The ECMWF Approach to Ensemble Prediction

Tim Palmer

University of Oxford, ECMWF.

With particular thanks to

Jan Barkmeijer, Roberto Buizza, Philippe Chapelet, Dennis Hartmann, Renate Hagedorn, Martin Leutbecher, Jean-Francois Mahfouf, Martin Miller, Franco Molteni, Robert Mureau, Thomas Petroliagis, Kamal Puri, David Richardson, Glenn Shutts, Stefano Tibaldi, Joe Tribbia….

… and all of ECMWF RD and OD

With thanks to Met Office staff

Doug Mansfield, James Murphy

METEOROLOGICAL OFFICE Met.O.971

THE METEOROLOGICAL MAGAZINE

No. 1372, November 1986, Vol. 115

551.509.33:551.509.5

Experimental monthly long-range forecasts for the United Kingdom

Part II. A real-time long-range forecast by an ensemble of numerical integrations

By J.M. Murphy and T.N. Palmer*

(Meteorological Office, Bracknell)

Summary

The use of an ensemble of integrations for long-range prediction has been studied with a hemispheric version of the Meteorological Office 5-level general circulation model. Some results, showing the potential of the technique, are described. The method is now being used with the global 11-level model to produce real-time long-range forecasts for the long-range forecasting conference in the Synoptic Climatology Branch of the Meteorological Office. Results from the first of these real-time ensemble forecasts are discussed.

1. Introduction

The short-range predictive skill of numerical weather prediction (NWP) models has steadily improved over the years. Despite this, attempts to use such models to forecast the instantaneous state of the atmosphere a month into the future have not enjoyed much success. The fundamental reasons for this lie not only with deficiencies in the numerical models, but also with the very equations of motion which the models integrate.

Specifically, the difference between two or more integrations of an NWP model whose initial states differ by a small amount (representing, say, analysis error) will increase with time until at some stage the integrations are completely independent of one another, in the sense that they can be thought of as random states in some climatological distribution. This suggests that the atmosphere has some 'limit of deterministic predictability' and attempts to estimate this (e.g. Lorenz 1982, Mansfield 1986) suggest that, on average, it is considerably less than 1 month. This limit can be extended by considering the model's forecast of only the planetary-scale modes and/or time-averaged fields (Shukla 1981), though this approach ignores a fundamental problem that forecasting on the monthly time-scale has a marked probabilistic element, and is not strictly deterministic. The multivariate statistical model (Maryon and Storey 1985, Folland and Woodcock 1986), the backbone of the operational long-range forecasting system in the Meteorological Office, has this notion built into its basic formulation; it does not predict one pattern of surface pressure, but assigns probabilities to a number of pre-defined patterns.

* Now on secondment to the European Centre for Medium Range Weather Forecasts, Shinfield Park, Reading.

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1985: The First Semi-Operational Real-Time Ensemble Forecast

Q. J. R. Meteorol. Soc. (1988), **114,** pp. 691–713 551.509.33

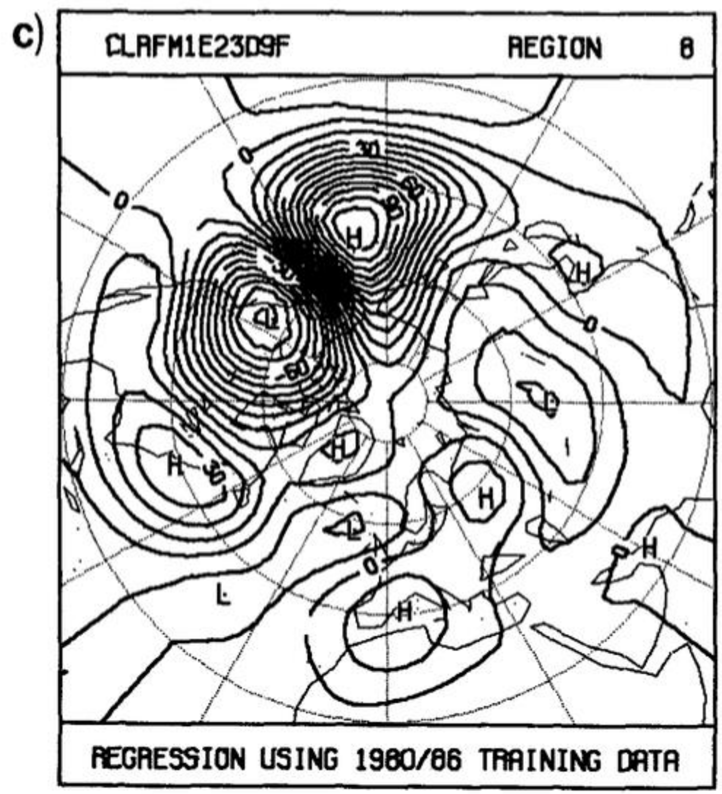
Medium and extended range predictability and stability of the Pacific/North American mode

By T. N. PALMER
European Centre for Medium Range Weather Forecasts, Reading

(Received 14 April 1987; revised 22 October 1987)

SUMMARY

It is shown from an assessment of a small set of extended range forecasts from two centres, and from a much larger set of medium range forecasts from one centre, that variability in predictive skill is strongly related to fluctuations in the Pacific/North American (PNA) mode of low frequency variability. A hypothesis is put forward that this is associated with the dependence of large-scale instability of the forecast flow on the amplitude of the PNA mode. The hypothesis is tested in a barotropic model using as basic states, composite skilful and unskilful cases from the set of medium range forecasts and individual monthly mean fields. Results from the



Cf Miyakoda et al, 1982

Integrations with a Barotropic Vorticity Equation Model

VOL. 40, NO. 6 JOURNAL OF THE ATMOSPHERIC SCIENCES JUNE 1983

Barotropic Wave Propagation and Instability, and Atmospheric Teleconnection Patterns

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G. W. BRANSTATOR
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(Manuscript received 22 October 1982, in final form 28 January 1983)

ABSTRACT

A global barotropic model, linearized about the 300 mb climatological mean January flow, is perturbed by applying a series of localized forcings distributed throughout the tropics and subtropics. Structures which resemble the observed "Pacific/North American" and "East Atlantic" teleconnection patterns noted by Wallace and Gutzler (1981) tend to recur in the responses. Similar patterns are found to result from the dispersion of isolated initial perturbations placed at a variety of locations in the tropics and midlatitudes.

It is shown that these structures are related to the most rapidly growing mode associated with barotropic instability of the zonally-varying climatological basic state. In the absence of damping, this mode has an e-folding time of about a week and a period close to 50 days. In localized regions the instantaneous growth rates can be competitive with those of baroclinic instability. These episodes of rapid local barotropic growth are interspersed with intervals in which the local perturbation relaxes as energy disperses throughout the

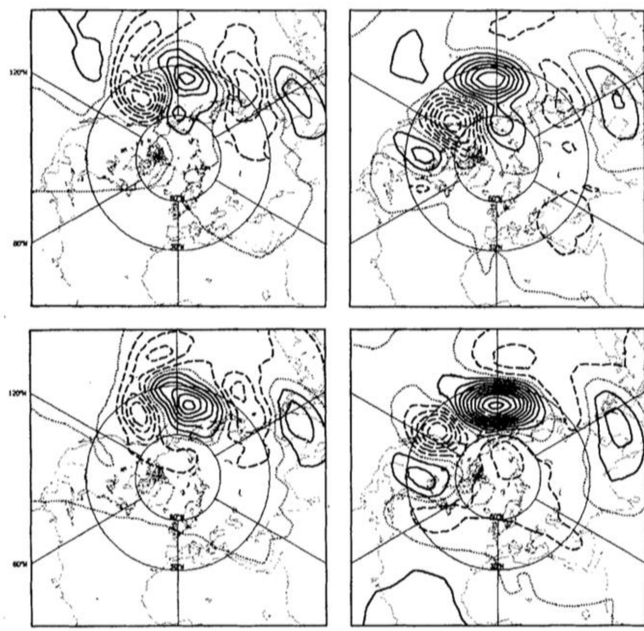


Figure 9. Perturbation streamfunction from integrations of a barotropic model with the two basic states shown in Fig. 8, and identical perturbations positioned at 30°N 120°E. The top diagrams are for basic state B−, the bottom for B+. (a) Day 2; (b) day 4; (c) day 9; (d) day 30. For details see text and Simmons *et al.* (1983). The

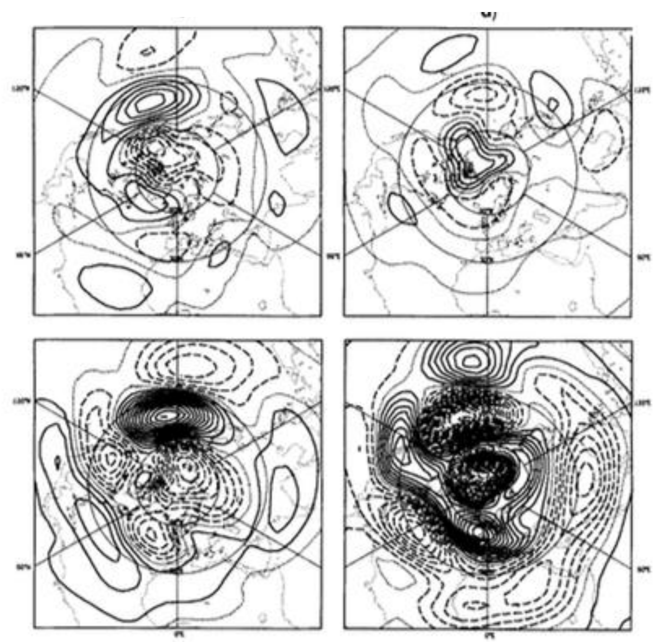
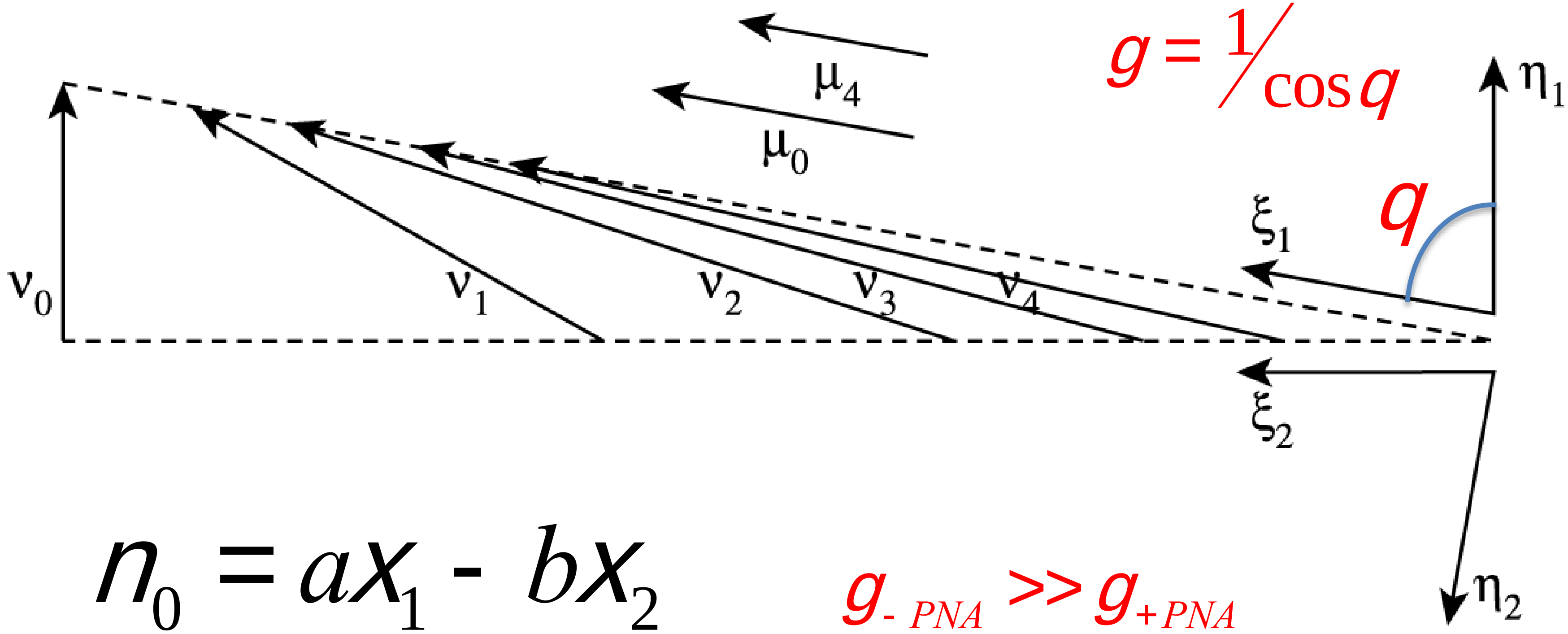


Figure 9 (continued)

If eigenvectors are not normal (operator not self-adjoint), perturbation growth is not bounded by the dominant eigenvalue



$g = {}^{1}\!/_{\cos q}$

$$n_0 = a x_1 - b x_2$$

$g_{-PNA} >> g_{+PNA}$

Zhang c. 1989

Q. J. R. Meteorol. Soc. (1993), **119**, pp. 269–298 551.509.333:551.513.1

Predictability and finite-time instability of the northern winter circulation

By FRANCO MOLTENI and T. N. PALMER*
European Centre for Medium-range Weather Forecasts, Reading

(Received 17 March 1992; revised 10 August 1992)

SUMMARY

The finite-time instability and associated predictability of atmospheric circulations are defined in terms of the largest singular values, and associated singular vectors, of the linear evolution operator determined from given equations of motion. These quantities are calculated in both a barotropic and a three-level quasi-geostrophic model, using as basic states realistic large-scale northern wintertime flows that represent the climatological state, regime composites, and specific realizations of these regimes. For time-invariant basic states, the singular vectors are compared with the corresponding normal-mode solutions; it is shown that the perturbations defined (at the initial time) by the singular vectors have much larger growth rates than the normal modes, and possess a more localized spatial structure.

The regimes studied have opposite values of the Pacific/North American (PNA) index, and growth rates for the barotropic basic states appear to confirm earlier studies that the barotropic instability of the negative

Computation of optimal unstable structures for a numerical weather prediction model

By R. BUIZZA[1,‡], J. TRIBBIA[2], F. MOLTENI[1] and T. PALMER[1], [1]*European Centre for Medium-Range Weather Forecasts, Shinfield Park, Reading RG2 9AX, England,* [2]*National Center for Atmospheric Research*, P.O. Box 3000, Boulder, Colorado 80307, USA*

(Manuscript received 30 November 1992; in final form 10 May 1993)

ABSTRACT

Numerical experiments have been performed to compute the fastest growing perturbations in a finite time interval for a complex numerical weather prediction model. The models used are the tangent forward and adjoint versions of the adiabatic primitive-equation model of the Integrated Forecasting System developed at the European Centre for Medium-Range Weather Forecasts and Météo France. These have been run with a horizontal truncation T21, with 19 vertical levels. The fastest growing perturbations are the singular vectors of the propagator of the forward

1434 JOURNAL OF THE ATMOSPHERIC SCIENCES VOL. 52, NO. 9

The Singular-Vector Structure of the Atmospheric Global Circulation

R. BUIZZA AND T. N. PALMER
European Centre for Medium-Range Weather Forecasts, Shinfield Park, Reading, Berkshire, United Kingdom

(Manuscript received 17 November 1993, in final form 20 April 1994)

ABSTRACT

The local phase-space instability of the atmospheric global circulation is characterized by its (nonmodal) singular vectors. The formalism of singular vector analysis is described. The relations between singular vectors, normal modes, adjoint modes, Lyapunov vectors, perturbations produced by the so-called breeding method, and wave pseudomomentum are outlined. Techniques to estimate the dominant part of the singular spectrum using large-dimensional primitive equation models are discussed. These include the use of forward and adjoint tangent propagators with a Lanczos iterative algorithm. Results are described, based first on statistics of routine calculations made between December 1992 and August 1993, and second on three specific case studies.

Results define three dominant geographical areas of instability in the Northern Hemisphere: the two regions of storm track cyclogenesis, and the North African subtropical jet. Singular vectors can amplify as much as tenfold over 36 hours, and in winter there are typically at least 35 independent singular vectors, which quadruple

Q. J. R. Meteorol. Soc. (2001), **127**, pp. 685–708

Tropical singular vectors computed with linearized diabatic physics

By J. BARKMEIJER*, R. BUIZZA, T. N. PALMER, K. PURI and J.-F. MAHFOUF
European Centre for Medium-Range Weather Forecasts, UK

(Received 2 December 1999; revised 6 July 2000)

SUMMARY

With the introduction of diabatic processes in the forward and adjoint tangent models of the European Centre for Medium-Range Weather Forecasts's model, it is possible to determine singular vectors (SVs) for situations where diabatic physics may be important in producing perturbation growth. In this paper, the linear physical parametrizations are used to compute SVs for the tropical region, or subsets thereof, with an optimization time of 48 h. Perturbation growth is measured in terms of the so-called total energy norm, augmented with a term for specific humidity.

Difficulties that may arise in computing tropical SVs, such as associated with spurious upper-tropospheric perturbation growth, are described. Also, the impact on the SV structure by including a specific-humidity term

From Buizza and Palmer, 1995

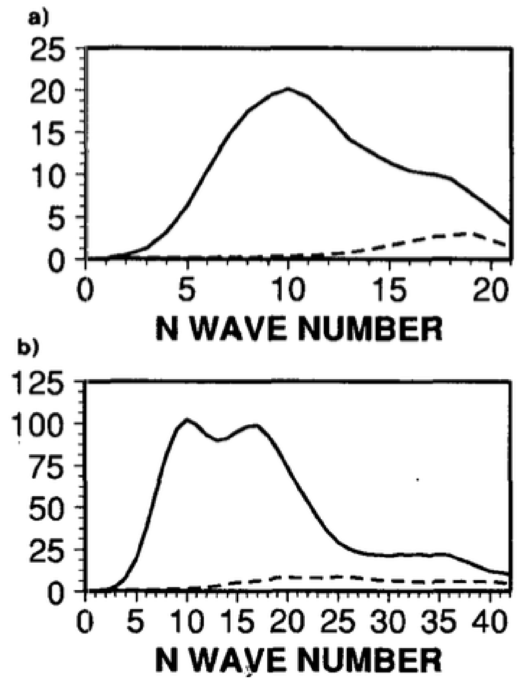


FIG. 12. Energy distribution of singular vector for 9 January case as a function of total wavenumber. Dashed: at initial time (×20); solid: at optimization time for (a) T21 calculation and (b) T42 calculation.

Use SVs to initialise EPS. Why?

1. Meteorologically balanced perturbations

2. Initial-time perturbations with amplitudes focussed on sub-synoptic wavenumbers where analysis errors (observation error and model error) are likely to be significant, and final-time perturbations on synoptic and smaller wavenumbers where forecast error is dominant.

3. Perturbations with growth rates that would compensate for the overly dissipative nature of the model at large wavenumbers.

4. Since we don’t have a good quantification of initial error (esp impact of model error on initial error - see below), focussing on potential worse-case perturbations is no bad thing. The main problem with ensemble prediction (to the present day) is underdispersion - overconfidence.

Q. J. R. Meteorol. Soc. (1993), **119**, pp. 299–323 551.509.313:551.509.333

Ensemble prediction using dynamically conditioned perturbations

By R. MUREAU, FRANCO MOLTENI and T. N. PALMER*
European Centre for Medium-range Weather Forecasts, Reading

(Received 17 March 1992; revised 10 August 1992)

SUMMARY

We apply the technique developed in the companion paper by Molteni and Palmer (1993) as a means of providing dynamically conditioned perturbations for ensemble forecasting with a primitive-equation model. Four wintertime initial states are chosen—three at random and one because of substantial development in the large-scale flow within four days, which the control forecast completely missed. A set of singular vectors are created using a quasi-geostrophic model linearized about basic states taken from data close to the chosen initial dates. These are interpolated onto the primitive-equation-model grid, and used as perturbations to the initial state. An ensemble forecast is made from the perturbed initial states. The dispersion of this ensemble is compared, for each date, with that from a second ensemble with initial perturbations constructed from 6-hour-forecast errors. Throughout the forecast period, it is found that the amplitude of the perturbations is noticeably larger using the singular vectors. The dispersion of the ensembles using the forecast-error perturbations did not indicate that the control forecast from the case with substantial development was likely to be poor. By contrast, the (envelope) dispersion of the ensemble using the singular vectors was notably larger for this case than the other three. A number of members of this ensemble were particularly skilful in predicting weather-related elements of the flow, such as low-level temperature change. It is found that the evolution of perturbations which are initially localized over the western Pacific, or western Atlantic, can develop blocking-like structures several days later over the eastern oceans. With the initial amplitudes used in this paper, the development of these structures is in part nonlinear.

The growth of the singular-vector perturbations was not as large in the primitive-equation model as in the quasi-geostrophic model, probably due to interpolation problems exacerbated by inconsistent orographic representation. Further work to overcome these, and other, problems is indicated.

TECHNICAL MEMORANDUM

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Ensemble Prediction

Palmer, T., F. Molteni, R. Mureau,
R. Buizza, P. Chapelet & J. Tribbia

Research Department

August 1992

European Centre for Medium-Range Weather Forecasts
Europäisches Zentrum für mittelfristige Wettervorhersage
Centre européen pour les prévisions météorologiques à moyen

Q. J. R. Meteorol. Soc. (1996), **122**, pp. 73–119

The ECMWF Ensemble Prediction System: Methodology and validation

By F. MOLTENI, R. BUIZZA, T. N. PALMER* and T. PETROLIAGIS
European Centre for Medium-Range Weather Forecasts, UK

(Received 1 August 1994; revised 24 May 1995)

SUMMARY

The European Centre for Medium-Range Weather Forecasts (ECMWF) Ensemble Prediction System (EPS) is described. In addition to an unperturbed (control) forecast, each ensemble comprises 32 10-day forecasts starting from initial conditions in which dynamically defined perturbations have been added to the operational analysis. The perturbations are constructed from singular vectors of a time-evolution operator linearized around the short-range-forecast trajectory. These singular vectors approximately determine the most unstable phase-space directions in the early part of the forecast period, and are estimated using a forward and adjoint linear version of the ECMWF numerical weather-prediction model. An appropriate norm is chosen, and relationships between the structures of these singular vectors at initial time and patterns showing the sensitivity of short-range forecast error to changes in the analysis are discussed. A methodology to perform a phase-space rotation of the singular vectors is described, which generates hemispheric-wide perturbations and renormalizes them according to analysis-error estimates from the data-assimilation system.

The validation of the ensembles is given firstly in terms of scatter diagrams and contingency tables of ensemble spread and control-forecast skill. The contingency tables are compared with those from a perfect-model ensemble system; no significant differences are found in some cases. Brier scores for the probability of European flow clusters are presented, which indicate predictive skill up to forecast-day 8 with respect to climatological probabilities. The

But now …. Perturbations produced by Ensemble Data Assimilation (EDA)…. Surely no need for SVs any more??

Quarterly Journal of the Royal Meteorological Society ***Q. J. R. Meteorol. Soc.*** **150: 1–1 (2020?)**

RMetS
Royal Meteorological Society

Farewell Singular Vectors

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Atmospheric, Oceanic and Planetary Physics, University of Oxford, UK
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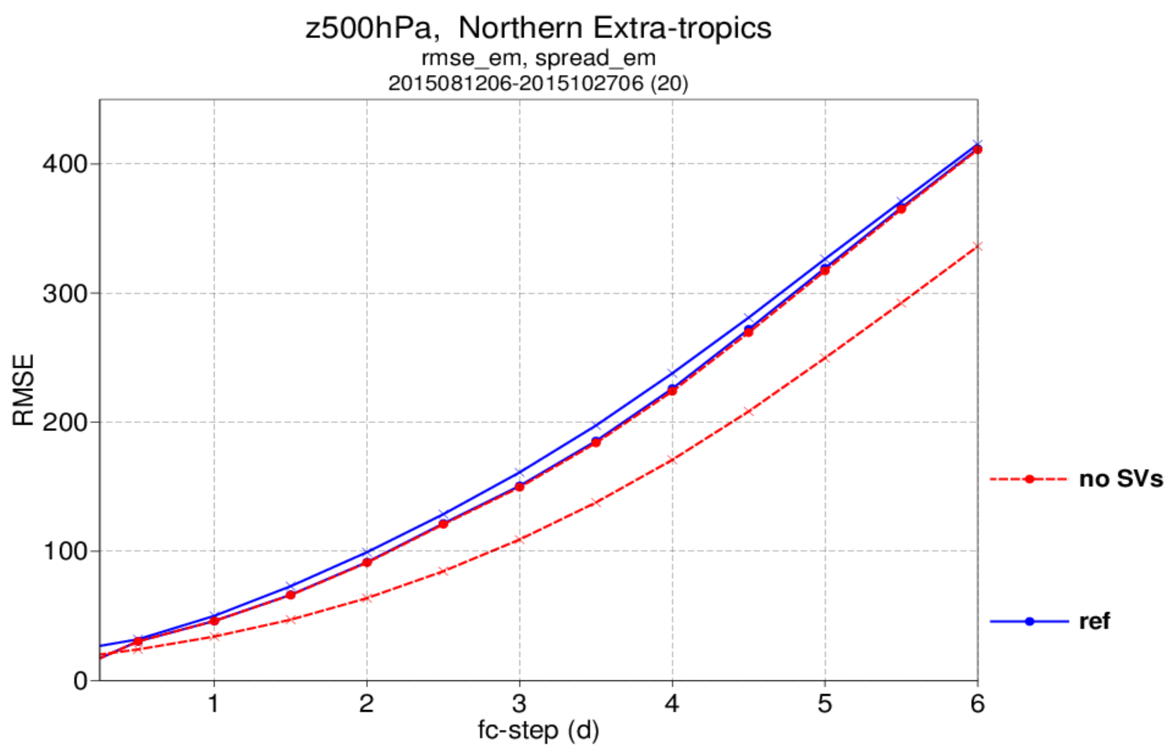
To be determined.

Key Words: Singular vectors, ensemble forecasting, uncertainty

Received . . .

Impact of SVs on ENS



Oper like setup, TCo399, 20 Initial dates

Simon Lang: Personal Communication

Stochastic Physics

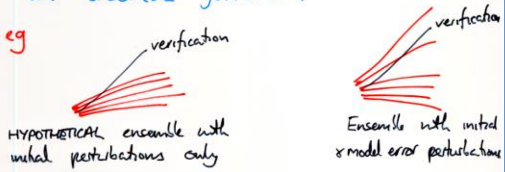
Workshop on New Insights and Approaches to Convective Parametrization 4-7 November 1996

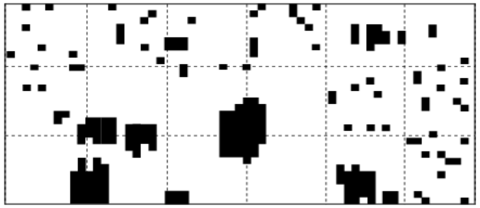
Thoughts on 'parametrizing' scales that are only somewhat smaller than the smallest resolved scales

– with application to convection and orography

- In quasi-2D flow there can be a strong inverse energy cascade from sub-cyclone to cyclone scales (cf singular vector analysis).
- It is important to try to quantify these types of small-scale spatially coherent model error in order to assess their impact on the predictability of cyclone-scale forecasts.
- What is the pdf of model error associated with the misrepresentation of coherent structures near the ~~predictability~~ truncation limit.
- Should this pdf be represented in an ensemble forecast?

eg





Probability of an "on"cell proportional to CAPE and number of adjacent "on" cells – "on" cells feedback to the resolved flow

Stochastically Perturbed Parameterisation Tendencies (SPPT)

A Holistic Scientifically Justified Approach to Representing Model Uncertainty

- Operational scheme in ECMWF's ensemble prediction system
- Perturbations to total parametrised tendency of physical processes with multiplicative noise

$$\dot{X}_r = \dot{X}_p + r\dot{X}_p \qquad \textit{for } X=\{u,v,T,q\}$$

- *r* is a uni-variate random number described through a spectral pattern generator which is smooth in space and time
- Spectral coefficients of *r* are described with an AR(1) process
- Gaussian distribution, truncated at ±2s

Q. J. R. Meteorol. Soc. (1999), **125**, pp. 2887–2908

Stochastic representation of model uncertainties in the ECMWF Ensemble Prediction System

By R. BUIZZA*, M. MILLER and T. N. PALMER
European Centre for Medium-Range Weather Forecasts, UK

(Received 18 August 1998; revised 19 March 1999)

SUMMARY

A stochastic representation of random error associated with parametrized physical processes ('stochastic physics') is described, and its impact in the European Centre for Medium-Range Weather Forecasts Ensemble Prediction System (ECMWF EPS) is discussed. Model random errors associated with physical parametrizations are simulated by multiplying the total parametrized tendencies by a random number sampled from a uniform distribution between 0.5 and 1.5. A number of diagnostics are described and a choice of parameters is made. It is shown how the scheme increases the spread of the ensemble, and improves the skill of the probabilistic prediction of weather parameters such as precipitation. A choice of stochastic parameters is made for operational implementation. The scheme was implemented successfully in the operational ECMWF EPS on 21 October 1998.

KEYWORDS: Ensemble forecasting Model errors Numerical weather prediction Parametrization

1. INTRODUCTION

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ROYAL METEOROLOGICAL SOCIETY

Vol. 127 JANUARY 2001 Part B No. 572

Q. J. R. Meteorol. Soc. (2001), **127**, pp. 279–304

A nonlinear dynamical perspective on model error: A proposal for non-local stochastic–dynamic parametrization in weather and climate prediction models*

By T. N. PALMER†
European Centre for Medium-Range Weather Forecasts, UK

(Received 2 February 2000; revised 11 September 2000)

SUMMARY

Conventional parametrization schemes in weather and climate prediction models describe the effects of subgrid-scale processes by deterministic bulk formulae which depend on local resolved-scale variables and a number of adjustable parameters. Despite the unquestionable success of such models for weather and climate prediction, it is impossible to justify the use of such formulae from first principles. Using low-order dynamical-systems models, and elementary results from dynamical-systems and turbulence theory, it is shown that even if unresolved scales only describe a small fraction of the total variance of the system, neglecting their variability


TECHNICAL MEMORANDUM

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Stochastic Parametrization and Model Uncertainty

Palmer, T.N., R. Buizza, F. Doblas-Reyes, T. Jung, M. Leutbecher, G.J. Shutts, M. Steinheimer, A. Weisheimer

Research Department

October 8, 2009

This paper has not been published and should be regarded as an Internal Report from ECMWF. Permission to quote from it should be obtained from the ECMWF.

European Centre for Medium-Range Weather Forecasts
Europäisches Zentrum für mittelfristige Wettervorhersage
Centre européen pour les prévisions météorologiques à moyen terme

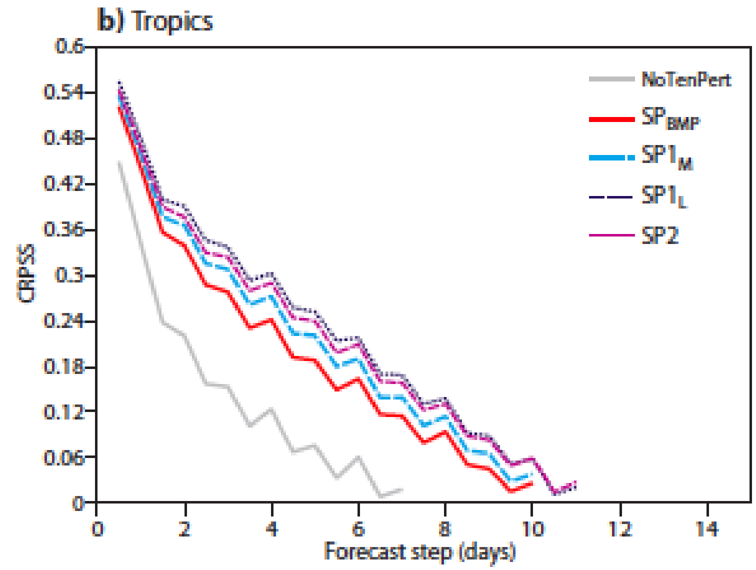
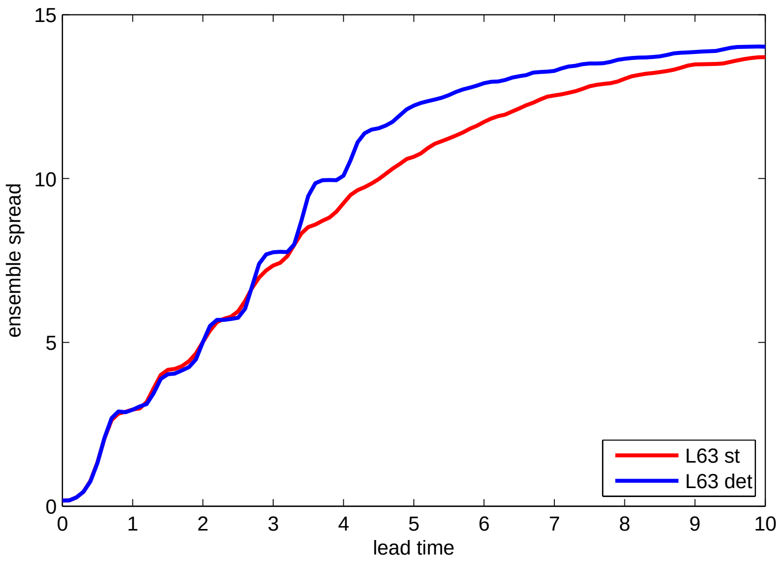


Figure 3: Continuous Ranked Probability Skill Score for 850 hPa temperature.

Spread L63 and L63 stoch.

$$\dot{X} = -\sigma X + \sigma Y + s\eta_1$$
$$\dot{Y} = -XZ + rX - Y + s\eta_2$$
$$\dot{Z} = XY - bZ + s\eta_3$$



Spread decreases (not increases!) with stochastic noise

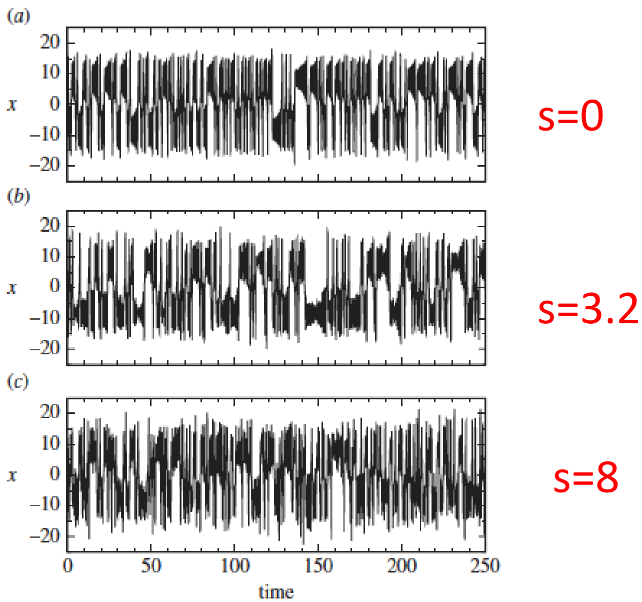
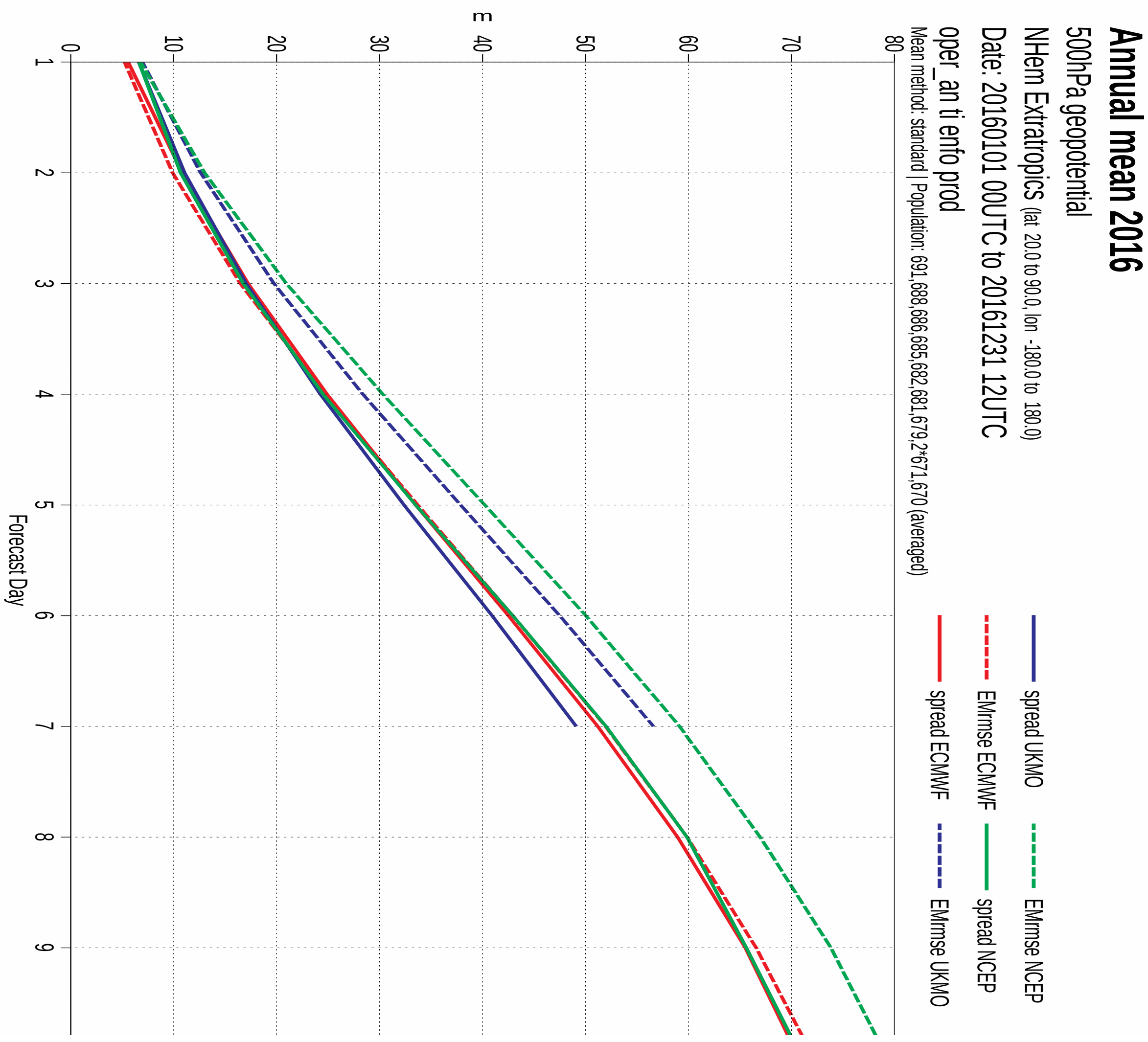


Figure 4. Lorenz '63 system: sample time series of x for noise levels (a) $\sigma = 0$, (b) $\sigma = 3.2$ and (c) $\sigma = 8$. At intermediate noise level, the distribution of regime residence times is shifted to larger values.

Kwasniok, 2014

ECMWF EPS spread/skill better balanced than other operational ensembles.



Martin Janousek: Personal Communication

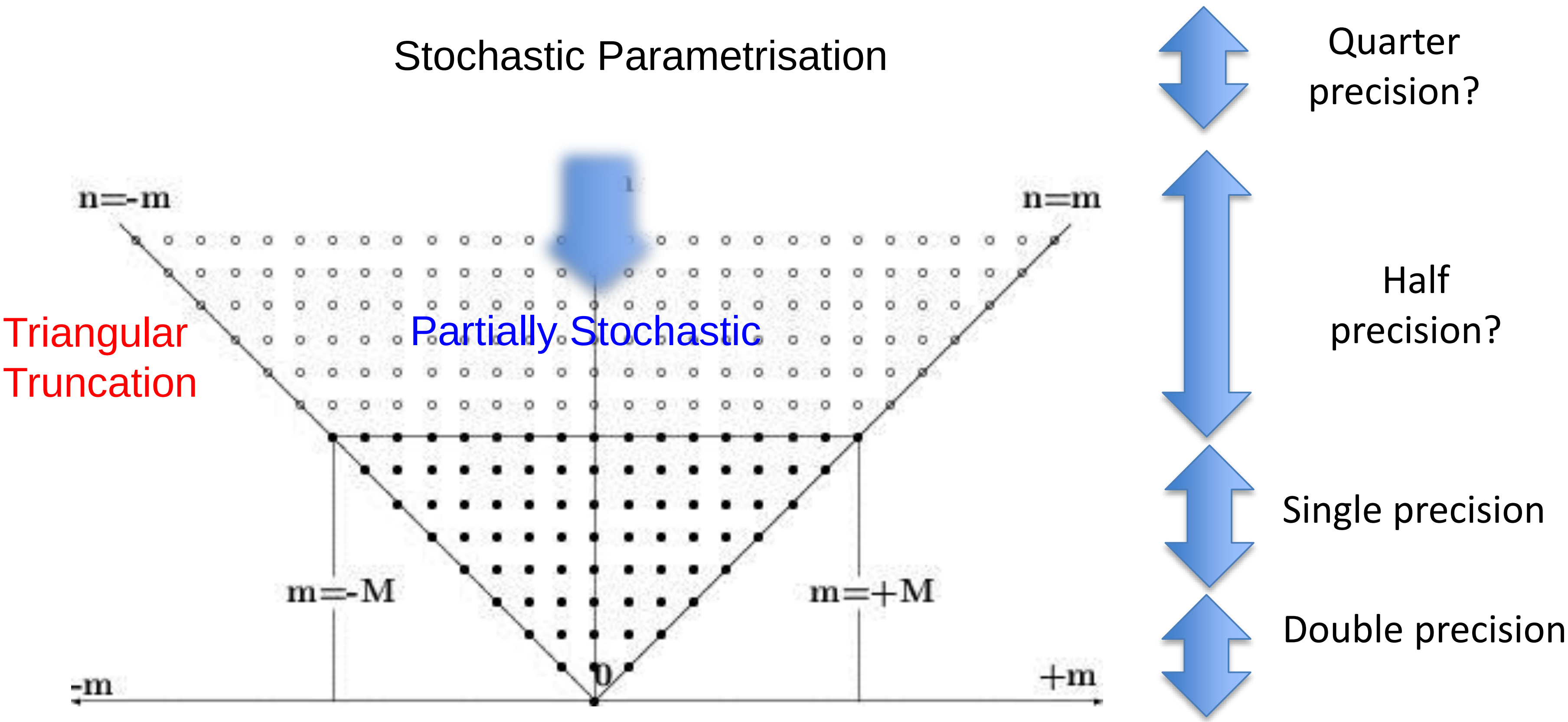
The Future: More Interaction Between SVs and SPPT?

Use EDA to set SV amplitudes regionally?

Ensemble Size vs Resolution

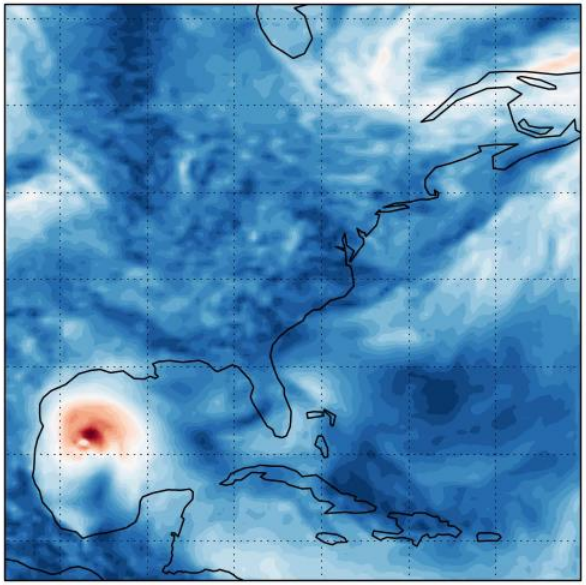
- We must not drop below 50 members. Needed to optimise probabilistic scores for high-impact weather (see Martin Leutbecher's talk).
- Two complementary routes to developing high-resolution (e.g. 5km) 50 member ensembles….

1. State-dependent precision….



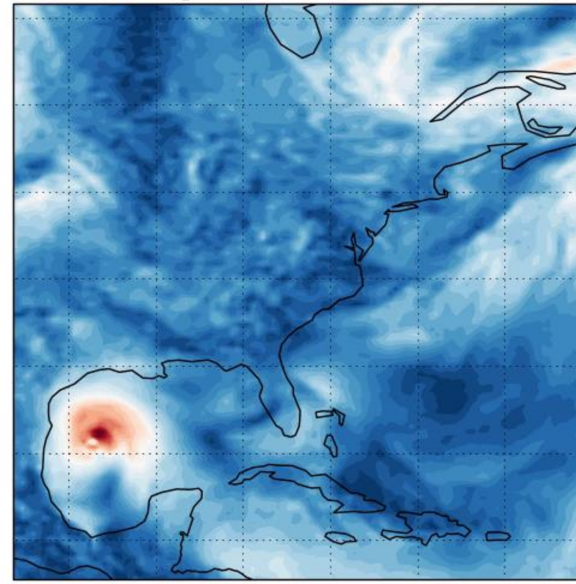
… a job for scientists

Double - 52 SBITS 0.00 h

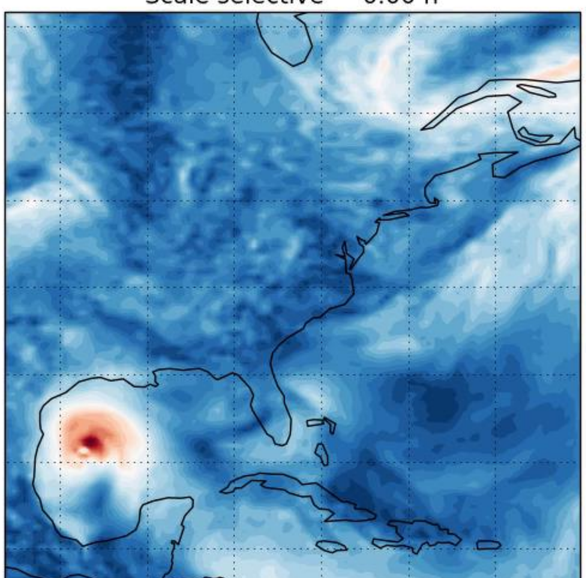


Hurricane Harvey

Single - 23 SBITS 0.00 h



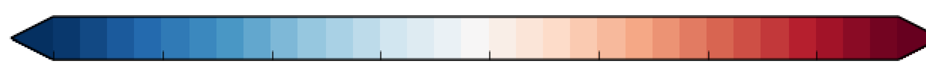
Scale selective 0.00 h



$n = 0$	52-bit significand
$0 < n$ £ 160	11-bit significand
160<n £ 320	9-bit significand
320<n £ 511	7-bit significand

25/08/17 00:00
850hP wind speed
T511L91

Matthew Chantry, Oxford – Peter Düben, ECMWF.



2. Make the case for much greater computing capability, so ECMWF can remain the World No 1.

SCIENCE —

The European weather forecast model already kicking America's butt just improved

Better resolution will allow the world's best model to improve local forecasts.

ERIC BERGER (US) - 12/3/2016, 08:15

Why Are Europeans Better at Predicting Weather?

Wednesday's snow no-show in Washington was another misfire by U.S. forecasters.

By Peter Miller, for National Geographic News

PUBLISHED MARCH 8, 2013

... a job for management

Extra Slides

The application of ensemble ideas to monthly (and seasonal) forecasting was not controversial.

What was more controversial is that ensemble forecast methods should be developed within what was referred to as “the limit of deterministic predictability”. Medium-range ensemble forecasting was treated with scepticism.

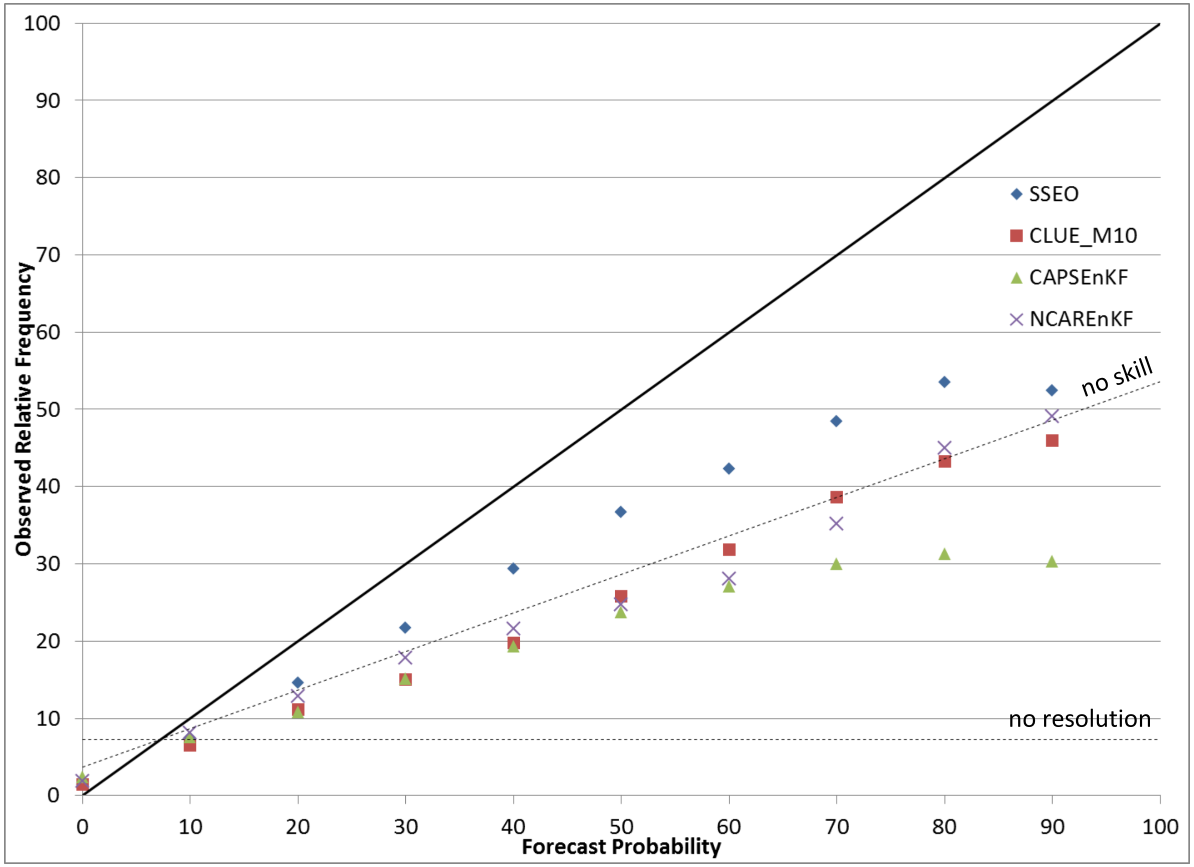
Instead of probabilistic prediction, the thought at the time was that we should be trying to “forecast the forecast skill” of the deterministic forecast.

This turned out to be a forlorn hope, though it led to some very important scientific spin offs, such as how to perturb the initial conditions in a medium-range ensemble forecast.

NOAA Hazardous Weather Testbed Spring Forecasting Experiment (I. Jirak and A. Clark)

Neighborhood Reflectivity Verification: *CLUE*

Comparison to SSEO: Reliability



Mesoscale Area of Interest
1-km AGL Reflect. >40 dBZ
20160502-20160603
00Z cycle; fh013-030

40-km Radius of Influence
10 grid-point Gaussian smoothing parameter

SSEO: 7-member multi-model
CLUE_M10: 5 ARW, 5 NMMB
CAPSEnKF: 9-member ARW
NCAREnKF:10-member ARW

$$\mathbf{x}'(t) = L(t, t_0)\mathbf{x}'(t_0)$$

Let $\|\mathbf{x}\|$ denote the perturbation's energy.

Let $(\mathbf{x}; \mathbf{y})$ denote the corresponding inner product.

Then

$$\max_{\mathbf{x}(t_0) \neq 0}(\|\mathbf{x}(t)\| / \|\mathbf{x}(t_0)\|) = \sigma_1$$

where σ_1 is the largest eigenvalue for

$$(LL^*)\mathbf{v}_i(t) = \sigma_i^2 \mathbf{v}_i(t)$$

i.e. the largest singular value of L

The corresponding singular vectors, ranked by the size of σ_i define the fastest growing perturbations

"If more realistic models with many thousand variables also have the property that a few of the eigenvalues of AA^T are much larger than the remaining, a study based upon a small ensemble of initial errors should..give a reasonable estimate of the growth rate of random error." Lorenz (1965)

Lorenz (1965): A Study of the Predictability of a 28-Variable Atmospheric Model, Tellus.