Numerical Weather Prediction

Weather Forecasting then: Weather rules, have a look to the west …
Weather Forecasting today: Use of super-computers.

Idea of Numerical Weather Prediction (NWP): L.F.Richardson 1921

Dynamics of the atmosphere can be described by six parameters.

6 Parameters: Temperature, pressure, humidity, wind (u,v,w)
6 Equations: Newton: Force = mass * acceleration
Laws of thermodynamics
Conservation of mass (continuity equation)
Hydrostatic equation

This system of equations can be solved! Experiment with students…

NUMERICAL WEATHER PREDICTION

Primitive Equations to compute global atmospheric flow

Three main sets of Balance Equations

1. **Continuity Equation**
   Representing the Conservation of Mass

2. **Conservation of momentum (Navier-Stokes-Equations)**
   Describing the atmospheric flow over the surface

3. **Thermal Energy Equation**
   Describing the Temperature of the System with sinks and sources

Numerical Weather Prediction

Primitive Equations to compute global atmospheric flow

1. **Pressure Gradient Force: Force = mass * acceleration (Newton)**
2. **Navier-Stokes-Equations describing friction near surface**
3. **Equation of motion for 3 components x,y,z**
4. **Continuity Equation describing conservation of mass**
5. **Thermal Energy Equations to comply with the Laws of Thermodynamics**

**With a given initial state (numerical analysis of observations)
this set of equations describes the rate of change of the system
so that numerical integration allow to compute the system in the future,
Weather Forecast.**

Forces that cause atmospheric motion

Forces that cause atmospheric motion include the pressure gradient force, gravity, and viscous friction. Together, they create the forces that accelerate our atmosphere.

The pressure gradient force causes an acceleration forcing air from regions of high pressure to regions of low pressure. Mathematically, this can be written as:

$$\frac{f}{m} = \frac{1}{\rho}\frac{dp}{dx}.$$

The gravitational force accelerates objects at approximately 9.8 m/s^2 directly towards the center of the Earth.

The force due to viscous friction can be approximated as:

$$f_r = \frac{f}{a}\frac{1}{\rho}\mu\left(\nabla\cdot(\mu\nabla v) + \nabla(\lambda\nabla\cdot v)\right).$$

Using Newton's second law, these forces (referenced in the equations above as the accelerations due to these forces) may be summed to produce an equation of motion that describes this system. This equation can be written in the form:

$$\frac{dv}{dt} = -(1/\rho)\nabla p - g(r/r) + f_r$$

$$g = g_e.$$

Therefore, to complete the system of equations and obtain 6 equations and 6 variables:

- $\frac{dv}{dt} = -(1/\rho)\nabla p - g(r/r) + (1/\rho)\left[\nabla\cdot(\mu\nabla v) + \nabla(\lambda\nabla\cdot v)\right]$
- $c_v\frac{dT}{dt} + p\frac{d\alpha}{dt} = q + f$
- $\frac{d\rho}{dt} + \rho\nabla\cdot v = 0$
- $p = nT.$

where n is the number density in mol, and T:=RT is the temperature equivalent value in Joule/mol.

Numerical Weather Prediction

Courant – Friedrich – Lewy Condition (CFL)

The Courant–Friedrichs–Lewy or CFL condition is a condition for numerical stability

The distance that any information travels during the timestep length within the mesh must be lower than the distance between mesh elements.

In other words, information from a given cell or mesh element must propagate only to its immediate neighbors.

$$C = a\frac{\Delta t}{\Delta x}$$

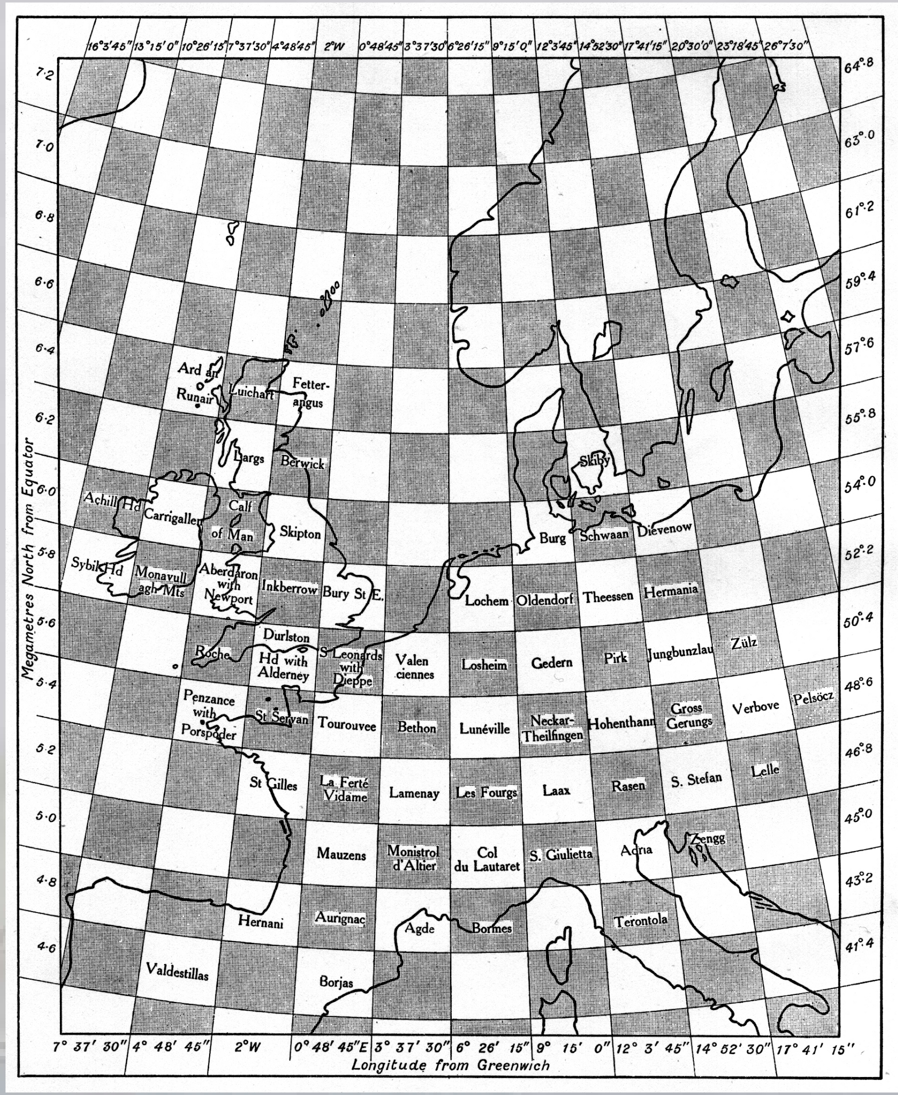
α = characteristic speed so that
C = Courant number becomes dimensionless

C ≤ 1 is necessary for numerical stability

If C > 1, the numerical viscosity would be negative (!?)

Numerical Weather Prediction - then and now

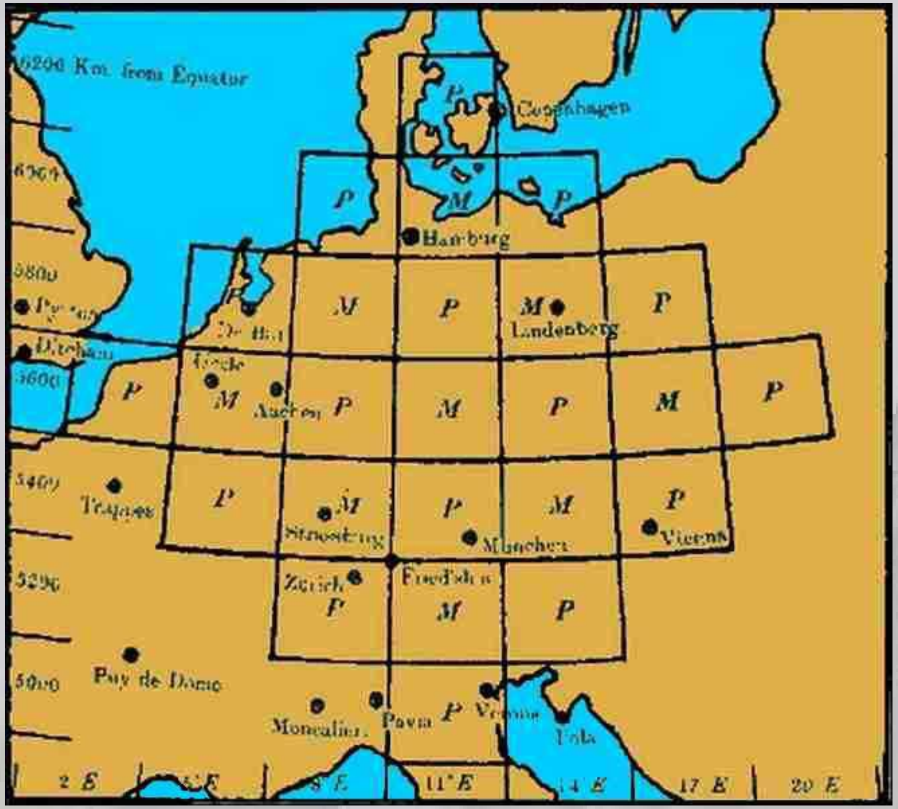
L.F.Richardson 1921



Deutscher Wetterdienst 2021

Numerical Weather Prediction - then and now

L.F.Richardson 1921



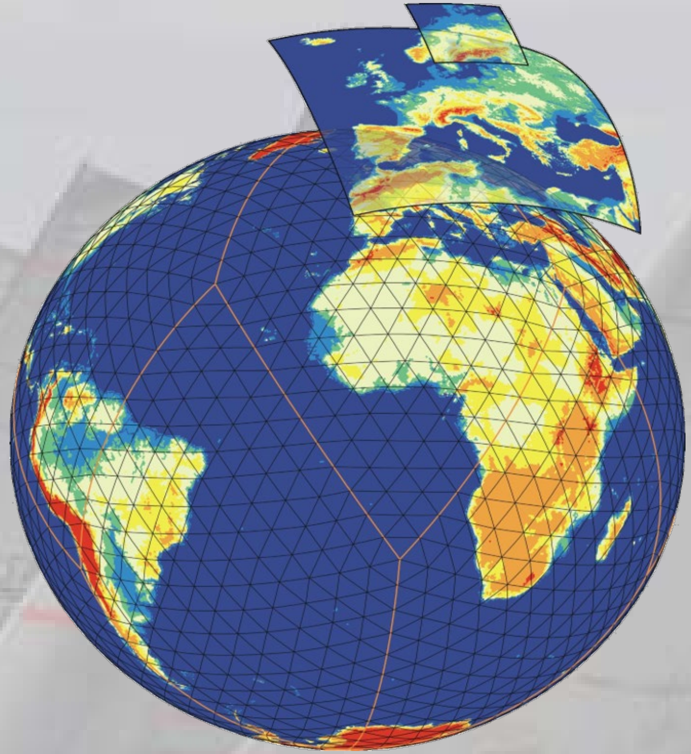
Problem :

1921: runtime > realtime ...

2018: H + 24: 20 minutes

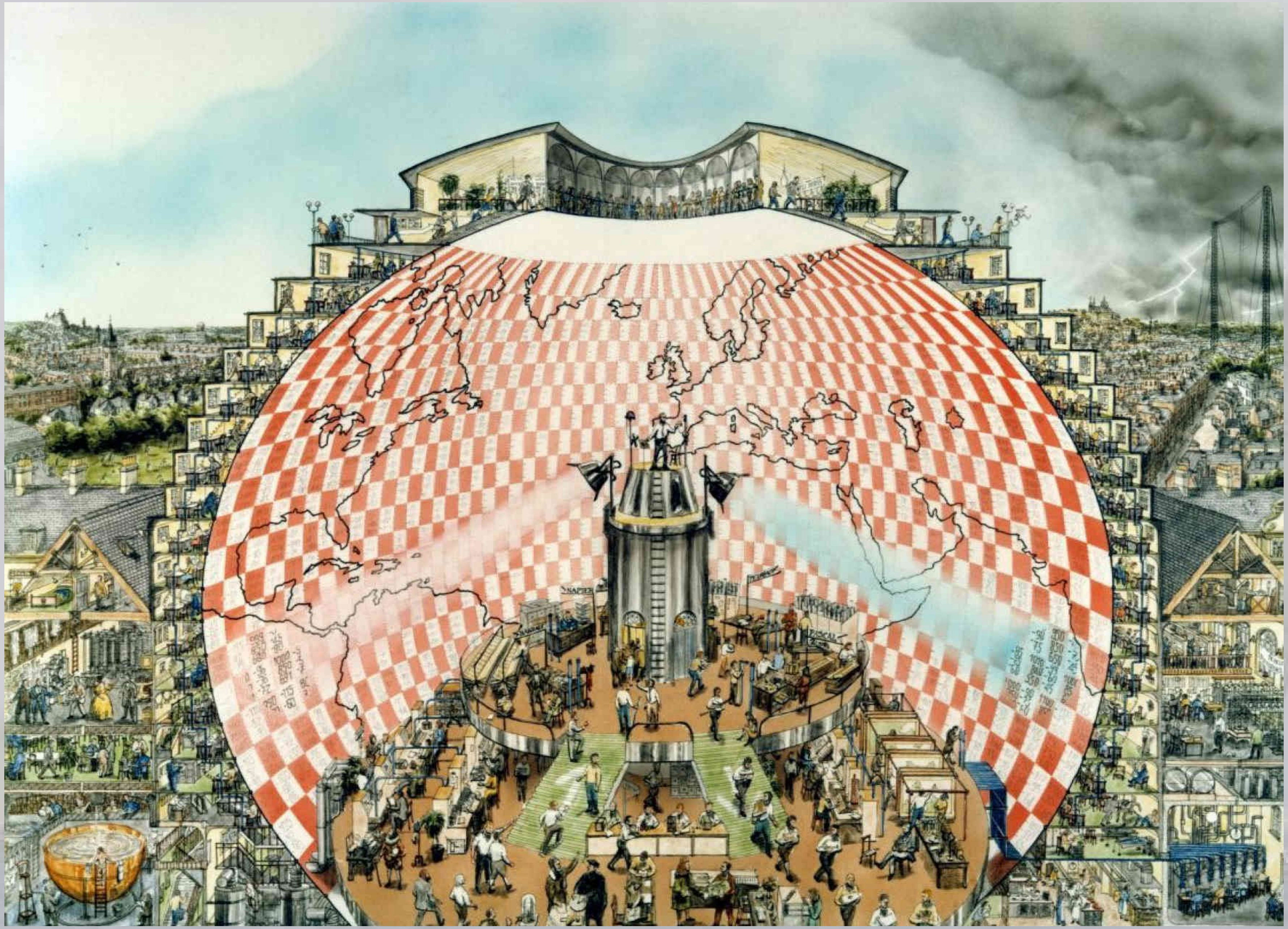
H +174: 2 hours

Deutscher Wetterdienst 2021

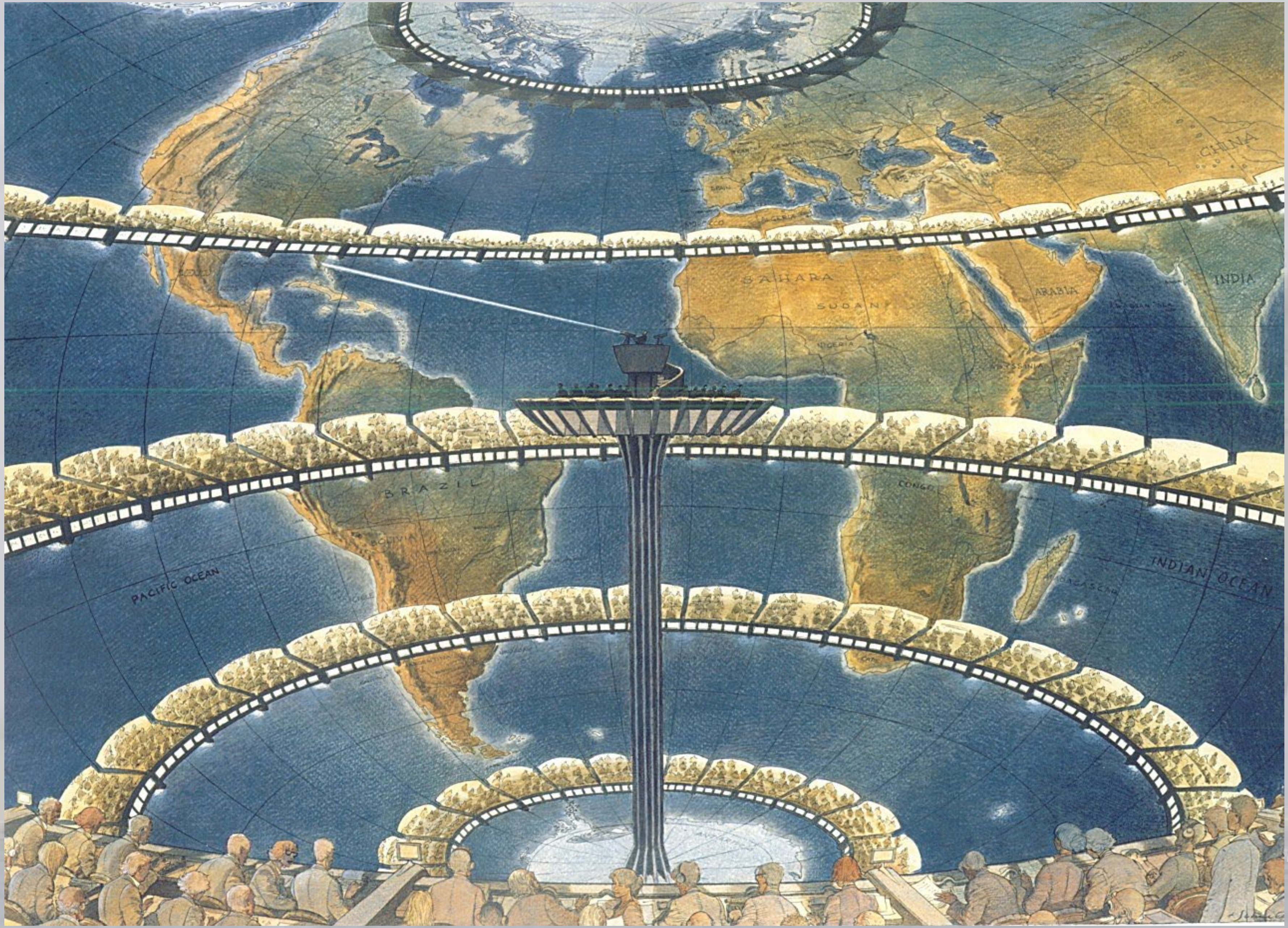


Model	ICON	EU	DE
Resolution / km	13	6.5	2.2
Layers	90	60	65
Gridpoints/ Mio	265	40	30

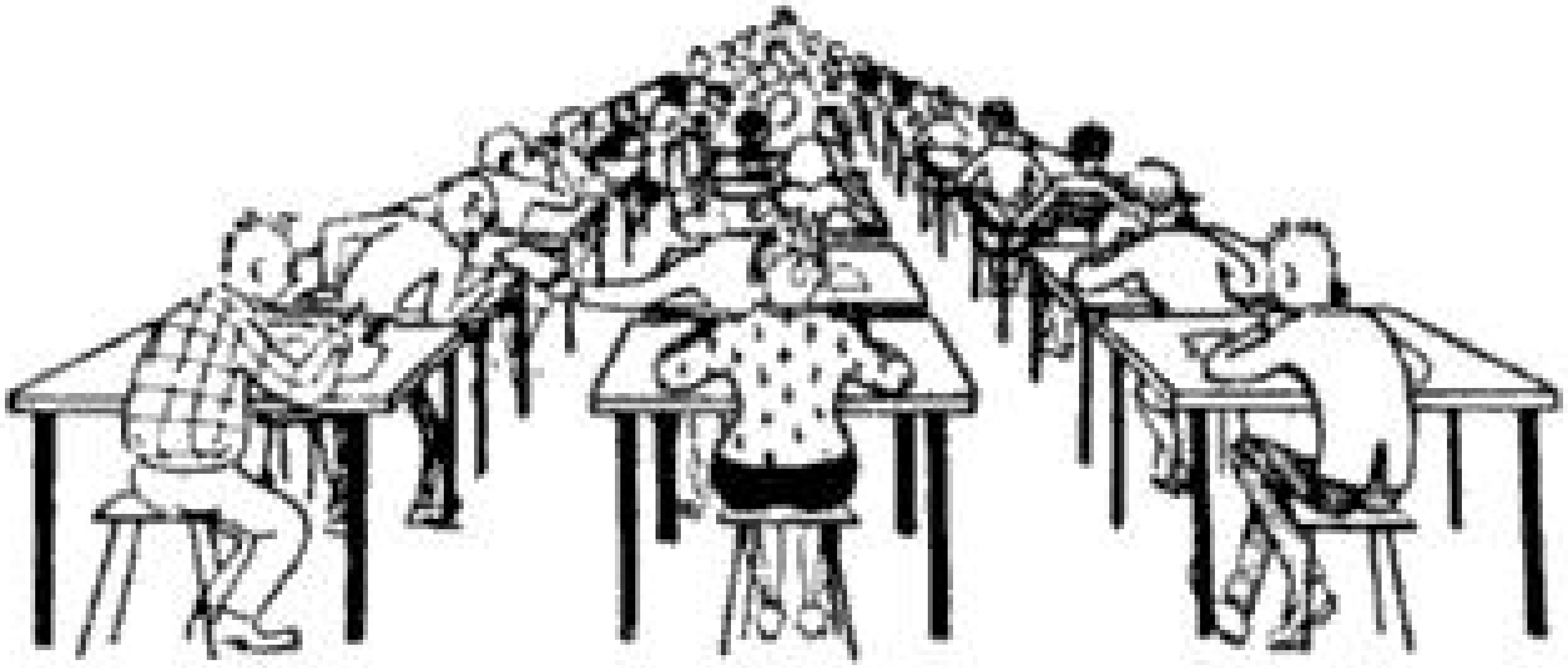
64K 'COMPUTERS' FORECAST FACTORY 1921



64K 'COMPUTERS' FORECAST FACTORY 1921

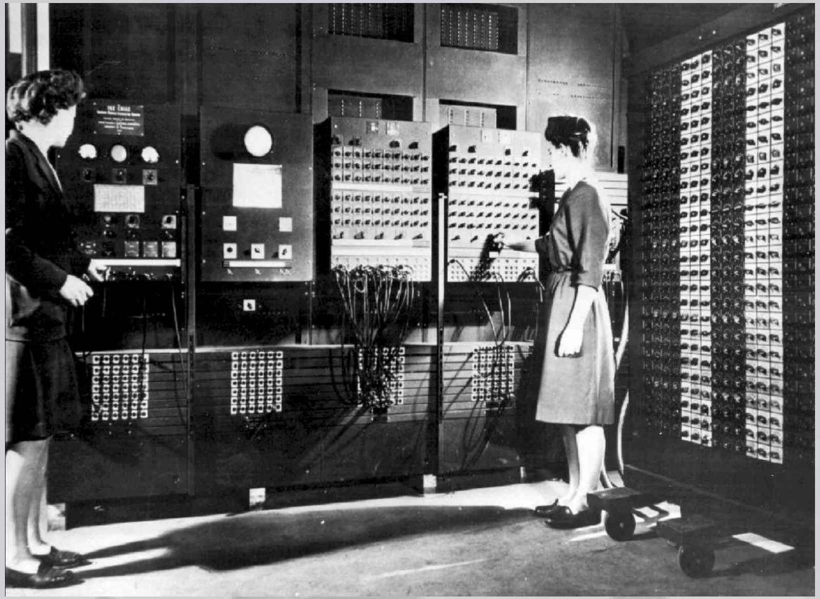


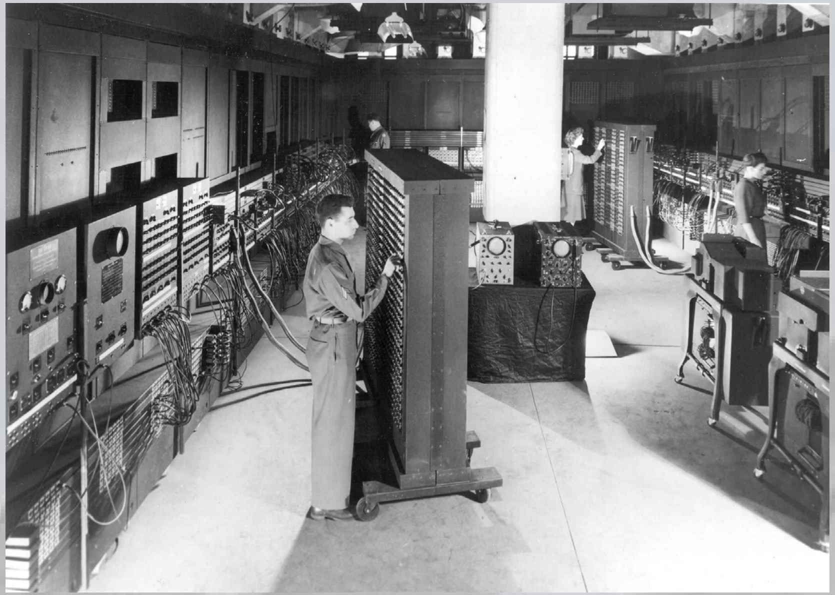
64K 'COMPUTERS' FORECAST FACTORY 1921

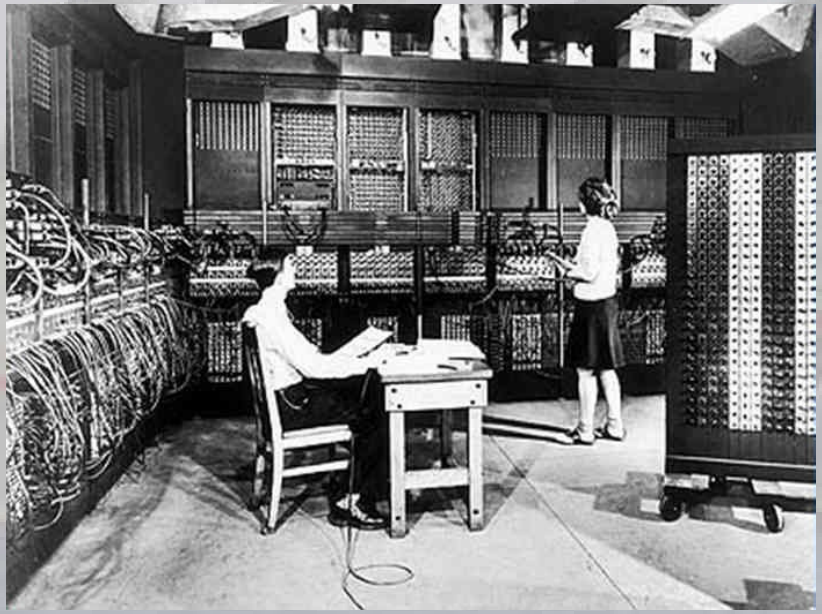


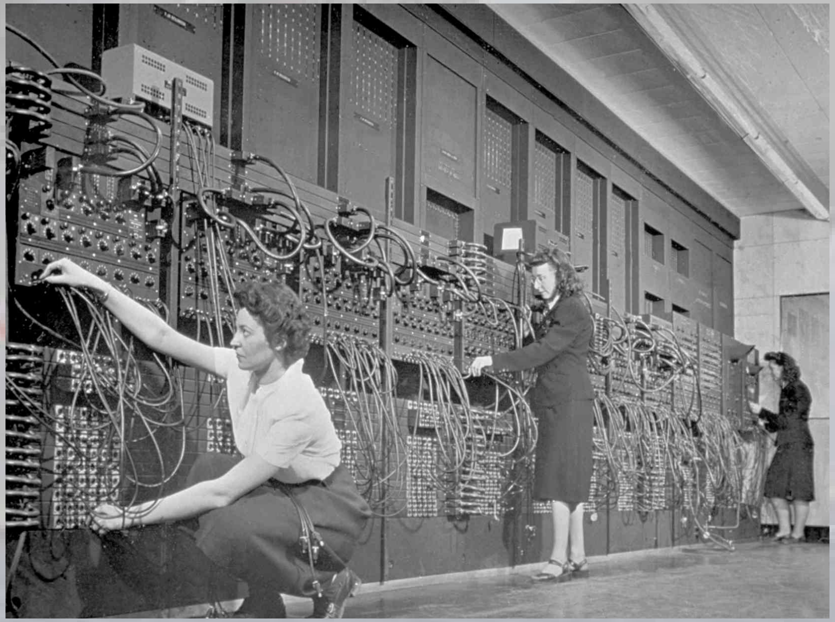
"64,000 computers would be needed to race the weather for the whole globe..." A cartoon showing Richardson's vision of a central forecasting factory.
(L.S. Gandin (1965) 'Machines forecast the weather', Gidrometeoizdat, Leningrad)

SUPER COMPUTERS IN METEOROLOGY ENIAC 1946









Publications for Use of Supercomputers in NWP

SVENSKA GEOFYSISKA FÖRENINGEN

VOLUME 2, NUMBER 4 **Tellus** NOVEMBER 1950

A QUARTERLY JOURNAL OF GEOPHYSICS

Numerical Integration of the Barotropic Vorticity Equation

By J. G. CHARNEY, R. FJÖRTOFT[1], J. von NEUMANN

The Institute for Advanced Study, Princeton, New Jersey[2]

(Manuscript received 1 November 1950)

Publications for Use of Supercomputers in NWP

Numerical Integration of the Barotropic Vorticity Equation

By J. G. CHARNEY, R. FJÖRTOFT[1], J. von NEUMANN

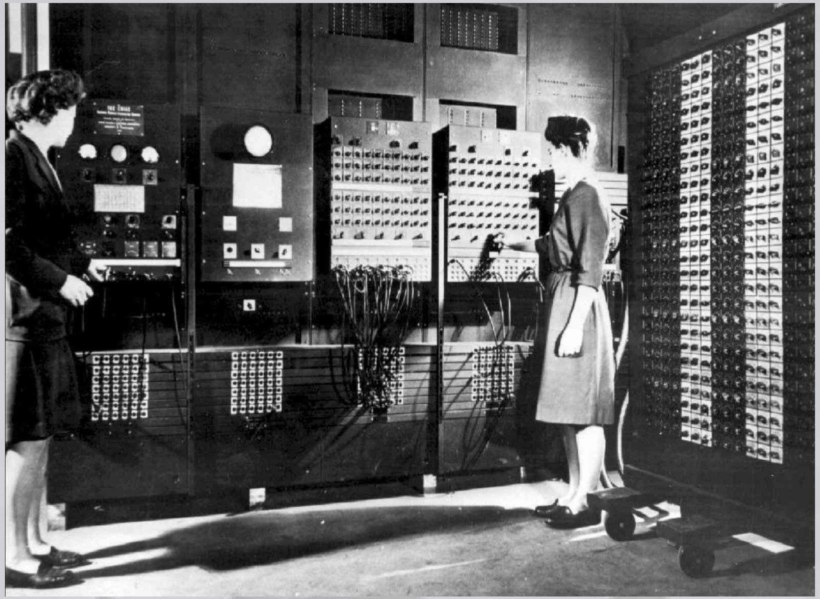
The Institute for Advanced Study, Princeton, New Jersey[2]

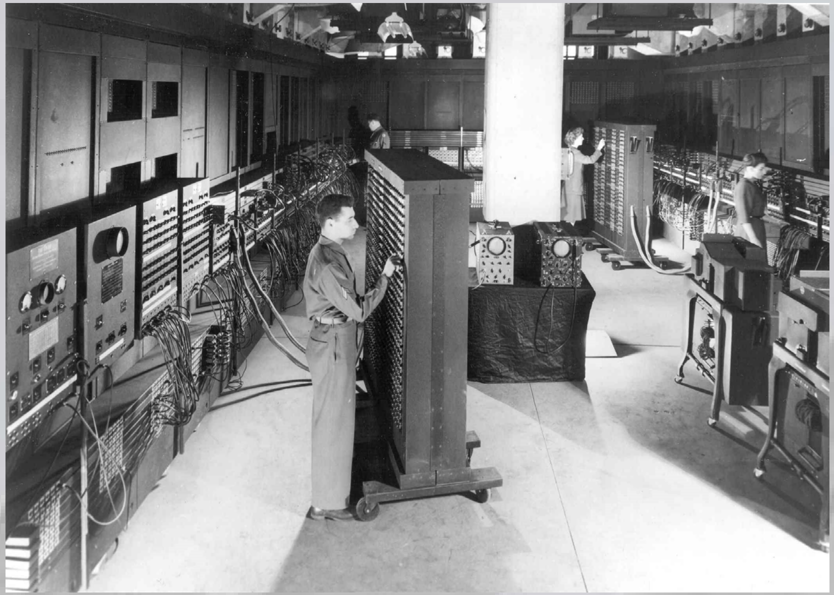
(Manuscript received 1 November 1950)

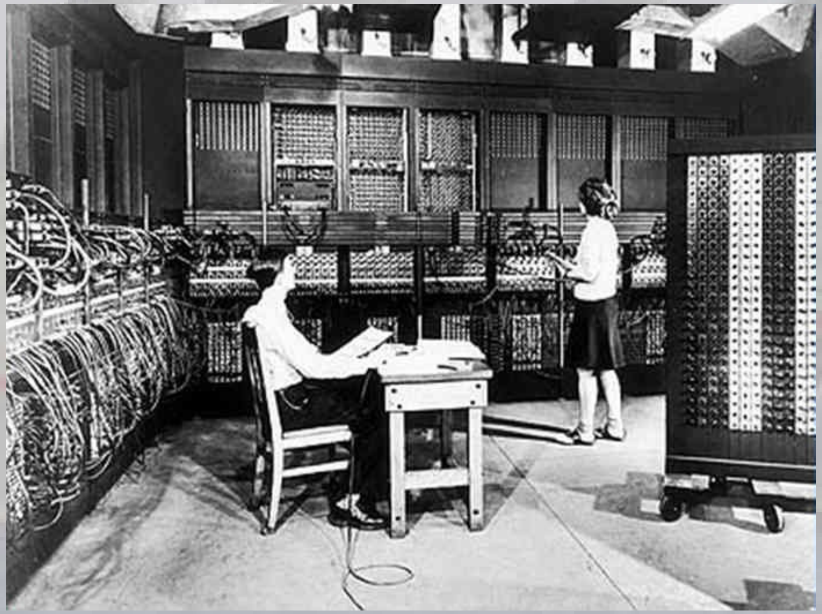
Abstract

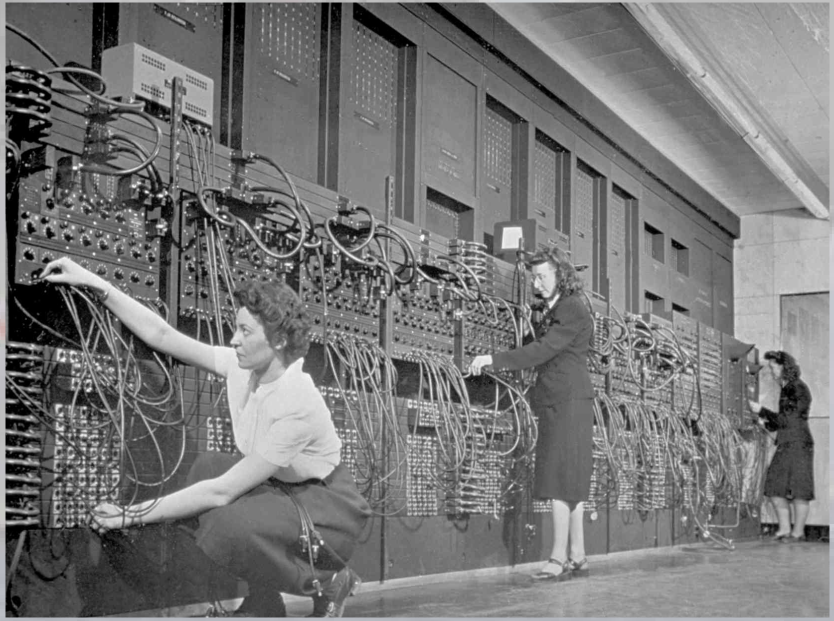
A method is given for the numerical solution of the barotropic vorticity equation over a limited area of the earth's surface. The lack of a natural boundary calls for an investigation of the appropriate boundary conditions. These are determined by a heuristic argument and are shown to be sufficient in a special case. Approximate conditions necessary to insure the mathematical stability of the difference equation are derived. The results of a series of four 24-hour forecasts computed from actual data at the 500 mb level are presented, together with an interpretation and analysis. An attempt is made to determine the causes of the forecast errors. These are ascribed partly to the use of too large a space increment and partly to the effects of baroclinicity. The rôle of the latter is investigated in some detail by means of a simple baroclinic model.

SUPER COMPUTERS IN METEOROLOGY ENIAC 1946









SUPER COMPUTERS IN METEOROLOGY TODAY

DWD NEC SX-9 2008 - 2014

DWD Cray XC-40 2013 - today

UK Metoffice Cray XC-40

European Center ECMWF Cray XC-40

AIRCRAFT 1927 – 1969 – 2007 – TODAY

TECHNOLOGICAL PROGRESS – ASYMPTOTICALLY TOWARDS OPTIMUM

1927 Spirit of St.Louis

1969 Boeing B747-100 Concorde

2007 Boeing 747-400 Airbus A380

Today Airbus A350, Boeing 777

COMPUTATION TIME FOR A 3-DAY-FORECAST …

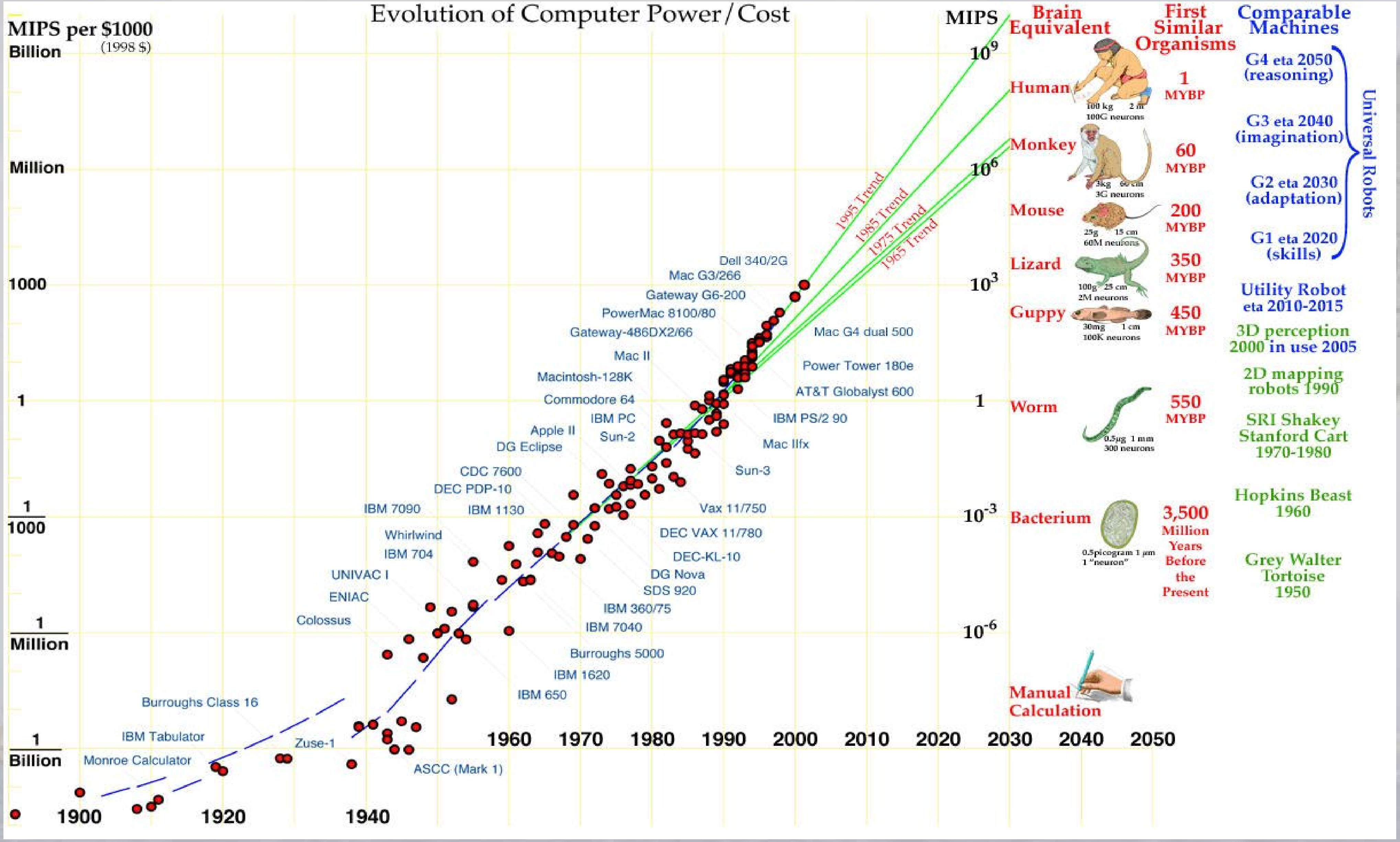
A 3-day-forecast requires approx. 1 Trillion (1 000 000 000 000 000 = 10^{15}) floating-point-operations (FLOP) which can be achieved as follows:

	Computer power				runtime	increase
Pocket computer	ca.	1	FLOP/s		32 Mio. years	
ENIAC 1946 USA	ca.	5	10^3	KILO	6.000 years	* 5.000
Laptop	ca.	1	10^9	GIGA	12 days	* 200.000
Supermarket PC	ca.	3.5	10^9	GIGA	3 days	* 3.5
DWD HPC Cray XC40	ca.	50	10^12	TERA	< 1 hour	* 15.000
TOP-500 #1 2020 CHINA	ca.	100	10^15	PETA	< 1 minute	* 20
TOP-500 #1 2022 USA	ca.	1	10^18	EXA		

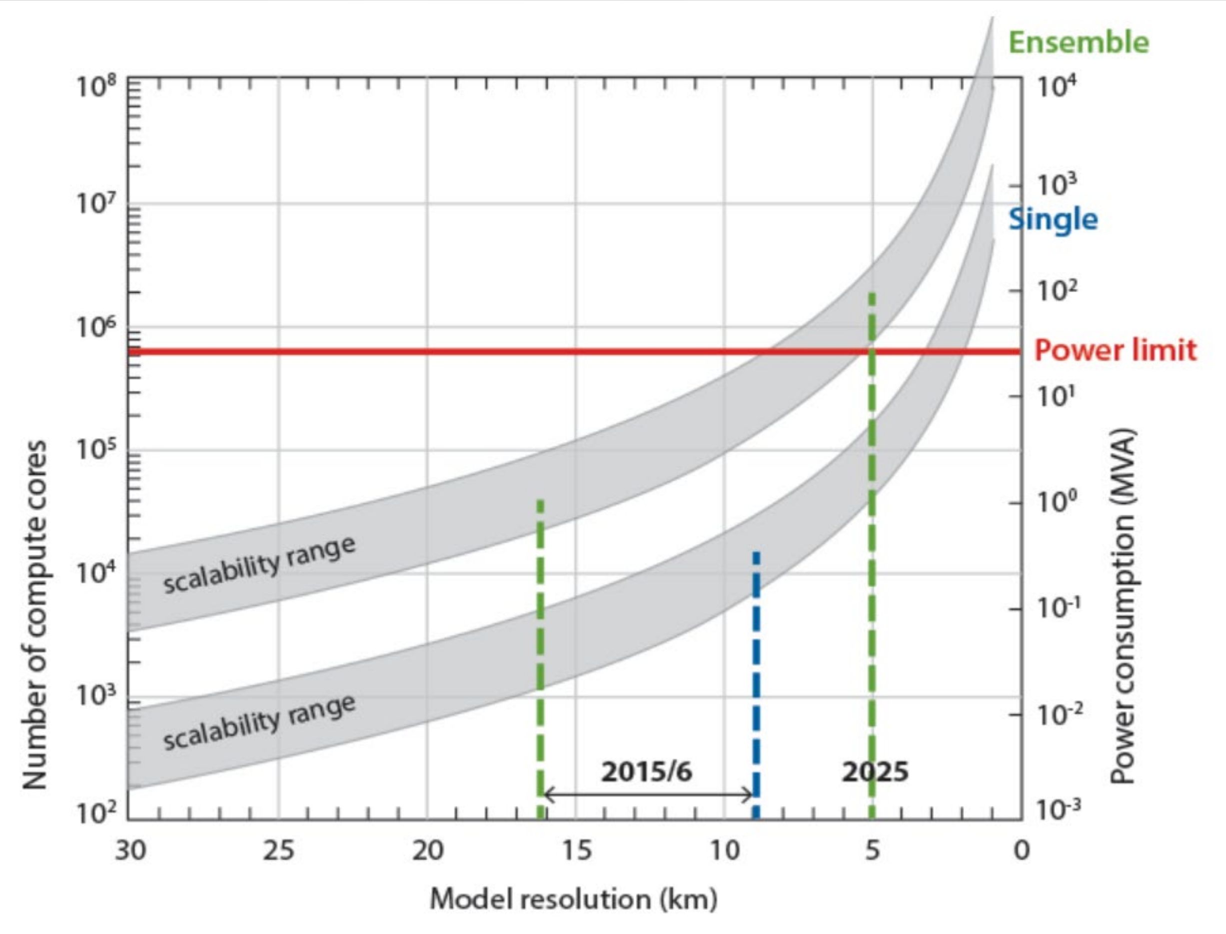
2022 TOP-500 SUPER COMPUTERS #1 FRONTIER USA EXA-FLOPS

Rank 1	System
TOP500 NOV 2022	Frontier - HPE Cray EX235a, AMD Optimized 3rd Generation EPYC 64C 2GHz, AMD Instinct MI250X, Slingshot 11, HPE DOE/SC/Oak Ridge National Laboratory United States

Moore's Law of Growth of Computer Power



How will it go on ? What can we expect from the computers in the future ?



The goal is to increase the model resolution, which requires more powerful computers. These will be developed, but… They need more electrical power and the budget for power is limited. Currently it would allow a global model resolution of 3 km for single run and 7 km for ensemble run.

Codes in Meteorological Operations

Requirement: Bring data into a formalized code to allow easier

- **Telecommunications**
- **Data processing**
- **Data compression**

Code-Form Alphanumeric to comply with RTTY regulations, e.g. groups of 5-characters…

Today mostly binary for computerized decoding

Managed by WMO World Meteorological Organisation, Geneva

Used worldwide by all countries to allow global operations

Codes in Meteorological Operations

Codes for Surface Observations
FM12 SYNOP Synoptic Surface Observation

```
################################################################################
#  SYNOPS from 10091, Arkona (Germany) | 54-41N | 013-26E | 42 m
################################################################################
202212041800 AAXX 04181 10091 07471 80908 10058 20043 30172 40224 58004 69902 7//65 222//
                00092 333 10060 20039 3/004 55300 20000 30000
                41216 69907 88/10 91017 90760 91118 90760 91216==

################################################################################
#  SYNOPS from 10113, Norderney (Germany) | 53-43N | 007-09E | 11 m
################################################################################
202212041800 AAXX 04181 10113 05574 80808 10053 20022 30194 40214 53002 60002
                333 10054 20005 3/000 55300 20000 30000 60007
                83/21 88/31 91012 90760 91114 90760 91209==

################################################################################
#  SYNOPS from 10124, Leuchtturm Alte Weser (Germany) | 53-52N | 008-08E | 30 m
################################################################################
202212041800 AAXX 04181 10124 46/// /0511 10050 20030 30173 40212 53001
                333 10050 20006 55300 90760 91114==

################################################################################
#  SYNOPS from 10131, Cuxhaven (Germany) | 53-52N | 008-42E | 5 m
################################################################################
202212041800 AAXX 04181 10131 05464 70607 10050 20031 30200 40215 55001 60002
                333 10050 20012 3/001 55300 20000 30000 60007
                87/13 91009 90760 91112 90760 91209==

################################################################################
#  SYNOPS from 10147, Hamburg-Fuhlsbuettel (Germany) | 53-38N | 010-00E | 16 m
################################################################################
202212041800 AAXX 04181 10147 05363 80706 10042 20024 30195 40214 55000 60002
                333 10043 21002 3/000 55300 20000 30000 41188
                60007 88/09 91010 90760 91110 90760 91207==
```

Codes in Meteorological Operations

FM15 METAR Surface Observation for Aviation

METAR/SPECI from EDDF, Frankfurt/Main (Germany).

SA	04/12/2022 22:50->	**METAR EDDF 042250Z AUTO 01004KT 9999 -RA FEW007 BKN016 02/01 Q1015 BECMG BKN013=**
SA	04/12/2022 22:20->	**METAR EDDF 042220Z AUTO 02006KT 350V050 9000 -RADZ BKN016 BKN024 02/01 Q1015 TEMPO BKN014=**
SA	04/12/2022 21:50->	**METAR EDDF 042150Z AUTO 03005KT 360V060 9999 -RADZ FEW006 OVC017 03/01 Q1015 NOSIG=**
SA	04/12/2022 21:20->	**METAR EDDF 042120Z AUTO 03007KT 9999 -RA OVC019 03/01 Q1014 NOSIG=**
SA	04/12/2022 20:50->	**METAR EDDF 042050Z AUTO 04009KT 9999 BKN020 03/01 Q1014 NOSIG=**
SA	04/12/2022 20:20->	**METAR EDDF 042020Z AUTO 04010KT 9999 -DZ BKN021 03/01 Q1014 NOSIG=**
SA	04/12/2022 19:50->	**METAR EDDF 041950Z AUTO 04010KT 9999 FEW009 BKN025 OVC032 03/01 Q1014=**
SA	04/12/2022 19:20->	**METAR EDDF 041920Z AUTO 03009KT 9999 BKN020 OVC031 03/01 Q1014 NOSIG=**
SA	04/12/2022 18:50->	**METAR EDDF 041850Z AUTO 05010KT 9999 BKN019 03/01 Q1014 NOSIG=**
SA	04/12/2022 18:20->	**METAR EDDF 041820Z AUTO 02009KT 9999 -RA FEW016 03/01 Q1013 NOSIG=**
SA	04/12/2022 17:50->	**METAR EDDF 041750Z AUTO 02008KT 9999 -RA SCT018 03/01 Q1013 BECMG OVC013=**
SA	04/12/2022 17:20->	**METAR EDDF 041720Z AUTO 02008KT 9999 -RA BKN016 03/00 Q1014 BECMG OVC013=**
SA	04/12/2022 16:50->	**METAR EDDF 041650Z AUTO 03009KT 9999 OVC015 03/00 Q1014 BECMG OVC013=**
SA	04/12/2022 16:20->	**METAR EDDF 041620Z AUTO 03009KT 9999 OVC014 03/00 Q1014 TEMPO OVC015=**

CODES IN METEOROLOGICAL OPERATIONS

FM35 TEMP Aerological Observations (Radiosonde)

TEMP from 10035, Schleswig (Germany)

TTDD	03/12/2022 23:00->	TTDD 0323/ 10035 11879 61576 22492 64975 33453 63177 44328 69573 55270 69973 66205 64578 77099 66177 88088 68774 99063 64378 21212 11929 31505 22897 33507 33857 31506 44821 01005 55788 34002 66745 30509 77664 31514 88604 34010 99586 32009 11562 31507 22545 35506 33537 34005 44532 33005 55502 32014 66491 33017 77435 35014 88397 33510 99387 32511 11373 33512 22344 32015 33298 34018 44264 32020 55250 33020 66225 31026 77215 32029 88181 32515 99156 32525 11143 32518 22138 30514 33136 30014 44118 29022 55113 30025 66105 30522 77099 29525 88088 31021 99080 29036 11063 29036 31313 42408 82245==
TTCC	03/12/2022 23:00->	TTCC 03230 10035 07820 64175 32011 05026 64775 32015 03335 69173 34018 02580 64977 32023 01000 65977 29525 88879 61576 33507 88328 69573 32519 77080 29036 41103 31313 42408 82245==
TTBB	03/12/2022 23:00->	TTBB 03238 10035 00018 01618 11874 06501 22850 04100 33807 05113 44726 10900 55721 08921 66703 09528 77670 11145 88650 11766 99598 16562 11584 16771 22549 20357 33499 26156 44420 35958 55325 50748 66301 54342 77291 55547 88269 54766 99254 57364 11213 53377 22100 59178 21212 00018 07005 11989 08514 22884 08022 33821 11012 44801 09509 55745 09010 66683 13008 77626 10011 88612 11508 99584 09008 11556 10008 22533 09507 33518 07007 44508 08006 55470 08009 66456 06510 77427 07509 88407 06508 99399 08508 11379 06010 22289 07516 33267 10007 44262 09005 55257 07506 66250 08508 77242 05008 88219 07009 99214 08505 11199 08502 22173 07005 33163 02005 44159 05007 55153 05505 66150 03506 77147 04505 88137 01006 99123 02005 11120 04505 22110 35505 33100 35505 31313 42408 82245==
TTAA	03/12/2022 23:00->	TTAA 03231 10035 99018 01618 07005 00201 00619 08512 92820 04300 08017 85483 04100 09013 70997 09531 11510 50552 25956 08007 40710 38757 08008 30900 54343 07515 25016 56964 08508 20159 54577 09502 15342 55579 03506 10599 59178 35505 88291 55547 07516 77999 31313 42408 82245==

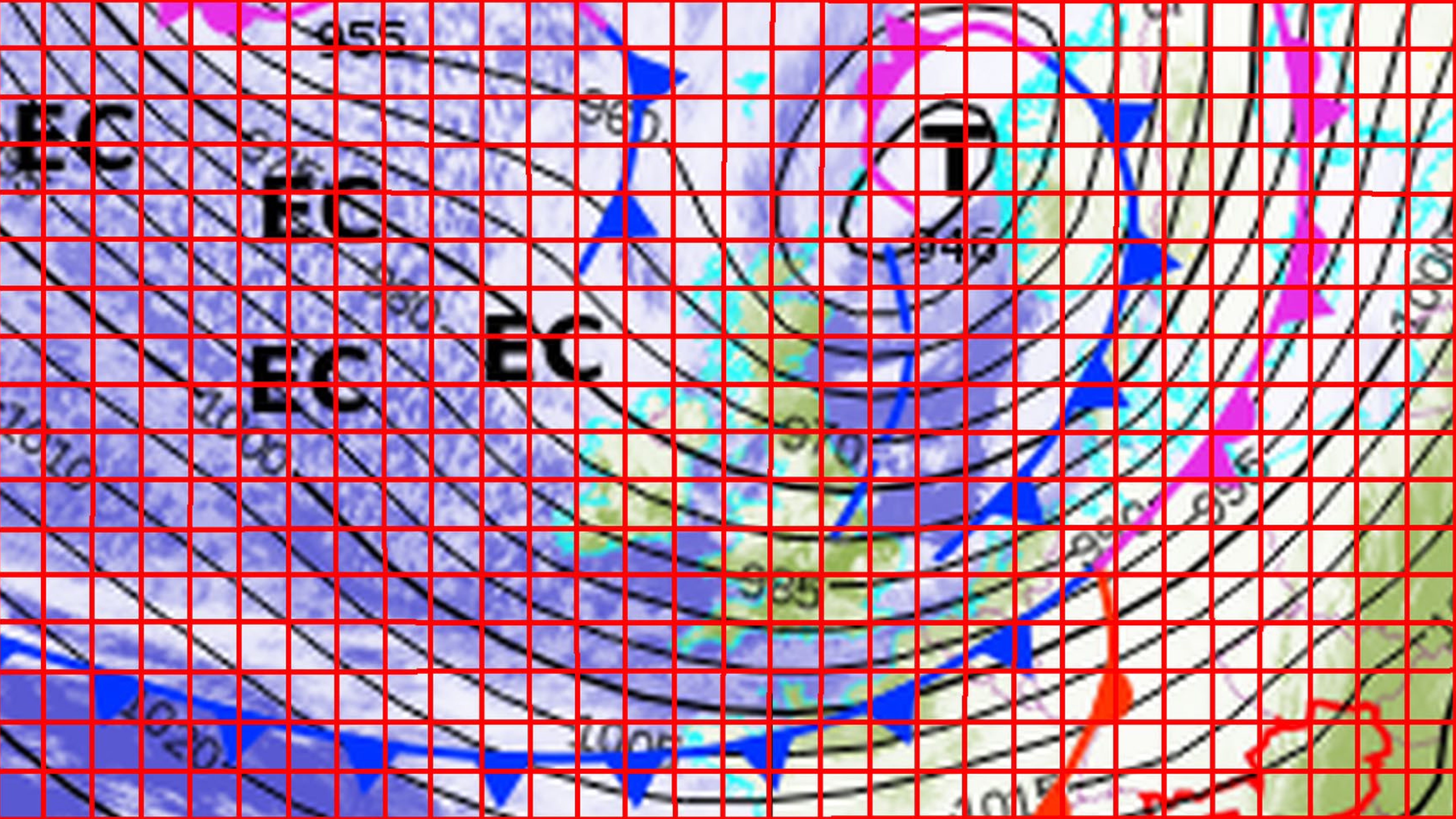
Codes in Meteorological Operations

FM94 BUFR Synoptic Surface Observation

A BUFR is a binary code to encode meteorological data. The BUFR consists of sections. The following picture illustrates the different sections and their content.

CONTINUOUSBINARYSTREAM					
Section 0	Section 1	Section 2	Section 3	Section 4	Section 5

Section Number	Name	Contents
0	Indicator Section	"BUFR" (coded according to the CCITT International Alphabet No. 5, which is functionally equivalent to ASCII), length of message, BUFR edition number
1	Identification Section	Length of section, identification of the message
2	Optional Section	Length of section and any additional items for local use by data processing centers
3	Data Description Section	Length of section, number of data subsets, data category flag, data compression flag, and a collection of data descriptors which define the form and content of individual data elements
4	Data Section	Length of section and binary data
5	End Section	"7777" (coded in CCITT International Alphabet No. 5)



EC
EC
EC
EC
T
955
960
945
980
970
985
990
995
1005
1010
1015
1020

Codes in Meteorological Operations

FM92 GRIB Synoptic Surface Observation

- **GRIdded Binary**
- **Is a ‘table-driven‘ Code**
  - **All Metadata are include (Model, Time-Date, Parameter etc)**
- **Is nor readable by man, only for computer processing (binary)**
- **Requires special programs for visualization**
- **Is available in the web as meteorological charts**
  - **www.passageweather.com** — **Full set, single charts**
  - **www.vorticity.de** — **Selected sets, visualized with classic charts, HINDCAST verification etc**

Codes in Meteorological Operations

FM92 GRIB Synoptic Surface Observation

- **Advantages of GRIB**
- **Easy selection of areas of interest (ship‘s position)**
- **Easy integration of weather information into navigation systems (moving map)**

- **Disadvantages**
- **Just read as ‚Wind at position N45 W030 : 250° 25knots**
- **is binary information: right or wrong**

Important is the synoptic interpretation of GRIB charts to understand what‘s going on in the atmosphere

North Atlantic Wind   Sea   MSL Pressure

Numerical Weather Prediction …

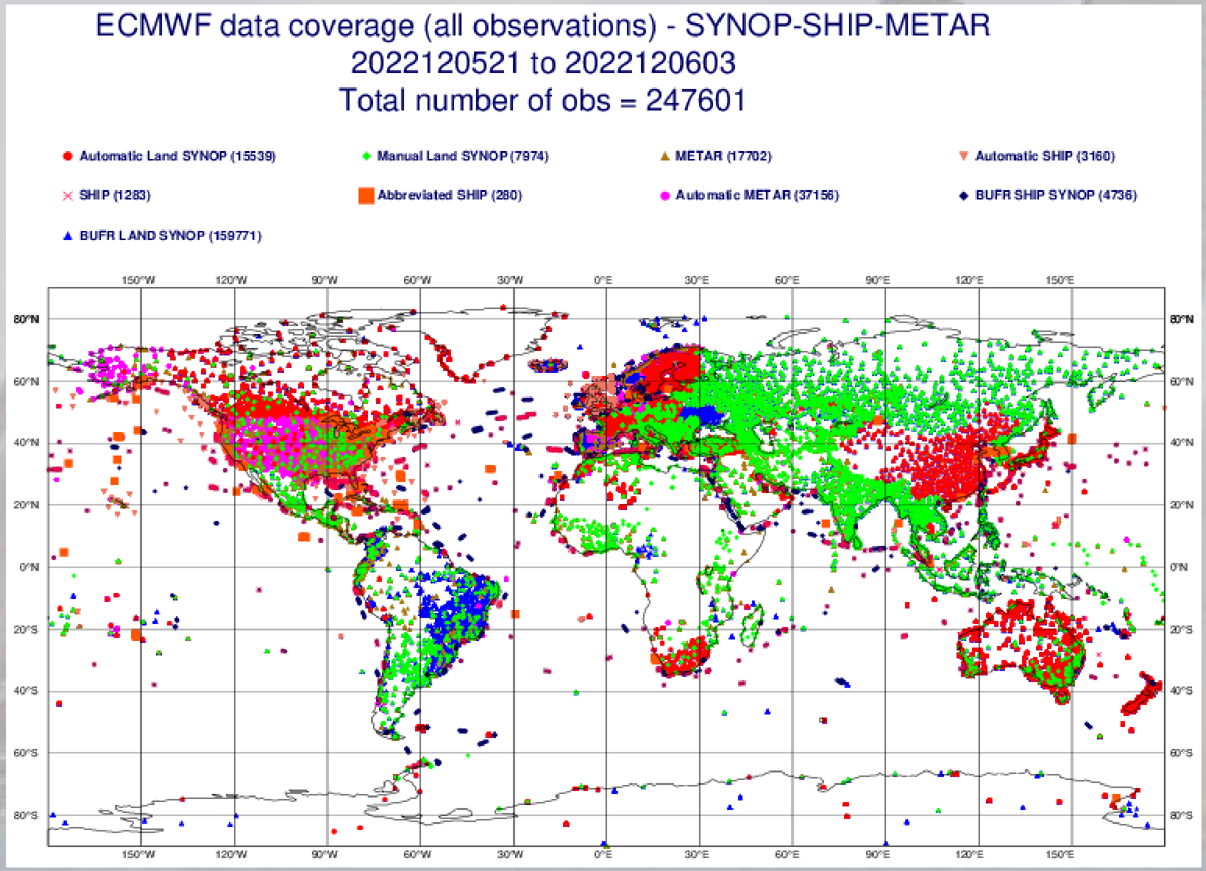
… is an initial value problem – Problems:

1. **Initial State, i.e. Observations…**
2. **Physical Modelling**
3. **Physical (subscale) Parametrization**

Solution of these Problem:

Numerical Weather Prediction …

1. Initial State, i.e. <u>Observations</u> …



Numerical Weather Prediction …

1. Initial State, i.e. Observations…
2. <u>Physical Modelling</u>
3. Parameterization

   Mathematical Describtion of sub-scale processes

   e.g. Shower / Thunderstorms

   boundary layer phenomena etc

As long as that is required – DMO post-processing is appropriate, e.g. MOS – Model Output Statistics

Post-Processing: Statistical Interpretation

Multiple linear regression equations …

- **MOS   Model Output Statistics**

  … between observations
  and forecasts of numerical models

- **PP   Perfect Prog**

  … between observations
  and analyses

Post-Processing: MOS Model Output Statistics

Predictand   **Predictors…**

- StF_T2m = const * DMO_T2m
  – const * rH_1000_hPa
  + const

- Know-How is in the definition of predictors
  - Wind components (coastlines, mountains)
  - Upper-air flow patterns (vorticity)
  - TS-Indices, binary-predictors (model changes)

Post-Processing: MOS Model Output Statistics

- **MOS Pros**
  - ➢ **Each observed parameter can be forecasted (also visibility, ceiling, even the forecast error)**
  - ➢ **Correction of systematic model errors**
  - ➢ **Consideration of local topography**
  - ➢ **Is quasi "Parameterization" of synoptic experience**

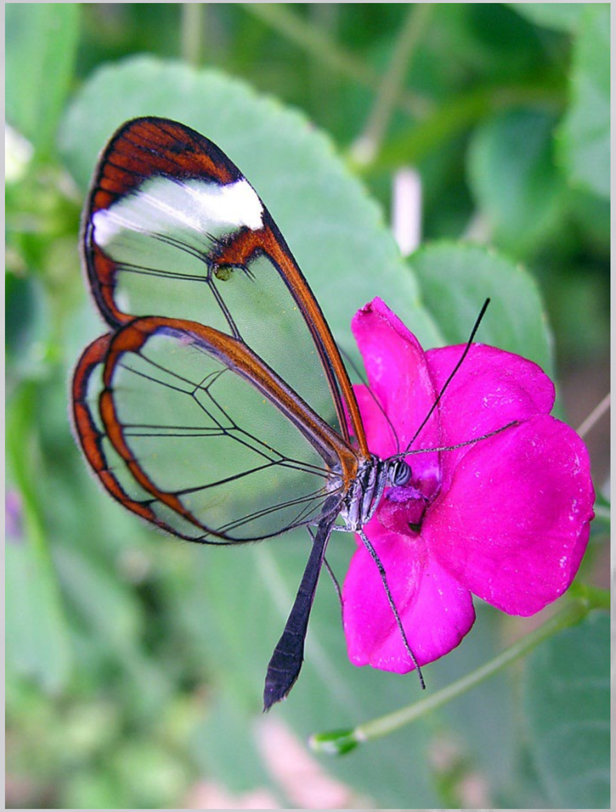
- **MOS Cons**
  - ➢ **Depends on specific NWP - models**
  - ➢ **Model changes have to be considered**

Post-Processing: Perfect Prog

- **PP Pros**
  - ➢ **Long time-series available (Re-Analysis)**
  - ➢ **Independent from NWP-model used**

- **PP Cons**
  - ➢ **Does not correct for model errors**
  - ➢ **Limited predictands (e.g. no visibility)**

Butterfly effect

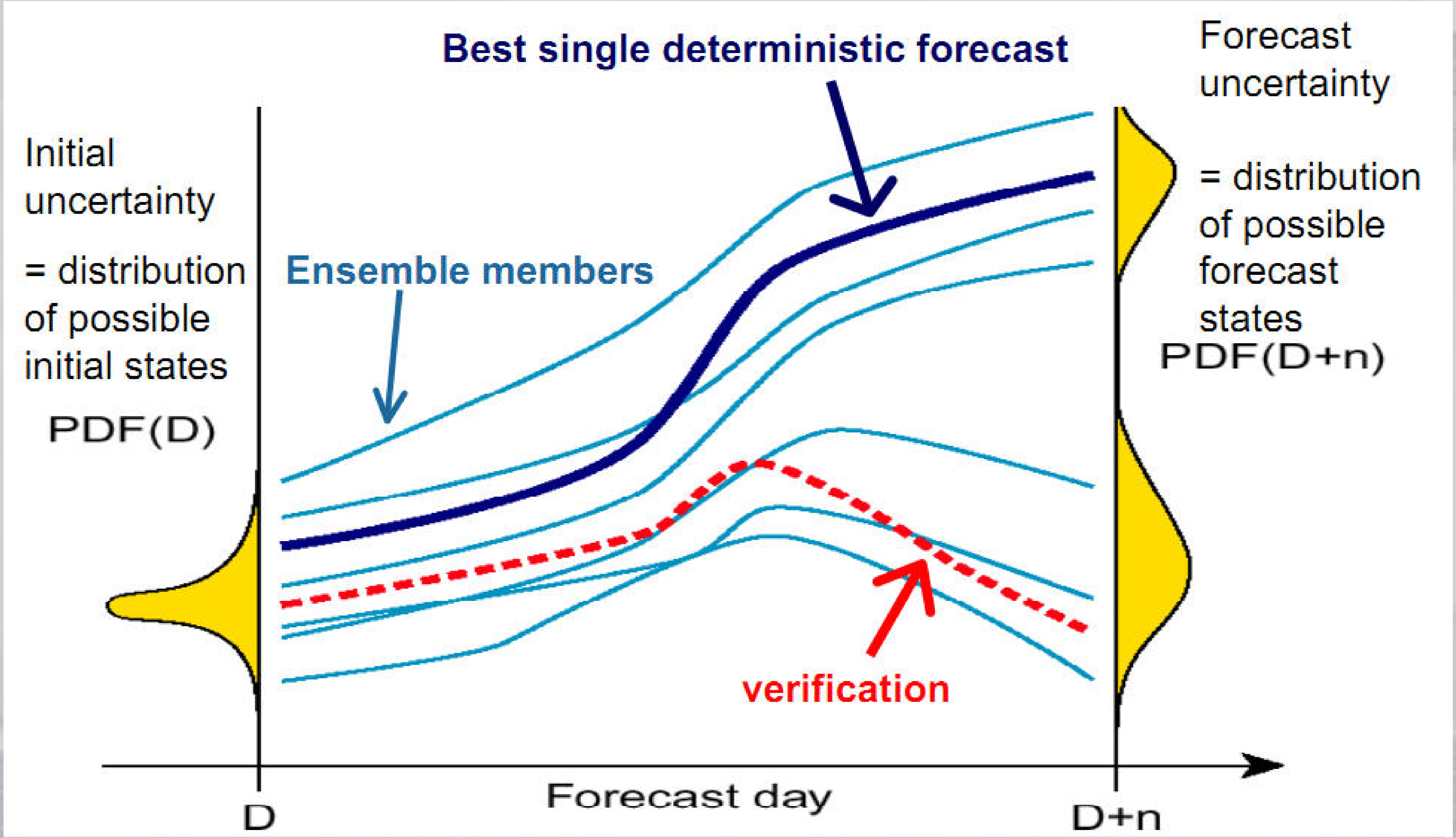


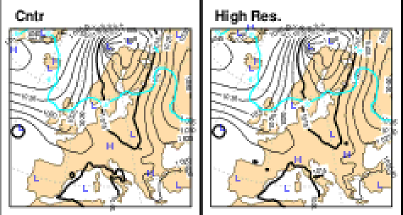
Edward Lorenz 1972

Predictability:

Does the flap of a butterfly’s wings in Brazil set off a tornado in Texas ?

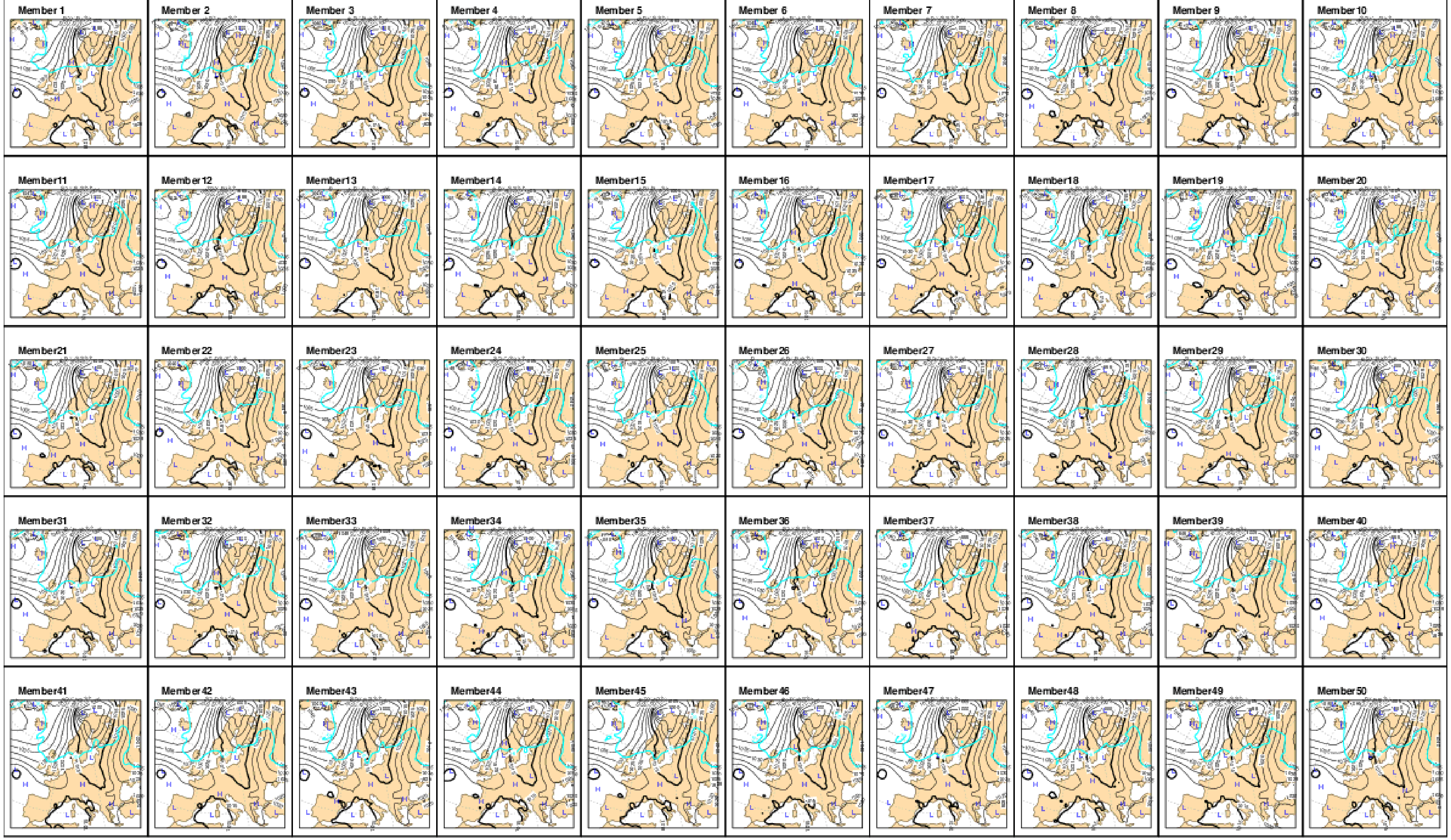
Another Forecast Optimization: Ensemble Forecast

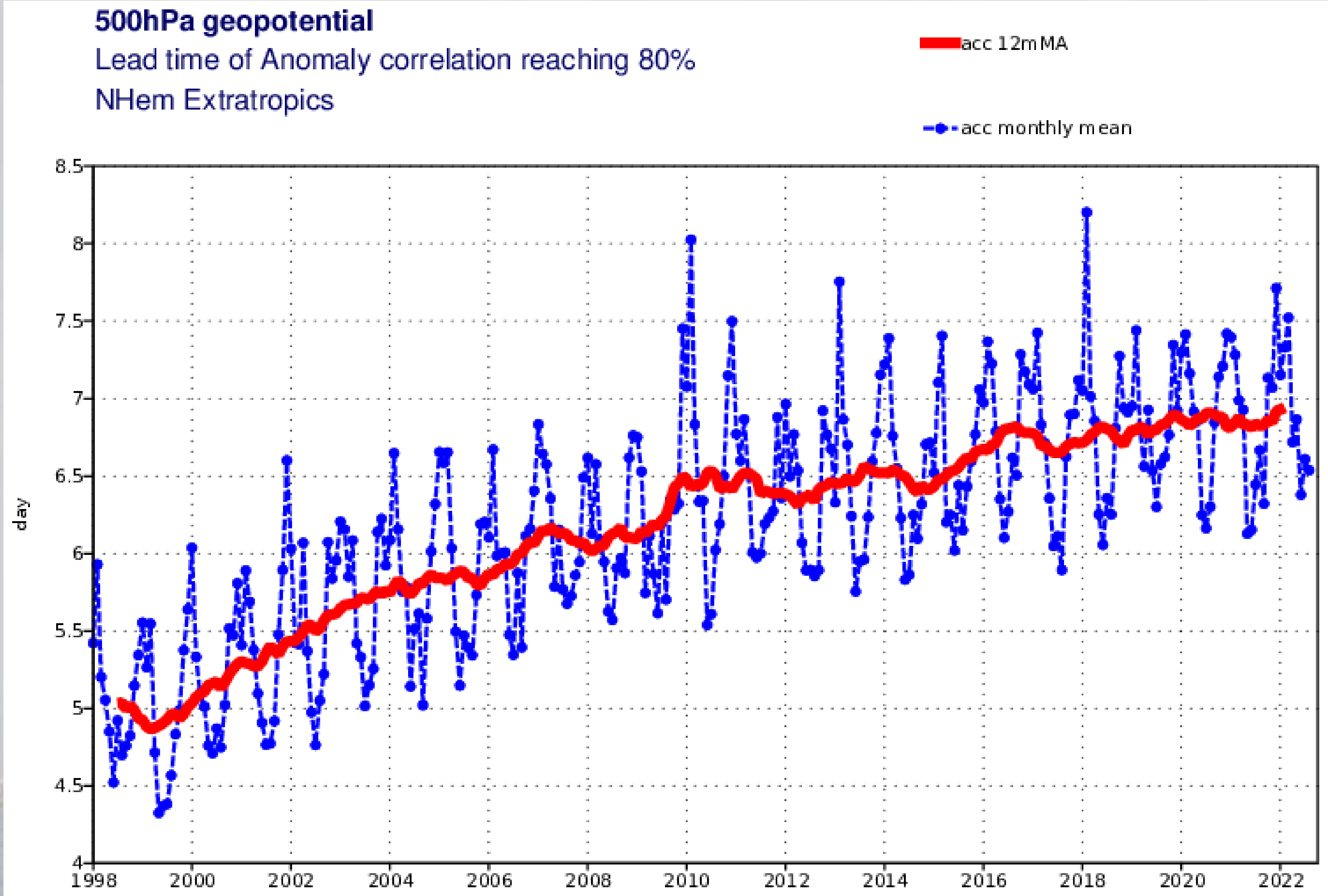


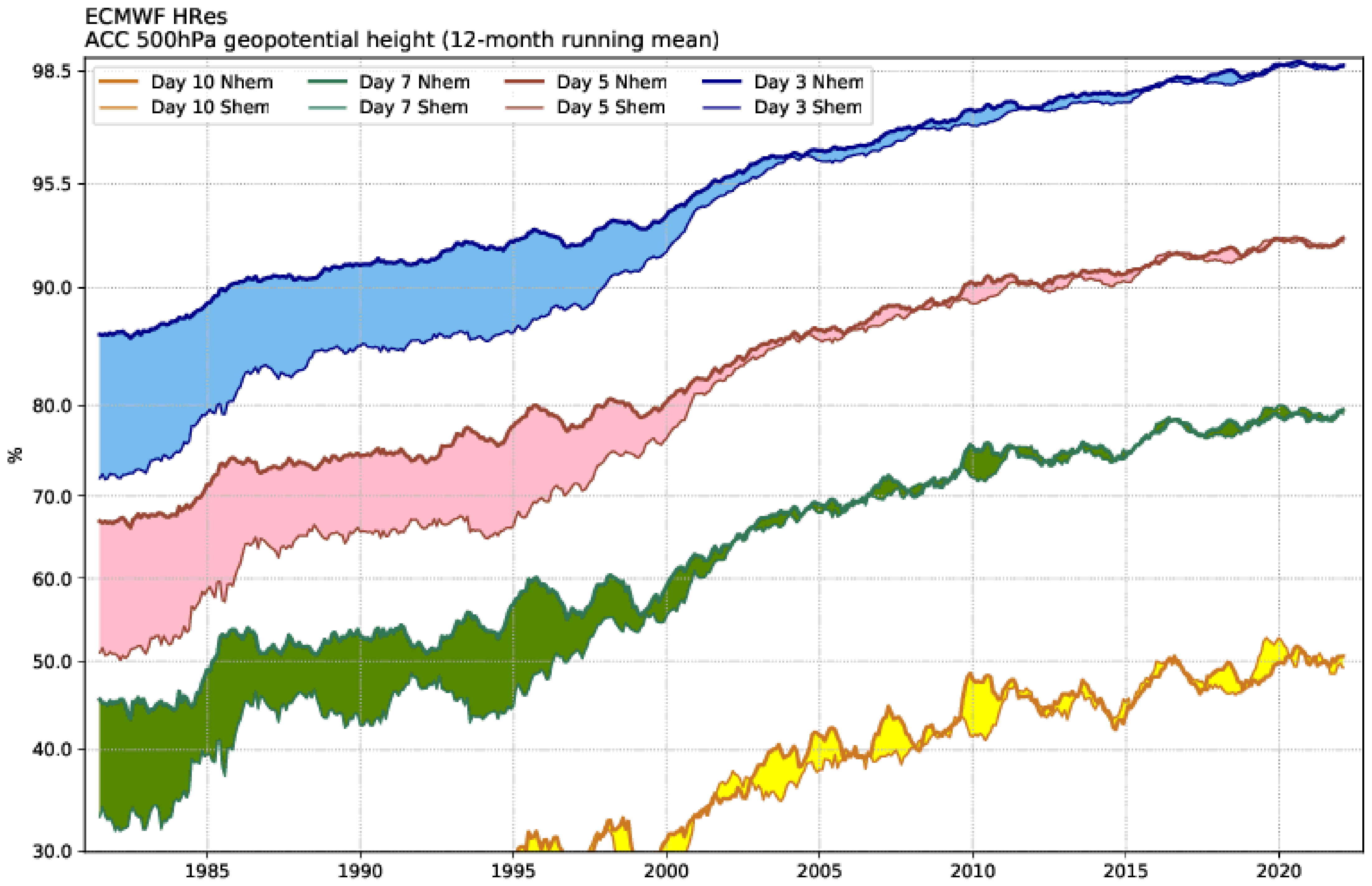


ECMWF ENSEMBLE FORECASTS

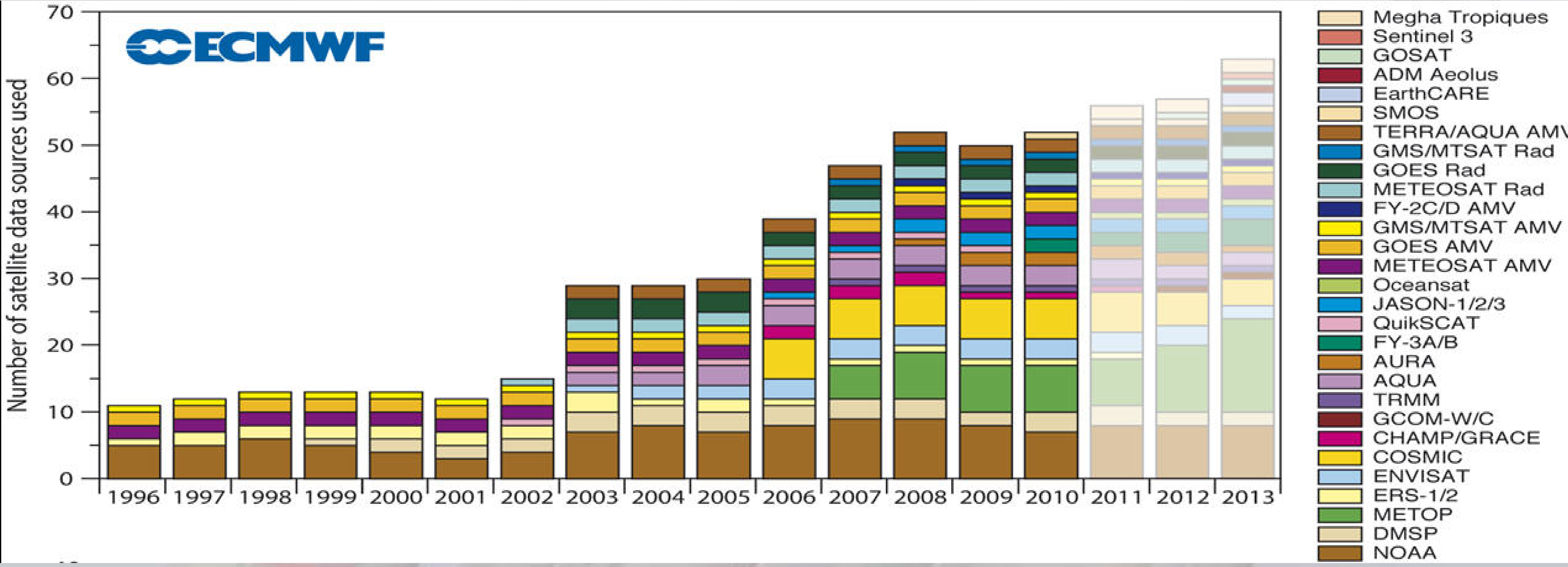
Tuesday 06 December 2022 0000 UTC ECMWF forecast t+12 VT:Tuesday 06 December 2022 1200 UTC
MSLP (contour every 5hPa) Temperature at 850hPa (only -6 and 16 isolines are plotted)



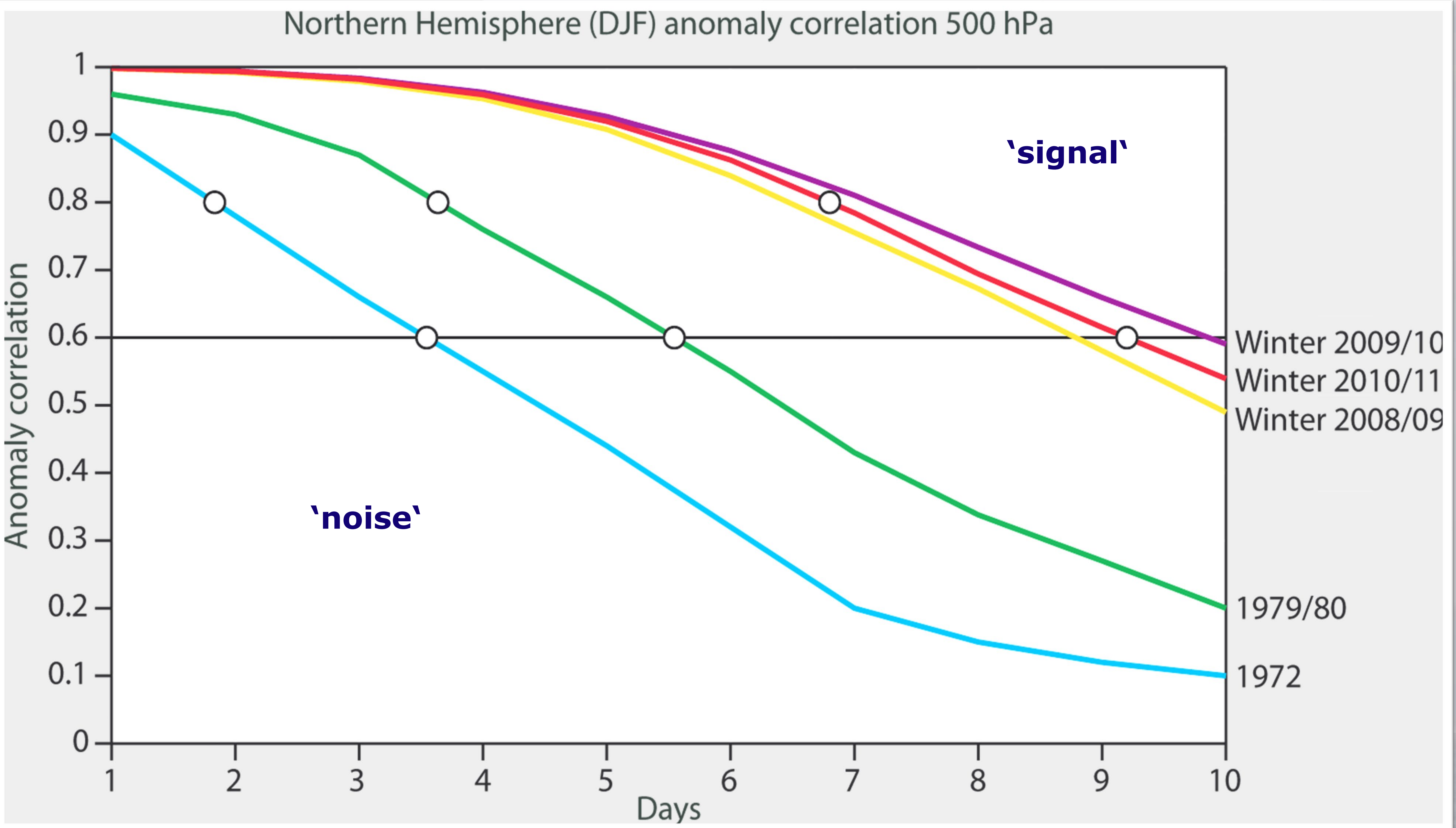

500hPa geopotential
Lead time of Anomaly correlation reaching 80%
NHem Extratropics
acc 12mMA
acc monthly mean
day
8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020
2022



ECMWF HRes
ACC 500hPa geopotential height (12-month running mean)
Day 10 Nhem
Day 10 Shem
Day 7 Nhem
Day 7 Shem
Day 5 Nhem
Day 5 Shem
Day 3 Nhem
Day 3 Shem
%
98.5
95.5
90.0
80.0
70.0
60.0
50.0
40.0
30.0
1985
1990
1995
2000
2005
2010
2015
2020

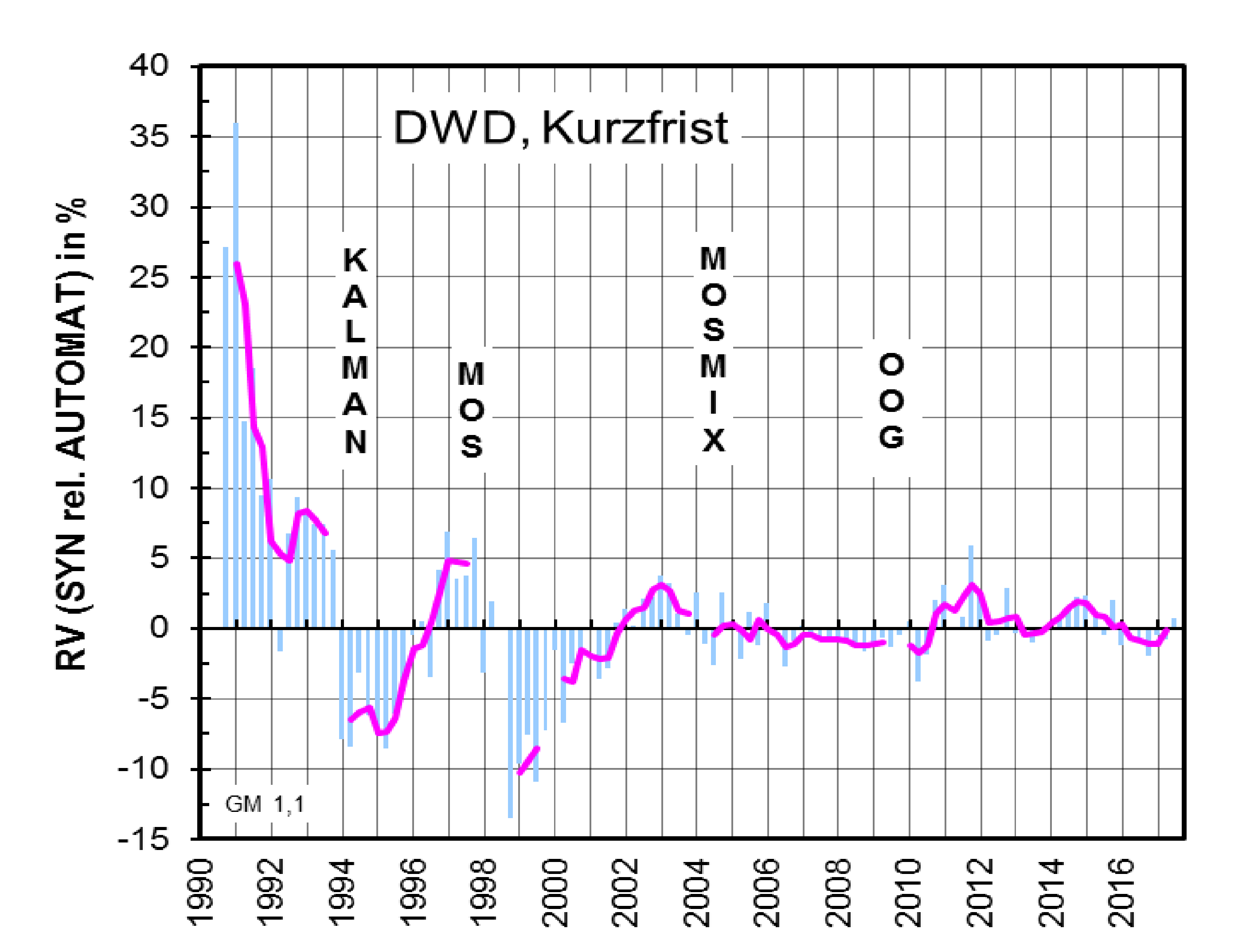


ECMWF
Number of satellite data sources used
0
10
20
30
40
50
60
70
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
Megha Tropiques
Sentinel 3
GOSAT
ADM Aeolus
EarthCARE
SMOS
TERRA/AQUA AMV
GMS/MTSAT Rad
GOES Rad
METEOSAT Rad
FY-2C/D AMV
GMS/MTSAT AMV
GOES AMV
METEOSAT AMV
Oceansat
JASON-1/2/3
QuikSCAT
FY-3A/B
AURA
AQUA
TRMM
GCOM-W/C
CHAMP/GRACE
COSMIC
ENVISAT
ERS-1/2
METOP
DMSP
NOAA



Northern Hemisphere (DJF) anomaly correlation 500 hPa
Anomaly correlation
Days
'signal'
'noise'
Winter 2009/10
Winter 2010/11
Winter 2008/09
1979/80
1972
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
2
3
4
5
6
7
8
9
10

Comparison: WoMan (+NWP!) vs NWP + Post Processing



RV (Reduction of variance) describes quality improvement.
Positive values: Man (+computer!) is better than computer.
A method promising 15% RV reduction is worth to be used!

QUESTIONS YOU SHOULD BE ABLE TO ANSWER

Numerical Weather Prediction NWP

- ✓ How would you describe NWP?
  - ✓ NWP is an initial state problem, characterized by 6 equations (primitive equations, some of them time-dependent) for 6 variables (Pressure, Humidiy, density, 3 wind components) . These equations are computed for the future: forecast!

- ✓ What are typical resolutions (grid mesh-size) for NWP model?
  - ✓ Global tens of km, Regional (fine-mesh) a few km

- ✓ Which is the problem of the limited mesh-size
  - ✓ There are (sub-grid) phenomena that cannot be resolved by the model, e.g. shower, thunderstorm, land-sea-breeze, local valley winds. These phenomena are parameterized, i.e. decribed by formulas.

- ✓ What is required for numerical stable modelruns?
  - ✓ Compliance with the Courant-Friedrich-Lewy-condition
  - ✓ Ratio between mesh-size and timestep (violated by Richardson 1921)

QUESTIONS YOU SHOULD BE ABLE TO ANSWER

Numerical Weather Prediction

- ✓ How can you improve forecasts based on the DMO (Direct Model Output)
  - ✓ By statistical post-processing. This covers adaptive filters (Kalman) and statistical post-processing, typical MOS (Model Output Statistics) and PP (Perfect Prog)

- ✓ What is the difference between MOS and Perfect Prog?
  - ✓ Both are based on multiple linear regression equations …
  - ✓ … MOS between observations and DMO Model Output field (typical 5 years)
  - ✓ … Perfect Prog between observations and Analyses only (typical 40 years)

- ✓ What are main Pros and Cons of both?
  - ✓ MS Pros: corrects systematic NWP errors,
  - ✓ MS-Pros: allows forecast of all observed parameters (not computed by the model though)
  - ✓ MS-Cons: Model-specific development, model changes have to be corrected for
  - ✓ PP-Pros: Information of 40 years is used
  - ✓ PP-Pros: Can be used for any model, not model-specific (Forecast considered Perfect, PP)
  - ✓ PP-Cons: Can be used for any model, not model-specific: does not correct model errors

QUESTIONS YOU SHOULD BE ABLE TO ANSWER

Numerical Weather Prediction

- ✓ What is the idea behind Ensemble Forecast Technology?
  - ✓ NWP models are sensitive against infinitesimal errors in the initial state, therefore 50 simplified model versions are run with infinitesimal changes of the initial state and the results are interpreted by ‘clustering‘

Please check vorticity – ENG – MISCellaneous

https://www.vorticity.de//vorticity_en.php#0_ANKER_V

QUESTIONS YOU SHOULD BE ABLE TO ANSWER

Numerical Weather Prediction

- ✓ What
  - ✓ Mo
- ✓ What
  - ✓ Mo
- ✓ What
  - ✓ Mo
- ✓ What
  - ✓ Mo

QUESTIONS YOU SHOULD BE ABLE TO ANSWER

Numerical Weather Prediction

- ✓ What
  - ✓ Mo
- ✓ What
  - ✓ Mo
- ✓ What
  - ✓ Mo
- ✓ What
  - ✓ Mo

QUESTIONS YOU SHOULD BE ABLE TO ANSWER

Numerical Weather Prediction

- ✓ What
  - ✓ Mo
- ✓ What
  - ✓ Mo
- ✓ What
  - ✓ Mo
- ✓ What
  - ✓ Mo

More Questions you should be able to answer…

Will follow later … CCA…