ECMWF IFS: from cycle 47r1 to 47r2 and beyond …

Gianpaolo Balsamo

Many thanks to all ECMWF Research & Forecast Department Colleagues who provided input for this talk

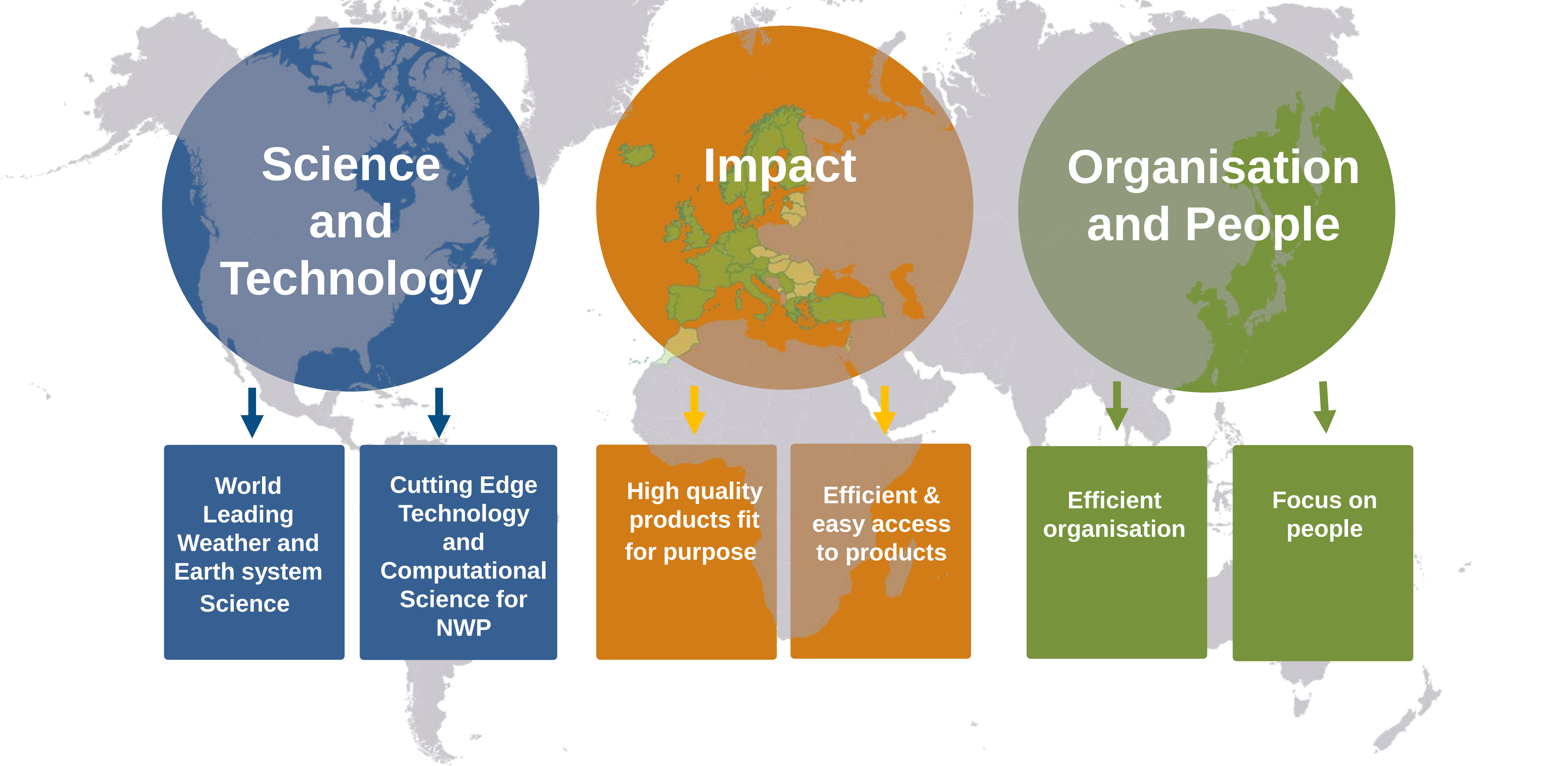
42nd EWGLAM and 27th SRNWP meeting

Online event 2020

ECMWF global forecasting & monitoring

- Make skillful ensemble predictions of high impact weather up to two weeks ahead
  - Resolution increase is key in delivering this strategy - stronger ensemble signal with high resolution
- Today's numerical weather prediction system:
  - **Daily: 10 day, 9km horizontal resolution 137 vertical levels forecast initialised by 4D-VAR analysis**
  - **Daily: 15 day forecast produced by 51 member 18km, 91 level ensemble with perturbed initial conditions to quantify uncertainty**
  - **Weekly: 46 day forecast (extended range) - 51 member 36km ensemble with 91 levels**
  - **Monthly: 7-months forecast (seasonal) – 51 member 36km ensemble with 91 levels**
  - **Copernicus Atmospheric Monitoring Service:**
    - **Daily atmospheric composition forecasts (GHG, aerosols, dust, volcanic plumes etc)**
    - **Global re-analysis**
  - **Copernicus Climate Change Service:**
    - **ERA5 (hourly, 31km), ERA5T (near real time), ERA5L (hourly 9km, land only)**
- **2025**
  - Towards a seamless ENS prediction system with high horizontal (near 5km) and vertical resolution (137L)

ECMWF new 10-year strategy 2021-2030



ECMWF Integrated Forecasting System and its cycles

- Global hydrostatic primitive equation dynamical core, with grid-point physics at 9/18 km (HRES/ENS)
- Spectral transform in the horizontal vertical finite element, semi-implicit, semi-Lagrangian
- Initial conditions produced by 4D-VAR data assimilation system that relies on a tangent-linear and adjoint version of the non-linear model
- Continuous improvement of skill with release of a new operational cycle roughly once per year
  - CY46R1 June 2019
  - CY47R1 June 2020
  - CY47R2: single precision forecasts with increased vertical ENS resolution, operational in first half of 2021, then ported on New Super-computer in Bologna at the beginning of 2022
  - CY48R1: major upgrade in the atmospheric physics, land cryosphere, dynamics, data assimilation, foreseen at the end of 2022 (or beginning 2023)

CY47R1 : main 4D-VAR & + Model changes

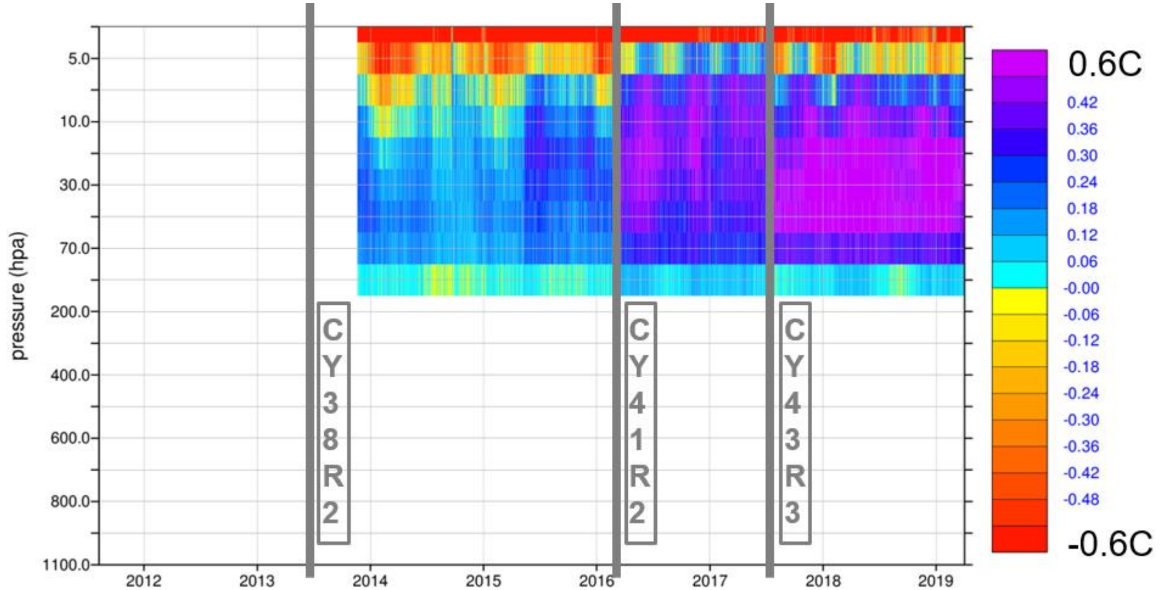
Data assimilation and Observation highlights

- Revised weak-constraint 4D-Var
- Situation-dependent skin temperature background error variances from EDA
- Shorter timestep in last 4D-Var minimisation (450 second in inner/outer loop)
- First guess in delayed cutoff 12-hour 4D-Var obtained from early delivery
- Revised ATMS observation errors
- Channel specific aerosol rejections for IR sounders
- Spline interpolation in the 2D GPS-RO bending angle operator

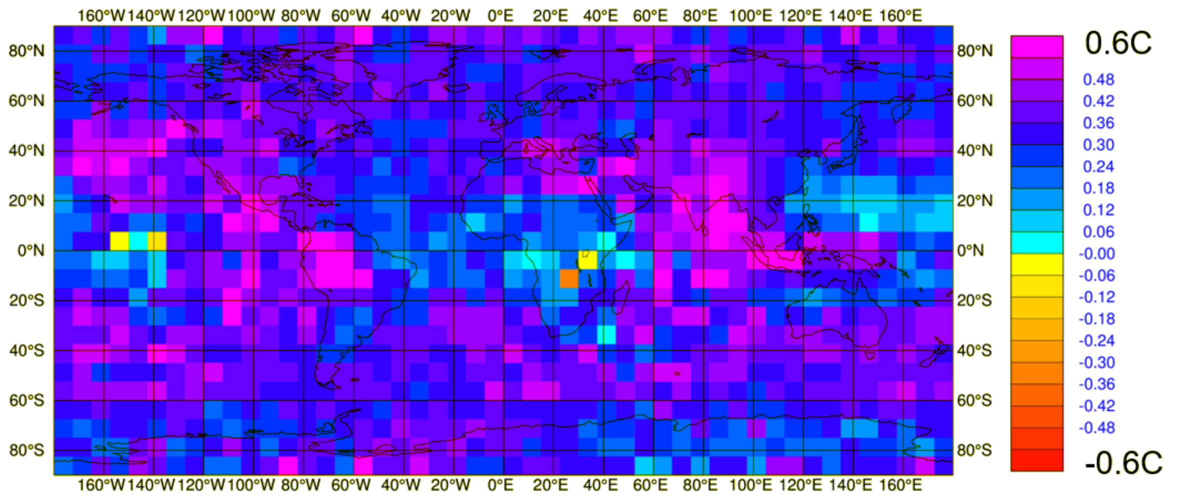
Model Upgrades

- Radiation improvements (new MODIS albedo climatology depends on sun angle)
- Limiting Charnock parameter for high winds to improve Hurricane wind/pressure forecasts
- Quintic vertical interpolation in the semi-Lagrangian advection for temperature and humidity

Temperature bias in the operational IFS model



The short-term model bias is estimated by comparing the 12-hour first-guess trajectory with GPS-RO temperature retrievals



→ bias increased with last horizontal resolution (Tco1279 in CY41R2)

→ bias increased with last radiative scheme (CY43R3)

→ GPS-RO reveals the large scale structure of the model error in the stratosphere

Bias between 70hPa and 100hPa (1 Oct. 2018 to 1 Feb. 2019)

WC 4D-VARSlides: courtesy of P. Laloyaux

New model error specification in weak-constraint 4D-Var

Unknown forcing is introduced in the model equations (additive, Gaussian, constant within the assimilation window, no cross-correlation with the background error)

$$\mathbf{x}_k = \mathcal{M}_{k,k-1}(\mathbf{x}_{k-1}) + \eta \qquad \text{for} \qquad k = 1, \ldots, N.$$

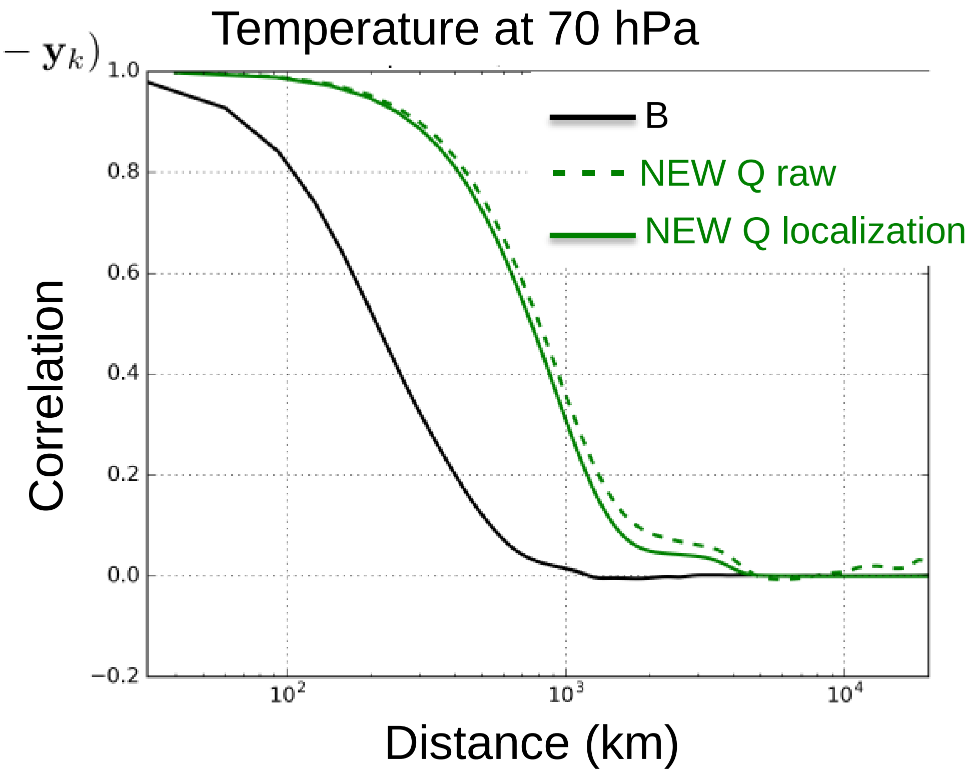
Observations can be fitted by changing the **initial state** or the **model forcing**

$$\begin{aligned} J(\mathbf{x}_0, \boldsymbol{\eta}) = & \frac{1}{2}\left(\mathbf{x}_0 - \mathbf{x}_0^b\right)^{\mathrm{T}} \mathbf{B}^{-1} \left(\mathbf{x}_0 - \mathbf{x}_0^b\right) \\ & + \frac{1}{2}\left(\boldsymbol{\eta} - \boldsymbol{\eta}^b\right)^{\mathrm{T}} \mathbf{Q}^{-1} \left(\boldsymbol{\eta} - \boldsymbol{\eta}^b\right) \\ & + \frac{1}{2}\sum_{k=0}^{N} \left(\mathcal{H}_k(\mathbf{x}_k) - \mathbf{y}_k\right)^{\mathrm{T}} \mathbf{R}_k^{-1} \left(\mathcal{H}_k(\mathbf{x}_k) - \mathbf{y}_k\right) \end{aligned}$$

Horizontal correlation in the covariance matrices

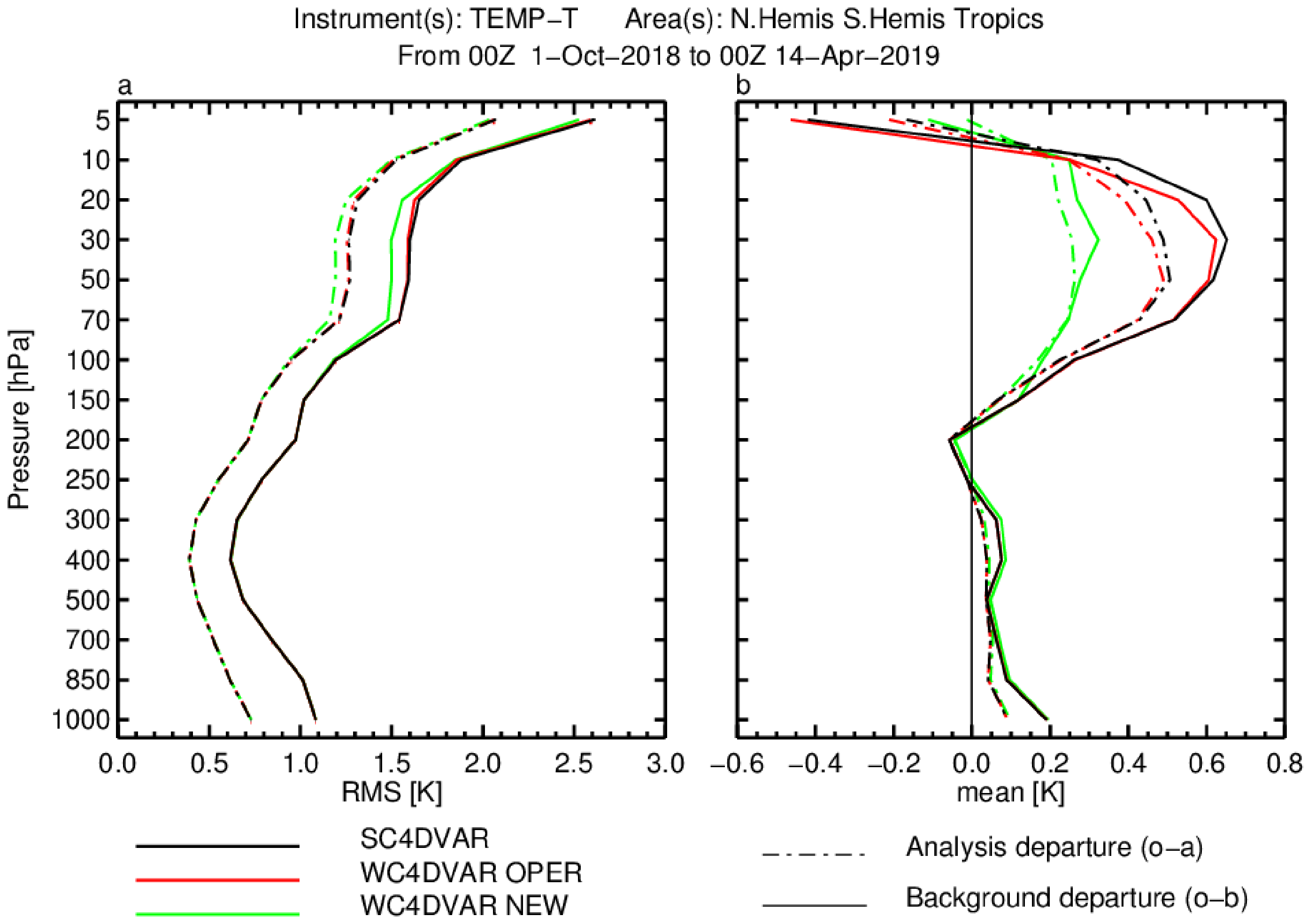
→ **B** corrects the small scales

→ **Q** corrects the large scale



ECMWF

Weak-constraint 4D-Var with scale separation

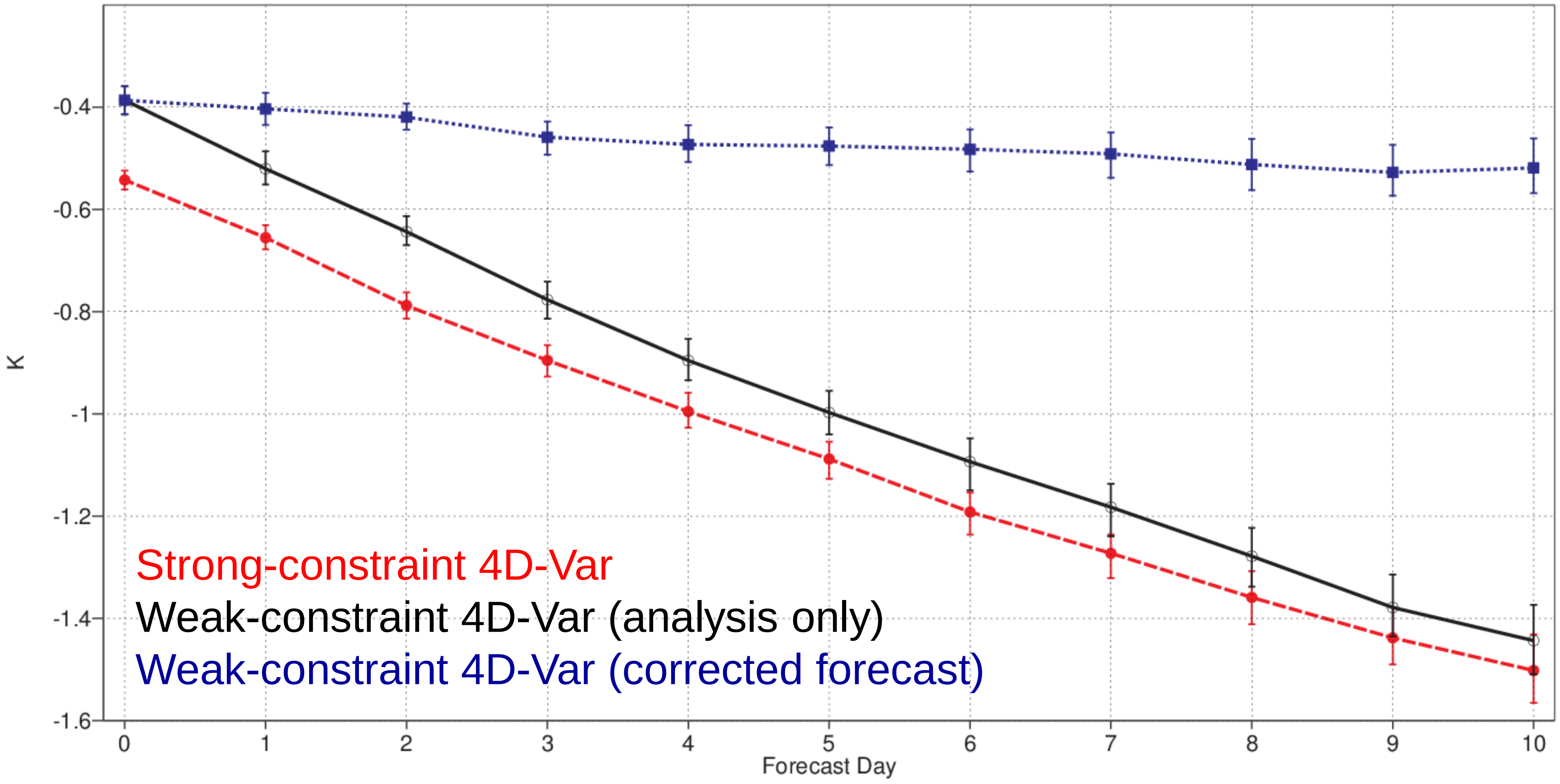


→ temperature bias is reduced up to 50% with respect to radiosondes and GPS-RO (RMSE is reduced up to 6%)

→ implemented in CY47R1 above 100hPa where the model bias is significant

Impact of weak-constraint 4D-Var forcing on forecast skills

Mean forecast error against radiosonde temperature (70hPa)



Forecast lead time (day)

In the corrected forecast

→ the model error estimation η is applied as a constant model forcing over 10 days

→ the forecast model is not biased anymore and mean error does not increase

Matching timestep with non-linear model in the last minimization of 4D-VAR

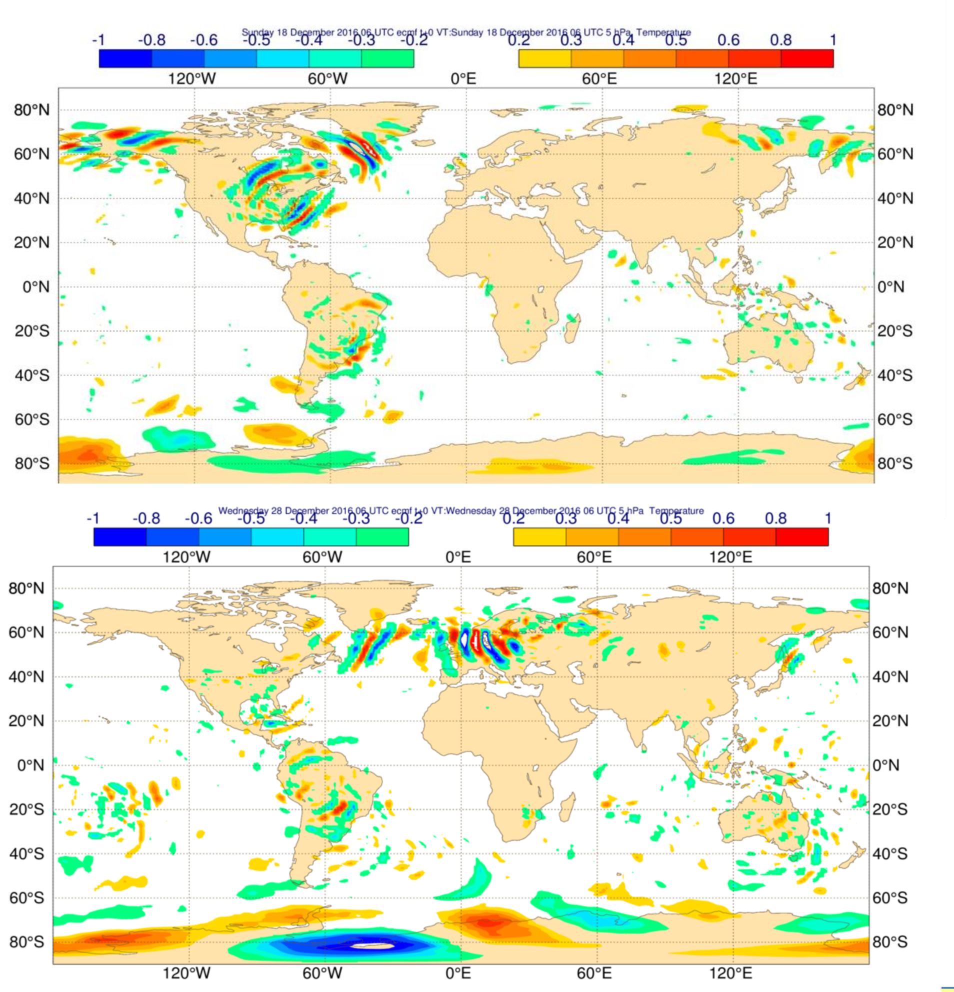
In CY46R1:

- 4 outer loops in minimization all at lower resolution than forecast model
- Due to coarser resolution a longer timestep can be used for TL/AD models

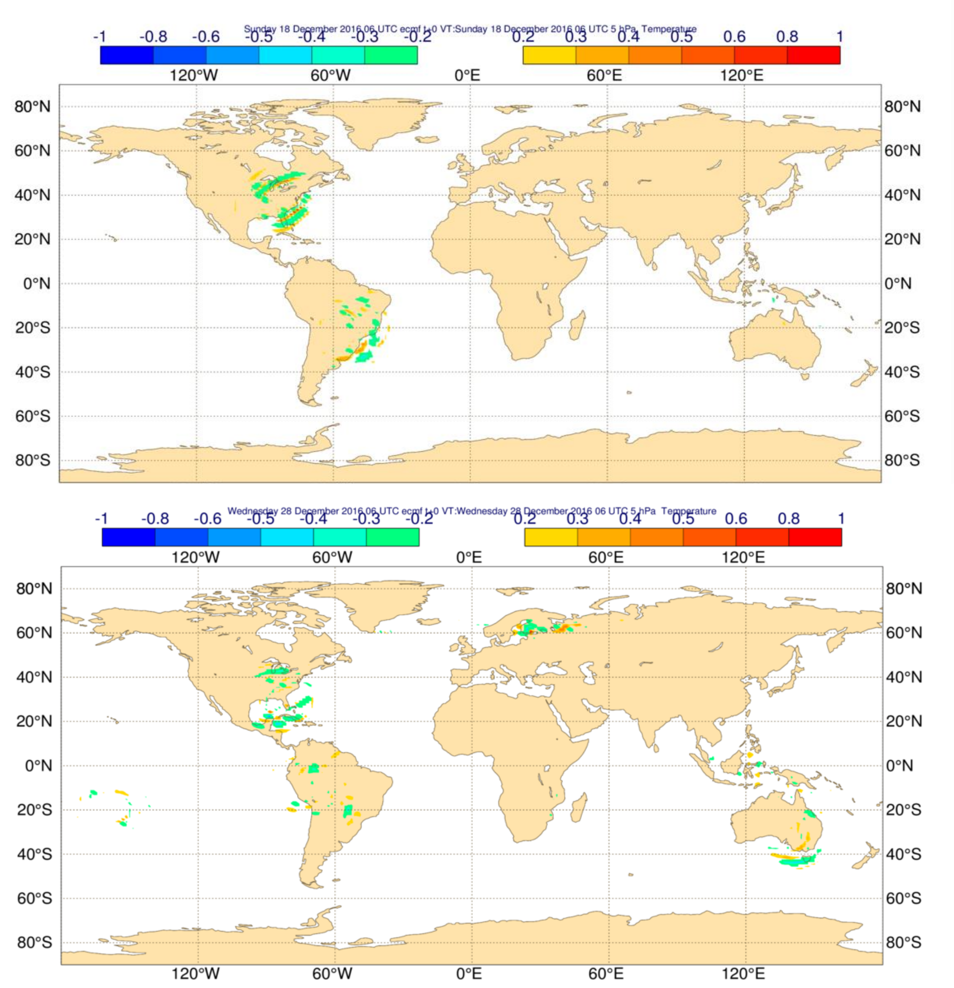
In CY47R1:

- Use the same timestep with the 9km forecast model (450s) at the last outer loop minimization
- Although more expensive it ensures consistency between the inner and outer loops which makes the speed of gravity waves more comparable.
- It has positive impact in scores increasing the overall minimization computational cost by 8%.

Difference between analysis increments computed by **nonlinear and linearised** models 9 hours in the assimilation window (**temperature ~5 hPa**)



Nonlinear Model tstep=450s; Linearised Model tstep=900s

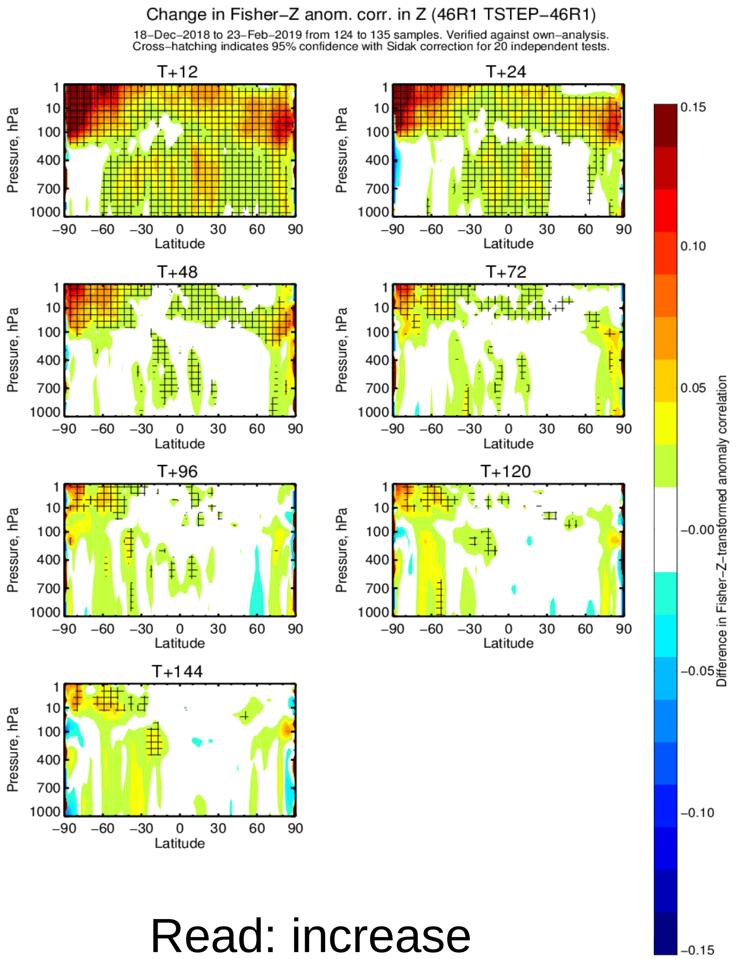


Nonlinear Model tstep=450s; Linearised Model tstep=450s

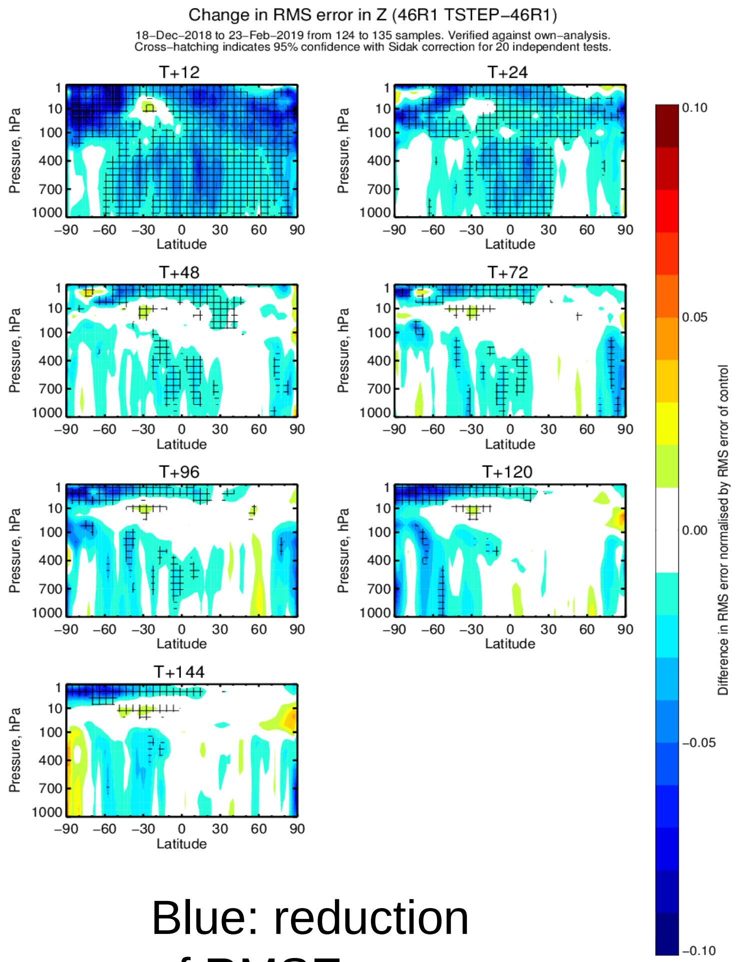
Slides courtesy of M. Bonavita

Inner/Outer loop time-step matching

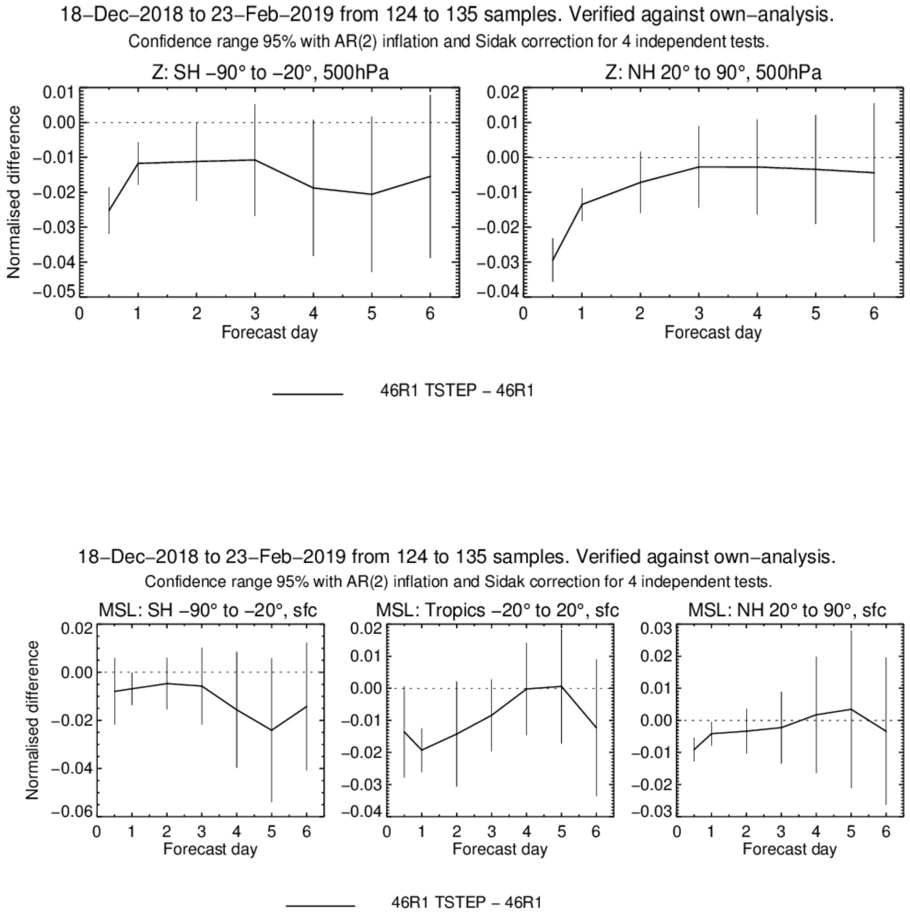
- CY46R1 experimentation at HRES resolution (18/12/2018-23/02/2019)



Read: increase in ACC against control

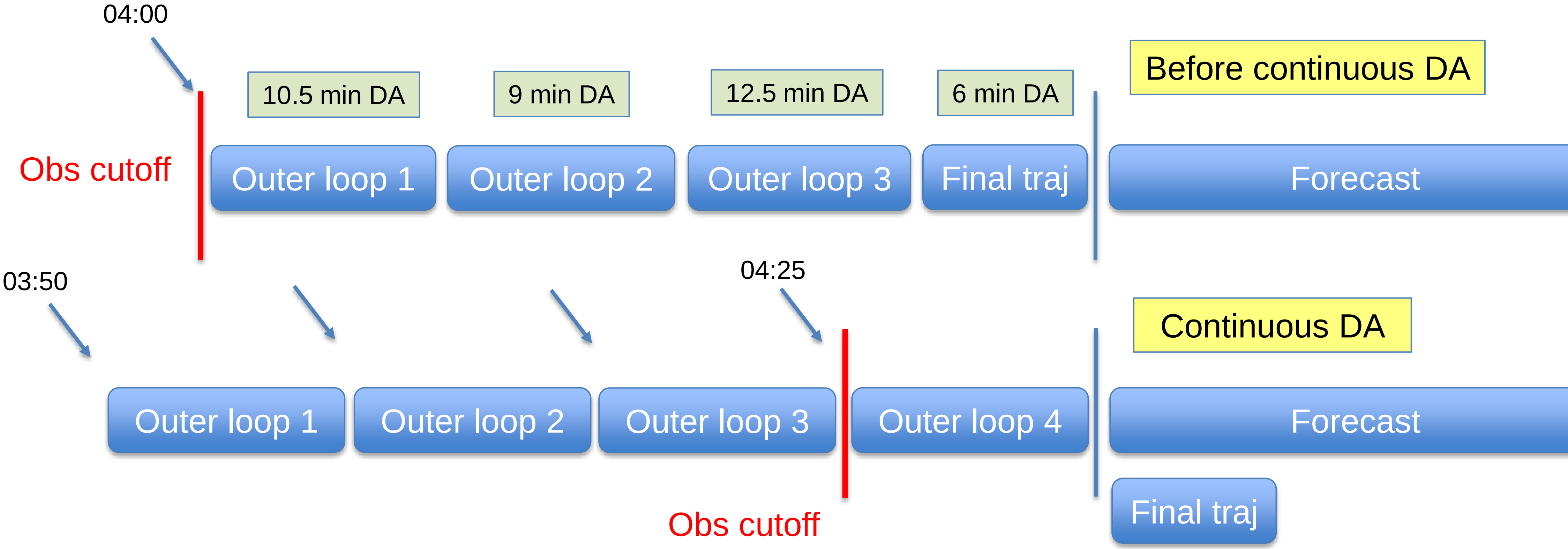


Blue: reduction of RMSE against control



Continuous Data Assimilation changes Early Delivery (DA) in CY46R1

- New observations added in each outer loop
- Early Delivery assimilation window from 6h to 8h, ensures **all** observations that have arrived can be assimilated (LWDA unchanged at 12h)
- Outer loops from 3 to 4
- Allows to assimilate more observations improving analysis quality



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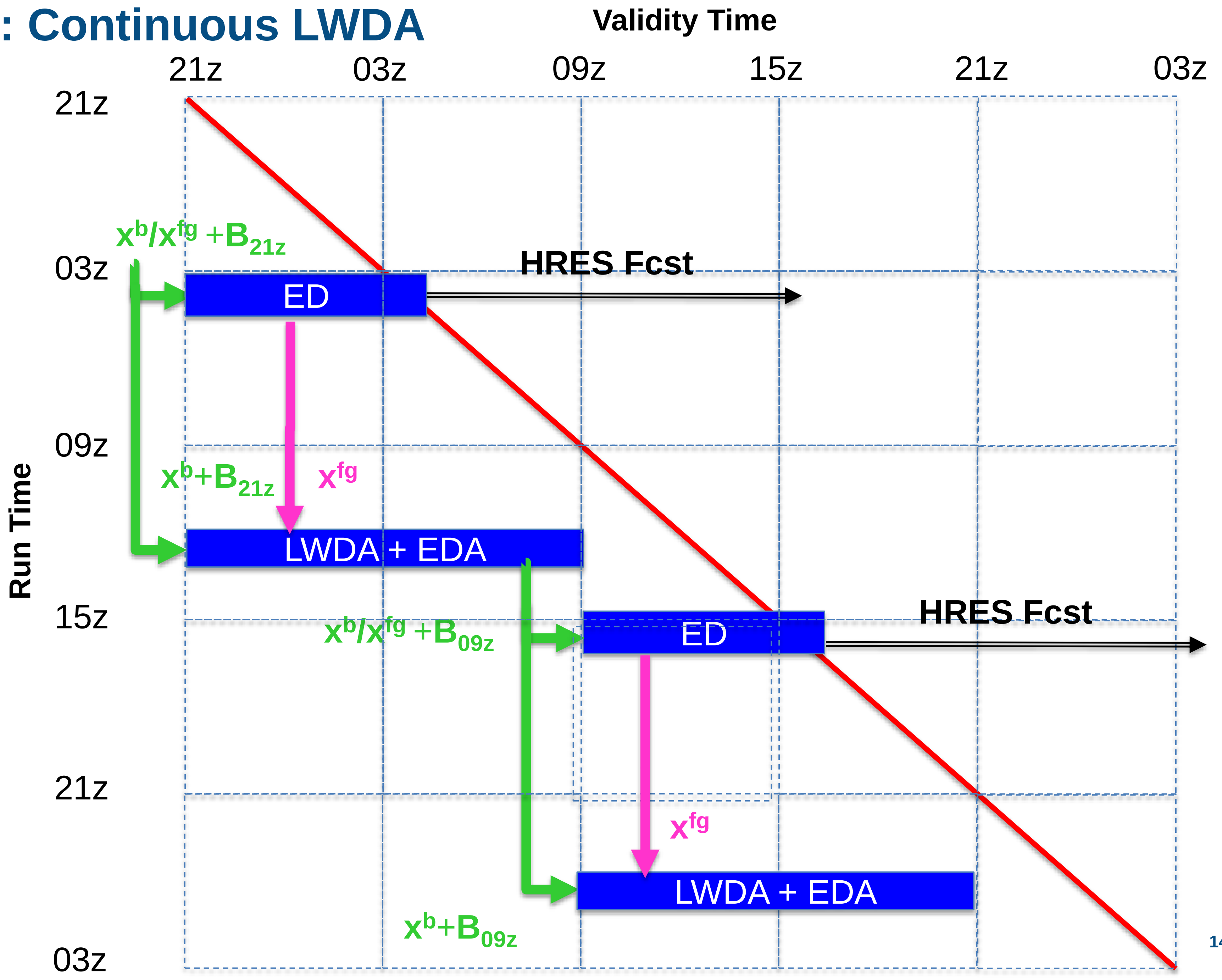
Slide courtesy of P. Lean

DA schedule 47R1: Continuous LWDA

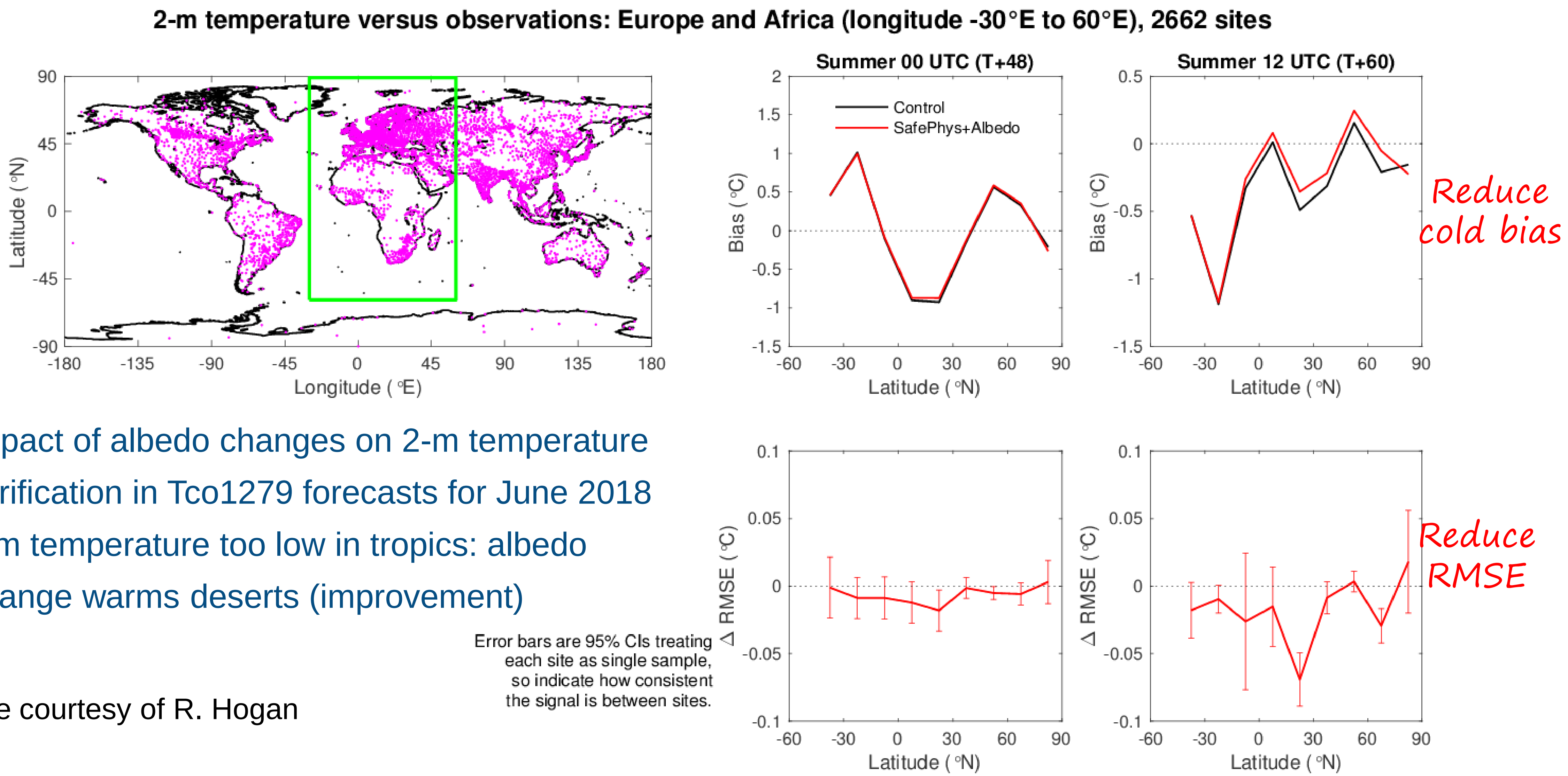
Currently the "background" forecast provides "first guess" for LWDA

With continuous LWDA the ED analysis is used as "first guess" for the next LWDA: the LWDA analysis is warm-started from a better first guess.



Slide courtesy of E. Holm

Model improvements: Albedo changes for CY47R1



- Impact of albedo changes on 2-m temperature verification in Tco1279 forecasts for June 2018
  2-m temperature too low in tropics: albedo change warms deserts (improvement)

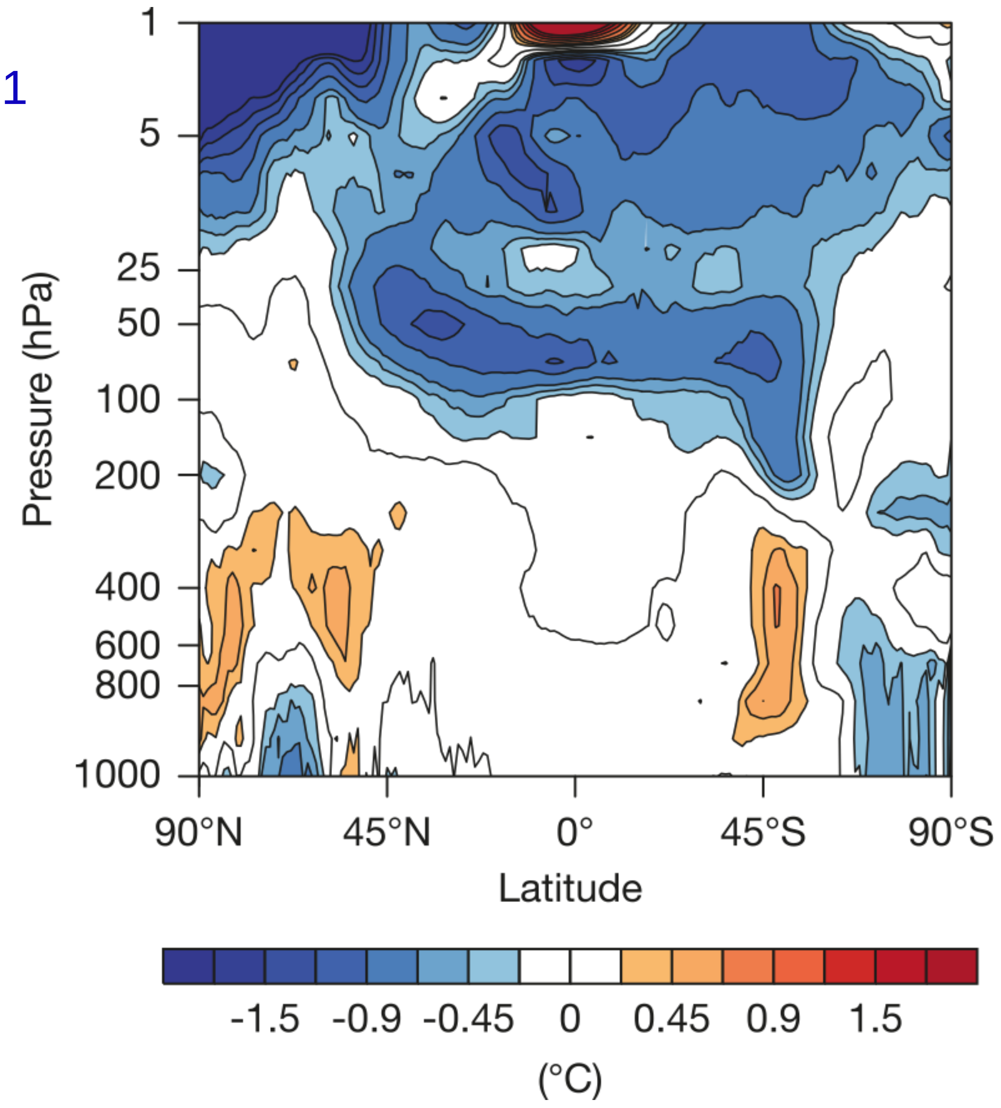
Slide courtesy of R. Hogan

Quintic interpolation improves the Stratosphere – I of III

A long standing issue elegantly solved.

A quintic interpolation provides an elegant and cost-effective solution

CY46R1



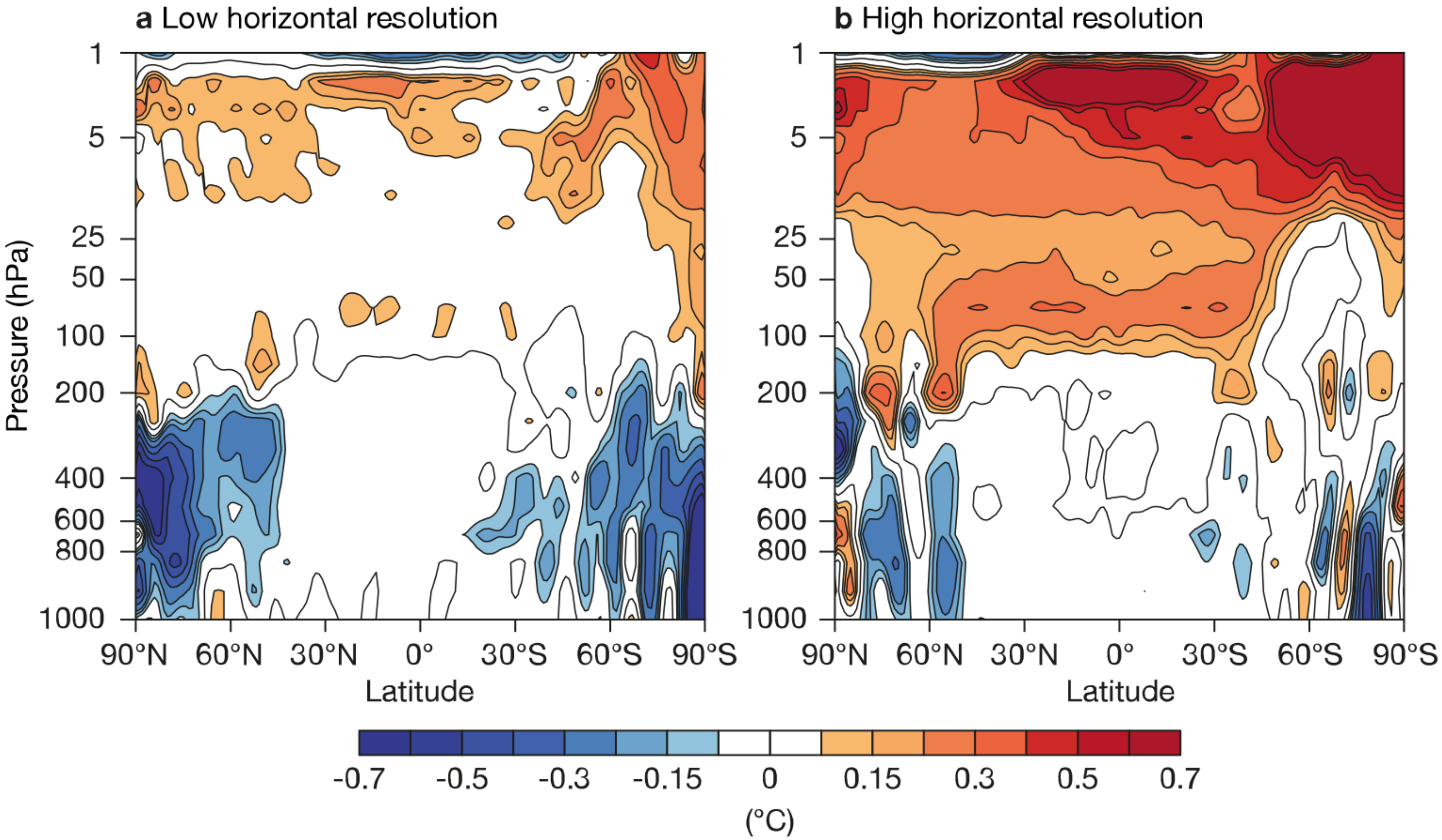
Difference in zonally (latitudinally) averaged **temperature** between forecasts at **TCo1279** horizontal resolution (about 9 km) and **TL255** horizontal resolution (about 79 km).
Mean values over 31 forecasts starting in December 2017 and valid at day 10 are shown.
Blue indicate high resolution forecasts are colder.

ECMWF

Quintic interpolation improves the Stratosphere – II of III

for CY47R1

Differences in zonally (latitudinally) averaged **temperature** between quintic and cubic vertical interpolation forecasts for (a) **TL255** horizontal resolution (79 km) and (b) **TCo1279** horizontal resolution (9 km) **with Q.I.** Mean values over 31 forecasts starting in July 2017 and valid at day 10 are shown.
The plots show that **quintic vertical** interpolation **warms** the stratosphere **more at high** horizontal **resolution**.



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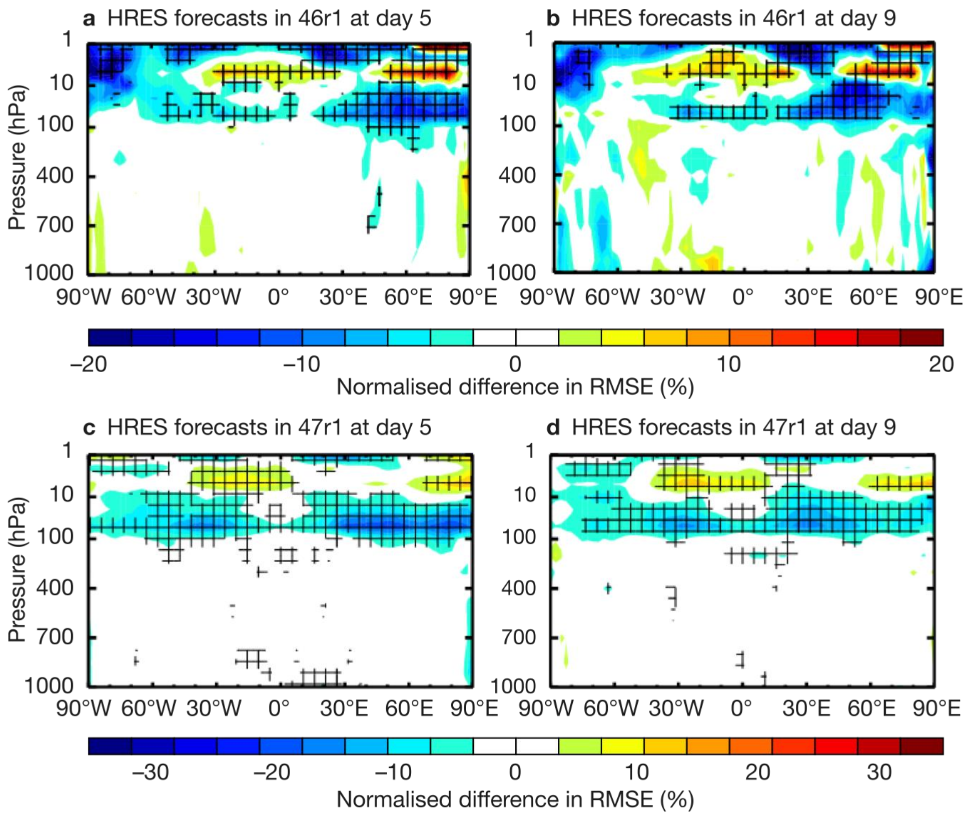
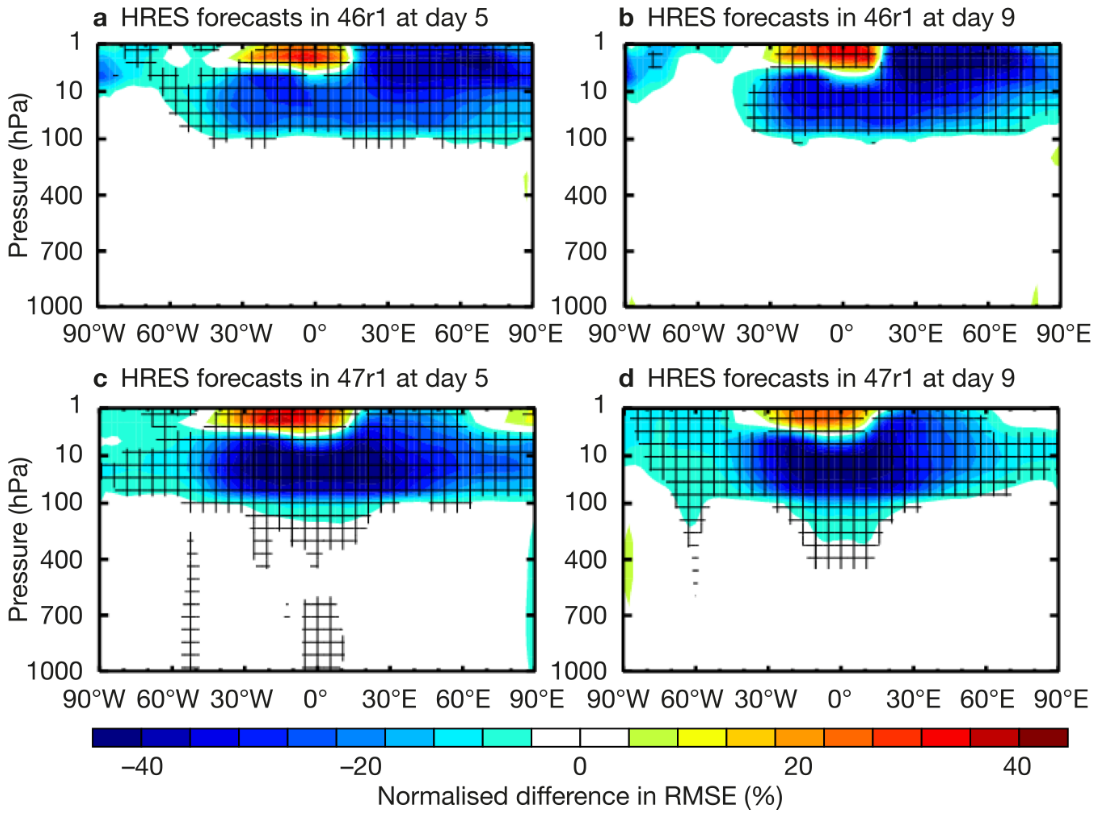
Quintic interpolation improves the Stratosphere – III of III

Tests have shown that it leads to more physical model behaviour, reduced sensitivity to horizontal resolution, and improve the forecast skill in the lower to mid-stratosphere.



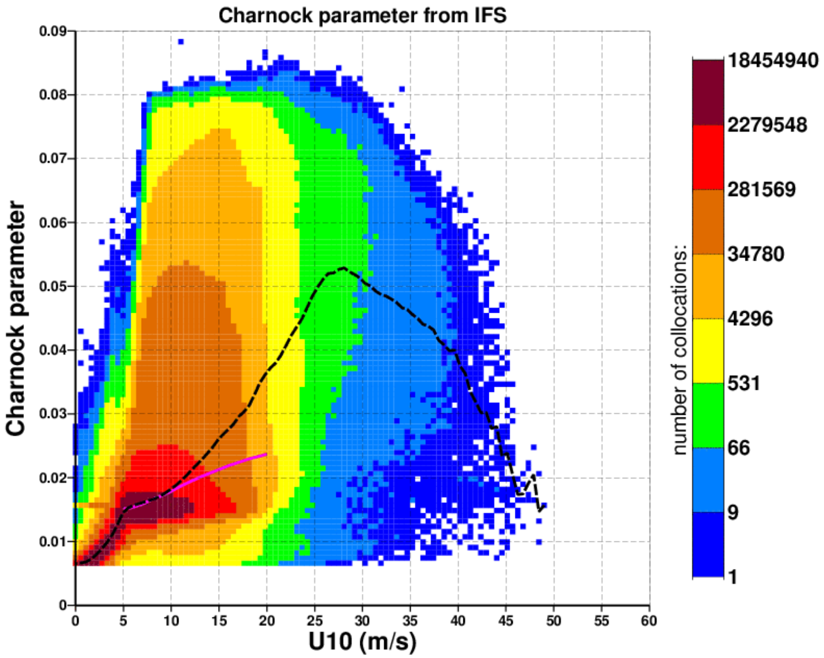


See further details on the ECMWF Newsletter article**:**
https://www.ecmwf.int/en/newsletter/163/meteorology/quintic-vertical-interpolation-improves-

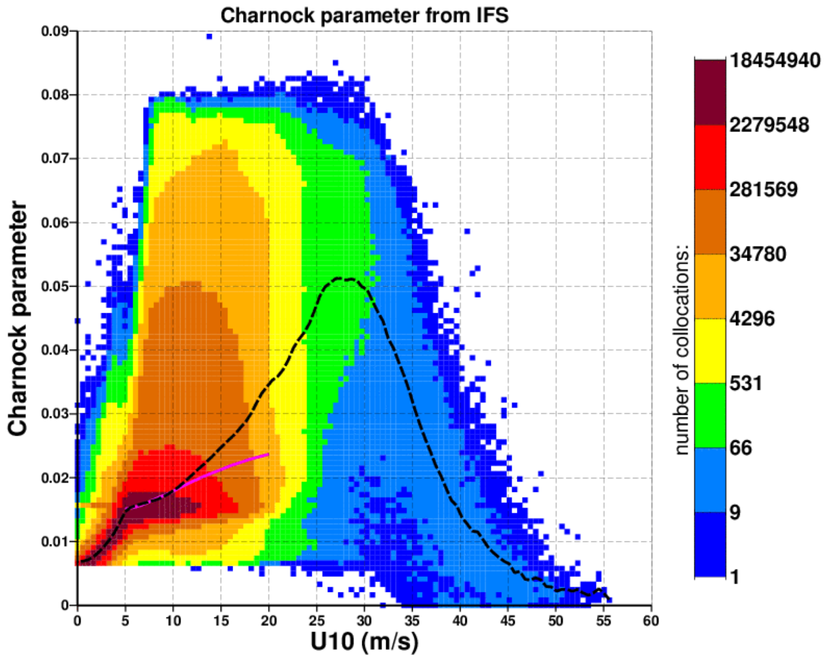
Charnock coefficient update for CY47R1

for CY47R1

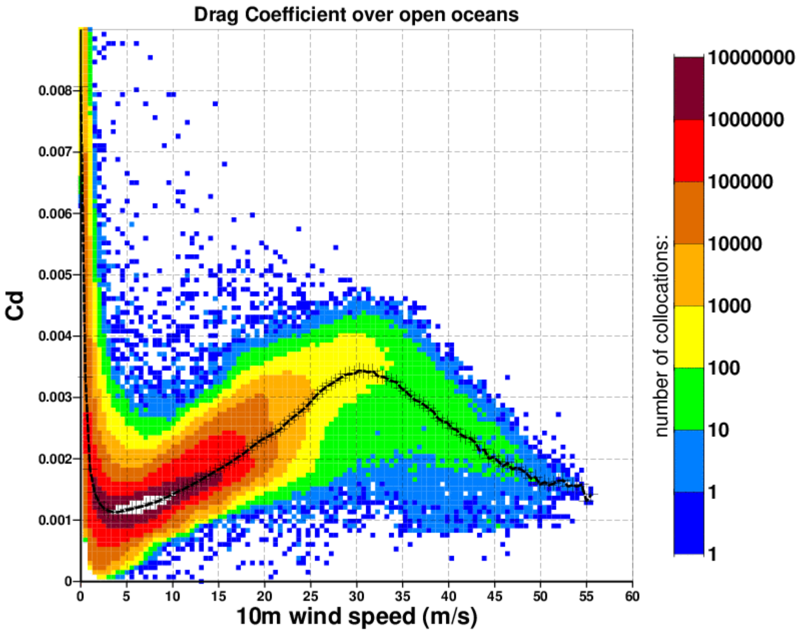
CY46R1



Forecast data from stream da, class rd, expver h9f7, all Sea points with sea ice cover <= 0.3
from 20190902 12UTC, for steps from 1 to 240 by 1



Forecast data from stream da, class rd, expver h9ha, all Sea points with sea ice cover <= 0.3
from 20190902 12UTC, for steps from 1 to 240 by 1



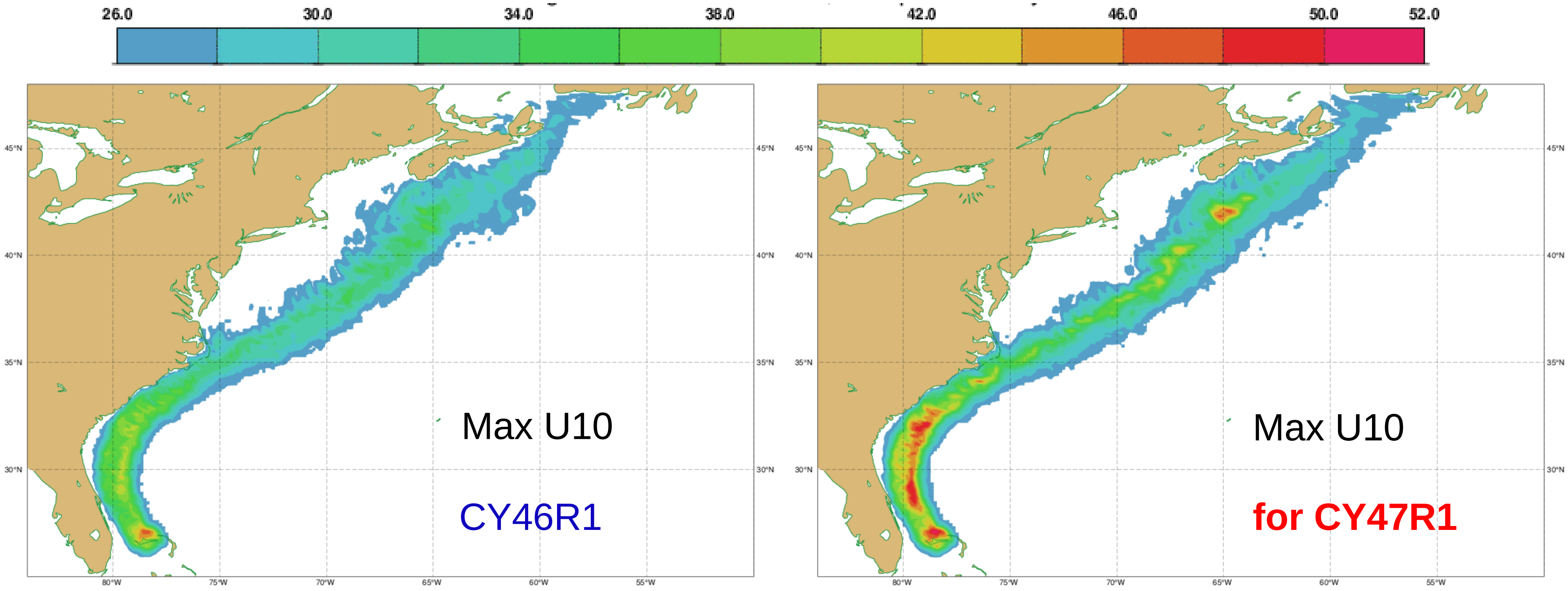
TCo1279 forecast
h9ha from 20190902 12 UTC, step 1 to 240 by 1

Tco1279 forecast from 2 September 2019, 12 UTC, hourly steps 1 to 240 hours, full coupling to NEMO, starting from DA initial conditions

Work of Jean Bidlot. See also the cycle News item: https://www.ecmwf.int/en/about/media-centre/news/2020/ifs-upgrade-greatly-improves-forecasts-stratosphere

Drag coefficient now fits better observations for strong winds over 30m/s compared with CY46R1 which was too big

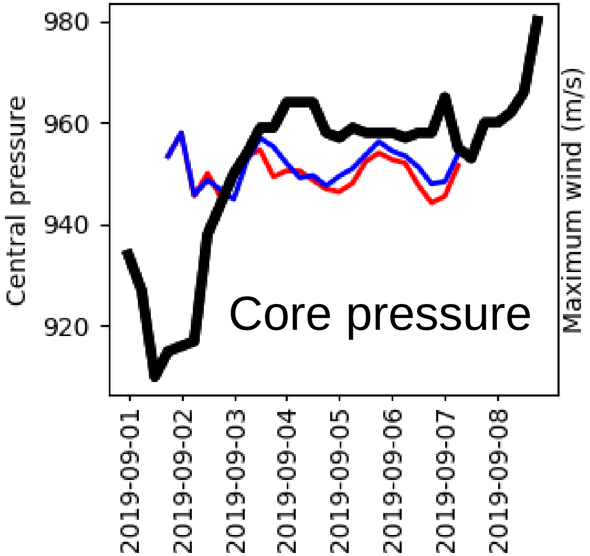
Impact during Dorian, Tco1279 forecast from 2 September 2019, 12 UTC

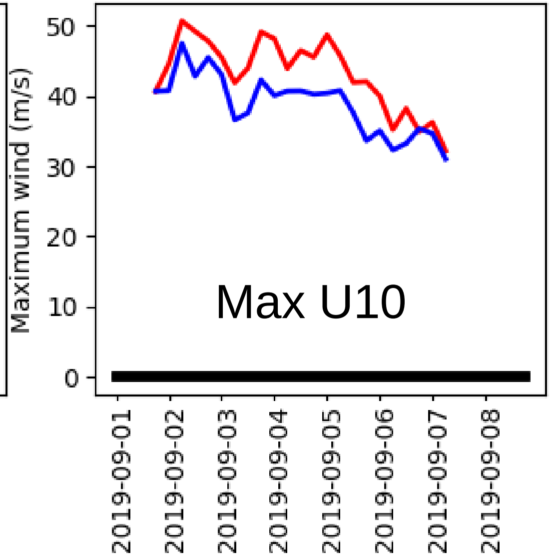


observations

CY46R1

for CY47R1

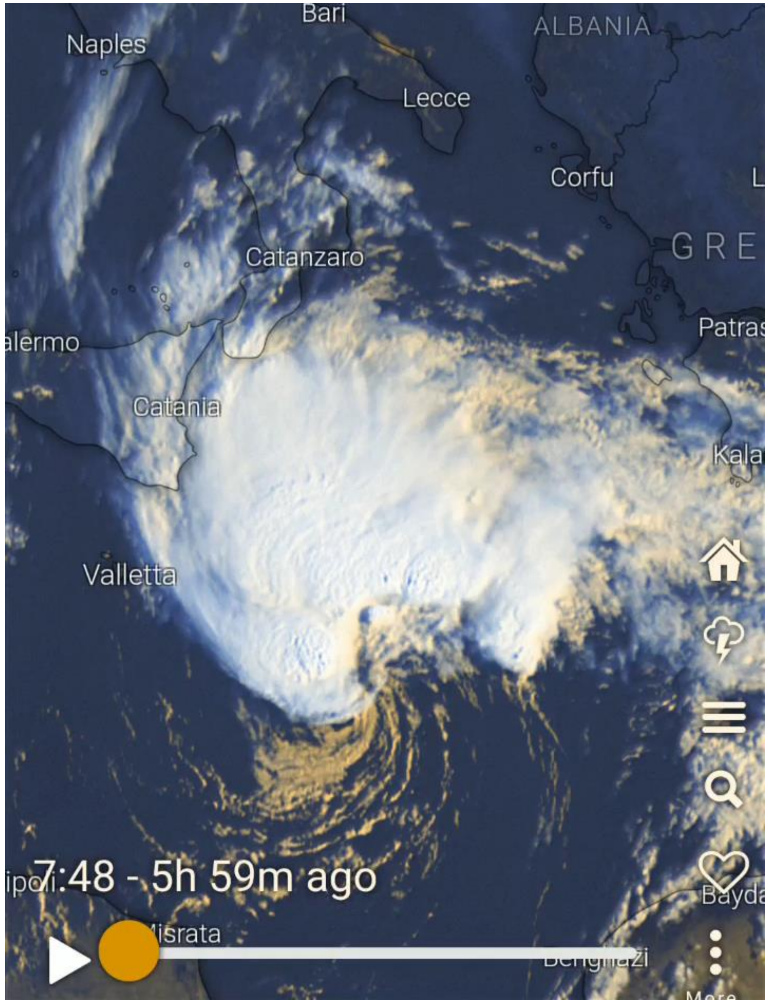


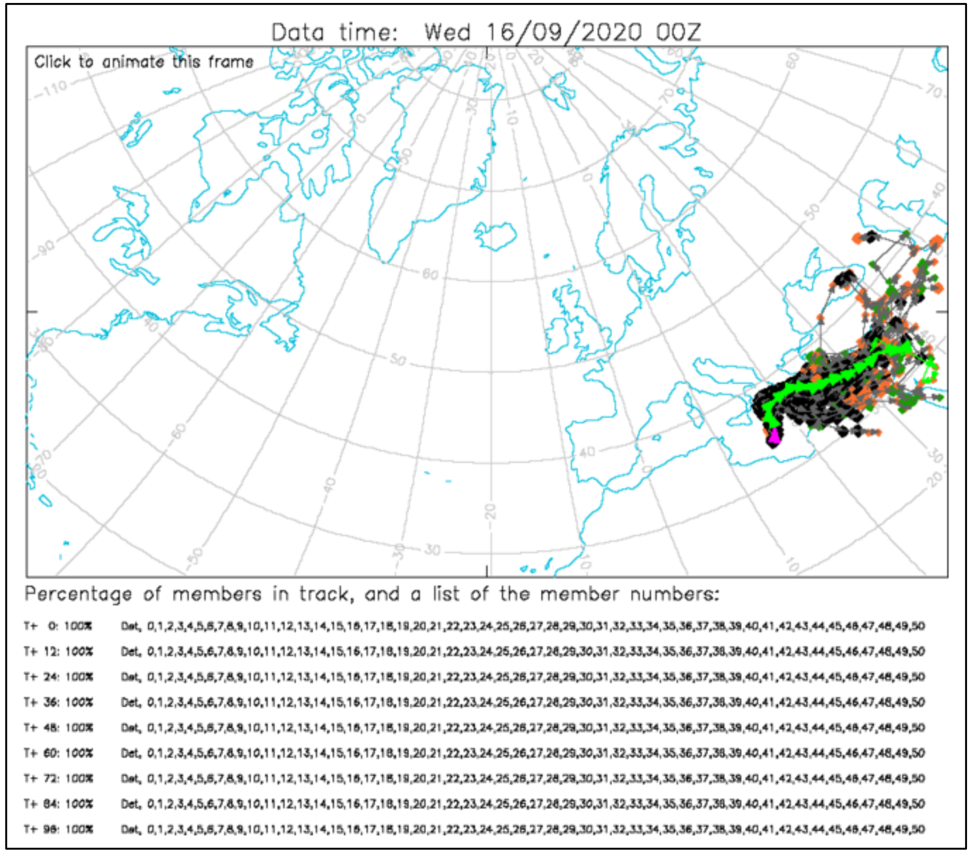


ECMWF

Ianos forecast from 20200916, 0 UTC:

- Medicane Ianos caused widespread problems in Greece (studied in the ECMWF Daily Reports & ECMWF Weather Discussions)
- Currently no dedicated products exist, as the region is not configured, and there is not a formal reporting centre (ref: WMO)
- Existing Tracking Algorithm (used for Tropical Cyclones worked well on this event. Climatologically there are about 2 events/year

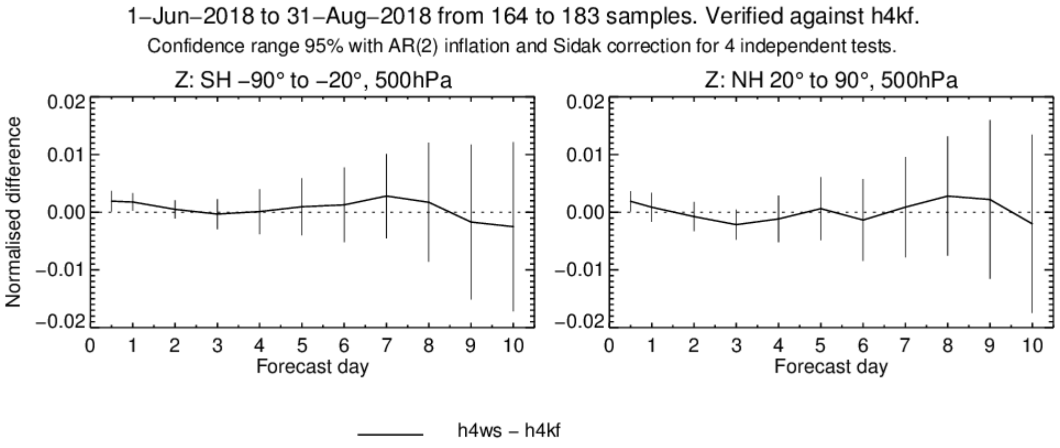


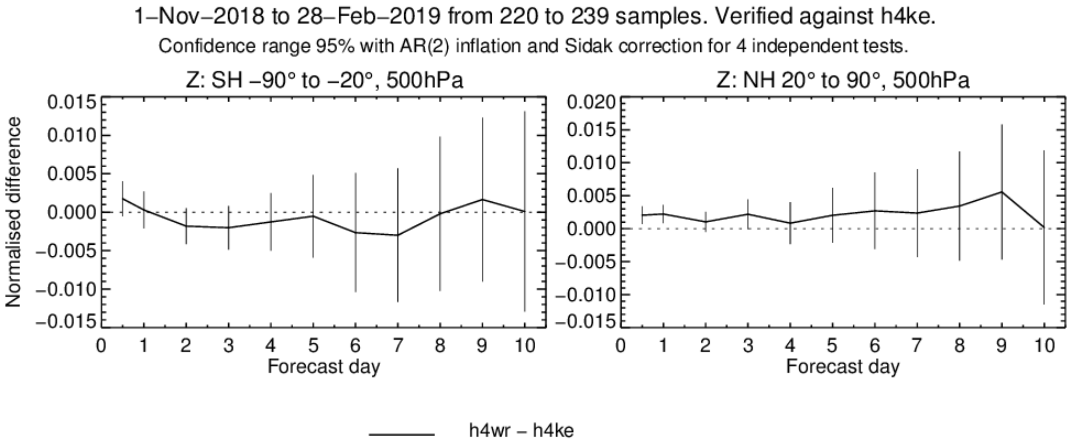


Courtesy of Tim Hewson, Frederic Vitart

CY47R2: single precision forecasts for efficiency

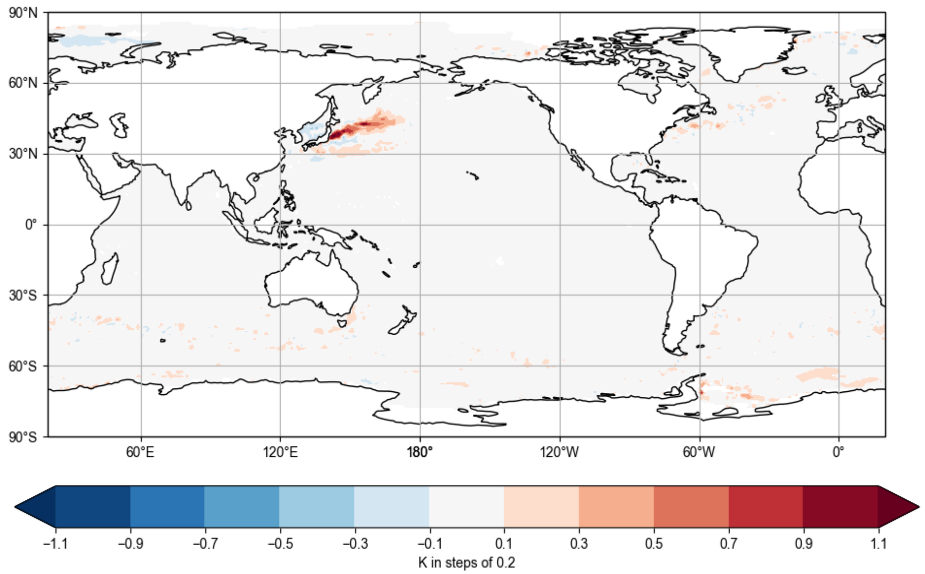
- Single precision already used for RD experimentation in CY46R1
- Results are overall neutral compared with double precision:
  - Also tested on extreme weather such as TCs: tracks and intensity unaffected
  - A small degradation near the poles at high resolution more noticeable at winter is currently investigated
- Reduces cost of atmospheric component of forecast by 40%
- We are aiming to have single-precision IFS operational in CY47R2 in 2021 Q1/Q2



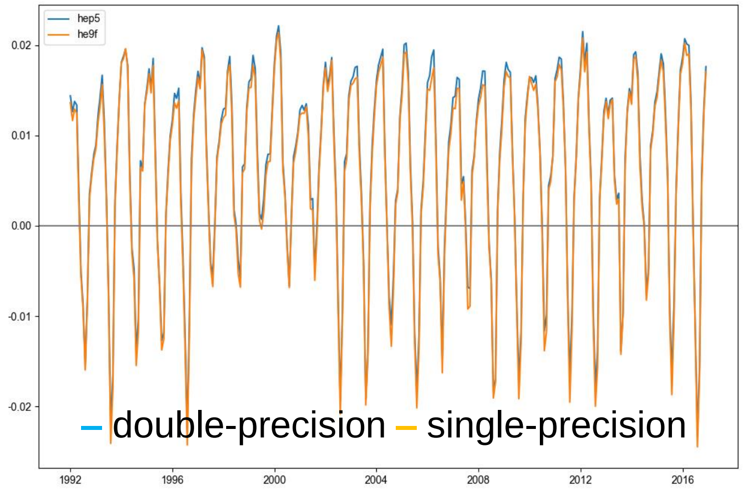


Ocean: progress towards use of single precision

Courtesy of Sam Hatfield, Michail Diamantakis



SST ΔRMSE (single – double) w.r.t. ESA CCI product



Sea-ice concentration Northern Hemisphere bias w.r.t. OSI CDR product

- 40-year single-precision high-res (¼°) NEMO+SI3 runs complete
- Mostly neutral w.r.t. double-precision but ~1K SST differences in Kuroshio
- Bugs fixed and communicated to NEMO consortium
- Speed-up between 1.2x and 1.7x depending on I/O etc.
- Next step: fully single-precision coupled atmosphere-ocean simulations

A look towards ECMWF future IFS upgrades

BOLOGNA NEW DATA CENTRE

48r1

- **Single precision** – operational implementation (HRES fc, ENS, extended-range)
- **Unified vertical resolution (ENS, extended-range to match existing HRES L137)**
- **ENS horizontal resolution increase to 9-11 km** see ENS dedicated presentation
- Daily extended-range ensembles (51 members)
- **Moist physics framework upgrade**, **multi-layer snow scheme**
- pySuite-based analysis suites

49r1

- OOPS and COPE operational implementation
- NEMO 4, SI3 New ocean and Sea-ice models
- Multi-layer surface variables / multi-layer soil/ice scheme / Upgraded Surface Mapping (See the ECMWF Surface dedicated presentation)

A decade of accelerated performance & improvements is ahead!

3-hourly accumulated radiative fluxes at the top of the atmosphere

1.4 km | 9 km | 9 km w/o deep

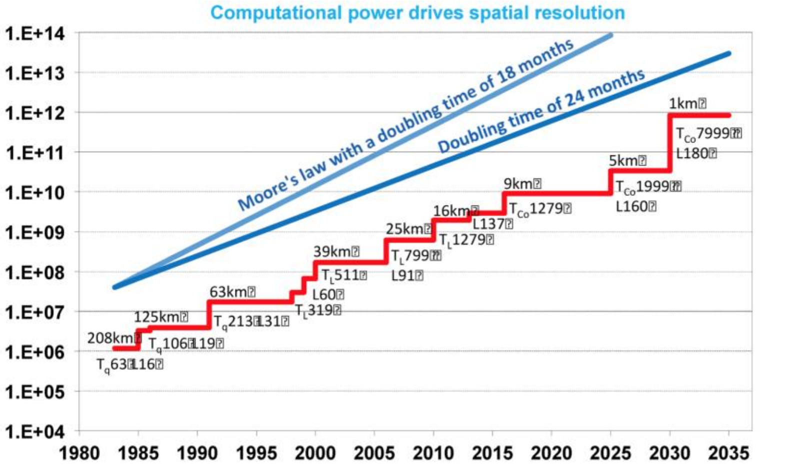


Figure 2. "Understanding grows only logarithmically with the number of floating point operations." (John P. Boyd). The progress in the degrees of freedom (vertical levels × grid columns × prognostic variables) of the ECMWF

A baseline for global weather and climate simulations at 1 km resolution

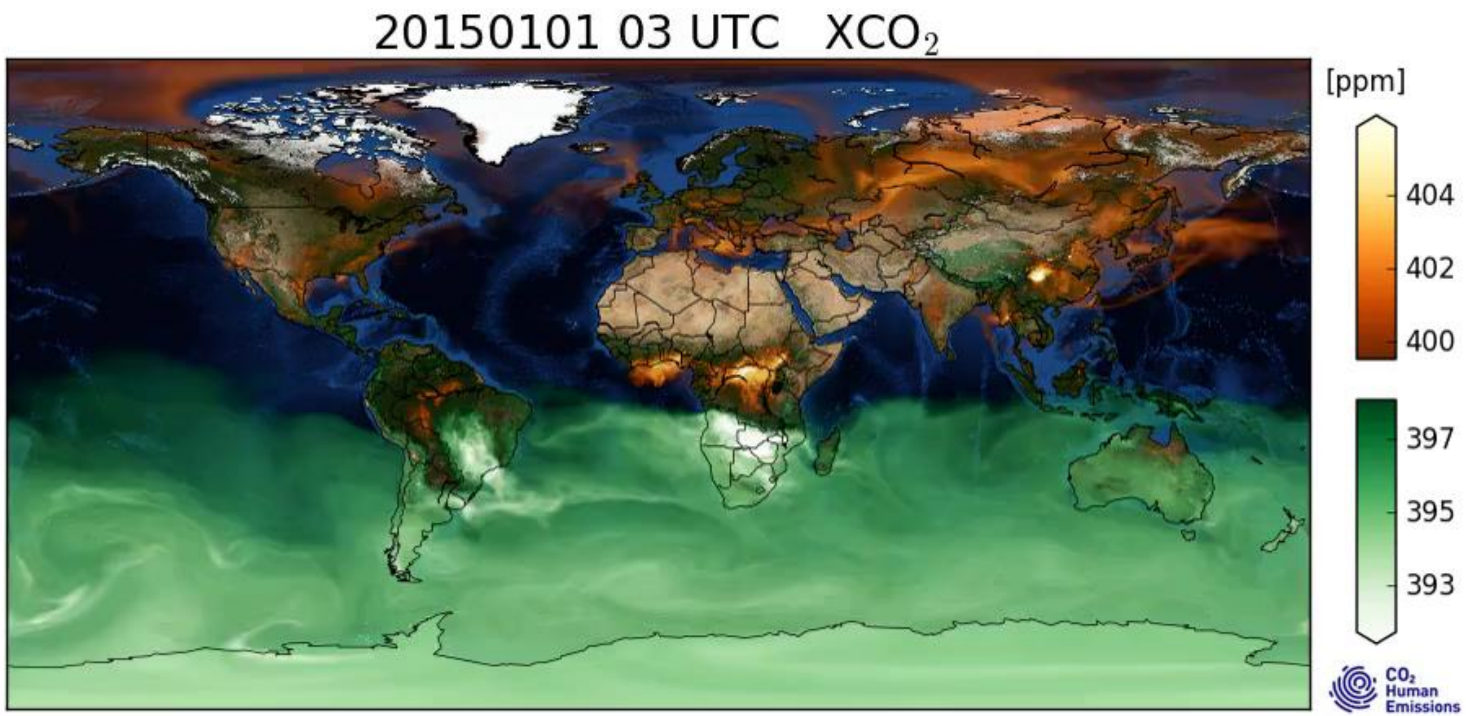
powered by advanced HPC (towards exascale)

Nils P. Wedi[1], Inna Polichtchouk[1], Peter Dueben[1], Valentine G. Anantharaj[2], Peter Bauer[1], Souhail Boussetta[1], Philip Browne[1], Willem Deconinck[1], Wayne Gaudin[3], Ioan Hadade[1], Sam Hatfield[1], Olivier Iffrig[1], Philippe Lopez[1], Pedro Maciel[1], Andreas Mueller[1], Sami Saarinen[1], Irina Sandu[1], Tiago Quintino[1], Frederic Vitart[1] *(JAMES, 2020, accepted)*

Courtesy of Nils Wedi, opening keynote at the ECMWF Annual Seminar 2020

See All AS2020 presentations online at
https://events.ecmwf.int/event/167/overview

Monitoring CO_2 at km-scale with IFS (CHE/CAMS)



User requirements from:

- EUMETSAT (S-4/-5)
- MicroCarb
- flight campaigns
- boundary conditions

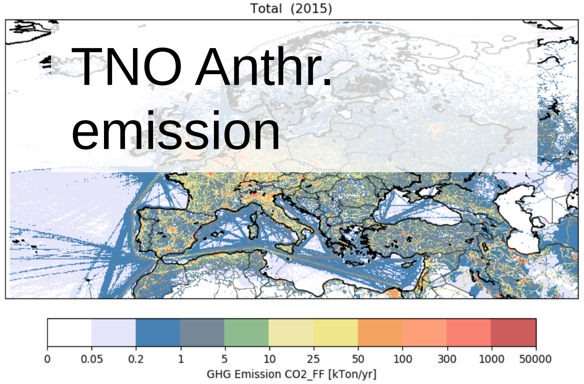
CO_2, CH_4, and linear CO at Tco1279 (~9km) L137 in ECMWF IFS

- CTESSEL NEE (+bias correction)
- EDGAR+CAMS81 anthropogenic emissions
- SOCAT Carbo-Scope, CMEMS ocean fluxes
- GFAS biomass burning
- IFS transport (Bermejo & Conde mass fixer)

Developments are aligned with ECMWF's Earth system modelling strategy (e.g., strengthen IFS land surface modelling).

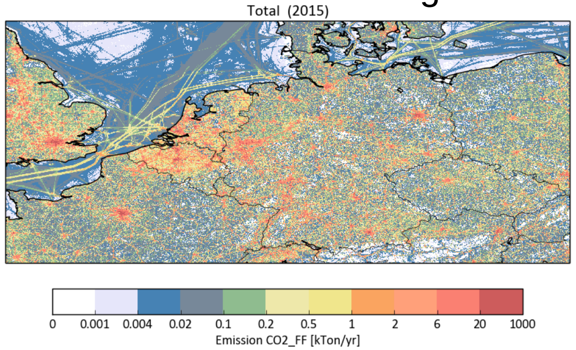
Thanks to Anna Agusti-Panareda ECMWF, CAMS and CHE Project Team

Involving Regional/Local-scales: benefit of NWP experience



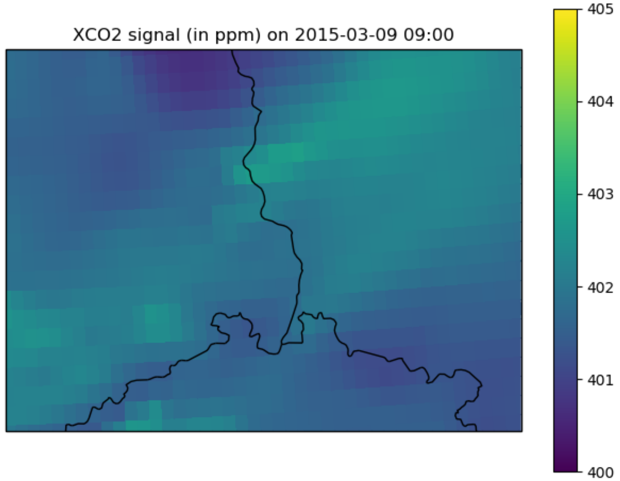
5x5 km emission over Europe

1x1 km emission on a Target Domain

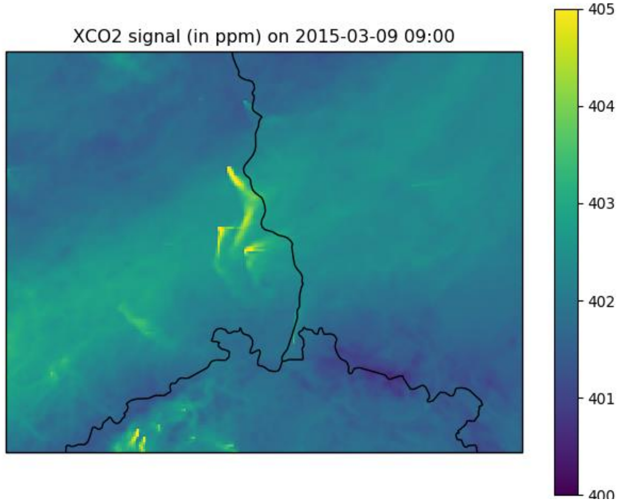


https://doi.org/10.5194/acp-2019-696

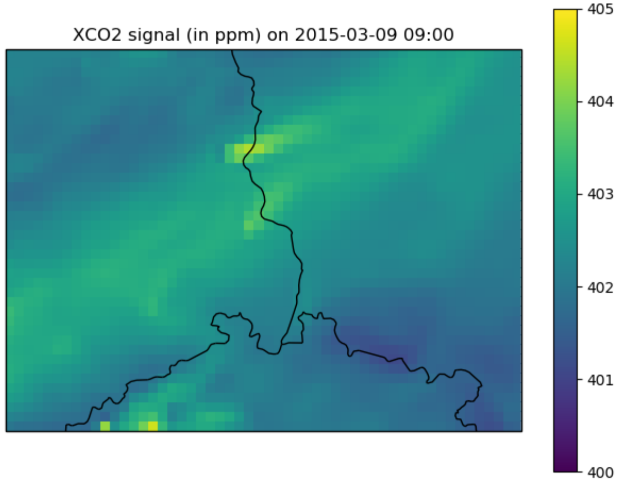
Tier-1 (CAMS), 9km, EDGAR emissions

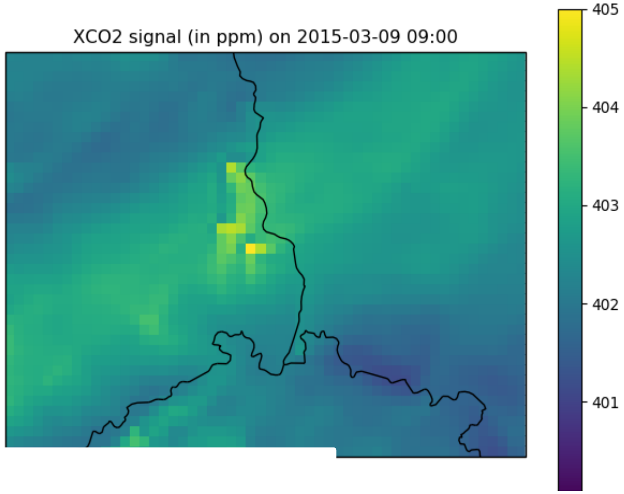


COSMO 1km, TNO emissions



Point sources will need km-scale!





COSMO 5km, EDGAR emissions

COSMO 5km, TNO emissions

Thanks to Ingrid Super, Hugo Denier van der Gon, TNO

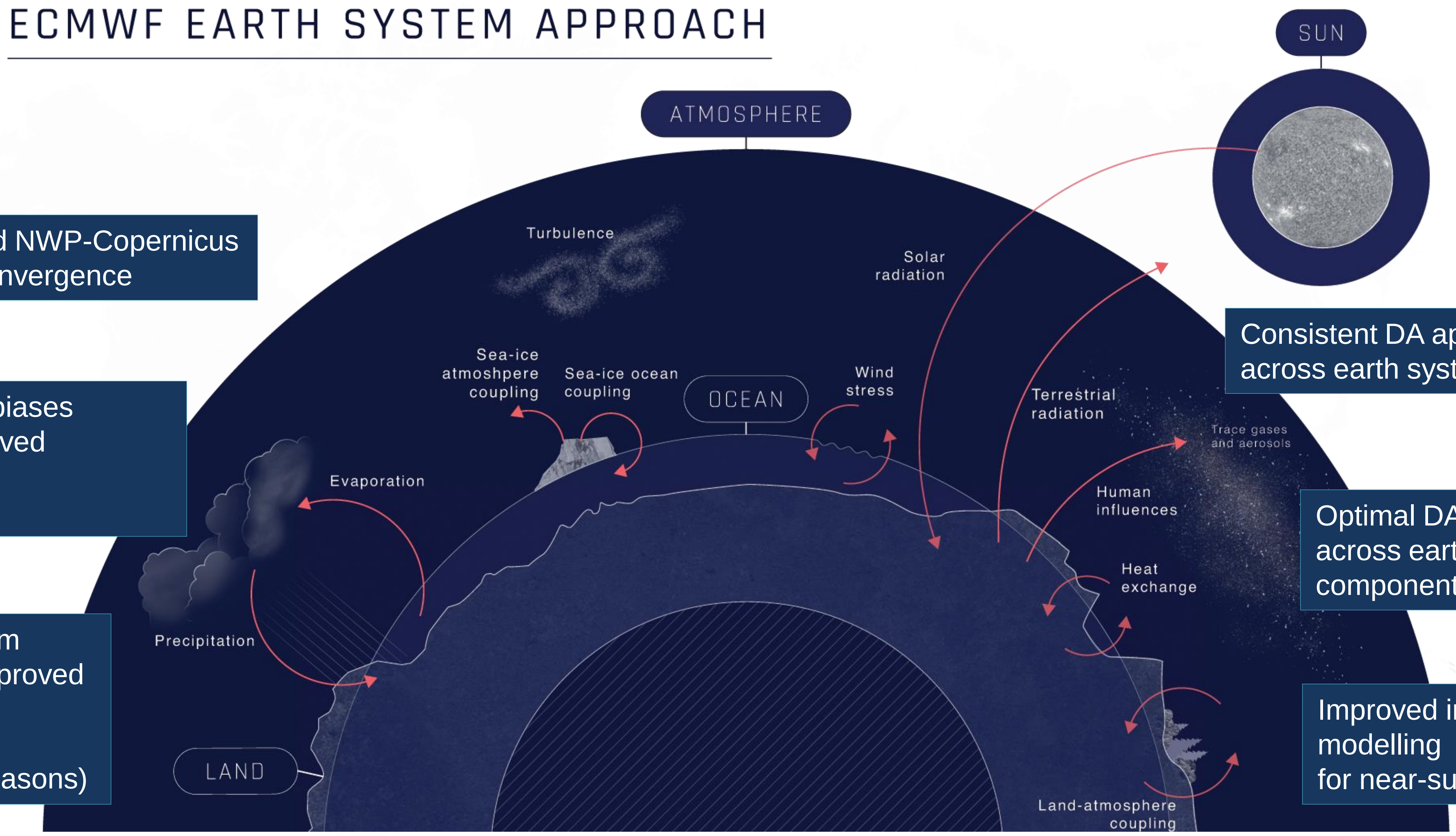
Thanks to Jean-Matthieu Haussaire, Dominik Brunner, EMPA

Earth System Science: moving forward

Further enhanced NWP-Copernicus synergies and convergence

Reduced model biases resulting in improved predictions on all timescales

Extra earth system complexity for improved meteorological predictions
(e.g. transition seasons)



Consistent DA approaches across earth system components

Optimal DA coupling across earth system components

Improved interface modelling
for near-surface weather