McICA: A state-of-the-art method for representing cloud-radiation interactions in GCMs?

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ECMWF

* **McICA, the Monte-Carlo Independent Column Approximation**
* **The ECMWF McICA configuration**
* **Practical implementation**
* **Results in 13-month simulations at T_L159 L91**
* **Impact on forecasts at T_L511 L91 and analysis at T_L799 L91**

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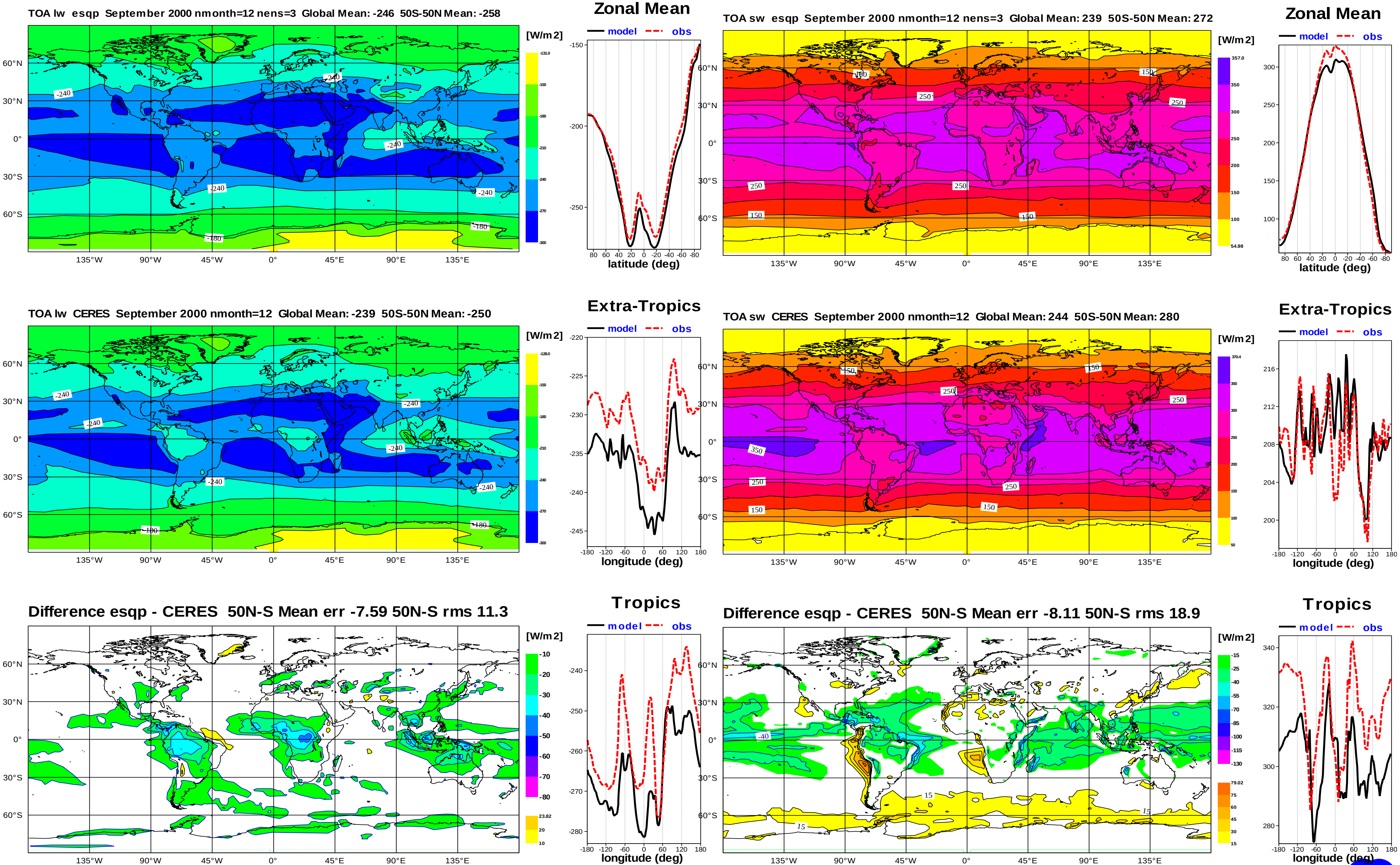
The problem in ECMWF model “climate” runs?



Some references

- In most GCM radiation schemes, unresolved variability of cloudy atmospheres is either neglected or incorporated into the radiation schemes through a modification of the cloud optical thickness (ECMWF uses a 0.7 factor from Cahalan et al., 1994)
- McICA was proposed by Barker et al. (2002) and Pincus et al. (2003) as a radical alternative for estimating domain averages through sampling "sub-grid scale columns unresolved by the GCM" … generated by a stochastic cloud generation algorithm.
- A full description of the McICA approach with details on the cloud generators and other computational aspects can be found in the following publications:
  - Barker et al., 2002: GCSS/ARM Workshop, Kananaskis, Alb
  - Pincus et al., 2003: JGR, 108D, 4376
  - Barker, Raisanen, 2004: QJRMS 130,1905-1920
  - Raisanen et al., 2004: QJRMS 130, 2047-2067
  - Raisanen, Barker, 2004: QJRMS 130, 2069-2085
  - Barker, Raisanen, 2005: QJRMS 131, 3103-3122
  - Raisanen et al., 2005: J. Climate 18, 4715-4730.

Abbreviations:

- CKD: Correlated k-distribution
- McICA: Monte-Carlo Independent Column Approximation
- PPH: Plane Parallel Homogeneous
- RT: Radiative Transfer
- RRTM: Rapid Radiative Transfer Model (_LW: longwave, _SW: shortwave)
- SW6: presently operational SW radiation scheme with 6 spectral intervals

What is the Monte-Carlo Independent Column Approximation?

The CKD approach for 1-D PPH columns is

$$\mathrm{F}_n = \sum_{k=1}^{K} c_k F_{n,k} \quad \textbf{(1)}$$

Correlated-k distributed absorption coefficients (see Lacis and Oinas, 1991, JGR)

- The ICA approach for domain averages is **(ICA: Independent Column Approx.)**

$$\langle \mathrm{F} \rangle = \frac{1}{N} \sum_{n=1}^{N} \mathrm{F}_n \quad \textbf{(2)}$$

- Combining (1) and (2) gives

$$\langle \mathrm{F} \rangle = \frac{1}{N} \sum_{n=1}^{N} \sum_{k=1}^{K} c_k F_{n,k} \quad \textbf{(3)}$$

- For a grid-box in which there are N-N_c clear- and N_c cloudy-sky sub-columns, (3) can be written as

$$\langle \mathrm{F} \rangle = \frac{1}{N} \left(\sum_{n=1}^{N-Nc} \sum_{k=1}^{K} c_k F_{n,k}^{clr} + \sum_{n=1}^{Nc} \sum_{k=1}^{K} c_k F_{n,k}^{cld} \right) \quad \textbf{(4)}$$

What is McICA?

- Which can be simplified to

$$\langle \mathrm{F} \rangle = (1 - A_c)\left(\sum_{k=1}^{K} c_k F_{n,k}^{clr} \right) + A_c \left(\frac{1}{N_c} \sum_{n=1}^{Nc} \sum_{k=1}^{K} c_k F_{n,k}^{cld} \right)$$

$$= (1 - A_c)\mathrm{F}_{clr} + A_c \langle \mathrm{F}_{cld} \rangle$$

- The hypothesis is that $\langle \mathrm{F}_{cld} \rangle$ can be given by $\sum_{k=1}^{K} c_k F_{rdm\{1,\ldots,Nc\},k}^{cld}$

- In which case, it follows (see Barker et al. 2002, Barker and Raisanen, 2005) that

$$E(\langle \mathrm{F}_{cld} \rangle) = \lim_{T->\infty} \frac{1}{T} \left(f_{1,1} c_1 F_{1,1}^{cld} + \ldots + f_{Nc,1} c_1 F_{Nc,1}^{cld} + f_{1,K} c_K F_{1,K}^{cld} + \ldots + f_{Nc,K} c_K F_{Nc,K}^{cld} \right)$$

$$= \frac{1}{N_c} \sum_{k=1}^{K} \sum_{n=1}^{Nc} c_k F_{n,k}^{cld}$$

The model is unbiased in the ICA sense, so for T=K * N_c large enough, an unbiased value can be obtained using a different random cloud profile for each k-coefficient

Constraints to use McICA

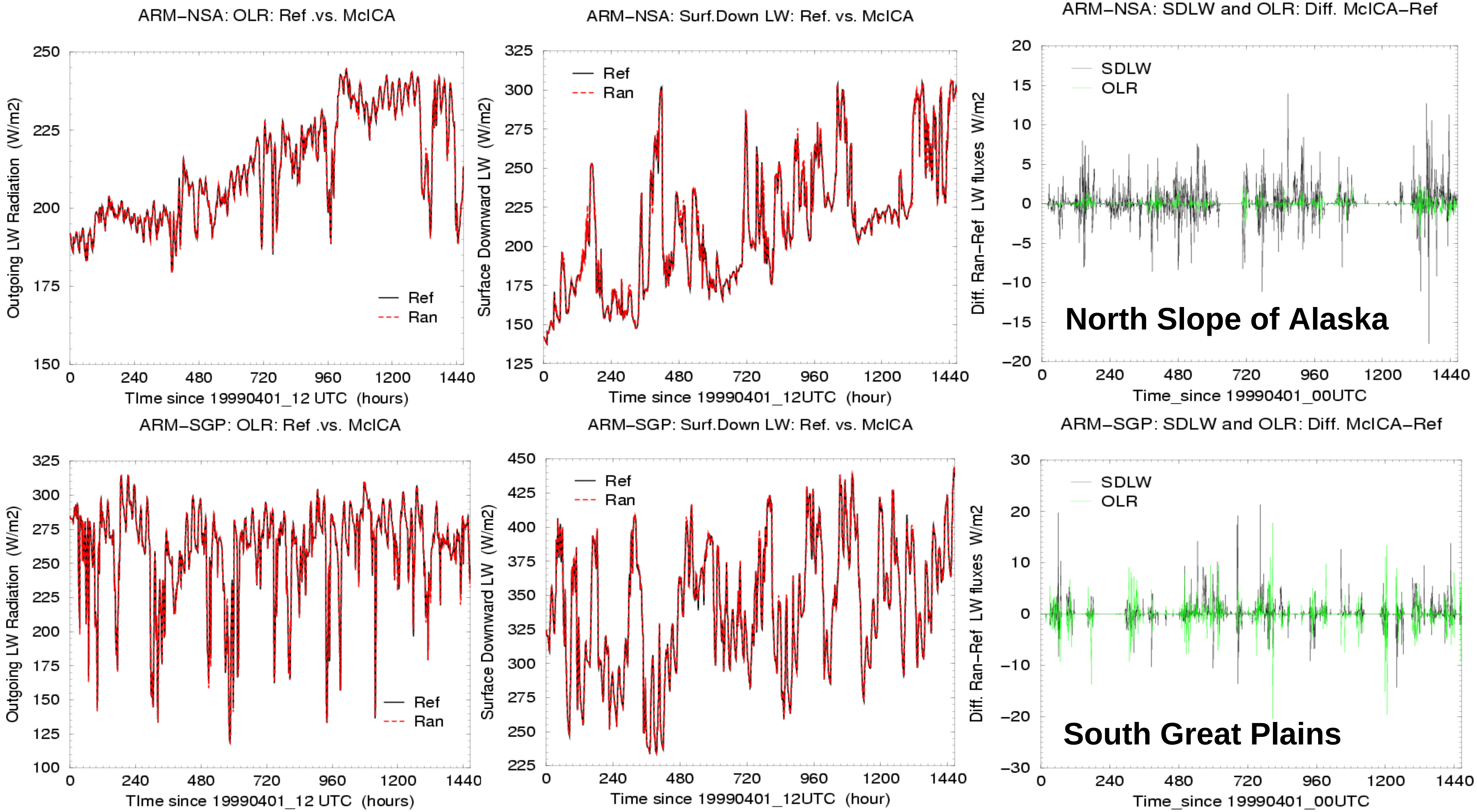
- Either a RT scheme with a large number of equivalent monochromatic transmission calculations (g-point radiation scheme as RRTM), or if dealing with a RT with small number of spectral intervals (as the operational SW6), need to repeat calculations to provide a big enough sample.
- As “more modern” (spectroscopic database) and well validated (at the various ARM sites), RRTM_SW was adopted as SW scheme.

- *Specific to ECMWF*: The sampling is done over both the clear-sky and cloudy parts of a given grid-box to prevent imbalance between various grib-box computations.

The ECMWF McICA configuration = RRTM_SW + McICA + cloud optical properties

- RRTM_SW from AER, Inc, with reduced number of g-points from the original 224 to 112
  - RRTM_SW is more expensive than SW6 (see later)
- McICA version for both RRTM_LW and RRTM_SW: no cloud fraction anymore: a layer is either clear-sky or overcast
  - McICA does not cost anything (as such)
- Random generator (Raisanen and Barker, 2004) gives 0 or 1 cloud for each layer and each of the 140 (112) g-points of the LW (SW) radiation scheme for either a maximum-random or a generalized overlap assumption, with loose constraint over the total cloudiness
- "New" cloud optical properties (see next table, main point: D_e=f(IWC,T))
- In the following, results are shown for the generalized overlap (a la Hogan and Illingworth, 2000) with a decorrelation length of 2km for cloud fraction, and 1km for cloud condensate (see later)

McICA: Tests with 1-D radiation code: LW



OLR **SDLW** **Differences McICA-Ref**

NB: 1 draw for McICA

Table 1: Characteristics of the longwave and shortwave radiation schemes

	RRTM_LW	RRTM_SW
Solution of RT Equation	two-stream method	two-stream method
Number of spectral intervals	16 (140 g-points)	14 (112 g-points)
Absorbers	H_2O, CO_2, O_3, CH_4, N_2O, $CFC11$, $CFC12$, aerosols	H_2O, CO_2, O_3, CH_4, N_2O, $CFC11$, $CFC12$, aerosols
Spectroscopic database	HITRAN, 2000	HITRAN, 2000
Absorption coefficients	from LBLRTM line-by-line model	from LBLRTM line-by-line model
Cloud handling	true cloud fraction	true cloud fraction
Cloud optical properties		
method	16-band spectral emissivity w approximate scattering	14-band τ, g, ω
Data: ice clouds	Ebert & Curry, 1992 Fu et al. 1998	Ebert & Curry, 1992 Fu, 1996
water clouds	Smith & Shi, 1992 Lindner and Li, 2000	Fouquart, 1987 Slingo, 1989
Cloud overlap assumption set up in cloud generator	maximum-random or generalized	maximum-random or generalized
Reference	Mlawer et al., 1997 Morcrette et al., 2001	Mlawer and Clough, 1997

Results of experimentation

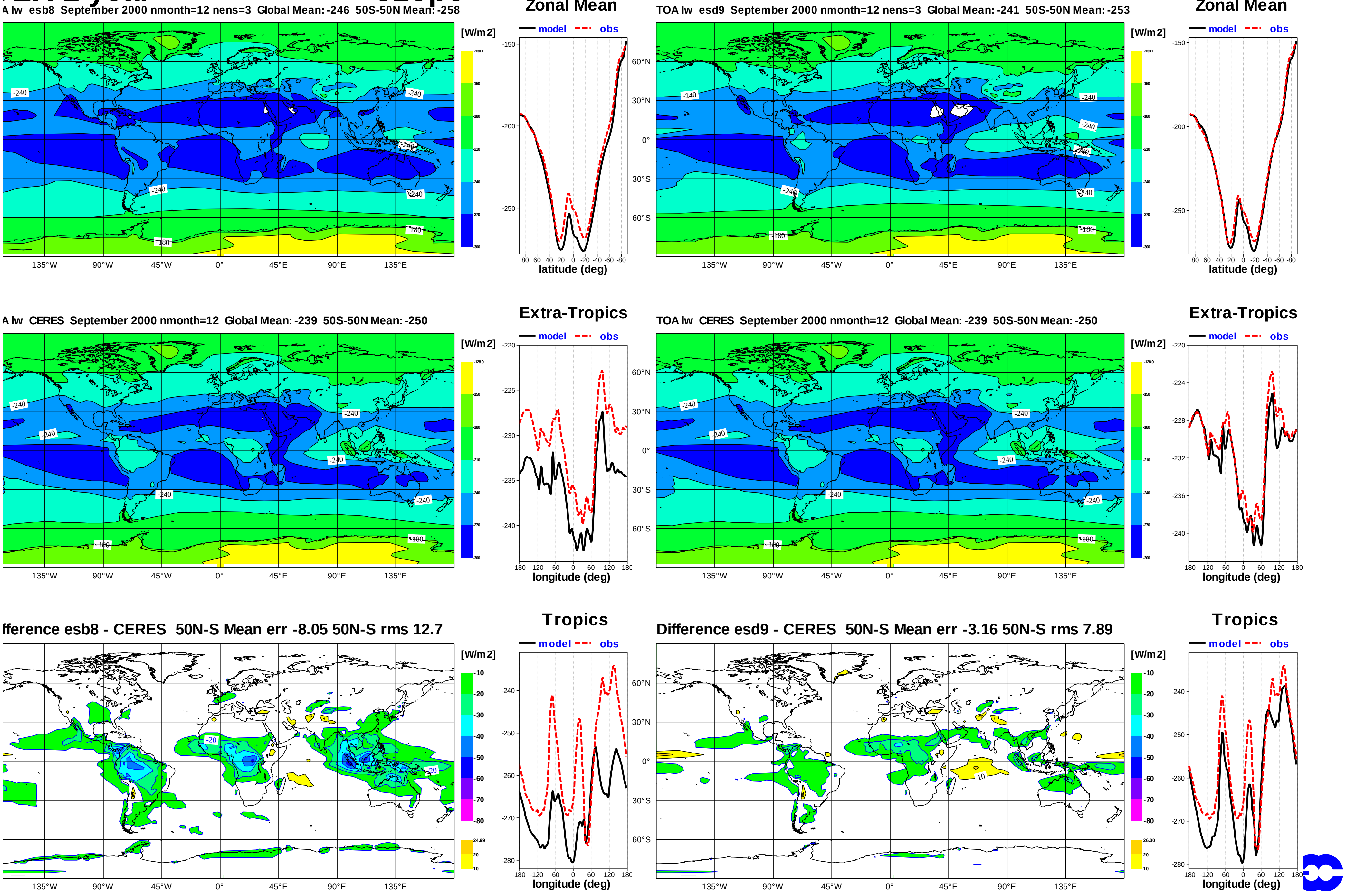
- In the following, results are shown for the generalized overlap (Hogan and Illingworth, 2000) with a decorrelation length of 2km for cloud fraction, and 1km for cloud condensate (see later)
  - Ensembles of 3 T_L159 L91 13-month simulations based on:
    - ➔Cy31 operational = 31ope
    - ➔Cy31R1 with improved cloud entrainment (P. Bechtold) = 31R1p

- Results of T_L511 L91 10-day forecasts

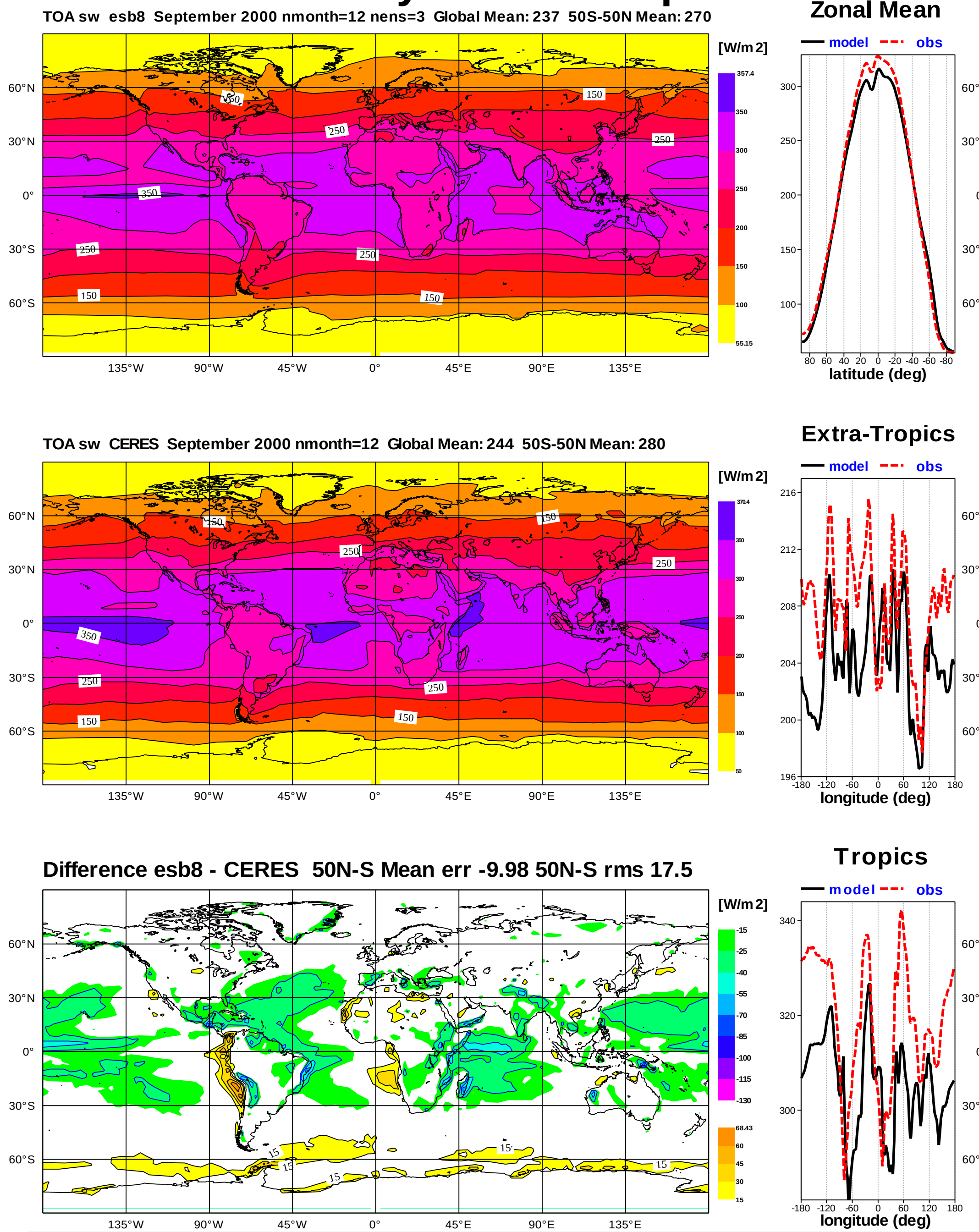
- Results of T_L799 L91 analyses for May 2006

OLR 1 year 31ope

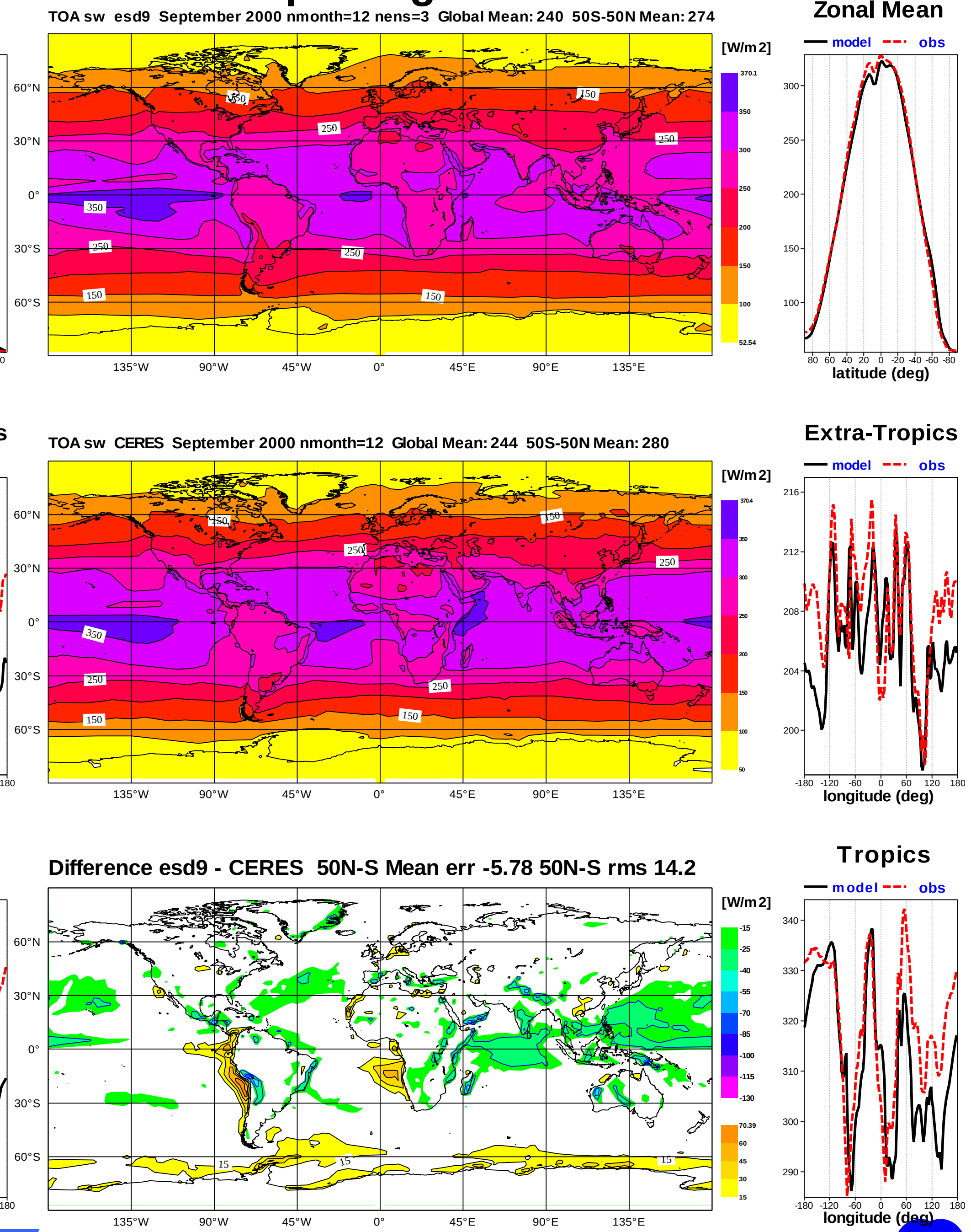
31+McICA package



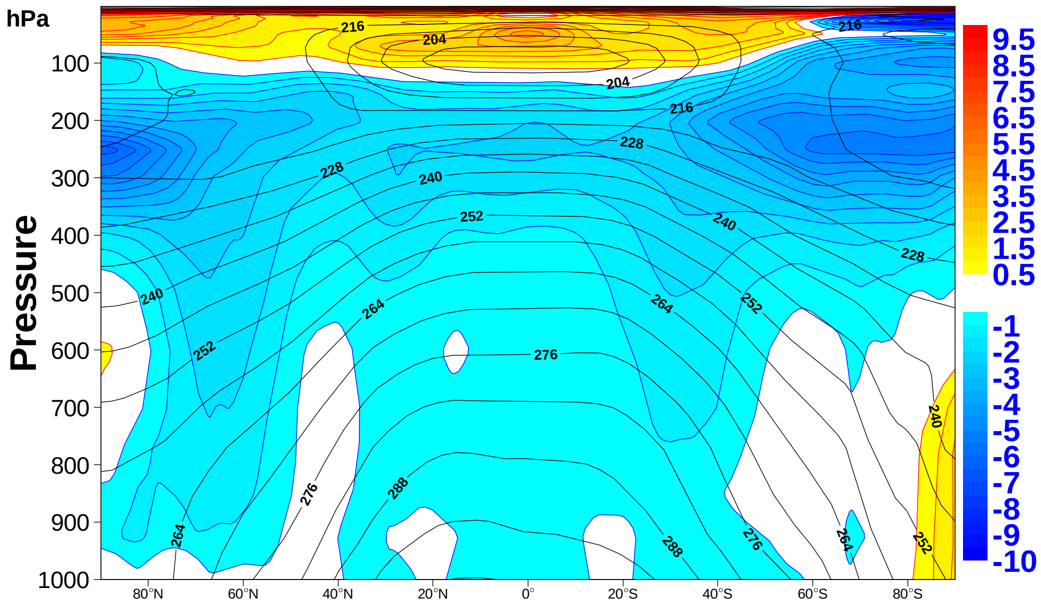
Absorbed SW 1 year 31ope



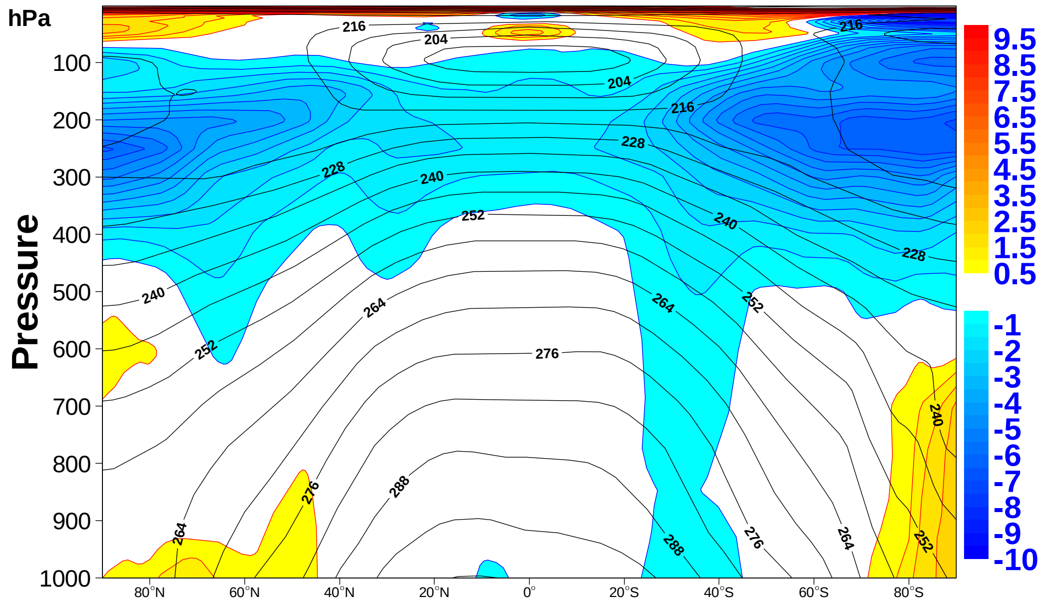
31+McICA package

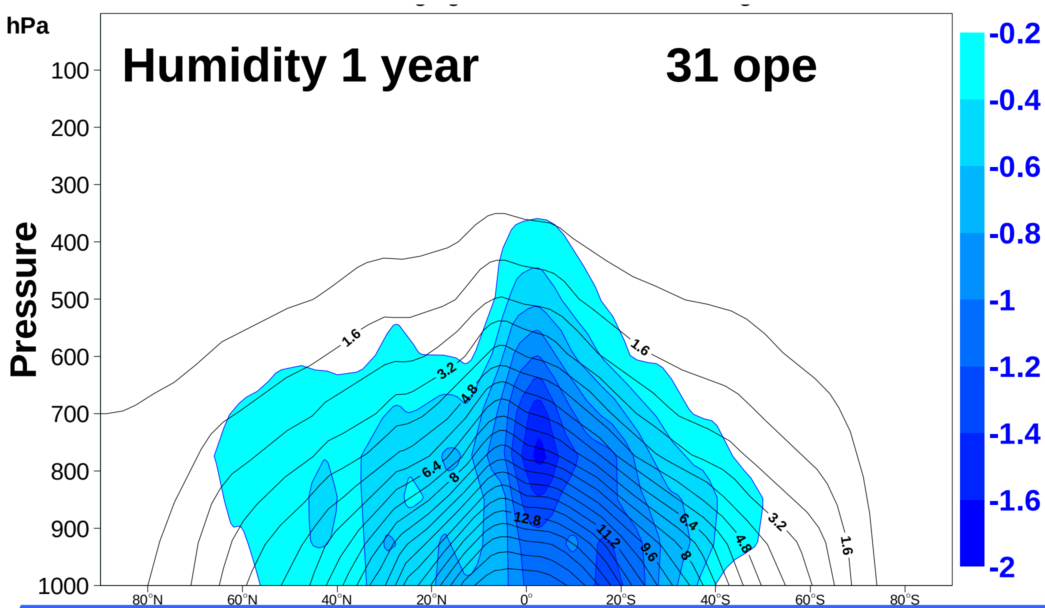


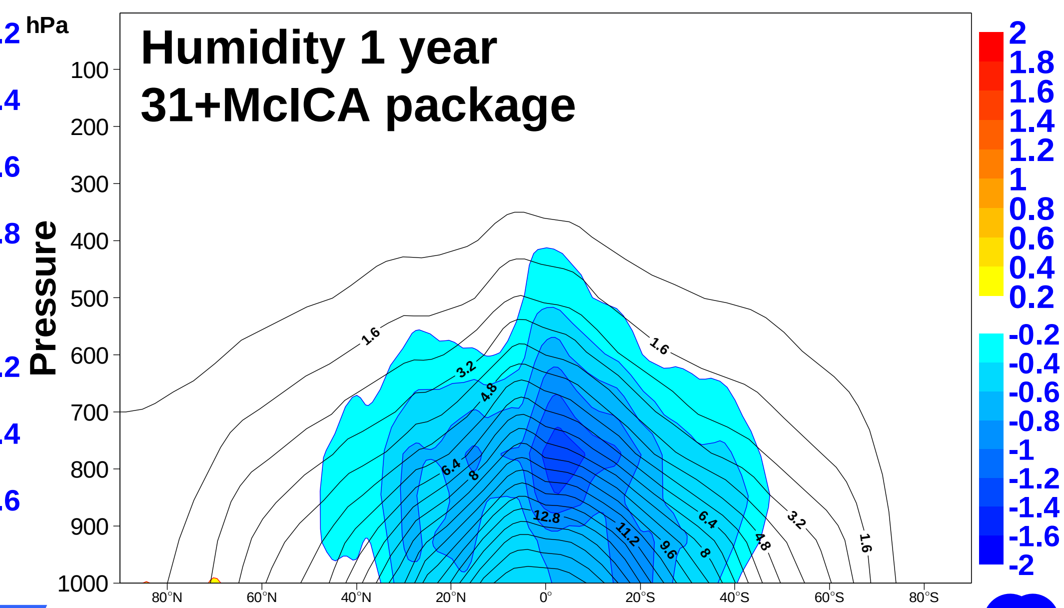
Temperature 1 year   31 ope



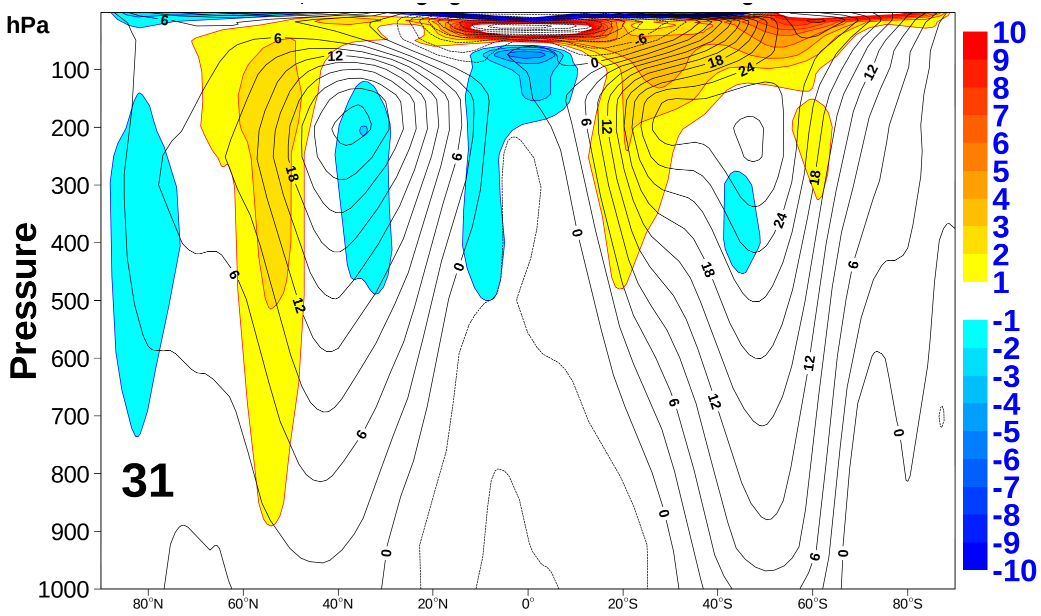
Temperature 1 year 31+McICA package



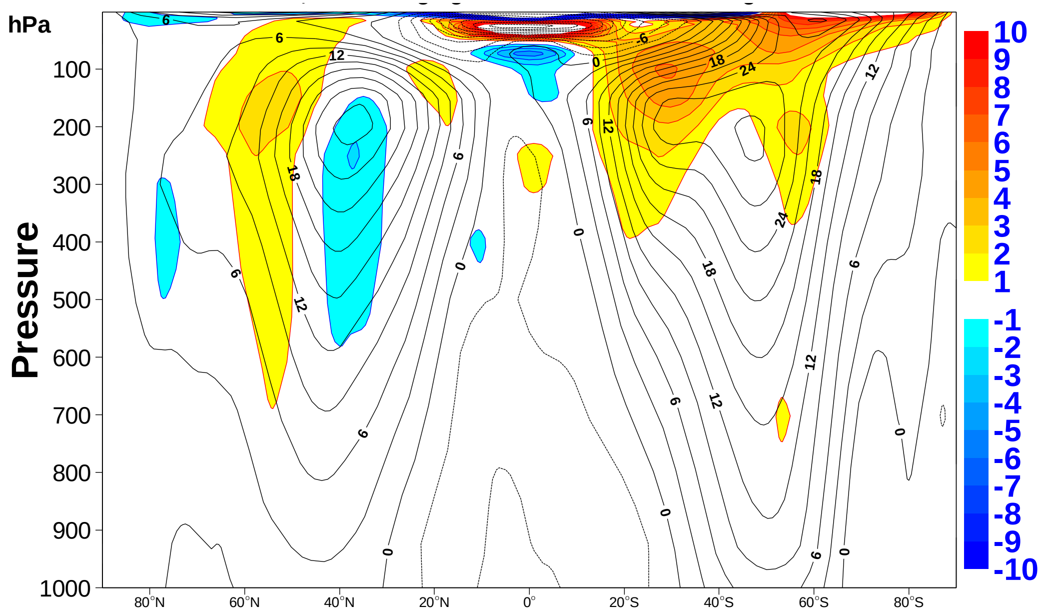




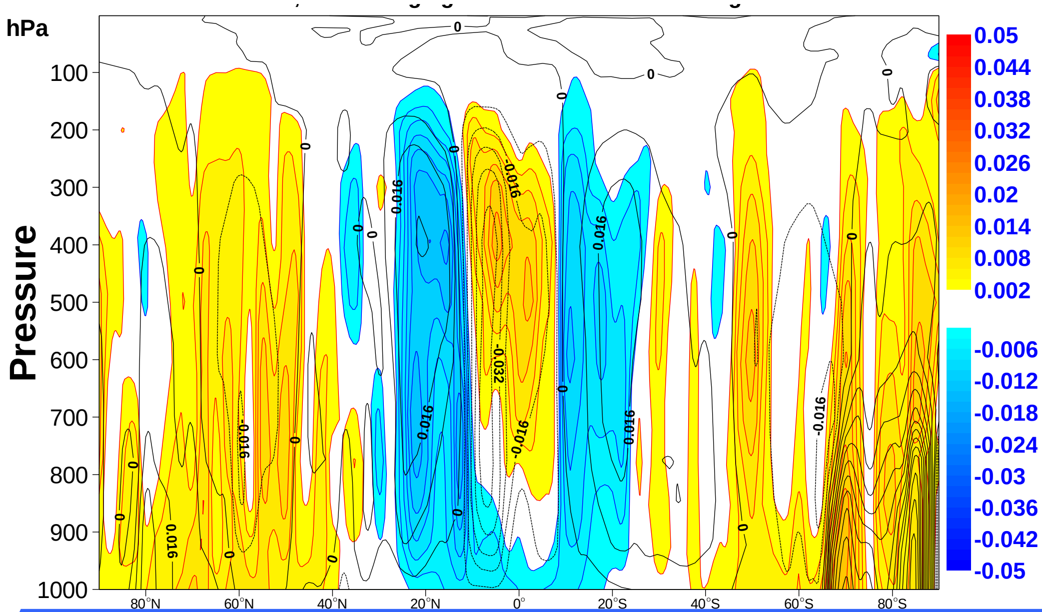
Zonal Wind 1 year 31 ope



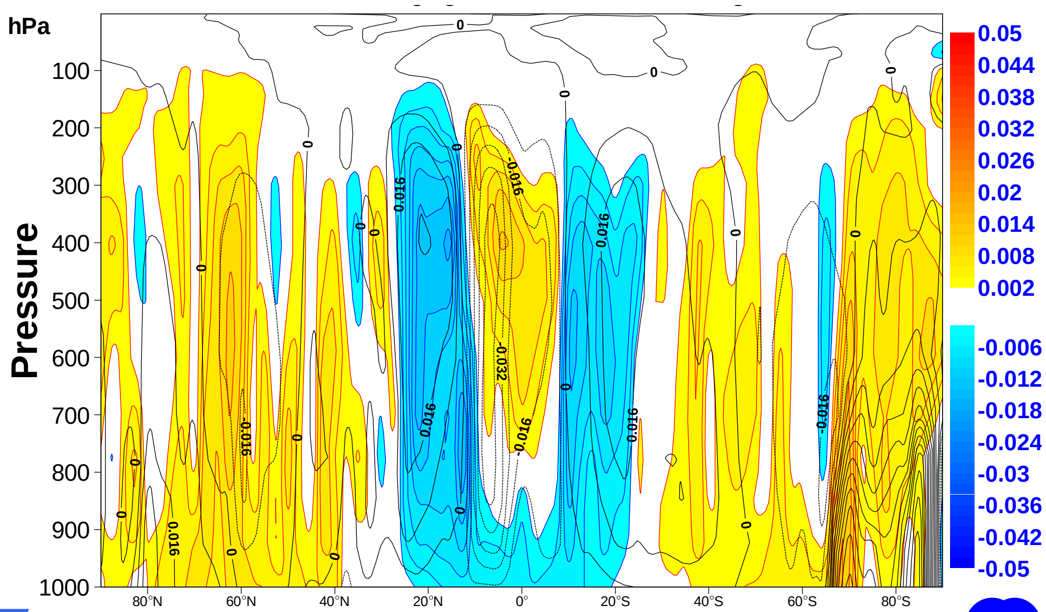
Zonal Wind 1 year 31+McICA package



Vert.Veloc. 1 year 31 ope

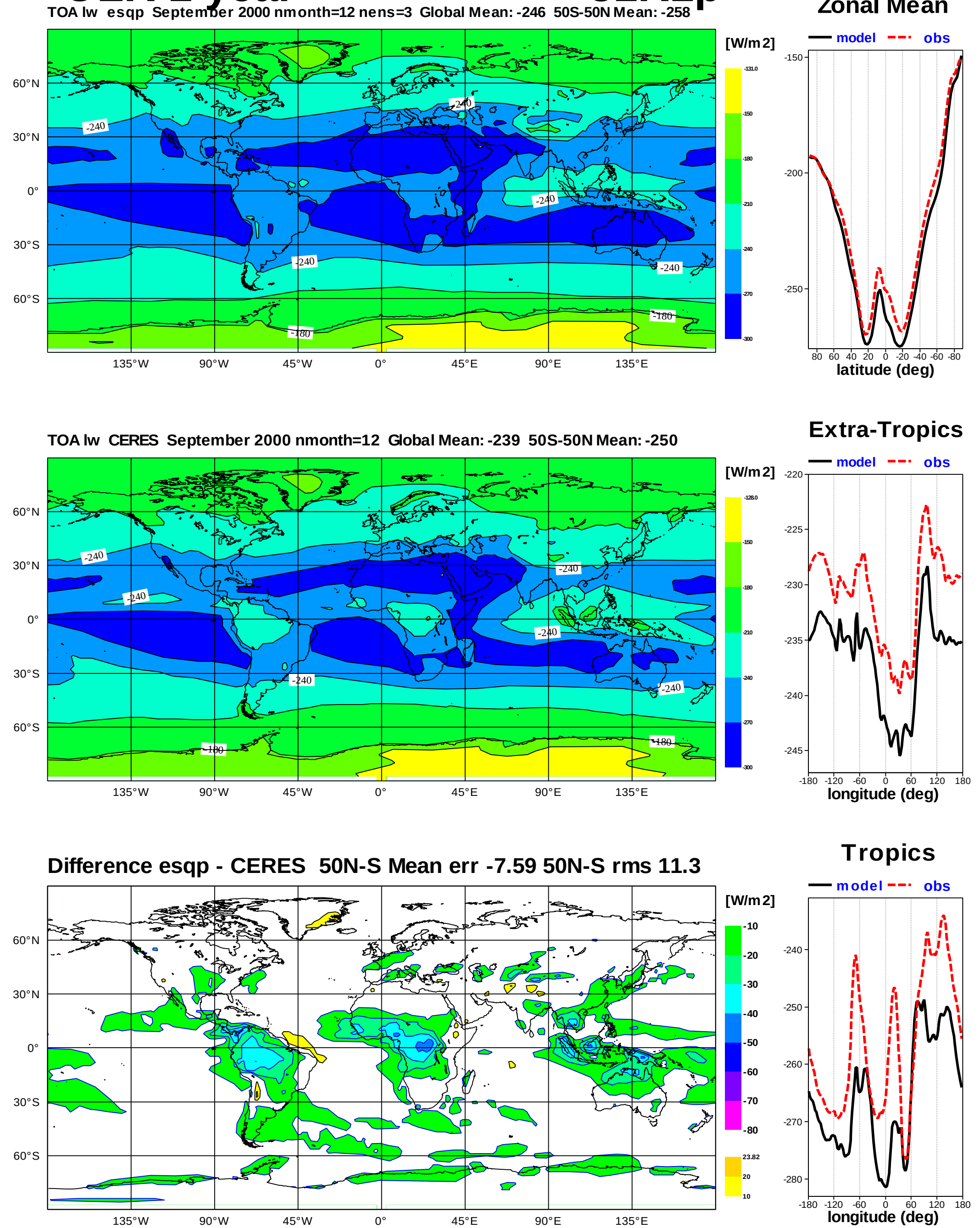


Vert.Veloc. 1 year 31+McICA package

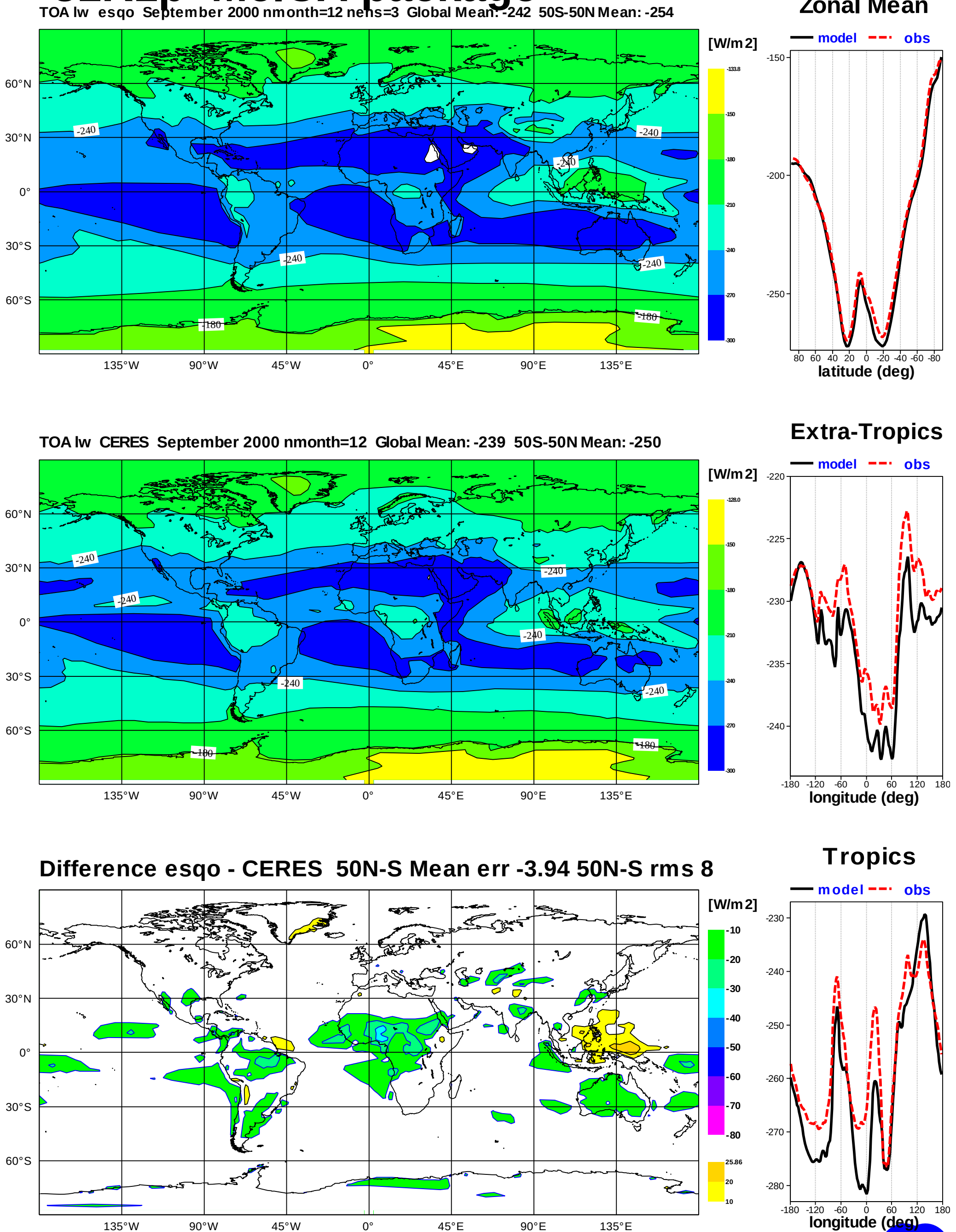


ECMWF

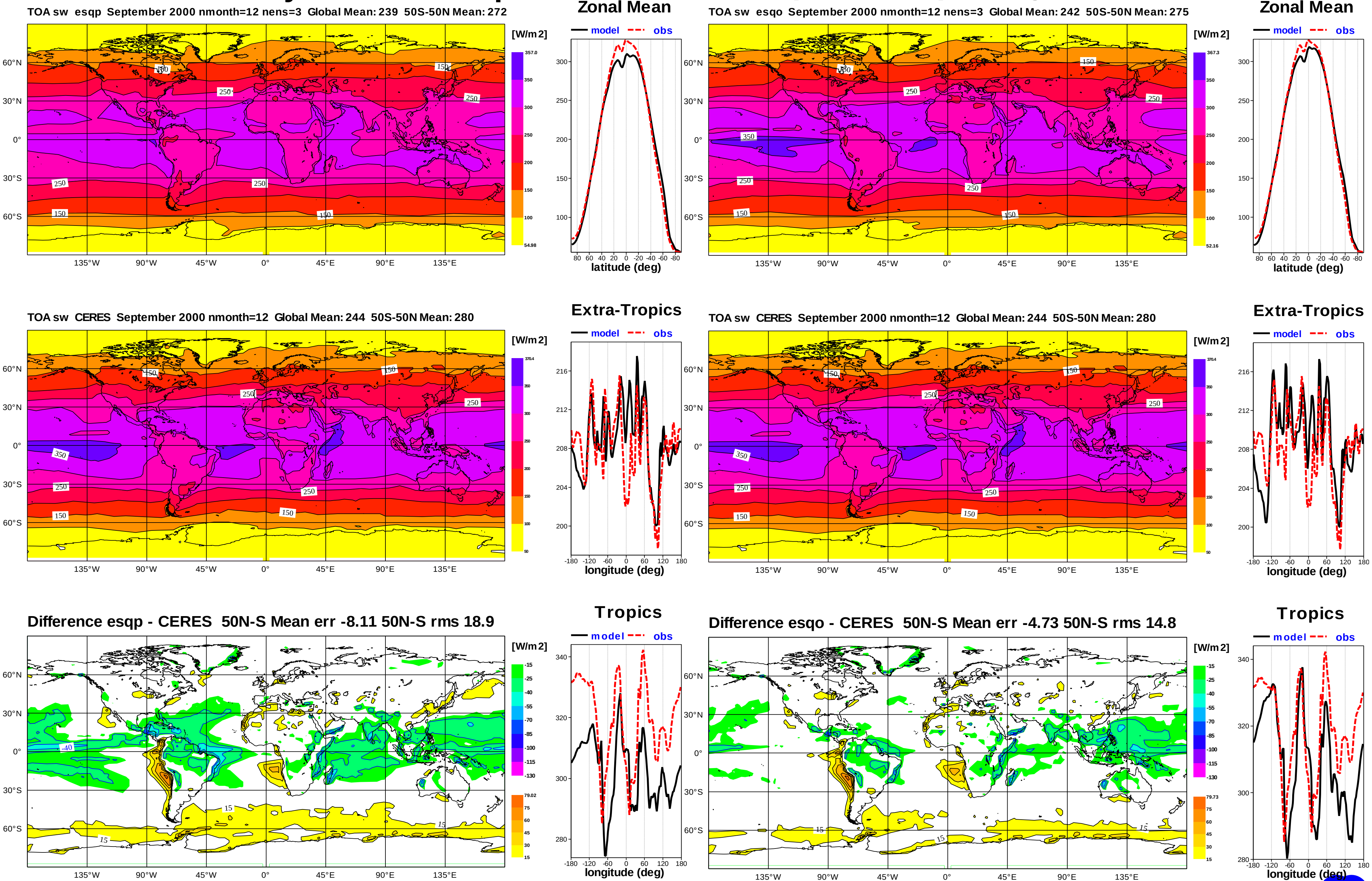
OLR 1 year 31R1p



31R1p+McICA package



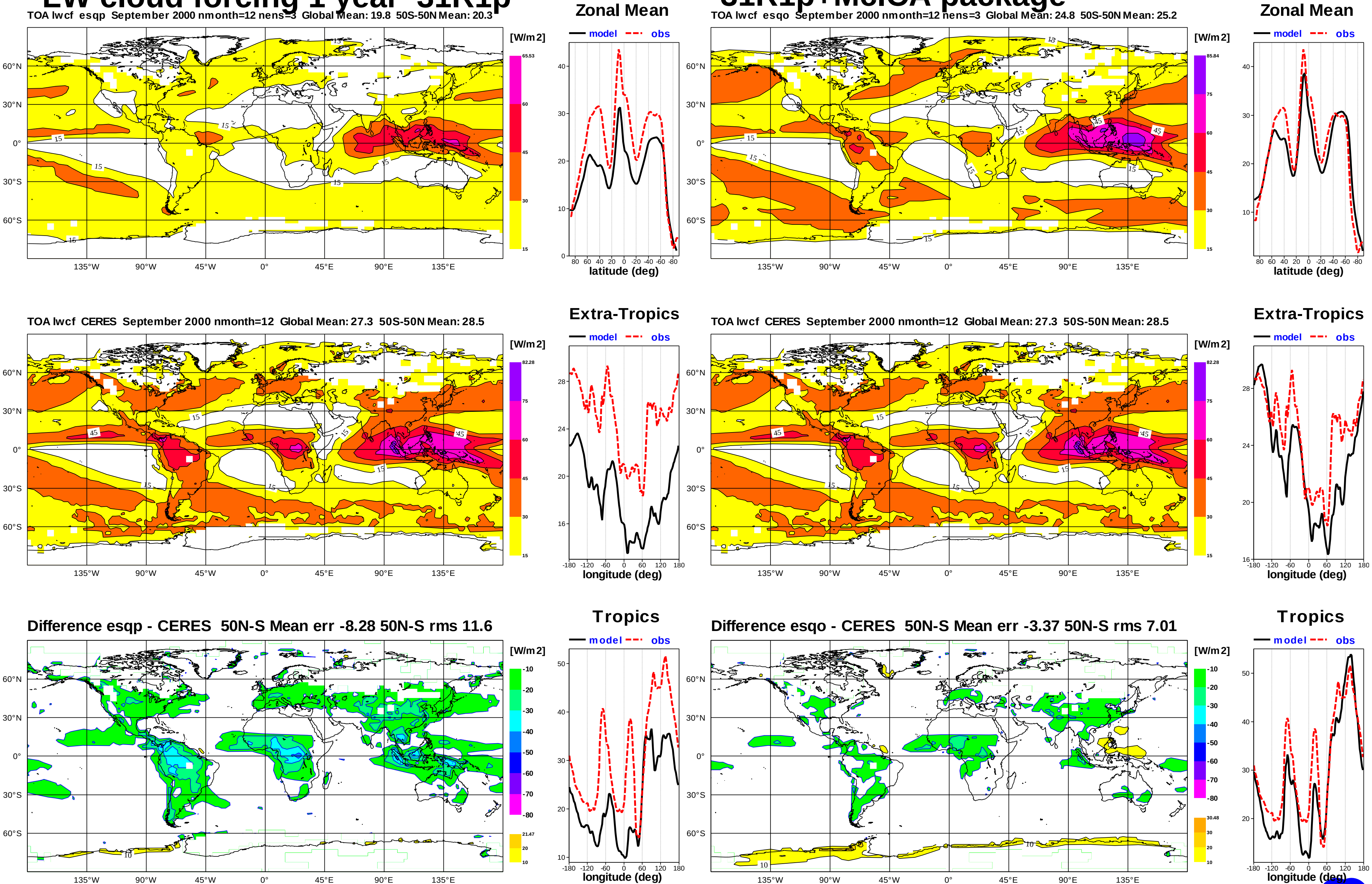
Absorbed SW 1 year 31R1p 31R1p+McICA package



ECMWF

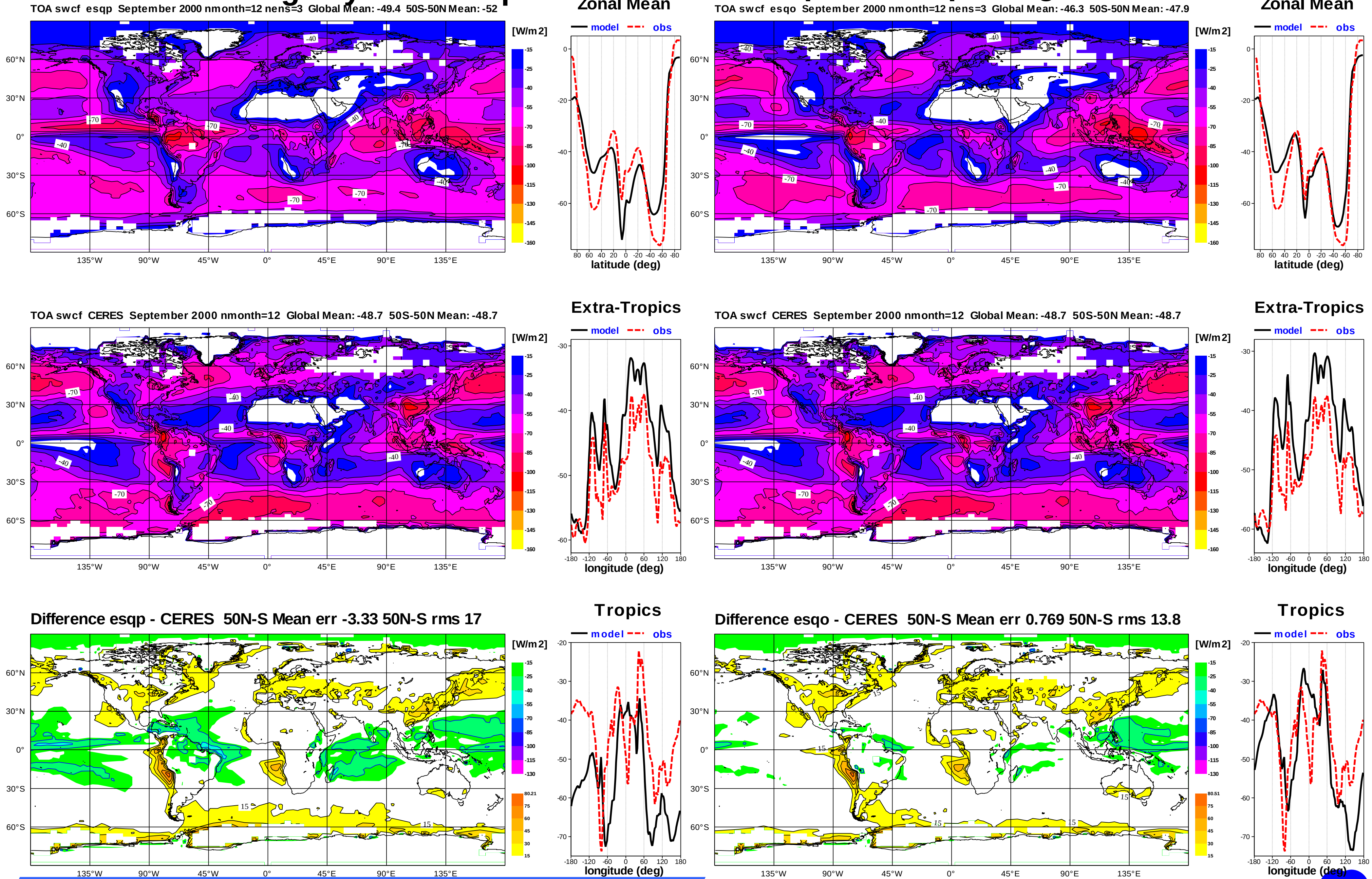
LW cloud forcing 1 year 31R1p

31R1p+McICA package



SW cloud forcing 1 year 31R1p

31R1p+McICA package



ECMWF

Table 2: Results from 13-month simulations at T_L159 L91. Radiative fluxes at TOA are compared to CERES measurements.

All quantities in W m^{-2}

	Annual		DJF		JJA	
OLR	-239.0		-236.0		-242.0	
cy31	-8.1	12.7	-6.1	15.0	-5.1	12.8
cy31+McICA	-3.2	7.9	-1.1	10.1	-0.6	10.5
cy31R1p	-7.6	11.2	-5.4	12.9	-5.0	11.9
cy31R1p+McICA	-3.9	8.0	-1.3	10.0	-1.5	11.2
Absorbed SW	244.0		251.0		238.0	
cy31	-10.0	17.5	-15.6	23.9	-9.2	19.7
cy31+McICA	-5.8	14.2	-11.4	20.5	-5.3	18.6
cy31R1p	-8.1	18.9	-13.9	25.0	-7.1	20.6
cy31R1p+McICA	-4.7	14.8	-10.8	20.8	-4.2	19.2
LW Cloud Forcing	27.3		26.8		26.1	
cy31	-9.6	13.6	-10.4	16.5	-8.3	14.1
cy31+McICA	-4.0	7.9	-4.8	10.3	-3.0	9.7
cy31R1p	-8.3	11.6	-9.1	14.2	-7.2	12.4
cy31R1p+McICA	-3.4	7.0	-4.1	9.4	-2.3	9.5
SW Cloud Forcing	-48.7		-52.8		-45.1	
cy31	-5.2	15.4	-4.1	18.6	-6.3	18.2
cy31+McICA	-0.2	12.9	0.5	17.0	-1.3	17.3
cy31R1p	-3.3	17.0	-2.4	20.1	-4.3	19.1
cy31R1p+McICA	0.8	13.8	1.1	17.3	-0.4	18.0

Table 3: Results from 13-month simulations at T_L159 L91. Total cloud cover (%) is compared to ISCCP D2 data, total column water vapour (kg m^{-2}) and liquid water (g m^{-2}) to SSM/I data, The total precipitation (mm day^{-1}) compared to GPCP or SSM/I data.

	Annual		DJF		JJA	
Total Column Water Vapour	29.0		27.7		29.3	
cy31	-2.10	3.65	-2.27	4.29	-1.73	3.69
cy31+McICA	-1.67	3.13	-1.80	3.63	-1.25	3.32
cy31R1p	-1.80	3.34	-2.00	4.00	-1.43	3.37
cy31R1p+McICA	-0.99	2.84	-1.29	3.33	-0.47	3.30
Total Cloud Cover	62.2		62.9		61.4	
cy31	-6.0	10.3	-5.7	12.3	-5.4	11.8
cy31+McICA	-5.3	9.5	-4.9	11.2	-4.7	11.4
cy31R1p	-4.0	11.0	-3.8	12.5	-3.7	13.0
cy31R1p+McICA	-2.2	10.9	-1.4	11.4	-2.2	13.4
Total Column Liquid Water	82.2		80.4		84.3	
cy31	1.7	22.1	3.1	33.4	-1.1	30.6
cy31+McICA	0.9	22.4	2.1	32.8	-1.2	30.8
cy31R1p	-8.1	22.4	-6.5	31.9	-11.1	31.6
cy31R1p+McICA	-6.0	21.0	-4.8	30.9	-8.7	29.8
Total Precipitation gpcp	2.61		2.58		2.63	
cy31	0.45	1.39	0.42	1.88	0.43	1.75
cy31+McICA	0.40	1.21	0.37	1.60	0.41	1.72
cy31R1p	0.32	1.27	0.30	1.68	0.31	1.80
cy31R1p+McICA	0.24	1.14	0.22	1.56	0.24	1.71
Total Precipitation ssmi	3.80		3.57		3.66	
cy31	0.67	2.45	0.57	3.56	0.44	3.90
cy31+McICA	0.50	2.23	0.38	3.32	0.35	3.81
cy31R1p	0.43	2.35	0.34	3.49	0.28	3.87
cy31R1p+McICA	0.22	2.17	0.13	3.33	0.10	3.70

Table 4: Results from 13-month simulations at T_L159 L91. The surface fluxes over the ocean are compared to the Da Silva climatology.

All quantities in W m^{-2}

OCEAN only	Annual	DJF	JJA
Net Solar Radiation	155.2	163.7	143.7
cy31	8.4	15.1	0.3
cy31+McICA	15.6	21.9	7.4
cy31R1p	11.5	18.8	3.0
cy31R1p+McICA	17.0	23.9	7.7
Net Longwave Radiation	-51.8	-52.5	-50.4
cy31	0.6	1.0	1.3
cy31+McICA	-0.1	0.3	0.6
cy31R1p	-4.3	-4.0	-3.4
cy31R1p+McICA	-4.0	-3.9	-3.1
Sensible Heat Flux	-11.0	-13.7	-9.0
cy31	-4.7	-3.0	-5.9
cy31+McICA	-3.5	-2.0	-4.9
cy31R1p	-3.0	-1.6	-4.2
cy31R1p+McICA	-1.4	0.0	-2.7
Latent Heat Flux	-96.5	-100.2	-94.2
cy31	-10.5	-7.7	-11.1
cy31+McICA	-7.2	-4.5	-7.9
cy31R1p	-6.3	-3.9	-6.6
cy31R1p+McICA	-1.7	0.4	-2.1
Surface Net Flux	-2.1	-0.9	-7.9
cy31	-8.1	3.6	-17.9
cy31+McICA	2.8	14.0	-6.8
cy31R1p	-4.0	7.3	-13.3
cy31R1p+McICA	7.8	18.7	-2.2

Conclusions from the TL159 L91 “climate” integrations

- The McICA package makes the clouds less radiative active, independent of the radiation scheme, independent of the cloud optical properties.
- So more shortwave radiation is available at the surface, and the surface net energy budget is worse with respect to Da Silva’s climatology. However, the changes in the position of the clouds are expected to improve the forcing of the ocean surface in climate integrations with a coupled ocean.

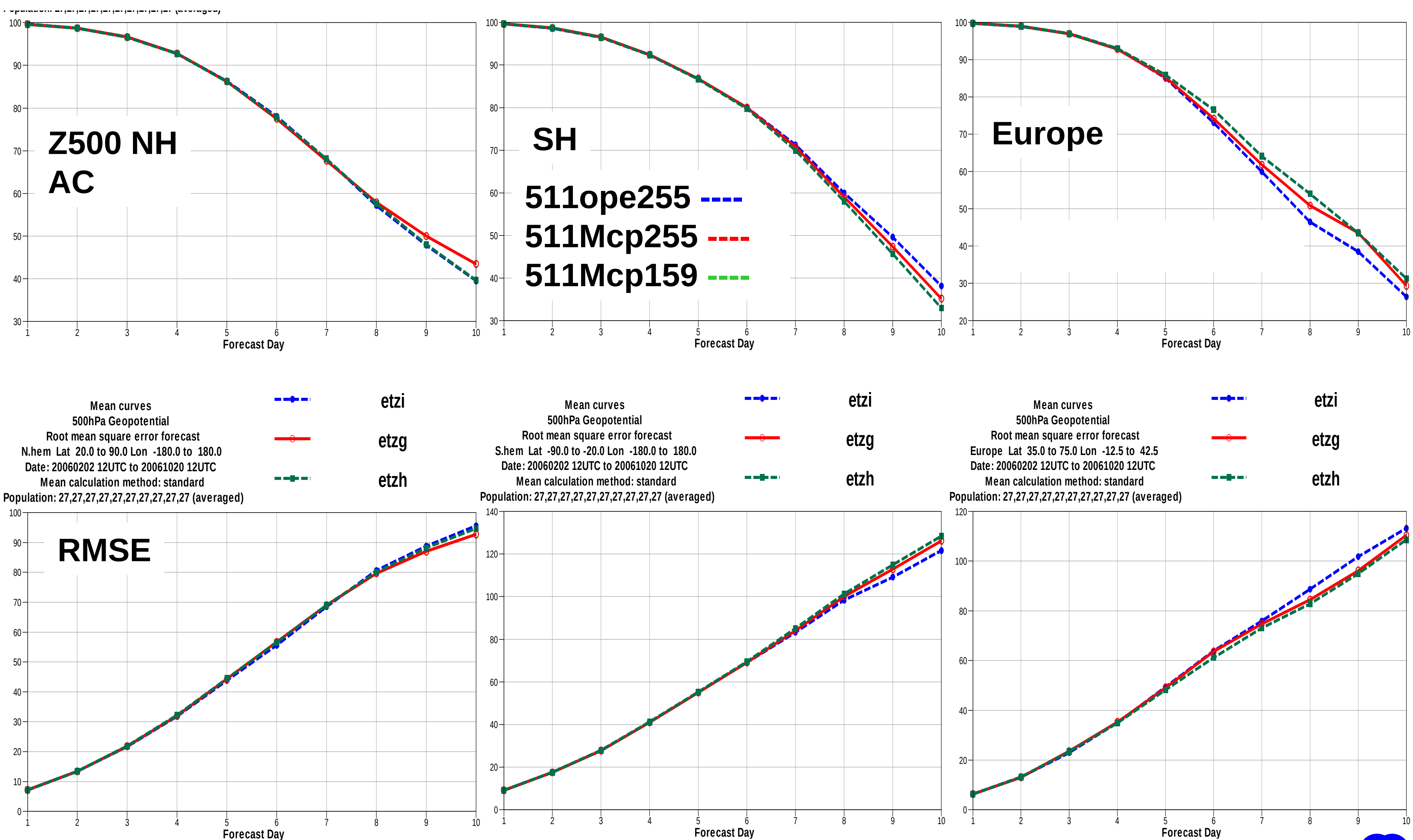
McICA package: Timing

- RRTM_SW is much more expensive than the operational SW6 (about 15 times: 112 g-points and 14 vs. 6 spectral intervals)
- The McICA approach actually slightly reduces the cost of RRTM_LW and _SW by dealing only with clear or overcast layers
- Nowadays, in the operational IFS, the full radiation is called once every hour on a radiation grid reduced by 2 with respect to the dynamical grid (e.g., T_L799 for dynamics –> T_L399 for radiation)
- It was found in the past (Morcrette, 2000) that a one hour “full radiation” time-step was slightly beneficial, allowing a better interaction between convection, cloud and radiative processes.
- Tests were done going back to 3 hours after the first 12 hours and with decreased horizontal resolution for radiation computations.

McICA package: Timing

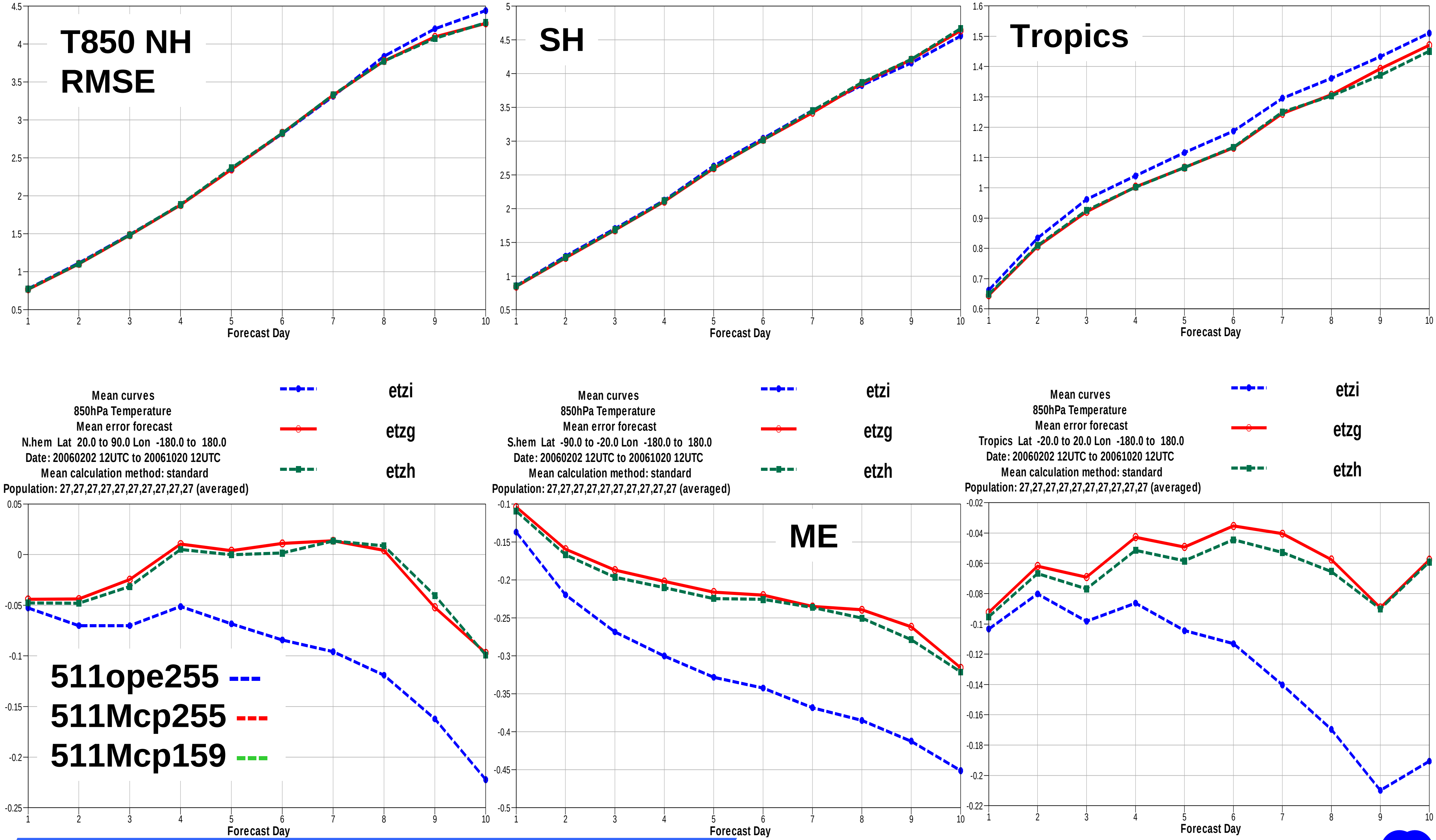
	Dyn	Rad	Freq	%Rad	Ratio	%Rad	Ratio	
Full radiation code called every 1 hour								
ref31R1	799	399	1	7.3	1.000			Operational configuration
McICA	799	399	1	33.5	1.441	26.8	1.277	
	799	319	1	25.2	1.266	19.5	1.201	**Future ope. configuration**
	799	255	1	18.6	1.154	14.0	1.148	
	799	159	1	9.5	1.014	7.0	1.075	
	799	95	1	5.0	0.970	3.6	1.038	
Full radiation code called every 3 hours								
	799	399	3	15.7	1.162	10.8	1.119	
	799	319	3	11.0	1.112	8.2	1.090	
	799	255	3			5.7	1.060	
ref31R1	399	159	3			4.8	1.000	Ensemble Prediction System
McICA	399	159	3			18.0	1.173	
ref31R1	159	63	3			8.5	1.000	"Climate runs"
McICA	159	63	3			29.5	1.329	
				Before Optimis^n		**After Optimis^n**		

Anomaly correlation and root-mean-square error of the geopotential at 500 hPa for 27 T_L511 L91 forecasts started every 10 days between 20060202 and 20061020.



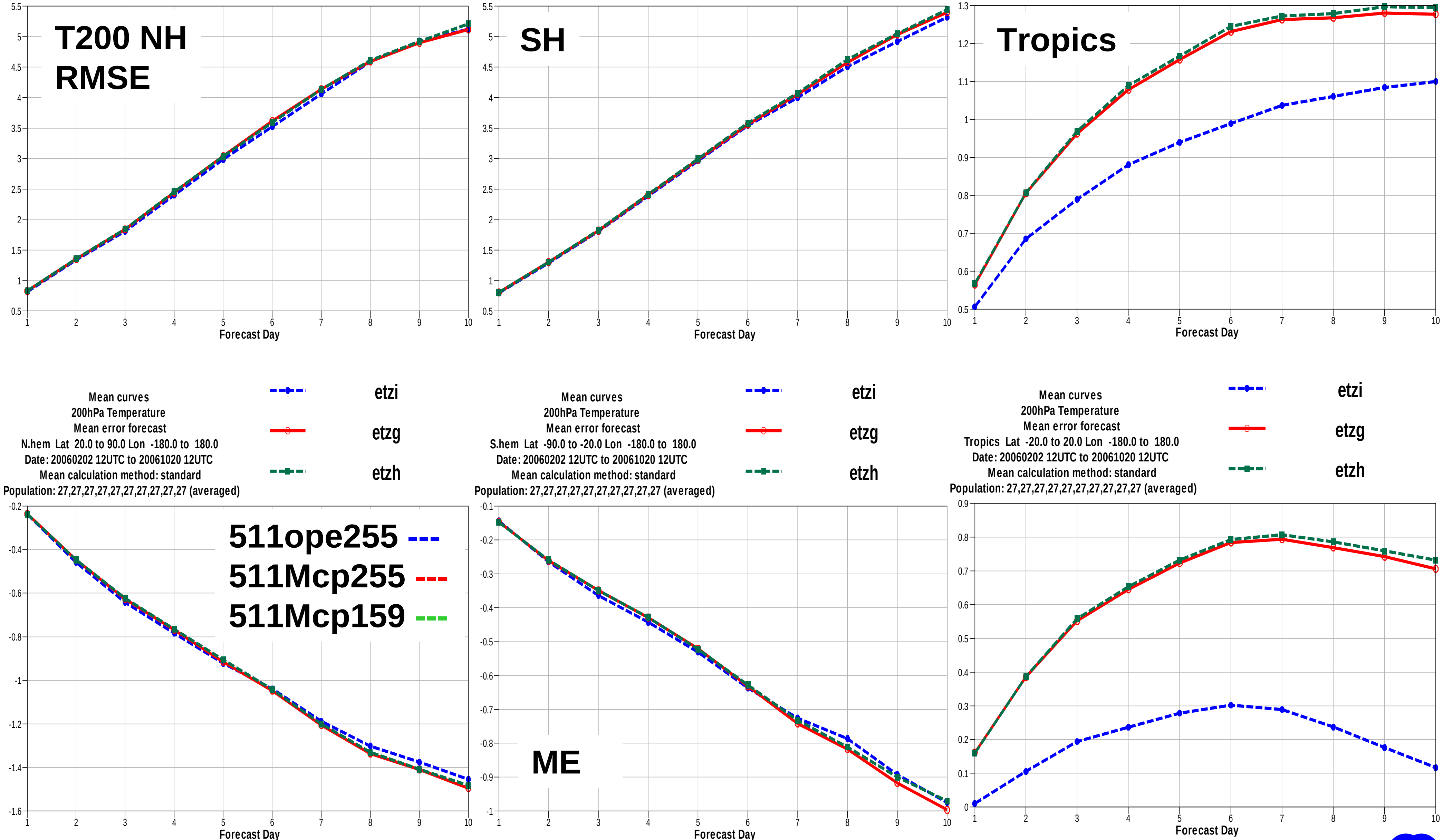
ECMWF

Root-mean-square error and mean error in temperature at 850 hPa for 27 T_L511 L91 forecasts started every 10 days between 20060202 and 20061020.

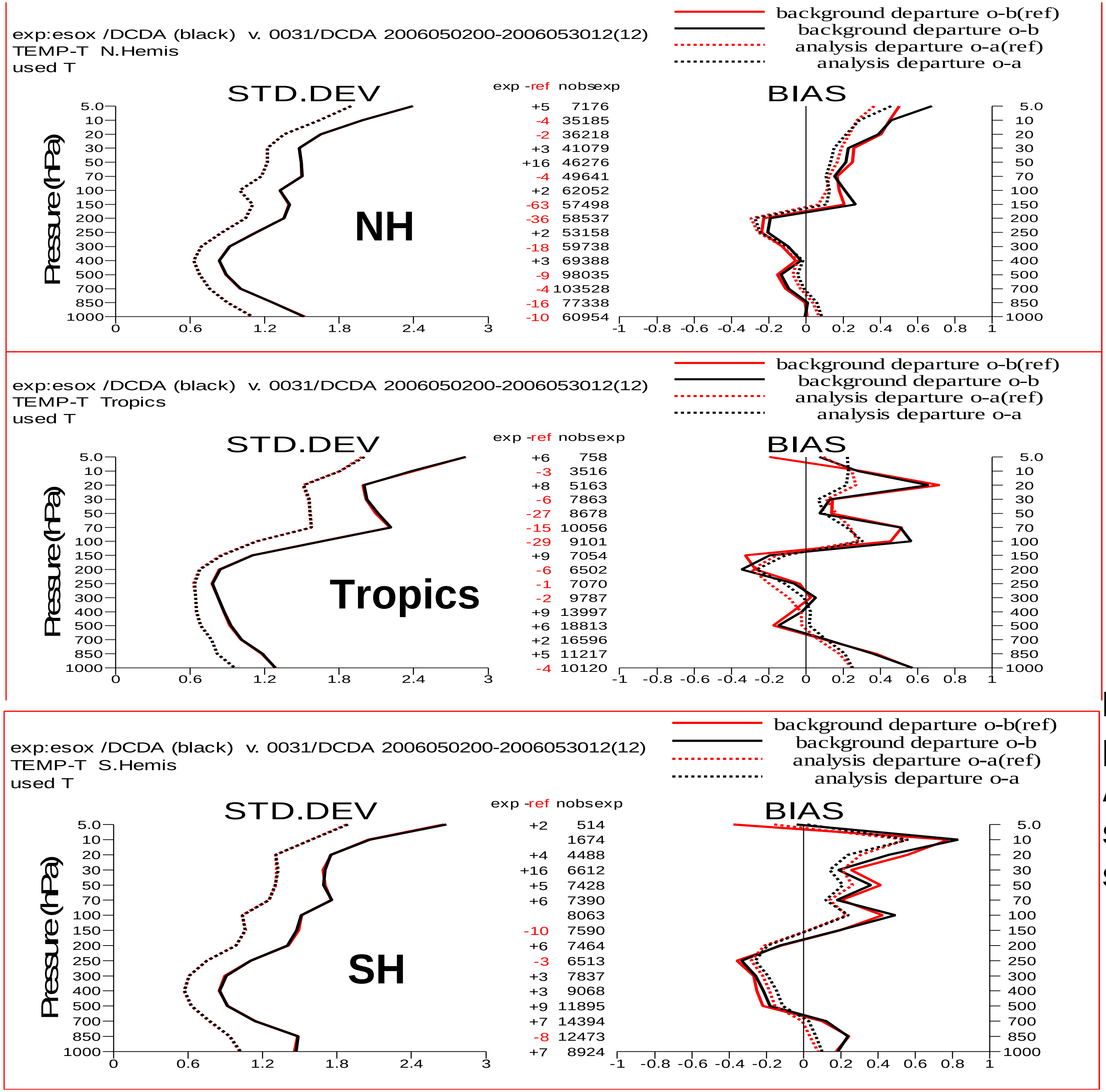


ECMWF

Root-mean-square error and mean error in temperature at 200 hPa for 27 T_L511 L90 forecasts started every 10 days from 20060202 and 20061020.



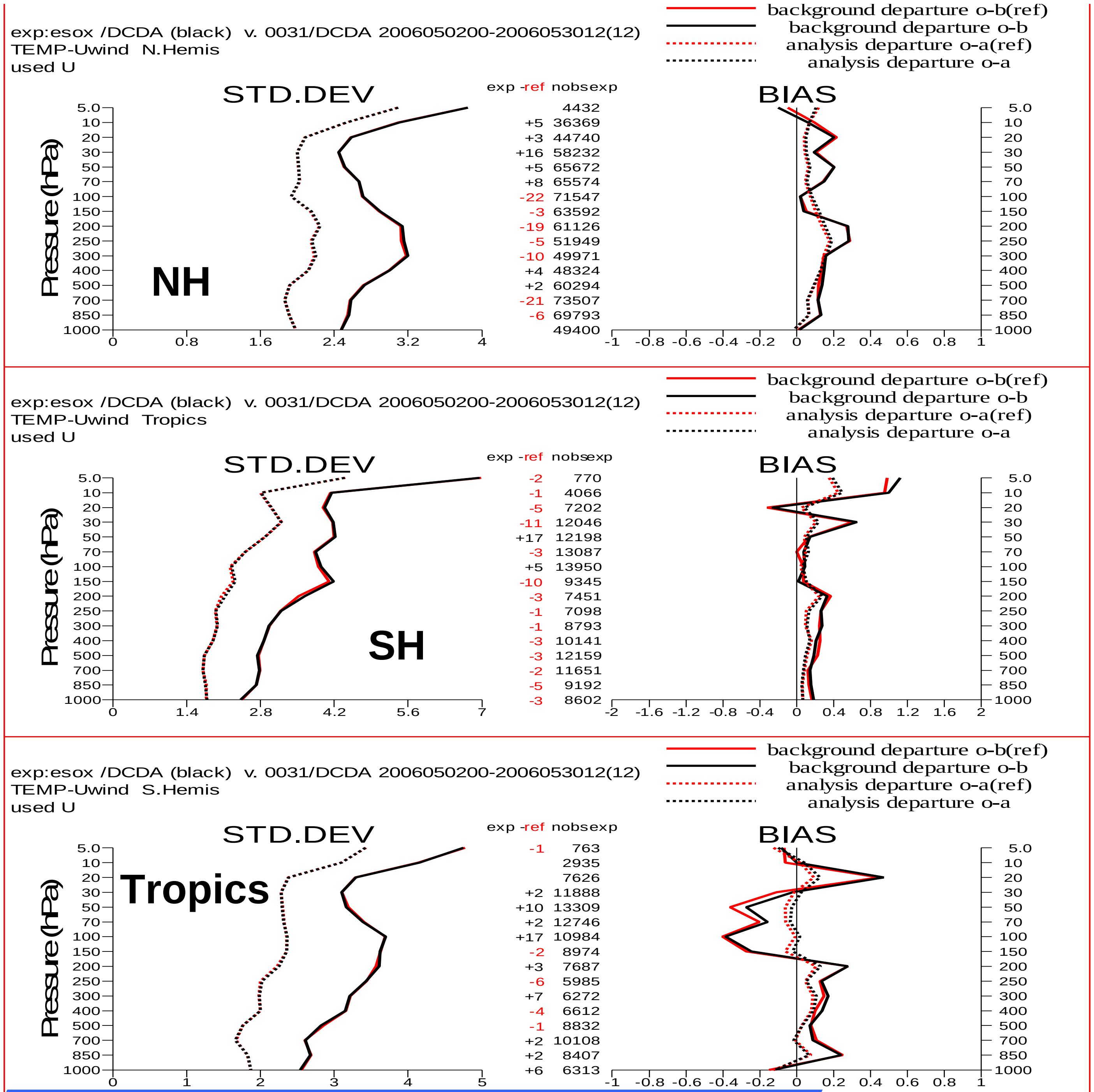
ECMWF



Comparison to radiosondes:
Temperature
Red: operational 31R1
Black: McICA

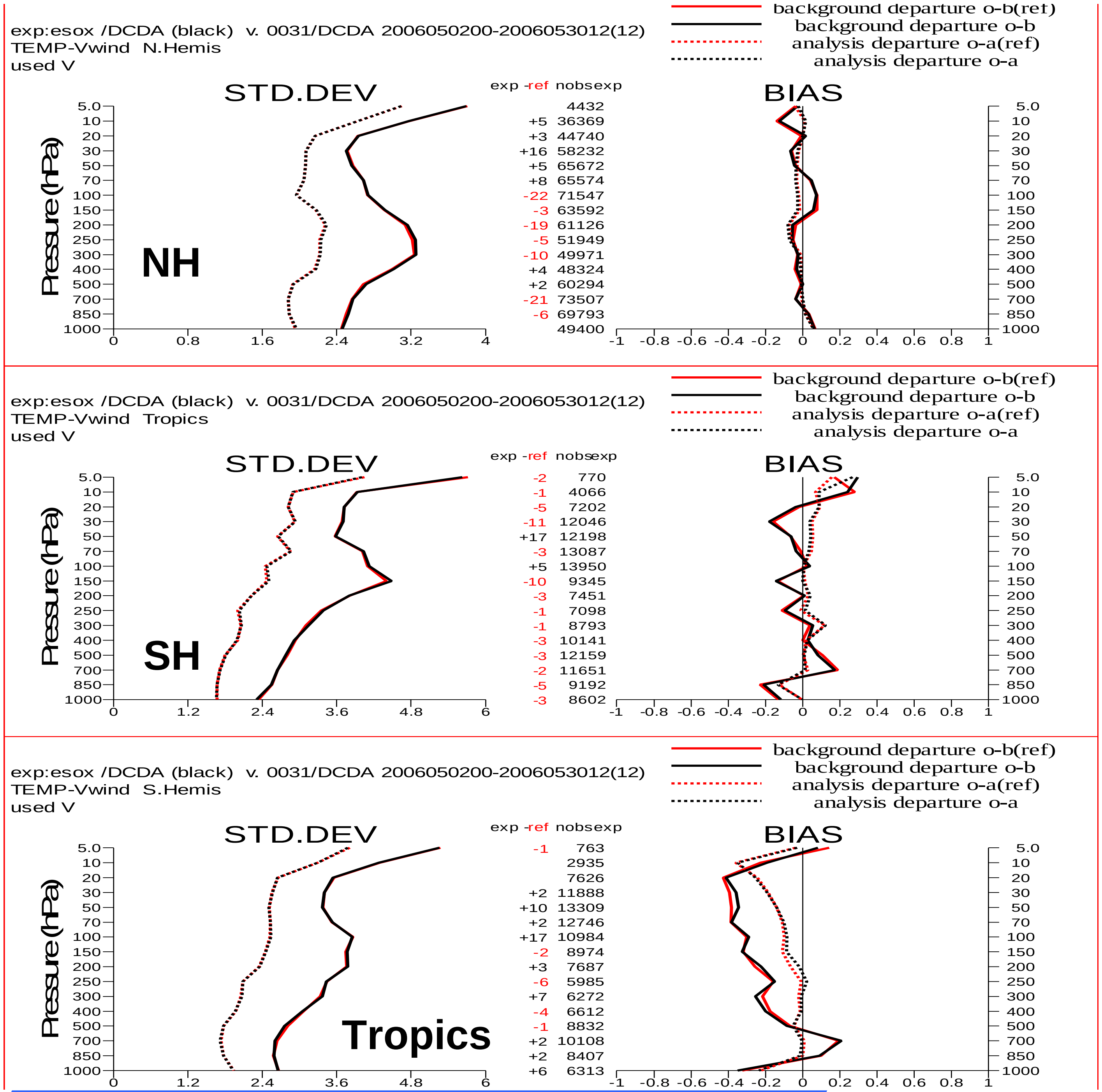
T_L799 L91 analysis run from 20060501 to 20060531, averaged between 0502_00 and 0530_12

NB: analysis has the McICA package only in the trajectory. Adjoint computations use the standard simplified radiation schemes.



Comparison to radiosondes: U-wind

T_L799 L91 analysis run from 20060501 to 20060531, averaged between 0502_00 and 0530_12

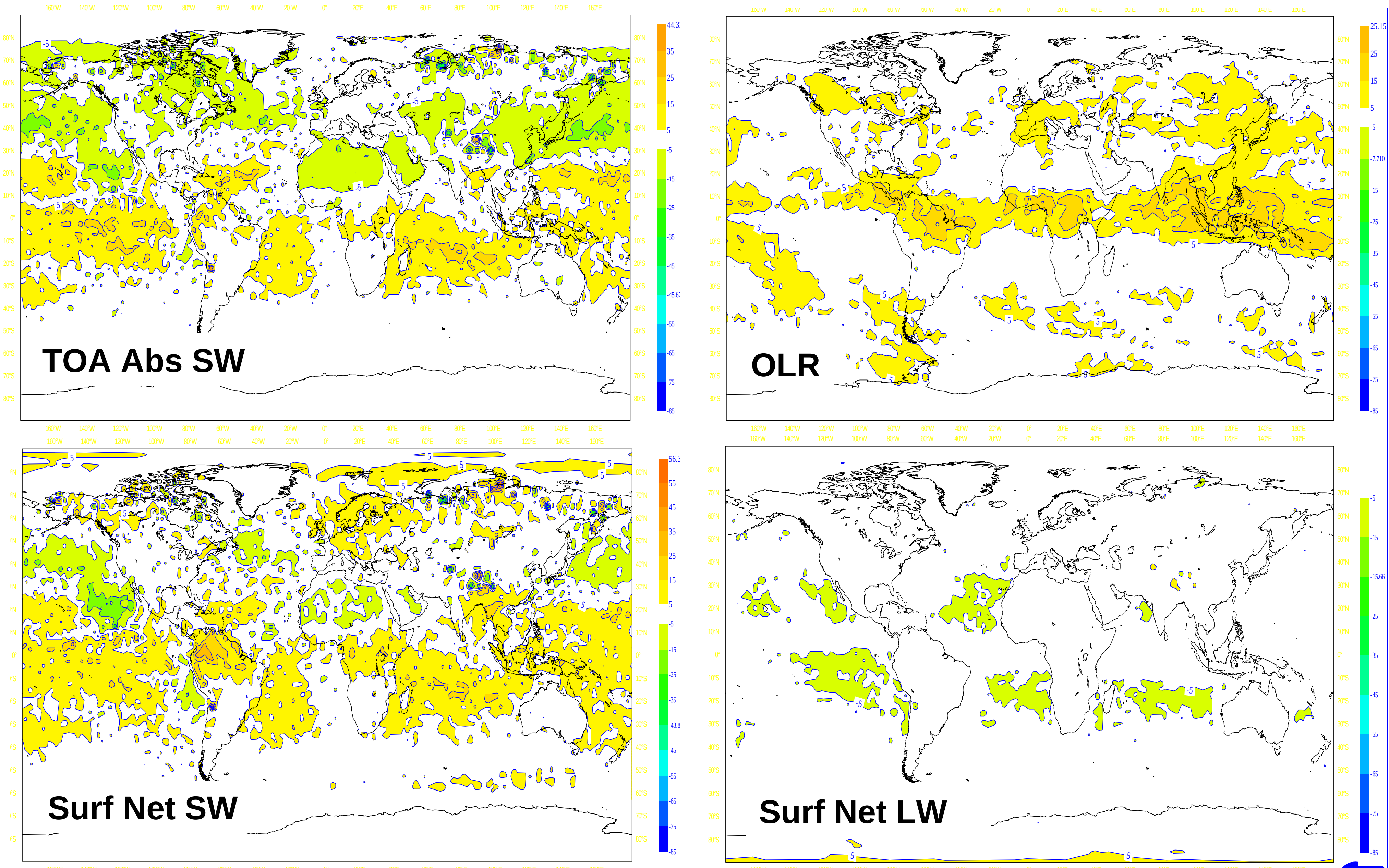


Comparison to radiosondes:
V-wind

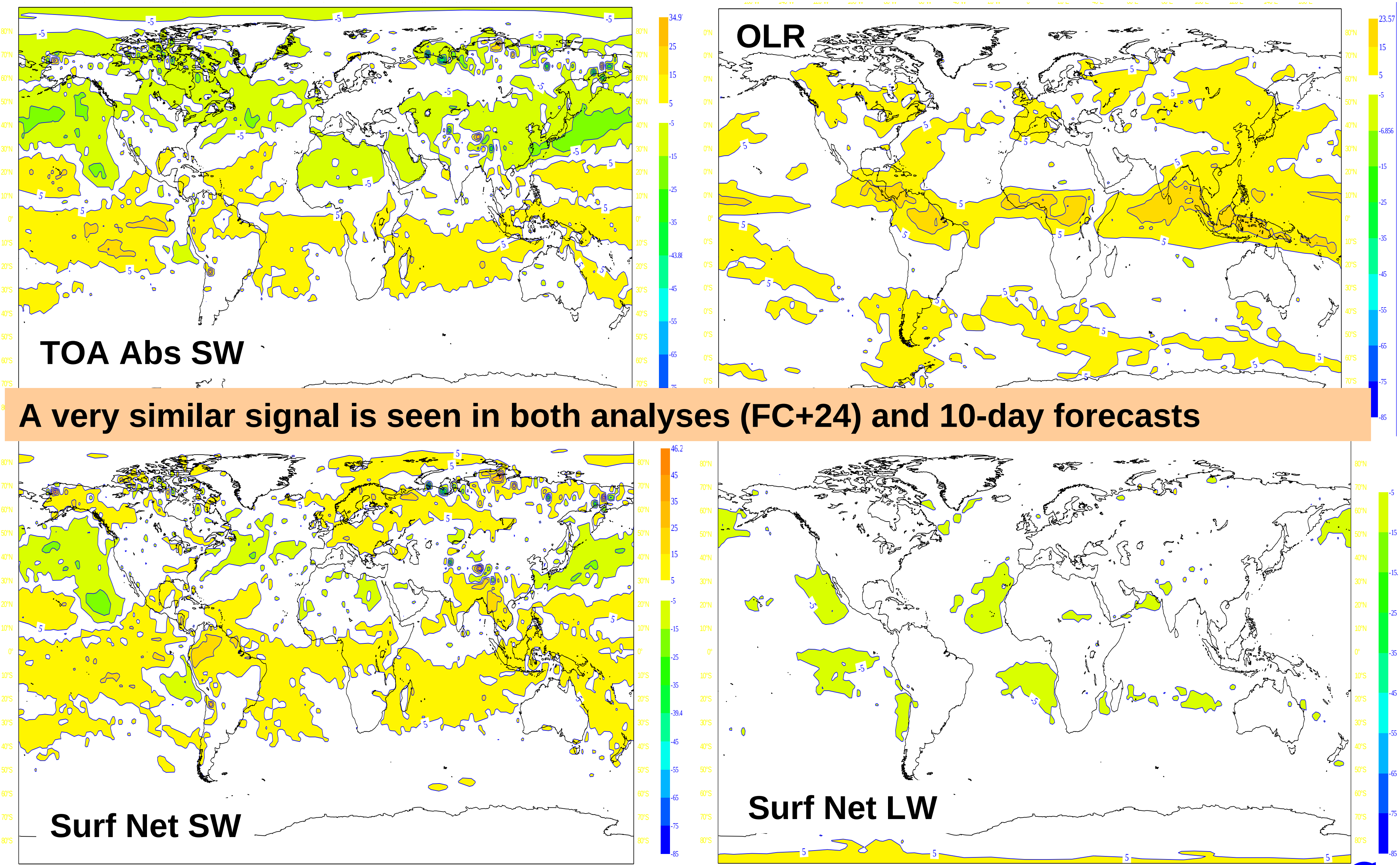
T_L799 L91 analysis run from 20060501 to 20060531, averaged between 0502_00 and 0530_12

Impact on analysis of temperature and wind is small, but generally positive

Differences in 24-hour forecasts started from 31R1+McICA package and 31R1 analyses averaged over the 31 forecasts for May 2006



Differences in 240-hour forecasts started from 31R1+McICA package and 31R1 analyses averaged over the 31 forecasts in May 2006



ECMWF

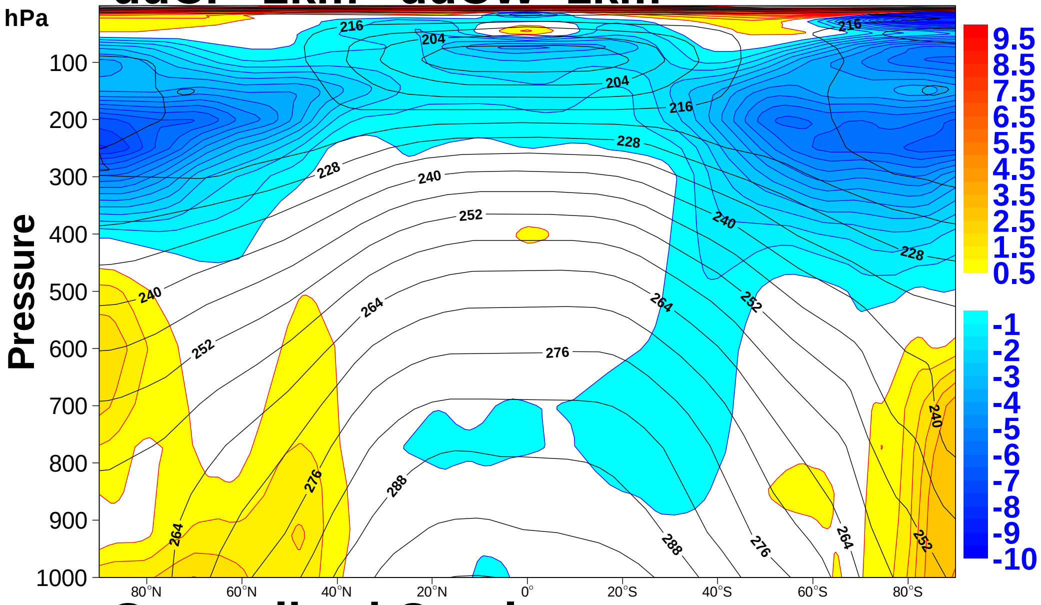
Impact of changes in decorrelation depths for CF and CW

- Within the cloud generator, different use various decorrelation depths for cloud fraction and cloud water
  - Generalized overlap with
    - ddCF=2 km, ccCW=1 km
    - ddCF=4 km, ccCW=2 km
    - ddCF=5 km, ccCW=1 km
  - Maximum-random overlap

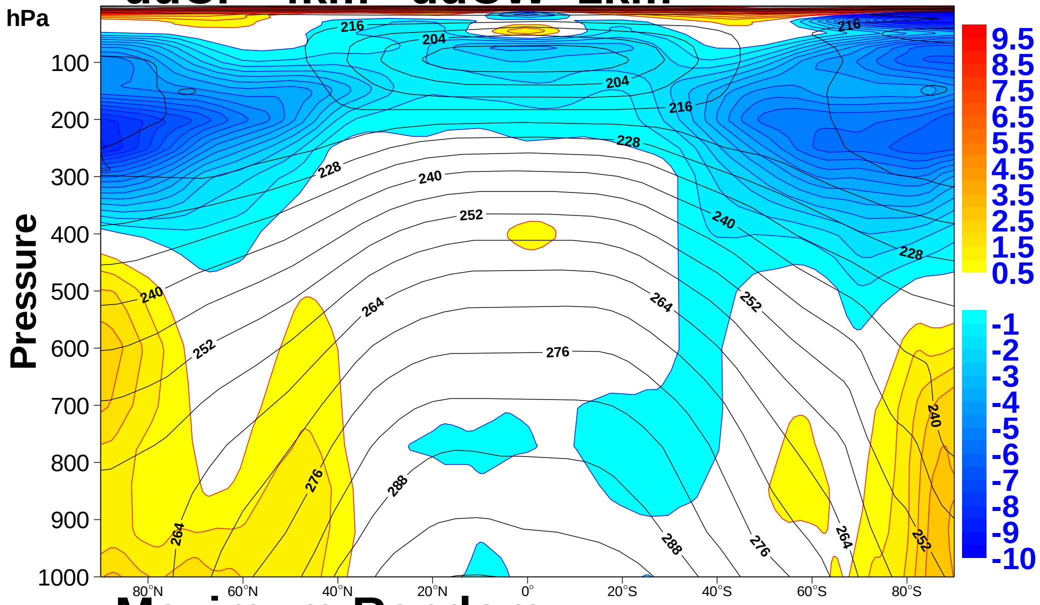
- Comparisons over 13-month simulations at T_L159 L91

- The overall impact of these assumptions is small

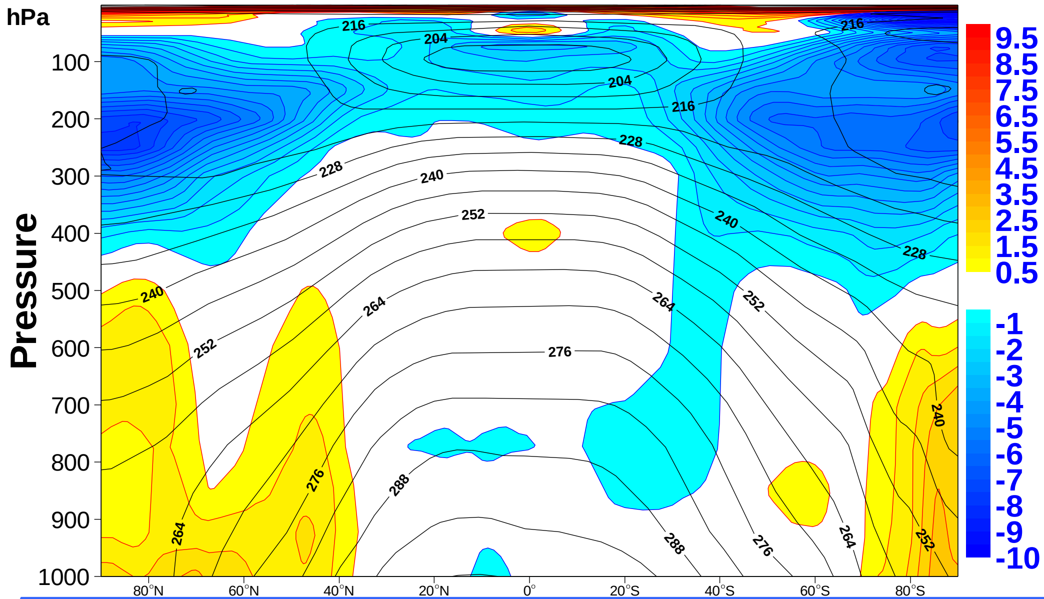
Generalized Overlap
ddCF=2km ddCW=1km



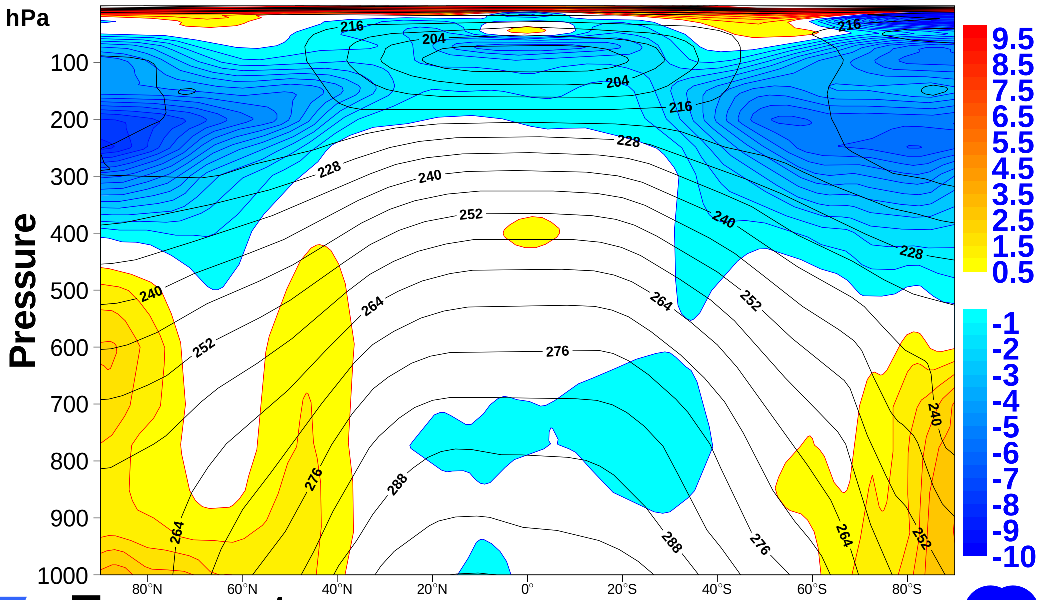
Generalized Overlap
ddCF=4km ddCW=1km



Generalized Overlap
ddCF=5km ddCW=1km



Maximum-Random
ddCF=5km ddCW=1km



Temperature

McICA: A state of the art method for representing cloud-radiation interactions in the ECMWF model!   - 1

- McICA allows a consistent approach on the definition of cloud overlap not only between LW and SW radiation, but also with other physical processes (precipitation/evaporation) (Jakob and Klein, 1999, 2000).
- RRTM_SW with 112 g-points is required to get the full benefit of McICA. It improves the temperature in the lower stratosphere.
- The operational radiation schemes uses Cahalan's homogeneity factors of 0.7 in both LW and SW to account for cloud inhomogeneities. McICA avoids the use of such factors. With McICA, clouds are made more transparent and the change in the distribution of the vertical cloud LW and SW radiative forcings appear to cure some systematic errors of the ECMWF IFS (shifting some of the convection back to tropical continents). This gives a marked improvement on the long term climate of the model. The exact mechanism requires further study.
- A similar improvement is seen in the short-term forecasts used as background for the analyses, and in the 10-day forecasts.

McICA: A state of the art method for representing cloud-radiation interactions in the ECMWF model! - 2

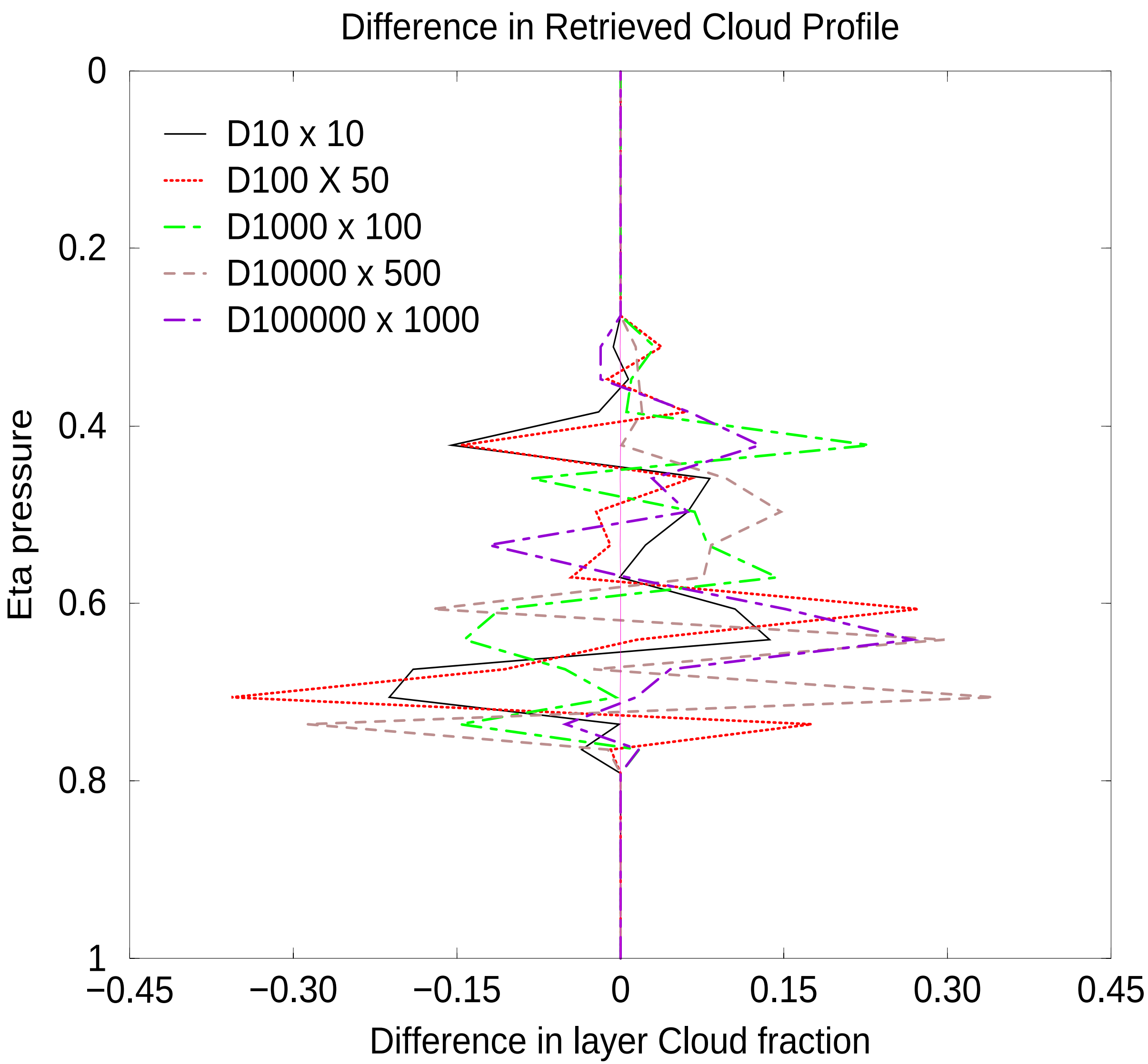
- Whereas McICA does not increase the computational burden, RRTM_SW does. Going for a slightly lower resolution for full radiation computations does not affect the quality of the forecasts.
- The model shows little dependence on the decorrelation depths used for cloud fraction and cloud water. But this formulation will allow further developments once knowledge of these quantities become available from CLOUDSAT measurements.
- The McICA approach appears particularly adapted to pdf-based cloud schemes

Perspectives:

The McICA package together with a new climatology of land surface albedo derived from MODIS observations will be pre-operationally tested in the near future.

Thank you for your attention!

Convergence of the cloud generator

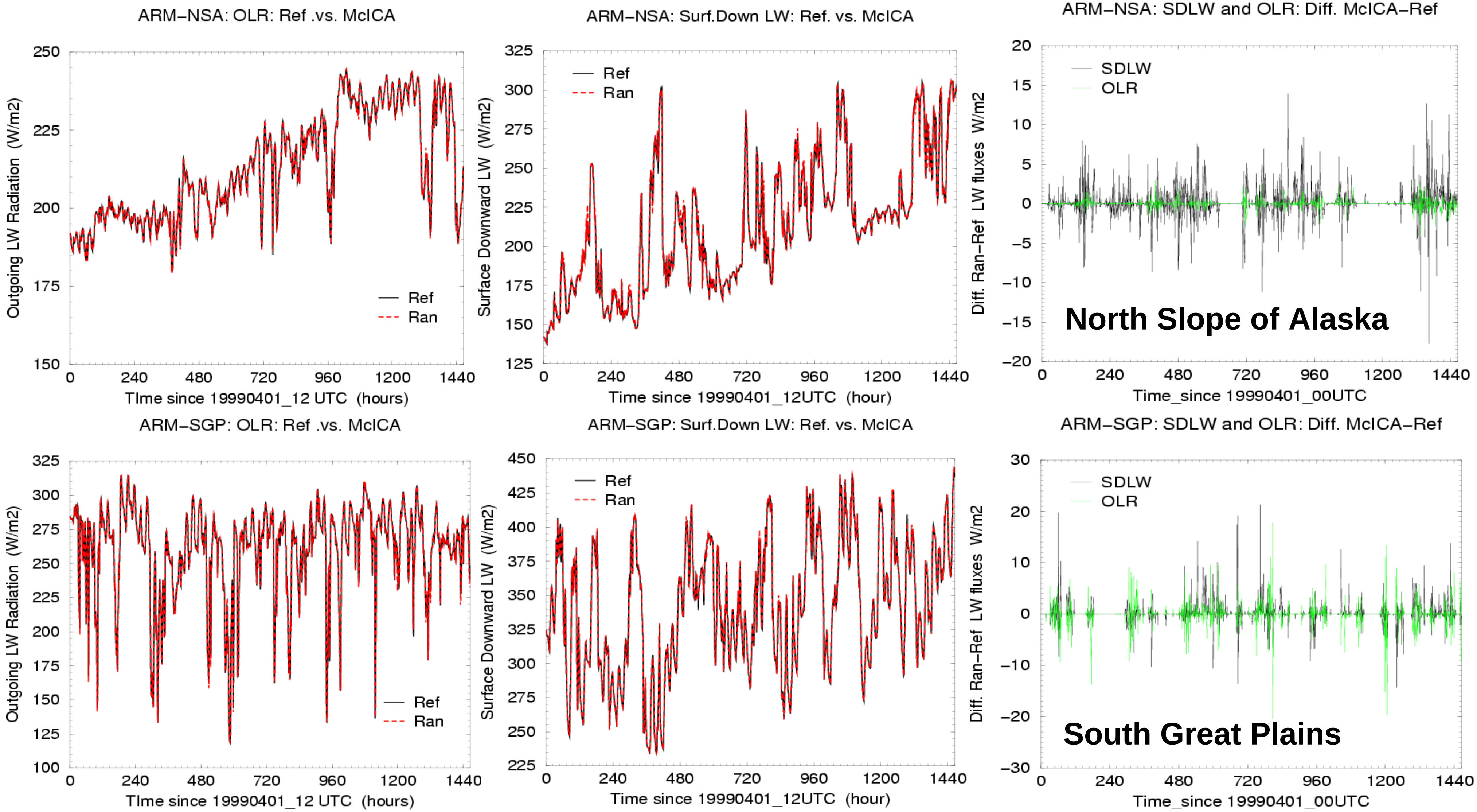


Difference in layer cloud fractions, produced by the cloud generator called N times.

Results are for a cloud profile over SGP in April 1999

Dn is the number of draws over the 112 g-points, xm is the multiplication factor

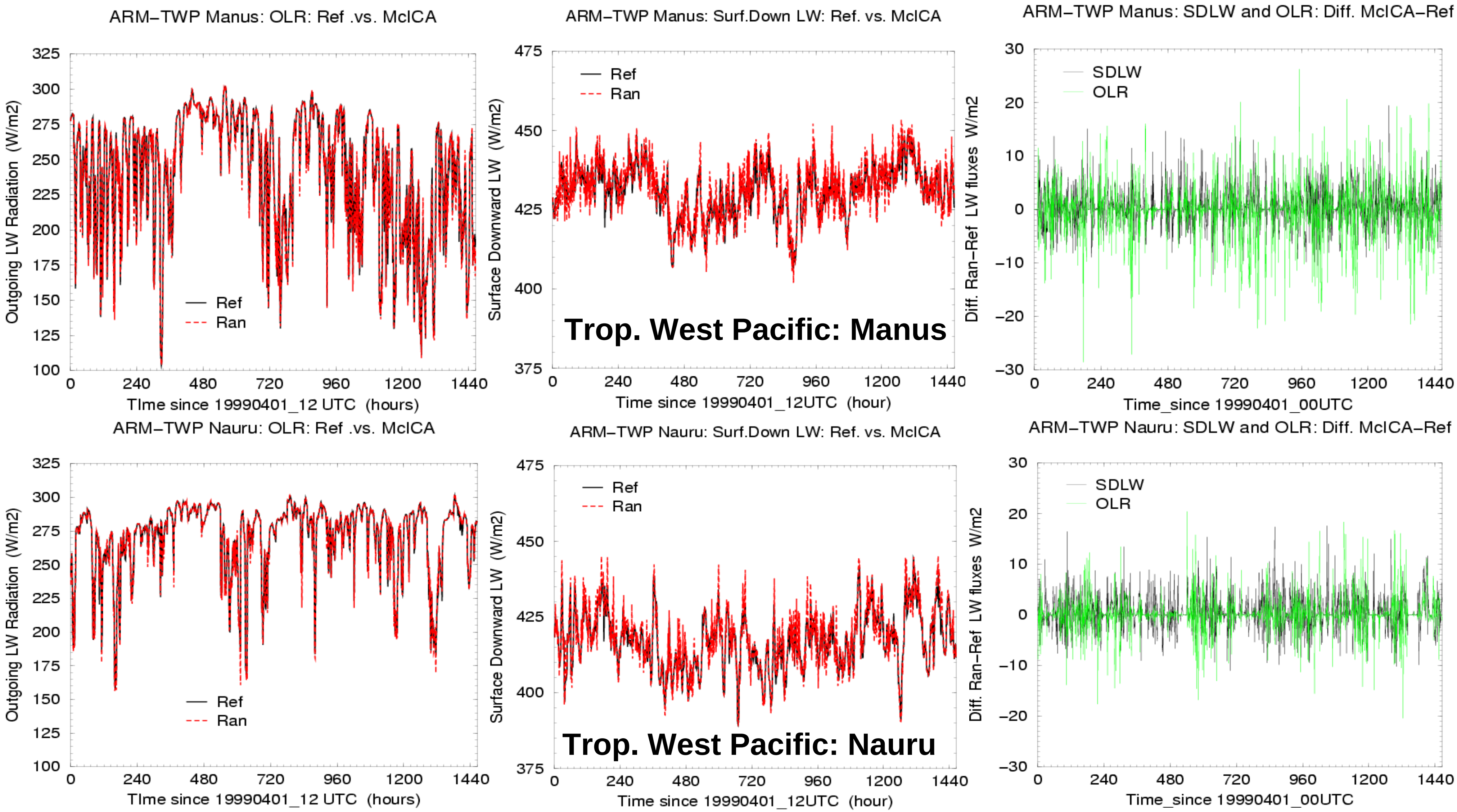
McICA: Tests with 1-D radiation code: LW



OLR **SDLW** **Differences McICA-Ref**

NB: 1 draw for McICA

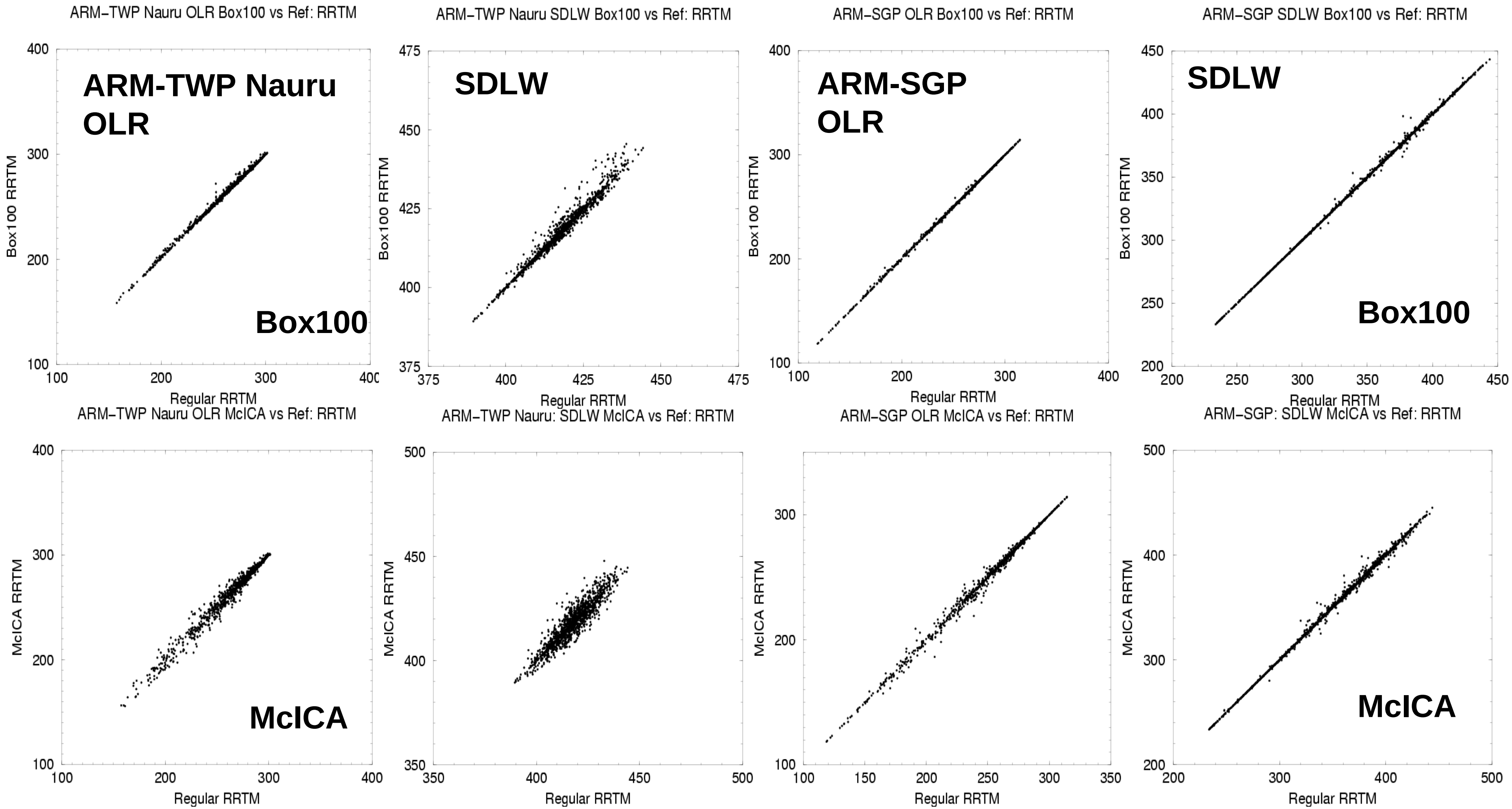
McICA: Tests with 1-D radiation code: LW



OLR **SDLW** **Differences McICA-Ref**

NB: 1 draw for McICA

It does work in the LW and SW



“Regular” RRTM = Reference= McICA code run over 10000 cloud draws

Questions for working groups

- How to get more (and global) information on decorrelation depths for cloud cover and cloud water

- Optical properties: mixed-phase clouds, ice clouds

- "Technical": Can a GCM run with different resolution for different physical processes? What is the best choice of resolution for cloud/clear-sky radiation processes?

- Within the framework of a 4D variational assimilation, how crude/simplified can the radiative parametrisation used within the assimilation be?