Short-range dynamical probabilistic prediction of extreme atmospheric events.

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ECODYC10. Dresden 25-29 January 2001

American Heritage Dictionary

- ex·treme:

  …

  3. Extending far beyond the norm

  4. Of the greatest severity, drastic

  …

AIMS

- What I mean by *extreme* ?
- Why is it *extreme*? Clues to prediction.
- Is it predictable? Why?
- How is extreme weather forecast nowadays?

What I mean by extreme?

Different definitions:

- Maxima/minima
- Magnitude
- Rarity
- Severity

"Man can believe the impossible,

but man can never believe the

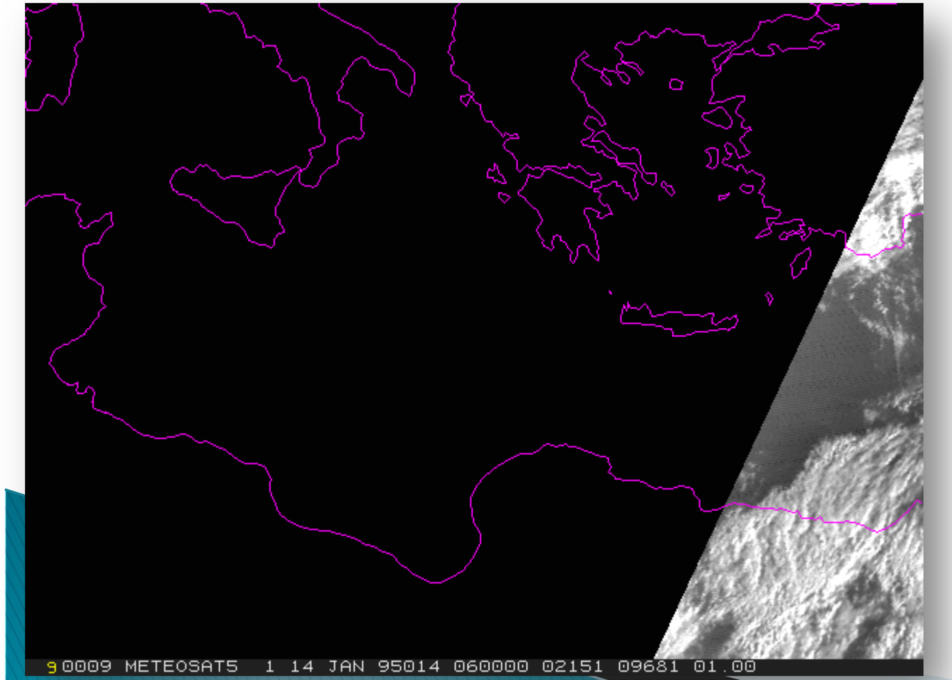
improbable." - Oscar Wilde

Gare Montparnasse, 22 October 1895

D. B Stephenson

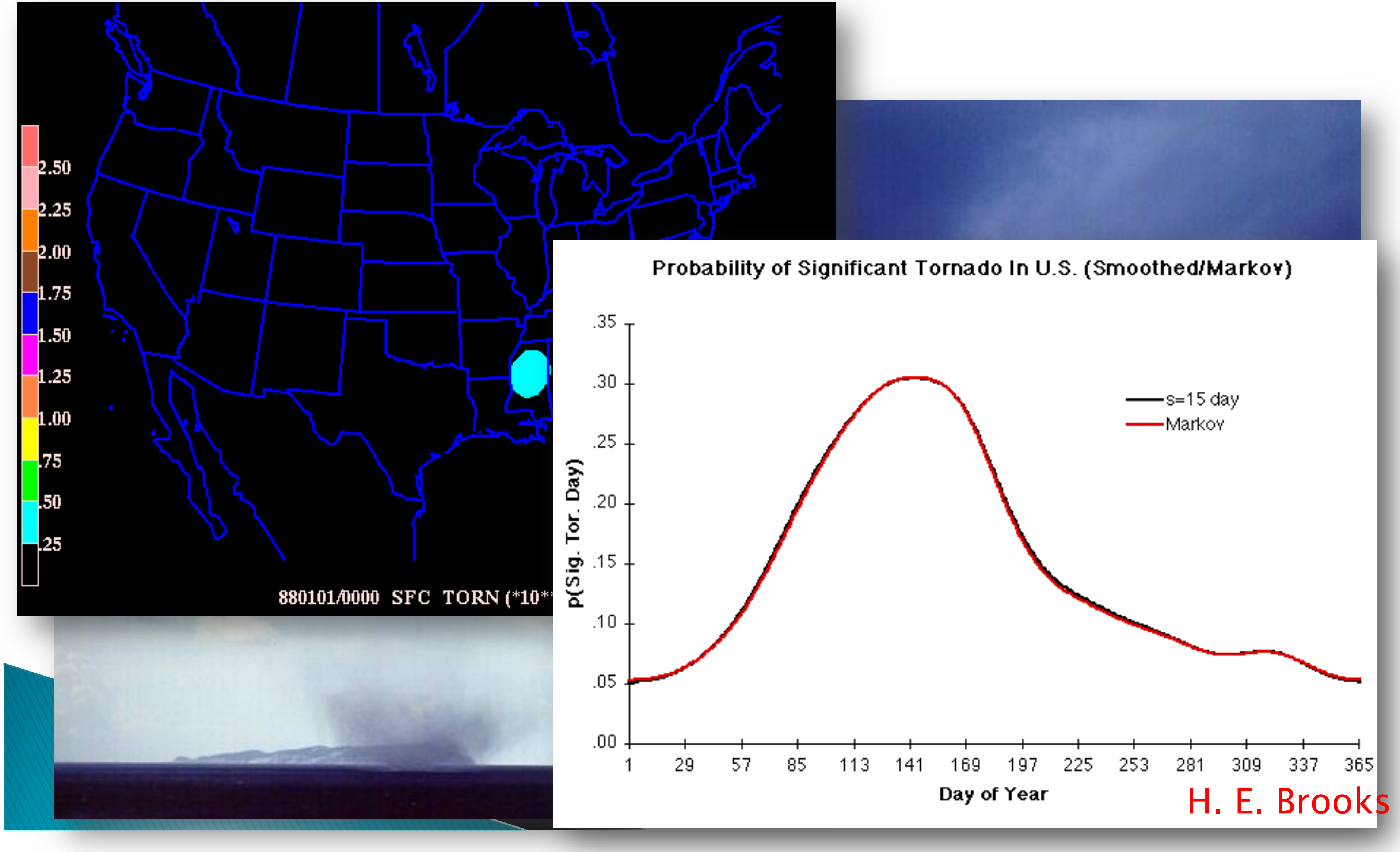
What is extreme weather?

- Magnitude exceeding thresholds (*far beyond the norm)*



What is extreme weather?

- Rarity (*far beyond normal frequency)*

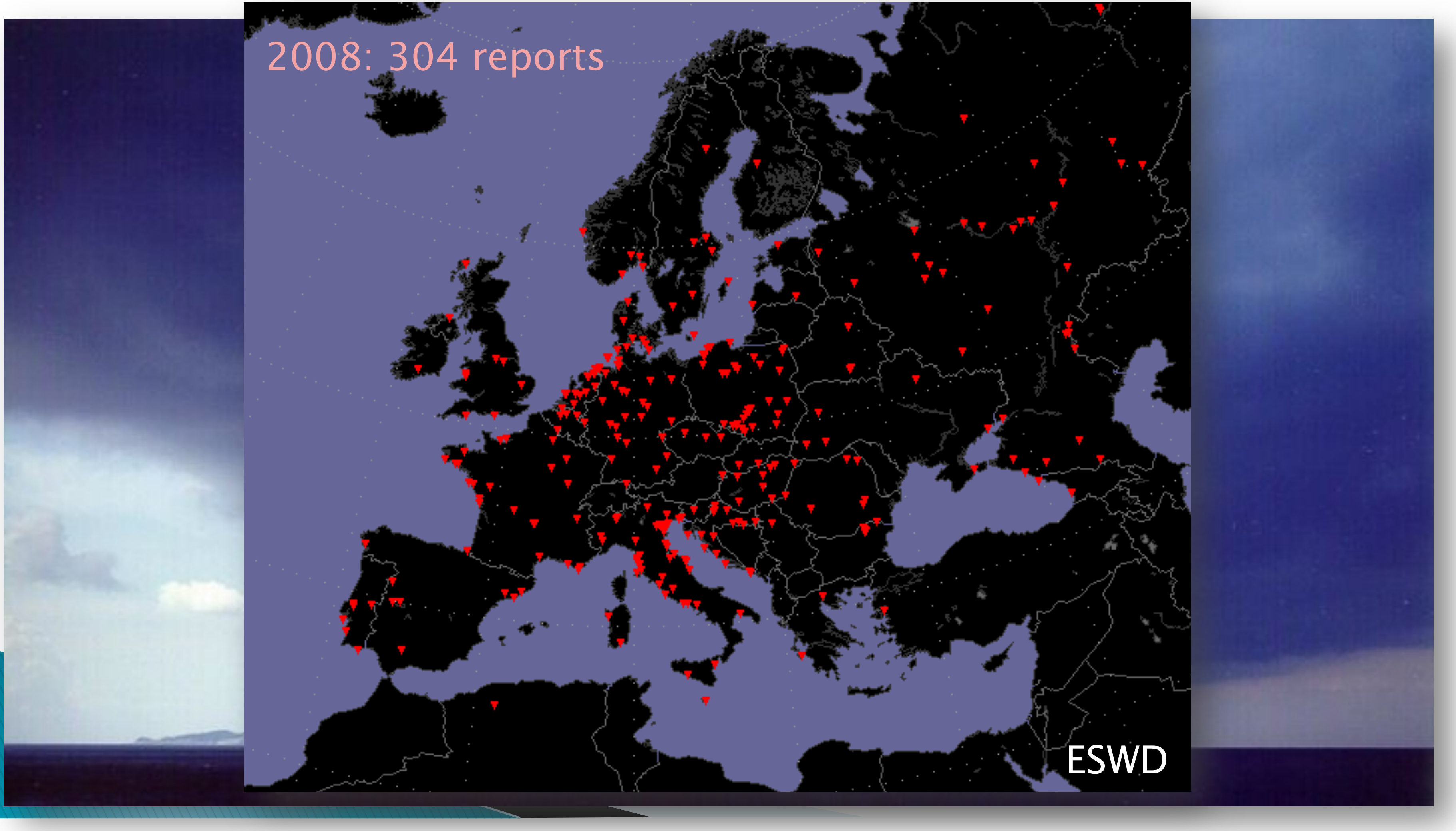


H. E. Brooks

What is extreme weather?

- Rarity (*far beyond normal frequency)*

Tornadoes in Europe?



What is extreme weather?

- Severity (*greatest severity, drastic*)




What is extreme weather?

- I'll use the "*4. of the greatest severity, drastic*" definition of extreme:
  - SPC: **Tornadoes, Large Hail and Strong winds**
  - ESWD: SPCs + **Heavy Rain**

Why is it extreme?

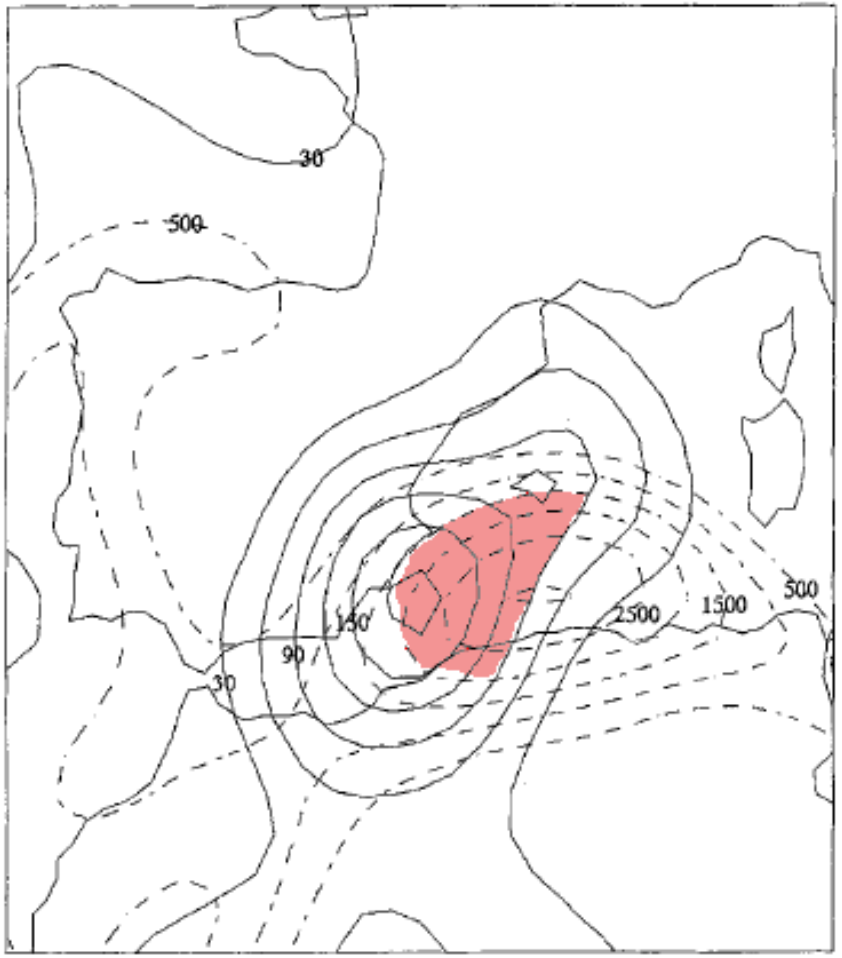
Why is it extreme *(severe,drastic)?*

Systems with high *energy density:*

- Tornadoes: *10^4 kWh in a very small volume [10^4 m^3]*
  (Hurricanes: 10^{10} kWh in $10^{15} m^3$)
- Strong Wind: 10^4 J/m^3
- Large hail: *10^2 J/m^2*
- *Heavy Rain*

Why is it rare *(far below frequent)?*

- Extreme events occur:



convec

nces

- Useful model

ingredients

  - Tornadoes: C

ear + Low LCL

  - Heavy rain: C

y + PW

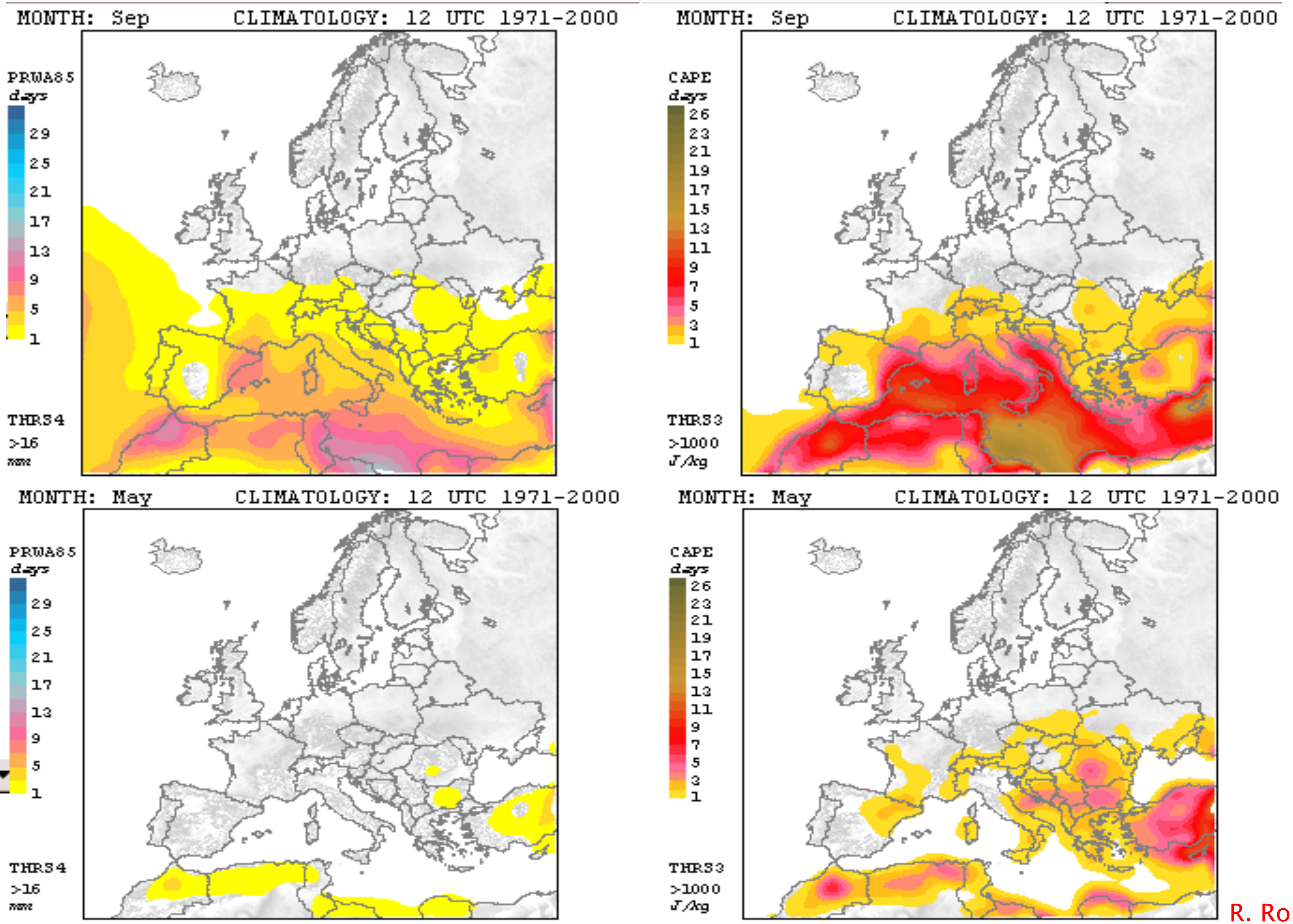
  - Large Hail: C

profile of T/H

Extreme weather is rare because overlap of all ingredients is rare

Why is it rare *(far below frequent)?*

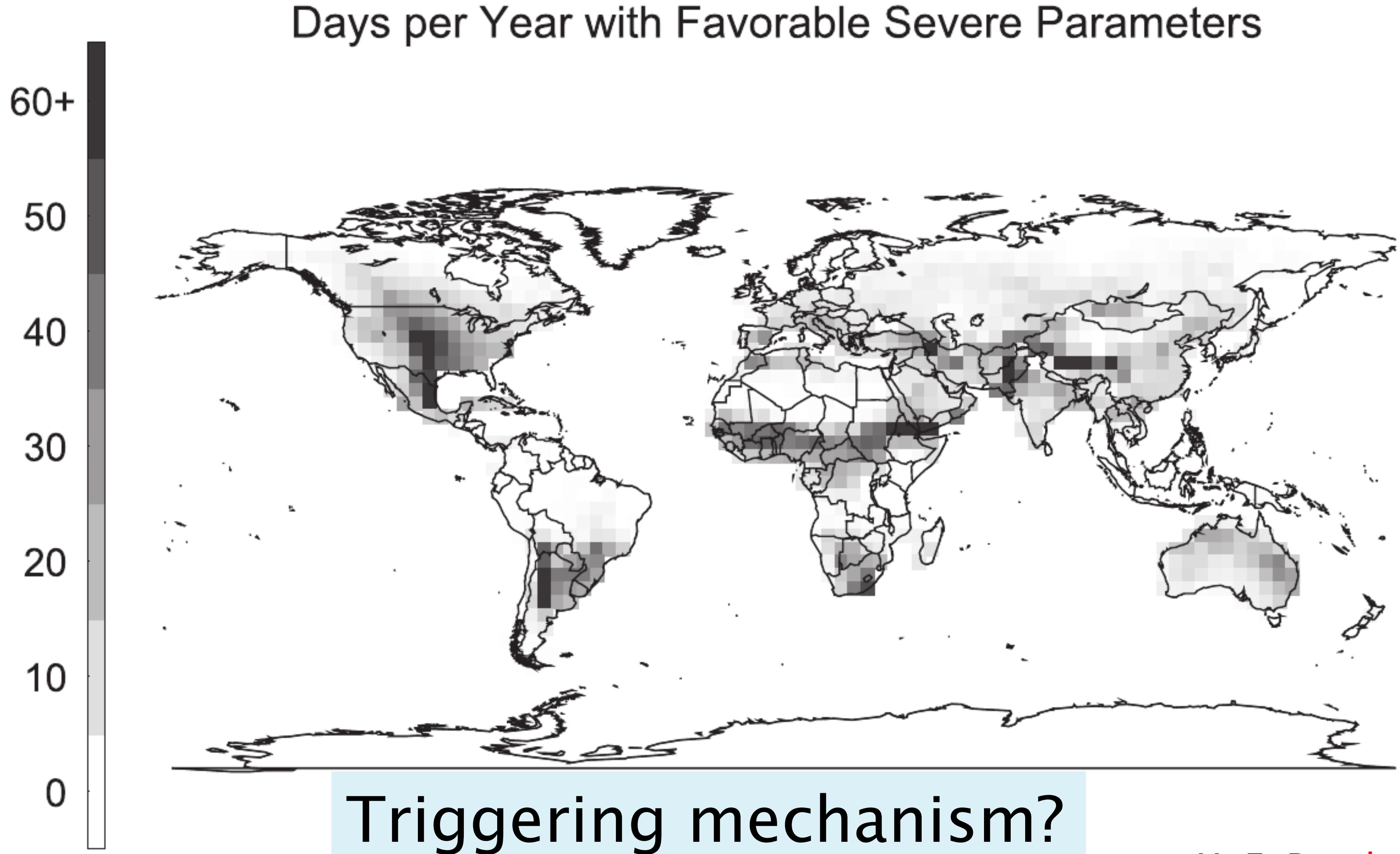
Extreme weather is rare because overlap of all ingredients is rare



R. Romero

Why is it rare *(far below frequent)?*

Extreme weather is rare because overlap of all ingredients is rare


Days per Year with Favorable Severe Parameters

Triggering mechanism?

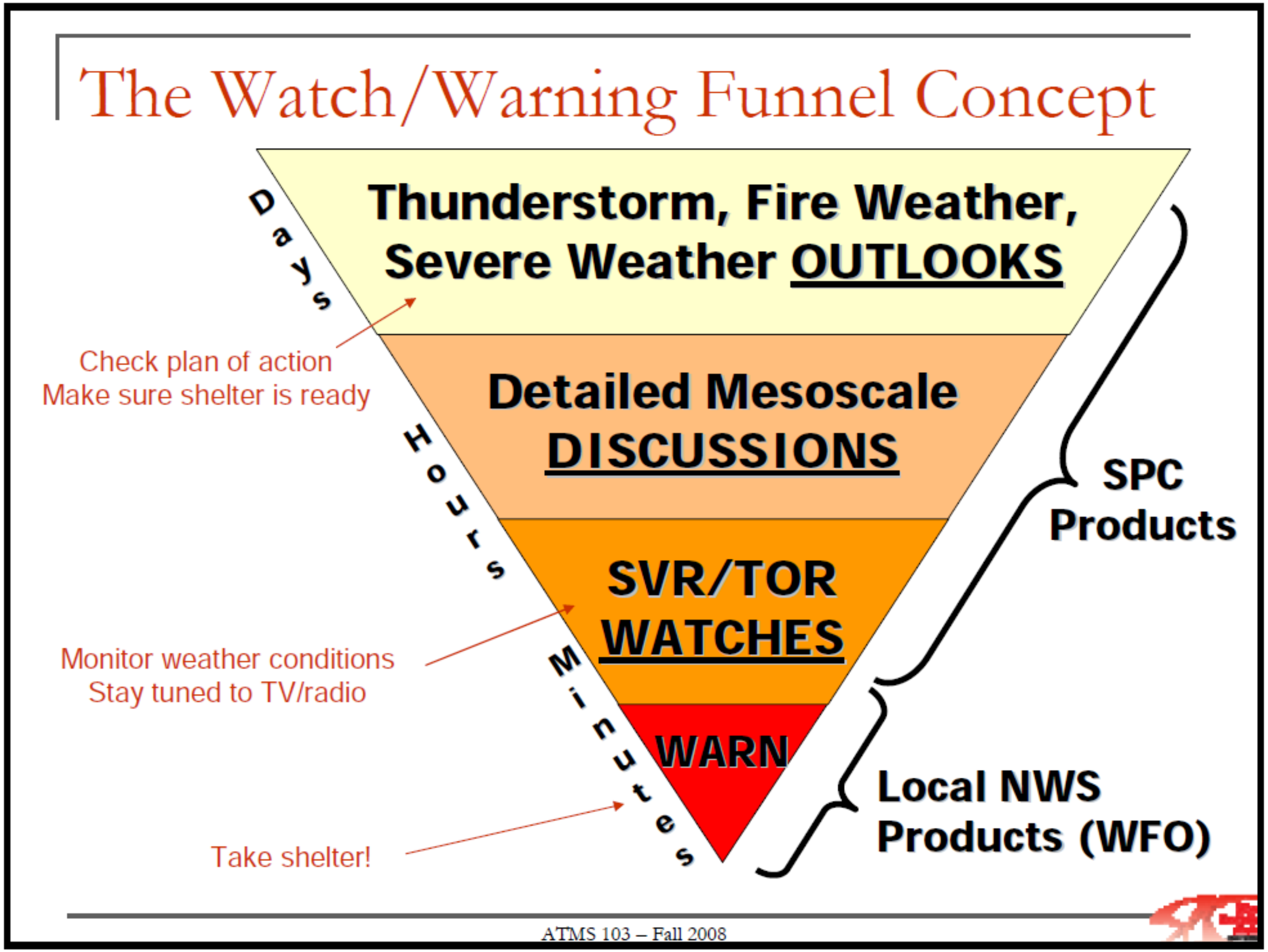
H. E. Brooks

Is it predictable?

“Predictable*??* Don’t even know how to define predictability in a useful way for severe weather!”

H. E. Brooks

Is it predictable?



The Watch/Warning Funnel Concept

Thunderstorm, Fire Weather, Severe Weather OUTLOOKS

Detailed Mesoscale DISCUSSIONS

SVR/TOR WATCHES

WARN

Days

Hours

Minutes

Check plan of action
Make sure shelter is ready

Monitor weather conditions
Stay tuned to TV/radio

Take shelter!

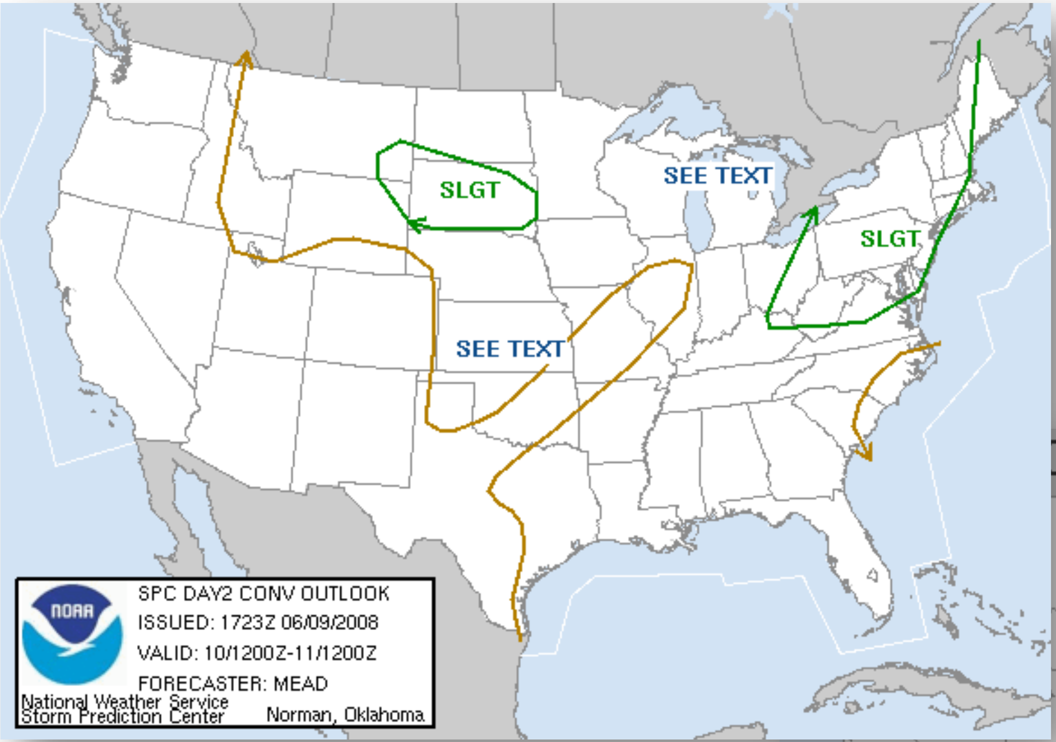
SPC Products

Local NWS Products (WFO)

ATMS 103 – Fall 2008

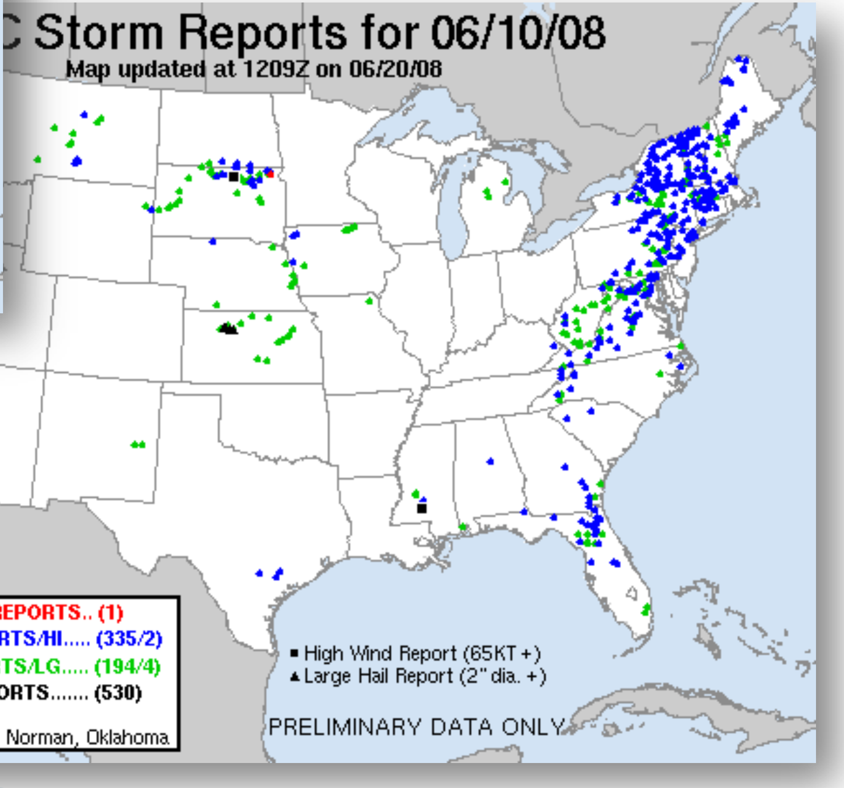
D. Imy

Is it predictable?



SPC 1DAY FORECAST

SEVERE REPORTS

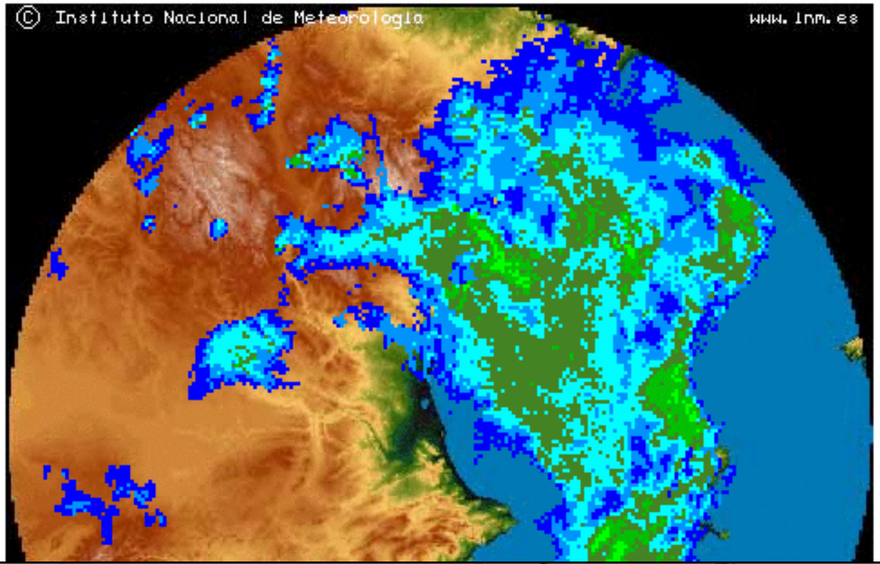


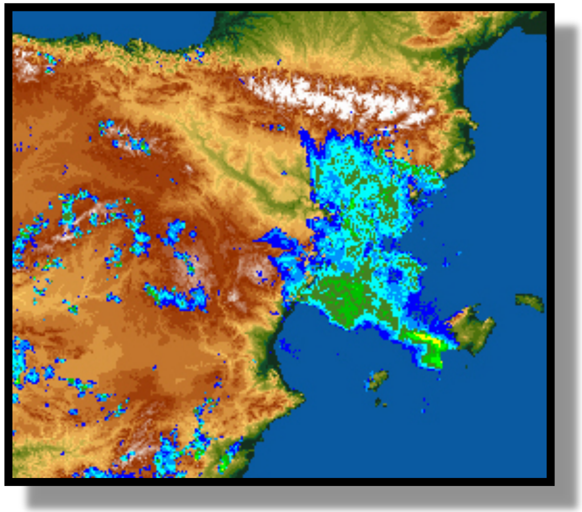
Is it predictable?

- Atmospheric convection (at least our models of it) is:
  - highly non-linear
  - chaotic (highly sensitive to environment)
- Crucial aspects for valuable forecasts:
  - Initiation (where and when)
  - Evolution (where and when)
  - Type or organization (how intense)
  - Intensity (how intense)

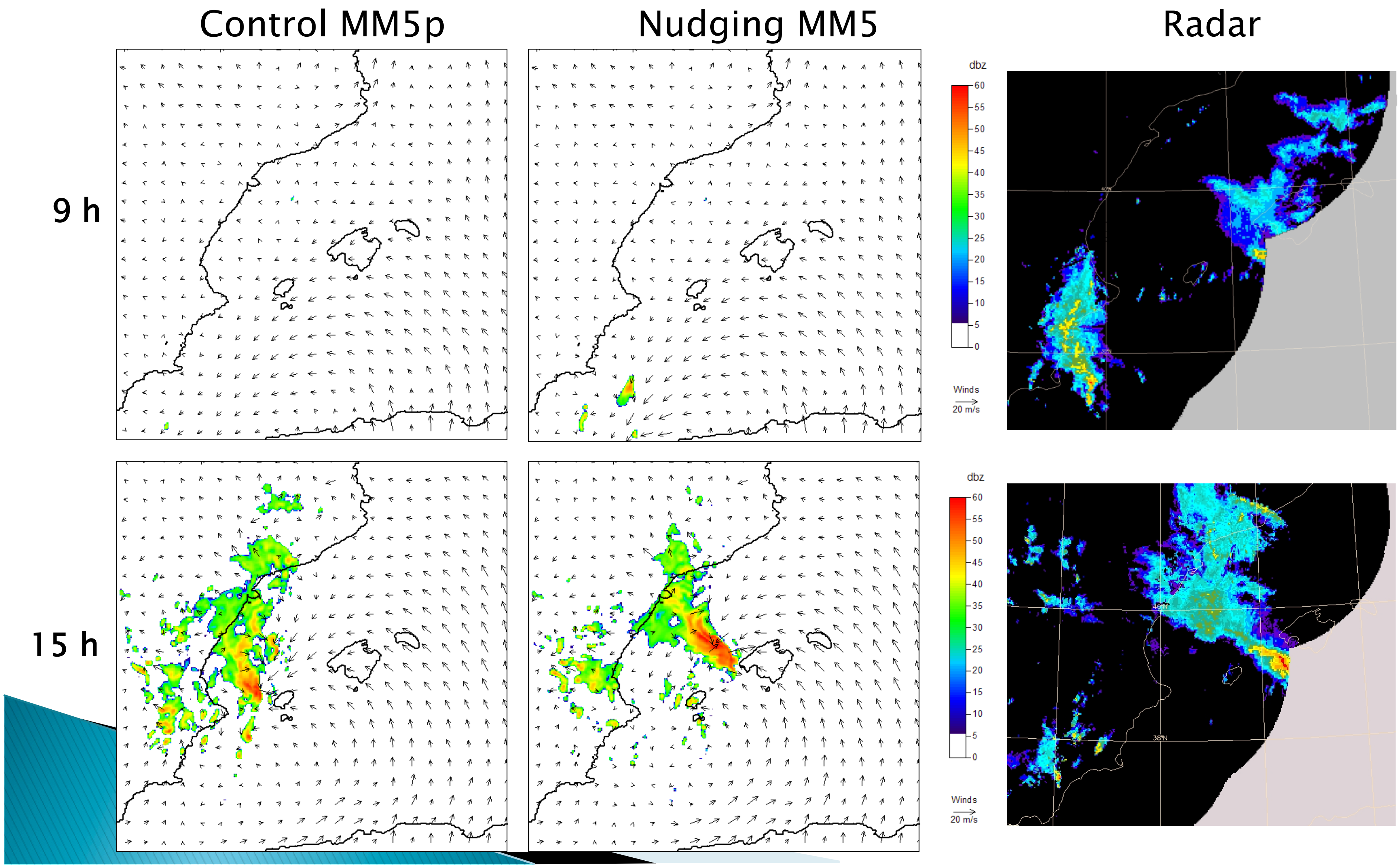
… depend on small scale structures not observed by regular observing systems (e.g. Stensrud and Frisch1994).

Limited predictability: 4th October 2007





Limited predictability: 4th October 2007



Control MM5p

Nudging MM5

Radar

9 h

15 h

Error growth

- Regarding error growth and scales (Lorenz 1993):
  1. Small errors in coarse structures double in ~ 2-3 days. As errors become larger the growth rate subsides
  2. Small errors in fine structure grow much faster, doubling in hours
  3. Errors in fine structure produce errors in the coarse structure (!!!!)
  4. Averaged and accumulated quantities might be more predictable than the systems responsible for them.

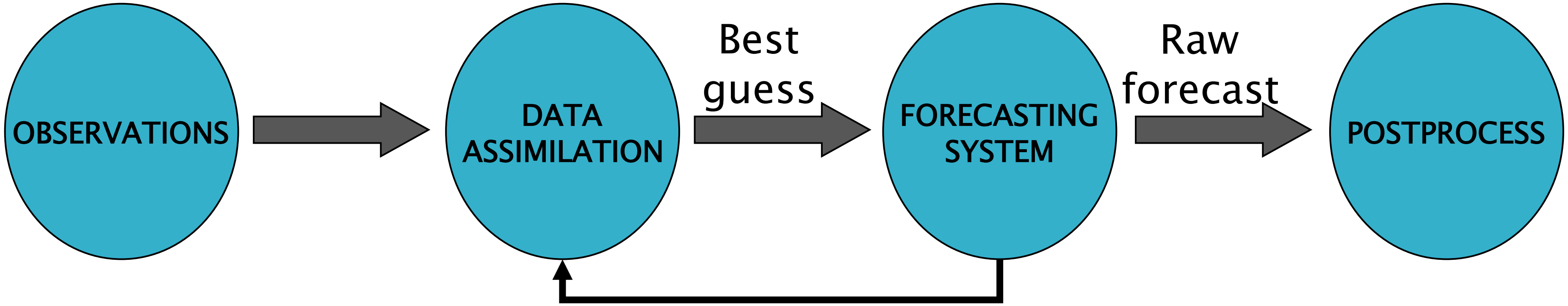
Is it predictable?

- NOAA/NWS target for tornado lead-time prediction:
  - 2004: 13 minutes for 2012
  - 2008: 30 minutes for 2025
  - 2010: “Warn of Forecast” project

How is it predicted?

- Few minutes: Nowcasting + Emergency management protocols
- Hours and days: Numerical forecasts

Numerical forecast



OBSERVATIONS

DATA ASSIMILATION

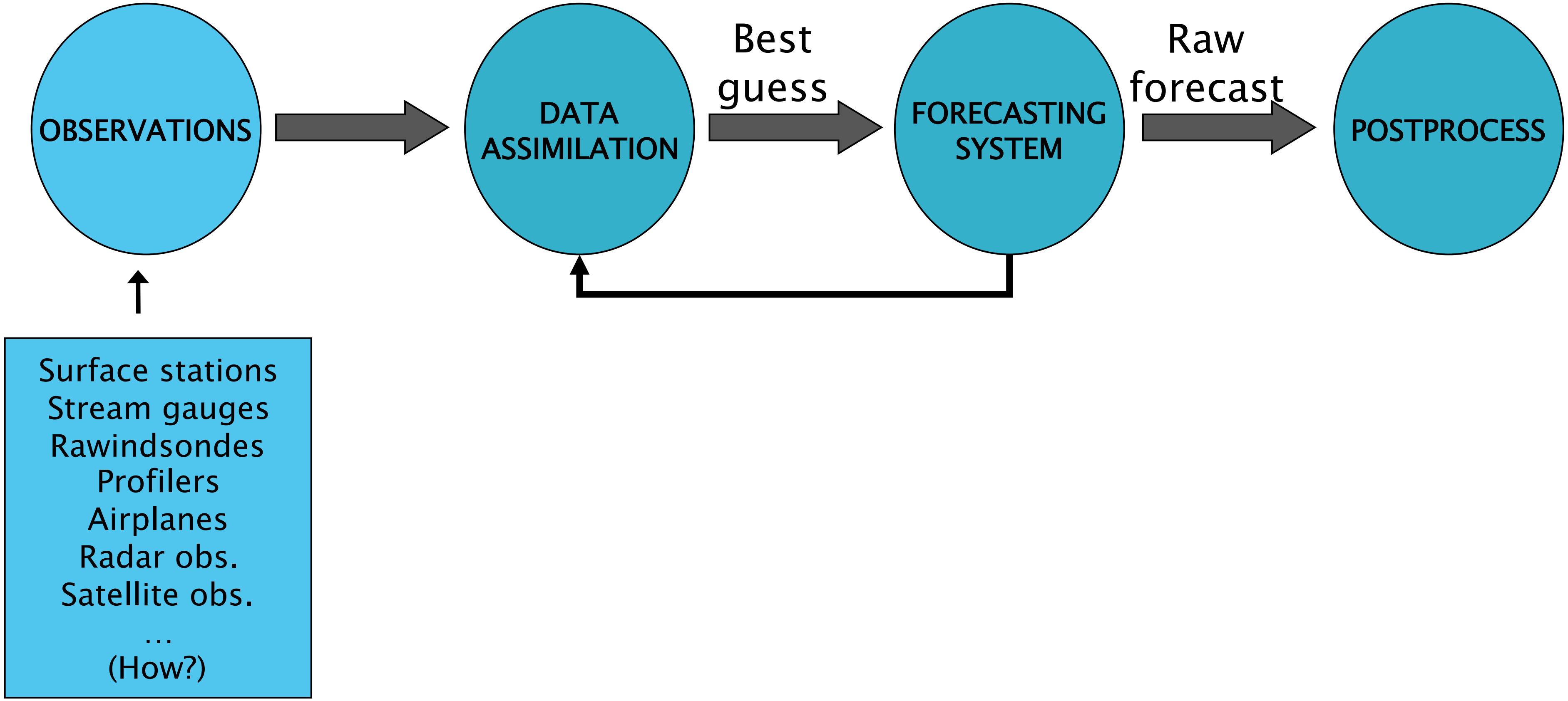
Best guess

FORECASTING SYSTEM

Raw forecast

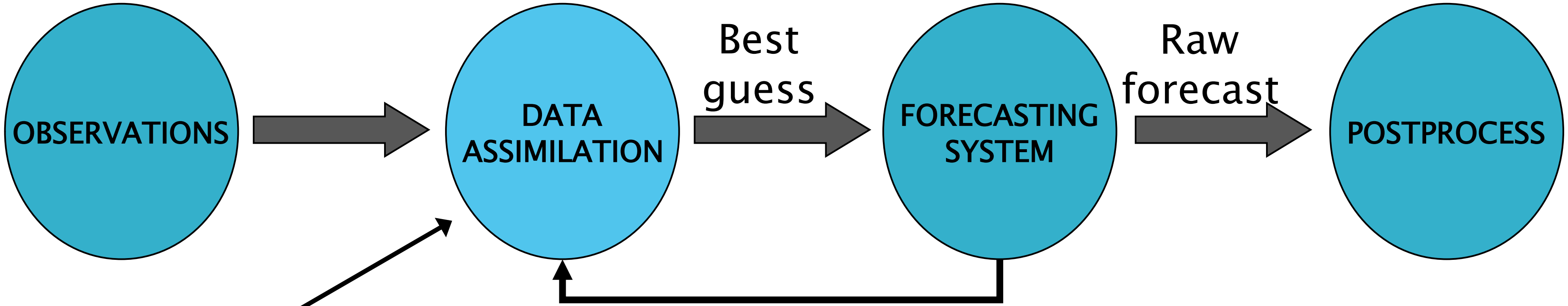
POSTPROCESS

Numerical forecast



Surface stations
Stream gauges
Rawindsondes
Profilers
Airplanes
Radar obs.
Satellite obs.
…
(How?)

Numerical forecast



OBSERVATIONS

DATA ASSIMILATION

Best guess

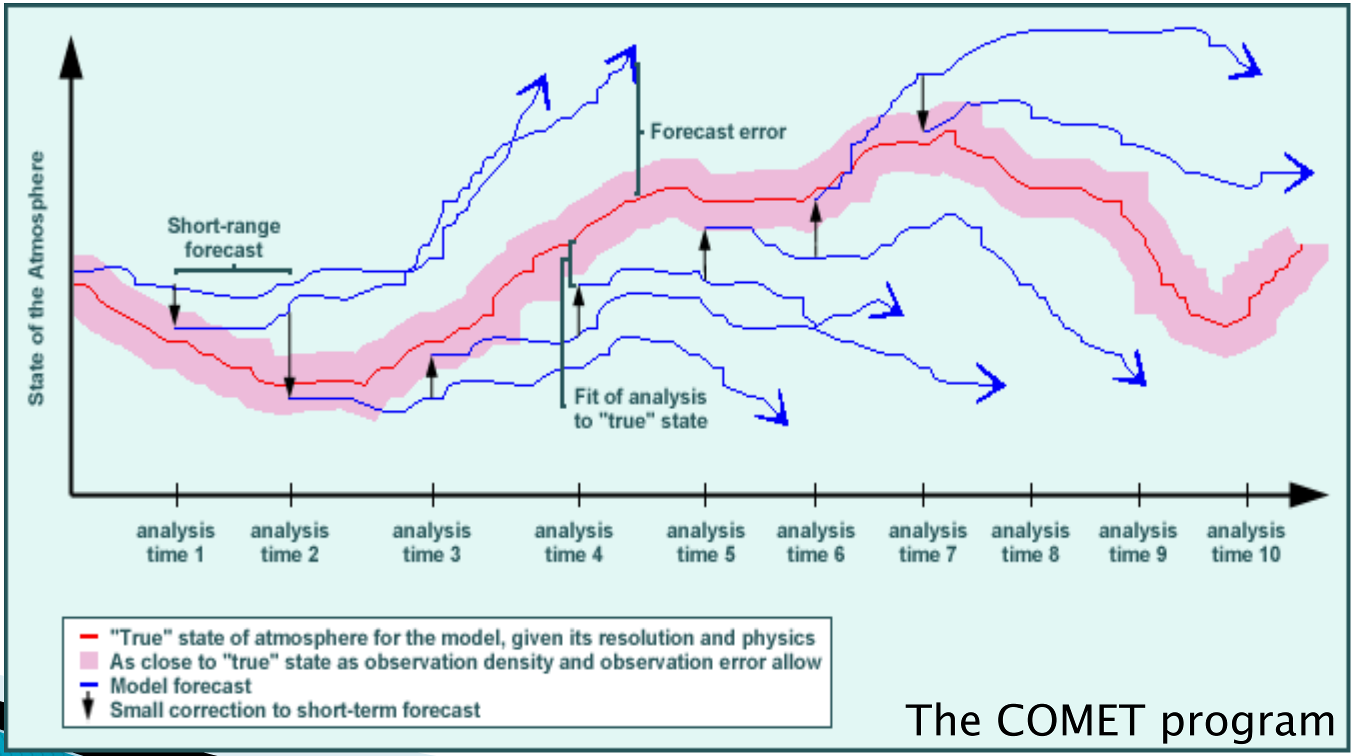
FORECASTING SYSTEM

Raw forecast

POSTPROCESS

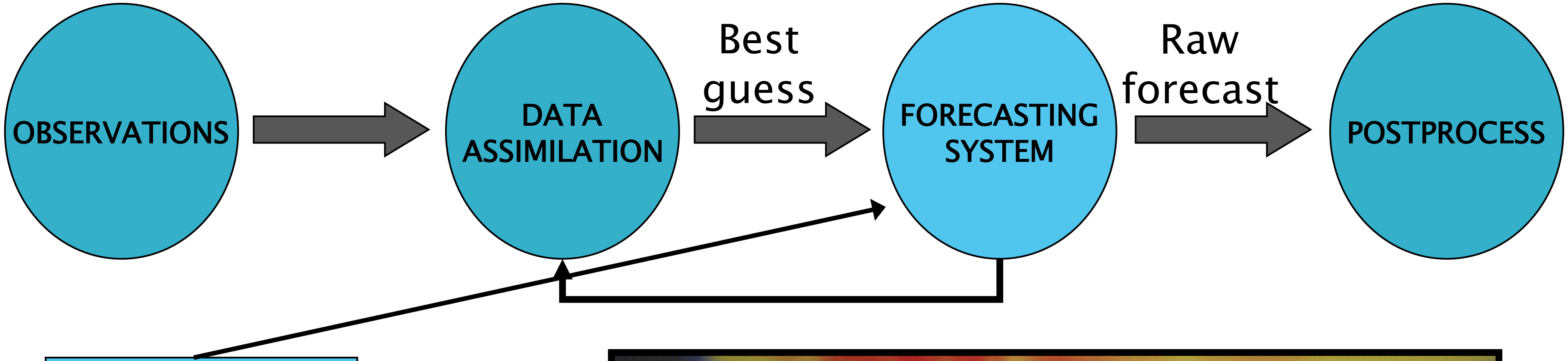
OI
Kalman Filters
3D-VAR
4D-VAR
Bayesian Stats.
Ensemble KF
…

ALSO
Lagged Avg.
Singular Vect
Bred Vect
Adj. methods
…



The COMET program

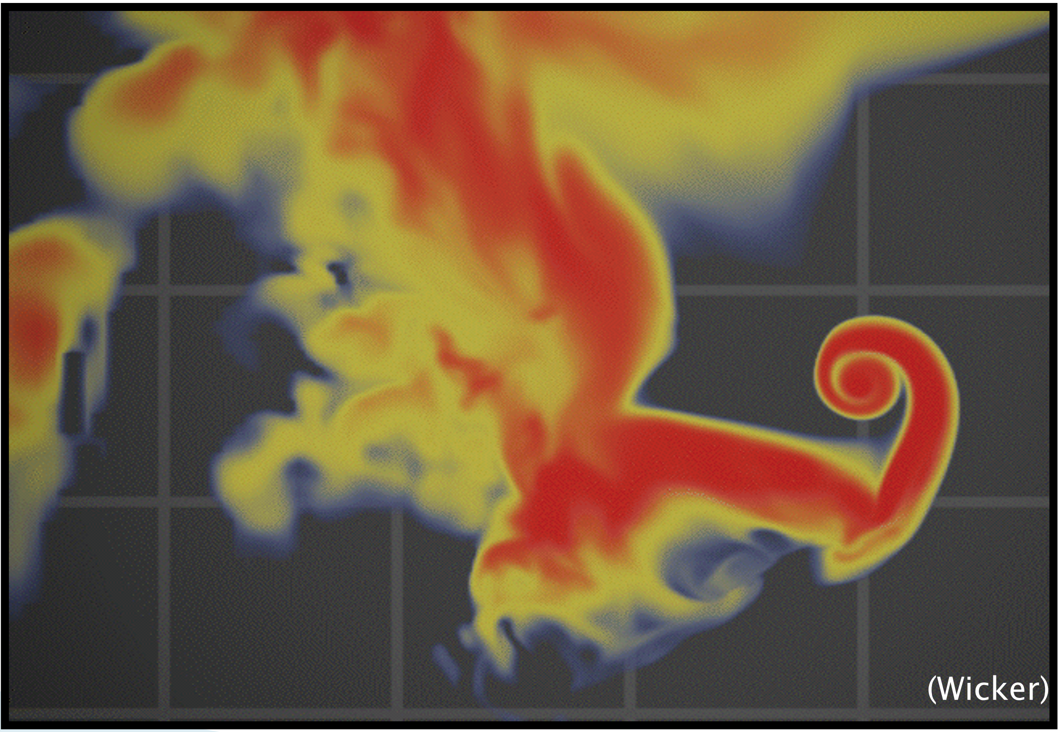
Numerical forecast



OBSERVATIONS
DATA ASSIMILATION
Best guess
FORECASTING SYSTEM
Raw forecast
POSTPROCESS

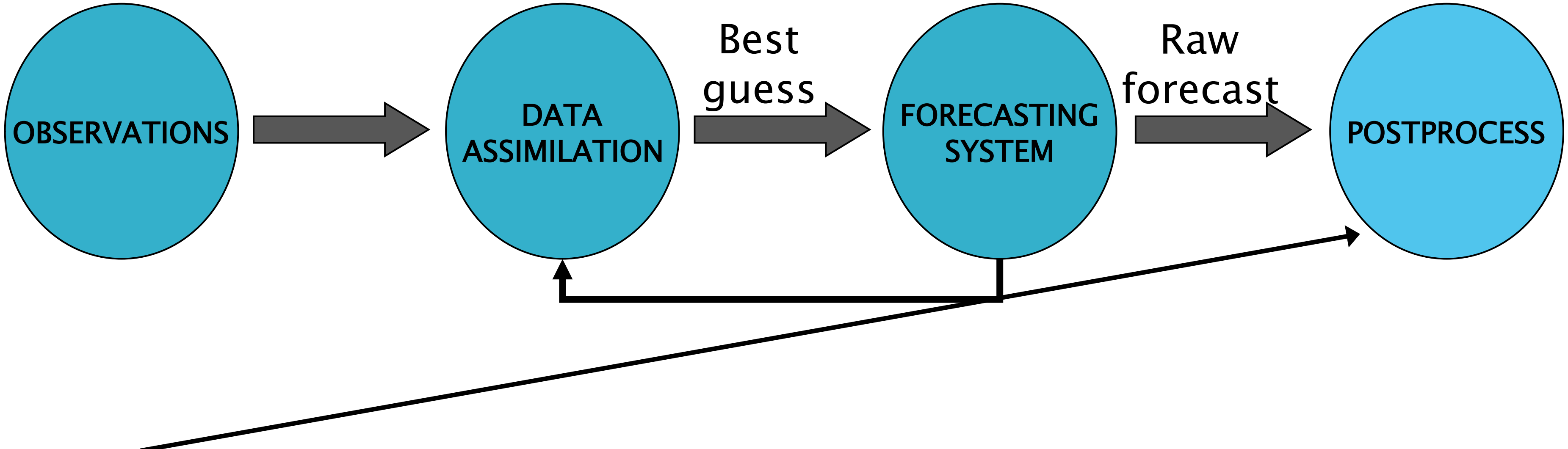
SINGLE MODEL
IFS, GFS, ETA, UK,
MM5, WRF,
HIRLAM, … (long)

ENSEMBLE
Multi-physics
Multi-model
Stochastic Physics



(Wicker)

Numerical forecast



OBSERVATIONS

DATA ASSIMILATION

Best guess

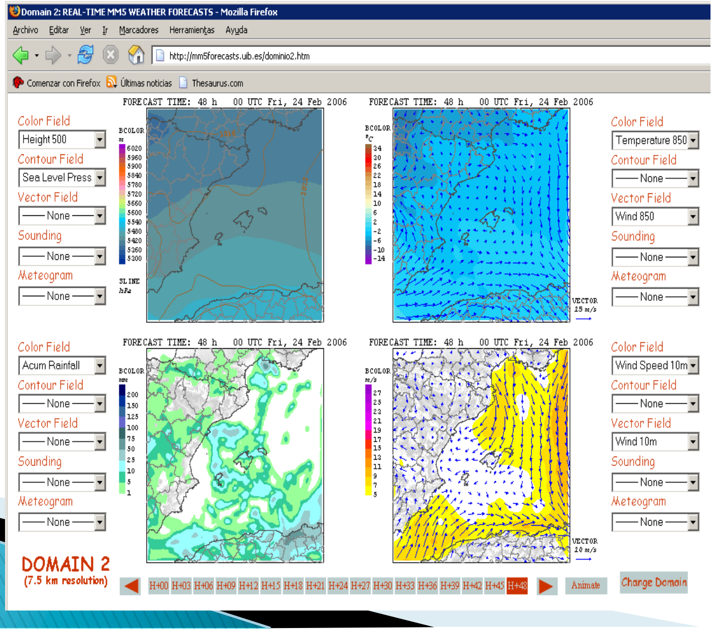
FORECASTING SYSTEM

Raw forecast

POSTPROCESS

CORRECTION
MOS, Multilinear regression, BIAS removal, calibration, human filter

END-USER DEMANDS
Adapted forecasts, Probabilistic products



Domain 2: REAL-TIME MM5 WEATHER FORECASTS - Mozilla Firefox

http://mm5forecasts.uib.es/dominio2.htm

FORECAST TIME: 48 h 00 UTC Fri, 24 Feb 2006

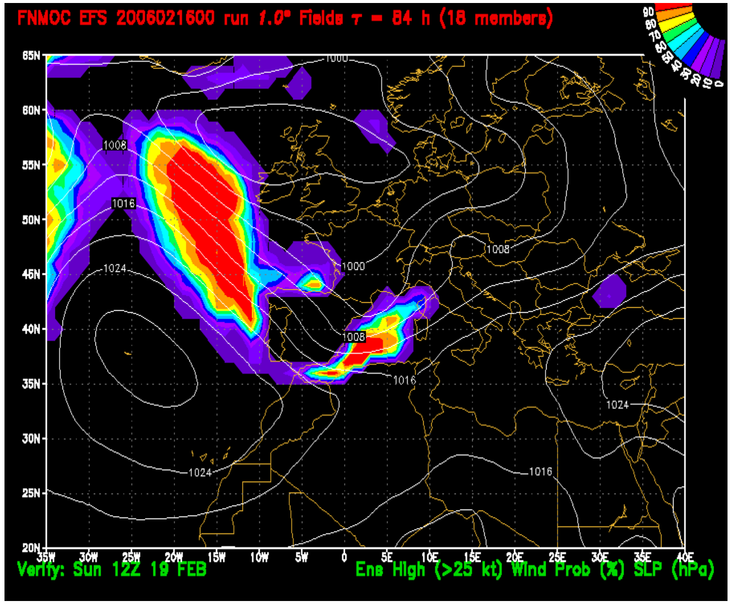
Color Field: Height 500
Contour Field: Sea Level Press
Vector Field: None
Sounding: None
Meteogram: None

Color Field: Temperature 850
Contour Field: None
Vector Field: Wind 850
Sounding: None
Meteogram: None

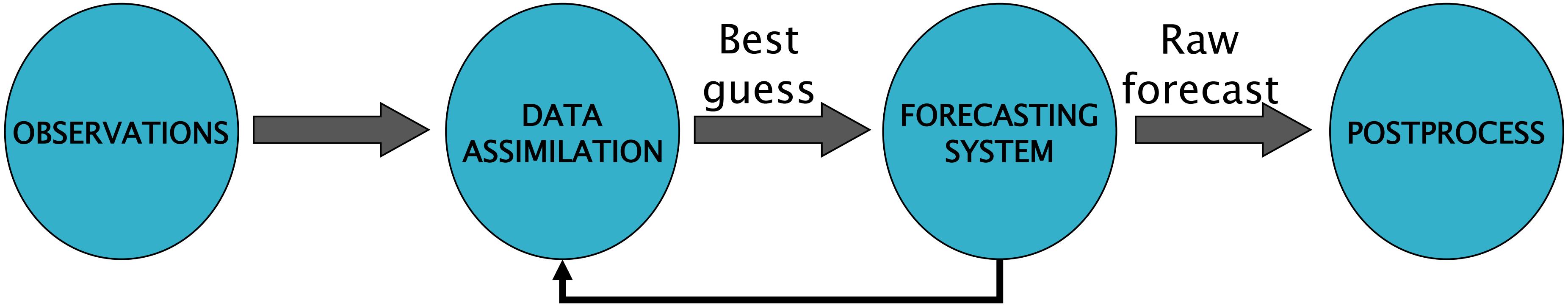
Color Field: Acum Rainfall
Contour Field: None
Vector Field: None
Sounding: None
Meteogram: None

Color Field: Wind Speed 10m
Contour Field: None
Vector Field: Wind 10m
Sounding: None
Meteogram: None

DOMAIN 2
(7.5 km resolution)



Numerical forecast. Errors



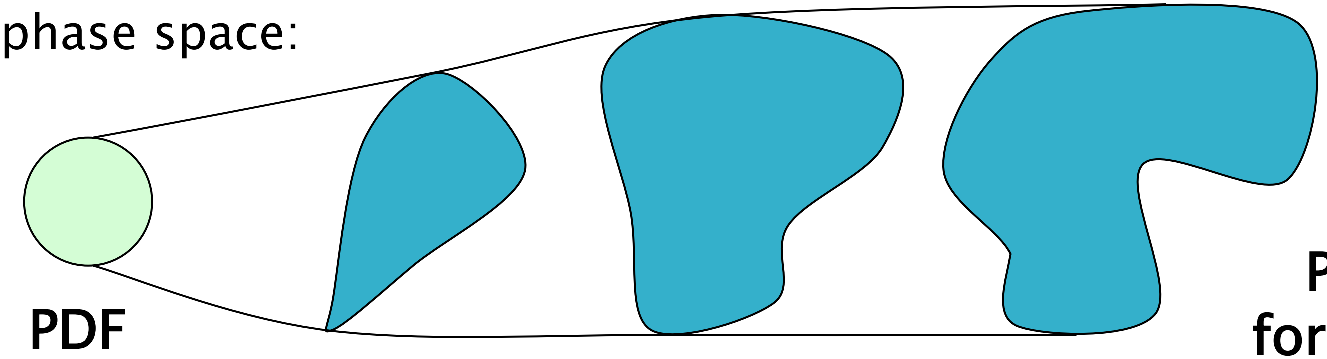
- Errors are present in each of the steps in the forecasting system, coping with (both reducing and accounting for) these errors is currently focus of active research
- “Forecasts cannot be used to their best advantage unless forecast uncertainty is quantified and expressed to users” (Winkler and Murphy,1979)
- Smith (2002): “to sell any forecast as unequivocal is to invite lawsuits”

Coping with errors

- The state of the atmosphere is described by a probability density function that we ought to evolve in time to get a forecast pdf:

$$\dot{\rho} = f(\rho)$$

In phase space:



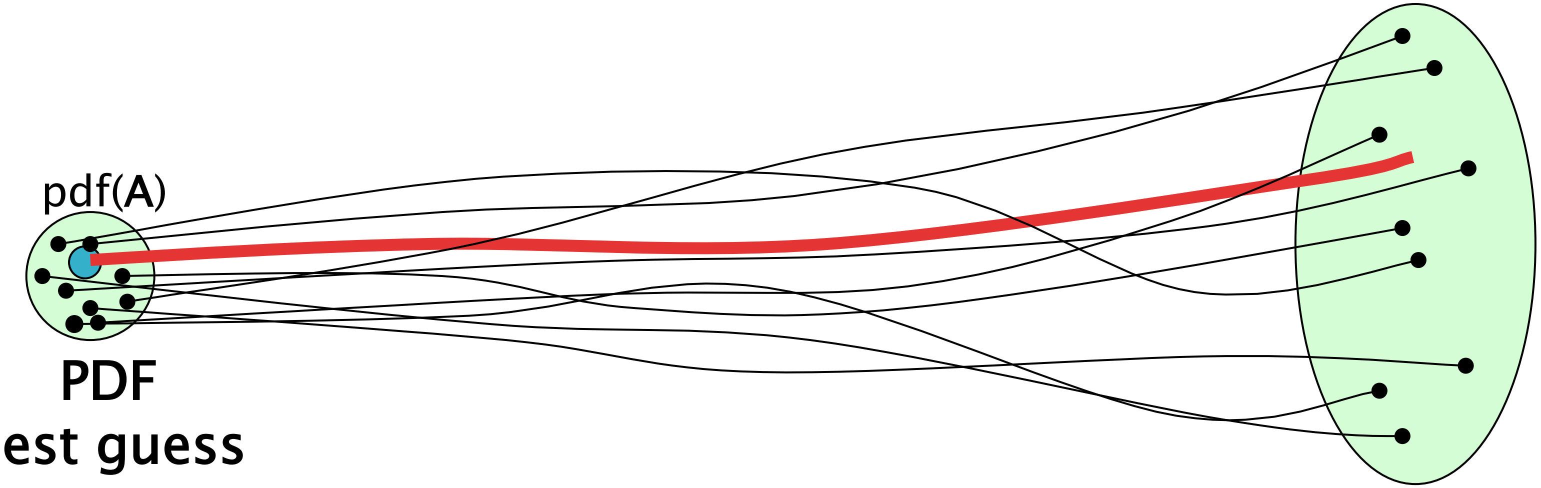
PDF
best guess

PDF
forecast

HOW??

Ensemble methods

- The Fokker-Plank equation cannot be solved yet and the current approximation is to explore the pdf of plausible atmospheric states taking an ensemble of samples and evolving each one independently

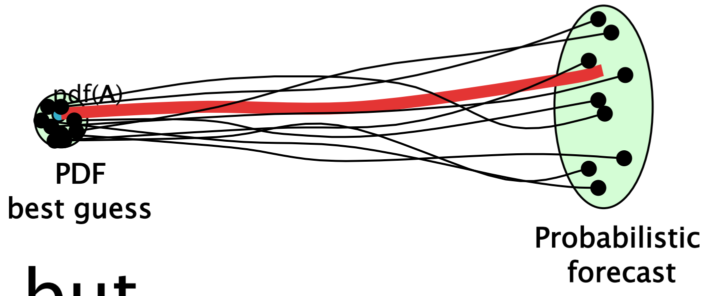


pdf(**A**)

PDF
best guess

Probabilistic
forecast

Coping with errors



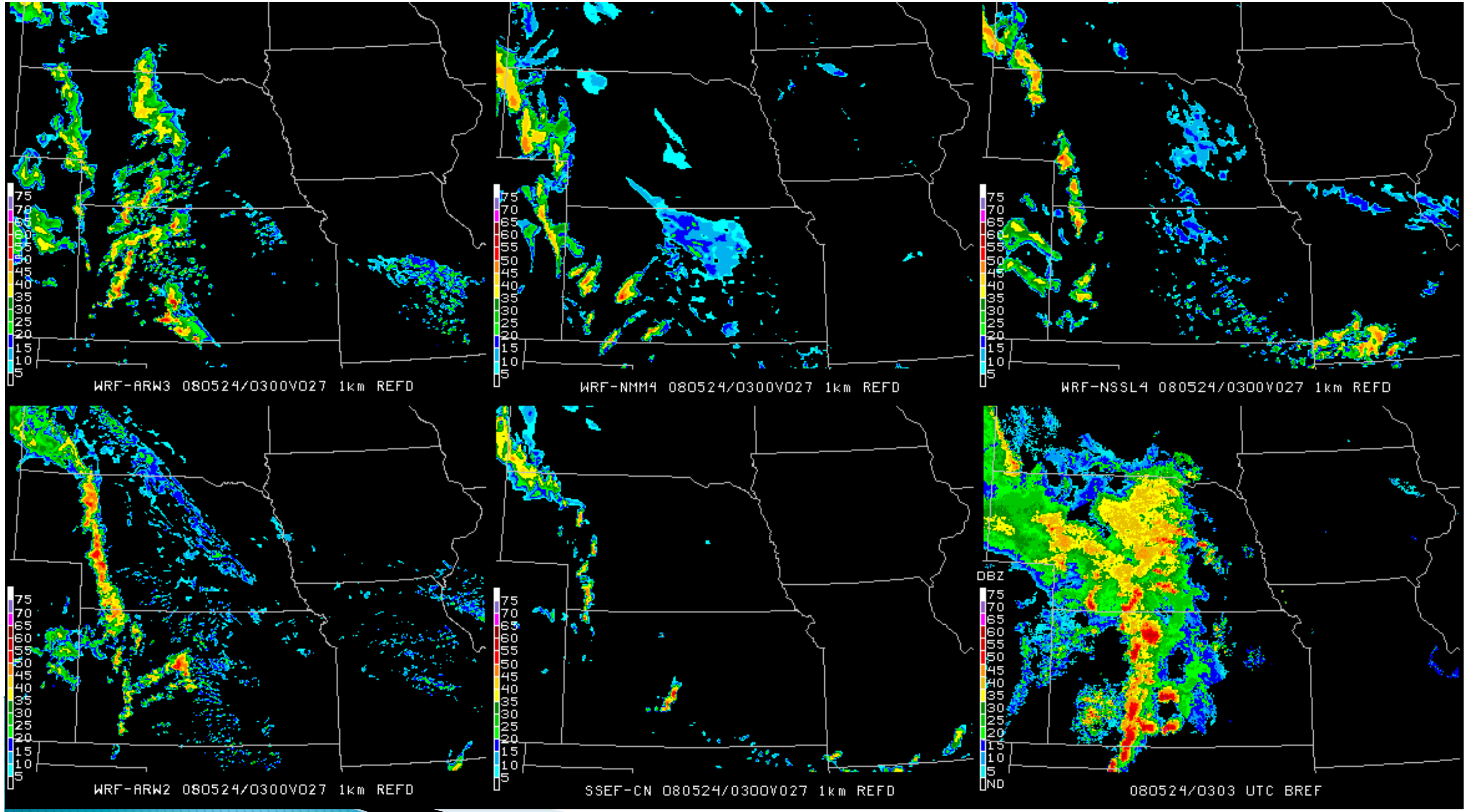
- The idea is clear (even clever) but…
- Hands on:
  - VERY expensive HR forecasts (limited members)
  - So, optimization of resources (bussiness) is crucial

How to sample the subspace of forecast uncertainties?

If we want to use ensembles of deterministic runs:

- Perturbing the observations
- Perturbing the IC
- Perturbing the model

Example: experimental ensemble



Jack Kain. SPC/NSSL Spring Program 2008

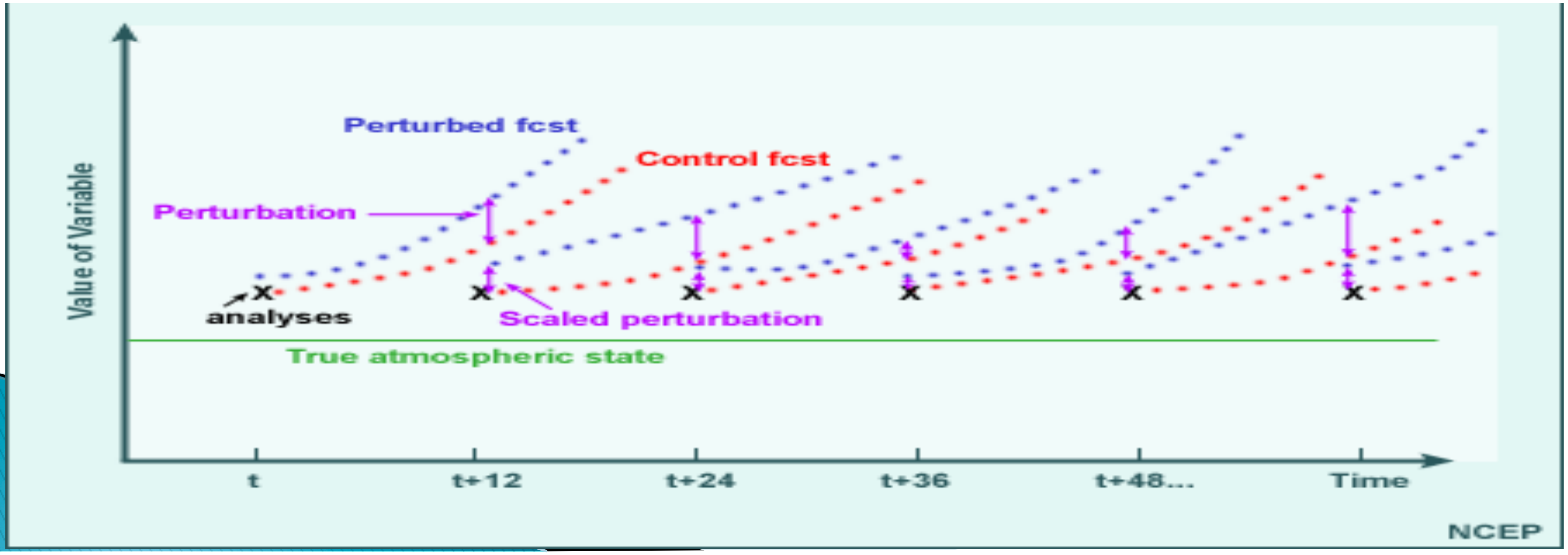
What's available? Ensemble methods

- Synoptic/large mesoscale:
  - Montecarlo (mid- 1900's).
  - EnKF: Multiple assimilation cycles with perturbed observations, modulated by previous ensemble performance statistics.
  - Most unstable nonlinear modes:
    - Singular Vectors: Tangent linear approximation (ECMWF)
    - Bred vectors: Future MU modes are estimated from past nonlinear MU modes (NCEP)

What’s available? Ensemble methods

Mesoscale (~ 5km res):

- Larger IC uncertainties: d.f. ↑ # obs ↓
- Shorter linear regime (~h)
- Presence of BC (mitigating diversity)
- Most unstable nonlinear modes:
  - ~~Singular Vectors~~
  - Bred vectors (SREF): best nonlinear estimate of growing modes.



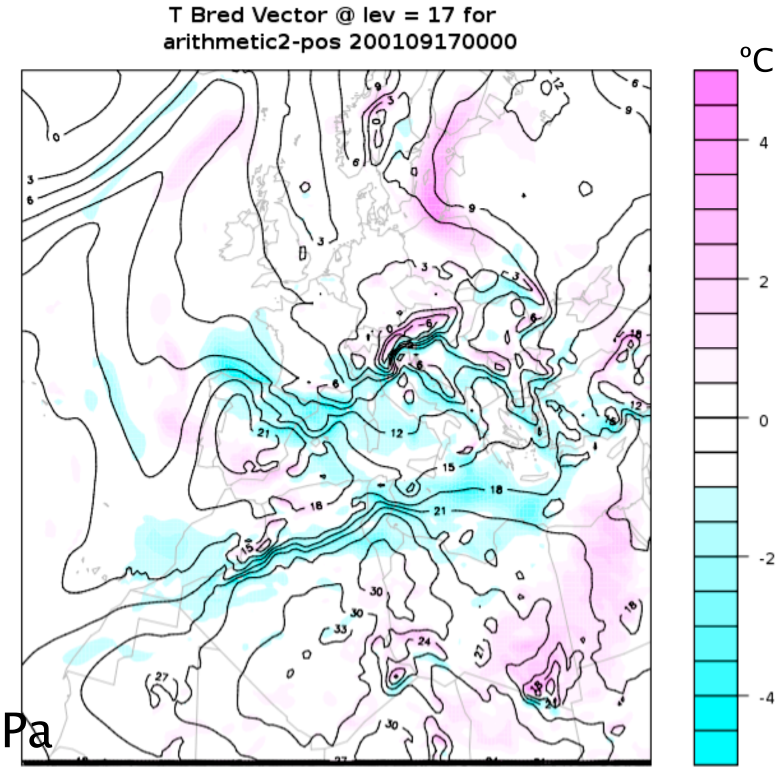
The breeding method

Bred vectors:

$$\overrightarrow{bv} = \frac{\overrightarrow{x_p} - \overrightarrow{x_c}}{\alpha} = \frac{\overrightarrow{\delta x}}{\alpha} \quad \text{with} \quad \alpha \; ; \quad f(\overrightarrow{bv}) = \text{cnt.}$$

Example of a typical rescaling function (SREF):

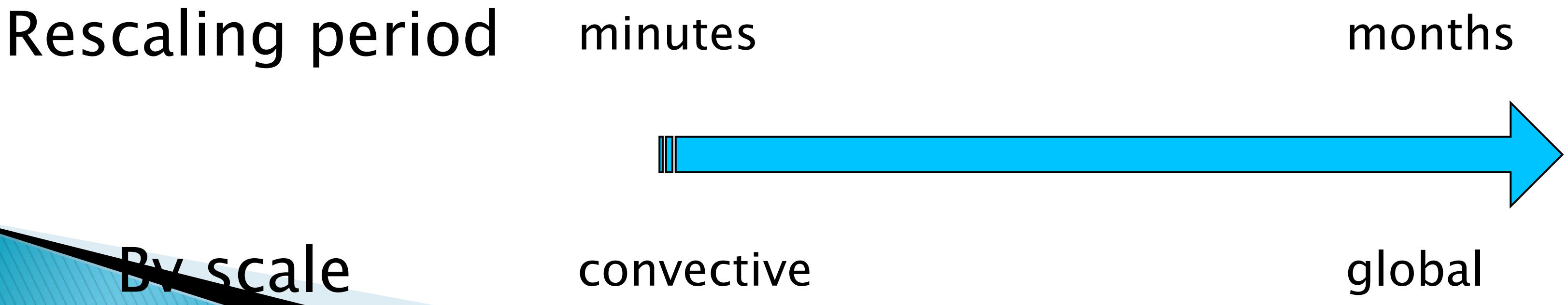
$$f(\overrightarrow{bv}) = \sqrt{\frac{1}{N}\sum (T_p - T_c)^2} \quad \text{(fixed RMS)}$$


T Bred Vector @ lev = 17 for arithmetic2-pos 200109170000

RMS = 0.75 for T at ~850hPa

The breeding method

- Bred vectors characteristics:
  - The spread of an ensemble depends on the growth rate of its members
  - The growth rate of IC perturbations depends on their scale and amplitude (besides location)
  - The scale of bv can only be controlled through the rescaling period (fixed by analysis times)



Rescaling period minutes months

Bv scale convective global

The breeding method

- From theory of finite fluctuations on dynamical systems:

"The scale of bvs can also be controlled by using a different rescaling function:

$$f(\overrightarrow{\mathbf{bv}}) = \prod (T_p - T_c)^{1/N} \quad \text{(fixed geometric mean)}$$

which is shown to apply for 1D toy models."

The analysis characterize perturbations with:

ln(ρ): Amplitude (Controlled)

$$\ln(\rho) = \overline{\ln(\overrightarrow{\delta x})} = \ln \prod \delta x^{1/N}$$

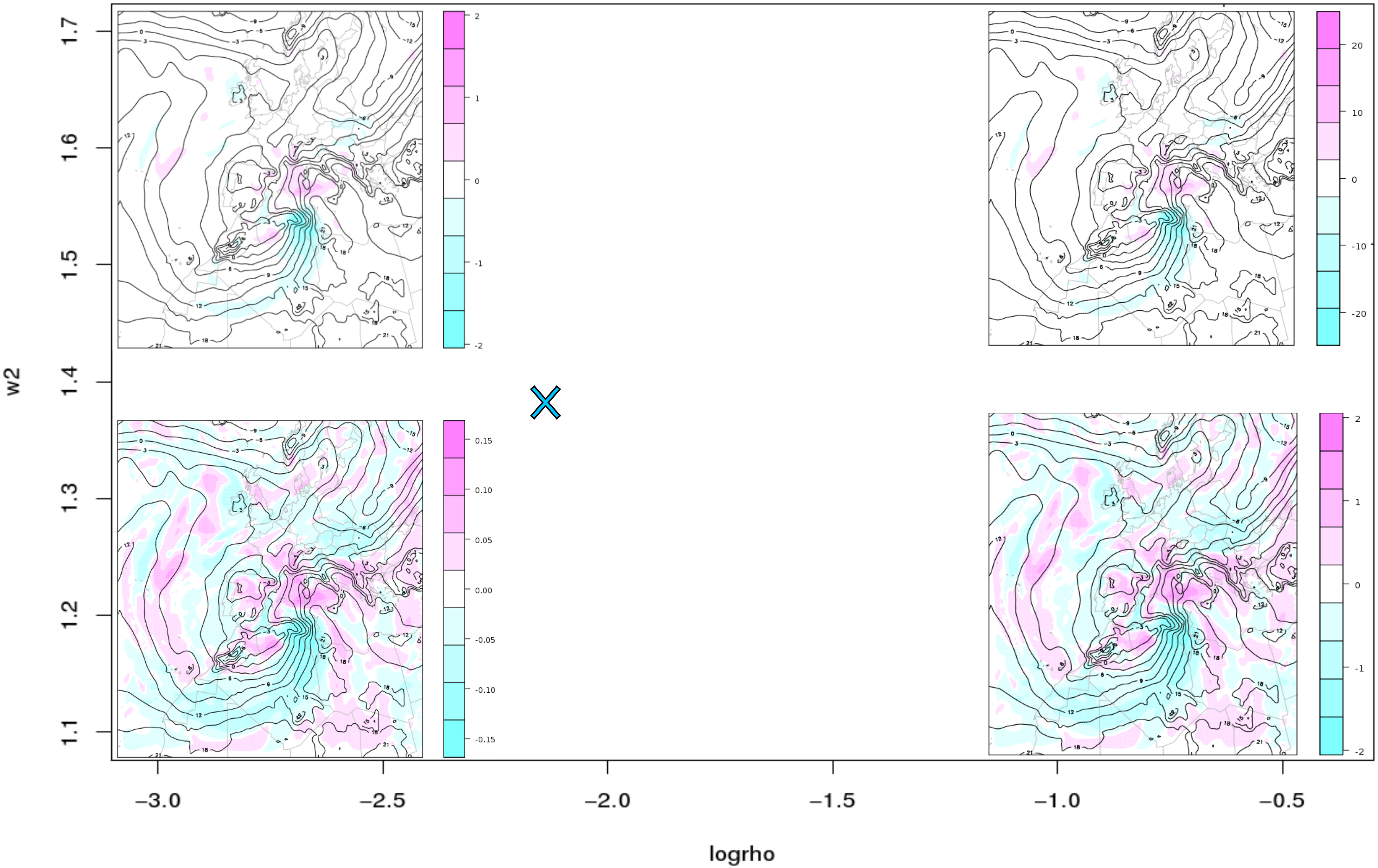
ω^2: Scale

$$\omega^2 = \overline{\left(\ln(\overrightarrow{\delta x}) - \ln(\rho)\right)^2}$$

(Provided)

The breeding method

ω2 vs ln(ρ) diagram:

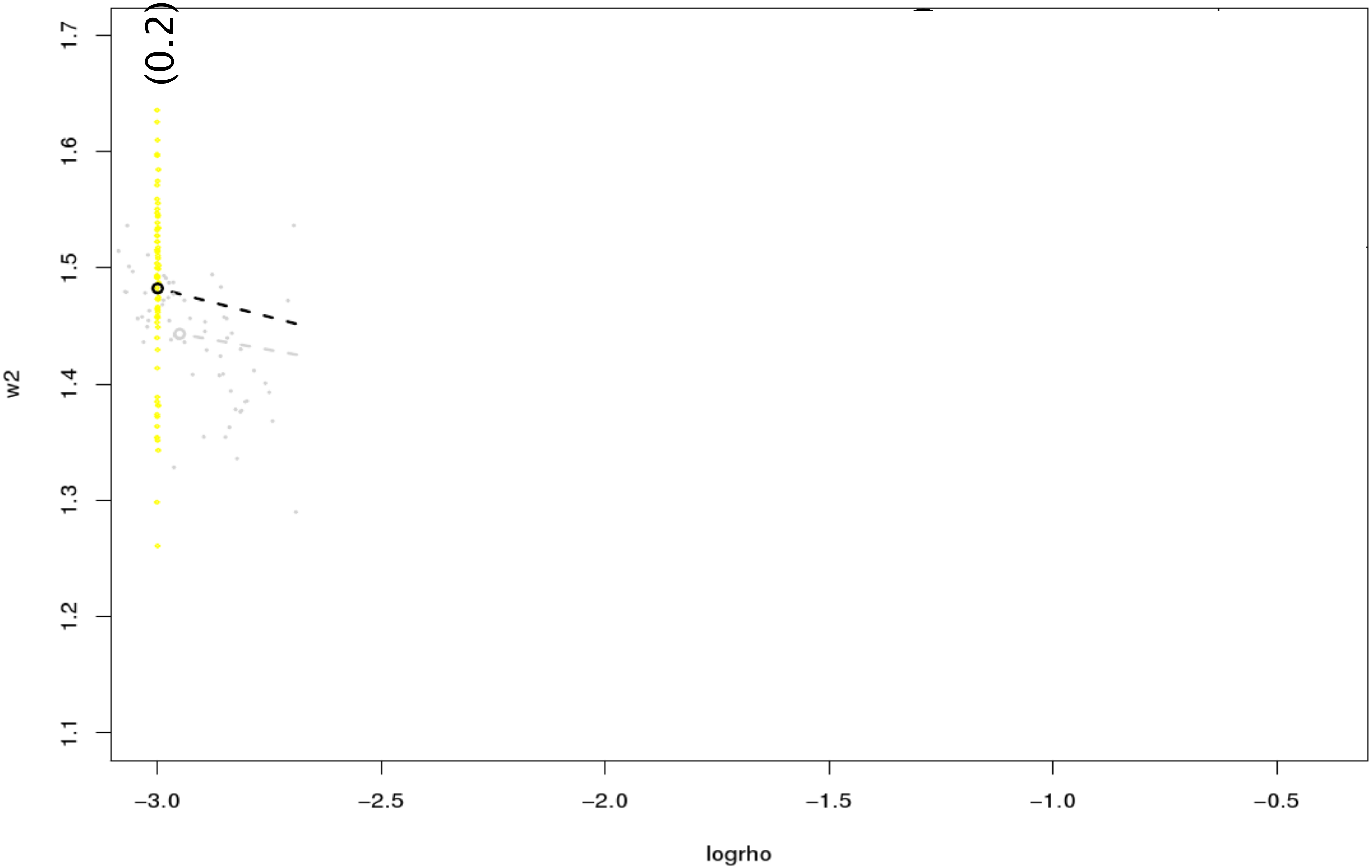


The breeding method

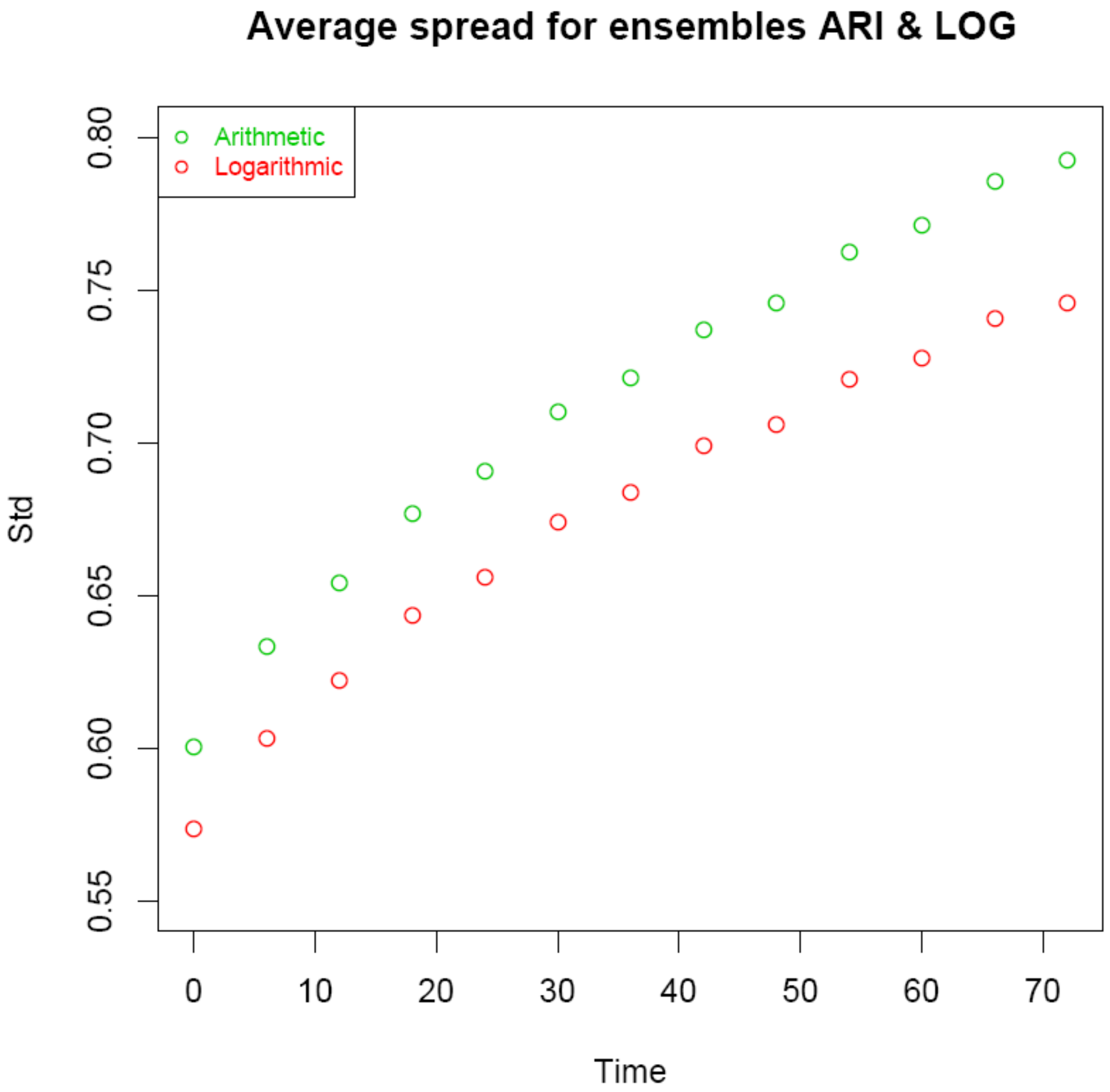
Is the logarithmic rescaling any different from the RMS based for realistic weather models (MM5 or WRF)?

The breeding method

Is logarithmic rescaling different than RMS based?



The breeding method



New (proposed) generation method

Is ω^2 (scale) really uncontrollable (given by the model dynamics only)?

New generation method

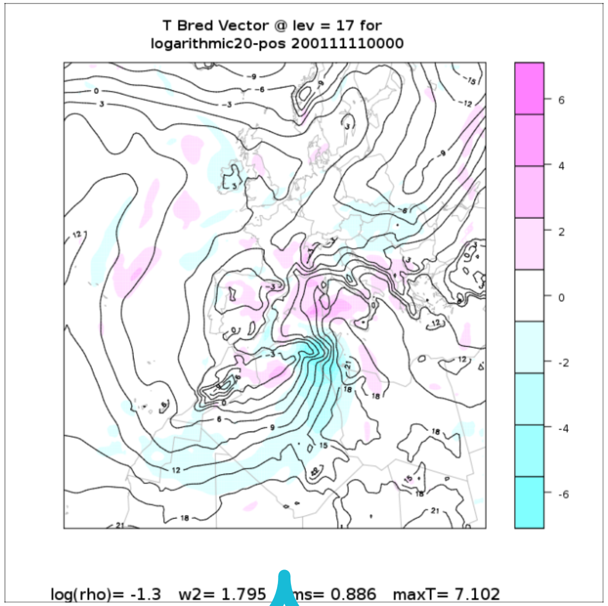
The scale of the perturbation can be modified with:

$$\overrightarrow{sbv^*} = \frac{\overrightarrow{(\delta x^{1/\beta})}}{\alpha} \quad \text{with} \quad \beta = \frac{\omega}{\omega^*}$$

In fact:

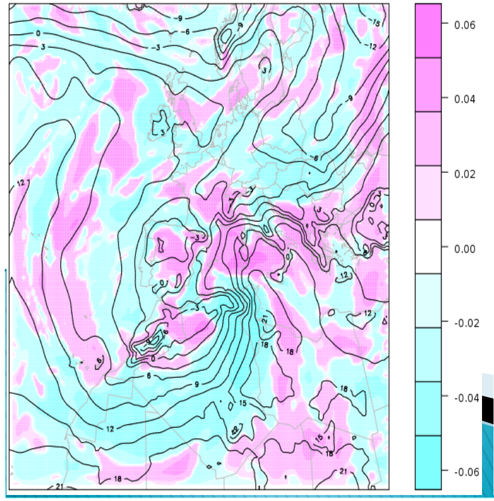
Any single perturbation δx (not only bvs) can be used to generate a new set of perturbations with prescribed amplitude AND SCALE.

New generation method

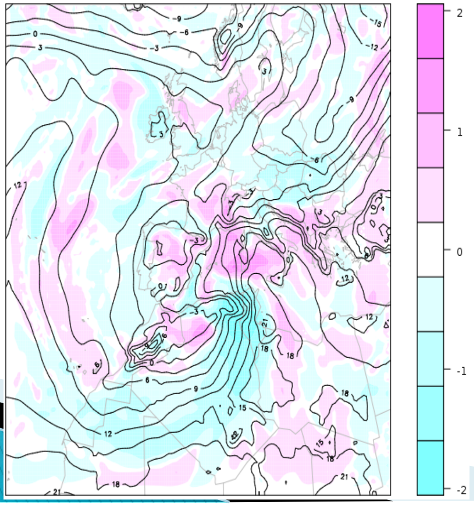


$\ln(\rho) = -1.3$
$\omega^2 = 1.8$

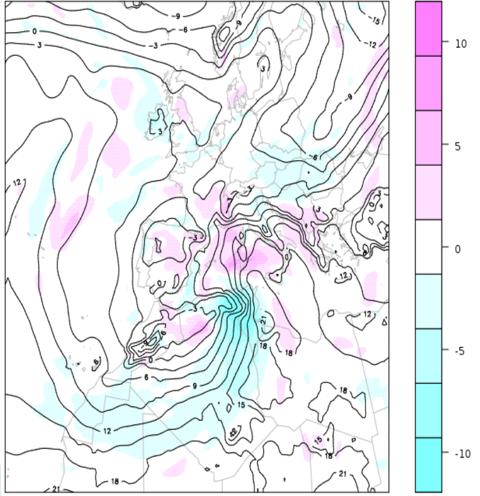
$\ln(\rho) = -3.5$
$\omega^2 = 0.1$



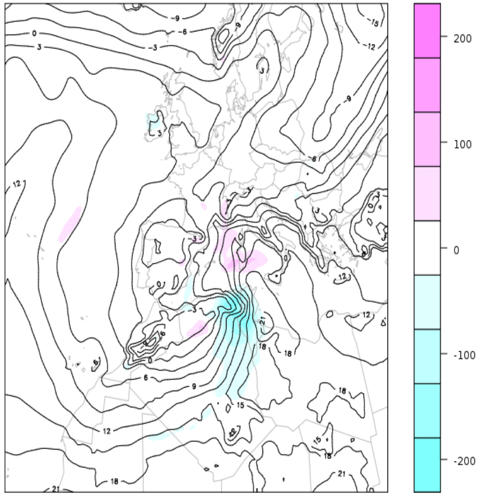
$\ln(\rho) = -1$
$\omega^2 = 0.5$



$\ln(\rho) = -.5$
$\omega^2 = 1.5$

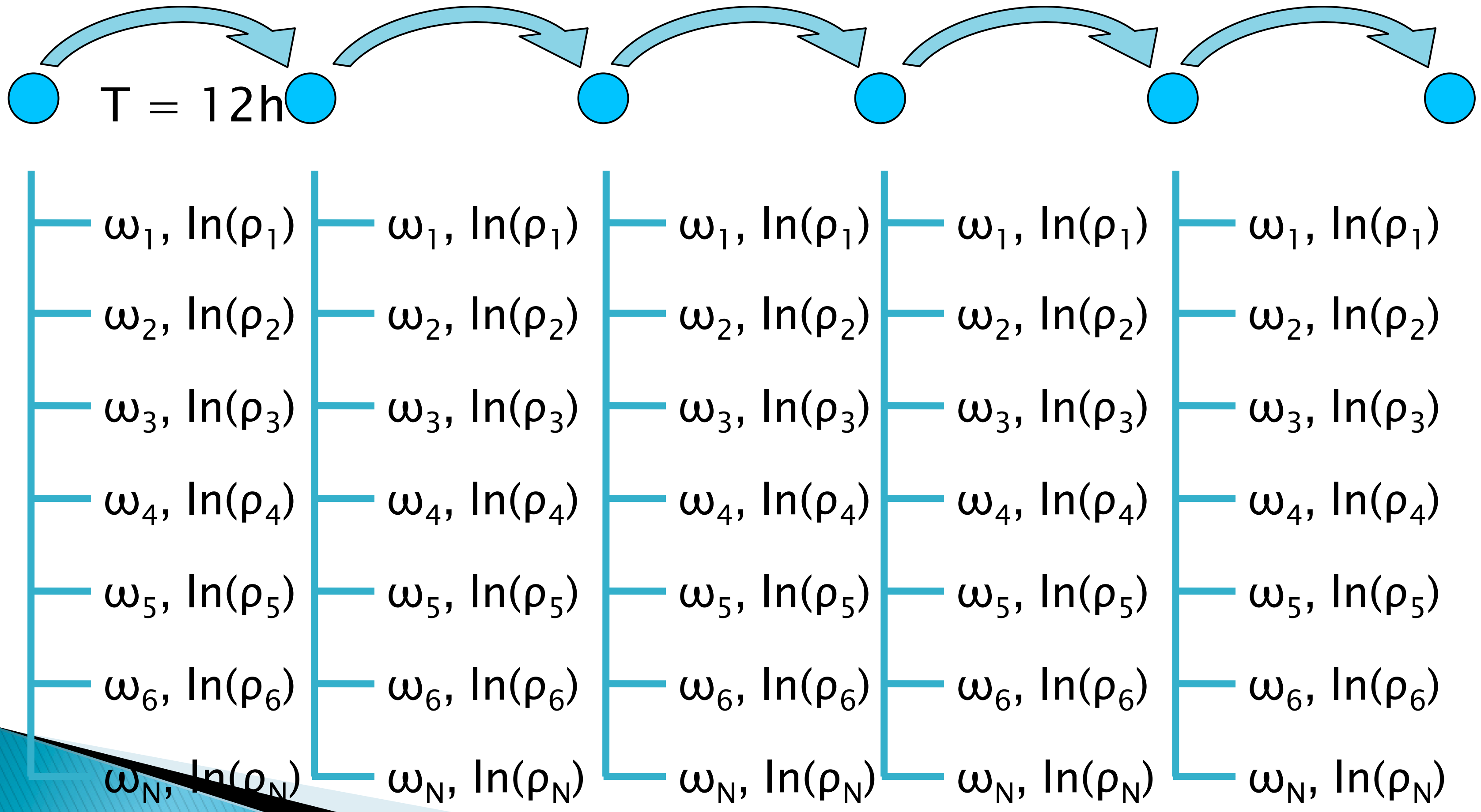


$\ln(\rho) = 0$
$\omega^2 = 5$



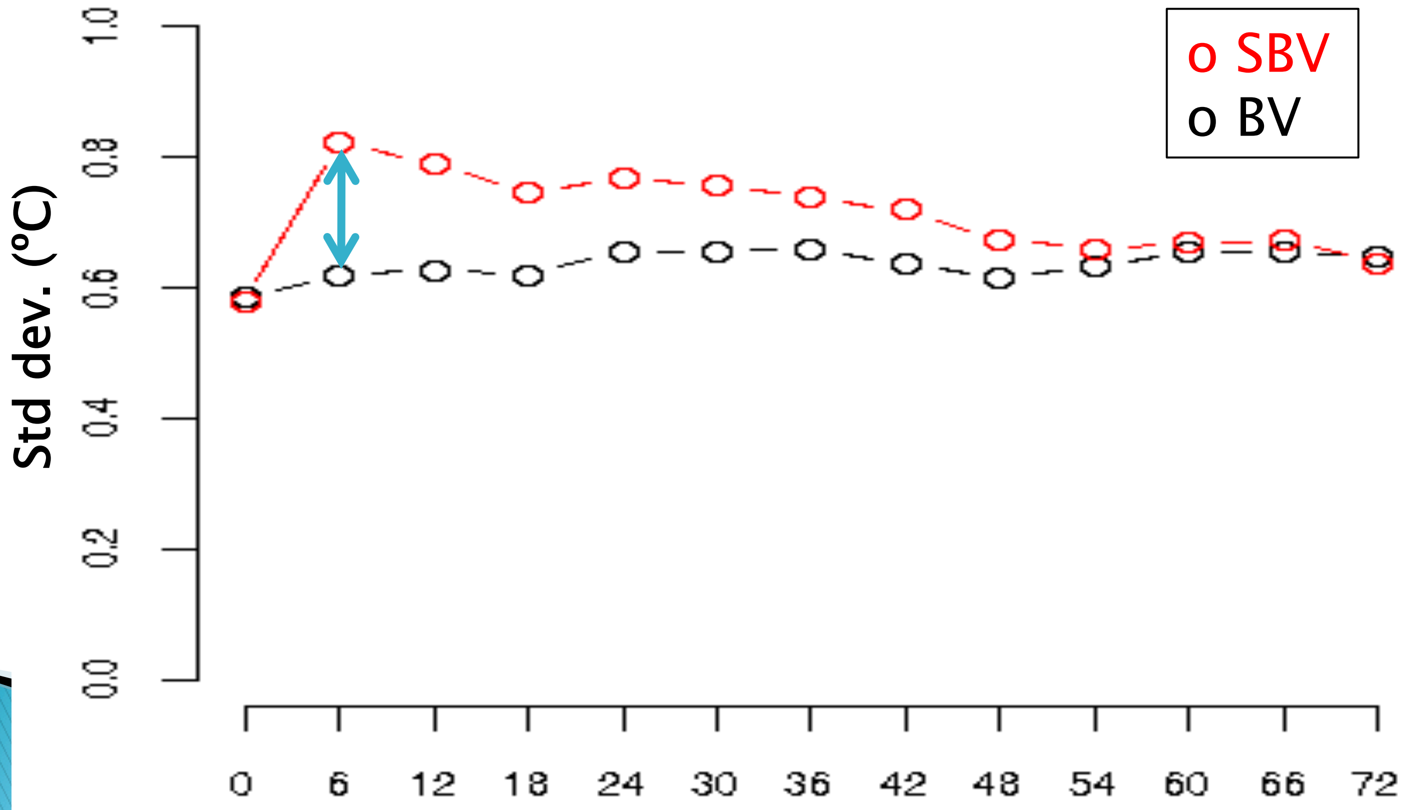
New generation method

- A full ensemble can be generated from (even) a single bred cycle:



New generation method

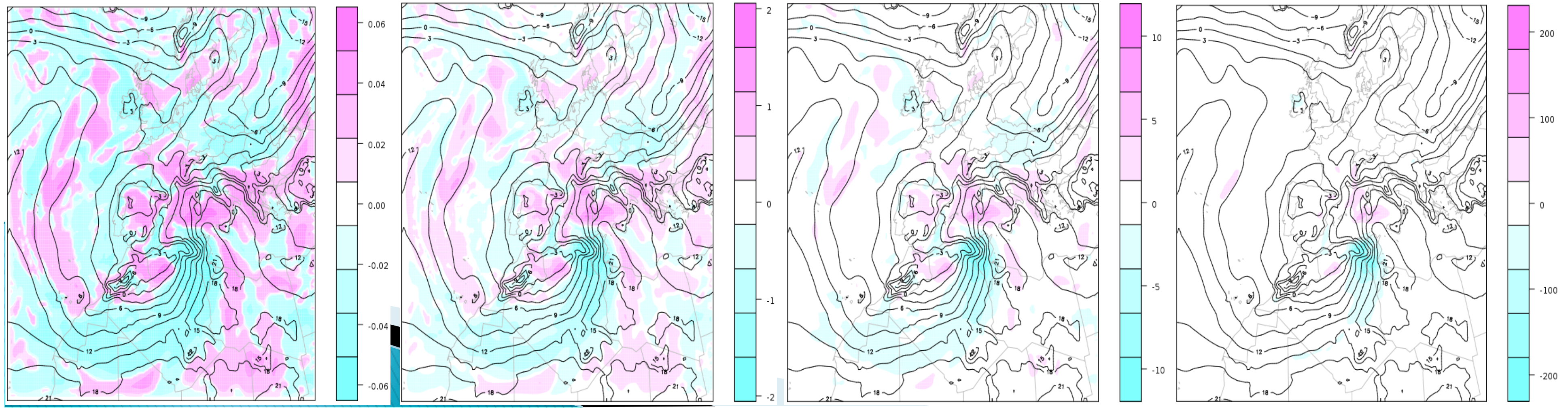
- Comparing this “scaled bv” with standard bv:
  - Test over 30 cycles (15 days) with convective activity over the Western Mediterranean
  - Low mesoscale and convective scale perturbations are generated here



‘À la carte’ perturbations

- One step further consists in adding diversity to the ensemble by mixing bred cycles to build the set of IC

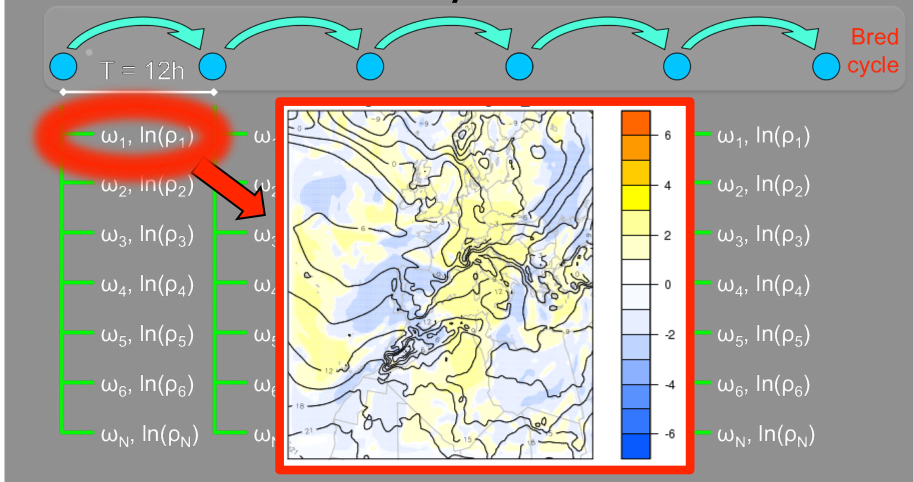
$$ICP_i = \sum_j \gamma_j \overrightarrow{sbv_j} = \sum_j \gamma_j \frac{\overrightarrow{\delta x_j^{1/\beta_j}}}{\alpha_j} \text{ ; where j determines BC and sbv}$$



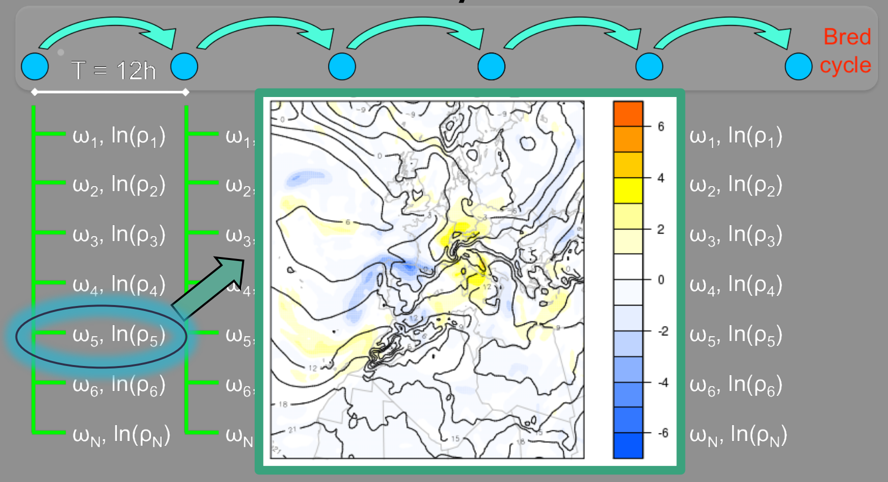
‘À la carte’ perturbations

- Using various bred cycles, a number of different IC perturbations can be computed:

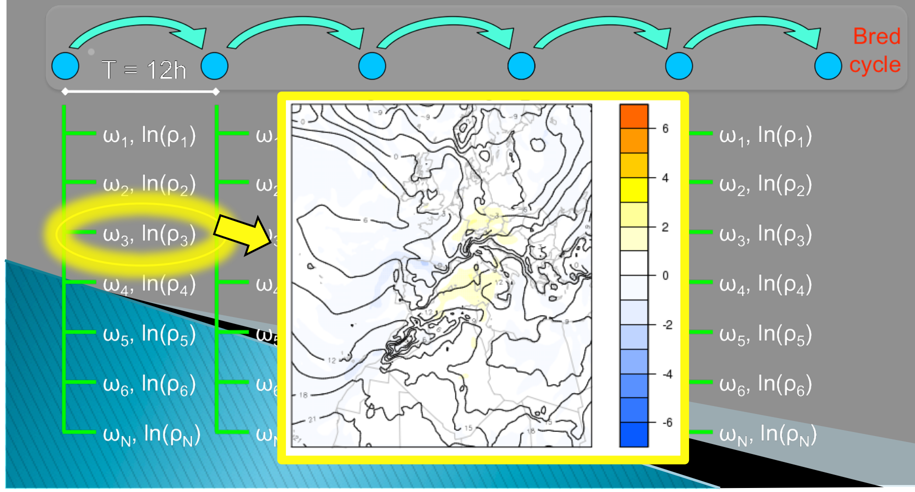
Bred Cycle A



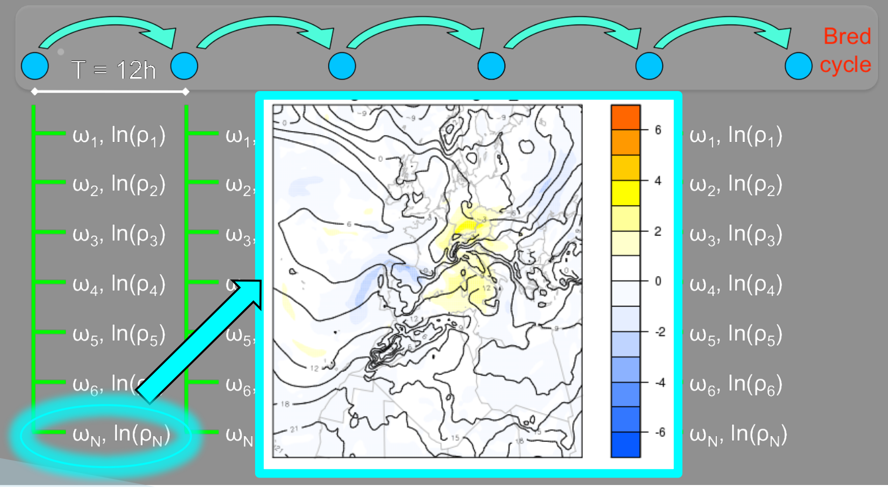
Bred Cycle B



Bred Cycle C

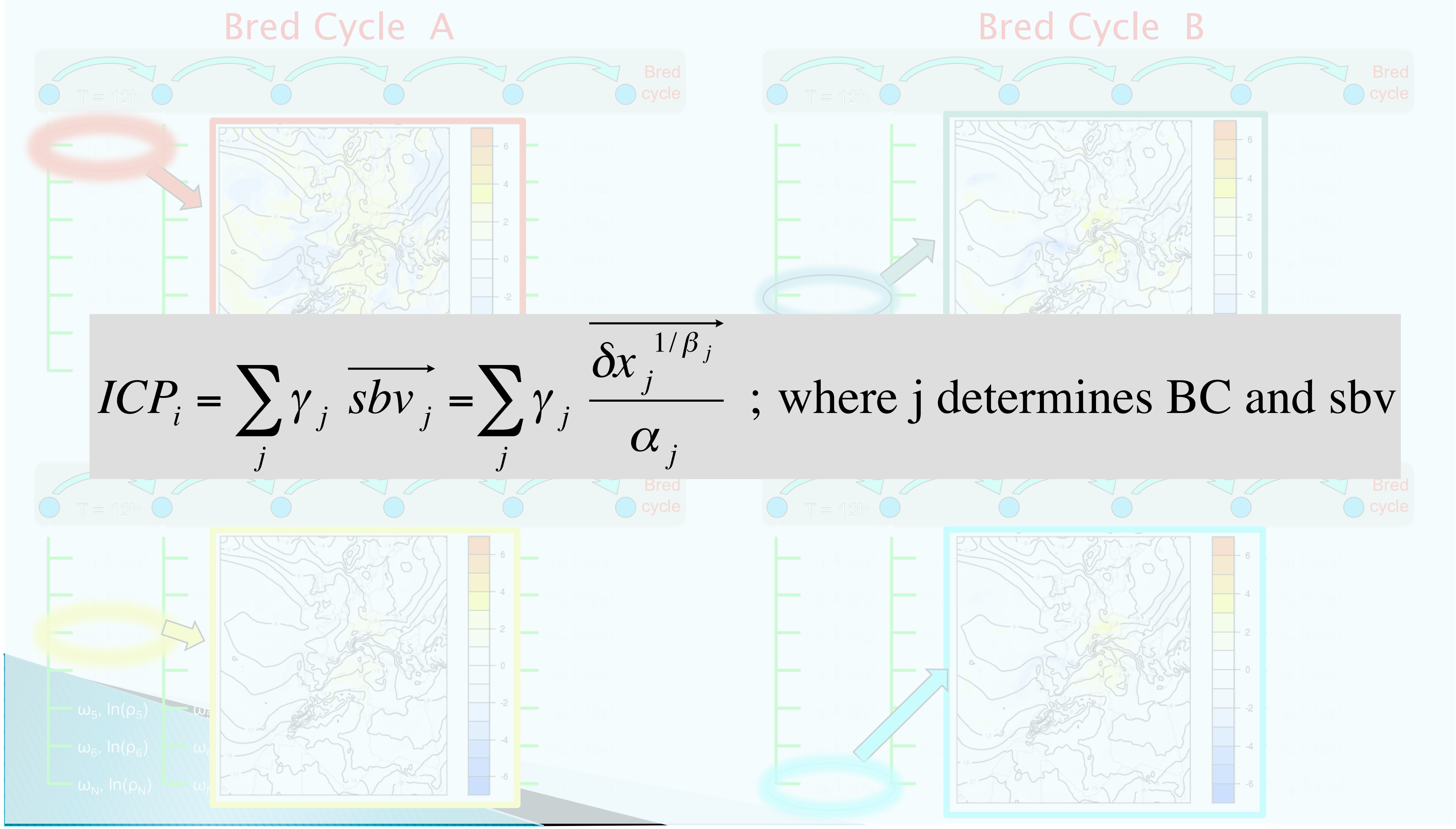


Bred Cycle D



‘À la carte’ perturbations

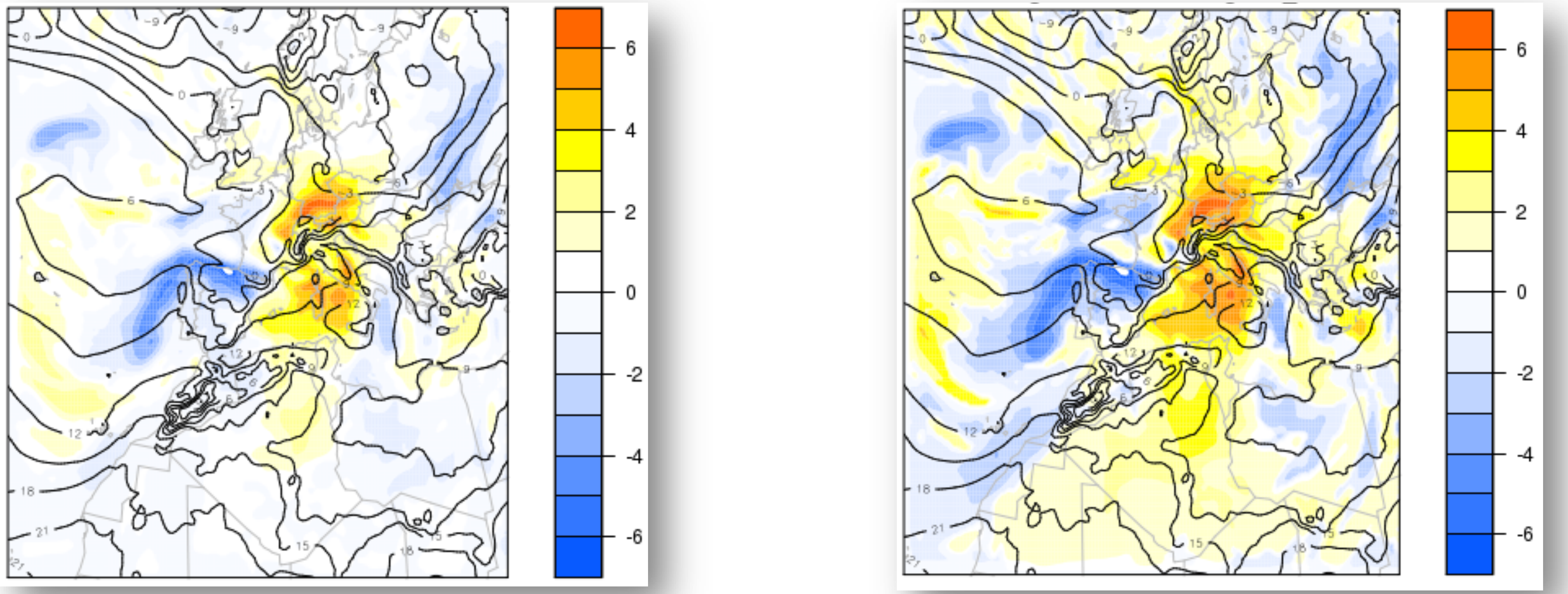
Using various bred cycles, a number of different IC perturbations can be computed:



$$ICP_i = \sum_j \gamma_j \overrightarrow{sbv}_j = \sum_j \gamma_j \frac{\overrightarrow{\delta x_j^{1/\beta_j}}}{\alpha_j}$$; where j determines BC and sbv

‘À la carte’ perturbations

- Currently defining global rescaling coefficients (ϒ)
- ICP examples:



SUMMARY

- What is *extreme weather* ?
  - Not strictly defined. Practical definitions used.
- Why is it *extreme*?
  - Ingredients coincide rarely
- Is it predictable? Why?
  - Not within useful lead-times. Very sensitive to poorly observed scales
- How is extreme weather forecast nowadays?
  - Ensemble methods. Not yet solutions for extreme (HR). Still working on it…

Thanks!

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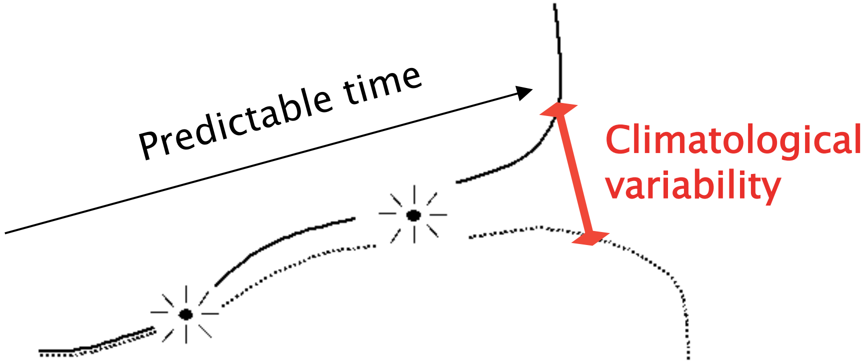
Definition of predictability

- *Predictability: the quality of being predictable*
  "The predictability of *<something>* …"

This quality refers to a certain forecast entity, and by defining one, we are implicitly setting a space-temporal scale, which sets its predictability limit.

Definition of predictability

- Predictability time: time at which two solutions obtained from slightly differing initial states are as different from each other as two random states of the system (Lorenz 1963).



Predictability time depends, besides growth, on how “differing” the initial states are. The attribution of indistinguishable states might be simply assigned by technical limitations.

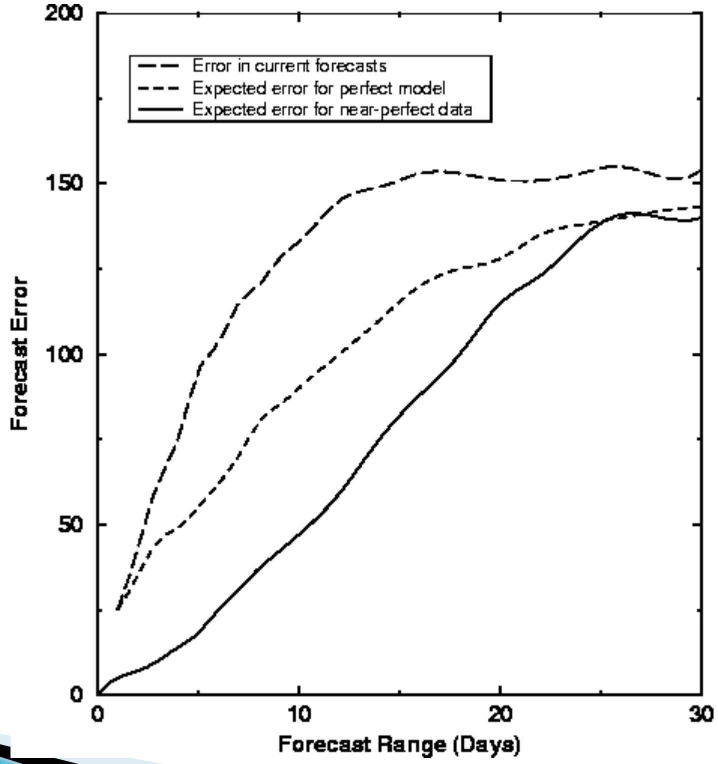
Definition of predictability

- Predictability time: time at which initial conditions error is doubled [Smagorinsky (1963), Mintz(1964), Leith (1965)]

Predictability time not really informative about predictive capability of the system

(practical) Definition of predictability

- Predictability time: time at which two solutions compatible with “best guess uncertainty” become intolerably different



Predictability time depends on how “tolerant” the end-user is

(Dyn Sys) Definition of predictability

- Predictability time: time at which the system asymptotically evolves into its (strange) attractor

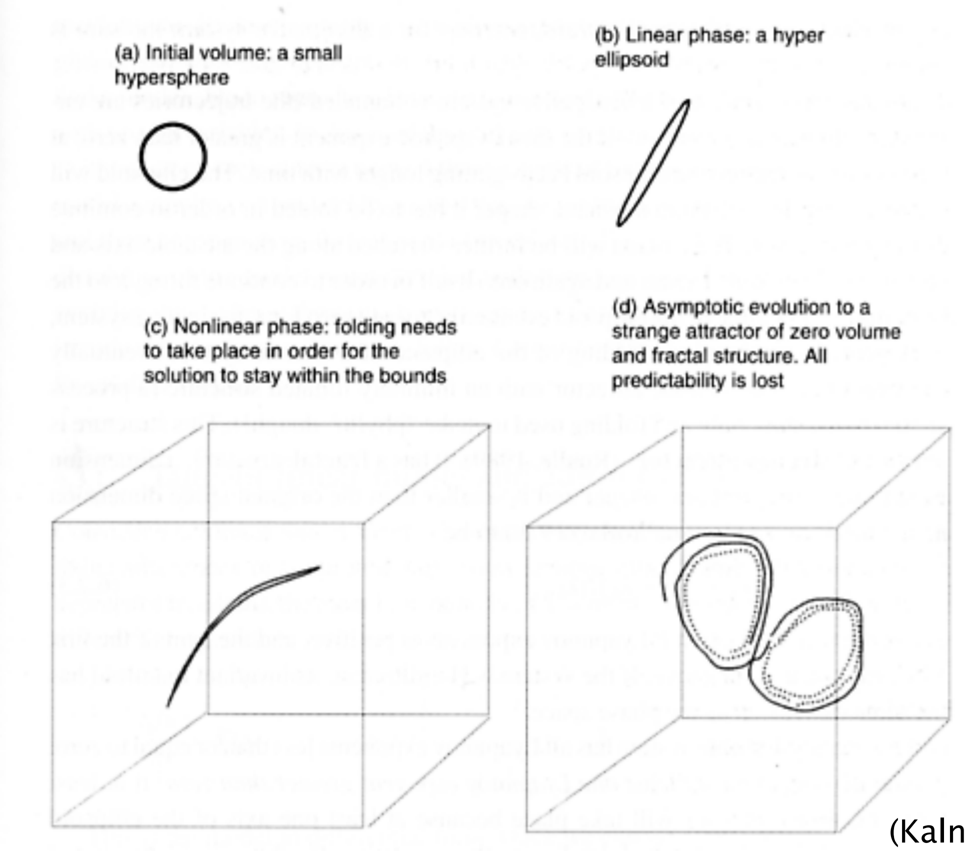
Error growth in a dynamical system:

$$\left|\delta(t)\right| = \delta_0 e^{\lambda_L t}$$

Predictability time:

$$t^* \approx \frac{1}{\lambda_L} \ln \frac{\Delta}{\delta_0}$$

(May not be appropriate for high-dimensional finite systems)



(Kalnay 2003)

(Dyn Sys) Definition of predictability

- Predictability time: time at which a system trajectory is attracted to the neighborhood of a statistically stationary solution

Let us consider some ensemble (distribution) of initial states P_0 and its evolution $P(t)$.

If the system has the invariant (mixing) measure

$$P(t) = G(t)(P_0) \xrightarrow[t\to\infty]{} P_{st}\;, \quad \psi(t) = G(t)(\psi_0).$$

where P_{st} is the stationary distribution of points in the system phase space (e.g climatology).

When $P(T) \approx P_{st}$ all information about the initial distribution P_0 is lost.

Let us call T as the predictability limit ***(Dymnikov, Izvestiya, 2004).***

Conventions

- “Kinds of predictability”: attribute the predictability limits to sources of errors (infinitesimal)
  - Predictability of *1st kind*: limited by the errors in the estimate of the state of the system (initial and boundary conditions)
  - Predictability of *2nd kind*: limited by the errors and deficiencies in the model (errors *per se*, resolution, discrete nature, parameterizations)