Recent Developments at ECMWF

Nils Wedi

Thanks to Martin Miller, Agathe Untch, Peter Bechtold,
Dick Dee and Mats Hamrud for their contributions to these slides.

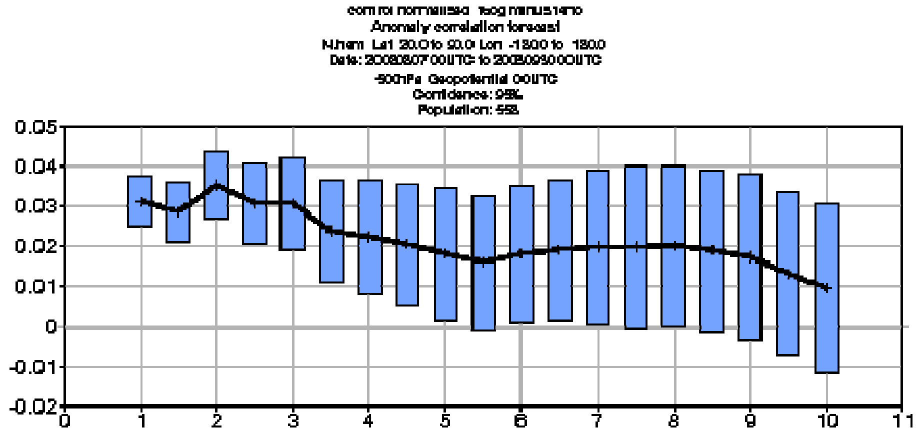
Overview

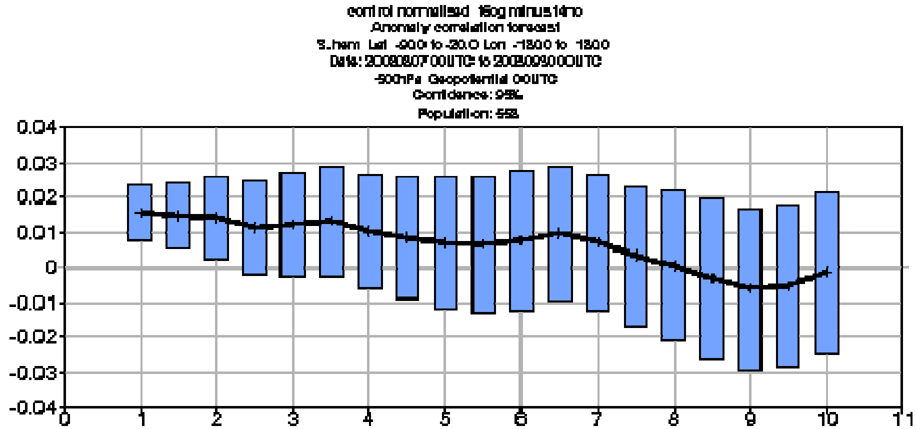
- The current operational cycle CY35R3
- Improvements in the Stratosphere
- 1989-2009 ERA-Interim
- The next high resolution implementation T_L1279
- Testing of the non-hydrostatic IFS

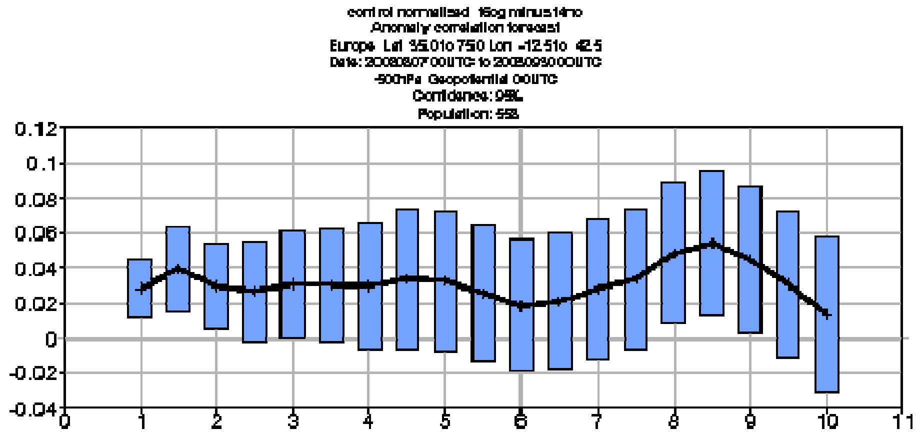
The current operational cycle 35r3

- **Non-orographic gravity wave scheme**
- **New trace gas climatology**
- *Revision of the snow scheme*
- *New structure of the surface analysis*
- *Improved assimilation of land-surface sensitive channels*
- **Assimilation of total column ozone data from METOP; water vapour data from MERIS; cloud-affected radiances for infra-red instruments**
- **Various changes to 4D-VAR: new humidity formulation in 4D-Var, improved quality control (for conventional obs), weak-constraint 4D-Var (stratospheric model error)**

- ♦ **CY35R3 anomaly correlation between forecast and operational analysis deviations from climate with statistical significance based on 95% confidence interval.**
- ♦ **Extensive testing: 558 days of assimilation and forecast!**







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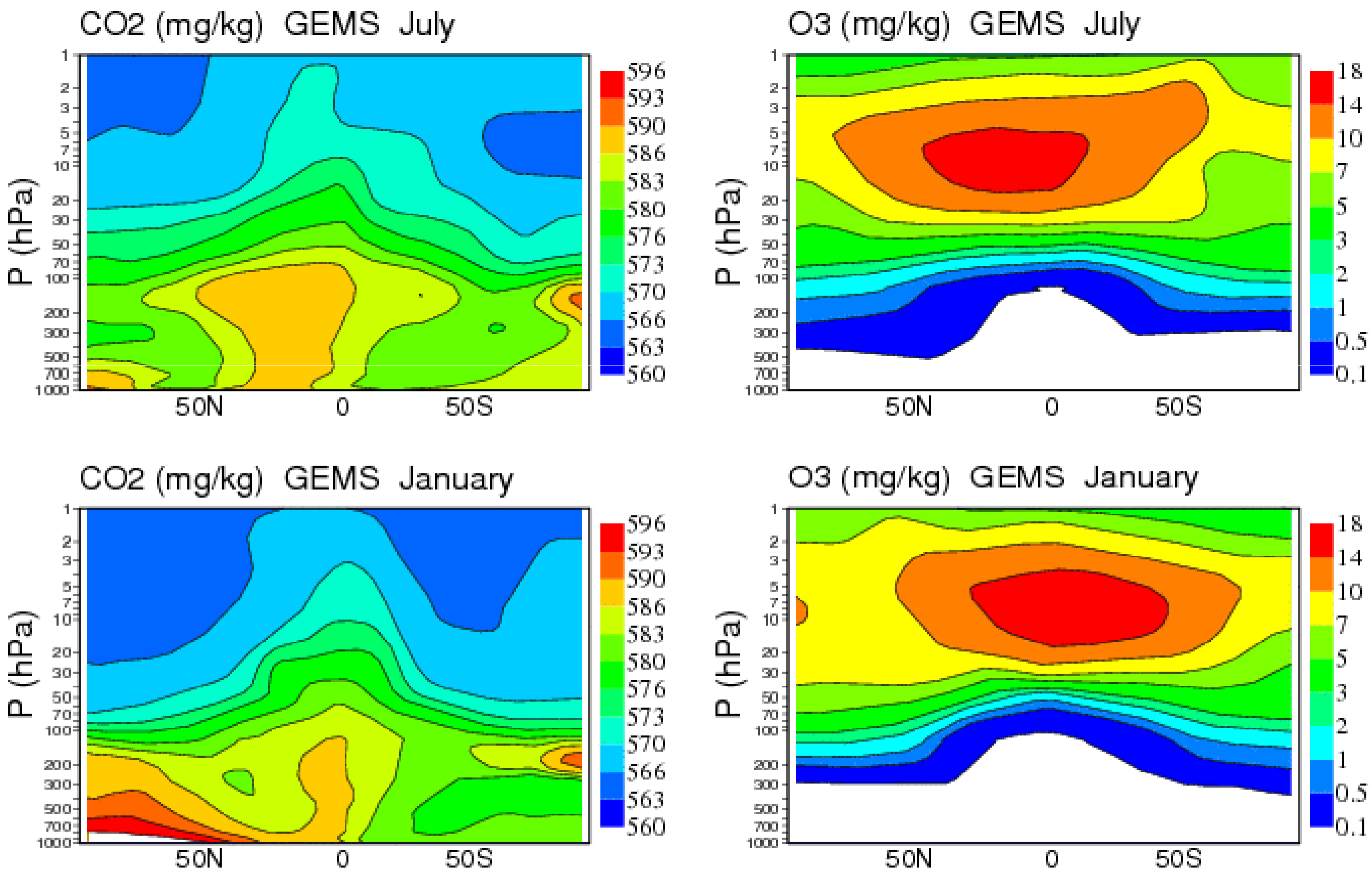
Improvements in the Stratosphere

- New trace gas climatology
- Non-orographic gravity wave scheme *(Warner and McIntyre, 1996; Scinocca, 2003, ECMWF Newsletter 2009)*
  - Define launch height (450hPa, *Ern et al., 2006*)
  - *Define amplitude and shape of the launch spectrum of waves with various vertical wavenumbers, propagating directions + horizontal phase speeds*
  - *Dissipation mechanisms: critical level filtering by the prevailing (model) winds and nonlinear dissipation due to wave steepening and breaking*

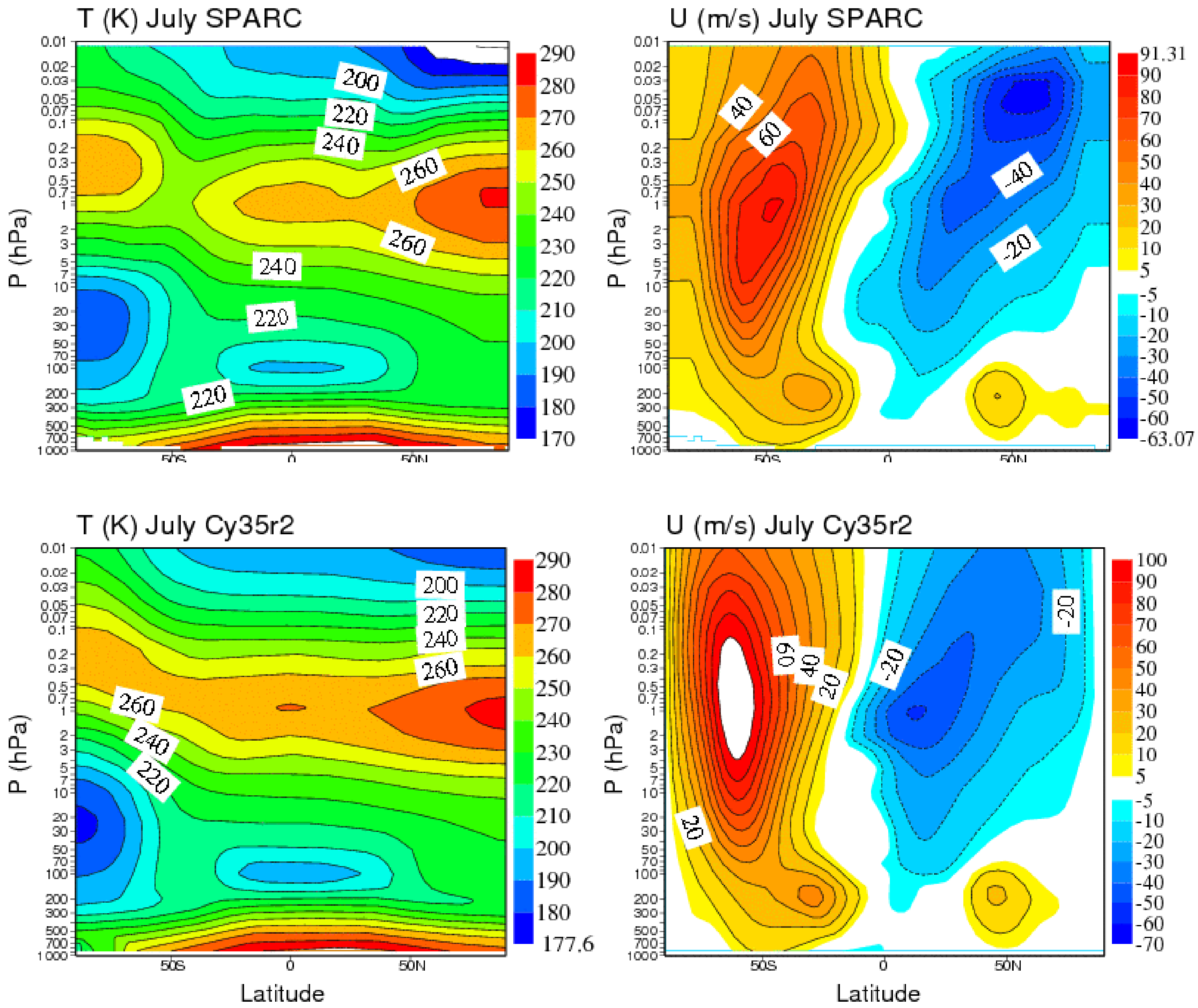
CO2 and O3 zonal mean concentrations from GEMS as used in Cy35r3



July climatology

SPARC

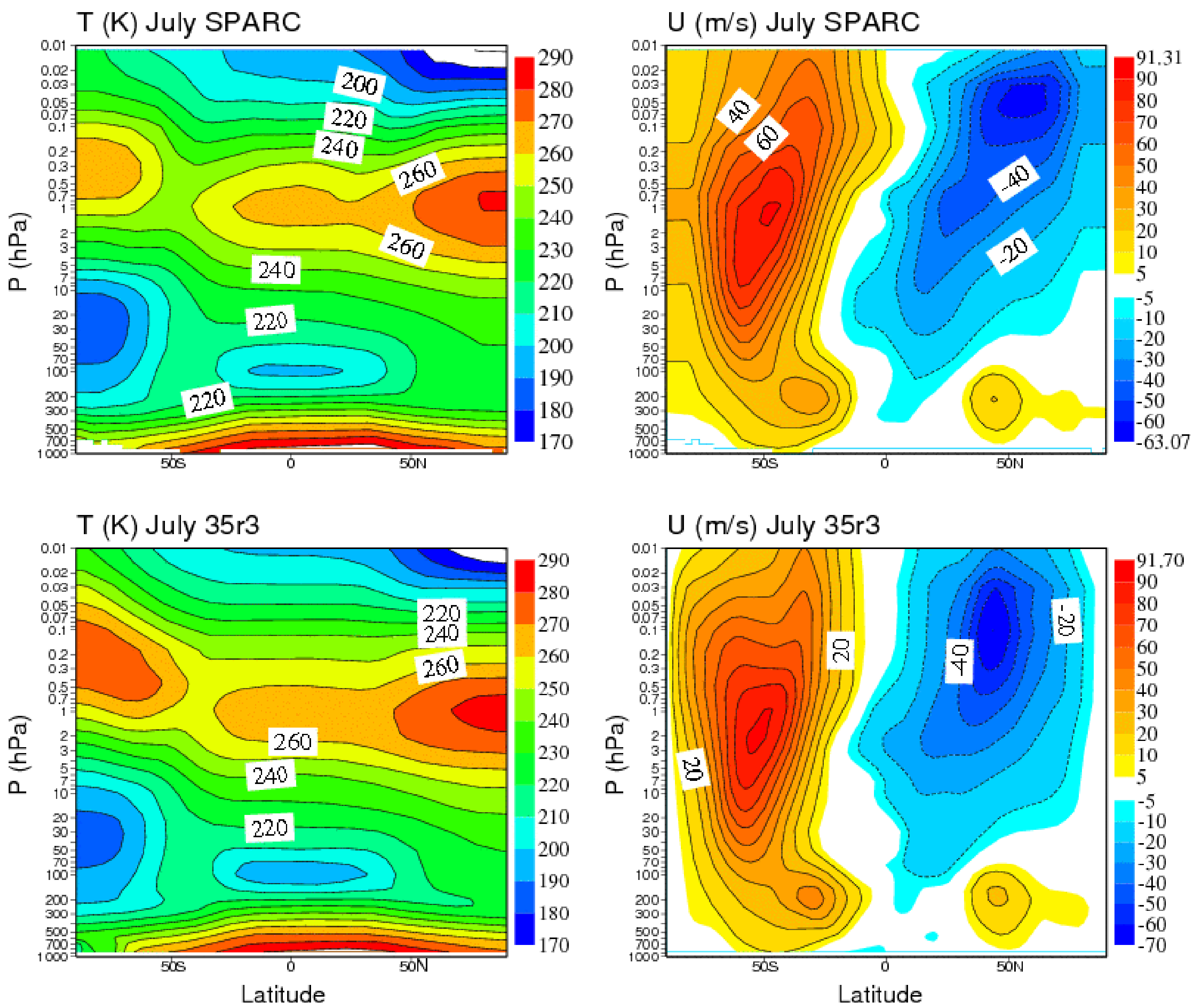
35r2



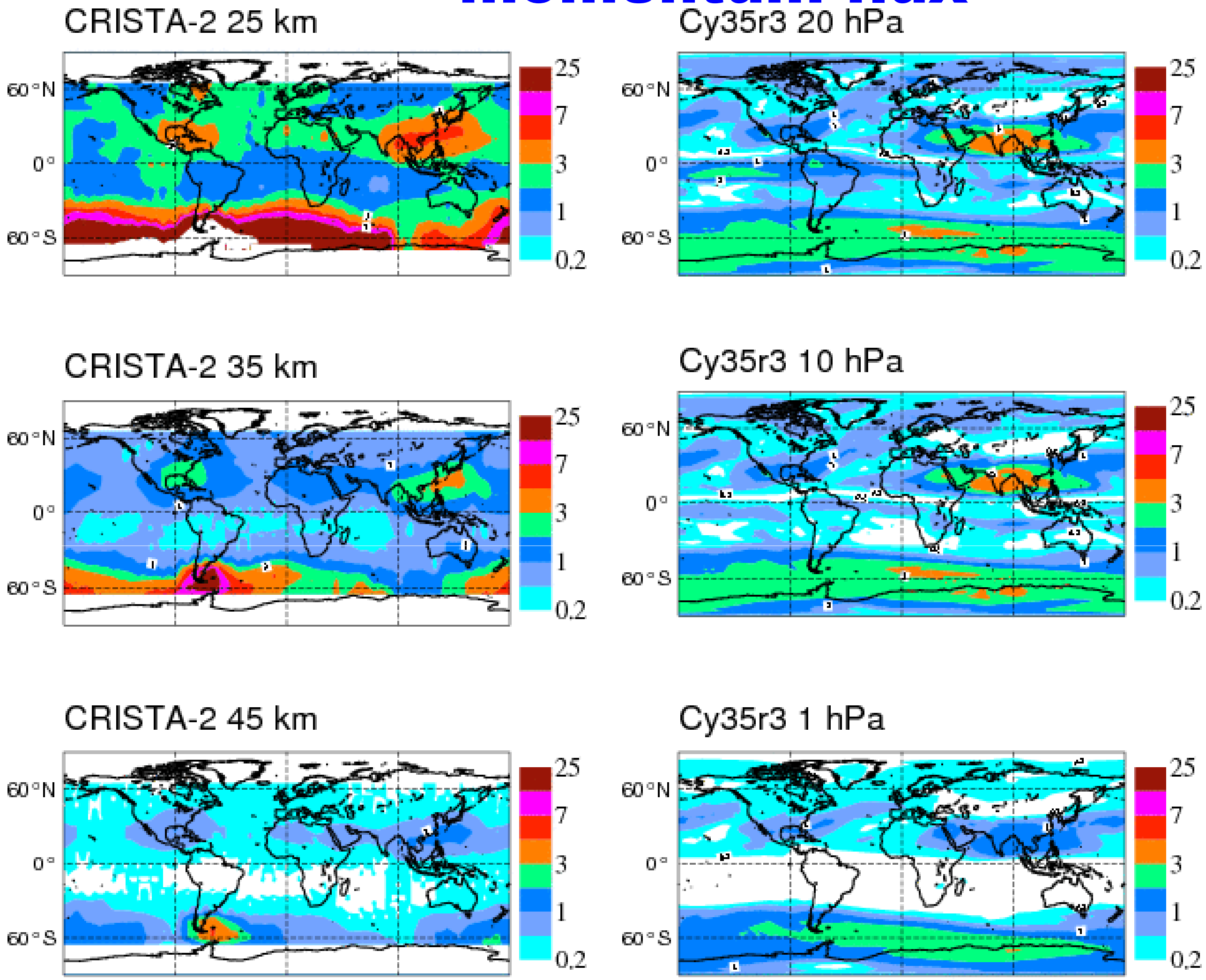
July climatology

SPARC

35r3



Parametrized non-orographic gravity wave momentum flux



Comparison of observed and parametrized GW momentum flux for 8-14 August 1997 horizontal distributions of absolute values of momentum flux (mPa) Observed values are for CRISTA-2 (Ern et al. 2006). Observations measure temperature fluctuations with infrared spectrometer, momentum fluxes are derived via conversion formula.

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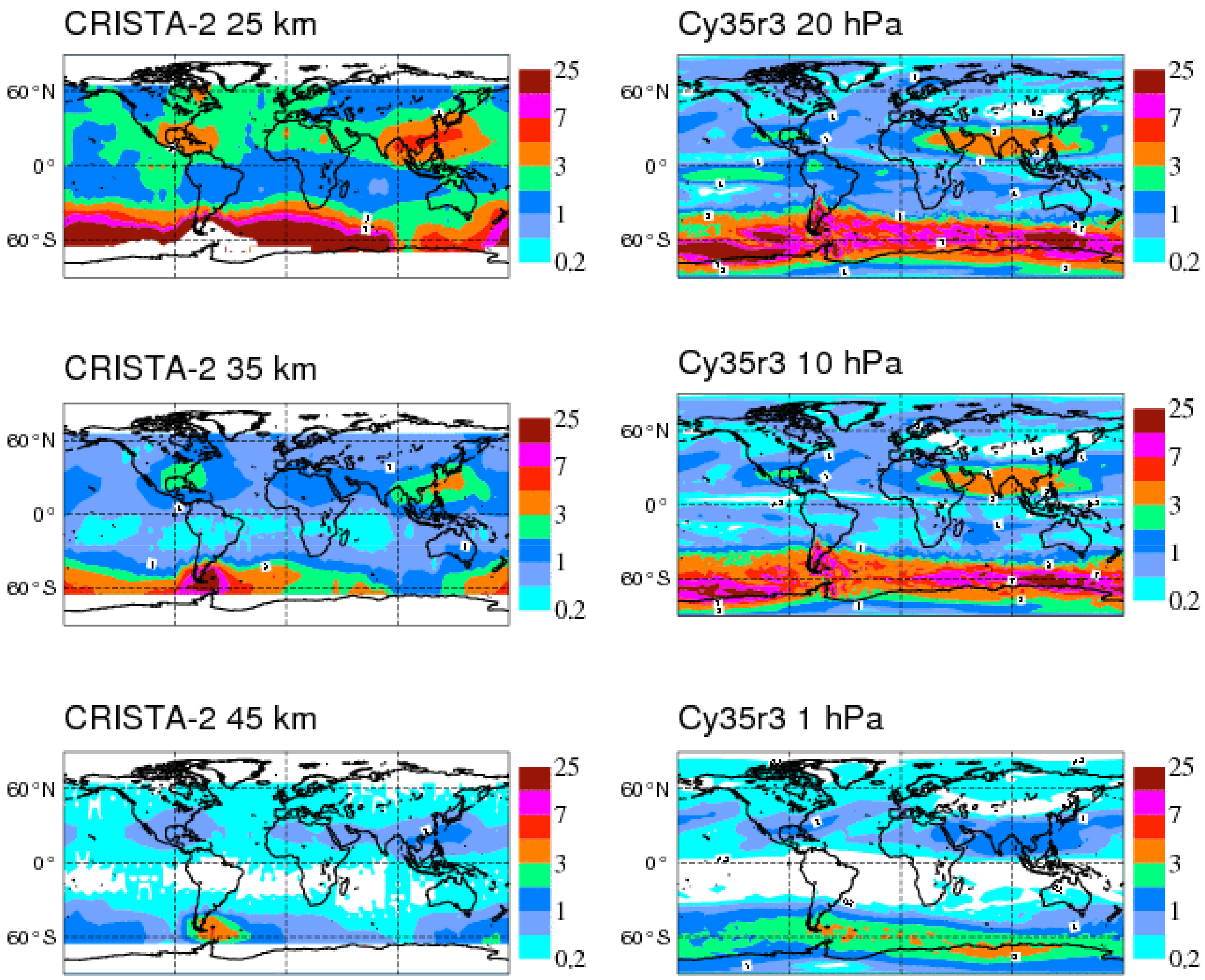
Total = resolved + parametrized wave momentum flux



A. Orr, P. Bechtold, J. Scinoccia, M. Ern, M. Janiskova (JAS 2009 to be submitted)

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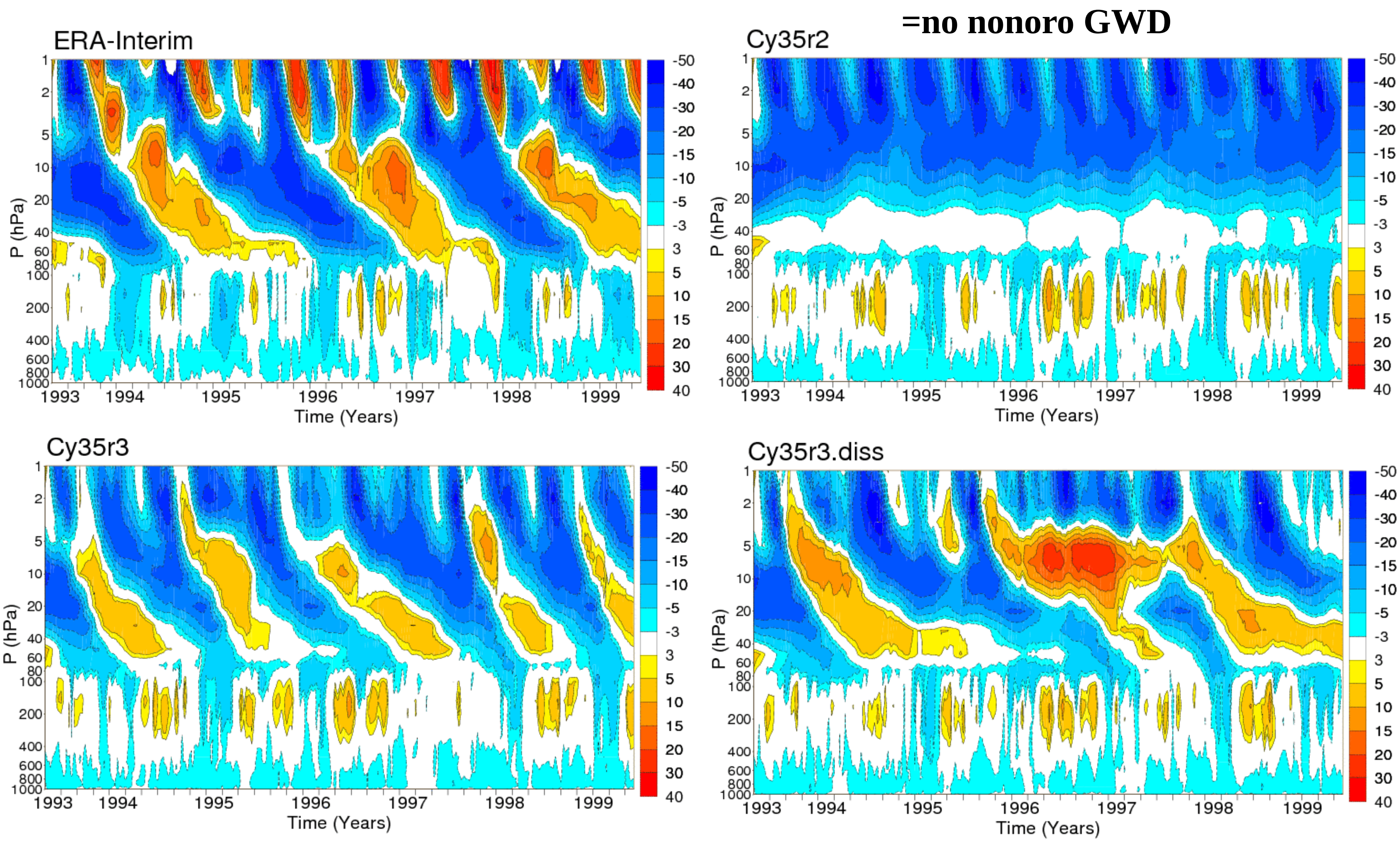
QBO : Hovmöller from free 6y integrations



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ERA-Interim

- 20+ years: 1989-2009, continuing near-real time
- Resolution: T255L60, 6-hourly (3-hourly for surface)
- Forecast model version late 2006 (Cy31r2)
- Analysis using 12-hourly 4D-Var
- Variational bias correction of radiance data (VarBC)

- Member states: full access via MARS
- Public web access via ECMWF Data Server
- Copy of complete archive at NCAR (http:// dss.ucar.edu)

Please visit: http://www.ecmwf.int/research/era

Atmospheric reanalysis at ECMWF

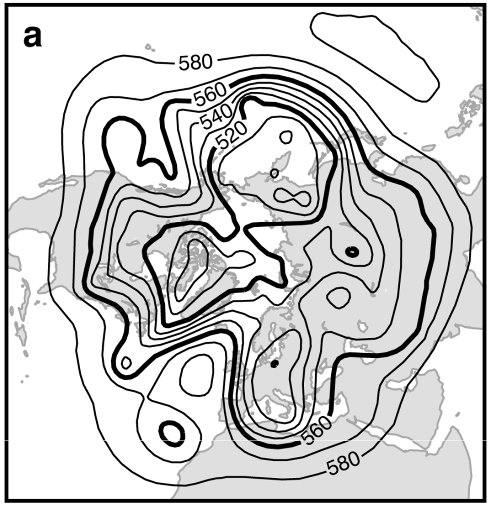
	ERA-15	ERA-40	ERA-Interim	ERA-75 (target)
TIME PERIOD	*1979-1993*	*1957-2002*	*from 1989 onwards*	*from 1938 onwards*
USERS	Meteorologists and Atmospheric Scientists			
		Climate Scientists and Wider Earth Science Community		
			Additional "Environmental Users"	
				European Stakeholders **GMES Core & Downstream services**
INPUT DATA ACCESS	Mixed Observational Data Formats in Archive			Unified, Consolidated Database Facility
		Observation Quality Feedback Information		
				Internet Access
GRIDDED PRODUCTS	**Model Fields (GRIB format)**			
				Real-time Product Database **Essential Climate Variables** **Internet Access**
ATMOSPHERE	Assimilation OI 31 levels 150km	Assimilation 3DVAR 60 levels 125km	**Assimilation 4DVAR** **60 levels** **80km**	**Assimilation weak-constraint 4DVAR** **91 levels** **40 km** **Improved Observations**
LAND	Forcing	Model	**Improved Model**	**Improved Model & Assimilation Coupling**
OCEAN & SEA-ICE	SST/ice Forcing	**Improved SST/ice Forcing** **Wave Model**		**Improved SST/ice Coupling**
CHEMISTRY		Forcing	**Improved Forcing**	**Improved Interaction**
IMPACT	Enhance Understanding of Atmospheric Variability, Leading to Improved Models			
		Investigate Past Weather and Climate, Assess Observing System Impact		
			Monitor Near Real-time Climate with Traceability to Input Data	
				Facilitate Environmental Decisions, Enable New Applications of GMES, Assess Regional Climate Change & Risks via Regional Reanalyses, Improve Earth System Modeling, Maximize Benefits from Earth Observation Infrastructure

Reanalysis of sparse observations

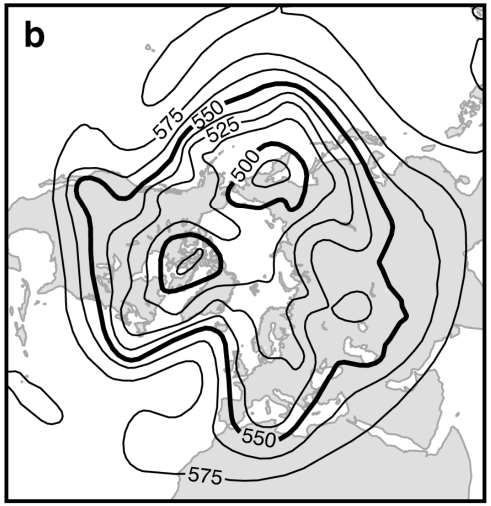
Whitaker, Compo, and Thépaut 2009

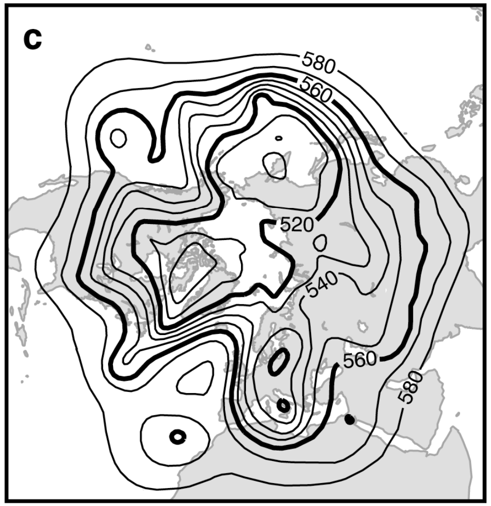
4D-Var CONTROL
All observations

(15 February 2005 00 UTC)



3D-Var
“Surface pressure observations only”



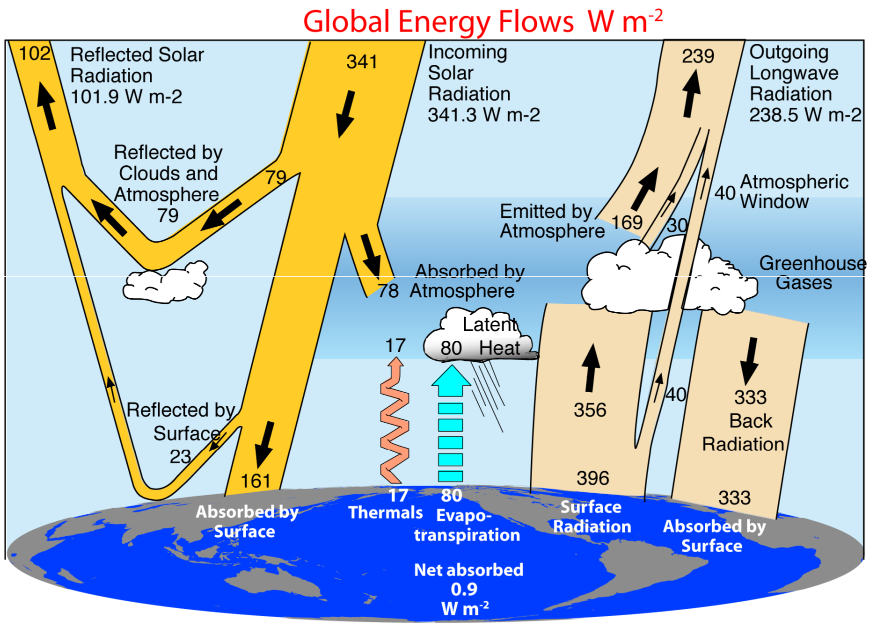


4D-Var
“Surface pressure observations only”

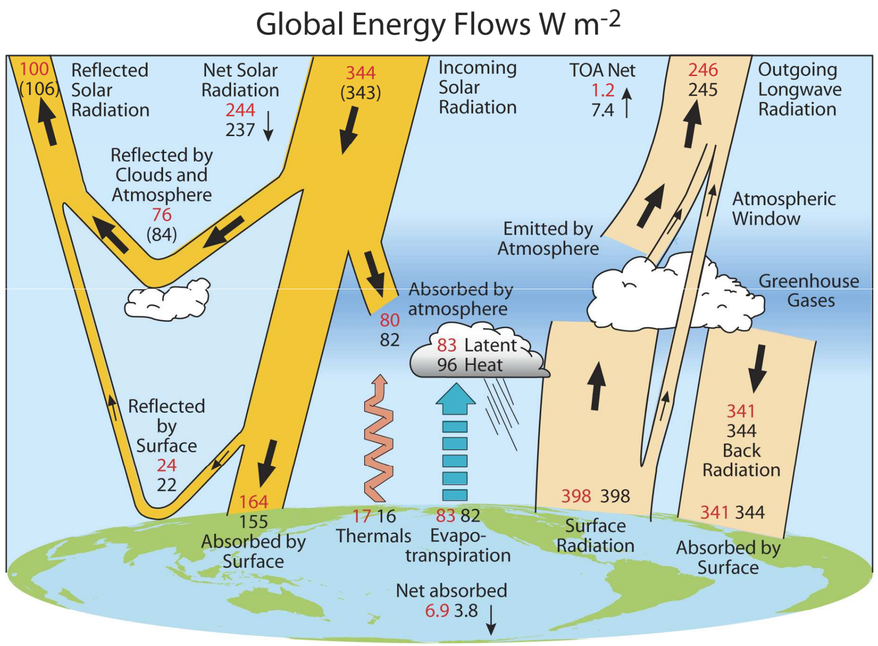
ECMWF

Energy budget

Trenberth *et al.* 2009:
Earth's global energy budget



ERA-Interim 1989-2008 ERA-40 1989-2001



- TOA balance improved in ERA-Interim
- Surface energy balance worse, esp. over oceans

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Mean age of air in the lower stratosphere

Based on 20-year CTM runs, using reanalysed winds from ERA-40 and ERA-Interim

Observational estimates derived from ER-2 aircraft measurements of CO2 and SF6

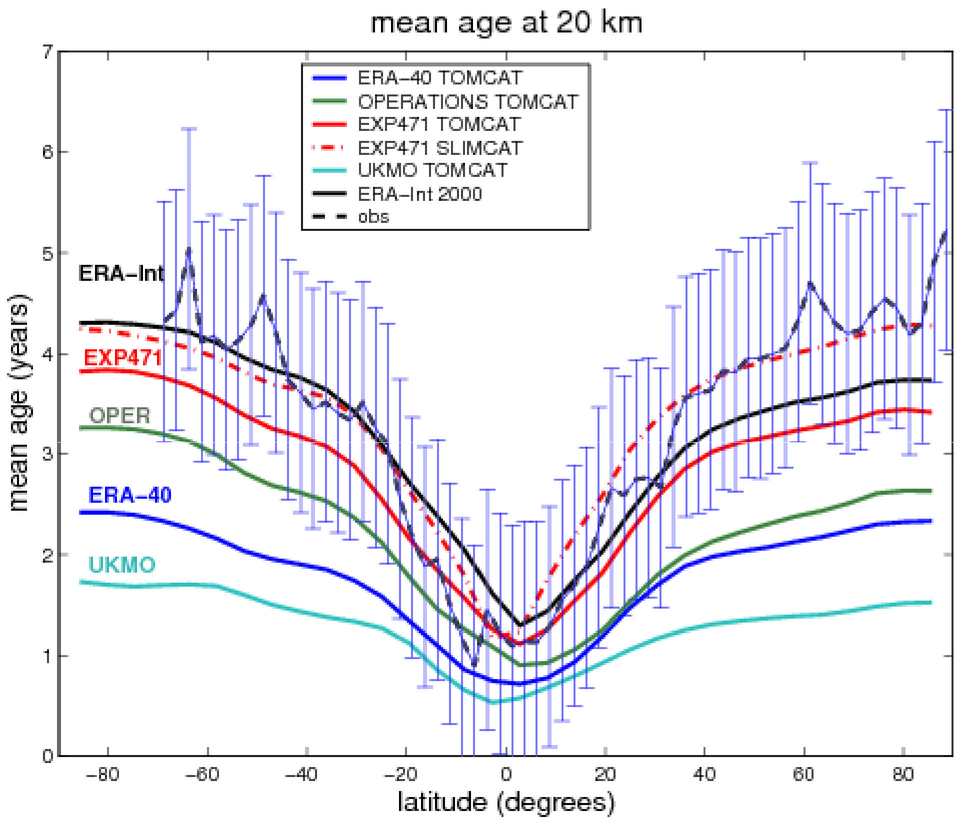

Figure updated from Monge-Sanz *et al.* 2007

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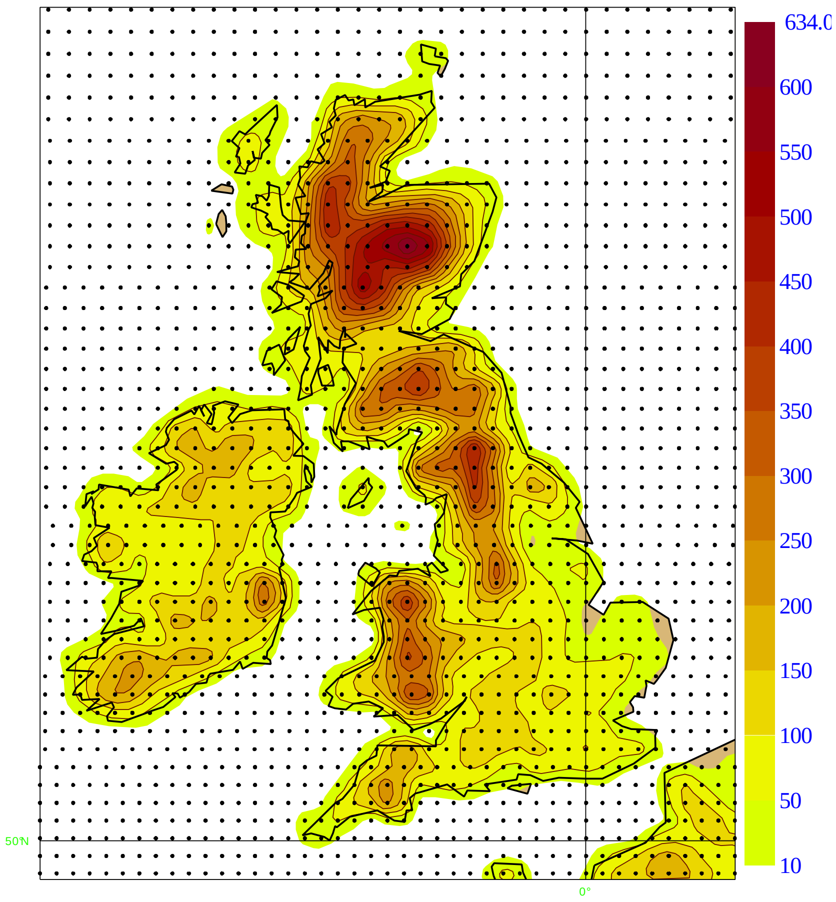
High resolution T_L1279

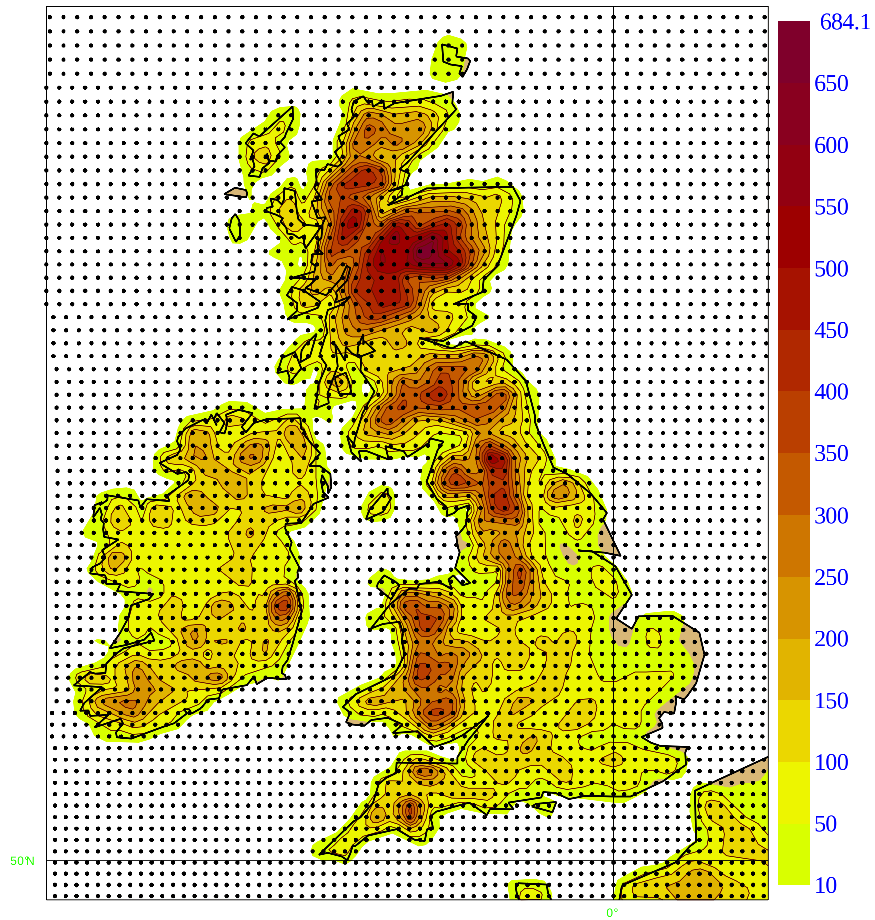
- 4D-Var configuration tested extensively
  - T1279 L91 outer loop (time-step 600s)
  - T159/T255/T255 inner loops (time-steps 1800s)
- Ongoing validation, so far 267 days of assimilation and forecast with CY35R3

T799



25 km grid-spacing
(843,490 grid-points)

T1279



16 km grid-spacing
(2,140,704 grid-points)

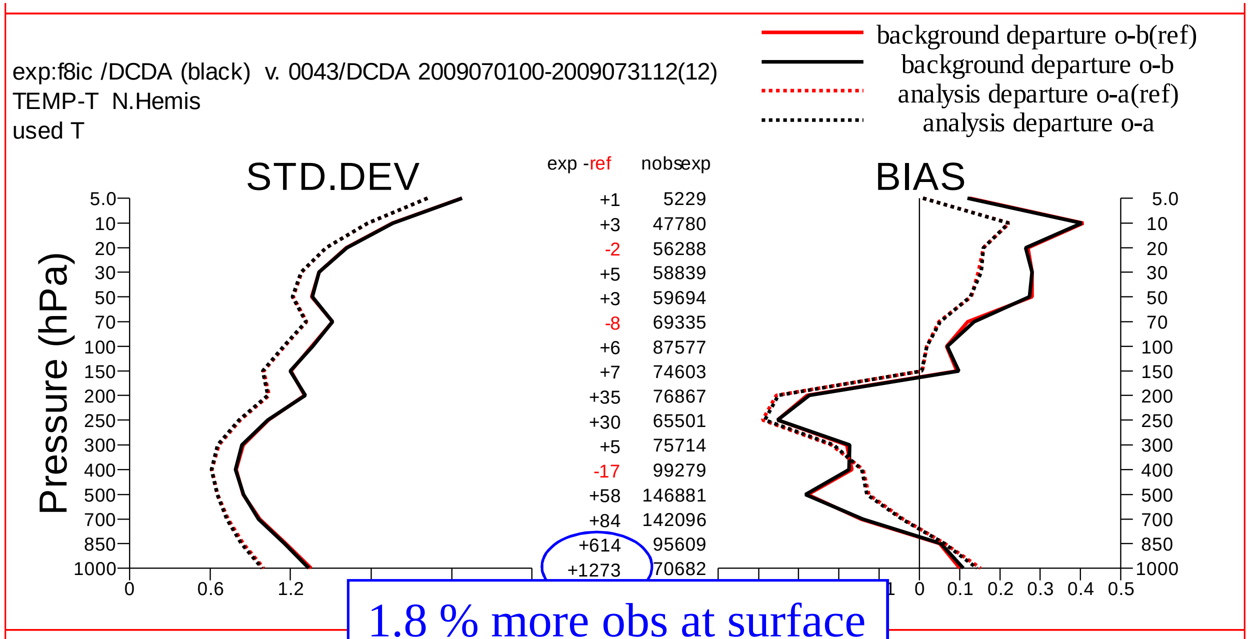
(thanks to Mariano Hortal who actually created these grids)

Fit to TEMP T observations (average for July 2009)

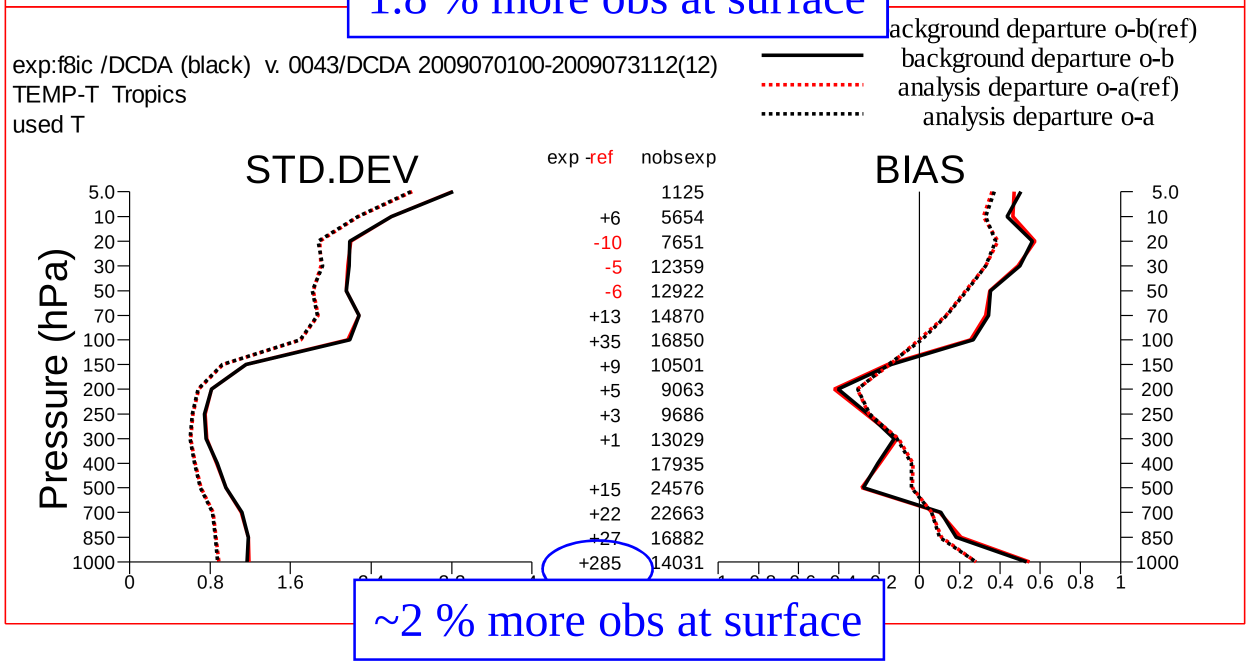
f8ic T1279 (black)

Control (red) 35r3 e-suite 0043

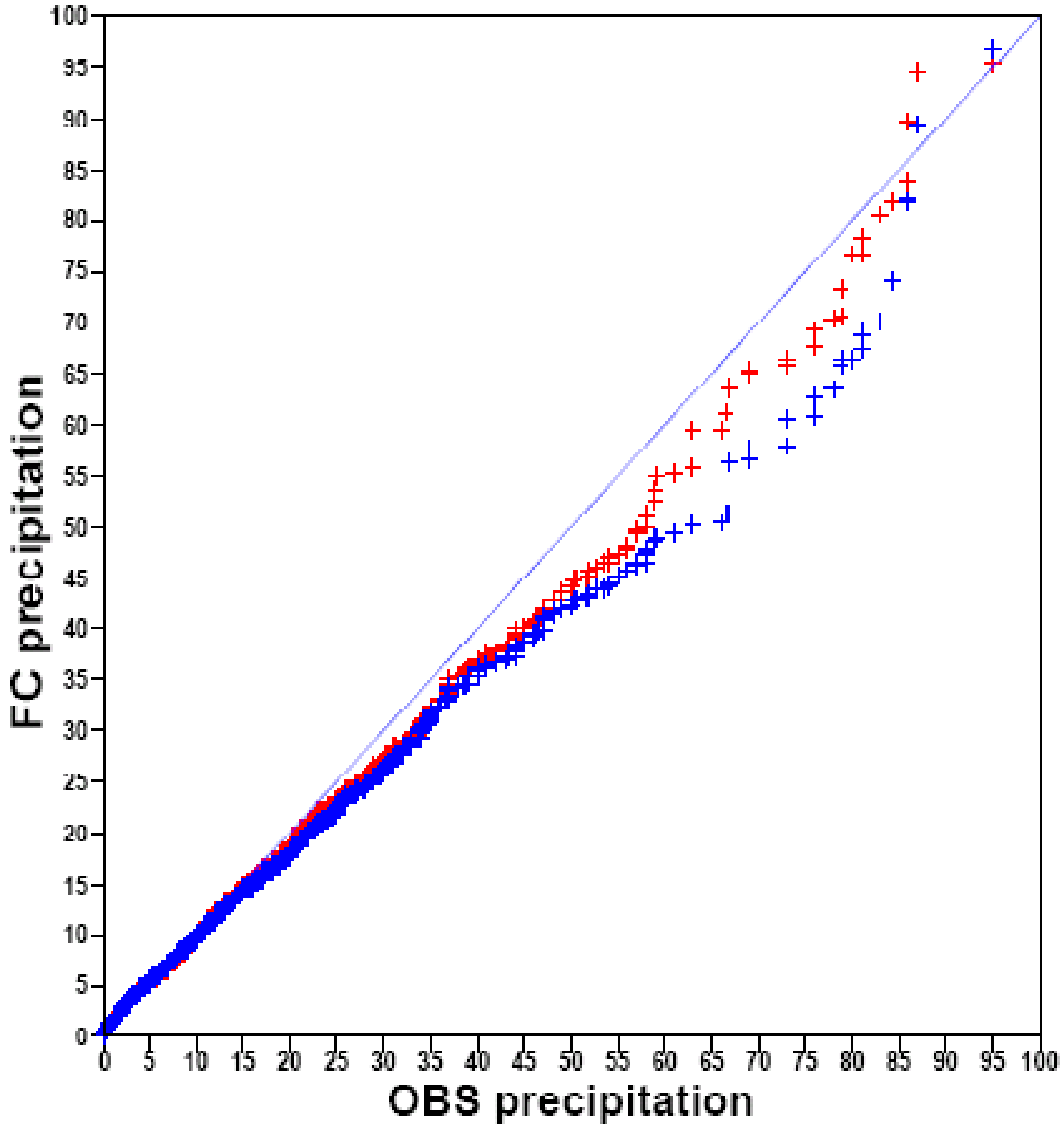
NH



Tropics



T1279 & T799 versus Obs precipitation Europe



T1279

T799

from 36h forecast winter

High resolution improves on high precipitation amounts

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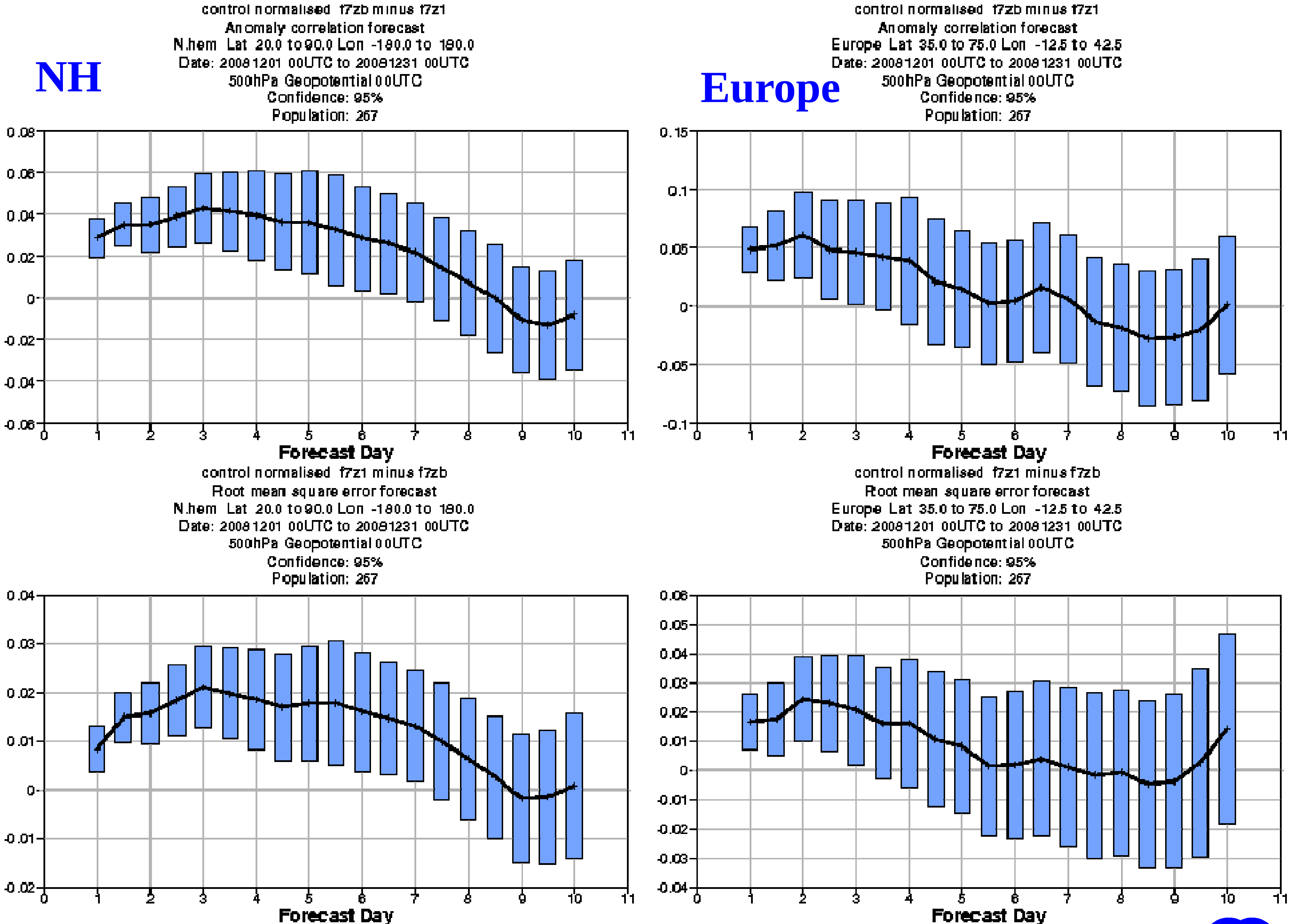
NH
control normalised f7zb minus f7z1
Anomaly correlation forecast
N.hem Lat 20.0 to 90.0 Lon -180.0 to 180.0
Date: 20081201 00UTC to 20081231 00UTC
500hPa Geopotential 00UTC
Confidence: 95%
Population: 267
Forecast Day
Europe
control normalised f7zb minus f7z1
Anomaly correlation forecast
Europe Lat 35.0 to 75.0 Lon -12.5 to 42.5
Date: 20081201 00UTC to 20081231 00UTC
500hPa Geopotential 00UTC
Confidence: 95%
Population: 267
Forecast Day
control normalised f7z1 minus f7zb
Root mean square error forecast
N.hem Lat 20.0 to 90.0 Lon -180.0 to 180.0
Date: 20081201 00UTC to 20081231 00UTC
500hPa Geopotential 00UTC
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control normalised f7z1 minus f7zb
Root mean square error forecast
Europe Lat 35.0 to 75.0 Lon -12.5 to 42.5
Date: 20081201 00UTC to 20081231 00UTC
500hPa Geopotential 00UTC
Confidence: 95%
Population: 267
Forecast Day

The nonhydrostatic IFS

- **Developed by Météo-France and its ALADIN partners** ***Bubnová et al., (1995); ALADIN (1997); Bénard et al. (2004,2005,2009)***
- **Made available in IFS/Arpège by Météo-France** ***(Yessad, 2008)***
- **Testing of NH-IFS described in Techmemo TM594** ***(Wedi et al. 2009)***

Hierarchy of test cases

- *Shallow water*
- **Acoustic waves**
- **Gravity waves**
- **Planetary waves**
- **Convective motion**
- **Idealized dry atmospheric variability and mean states**
- ***Moist simulations and dynamics-physics interaction***
- **Seasonal climate, intraseasonal variability**
- **Medium-range forecast performance at hydrostatic scales**
- ***High-resolution forecasts at nonhydrostatic scales***

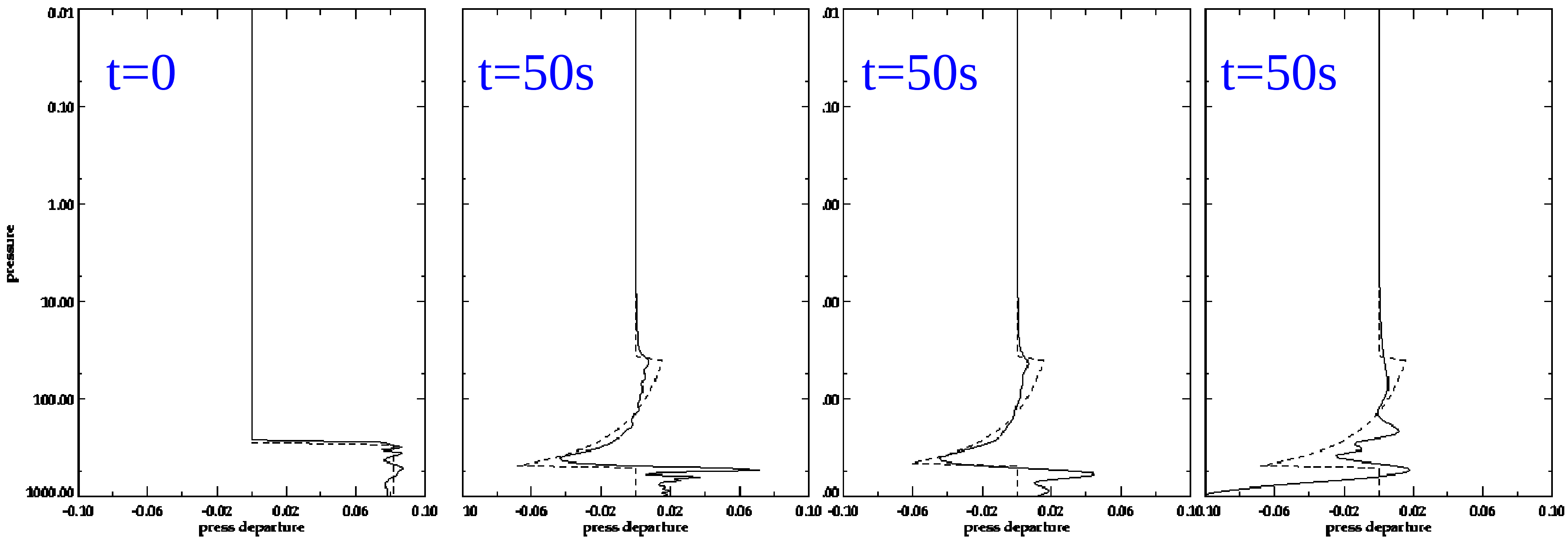
Local- and synoptic-scale simulations on the sphere ...

The size of the computational domain is reduced without changing the depth or the vertical structure of the atmosphere by changing the radius ($a < a_{Earth}$)

Wedi and Smolarkiewicz, Q. J. R. Meteorol. Soc. 135: 469-484 (2009)

A spherical acoustic wave in a stratified (isothermal) atmosphere

analytical solution in dashed line



explicit, dt=0.01s

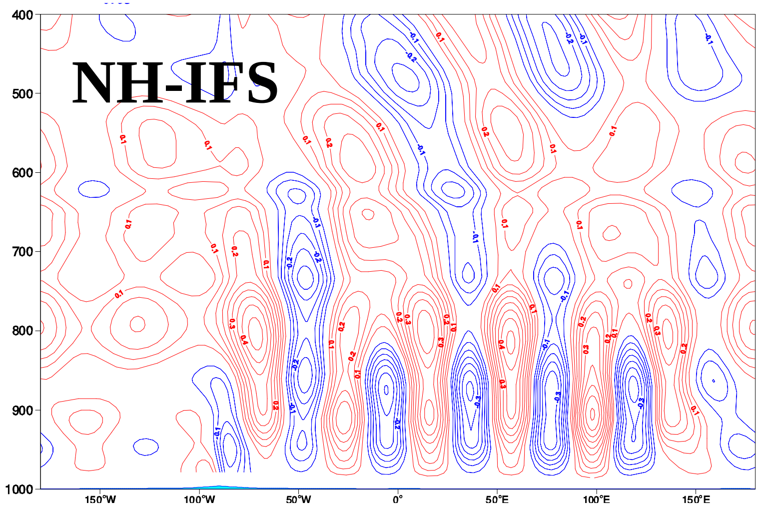
explicit, dt=0.01s

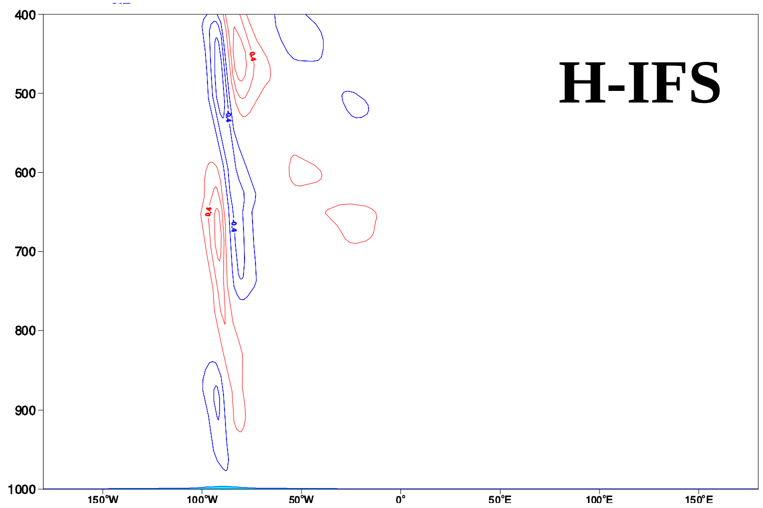
Semi-implicit, dt=1s

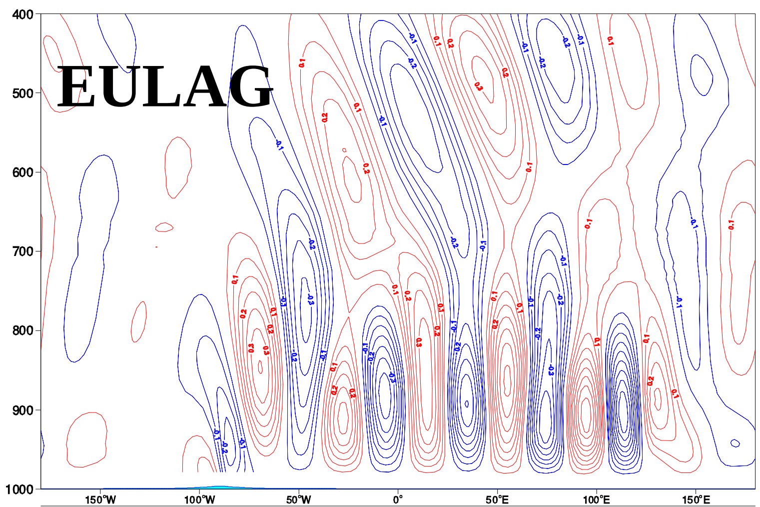
Semi-implicit, dt=10s

NH-IFS T_L159L91

Quasi two-dimensional orographic flow with linear vertical shear







The figures illustrate the correct horizontal (NH) and the (incorrect) vertical (H) propagation of gravity waves in this case (Keller, 1994). Shown is vertical velocity.

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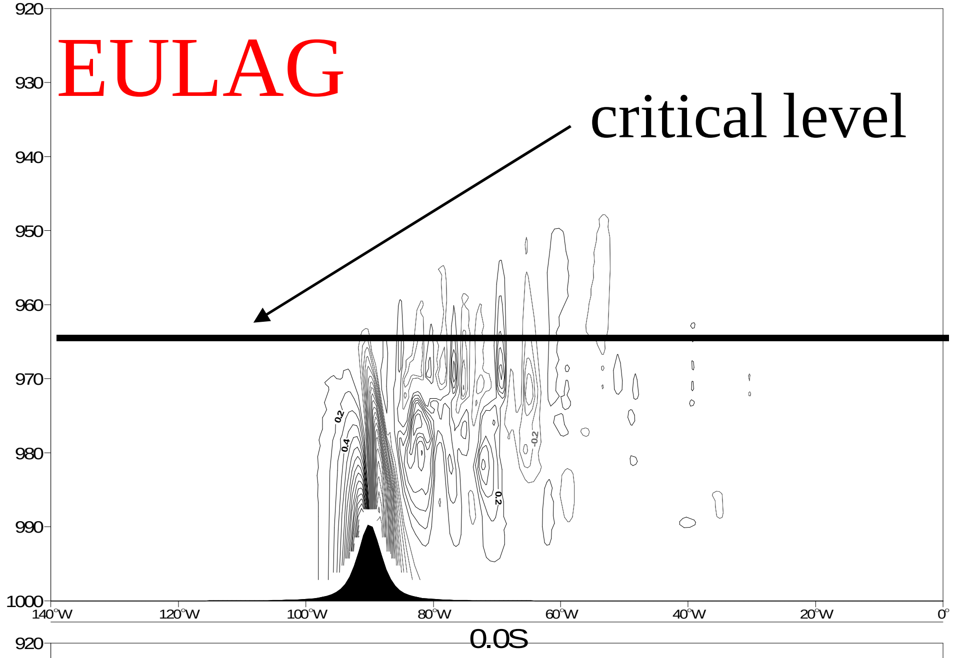
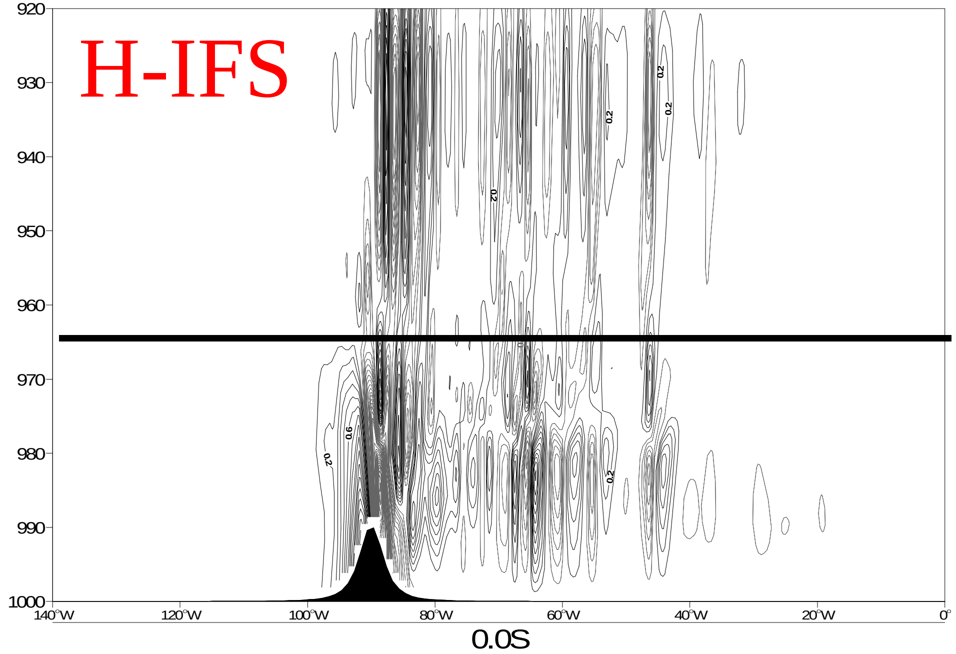
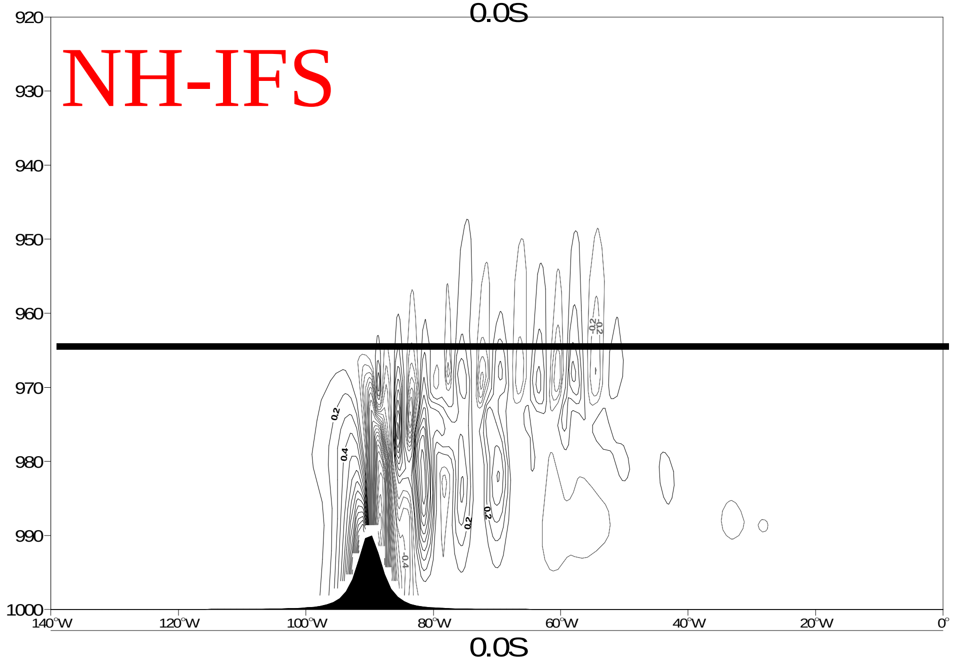
The critical level effect on linear and non-linear flow past a three-dimensional hill

LS5 $U_0 / NL_\lambda = 1$







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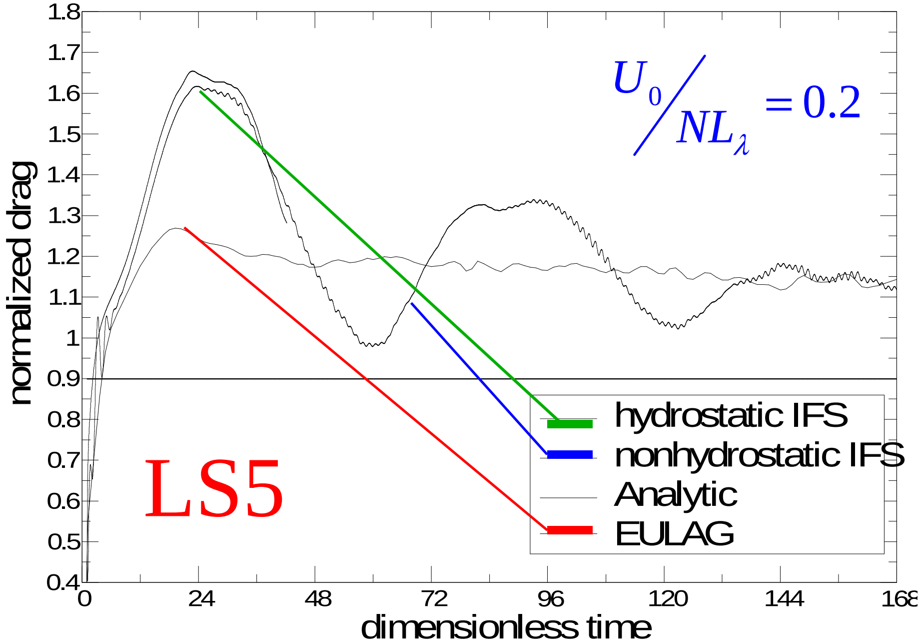
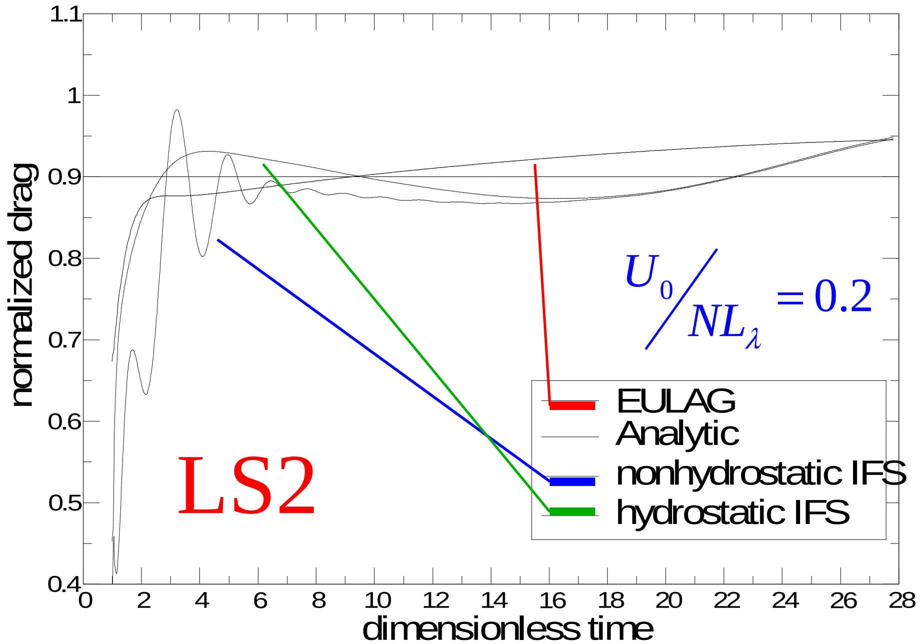
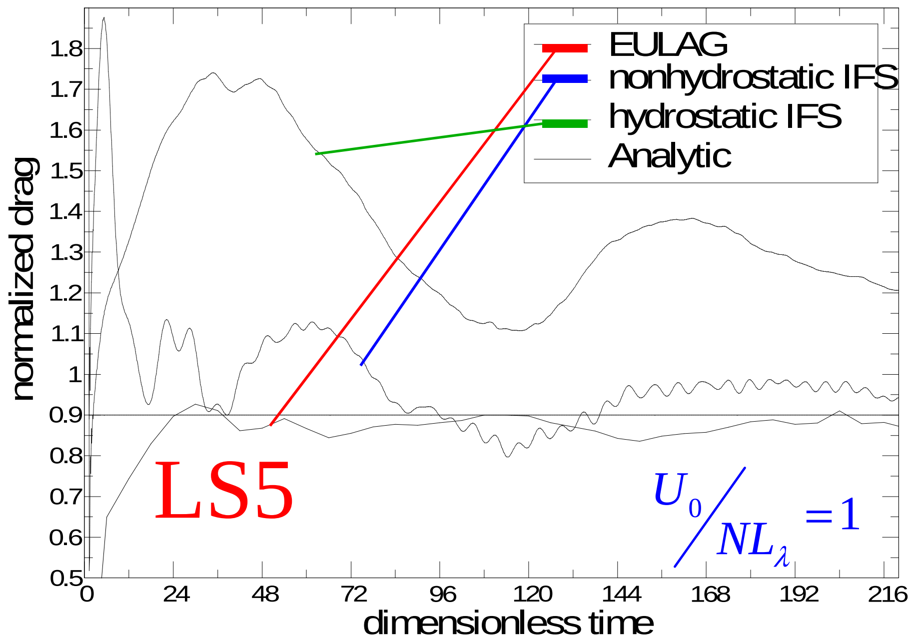
Mountain drag







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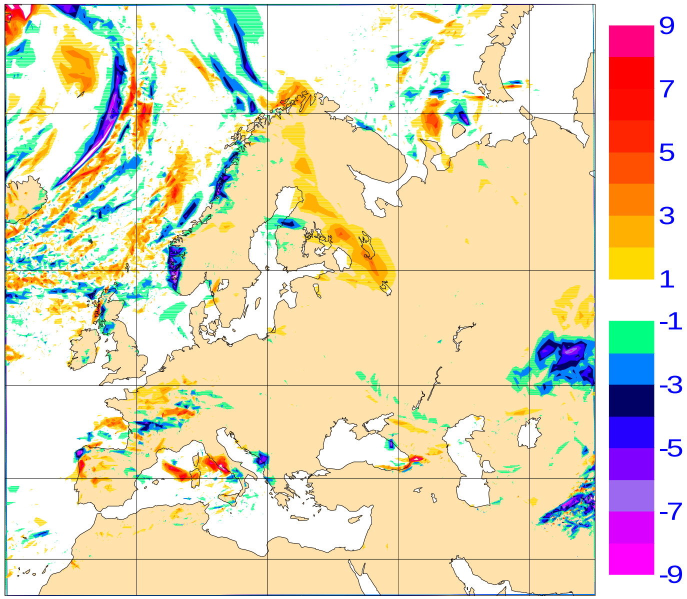
Medium-range forecast performance at hydrostatic scales

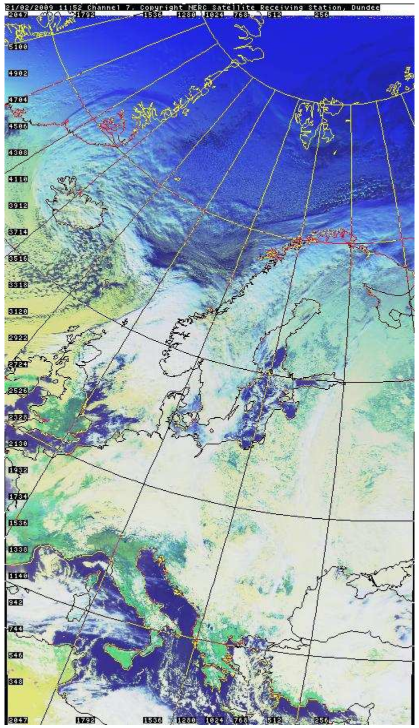
- Tropospheric scores are the same T799L91 (41 cases) 33r2, T1279 (49 cases) 35r1; Stratospheric scores the same with LVERTFE=T (here the NH-IFS model uses the linear system and the semi-implicit calculations in FD! -> Karim Yessad)
- So far physics coupling to the dynamics in the ICI scheme in final iteration only and using the hydrostatic physics “as is”. Open issues with physics-dynamics coupling towards cloud-resolving simulations!

T_L2047 ~ 10 km grid-size

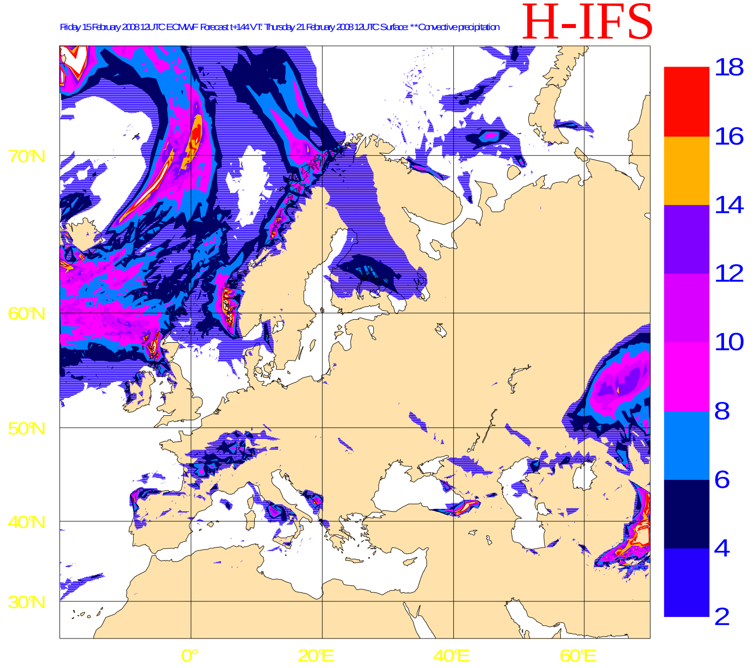
Total precipitation forecast difference at t0 + 6 days



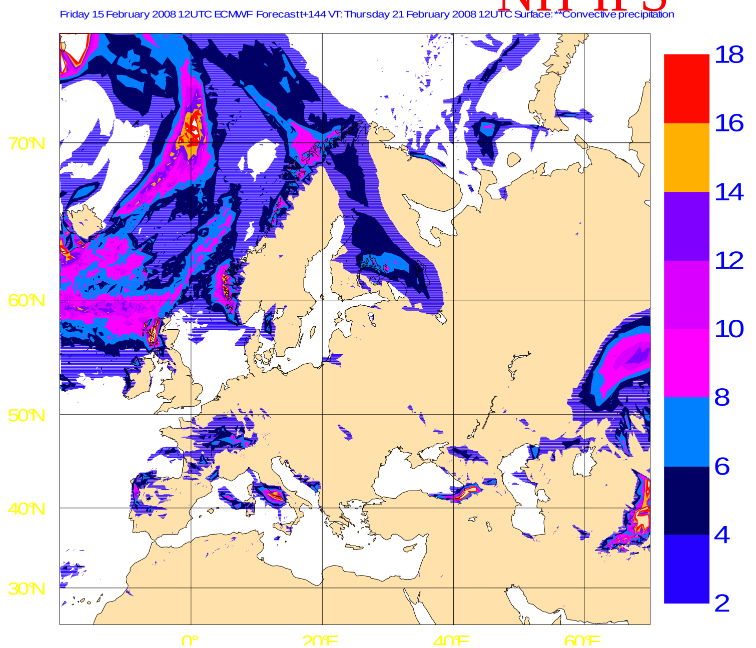
NH – H



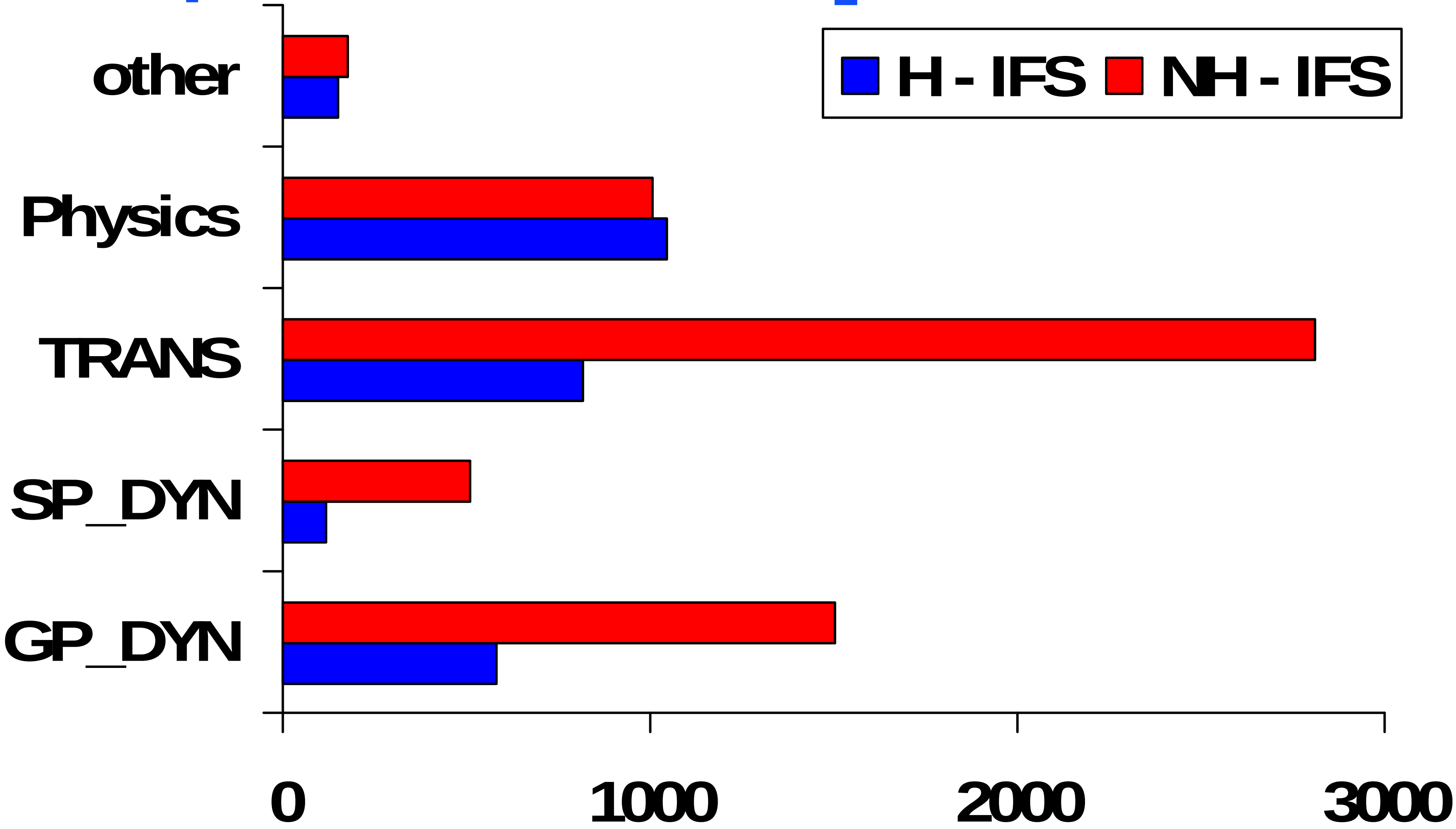
H-IFS



NH-IFS

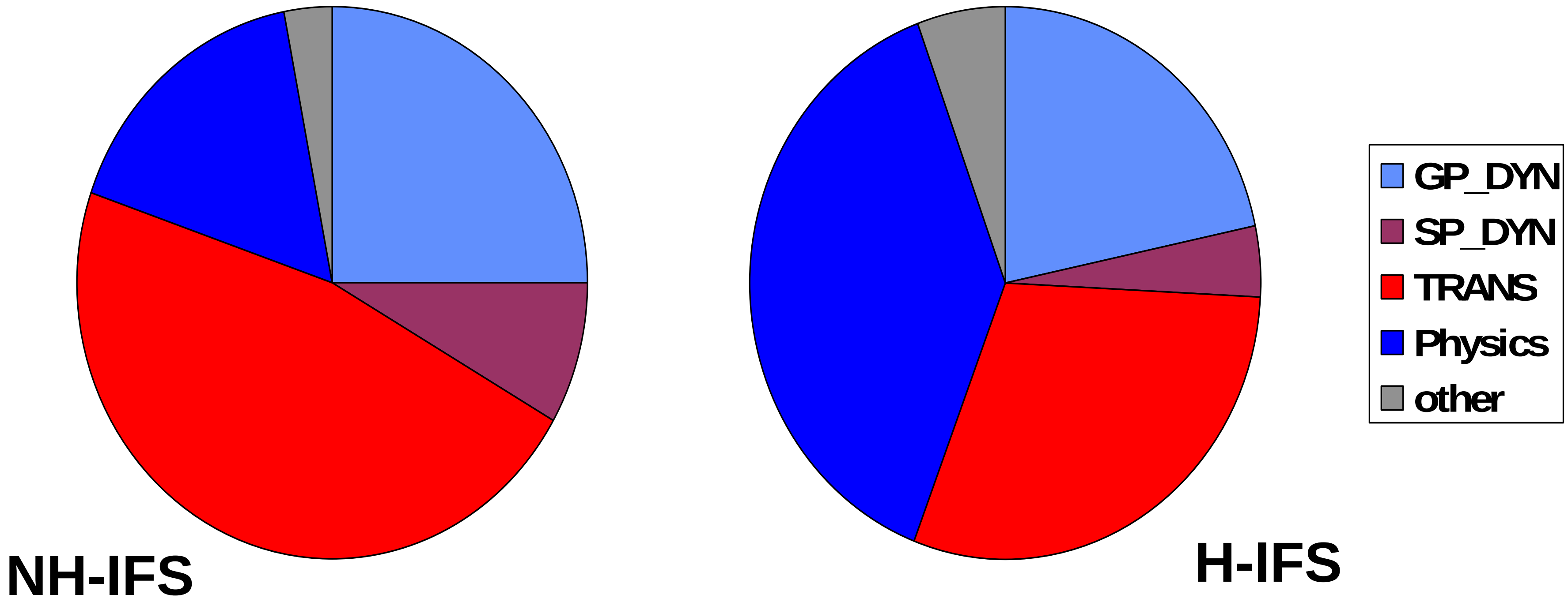


Computational Cost at T_L2047



Total cost increase 106 %

Computational Cost at T_L2047



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NH-IFS status summary

- Works reasonably well for various idealized test cases
- Deep and shallow atmosphere options available
- Seasonal climate and scores almost identical to hydrostatic model at hydrostatic scales
- Little or no benefit found so far at T_L2047
- Computational cost 2 x at T_L2047 is an issue !
  - Renewed interest in "Fast Legendre Transform" (*Tygert, 2008)*

Additional slides

Legendre transforms

- Changes to transform package went into cycle 35r3 that allow the computation of Legendre functions and Gaussian latitudes in double precision following *(Schwarztrauber, 2002)* (-> Mats Hamrud).
- **Note:** the increased accuracy 10^{-13} instead of 10^{-12} in the "Courtier and Naughton procedure" leads to slightly more points near the pole for all resolutions (in addition all resolutions have an odd feature of artificially excluding rows with 625 and 1250 points).

Fast Legendre transform

- Some time has been spent to start coding an ***FMM (fast multipole method)*** ***based Legendre transform*** following ***(Tygert, JCP, 2008).*** (-> Mats Hamrud and Mike Fisher).
- 1) A recursive ***Cuppen divide-and-conquer algorithm*** computes the Eigenvalues and Eigenvectors of a tridiagonal matrix and ("as-a-by-product") it allows to apply a square matrix of normalized Eigenvectors to any arbitrary vector (which is what we really want to do).
- 2) The arising ***matrix-vector multiply*** can be accelerated by using a ***FMM method*** as the Eigenvector elements have a special form ~$z/(d-\lambda)$, that is one can identify different levels/groups of interaction as a function of distance to the Eigenvalue λ.
- The devil is in the detail …

January

NH

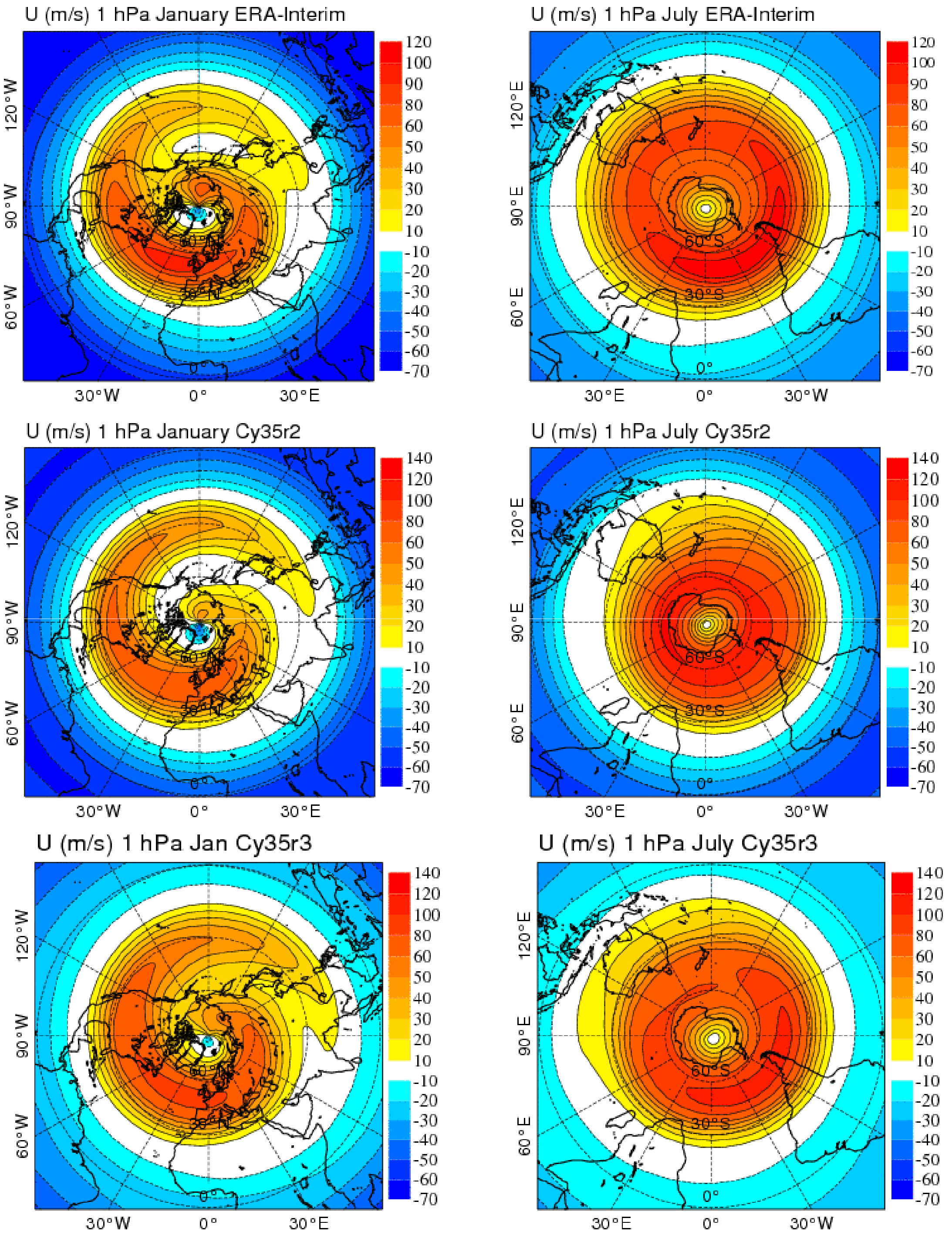
ERA

Cy35r2

Operational since March 2009

Cy35r3

Operational in summer 2009 with GWD + GHG



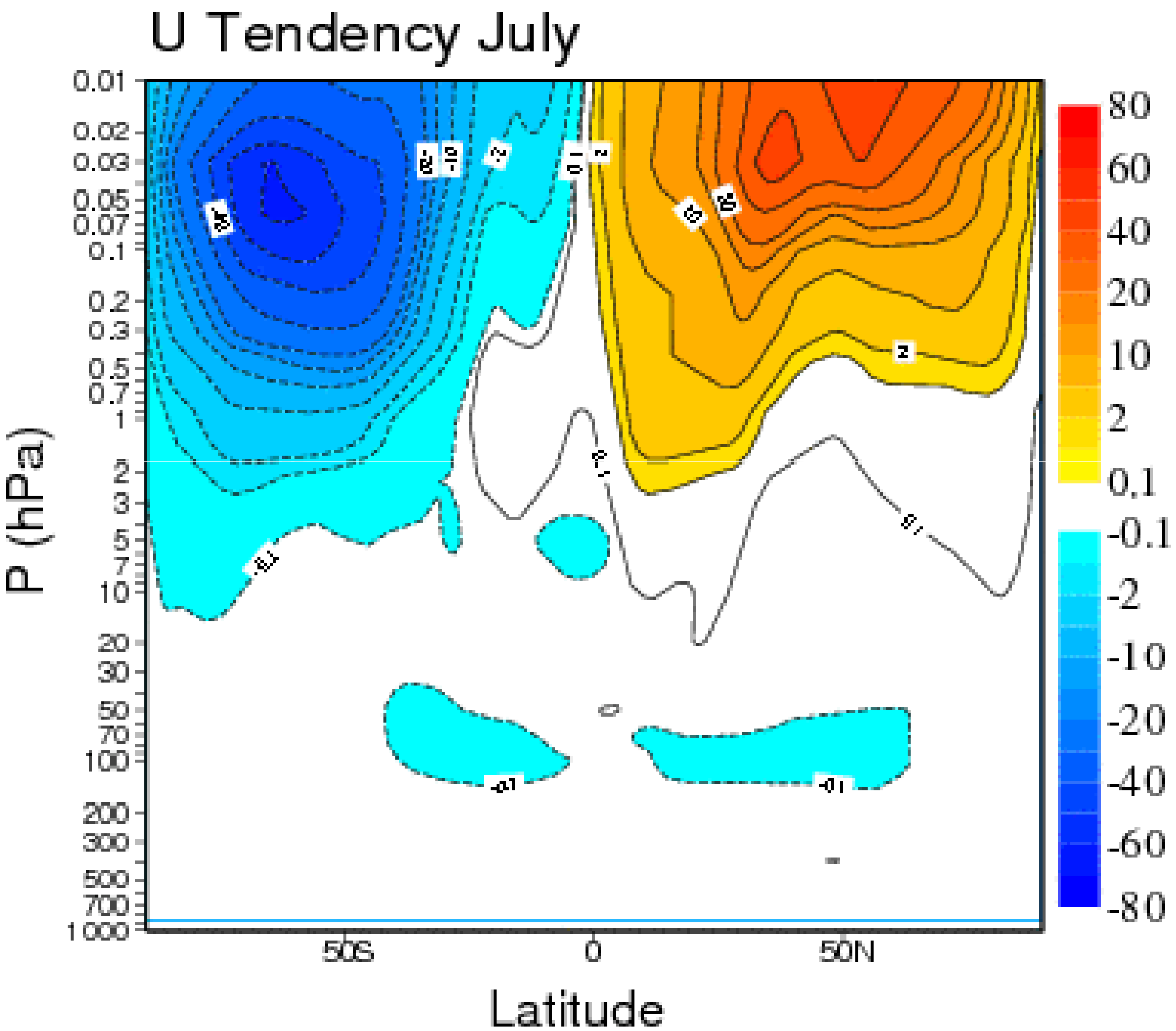
July

SH

Polar winter vortex

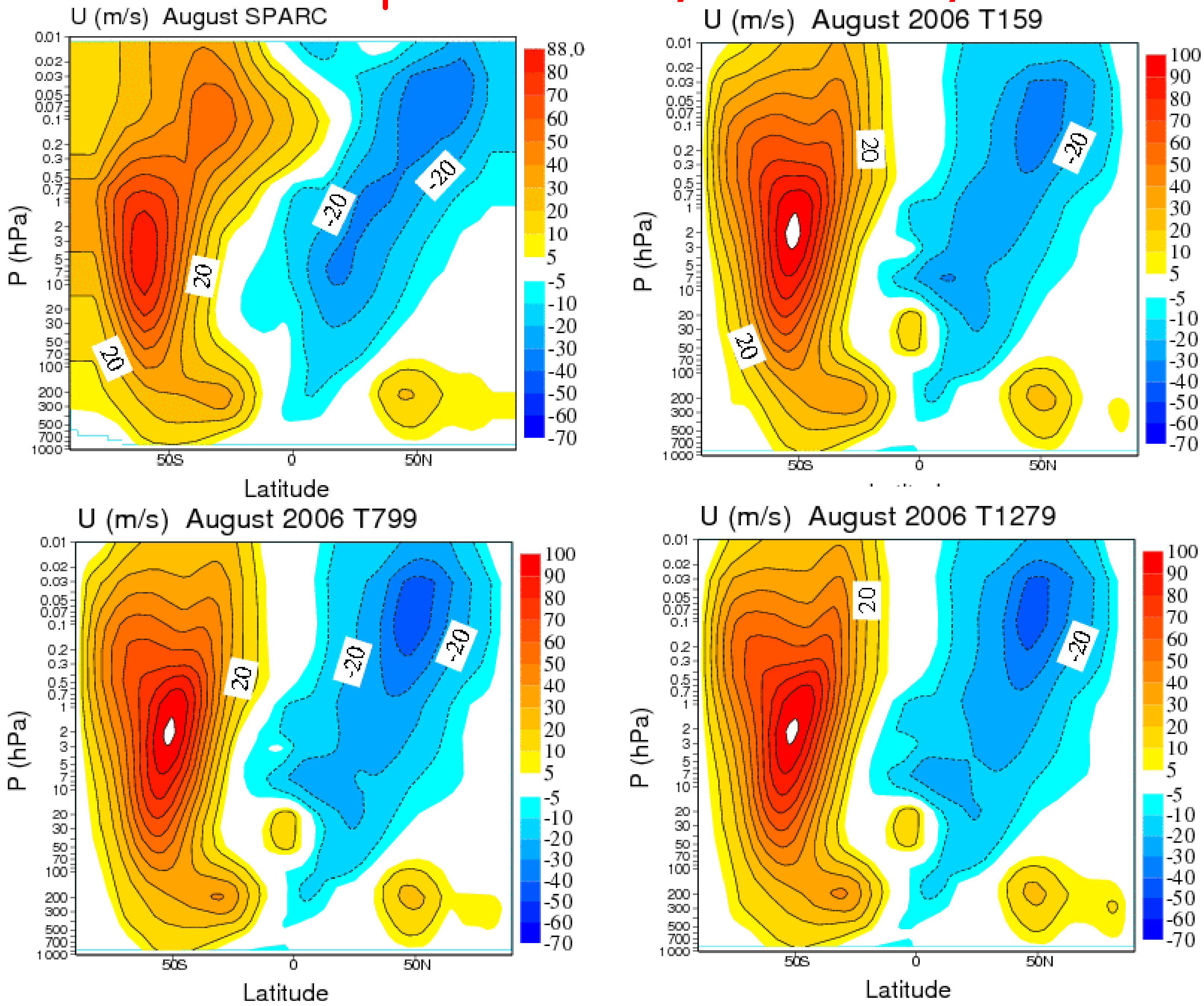
SH wintertime vortex is quasi-symmetric, but not NH polar vortex, due to braking quasi-stationary Rossby waves emanating in the troposphere

U Tendencies (m/s/day) July from non-oro GWD



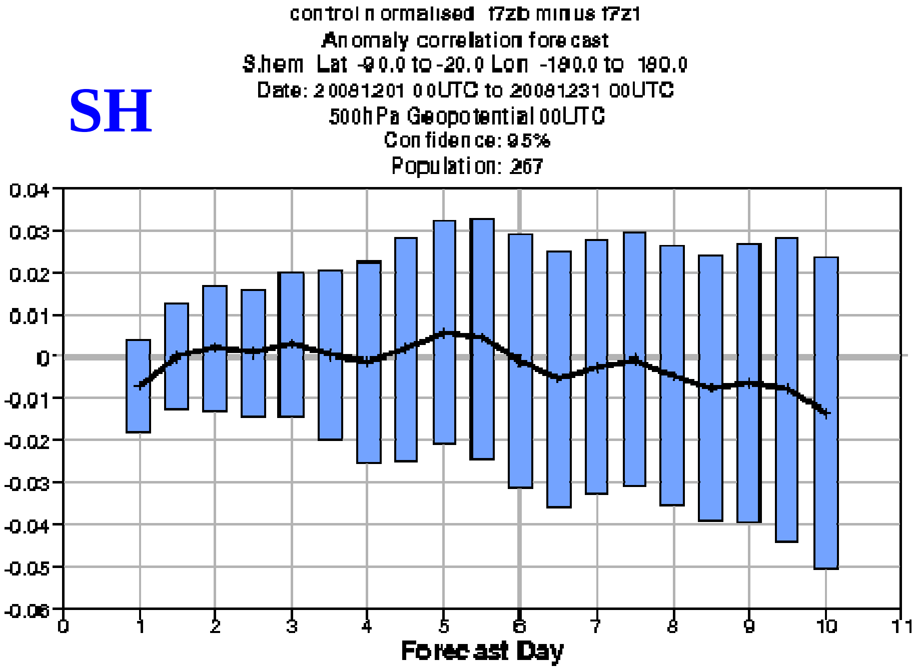
ECMWF

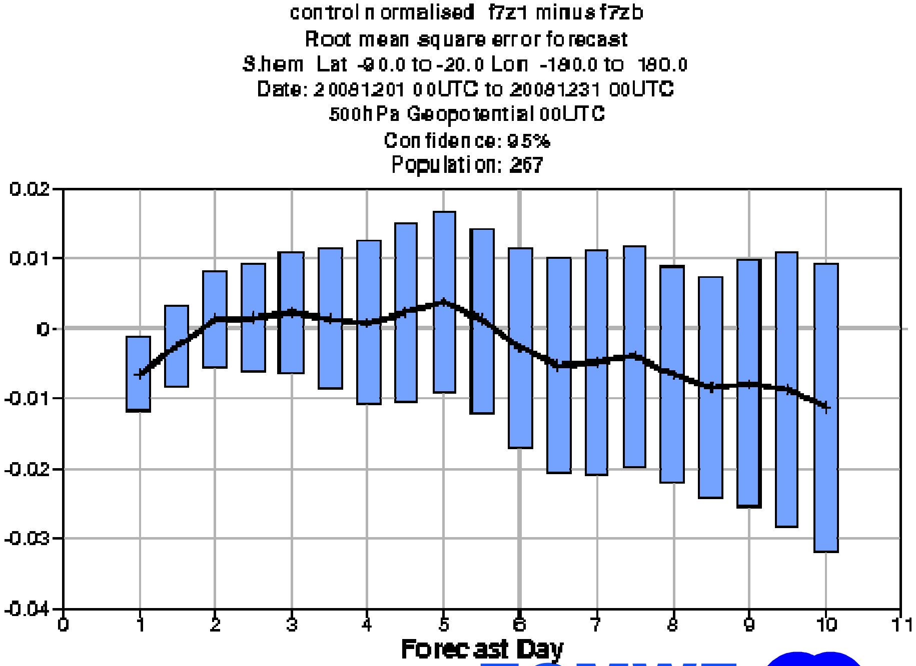
Resolution dependence Cy35r3 August



♦ **Influence less pronounced over SH as there is no orography, major driver in resolution upgrade !**

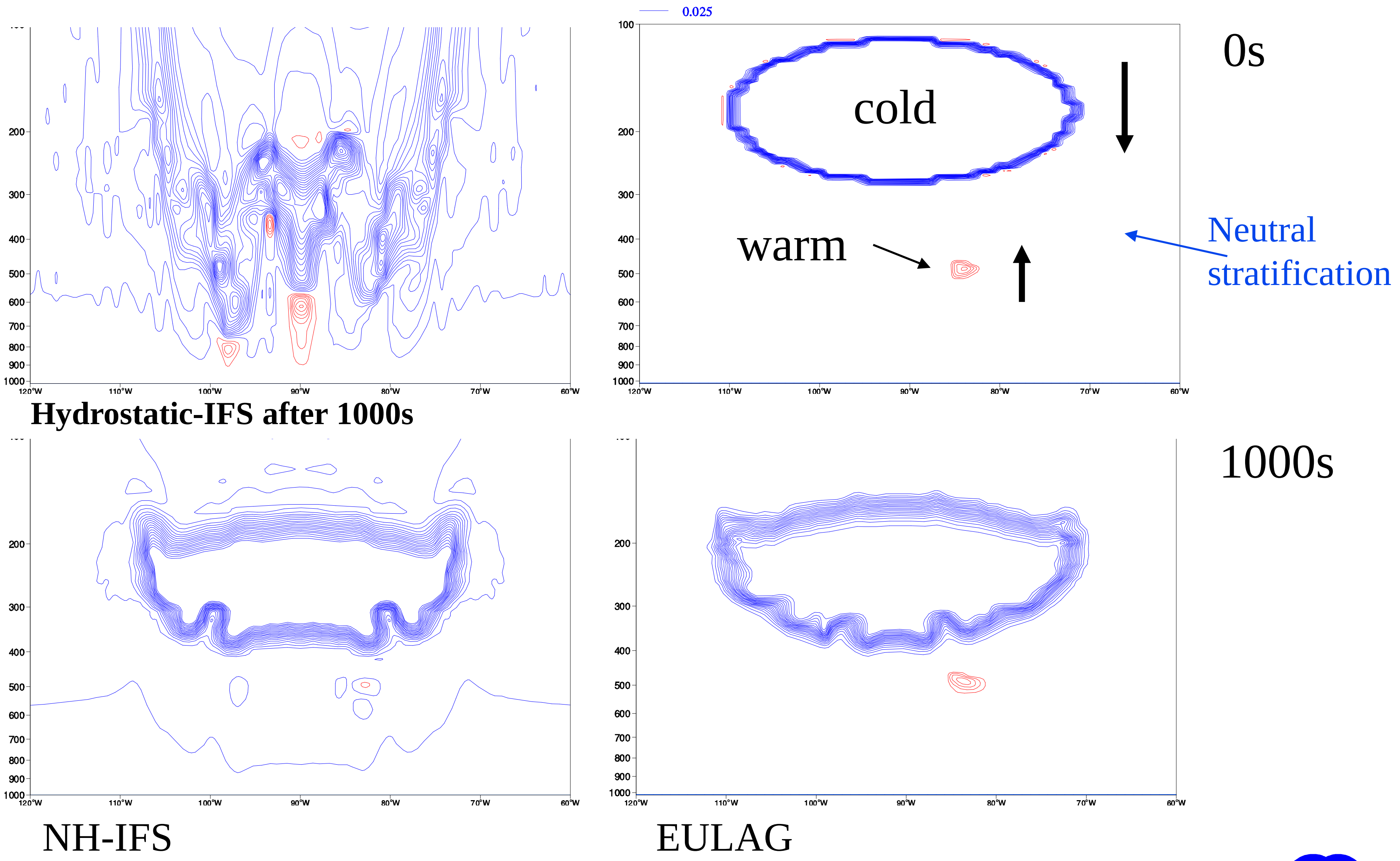
SH





ECMWF

Convective motion (3D bubble test)



ECMWF

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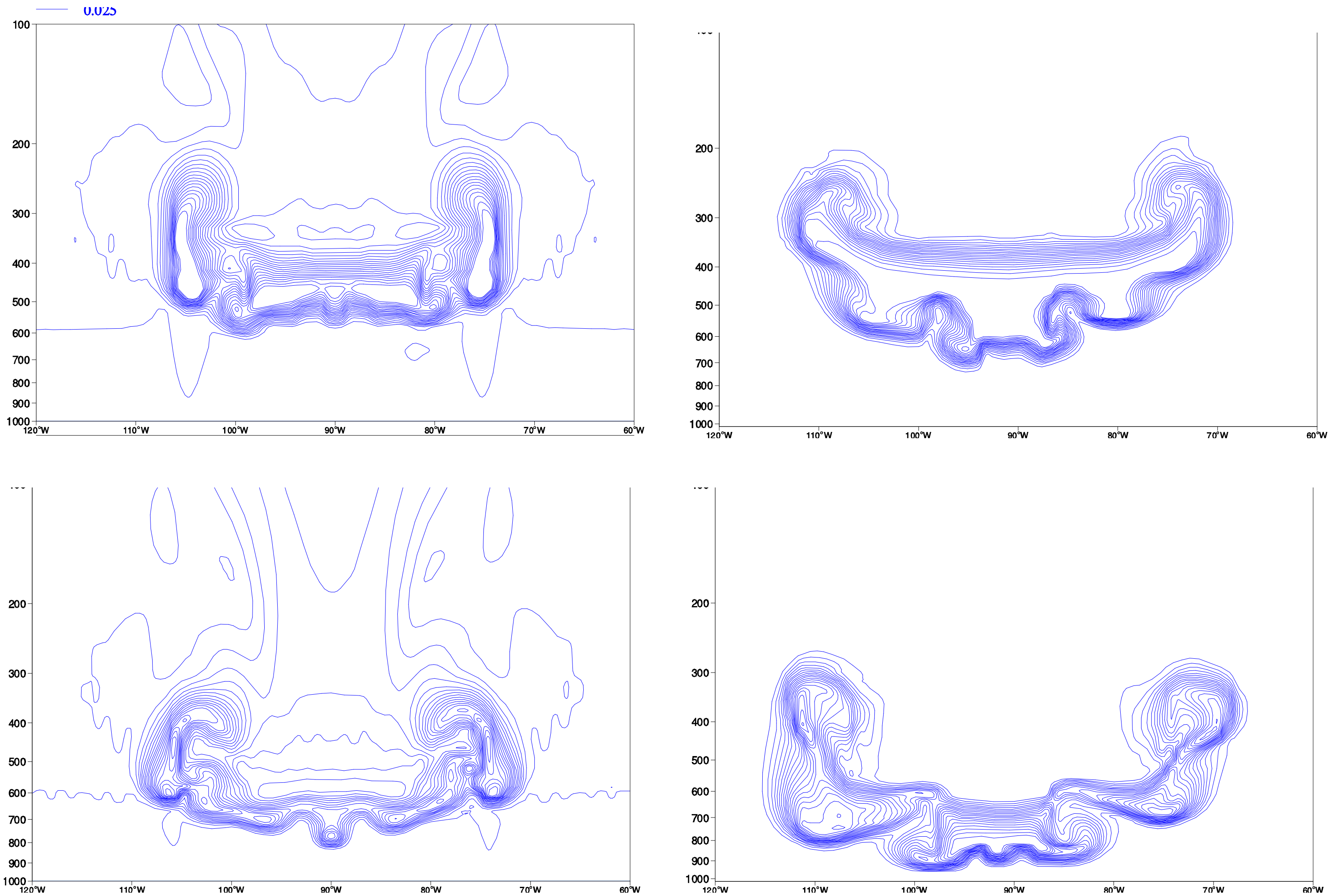


1800s

2400s

NH-IFS

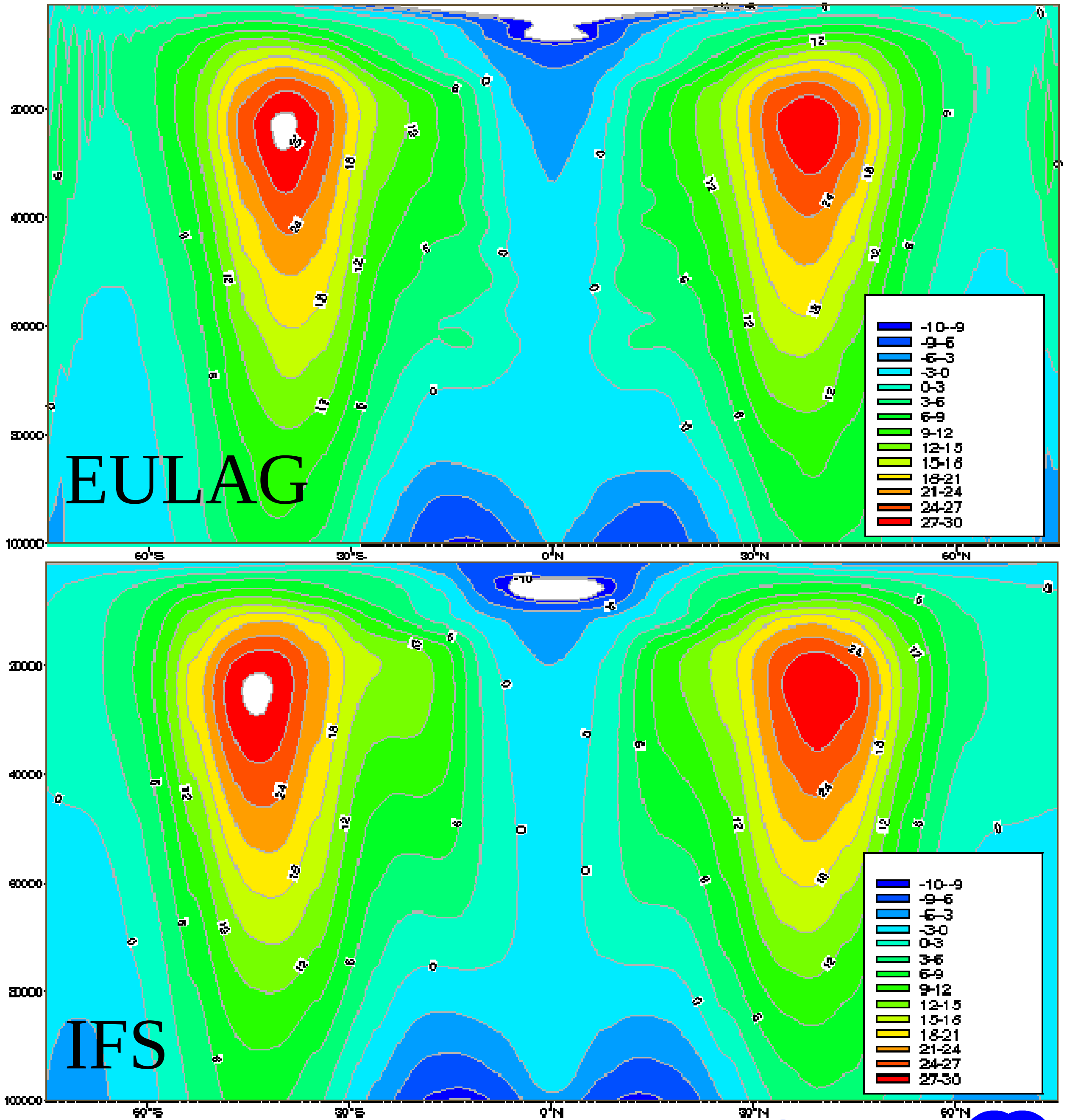
EULAG

Held-Suarez climate

$a = a_{Earth}/10$

$\Omega = 10 \times \Omega_{Earth}$

zonal-mean zonal wind U



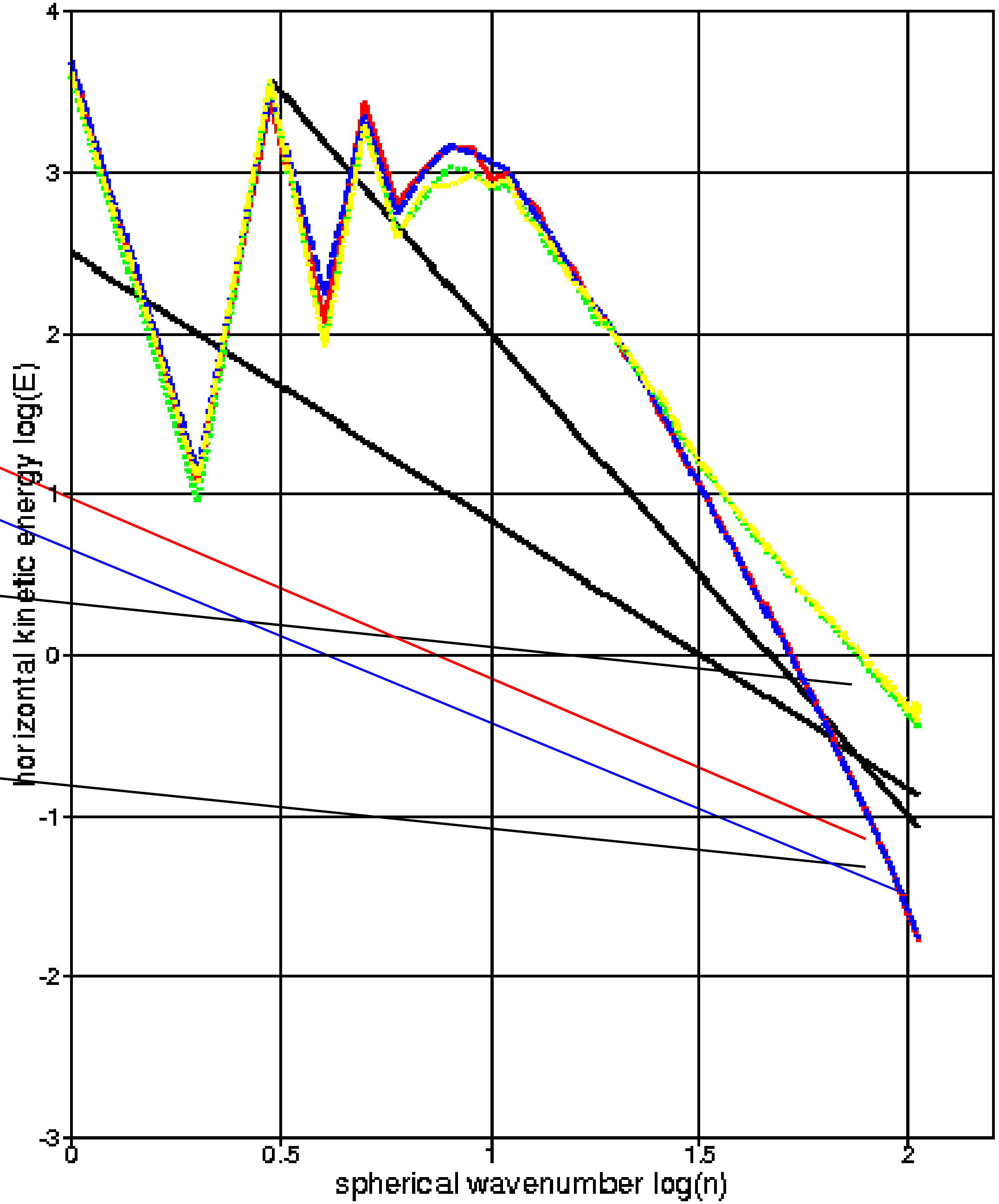
Held-Suarez climate

$a = a_{Earth}/10$

$\Omega = 10 \times \Omega_{Earth}$

EULAG

IFS

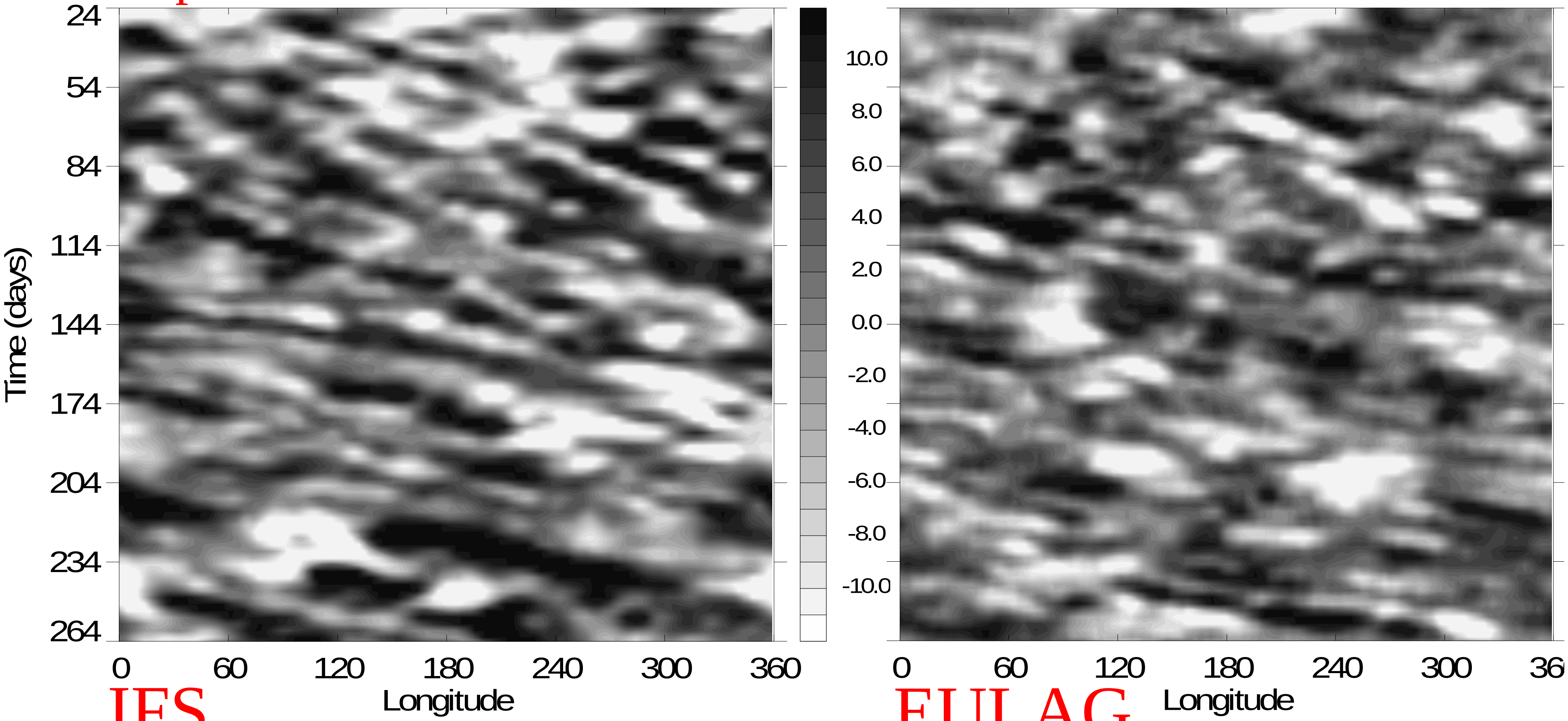


ECMWF

Held-Suarez climate $a=a_{Earth}/10$

Averaged 30ºN-50ºN

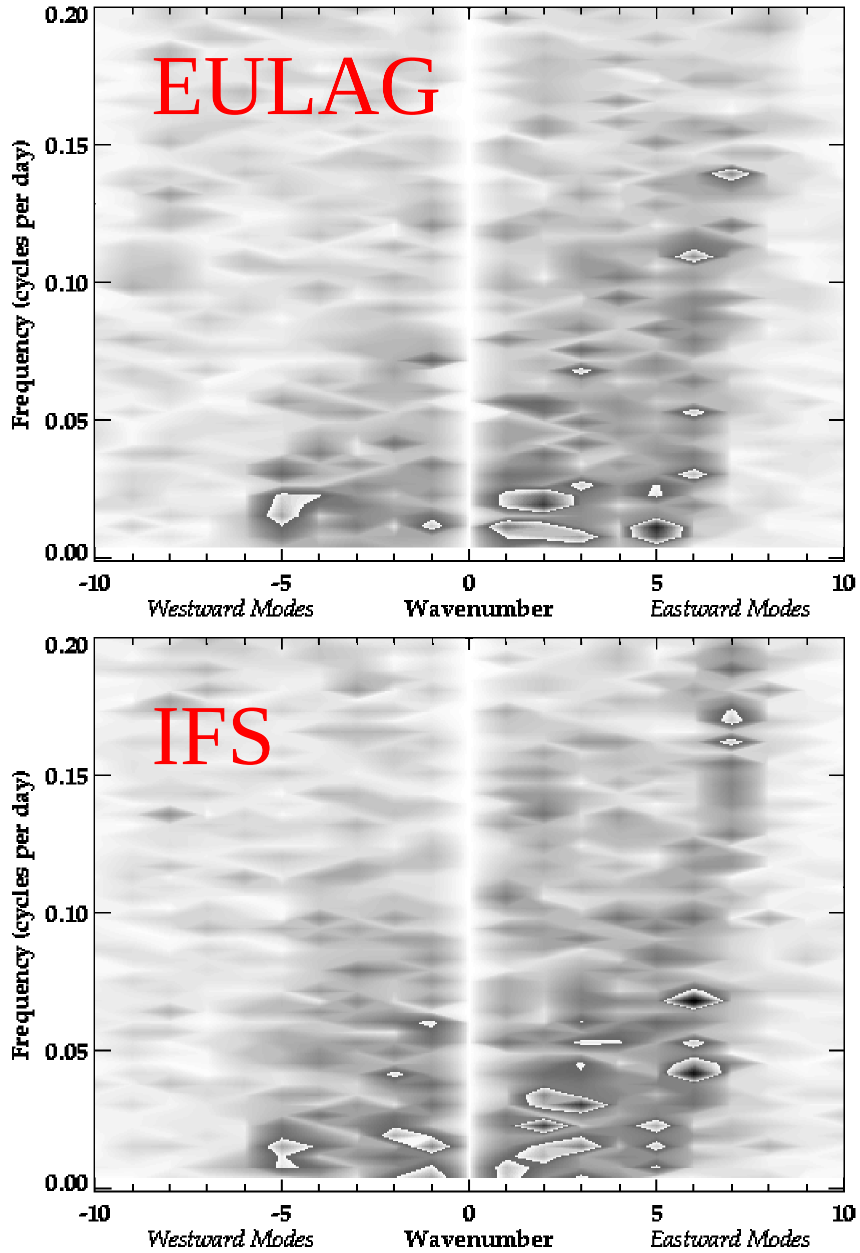
Temporal anomalies of zonal wind



IFS EULAG

Held-Suarez climate

wavenumber-frequency diagrams of zonal wind



e.g. Rossby wave dispersion:

$$\omega_R \approx \frac{2\Omega N^2 m}{n(n+1)N^2 + f^2 a^2 (\delta_A N^2 / c_s^2 + k_z^2 + \Gamma_A^2)}$$

ECMWF

Idealized dry atmospheric variability and mean states

- **Zonal mean states compare well with EULAG.**
- **Concern: Anomalous variability and wavenumber-frequency diagnostics very different !**
- **Concern: Held-Suarez spectra from wavenumber >20 considerably less energetic in horizontal modes compared to EULAG.**

Variability of organized convection

- **The formation of organized convection is sensitive to explicit or implicit viscosity in under-resolved simulations.**
- **The sensitivity is consistent with linear theory adapted to include the effect of anisotropy of viscosity (horizontal vs. vertical) at moderate Rayleigh number.**

(Piotrowski et al., J. Comput. Phys. 2009)

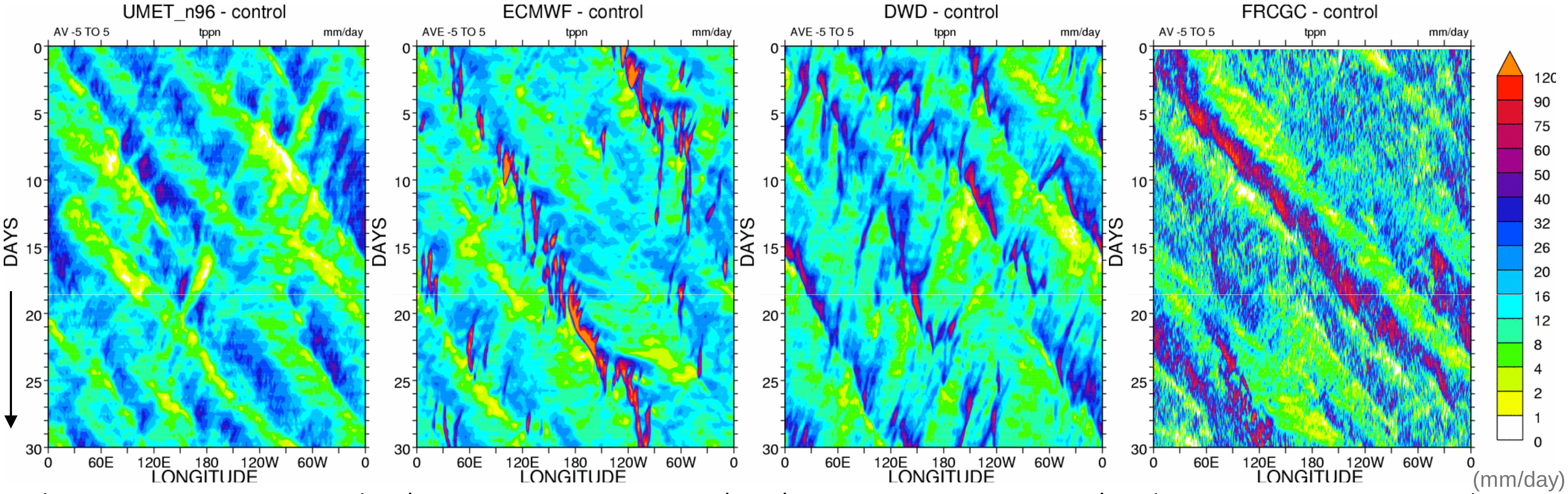
- **It suggests a careful control of the effective numerical viscosity in the numerical core ! (such as the dependence of the truncation error on the derivatives of the flow variables rather than the flow variables themselves).**

Tropical Variability (precipitation) Courtesy of D. Williamson

APE Aqua-Planet Experiment Project

Higher resolution models

average 5ºN-5ºS



pre-HadGAM1	IFS Cy29r2	GME	NICAM
N96 L38	T_L159 L60	Icosahedral L31	Icosahedral L54
1.25° x 1.875°	~125km grid	~100km grid	7km grid

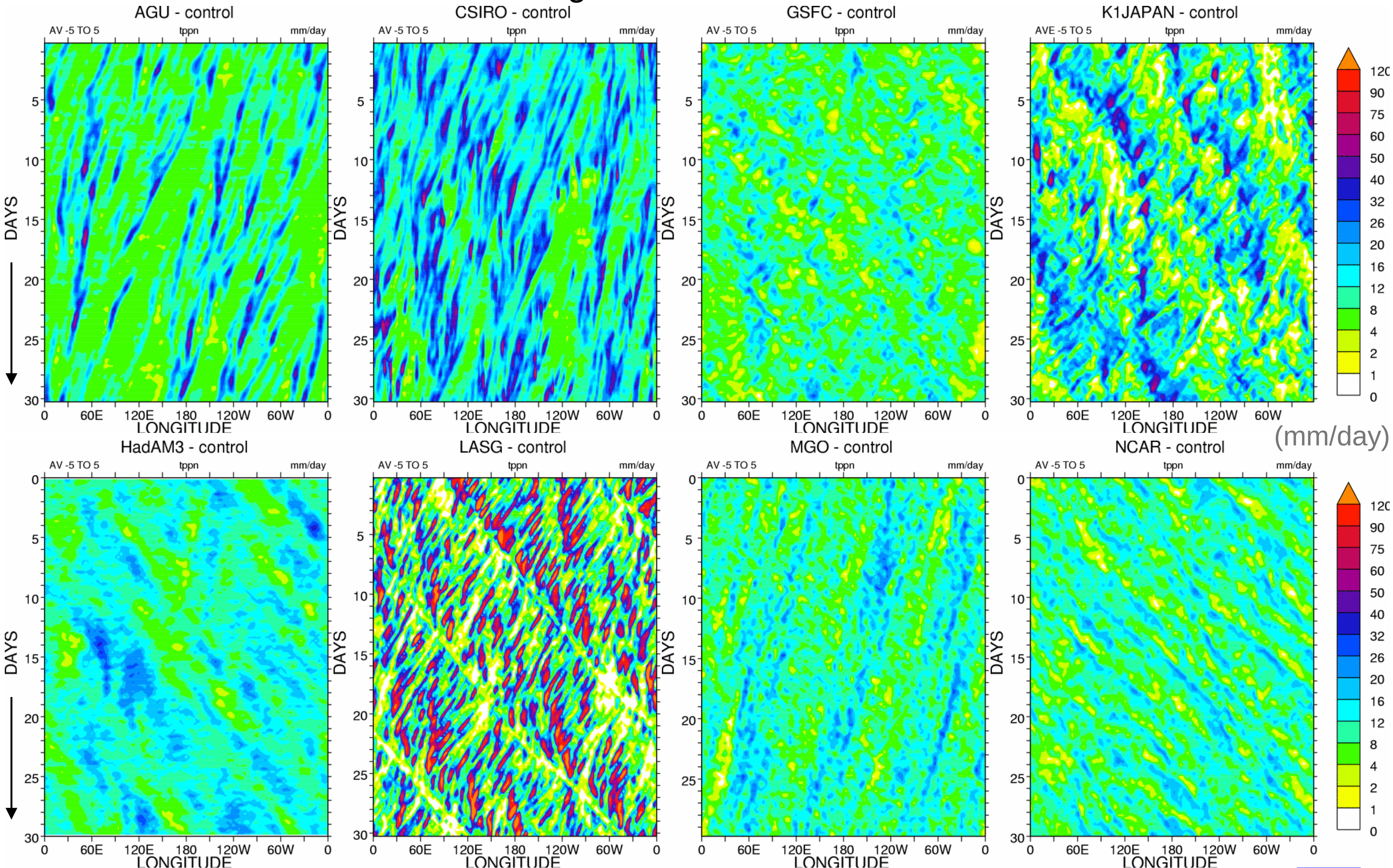
non-hydrostatic
no convective param.

ECMWF

Tropical Variability (precipitation)

Courtesy of D. Williamson

average 5ºN-5ºS



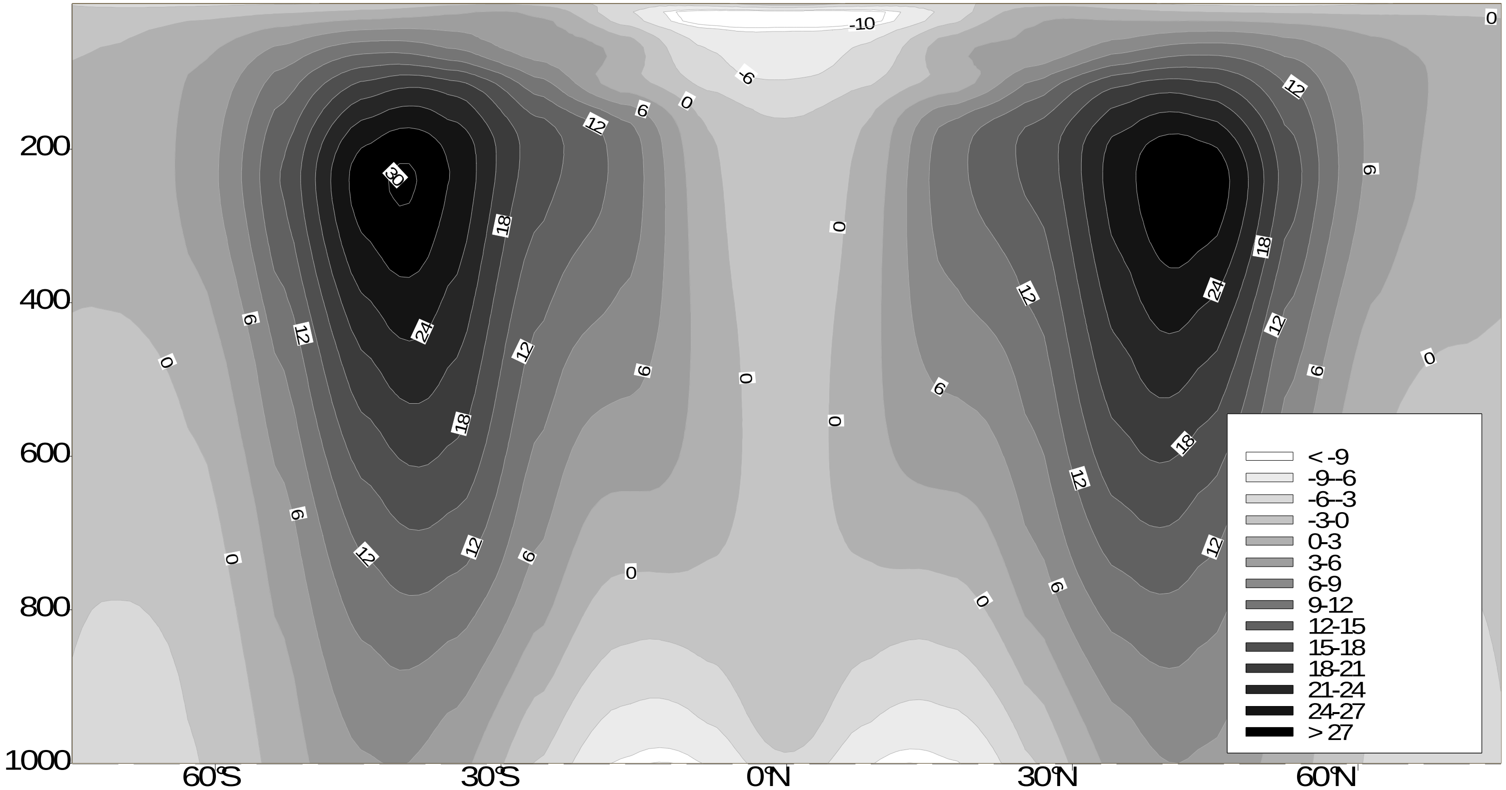
ECMWF

Deep vs. shallow atmosphere

- **Deep atmosphere formulation implemented by Karim Yessad (testing/bugfixing when he visited ECMWF; some remaining issues)** *(Staniforth, Wood QJRMS Vol. 129, 1289-1300, 2003)*

The influence of the shallow vs deep atmosphere model formulation

$$\Omega = 20 \times \Omega_{Earth} \quad a = a_{Earth}/20$$



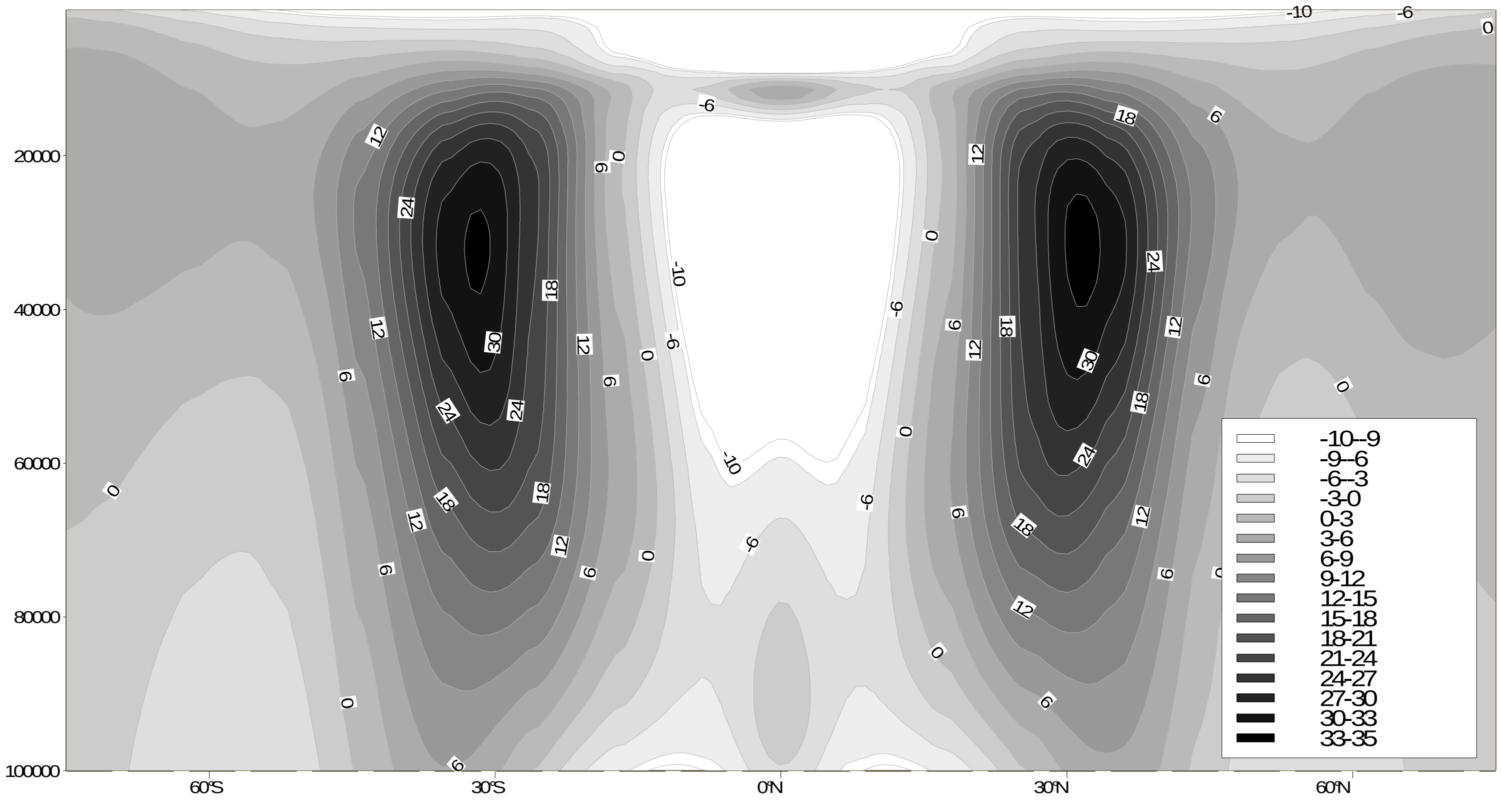
IFS Held-Suarez simulation with a shallow hydrostatic model

Simmons and Burridge 1981

ECMWF

The influence of the shallow vs deep atmosphere model formulation

$\Omega = 20 \times \Omega_{Earth}$ $a = a_{Earth}/20$

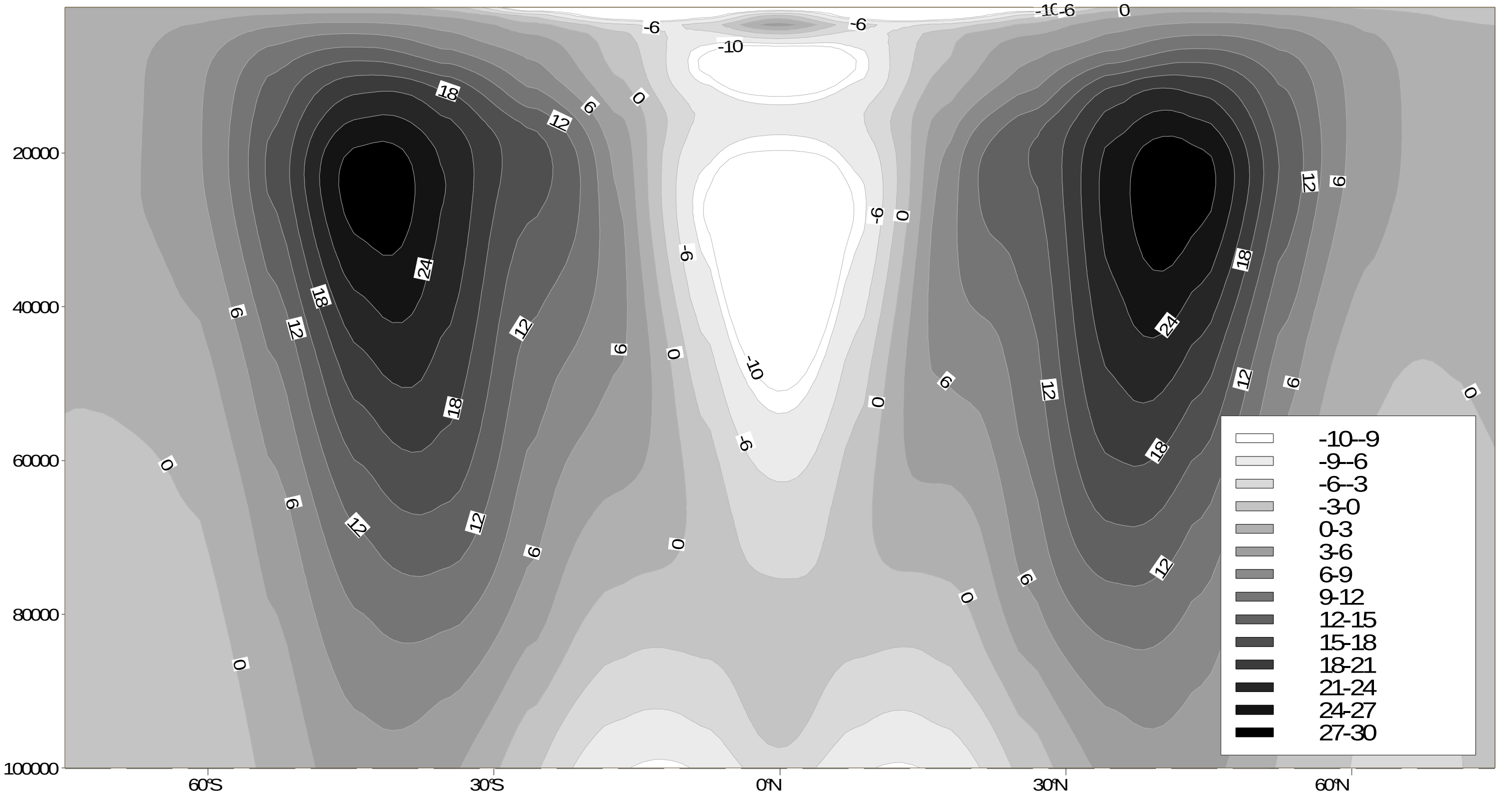


IFS Held-Suarez simulation with a deep hydrostatic model following *White and Bromley, 1995*

ECMWF

The influence of the shallow vs deep atmosphere model formulation

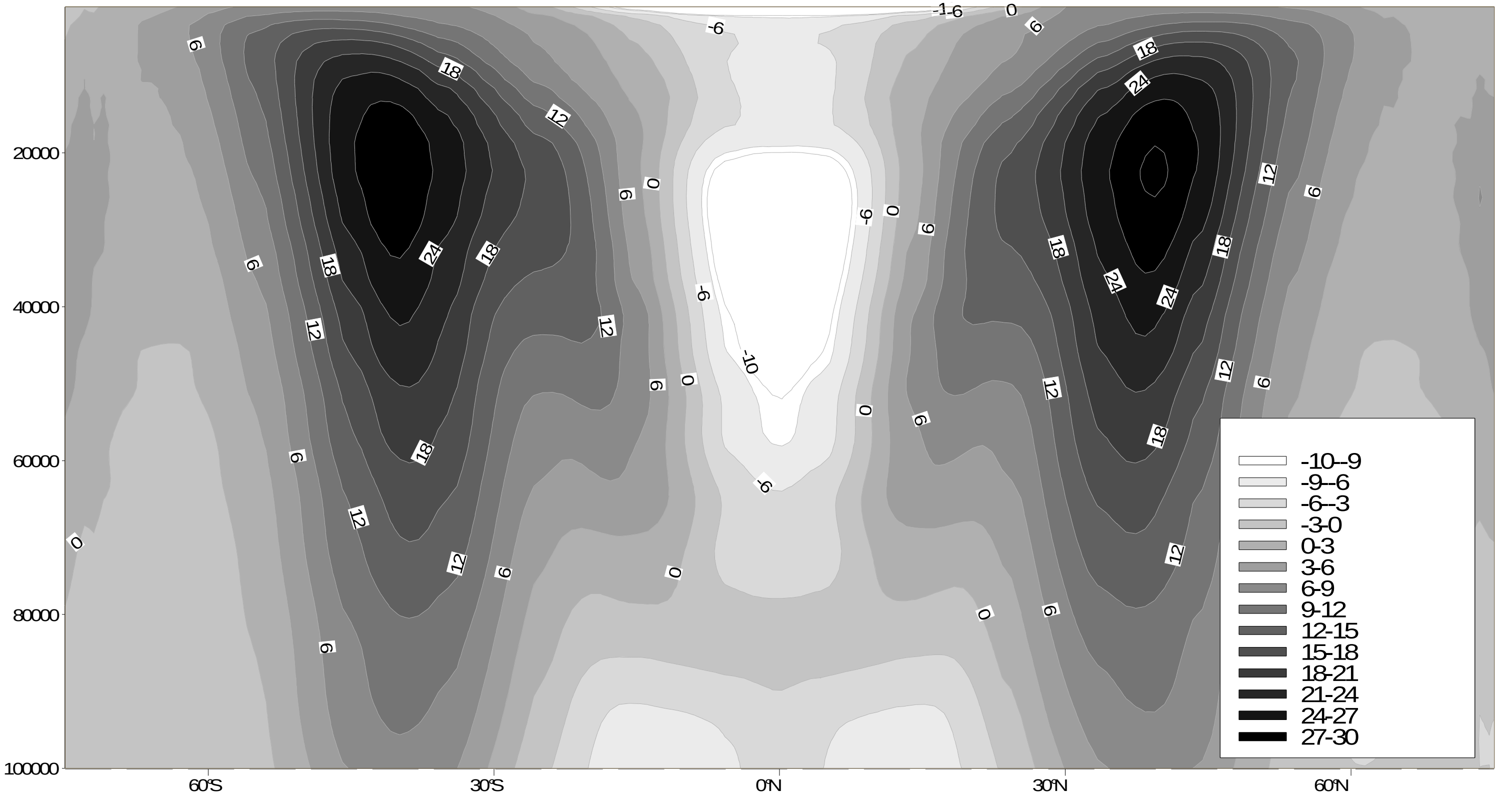
$$\Omega = 20 \times \Omega_{Earth} \quad a = a_{Earth}/20$$



IFS Held-Suarez simulation with a deep non-hydrostatic elastic model following *Wood and Staniforth 2003*

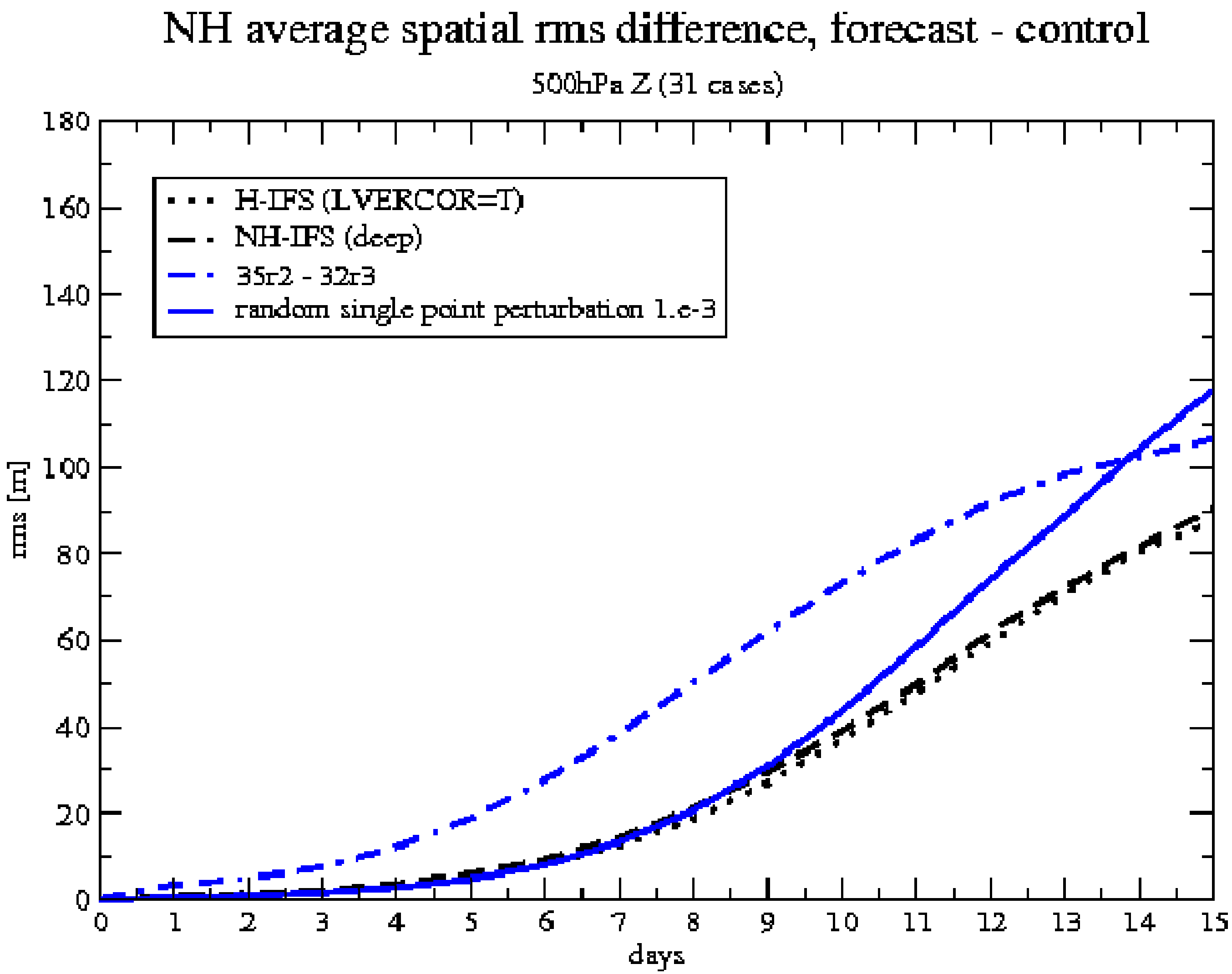
The influence of the shallow vs deep atmosphere model formulation

$$\Omega = 20 \times \Omega_{Earth} \quad a = a_{Earth}/20$$



EULAG Held-Suarez simulation with a deep non-hydrostatic anelastic model, Wedi and Smolarkiewicz, 2009

The influence of the H-shallow vs NH-deep atmosphere model formulation



Seasonal climate

- ***Shallow hydrostatic and nonhydrostatic*** **seasonal climate simulations are the same for T_L159L91 (13 month) 4 member ensemble except in the stratosphere (LVERTFE=F)**
- ***Deep hydrostatic*** **and** ***deep nonhydrostatic*** **seasonal climate simulations are very similar to the** ***shallow hydrostatic*** **simulations. Some warming of the polar regions and a cooling of the upper stratosphere can be noticed compared to the control.**