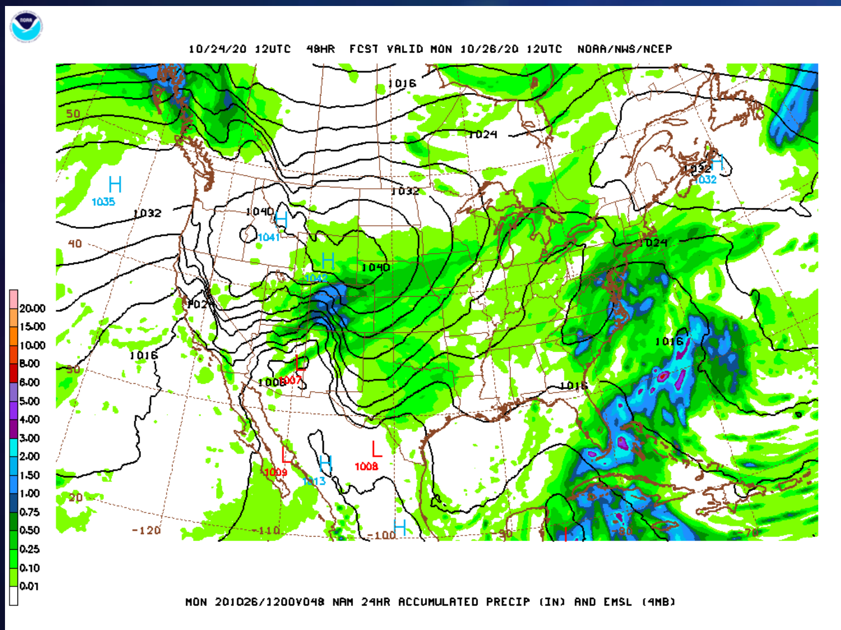
NEXRAD Was on the Horizon



Networking Was Expanding

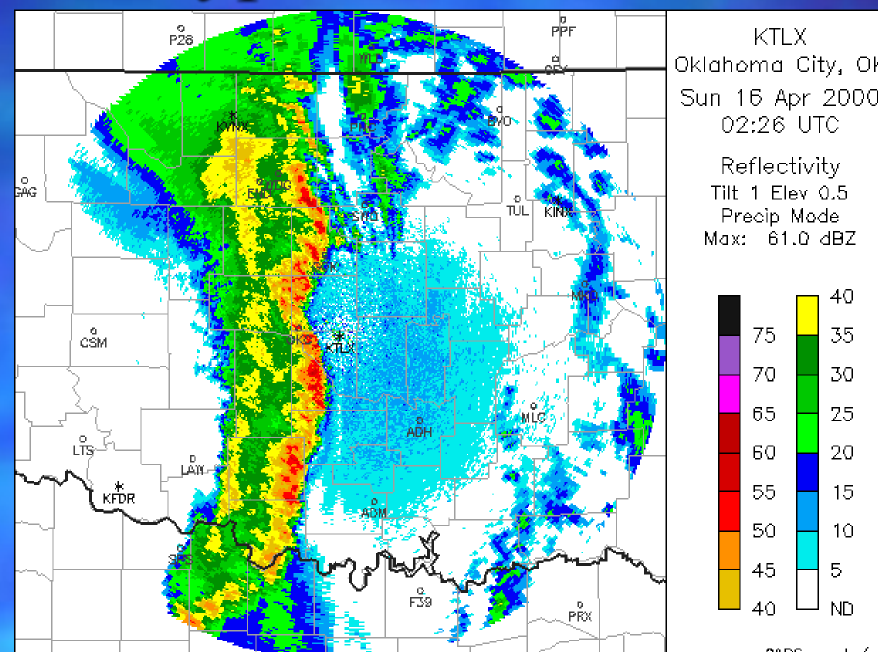


A Crazy Question: 1988

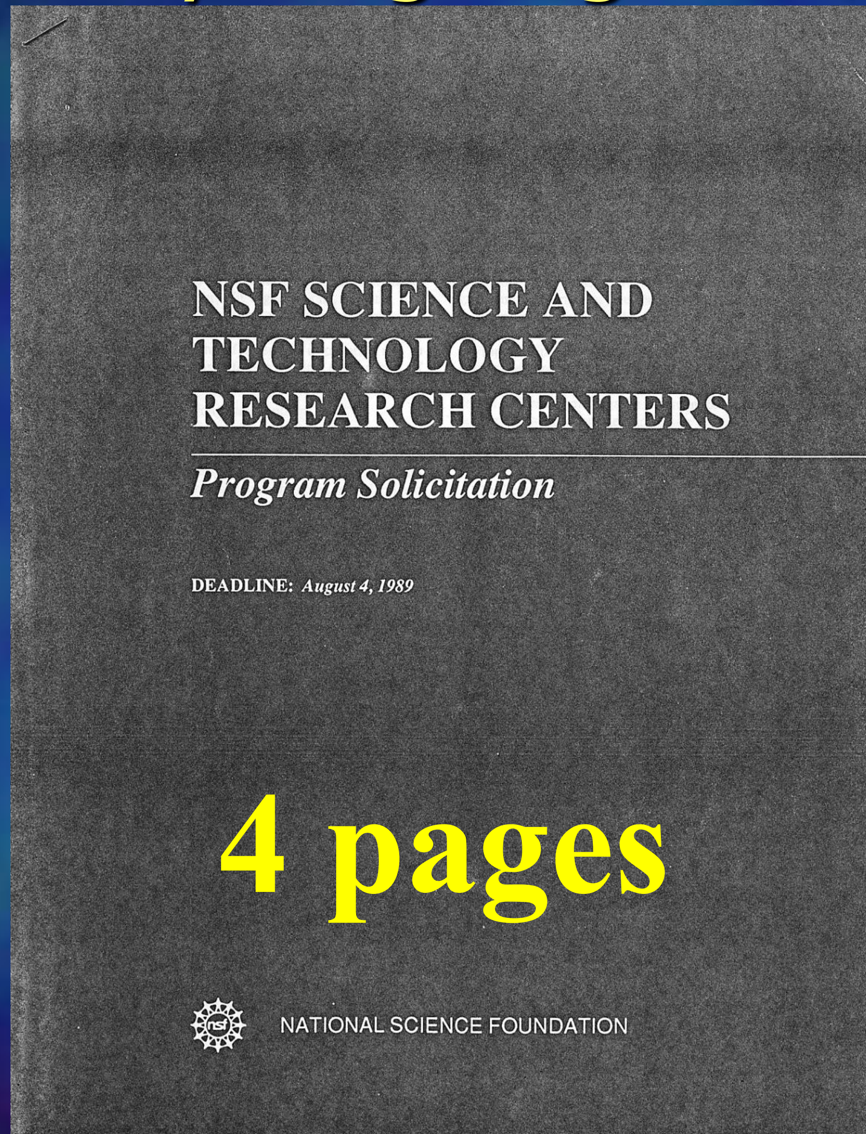


Can computer forecast model technology. . .

. . . explicitly predict this type of weather?



Then Came the Opportunity to Pull Everything Together…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4 pages

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And We Went for it…

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PI/PD NAME/TITLE	SOCIAL SECURITY NO.*	HIGHEST DEGREE & YEAR	SIGNATURE
Douglas K. Lilly, Director, CIMMS	560-30-8389	Ph.D., 1959	
ADDITIONAL PI/PD (TYPED) Kelvin K. Droegemeier	514-58-5314	Ph.D., 1985	
ADDITIONAL PI/PD (TYPED)			
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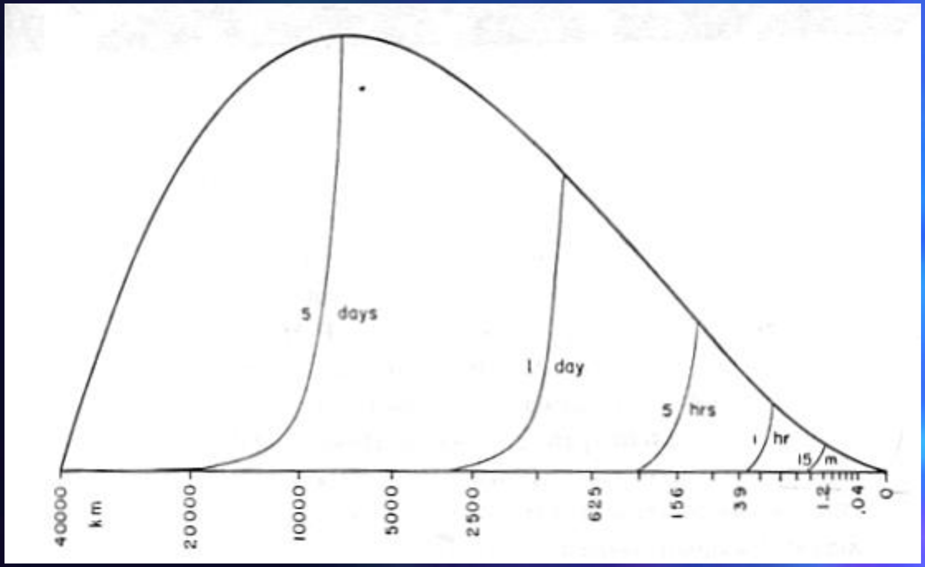
Theory and Simple Models Said this was IMPOSSIBLE



Deterministic Nonperiodic Flow[1]

EDWARD N. LORENZ

Massachusetts Institute of Technology

(Manuscript received 18 November 1962, in revised form 7 January 1963)

Finite systems of deterministic ordi
forced dissipative hydrodynamic flow
phase space. For those systems with b
unstable with respect to small modific
ably different states. Systems with bo
A simple system representing cellu
to be unstable, and almost all of them
The feasibility of very-long-range w

1. Introduction

Certain hydrodynamical systems exhibit s
flow patterns, while others oscillate in a regu
fashion. Still others vary in an irregular,
haphazard manner, and, even when observ
periods of time, do not appear to repeat th
history.

These modes of behavior may all be obse
familiar rotating-basin experiments, describ
et al. (1959) and Hide (1958). In these exp
cylindrical vessel containing water is rotat
axis, and is heated near its rim and cooled ne
in a steady symmetrical fashion. Under ce
tions the resulting flow is as symmetric and s
heating which gives rise to it. Under differen
a system of regularly spaced waves develop
gresses at a uniform speed without changin
Under still different conditions an irregular f
forms, and moves and changes its shape in
nonperiodic manner.

Lack of periodicity is very common in
tems, and is one of the distinguishing featur
lent flow. Because instantaneous turbulent f
are so irregular, attention is often confined
tistics of turbulence, which, in contrast to t
turbulence, often behave in a regular we
manner. The short-range weather forecast
is forced willy-nilly to predict the details c
scale turbulent eddies—the cyclones and an
which continually arrange themselves into n

[1] The research reported in this work has been spo
Geophysics Research Directorate of the Air For
Research Center, under Contract No. AF 19(604)-

The predictability of a flow which possesses many scales of motion

By EDWARD N. LORENZ, *Massachusetts Institute of Technology*[1]

(Manuscript received October 31, 1968, revised version December 13, 1968)

ABSTRACT

It is proposed that certain formally deterministic fluid systems which possess many scales of motion are observationally indistinguishable from indeterministic systems; specifically, that two states of the system differing initially by a small "observational error" will evolve into two states differing as greatly as randomly chosen states of the system within a finite time interval, which cannot be lengthened by reducing the amplitude of the initial error. The hypothesis is investigated with a simple mathematical model. An equation whose dependent variables are ensemble averages of the "error energy" in separate scales of motion is derived from the vorticity equation which governs two-dimensional incompressible flow. Solutions of the equation are determined by numerical integration, for cases where the horizontal extent and total energy of the system are comparable to those of the earth's atomsphere.

It is found that each scale of motion possesses an intrinsic finite range of predictability, provided that the total energy of the system does not fall off too rapidly with decreasing wave length. With the chosen values of the constants, "cumulus-scale" motions can be predicted about one hour, "synoptic-scale" motions a few days, and the largest scales a few weeks in advance. The applicability of the model to real physical systems, including the earth's atmosphere, is considered.

Introduction

The laws which govern the behavior of a fluid system—the principles of continuity of mass, momentum, and energy—are often stated in a form which relates the present rate of change of the state of the system to the present state of the system and its environment. Taken at face value, the laws expressed in this manner would imply that an isolated fluid system is deterministic; i.e., that the exact present state of the system completely determines the exact state at any future time. It would follows as a corollary that if we knew the exact present state of an isolated system, and if in addition we knew the equations of fluid dynamics in their exact form and possessed an exact method for solving them, we could predict the entire future of the system without error.

This is not to imply that fluid dynamicists generally believe that real fluid systems are deterministic. It is a fundamental principle of quantum mechanics, for example, that real systems are indeterministic, and presumably few fluid dynamicists would question the validity of quantum mechanical principles merely because they do not customarily make use of them. More likely, they would simply take it for granted that their equations need to be idealized to some extent, in view of the complexity of most real fluid systems, and that properties of the exact equations which are not pertinent to the problem under study need not be retained. In many familiar problems the question of determinism or indeterminism is of minor importance, and deterministic equations will yield acceptable results. It is often convenient to look upon an idealized equation as the exact equation for a model of a real system. A model may of course be deterministic by definition.

It is in problems of prediction that the question of determinism would seem to be of greatest importance. A familiar problem in this category is the practical problem of weather forecasting. Here also the uncertainty demanded by Heisenberg's Principle appears not to be very significant, because of the much greater uncertainty resulting from our failure to observe the state

[1] The research reported in this work has been sponsored by the Air Force Cambridge Research Laboratories, under Contract No. AF 19 (628)-5826.

Center for Analysis and Prediction of Storms

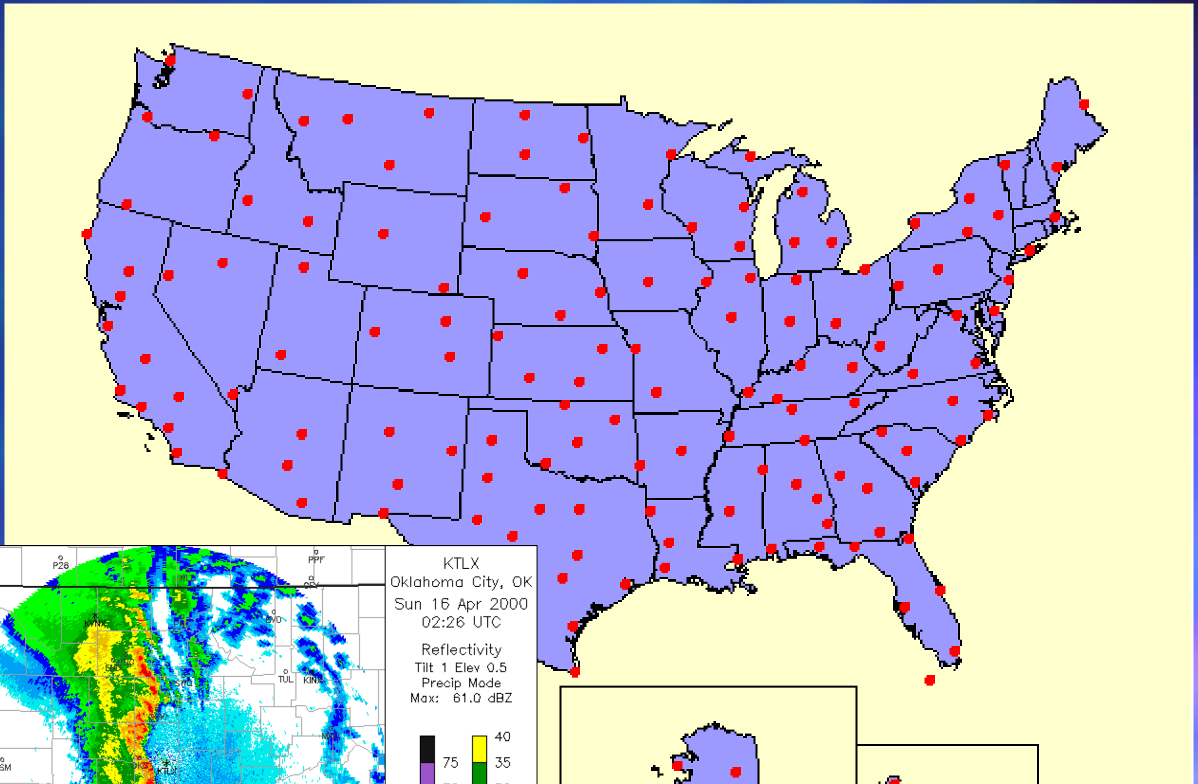
- One of the first 11 NSF Science and Technology Centers created in 1989
- <u>Mission</u>:
  - To demonstrate the practicability of numerically predicting high-impact storm-scale weather with an emphasis on deep convection
- “Graduated” in 2000, continues to operate today via various funding sources (33 years later)

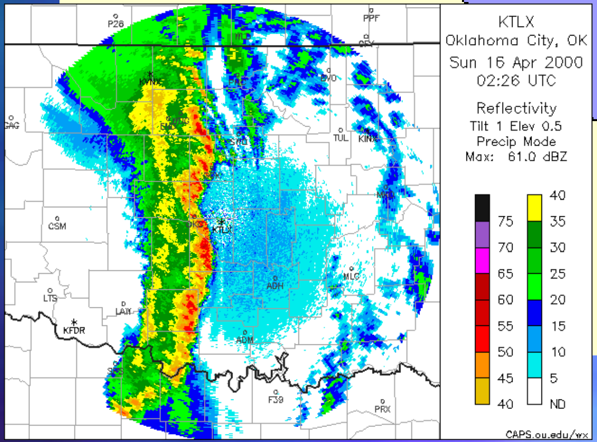
Getting the Necessary Data

To Numerically Predict These…

…We Need Observations on Scales Much Finer Than These!

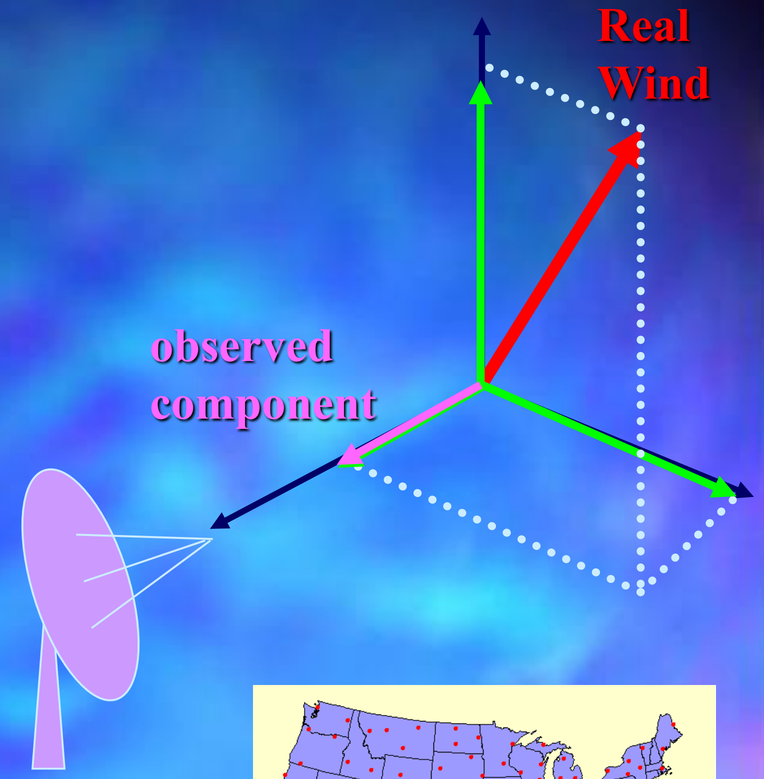
The Potential Solution: NEXRAD (1994)

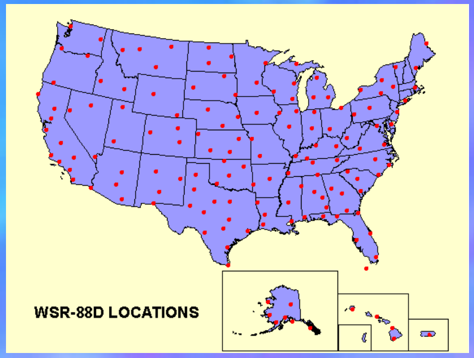




The Challenge With Doppler Radar

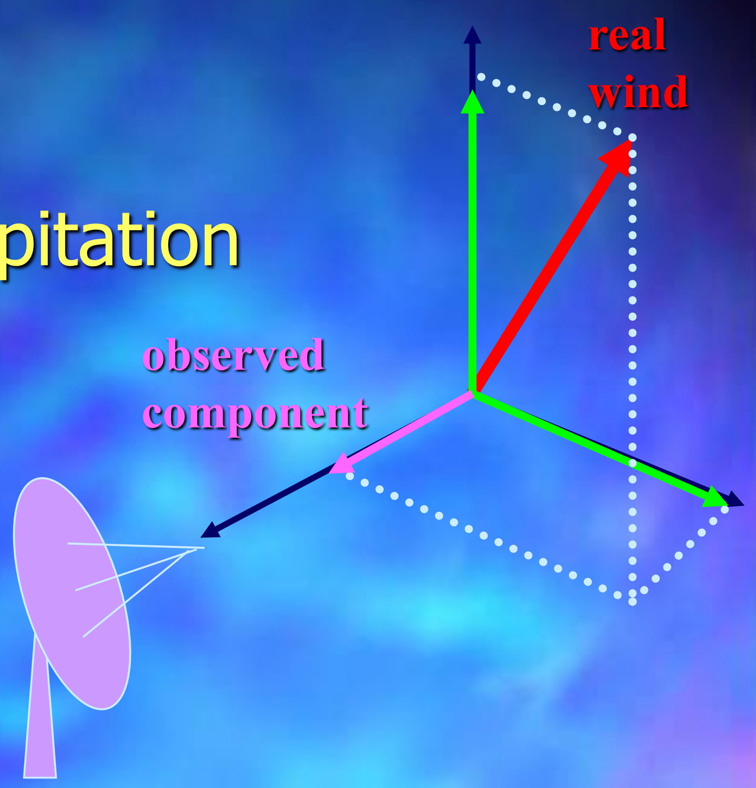
- The radar observes ...
  - one (radial) wind component
  - precipitation intensity
- The model needs...
  - 3 wind components
  - Temperature
  - Humidity
  - Pressure
  - Water substance (6-10 fields)
  - Turbulence
  - Many other variables….





Squeezing Blood Out of a Rock

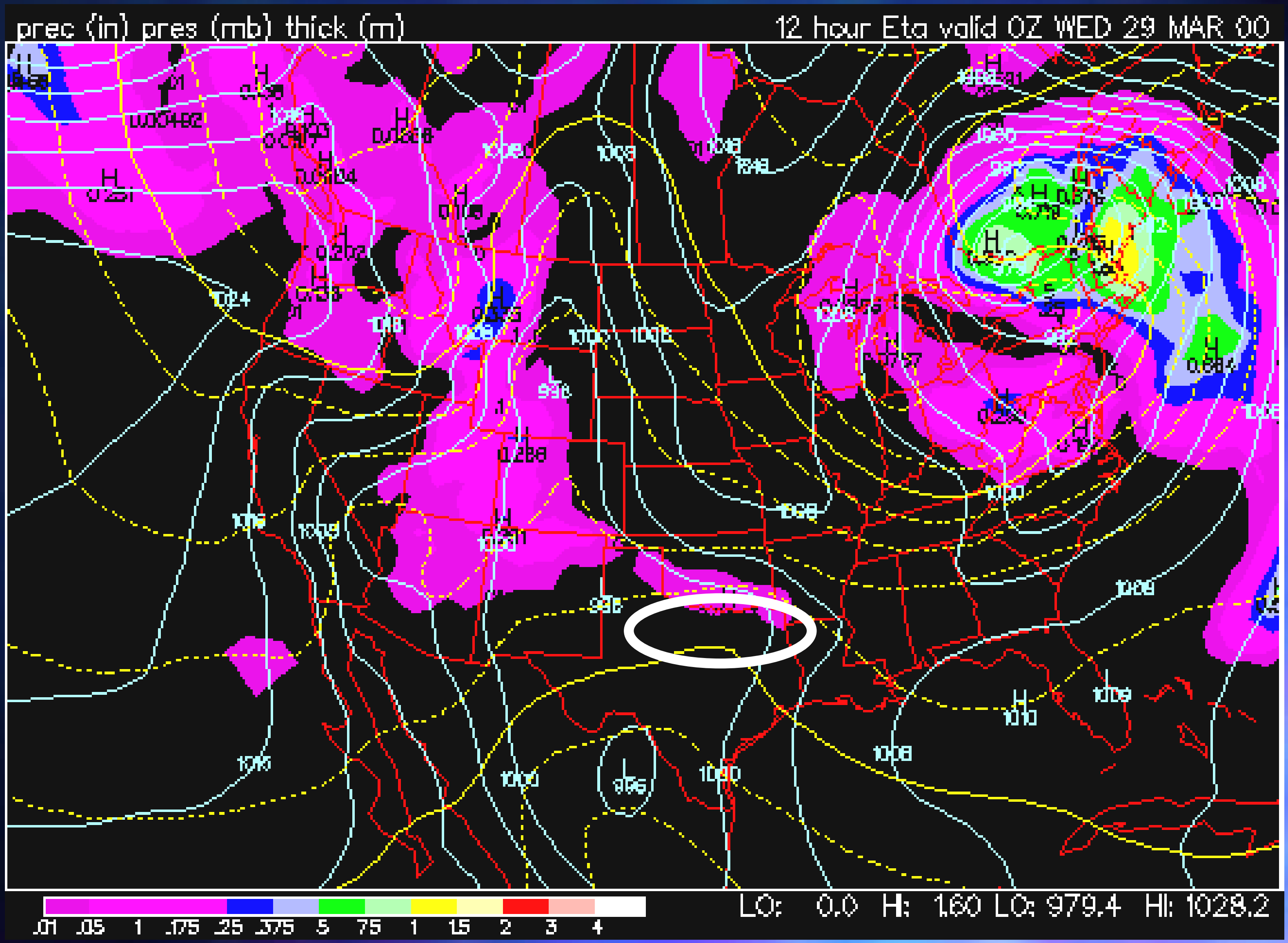
- Given a time series of only one wind component + precipitation in a 3D volume of the atmosphere....
- How does one estimate ALL of the other 20+ variables needed in the same volume? Uniqueness?
- A highly underdetermined problem!



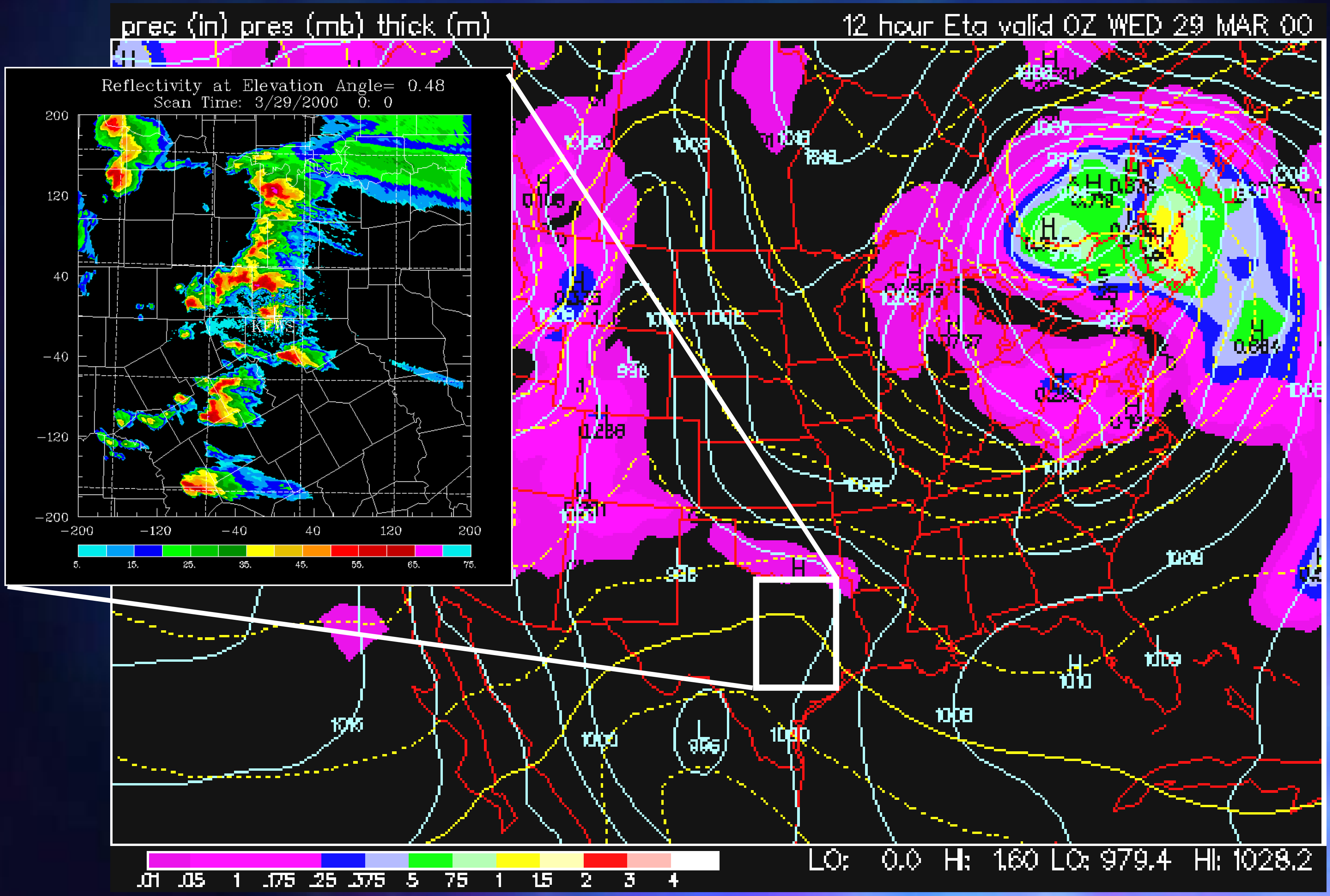
Example : March 28, 2000 Fort Worth Tornadic Storms

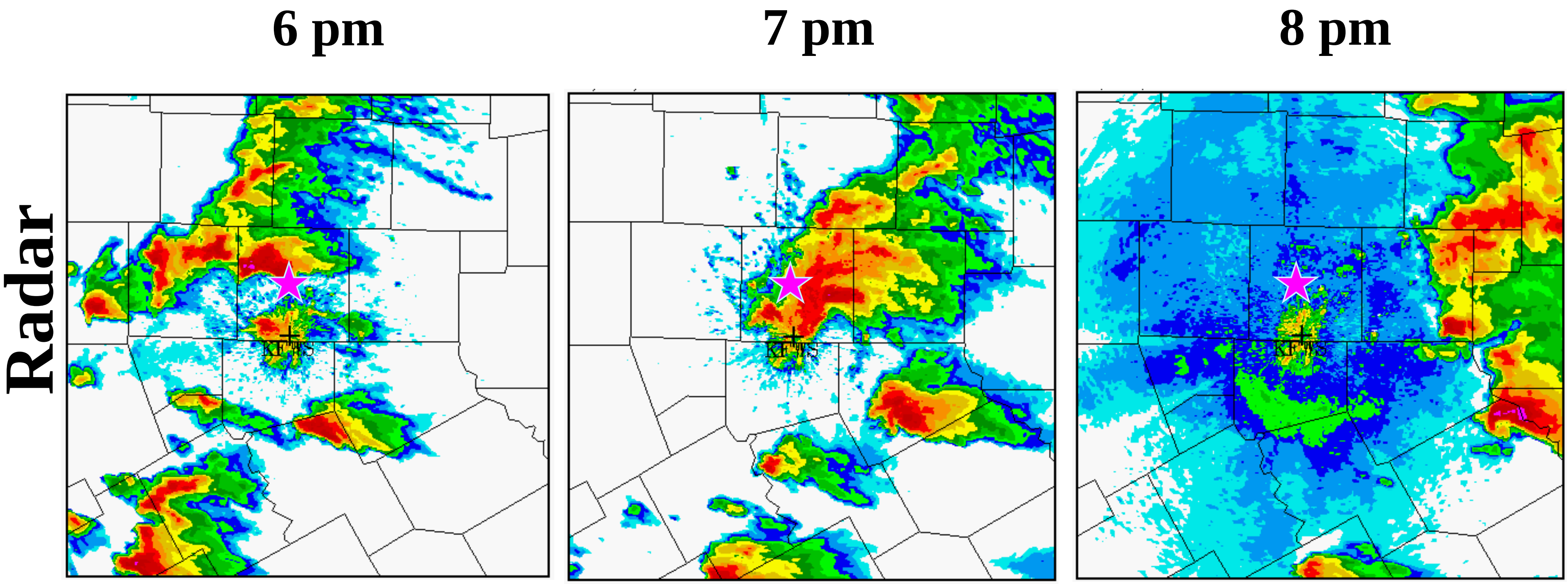

6:23 pm
Saginaw
Bedford
N.R.Hills
Hurst
Lake Worth
Haltom City
Tornado
Fort Worth
White Settlement
30
Handley
820
Westland
Zoo
20
Benbrook
4 WARN
DOPPLER RADAR
Edgecliff Vlg.
Forest Hill
Kennedale
35W

NWS 12-hr Computer Forecast Valid at 6 pm CDT
No Explicit Evidence of Precipitation in North Texas

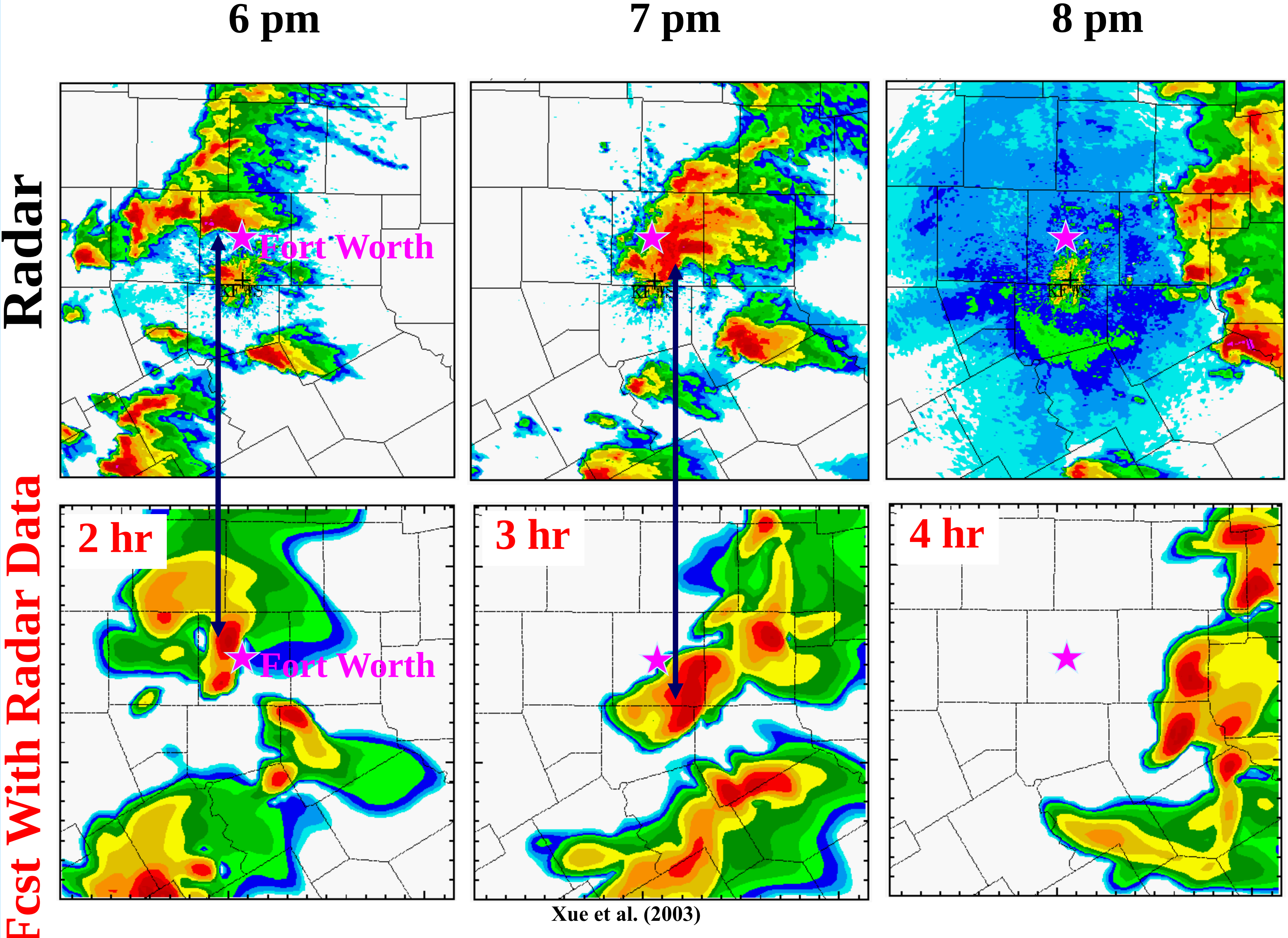


Reality Was Quite Different!

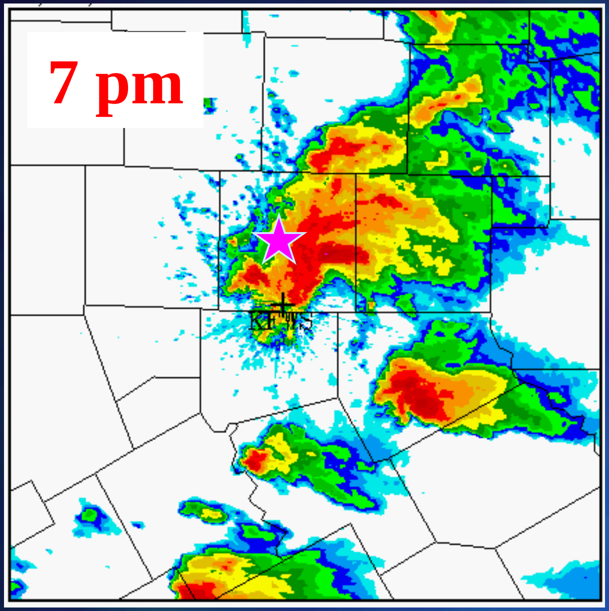




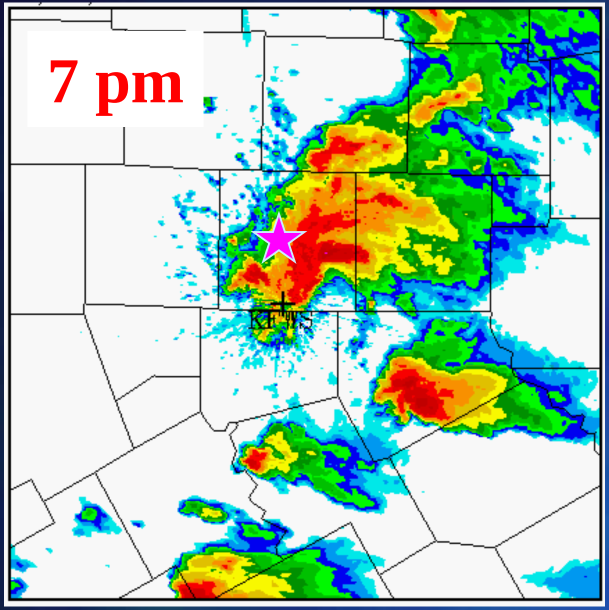
Hourly Radar Observations
(Fort Worth Shown by the Pink Star)

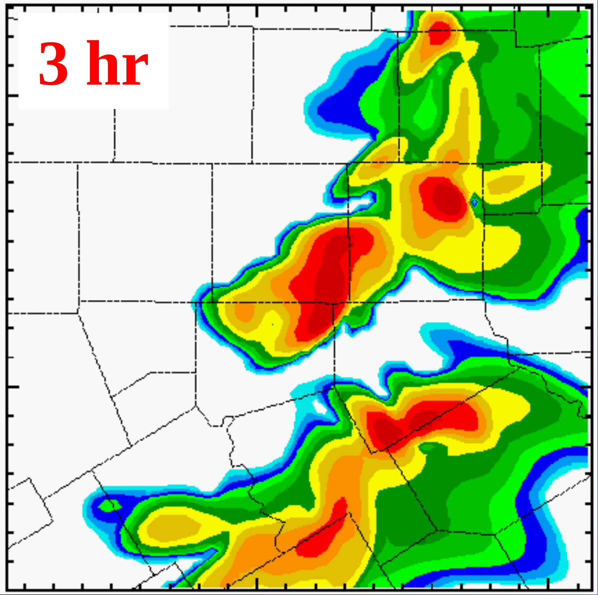


Xue et al. (2003)



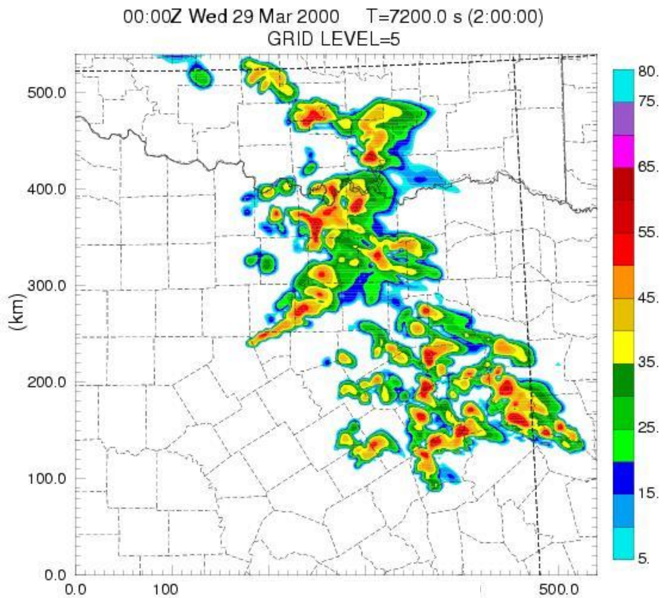
As a Forecaster Worried About This Reality…



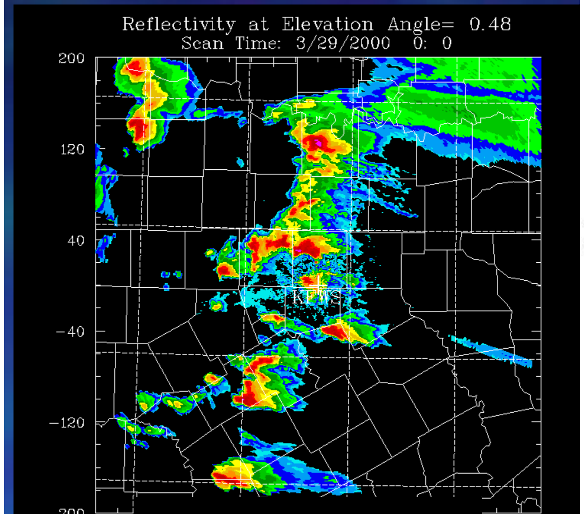


As a Forecaster Worried About This Reality…

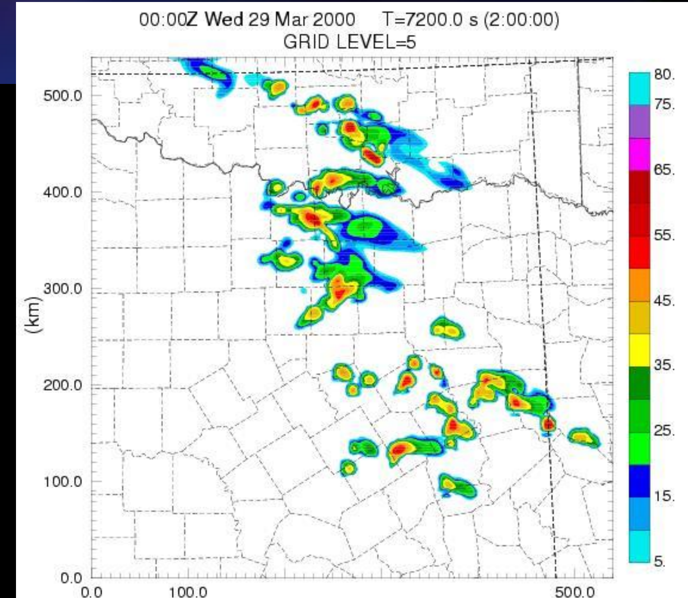
How Much Trust Would You Place in This Model Forecast?



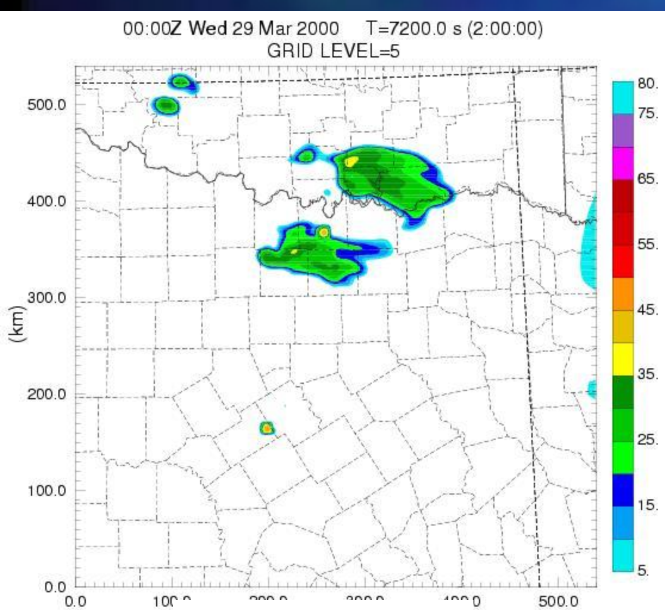
Forecast #1



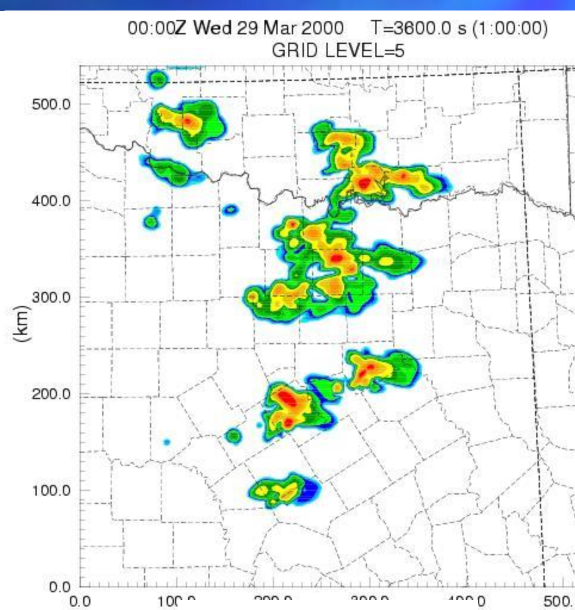
Actual Radar



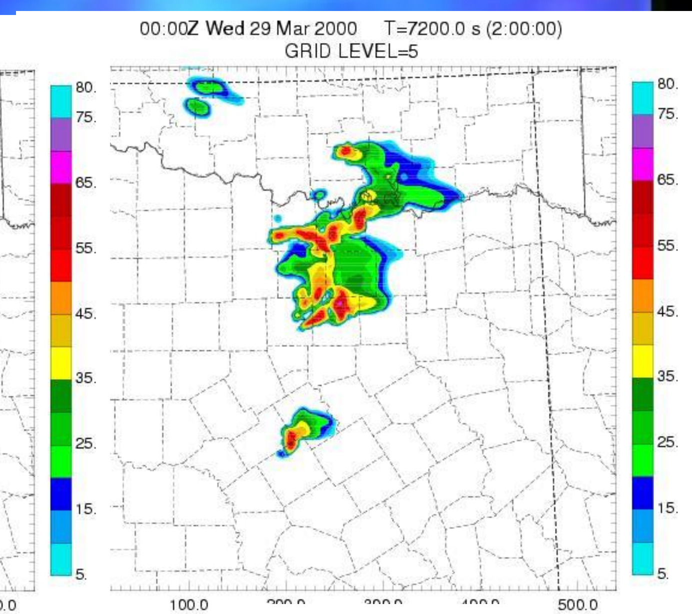
Forecast #2



Forecast #3

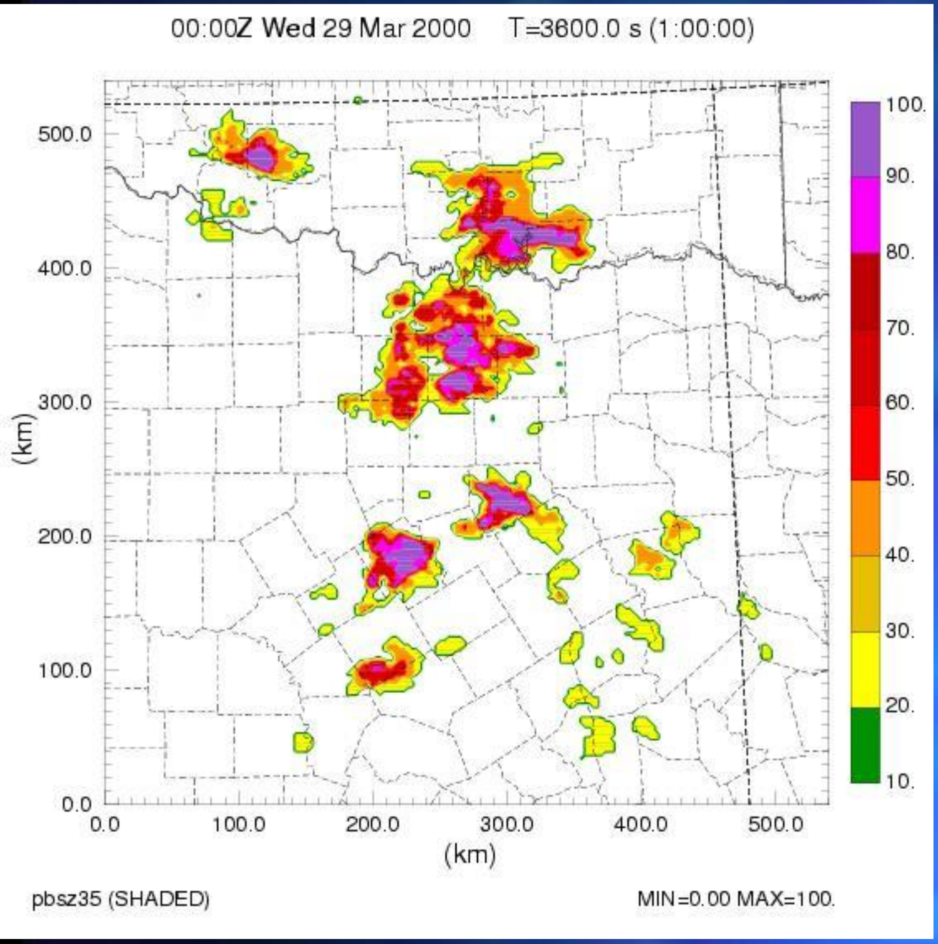


Forecast #4

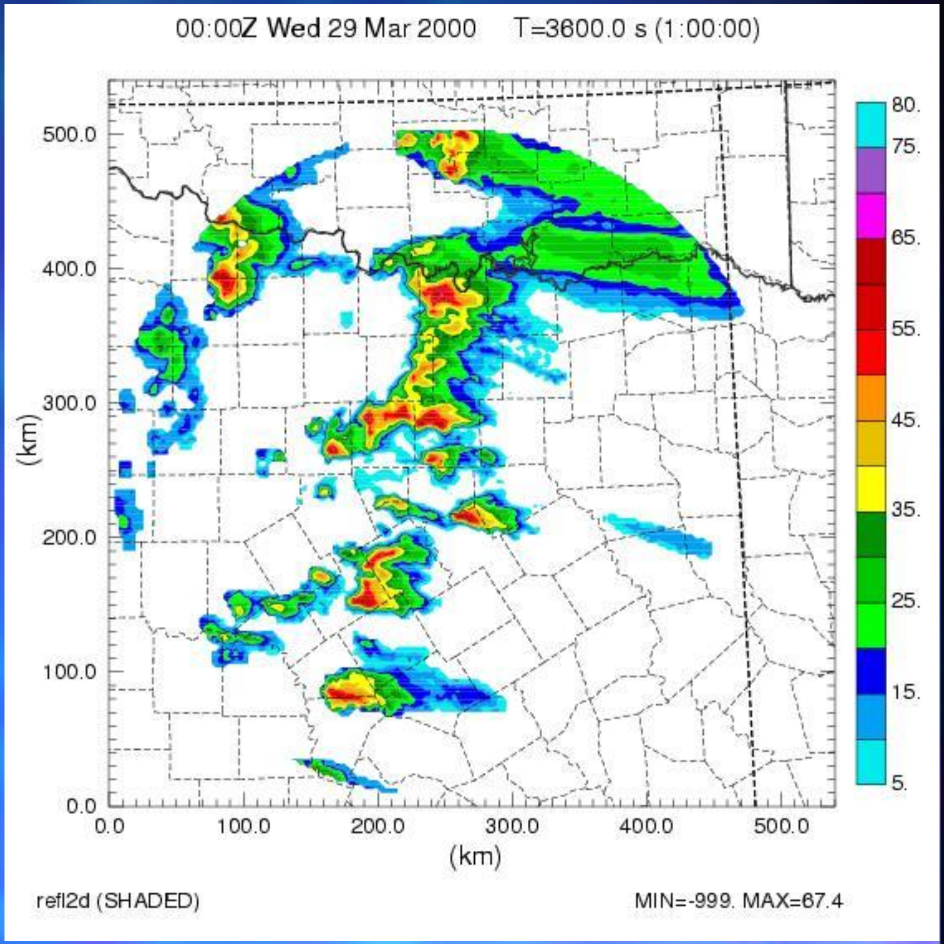


Forecast #5

Probability of Intense Precipitation

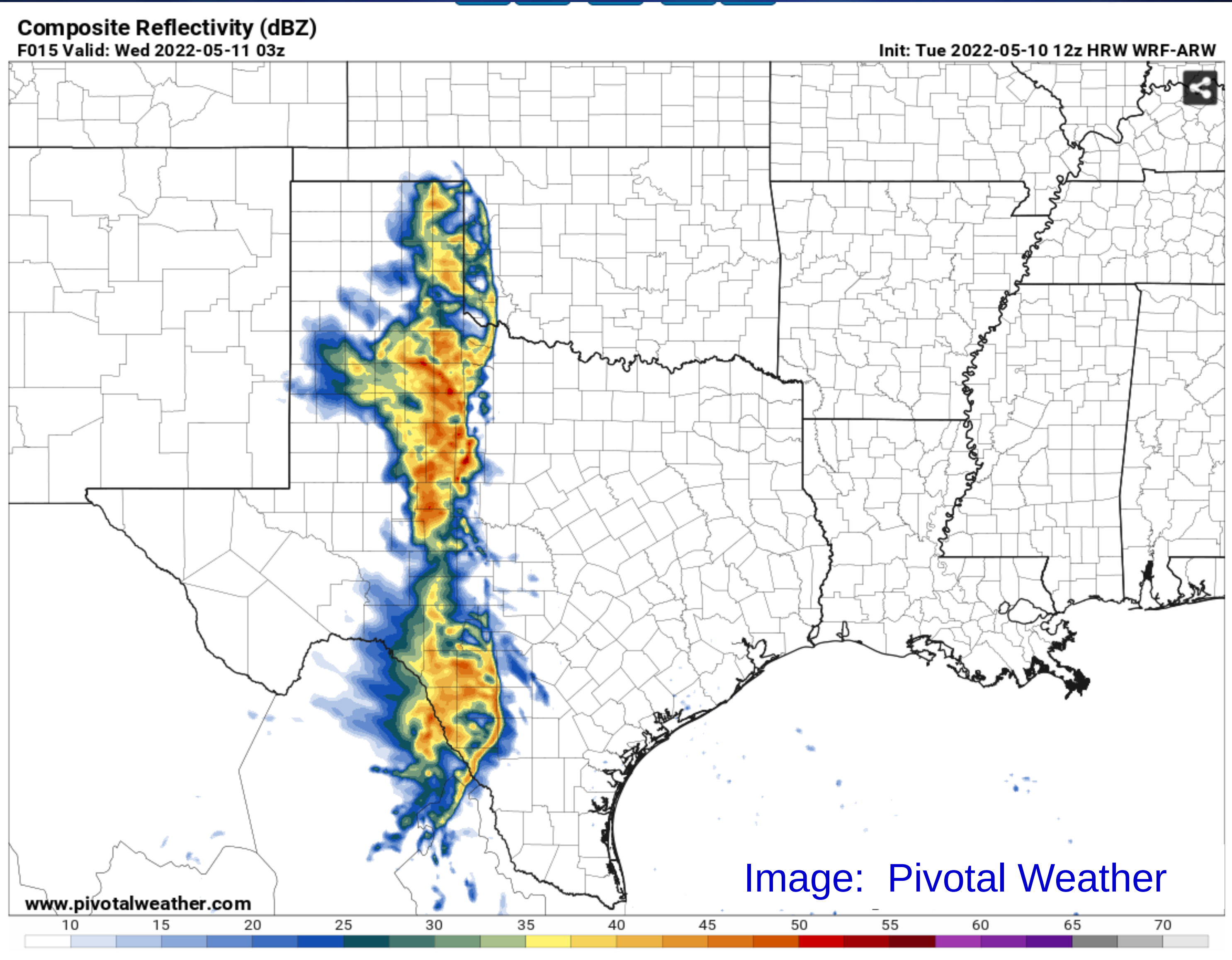


Model Forecast



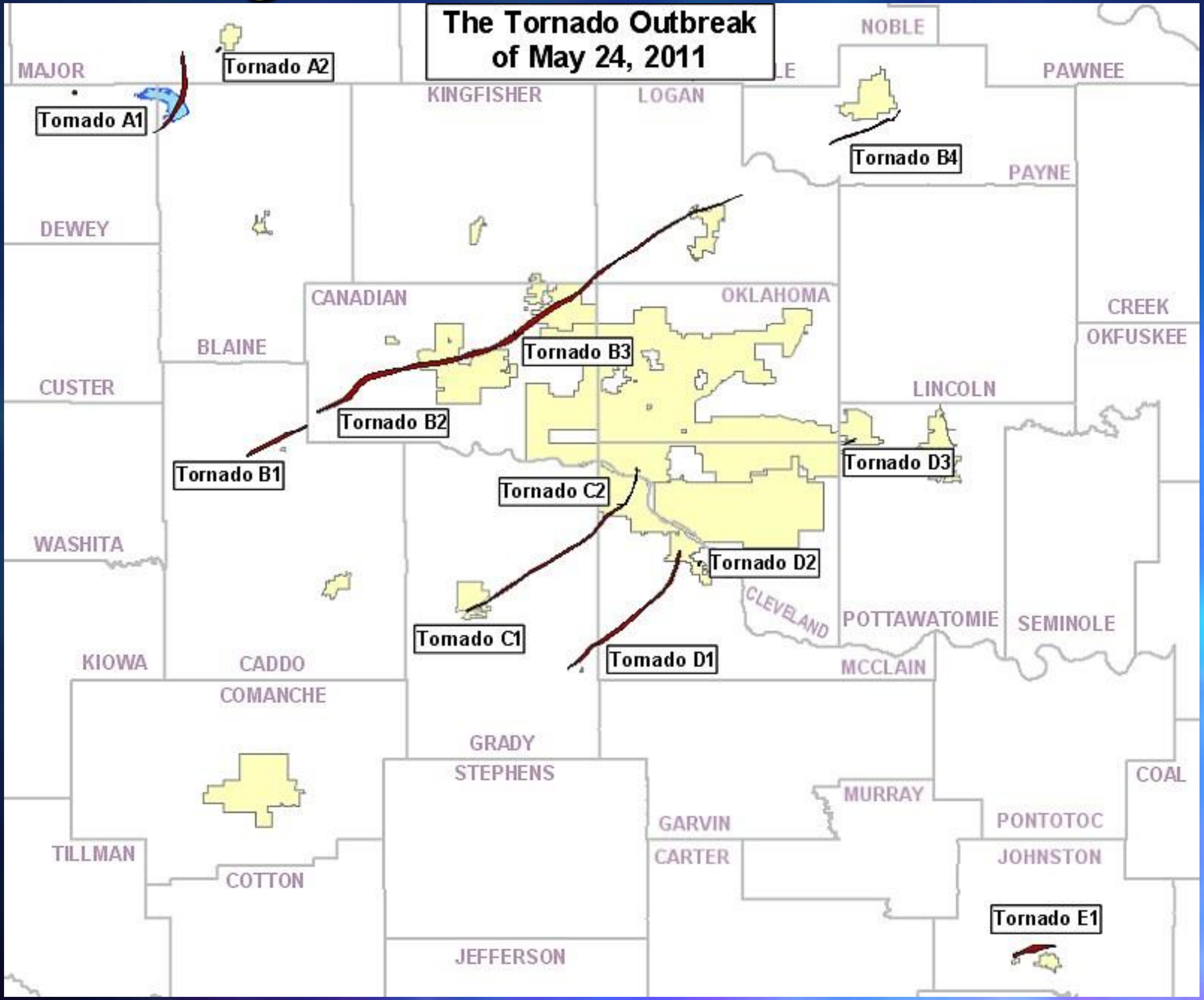
Radar Observations

Forecast from Today's Operational Model!



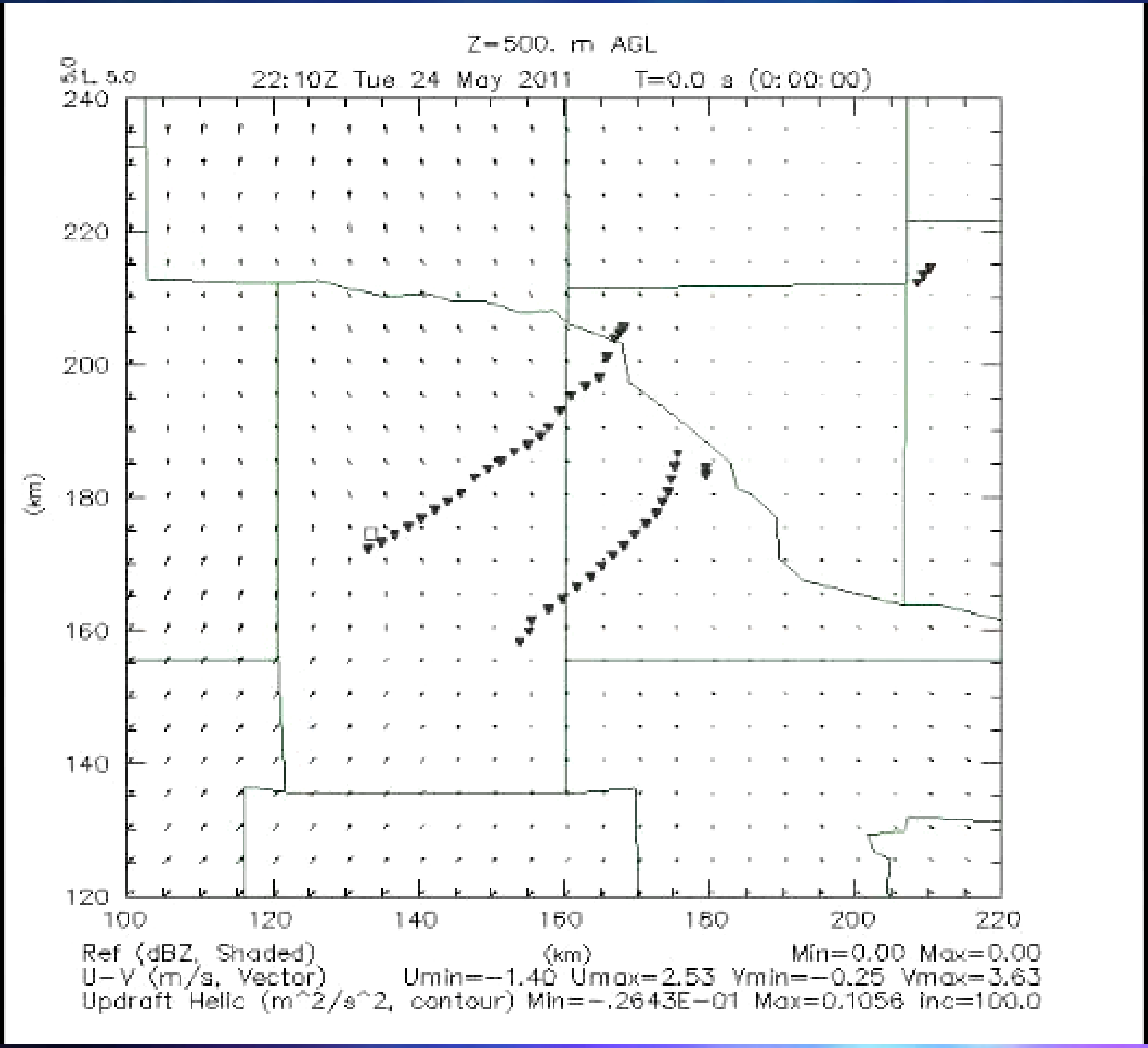
The Million Dollar Question: Will Computer Models Ever Be Able to <u>Predict</u> Tornadoes?

24 May 2011 Tornado Outbreak: Warning on a Numerical Forecast



NWS OUN Graphic

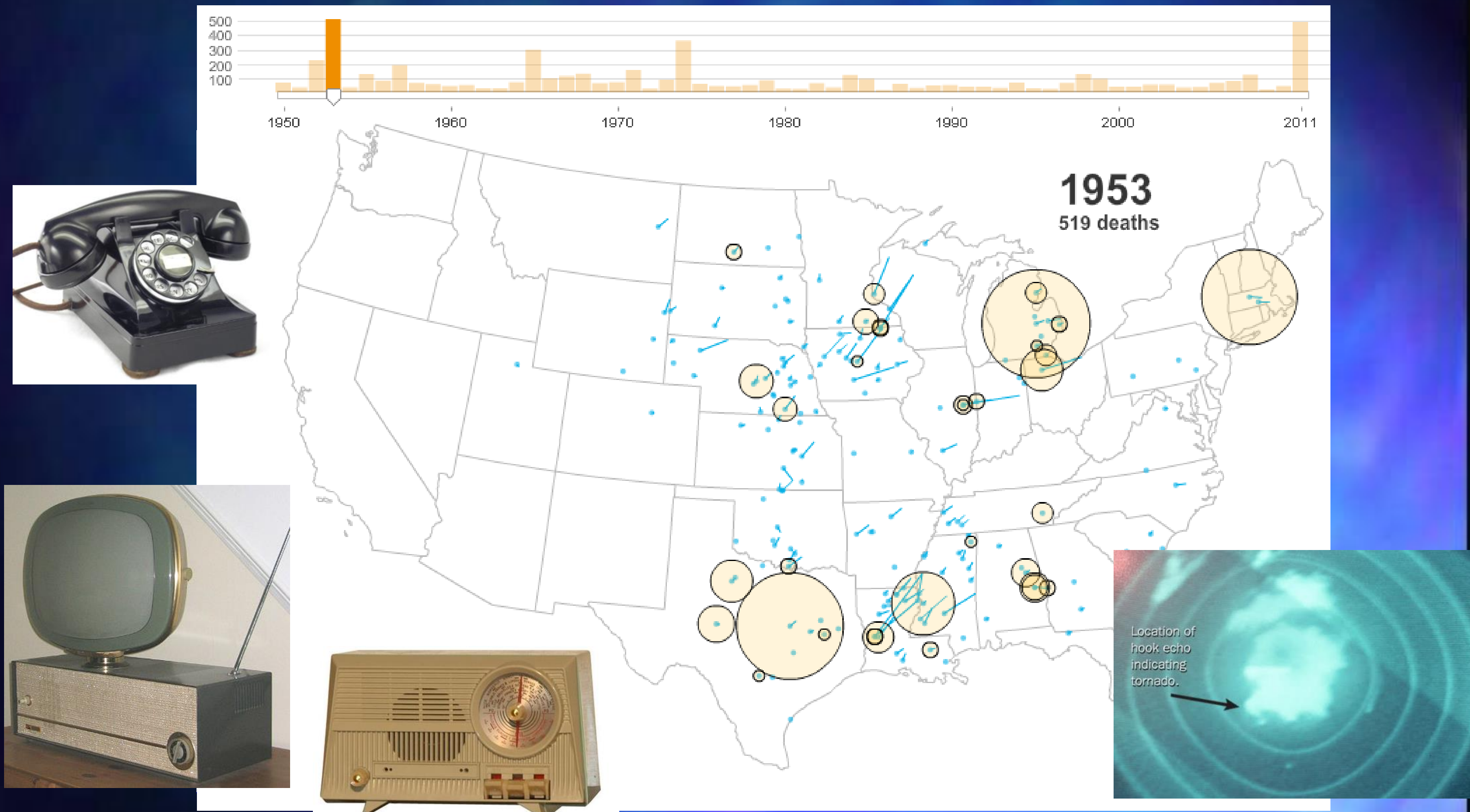
24 May 2011 Tornado Outbreak: Warning on a Numerical Forecast



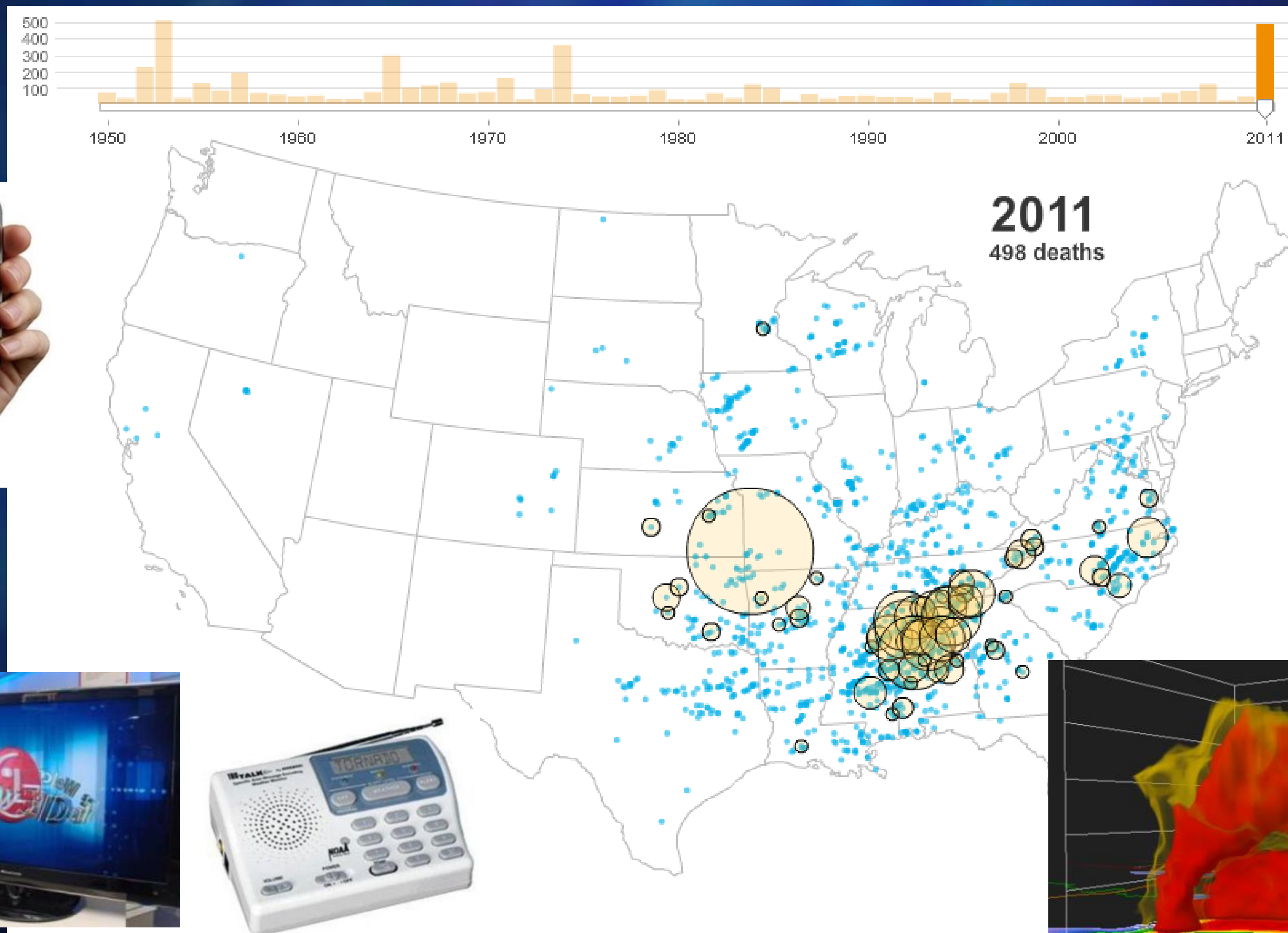
What Happens if We Succeed?!

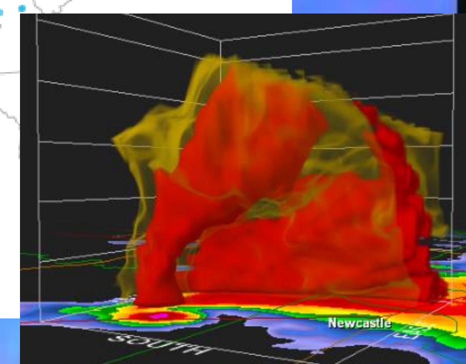
South OKC – May 31, 2013 (11 days following the latest devastating Moore tornado)

The Human Factor: Social and Behavioral Sciences

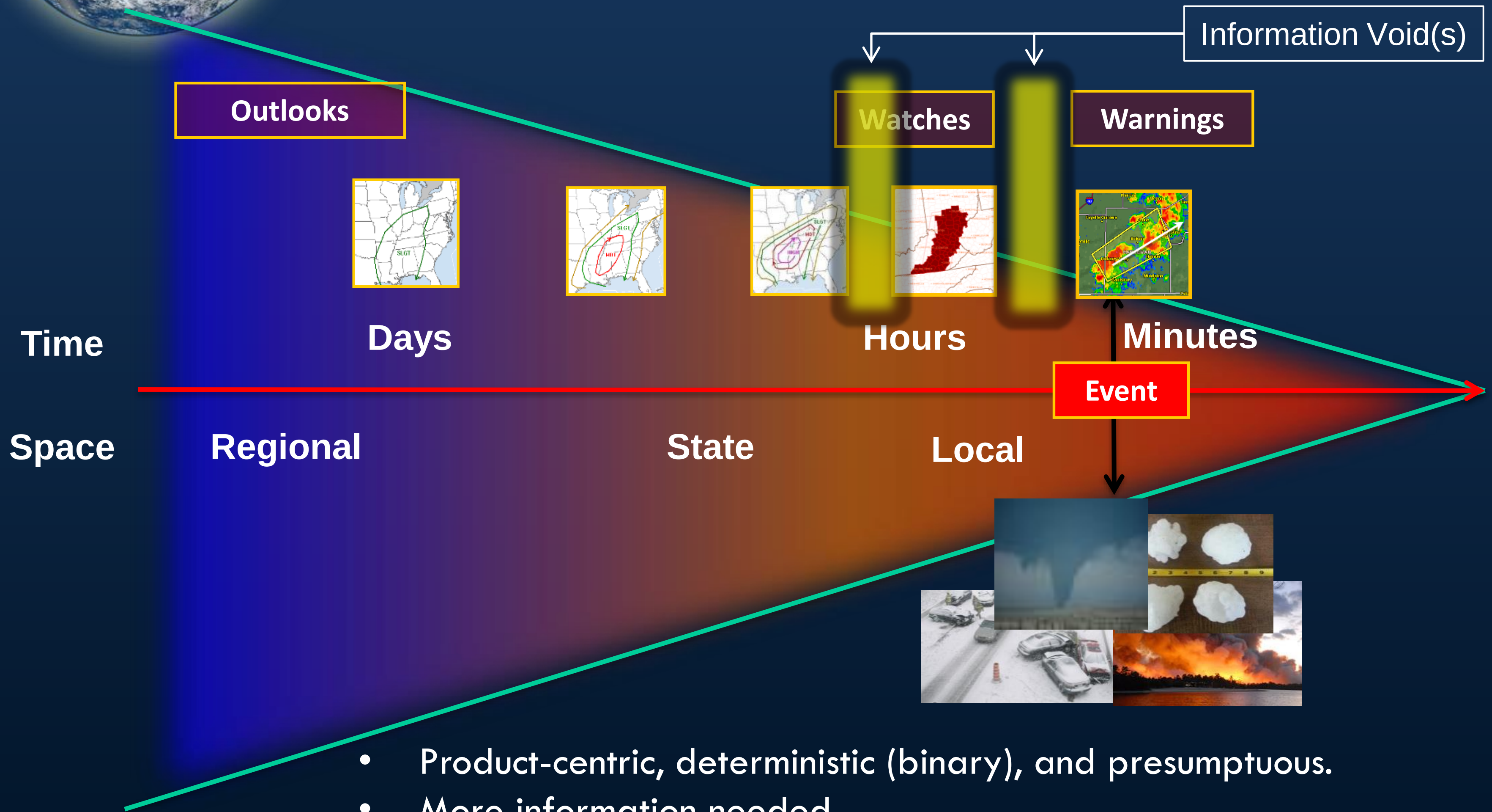


The Human Factor: Social and Behavioral Sciences





The Current Warning System



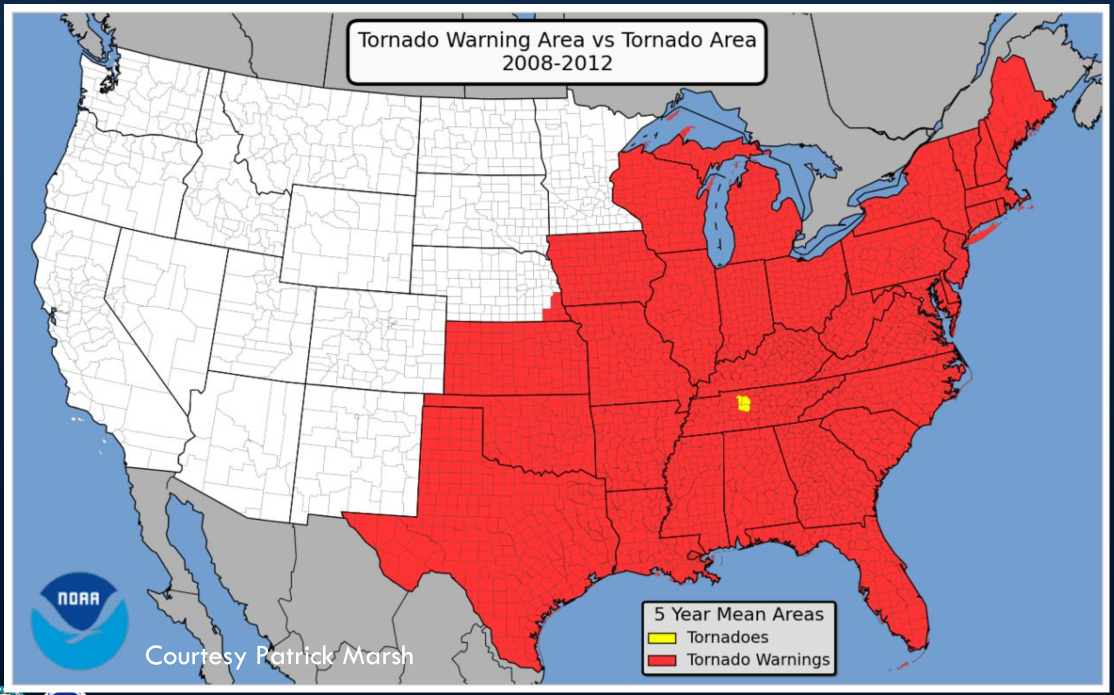
- Product-centric, deterministic (binary), and presumptuous.
- More information needed.
- More information available.

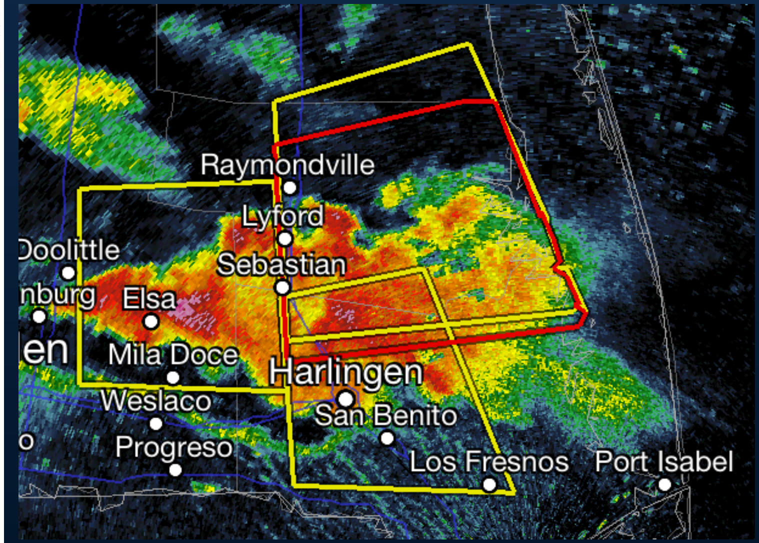
The Current Warning System

Warning polygons are messy!

Inherently "binary" (on/off; in/out)

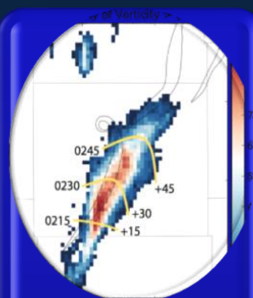
Large false alarm area.

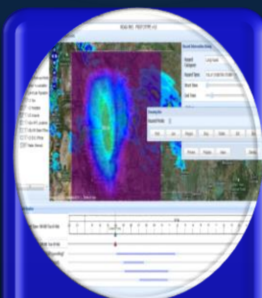


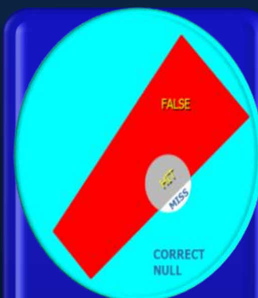


Courtesy NOAA/NSSL

A New Paradigm: Forecasting a Continuum of Environmental Threats (FACETs)



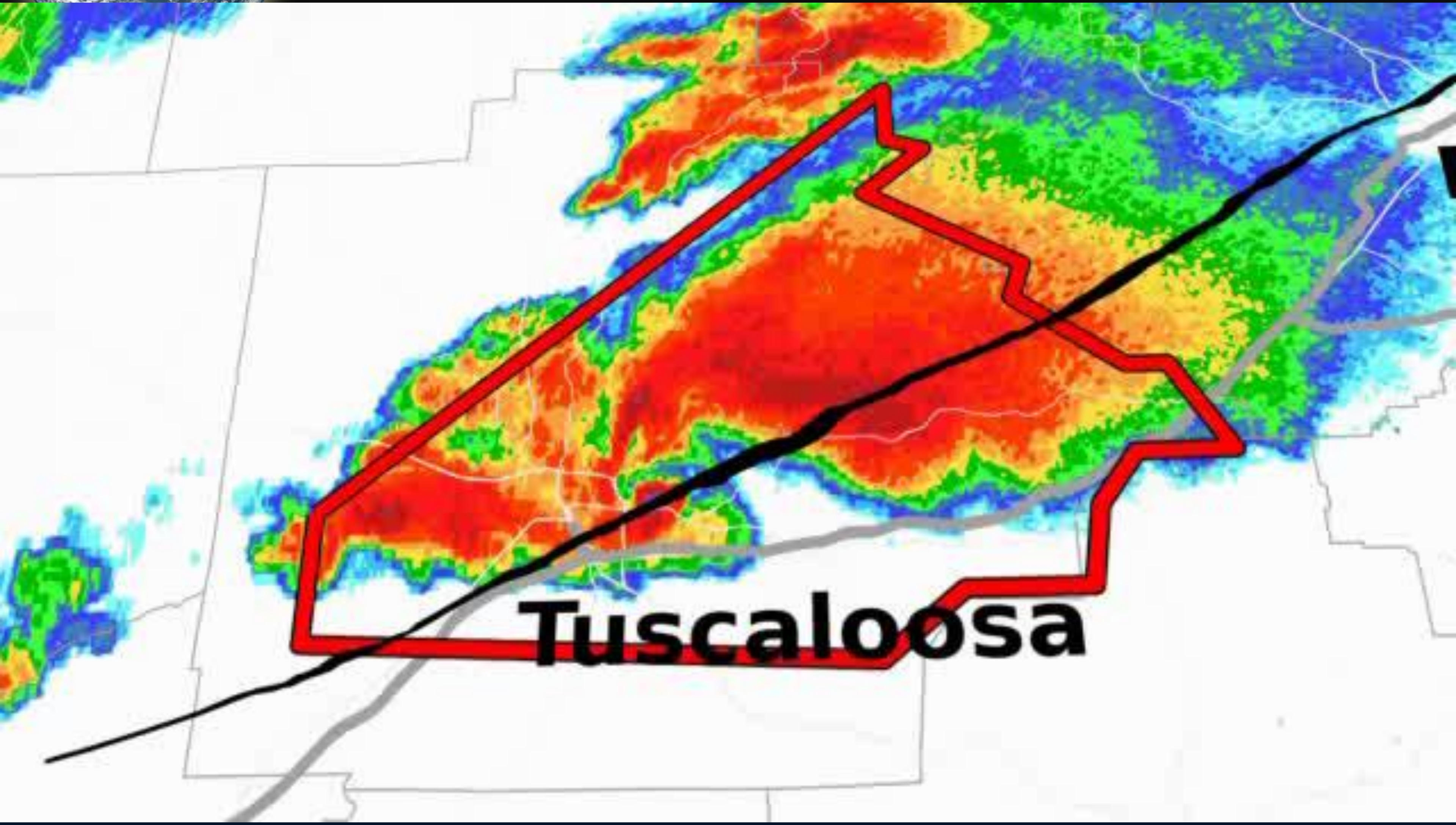




The Method of Warnings	Observations & Guidance	The Forecaster	Threat Grid Tools	Useable Output	Effective Response	Verification Methods

Courtesy NOAA/NSSL

The General Idea…



Courtesy NOAA/NSSL

Changing the Starting Point

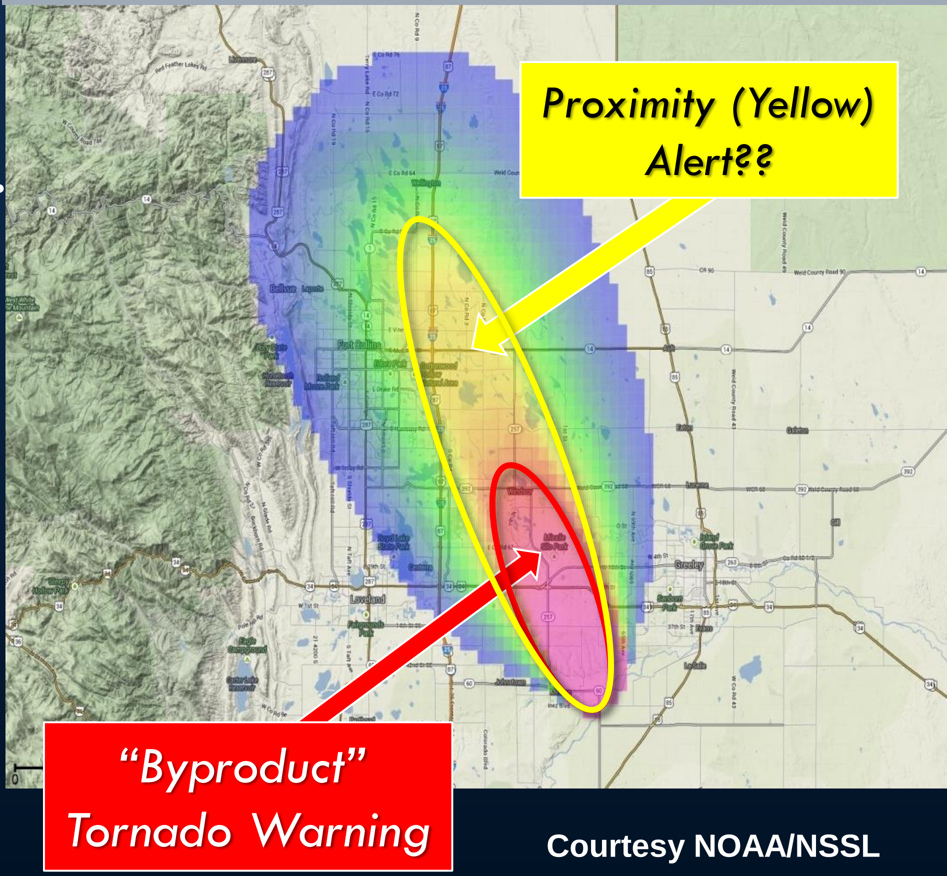
Move from “binary” polygons to Probabilistic Hazard Information (PHI)

- Grid-based threat probabilities.
  - Legacy warnings “fall out.”
  - New messages possible.
- Not only for tornadoes.
  - Winter weather, hail, lightning, flooding, etc.

30-Minute Threat: Tornado Probability

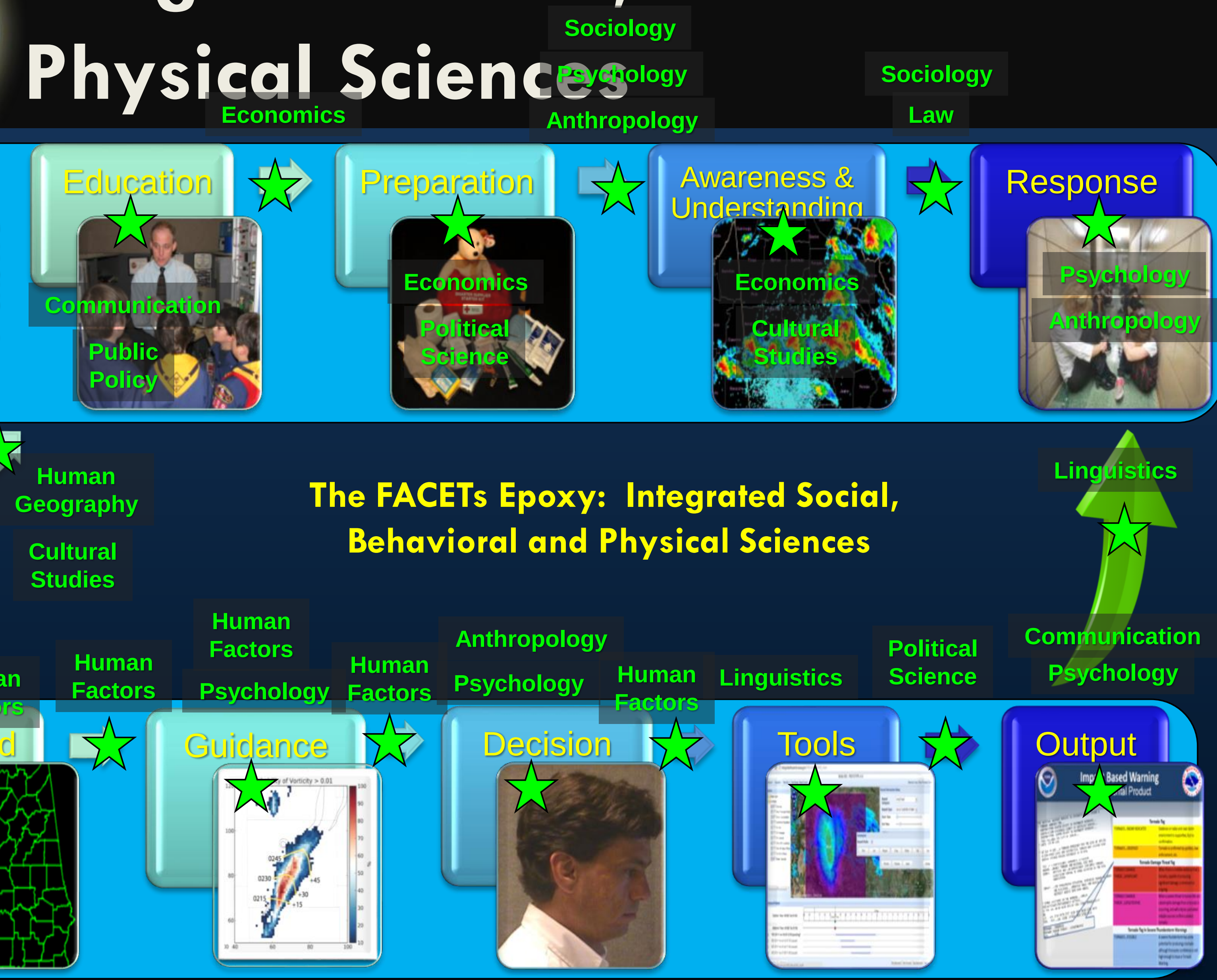
Valid 11:00 a.m. - 11:30 a.m. MDT

Last updated: 1 minute ago



Courtesy NOAA/NSSL

Integrated Social, Behavioral & Physical Sciences

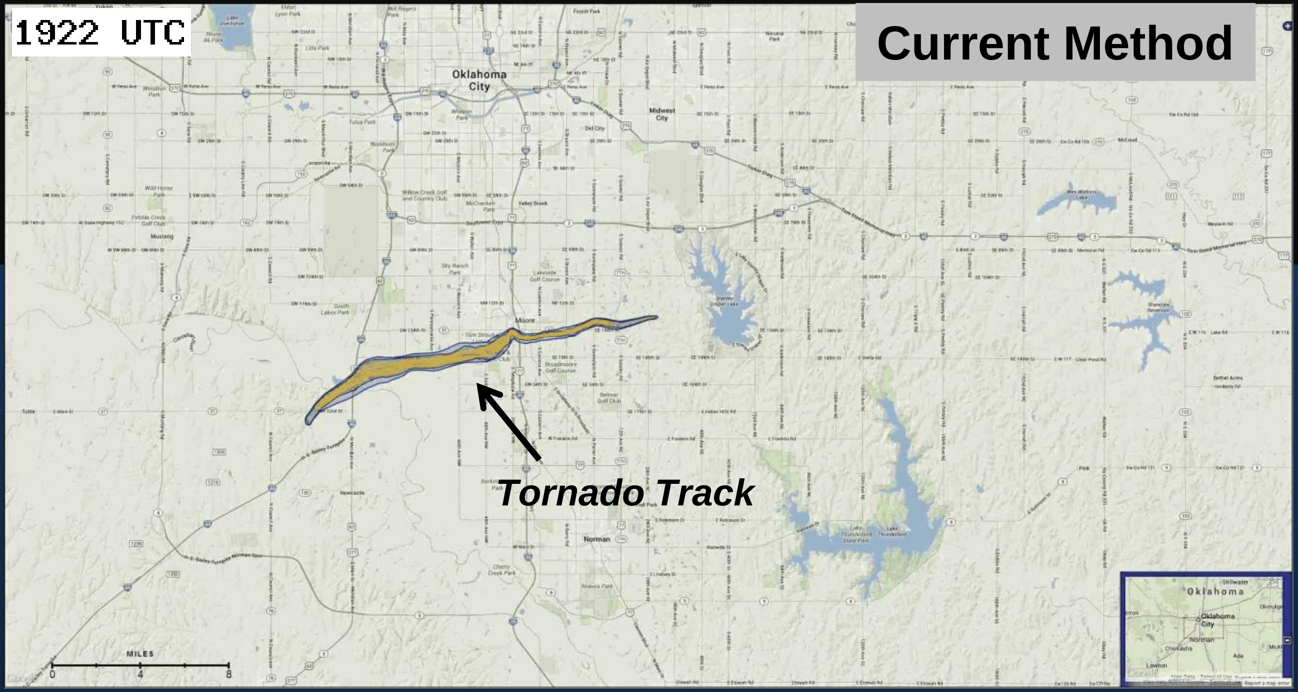


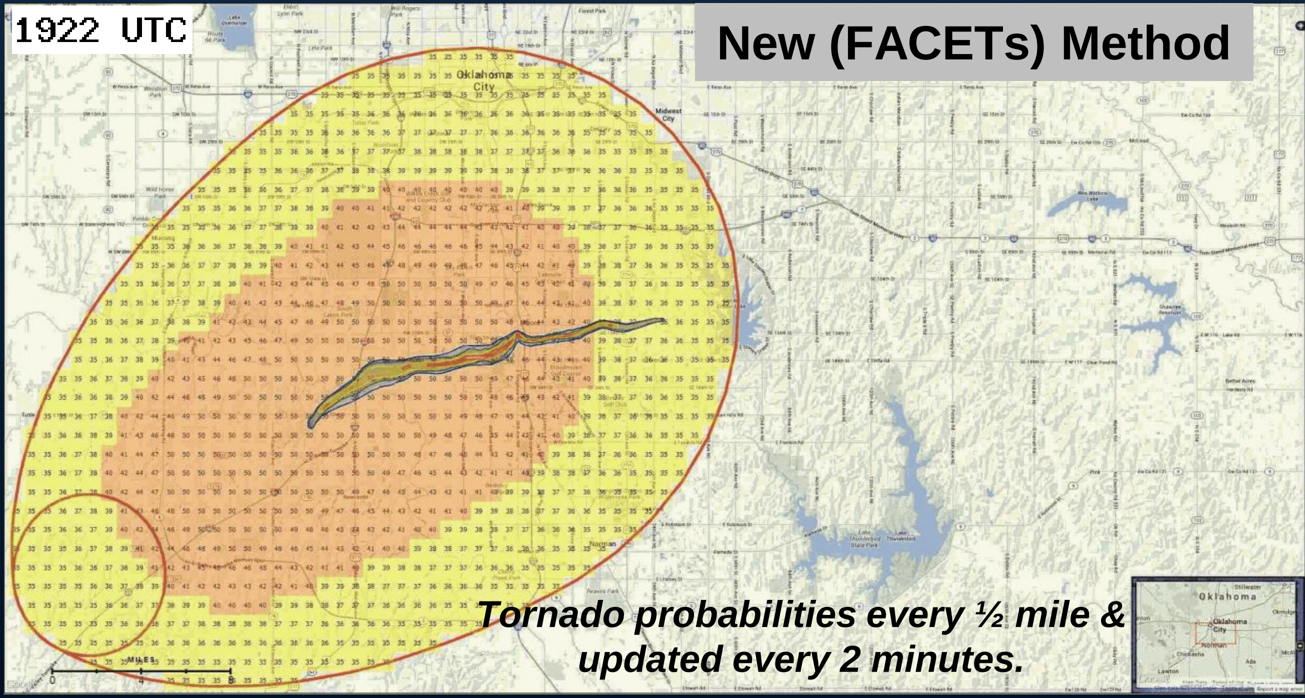
Courtesy NOAA/NSSL

FACETs Comparison: 20 May 2013 (Moore, OK)

Don't think "large, binary warning products."

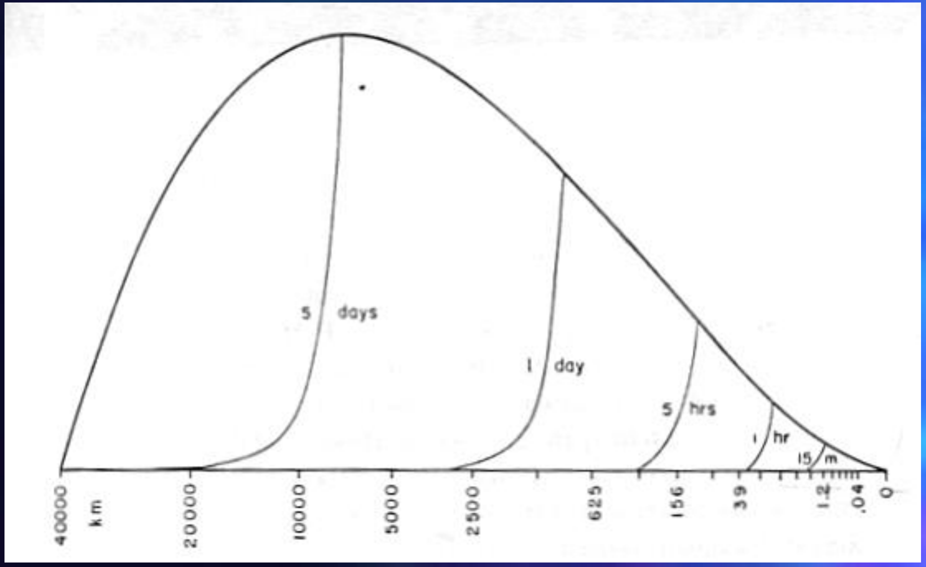
Think "continuous flow of relevant, actionable information for each neighborhood."

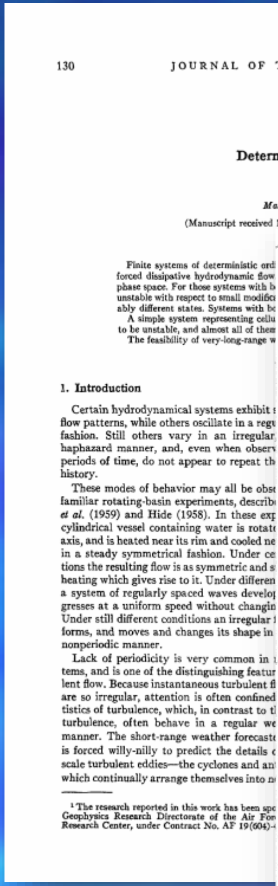




Courtesy NOAA/NSSL

HOW PREDICTABLE ARE SEVERE STORMS AND TORNADOES?





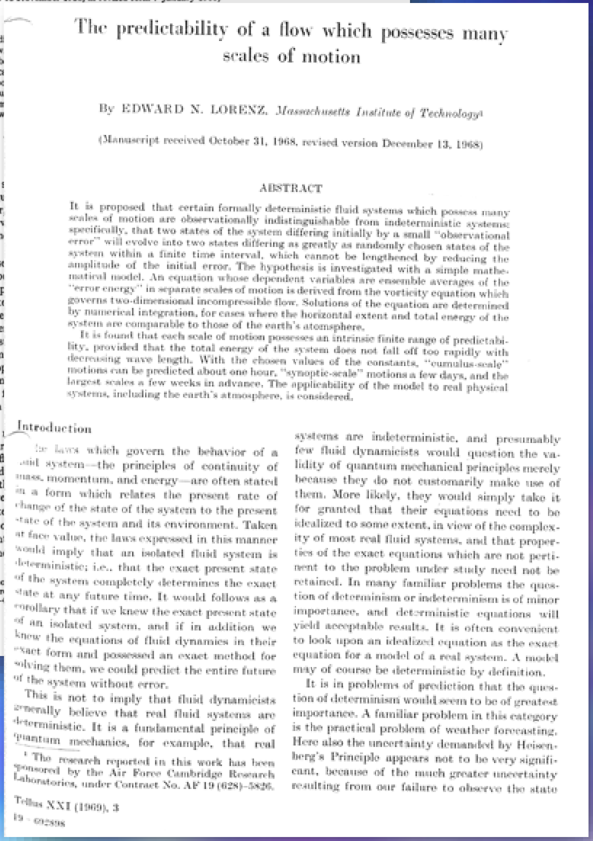
Deterministic Nonperiodic Flow[1]

EDWARD N. LORENZ

Massachusetts Institute of Technology

(Manuscript received 18 November 1962, in revised form 7 January 1963)

1. Introduction


The predictability of a flow which possesses many scales of motion

By EDWARD N. LORENZ, *Massachusetts Institute of Technology*[1]

(Manuscript received October 31, 1968, revised version December 13, 1968)

ABSTRACT

It is proposed that certain formally deterministic fluid systems which possess many scales of motion are observationally indistinguishable from indeterministic systems; specifically, that two states of the system differing initially by a small "observational error" will evolve into two states differing as greatly as randomly chosen states of the system within a finite time interval, which cannot be lengthened by reducing the amplitude of the initial error. The hypothesis is investigated with a simple mathematical model. An equation whose dependent variables are ensemble averages of the "error energy" in separate scales of motion is derived from the vorticity equation which governs two-dimensional incompressible flow. Solutions of the equation are determined by numerical integration, for cases where the horizontal extent and total energy of the system are comparable to those of the earth's atomsphere.

It is found that each scale of motion possesses an intrinsic finite range of predictability, provided that the total energy of the system does not fall off too rapidly with decreasing wave length. With the chosen values of the constants, "cumulus-scale" motions can be predicted about one hour, "synoptic-scale" motions a few days, and the largest scales a few weeks in advance. The applicability of the model to real physical systems, including the earth's atmosphere, is considered.

Introduction

The laws which govern the behavior of a fluid system—the principles of continuity of mass, momentum, and energy—are often stated in a form which relates the present rate of change of the state of the system to the present state of the system and its environment. Taken at face value, the laws expressed in this manner would imply that an isolated fluid system is deterministic; i.e., that the exact present state of the system completely determines the exact state at any future time. It would follows as a corollary that if we knew the exact present state of an isolated system, and if in addition we knew the equations of fluid dynamics in their exact form and possessed an exact method for solving them, we could predict the entire future of the system without error.

This is not to imply that fluid dynamicists generally believe that real fluid systems are deterministic. It is a fundamental principle of quantum mechanics, for example, that real systems are indeterministic, and presumably few fluid dynamicists would question the validity of quantum mechanical principles merely because they do not customarily make use of them. More likely, they would simply take it for granted that their equations need to be idealized to some extent, in view of the complexity of most real fluid systems, and that properties of the exact equations which are not pertinent to the problem under study need not be retained. In many familiar problems the question of determinism or indeterminism is of minor importance, and deterministic equations will yield acceptable results. It is often convenient to look upon an idealized equation as the exact equation for a model of a real system. A model may of course be deterministic by definition.

It is in problems of prediction that the question of determinism would seem to be of greatest importance. A familiar problem in this category is the practical problem of weather forecasting. Here also the uncertainty demanded by Heisenberg's Principle appears not to be very significant, because of the much greater uncertainty resulting from our failure to observe the state

[1] The research reported in this work has been sponsored by the Air Force Cambridge Research Laboratories, under Contract No. AF 19 (628)-5826.

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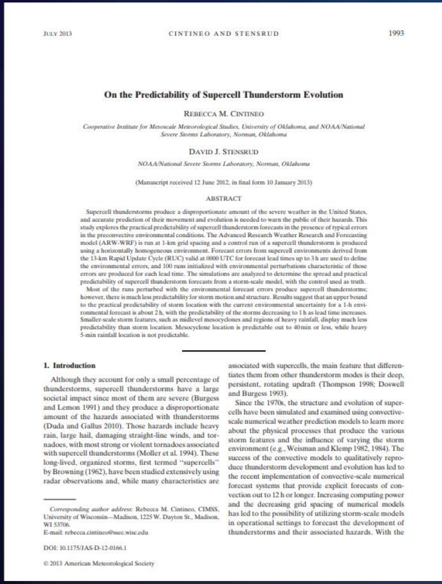
QUESTIONS REMAIN



On the Predictability of Supercell Thunderstorm Evolution

REBECCA M. CINTINEO

Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma, and NOAA/National Severe Storms Laboratory, Norman, Oklahoma

DAVID J. STENSRUD

NOAA/National Severe Storms Laboratory, Norman, Oklahoma

(Manuscript received 12 June 2012, in final form 10 January 2013)

ABSTRACT

Supercell thunderstorms produce a disproportionate amount of the severe weather in the United States, and accurate prediction of their movement and evolution is needed to warn the public of their hazards. This study explores the practical predictability of supercell thunderstorm forecasts in the presence of typical errors in the preconvective environmental conditions. The Advanced Research Weather Research and Forecasting model (ARW-WRF) is run at 1-km grid spacing and a control run of a supercell thunderstorm is produced using a horizontally homogeneous environment. Forecast errors from supercell environments derived from the 13-km Rapid Update Cycle (RUC) valid at 0000 UTC for forecast lead times up to 3 h are used to define the environmental errors, and 100 runs initialized with environmental perturbations characteristic of those errors are produced for each lead time. The simulations are analyzed to determine the spread and practical predictability of supercell thunderstorm forecasts from a storm-scale model, with the control used as truth.

Most of the runs perturbed with the environmental forecast errors produce supercell thunderstorms; however, there is much less predictability for storm motion and structure. Results suggest that an upper bound to the practical predictability of storm location with the current environmental uncertainty for a 1-h environmental forecast is about 2 h, with the predictability of the storms decreasing to 1 h as lead time increases. Smaller-scale storm features, such as midlevel mesocyclones and regions of heavy rainfall, display much less predictability than storm location. Mesocyclone location is predictable out to 40 min or less, while heavy 5-min rainfall location is not predictable.

1. Introduction

Although they account for only a small percentage of thunderstorms, supercell thunderstorms have a large societal impact since most of them are severe (Burgess and Lemon 1991) and they produce a disproportionate amount of the hazards associated with thunderstorms (Duda and Gallus 2010). Those hazards include heavy rain, large hail, damaging straight-line winds, and tornadoes, with most strong or violent tornadoes associated with supercell thunderstorms (Moller et al. 1994). These long-lived, organized storms, first termed "supercells" by Browning (1962), have been studied extensively using radar observations and, while many characteristics are associated with supercells, the main feature that differentiates them from other thunderstorm modes is their deep, persistent, rotating updraft (Thompson 1998; Doswell and Burgess 1993).

Since the 1970s, the structure and evolution of supercells have been simulated and examined using convective-scale numerical weather prediction models to learn more about the physical processes that produce the various storm features and the influence of varying the storm environment (e.g., Weisman and Klemp 1982, 1984). The success of the convective models to qualitatively reproduce thunderstorm development and evolution has led to the recent implementation of convective-scale numerical forecast systems that provide explicit forecasts of convection out to 12 h or longer. Increasing computing power and the decreasing grid spacing of numerical models has led to the possibility of utilizing storm-scale models in operational settings to forecast the development of thunderstorms and their associated hazards. With the

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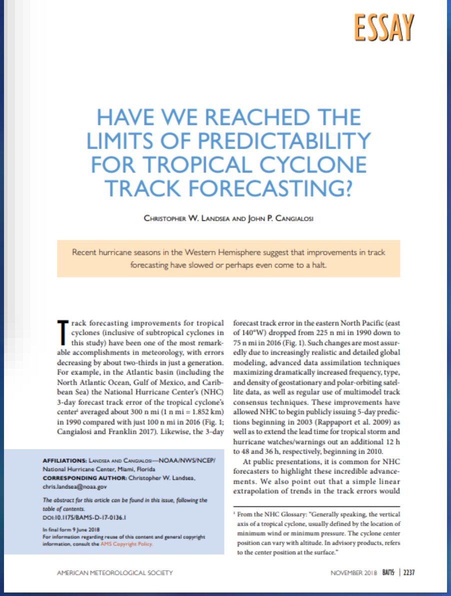
E-mail: rebecca.cintineo@ssec.wisc.edu

DOI: 10.1175/JAS-D-12-0166.1



ESSAY

HAVE WE REACHED THE LIMITS OF PREDICTABILITY FOR TROPICAL CYCLONE TRACK FORECASTING?

CHRISTOPHER W. LANDSEA AND JOHN P. CANGIALOSI

Recent hurricane seasons in the Western Hemisphere suggest that improvements in track forecasting have slowed or perhaps even come to a halt.

Track forecasting improvements for tropical cyclones (inclusive of subtropical cyclones in this study) have been one of the most remarkable accomplishments in meteorology, with errors decreasing by about two-thirds in just a generation. For example, in the Atlantic basin (including the North Atlantic Ocean, Gulf of Mexico, and Caribbean Sea) the National Hurricane Center's (NHC) 3-day forecast track error of the tropical cyclone's center[1] averaged about 300 n mi (1 n mi = 1.852 km) in 1990 compared with just 100 n mi in 2016 (Fig. 1; Cangialosi and Franklin 2017). Likewise, the 3-day forecast track error in the eastern North Pacific (east of 140°W) dropped from 225 n mi in 1990 down to 75 n mi in 2016 (Fig. 1). Such changes are most assuredly due to increasingly realistic and detailed global modeling, advanced data assimilation techniques maximizing dramatically increased frequency, type, and density of geostationary and polar-orbiting satellite data, as well as regular use of multimodel track consensus techniques. These improvements have allowed NHC to begin publicly issuing 5-day predictions beginning in 2003 (Rappaport et al. 2009) as well as to extend the lead time for tropical storm and hurricane watches/warnings out an additional 12 h to 48 and 36 h, respectively, beginning in 2010.

At public presentations, it is common for NHC forecasters to highlight these incredible advancements. We also point out that a simple linear extrapolation of trends in the track errors would

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CORRESPONDING AUTHOR: Christopher W. Landsea, chris.landsea@noaa.gov

The abstract for this article can be found in this issue, following the table of contents.
DOI:10.1175/BAMS-D-17-0136.1

In final form 9 June 2018

[1] From the NHC Glossary: "Generally speaking, the vertical axis of a tropical cyclone, usually defined by the location of minimum wind or minimum pressure. The cyclone center position can vary with altitude. In advisory products, refers to the center position at the surface."

What Is the Predictability Limit of Midlatitude Weather?

FUQING ZHANG AND Y. QIANG SUN

Department of Meteorology and Atmospheric Science, and Center for Advanced Data Assimilation and Predictability Techniques, The Pennsylvania State University, University Park, Pennsylvania

LINUS MAGNUSSON AND ROBERTO BUIZZA

European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom

SHIAN-JIANN LIN AND JAN-HUEY CHEN

NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey

KERRY EMANUEL

Lorenz Center, Massachusetts Institute of Technology, Cambridge, Massachusetts

(Manuscript received 7 September 2018, in final form 9 November 2018)

ABSTRACT

Understanding the predictability limit of day-to-day weather phenomena such as midlatitude winter storms and summer monsoonal rainstorms is crucial to numerical weather prediction (NWP). This predictability limit is studied using unprecedented high-resolution global models with ensemble experiments of the European Centre for Medium-Range Weather Forecasts (ECMWF; 9-km operational model) and identical-twin experiments of the U.S. Next-Generation Global Prediction System (NGGPS; 3 km). Results suggest that the predictability limit for midlatitude weather may indeed exist and is intrinsic to the underlying dynamical system and instabilities even if the forecast model and the initial conditions are nearly perfect. Currently, a skillful forecast lead time of midlatitude instantaneous weather is around 10 days, which serves as the practical predictability limit. Reducing the current-day initial-condition uncertainty by an order of magnitude extends the deterministic forecast lead times of day-to-day weather by up to 5 days, with much less scope for improving prediction of small-scale phenomena like thunderstorms. Achieving this additional predictability limit can have enormous socioeconomic benefits but requires coordinated efforts by the entire community to design better numerical weather models, to improve observations, and to make better use of observations with advanced data assimilation and computing techniques.

1. Introduction

Weather forecasting has improved dramatically since the introduction of numerical weather prediction (NWP) nearly six decades ago (Bauer et al. 2015). This has been accomplished through ever-increasing computing power, improved models running at ever-increasing resolution with more accurate representation of atmospheric physical processes, and more sophisticated four-dimensional data assimilating algorithms that can better ingest ever-increasing volumes and quality of in situ and remotely acquired observations (WMO 2015). A widely used measure of global NWP forecast quality is the anomaly correlation coefficient (ACC) of 500-hPa geopotential height between the forecasts and observations. In practice, 60% is usually used as a threshold for measure of skillful synoptic-scale weather forecast. Examining the evolution of ACC (Fig. 1), useful deterministic forecasts by arguably the most advanced NWP model at the European Centre for Medium-Range Weather Forecasts (ECMWF) could at best be made up to around 10 days: this number was 7 days 30 years ago (Simmons and Hollingsworth 2002; Bauer et al. 2015).

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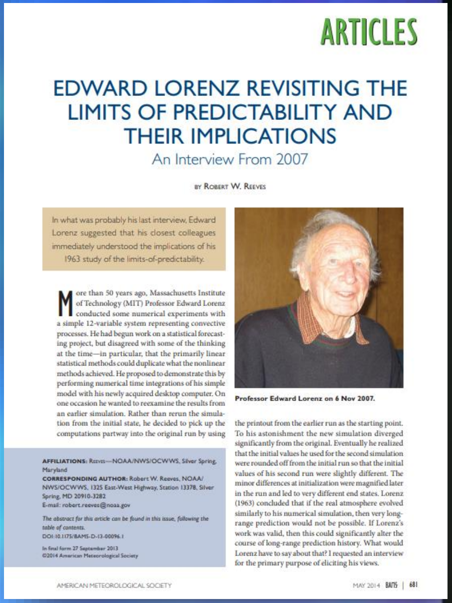

ARTICLES

EDWARD LORENZ REVISITING THE LIMITS OF PREDICTABILITY AND THEIR IMPLICATIONS

An Interview From 2007

BY ROBERT W. REEVES

In what was probably his last interview, Edward Lorenz suggested that his closest colleagues immediately understood the implications of his 1963 study of the limits-of-predictability.

Professor Edward Lorenz on 6 Nov 2007.

More than 50 years ago, Massachusetts Institute of Technology (MIT) Professor Edward Lorenz conducted some numerical experiments with a simple 12-variable system representing convective processes. He had begun work on a statistical forecasting project, but disagreed with some of the thinking at the time—in particular, that the primarily linear statistical methods could duplicate what the nonlinear methods achieved. He proposed to demonstrate this by performing numerical time integrations of his simple model with his newly acquired desktop computer. On one occasion he wanted to reexamine the results from an earlier simulation. Rather than rerun the simulation from the initial state, he decided to pick up the computations partway into the original run by using the printout from the earlier run as the starting point. To his astonishment the new simulation diverged significantly from the original. Eventually he realized that the initial values he used for the second simulation were rounded off from the initial run so that the initial values of his second run were slightly different. The minor differences at initialization were magnified later in the run and led to very different end states. Lorenz (1963) concluded that if the real atmosphere evolved similarly to his numerical simulation, then very long-range prediction would not be possible. If Lorenz's work was valid, then this could significantly alter the course of long-range prediction history. What would Lorenz have to say about that? I requested an interview for the primary purpose of eliciting his views.

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Earth System Predictability Research and Development Strategic Framework and Roadmap

A Report by the

FAST TRACK ACTION COMMITTEE ON EARTH SYSTEM PREDICTABILITY RESEARCH AND DEVELOPMENT

of the

NATIONAL SCIENCE & TECHNOLOGY COUNCIL

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