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

Année Universitaire 2012-2013

Modélisation Numérique de l'Écoulement Atmosphérique et Assimilation de Données

Olivier Talagrand

Cours 3

29 Mars 2013

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

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

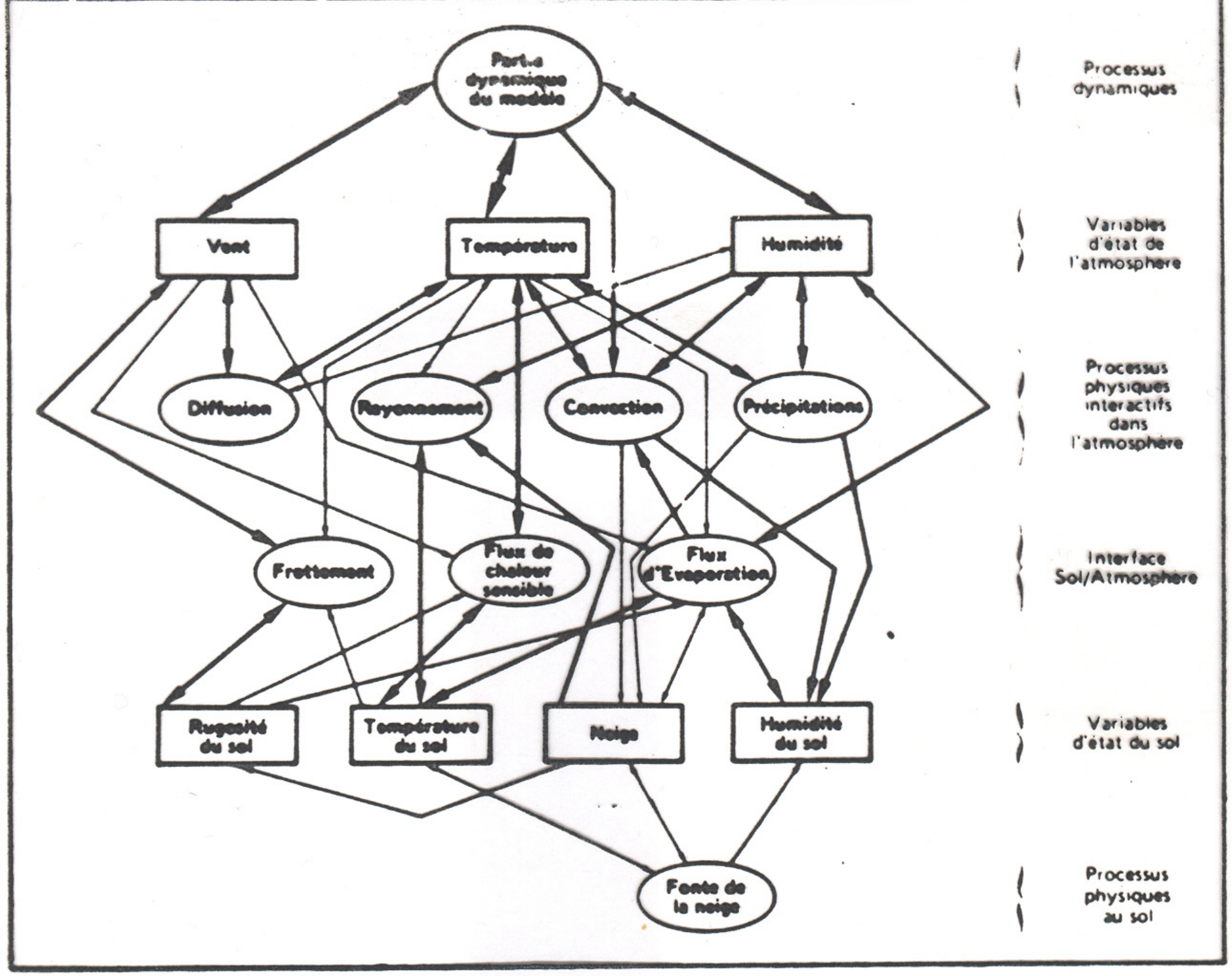
- Equation d’état

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

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

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

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)

Depuis le 26 Janvier 2010

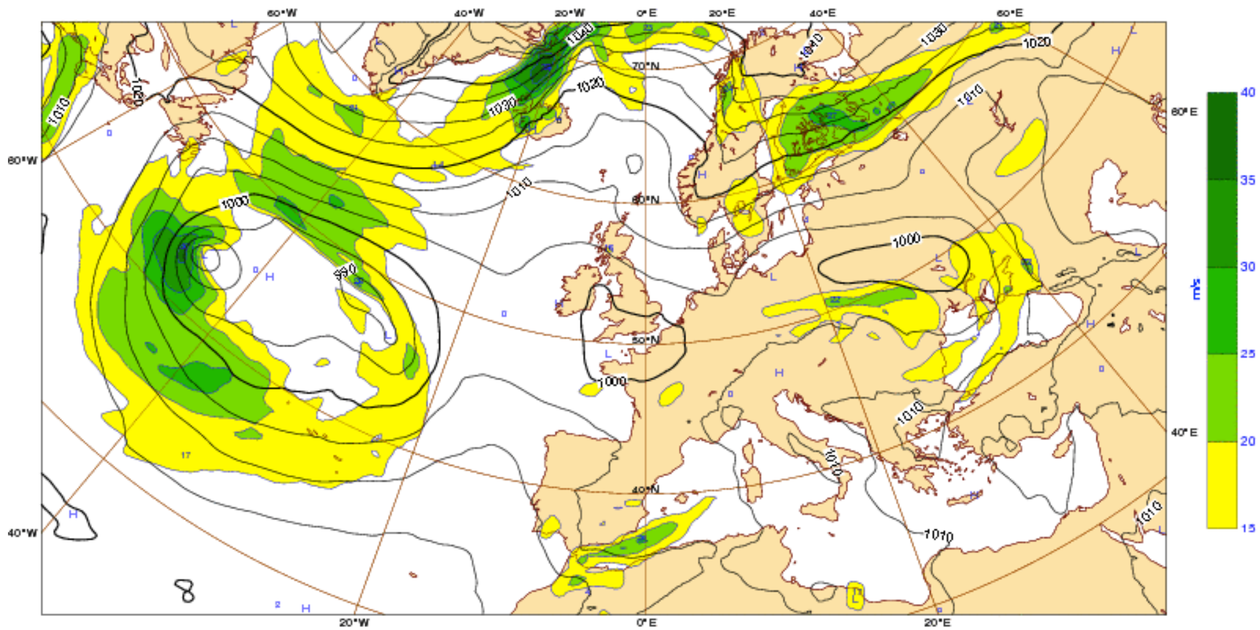
Troncature triangulaire T1279 (résolution horizontale ≈ 16 kilomètres)

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

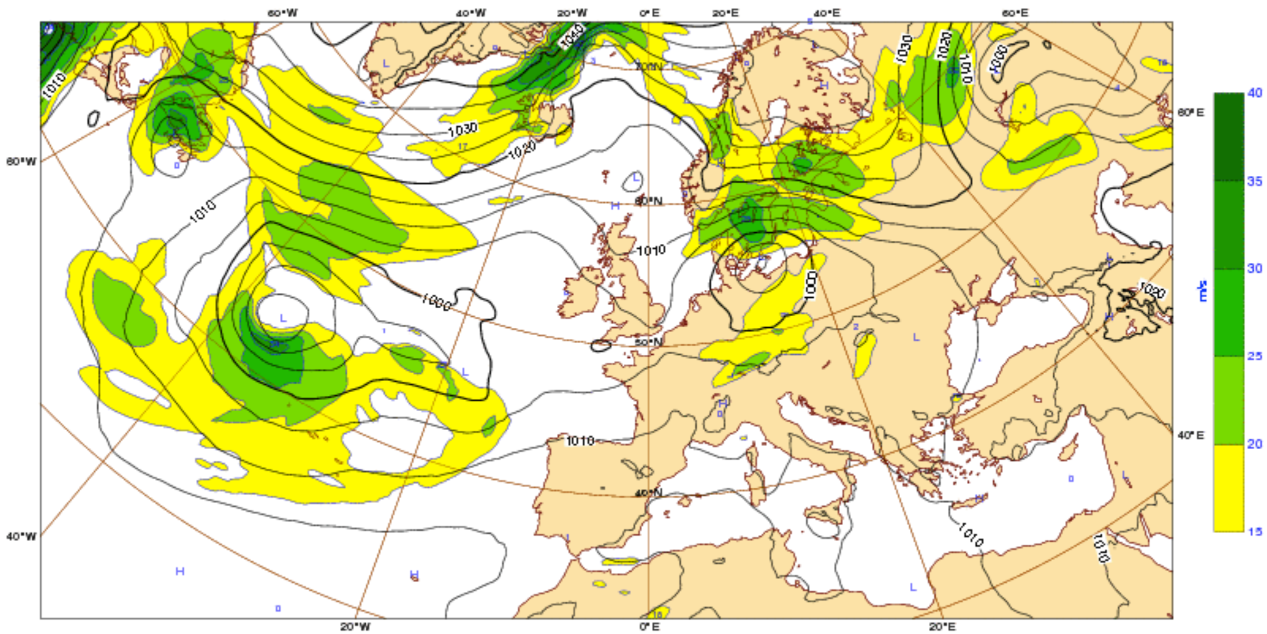
Dimension du vecteur d'état correspondant $\approx 1{,}5\ 10^9$

Pas de discrétisation temporelle : 10 minutes

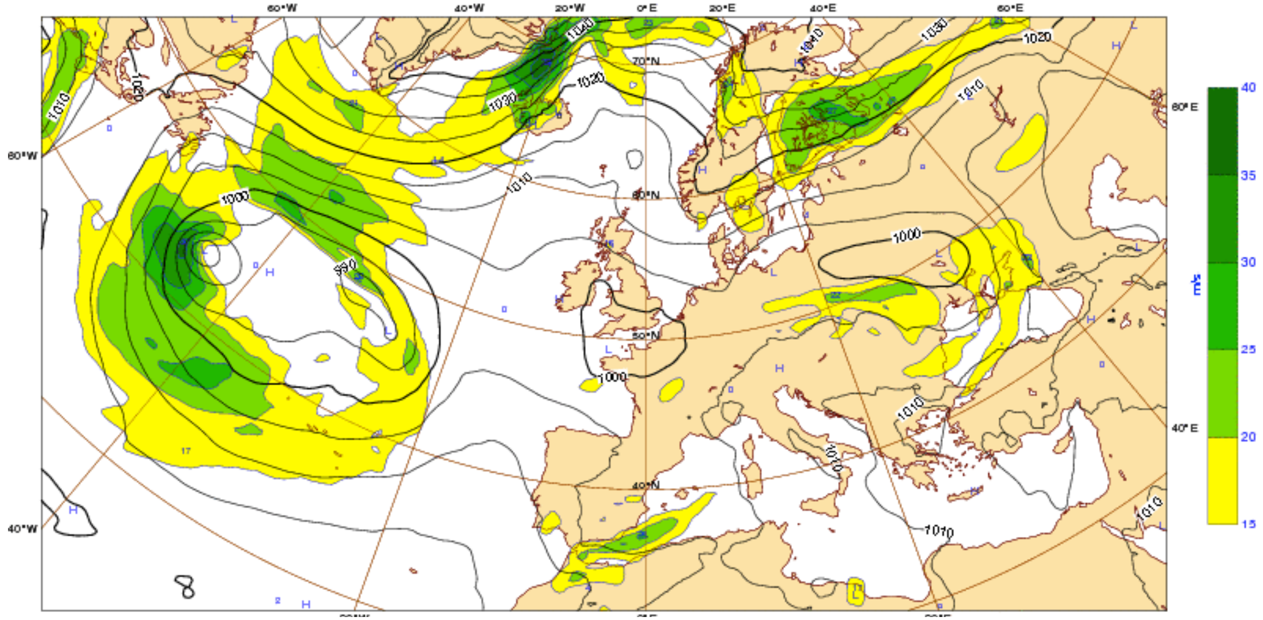
Wednesday 20 March 2013 00UTC ©ECMWF Analysis t+000 VT: Wednesday 20 March 2013 00UTC
Surface: Mean sea level pressure / 850-hPa wind speed



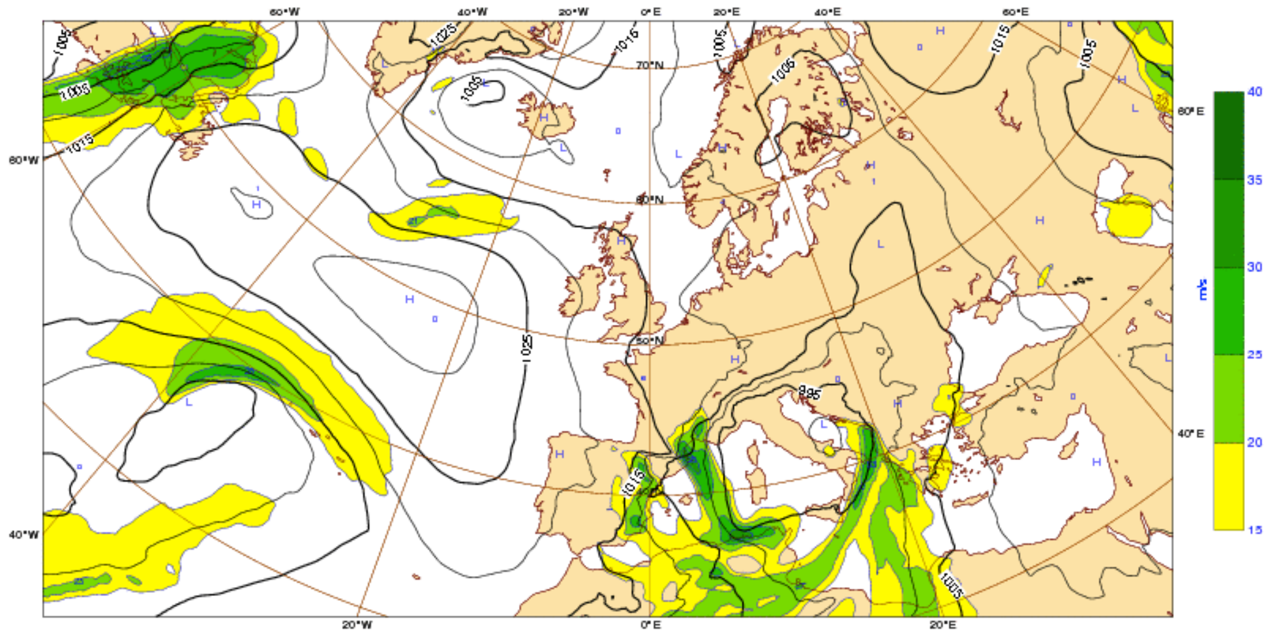
Thursday 14 March 2013 00UTC ©ECMWF Forecast t+144 VT: Wednesday 20 March 2013 00UTC
Surface: Mean sea level pressure / 850-hPa wind speed



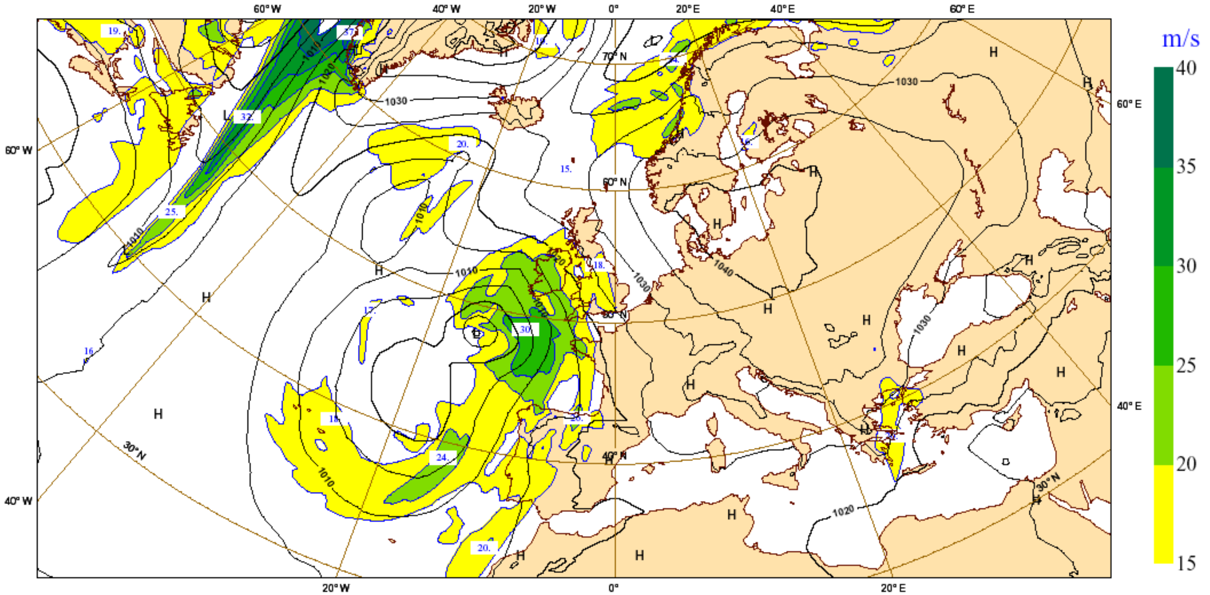
Wednesday 20 March 2013 00UTC ©ECMWF Analysis t+000 VT: Wednesday 20 March 2013 00UTC
Surface: Mean sea level pressure / 850-hPa wind speed



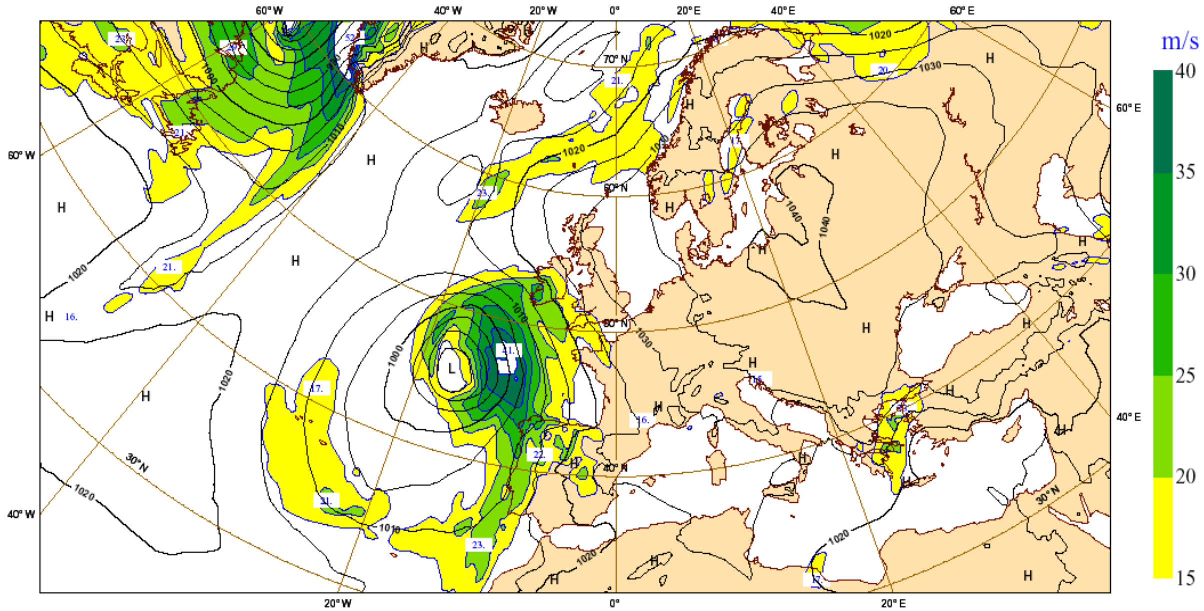
Thursday 14 March 2013 00UTC ©ECMWF Analysis t+000 VT: Thursday 14 March 2013 00UTC
Surface: Mean sea level pressure / 850-hPa wind speed



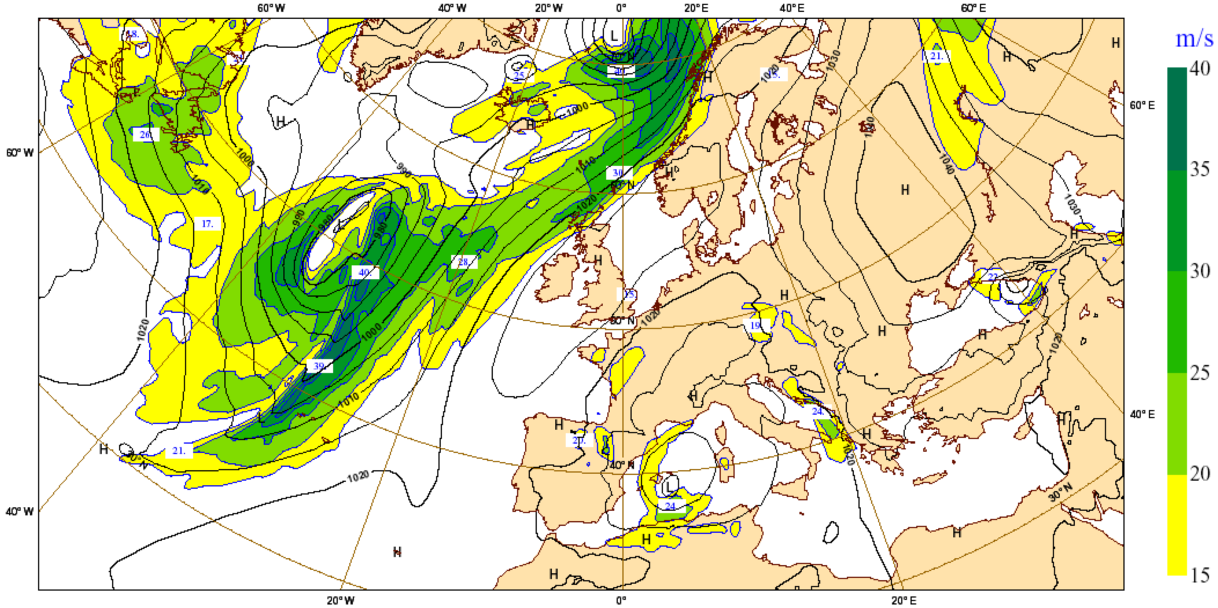
Monday 7 November 2011 00UTC ©ECMWF Forecast t+144 VT: Sunday 13 November 2011 00UTC
Surface: Mean sea level pressure / 850-hPa wind speed



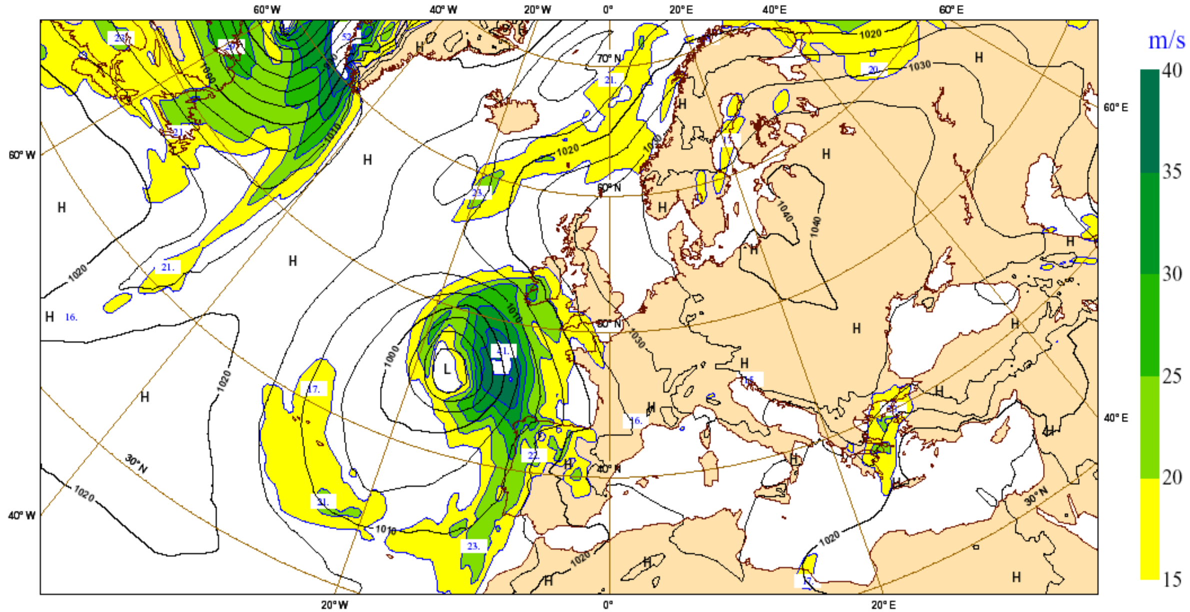
Sunday 13 November 2011 00UTC ©ECMWF Analysis t+000 VT: Sunday 13 November 2011 00UTC
Surface: Mean sea level pressure / 850-hPa wind speed



Monday 7 November 2011 00UTC ©ECMWF Analysis t+000 VT: Monday 7 November 2011 00UTC
Surface: Mean sea level pressure / 850-hPa wind speed



Sunday 13 November 2011 00UTC ©ECMWF Analysis t+000 VT: Sunday 13 November 2011 00UTC
Surface: Mean sea level pressure / 850-hPa wind speed



Résultats extraits de

Richardson *et al.*, 2010, *Verification statistics and evaluations of ECMWF forecasts in 2009-2010*, Memorandum Technique 635 CEPMMT, Reading, GB.

Disponible à l'adresse

http://www.ecmwf.int/publications/library/ecpublications/_pdf/tm/601-700/tm635.pdf

(voir aussi http://www.ecmwf.int/publications/library/ecpublications/_pdf/tm/601-700/tm654.pdf)

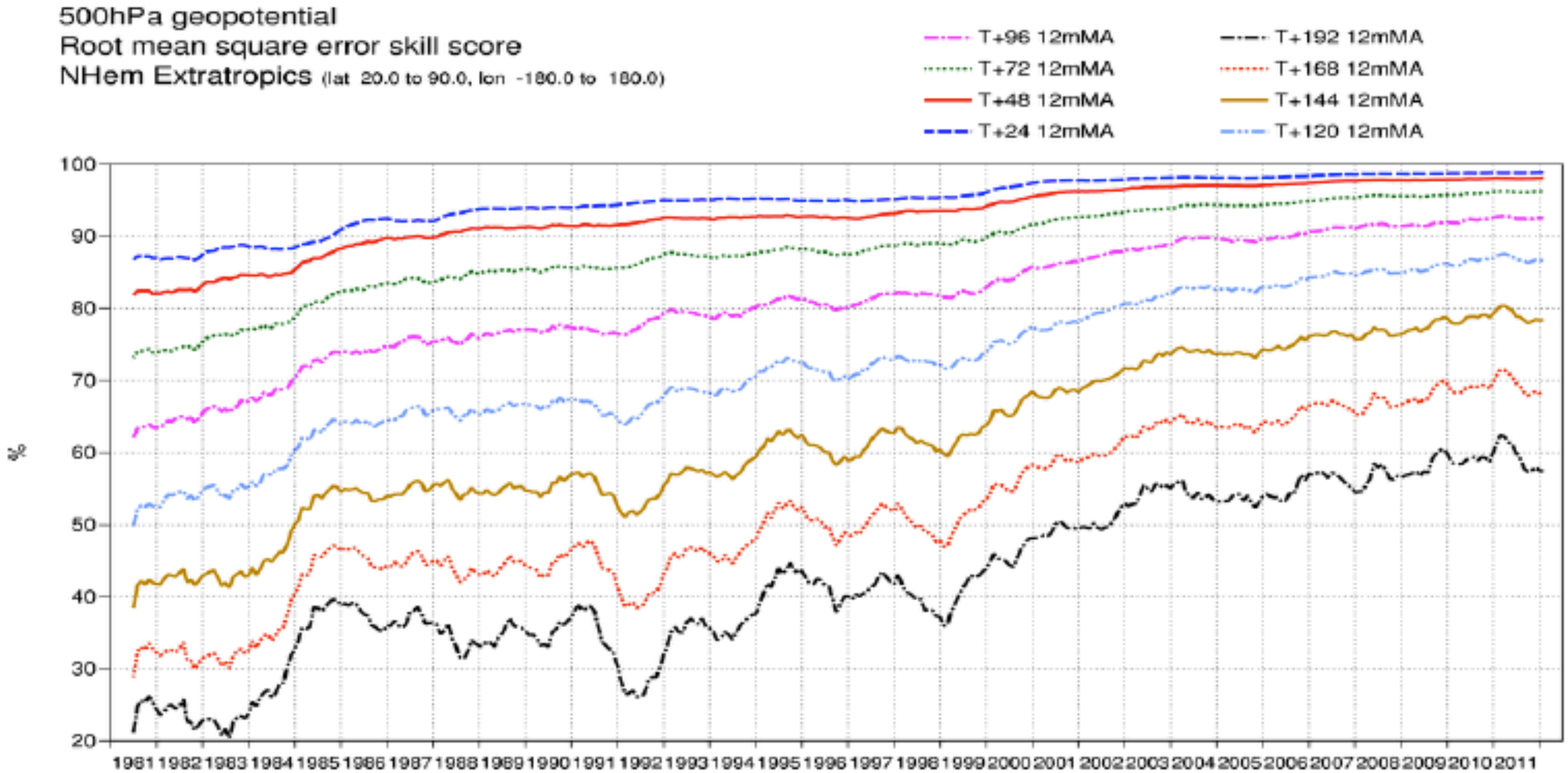


Figure 2: 500 hPa geopotential height skill score for Europe (top) and the northern hemisphere extratropics (bottom), showing 12-month moving averages for forecast ranges from 24 to 192 hours. The last point on each curve is for the 12-month period August 2011–July 2012.

Persistence = 0 ; climatology = 50 at long range

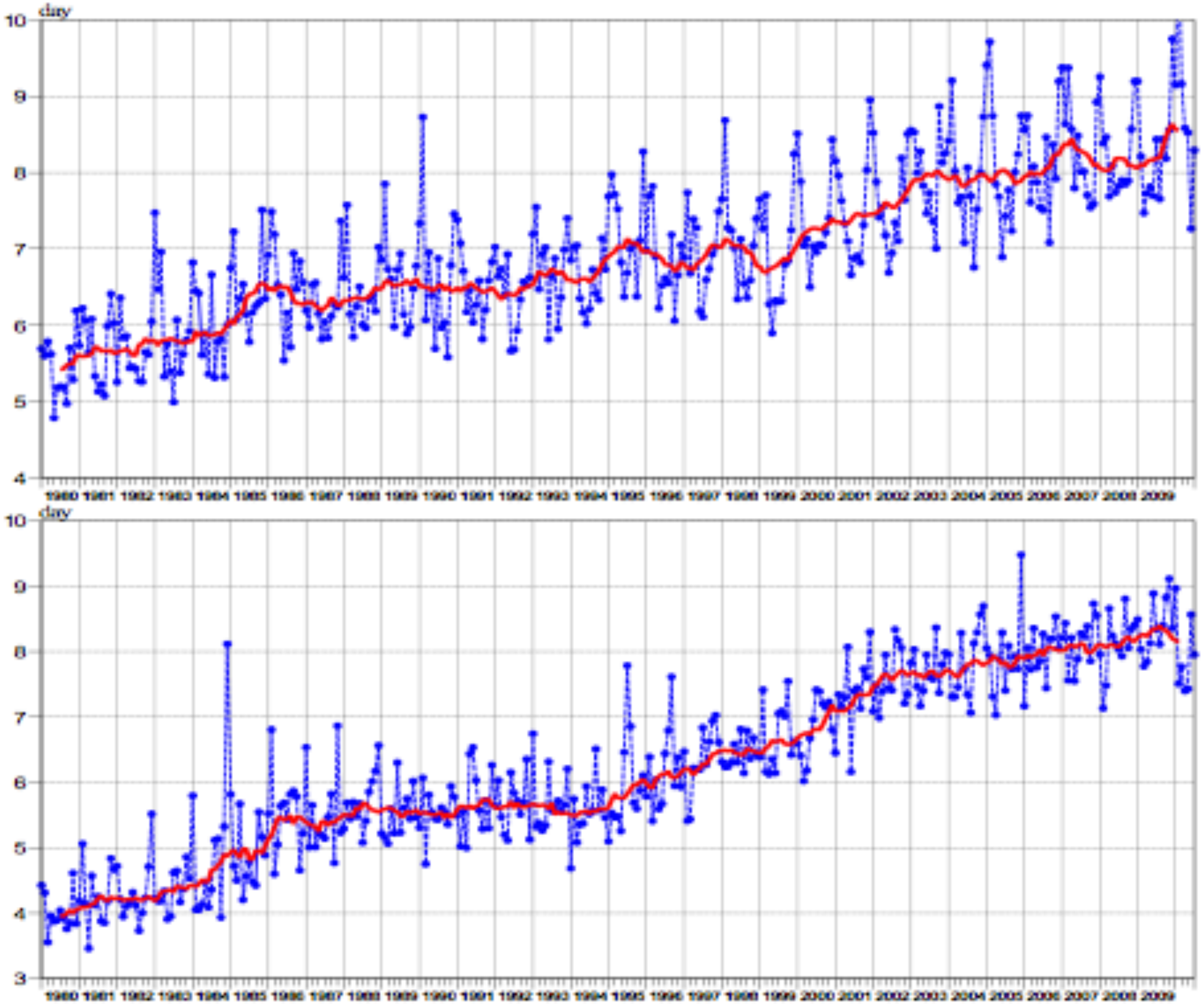


Figure 2: Evolution with time of the 500 hPa geopotential height forecast performance – each point on curves is the forecast range at which the monthly mean (blue lines) or 12-month mean centred on that month (red line) of the forecast anomaly correlation with the verifying analysis falls below 60% for Europe (top), northern hemisphere extratropics (centre) and southern hemisphere extratropics (bottom). If the monthly mean correlation remains above 60% throughout the 10-day forecast range, this is indicated by the absence of a blue symbol for that month (e.g. northern hemisphere and Europe for February 2010).

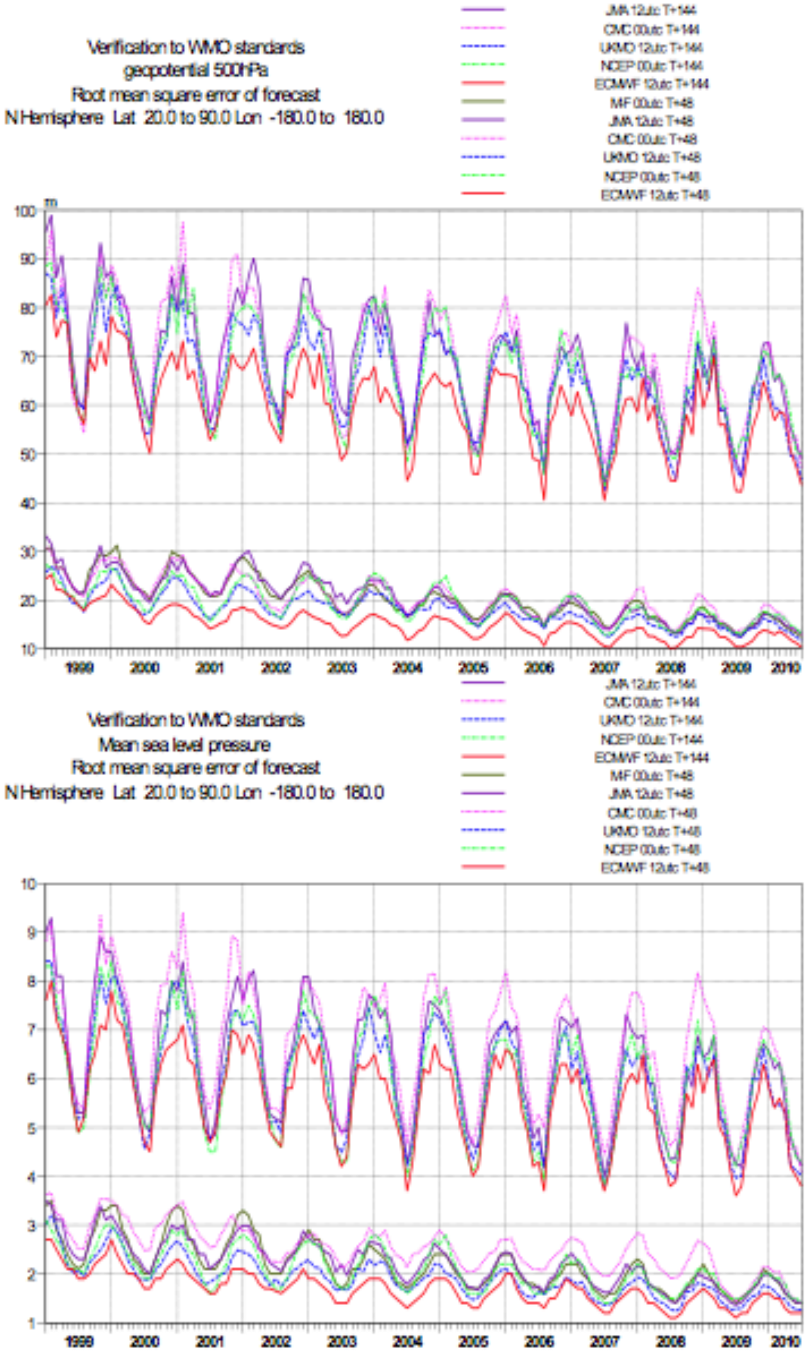


Figure 11: WMO/CBS exchanged scores from global forecast centres. RMS error over northern extratropics for 500 hPa geopotential height (top) and MSLP (bottom). In each panel the upper

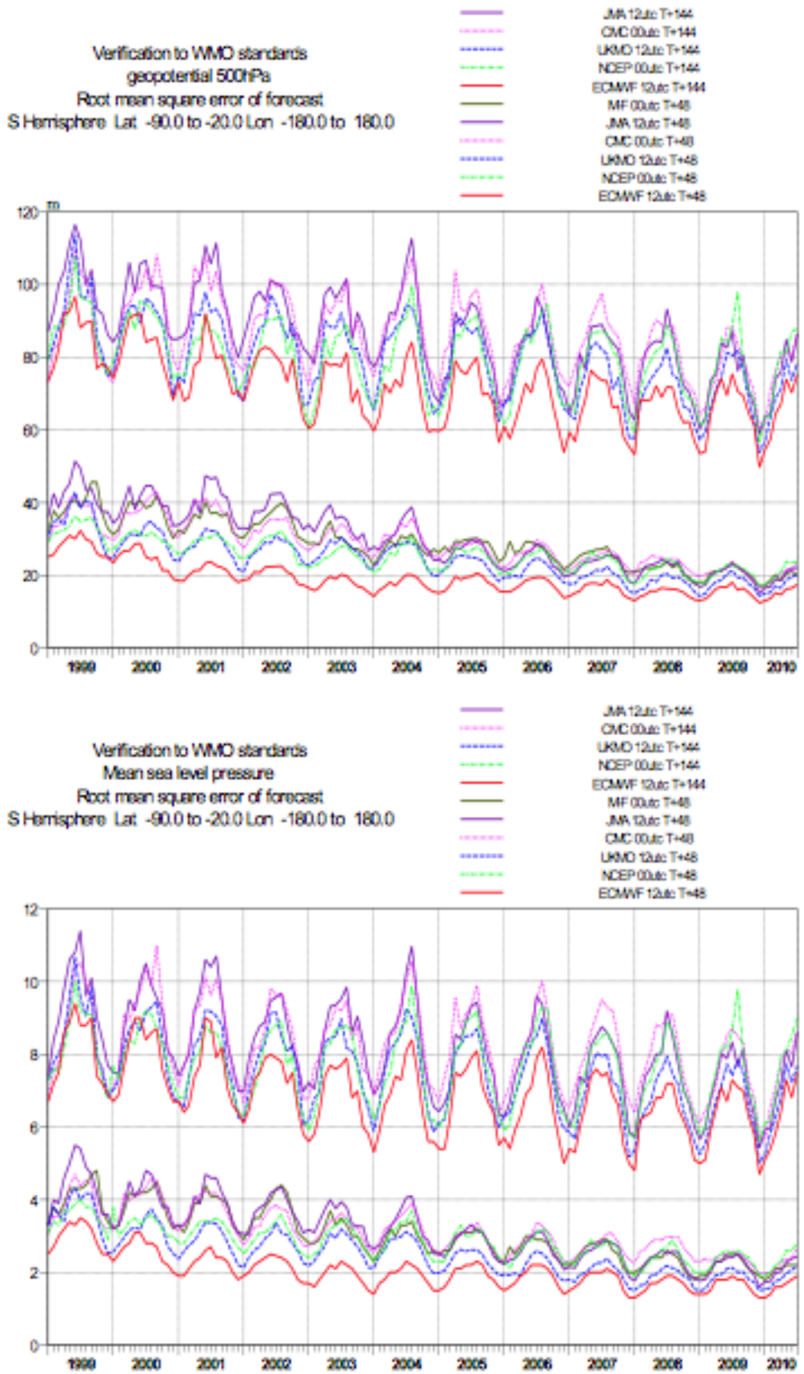


Figure 12: As Figure 11 for the southern hemisphere.

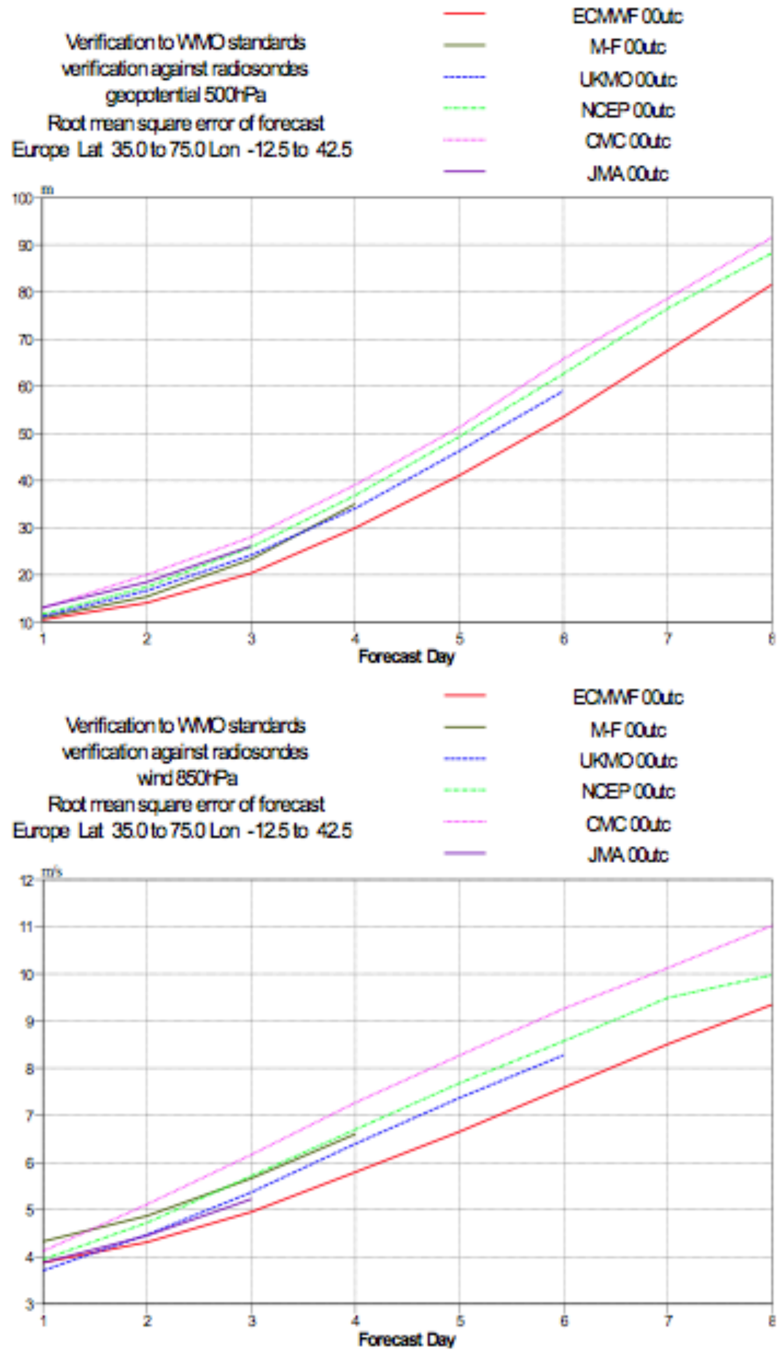


Figure 13: WMO/CBS exchanged scores using radiosondes: 500 hPa height (top) and 850 hPa wind(bottom) RMS error over Europe (annual mean August 2009 – July 2010).

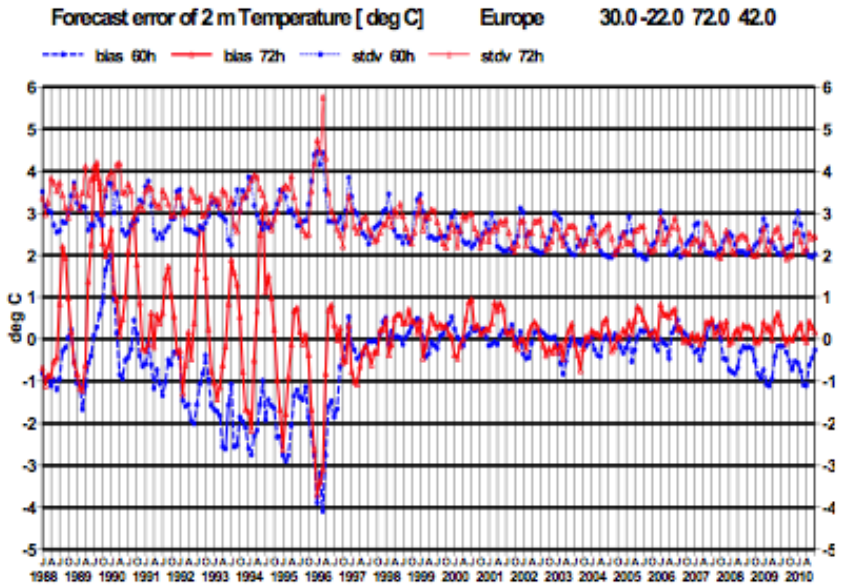


Figure 16: Verification of 2 metre temperature forecasts against European SYNOP data on the GTS for 60-hour (night-time) and 72-hour (daytime) forecasts. Lower pair of curves show bias, upper curves are standard deviation of error.

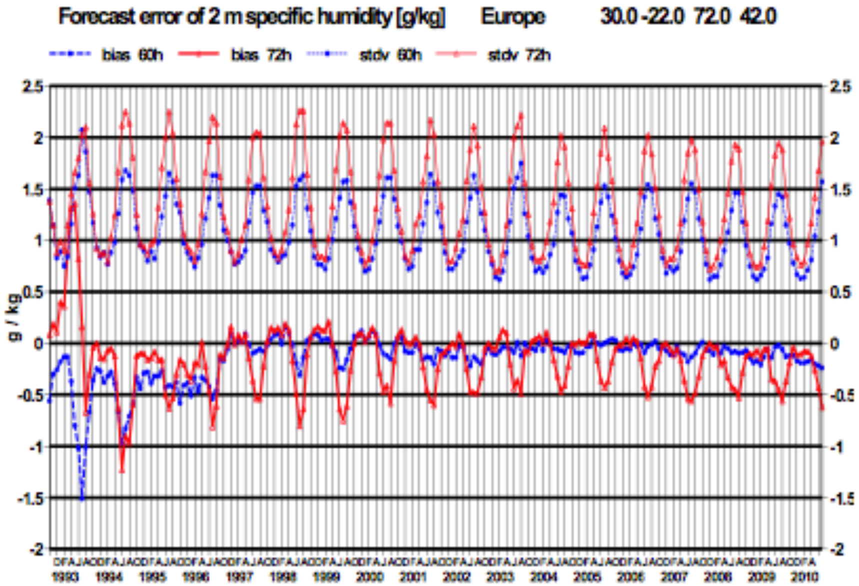
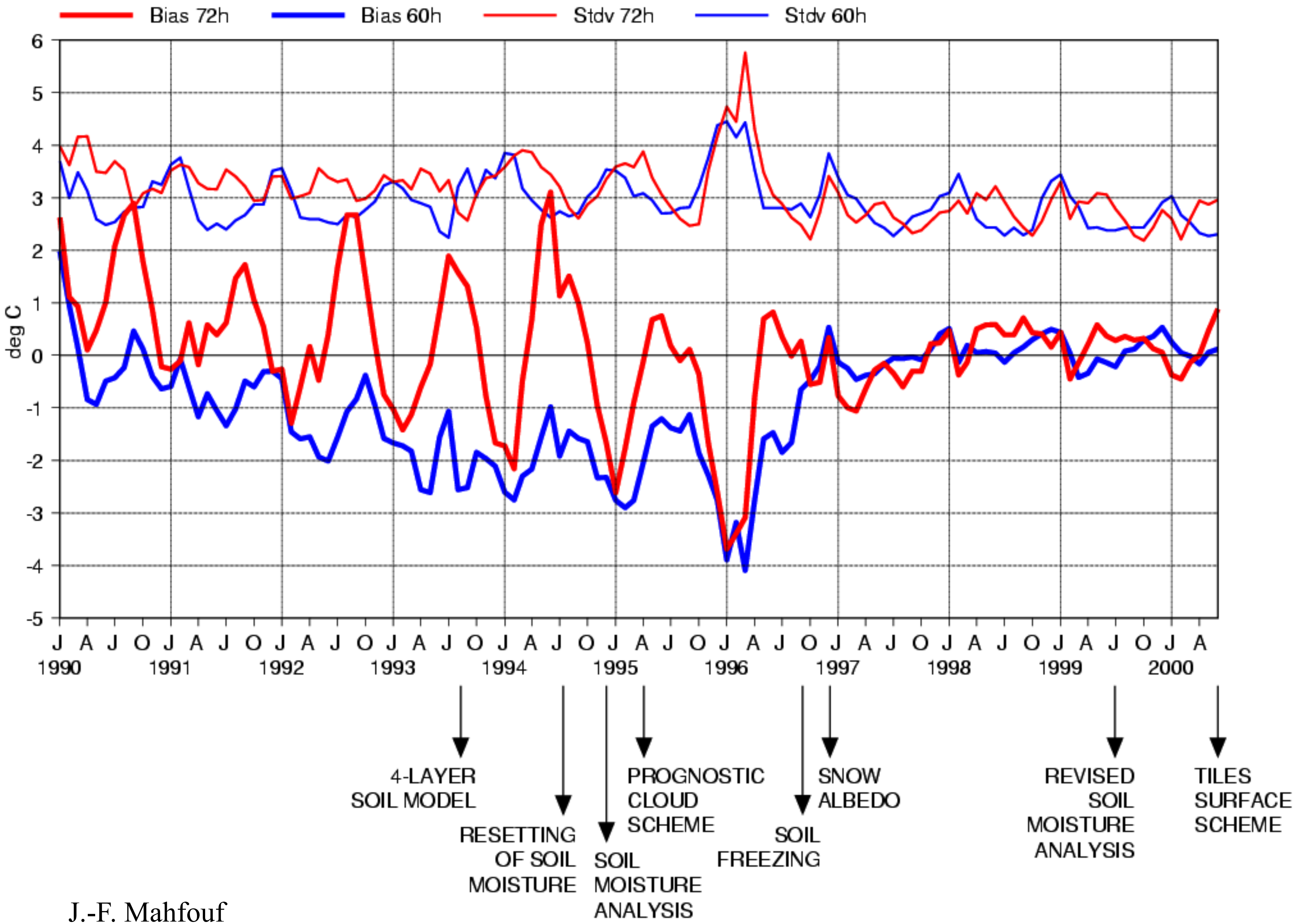


Figure 17: Verification of 2 metre specific humidity forecasts against European SYNOP data on the GTS for 60-hour (night-time) and 72-hour (daytime) forecasts. Lower pair of curves show bias, upper curves are standard deviation of error.



Bias 72h
Bias 60h
Stdv 72h
Stdv 60h
deg C
6
5
4
3
2
1
0
-1
-2
-3
-4
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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

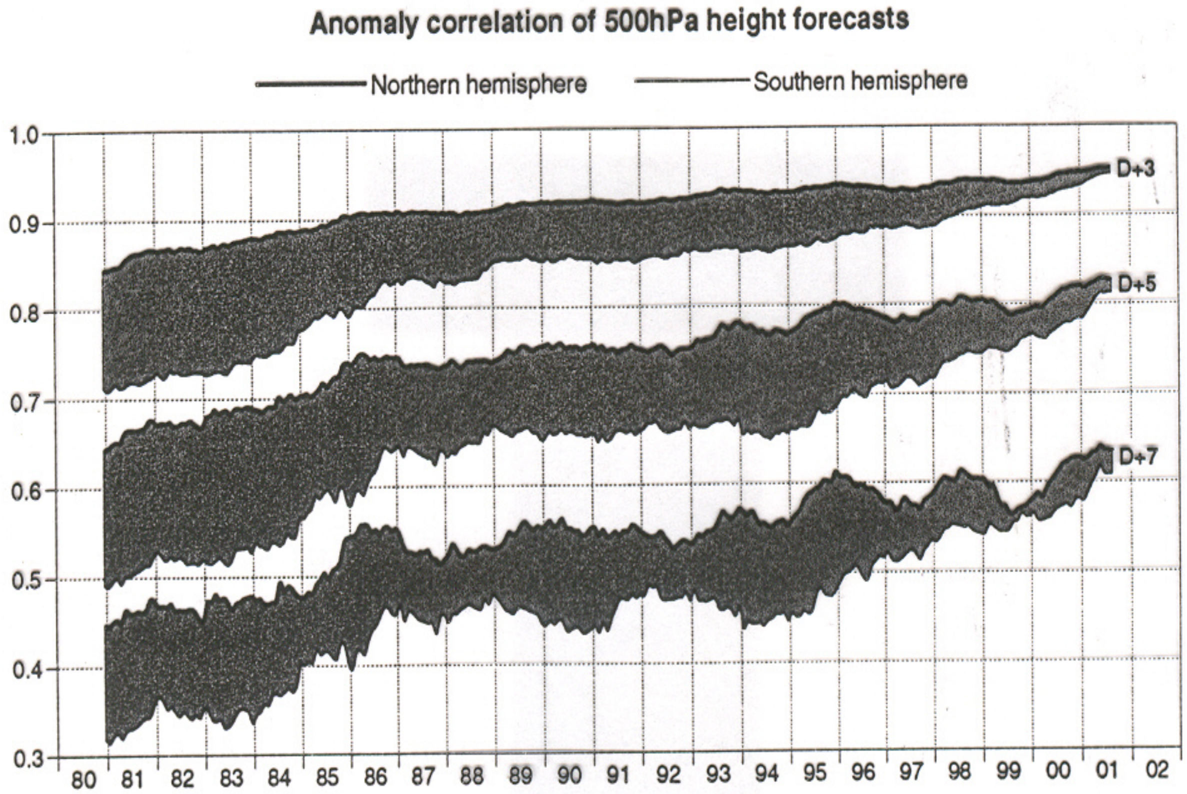


Fig 4. Anomaly correlation coefficients of 3-, 5- and 7-day ECMWF 500hPa height forecasts for the extratropical northern and southern hemispheres, plotted in the form of annual running means of archived monthly-mean scores for the period from January 1980 to August 2001. Values plotted for a particular month are averages over that month and the 11 preceding months. The shading shows the differences in scores between the two hemispheres at the forecast ranges indicated.

Simmons et Hollingsworth, 2002, *Q. J. R. Meteorol. Soc.*, **128**, 647-677

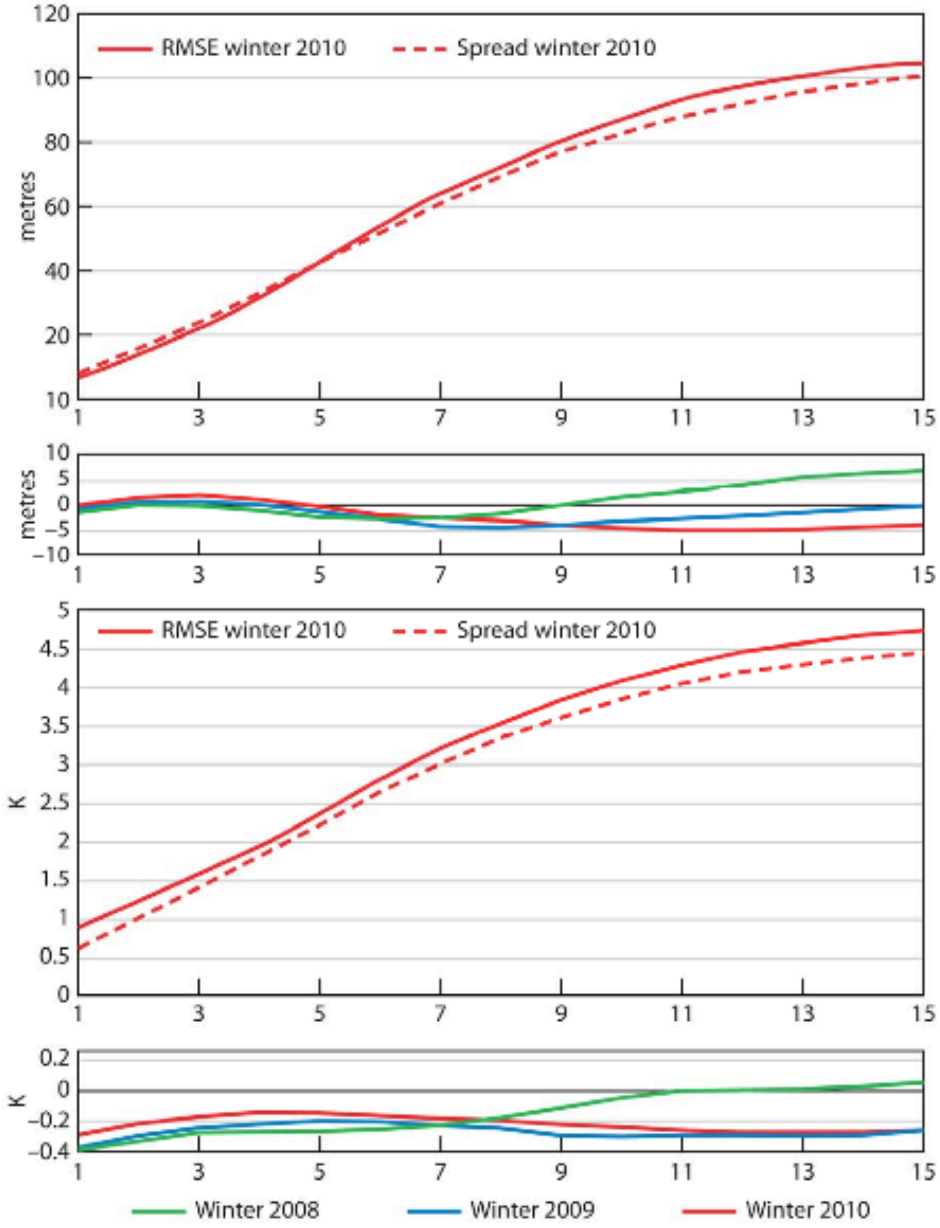


Figure 8: Ensemble spread (standard deviation, dashed lines) and root mean square error of ensemble-mean (solid lines) for winter 2009-2010(upper figure in each panel), complemented with differences of ensemble spread and root mean square error of ensemble-mean for last 3 winter seasons (lower figure in each panel, negative values indicate spread is too small); plots are for 500 hPa geopotential (top) and 850 hPa temperature (bottom) over the extra-tropical 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, …)

- …

Fig. 1: Members of day 7 forecast of 500 hPa geopotential height for the ensemble originated from 25 January 1993.

Figure 6 Hurricane Katrina mean-sea-level-pressure (MSLP) analysis for 12 UTC of 29 August 2005 and t+84h high-resolution and EPS forecasts started at 00 UTC of 26 August:

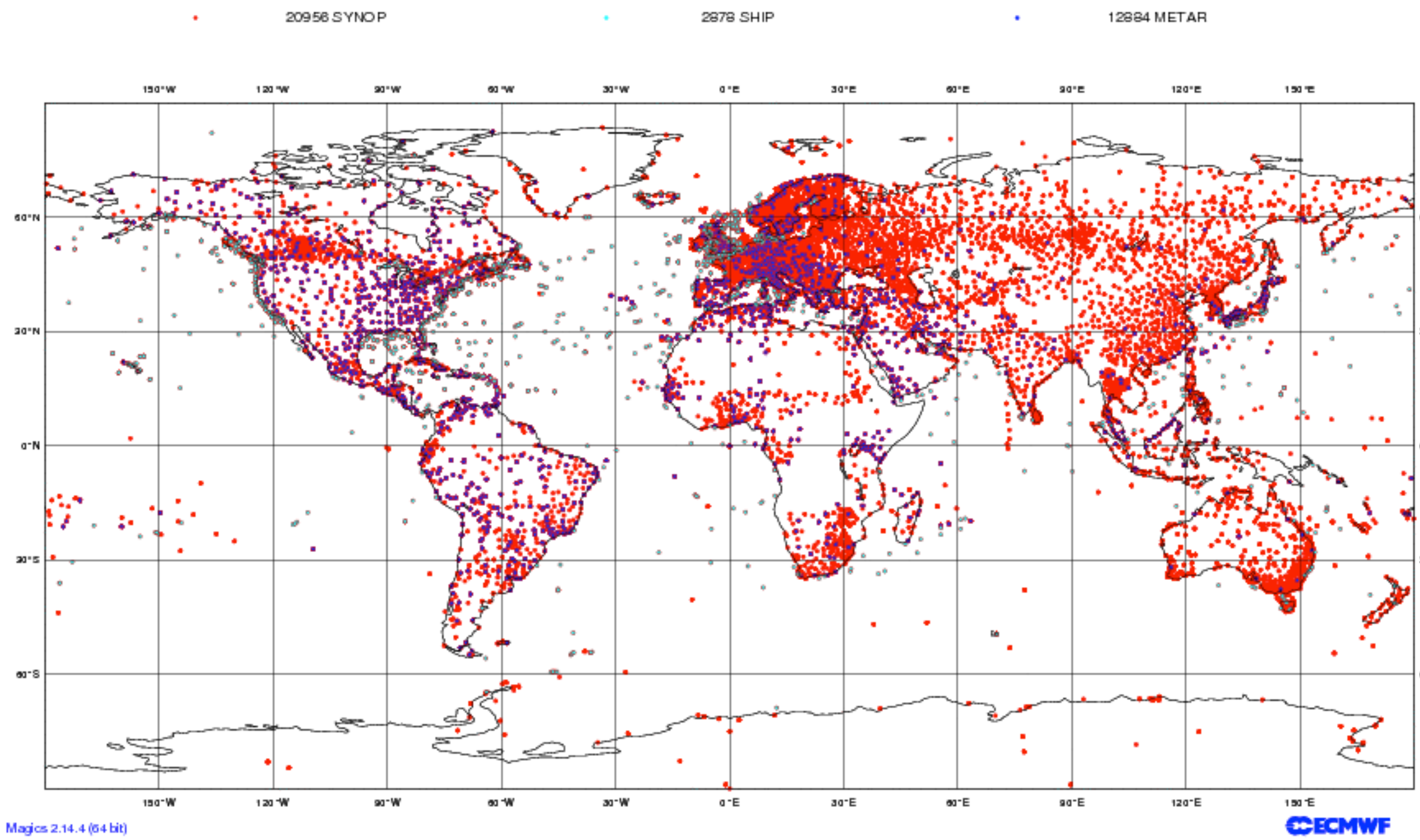
1st row: *1st panel: MSLP analysis for 12 UTC of 29 Aug*
2nd panel: MSLP t+84h T_L511L60 forecast started at 00 UTC of 26 Aug
3rd panel: MSLP t+84h EPS-control T_L255L40 forecast started at 00 UTC of 26 Aug
Other rows: 50 EPS-perturbed T_L255L40 forecast started at 00 UTC of 26 Aug.

The contour interval is 5 hPa, with shading patters for MSLP values lower than 990 hPa.

Pourquoi les météorologistes ont-ils tant de peine à prédire le temps avec quelque certitude ? Pourquoi les chutes de pluie, les tempêtes elles-mêmes nous semblent-elles arriver au hasard, de sorte que bien des gens trouvent tout naturel de prier pour avoir la pluie ou le beau temps, alors qu'ils jugeraient ridicule de demander une éclipse par une prière ?[...] un dixième de degré en plus ou en moins en un point quelconque, le cyclone éclate ici et non pas là, et il étend ses ravages sur des contrées qu'il aurait épargnées. Si on avait connu ce dixième de degré, on aurait pu le savoir d'avance, mais les observations n'étaient ni assez serrées, ni assez précises, et c'est pour cela que tout semble dû à l'intervention du hasard.

H. Poincaré, *Science et Méthode*, Paris, 1908

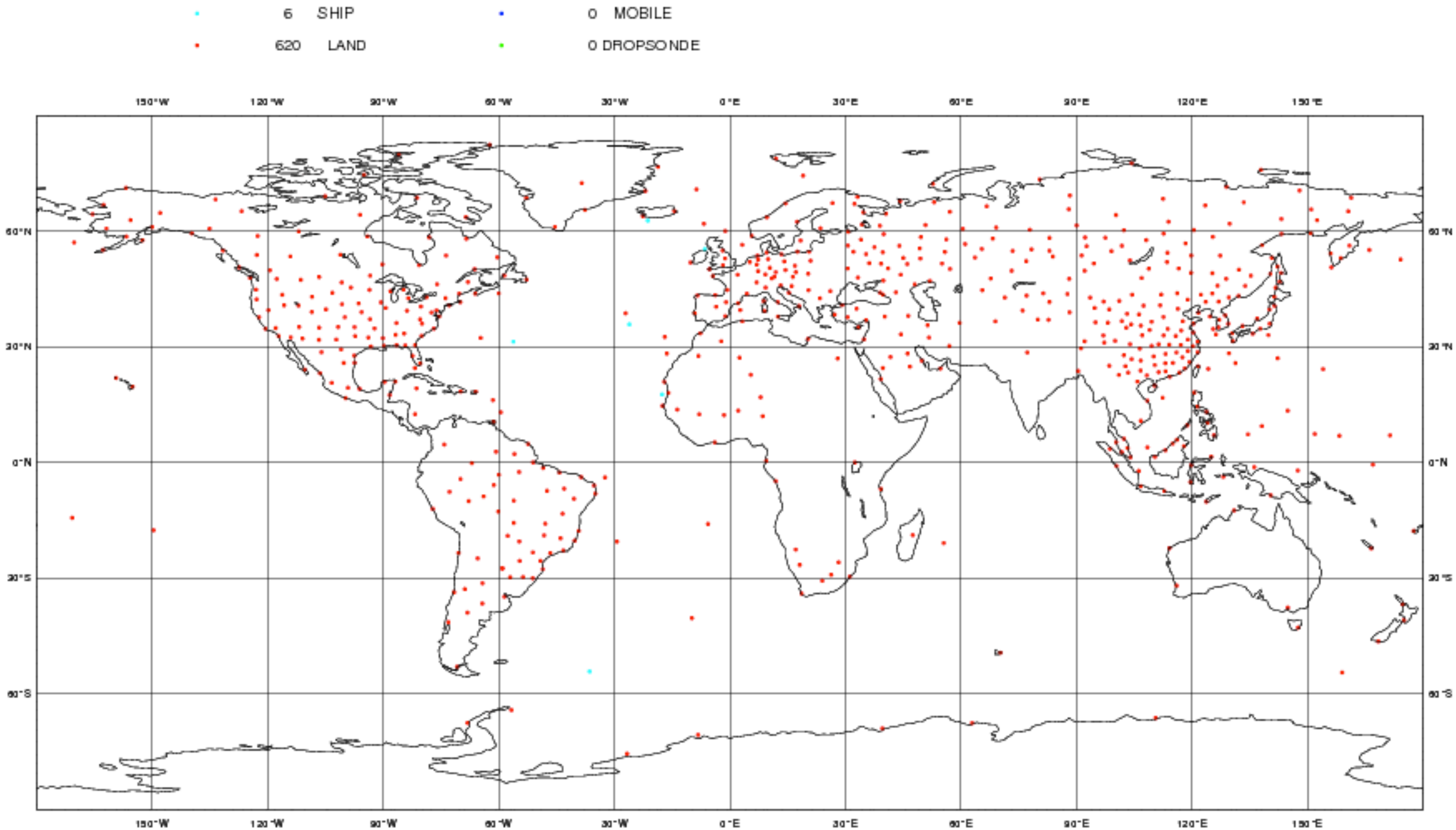
ECMWF Data Coverage (All obs DA) - Synop-Ship-Metar
28/Mar/2013; 12 UTC
Total number of obs = 36718



ECMWF Data Coverage (All obs DA) - Temp

28/Mar/2013; 12 UTC

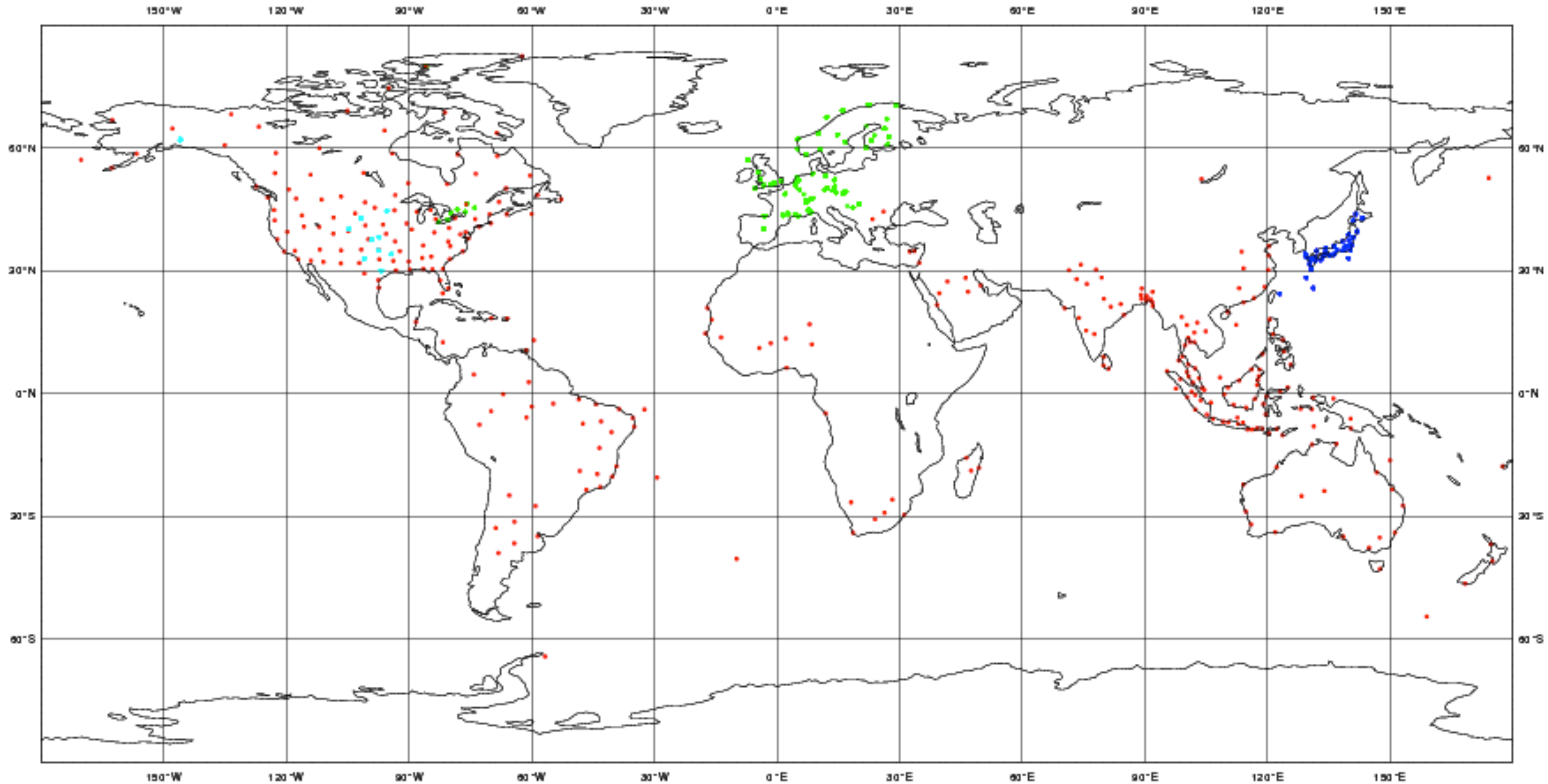
Total number of obs = 626



Magics 2.14.4 (64 bit)

ECMWF Data Coverage (All obs DA) - Pilot-Profiler
28/Mar/2013; 12 UTC
Total number of obs = 1898

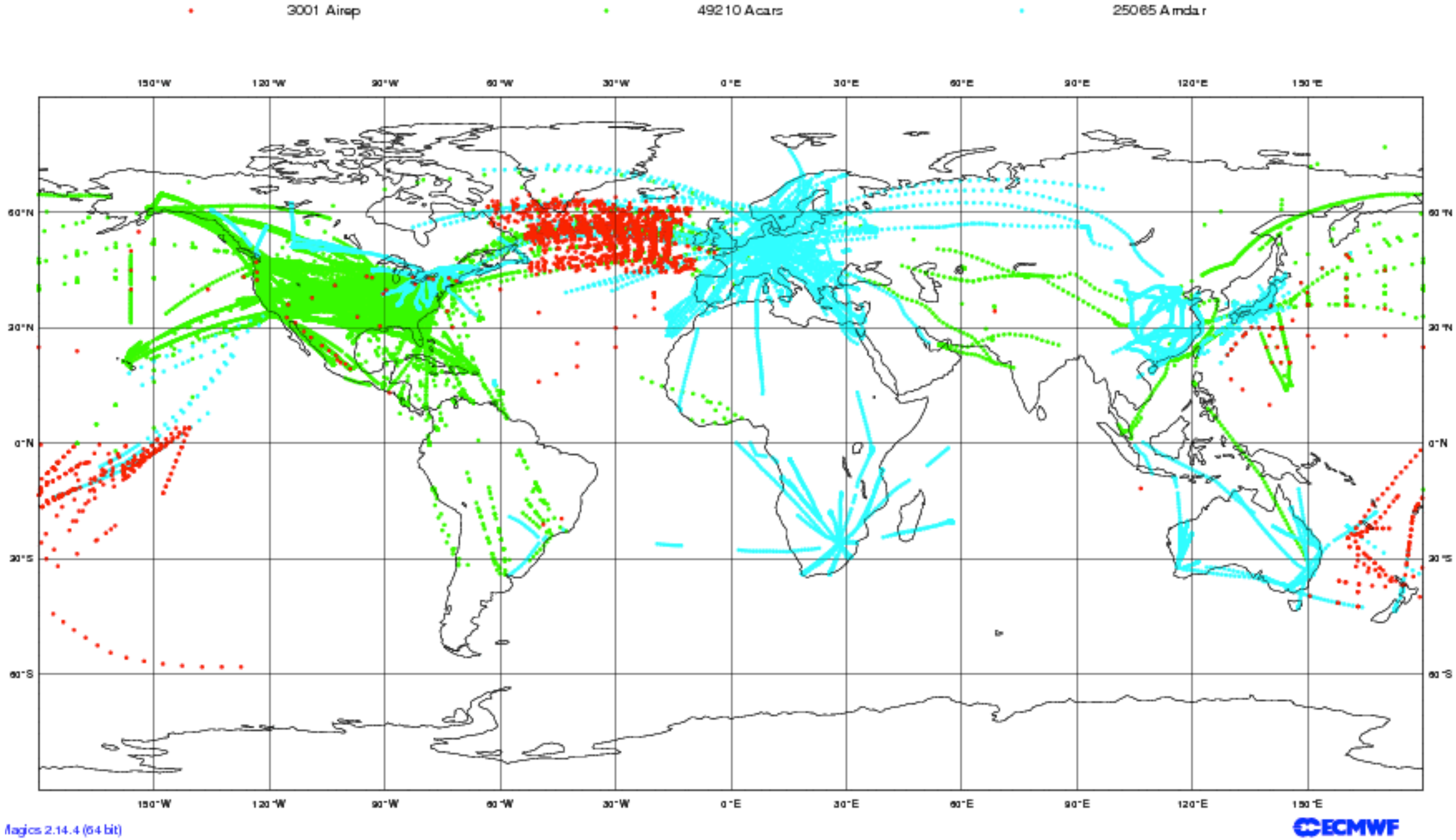
90 US-PROF
198 JP-PROF
314 PILOT
1296 EU-PROF



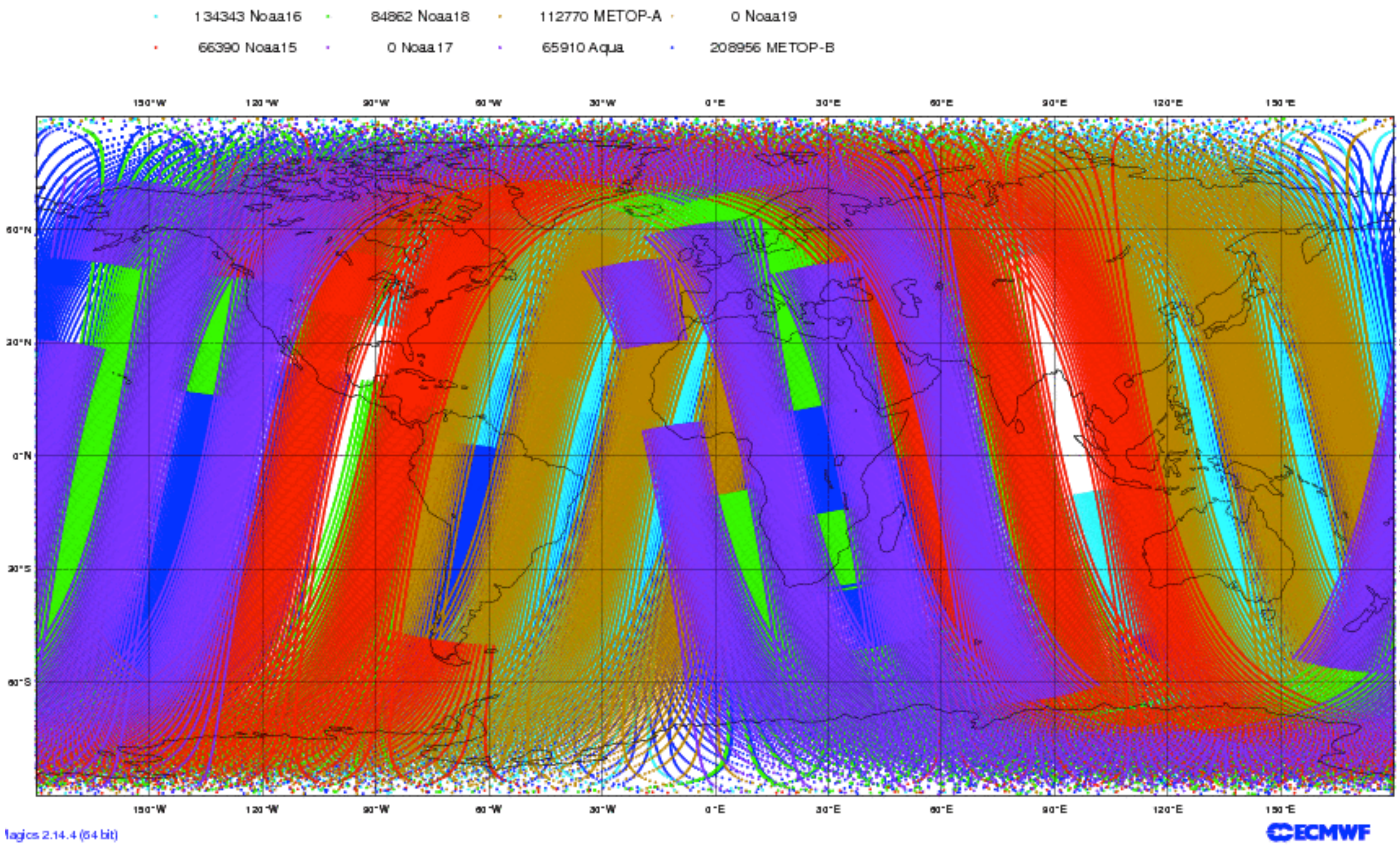
Magics 2.14.4 (64 bit)

ECMWF

ECMWF Data Coverage (All obs DA) - Aircraft
28/Mar/2013; 12 UTC
Total number of obs = 77276



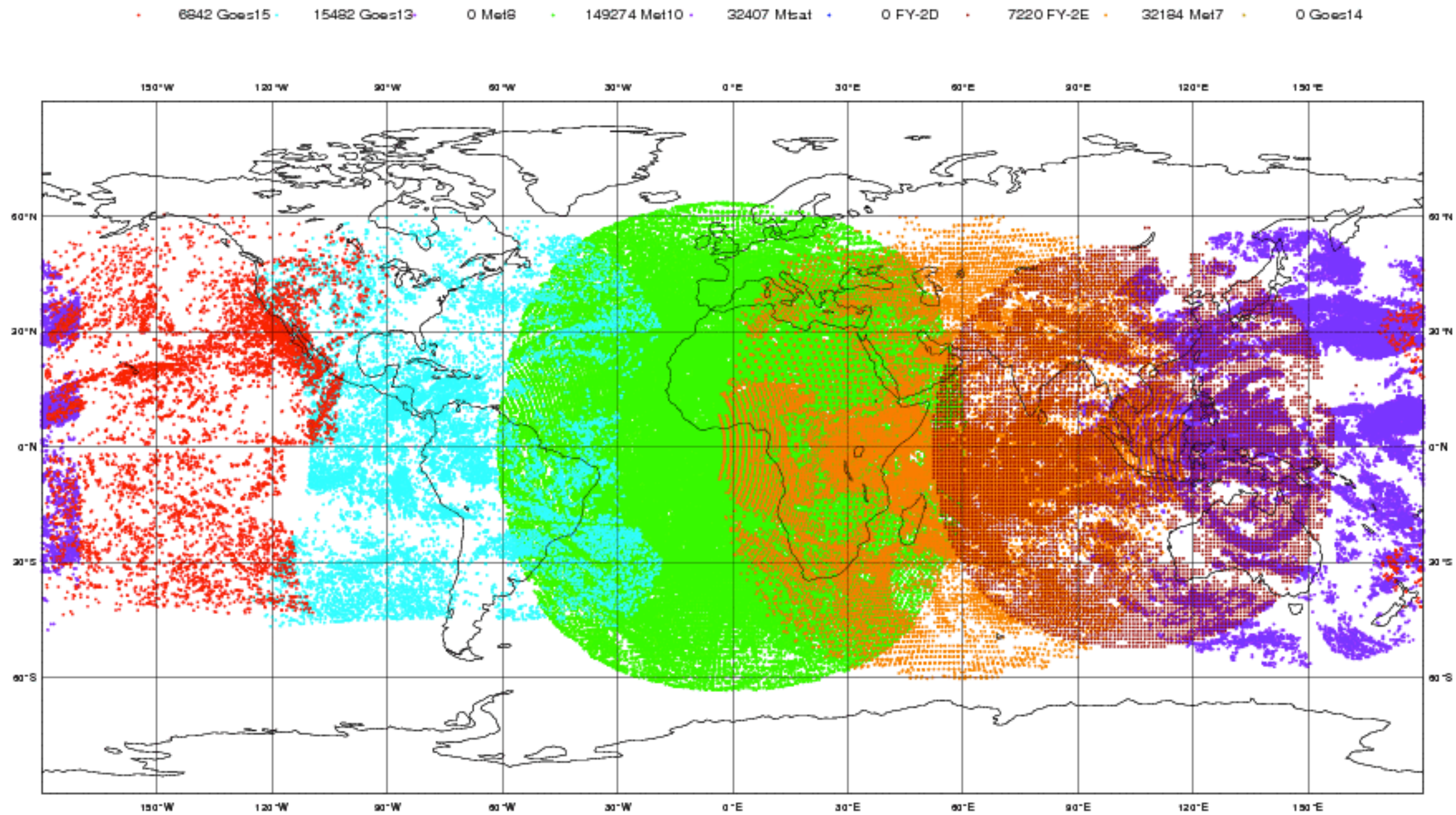
ECMWF Data Coverage (All obs DA) - AMSU-A
28/Mar/2013; 12 UTC
Total number of obs = 673231



ECMWF Data Coverage (All obs DA) - AMV WV

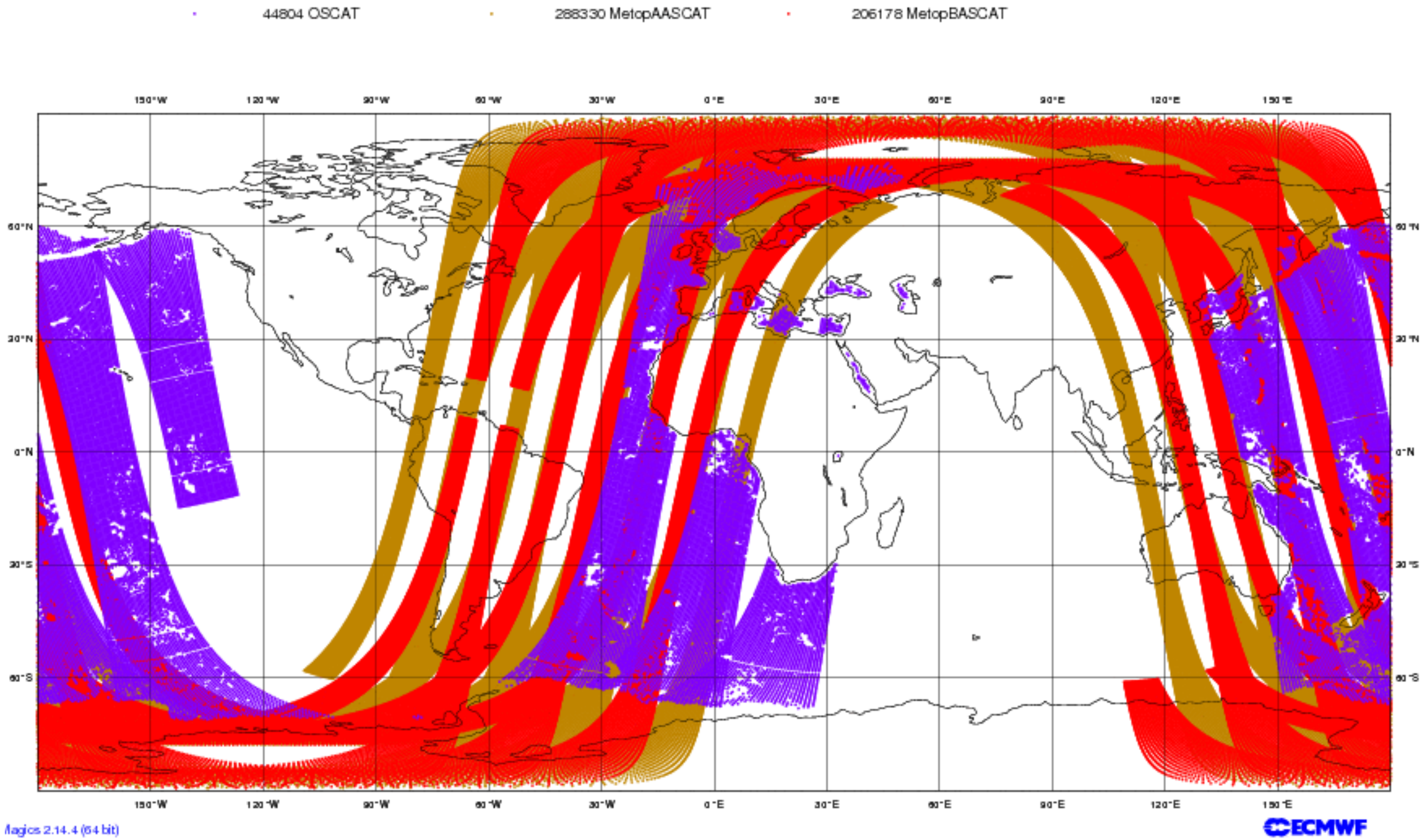
28/Mar/2013; 12 UTC

Total number of obs = 243409

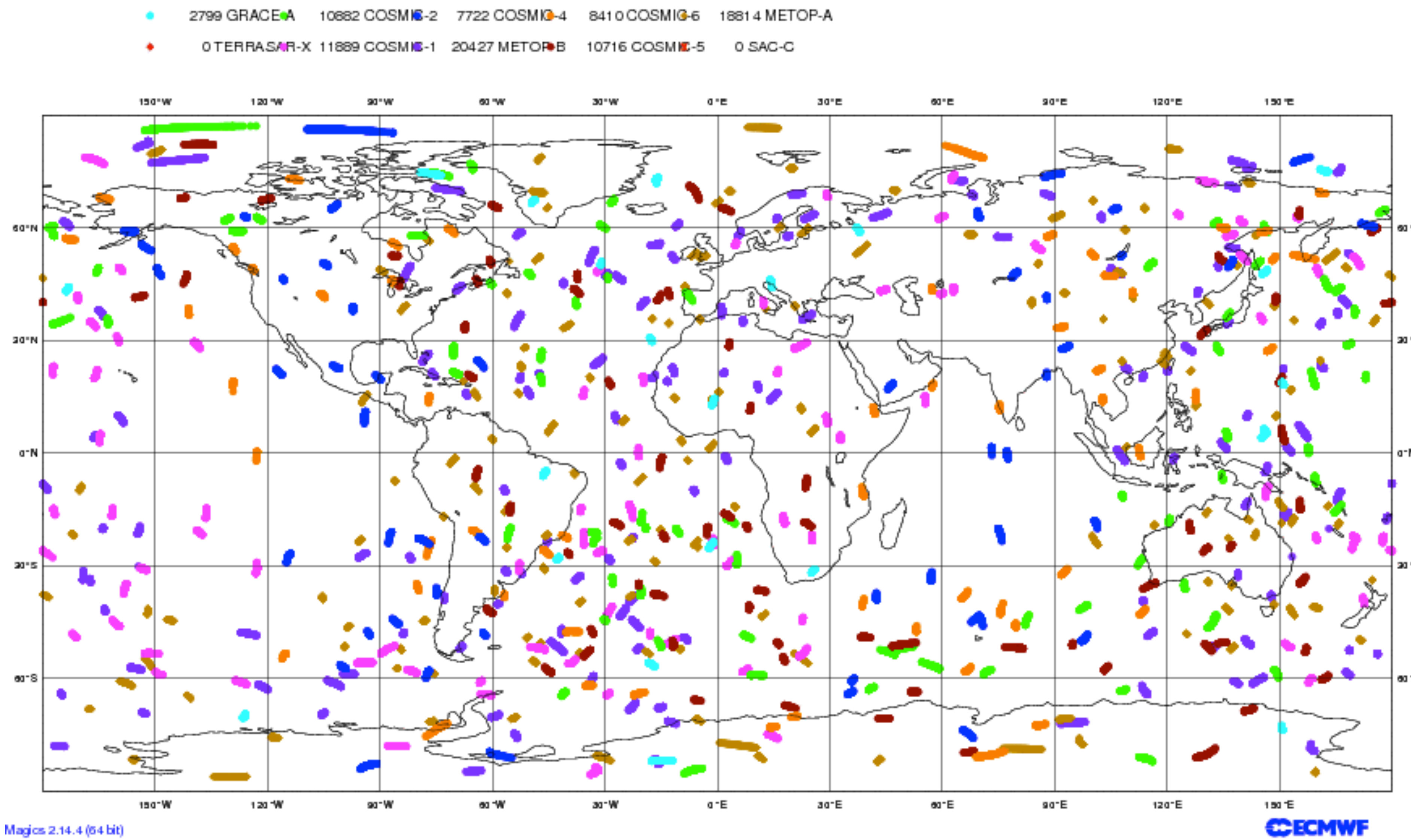


Magics 2.14.4 (64 bit)

ECMWF Data Coverage (All obs DA) - SCAT
28/Mar/2013; 12 UTC
Total number of obs = 539312



ECMWF Data Coverage (All obs DA) - GPSRO
28/Mar/2013; 12 UTC
Total number of obs = 91659



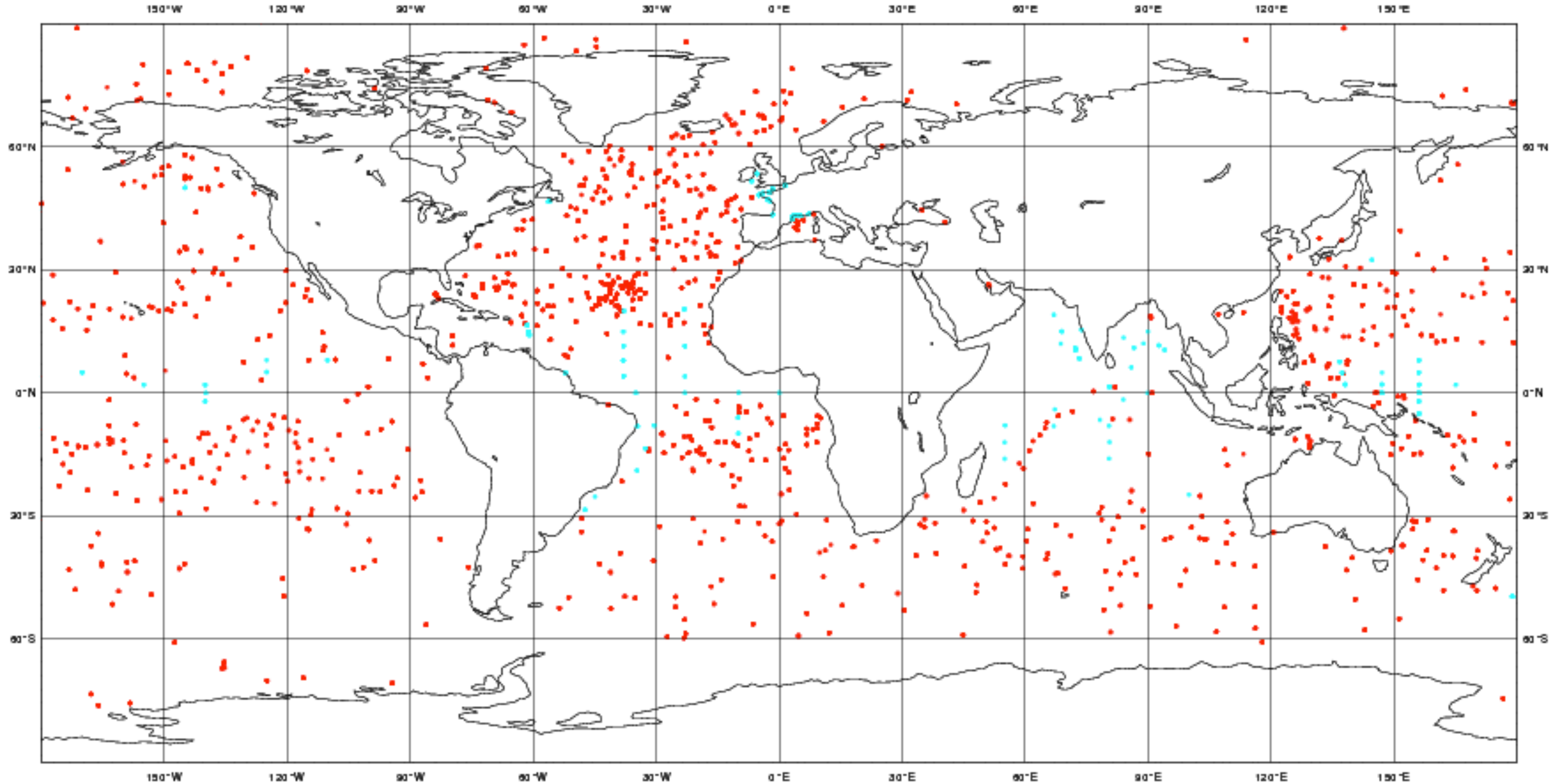
ECMWF Data Coverage (All obs DA) - Buoy

28/Mar/2013; 12 UTC

Total number of obs = 6064

5659 DRIFTER

405 MOORED



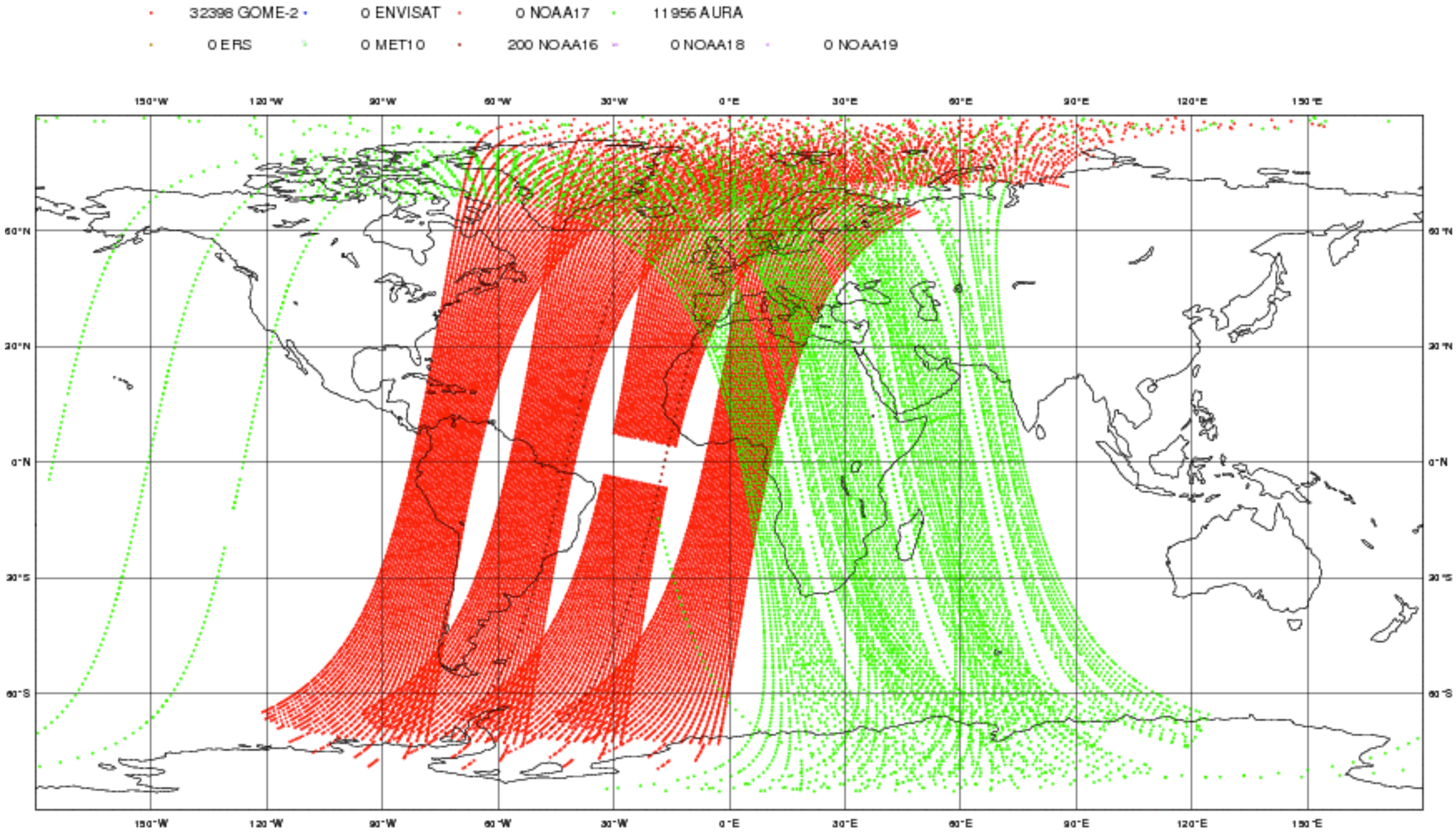
Magics 2.14.4 (64 bit)

ECMWF

ECMWF Data Coverage (All obs DA) - OZONE

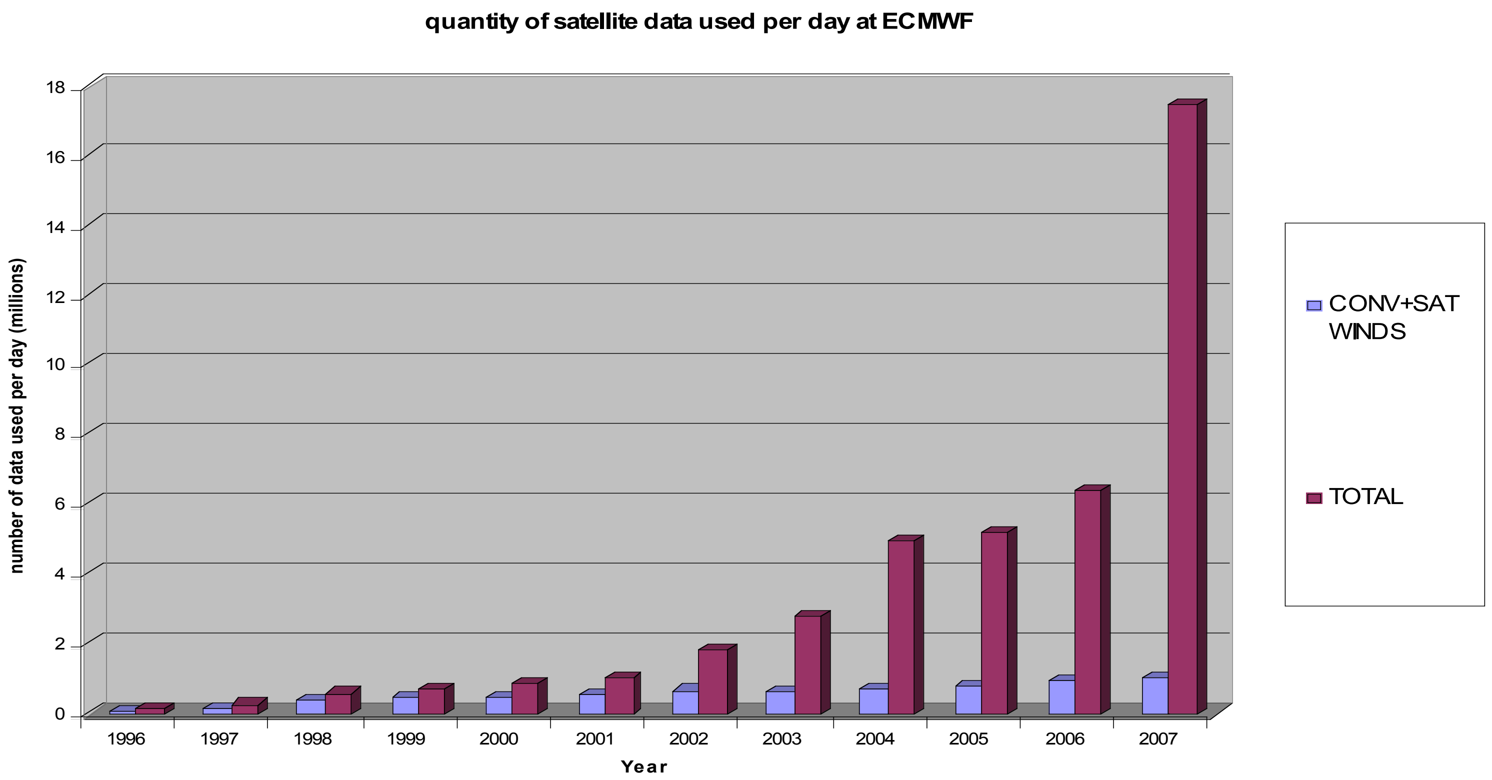
28/Mar/2013; 12 UTC

Total number of obs = 44554



Iagics 2.14.4 (64 bit)

December 2007: Satellite data volumes used: around 18 millions per day



Value as of March 2010 : 25 millions per day

- Observations *synoptiques* (observations au sol, radiosondages), effectuées simultanément, par convention internationale, dans toutes les stations météorologiques du globe (00:00, 06:00, 12:00, 18:00 TU)

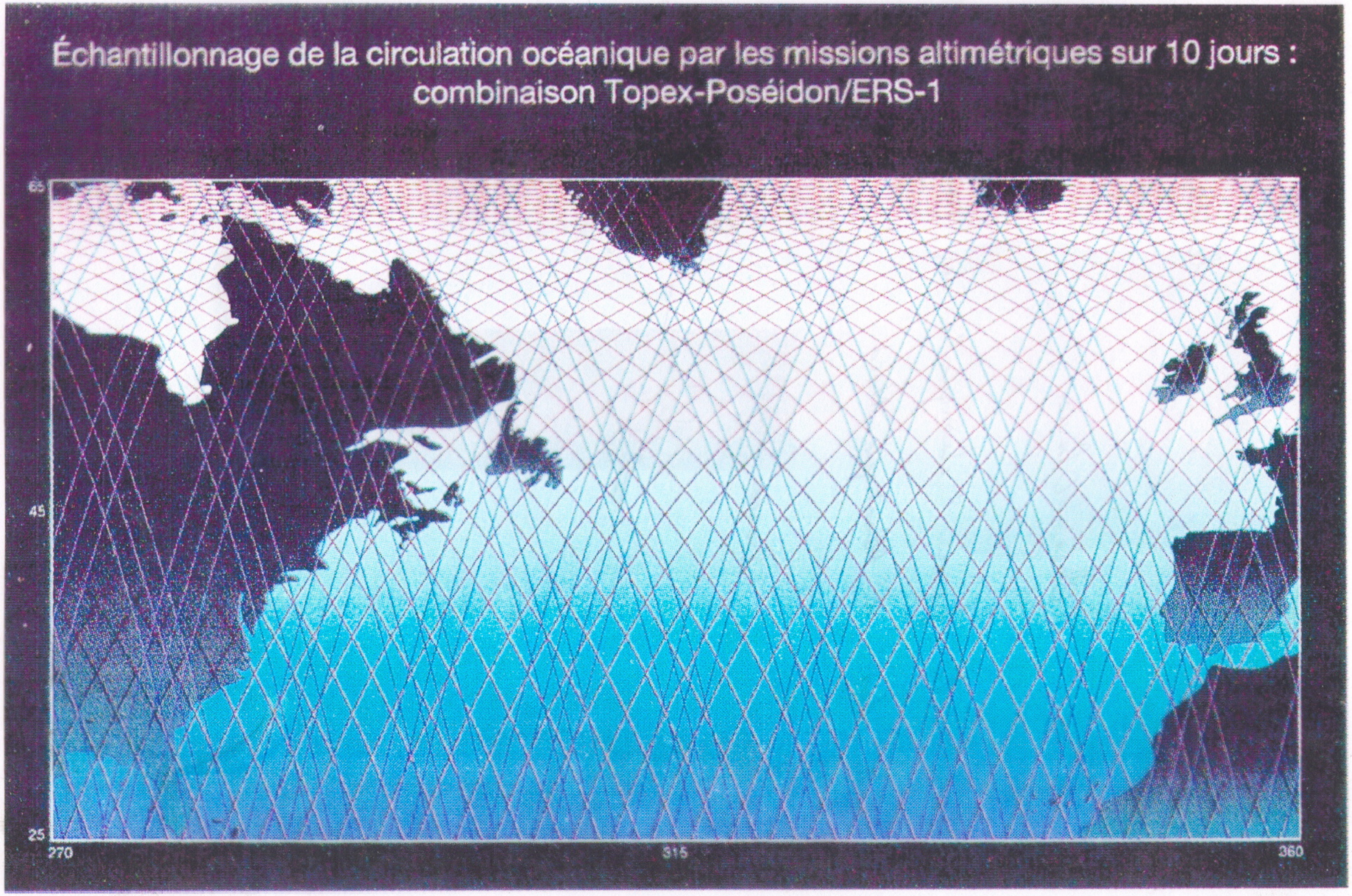
- Observations *asynoptiques* (satellites, avions), effectuées plus ou moins continûment dans le temps.

- Observations *directes* (température, pression, composantes du vent, humidité), portant sur les variables utilisées pour décrire l'état de l'écoulement dans les modèles numériques

- Observations *indirectes* (observations radiométriques, …), portant sur une combinaison plus ou moins complexe (le plus souvent, une intégrale d'espace unidimensionnelle) des variables utilisées pour décrire l'état de l'écoulement

$$y = H(\boldsymbol{x})$$

H : *opérateur d'observation* (par exemple, équation de transfert radiatif)



S. Louvel, Doctoral Dissertation, 1999

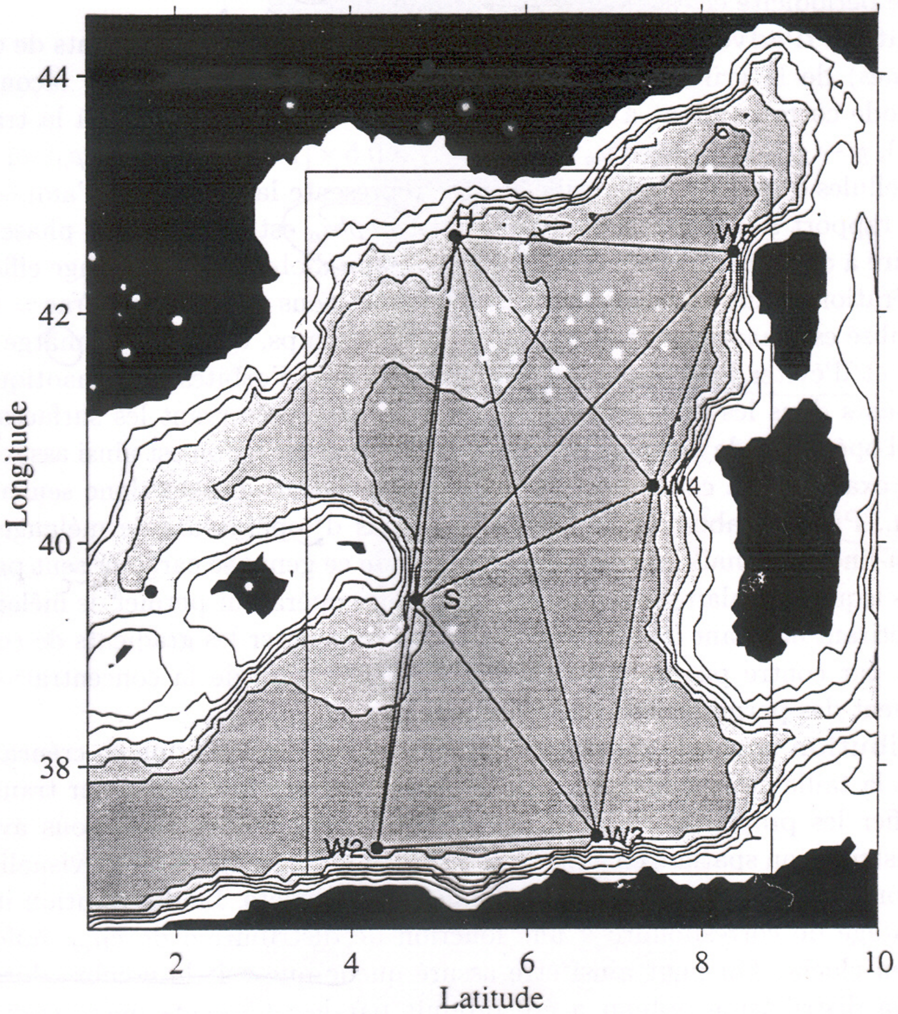


FIG. 1 – *Bassin méditerranéen occidental: réseau d'observation tomographique de l'expérience Thétis 2 et limites du domaine spatial utilisé pour les expériences numériques d'assimilation.*

E. Rémy, Doctoral Dissertation, 1999

Purpose of assimilation : reconstruct as accurately as possible the state of the atmospheric or oceanic flow, using all available appropriate information. The latter essentially consists of

- The observations proper, which vary in nature, resolution and accuracy, and are distributed more or less regularly in space and time.

- The physical laws governing the evolution of the flow, available in practice in the form of a discretized, and necessarily approximate, numerical model.

- 'Asymptotic' properties of the flow, such as, *e. g.*, geostrophic balance of middle latitudes. Although they basically are necessary consequences of the physical laws which govern the flow, these properties can usefully be explicitly introduced in the assimilation process.

Assimilation is one of many '*inverse problems*' encountered in many fields of science and technology

- solid Earth geophysics
- plasma physics
- 'nondestructive' probing
- navigation (spacecraft, aircraft, ….)
- …

Solution most often (if not always) based on Bayesian, or probabilistic, estimation. 'Equations' are fundamentally the same.

Difficulties specific to assimilation of meteorological observations :

- Very large numerical dimensions ($n \approx 10^6$-10^9 parameters to be estimated, $p \approx$ 1-3.10^7 observations per 24-hour period). Difficulty aggravated in Numerical Weather Prediction by the need for the forecast to be ready in time.

- Non-trivial, actually chaotic, underlying dynamics

Coût des différentes composantes de la chaîne de prévision opérationnelle du CEPMMT (septembre 2011, J.-N. Thépaut) :

4DVAR: 17%

EDA: 15%

Modèle déterministe: 13%

EPS: 53%

autre: 2%

L'EDA fournit à la fois les variances d'erreur d’ébauche du 4D-Var, et les perturbations initiales (en complément des vecteurs singuliers) de l'EPS.

$z_1 = x + \zeta_1$ density function $p_1(\zeta) \propto \exp[- (\zeta^2)/2s_1]$

$z_2 = x + \zeta_2$ density function $p_2(\zeta) \propto \exp[- (\zeta^2)/2s_2]$

ζ_1 and ζ_2 mutually independent

$P(x = \xi \mid z_1, z_2)$?