Severe-weather and extreme-event forecasting using ensembles

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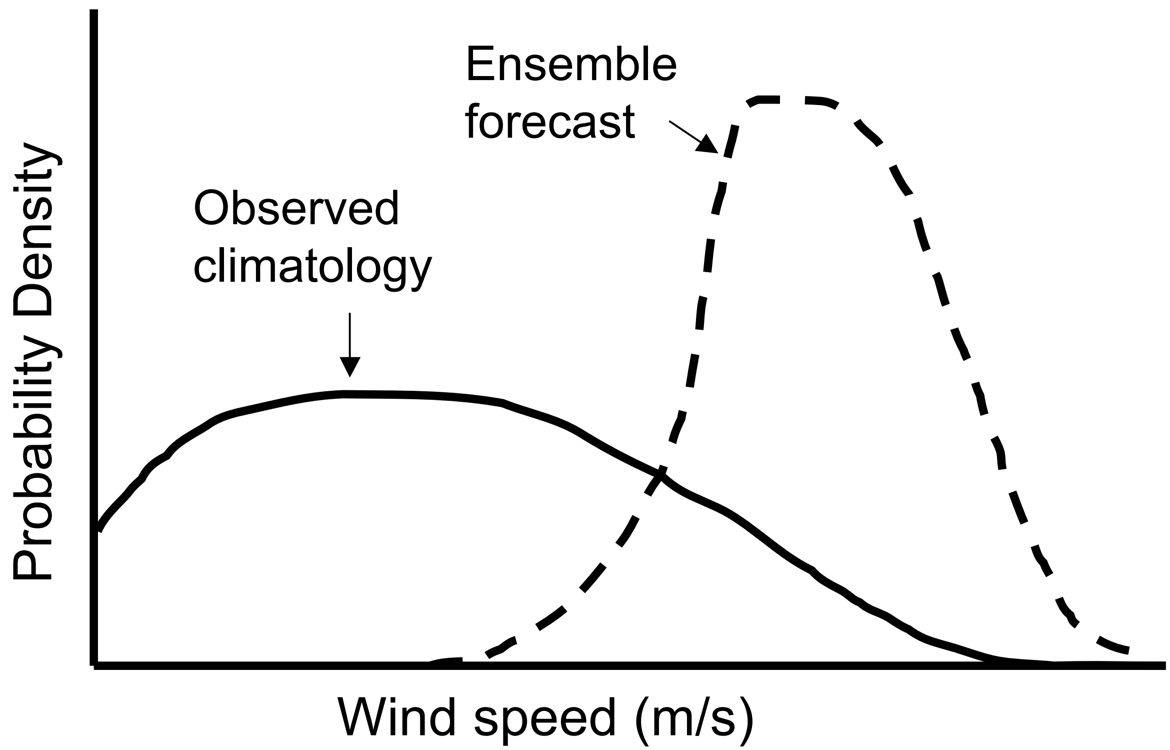
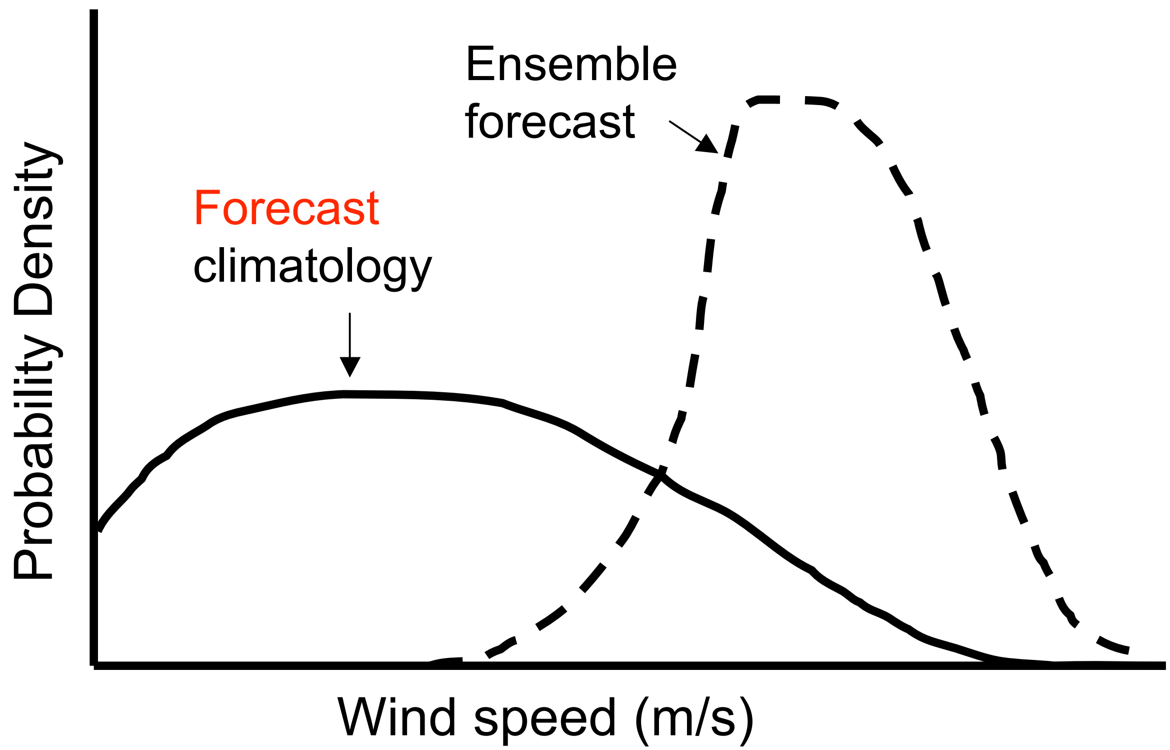
Is this a predictable extreme event?



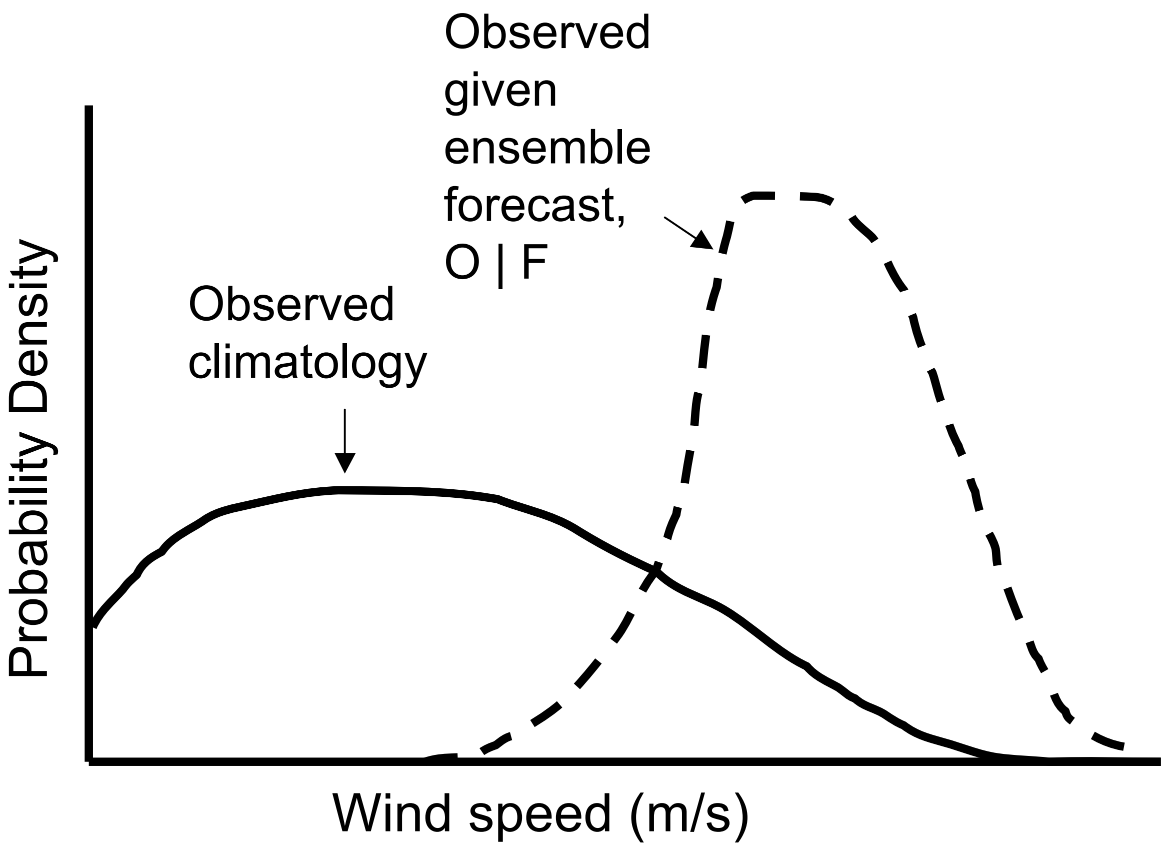
A: Not necessarily so. Perhaps the ensemble forecast is strongly biased toward high wind speeds.

Is this a predictable extreme event?



A: Not necessarily so. Is there a strong correlation between F' and O', so that a high forecast anomaly indicates a high observed anomaly?

Is this a predictable extreme event?



A: Yes.

Some proposed general characteristics of predictability

- If extreme event is large in scale, or if it is driven by large scales, or if there strong flow to sweep mesoscale perturbations away from convective source region ➔ possible days of predictability.

- Not driven by large scales ➔ more classical Lorenz ‘69 predictability ➔ hours of predictability. Also, model errors may be more pronounced, limiting predictive ability.

Predictability vs. predictive ability

- **Predictability**: the timescale at which a phenomenon can be predicted with skill relative to climatology. An innate characteristic of the atmospheric environment and the phenomenon.
  - Commonly estimated from perfect-model twin experiments (which are too optimistic).
- **Predictive ability**: the time span at which the modeling system to make a skillful prediction of the event in question.
- Time span of predictive ability < time span of predictability due to model error.

Example of possible extended mesoscale predictive ability: SREF probability of “significant tornado”

48 hr *SREF Forecast Valid 21 UTC 7 April 2006*

Prob (MLCAPE $\geq$ 1000 Jkg^{-1})

X

Prob (6 km Shear $\geq$ 40 kt)

X

Prob (0-1 km SRH $\geq$ 100 m^2s^{-2})

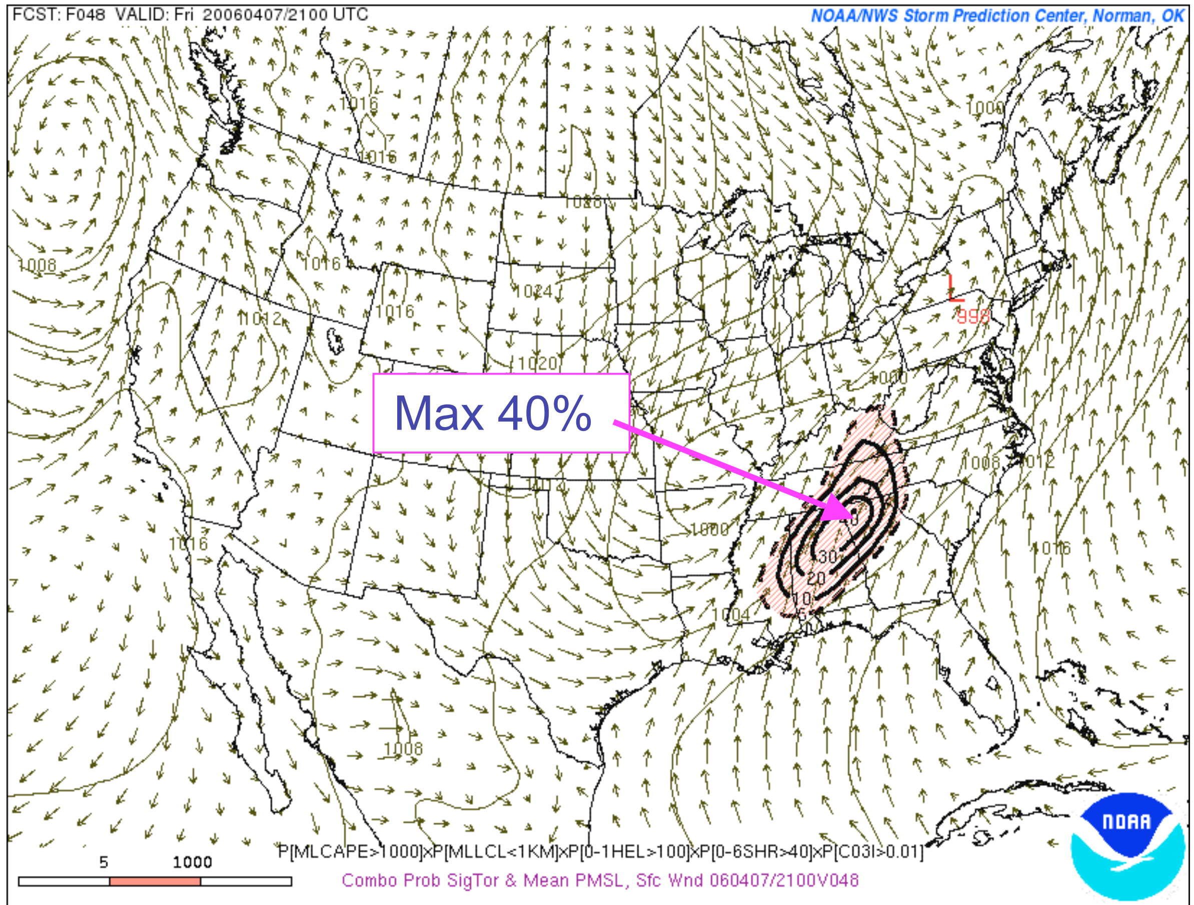
X

Prob (MLLCL $\leq$ 1000 m)

X

Prob (3h conv. Pcpn $\geq$ 0.01 in)

Shaded Area Prob $\geq$ 5%



Example from David Bright, SPC, using Jun Du’s NCEP SREF system

(MLCAPE = CAPE using lowest 100 hPa)

Example of possible extended mesoscale predictive ability: SREF probability of “significant tornado”

36 hr *SREF Forecast Valid 21 UTC 7 April 2006*

Prob (MLCAPE $\geq$ 1000 Jkg^{-1})

X

Prob (6 km Shear $\geq$ 40 kt)

X

Prob (0-1 km SRH $\geq$ 100 m^2s^{-2})

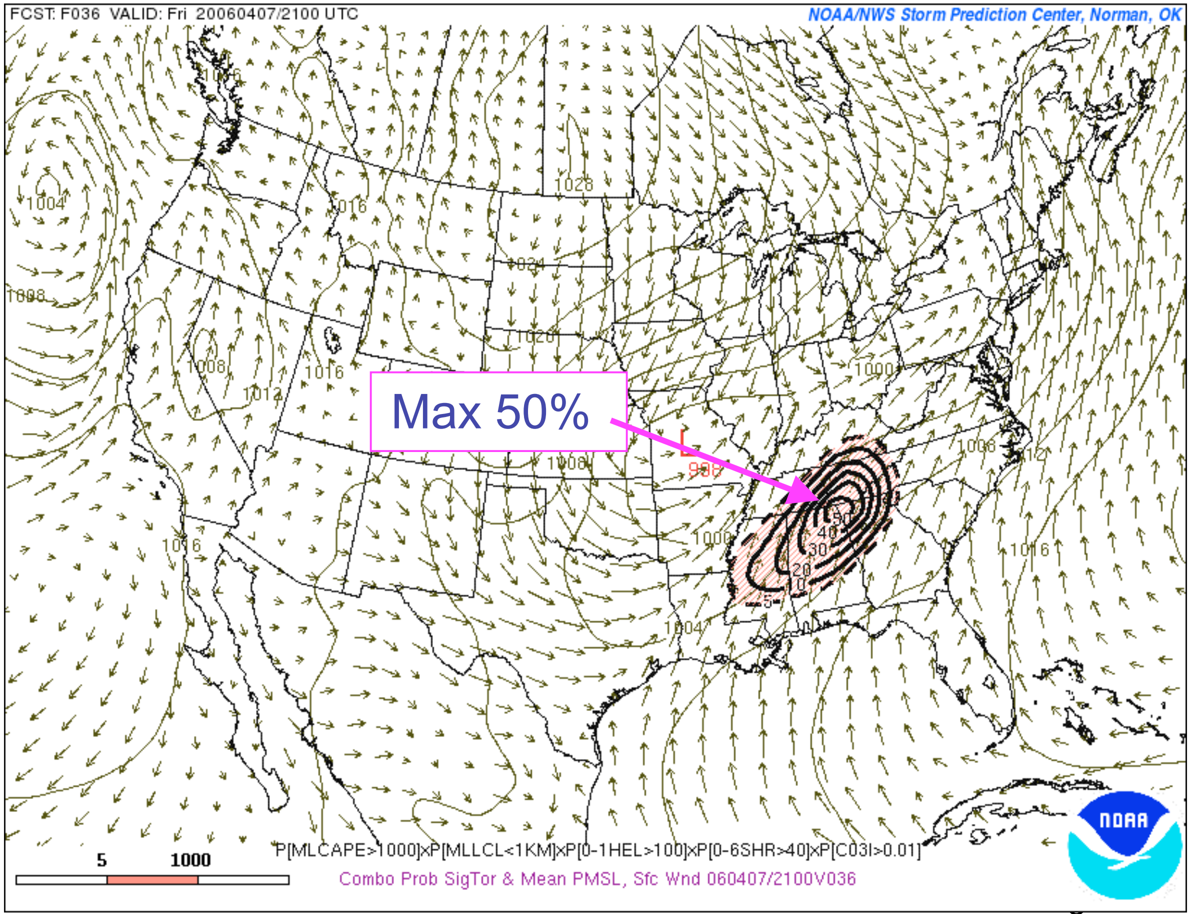
X

Prob (MLLCL $\leq$ 1000 m)

X

Prob (3h conv. Pcpn $\geq$ 0.01 in)

Shaded Area Prob $\geq$ 5%



Example of possible extended mesoscale predictive ability: SREF probability of "significant tornado"

24 hr *SREF Forecast Valid 21 UTC 7 April 2006*

Prob (MLCAPE $\geq$ 1000 Jkg^{-1})

X

Prob (6 km Shear $\geq$ 40 kt)

X

Prob (0-1 km SRH $\geq$ 100 m^{2}s^{-2})

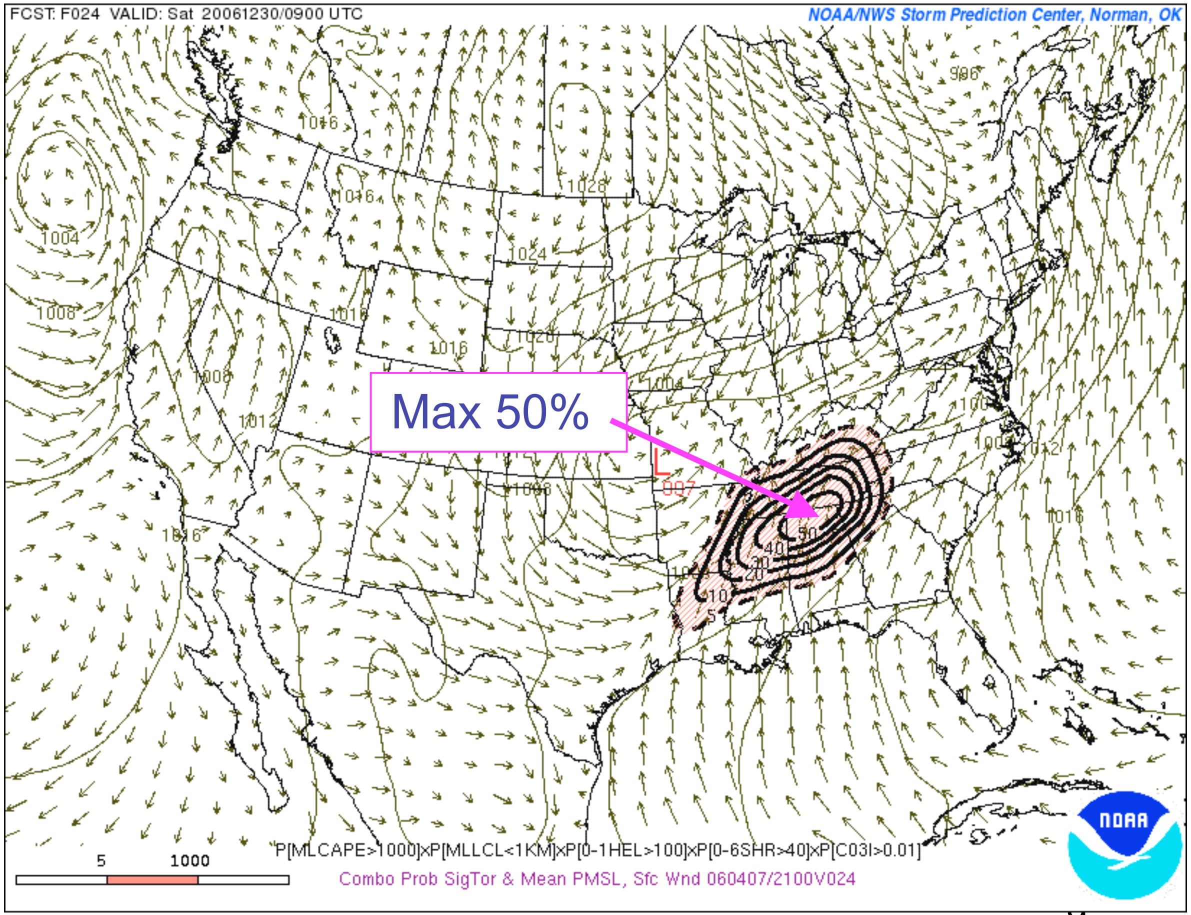
X

Prob (MLLCL $\leq$ 1000 m)

X

Prob (3h conv. Pcpn $\geq$ 0.01 in)

Shaded Area Prob $\geq$ 5%



Example of possible extended mesoscale predictive ability: SREF probability of “significant tornado”

12 hr *SREF Forecast Valid 21 UTC 7 April 2006*

Prob (MLCAPE $\geq$ 1000 Jkg^{-1})

X

Prob (6 km Shear $\geq$ 40 kt)

X

Prob (0-1 km SRH $\geq$ 100 m^2s^{-2})

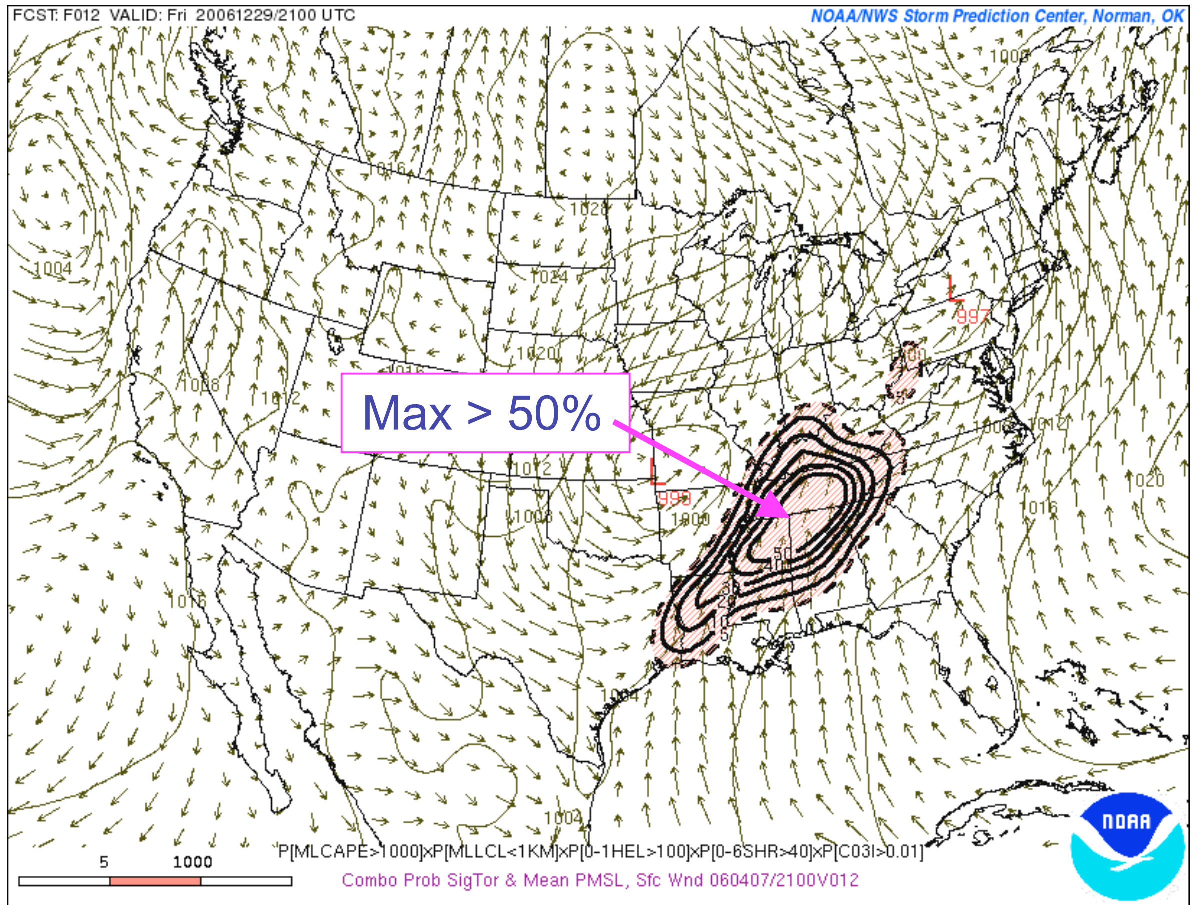
X

Prob (MLLCL $\leq$ 1000 m)

X

Prob (3h conv. Pcpn $\geq$ 0.01 in)

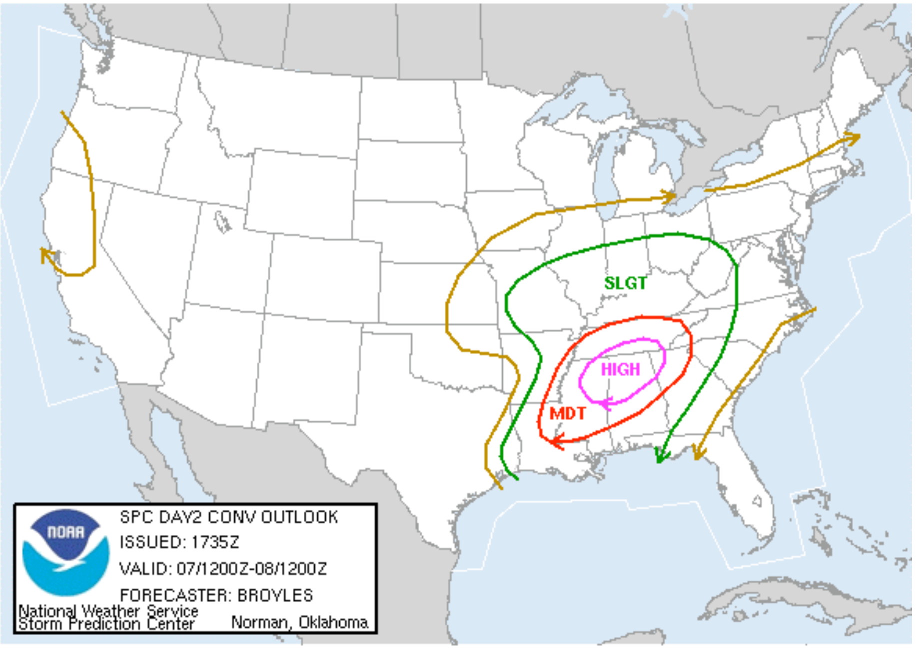
Shaded Area Prob $\geq$ 5%

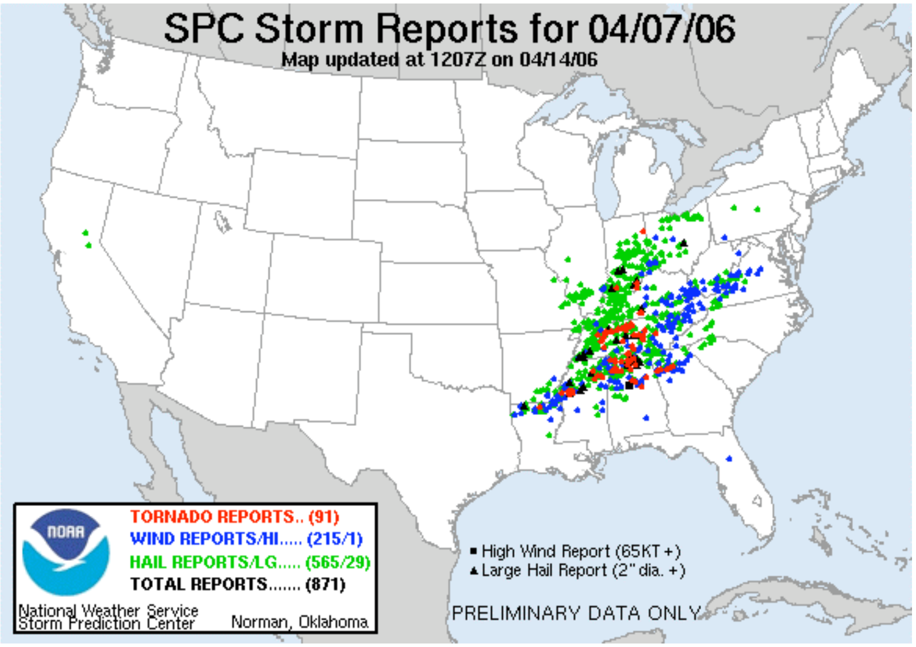


Tornadoes related to large-scale patterns of instability and shear, often predictable several days hence.

Tornado outbreak of April 7, 2006

- **First ever** day-2 outlook "high risk" of severe weather issued by NOAA Storm Prediction Center; in past have been cautious.
- Diagnostics from SREF and good past SREF performance aided forecaster confidence
- > 800 total severe reports, 3 killer tornadoes,10 deaths

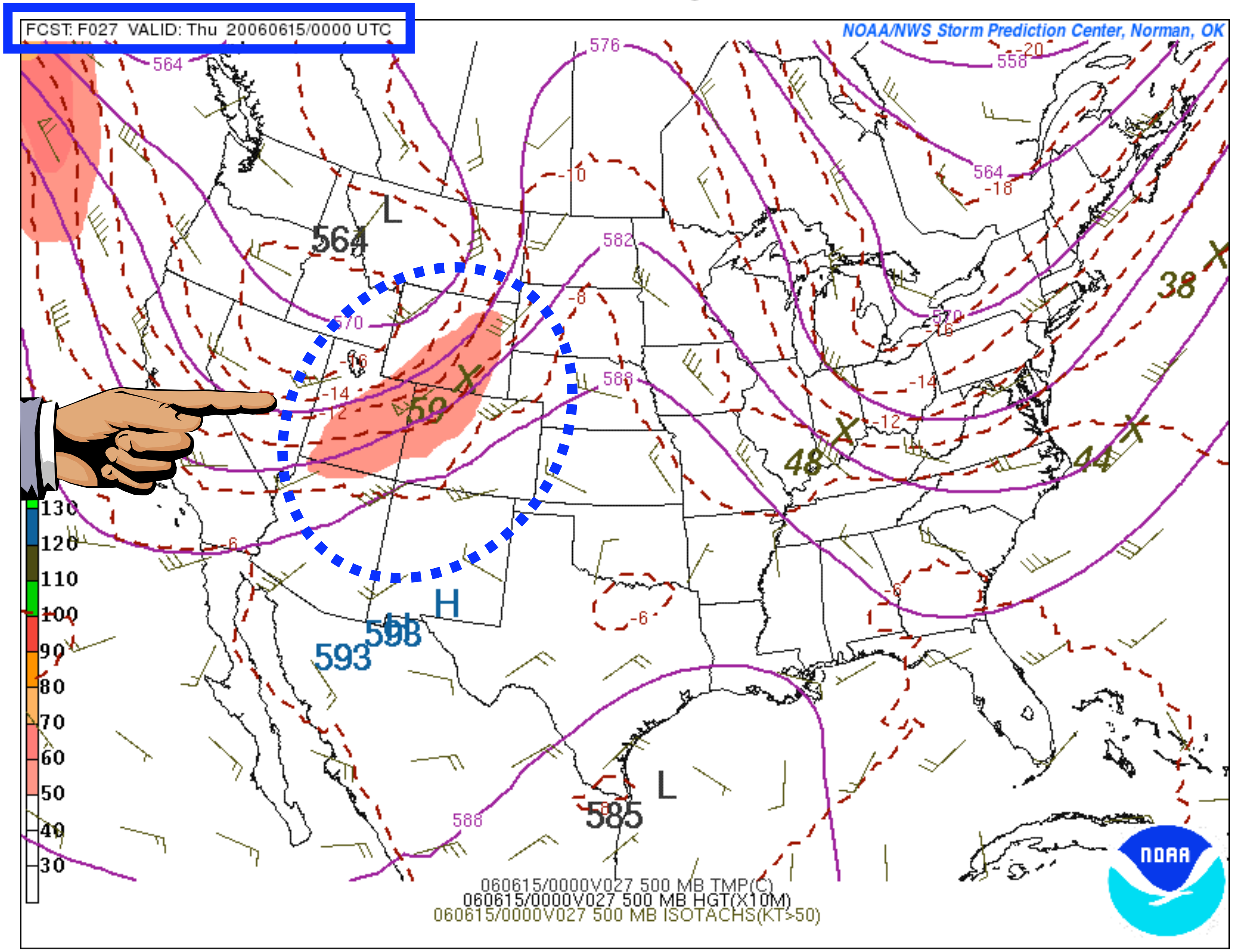




Example of predicting extreme event from ensemble's large-scale environment : US fire-weather forecasting

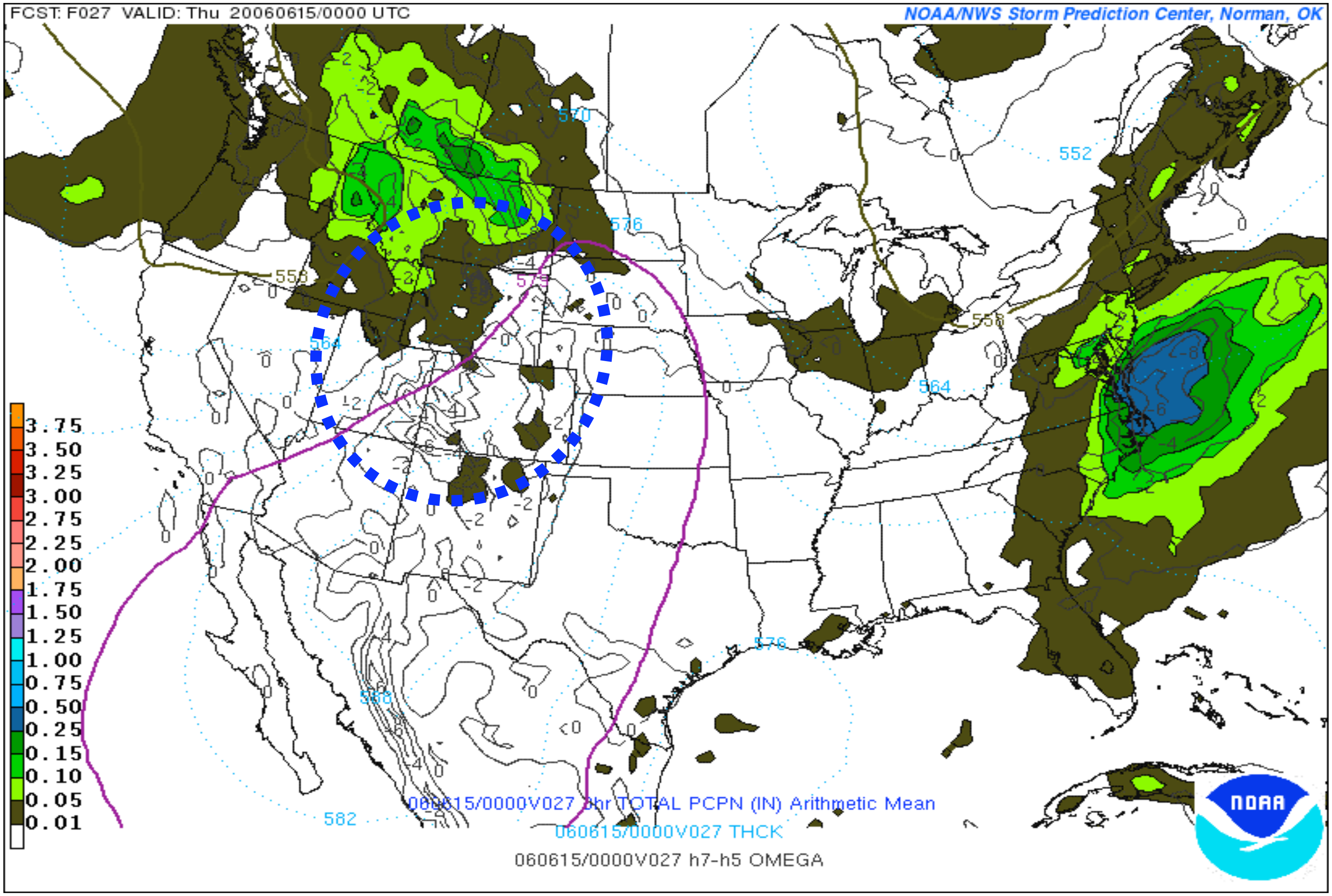
- Ingredients from large-scale conditions:
  - High wind speeds
  - Hot temperatures
  - Low relative humidity near surface
  - Little rainfall

SREF 500 hPa mean height, wind, temperature



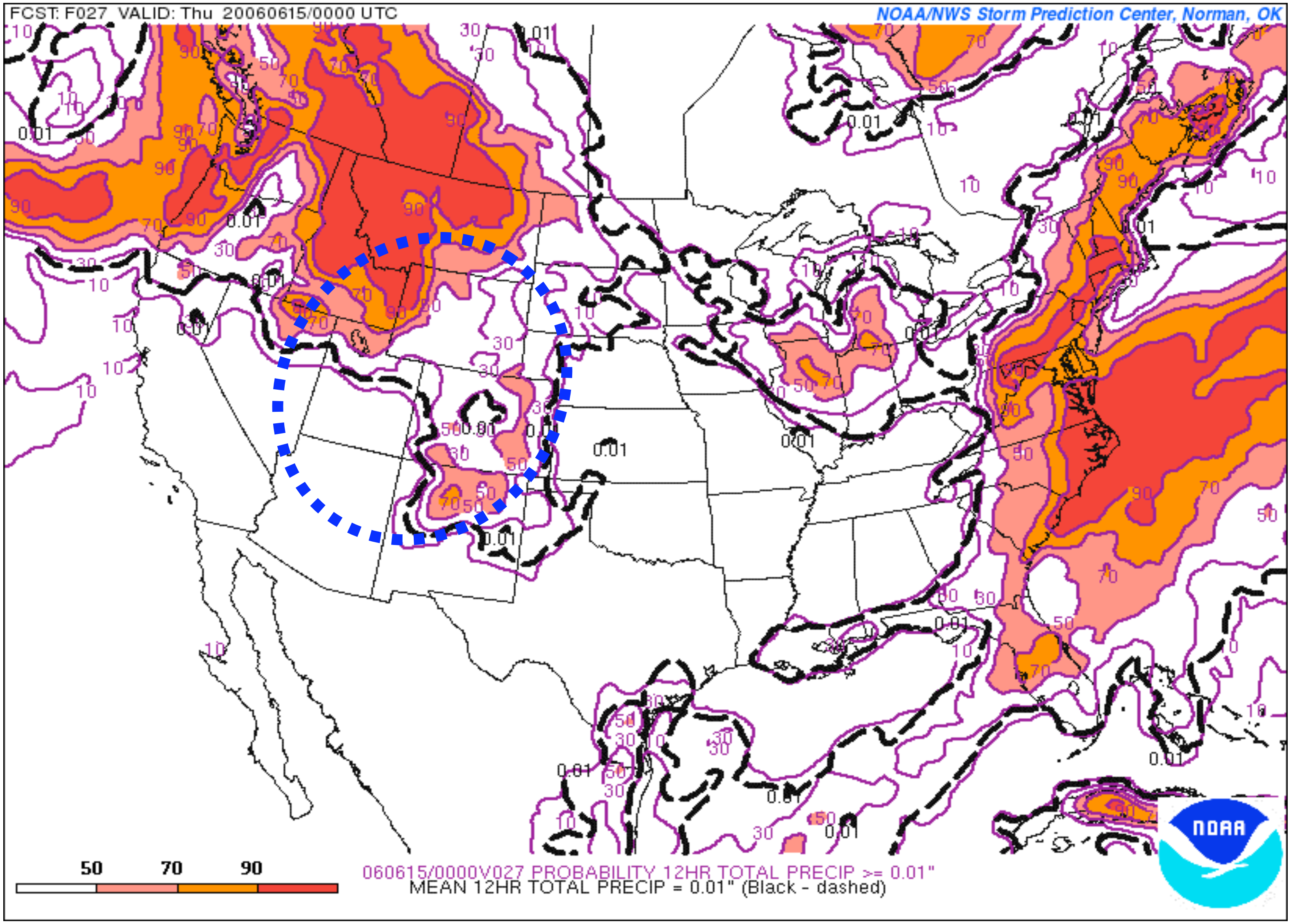
Following plots courtesy of David Bright, NOAA/NCEP/SPC, using Jun Du's NCEP SREF system

SREF mean precipitation, vertical velocity, thickness



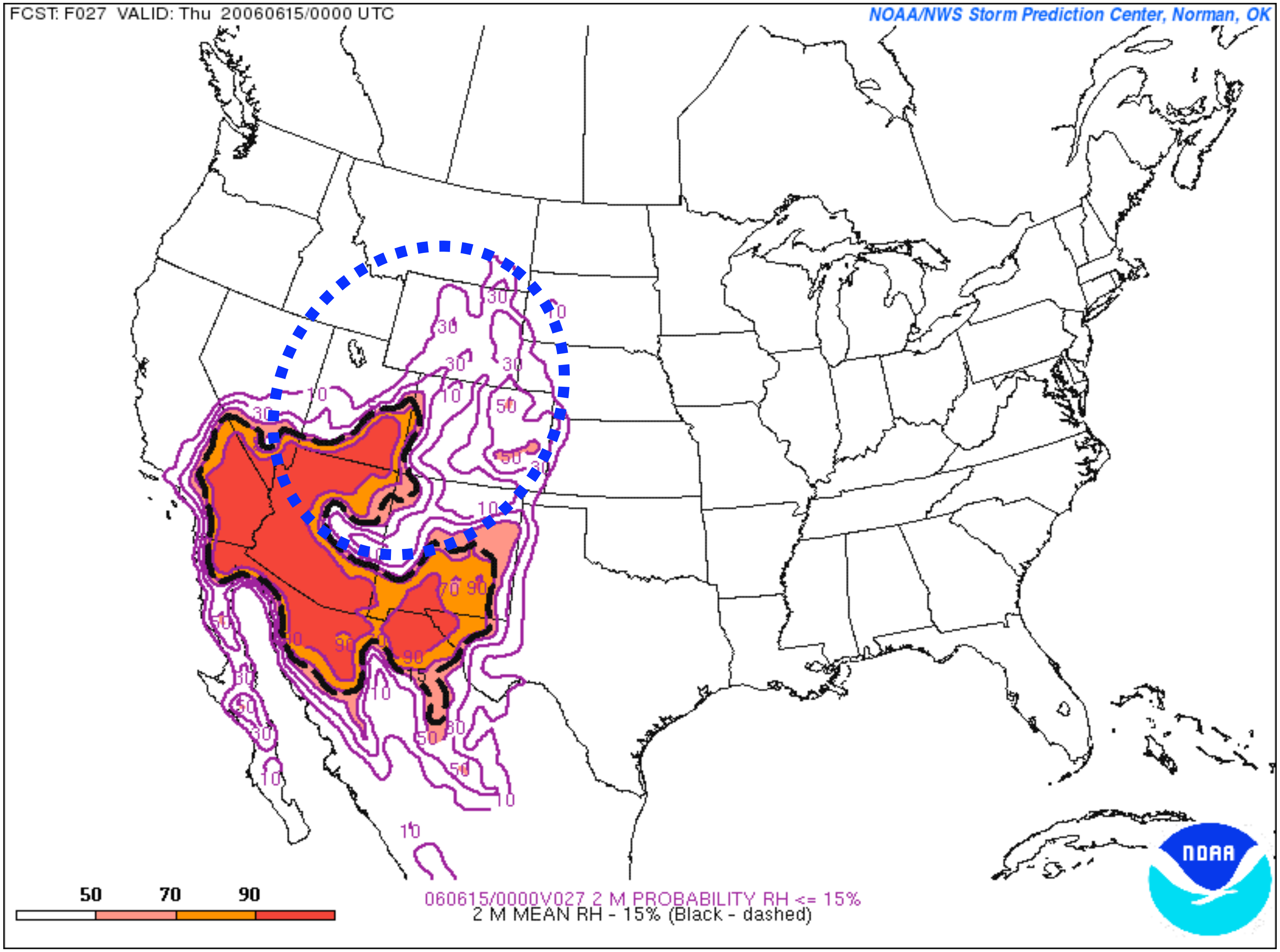
Over desert southwest US, little model forecast mean precipitation, and very warm conditions (purple is mean 5790 m 1000-500 hPa thickness).

SREF Pr[P12I ≥ .01”] and Mean P12I = .01” (dash)



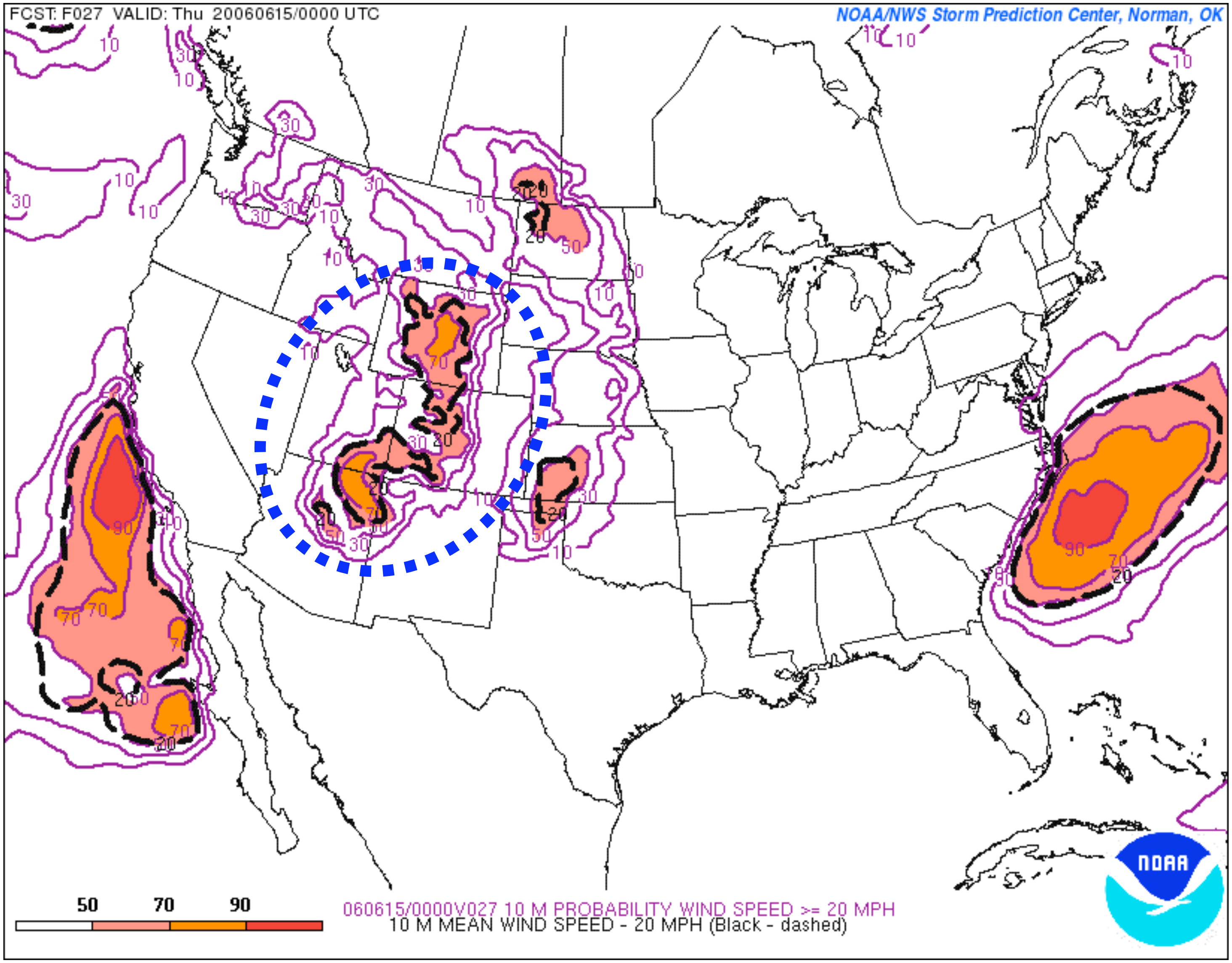
Some members forecasting precipitation over Colorado, New Mexico, but southern Utah and Arizona forecast dry.

SREF Pr[RH ≤ 15%] and Mean RH = 15% (dash)



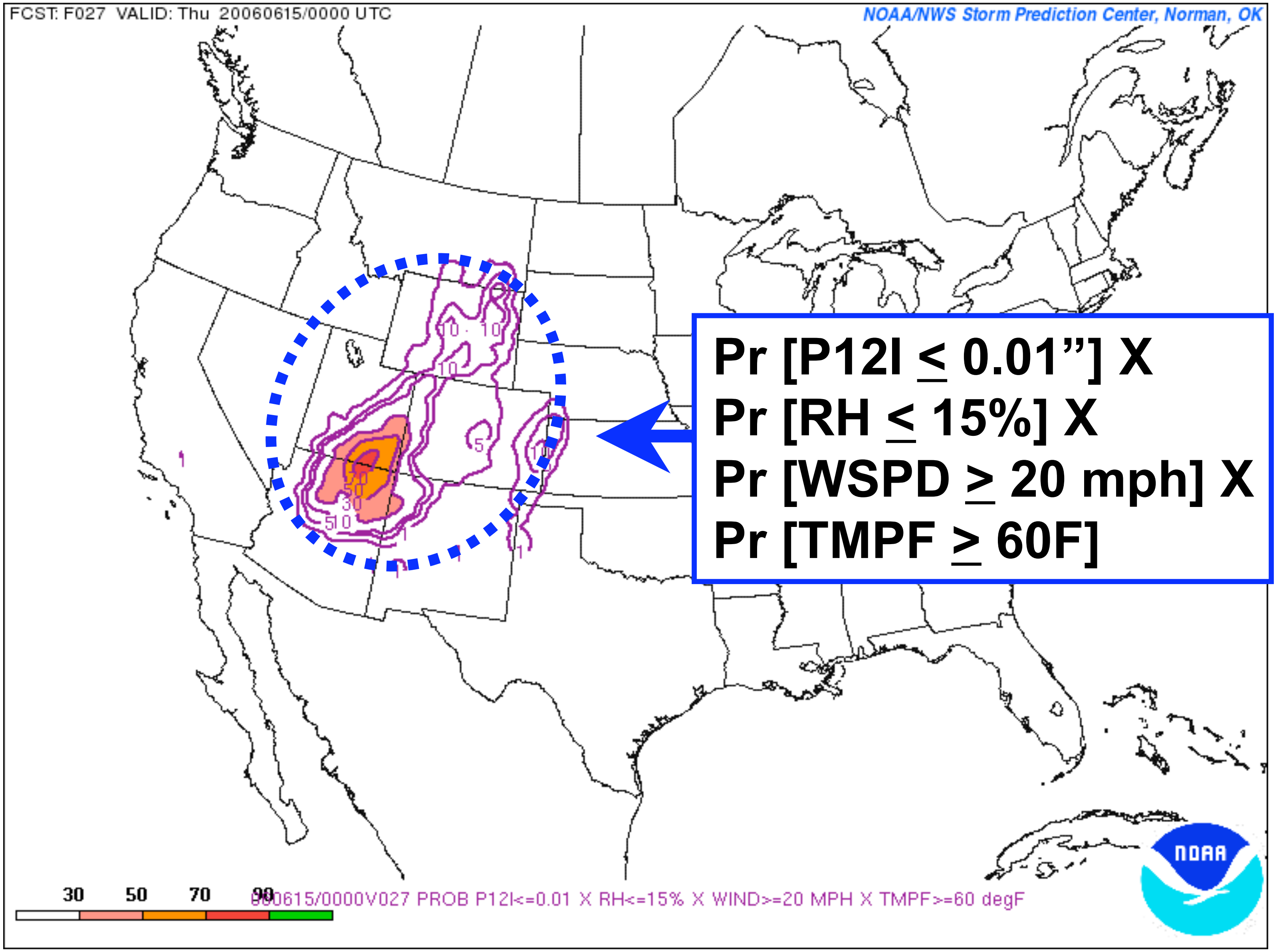
very low near-surface relative humidity over Arizona, southern Utah

SREF Pr[WSPD ≥ 20 mph] and Mean WSPD = 20 mph (dash)



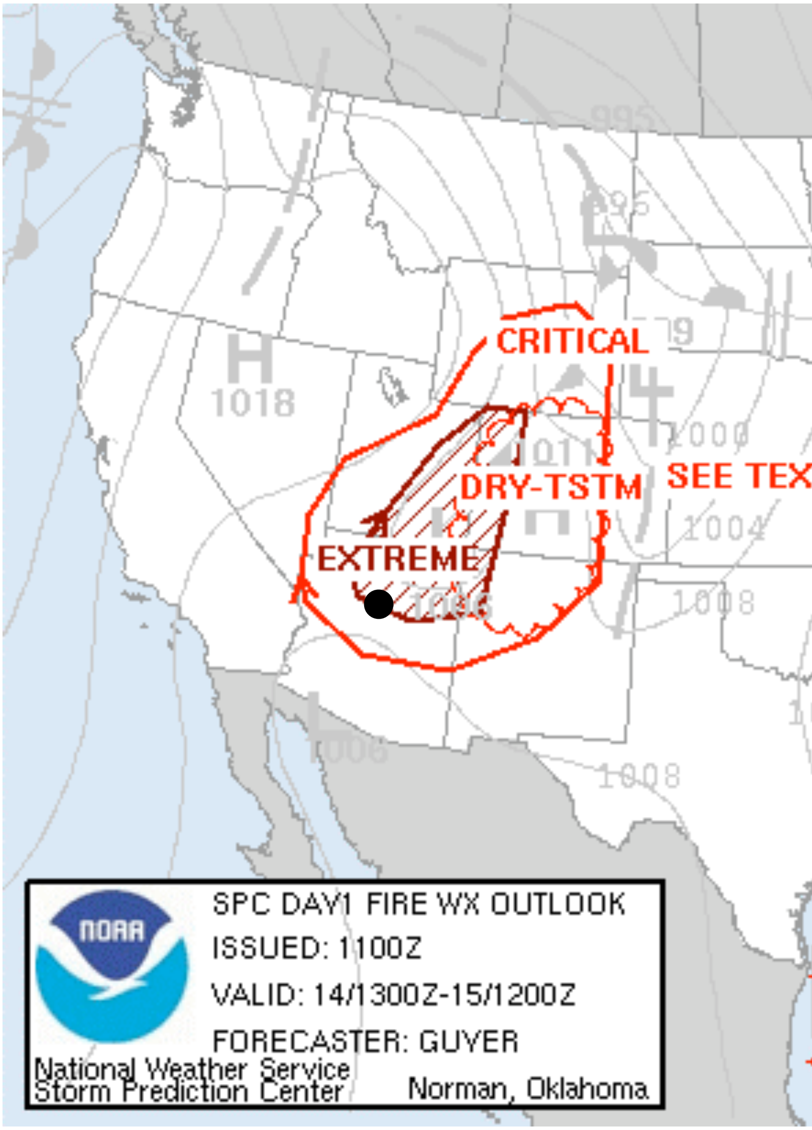
Many of the members are forecasting gusty winds.

SREF Combined or Joint Probability



Joint probability of fire-weather ingredients.

NOAA SPC Operational Outlook
(Uncertainty communicated in accompanying text)



The Woody Fire burns toward homes Wednesday in Flagstaff, Ariz. The blaze threatened five subdivisions on the west side of Flagstaff, forcing more than 100 homes to evacuate Wednesday night.

Associated Press

Wildfire near Flagstaff forces some evacuations

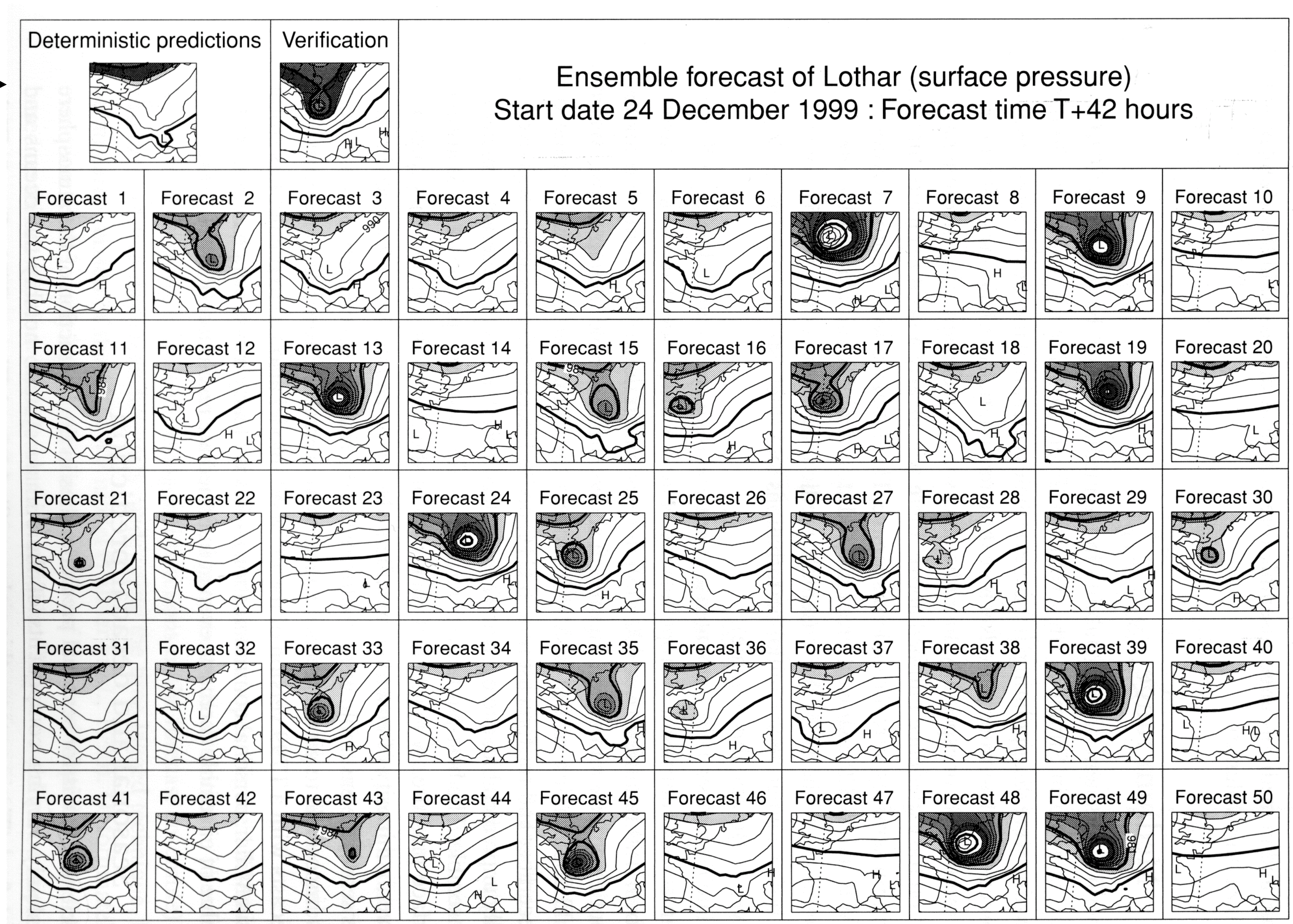
Associated Press

June 14, 2006

FLAGSTAFF - More than 100 homes remained evacuated Wednesday night as a wind-whipped wildfire threatened five subdivisions on the west side of Flagstaff, sending scores of people to shelters set up by the American Red Cross.

European example: “Lothar” storm, 1999

deterministic forecast totally misses damaging storm over France; some ensemble members forecast it well.



from Tim Palmer’s book chapter, 2006, in “*Predictability of Weather and Climate*”.

Dutch storm, 1 February 1953 ECMWF reanalysis & reforecast

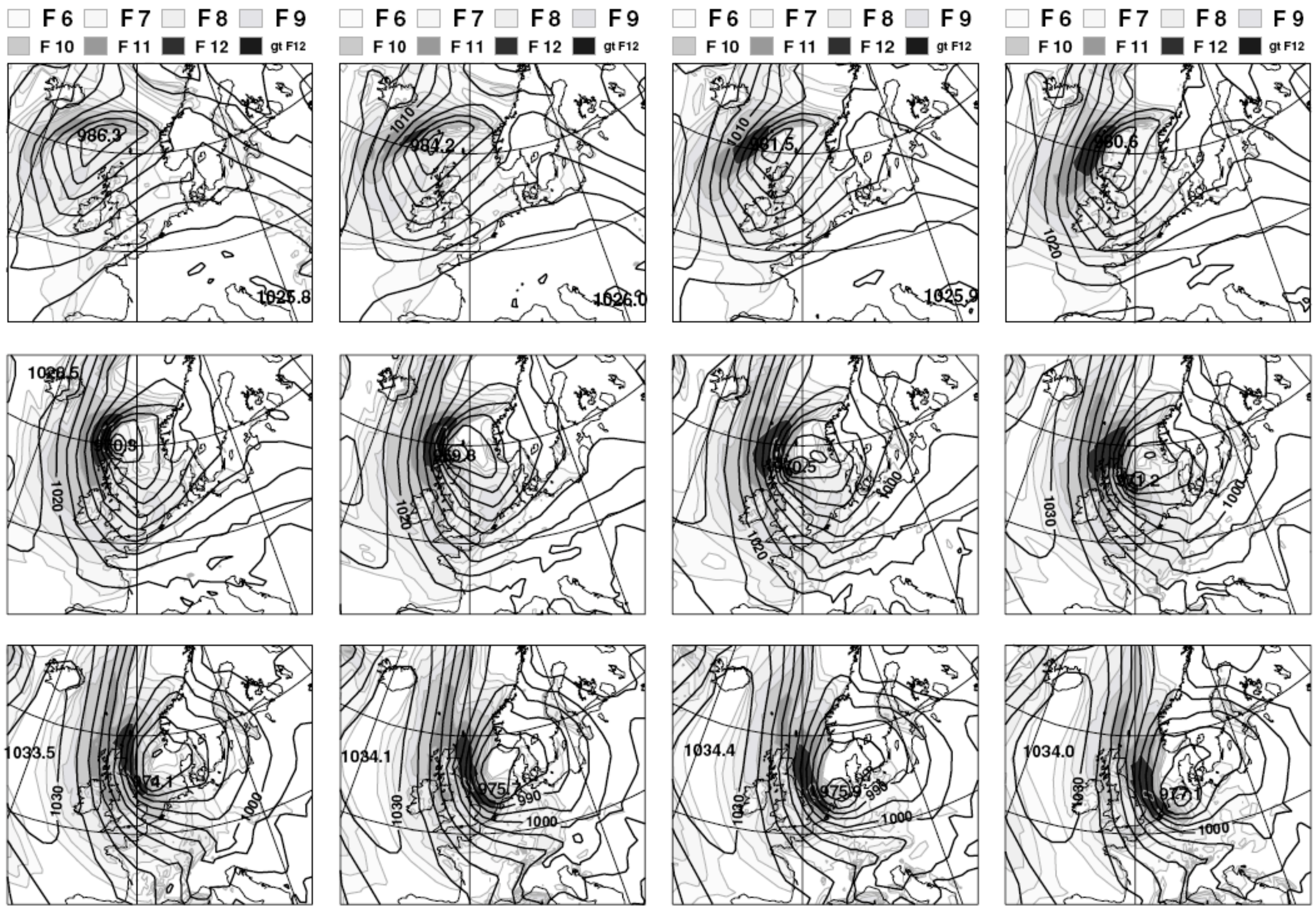


Figure 1. *Mean sea level pressure (contours in hPa) and maximum wind gustiness (shading in Bft) for intervals of 3 hours from 15 UTC on 30 January 1953 (upper left panel) to 00 UTC on 1 February 1953 (lower right panel). The upper row is based on 3, 6, 9 and 12-hour forecasts using the high-resolution system (HRES in Table 1) started at 12 UTC on 30 January 1953. The middle and lower rows are based on corresponding forecasts but started at 00 UTC on 31 January and 12 UTC on 31 January 1953, respectively. Note that the maximum refers to 3-hour periods. Officially, the Beaufort scale does not have values greater than 12 Bft. Here, maximum gustiness greater than 12 Bft is used for values exceeding 40 m/s.*

- Sea-level pressure analyses and Beaufort wind scales shown. Prevalence of strong onshore winds for long period of time led to catastrophic flooding in the Netherlands.
- 50 dykes burst almost simultaneously, 1850 people killed, sea-level rise not seen in 400-500 years (estimated).

Ref: Jung et al., *Meteor. Appl.*, 2004 (part I).

Figure 1. *Verifying mean sea level pressure analysis (hPa) at 00 UTC on 1 February 1953 (upper left panel) along with corresponding 108-hour forecast started at 12 UTC on 27 January 1953. Shown is the deterministic T511 forecast (HRES), the EPS control forecast (CNTL), and 50 members of the ensemble (Forecast 1–50, ENS). Contour interval is 5 hPa.*

Dutch storm, 1 February 1953 ECMWF reanalysis & reforecast

- 108-h forecast shown here. Hints in a few members of intense winds extending toward the Dutch coast.

Ref: Jung et al., *Meteor. Appl.*, 2005 (part II).

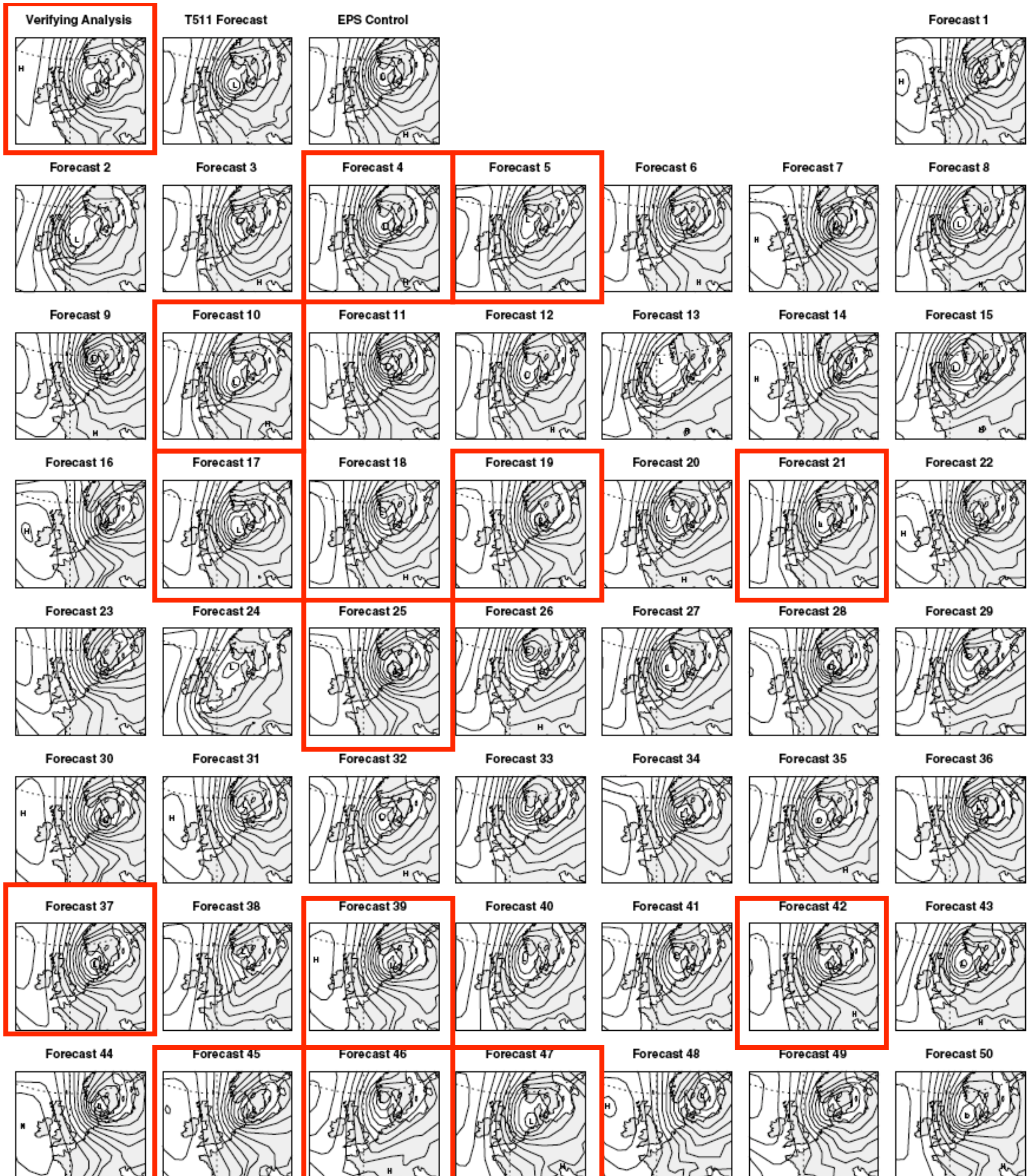


Figure 3. *As Figure 1 except for 60-hour forecasts started at 12 UTC on 29 January 1953.*

Dutch storm, 1 February 1953 ECMWF reanalysis & reforecast

- 60-h forecast shown here. Now there are many more members with tight pressure gradients extending toward the Dutch coast.

Ref: Jung et al., *Meteor. Appl.*, 2005 (part II).

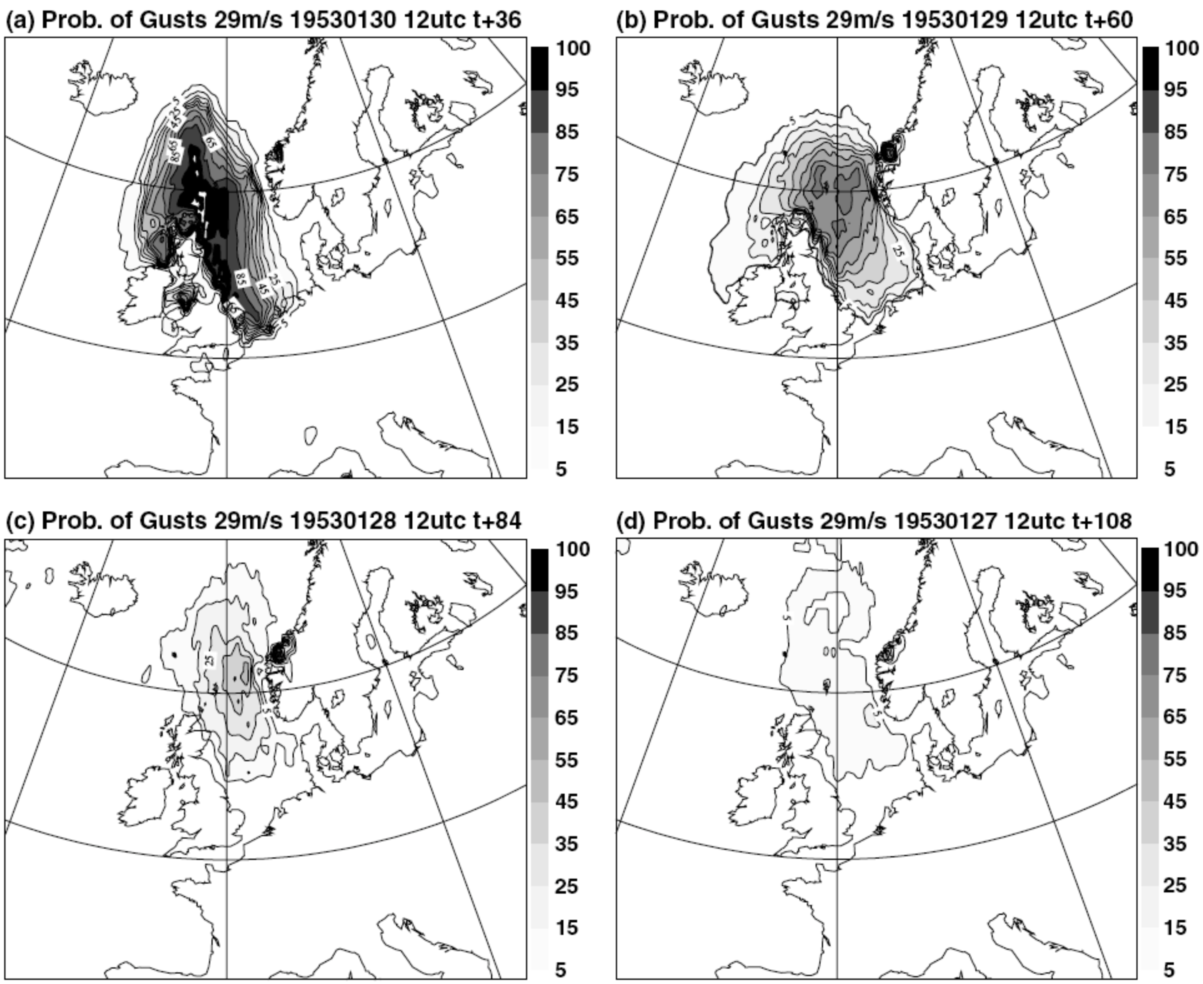


Figure 5. *Probability (%) of maximum wind gusts exceeding 29 m/s (11 Bft) for (a) 36, (b) 60, (c) 84, and (d) 108-hour ensemble forecasts verifying at 00 UTC on 1 February 1953. The probabilities have been estimated using the control forecast (CNTL) along with 50 perturbed ensemble members (ENS).*

Dutch storm, 1 February 1953 ECMWF reanalysis & reforecast

- Probabilities from 51-member ensemble show, however, that only by 36 h in this figure do high probabilities of strong gusts extend to the Dutch coast.
- Predictive ability of this storm was assessed by authors as 48 h.

Ref: Jung et al., *Meteor. Appl.*, 2005 (part II).

Hamburg storm, 17 February 1962

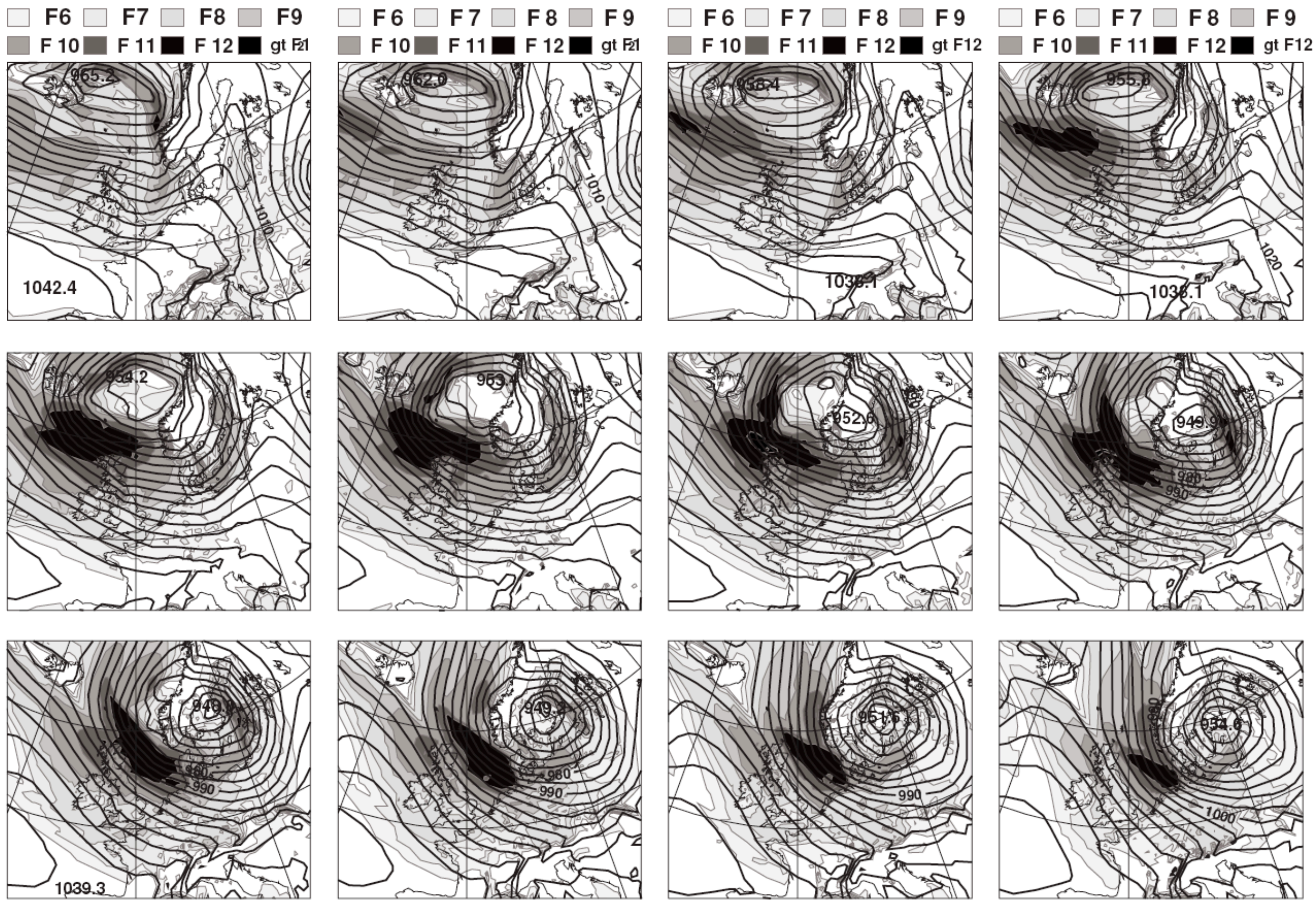


Figure 6. *As for Figure 1, except for the Hamburg storm. Results are for 3-hour intervals from 15 UTC on 15 February 1962 (upper left panel) to 00 UTC on 17 February 1962 (lower right panel) using HRES.*

Ref: Jung et al., *Meteor. Appl.*, 2004 (part I).

- Here, sea-level pressure and maximum wind gustiness.
- Hamburg, 70 km upstream of mouth of Elbe, flooded on storm surge. 340 killed.

Hamburg storm, 17 February 1962 ECMWF reanalysis & reforecast

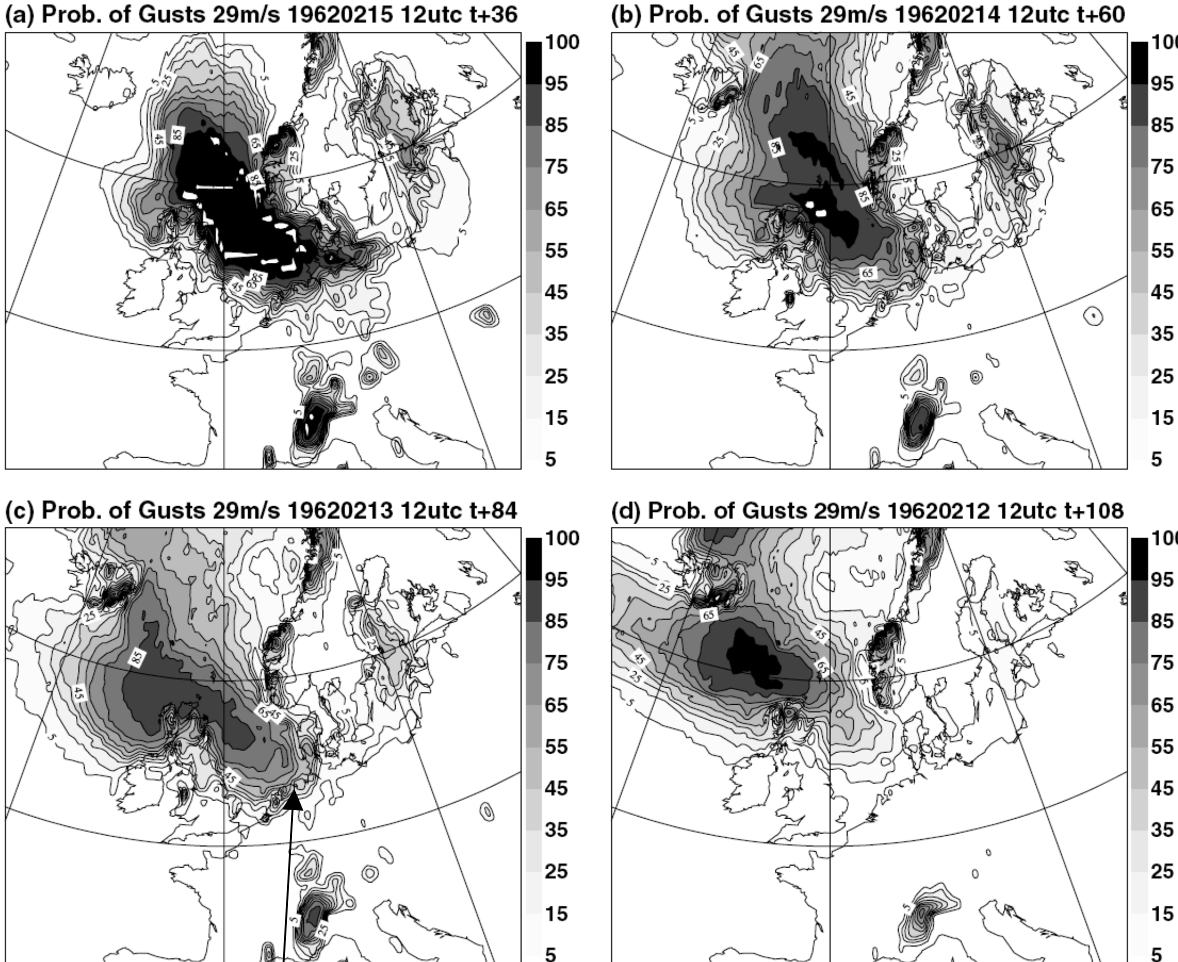


Figure 6. *Probability (%) of maximum gusts greater than 29 m/s (11 Bft) for (a) 36, (b) 60, (c) 84, and (d) 108-hour forecasts verifying at 00 UTC on 17 February 1962. Probability estimates are based on the control forecast (CNTL) and all 50 ensemble members (ENS).*

- Probabilities from 51-member ensemble show that by 84 h a significant fraction of members had gusts to the German coast, indicating the possibility of a storm surge up the Elbe River.
- Predictive ability of this storm was assessed by authors as 84 h.

Ref: Jung et al., *Meteor. Appl.*,2005 (part II).

Great October storm,
15-16 September 1987

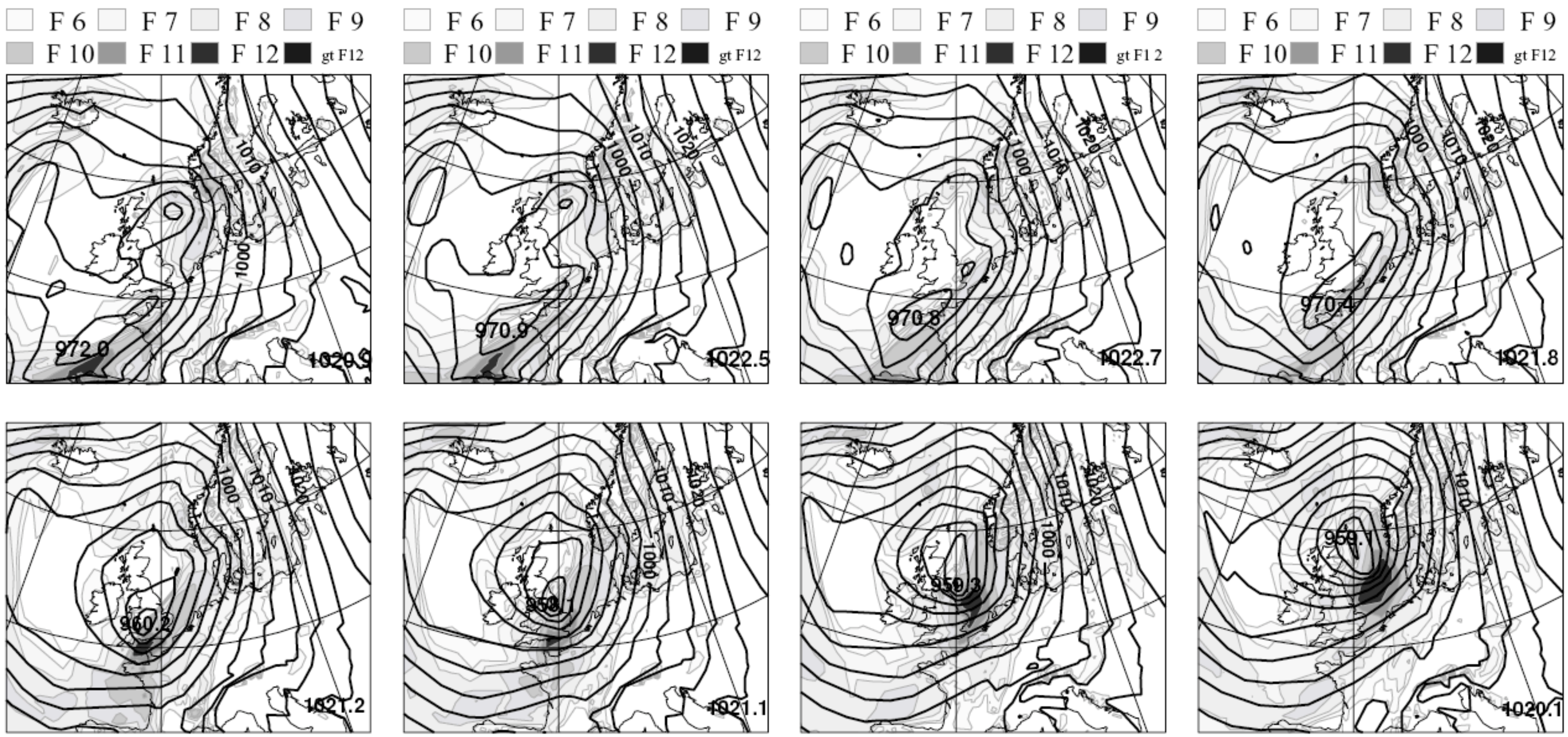


Figure 12. *As for Figure 1, except for the Great October Storm. Forecasts are for intervals of 3 hours from 15 UTC on 15 October (upper left panel) to 12 UTC on 16 October 1962 (lower right panel). Note that the values are forecast (3, 6, 9, and 12-hour forecasts from left to right) using HRES.*

- SE England, NW France; 20 lives lost, > $200,000,000 damage

Ref: Jung et al., *Meteor. Appl.*, 2004 (part I).

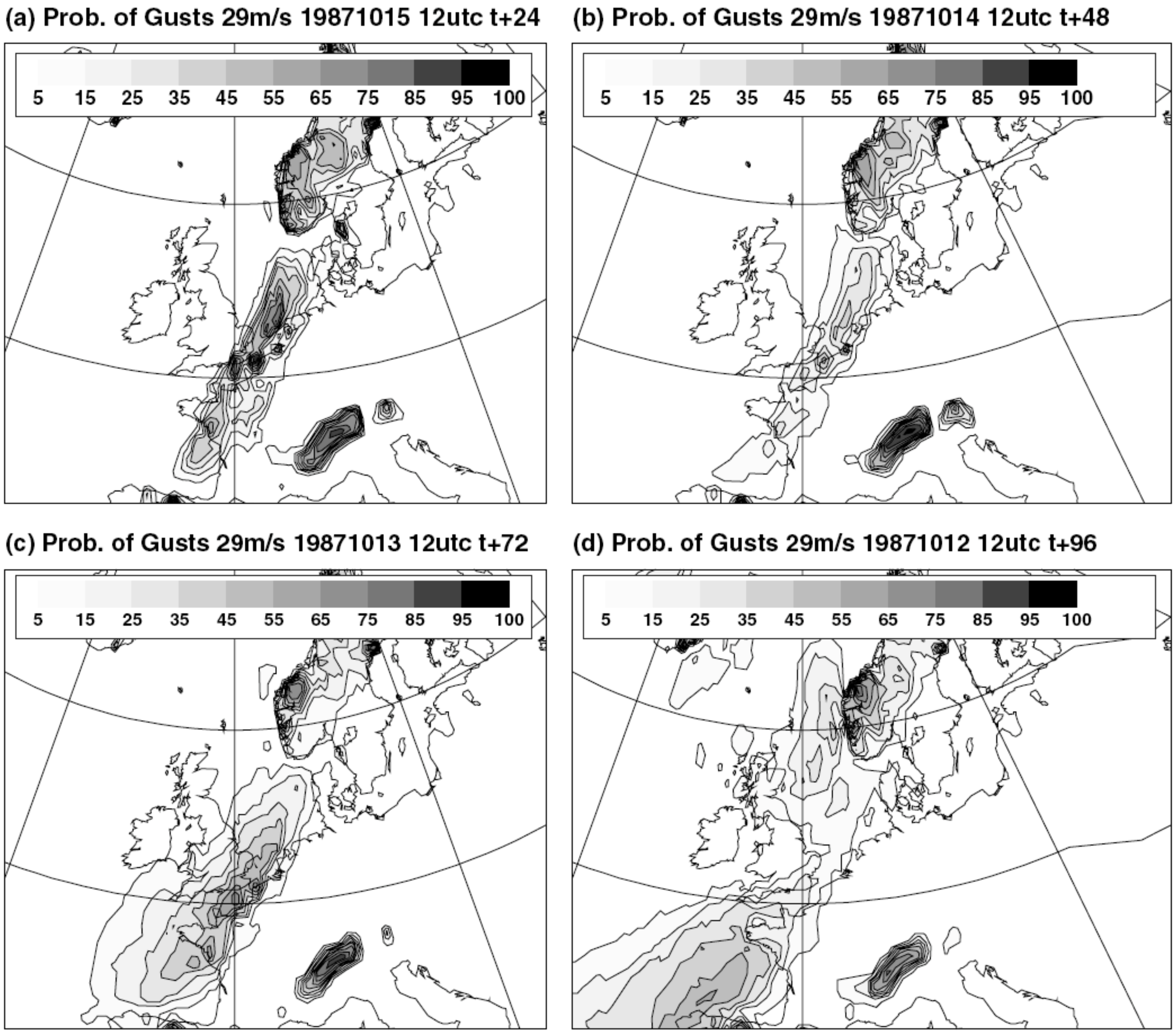


Figure 8. *As Figure 7, except for (a) 24-hour, (b) 48-hour, (c) 72-hour, and (d) 96-hour forecasts verifying at 12 UTC on 16 October 1987. Maximum values of wind strength are based on the 12-hour period 00 UTC on 16 October to 12 UTC on 16 October.*

Great October storm, 15-16 September 1987 reanalysis and reforecast

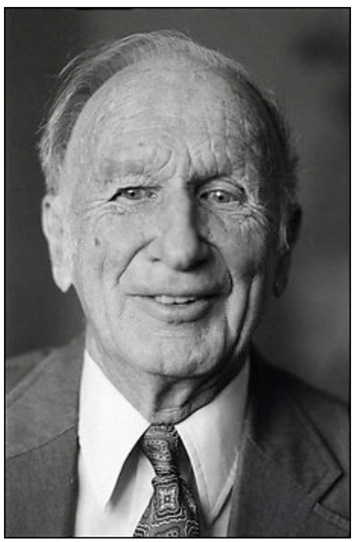
- Indications of track and intensity were seen up to 96 h in advance, according to authors.

Ref: Jung et al., *Meteor. Appl.*, 2005 (part II).

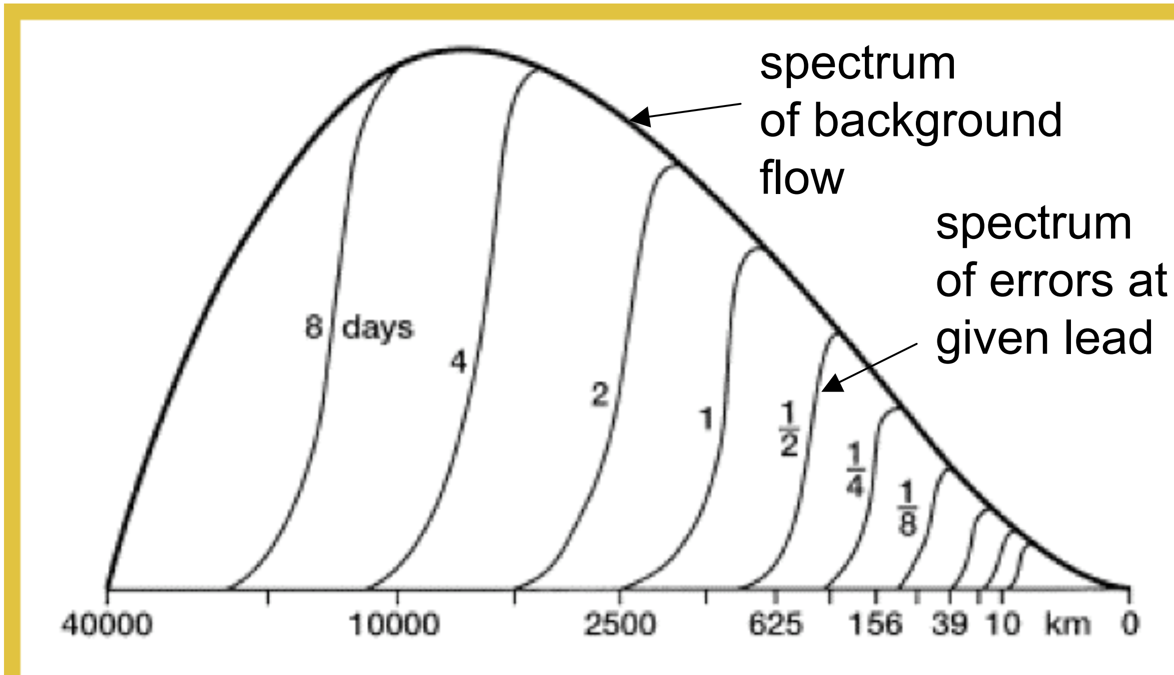
What about predictability of extreme weather events from small-scale features?

Lorenz's 1969 "*Predictability of flow possessing many scales of motion*"

- Simple system with E_k proportional to $k^{-5/3}$ in sub-synoptic scales
- Suppositions: small scales saturate quickly, errors spread upscale much more quickly for smallest scales than for slightly larger scales.
- Implies finite time limit of predictability

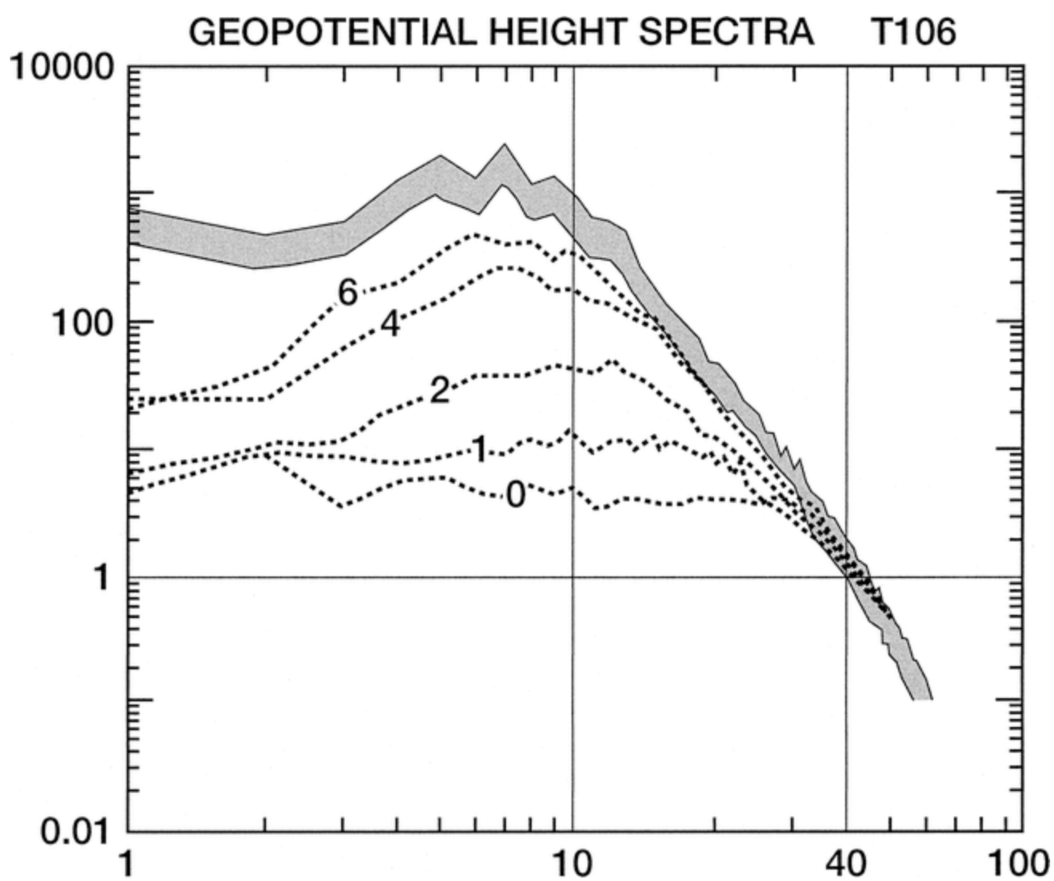


Ed Lorenz,
1918-2008



Ref: Lorenz, 1969, *Tellus*, p. 303; Nastrom and Gage, *JAS*, 1985 for evidence of -5/3 power law in mesoscale.

Predictability theory, updated

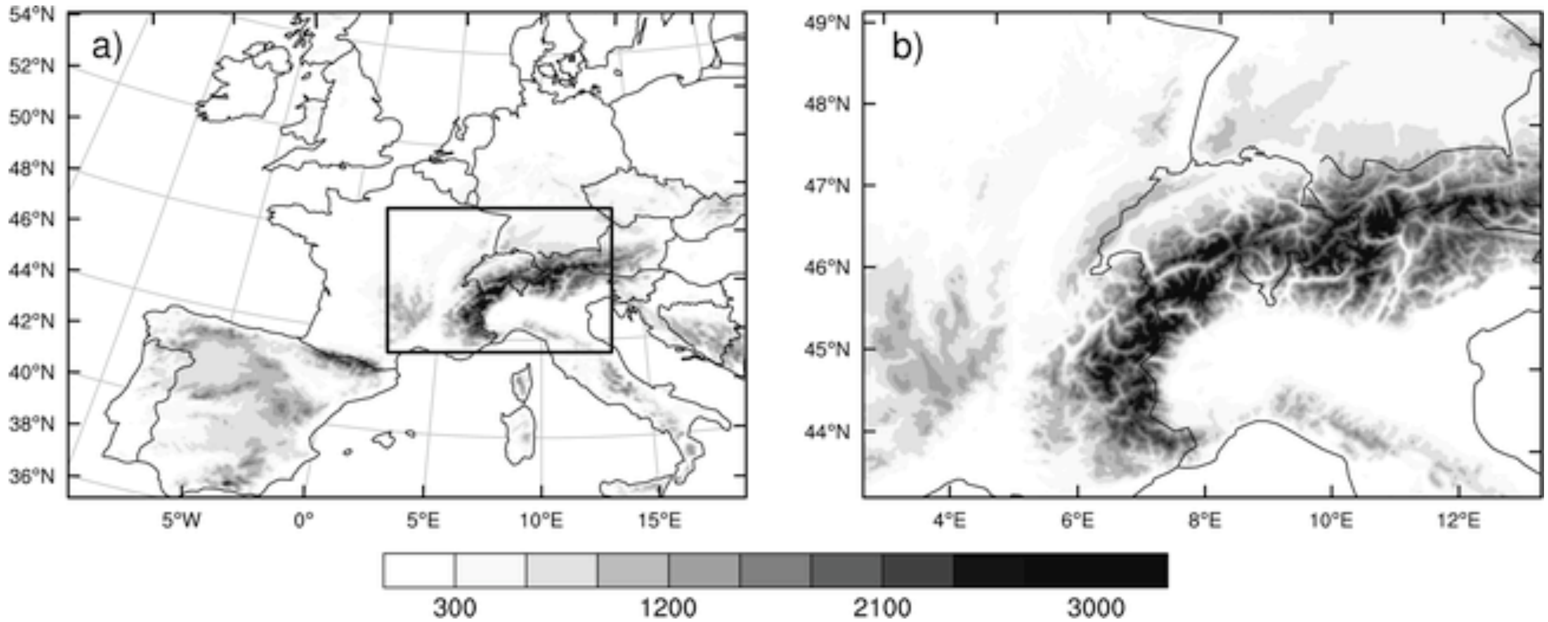


Errors in small scales grow very rapidly, until they project on synoptic scales. Thereafter, slower, more modal growth. Mix of Lorenz '69 ideas and slower modal growth.

…but this doesn't really provide intuition about situations when intense mesoscale features are predictable and when they are not.

Ref: Tribbia and Baumhefner, March 2004 *MWR*

Understanding predictable and less predictable intense precipitation events in the Alps



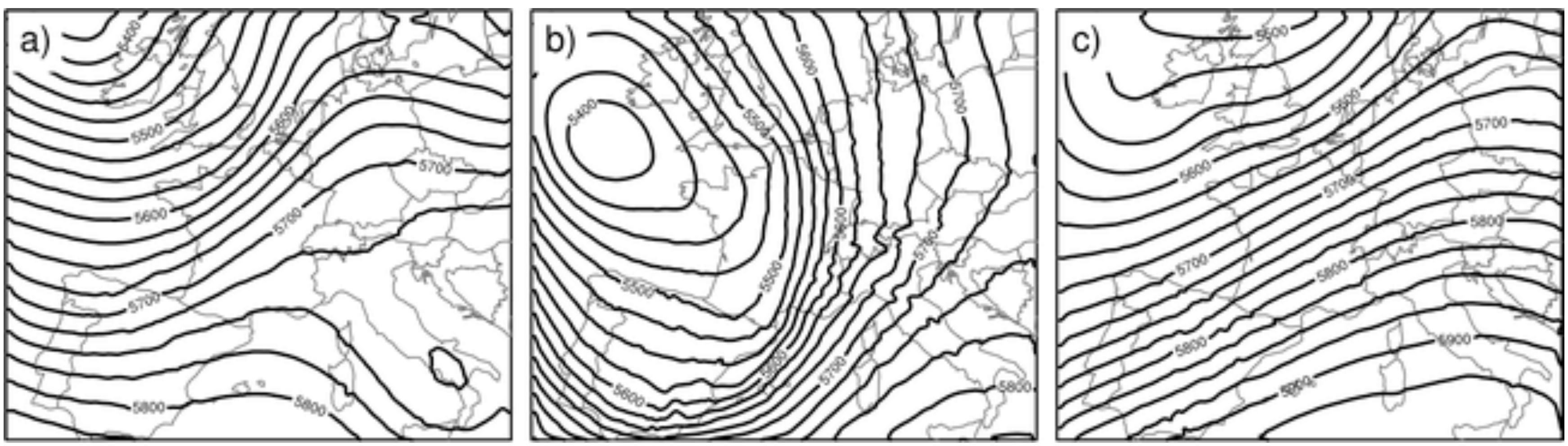
- Integration domains and topography (m) of the (a) 7- and (b) 2.2-km LM simulations. Six-member ensemble in the interior domain using shifting initialization times. LBCs for larger domain from ECMWF forecast.

Ref: Hohnegger et al., August 2006 *MWR*.

Understanding predictable and less predictable intense precipitation events in the Alps

500-hPa initial conditions for 3 cases

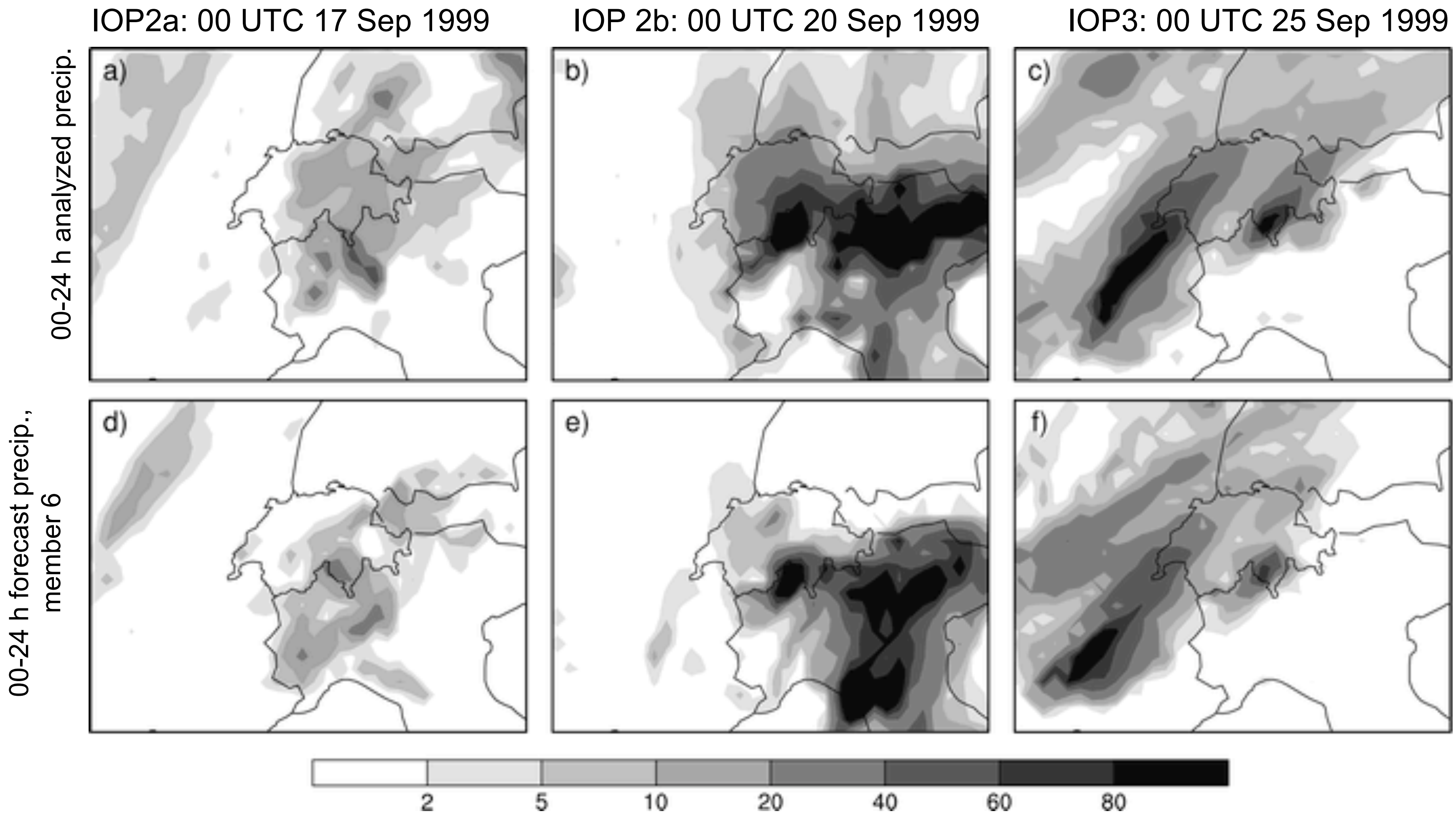
IOP2a: 00 UTC 17 Sep 1999 — IOP 2b: 00 UTC 20 Sep 1999 — IOP3: 00 UTC 25 Sep 1999



- Data from Mesoscale Alpine Program (MAP), Bougeault et al., *BAMS*, 2001.

Ref: Hohnegger et al., August 2006 *MWR*.

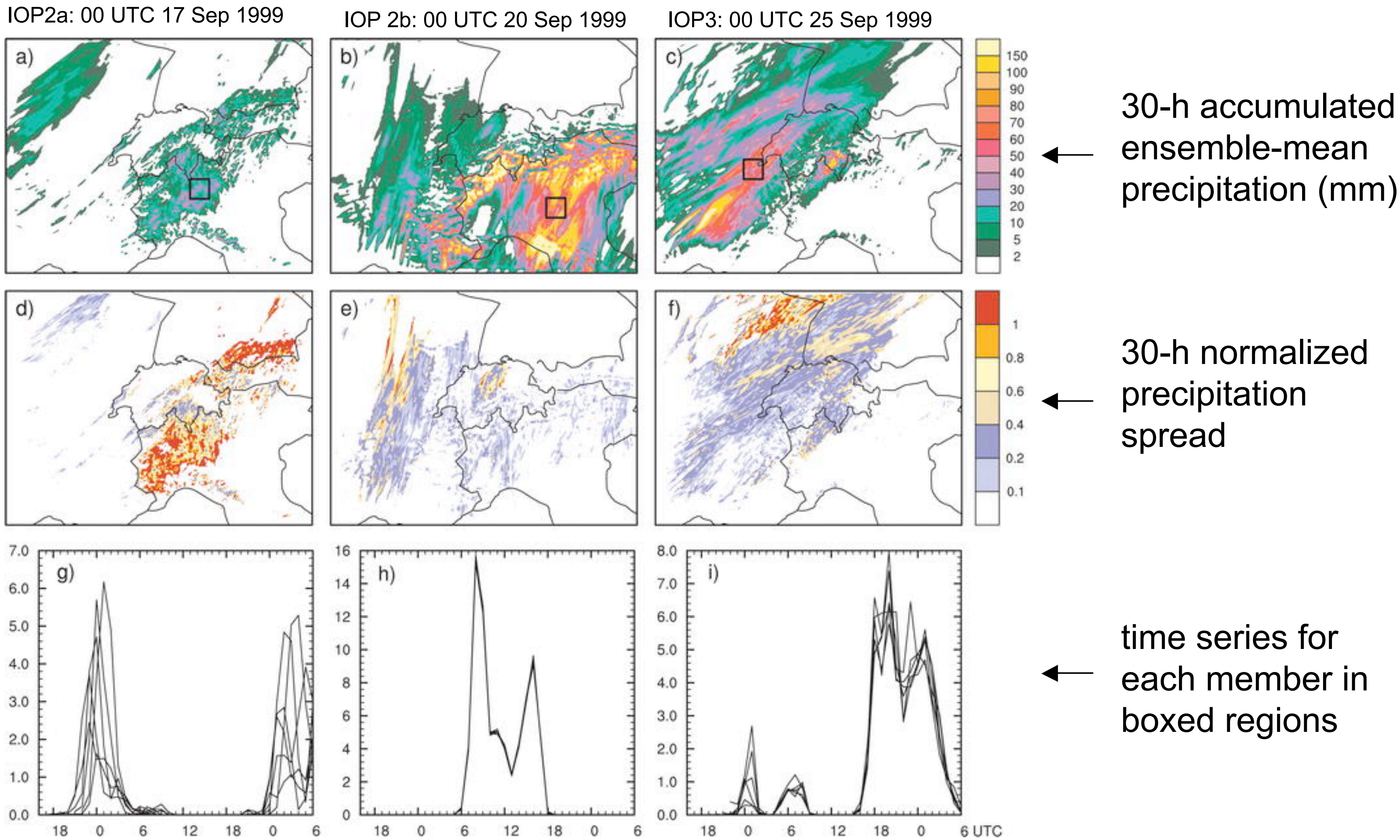
Understanding predictable and less predictable intense precipitation events in the Alps



- Reasonable correspondence between model forecast and analyzed precipitations.

Ref: Hohnegger et al., August 2006 *MWR*.

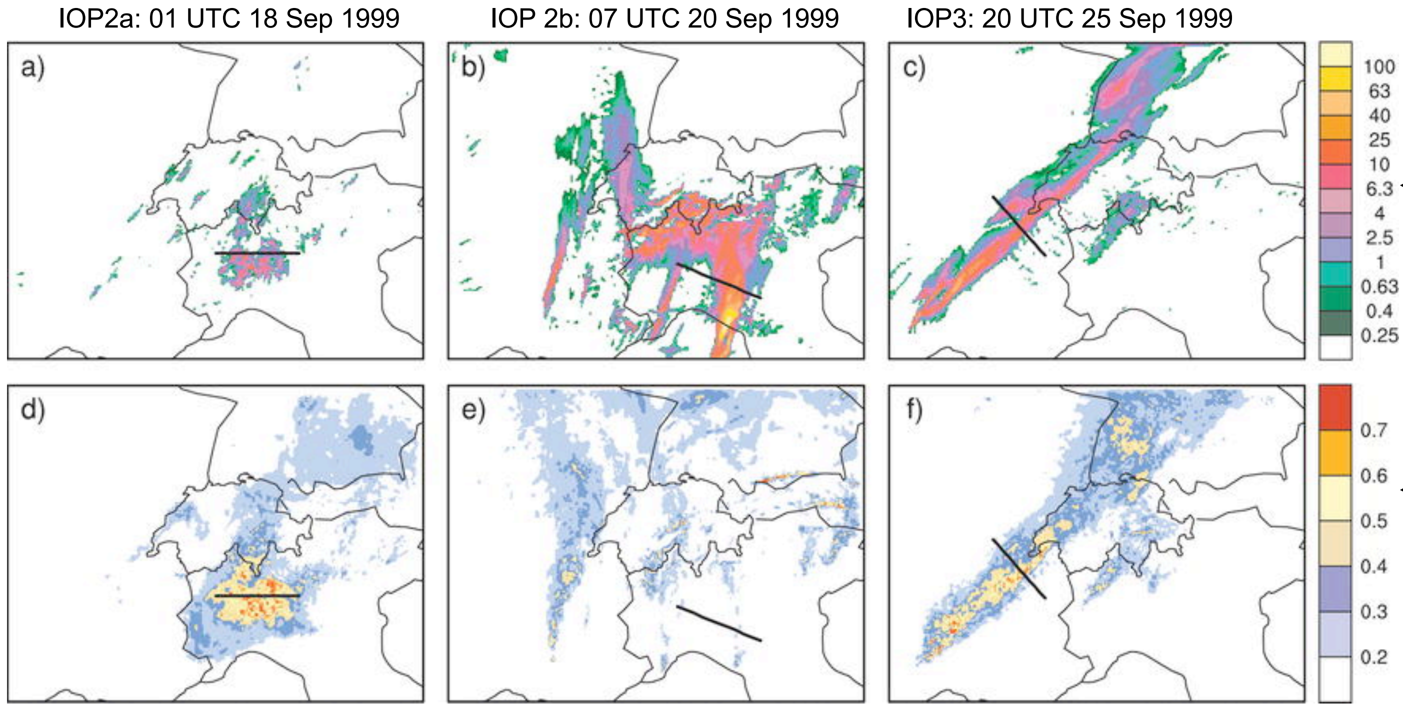
Understanding predictable and less predictable intense precipitation events in the Alps



Ref: Hohnegger et al., August 2006 *MWR*

- Normalized spread: IOP2a > IOP3 >> IOP2b. Why?

Understanding predictable and less predictable intense precipitation events in the Alps



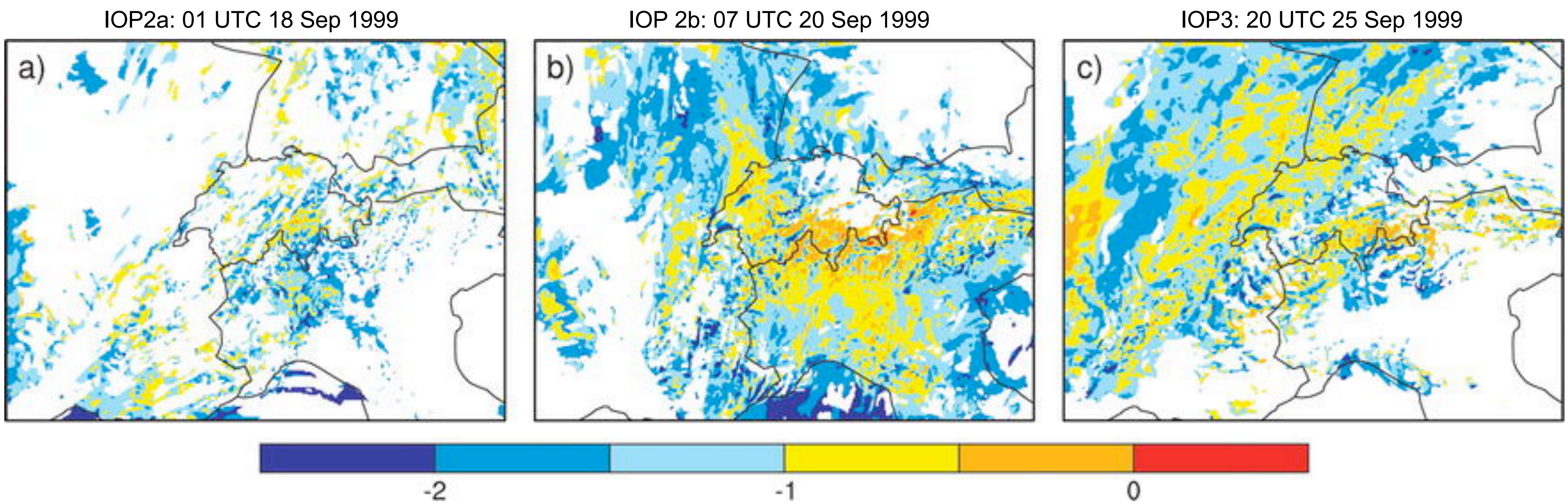
1-h accumulated ensemble-mean precipitation (mm)

sfc-500 hPa temperature spread

- Temperature spread particularly small in IOP2b's precipitation region. Why?

Ref: Hohnegger et al., August 2006 *MWR*

Understanding predictable and less predictable intense precipitation events in the Alps

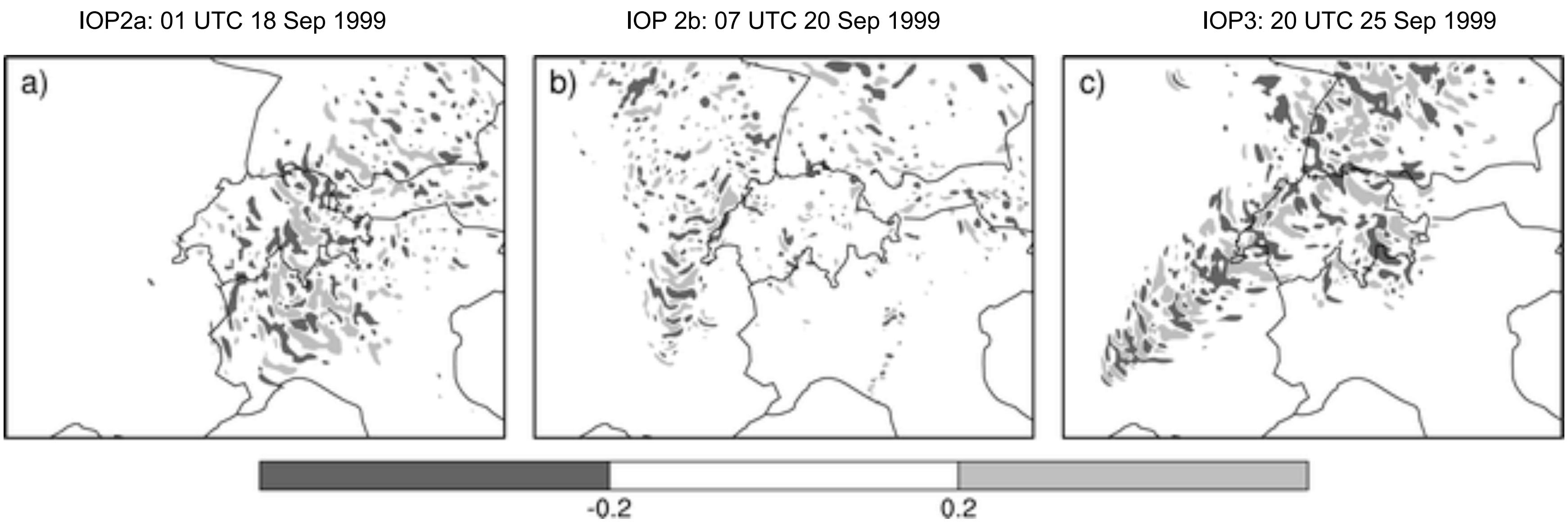


Vertical minimum of the moist Brunt–Väisälä frequency N^2_m (10^{-4} s^{-2}) derived for ensemble member 6. Cloud-free grid points are masked in white.

- IOP2b has plenty of moist instability relative to the other IOPs, so instability is not the source of unpredictability.

Ref: Hohnegger et al., August 2006 *MWR*

Understanding predictable and less predictable intense precipitation events in the Alps

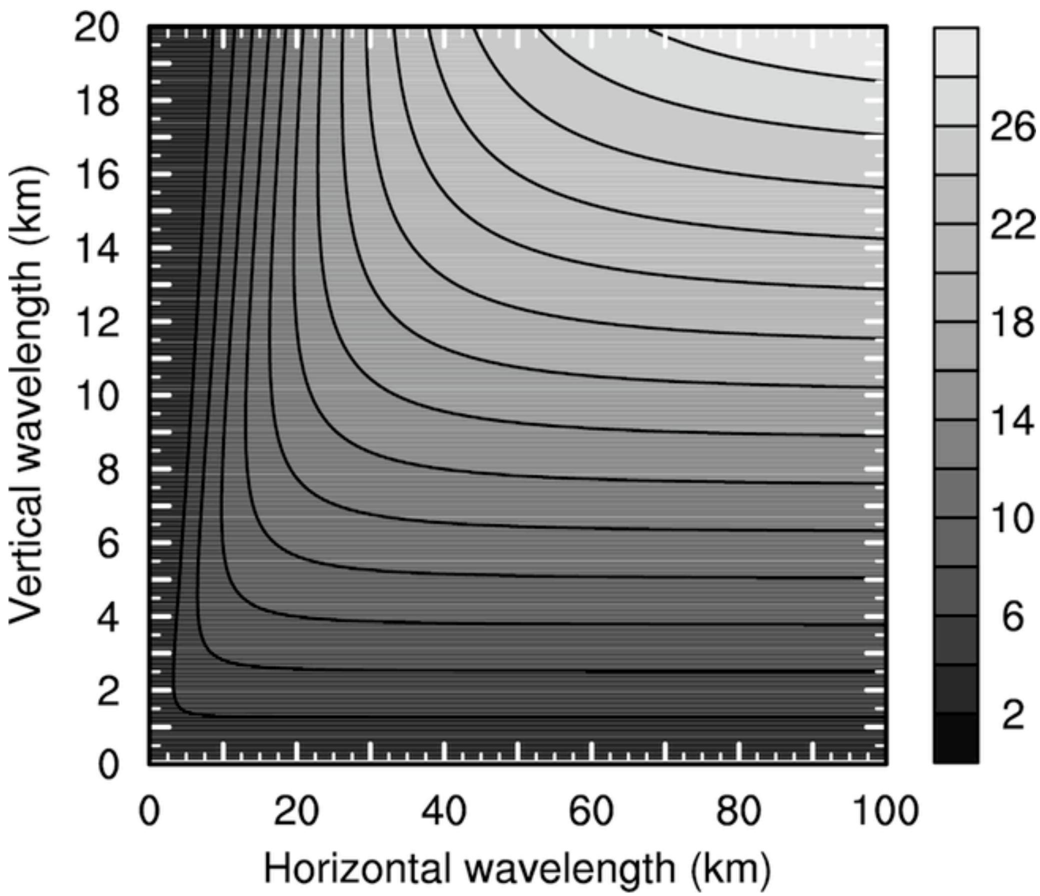


Temperature difference (K) between ensemble members 5 and 6 at a height of 13.6 km.

- Perturbations related to internal gravity wave activity.

Ref: Hohnegger et al., August 2006 *MWR*

Understanding predictable and less predictable intense precipitation events in the Alps



Theoretically derived critical wind speed U_{crit} (m s–1) allowing upstream propagation of energy as a function of horizontal and vertical wavelengths and for N = 0.01 s–1 [see Eq. (4)]

Consider propagation of gravity waves in a dry airstream, uniform stratification and windspeed. Linear analysis as in Holton text (2004, eq. 7.45a)

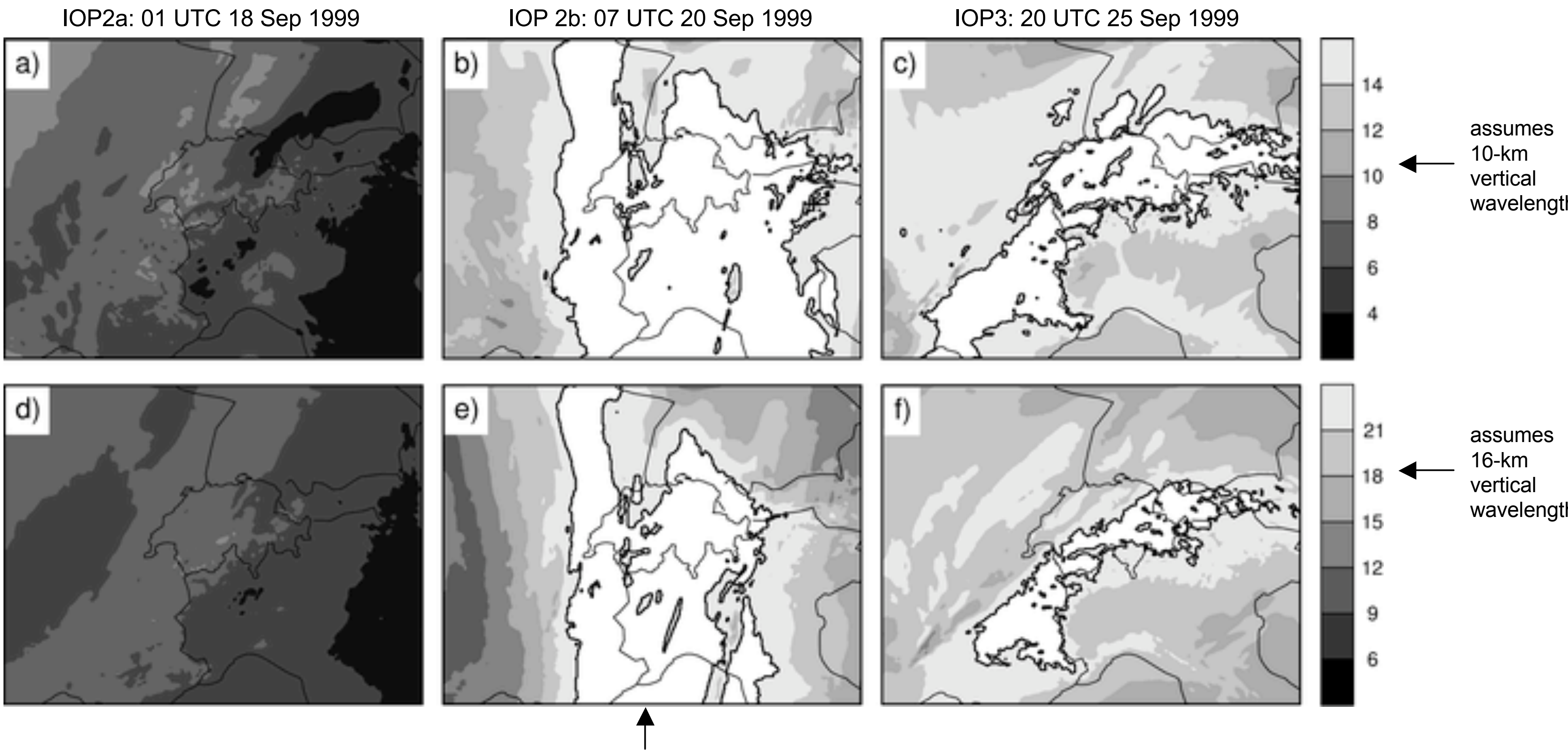
$$U_o \leq \frac{Nm^2}{(m^2 + k^2)\sqrt{m^2 + k^2}} = U_{\mathrm{crit}}. \qquad (4)$$

where *k* and *m* are the vertical and horizontal wavenumber, N^2 is Brunt-Väisälä frequency. When windspeed is less than critical, gravity waves can propagate against mean flow and stay in source region long enough to grow, else they are swept out of growth region. Plot shows that deep gravity waves have higher critical speed threshold and can propagate upstream under broader range of conditions.

Ref: Hohnegger et al., August 2006 *MWR*

Understanding predictable and less predictable intense precipitation events in the Alps

Ensemble mean of the horizontal wind velocity U_o (m s−1). Values larger than U_{crit} inhibiting upstream energy propagation are masked in white. Values for U_o and N have been averaged over half a vertical wavelength.



IOP2b's winds above critical threshold, prohibiting local growth of perturbations from gravity-wave activity.

Ref: Hohnegger et al., August 2006 *MWR*

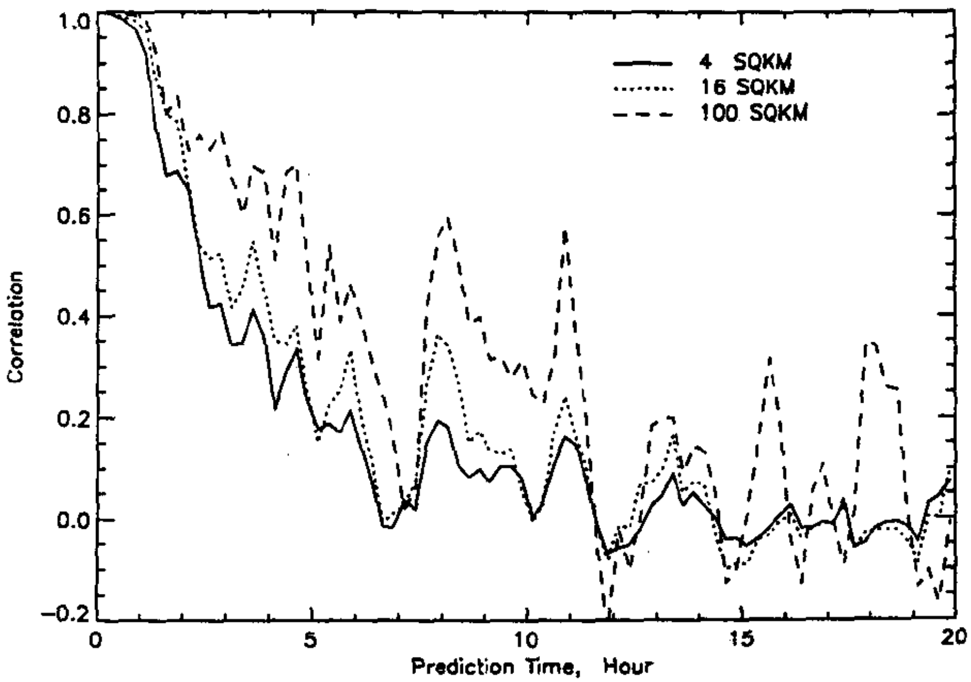
Synthesizing Hohnegger et al.

- Mesoscale perturbations get stimulated in regions of moist convection[1].
- Perturbations may grow locally if they can remain in a region of moist instability, reducing predictability. High wind speeds tend to sweep the nascent perturbations away from genesis region.[2]
- Reinforces hypothesis that mesoscale predictability is lengthened when large-scale forcing is strong.

[1] See also Zhang et al. 2003 *JAS*, Bei and Zhang, *QJRMS*, 2007.
[2] See also Huerre and Monkewitz 1985 *J. Fluid Mech*, Snyder and Joly 1998 *QJRMS,* and literature on "local baroclinic instability"

Predictability of convective precipitation without large-scale forcing

Correlation between control and perturbed rainfall field for 15-min. accumulations.

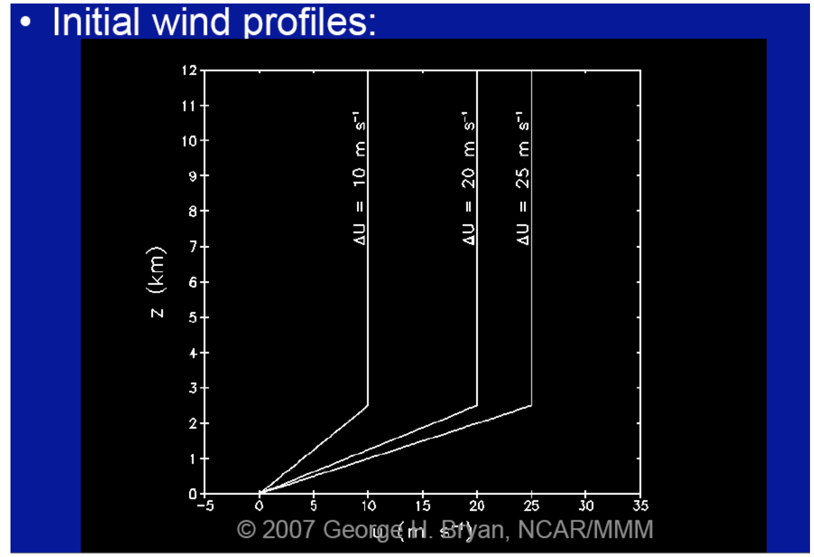


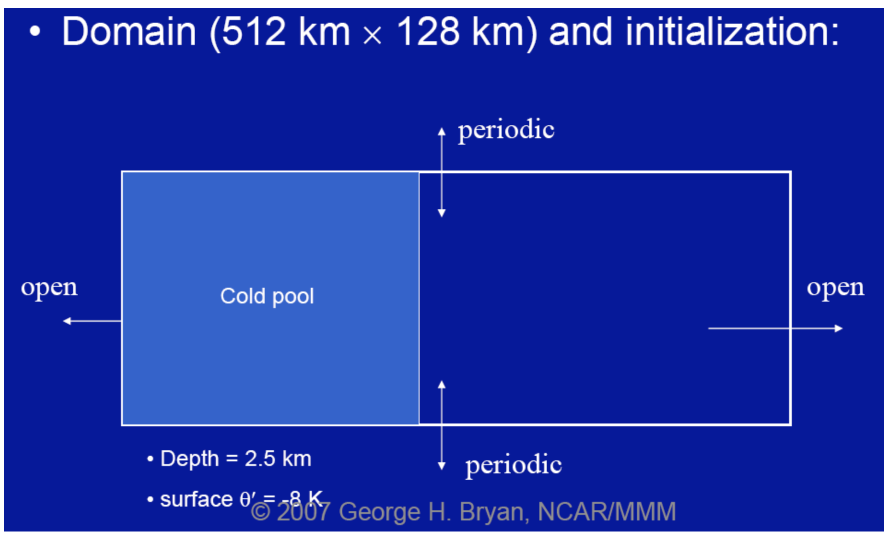
- Tropical simulation of convection using grid point model with periodic boundary conditions, integrated to statistical equilibrium. Then control and slightly perturbed simulations are compared.
- Main points:
  - Without large-scale external forcing, small-scale convective precipitation predictability lost in ~ 6h, more consistent with Lorenz 1969. Much faster than baroclinic scales.
  - Averaging over larger grid areas results in enhanced estimates of predictability.

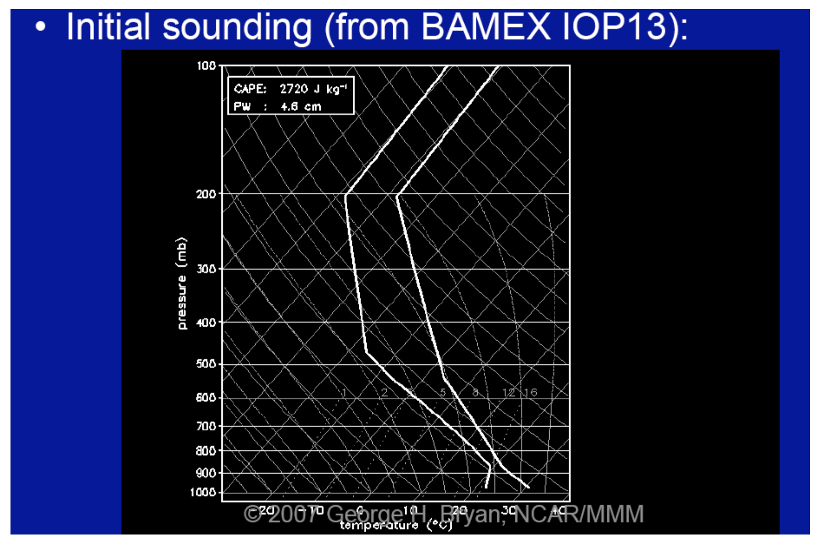
Ref: Islam et al., *JAM*, 1993. See also Hohnegger and Schär, *BAMS*, Nov. 2007.

Model error at mesoscale:
(1) errors from insufficient grid spacing

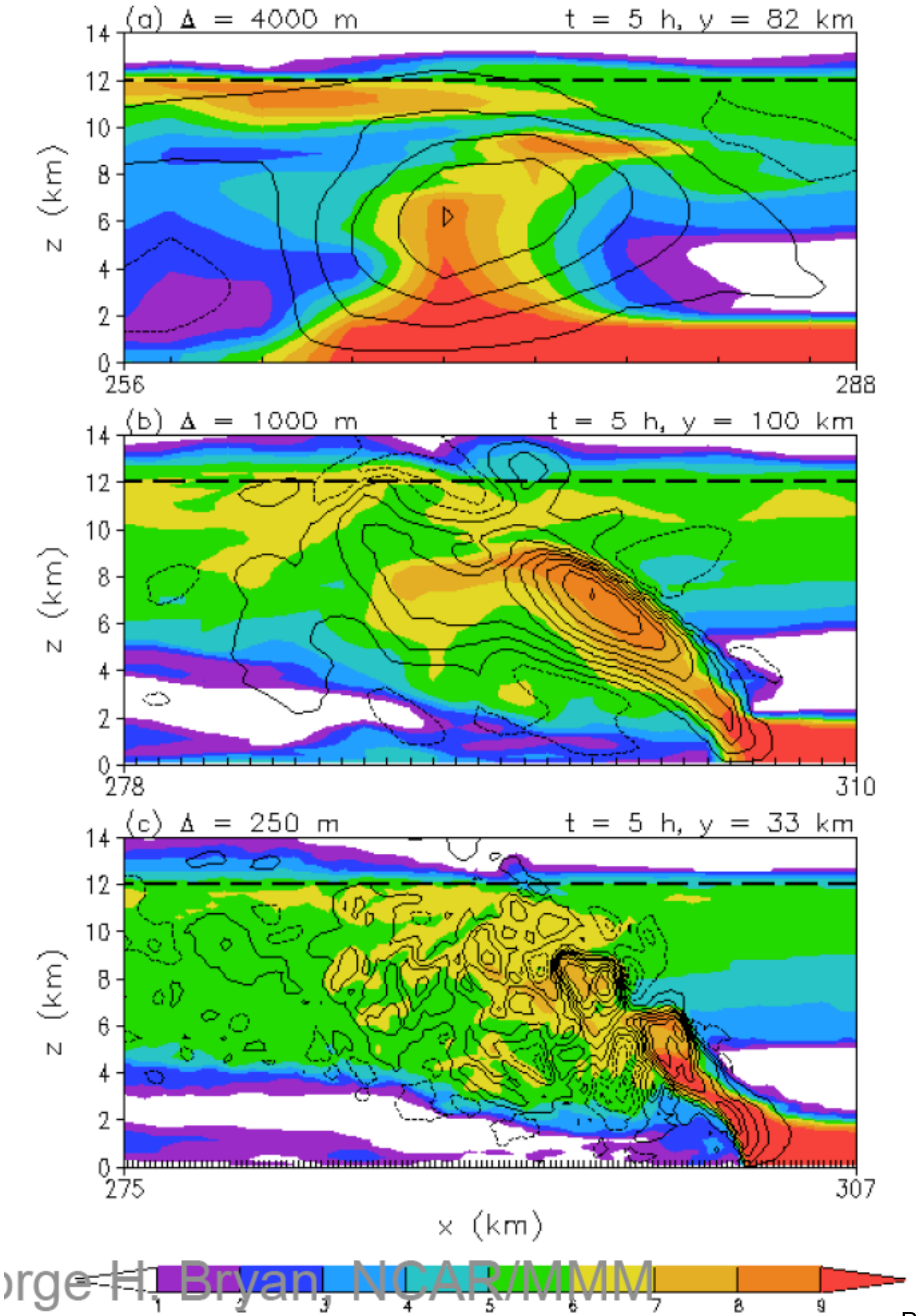
- George Bryan (NCAR) tested convection in simple models with grid spacings from 8 km to 125 m







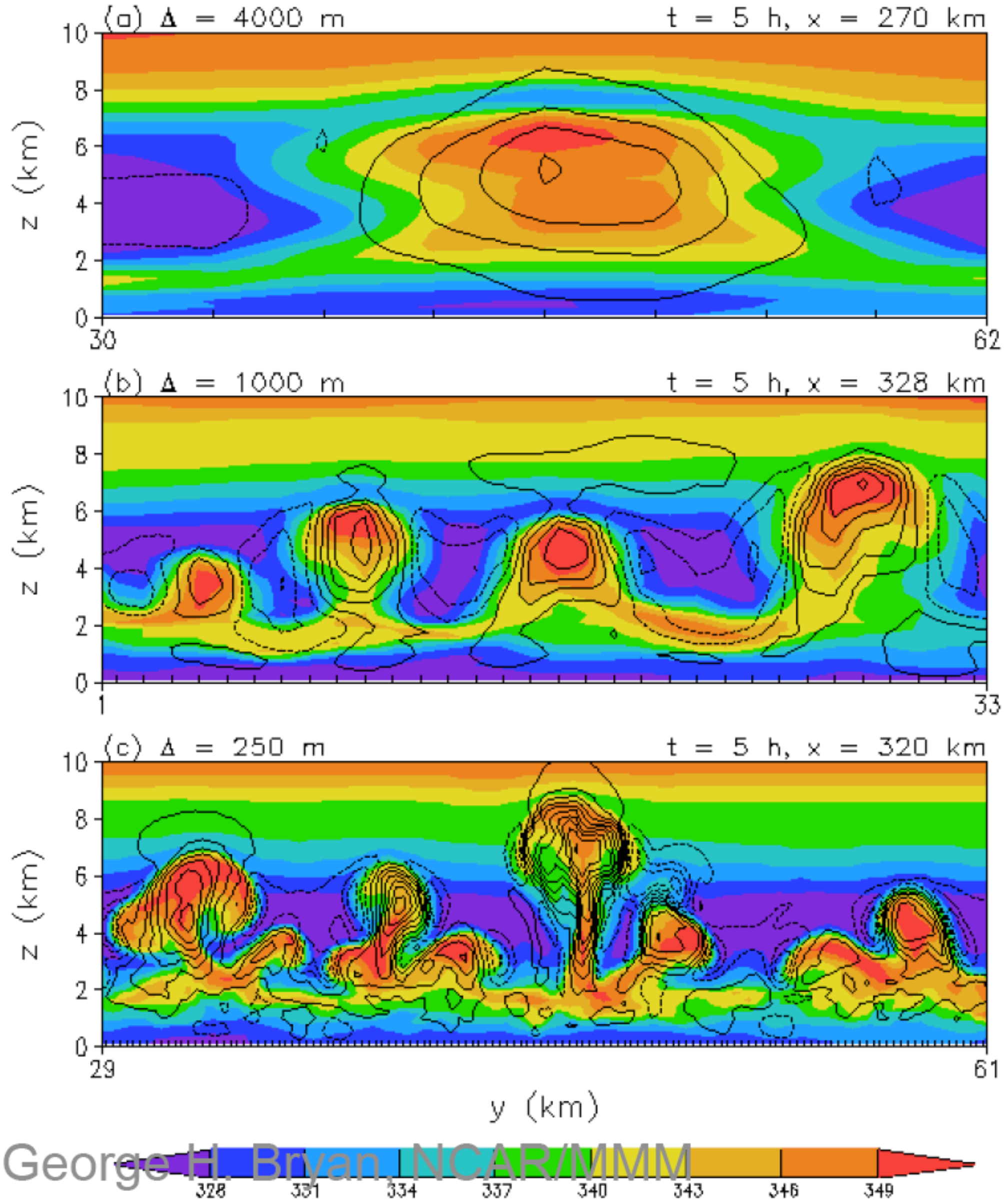
Ref: http://www.mmm.ucar.edu/people/bryan/Presentations/bryan_2007_nssl_resolution.pdf



4 km, 1 km, 0.25 km

- *Across* the squall line vertical cross section for 25 ms^{-1} wind shear. Shading: mixing ratio (g kg^{-1}); contours (vertical velocity (every 4 ms^{-1}).
- Dramatic changes in structure of squall line, updraft, positioning of cold pool.

Ref: http://www.mmm.ucar.edu/people/bryan/Presentations/bryan_2007_nssl_resolution.pdf



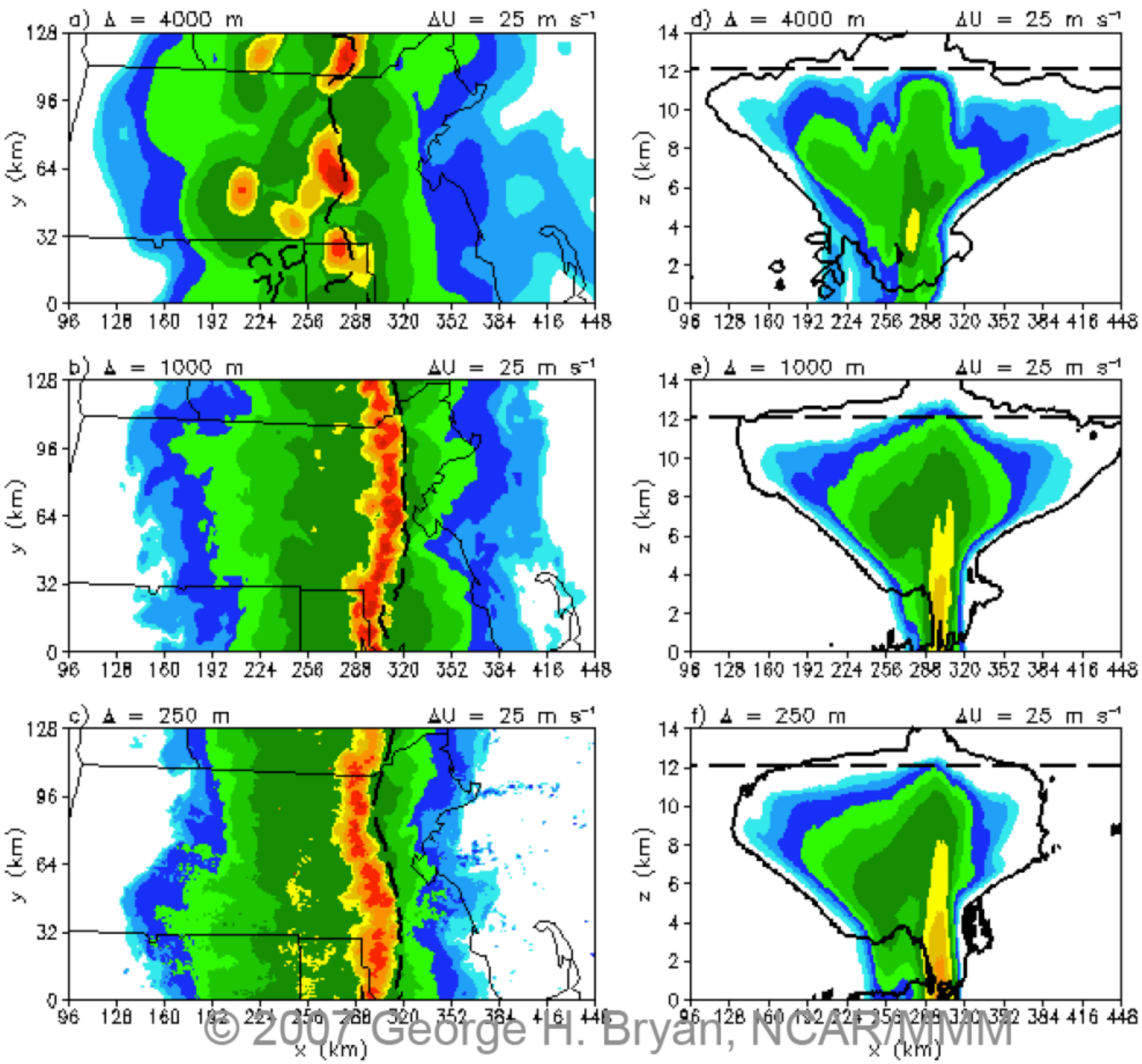
' George H. Bryan, NCAR/MMM

4 km,
1 km, 0.25 km

- *Along* the squall line vertical cross section for 20 ms^{-1} wind shear. Shading: mixing ratio (g kg^{-1}); contours (vertical velocity (every 4 ms^{-1}).
- Updrafts increase in number and intensity with increasing resolution, decrease in size.

Ref: http://www.mmm.ucar.edu/people/bryan/Presentations/bryan_2007_nssl_resolution.pdf

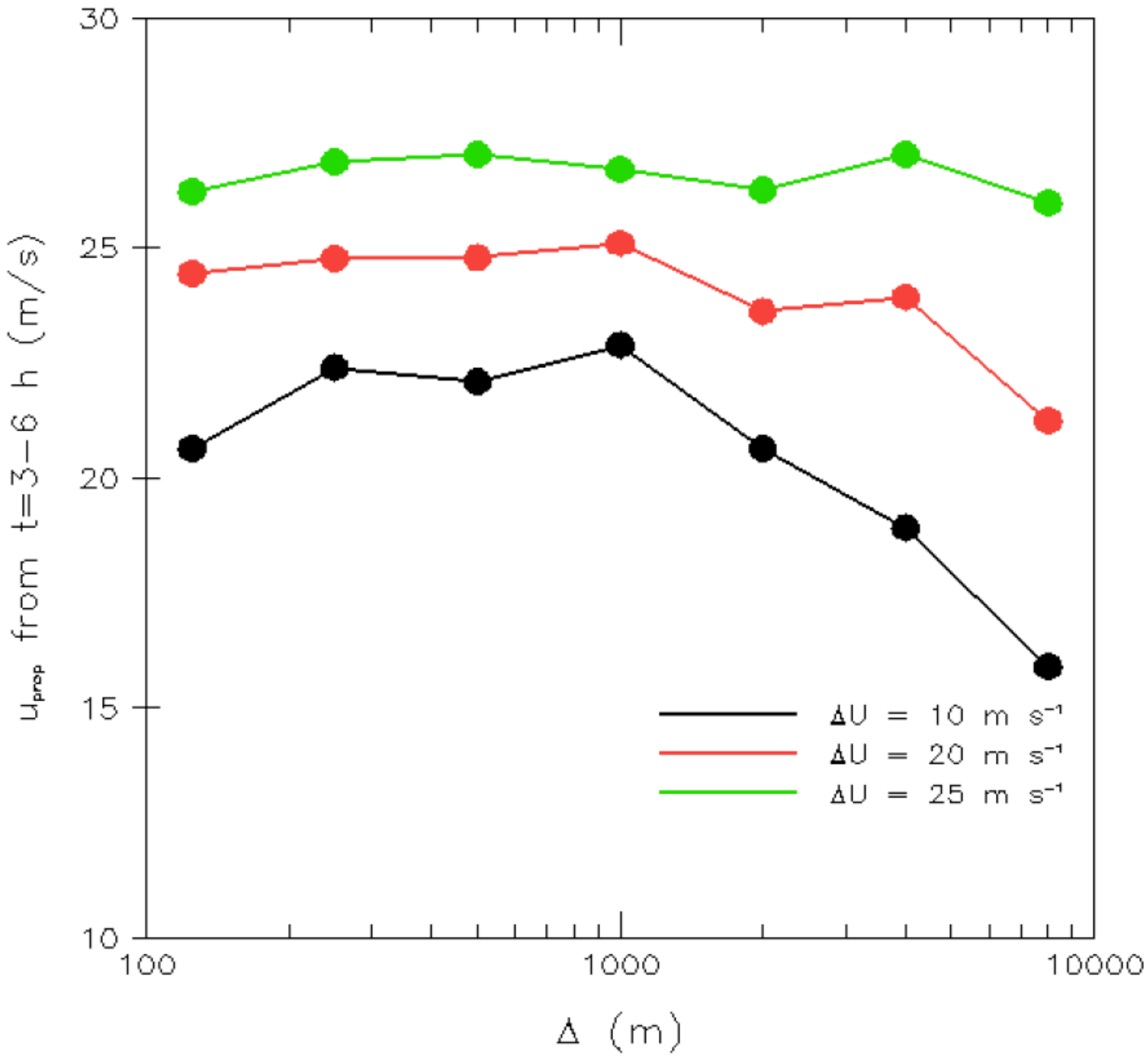
4 km, 1 km, 0.25 km



- Plan view and N-S integrated vertical cross section for 25 ms^{-1} wind shear. Shading: mixing ratio (g kg^{-1}); contours (vertical velocity (every 4 ms^{-1}).
- Here, 1 km and 4 km differences aren't as noticeable.

Ref: http://www.mmm.ucar.edu/people/bryan/Presentations/bryan_2007_nssl_resolution.pdf

4 km, 1 km, 0.25 km



- System propagation approximately converged at 1 km for high-shear cases.
- For low-shear environment (more weakly forced) resolutions above 1 km are increasingly inadequate.

Ref: http://www.mmm.ucar.edu/people/bryan/Presentations/bryan_2007_nssl_resolution.pdf

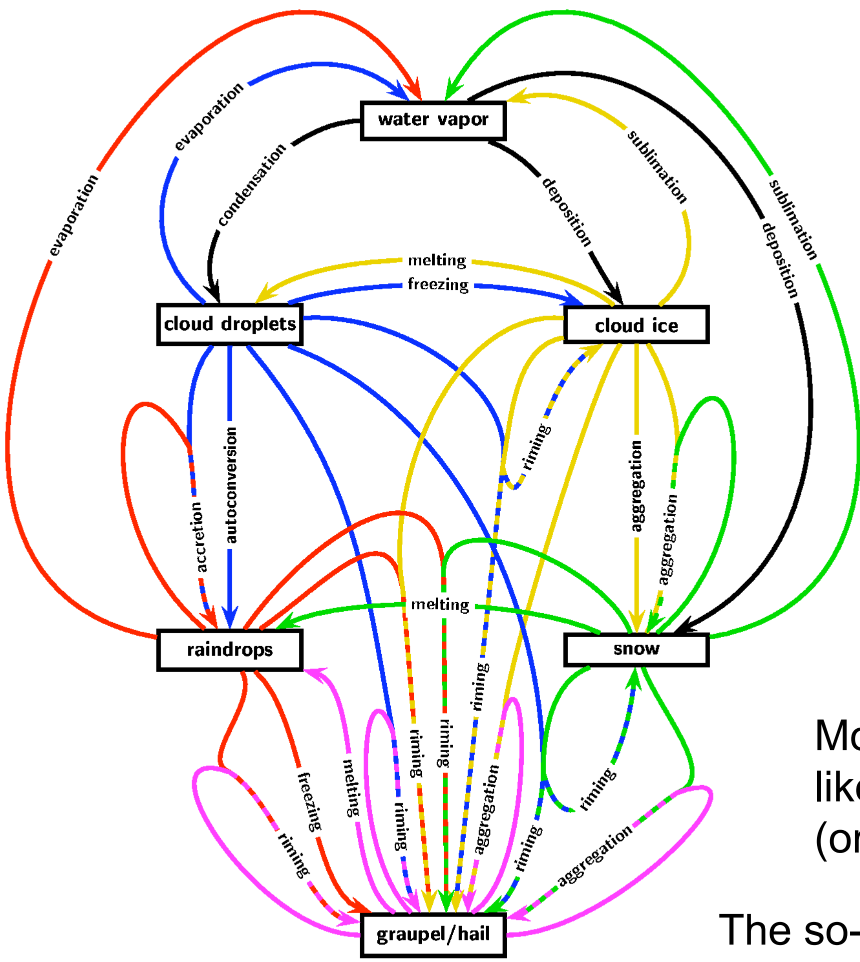
Model errors at mesoscale:

(2) those darn parameterizations!

- Land-surface parameterization
- Boundary-layer parameterization
- Convective parameterization
- Microphysical parameterization
- etc.

Model error at mesoscale:

Example: cloud microphysical processes



Conversion processes, like snow to graupel conversion by riming, are very difficult to parameterize but very important in convective clouds.

Especially for snow and graupel the particle properties like **particle density** and **fall speeds** are important parameters. The assumption of a constant particle density is questionable.

Aggregation processes assume certain collision and sticking efficiencies, which are not well known.

Most schemes do not include **hail processes** like wet growth, partial melting or shedding (or only very simple parameterizations).

The so-called **ice multiplication** (or Hallet-Mossop process) may be very important, but is still not well understood

from Axel Seifert presentation to NCAR ASP summer colloquium

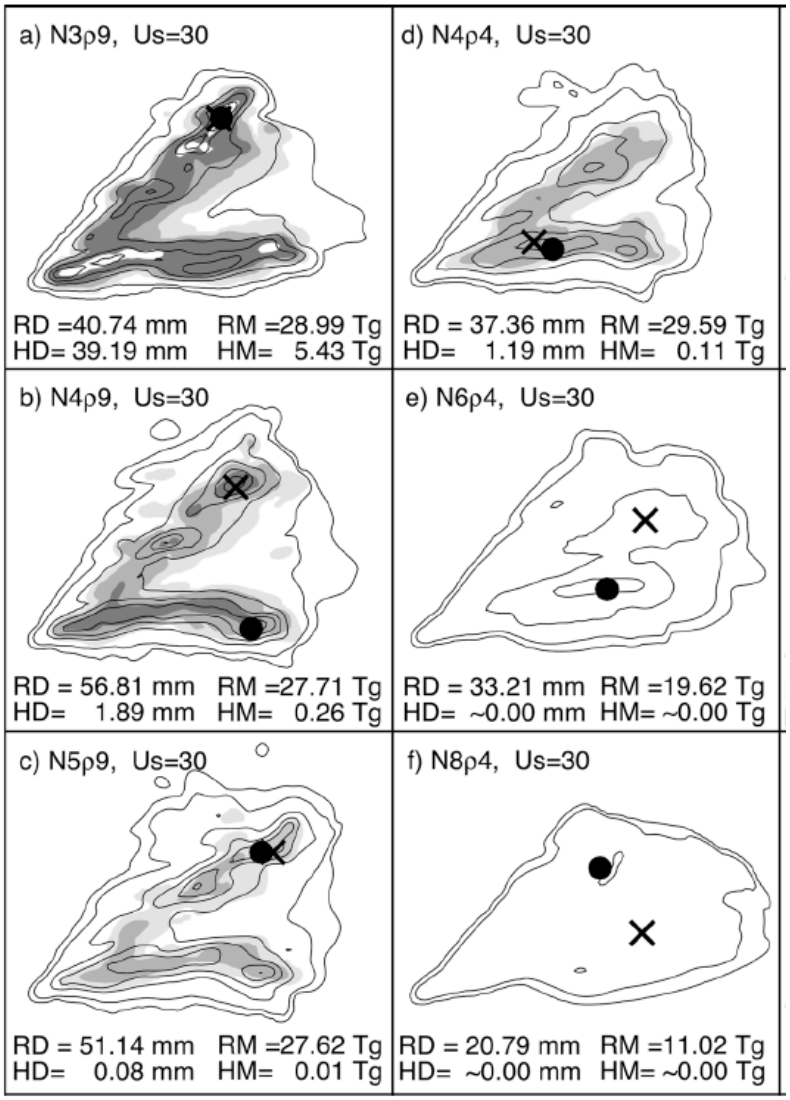
Model error at mesoscale:

Summary of microphysical issues in convection-resolving NWP

- Many fundamental problems in cloud microphysics are still unsolved.
- The lack of in-situ observations makes any progress very slow and difficult.
- Most of the current parameterization have been designed, operationally applied and tested for stratiform precipitation only.
- Most of the empirical relations used in the parameterizations are based on surface observation or measurements in stratiform cloud (or storm anvils, stratiform regions).
- Many basic parameterization assumptions, like N_0=const., are at least questionable in convective clouds.
- Many processes which are currently neglected, or not well represented, may become important in deep convection (shedding, collisional breakup, ...).
- One-moment schemes might be insufficient to describe the variability of the size distributions in convective clouds.
- Two-moment schemes haven‘t been used long enough to make any conclusions.
- Spectral methods are overwhelmingly complicated and computationally expensive. Nevertheless, they suffer from our lack of understanding of the fundamental processes.

from Axel Seifert presentation to NCAR ASP summer colloquium

Sensitivity of deep convective storms to graupel properties in a microphysical parameterization



Effect of assumed graupel density and particle size distribution, i.e. size and fall speed, in a storm split spawning supercells. Contours: rain isohyets: shading: hail/graupel depths greater than .01, 0.1, 1, and 10 mm. • : location of maximum graupel accumulation. × : location of maximum hail accumulation.

Plausible changes in microphysical parameterizations can cause large changes in precipitation amount, type, and location.

Ref: Gilmore et al., Nov 2004 MWR

Synthesis

- If extreme events are driven by large scales and for phenomena that are not particularly sensitive to model error ➔ days of predictability.
- If extreme events are from mesoscale events more divorced from large scales, or if related to phenomena with large model errors ➔ hours of predictability.
- Model error large at mesoscale, can lead to significant gap between predictive ability and predictability.