国际数值预报现状和发展

沈学顺

中国气象局数值预报中心

提纲

- 背景介绍
- 国际数值预报现状和水平
- 未来发展

一、背景介绍

What is Numerical Weather Prediction?

- The technique used to obtain an objective forecast of the future weather (up to possibly two weeks) by solving a set of governing equations that describe the evolution of variables that define the present state of the atmosphere.
- Feasible only using computers

Equations

- **Conservation of mass**
- **Conservation of momentum**
- **Conservation of energy**

$$\frac{d\vec{V}}{dt} = -\frac{1}{\rho}\cdot\nabla P - 2\vec{\Omega}\times\vec{V} - \vec{g} + \vec{F}_{\vec{V}}$$ ← 运动方程

$$C_p\frac{dT}{dt} - \alpha\frac{dP}{dt} = Q_T + F_T$$ ← 热力方程

$$\frac{1}{\rho}\frac{d\rho}{dt} = -\nabla\cdot\vec{V}$$ ← 质量守恒方程

$$P = R\rho T$$ ← 状态方程

To solve the equations:

1. Numerical procedures to solve the equations with computer

   from the scale of the continuum to the mean grid size scale

   - approximations used to estimate each term
   - approximations used to integrate model forward in time
   - boundary conditions

2. Approximations of unresolved parts due to discretization (〜closure), radiation, microphysics (cloud), interaction with other sphere (ocean, land surface)

   parameterizations

3. Initial conditions

   - Observing systems, objective analysis, initialization, and data assimilation

Accuracy of NWP

- Good initial conditions
- A more correct set of equations
- More accurate numerical methods
- More correct physical forcing formulations: physical processes

Scales of weather elements/models

Global

- Long waves

Synoptic

- Jet streams
- High and low pressure centers
- Troughs and ridges
- Fronts

Meso

- Thunderstorms
- Convective complexes
- Tropical storms
- Land/sea breezes
- Mountain/valley breezes
- Downslope wind storms
- Gap flows
- Cold air damming
- Nocturnal low-level jets
- Lake-effect snow bands

Local

- Street-canyon flows
- Channeling around buildings, wakes
- Vertical transport on upwind and warm faces of buildings
- Flow in subway

Progresses of NWP model

- Charney et al. 1950: non-divergent barotropic equations
- Charney et al. 1956: quasi-geospheric barotropic equations
- Charney et al. 1962: filtered baroclinic equations
- Schuman and Hovermale, 1968: primitive equations
- ECMWF, 1979 ～present: primitive equations
- UKMO, CMC, CMA 1990s～present: fully compressible non-hydrostatic equations

Over last 3 decades

NWP systems are improving by 1 day of predictive skill per decade. This has been due to:

1. *Model improvements, especially resolution.*

1. *Careful use of forecast & observations, allowing for their information content and errors.* *Achieved by variational assimilation e.g. of satellite radiances. (Simmons & Hollingsworth 2002)*

1. *Advanced assimilation using forecast model: 4D-Var*

1. *Better observations.*

Andrew Lorenc

From the simple equations to full equations

- Conservation of mass
- Conservation of momentum
- Conservation of energy

Primitive equations hydrostatic approximation

$$\frac{du}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + fv + F_x$$

$$\frac{dv}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial y} - fu + F_y$$

$$\frac{\partial p}{\partial z} = -\rho g$$

$$\frac{1}{\rho}\frac{d\rho}{dt} = -\nabla \bullet \vec{V}$$

$$C_p \frac{dT}{dt} - \alpha \frac{dp}{dt} = Q_T + F_T$$

$$\frac{dq}{dt} = Q_q + F_q$$

$$p = \rho R T$$

Full equations

$$\frac{d\vec{V}}{dt} = -\frac{1}{\rho} \bullet \nabla P - 2\vec{\Omega} \times \vec{V} - \vec{g} + \vec{F}$$

$$\frac{1}{\rho}\frac{d\rho}{dt} = -\nabla \bullet \vec{V}$$

$$C_p \frac{dT}{dt} - \alpha \frac{dp}{dt} = Q_T + F_T$$

$$\frac{dq}{dt} = Q_q + F_q$$

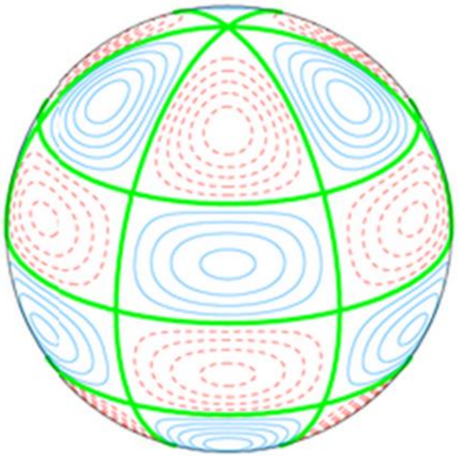
$$p = \rho R T$$

Typical NWP models

Spectral model: ECWMF, JMA GSM/Japan, NCEP GFS/US, Meteo France

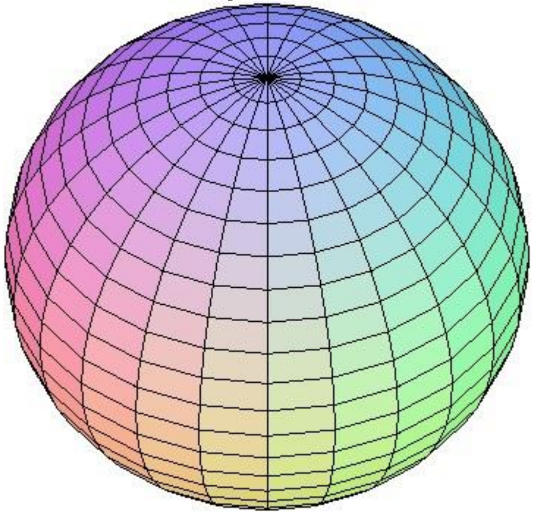
Primitive equations

Hydrostatic approximation



Grid point model: UKMO/UK, CMC/CANADA, GME/DWD, GRAPES/CMA

Fully compressible non-hydrostatic equations



Regional NWP models: grid point, non-hydrostatic

WRF, RAMS, MM5,COSMO-EU/DE, MSM & LFM/Japan,

ALADIN/EU, AROME/France, LAM/Canada, GRAPES_Meso/CMA

NWP becomes core of daily weather forecast

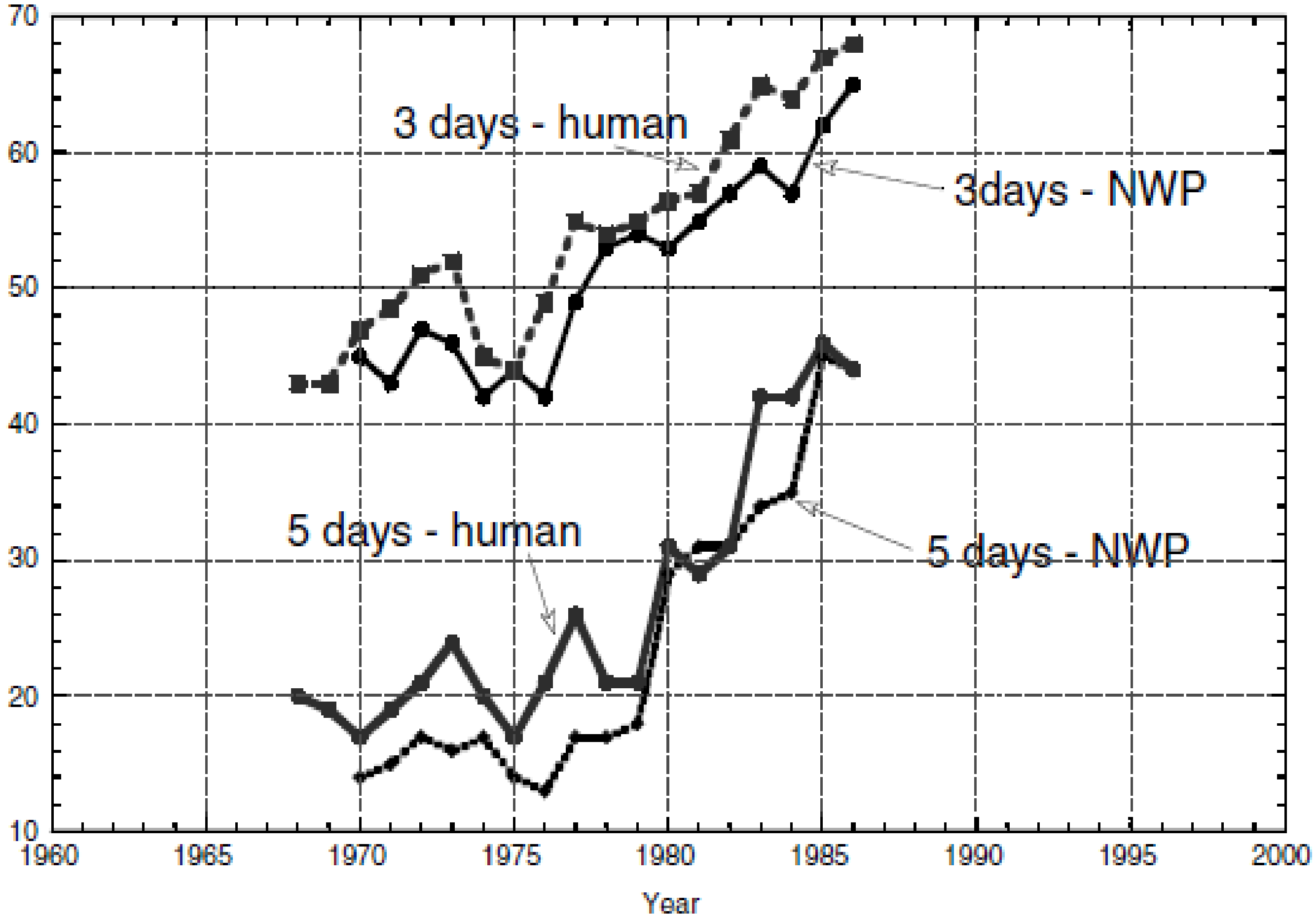
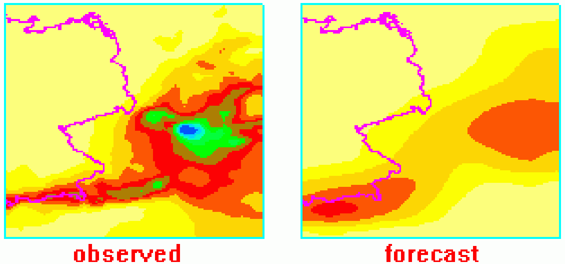


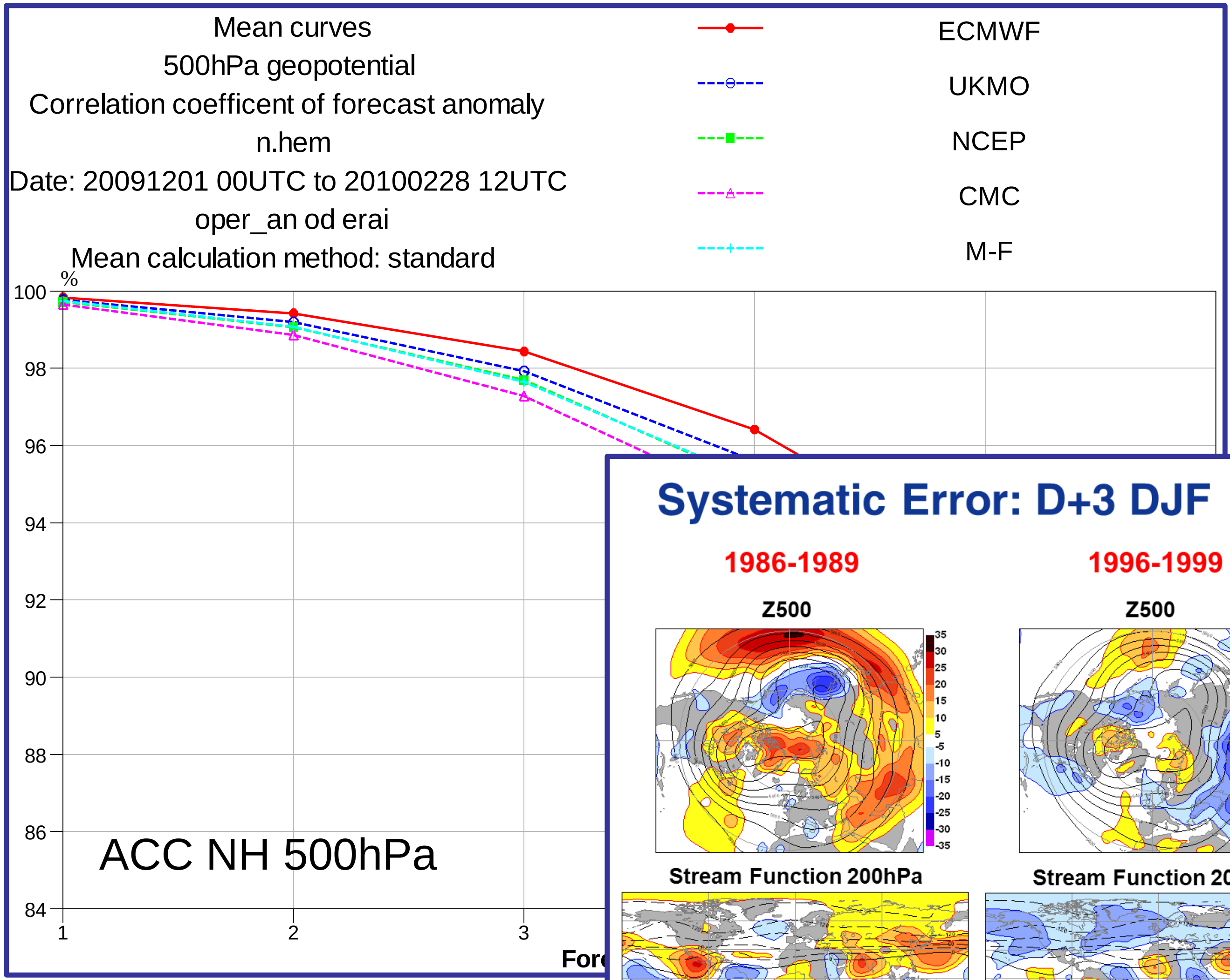
Figure 1.5.2: Hughes data: comparison of the forecast skill in the medium-range from NWP guidance and from human forecasters.

Kalney, 2003

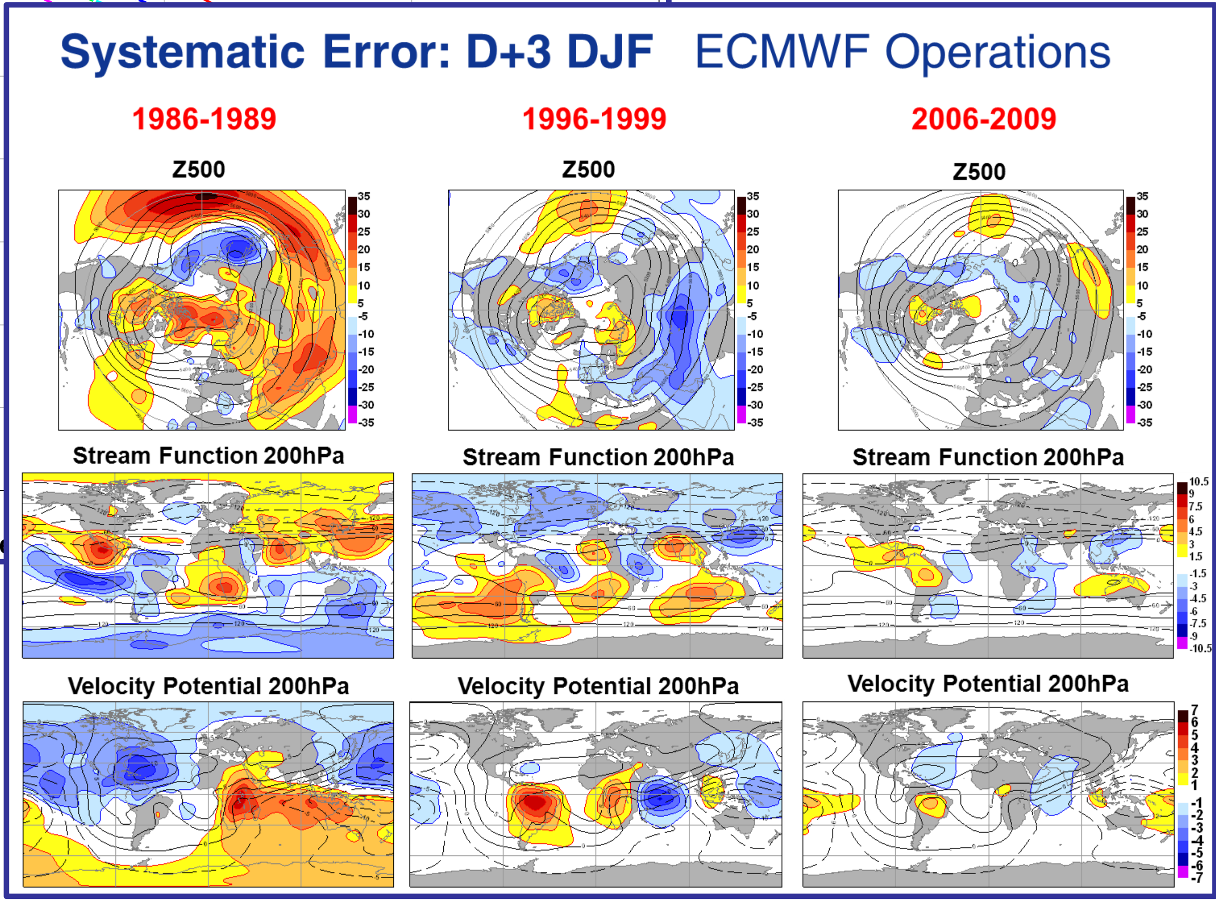
How to evaluate the NWP skill?



- ***"Eyeball" verification:***
- ***Scatter plot***
- ***"Objective" verification:***
  - Mean error (bias) : $$Mean\ Error = \frac{1}{N}\sum_{i=1}^{N}(F_i - O_i)$$
  - Bias: $$bias = \frac{\frac{1}{N}\sum_{i=1}^{N}F_i}{\frac{1}{N}\sum_{i=1}^{N}O_i}$$
  - Mean absolute error: $$MAE = \frac{1}{N}\sum_{i=1}^{N}|F_i - O_i|$$
  - Anomaly correlation: $$AC = \frac{\sum(F-C)(O-C)}{\sqrt{\sum(F-C)^2}\cdot\sqrt{\sum(O-C)^2}}$$
  - Root mean square error: $$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(F_i - O_i)^2}$$



Mean curves
500hPa geopotential
Correlation coefficent of forecast anomaly
n.hem
Date: 20091201 00UTC to 20100228 12UTC
oper_an od erai
Mean calculation method: standard
ECMWF
UKMO
NCEP
CMC
M-F
%
100
98
96
94
92
90
88
86
84
1
2
3
ACC NH 500hPa



Systematic Error: D+3 DJF ECMWF Operations
1986-1989
1996-1999
2006-2009
Z500
Z500
Z500
Stream Function 200hPa
Stream Function 200hPa
Stream Function 200hPa
Velocity Potential 200hPa
Velocity Potential 200hPa
Velocity Potential 200hPa

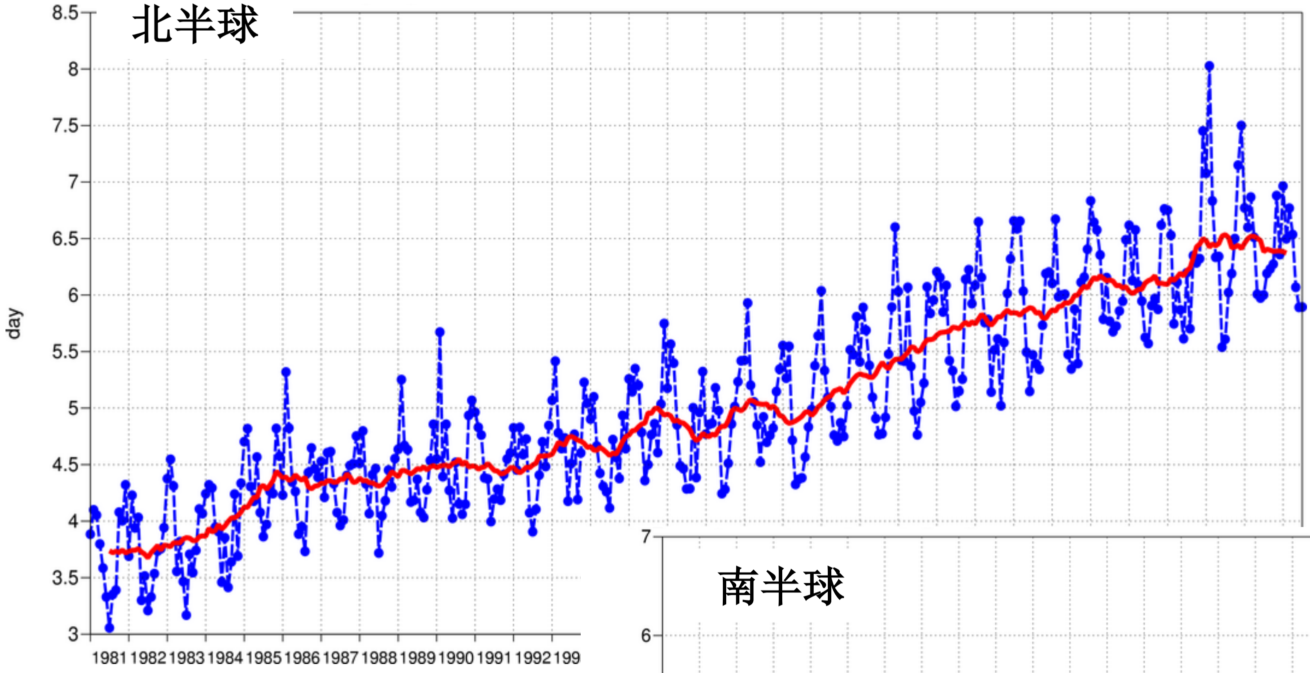
二、国际业务数值预报现状

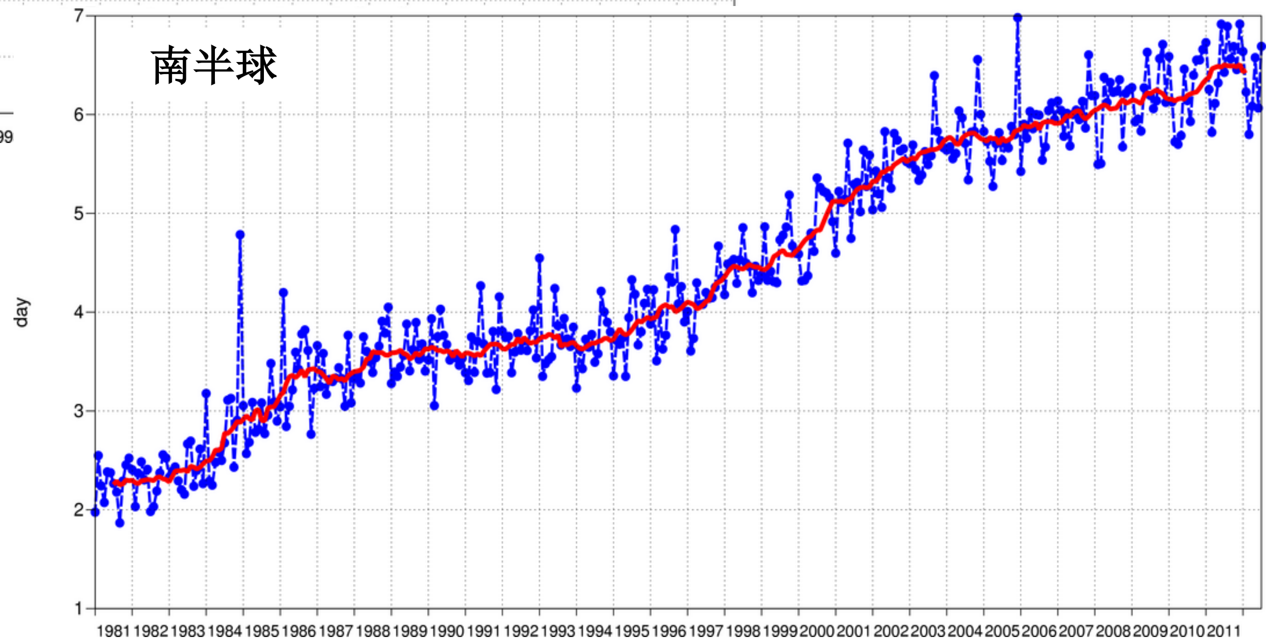
国别/模式	全球模式	区域模式
ECMWF 欧洲中心	**T_L1279 L137（～16km）** **4D-Var 12h (EDA);** **T_L1279 with T_L255 final inner loop; L137**	
UKMO 英国气象局	**UM 25km L70** **Hybrid 4D-Var at 60km L70**	**600x360; 12 km; L70** **768x960; 1.5 km; L70** **4D-Var 24km** **3D-Var 1.5km**
NCEP 美国国家环境预报中心	**T574 （～ 27km）; L64 (7.5d)** **T190; L64 (16d)** **Hybrid EnKF - 3DVar GSI**	**1371x1100; 4 km; L70** **595x625; 6 km; L70** **373x561; 3 km; L70** **241x241; 3 km; L70** **GSI** **12/6/4/3 km**
CMC 加拿大气象局	**(0.35° x0.23°) L80** **4D-Var** **(0.9° x0.9°),** **(0.35° x0.23°) L80**	**10 km; L80** **LAMs at 2.5km; L58** **3D-Var 55 km L80** **Local: 3D-Var 10 km L58**

度量全球预报可用预报时效

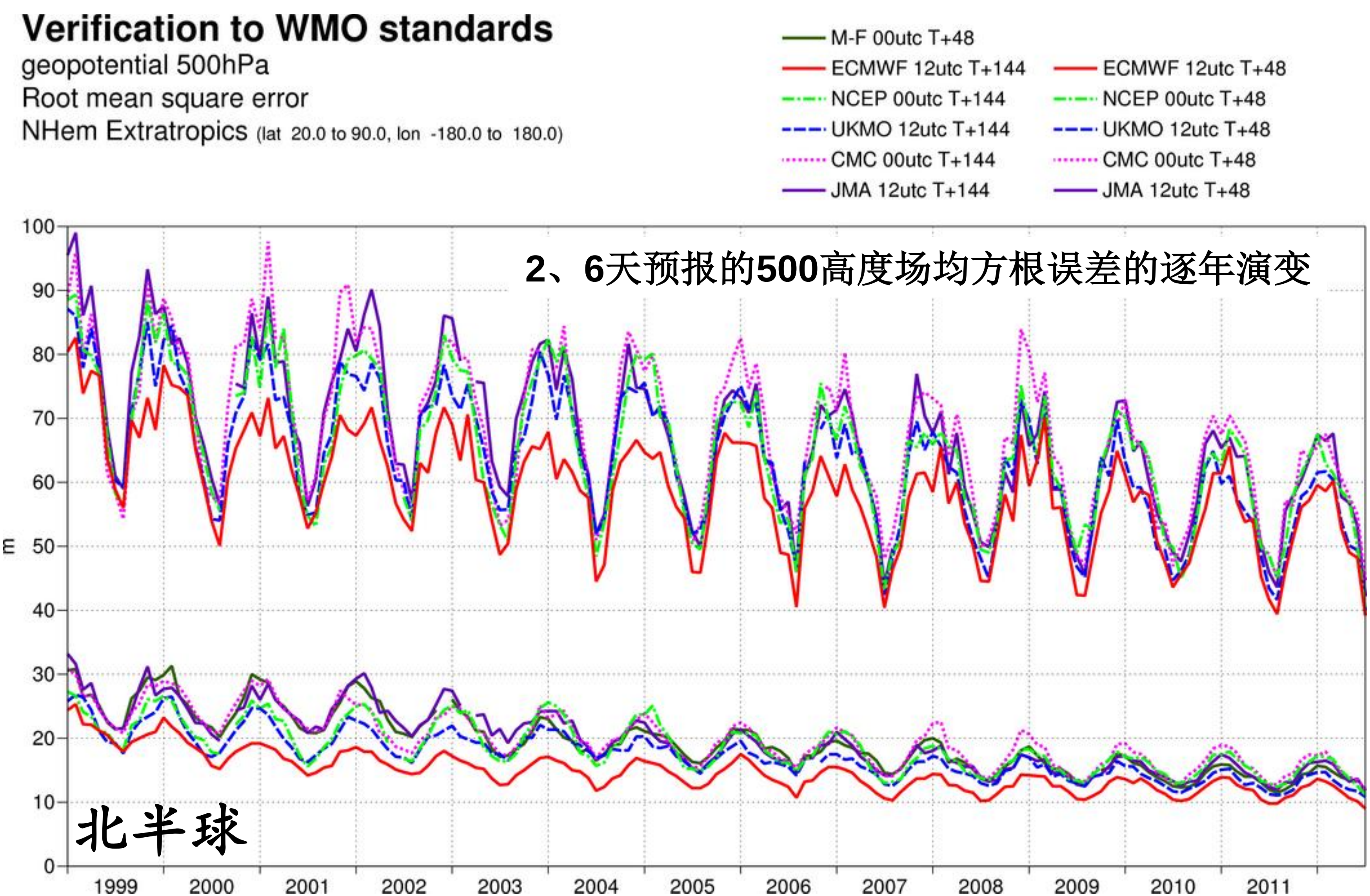
将用距平相关系数0.8

Z500, Time series of **ACC=0.8**



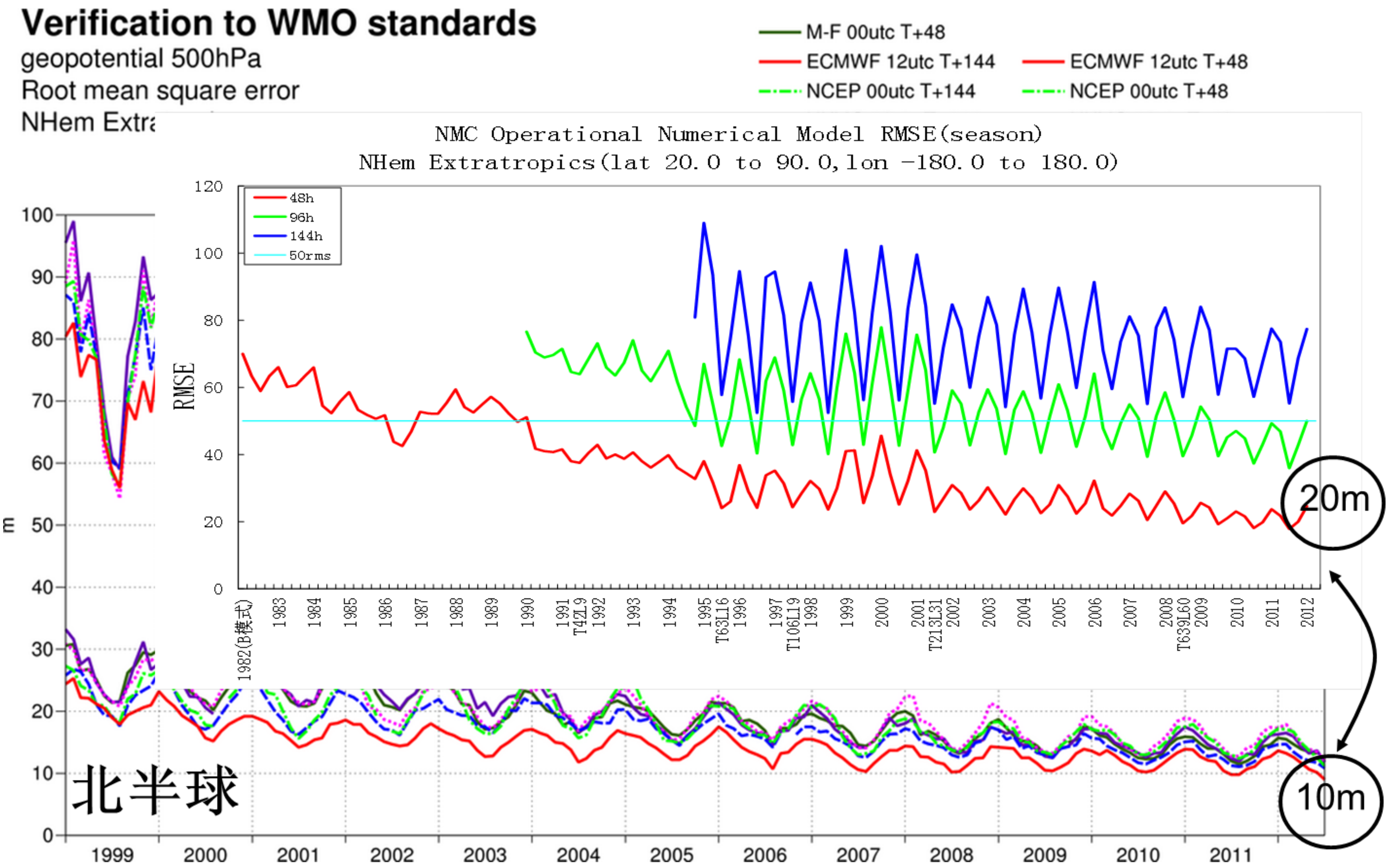


世界各国数值预报水平



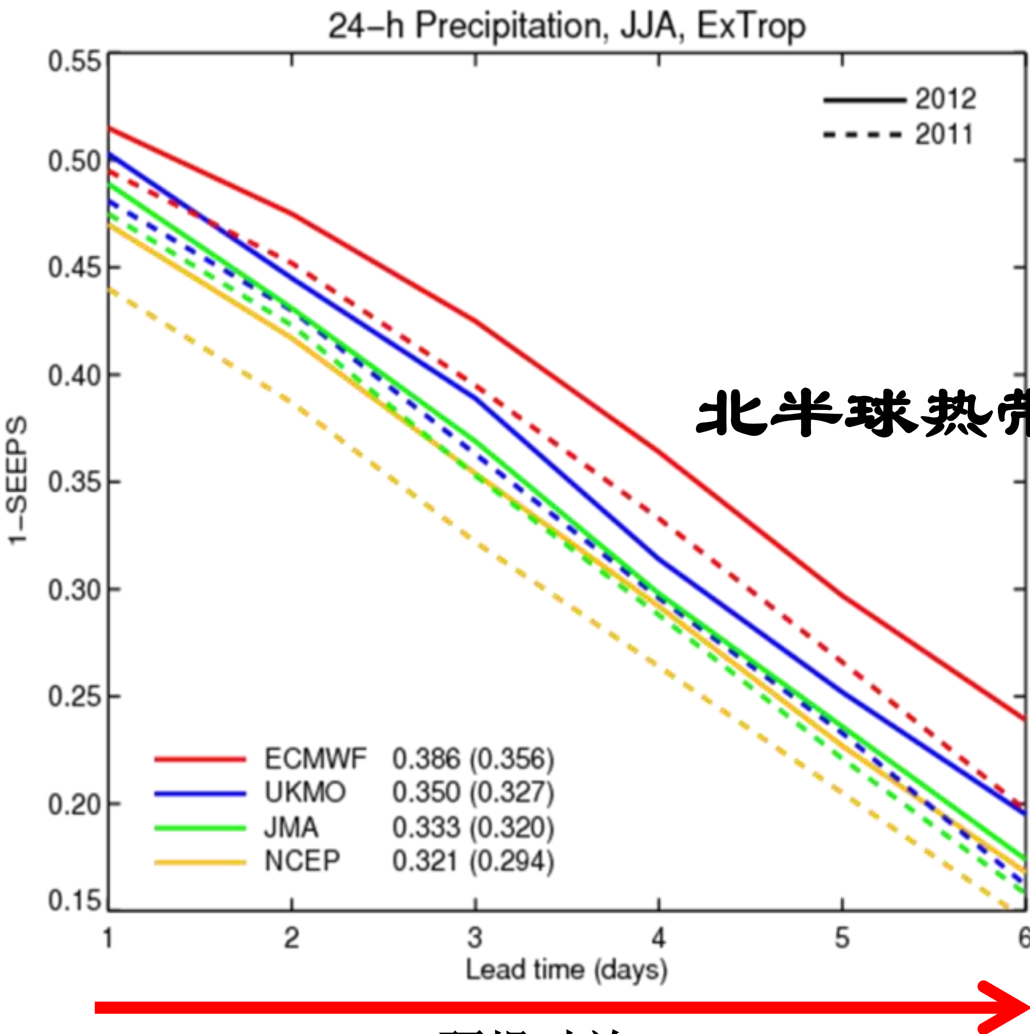
Verification to WMO standards
geopotential 500hPa
Root mean square error
NHem Extratropics (lat 20.0 to 90.0, lon -180.0 to 180.0)
M-F 00utc T+48
ECMWF 12utc T+144
ECMWF 12utc T+48
NCEP 00utc T+144
NCEP 00utc T+48
UKMO 12utc T+144
UKMO 12utc T+48
CMC 00utc T+144
CMC 00utc T+48
JMA 12utc T+144
JMA 12utc T+48
2、6天预报的500高度场均方根误差的逐年演变
m
0
10
20
30
40
50
60
70
80
90
100
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
北半球

世界各国数值预报水平



Verification to WMO standards
geopotential 500hPa
Root mean square error
NHem Extra
M-F 00utc T+48
ECMWF 12utc T+144
ECMWF 12utc T+48
NCEP 00utc T+144
NCEP 00utc T+48
NMC Operational Numerical Model RMSE(season)
NHem Extratropics(lat 20.0 to 90.0,lon -180.0 to 180.0)
48h
96h
144h
50rms
RMSE
1982(B模式)
T42L9
T63L16
T106L19
T213L31
T639L60
20m
10m
北半球
m

Precipitation skill - deterministic



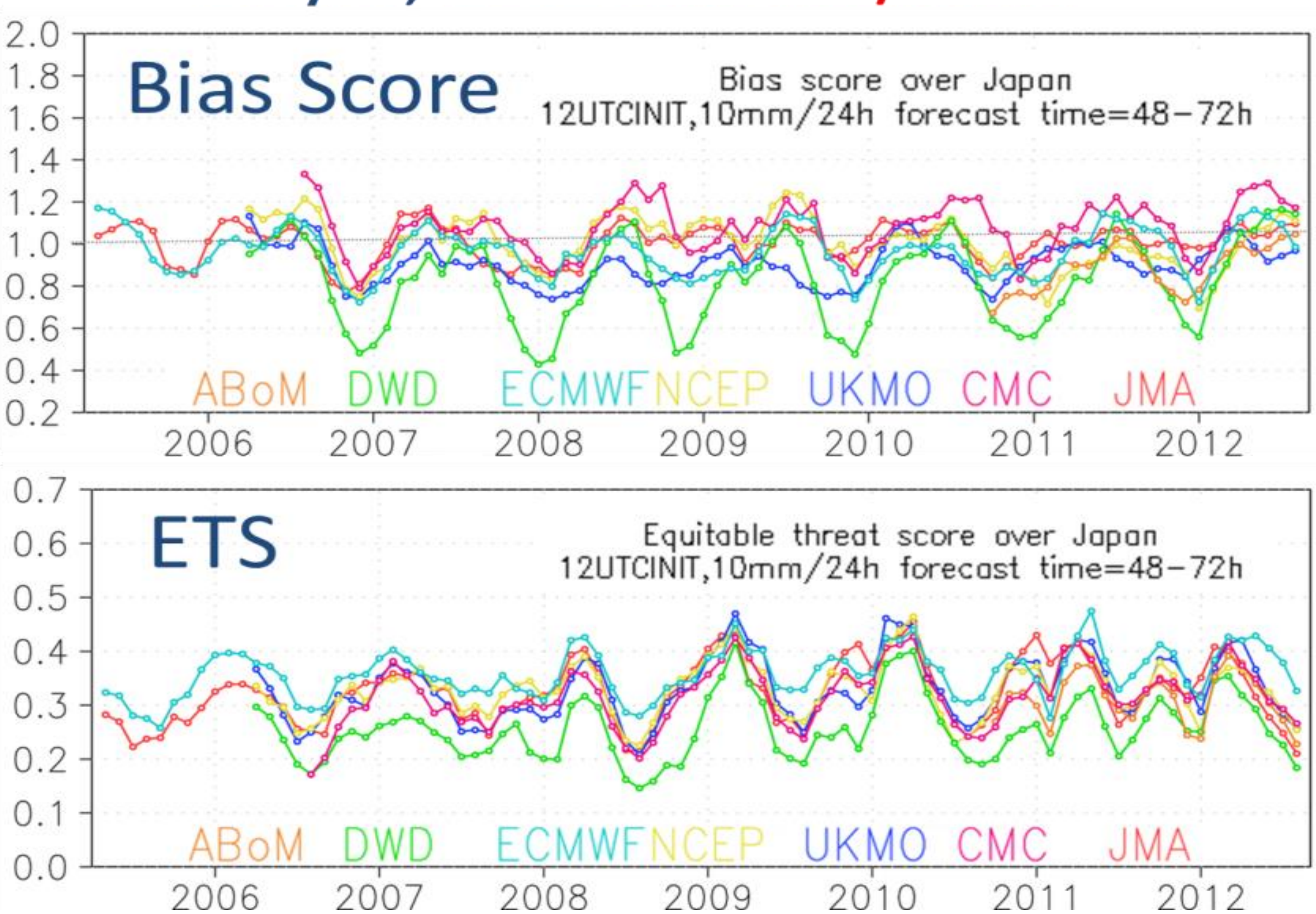
全球模式

北半球热带外降水的预报评分

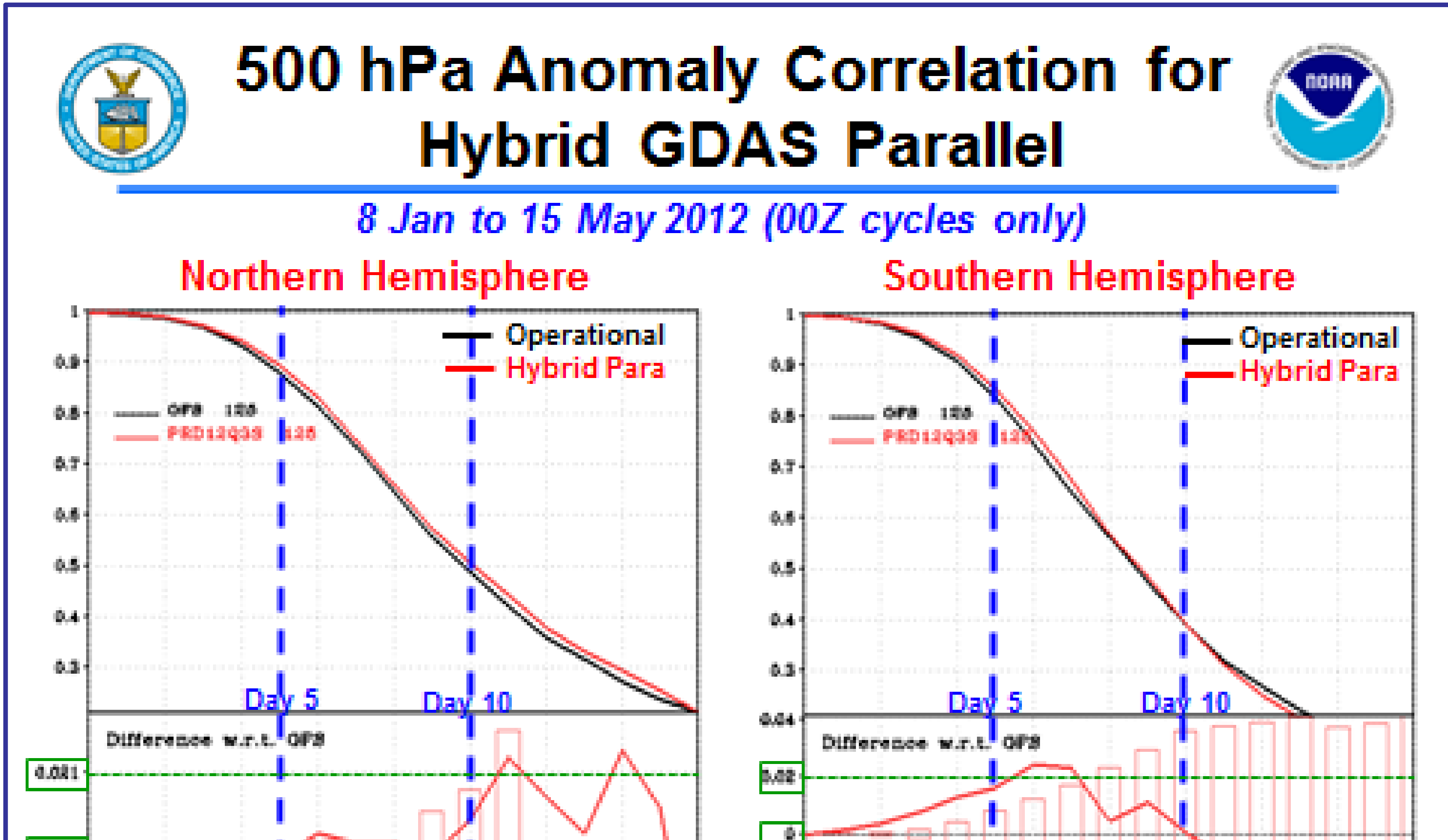
预报时效

各主要业务中心模式对日本降水预报评分的比较

Day 3, over 10mm/24hr



NCEP stands out of other centers

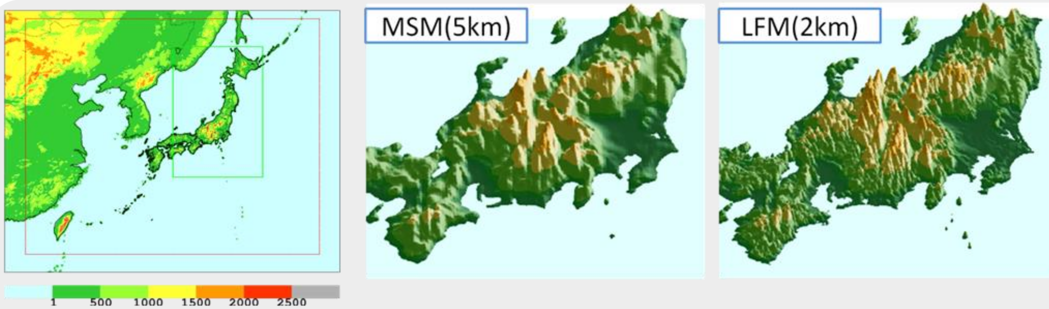


- **Hybrid system**
  - Most of the impact comes from this change
  - Uses ensemble forecasts to help define background error

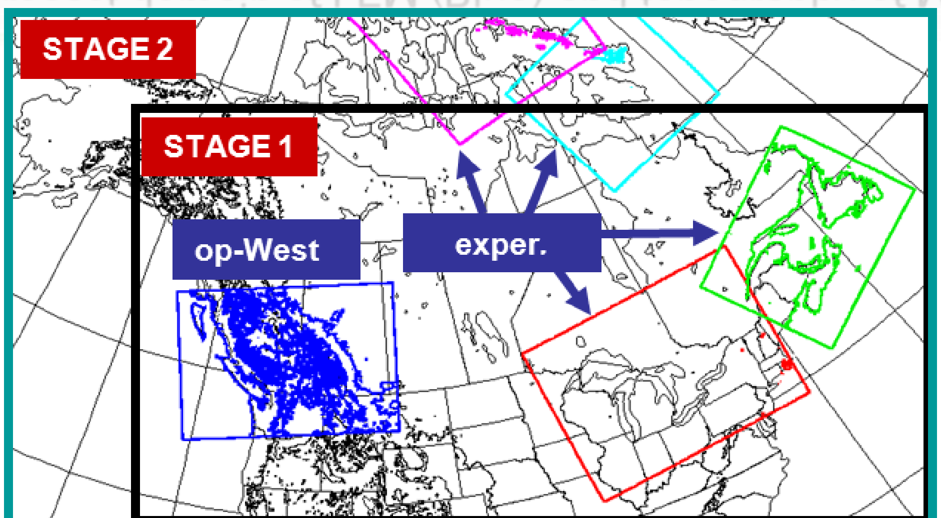
全球模式物理过程

- **No new development of physics**
- **But becomes more physical & comprehensive**
  - Comprehensive cloud microphysics
  - Eddy diffusion – Mass flux (EDMF) scheme
  - Detailed treatment of fractional clouds in Radiation scheme: RRTM
  - Non-orographic GWD
  - Small-scale orographic turbulence

高分辨率中尺度预报



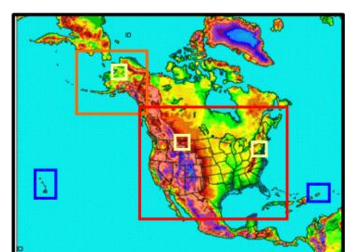
Forecast domain of LFM (Blue) and topography of MSM and LFM



Operational Mesoscale Modeling for CONUS:

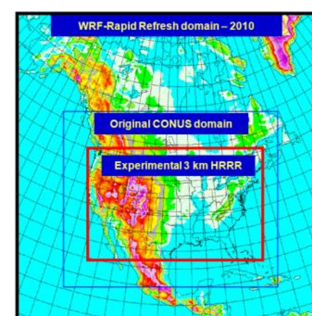
North America Model (NAM)

- *Implemented 18 October 2011*
- NEMS based NMM
- Outer grid at 12 km to 84hr
- Multiple Nests Run to ~48hr
  - 4 km CONUS nest
  - 6 km Alaska nest
  - 3 km HI & PR nests
  - 1.3km DHS/FireWeather/IMET



Rapid Refresh (RAP)

- *Implemented 1 May 2012*
- WRF-based ARW
- Use of GSI analysis
- Expanded 13 km Domain to include Alaska
- Experimental 3 km HRRR



各业务中心中尺度数值预报的共同点

现状：

- 水平分辨率高于5公里，且向云分辨尺度发展
  - Operational limited area models at > 5km horizontal resolution
- 各国根据地域灾害天气特点，有不同的应用侧重点
  - NOAA—Severe Wx (convection, hurricanes) and aviation
  - Meteo France---Fog
  - CMA– Flooding
  - UKMO & JMA—Coastal phenomena
  - BOM—coasts and cities
  - ECMWF—global application
- 快速同化预报更新系统的业务应用
  - Move toward rapidly updating systems—hourly DA and forecasts

挑战：

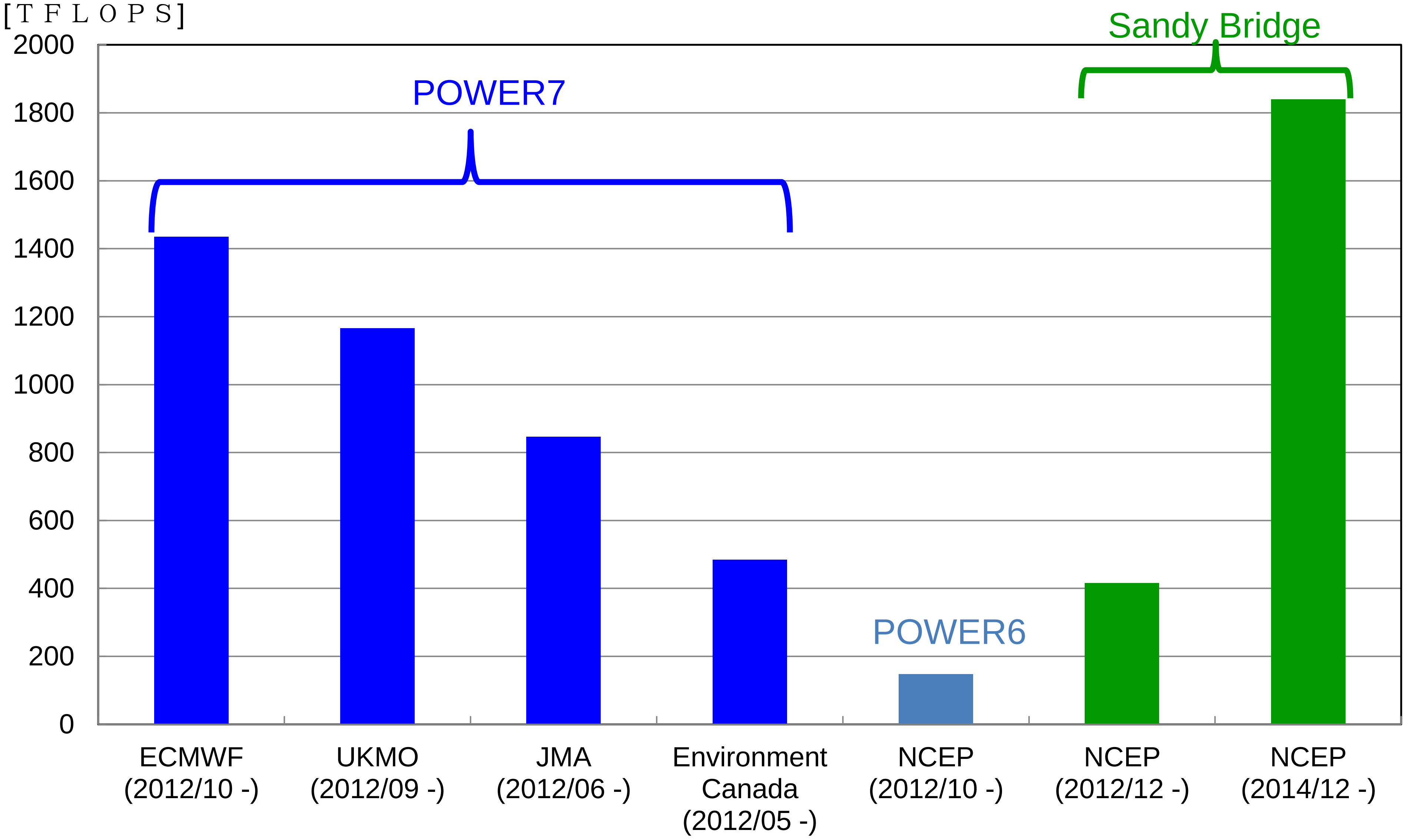
- Data Assimilation methodology and control variables
- Physical representations
- Prediction of sensible weather elements
- Nesting & Computational costs
- Verification (development & customer)
- High resolution ensemble systems

中尺度数值预报模式和同化的特点

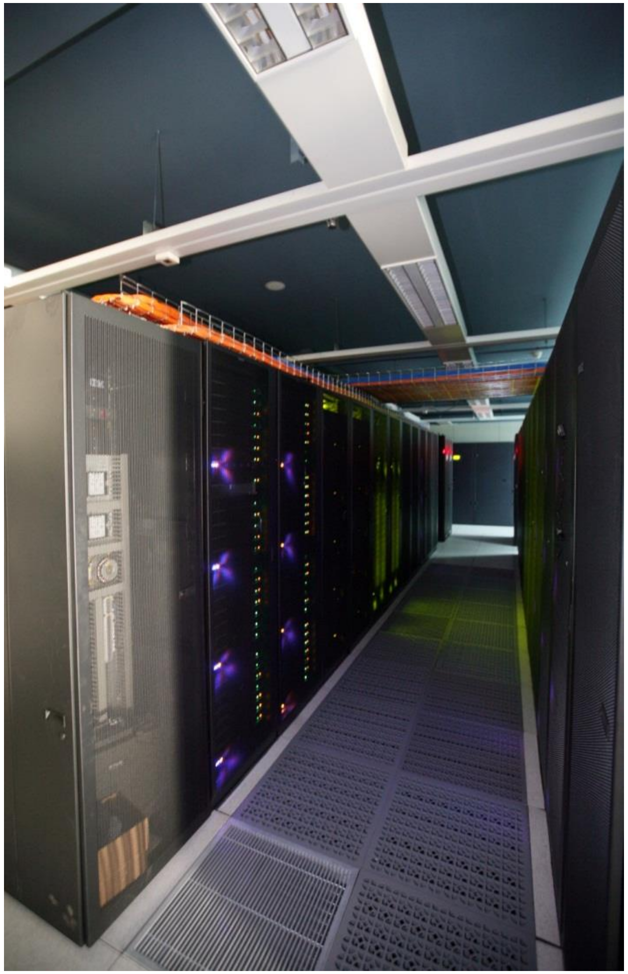
- 模式动力框架: 非静力全可压方程组
  - 欧拉模式：**WRF, ARPS, RAMS, MSM&LFM/JMA**
    - **split scheme for fast and slow modes & higher-order advection scheme**
  - 半隐式半拉格朗日模式**SISL : GRAPES, UM/UKMO**
- 模式物理过程: Column physics → 3-D physics
  - **3D turbulence**
  - **3D precipitation process**
- 资料同化
  - **3DVAR+latent heat nudging: UK, JMA(2km) , BoM**
  - **3DVAR: NCEP (GSI)**
  - **4DVAR: JMA(5km)**
  - **Nudging: DWD**

三、国际业务数值预报未来发展

HPC at NWP centers



2013年7月
CMA New HPC System Introduction (ss1)



Subsystem	SS1
Site	Beijing（NMIC）
Performance (TFlops)	**508.93**
Storage (TB)	2109.38
Total CPU Cores	**17920**
Nodes	560
Memory (GB)	81792
I/O Nodes	40
Network	Infiniband
Total Racks	32

全球模式未来发展

- 高分辨率、高精度
- 高可扩展性

以欧洲中心为例

ECMWF High-resolution modelling developments
(inputs: Nils Wedi, Mats Hamrud, George Mozdzynski, Jean Bidlot, Geir Austad, Sinisa Curic)

Current and planned resolutions:

IFS model resolution	Envisaged Operational Implementation	Grid point spacing (km)	Time-step (seconds)	Estimated number of cores[1]
T1279 H[2]	2010 (L91) 2013 (L137)	16	600	1100 1600
T2047 H	2014-2015	10	450	6K
T3999 NH[3]	*2020-2021*	*5*	*240*	*80K*
T7999 NH	*2025-2026*	*2.5*	*30-120*	*1-4M*

1 - a gross estimate for the number of 'Power7' equivalent cores needed to achieve a 10 day model forecast in under 1 hour (~240 FD/D), system size would normally be 10 times this number.
2 – Hydrostatic Dynamics
3 – Non-Hydrostatic Dynamics

More speculative: extrapolated capability more than firm plans

国际业务数值预报未来发展计划

- **DWD ICOMEX**：ICOsahedral grid Models for Exascale Earth system simulations (2-11-2014)
- **UKMO Gung-Ho**: Development of the Next Generation Dynamical Core for the UK MetOffice (2 phases, 2011-2013, 2013-2016)
- **ECMWF CRESTA**: Collaborative Research into Exascale System-ware, Tools & Applications (2011-2014)

Mega	10^6
Giga	10^9
Tera	10^{12}
Peta	10^{15}
Exa	10^{18}
Zetta	10^{21}
Yotta	10^{24}

ECMWF Roadmap toward a highly scalable and affordable high-resolution forecasting and assimilation system – from Nils Wedi 2012

IFS model: current and planned model resolutions

IFS model resolution	Envisaged Operational Implementation	Grid point spacing (km)	Time-step (seconds)	Estimated number of cores[1]
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T2047 H	2014-2015	10	450	6K
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T7999 NH	2025-2026	2.5	30-120	1M

1 - a gross estimate for the number of 'Power7' equivalent cores needed to achieve a 10 day model forecast in under 1 hour (~240 FD/D), system size would normally be 10 times this number.
2 – Hydrostatic Dynamics
3 – Non-Hydrostatic Dynamics

How far can we go with ...

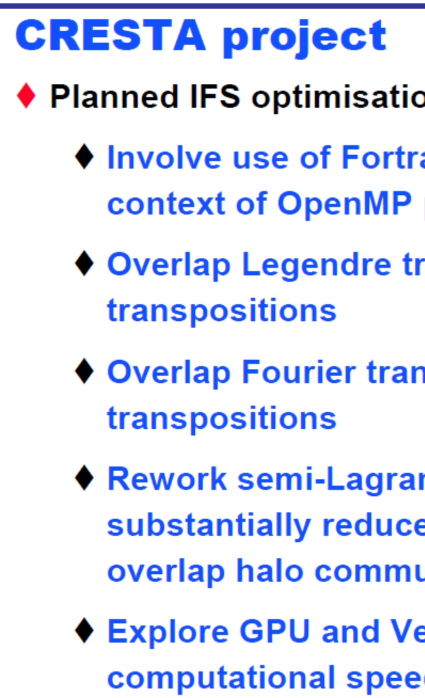
technology applied at ECMWF for the last 30 years …

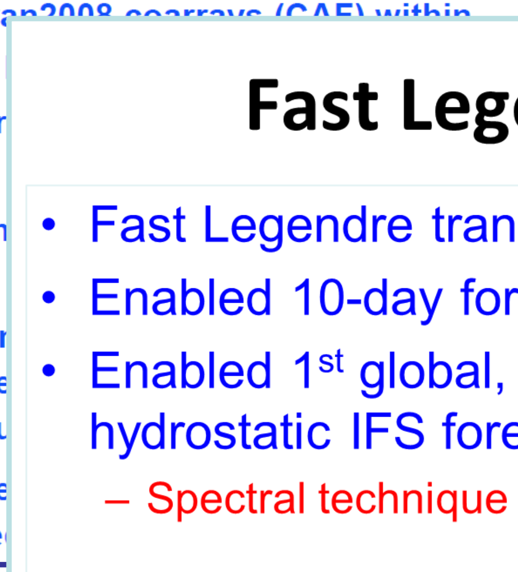
A spectral transform, semi-Lagrangian, semi-implicit (compressible) (non-)hydrostatic model?

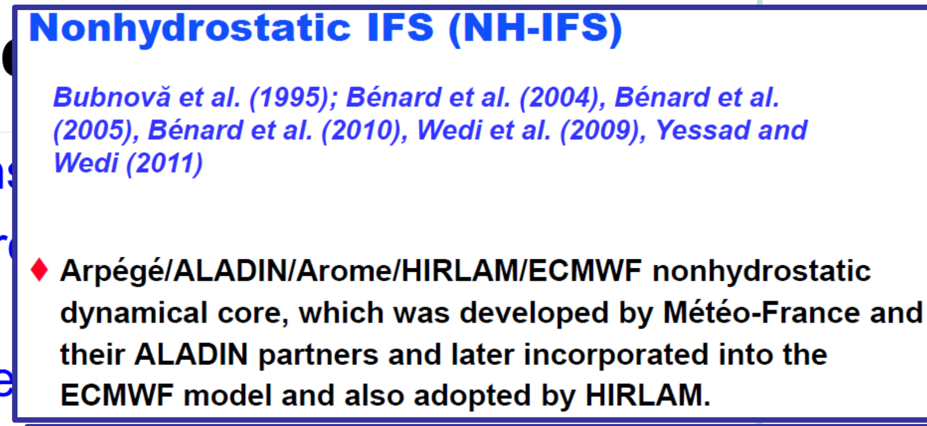
-Computational efficiency on and affordability of future MPP architectures ?
-Accuracy and predictability at cloud-resolving scales ?

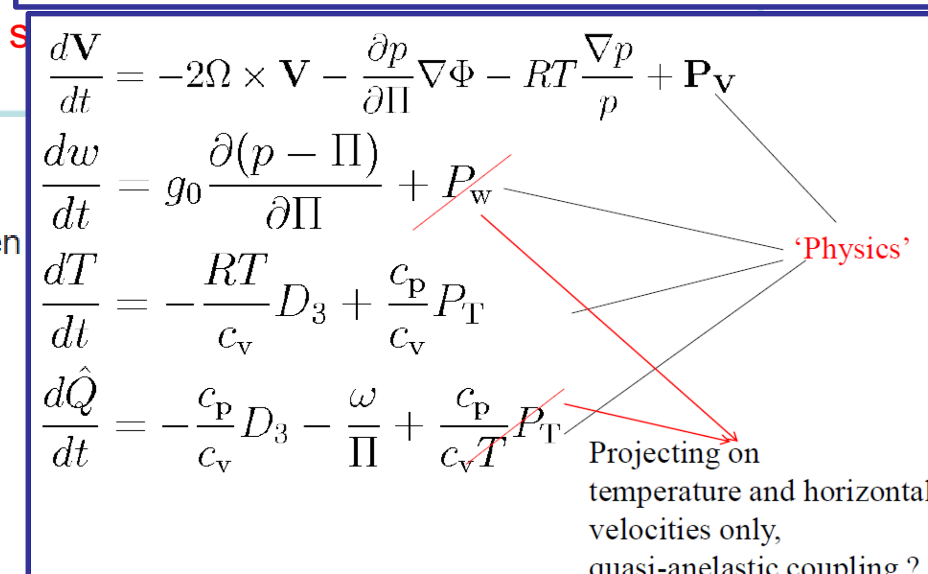
The spectral transform method, dead or alive ?

CRESTA project + Meteo France NH-IFS

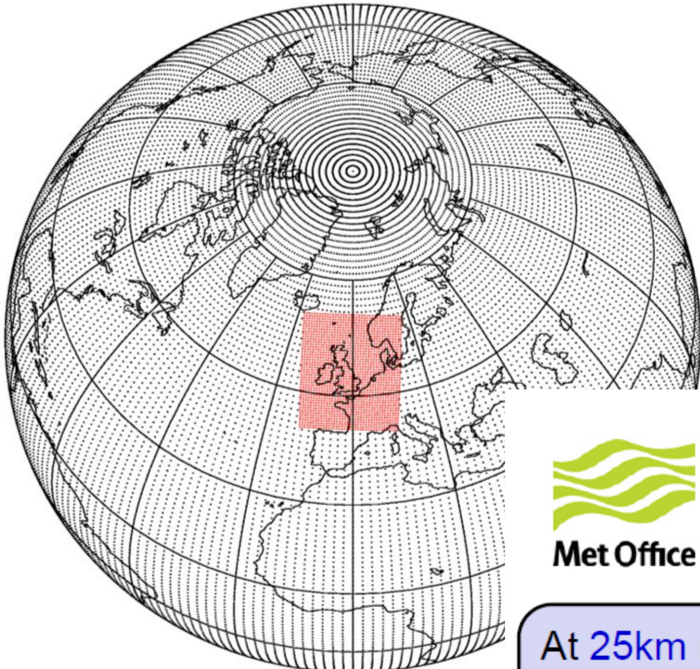








Mats Hamrud	ECMWF
Nils Wedi	ECMWF
Jens Doleschal	Technische Universität Dresden
Harvey Richardson	Cray UK



UKMO: Fully compressible equations

25kmx12kmx1.5km

Problems with a long-lat grid

Met Office

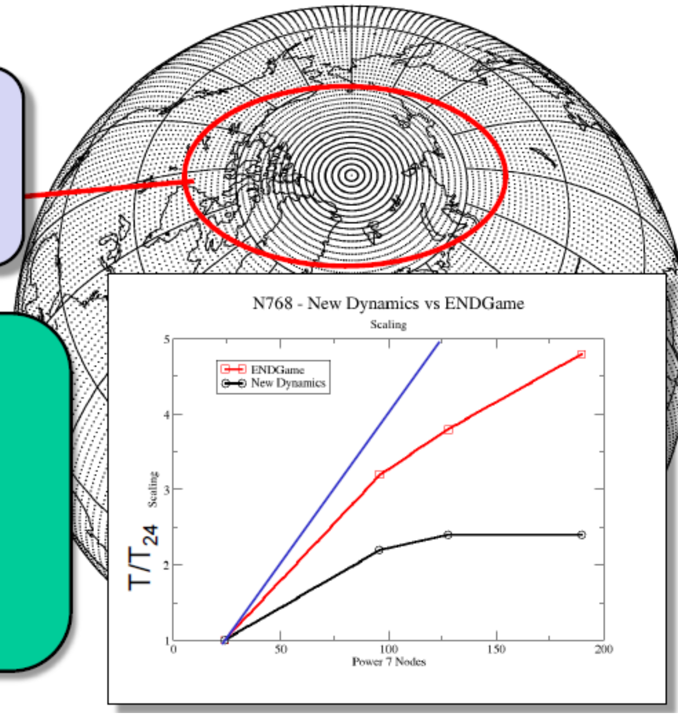
At 25km resolution, grid spacing near poles = 75m

At 10km reduces to 12m!

3rd Gen dynamical core (ENDGame) improved scaling

Weak CFL ➔ Δt↓ as Δx↓ (implicit scheme)

Data parallel in 2-D

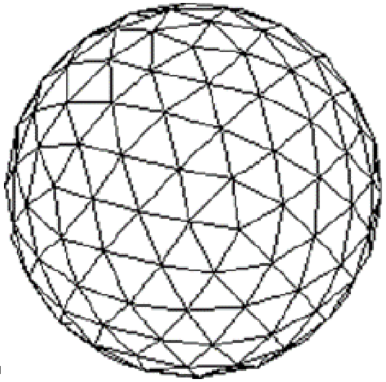


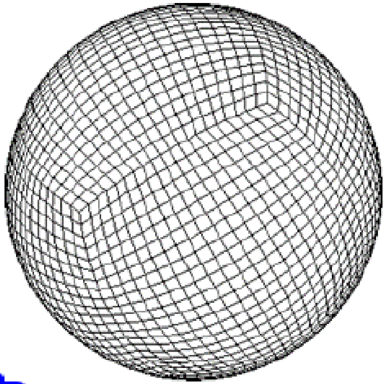
工合

GungHo!

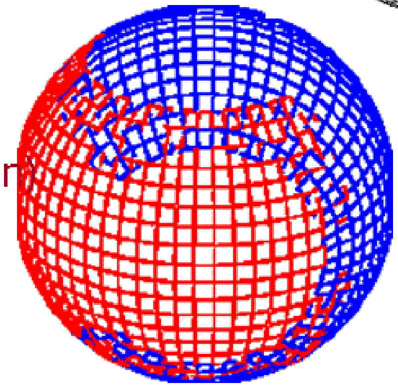
Issues

- Weakness of New Dynamics formulation (accuracy, stability, conservation)
- Limited scalability
- Need for overhaul of UM code (approaching 25 years old)





- Completely new model ~2018-2020 (NGWCP/Gung-Ho)
  - Non latitude-longitude grid
  - Possible move away from implicit to explicit scheme (avoid solver)
  - Possible changes to advection scheme (away from semi-Lagrangian)
- *What to do in the mean time?*



Globally

Uniform

Next

Generation

Highly

Optimized

GungHo Themes: Phase 1

- Quasi-Uniform Grids (icosahedral; kites/balanced triangles; cubed-sphere; Yin-Yang)
- Advection schemes (conservation, SL, ...)
- Time schemes (explicit vs. implicit)
- Test cases
- Computational science aspects

GungHo Themes: Phase 2

- Refinement & testing of Phase 1 proposal
- Vertical aspects
  - Choice of variables
  - Grid & Staggering
  - Discretization
- Code development and testing

5 Year Project

- "To research, design and develop a new dynamical core suitable for operational, global and regional, weather and climate simulation on massively parallel computers of the size envisaged over the coming 20 years."

  - Bath University - Rob Scheichl and Eike Mueller;
  - Exeter University - John Thuburn;
  - Imperial University – Colin Cotter and David Ham;
  - Leeds University – Sarah-Jane Lock, Alan Gadian and Stephen Mobbs;
  - Manchester University – Rupert Ford and Graham Riley;
  - Reading University – Hilary Weller
  - Daresbury Laboratory – Stephen Pickles.

- 5 FTEs from NERC (Bath, Exeter, Imperial, Leeds, Manchester, Reading)
- 2 FTEs from STFC (Science & Technology Facilities Council, Daresbury - Hartree Centre)

高精度、高可扩展性-模式的发展趋势

-基于有限元空间离散化-

In the recent years more and more **finite-element (FE) based methods** are upcoming in atmospheric modelling

Dynamics

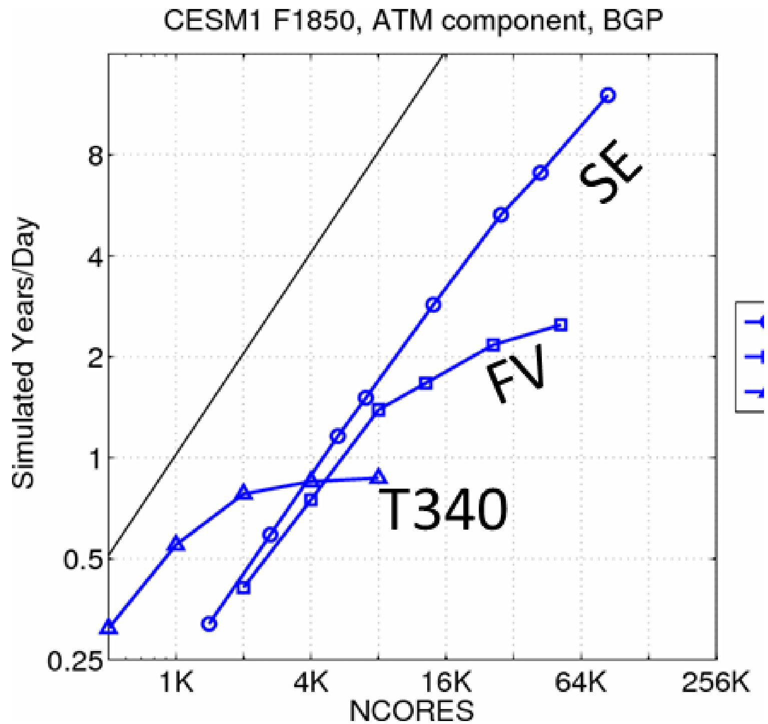
- Non-hydrostatic full equation

Space Discretization

- Finite elements
- spectral elements
- Continuous Galerkin
- Discontinuous Galerkin
- MCV

高可扩展性

25 km timings



WGNE-27 by Julio Bacmeister

... **FE-based methods**:

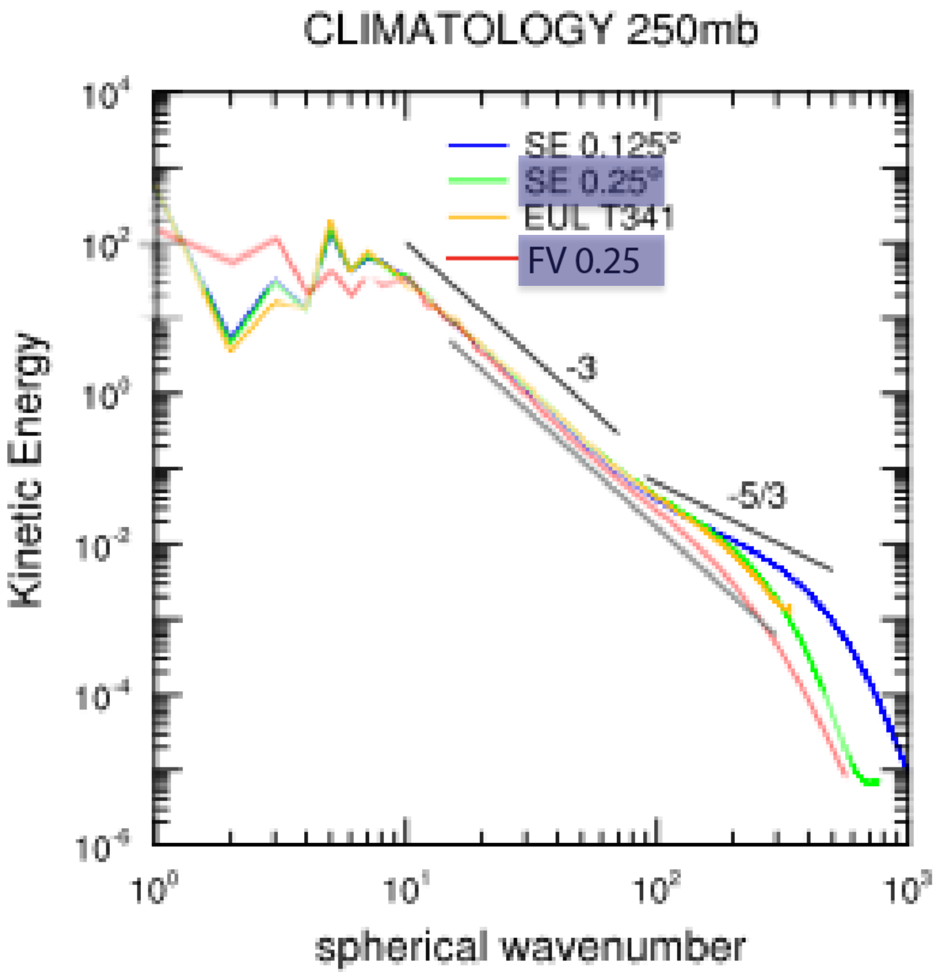
- computational intensity (= # of calculations : # of memory accesses) is high
  → advantages on new computer architectures (GPU's, ...) → scalability

- General problem in these FE-like schemes: small Courant number
  e.g. CFL ~ 1 / (1 + 2*p), p=Polynomial degree
  for the Discontinuous Galerkin (DG) Method

  → Combination with other schemes:
  Semi-Lagrangian-DG

高精度

Horizontal Kinetic Energy spectra



CAM-SE has higher effective resolution for given nominal resolution

WGNE-27 by Julio Bacmeister

物理过程的发展

Seamless or All-purpose or Scale-aware **physics**

Global :	15km - 50km	**Planned: <5km – 20km**
Regional :	2km - 12km	**Planned: <1km – 2km**

Fundamentals

To resolve a structure in the horizontal to a reasonable accuracy requires at least 6 – 8 Δx.

- Most deep convective updraughts (downdraughts) are a few kms wide at most .
- Some ensembles of updraughts organized ~10kms
- Organization of deep convection into MCS etc >> 10kms

This implies

- Δx< < 500m to resolve updraught
- Δx~1km to resolve ensemble of updraughts
- Δx~ a few kms to resolve some well-organized systems but not the individual cells

According to M. Miller

模式物理过程发展的“灰色地带”计划

The Grey Zone Project

A WGNE-GASS initiative

Grey Zone committee: Pier Siebesma, Martin Miller, Andy Brown, Jeanette Onvlee

Motivation

(1) Increased use of (operational) models in the “grey zone” (Dx = 1 ~10km)

(2) This has led to **the “wrong” perception** that these “grey-zone” models, when operating without (deep) convection parameterizations, can realistically represent turbulent transport of heat, moisture and momentum.

(3) Hence there is **a urgent need for a systematic analysis of the behavior of models operating in the “grey-zone” and assess what should and should not be done**

“The Grey Zone Project”

资料同化技术的发展

- Hybrid EnKF/3DVAR – NCEP
- EDA+4DVAR – ECMWF
- Hybrid 4DVAR or 4DEnVAR – UKMO
- EnVAR – CANADA

Further development of traditional 3DVAR and 4DVAR

中小尺度数值预报
(Very) High Resolution

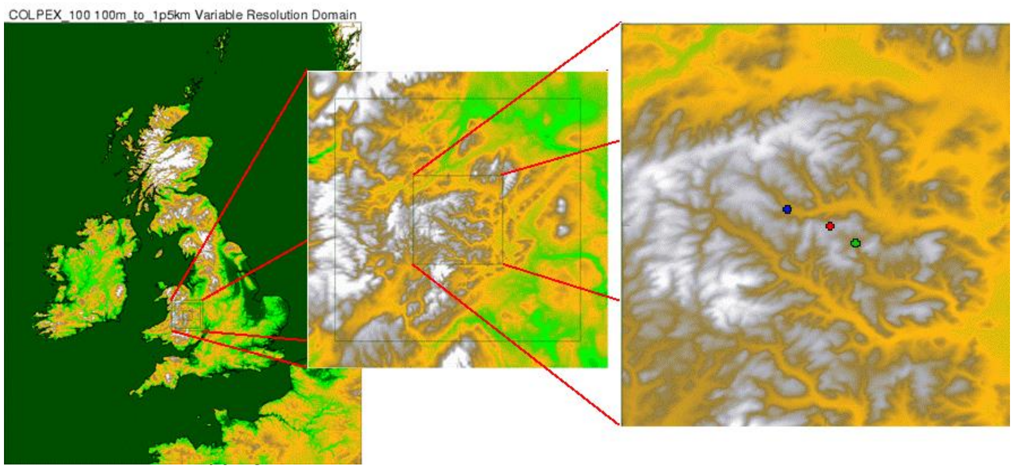
～100m resolution deterministic forecast

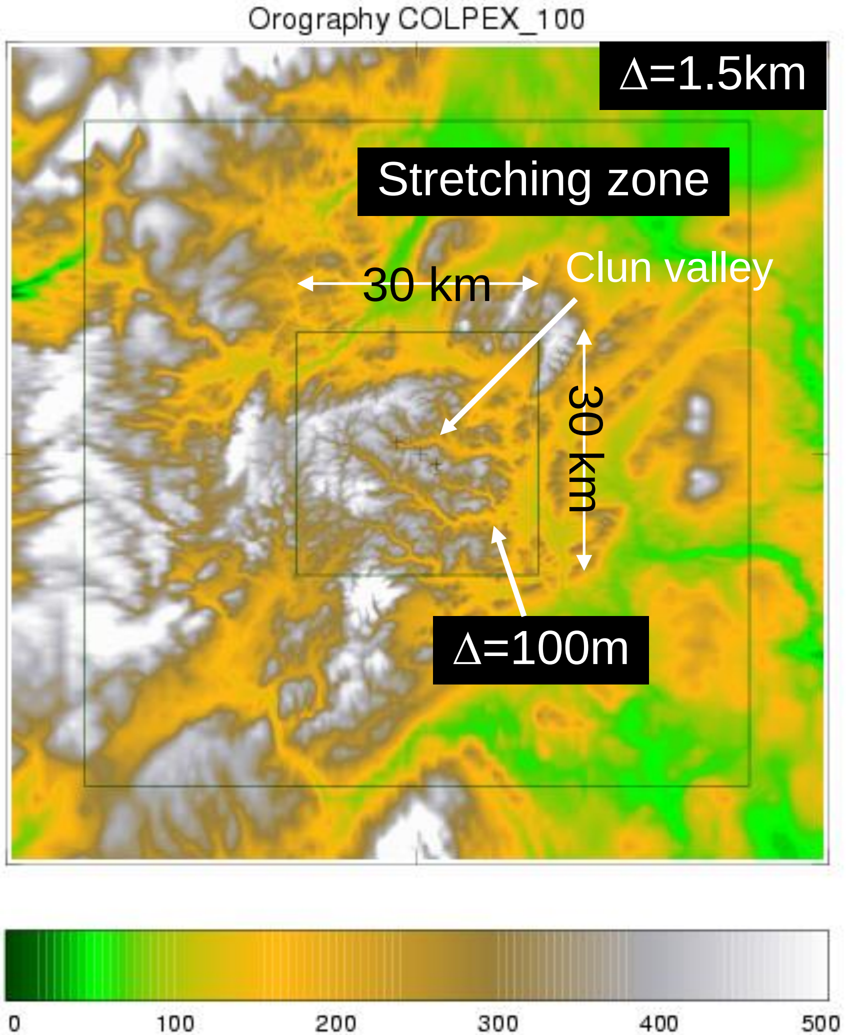
～ km resolution ensemble forecast

High resolution simulations of cold air pooling in valleys

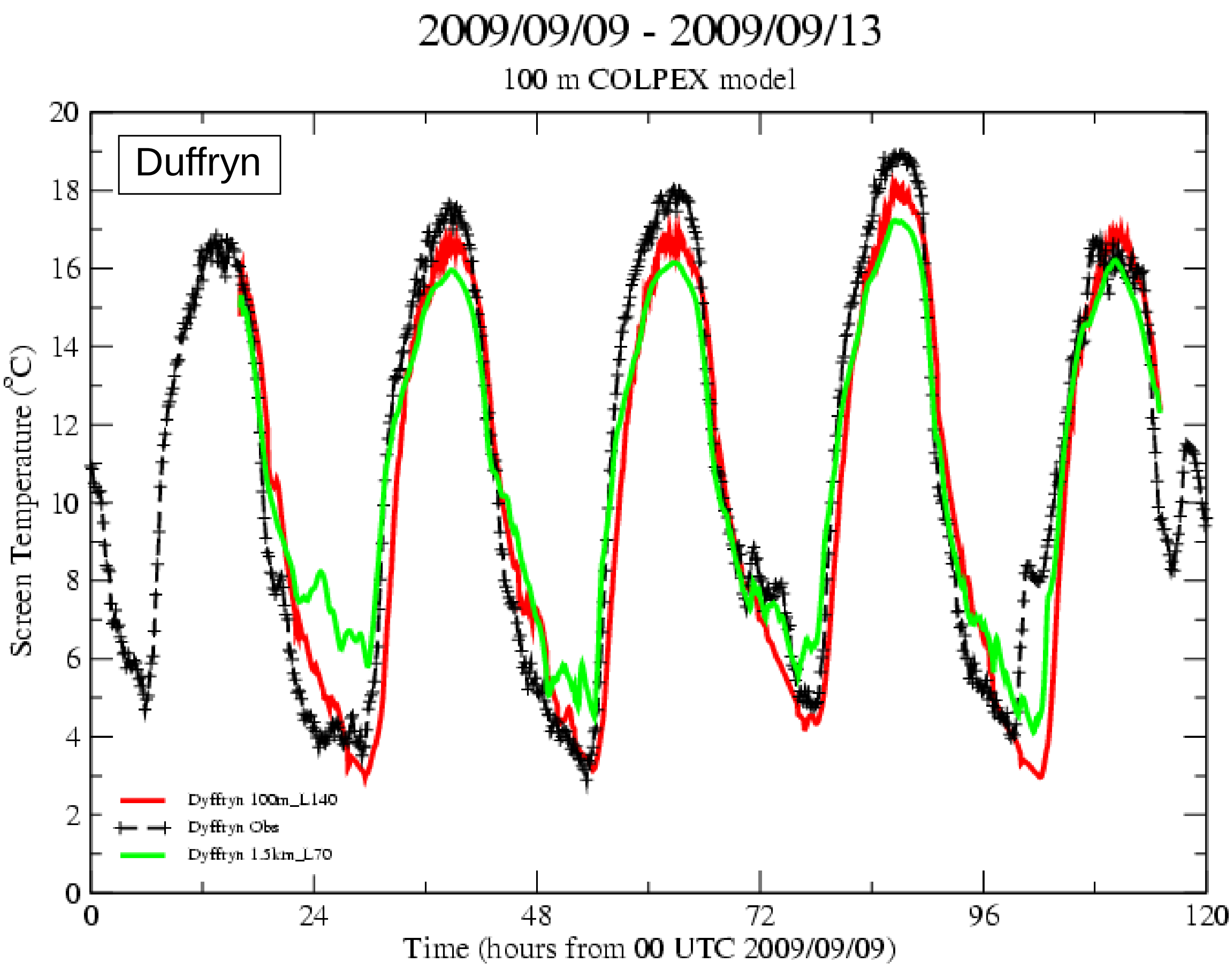
Met Office

- Very high resolution simulations using the Met Office Unified Model
- Nested from 4 km resolution domain to 1.5 km, and then **100 m model** via a horizontally stretched grid
- Enhanced vertical resolution: 12 levels below 112 m vs 5 levels in operational model





Model screen temperature: Δ=100m L140 vs Δ=1.5km L70



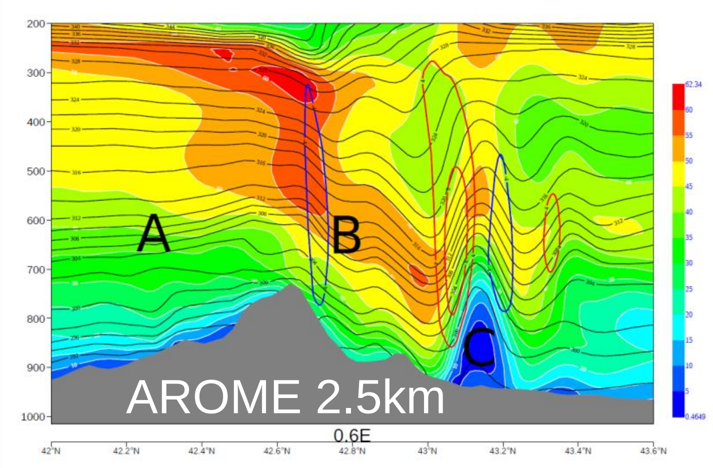
Temperature minima well represented

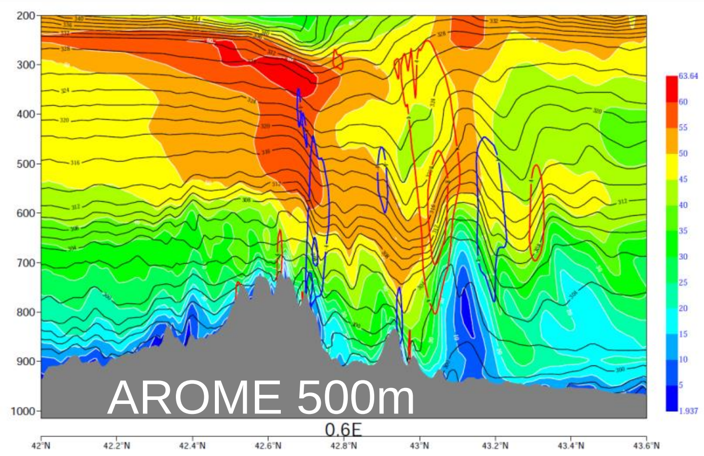
Daytime temperatures too cold

Clear benefit of 100m resolution over 1.5km

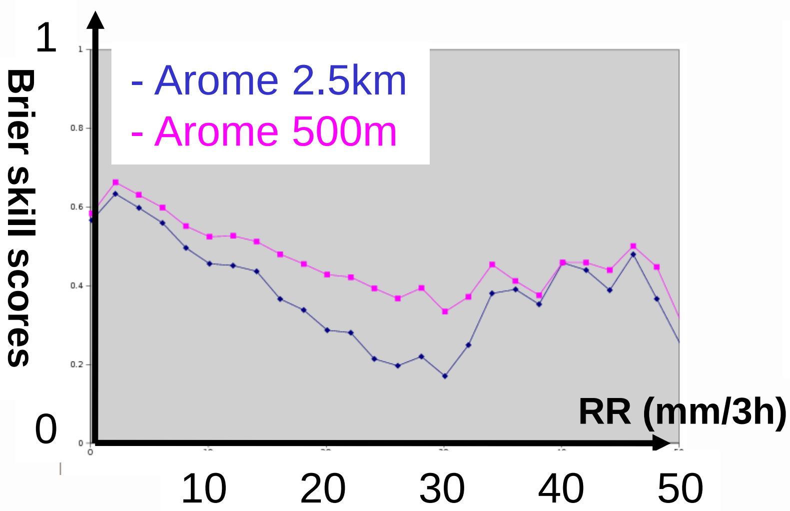
AROME 500m configuration

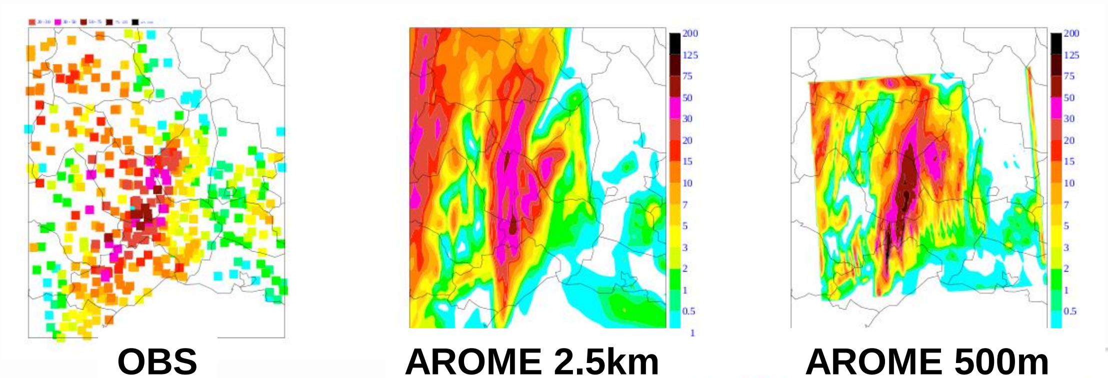
Cross section over the Pyrenees for the Xynthia storm case.
Small scales Trapped Lee waves well captured at 500m res.





Heavy precipitations cases over south-east of France, 2-8 November 2011





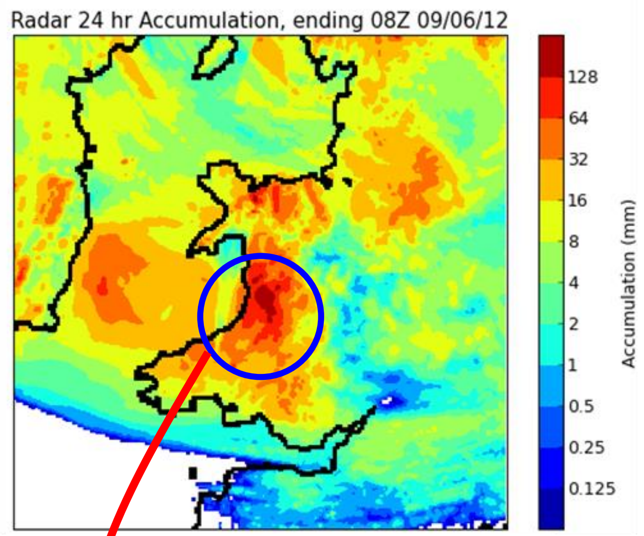
3/11/2012 18-21h RR

中小尺度数值预报面临的挑战

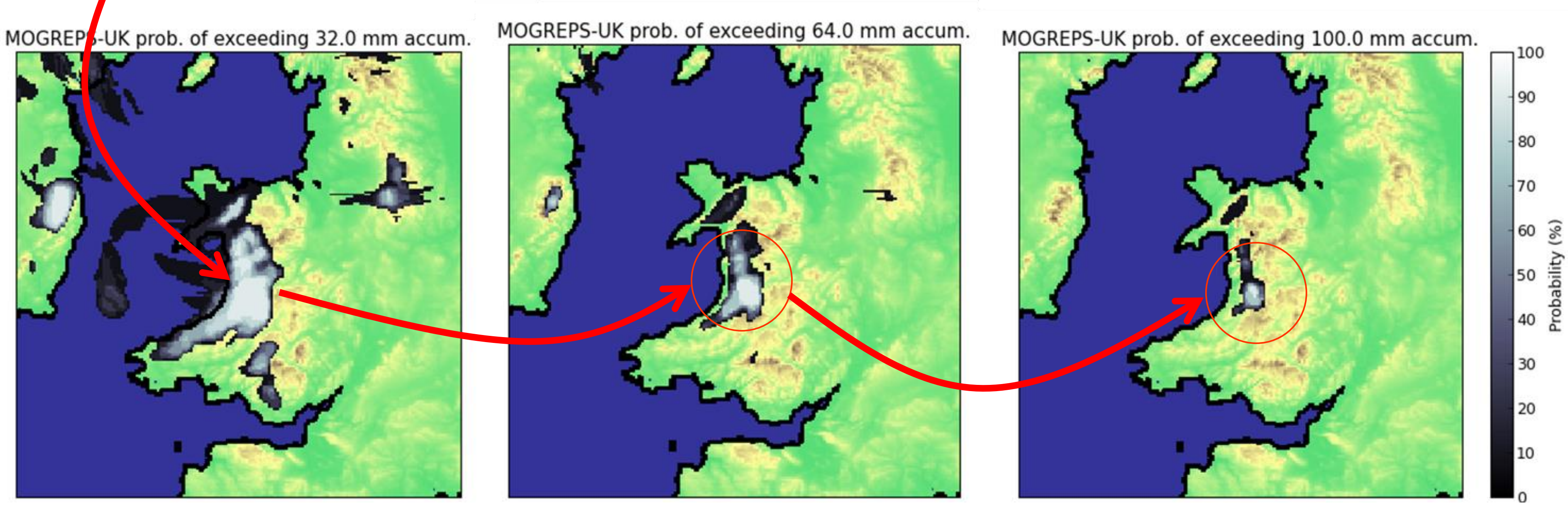
1. 资料同化方法
2. 模式动力框架、物理过程
3. **Prediction of sensible weather elements**
    - Cloud, near-surface temperature, precipitation and phase etc.
    - Rather than traditional synoptic scores
4. **Nesting & Computational costs**
5. **Verification (development & customer)**

UK Ensemble

From WGNE-28 by A. Brown



- 12 member 2.2km ensemble
- Running 4 times per day
- Currently nested in regional (18km) ensemble
- From this autumn will switch to direct nesting in enhanced resolution (33km) global ensemble



五个方面值得关注

1. 高可扩展性、高分辨率、高精度下一代模式

   Scalability and efficiency on massively parallel computer architectures with O(10^4+) cores

   ENDGAME/UK→GungHo

   ICON/DWD

   Non-hydrostatic IFS/ECMWF

2. 多尺度通用模式物理过程的发展

   Seamless physics & Grey-Zone project

3. 资料同化新技术: **EnDA, hybrid DA (3DVAR +EnKF), En-VAR**
4. 高分辨率中尺度预报、km-scale 中尺度集合预报及其应用

   convection-permitting EPS

   12 member 2.2km ensemble/UK

   PEARO 2.5km/Meteo France

5. 化学数值天气预报

THANK YOU