Deterministic Forecasting, Predictability and Ensemble Prediction

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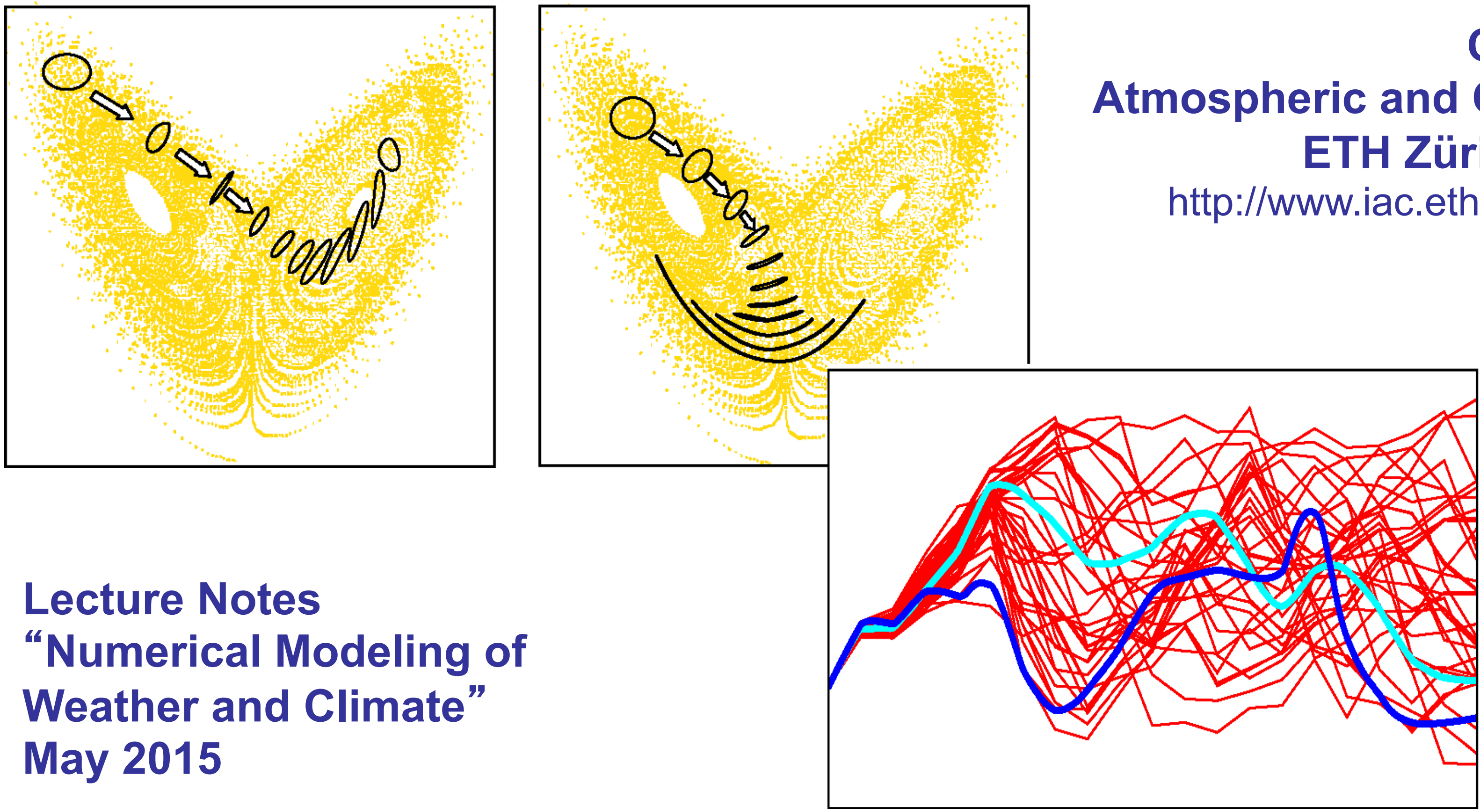


Lecture Notes
“Numerical Modeling of Weather and Climate”
May 2015

Outline

Deterministic forecasting

Example of a misforecast

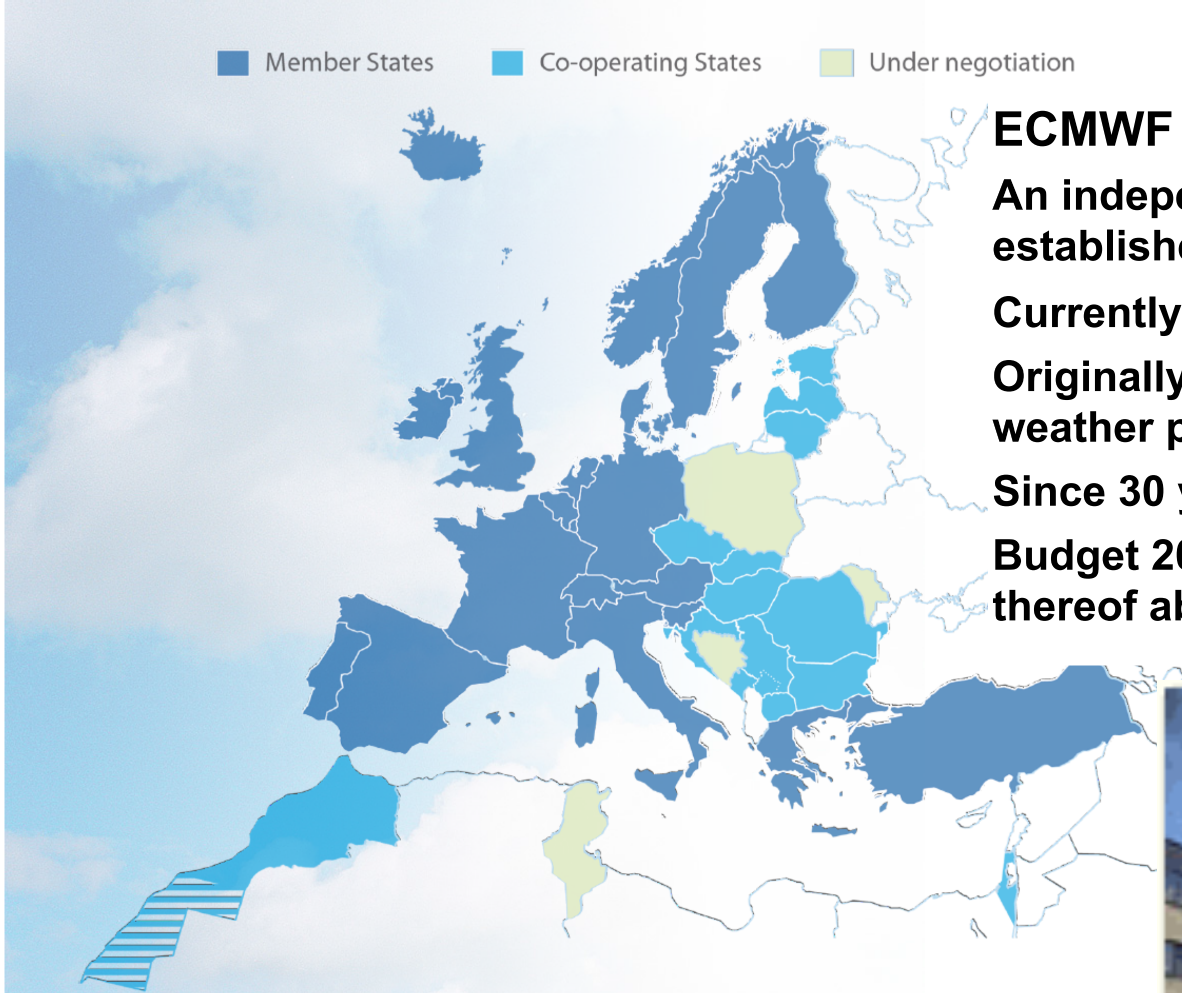
Chaos theory and predictability

Ensemble prediction

Limited-area forecasting

Examples

European Center for Medium-Range Weather Forecasts



ECMWF

An independent intergovernmental organisation established in 1975

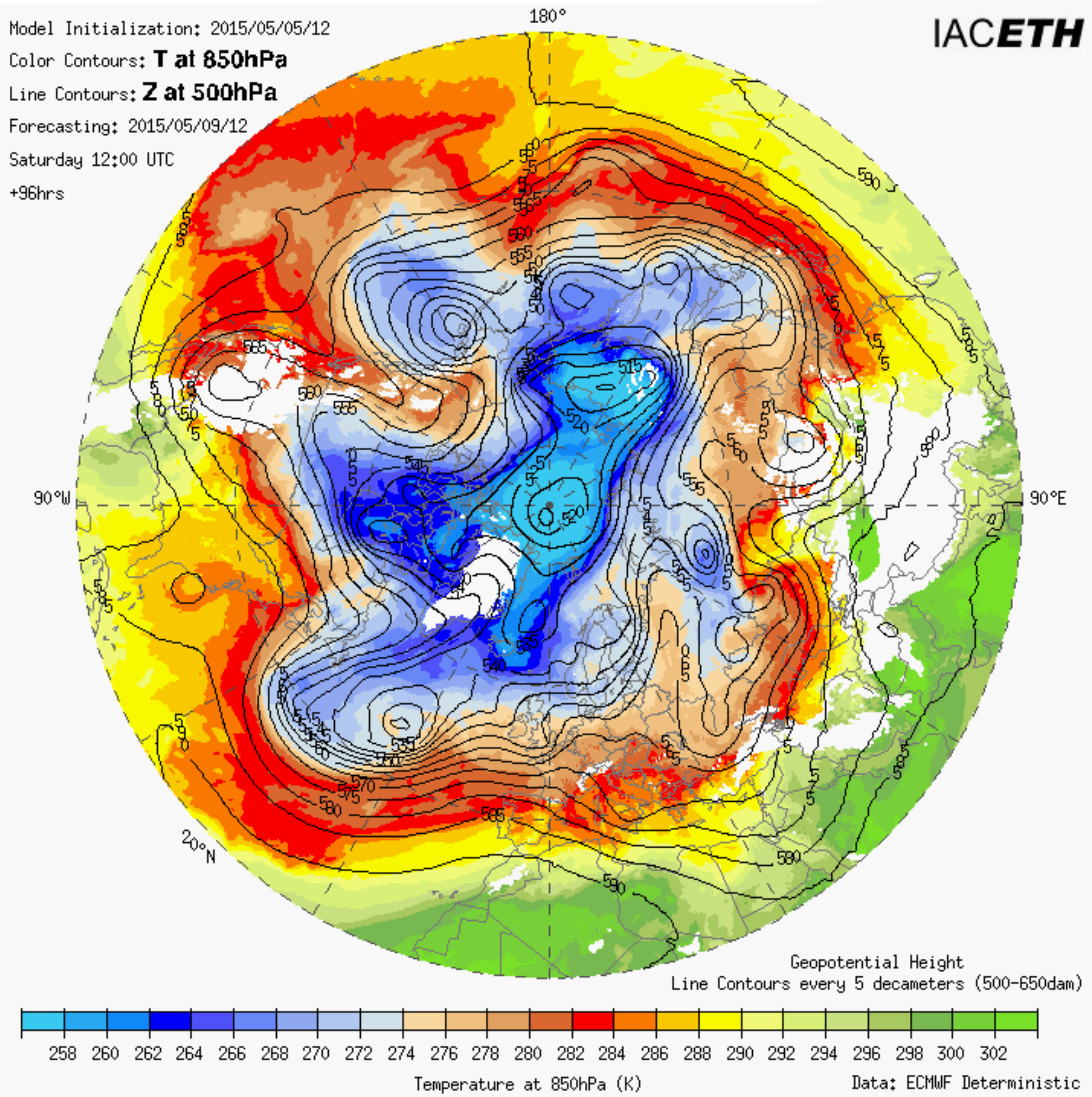
Currently 20 members and 14 cooperating states

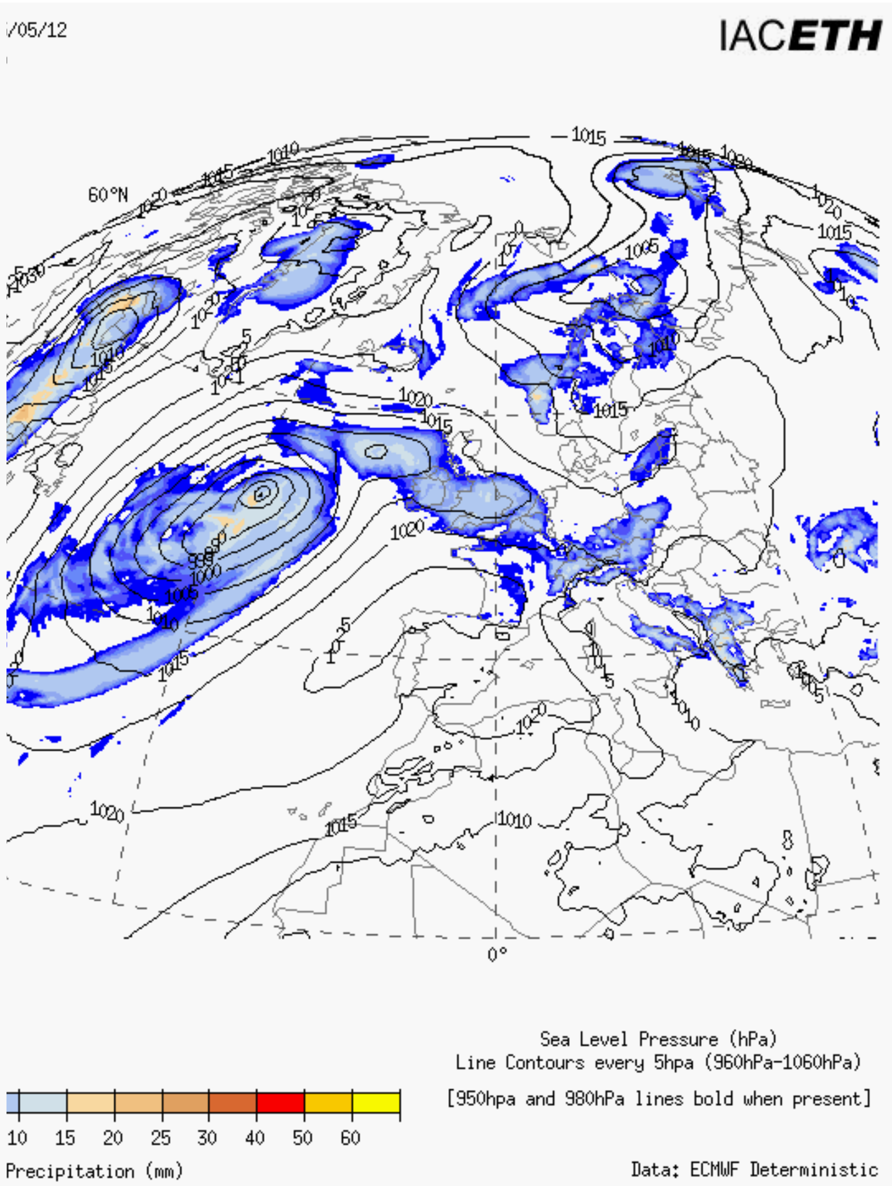
Originally founded for medium-range numerical weather prediction (day 3-10).

Since 30 years, leading NWP center

Budget 2010: 39 Mio £,
thereof about 16 Mio £ for computer hardware

Deterministic forecast for Sat, May 9 (+96h)





Validation of deterministic models – skill scores

RMSE (root mean squared error) of a specific forecast

$$RMSE_{fc} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\phi_{fc} - \phi_{obs}\right)^2}$$

ϕ_{fc} forecasted field (e.g. 500 hPa geopot.)
ϕ_{obs} observed field (analysis)

i runs over all grid points of a domain (e.g. Europe or Northern Hemisphere).

Validation of forecasts must respect the fact that even a trivial forecast (such as persistence) has some skill. Validation measures should thus be relative to some trivial forecast.

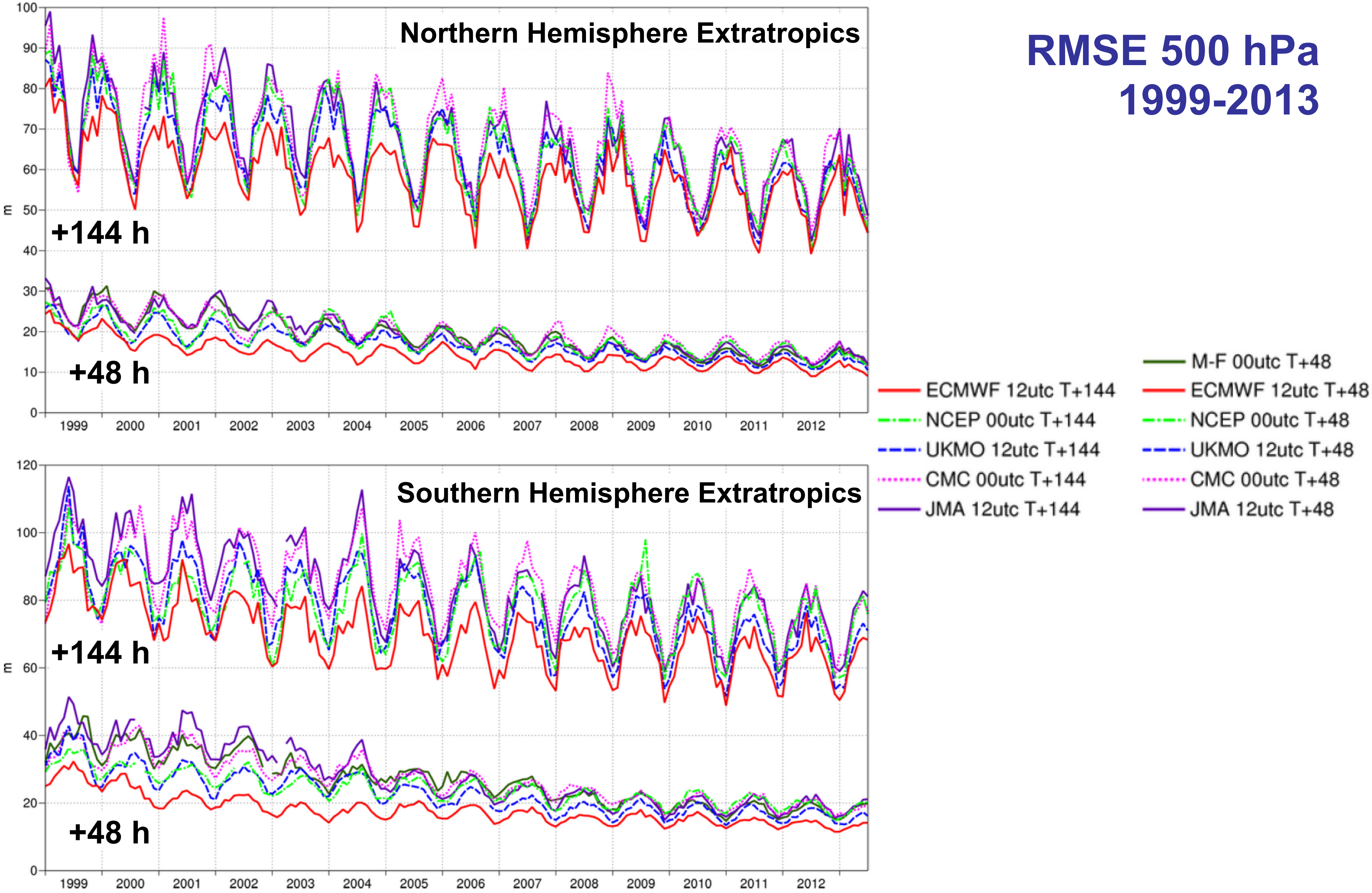
To this end, skill scores express the reduction in $RMSE$ achieved by the model, with respect to persistence (forecast obtained by persisting the initial analysis):

$$SS = \left(1 - \frac{RMSE_{fc}}{RMSE_{per}}\right)$$

$RMSE_{per}$ is same as $RMSE_{fc}$, but using persistence forecast

Skill scores are usually expressed in percent. A skill of 0% implies that the forecast is no better than the persistence forecast.

RMSE 500 hPa 1999-2013



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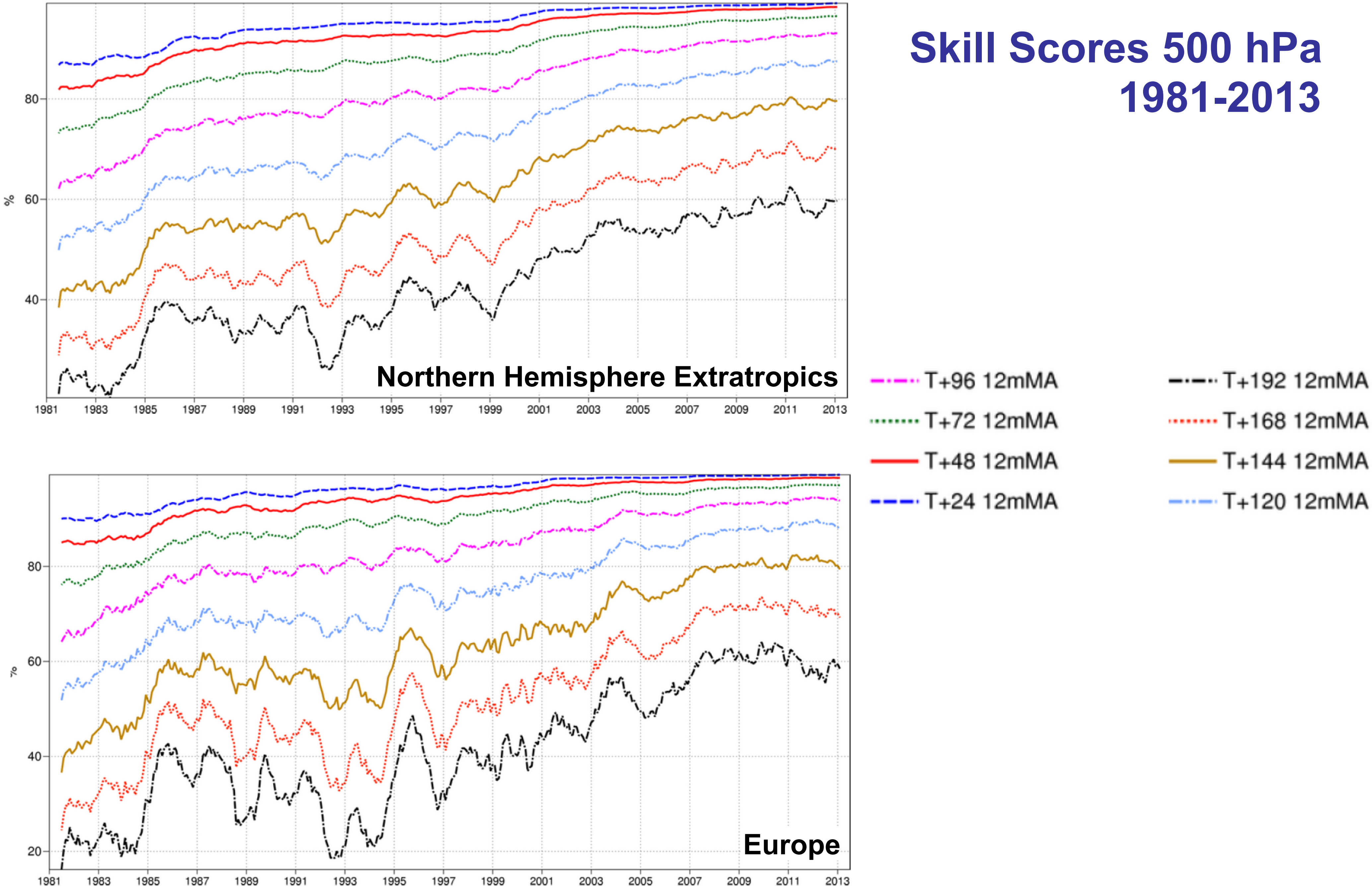
(ECMWF 2013, TM710)

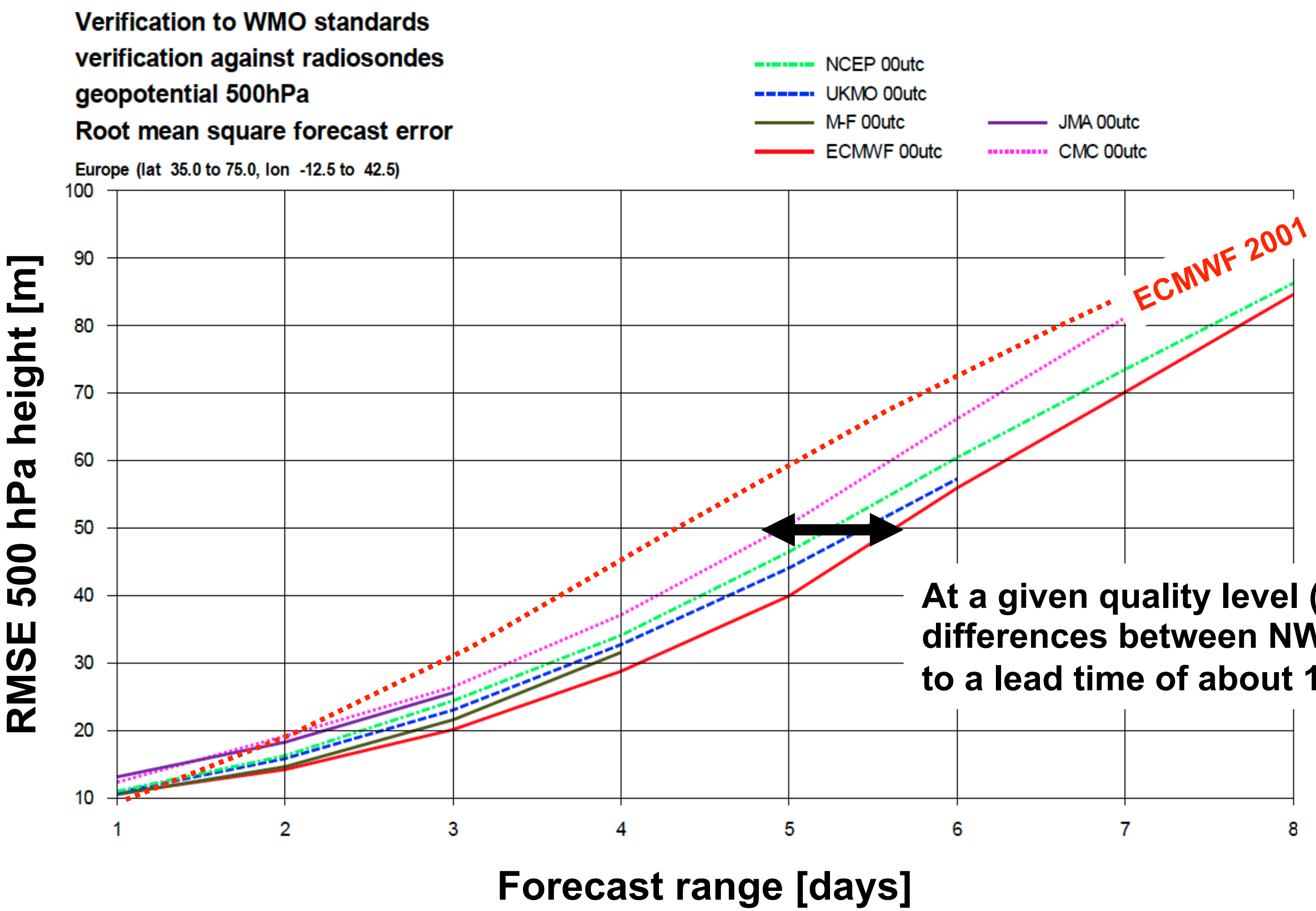
Skill Scores 500 hPa 1981-2013



Schär, ETH Zürich

(ECMWF 2013, TM710)

Comparison between different models



At a given quality level (e.g. RMSE=50 m), differences between NWP centers amount to a lead time of about 1 day.

(ECMWF 2011, 2001)

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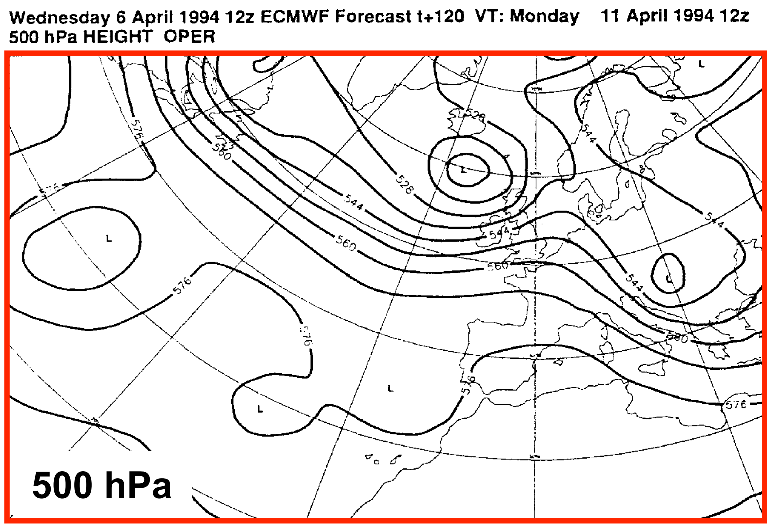
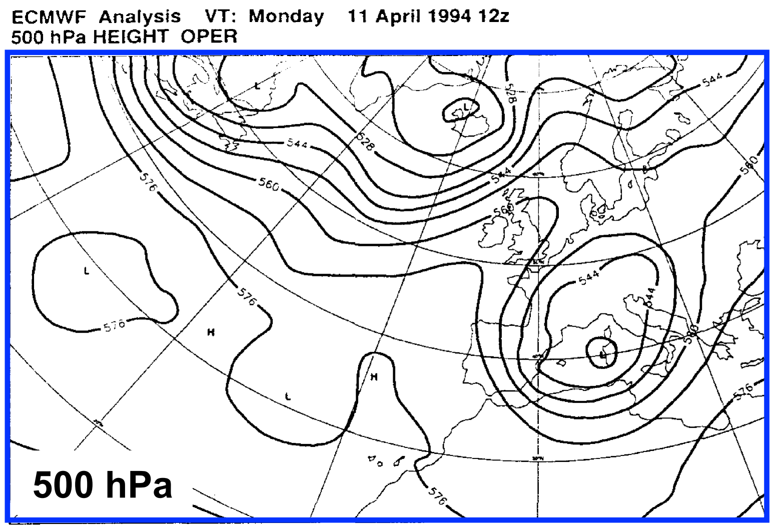
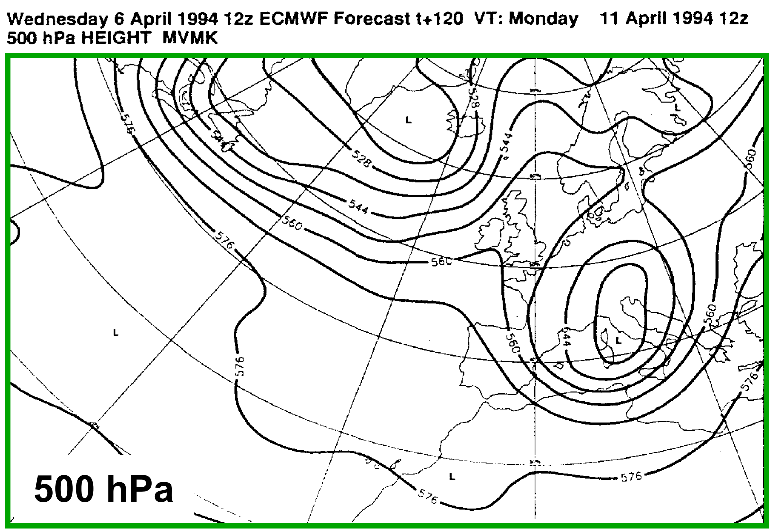
An Example of a Misforecast …



Operational 120 h forecast



Verifying Analysis

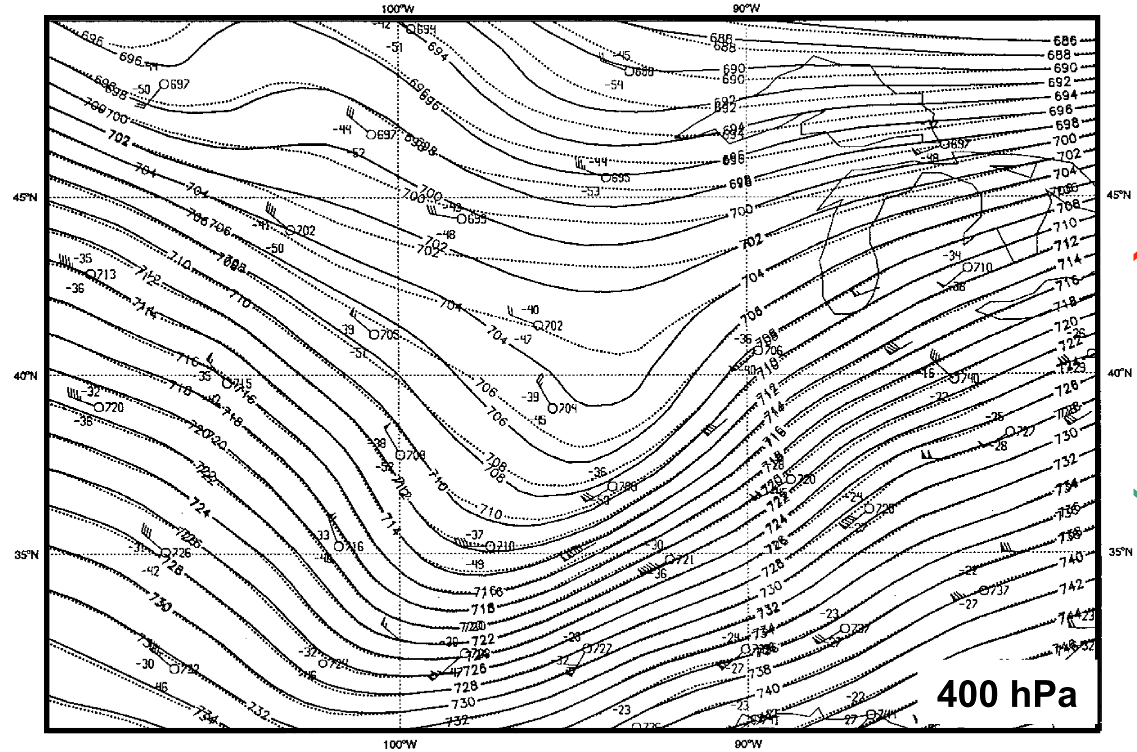


Forecast from slightly different initial conditions

(ECMWF 1994)

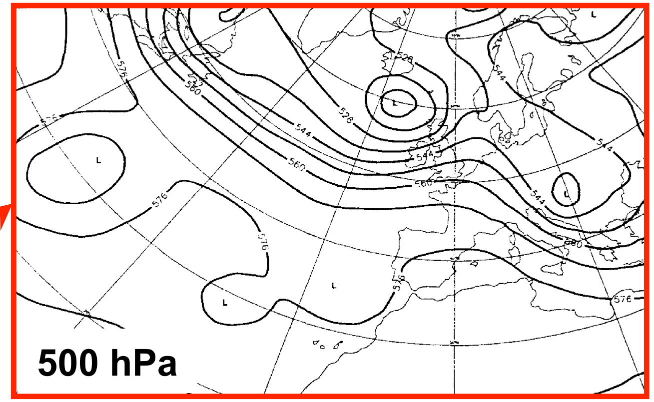
… and its Origin

Initial conditions (dotted lines)



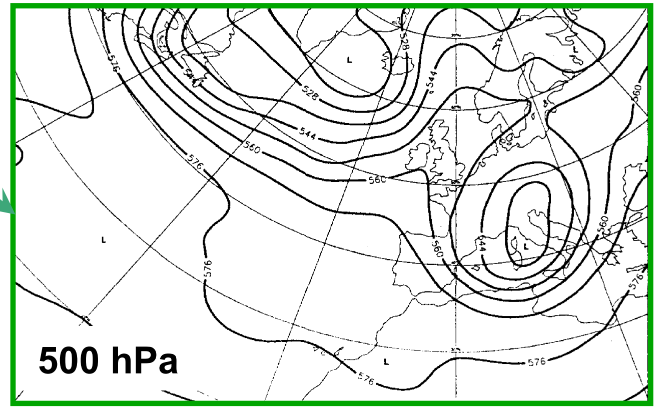
Initial conditions (full lines)

Wednesday 6 April 1994 12z ECMWF Forecast t+120 VT: Monday 11 April 1994 12z
500 hPa HEIGHT OPER



Operational 120 h forecast

Wednesday 6 April 1994 12z ECMWF Forecast t+120 VT: Monday 11 April 1994 12z
500 hPa HEIGHT MVMK



Modified forecast

(ECMWF 1994)

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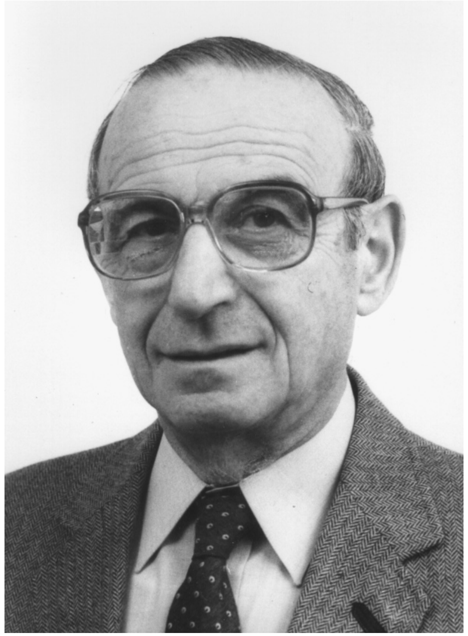
Rott Pendulum



Nikolaus Rott, 1918-2006, Prof. for Fluid Dynamics (ETH Zürich)

With his pendulum, Rott discovered „non-linear coupling.“ In his paper he briefly mentioned the chaotic nature of his pendulum.

A Multiple Pendulum for the Demonstration of Non-linear Coupling

By Nikolaus Rott, Swiss Federal Institute of Technology, Zurich

To Professor Hans Ziegler, on his sixtieth birthday

1. Introduction

The double pendulum is a classical device for the investigation of coupled motions; for small amplitudes the whole problem is linear, including the coupling effects. There exists, however, a very special arrangement, for which the leading coupling term is quadratic: this occurs when in the equilibrium position, the two pivots are aligned in a

ZAMP, 1970,
Vol. 21 (4), 570-582

this leads to

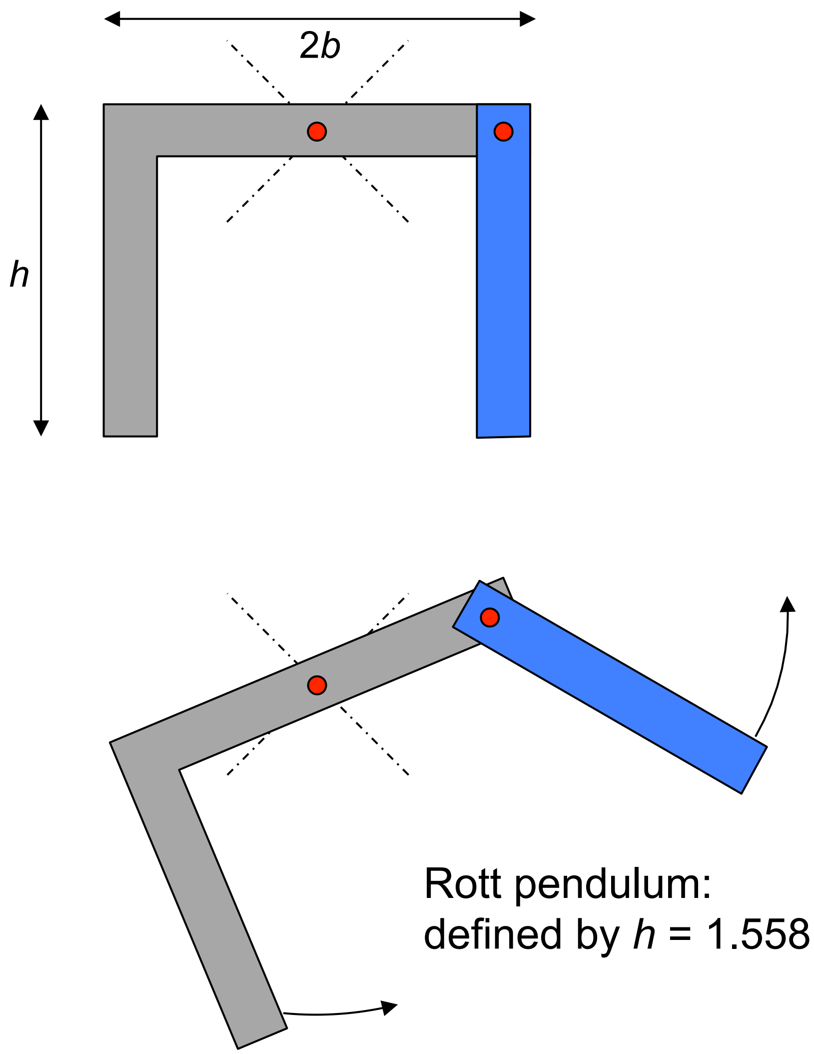
$$\frac{df}{dt} = e^{i\varepsilon t}(i\eta\,\omega^2/2\lambda)\,\bar{f}g \qquad (19)$$

$$\frac{dg}{dt} = e^{-i\varepsilon t}(i\xi\,\lambda^2/\omega)\,f^2 \qquad (20)$$

It can be seen a posteriori that these equations always hold in the limit of small magnitudes (i.e., amplitudes) of f and g. Equations (19) and (20) show that d/dt itself is proportional to the amplitude of f and g. Thus, if the three quantities f, g, and d/dt are considered on equal footing, all terms omitted are of higher order than those retained.

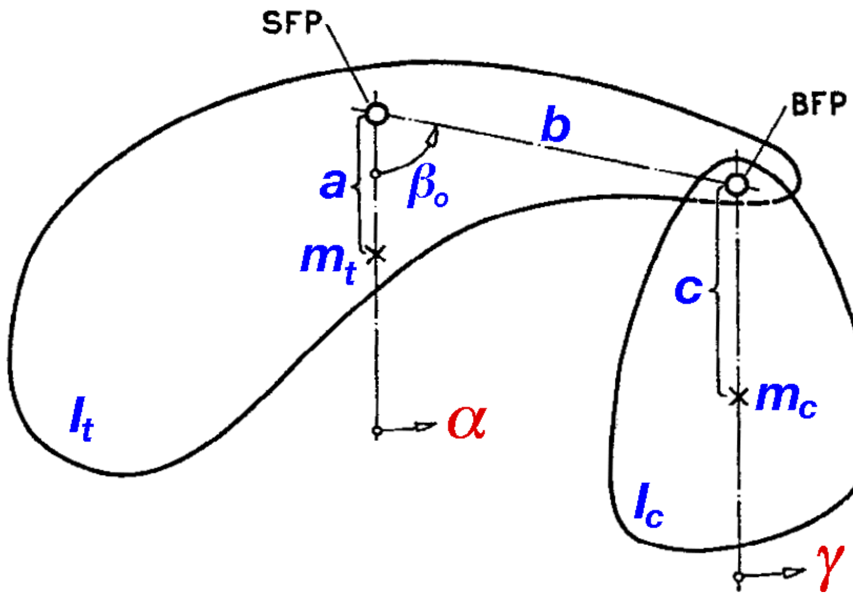
Original manuscript
(ETH Library)

Standard Rott pendulum



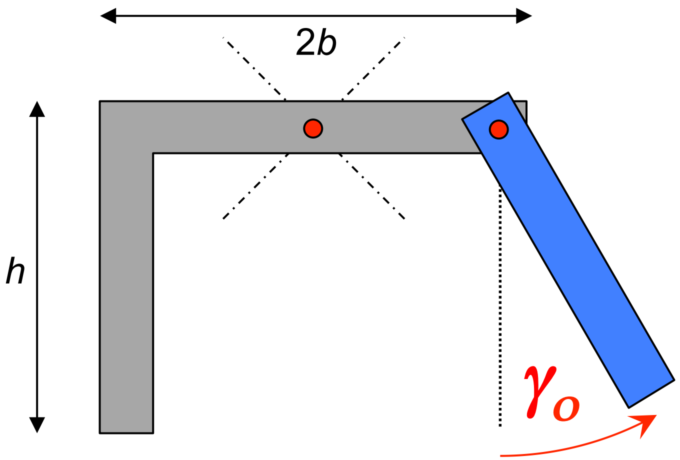
Rott pendulum:
defined by $h = 1.558\ b$

General Rott pendulum



Simple physical model of a chaotic system.

Nonlinear coupling with the Rott pendulum

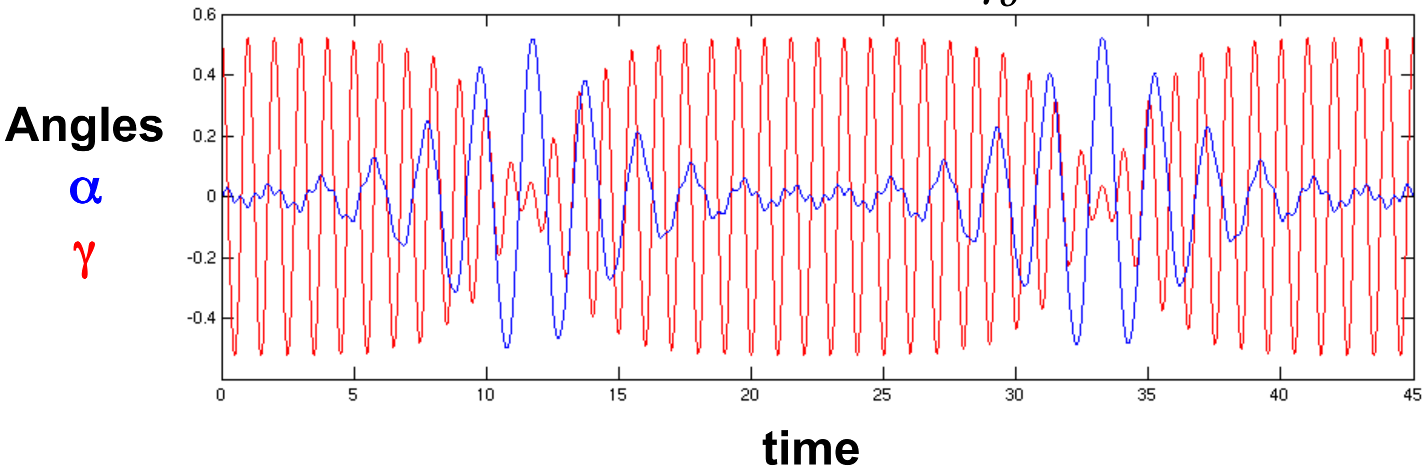


Standard Rott pendulum

- **resonant periods (ratio 1:2) implies $h = 1.558\, b$**
- **release from rest with $\alpha = 0$, $\gamma_o > 0$.**

=> nonlinear resonance

Numerical solution for $\gamma_o = 30º$



From resonance to chaos

In his paper, Rott (1970) restricts attention to nonlinear resonance. His analytical equations describe the system for angles up to about 30º from rest position.

> **"The author has built a model (followed by many others) which has shown that indeed this exchange of energy between the two oscillating bodies is periodic; while the 'exchange' period contains many 'pendulum' periods, it reproduces itself with great accuracy, which makes the pendulum motion very fascinating to watch."**

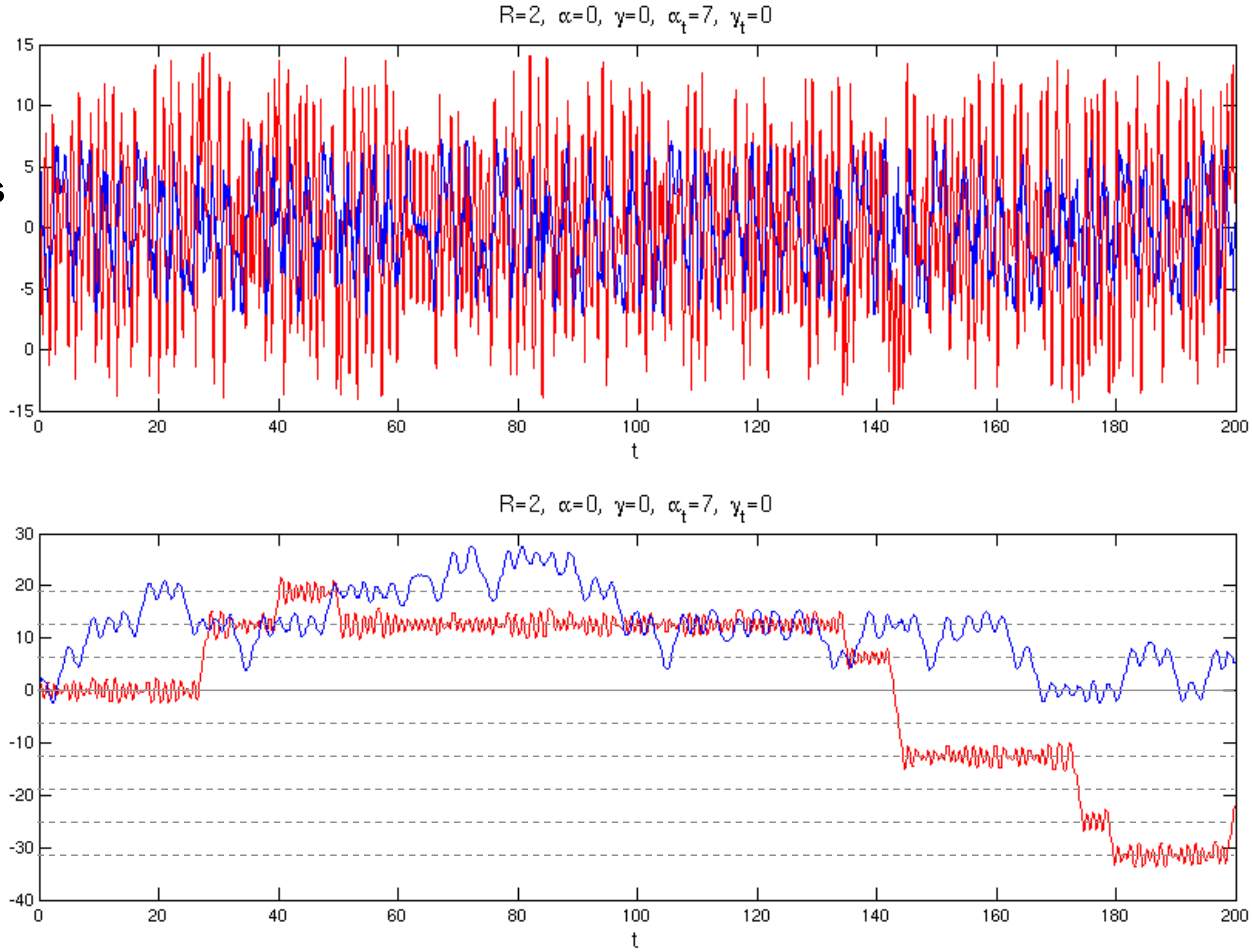
There is only one brief reference to the chaotic regime:

> **"If the design permits … full rotations, surprising motions with a total lack of periodicity can be realized. Those are in strong contrast with the motions in the region of quadratic coupling, where the tendency to periodicity dominates."**

Rott does not mention the Lorenz (1963) paper, he probably was not aware of it.

Chaos with the Rott pendulum

angular velocities
$d\alpha/dt$
$d\gamma/dt$



Angles
α
γ

full rotations

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Chaos theory with the Lorenz model

Deterministic chaos:

- Property of a bounded nonlinear dynamical system.
- Sensitivity with respect to initial conditions.
- Behavior of system appears random, but it is deterministic in the sense that its future dynamics is defined by the initial conditions.

Edward N. Lorenz, 1917-2008
Prof. for Meteorology
(MIT, Cambridge)

Deterministic Nonperiodic Flow[1]

EDWARD N. LORENZ

Massachusetts Institute of Technology

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

ABSTRACT

Finite systems of deterministic ordinary nonlinear differential equations may be designed to represent forced dissipative hydrodynamic flow. Solutions of these equations can be identified with trajectories in phase space. For those systems with bounded solutions, it is found that nonperiodic solutions are ordinarily unstable with respect to small modifications, so that slightly differing initial states can evolve into considerably different states. Systems with bounded solutions are shown to possess bounded numerical solutions.

A simple system representing cellular convection is solved numerically. All of the solutions are found to be unstable, and almost all of them are nonperiodic.

The feasibility of very-long-range weather prediction is examined in the light of these results.

Lorenz, E.N., 1963: Deterministic non-periodic flow. J. Atmos. Sci., 20, 130-141

See also: James Gleick: *Chaos: making a new Science*. Minerva, London

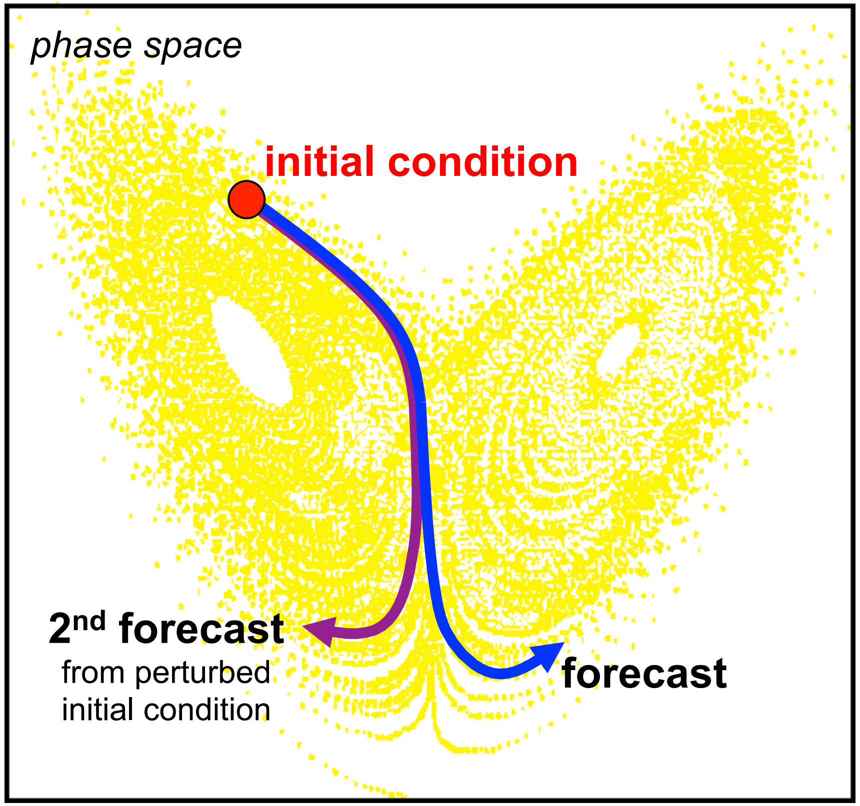
The Lorenz (1963) model:
A simple dynamical system that exhibits chaotic behavior:

$$\begin{aligned}\dot{X} &= -\sigma X + \sigma Y \\ \dot{Y} &= -XZ + rX - Y \\ \dot{Z} &= XY - bZ\end{aligned}$$

Variables: X, Y, Z

Standard settings of parameters:
$\sigma = 10,\ r = 28,\ b = 8/3$

Phase space, trajectories and orbits



Projection of phase space on (*x,z*)-plane

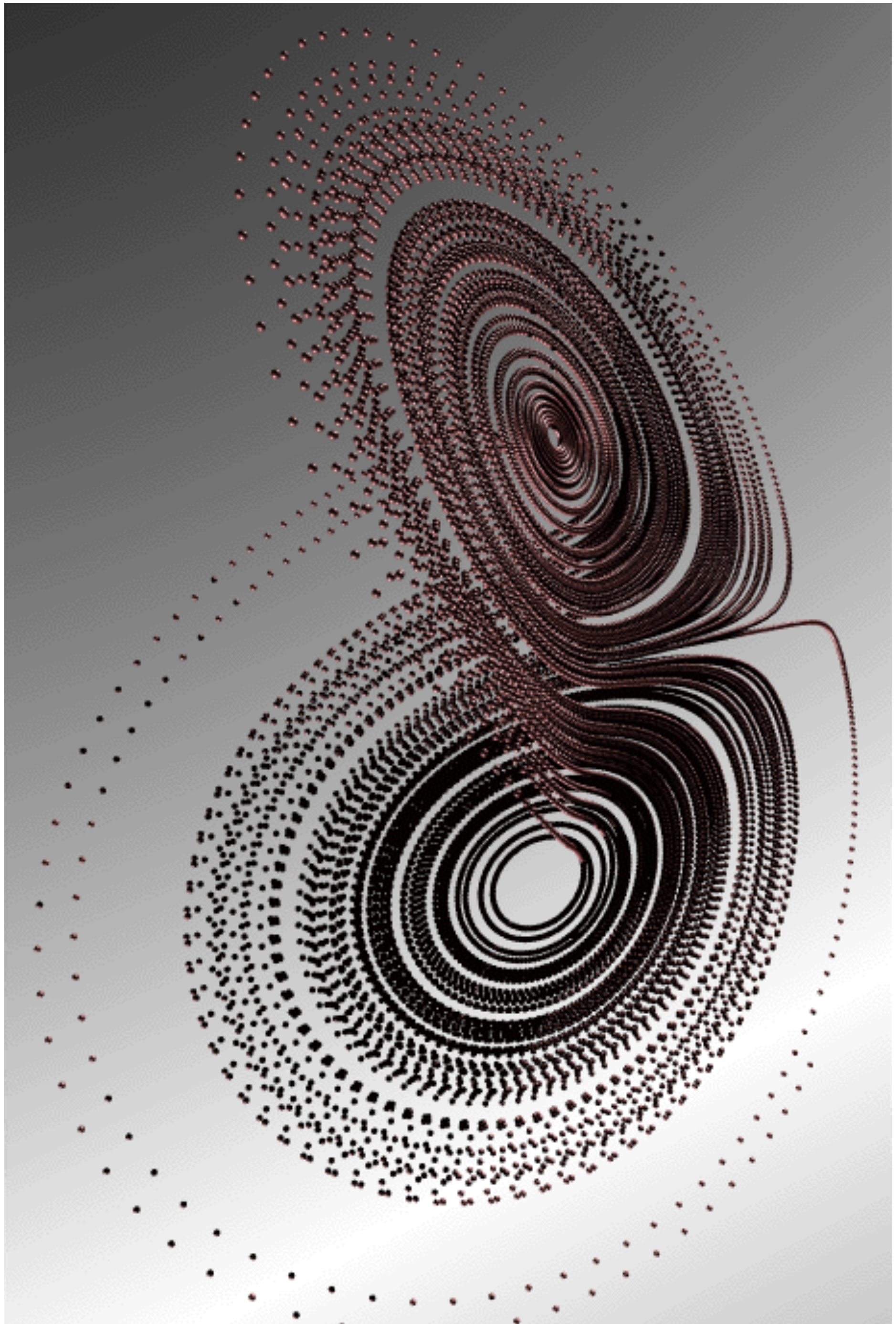
The **phase space** is spanned by the free variables of the system. The Lorenz equations have 3 degrees of freedom, this yields a three-dimensional phase-space.

Global atmospheric model:
up to 10^9 degrees of freedom.

Each point in phase space defines a state of the system. The evolution of the system is given by a **trajectory** (or **orbit**) in phase space.

The sensitivity of the system to initial conditions is evident from the divergence of initially nearby phase-space trajectories.

(Palmer, ECMWF)



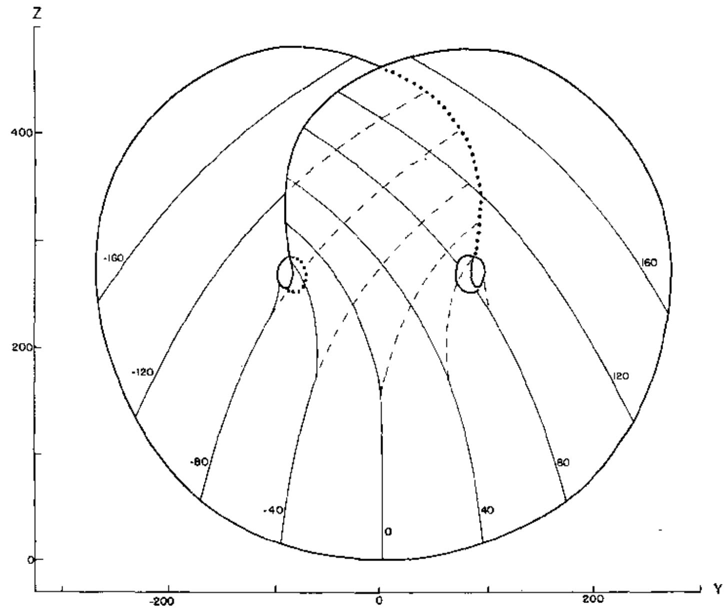
(Ian Stewart, 2000, Nature, pp949)

Lorenz attractor

The **attractor** is the fraction of phase space, to which the system converges after long time.

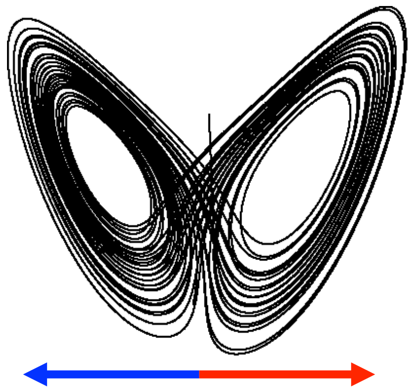
For simple dynamical systems, the attractor is usually a fixpoint (stationary solution) or a periodic orbit (periodic solution).

For chaotic dynamical systems, attractors are referred to as “strange attractors”. In the case of the Lorenz system, the attractor consists of two interconnected surfaces.



(Lorenz, 1963)

Bifurcations in the Lorenz model



Governing equations:

$$\frac{dX}{dt} = -\sigma X + \sigma Y$$
$$\frac{dY}{dt} = -XZ + rX - Y$$
$$\frac{dZ}{dt} = XY - bZ$$

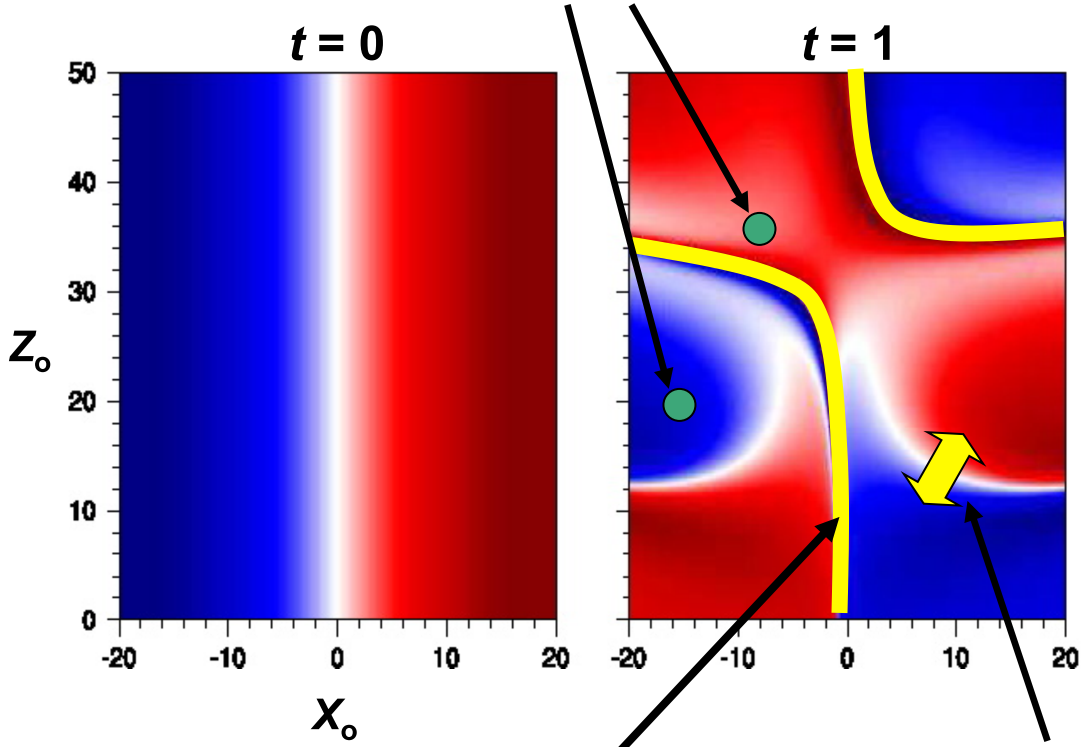
Initial conditions:

X_o=[-20, 20]

Y_o=1

Z_o=[0, 50]

These initial conditions end up in the left or right wing of the attractor, respectively



Maps of

$X=X(X_o, Y_o, Z_o, t)$

Bifurcation (abrupt sensitivity)

High sensitivity to initial conditions (cf. singular vector)

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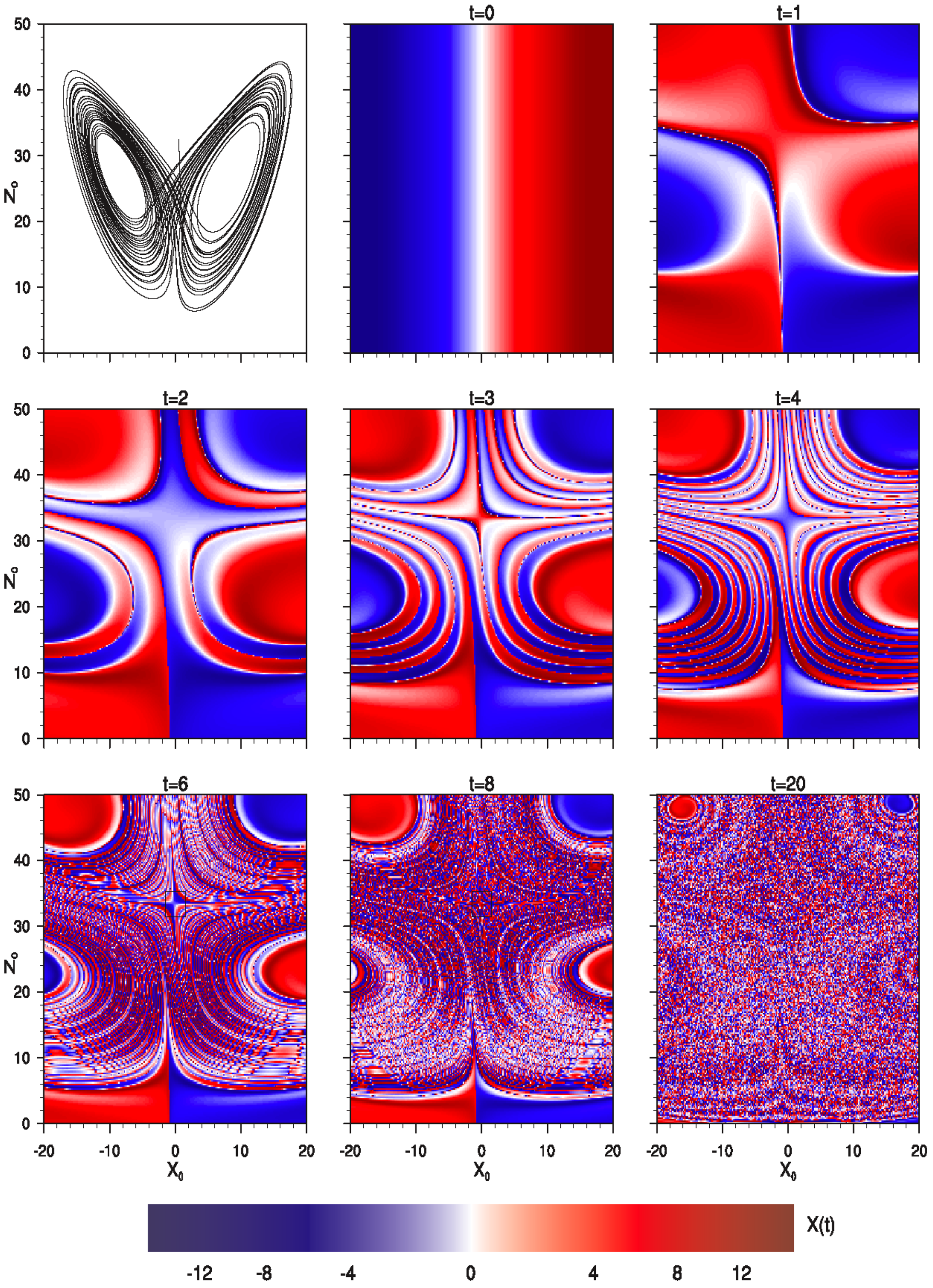
(Hohenegger and Schär, 2007)



Predictability in the Lorenz model

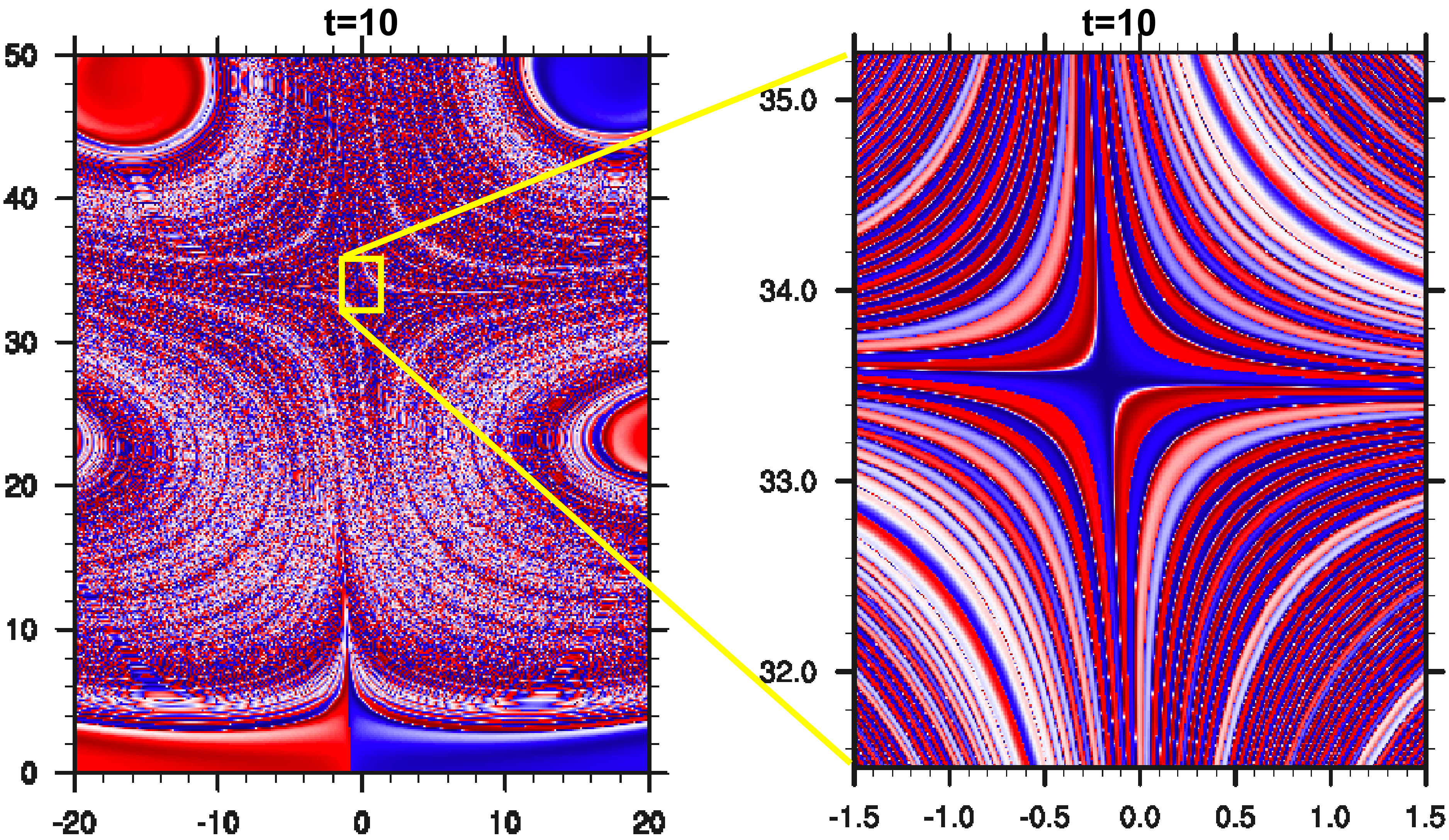
Maps of $X=X(X_o, Y_o, Z_o, t)$ as a function of time

As time proceeds, there is a complete loss of predictability in most of the phase space

The phase space is fragmented by bifurcations

(Hohenegger and Schär, 2007)

Fractal nature of attractor



(Hohenegger and Schär, 2007)

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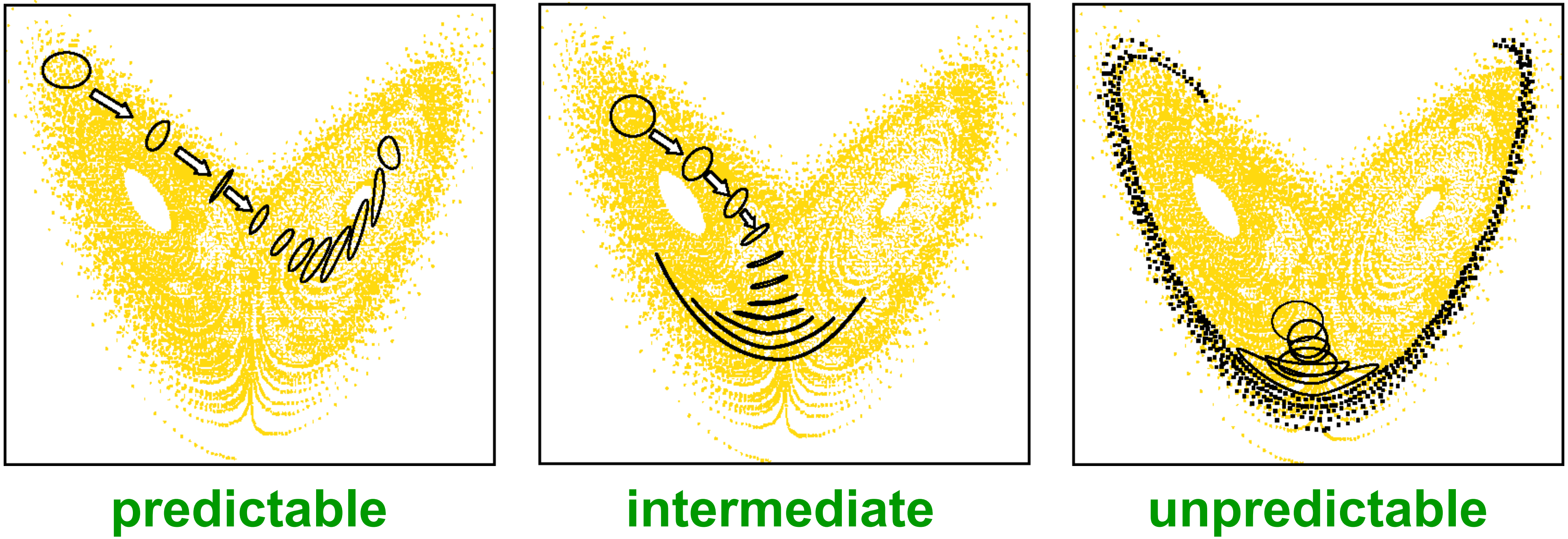
Predictability in the Lorenz-Attractor



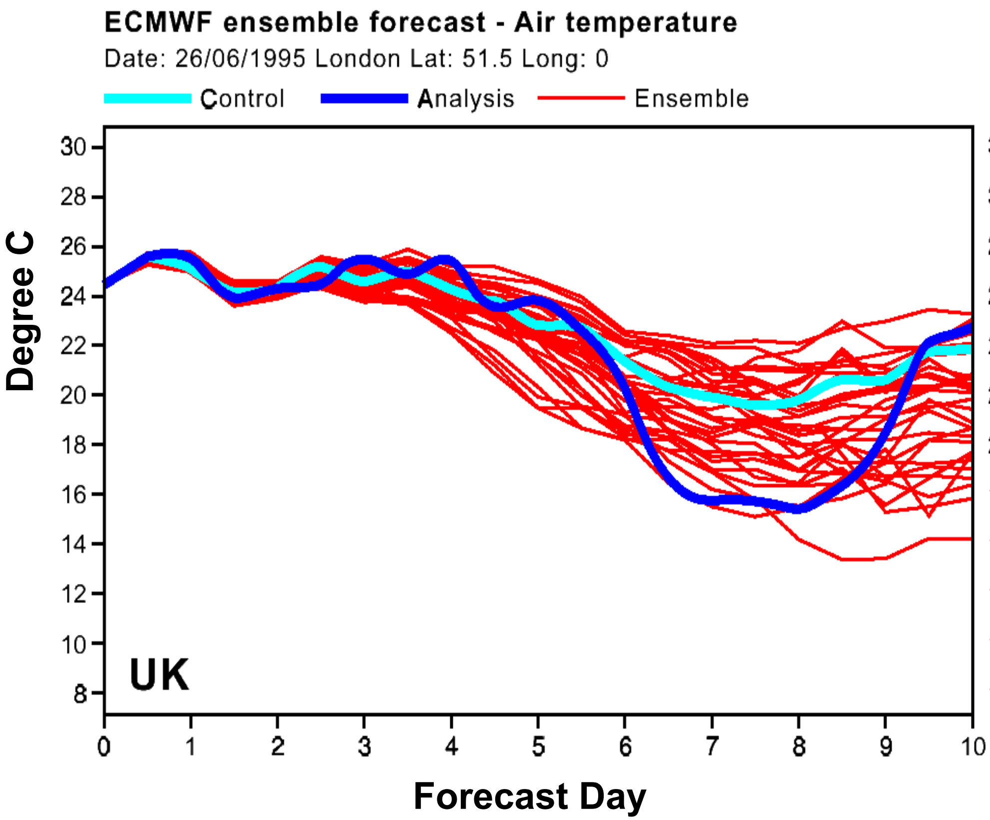
Predictability depends upon position of initial conditions in phase space.
=> There is some potential to provide a priori information on reliability of forecast.

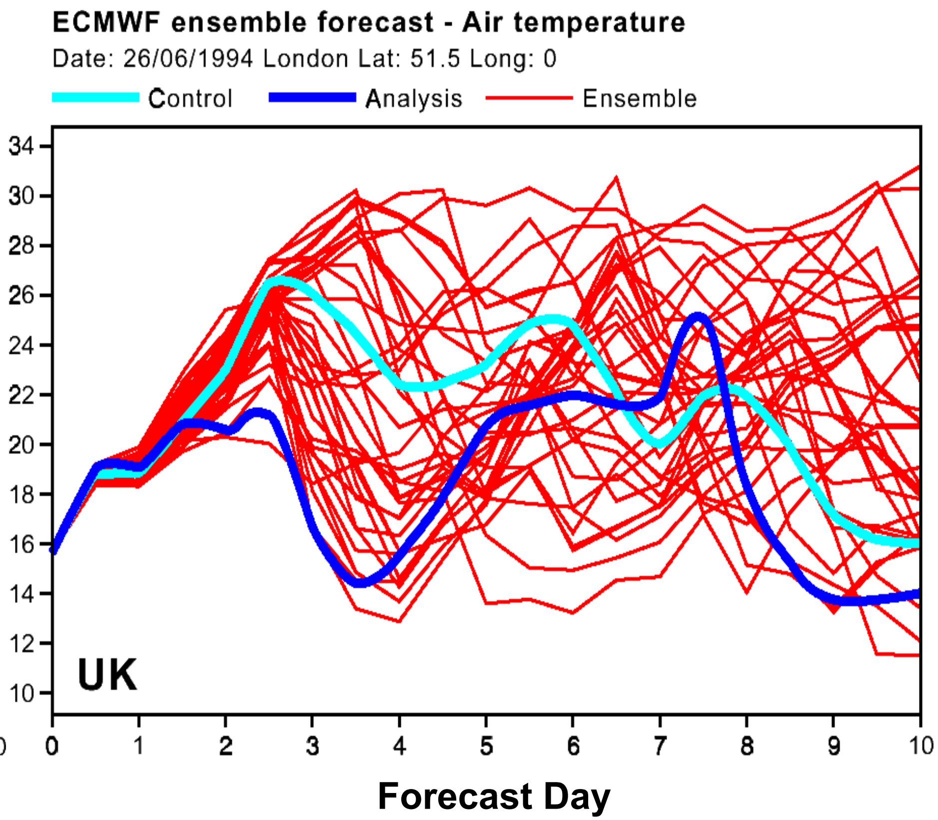
Basic idea of ensemble forecasting:
=> Conduct series of forecast from slightly different initial conditions.
=> Variations in initial conditions represent uncertainty due to observations and analysis.

(Palmer et al. 1996, Buizza et al. 1999)

Ensemble Forecasting

Many forecasts from slightly different initial conditions

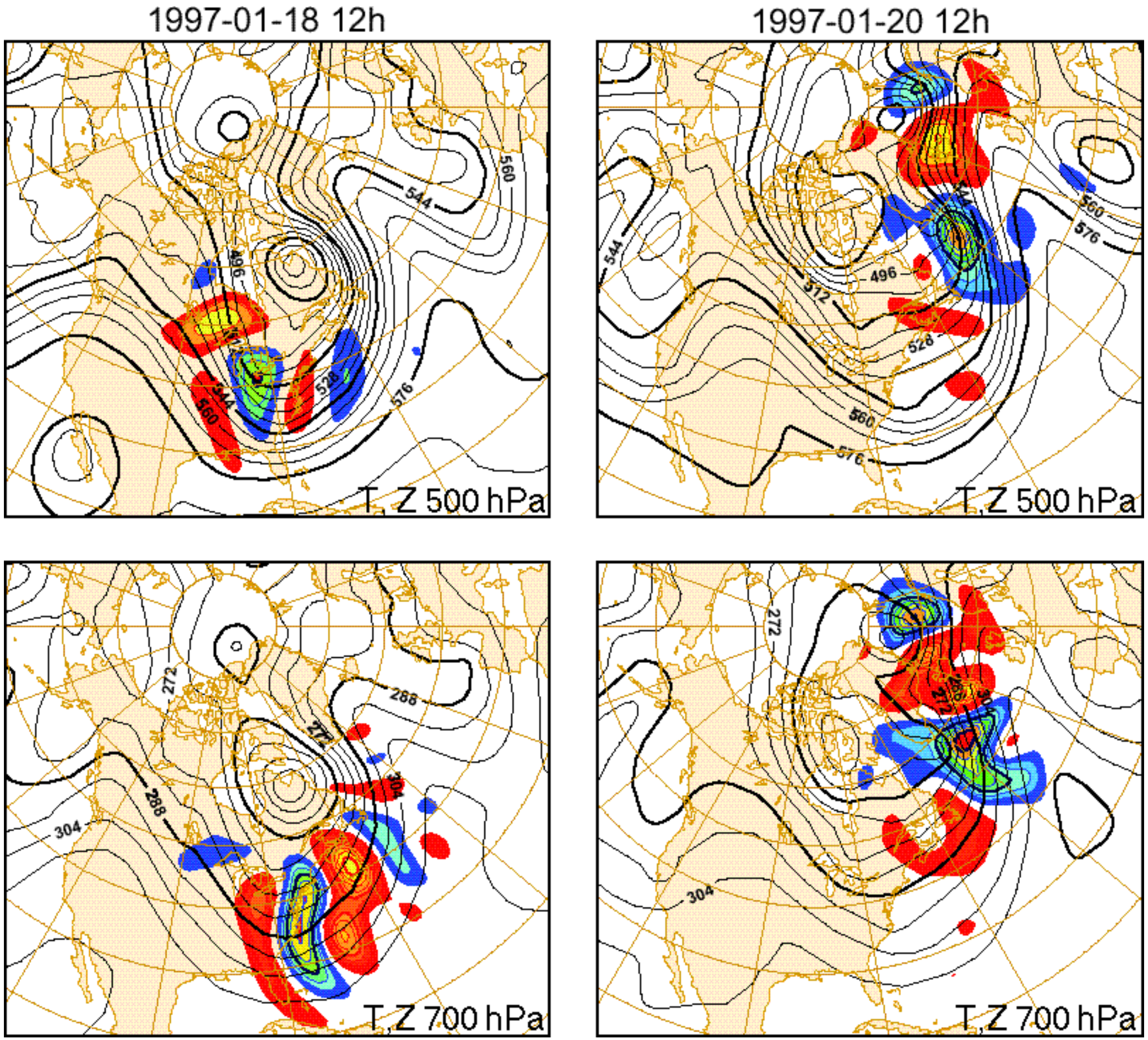




predictable **unpredictable**

(Buizza et al. 2000)

Initial Atmospheric Perturbations



Atmospheric state has many degrees of freedom. Full sampling of uncertainty is not possible.

Initial perturbations are defined by singular vectors (SV) of the observed state.

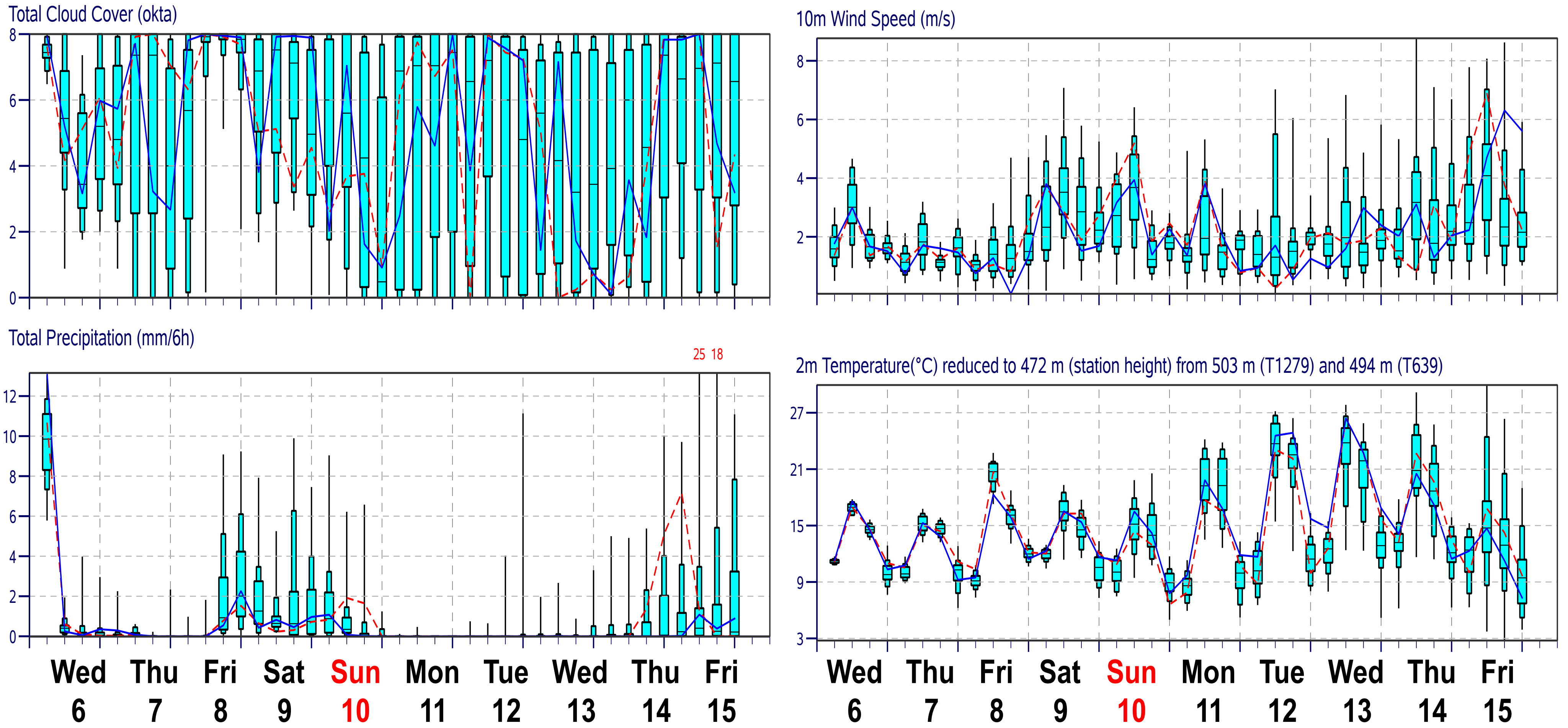
Singular vectors are perturbations with maximum linear growth over a selected time period.

In the extratropics, the SVs resemble baroclinic wave structures.

(ECMWF, Buizza et al. 2000)

Probabilistic Meteogram from May 6, 00 UTC (Zürich)

ENS Meteogram
Zürich, Switzerland 47.35°N 8.4°E (EPS land point) 472 m
High Resolution Forecast and ENS Distribution Wednesday 6 May 2015 00 UTC



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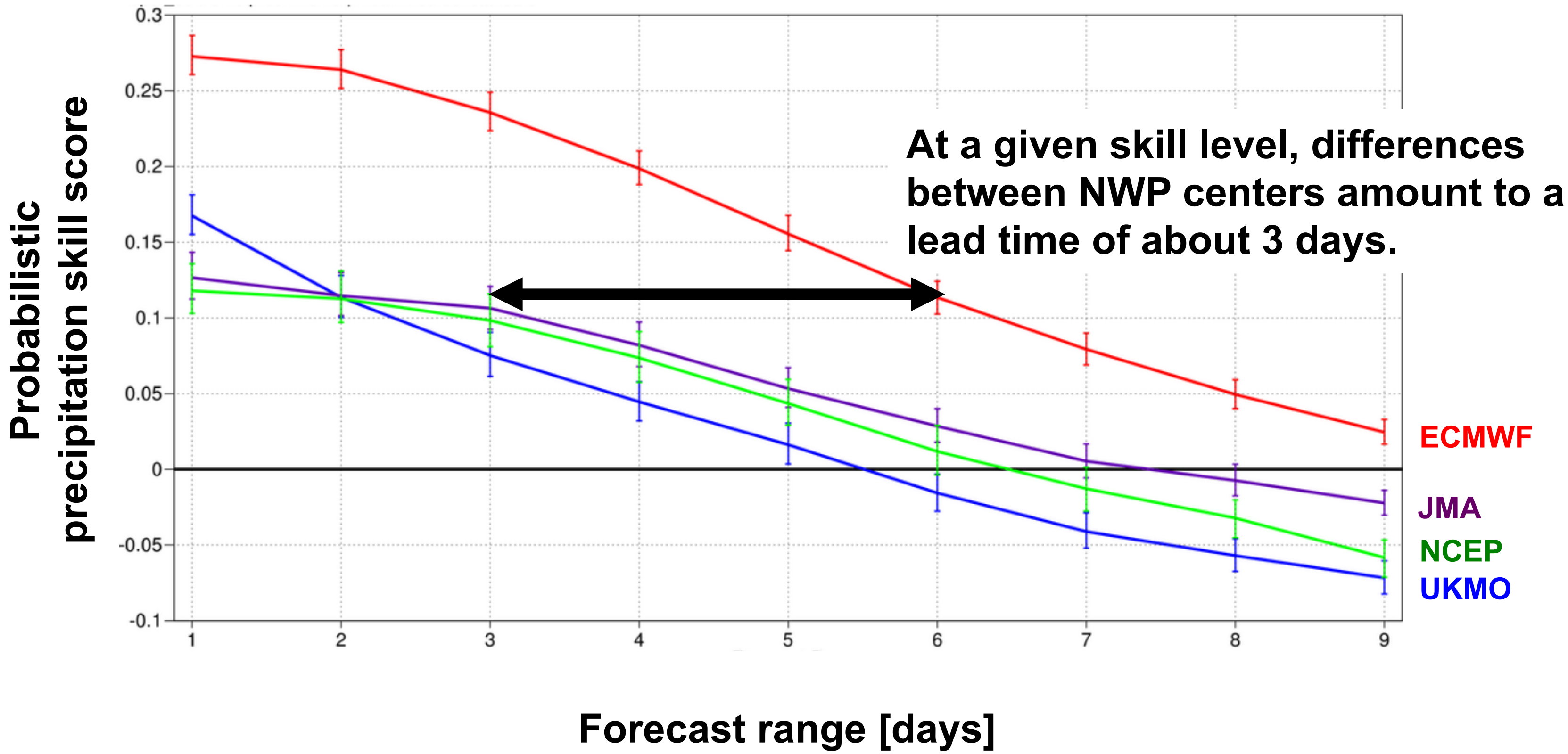
(ECMWF)

Comparison between different EPS systems

Validation against synoptic precipitation data in NH extratropics
August 2012 – July 2013



- Some of ECMWF's lead is due to higher computational resolution
- Some fraction of this gain can be made up by using limited-area models, model-output statistics, and/or a regionally experienced forecaster

(ECMWF 2013)

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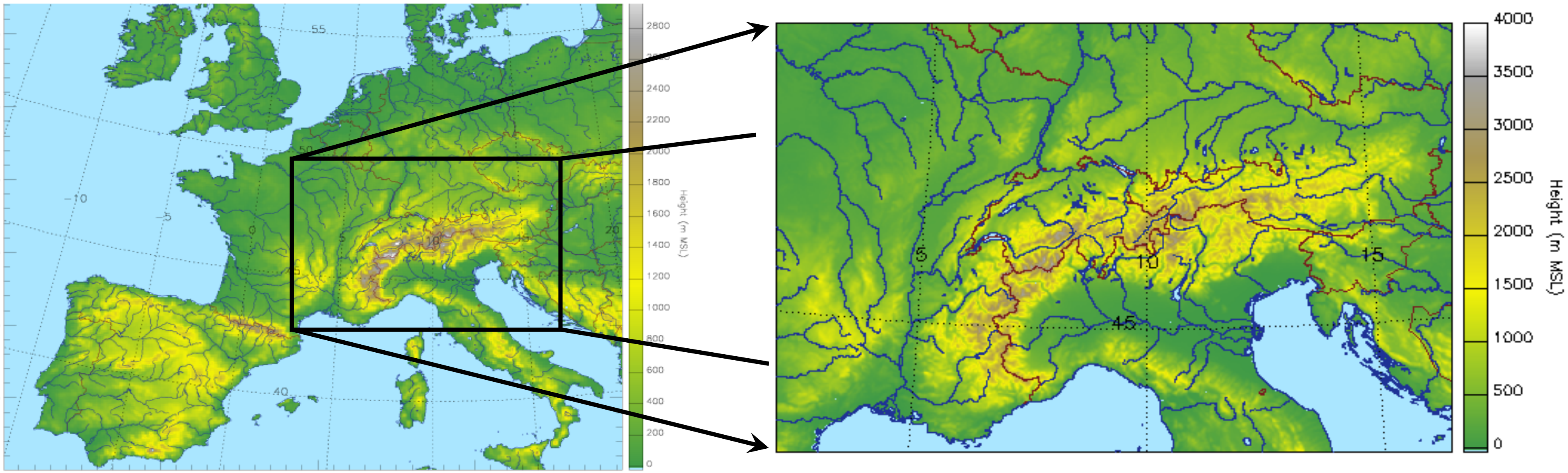
The NWP system COSMO at MeteoSwiss

COSMO-7 at 6.6km resolution **COSMO-2 at 2.2km resolution**



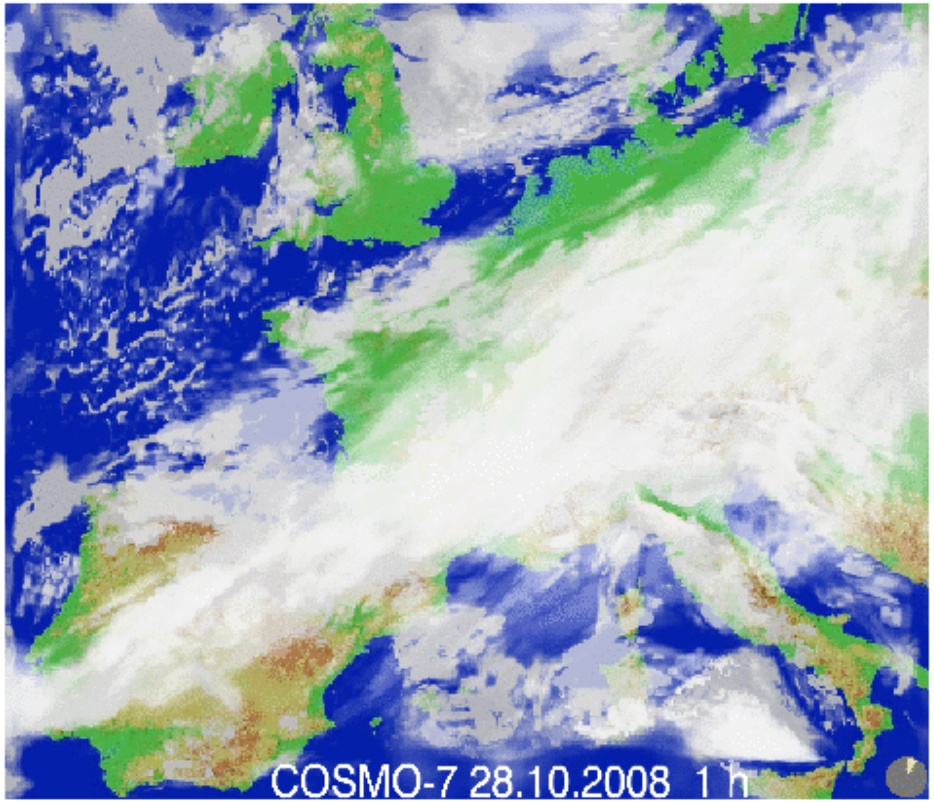
Mesh sizes:	3/50° ~ **6.6km**	1/50° ~ **2.2km**
Maximum height	3122m	3950m
Domains:	393x338x60 = 7'970'040 GP	520x350x60 = 10’920’000 GP
Forecasts	2 x 72h forecasts per day	7 x 33h and 1 x 47h forecasts per day (every 3h)
Initial conditions	nudging to observations	same, use of radar (latent heat nudging)

operational since 19 February 2008 **operational since 27 February 2008**

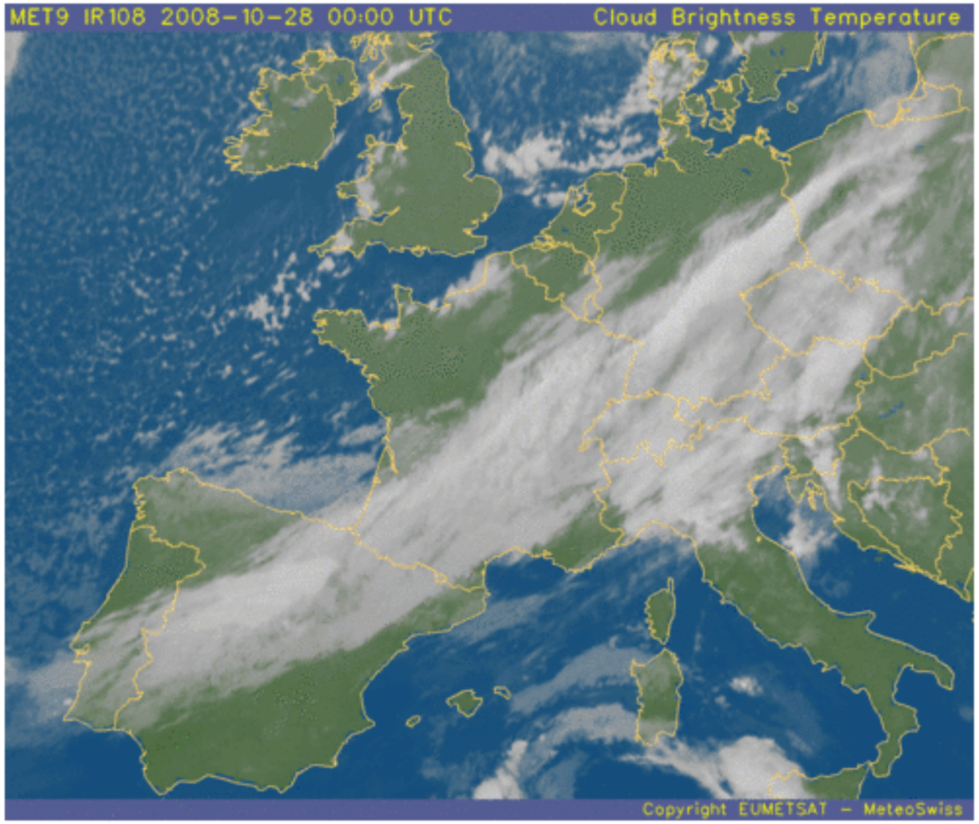
390 Gflops sustained (816 processors; 9% of peak) on Cray XT4 at CSCS, Manno

(MeteoSchweiz)

Forecasted versus real satellite pictures



Forecasted satellite picture (COSMO-7)



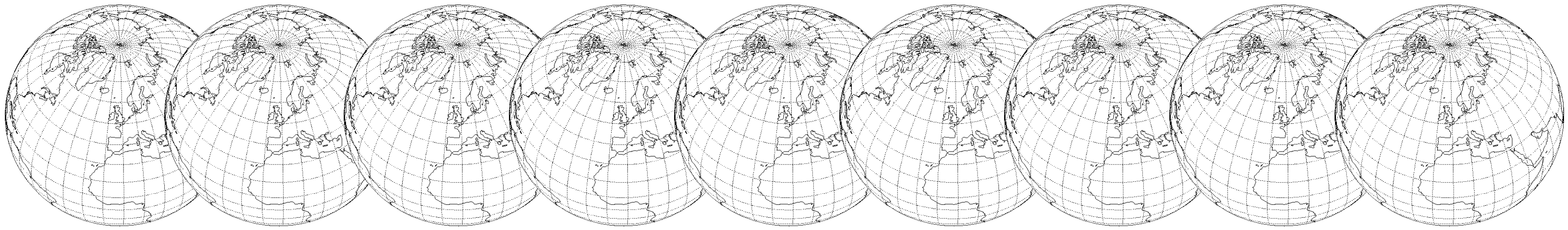
Observed satellite picture (IR, Meteosat)

1000 km

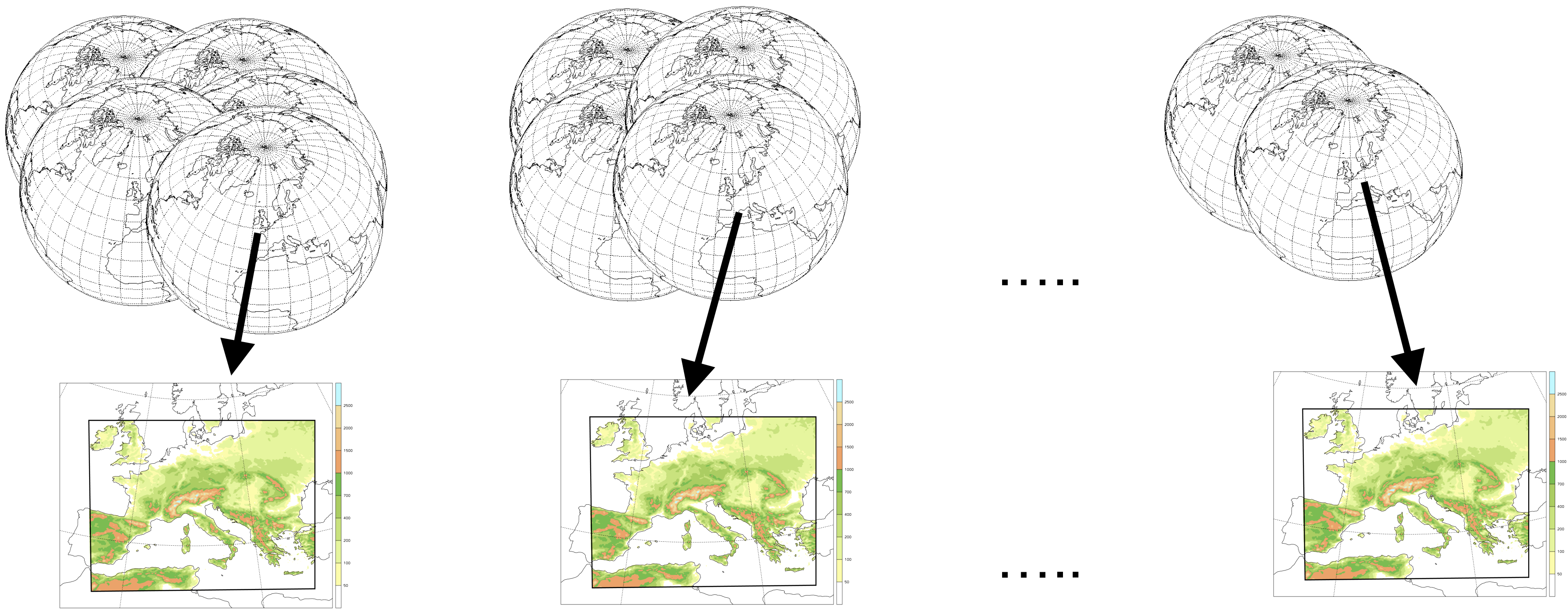
(MeteoSchweiz

Limited-area ensemble prediction system (LEPS)

50 ECMWF ensemble members with Δx~80 km



Clustering, selection of representative member, downscaling using LAM simulations



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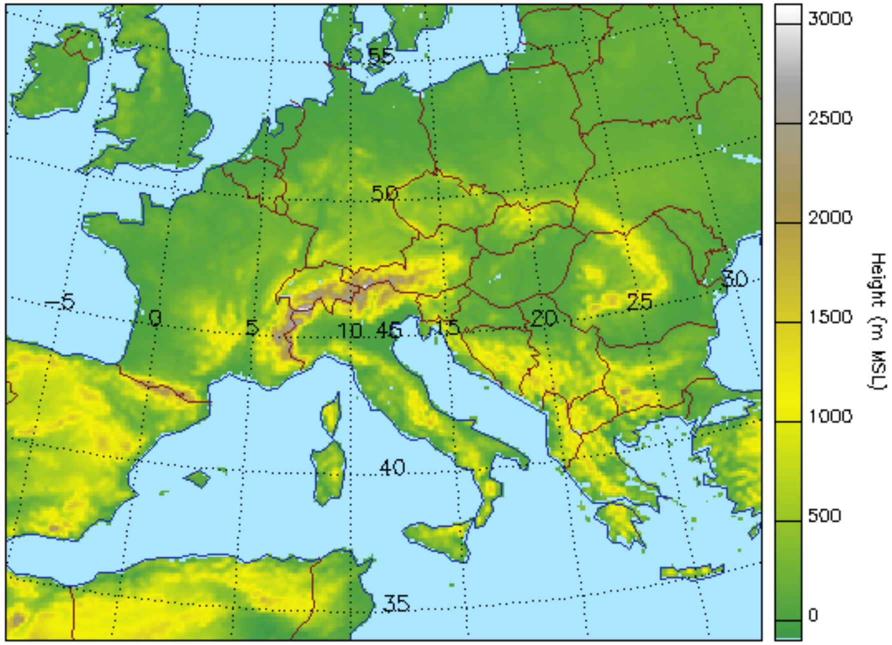
(Molteni et al. 2001; Marsigli et al. 2001)

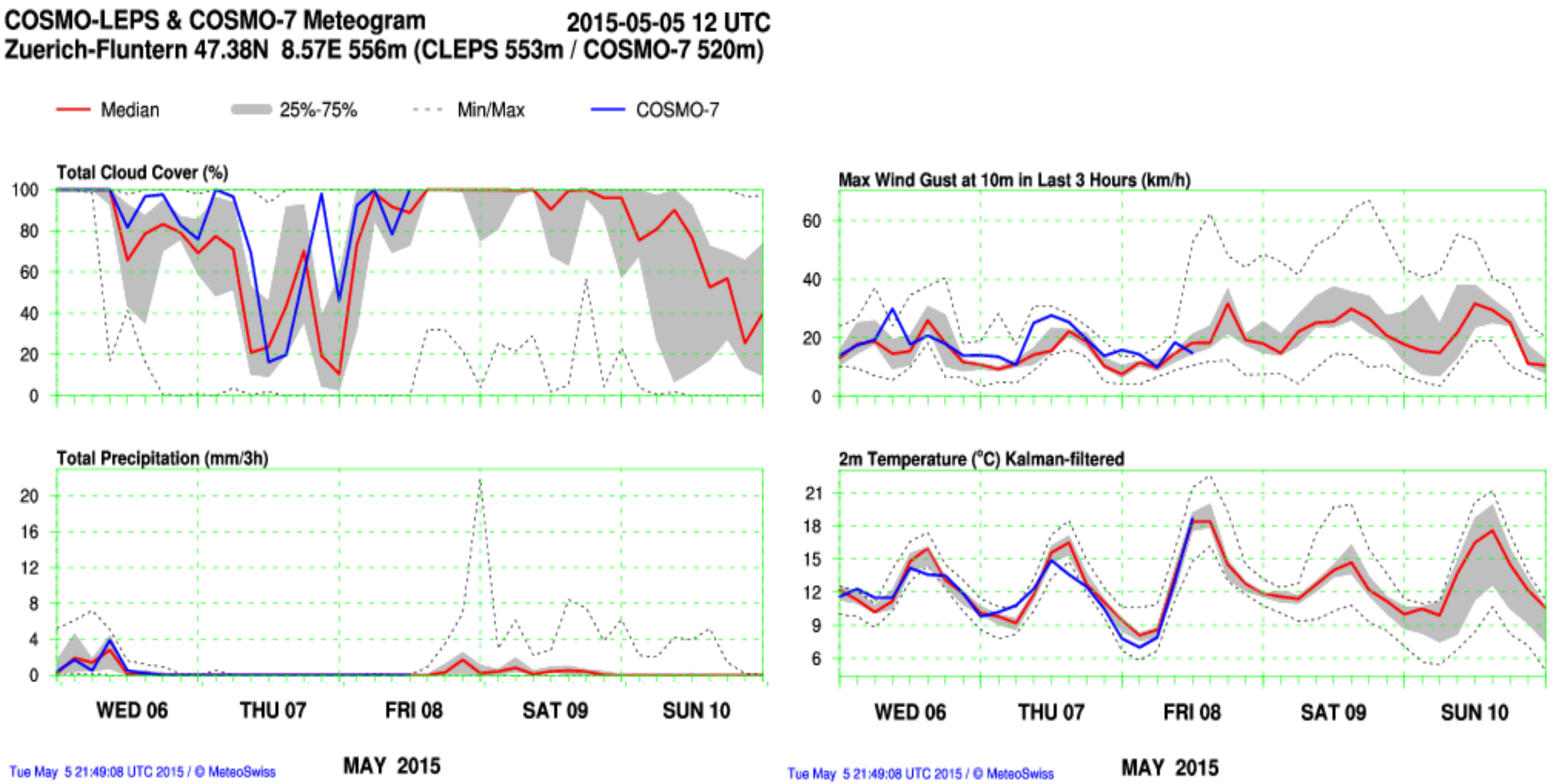
COSMO-LEPS: Limited-area ensemble prediction system

- Model-code: COSMO
- 132-h forecast
- Once a day
- Grid-spacing 10 km, 40 levels
- Ensemble with 16 members
- Based on ECMWF EPS
- Members weighted according to driving model population (ECMWF)



(André Walser, MeteoSwiss)

CLEPS Meteogram from May 5, 12 UTC (Zürich)



(MeteoSwiss)

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• Piedmont flood 1994 •

• Lothar storm 1999 •

• Hurricane Katrina 2005 •

• Alpine flood 2005 •

• Hurricane Sandy 2012 •

Piedmont 1994 Flooding

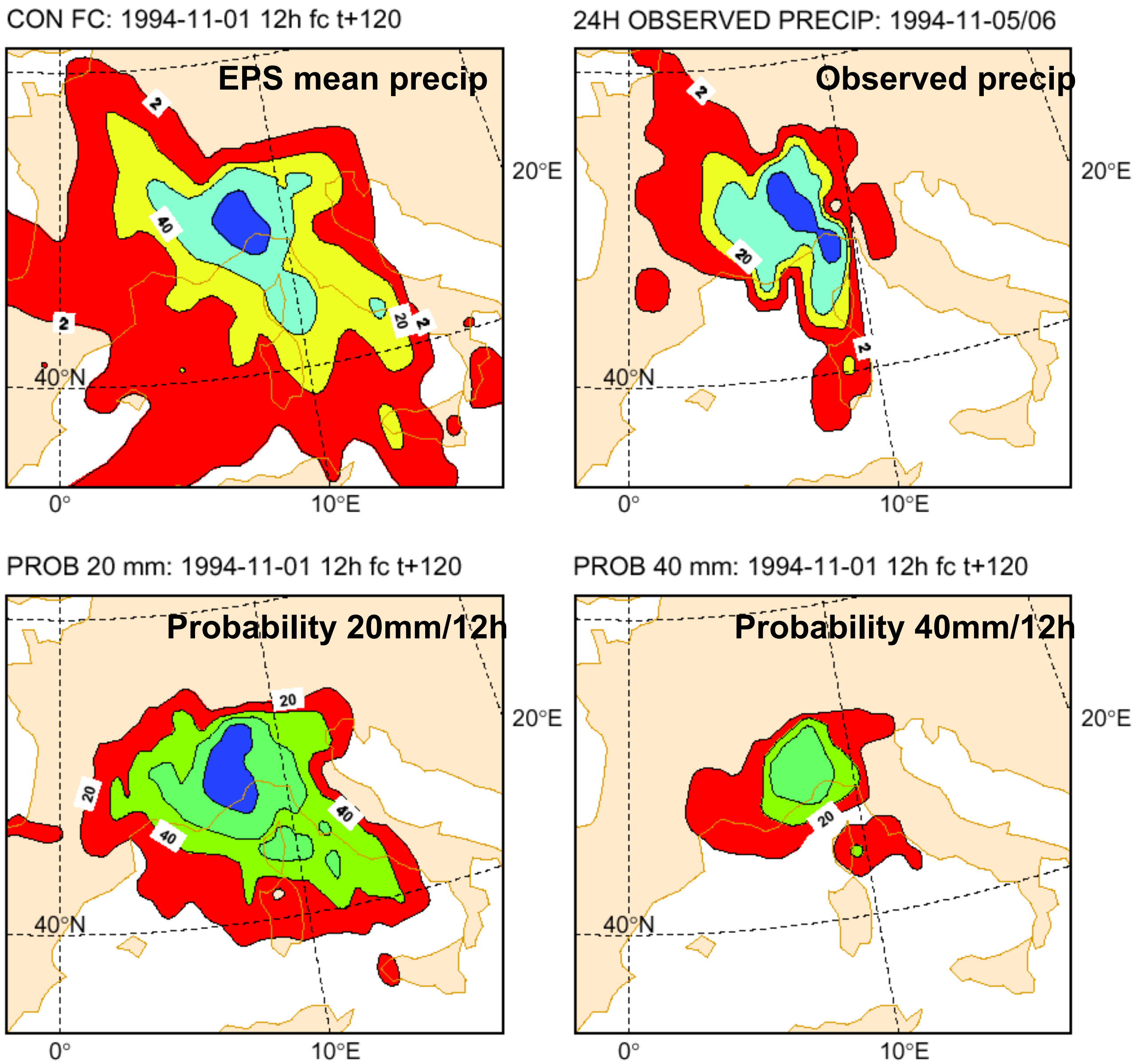
4-6 November 1994

One of the most devastating Alpine floods of the last century.

70 casualties
2000 people evacuated
150 bridges collapsed
~10 billion Euro damage

Poor performance of warning and response operation.

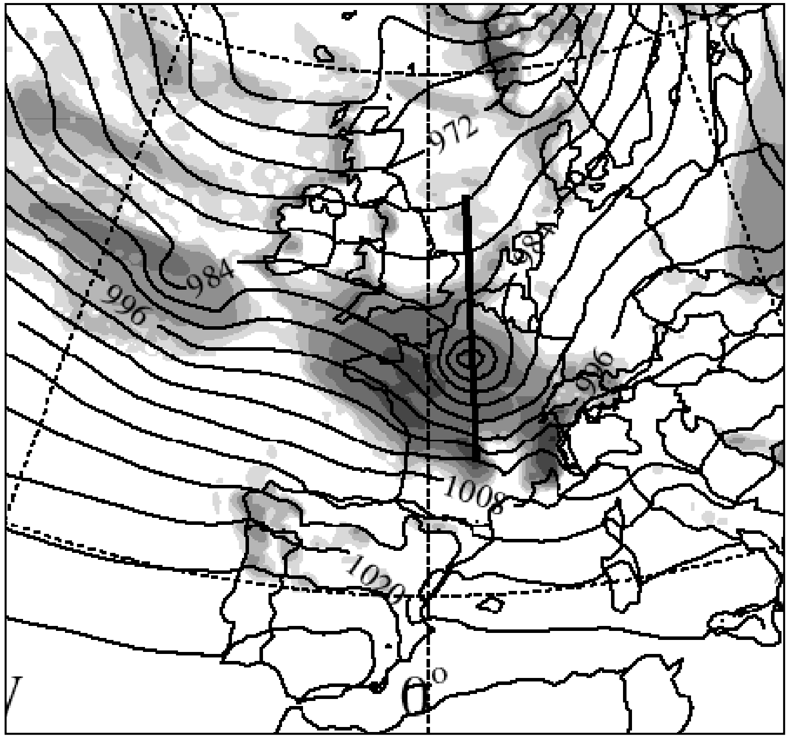
Research (see diagrams) shows that case is well predictable with a lead time of 5 days.



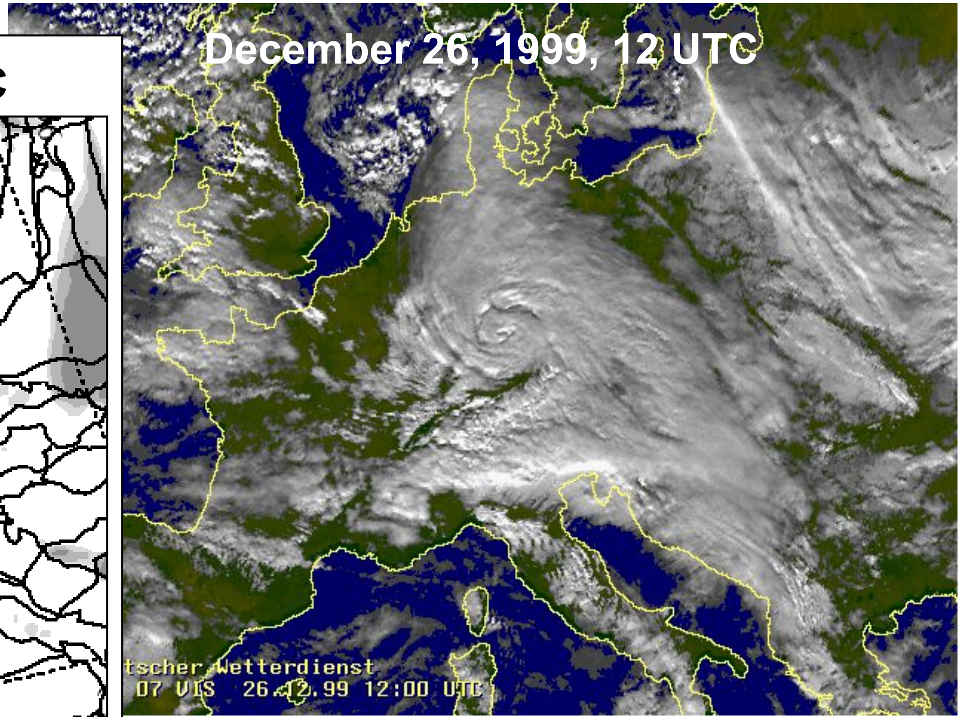
(ECMWF, Buizza 2000)

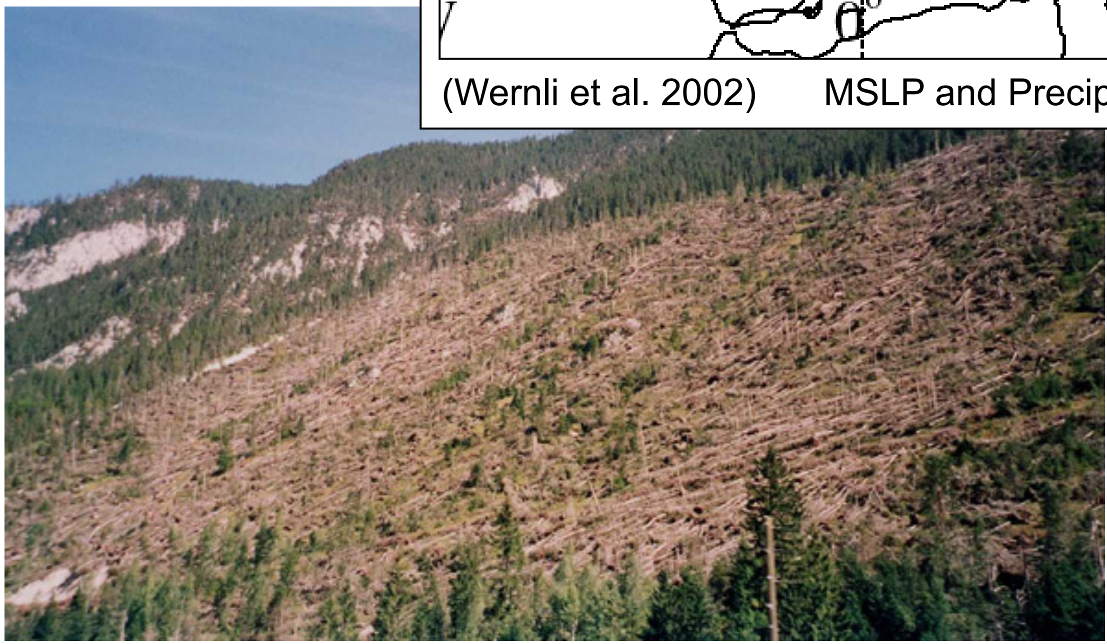
Lothar Storm

December 26, 1999, 06 UTC



(Wernli et al. 2002) MSLP and Precipitation

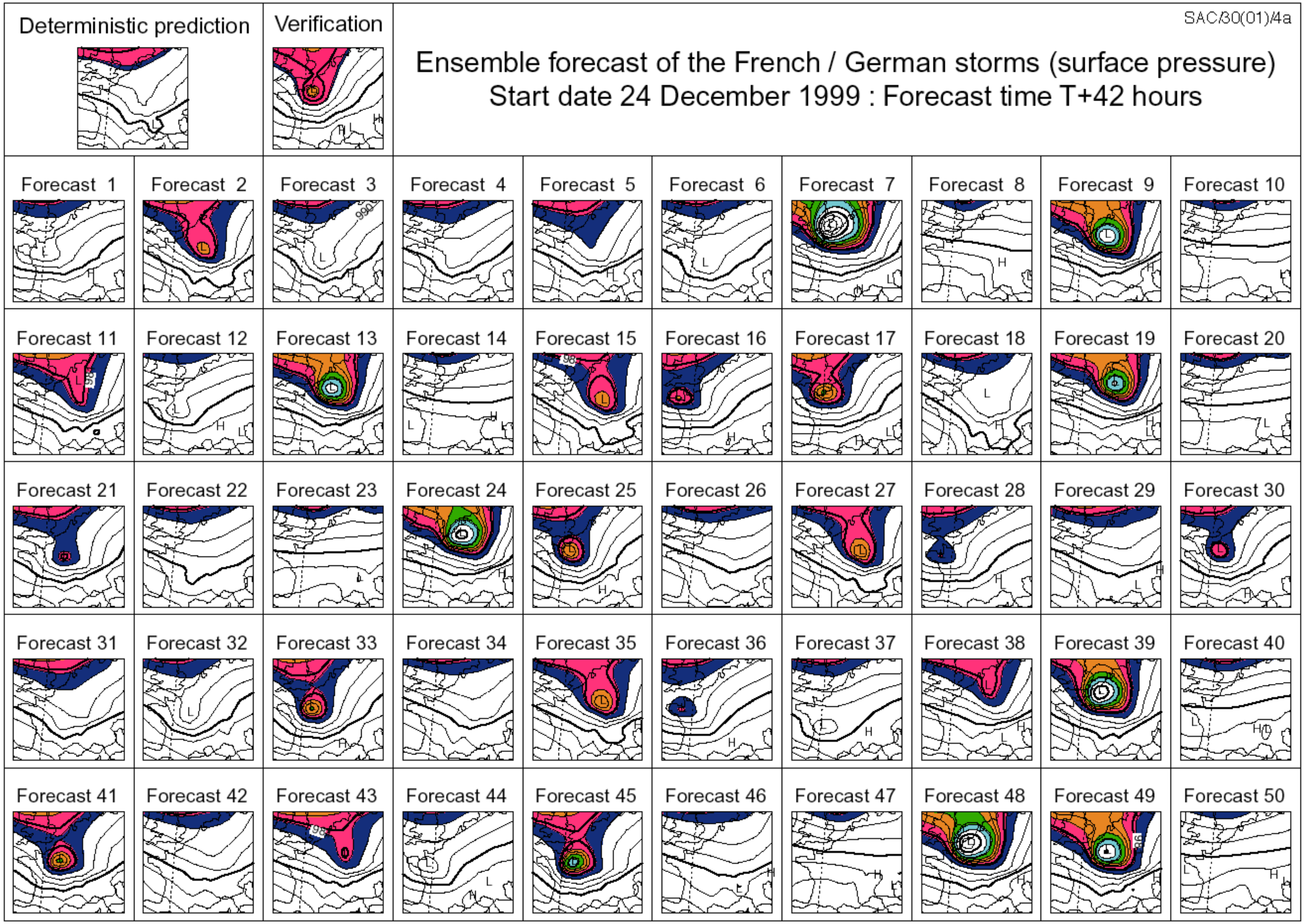




"Kritik wurde am Deutschen Wetterdienst geübt, der trotz modernster, kurz zuvor angeschaffter Computer keine Sturmwarnung herausgegeben hatte – im Gegensatz zu zahlreichen ausländischen und auch privaten deutschen Wetterdiensten."

http://de.wikipedia.org/, May 2007

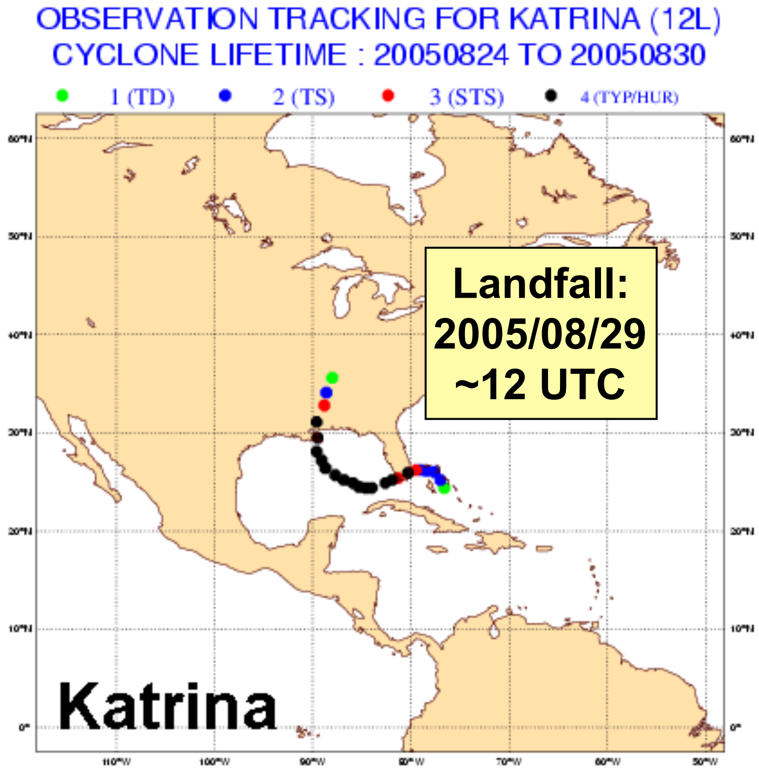
ECMWF ensemble forecast of 1999/12/24, 12 UTC



42h ensemble forecast captured event

(ECMWF, 2001)

Hurricane Katrina



Damage (SwissRe)

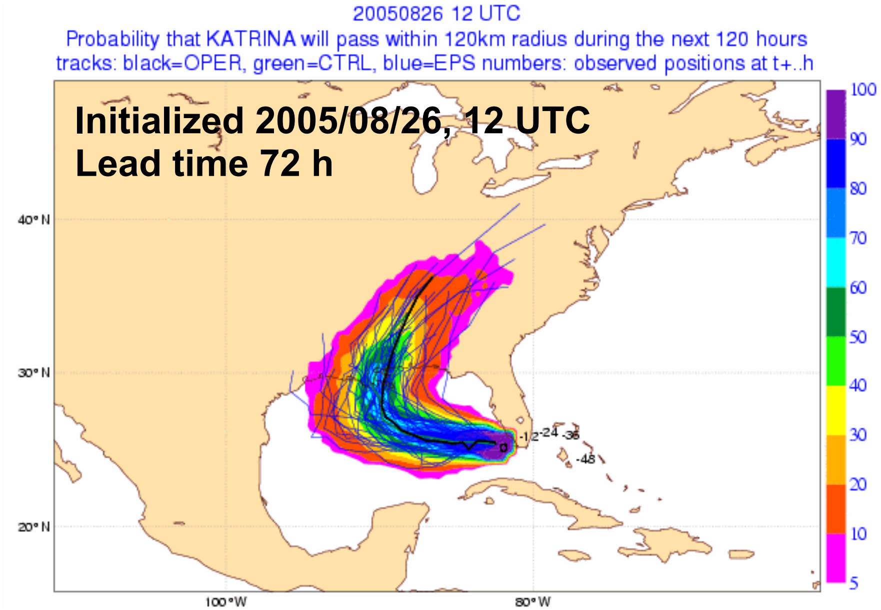
Fatalities: 1326

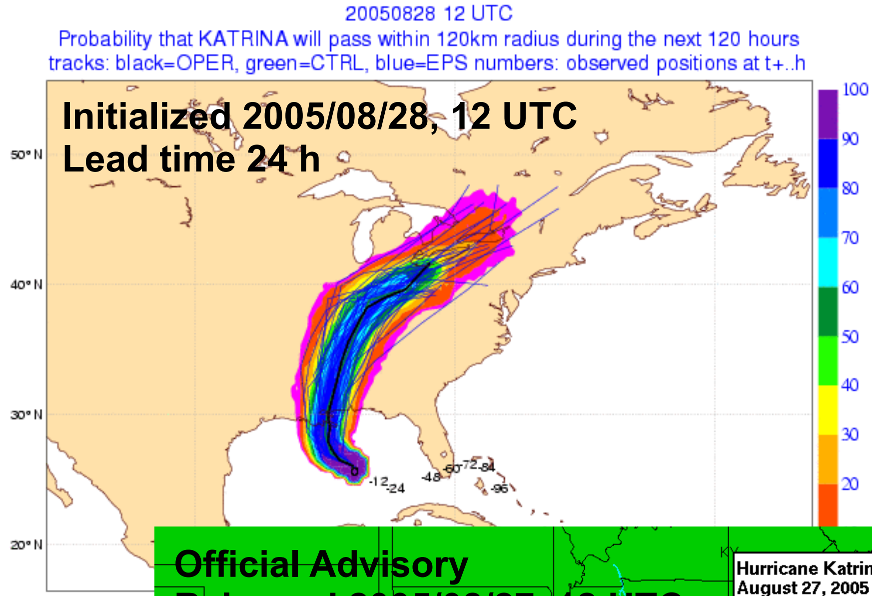
Insured damage:
ca. 45 Billions US$

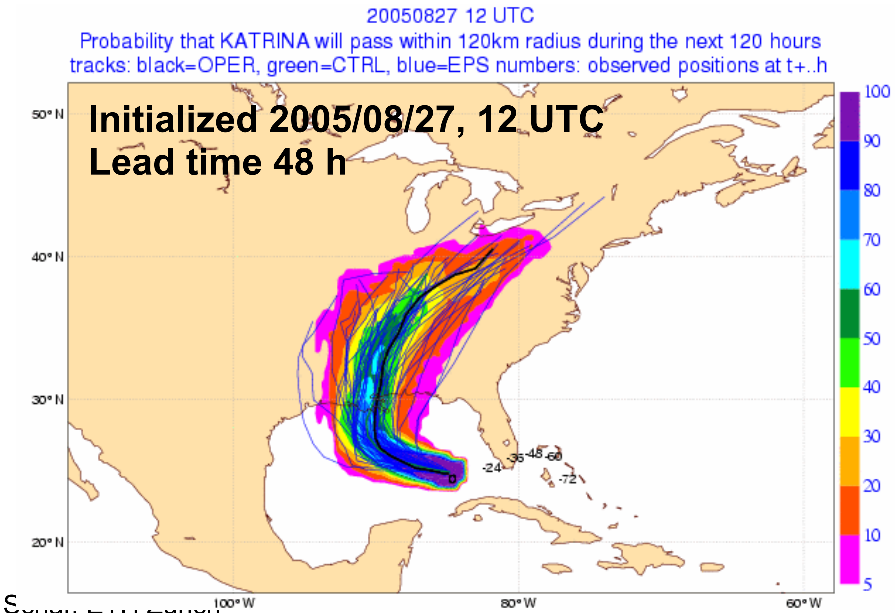
Total damage:
ca. 135 Billions US$

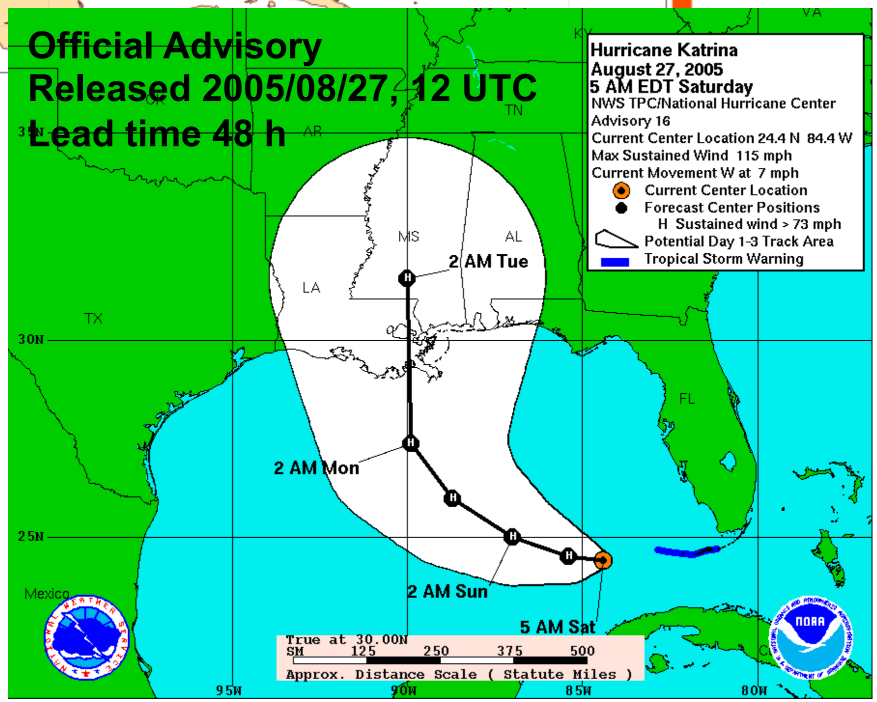
Named Atlantic Storms 2005:
Arlene
Bret
Cindy
Dennis
Emily
Franklin
Gert
Harvey
Irene
Jose
Katrina
Lee
Maria
Nate
Ophelia
Philippe
Rita
Stan
Tammy
Vince
Wilma
Alpha
Beta
Gamma
Delta

Ensemble forecast of Katrina

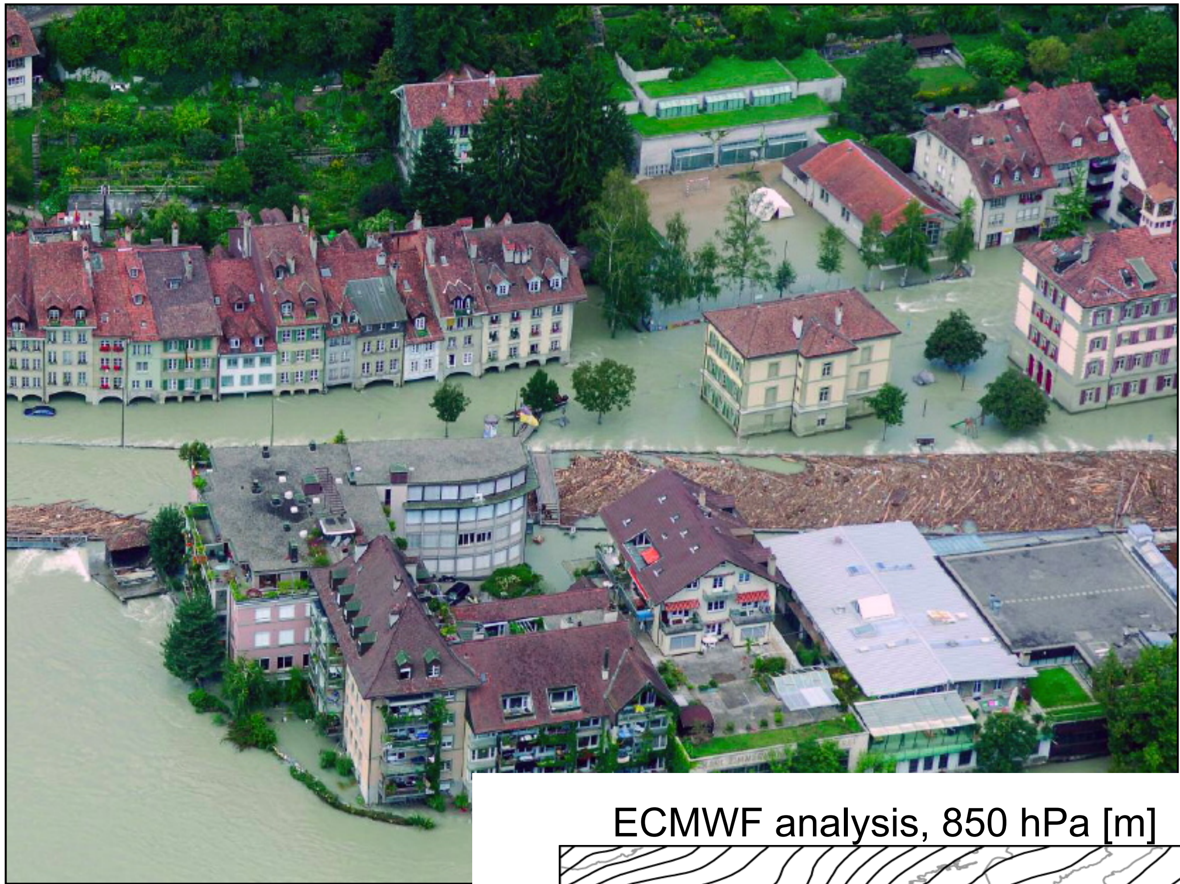


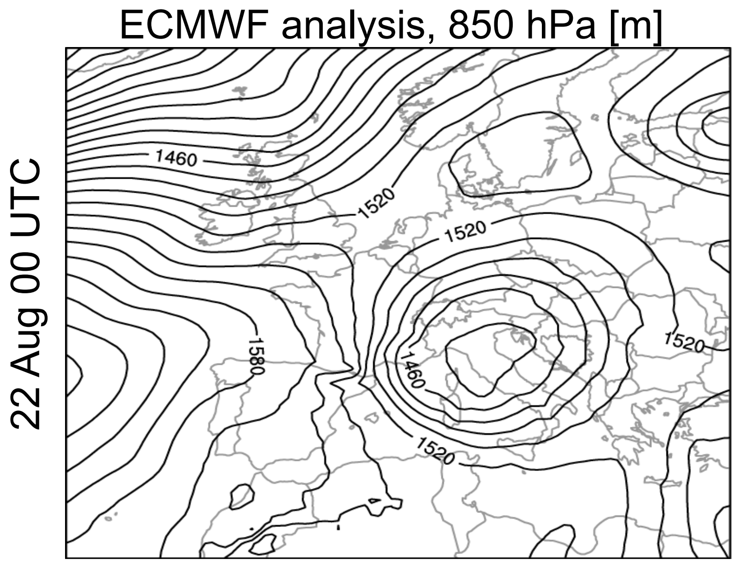






Flood August 2005





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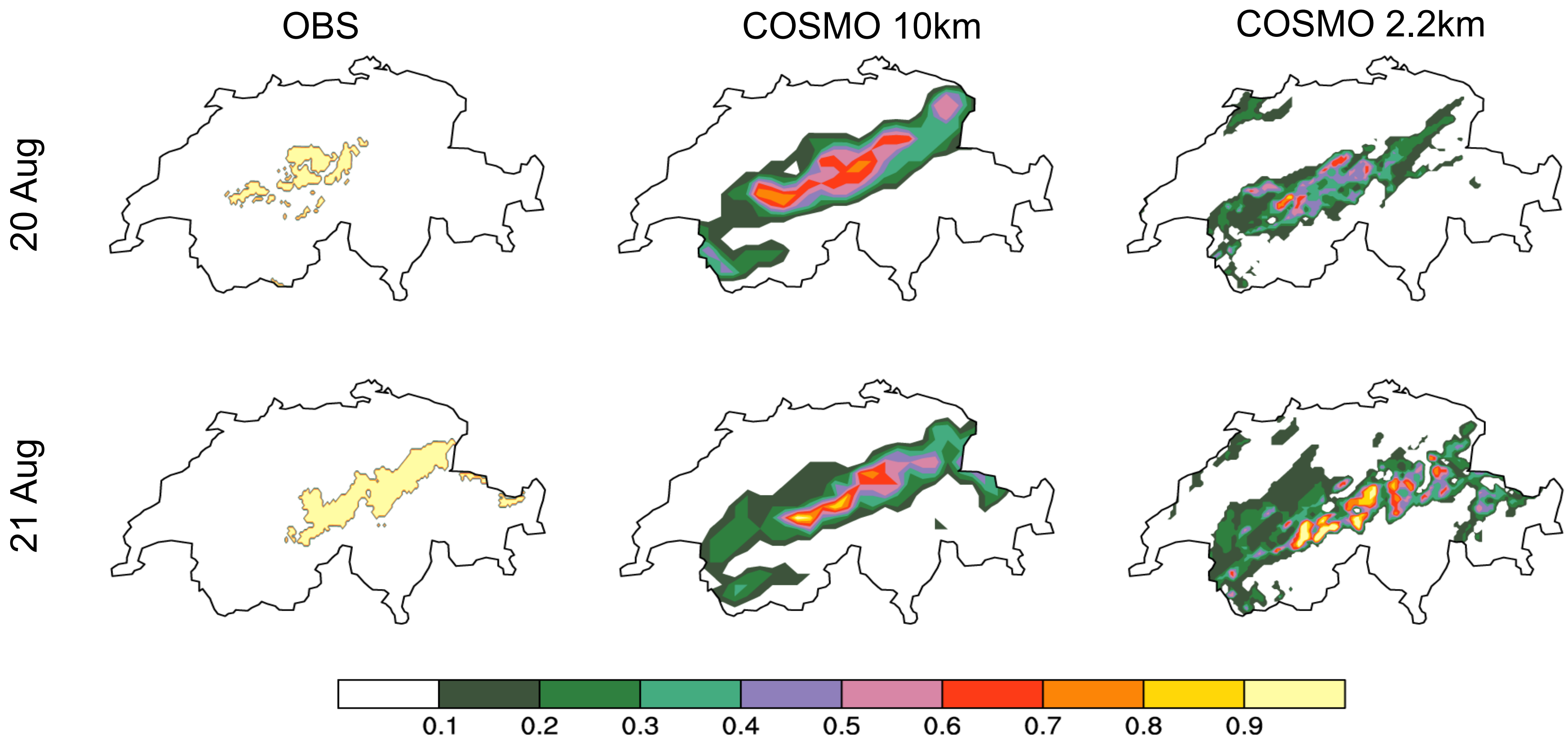
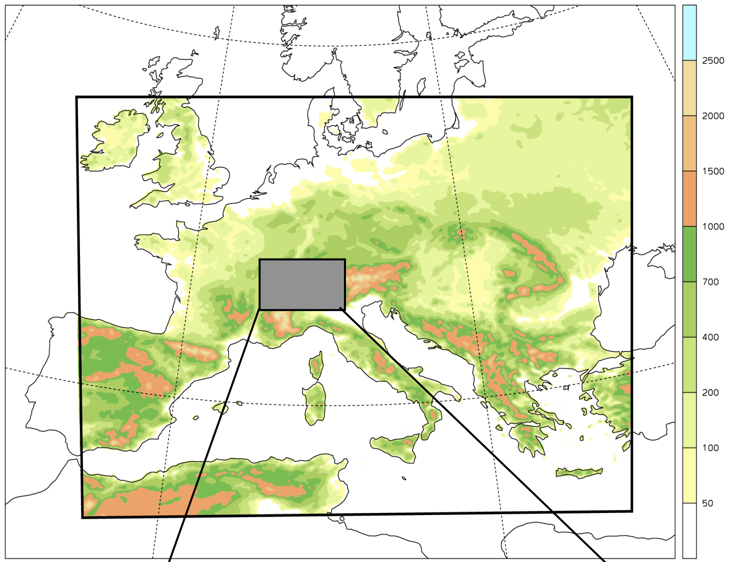
COSMO-LEPS => LM Δx=2.2km

Probability: Accumulated precipitation > 100 mm / day



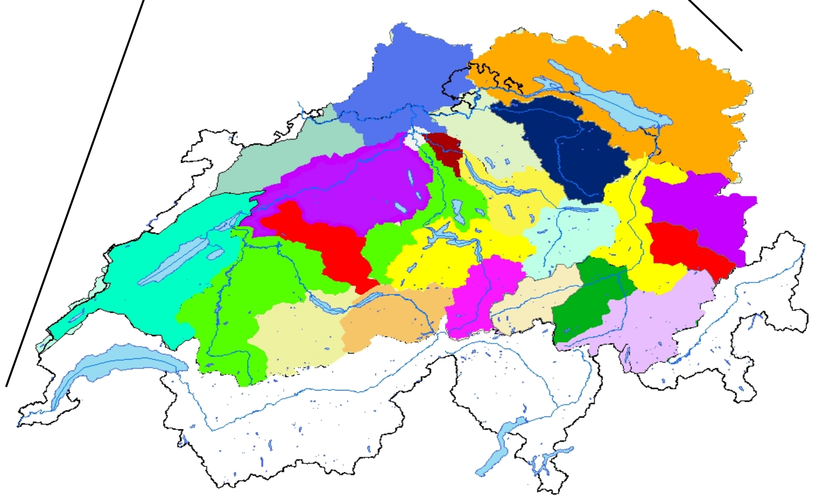
(Hohenegger et al. 2008)

Using COSMO-LEPS for hydrological forecasting



COSMO-LEPS Setup:

- quasi-operational since November 2002
- initial and boundary cond. from ECMWF EPS
- Integration period: 120 h
- Model: COSMO
- Grid-spacing: 10 km, 32 levels



Hydrological Model Setup:

- Rhine upstream of Basel (34550 km^2)
- Model: PREVAH (Gurtz et al. 1999)
- Driven by COSMO-LEPS
- A few test cases with 51 EPS members

Schär, ETH Zürich

(Mark Verbunt, Simon Jaun, ETH Zürich; André Walser, MeteoSchweiz; Chiara Marsigli, Bologna)

Scale-dependencies in hydrological forecasting

(a) major river basins (> 50'000 km^2)

- Short-term forecasting (lead times of ~1 day) can rely on conventional meteorological and hydrological observations (i.e. precipitation and runoff observations upstream) in combination with hydrological modeling.
- Results from large-scale weather forecasting models can successfully be applied to extend the forecasting range past 24 h.

(b) intermediate-scale catchments (1000-50'000 km^2)

- Combination of hydrological modeling and rainfall forecast is essential for short-term forecasting.
- Mesoscale atmospheric models with high horizontal resolutions needed, in particular in mountainous terrain.

(c) small-scale catchments (<1000 km^2)

- Intrinsic forecasting limits of the atmospheric dynamics become relevant, precipitation forecasting may be limited to a few hours (as individual thunderstorms and convective cells may become relevant). Current NWP models are not well suited, due to operational time constraints.
- Weather radar information and conventional precipitation measurements (nowcasting) may be the best choice at present.

Coupling of meteorological and hydrological models

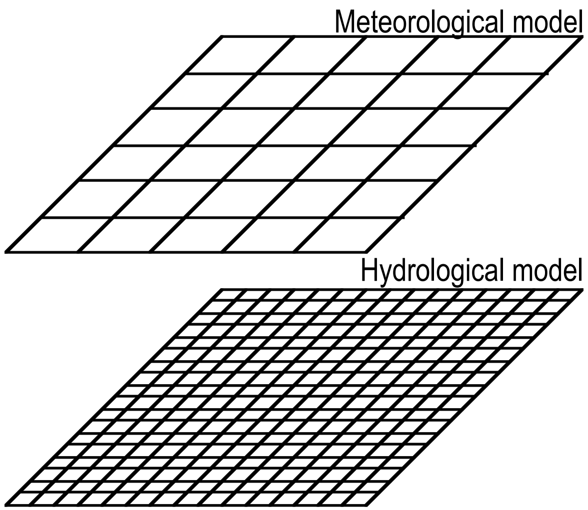
Atmospheric models:

General Circulation Models: Δx = 200 to 50 km

Limited-Area Models: Δx = 20 to 1 km

Hydrological models:

Distributed Hydrological Models: Δx = 5 km to 100 m

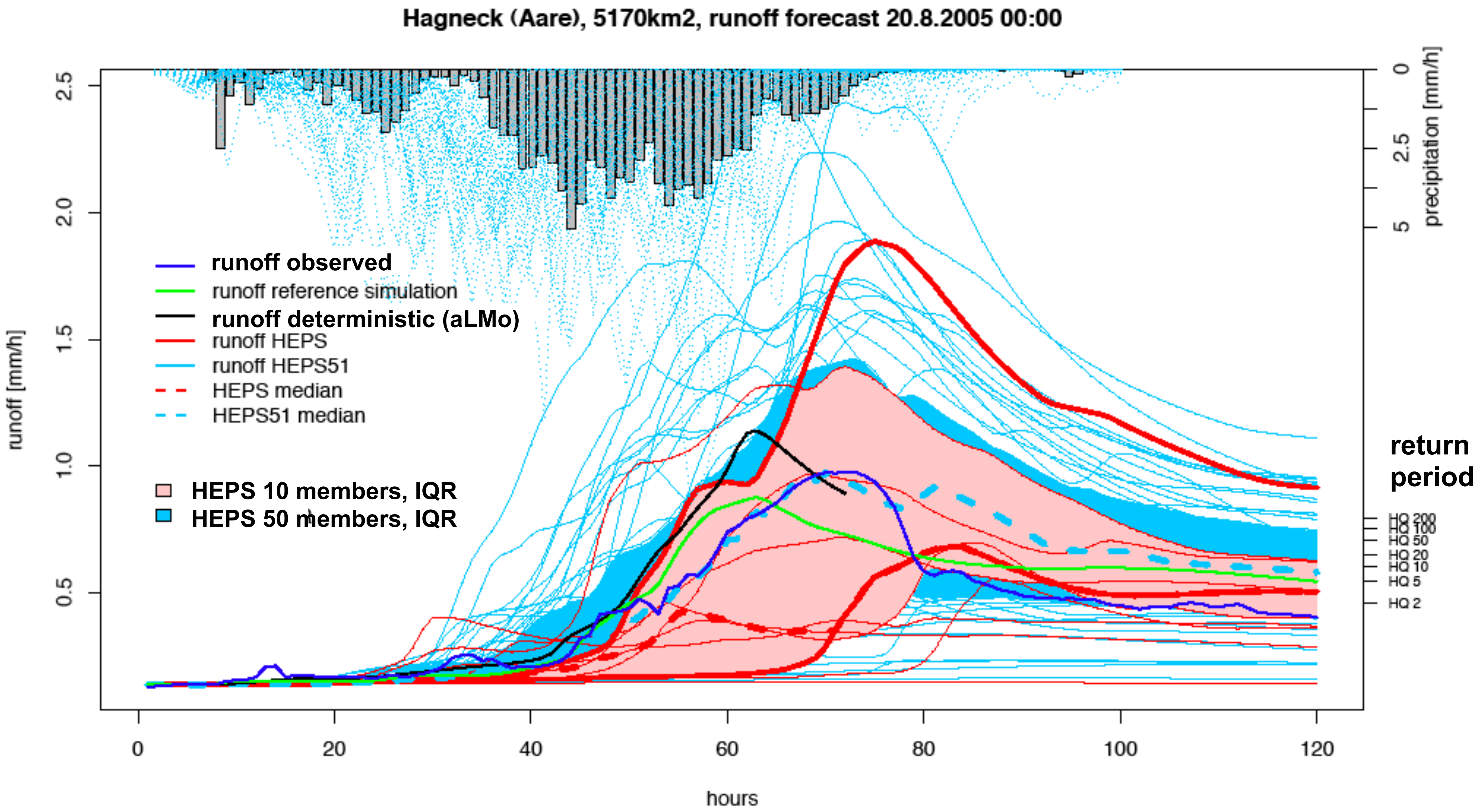


Disaggregation ↓ **Downscaling**

Aggregation ↑ **Upscaling**

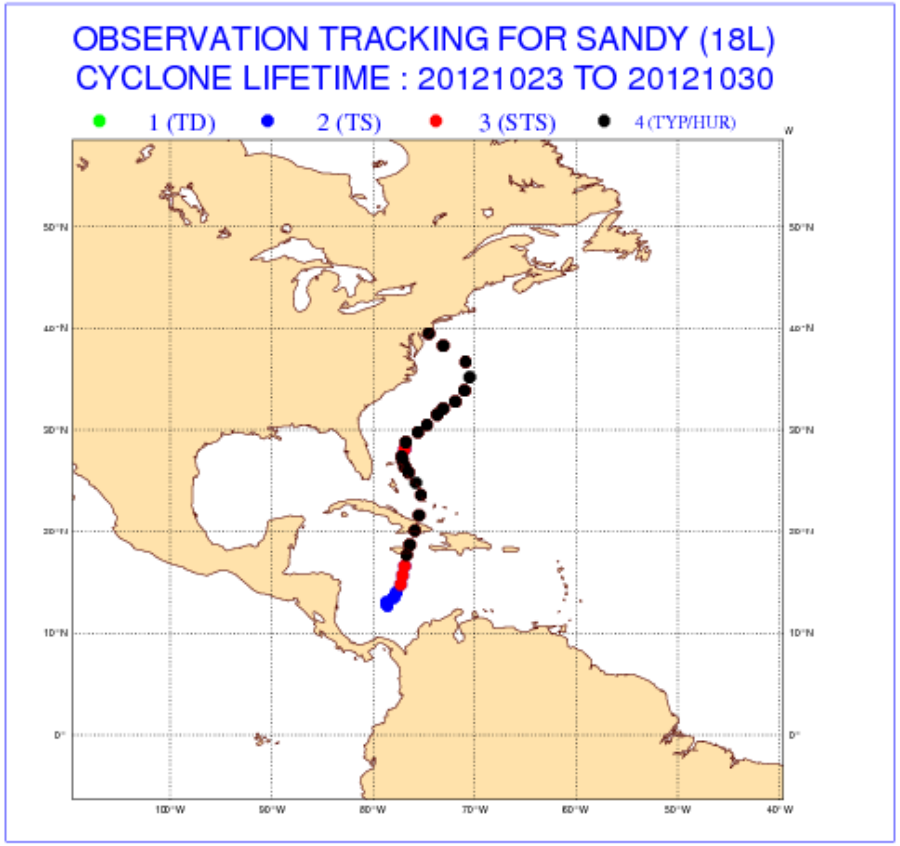
Currently, most forecasting systems restrict attention to one-way coupling

ECMWF => COSMO-LEPS => PREVAH

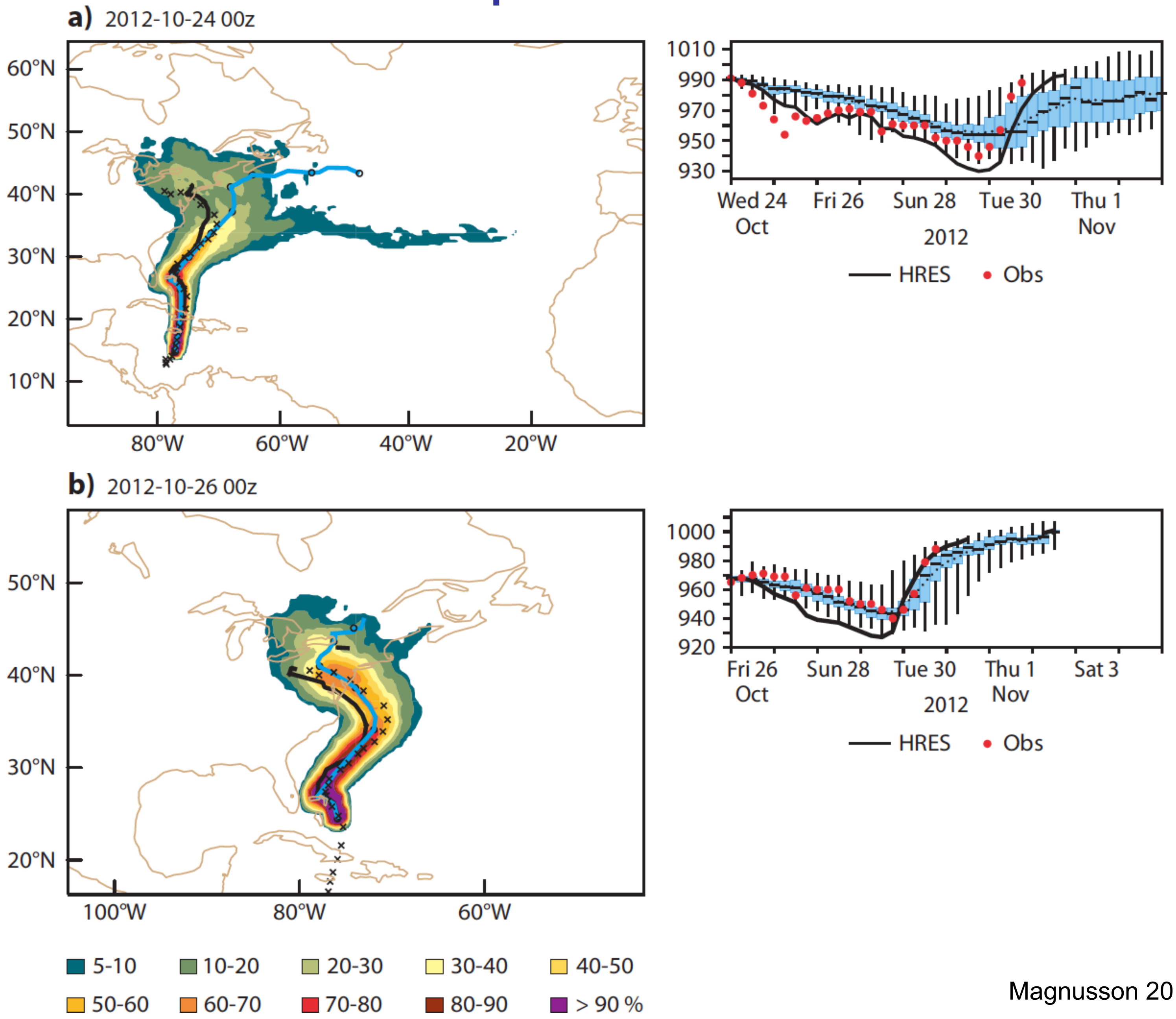


(Jaun et al. 2008)

Hurricane Sandy

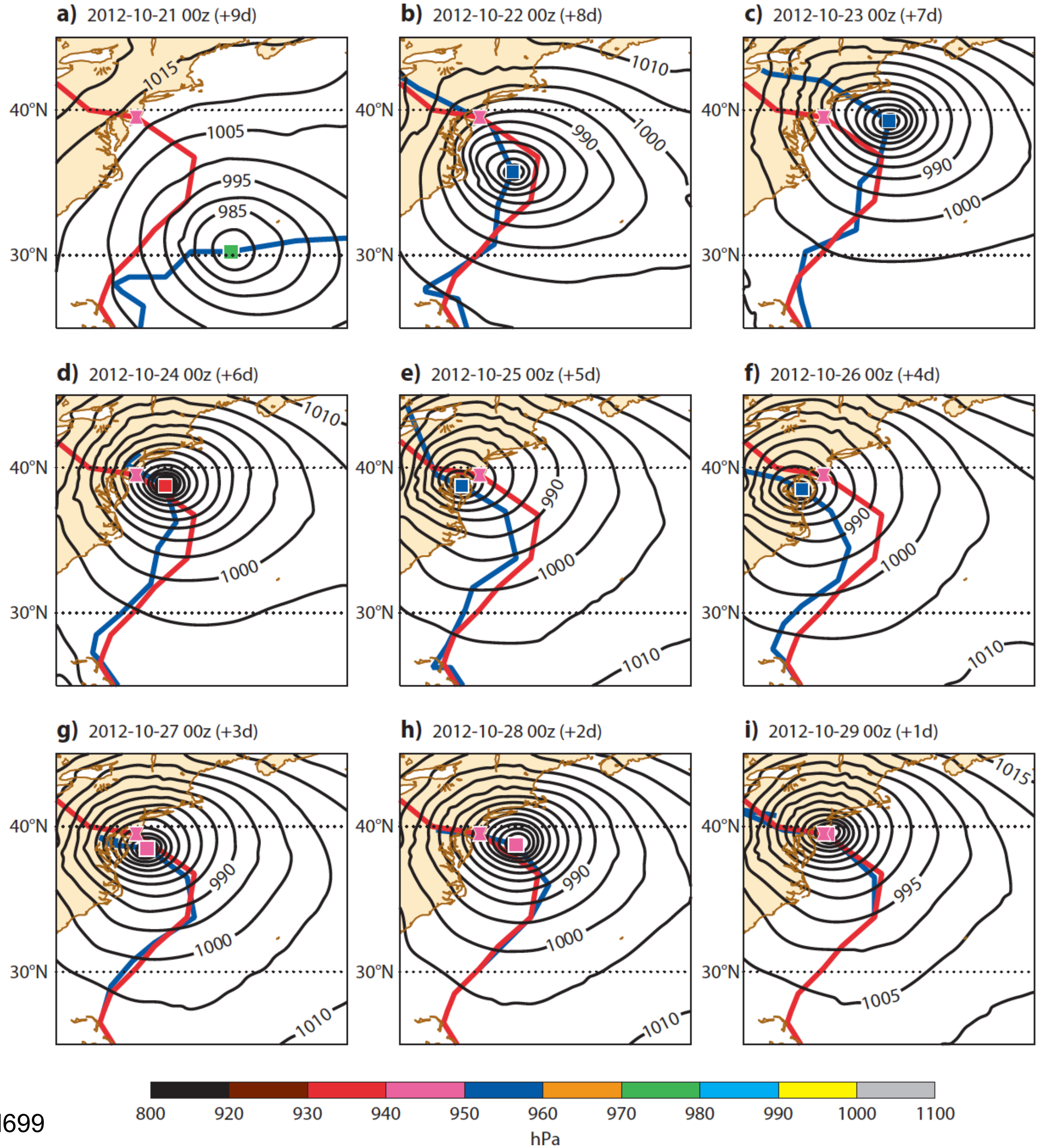


Strike probabilities



Magnusson 2013, ECMF, TM699

Surface forecasts



Schär, ETH Zürich

Magnusson 2013, ECMF, TM699

Summary

- Deterministic NWP has dramatically improved in the last 30 years. Today a 120h weather forecast is better than a 32h forecast in 1982.
- The atmosphere and the oceans are chaotic dynamical systems. This implies intrinsic predictability limitations, even a perfect model and perfect observations would not resolve the issue!
- Probabilistic forecasting techniques are superior for such systems! Operational ensemble predictions in NWP started about 1990, initially for medium-range NWP (> 3 days).
- Increasingly used in a wide range of applications, including:
  - short and medium-range NWP, including extremes events
  - hydrological prediction
  - monthly and seasonal forecasting
  - climate change