Dynamics developments in HIRLAM

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P.L. on dynamics in HIRLAM-B

Overview

- Vertical finite elements fulfilling the C1 constraint
- Upper nesting boundary conditions
- Quadratic and cubic grids
- Weak constraint boundary conditions
- “Slow start” of the forecast
- Future plans
  - Higher horizontal and vertical resolutions
  - Transversal issues with physics, chemistry and climate

Vertical finite elements

- The purpose of the present work is to provide a new vertical finite element technique making use of analytical properties of B-splines
- This allows to solve the following limitations
  - C1 Constraint
  - Invertibility of the integral and derivative operators

From Alvaro Subias

Vertical SI derivative and integral operators

- We develop matrices RVFEG, RVFES, RVFEN to be used inside sigam.F90, sitnu.F90 and their associated subroutines in non linear model

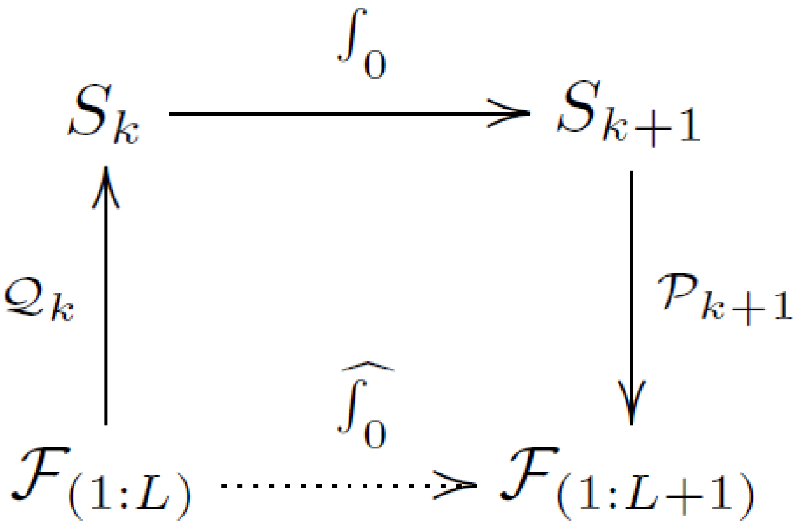
Derivatives and integrals of B-splines:

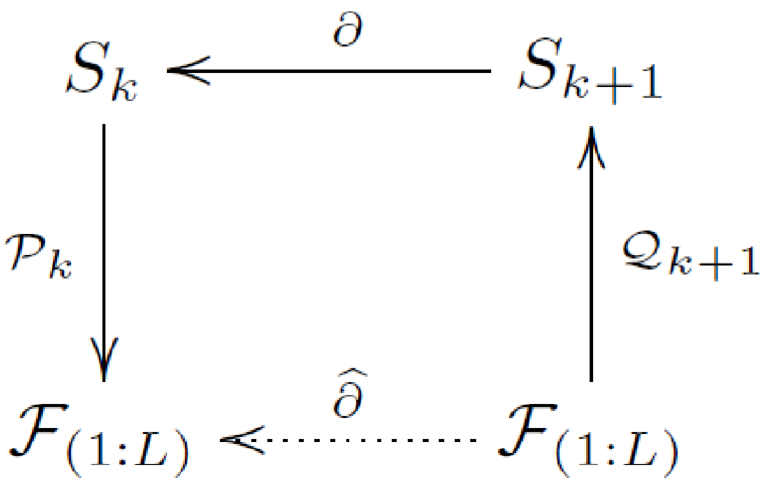
$$\frac{\partial}{\partial \eta} N_{i,k} = (k-1)\left[\frac{N_{i,k-1}}{\Delta_{i,k-1}} - \frac{N_{i+1,k-1}}{\Delta_{i+1,k-1}}\right]$$

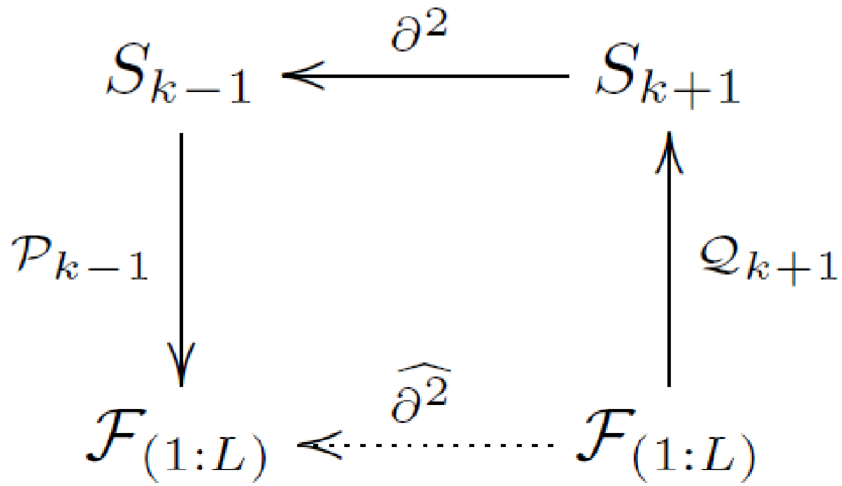
$$\int_0^{\eta} N_{i,k}\, d\eta = \frac{\Delta_{i,k}}{k} \sum_{s \geq i} N_{s,k+1} \qquad (\Delta_{i,k} = \eta_{i+k} - \eta_i)$$

i: node number; k: order of spline

Use of the projection operators







C1 constraint

It is the constraint which allows to arrive at a single Helmholtz equation in the non-hydrostatic Aladin model

G*S*-G*-S*+N*=0 => (G*-1)(S*-1)=(1-N*)

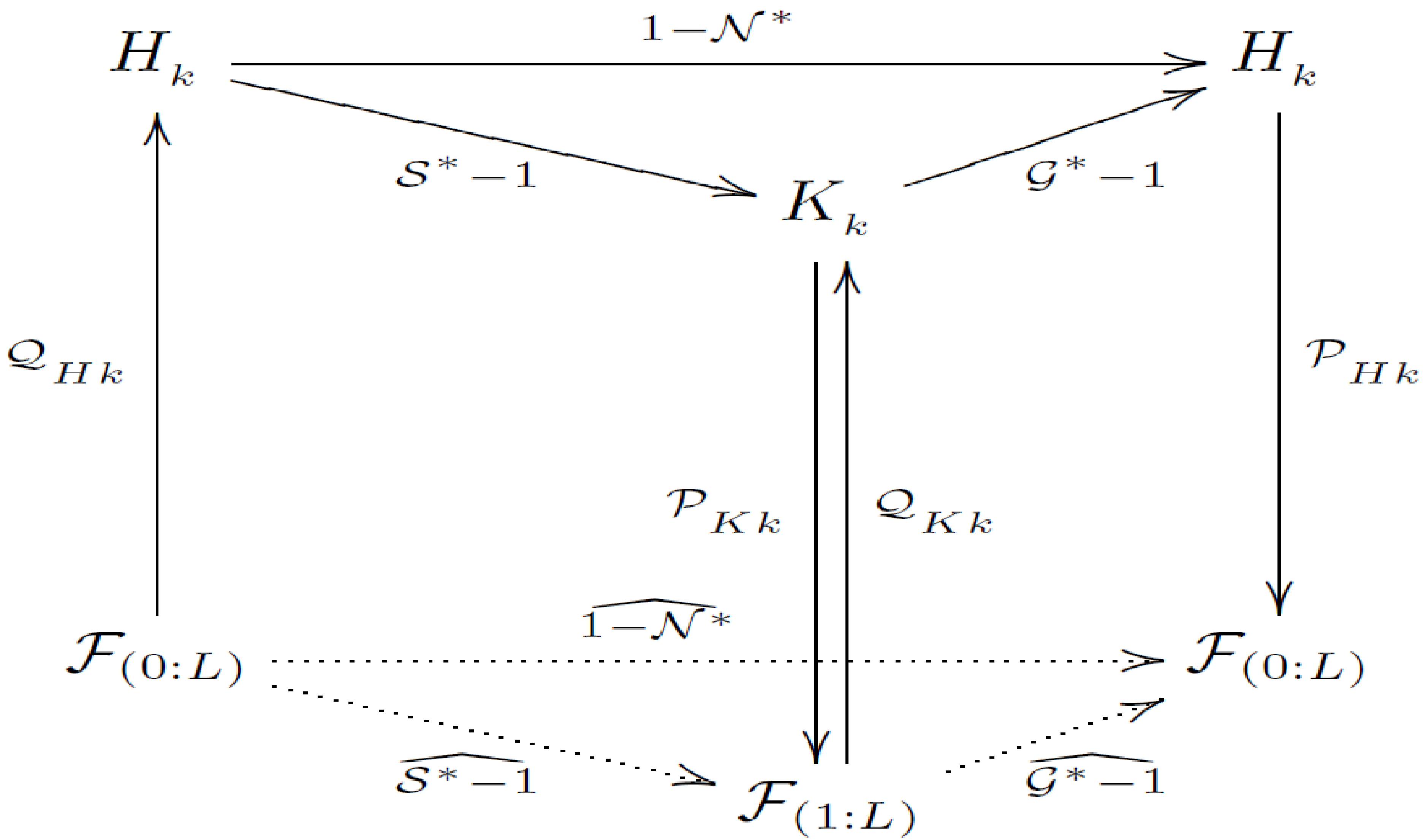
where

$$G^*X \equiv \int_{\eta}^{1} \frac{m^*}{\pi^*} X \, d\eta$$

$$S^*X \equiv \frac{1}{\pi^*} \int_{0}^{\eta} m^* X \, d\eta$$

$$N^*X \equiv \frac{1}{\pi_s^*} \int_{0}^{1} m^* X \, d\eta$$

C1 constraint (cont)



C1 constraint (cont)

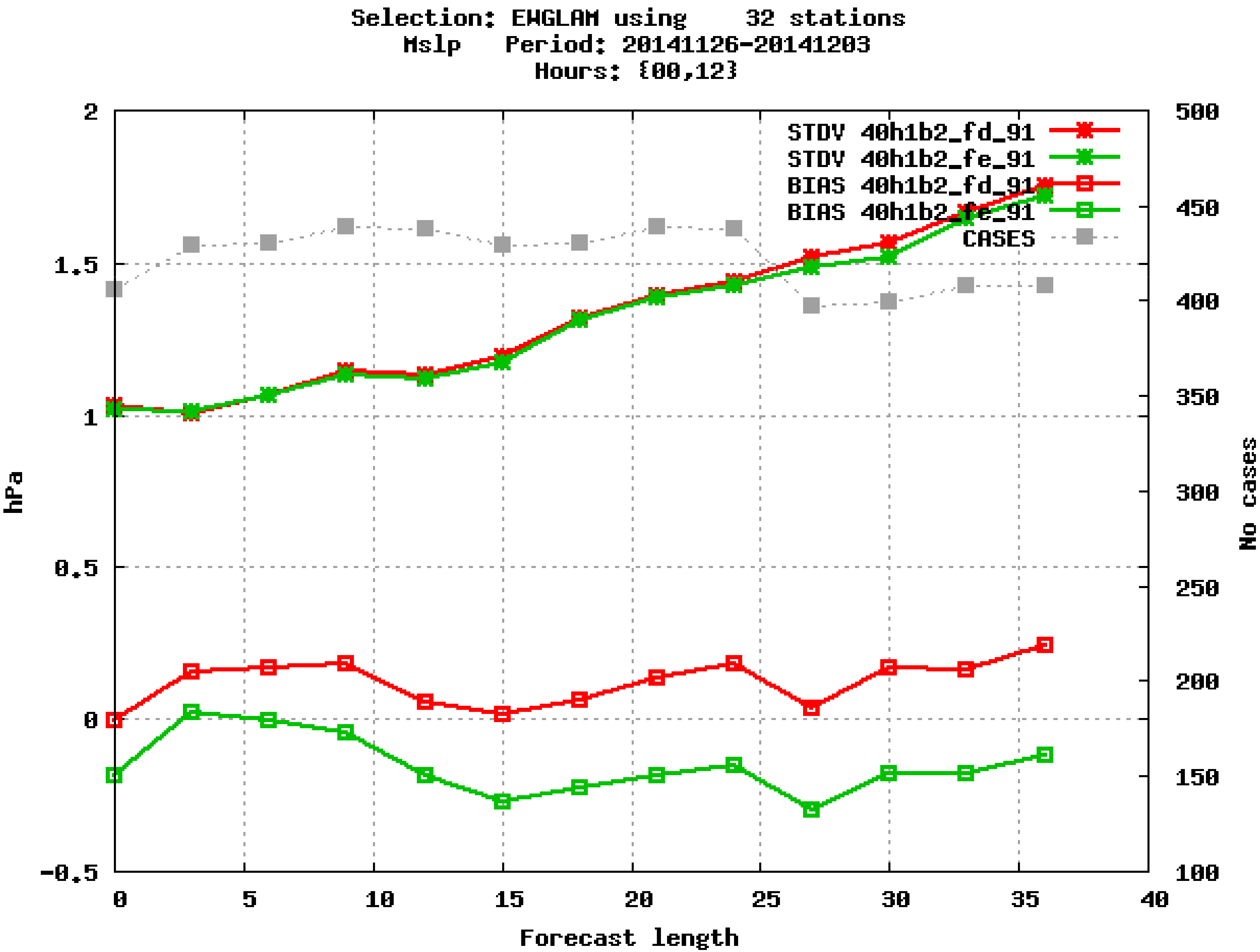
Functions H_k and K_k are related with the B-spines

$$H_k \equiv (\partial * - 1) N_{i,k}$$

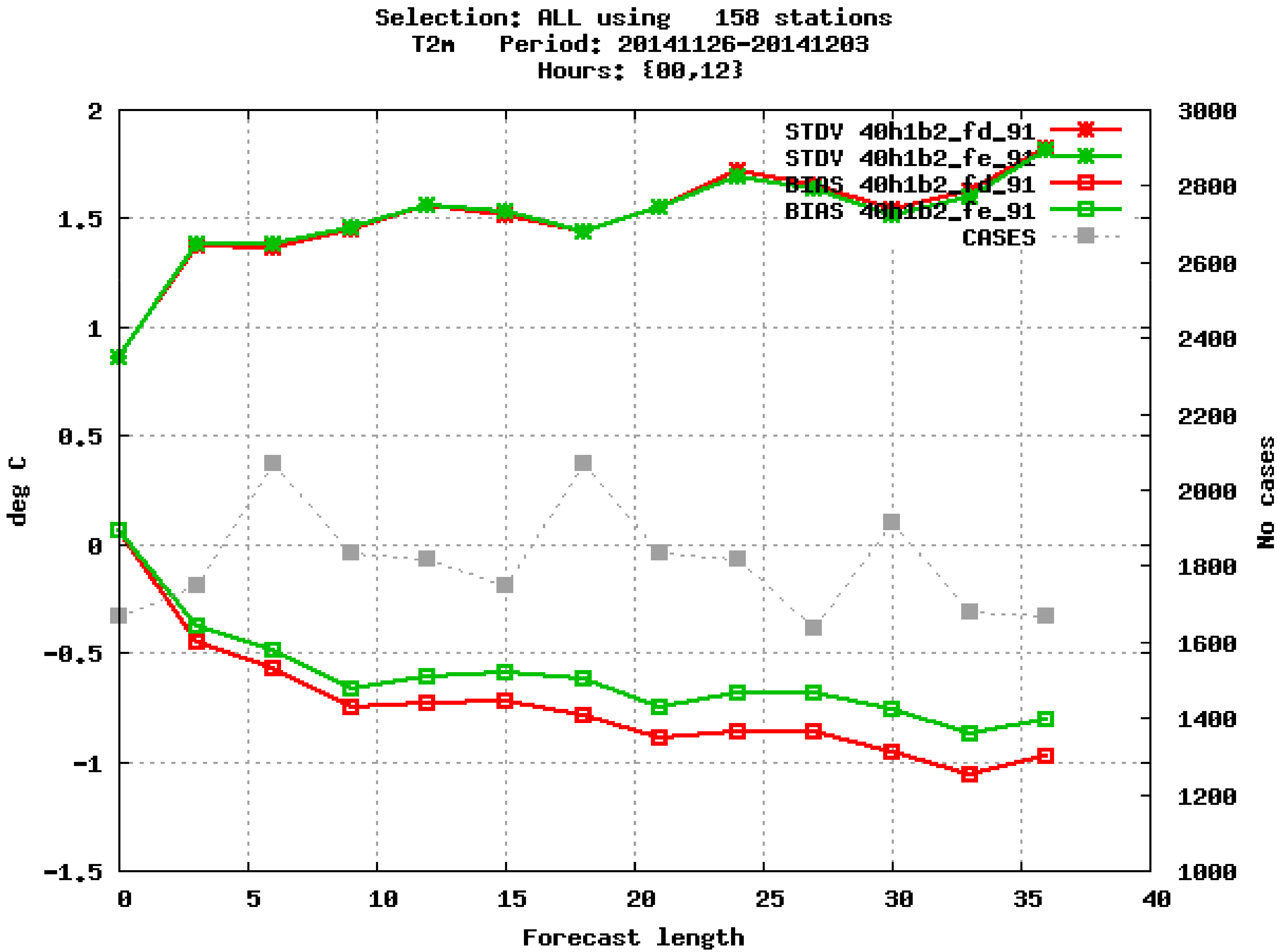
$$K_k \equiv \partial * N_{i,k}$$

Testing the new operators

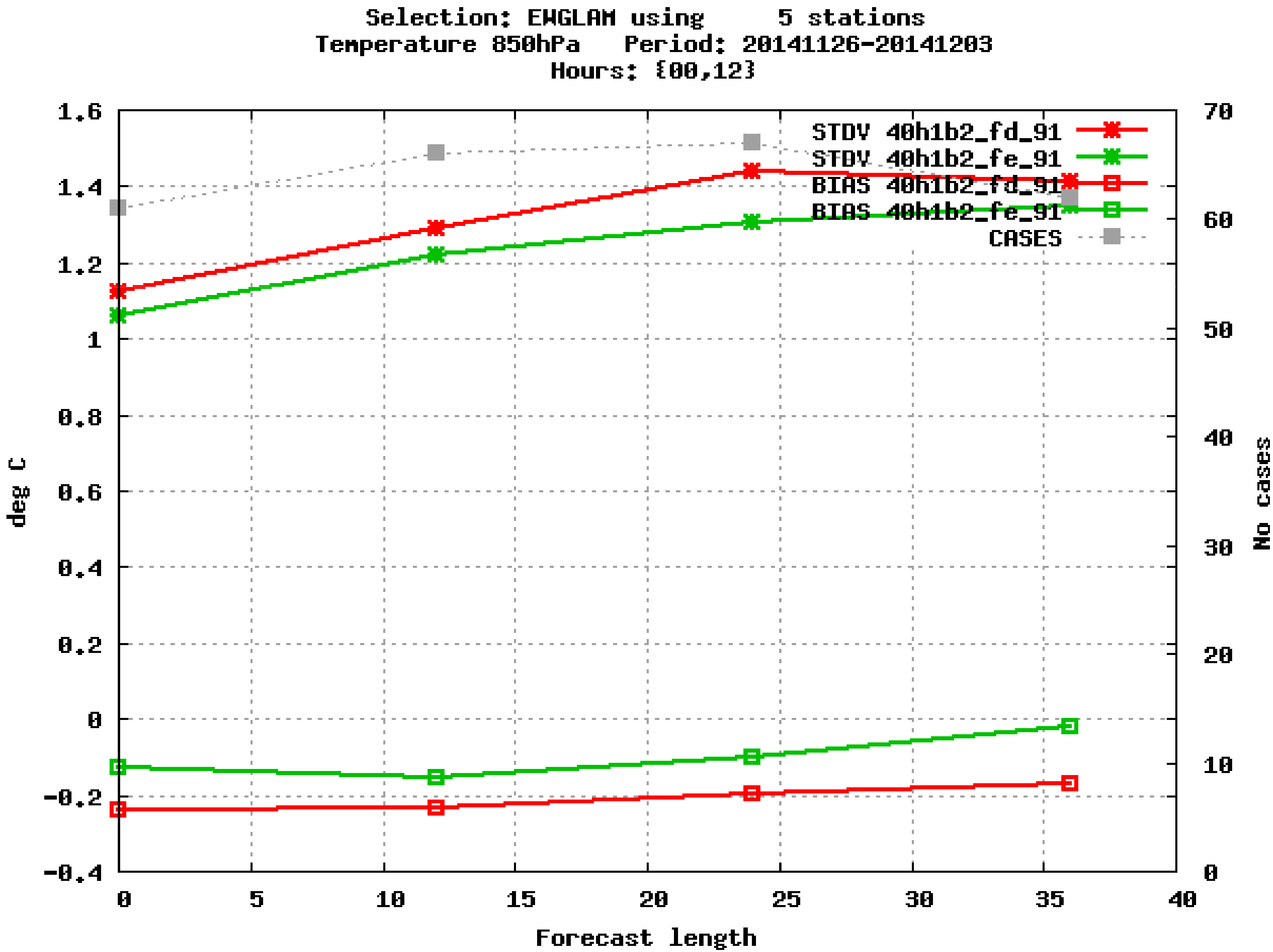
- The period from 2014-11-26 to 2014-12-03, very active period on the Iberian domain, was used to compare with the standard HARMONIE setup.
- CY40h1.1.beta.2
- 91 levels
- 2.5 km resolution using 60 s time step

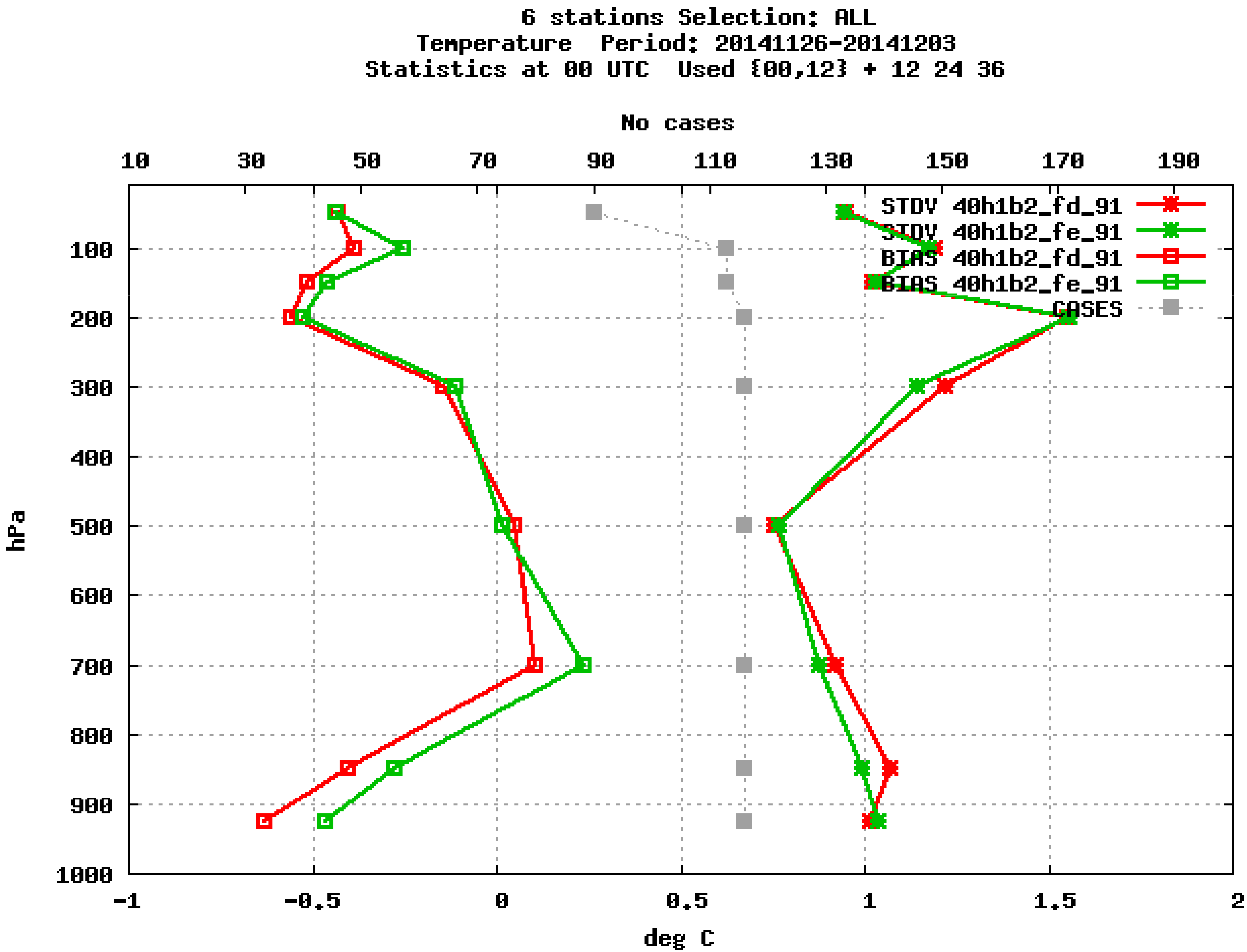


Selection: EWGLAM using 32 stations
Mslp Period: 20141126-20141203
Hours: {00,12}
STDV 40h1b2_fd_91
STDV 40h1b2_fe_91
BIAS 40h1b2_fd_91
BIAS 40h1b2_fe_91
CASES
hPa
No cases
Forecast length
2
1.5
1
0.5
0
-0.5
500
450
400
350
300
250
200
150
100
0
5
10
15
20
25
30
35
40



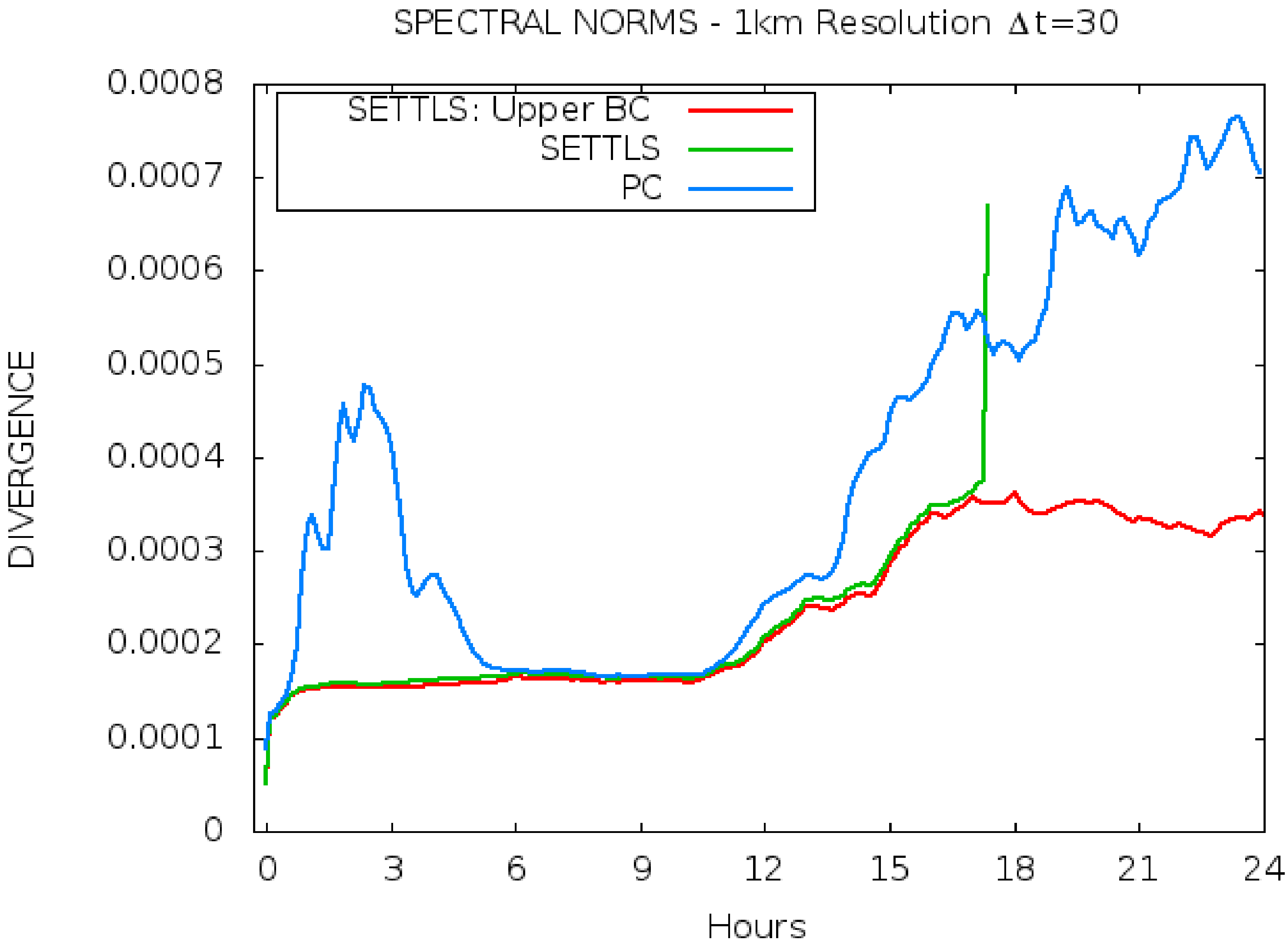
Selection: ALL using 158 stations
T2m Period: 20141126-20141203
Hours: {00,12}
STDV 40h1b2_fd_91
STDV 40h1b2_fe_91
BIAS 40h1b2_fd_91
BIAS 40h1b2_fe_91
CASES
deg C
No cases
Forecast length
2
1.5
1
0.5
0
-0.5
-1
-1.5
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
0
5
10
15
20
25
30
35
40


Selection: EWGLAM using 5 stations
Temperature 850hPa Period: 20141126-20141203
Hours: {00,12}
STDV 40h1b2_fd_91
STDV 40h1b2_fe_91
BIAS 40h1b2_fd_91
BIAS 40h1b2_fe_91
CASES
deg C
No cases
Forecast length
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
40


6 stations Selection: ALL
Temperature Period: 20141126-20141203
Statistics at 00 UTC Used {00,12} + 12 24 36
No cases
10
30
50
70
90
110
130
150
170
190
STDV 40h1b2_fd_91
STDV 40h1b2_fe_91
BIAS 40h1b2_fd_91
BIAS 40h1b2_fe_91
CASES
hPa
100
200
300
400
500
600
700
800
900
1000
-1
-0.5
0
0.5
1
1.5
2
deg C

Upper nesting boundary conditions

- Davies relaxation similar to the lateral boundaries was introduced in the upper boundary of the model.
- Some runs of the HARMONIE model at 2.5 km and higher resolutions exploded due to too strong wind or unrealistic temperatures at the upper levels.
- Use of the ICI (iterative centred implicit) otherwise called the predictor-corrector PC scheme avoided the explosion but introduced noise, particularly at low levels
- Introduction of the upper boundary conditions stabilized the runs without introducing supplementary noise

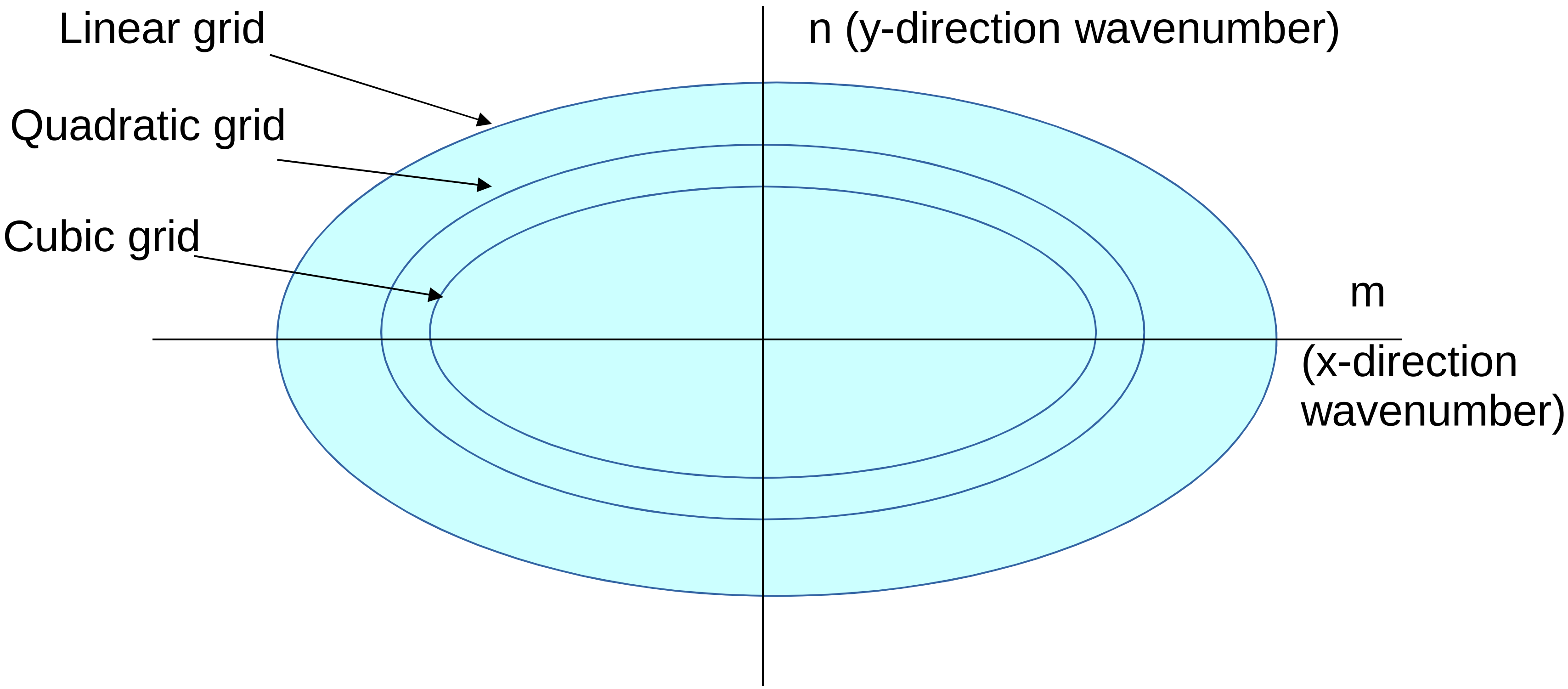

SPECTRAL NORMS - 1km Resolution Δt=30
SETTLS: Upper BC
SETTLS
PC
DIVERGENCE
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
0
3
6
9
12
15
18
21
24
Hours

Definition of quadratic and cubic grid

- For a given spectral resolution M in Fourier space
  - Linear grid is the one which allows exact transforms, in contains at least 2M+1 points
  - Quadratic grid is the one which eliminates quadratic aliasing and has at least 3M+1 points
  - Cubic grid eliminates cubic aliasing and should have at least 4M+1 points

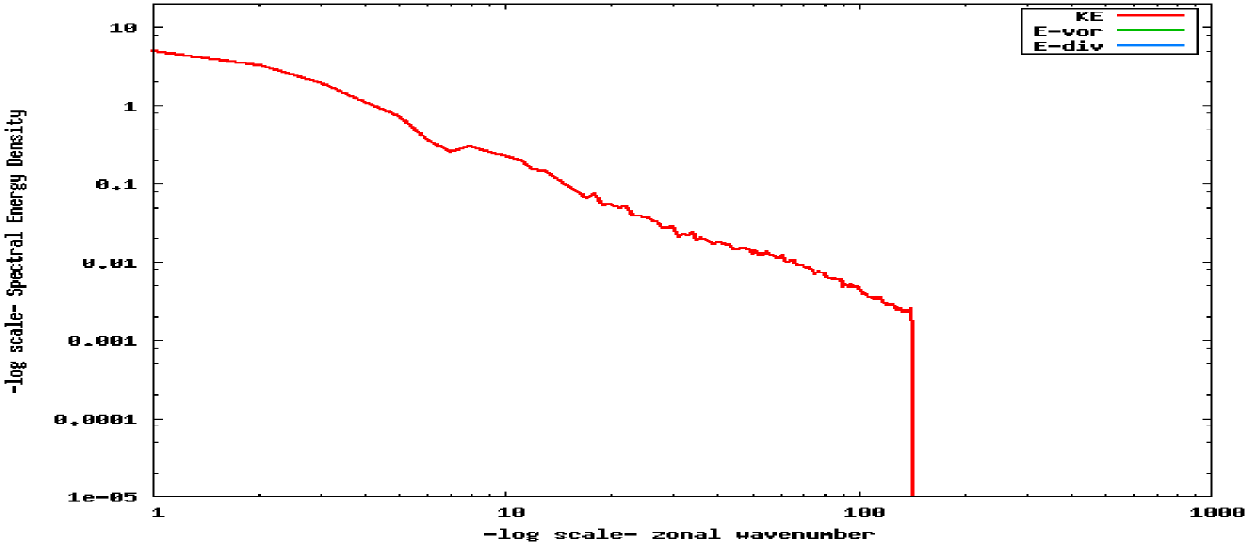
Elliptic truncation in quadratic and cubic grids for a given distribution of grid points in physical space

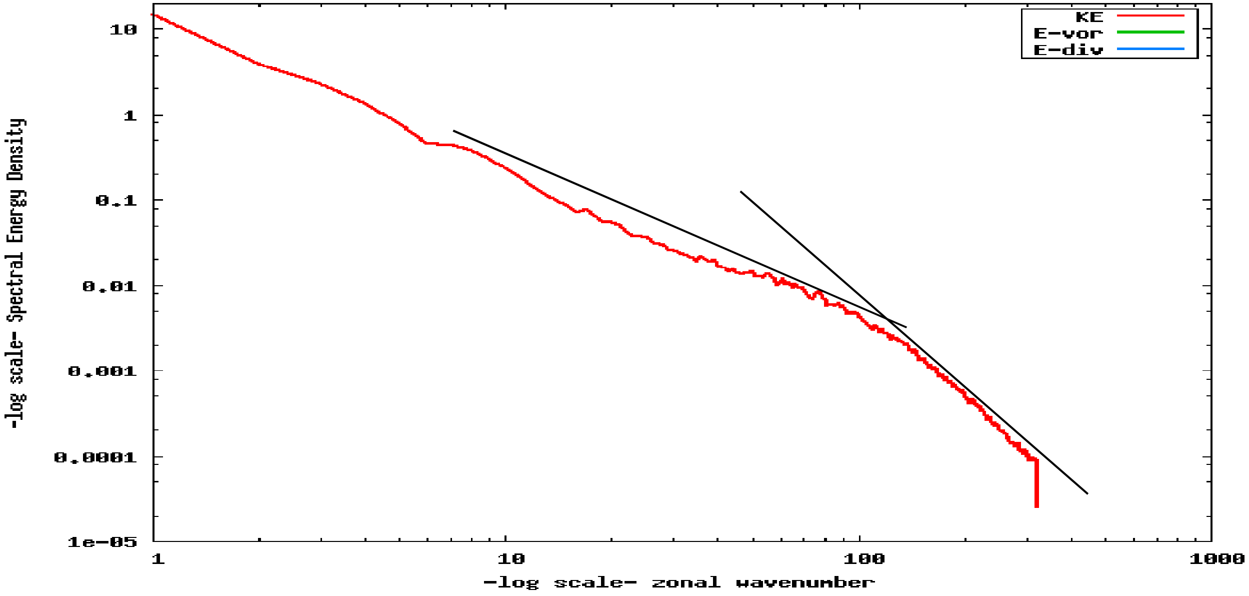
For a given number of points in x and y

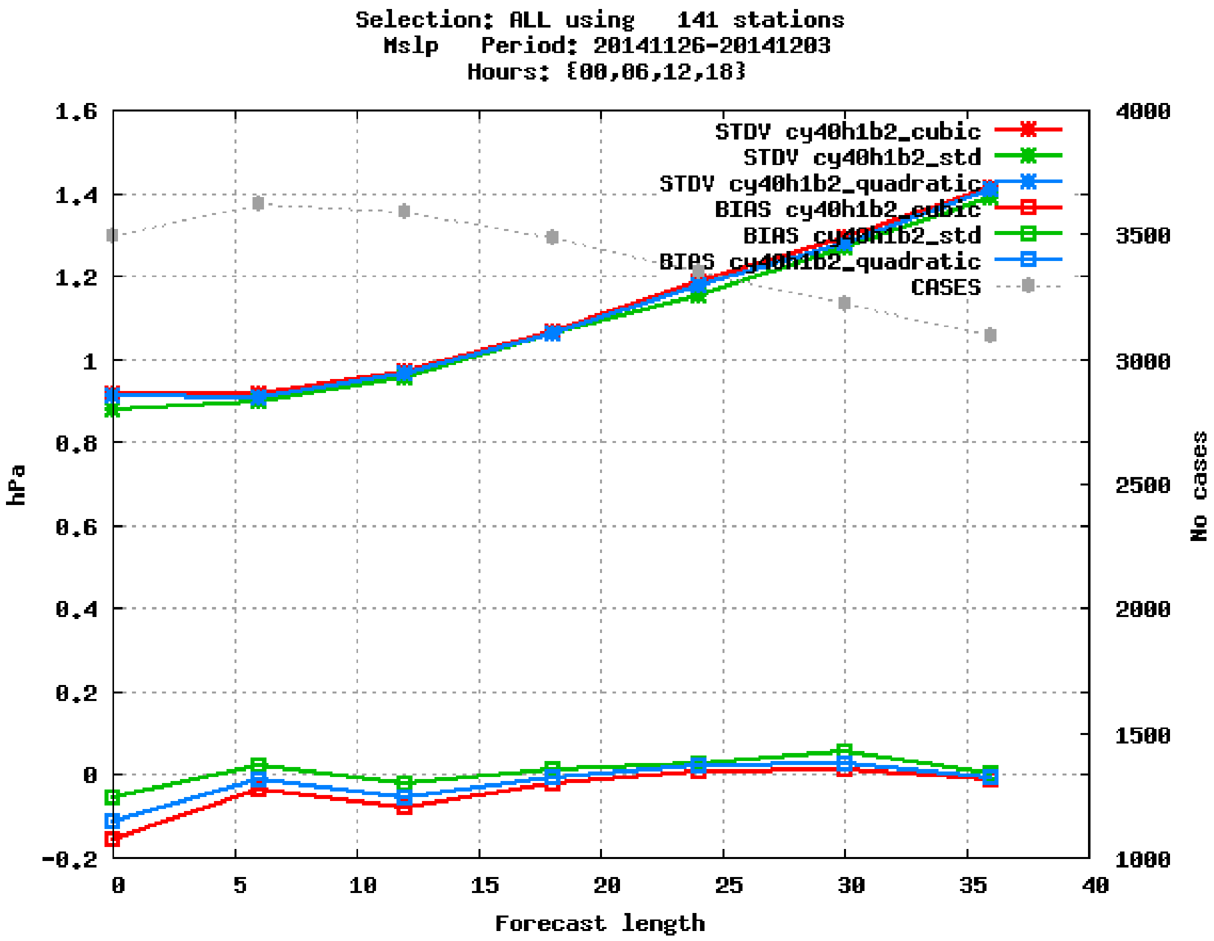


Runs using the cubic grid are stable with double the time step than using the linear grid

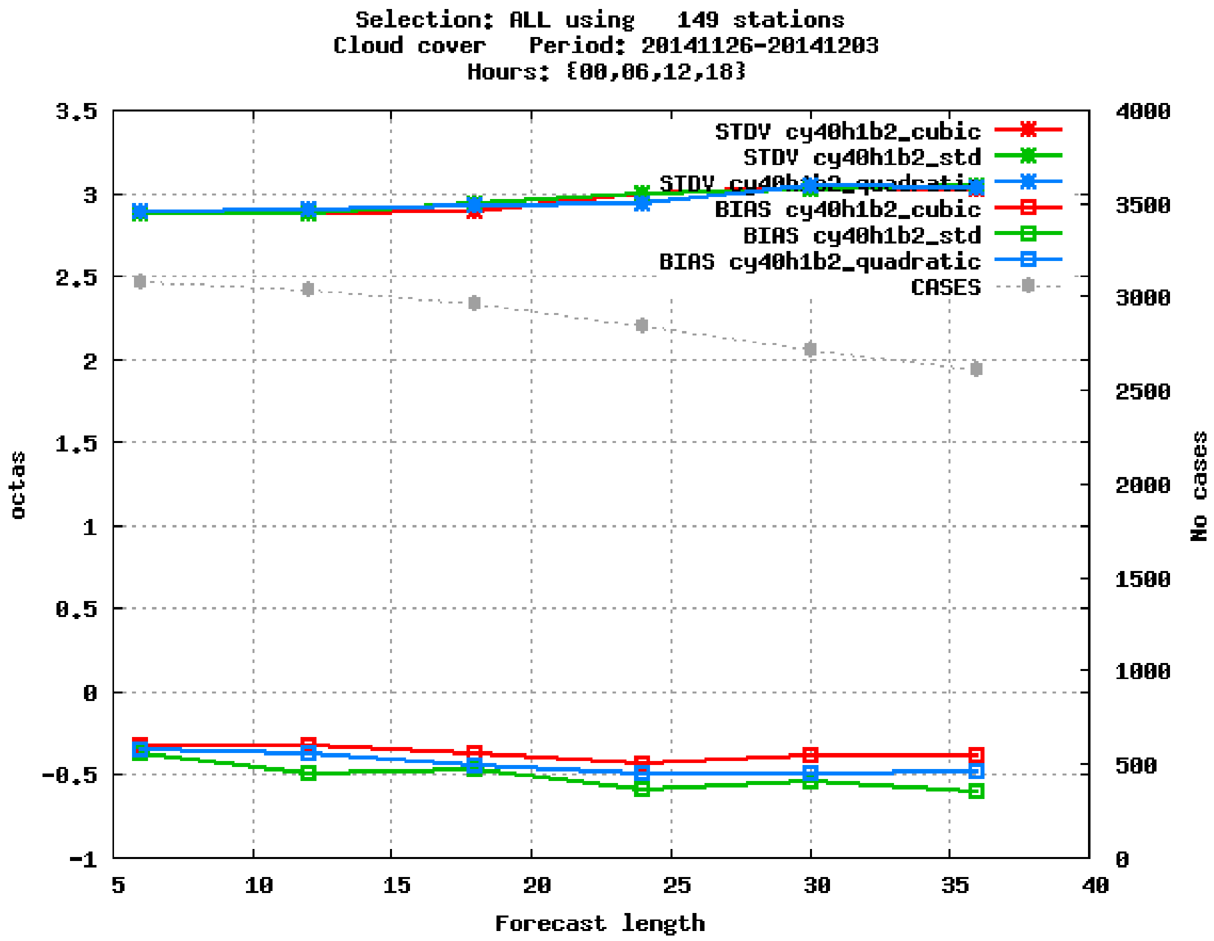
Kinetic energy spectra and effective resolution



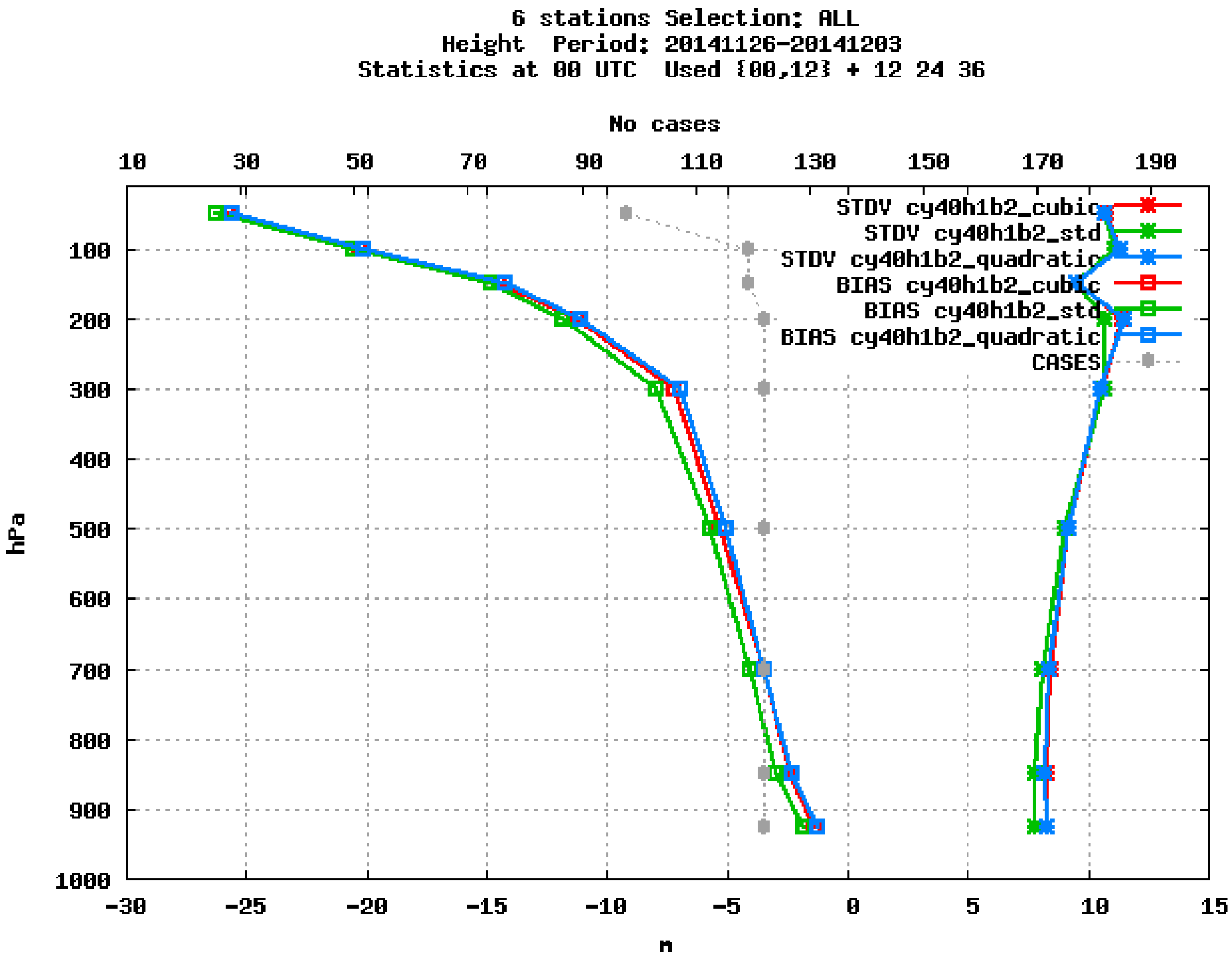




Selection: ALL using 141 stations
Mslp Period: 20141126-20141203
Hours: {00,06,12,18}
STDV cy40h1b2_cubic
STDV cy40h1b2_std
STDV cy40h1b2_quadratic
BIAS cy40h1b2_cubic
BIAS cy40h1b2_std
BIAS cy40h1b2_quadratic
CASES
hPa
No cases
Forecast length
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
4000
3500
3000
2500
2000
1500
1000
0
5
10
15
20
25
30
35
40



Selection: ALL using 149 stations
Cloud cover Period: 20141126-20141203
Hours: {00,06,12,18}
STDV cy40h1b2_cubic
STDV cy40h1b2_std
STDV cy40h1b2_quadratic
BIAS cy40h1b2_cubic
BIAS cy40h1b2_std
BIAS cy40h1b2_quadratic
CASES
octas
No cases
Forecast length
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
4000
3500
3000
2500
2000
1500
1000
500
0
5
10
15
20
25
30
35
40



6 stations Selection: ALL
Height Period: 20141126-20141203
Statistics at 00 UTC Used {00,12} + 12 24 36
No cases
10 30 50 70 90 110 130 150 170 190
STDV cy40h1b2_cubic
STDV cy40h1b2_std
STDV cy40h1b2_quadratic
BIAS cy40h1b2_cubic
BIAS cy40h1b2_std
BIAS cy40h1b2_quadratic
CASES
hPa
100 200 300 400 500 600 700 800 900 1000
-30 -25 -20 -15 -10 -5 0 5 10 15
m

Weak constraint boundary conditions

The SBP/SAT method (summation by parts and simultaneous approximation term) is designed to

- mimic the continuous integration-by-parts by discrete summation-by-parts (this makes it also conservative)
- be high-order accurate (choice of 2,4,6,8 and 10) in the interior and lowering of the order close to the boundaries (1,2,3,4 and 5).
- stable by the use SAT (weak boundary conditions)

Well-posedness (continuous) ,<=> Stability (discrete)

From Marco Kupiainen

Use of energy method for stability

The problem

$$u_t + u_x = 0$$

Is well-posed depending on the boundary conditions.

This can be shown using integration by parts within the energy method

Discrete scheme

$$u_x = P^{-1} Q u + O(h^p)$$

With P symmetric positive definite
and $Q+Q^T$ = diag (-1,0,......,0,1) (almost skew-symmetric)

The semi-discrete scheme is:

$$u_t = -P^{-1} Q u - \gamma P^{-1} E_0 (u - g(0,t))$$

Where E_0 = diag(1,0,.....,0)

Using the energy method and summation by parts
we can see that we need $\gamma \geq 1/2!$

Slow start of the forecast

- In some cases the forecast model “explodes” at the second time step
- There are two main causes for this:
  - Time extrapolation of the non-linear terms
  - Large values of the 3D divergence computed from the nesting hydrostatic model which produce unrealistic temperature tendencies
- A “slow start” of the model has been introduced during the NFOST first time steps
  - A first order treatment (avoiding time extrapolation) is applied to the non-linear terms
  - A limiter is applied to the value of the 3D divergence

Thanks!

Questions?

Future work

- Continue the development of vertical finite elements and weak constraint boundary conditions
- Go towards higher horizontal and vertical resolutions
- Collaborate with the physical parameterization, chemistry and climate people in dynamics issues arising
- Keep an eye and adapt as needed developments, mainly at ECMWF, related with exascale computing