The CMC 15km Global Deterministic Prediction System with the Yin-Yang grid.

Abdessamad Qaddouri and Vivian Lee

Environment Canada

Environnement Canada
Centre météorologique canadien

Environment Canada
Canadian Meteorological Centre

Canada

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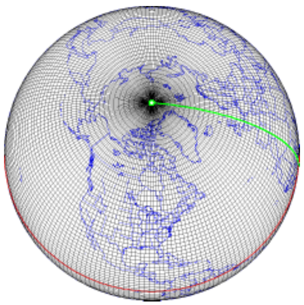
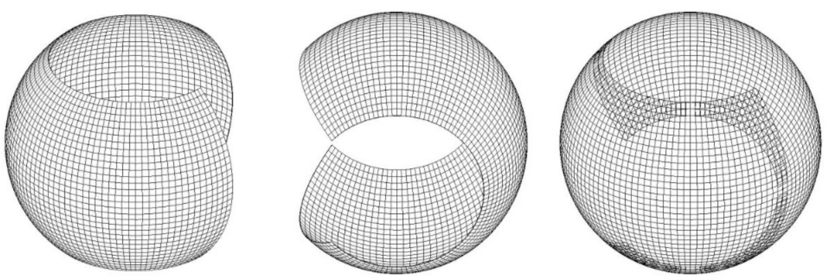
Outline

- Introduction and motivation
- Model problem and method
- Validation and Performance
- Ensemble-Variational assimilation
- Future Work



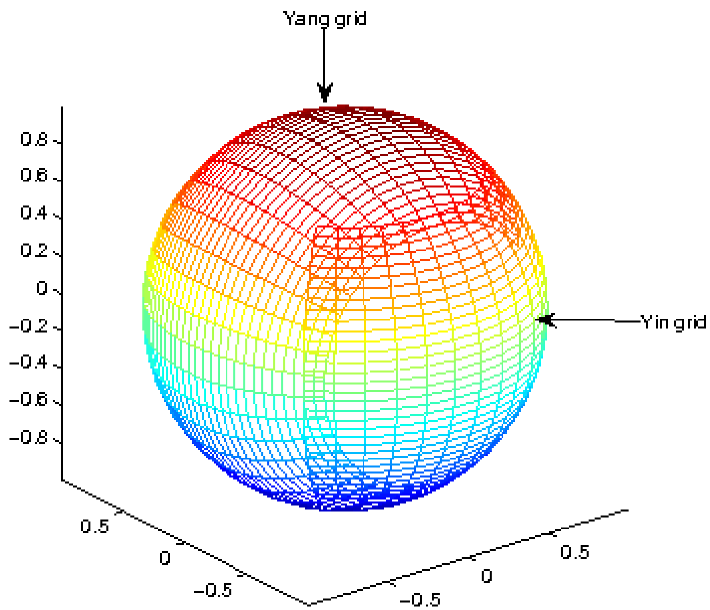
Global LatLon



Global Yin-Yang

Motivation

(Kageyama and Sato, Geochem. Geophys. Geosystems 2004)

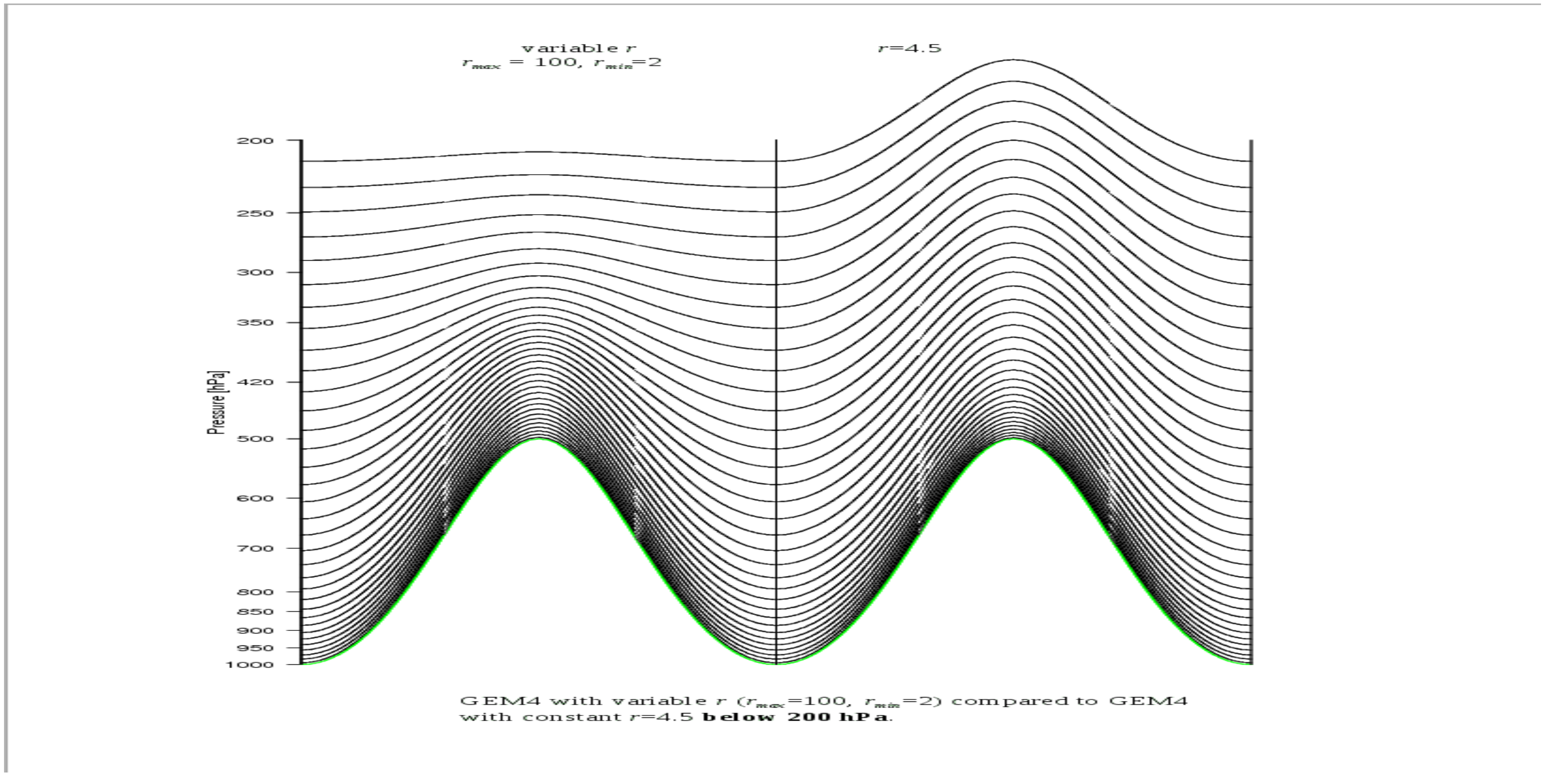


- Pole free composite grid
- Each piece is LatLon
- Numerical schemes on Lat/Lon adapted to Yin-Yang Schwarz method easily implemented (2 way-coupling of 2 LAM models)
- Algorithms for pole free grid is much easier to parallelize

Model problem

(Girard et al. 2010 CMC report)

- The hydrostatic primitives equations are in a log hydrostatic pressure terrain-following coordinate (lid 0.1mb)

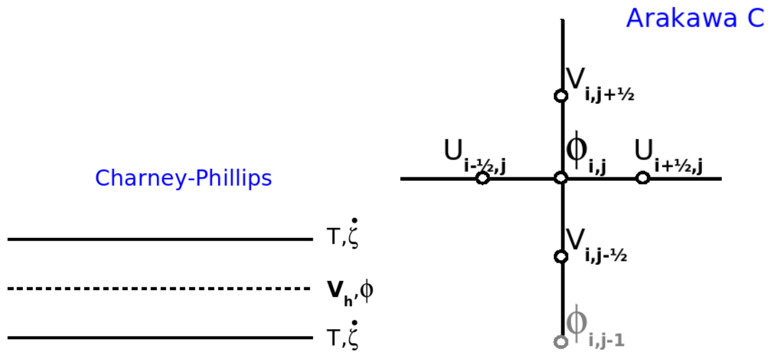


Below 200 hPa.Left : variable $r(r_{max} = 100, r_{min} = 2)$; Right : constant $r = 4.5$

Spatial discretization

(Girard et al. 2010 CMC report)

- Horizontal finite centred differences on Arakawa C grid
- Vertical finite differences on Charney-Phillips grid



Temporal discretization

(Côté and Staniforth 1988 Mon. Wea. Rev. ; Yeh at al. 2002 Mon. Wea. Rev.)

- The 2 time level semi-Lagrangian method with an implicit time discretization.

Boundary conditions

- Vertical : $\dot{\zeta} = 0 \quad at \quad \zeta = \zeta_{surf}, \zeta_{top}.$
- Horizontal : Dirichlet type

3D Elliptic Boundary value problem on Yin-Yang grid

(Qaddouri et al. 2008 Appl. Numer. Math. ; Qaddouri and Lee 2011 QJMRS)

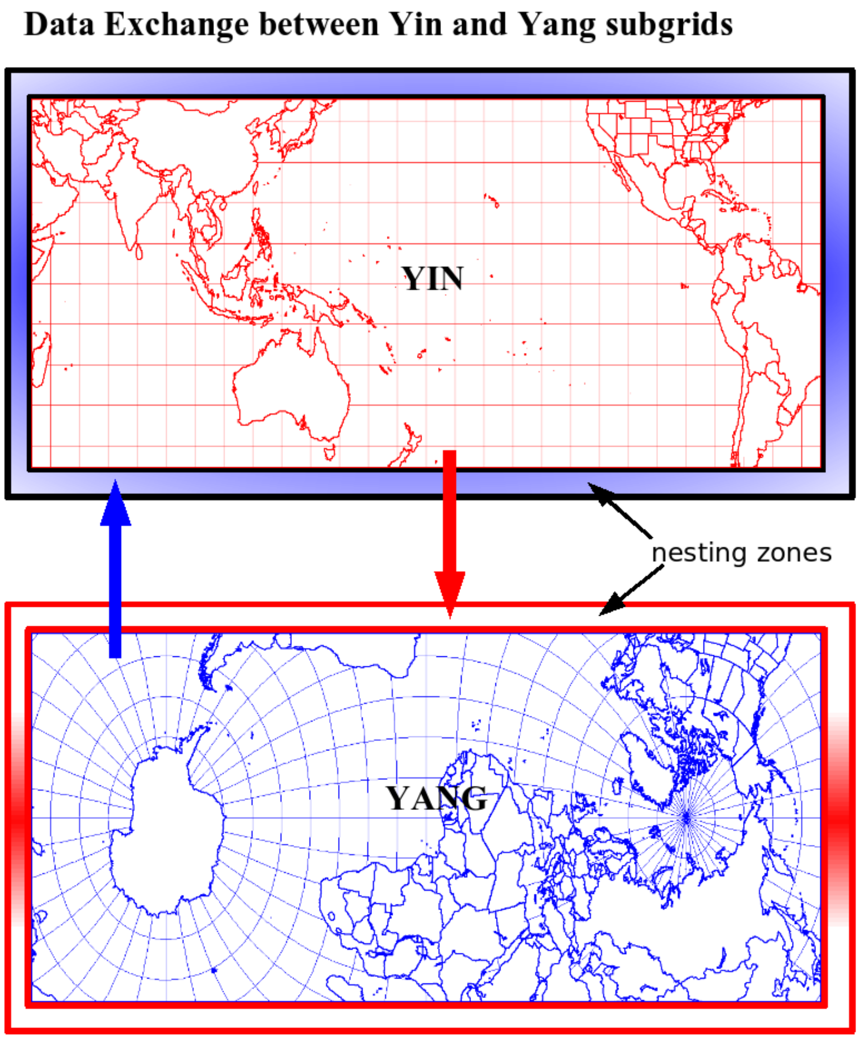
- The linear set of equations is reduced to the elliptic boundary value problem
- The Yin-Yang domain consists of 2 overlapping sub-domains

Solution with iterative Schwarz Method

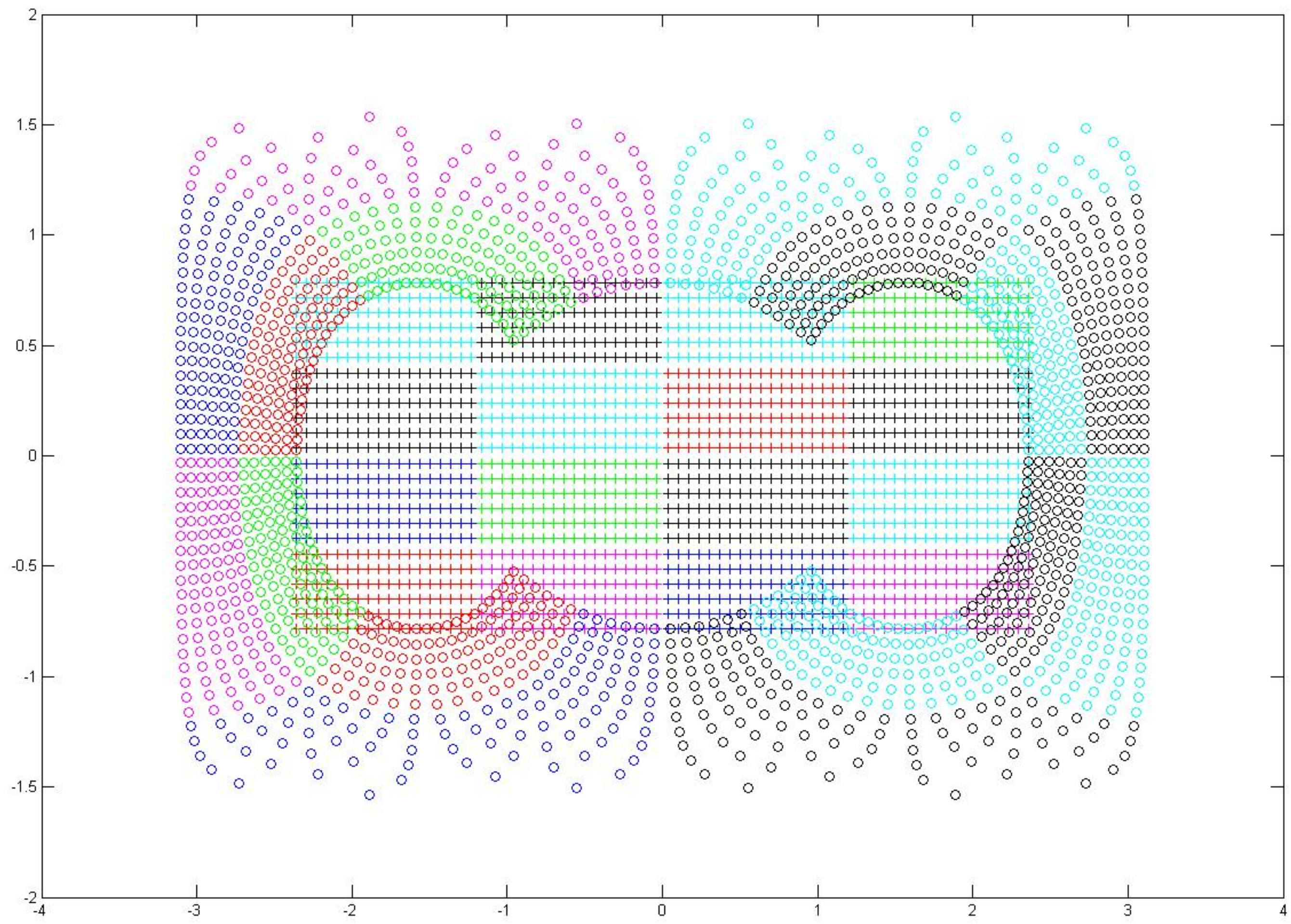
- To solve the global elliptic problem, we solve the sub-problems individually on each Yin and Yang domain and when needed, update the values at the interfaces
- This method is called the Schwarz Domain Decomposition Method
- The exchange of values at the interfaces is done by using Cubic Lagrange Interpolation

Parallel implementation

– Two-way coupling between 2 LAMs



Communication Pattern



Physical parametrizations in the GDPS

Physical Process	Description	Reference
Boundary layer turbulence	Turbulent kinetic energy (TKE) 1.5-order closure scheme	Belair et al. 1999, Bougeault and Lacarrere 1989
Orographic blocking	Low-level drag based on effective height, slope and eccentricity of subgrid-scale mountains	Zadra et al. 2003, Lott and Miller 1997
Orographic gravity wave drag	Upper-level drag due to breaking of mountain waves, based on the local Froude number	McFarlane 1987
Radiative transfer	Correlated k-distribution for gaseous transmission	Li and Barker 2005
Non-orographic gravity wave drag	Doppler-spread scheme with prescribed source spectrum	Hines 1997a,b
Methane oxidation	Simple estimate of stratospheric humidification due to methane oxidation	Charron et al. 2012
Grid-scale microphysics	Single prognostic variable for cloud water/ice	Sundqvist 1978, Pudykiewicz et al. 1992
Deep convection	Based on convective inhibition and release of convective available potential energy (CAPE)	Kain and Fritsch 1990, 1993
Shallow convection	Kuo-type closure (Kuo transient)	Belair et al. 2005
Land-surface interactions	Interactions between Surface, Biosphere and Atmosphere (ISBA) scheme, multilayer with 10 prognostic variables	Noilhan and Planton 1989, Belair et al. 2003a,b

Courtesy of Ayrton Zadra

Digital Filter and High-order diffusion

– Diabatic digital filter[1] with a 6 hour span.
– Scale selective implicit[2] or explicit [3] ∇^6 applied to variables(u,v,w,$\dot{\zeta}$)

1. Fillion, L., H. L. Mitchel, H. R. Ritchie and A. N. Staniforth, 1995 : The impact of a digital filter finalization technique in a global data assimilation system, *Tellus*, **47A**, 304-323.

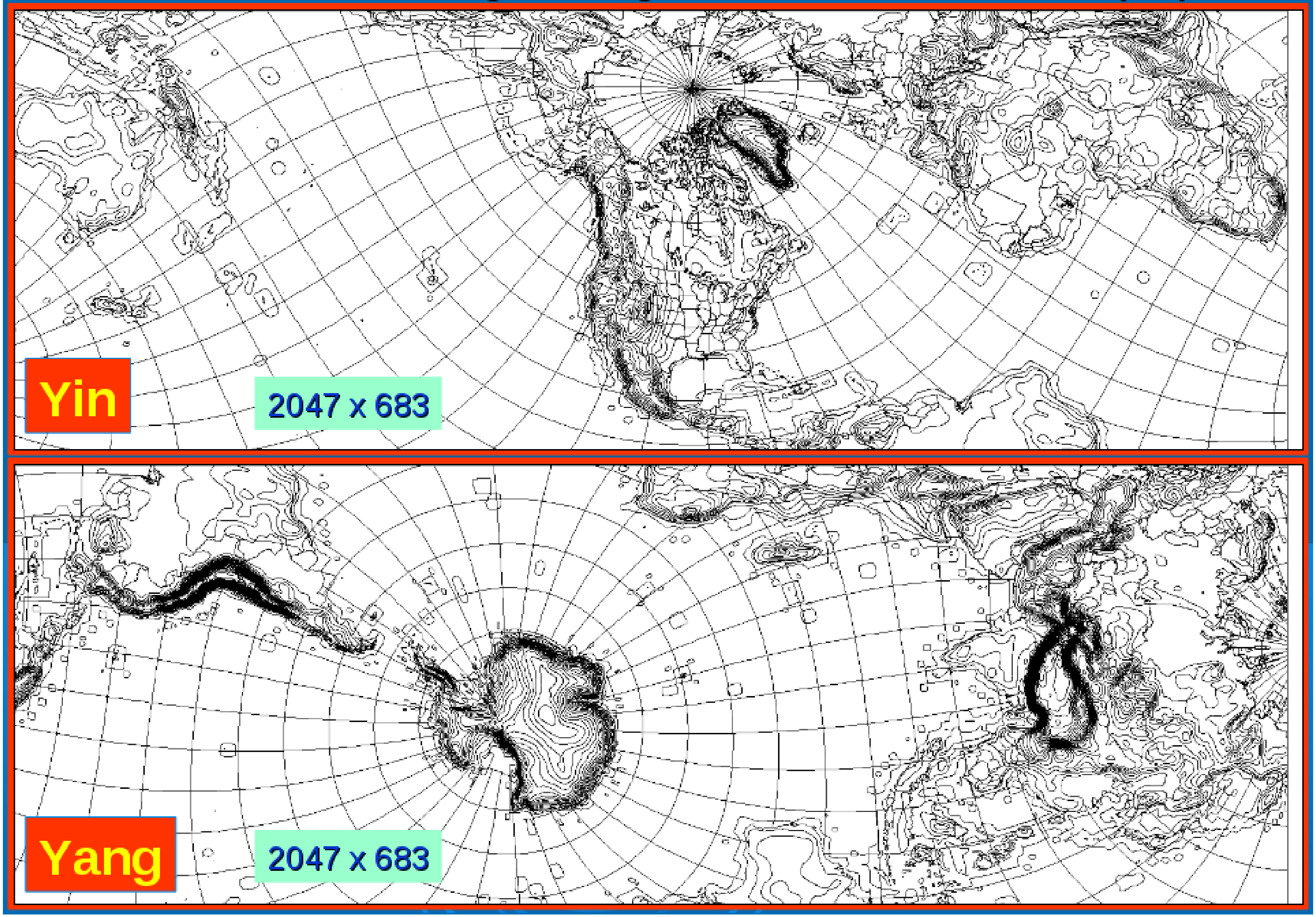
2. Qaddouri A.,and V.Lee 2008 : Solution of the implicit formulation of high order diffusion for the Canadian Atmospheric GEM model. Proc. 2008 Spring Simulation Multiconf., High Performance Computing Symp., J.A. Hamilton, Jr. et al. (eds), Soc. For Modeling and Simulation Internat., Ottawa, Canada, 2008, pp 362-367

3. Shuman, M.W.R. #57, p.357-361, eq #5. : 9-point filter

Geophysical fields

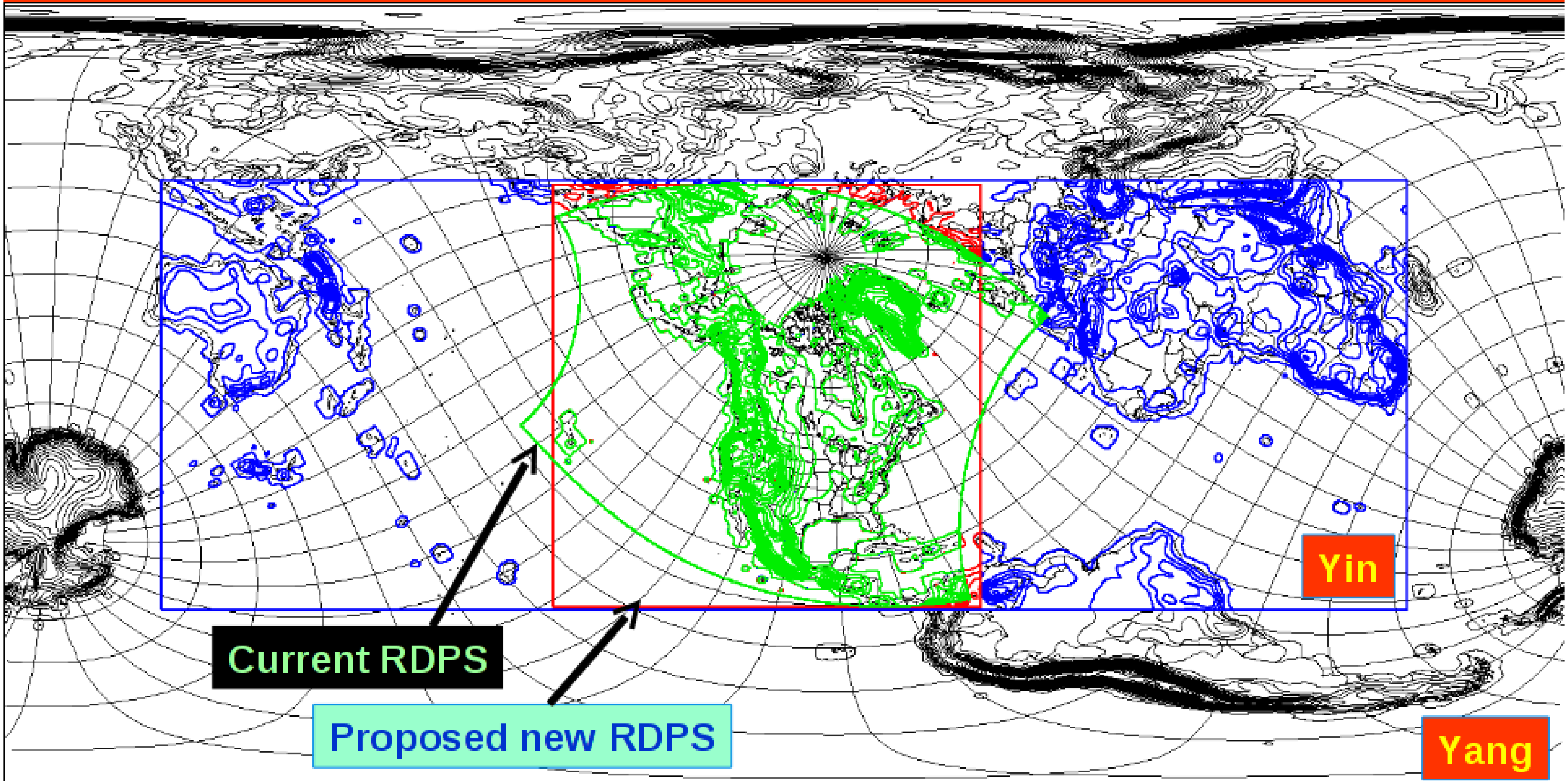
– are independently calculated on the Yin and Yang grids.

15 km Yin-Yang configuration: 2047 x 683 (x2)



Topography field *(Courtesy of Michel Desgagné)*

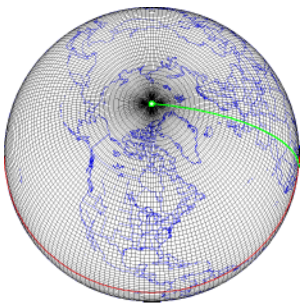
15 km Yin-Yang configuration
2047 x 683 (x2)



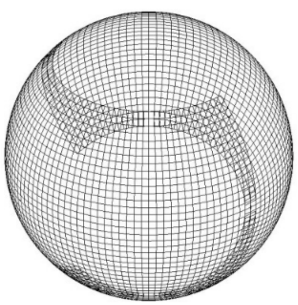
Courtesy of Michel Desgagné

Validation and Performance

- Objective evaluation of 5 days forecasts against observations.
- Verification is done for a set of 42 winter and 42 summer integrations initialized with analysis of 2008.
- Two configurations with the same model :

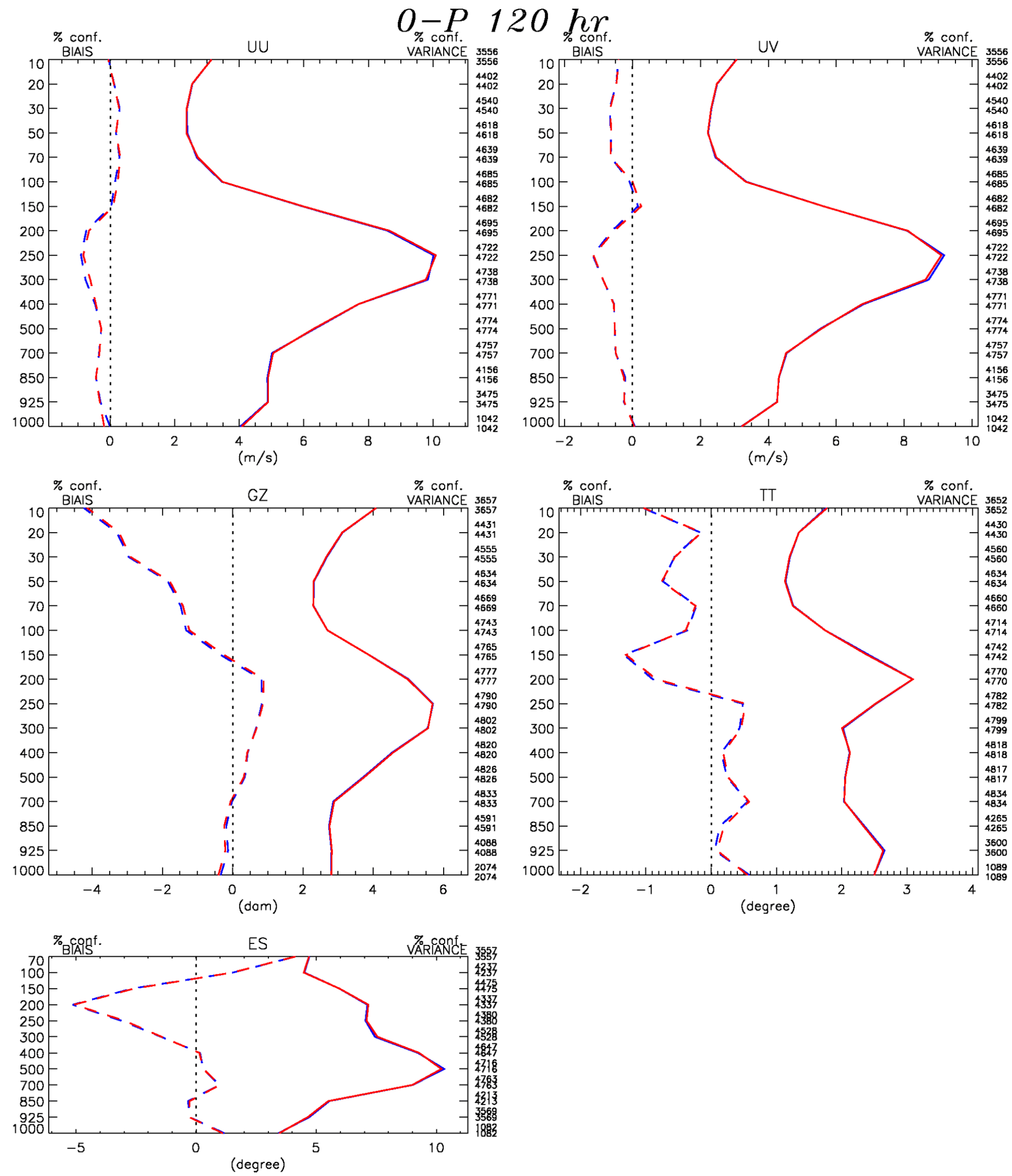


Global LatLon $(1728 \times 1335 \times 80)$ ($\sim 15km$ at 49^o north)



Global Yin-Yang $2{\times}(2047 \times 683 \times 80)$ ($\sim 15km$ at equator)

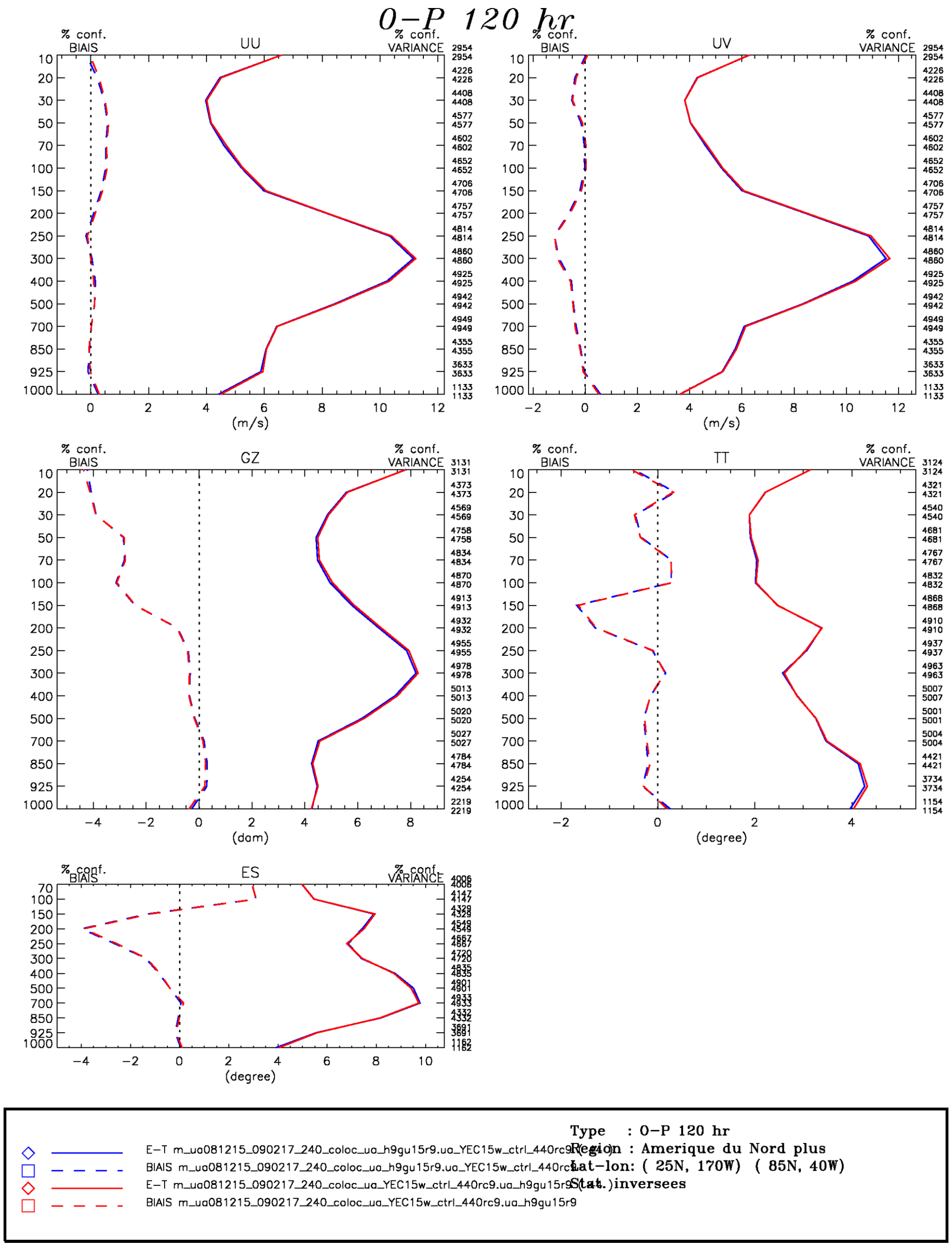
North America objective evaluation for 44 summer cases (120hr forecasts).



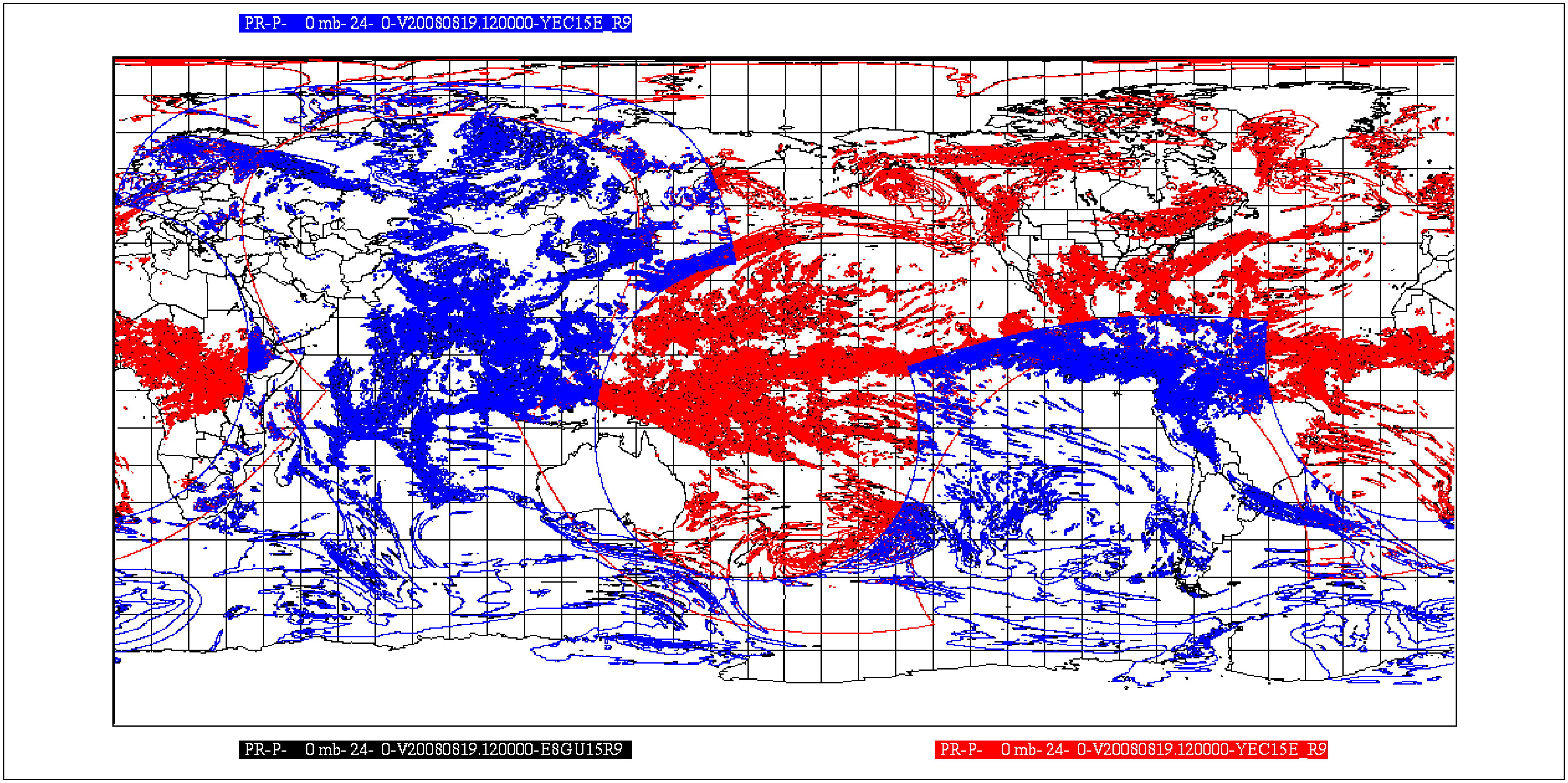
E−T m_ua080618_080821_240_coloc_ua_e8gu15r9.ua_YEC15e_ctrl_440rc9.ua_YEC15e_ctrl_440rc9
BIAIS m_ua080618_080821_240_coloc_ua_e8gu15r9.ua_YEC15e_ctrl_440rc9.ua_YEC15e_ctrl_440rc9
E−T m_ua080618_080821_240_coloc_ua_YEC15e_ctrl_440rc9.ua_e8gu15r9.ua_e8gu15r9
BIAIS m_ua080618_080821_240_coloc_ua_YEC15e_ctrl_440rc9.ua_e8gu15r9

Type : 0−P 120 hr
Region : Amerique du Nord plus
Lat−lon: (25N, 170W) (85N, 40W)
(Stat.) inversees

North America objective evaluation for 44 winter cases (120hr forecasts).

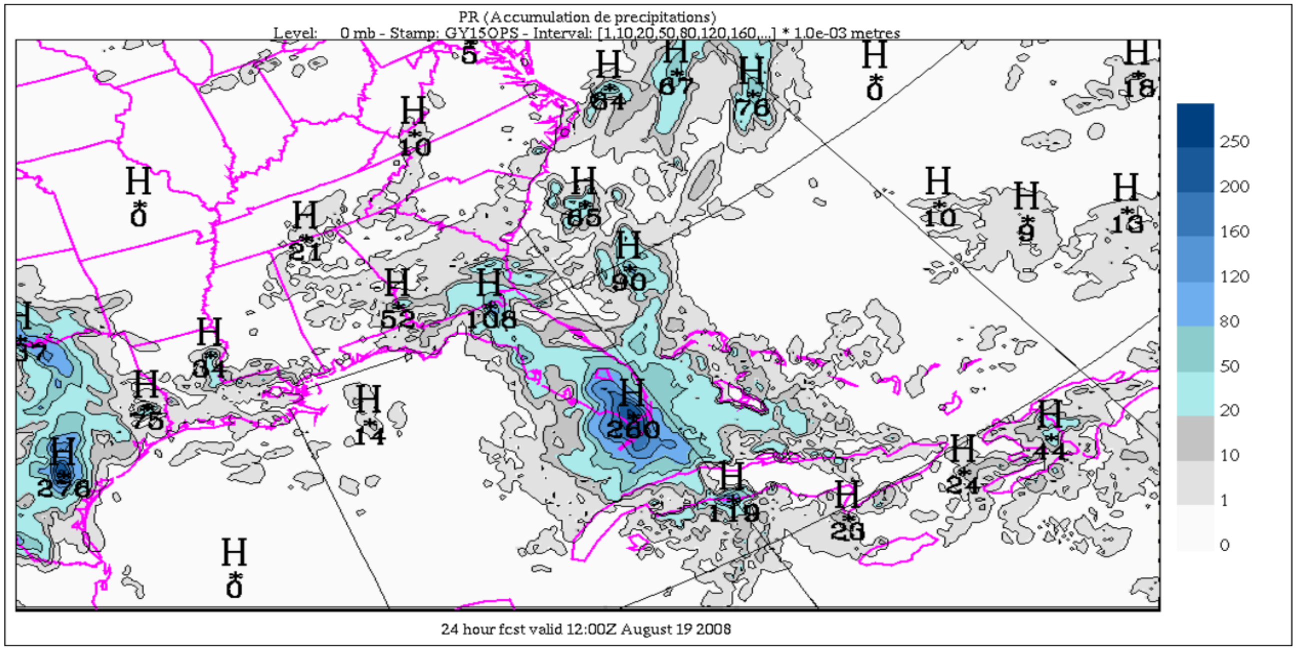


24 hour accumulated precipitation forecast

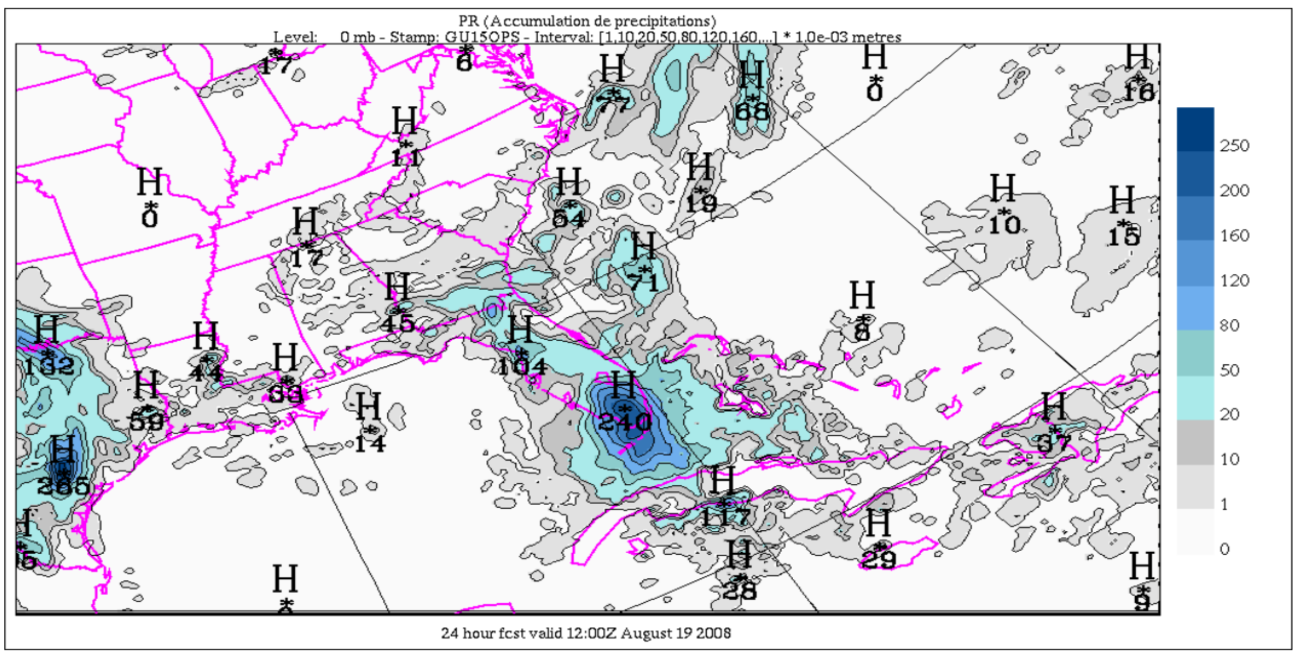


YIN and **YANG** precipitation field superimposed on the *precipitation* from the Global **LATLON** Grid

Hurricane Fay, Aug.19, 12Z, 2008: 24 hour accumulated precipitation forecast



Precipitation field from the GEM **Yin-Yang**



Precipitation field from the GEM **LATLON**

Timings(seconds) on IBM-P7 for 505(480+25) time steps (approx 26% of operational run) (10 day forecast = 1945(1920+25) time steps)[1]

	GEM LATLON (1728x1335x80L)	GEM Yin-Yang 2 x (2047x683x80L)
	184550400 pts	223696160 pts
PE topology Npx$X$Npy$X$OpenMP	(4x44x16)(44 nodes)	2x(20x30x2) (38 nodes)
Total time	1332	1398
DYNSTEP	623	768
ADW	434	287
SOL	111	233
BAC	13	85
PHYSTEP	355	451
HORDIFF ∇^6	131 (implicit)	27 (explicit)
VSPNG ∇^2	38 (implicit)	8 (explicit)
OUTDYN	123	85
OUTPHY	15	5
NESTBCS	N/A	50

1 - model timestep = 450sec

GEM Yin-Yang Timings(seconds) on IBM-P7 for 505(480+25) time steps

Number of Nodes	38	75	72
PE topology Npx$X$Npy$X$OpenMP	2 x (20x30x2)	2 x (20x30x4)	2 x (38x30x2)
TOTAL	1398	1082	1849
DYNSTEP	768	600	1353
ADW	287	205	188
SOL	233 (FFT)	199 (FFT)	1018 (Iterative)[1]
BAC	85	68	59
PHYSTEP	451	254	68
HORDIFF ∇^6	27	26	28
VSPNG ∇^2	8	6	6
OUTDYN	85	106	111
OUTPHY	5	17	17
NESTBCS	50	50	35

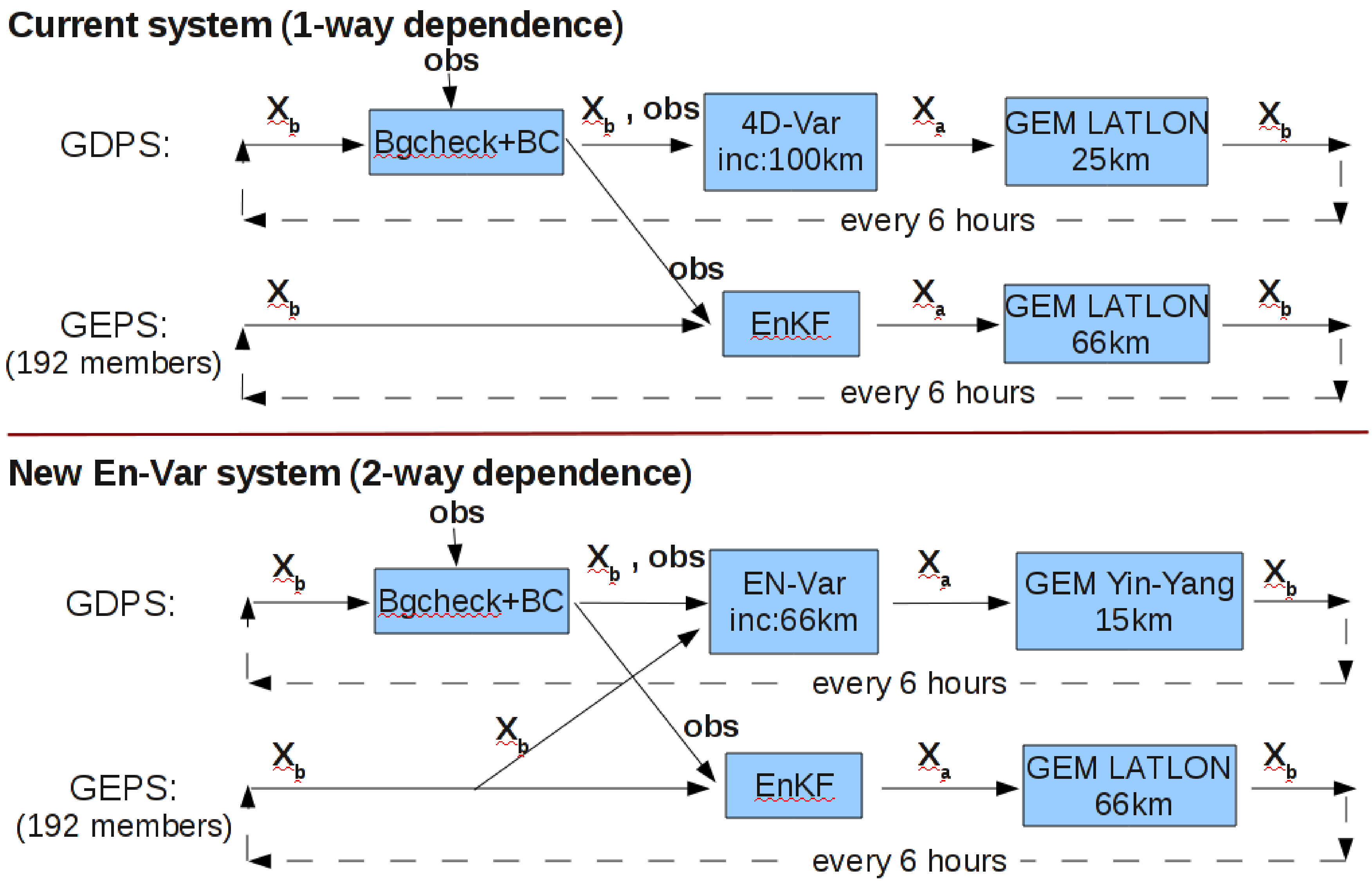
1 : FGMRES with Block-Jacobi preconditioner

Ensemble-Variational assimilation : En-Var

Buehner et al. 2010 Mon. Wea. Rev.

- Introduction
  - En-Var approach is being tested to replace 4D-Var
  - It is a hybrid approach using variational assimilation with EnKF 4D ensemble covariances
  - By making use of the 4D ensembles, En-Var performs a 4D analysis without 4D-Var
  - It is more computationally efficient ($10\% - 20\%$ of the computational resources), easier to maintain/adapt than 4D-Var

- Summary of Preliminary Results :
  - Produces similar quality forecasts as 4D-Var below 20hPa in the extra-tropics and, significant improvements in the tropics
  - for above 20hPa, scores are similar to 3D-Var but worse than 4D-Var (can probably improve this by raising the EnKF model top from 2hPa to 0.1hPa)



GDPS: Global Deterministic Prediction System
GEPS: Global Ensembles Prediction System
inc: Analysis Increment

Bgcheck: Background check
BC: Bias Correction

Courtesy of Mark Buehner

Future Work

- Global 15km Yin-Yang produces **450G** of output for an operational 10 day forecast
- Native output is on 2 grids, 2 files
- Optimize model to run in one hour

Thank you

Acknowledgements to : Mark Buehner, Michel Desgagné, Claude Girard, Michel Roch, Ayrton Zadra

Supplementary Slides

Model problem

(Girard et al. 2010 CMC report)

– The hydrostatic primitives equations (HPEs) in log-p coordinate

$$\frac{d\mathbf{V}_h}{dt} + f\mathbf{k}\times\mathbf{V_h} + RT\nabla_\zeta Bs + \nabla_\zeta \phi' = \mathbf{F^H}, \tag{1}$$

$$\frac{d}{dt}\ln\left(\frac{T}{T^*}\right) - \kappa\left[\frac{d}{dt}(Bs) + \dot{\zeta}\right] = F^T, \tag{2}$$

$$\frac{d}{dt}\left[Bs + \ln\left(1 + \frac{\partial B}{\partial\zeta}s\right)\right] + \nabla_\zeta\cdot\mathbf{V}_h + \frac{\partial\dot{\zeta}}{\partial\zeta} + \dot{\zeta} = 0, \tag{3}$$

$$\frac{T}{T^*} - \frac{\partial\left(\zeta - \phi'/RT^*\right)}{\partial(\zeta + Bs)} = 0, \tag{4}$$

– Some Operators and Fields

$$\frac{d}{dt} = \frac{\partial}{\partial t} + \frac{1}{\cos^2\theta}\left(U\frac{\partial}{\partial\lambda} + V\cos\theta\frac{\partial}{\partial\theta}\right) + \dot{\zeta}\frac{\partial}{\partial\zeta},$$

$$\nabla_\zeta\cdot\mathbf{V}_h = \frac{1}{\cos^2\theta}\left(\frac{\partial U}{\partial\lambda} + \cos\theta\frac{\partial V}{\partial\theta}\right),$$

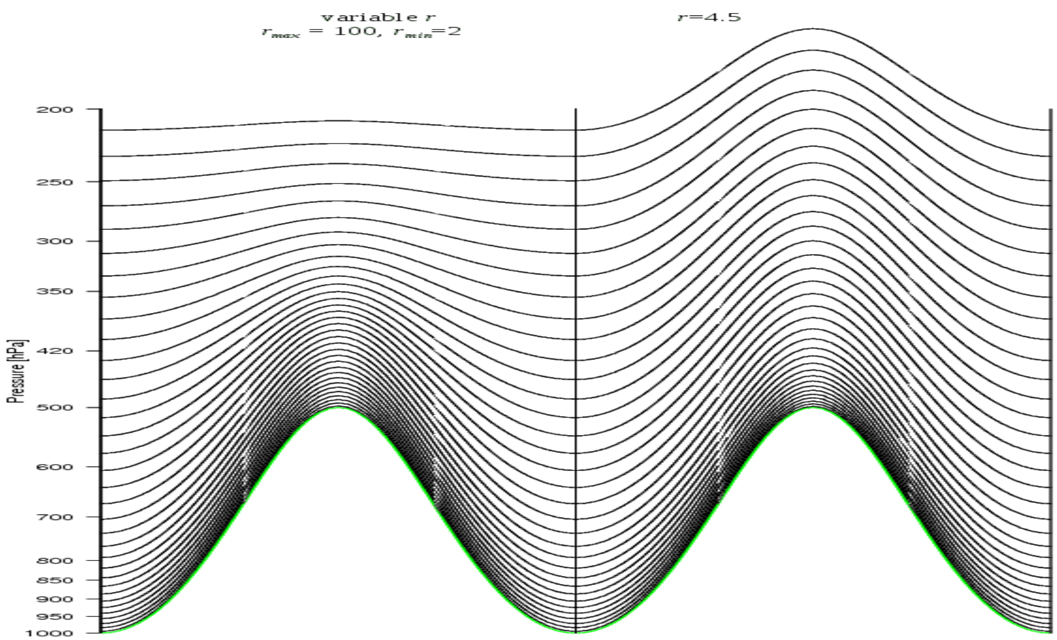
$$U = \frac{u\cos\theta}{a}, V = \frac{v\cos\theta}{a},$$

$$\nabla_\zeta = \frac{a}{\cos\theta}\left(\frac{1}{a^2}\frac{\partial}{\partial\lambda}, \frac{\cos\theta}{a^2}\frac{\partial}{\partial\theta}\right),$$

Vertical coordinate $\zeta = \ln p - Bs\,;\, B = \Lambda^r\,;\, s = \ln(p_{surf}/10^5)$

$\Lambda = \left((\zeta - \zeta_{top})/(\zeta_{surf} - \zeta_{top})\right)$;$0 \leq r = r_{max} - (r_{max} - r_{min})\,\Lambda \leq 30$

– log hydrostatic pressure hybrid terrain-following vert. coord. (lid 0.1mb)



GEM4 with variable r (r_{max}=100, r_{min}=2) compared to GEM4 with constant r=4.5 **below 200 hPa**.

Below 200 hPa.Left : variable $r(r_{max} = 100, r_{min} = 2)$; Right : constant $r = 4.5$

Solution with iterative Schwarz Method

- Domain $=$ 2 overlapping sub-domains (YIN/YANG)
- Solve HPEs equations iteratively on Sub-domains
  exchange variables at interfaces : Cubic Lagrange interpolation
- On each sub-domain : same local solver with the same time step

1. The 2 time level semi-Lagrangian method with an implicit time discretization.
2. Finite differences on horizontal Arakawa-C grid and on vertical Charney-Phillips grid

Spatial discretization

(Girard et al. 2010 CMC report)

– Vertical finite differences on Charney-Phillips grid

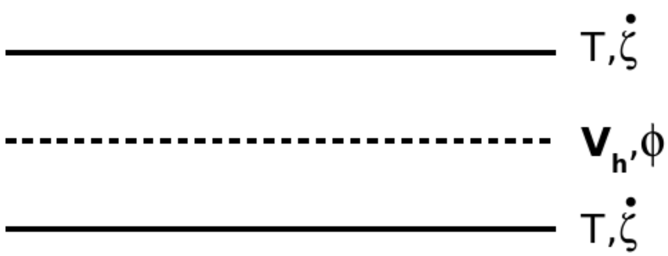
$$\frac{d\mathbf{V}_h}{dt} + f\mathbf{k}\times\mathbf{V_h} + R\overline{T}^{\zeta}\nabla_{\zeta}Bs + \nabla_{\zeta}\phi' = 0, \qquad (5)$$

$$\frac{d}{dt}\ln\left(\frac{T}{T^*}\right) - \kappa\left[\frac{d}{dt}\left(\overline{B}^{\zeta}s\right) + \dot{\zeta}\right] = 0, \qquad (6)$$

$$\frac{d}{dt}\left[Bs + \ln\left(1 + \delta_{\zeta}\overline{B}^{\zeta}s\right)\right] + \nabla_{\zeta}\cdot\mathbf{V}_h + \delta_{\zeta}\dot{\zeta} + \overline{\dot{\zeta}}^{\zeta} = 0, \qquad (7)$$

$$\frac{T}{T^*} + \left[\frac{\delta_{\zeta}\left(\zeta - \phi'/RT^*\right)}{\delta_{\zeta}\left(\zeta + Bs\right)}\right] = 0, \qquad (8)$$

Charney-Phillips

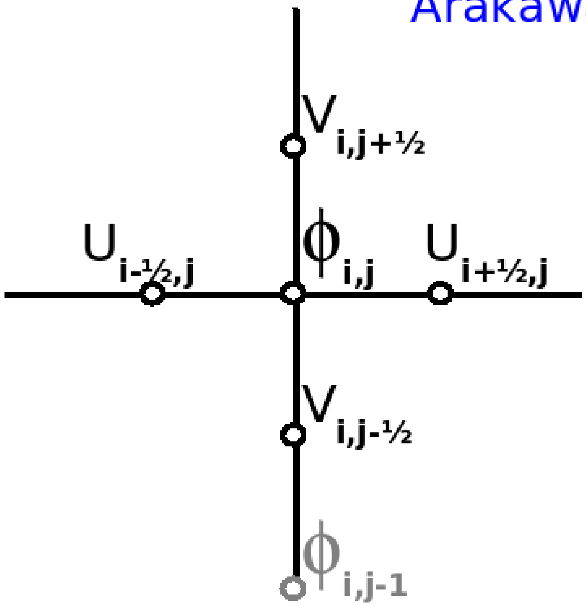


– Finite differences on Arakawa C grid

$$\frac{dU}{dt} - f\overline{V}^{\theta,\lambda} + R\overline{T}^{\zeta,\lambda}\frac{1}{a^2}\frac{\partial}{\partial\lambda}Bs + \frac{1}{a^2}\frac{\partial}{\partial\lambda}\phi' = 0$$

$$\frac{dV}{dt} + f\overline{U}^{\lambda,\theta} + R\overline{T}^{\zeta,\theta}\frac{\cos\theta}{a^2}\frac{\partial}{\partial\theta}Bs + \frac{\cos\theta}{a^2}\frac{\partial}{\partial\theta}\phi' = 0$$

Arakawa C



Temporal discretization

(Côté and Staniforth 1988 Mon. Wea. Rev. ; Yeh at al. 2002 Mon. Wea. Rev.)

– On each subdomain for each prognostic variable F

$$\frac{dF}{dt} + G = 0 \tag{9}$$

– Time discretization and weighted G terms along trajectory

$$\frac{F - F^{-}}{\Delta t} + \left[(\frac{1}{2} + \epsilon)G + (\frac{1}{2} - \epsilon)G^{-} \right] = 0. \tag{10}$$

– Approximate solution for a trajectory calculation

$$\begin{aligned} \frac{d\mathbf{r}}{dt} &= \mathbf{V_h}(\mathbf{r}, \zeta, \mathbf{t}) \qquad & \frac{d^2\mathbf{r}}{dt^2} &= -\mathbf{r}\frac{\mathbf{V_h^2}}{\mathbf{a^2}} \\ \frac{d\zeta}{dt} &= \dot{\zeta}(\mathbf{r}, \zeta, \mathbf{t}) \qquad & \frac{d^2\zeta}{dt^2} &= 0, \end{aligned} \tag{11}$$

Boundary conditions

– vertical :

$$\dot{\zeta} = 0 \quad \textit{at} \quad \zeta = \zeta_{surf}, \zeta_{top}. \tag{12}$$

– Horizontal : Dirichlet type

3D Elliptic boundary value problem on Yin-Yang grid

(Qaddouri et al. 2008 Appl. Numer. Math. ; Qaddouri and Lee 2011 QJMRS)

– Linear set of equations is reduced to EBVP

$$\triangle_\zeta P + \frac{\gamma}{\kappa\tau^2 RT^*}(\delta_\zeta^2 + \overline{\delta_\zeta}^\zeta)P = AP = R_E, \tag{13}$$

where $P = \phi' + RT^* Bs$

– with the following top and bottom boundary conditions :

$$\delta_\zeta P_{top} = C_{top}, \;\; (\delta_\zeta P_{bot} + \kappa \overline{P}^\zeta_{bot}) = C_{bot}.$$

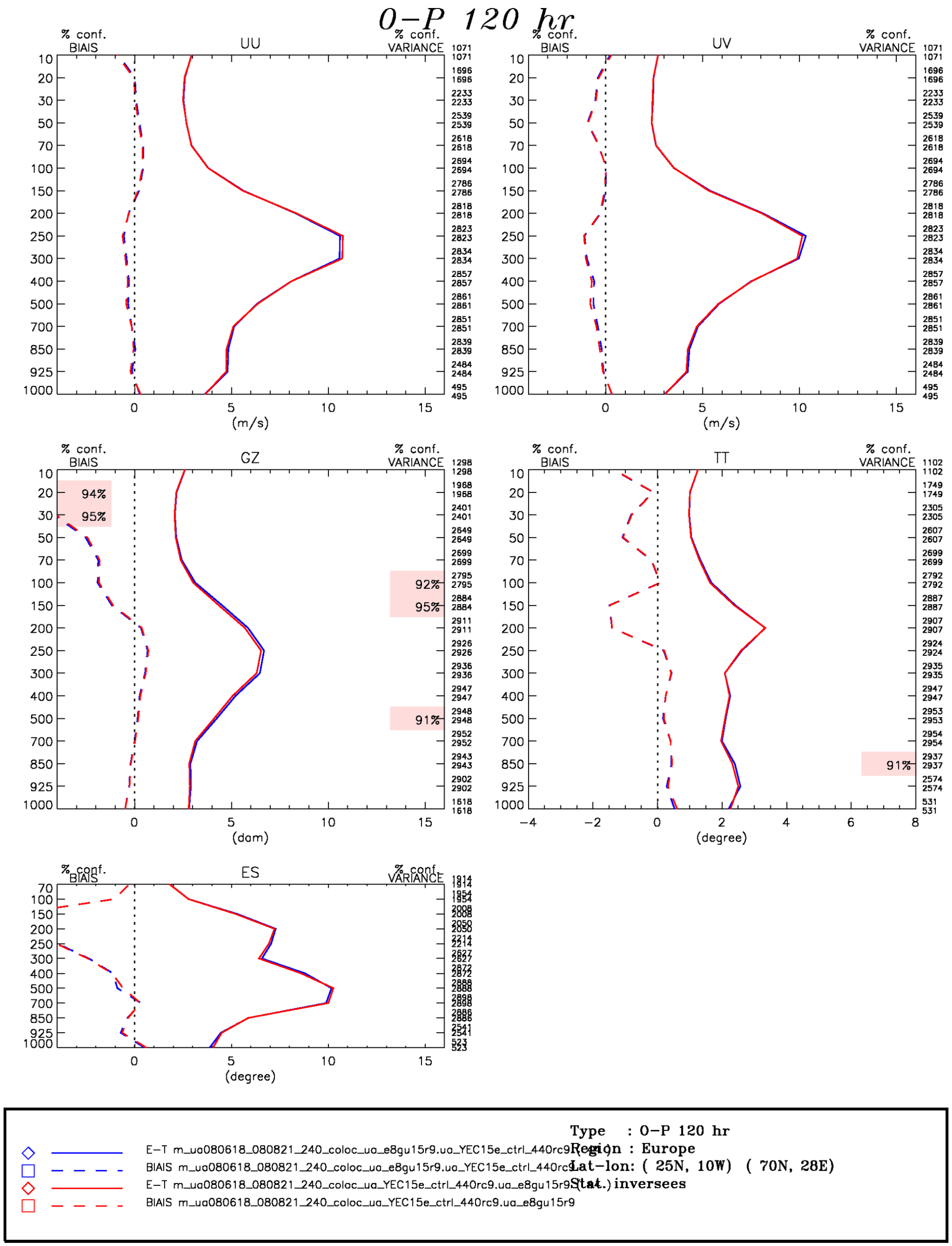
– R_E is the right-hand side , C_{top} and C_{bot} are constants and

$$a^2\triangle_\zeta = \frac{1}{\cos^2\theta}\frac{\partial^2}{\partial\lambda^2} + \frac{1}{\partial\sin\theta}\cos^2\theta\frac{\partial}{\partial\sin\theta}. \tag{14}$$

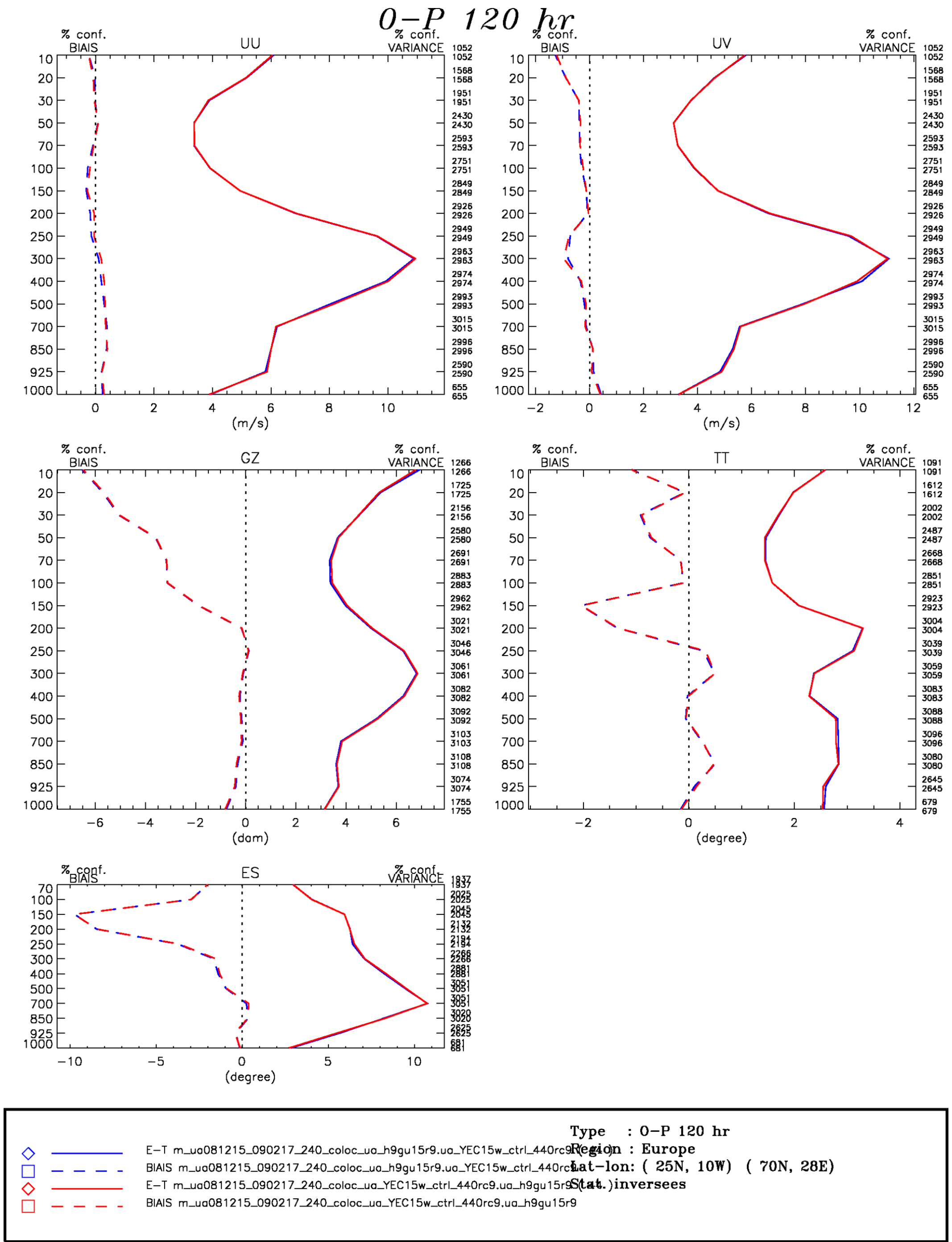
– Iterative solution

$$\begin{aligned} AP^{(1),k} &= R_E^{(1)} \quad \text{on } \Omega_1, & AP^{(2),k} &= R_E^{(2)} \quad \text{on } \Omega_2, \\ B_1^{(1)}P^{(1),k} &= B_1^{(1)}P^{(2),k-1}, \quad \text{on } \delta\Omega_1, & B_1^{(2)}P^{(2),k} &= B_1^{(2)}P^{(1),k-1}, \quad \text{on } \delta\Omega_2 \end{aligned}$$

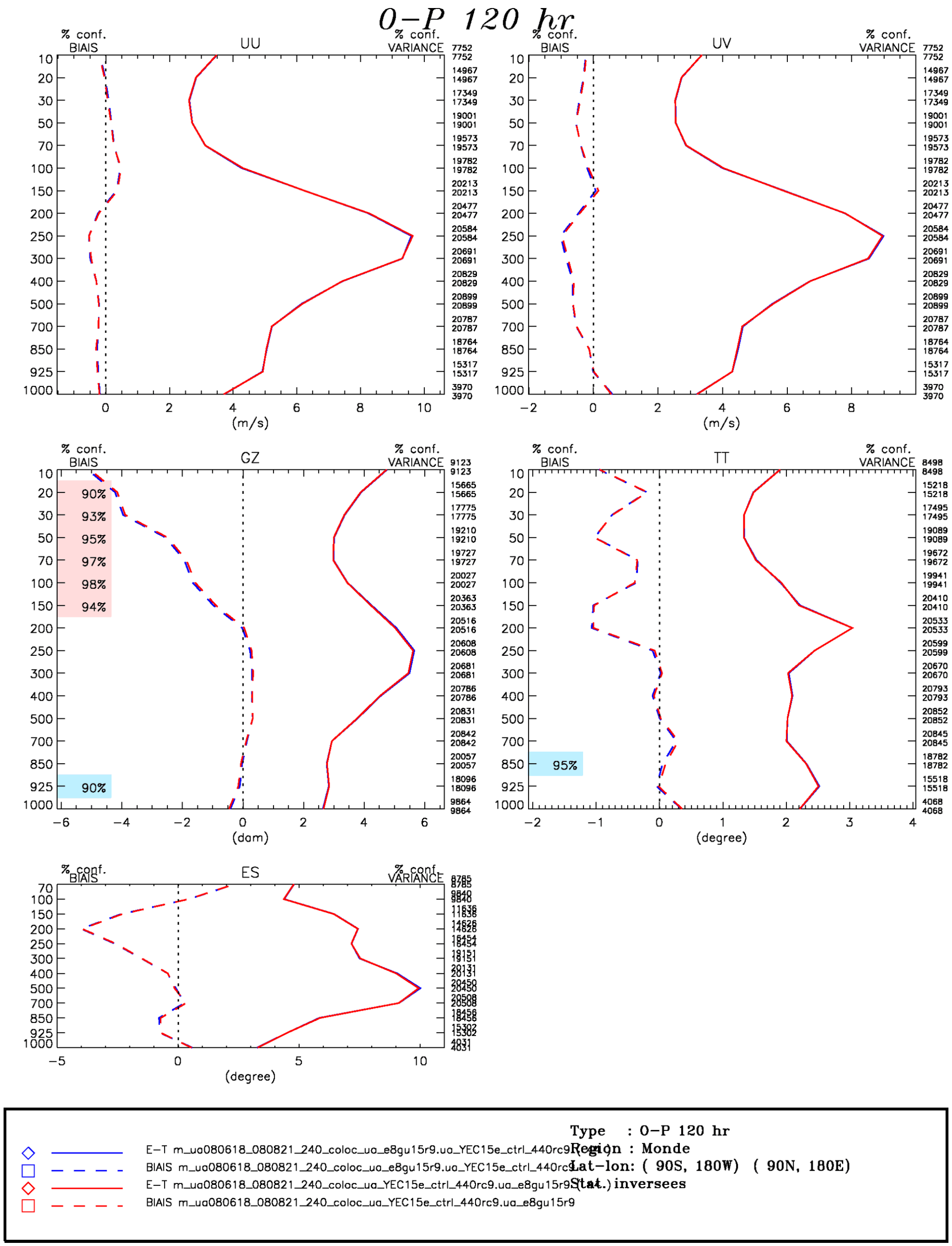
– Europe objective evaluation for 44 summer cases (120hr forecasts).



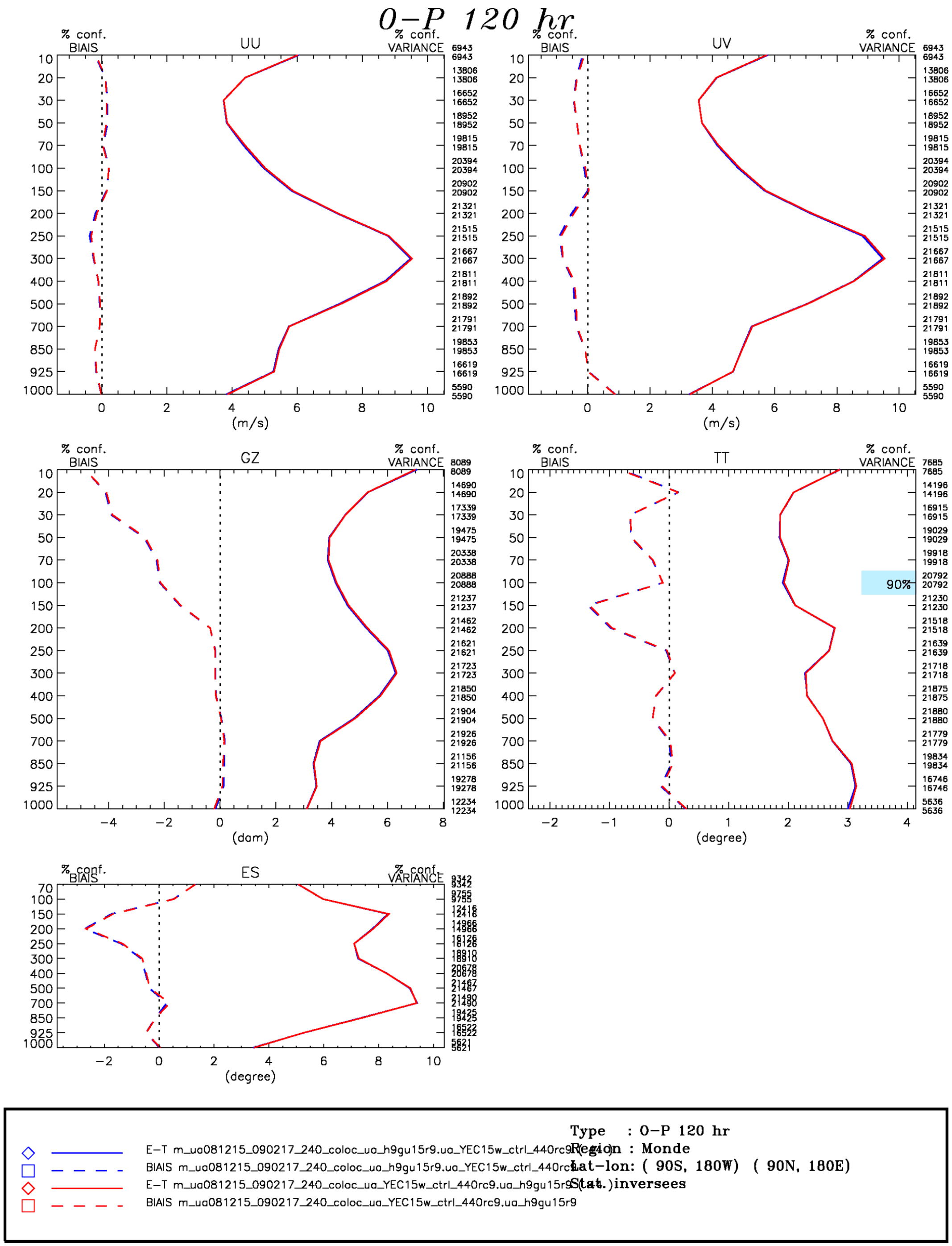
– Europe objective evaluation for 44 winter cases (120hr forecasts).



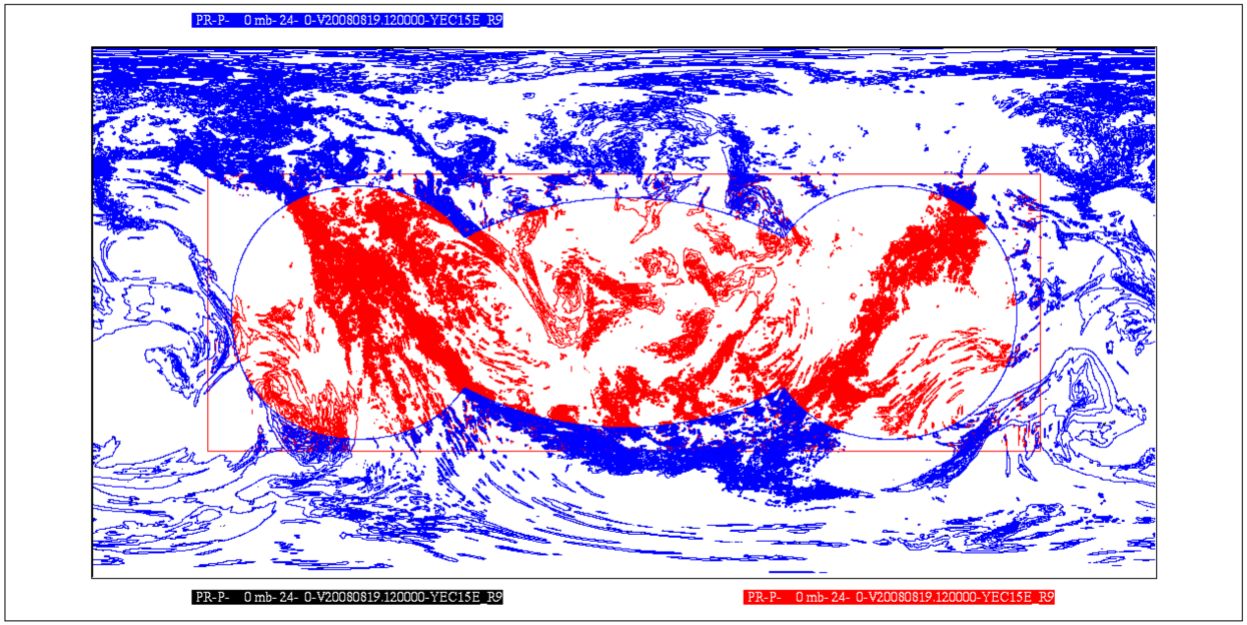
– World objective evaluation for 44 summer cases (120hr forecasts).



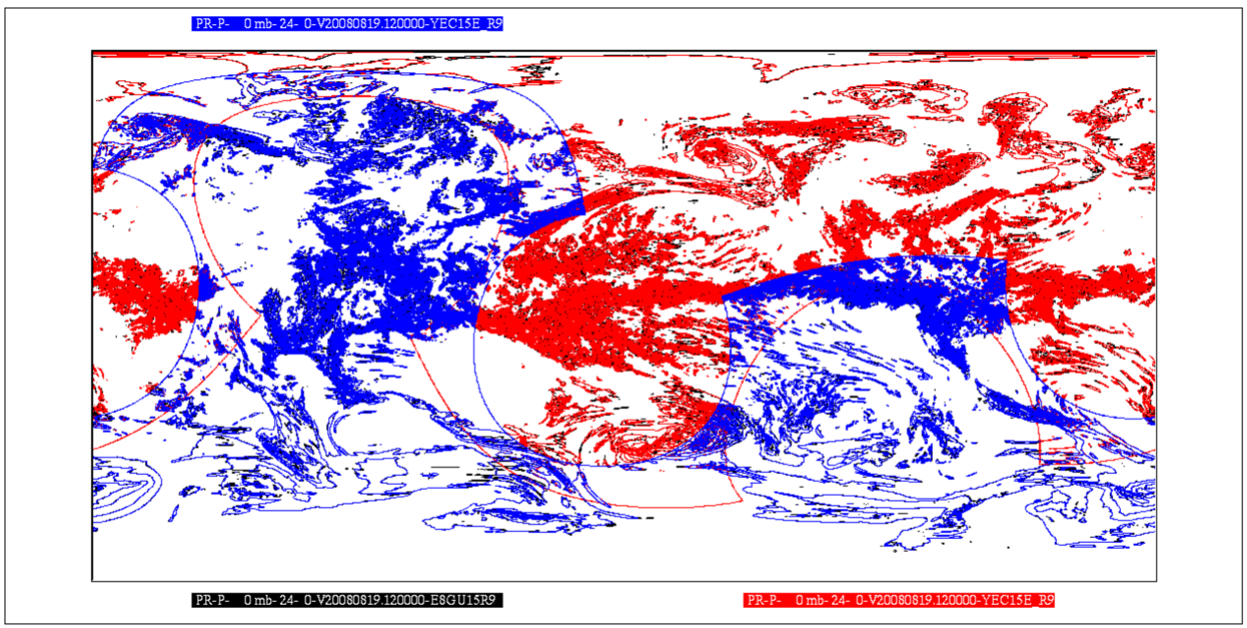
– World objective evaluation for 44 winter cases (120 hr forecasts).



24 hour precipitation forecast without geographical outline



Yin and Yang
precipitation field
superimposed
on the
Global **Yin-Yang** Grid



Yin and Yang
precipitation field
superimposed
on the *precipitation*
from the
Global **LATLON** Grid