École Doctorale des Sciences de l'Environnement d'Île-de-France

Année Universitaire 2013-2014

Modélisation Numérique de l'Écoulement Atmosphérique et Assimilation de Données

Olivier Talagrand

Cours 2

11 Avril 2014

Lois physiques régissant l'écoulement

- Conservation de la masse

  $D\rho/Dt + \rho\,\mathrm{div}\underline{U} = 0$

- Conservation de l'énergie

  $De/Dt - (p/\rho^2)\,D\rho/Dt = Q$

- Conservation de la quantité de mouvement

  $D\underline{U}/Dt + (1/\rho)\,\underline{\mathrm{grad}p} - \underline{g} + 2\,\underline{\Omega} \wedge \underline{U} = \underline{F}$

- Equation d'état

  $f(p, \rho, e) = 0$ $(p/\rho = rT,\ e = C_v T)$

- Conservation de la masse de composants secondaires (eau pour l'atmosphère, sel pour l'océan, …)

  $Dq/Dt + q\,\mathrm{div}\underline{U} = S$

Lois physiques doivent en pratique être discrétisées dans le temps et dans l'espace
$\Rightarrow$ *modèles numériques*, nécessairement imparfaits.

Les modèles utilisés pour la prévision météorologique de grande échelle et la simulation climatologique couvrent la totalité du volume de l'atmosphère. Ils sont, jusqu'à présent au moins, construits sur l'hypothèse *hydrostatique*

Dans la direction verticale :

$$\partial p/\partial z + \rho g = 0$$

Élimine l'équation du mouvement pour la direction verticale; en outre, l'écoulement est incompressible dans les coordonnées (x, y, p) $\Rightarrow$ nombre d'équations diminué de deux unités.

Approximation hydrostatique valide pour échelles horizontales > 20-30 km

Modèles non-hydrostatiques, plus coûteux, sont utilisés pour la météorologie de petite échelle.

In addition to hydrostatic approximation, the following approximations are (almost) systematically made in global modeling :

- Atmospheric fluid is contained in a spherical shell with negligible thickness. This does not forbid the existence within the shell of a vertical coordinate which, in view of the hydrostatic equation, can be chosen as the pressure p.

- The horizontal component of the Coriolis acceleration due to the vertical motion is neglected (this approximation, sometimes called the *traditional approximation*, is actually a consequence of the previous one).

- Tidal forces are neglected.

These approximations lead to the so-called (and ill-named) *primitive equations*

There exist at present two forms of discretization

- Gridpoint discretization

- (Semi-)spectral discretization (mostly for global models, and most often only in the horizontal direction)

Finite element discretization, which is very common in many forms of numerical modelling, is rarely used for modelling of the atmosphere. It is more frequently used for oceanic modelling, where it allows to take into account the complicated geometry of coast-lines.

Pressure p, although convenient for writing down the equations, is in fact rather inconvenient because lower boundary is not fixed in (x, y, p)-space.

So-called σ-coordinate. $\sigma \equiv p/p_S$, where p_S is pressure at ground level.

'Hybrid' coordinate.

Temporal discretization. Courant-Friedrichs-Lewy (CFL) condition for stability of explicit schemes

$$\Delta t / \Delta x < \alpha / c$$

where c is phase velocity of fastest propagating (wave) in the system, and α is an $O(1)$ numerical coefficient depending on particular scheme under consideration.

Significance : numerical propagation of signal must be at least as fast as physical propagation.

In hydrostatic atmosphere, fastest propagating wave : gravity wave with largest scale height, $c = \sqrt{(rT)} \approx 300$ m.s^{-1}.

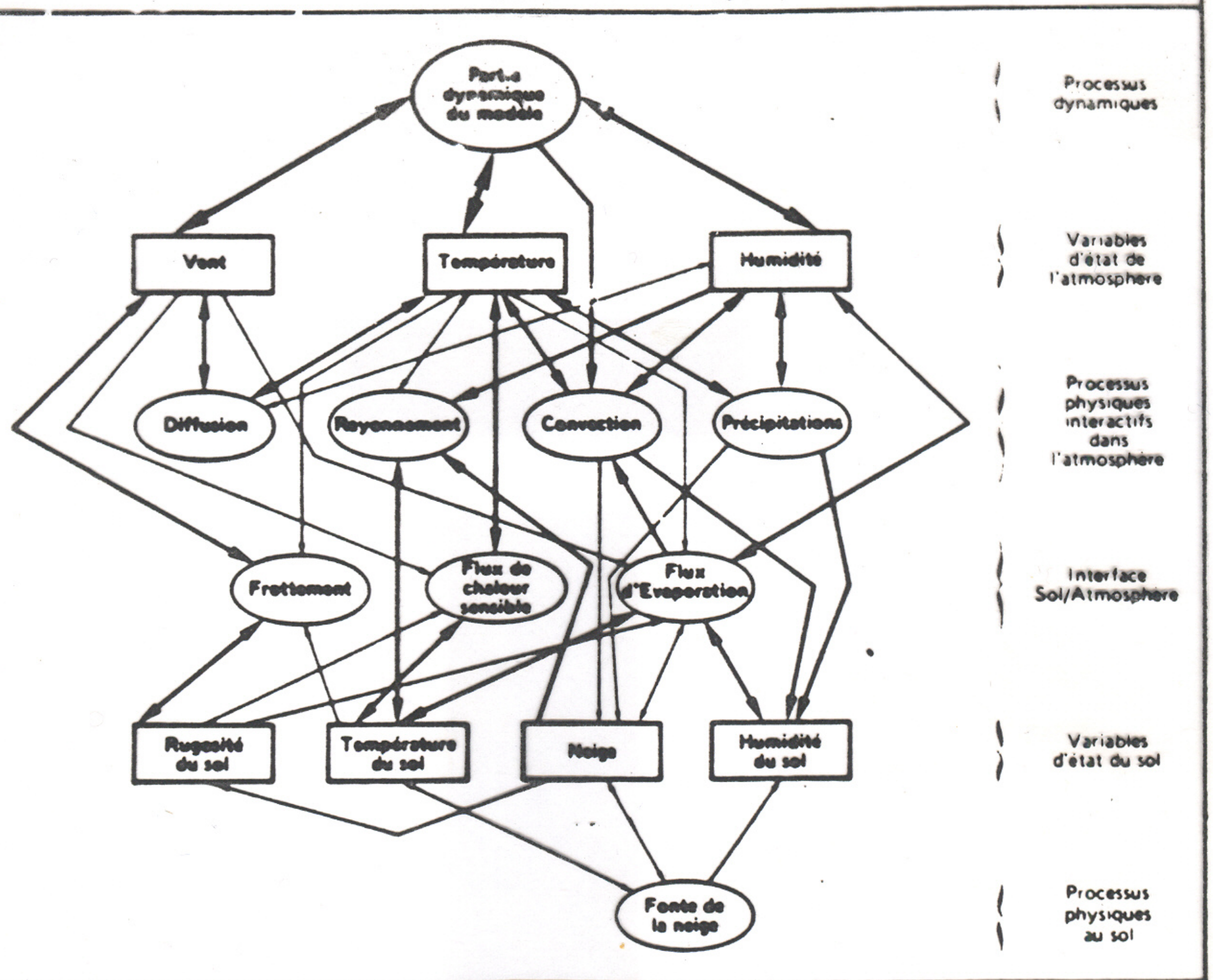
$$\Delta x = 30 \text{ km} \quad \Rightarrow \quad \Delta t = 100 \text{ s}$$

In the parlance of the trade, one distinguishes two different parts in models. The ‘dynamics’ deals with the physically reversible processes (pressure forces, Coriolis force, advection, …), while the ‘physics’ deals with physically irreversible processes, in particular the diabatic heating term Q in the energy equation, and also the parameterization of subgrid scales effects.

Numerical schemes have been progressively developed and validated for the ‘dynamics’ component of models, which are by and large considered now to work satisfactorily (although regular improvements are still being made).

The situation is different as concerns ‘physics’, where many problems remain (as concerns for instance subgrid scales parameterization, the water cycle and the associated exchanges of energy, or the exchanges between the atmosphere and the underlying medium). ‘Physics’ as a whole remains the weaker point of models, and is still the object of active research.

5 - SCHEMA DES INTERACTIONS PHYSIQUES DANS LE MODELE



Centre Européen pour les Prévisions Météorologiques à Moyen Terme (CEPMMT, Reading, GB)

(European Centre for Medium-range Weather Forecasts, ECMWF)

En avril 2014 :

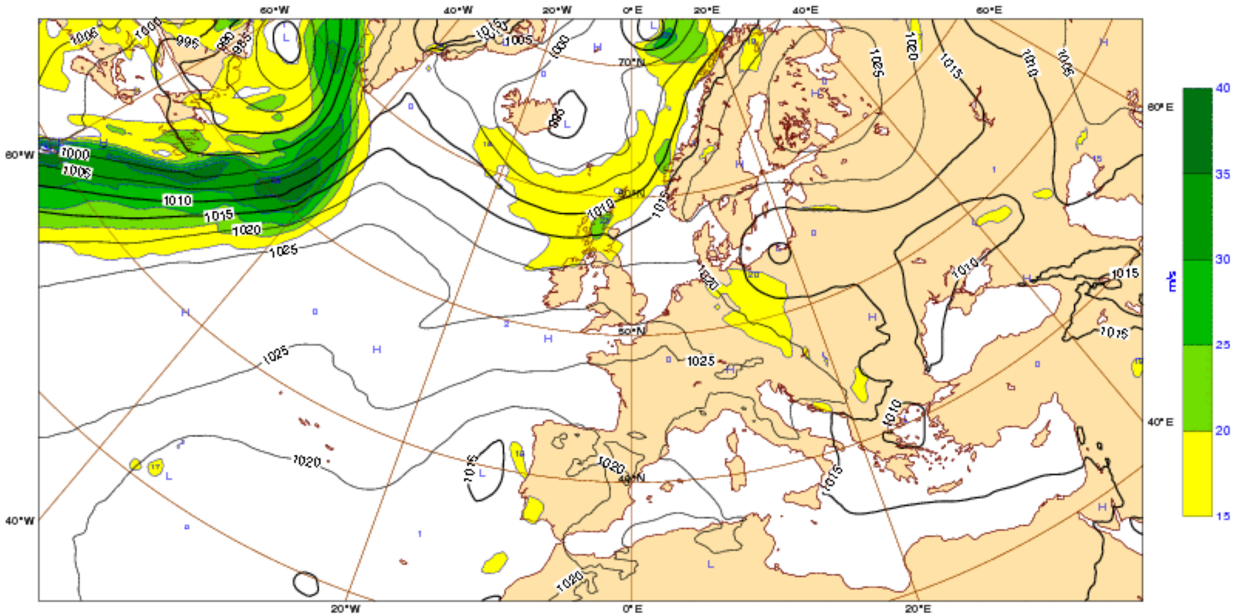
Troncature triangulaire T1279 (résolution horizontale ≈ 16 kilomètres)

137 niveaux dans la direction verticale (0 - 80 km)

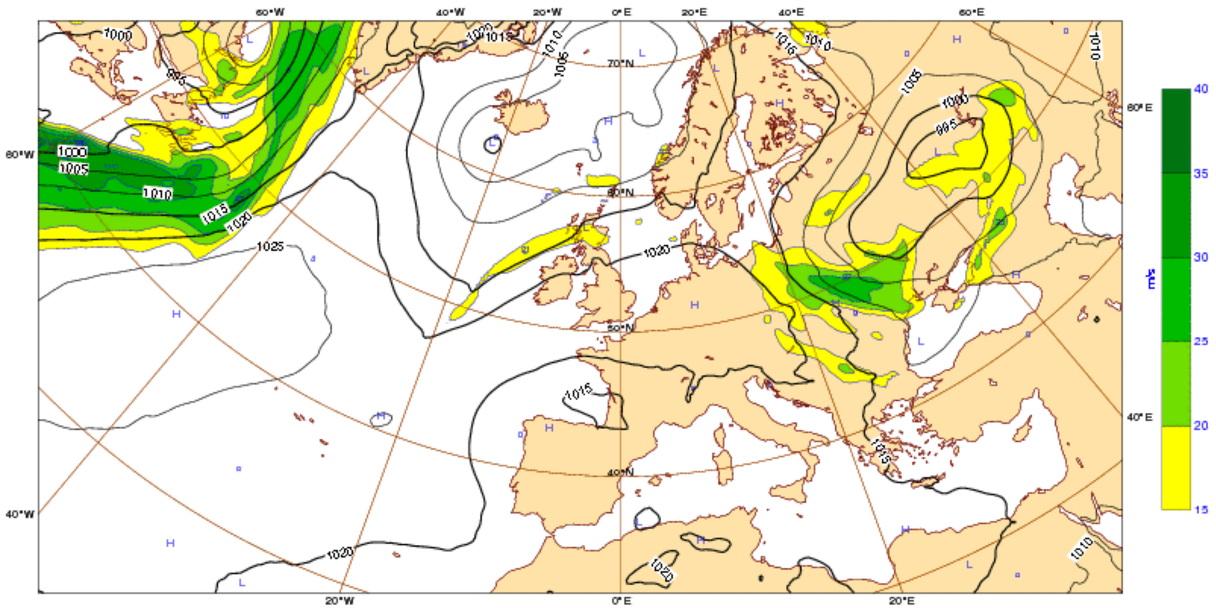
Dimension du vecteur d'état correspondant ≈ $2{,}3\ 10^9$

Pas de discrétisation temporelle : 10 minutes

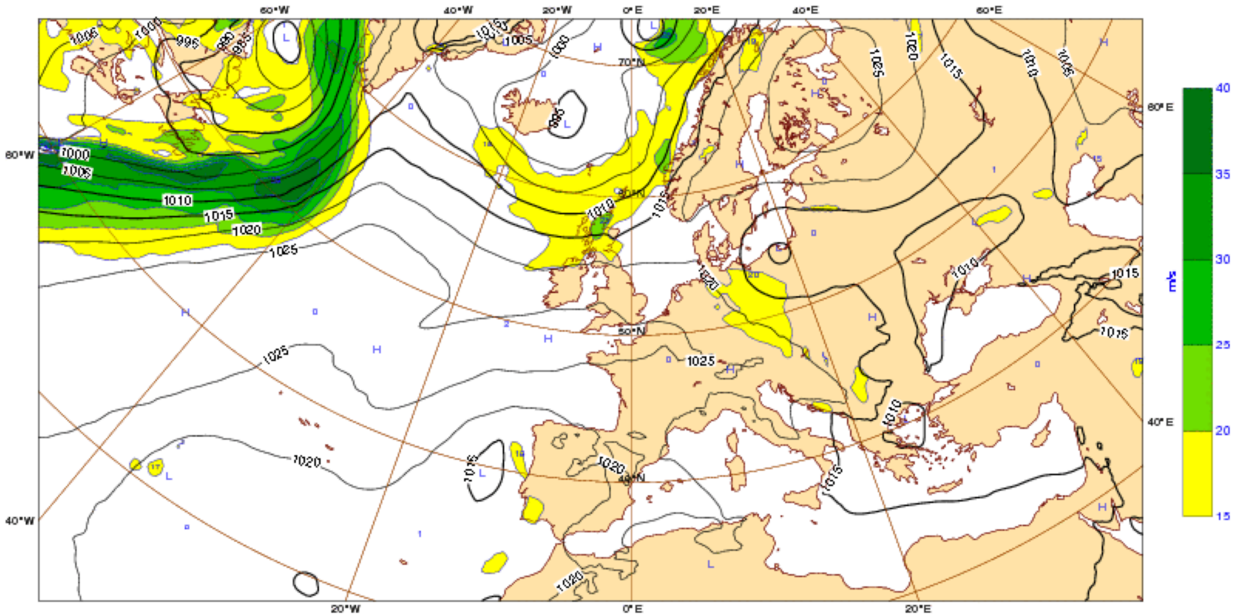
Thursday 10 April 2014 00UTC ©ECMWF Analysis t+000 VT: Thursday 10 April 2014 00UTC
Surface: Mean sea level pressure / 850-hPa wind speed



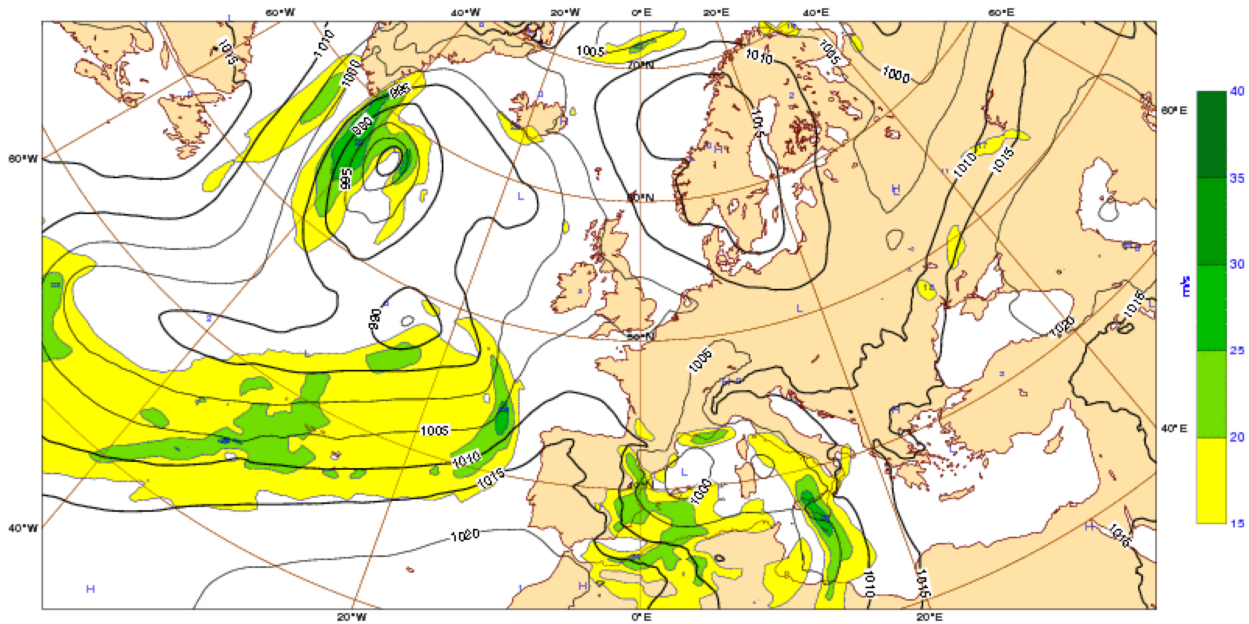
Friday 4 April 2014 00UTC ©ECMWF Forecast t+144 VT: Thursday 10 April 2014 00UTC
Surface: Mean sea level pressure / 850-hPa wind speed



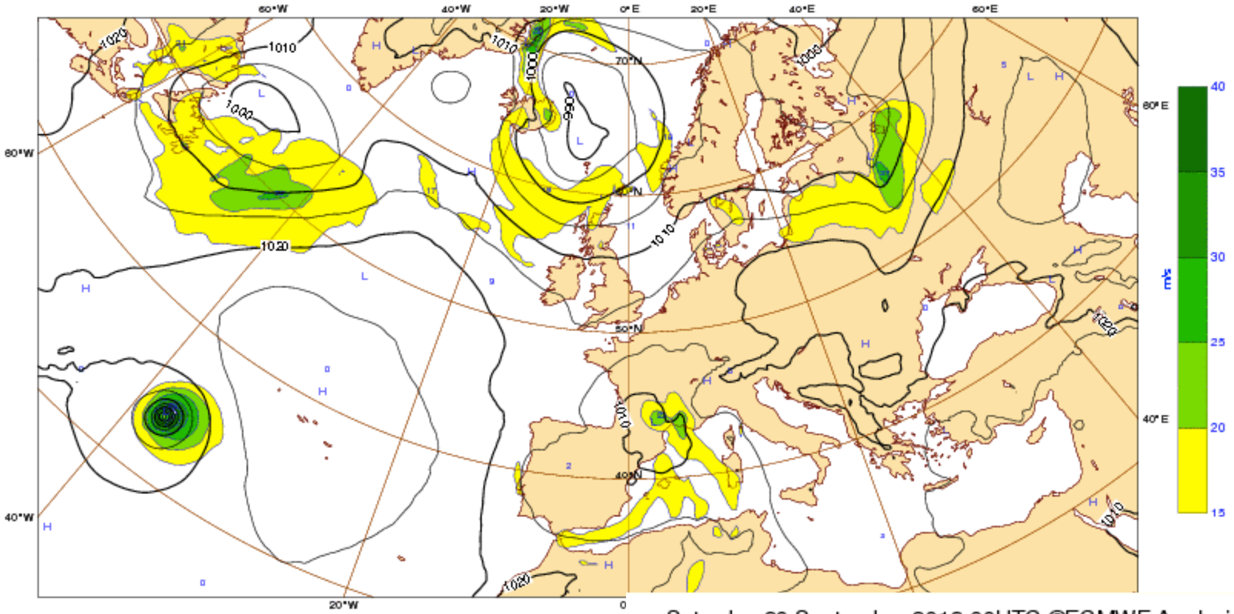
Thursday 10 April 2014 00UTC ©ECMWF Analysis t+000 VT: Thursday 10 April 2014 00UTC
Surface: Mean sea level pressure / 850-hPa wind speed



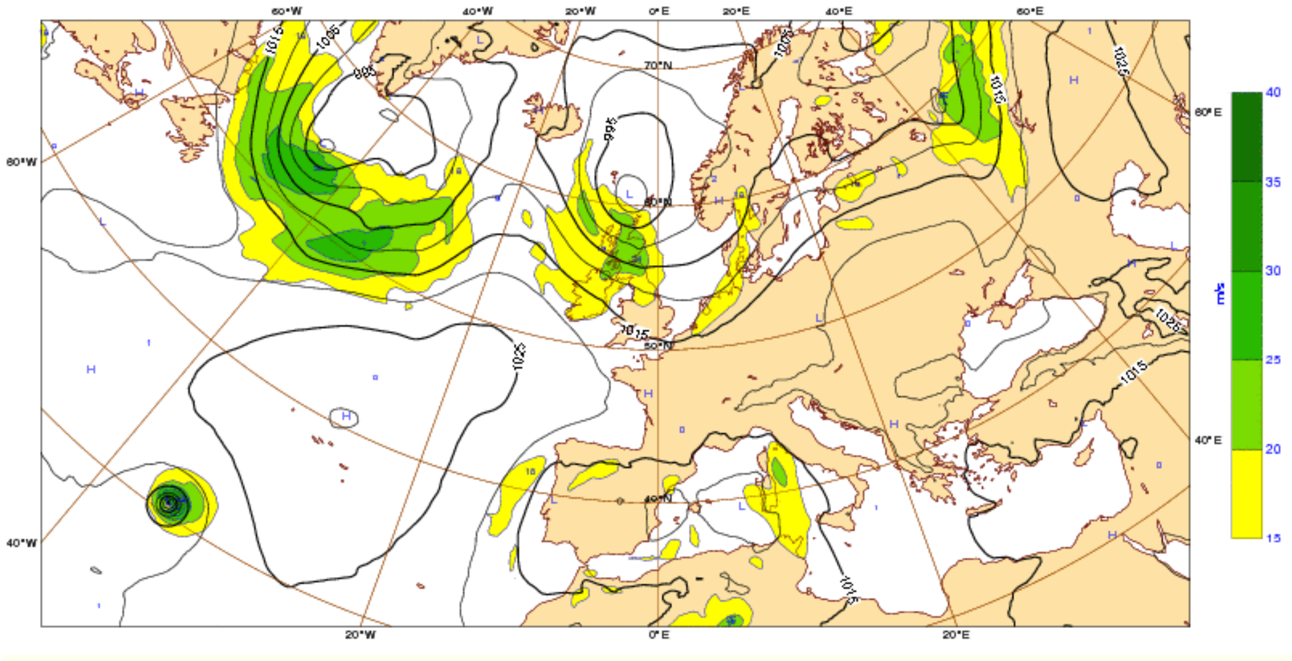
Friday 4 April 2014 00UTC ©ECMWF Analysis t+000 VT: Friday 4 April 2014 00UTC
Surface: Mean sea level pressure / 850-hPa wind speed



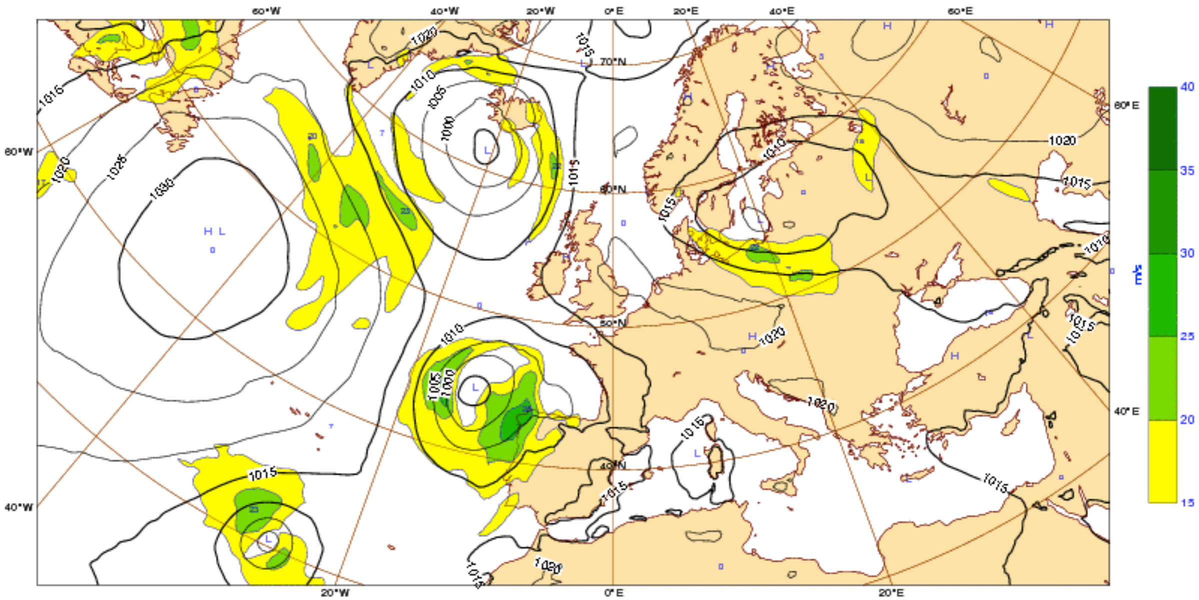
Sunday 23 September 2012 00UTC ©ECMWF Forecast t+144 VT: Saturday 29 September 2012 00UTC
Surface: Mean sea level pressure / 850-hPa wind speed



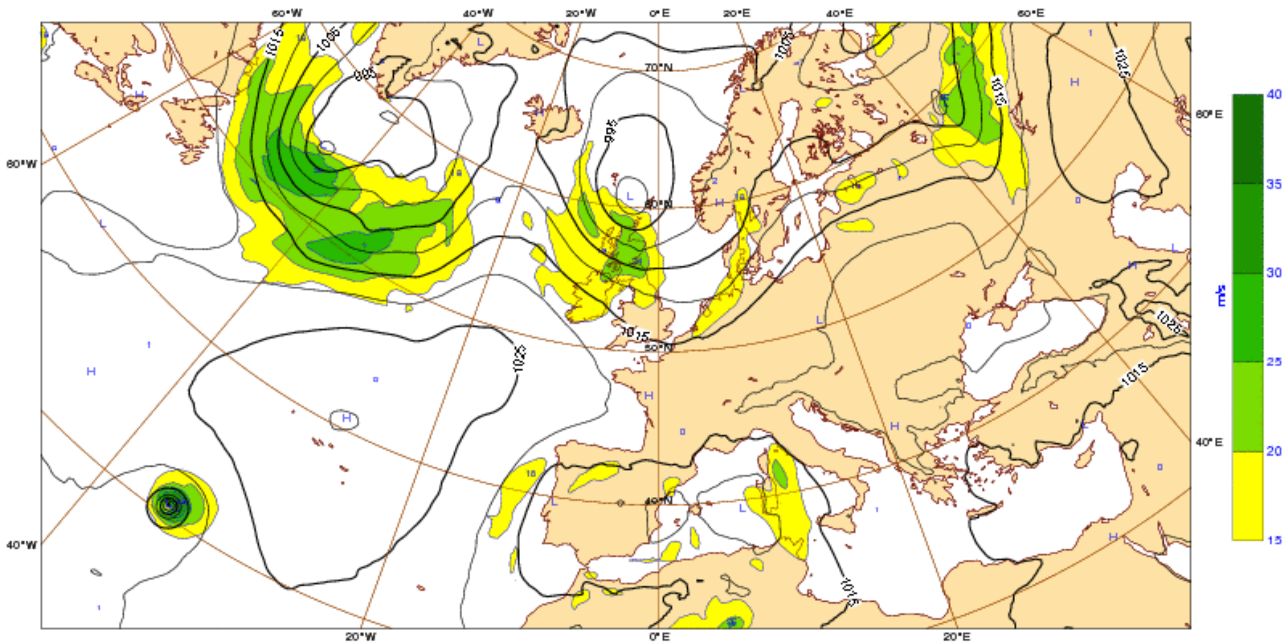
Saturday 29 September 2012 00UTC ©ECMWF Analysis t+000 VT: Saturday 29 September 2012 00UTC
Surface: Mean sea level pressure / 850-hPa wind speed



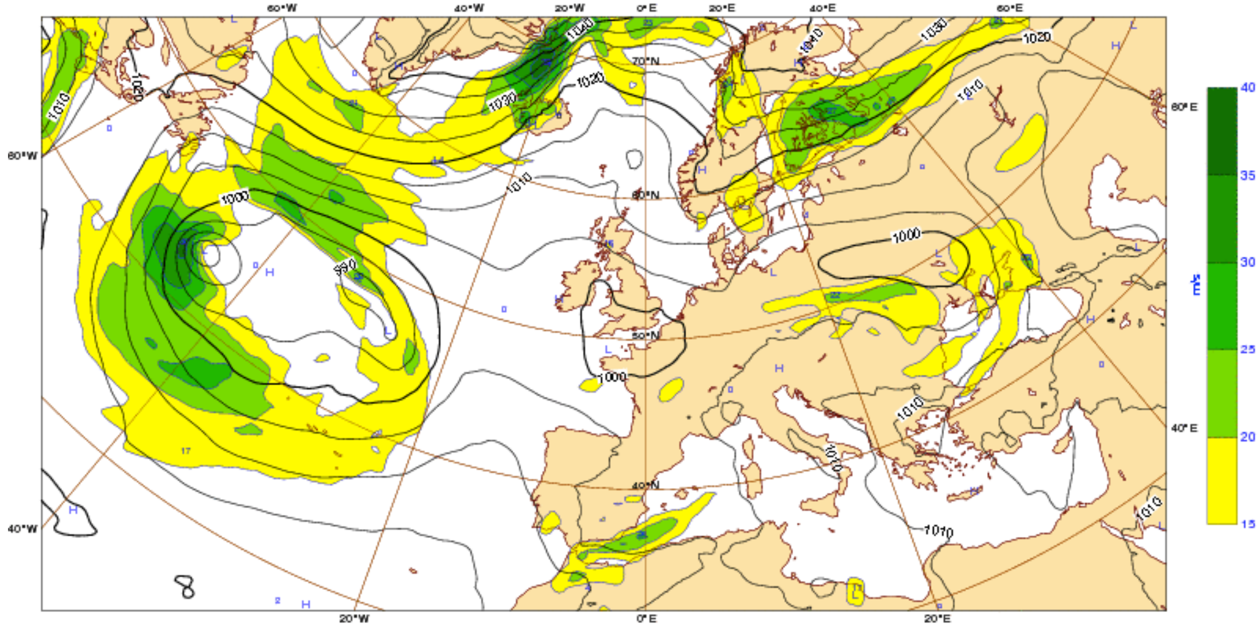
Sunday 23 September 2012 00UTC ©ECMWF Analysis t+000 VT: Sunday 23 September 2012 00UTC
Surface: Mean sea level pressure / 850-hPa wind speed



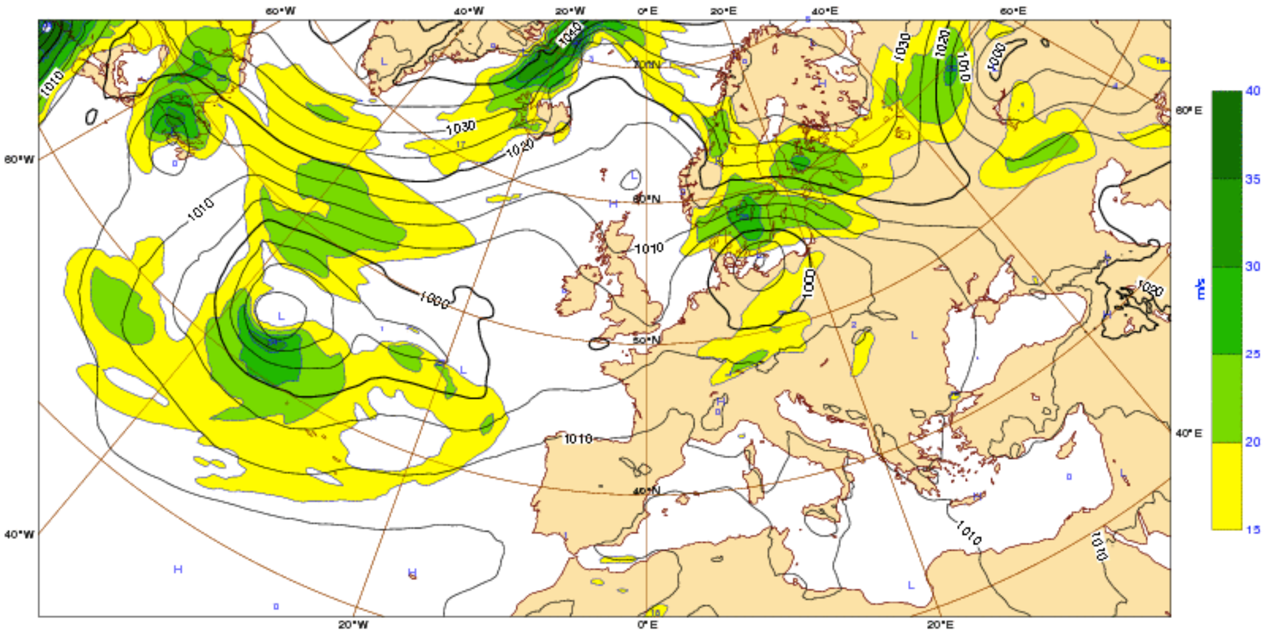
Saturday 29 September 2012 00UTC ©ECMWF Analysis t+000 VT: Saturday 29 September 2012 00UTC
Surface: Mean sea level pressure / 850-hPa wind speed



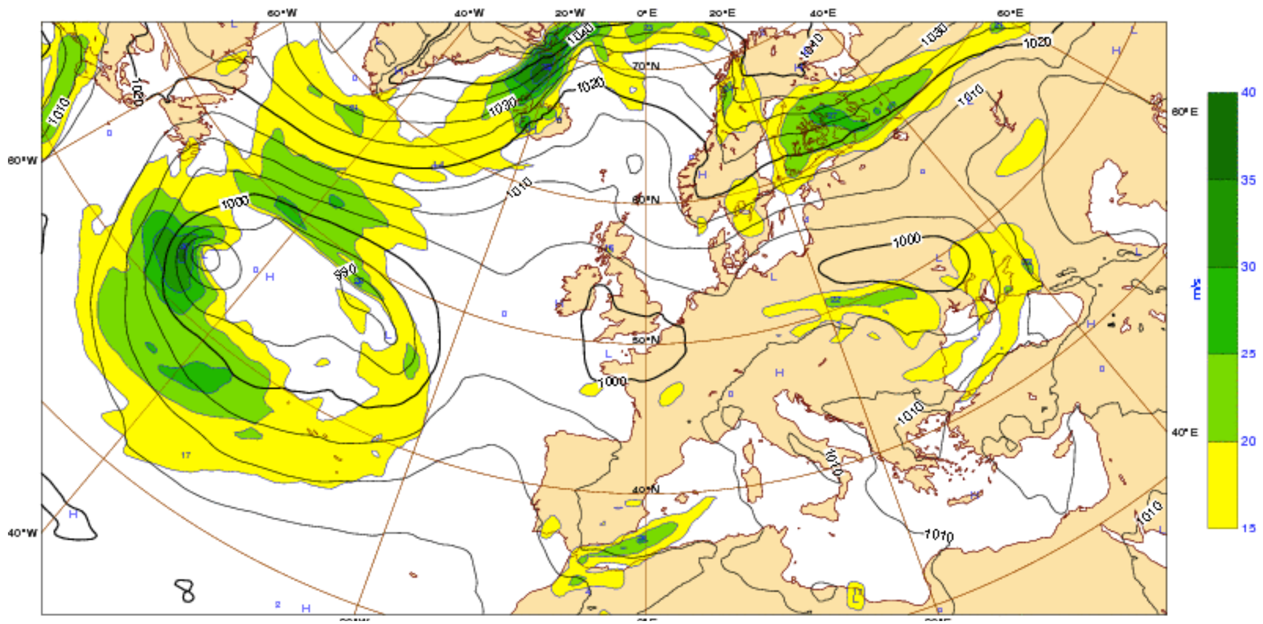
Wednesday 20 March 2013 00UTC ©ECMWF Analysis t+000 VT: Wednesday 20 March 2013 00UTC
Surface: Mean sea level pressure / 850-hPa wind speed



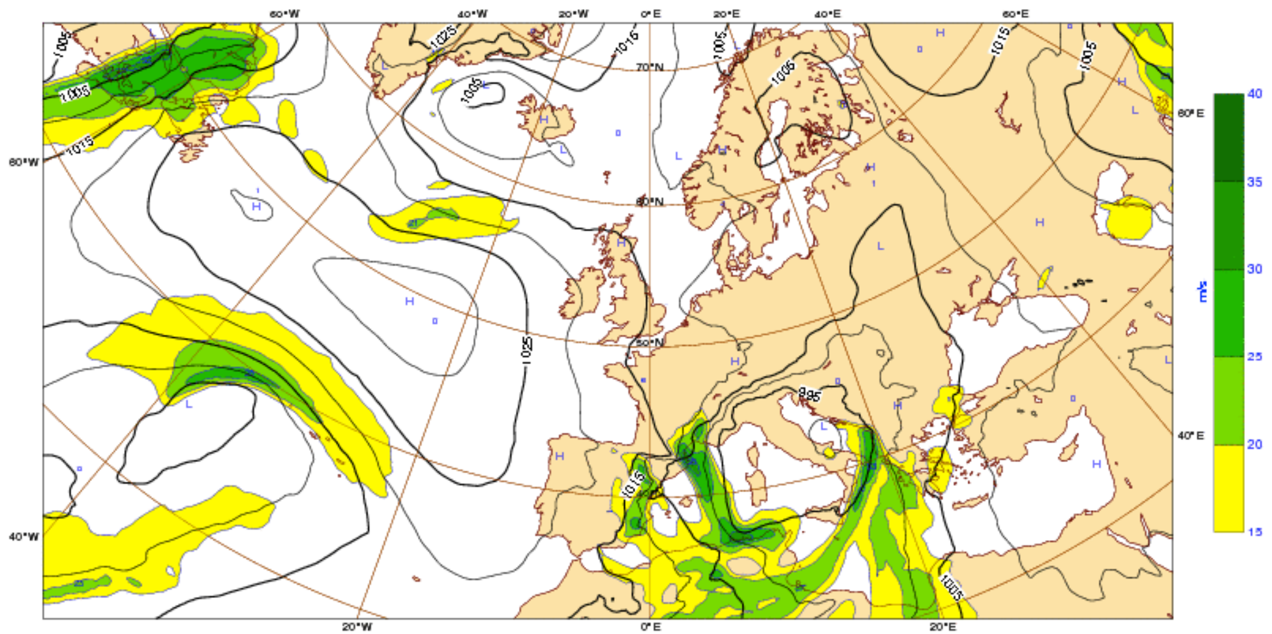
Thursday 14 March 2013 00UTC ©ECMWF Forecast t+144 VT: Wednesday 20 March 2013 00UTC
Surface: Mean sea level pressure / 850-hPa wind speed



Wednesday 20 March 2013 00UTC ©ECMWF Analysis t+000 VT: Wednesday 20 March 2013 00UTC
Surface: Mean sea level pressure / 850-hPa wind speed



Thursday 14 March 2013 00UTC ©ECMWF Analysis t+000 VT: Thursday 14 March 2013 00UTC
Surface: Mean sea level pressure / 850-hPa wind speed



Résultats extraits de :

Richardson *et al.*, 2013, *Evaluations of ECMWF forecasts including 2012-2013 upgrades*, Memorandum Technique 710, CEPMMT, Reading, GB.

Disponible à l'adresse

http://www.ecmwf.int/publications/library/ecpublications/_pdf/tm/701-800/tm710.pdf

(voir aussi l'ensemble du site du CEPMMT)

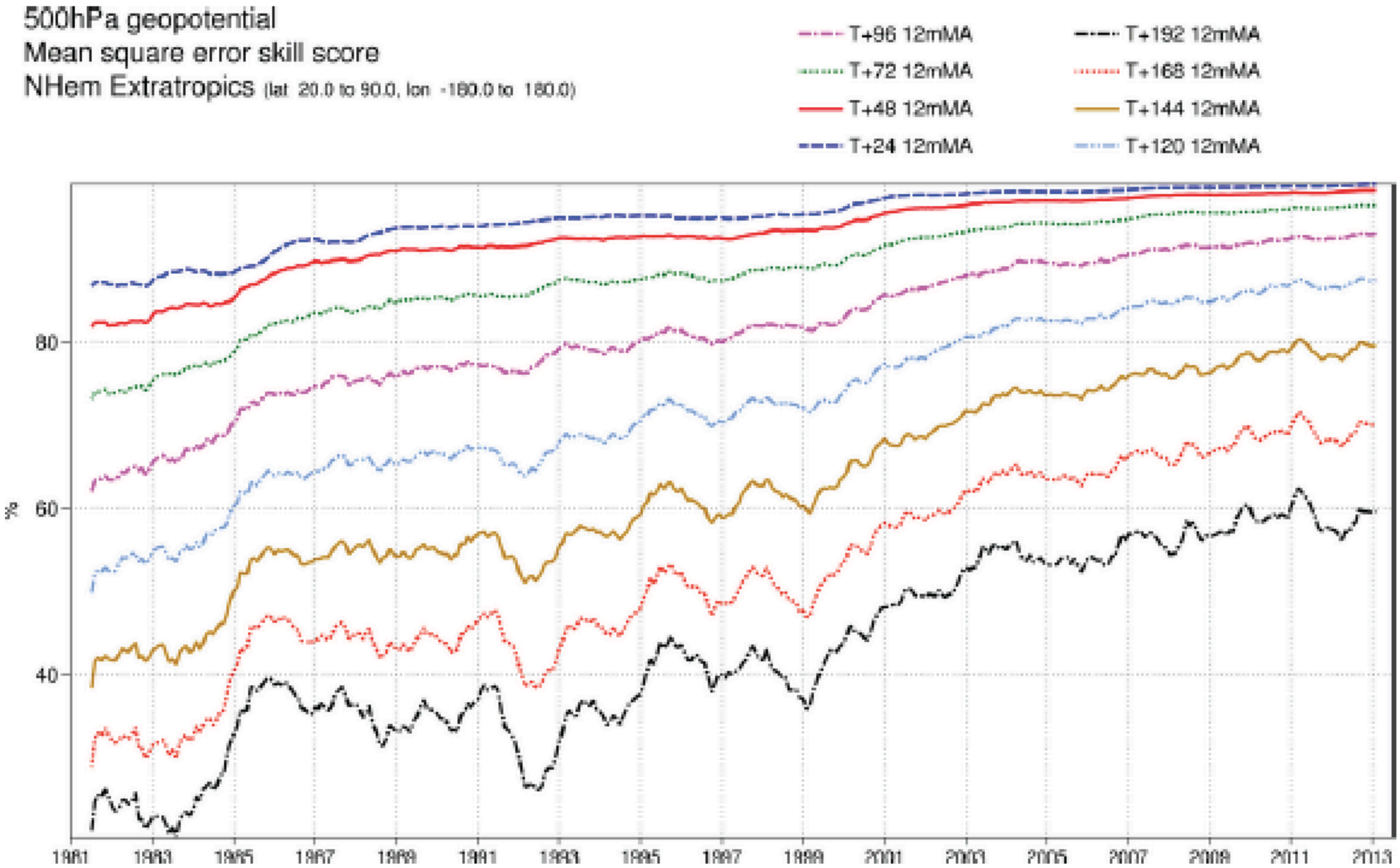


Figure 4: 500 hPa geopotential height skill score for Europe (top) and the northern hemisphere extratropics (bottom), showing 12-month moving averages for forecast ranges from 24 to 192 hours. The last point on each curve is for the 12-month period August 2012–July 2013.

Persistence = 0 ; climatology = 50 at long range

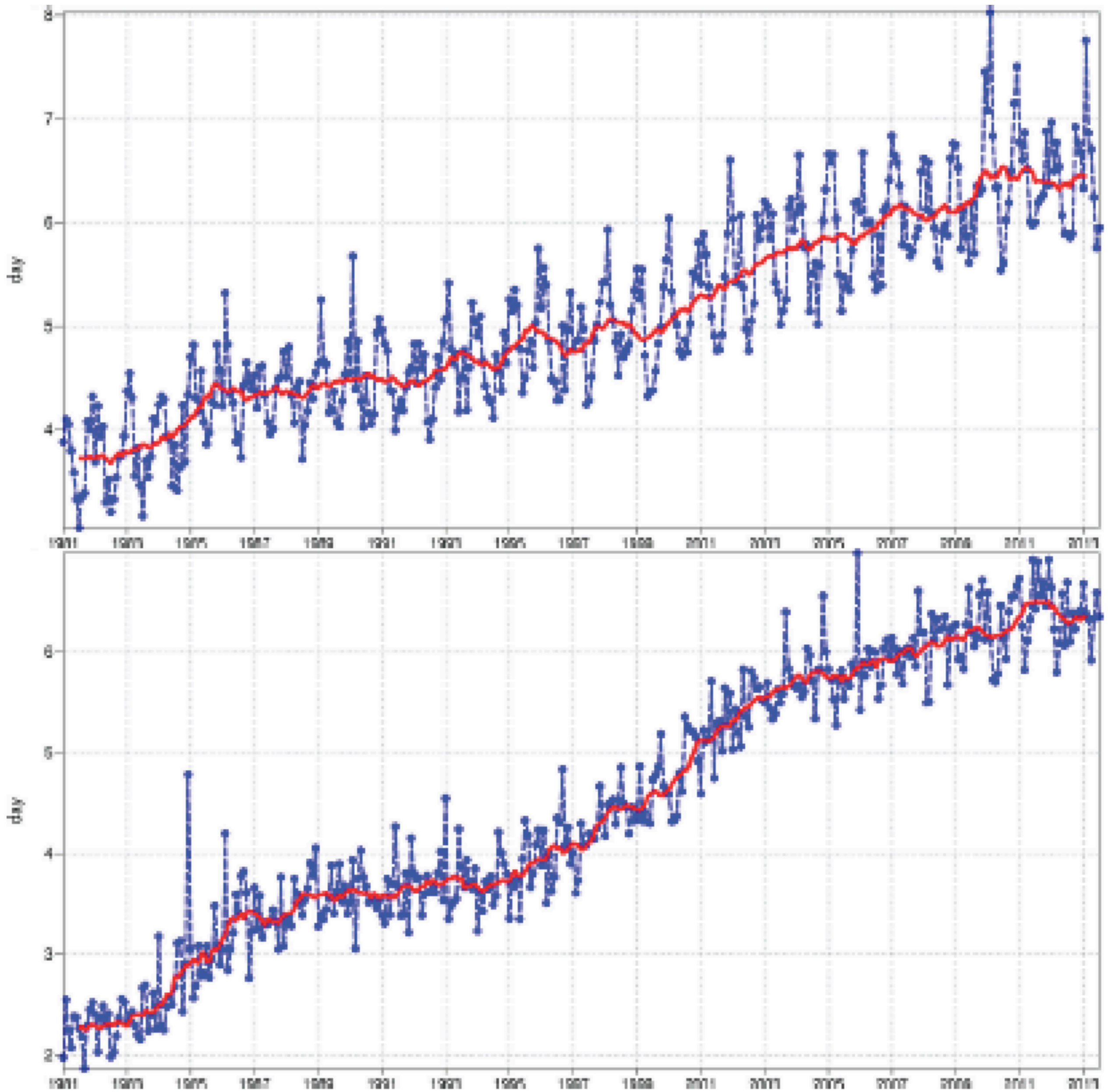
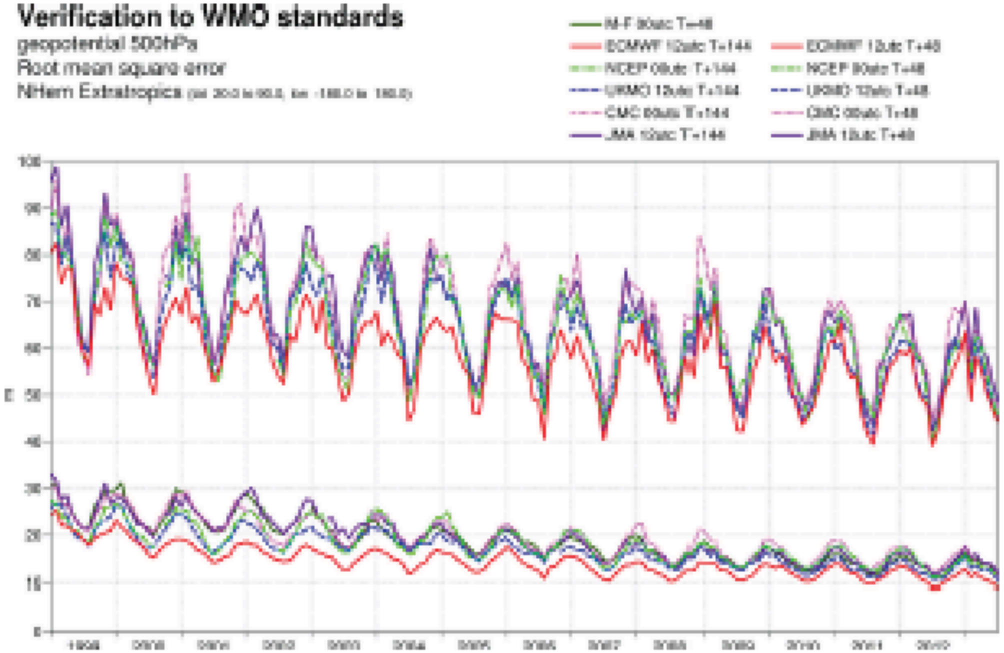


Figure 3: Primary headline score for the high-resolution forecasts. Evolution with time of the 500 hPa geopotential height forecast performance – each point on the curves is the forecast range at which the monthly mean (blue lines) or 12-month mean centred on that month (red line) of the forecast anomaly correlation (ACC) with the verifying analysis falls below 80% for Europe (top), northern hemisphere extratropics (centre) and southern hemisphere extratropics (bottom).



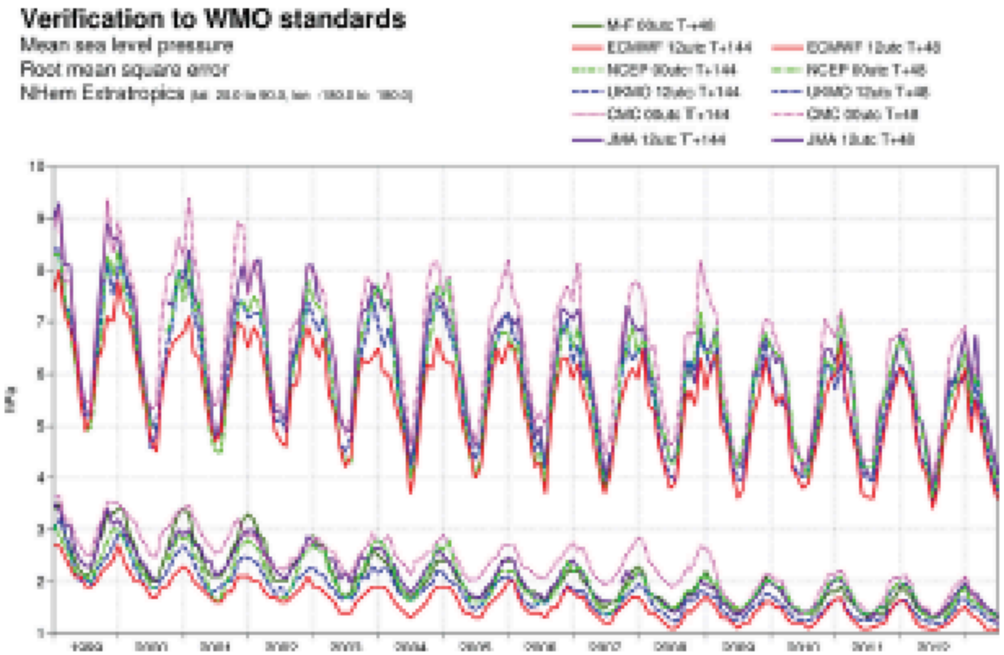
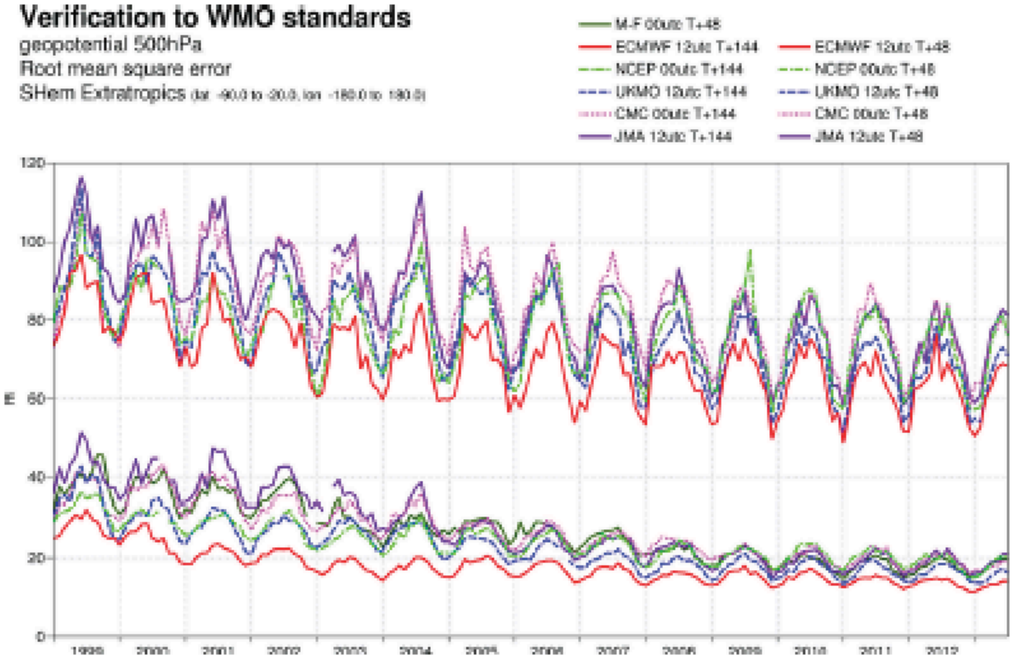


Figure 13: WMO-exchanged scores from global forecast centres. RMS error over northern extratropics for 500 hPa geopotential height (top) and mean sea level pressure (bottom). In each



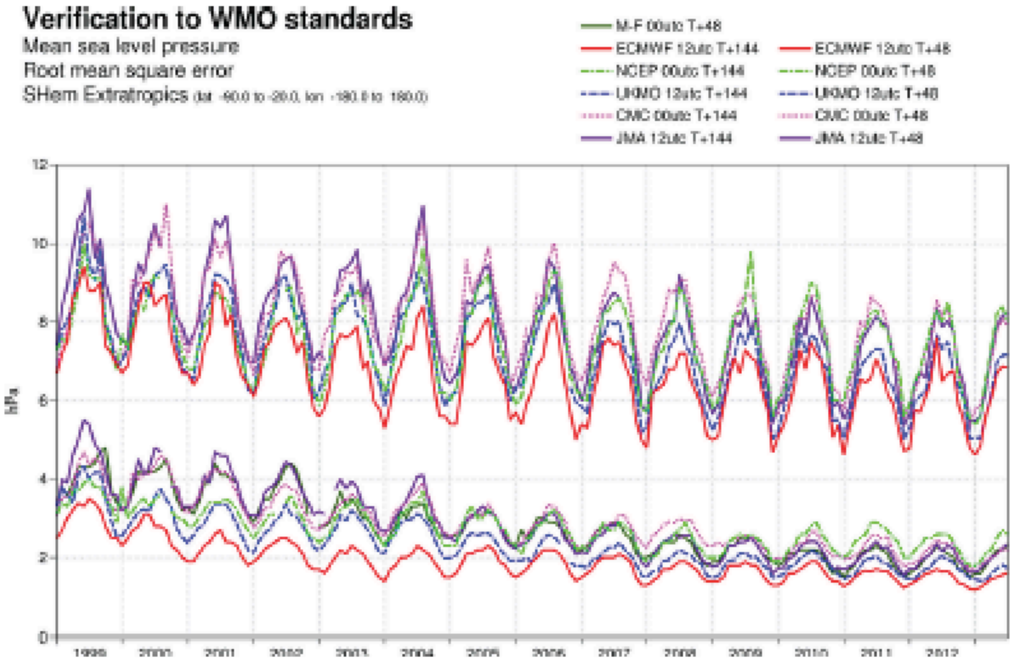
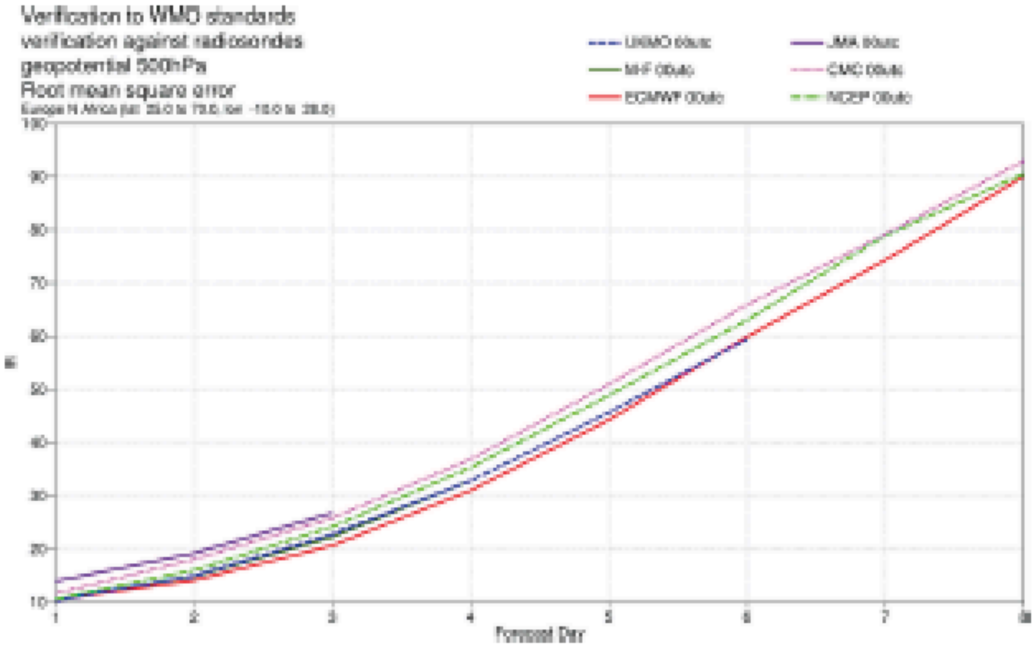


Figure 14: As Figure 13 for the southern hemisphere.



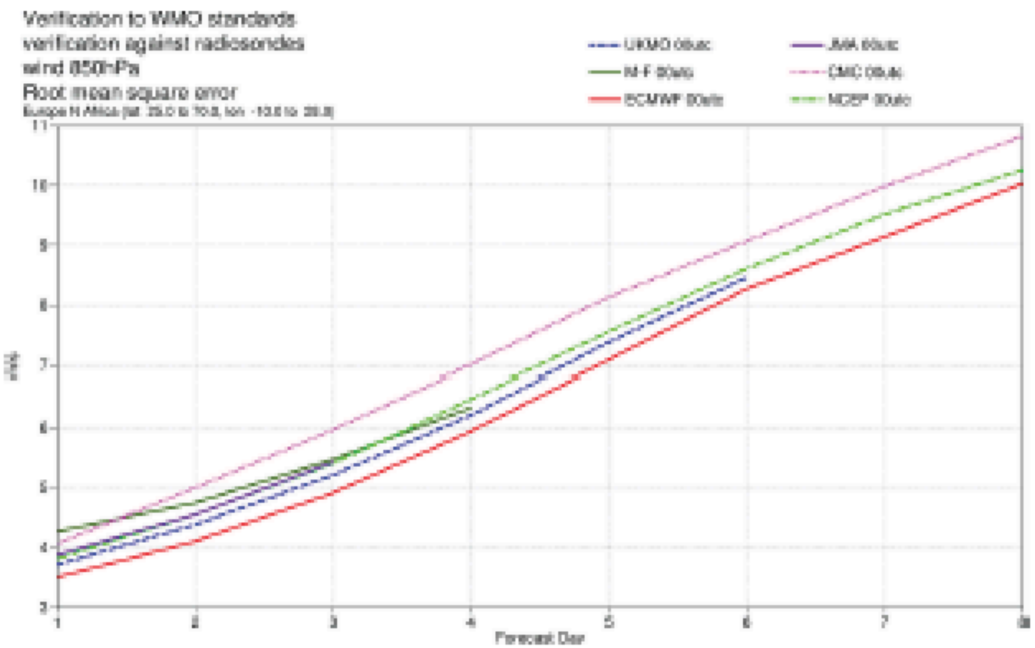


Figure 15: WMO-exchanged scores using radiosondes: 500 hPa height (top) and 850 hPa wind (bottom) RMS error over Europe (annual mean August 2012–July 2013).

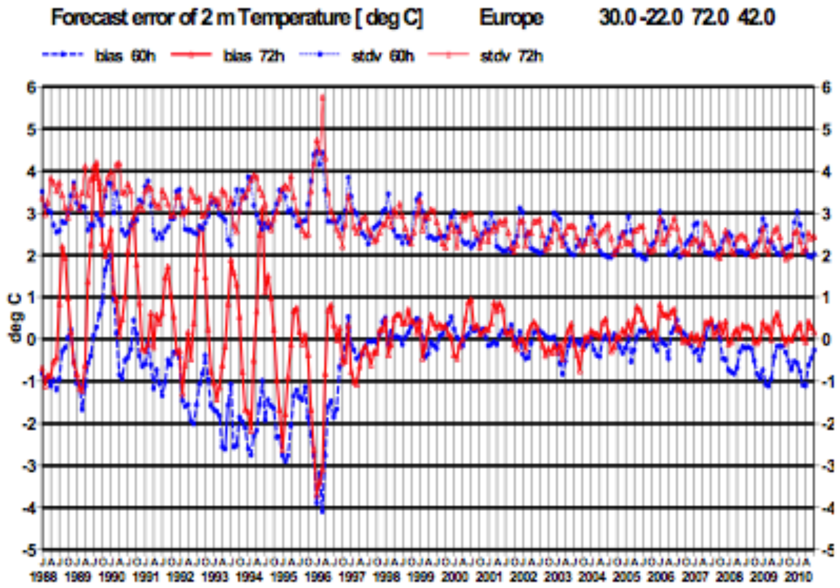


Figure 16: Verification of 2 metre temperature forecasts against European SYNOP data on the GTS for 60-hour (night-time) and 72-hour (daytime) forecasts. Lower pair of curves show bias, upper curves are standard deviation of error.

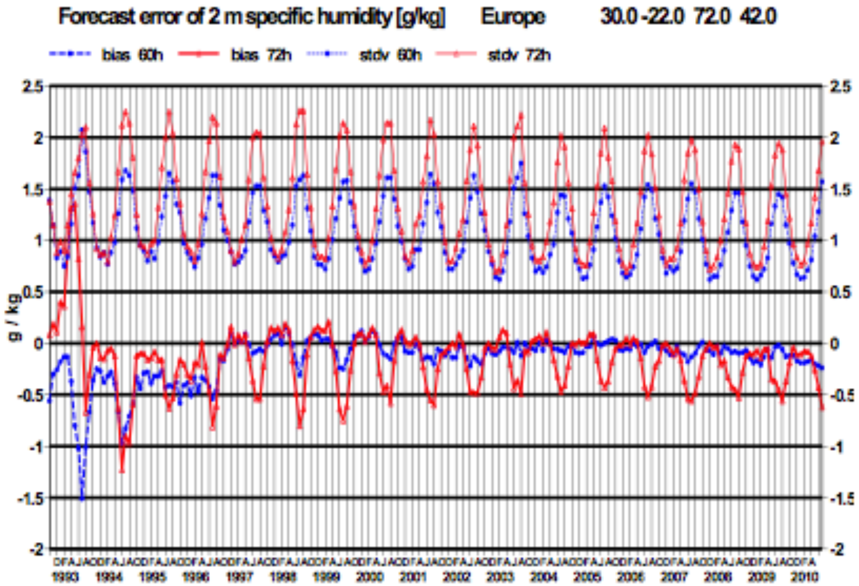
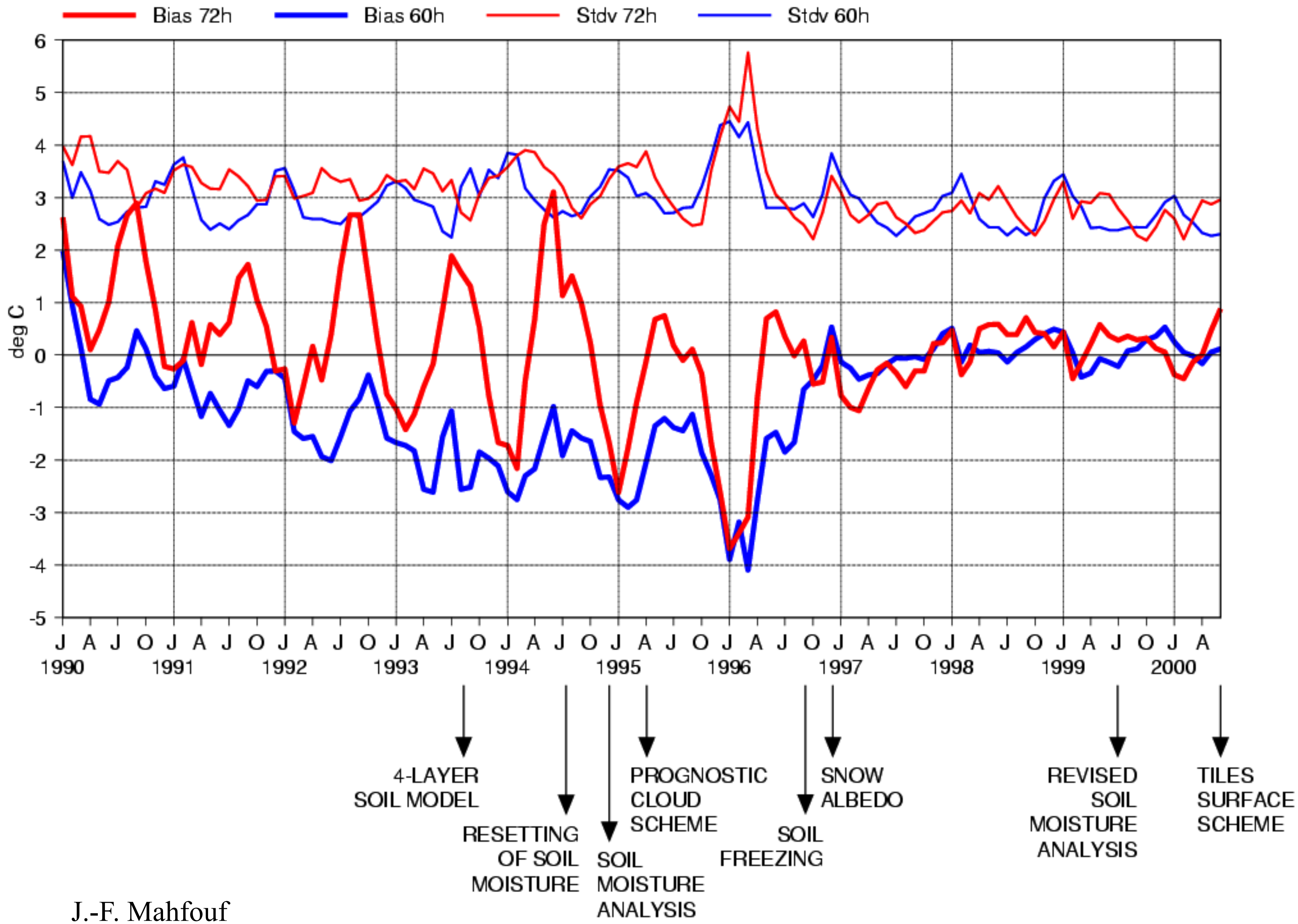
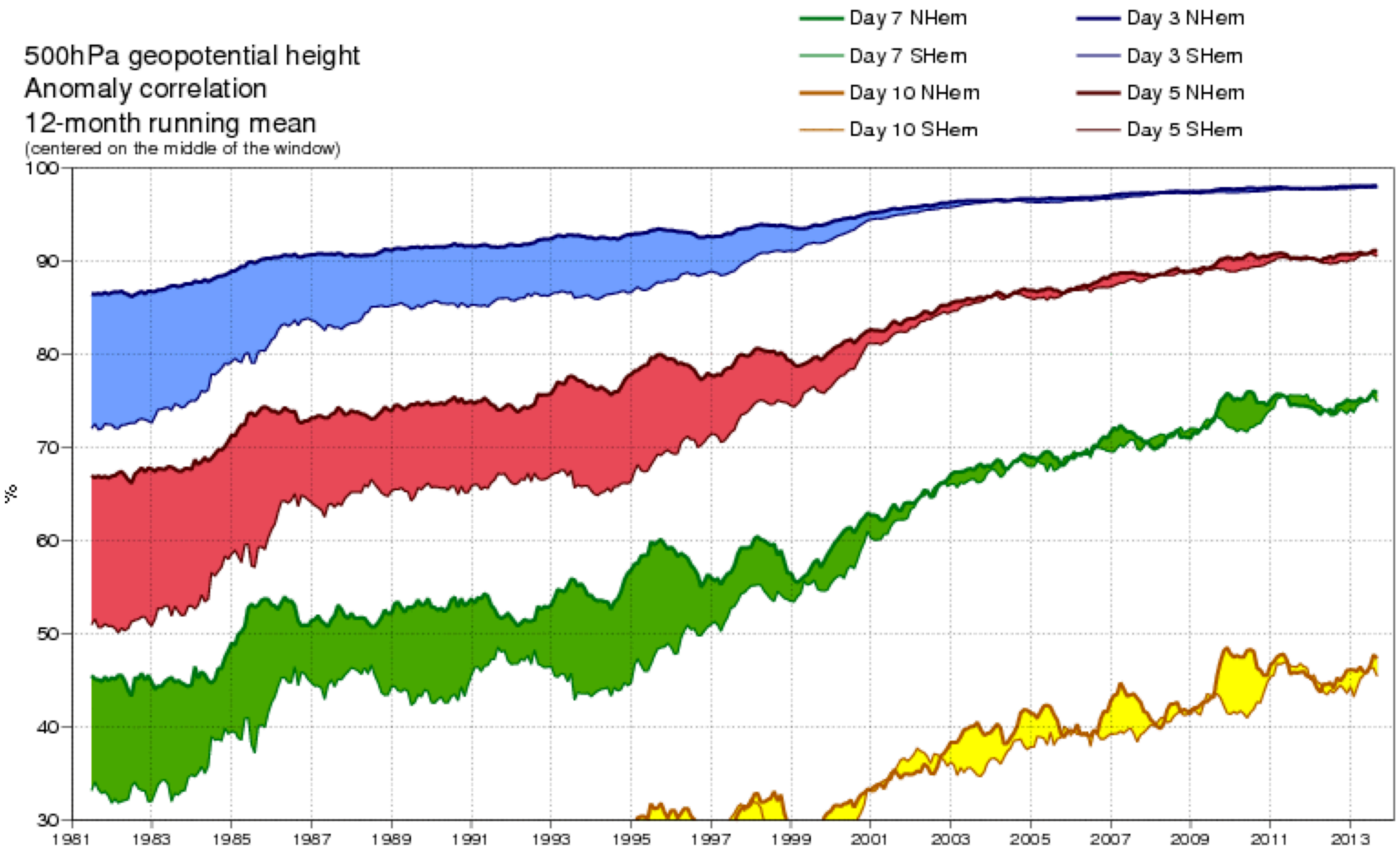


Figure 17: Verification of 2 metre specific humidity forecasts against European SYNOP data on the GTS for 60-hour (night-time) and 72-hour (daytime) forecasts. Lower pair of curves show bias, upper curves are standard deviation of error.



Bias 72h
Bias 60h
Stdv 72h
Stdv 60h
deg C
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
J A J O J A J O J A J O J A J O J A J O J A J O J A J O J A J O J A J O J A J O J A
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
4-LAYER SOIL MODEL
RESETTING OF SOIL MOISTURE
SOIL MOISTURE ANALYSIS
PROGNOSTIC CLOUD SCHEME
SOIL FREEZING
SNOW ALBEDO
REVISED SOIL MOISTURE ANALYSIS
TILES SURFACE SCHEME

J.-F. Mahfouf



500hPa geopotential height
Anomaly correlation
12-month running mean
(centered on the middle of the window)
Day 7 NHem
Day 7 SHem
Day 10 NHem
Day 10 SHem
Day 3 NHem
Day 3 SHem
Day 5 NHem
Day 5 SHem
%
100
90
80
70
60
50
40
30
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013

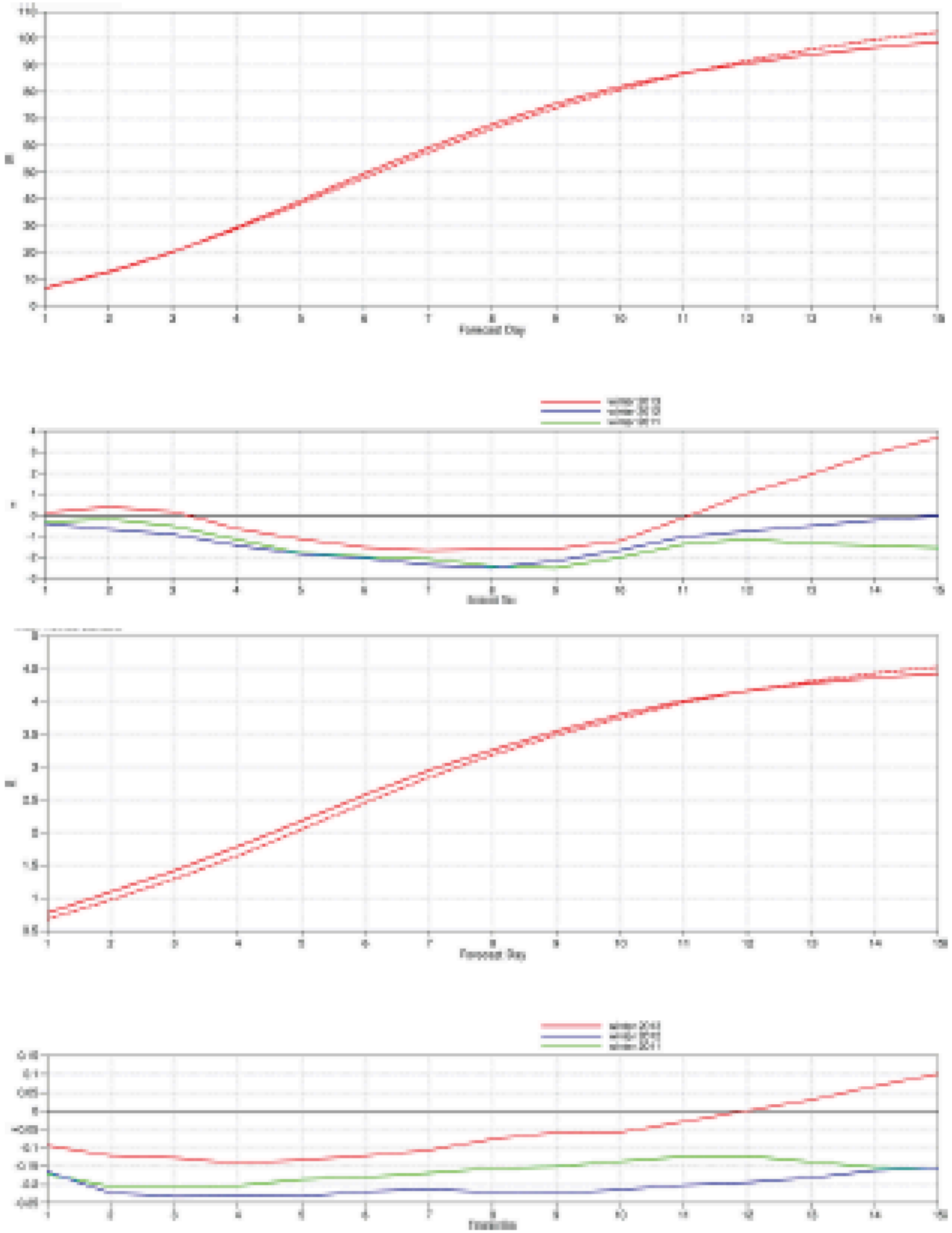


Figure 10: Ensemble spread (standard deviation, dashed lines) and RMS error of ensemble-mean (solid lines) for winter 2012–2013 (upper figure in each panel), and differences of ensemble spread and RMS error of ensemble mean for last three winter seasons (lower figure in each panel, negative values indicate spread is too small); plots are for 500 hPa geopotential (top) and 850 hPa temperature (bottom) over the extratropical northern hemisphere for forecast days 1 to 15.

Problèmes restants

- Cycle de l'eau (évaporation, condensation, influence sur le rayonnement absorbé ou émis par l'atmosphère)
- Échanges avec l'océan ou la surface continentale (chaleur, eau, quantité de mouvement, …)
- …