ECMWF research goals by 2025:

- **Ensemble-based analyses and predictions** that raise the international bar for quality and operational reliability reaching a 5 km horizontal resolution

Together - More collaboration:

- Partnering with universities and research institutes – OpenIFS
- Pooling expertise to improve **scalability**

ECMWF EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS

Colleagues & Peter Bechtold

ECMWF 2016-2025 strategy: overview

Research goals by 2025:

- **Ensemble-based analyses and predictions** that raise the international bar for quality and operational reliability reaching a 5 km horizontal resolution

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Horizontal resolution upgrade (March 2016 – CY41R2)

Grid res.	HRES	ENS LegA	ENS LegB/M'ly	4DV inner loops 1st	4DV inner loops 2nd	4DV inner loops 3rd	EDA Outer	EDA 1st	EDA 2nd
								TL159 ↓	TL159 ↓
128 km				TL255	TL255 ↓	TL255 ↓		TL191	TL191
64 km	41r1 ↓		TL319 ↓		TL319	TL399	TL399 ↓		
32 km	41r2	TL639 ↓	TCo319						
16 km	TL1279 ↓	TCo639 (D10 → D15)					TCo639		
9 km	TCo1279								

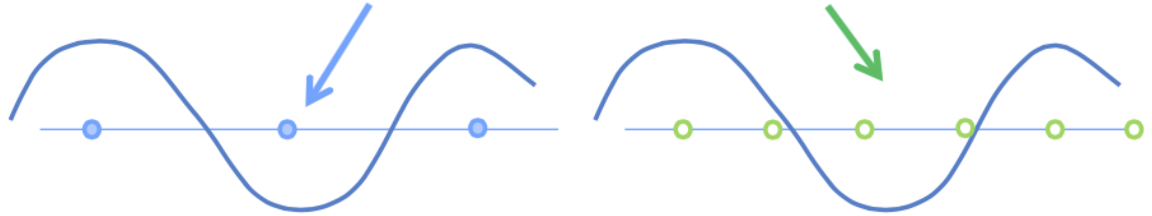
Holm et al., ECMWF Newsletter 147

Resolution upgrade: cubic octahedral reduced Gaussian grid

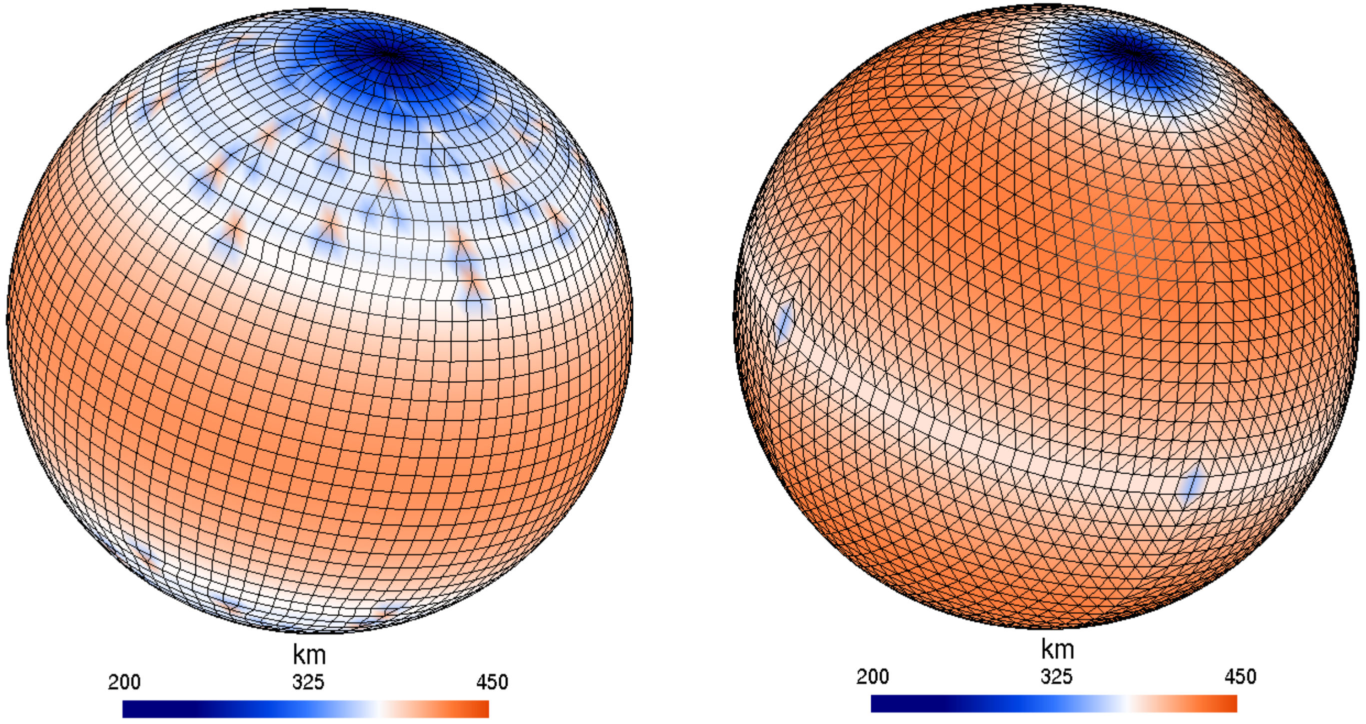
2N+1 gridpoints to N waves : T_L linear grid
4N+1 gridpoints to N waves : T_c cubic grid

- Mathematically more correct in the presence of cubic non-linearities in the equations
- Less numerical filtering – almost no numerical diffusion, no dealiasing
- Better mass conservation
- Less expensive than the equivalent linear grid

Where T_L refers to linear grid and T_C to cubic grid, respectively



N24 Reduced Gaussian | O24 Octahedral reduced Gaussian

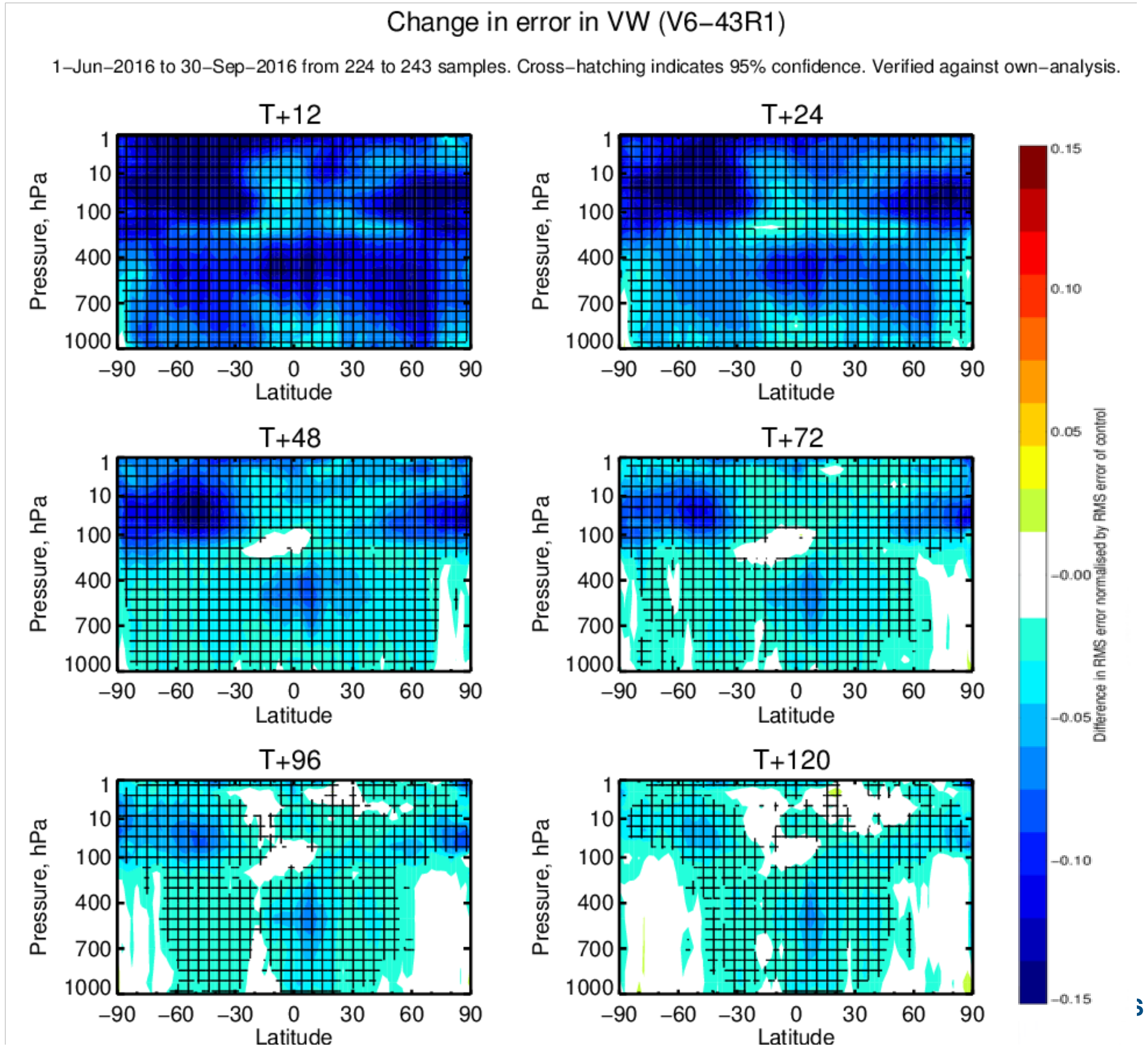


Malardel et al., ECMWF Newsletter 146

Outline

1. Recent IFS upgrades
    a. 11 July 2017 (CY43R3) - improved humidity analysis
    b. June 2018 (CY45R1) - Ocean coupling to the HRES forecast
2. CY46R1 and beyond….

Humidity Background Error Variances from EDA



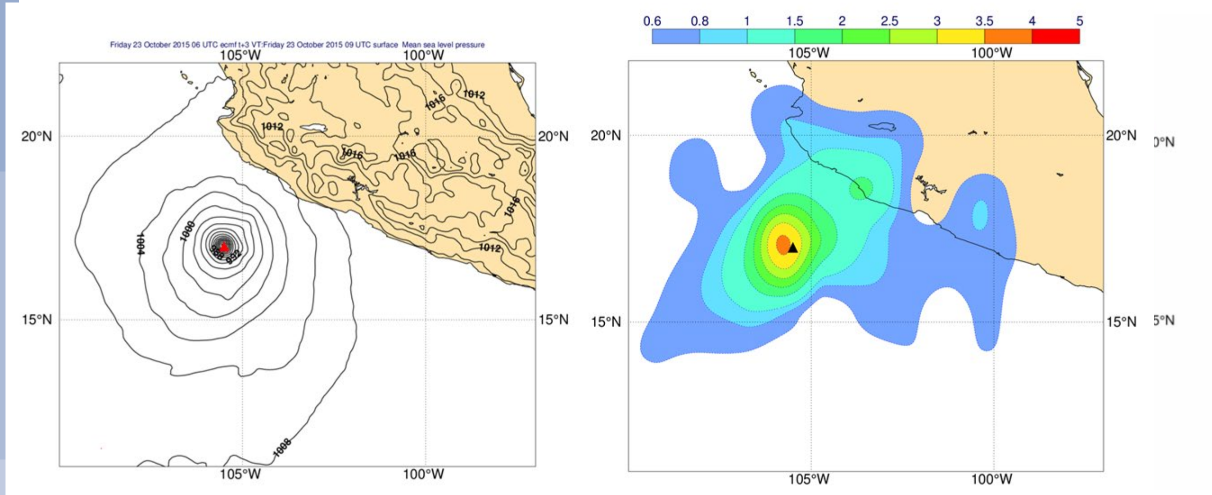
- Use background error variances from EDA instead of current errors which is a regression model of errors as a function of background RH and model level. Now consistent with other variables. This improves forecast fit to humidity-sensitive observations and reduces wind vector forecast errors
- New climatological B matrix from almost a year of latest 43R1 EDA samples. This improves in particular forecast fit to stratospheric AMSU-A channels

Normalized difference in RMS forecast wind errors 43R3 vs 43R1 20160601-20160930

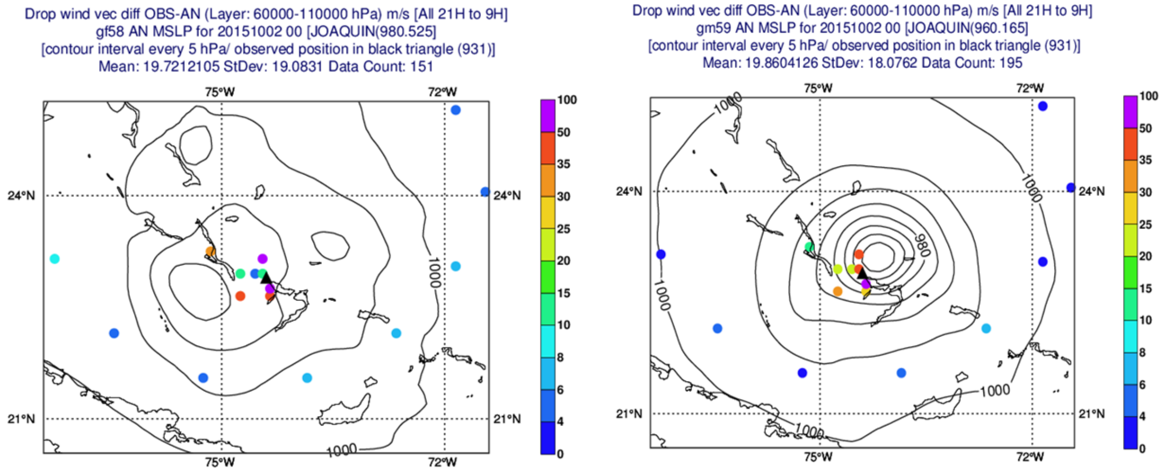
Better handling of Tropical Cyclones

- From CY41R1 issues with analyses of tropical cyclons: a) unrealistic small scale noise in bg forecasts and EDA error estimates, b) inadequate QC and obs errors for dropsonde wind observations
- Solutions implemented in CY43R3: a) revised wavelet space filtering of EDA error estimates, b) Adaptive QC and obs. errors for dropsondes

Hurricane Patricia
Left: Analysed MSLP *2015-10-23, 12 UTC*
Right: EDA MSLP errors (CY43R3)



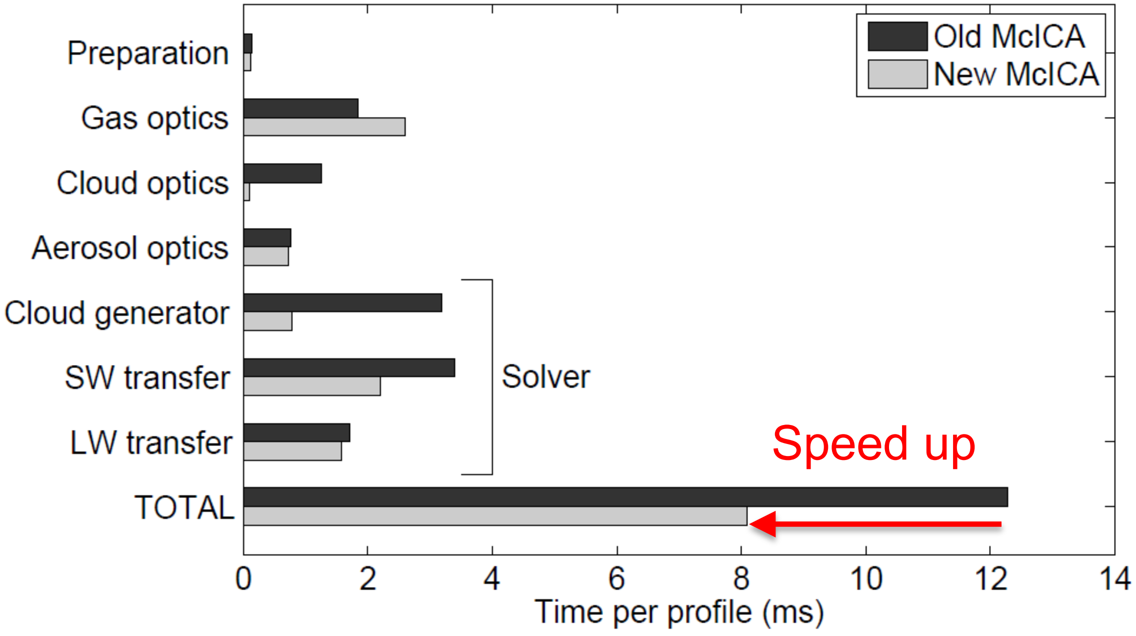
TC Joaquin
Left: Analysed MSLP *2015-10-02, 00 UTC* (CY41R2)
Right: Analysed MSLP *2015-10-02, 00 UTC* (CY43R3)

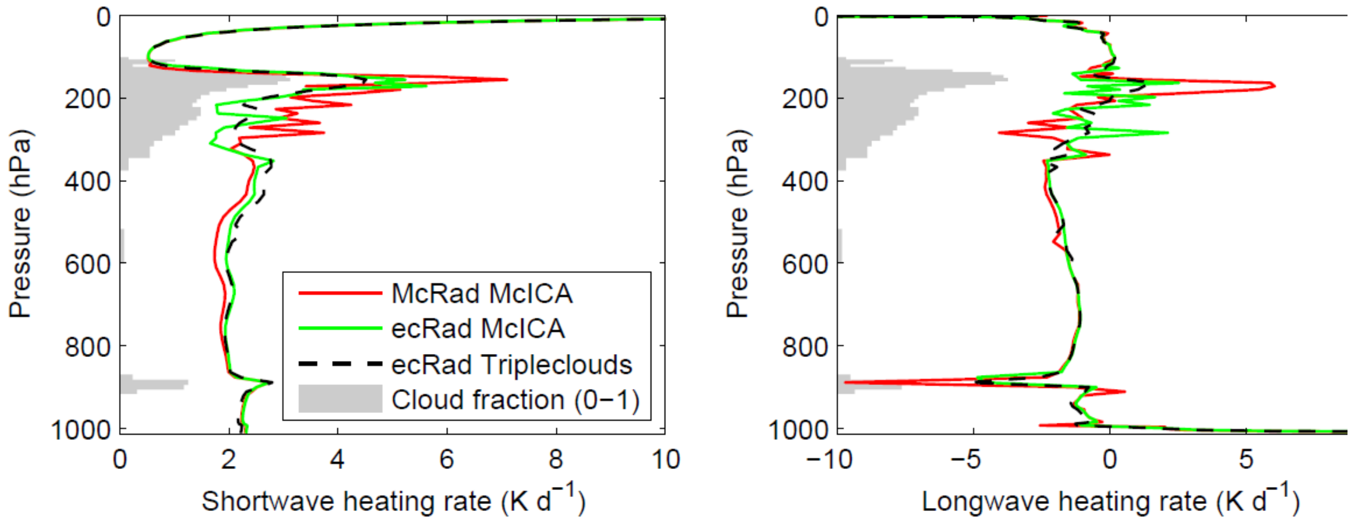


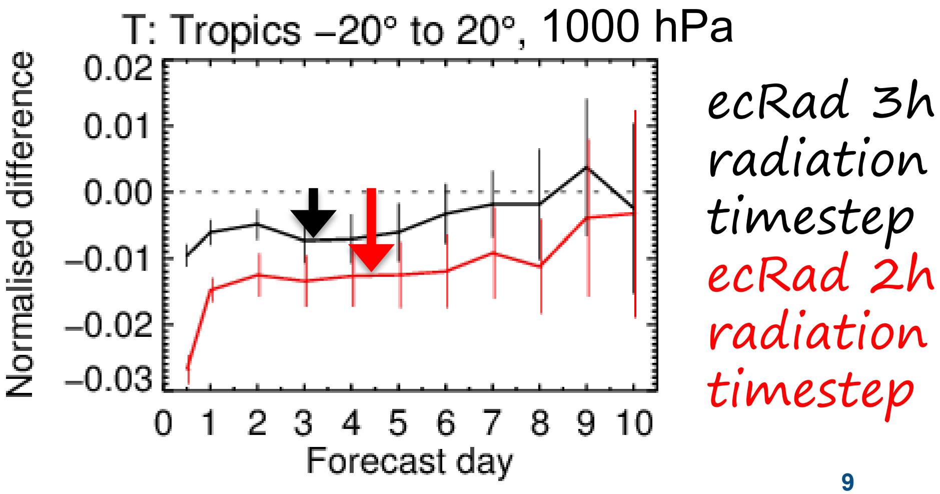
More details in *Bonavita et al, TM 810, 2017*

New radiation scheme (ecRad)

- Immediate benefits
  - Better solution to longwave equations improves stratosphere biases (see later)
  - 31-34% faster, far smaller memory footprint
  - Lower noise: slight reduction in temperature errors
- Longer term benefits
  - Flexibility and modularity: facilitate future developments
  - Option to use new "SPARTACUS" solver for representing 3D radiative effects
  - Feedback from users of public version (e.g. ecRad in Meso-NH)



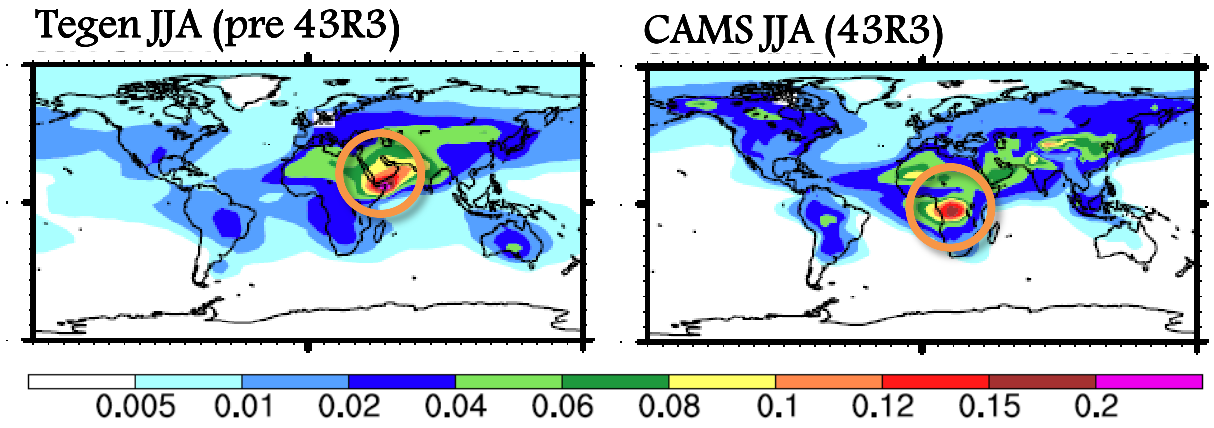




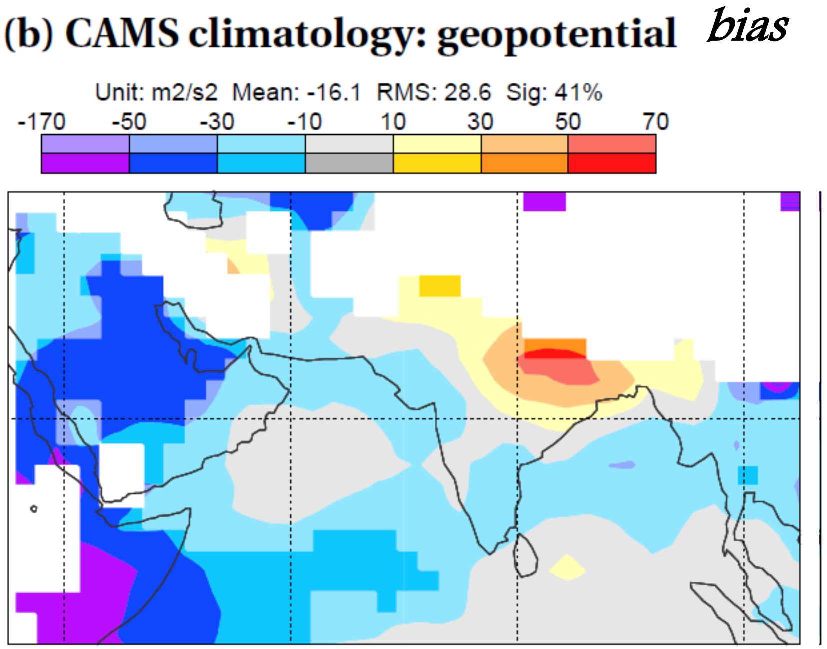
Hogan and Bozzo, TM787, 2017

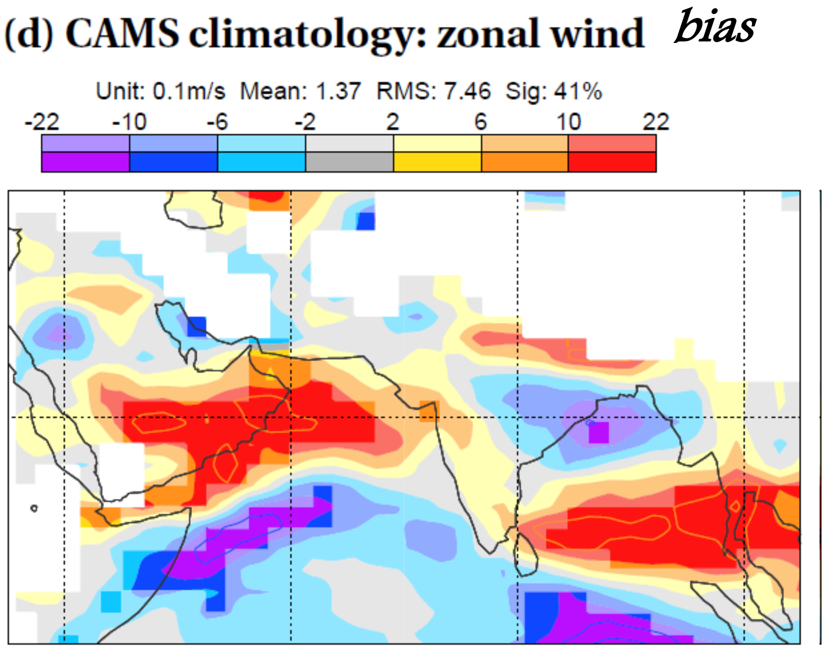
Aerosols

- Atmospheric forcing depends on *absorption* optical depth:



- Reduced absorption over Arabia in new CAMS climatology weakens the overactive Indian Summer Monsoon, halving the overestimate in monsoon rainfall
- Increased absorption over Africa degraded 850-hPa temperature, traced to excessive biomass burning in CAMS
- *We can measure the impact of aerosols on the tropical atmosphere more easily than the absorption optical depth itself! Use to provide information on aerosol errors?*





Bozzo et al, TM 801, 2017

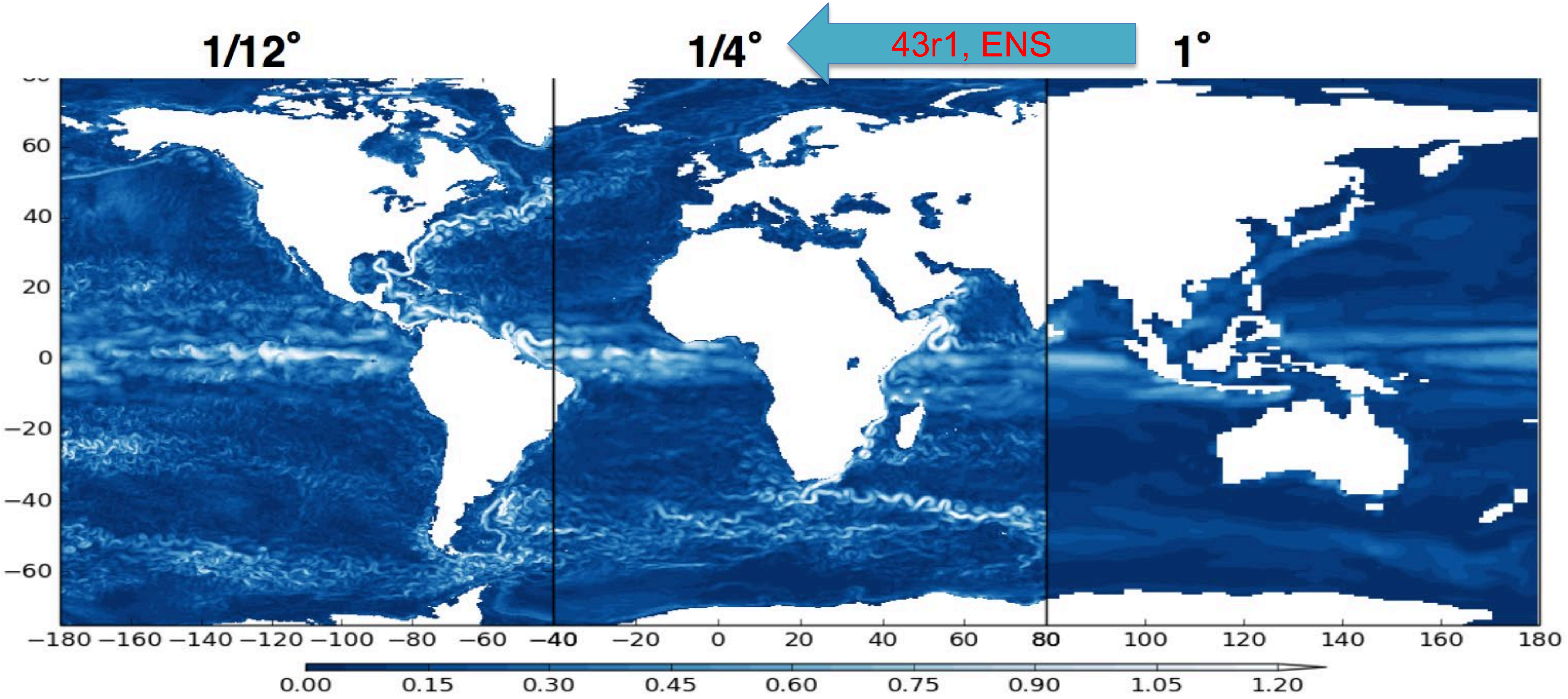
Outline

1. Highlights of recent and forthcoming IFS upgrades
   a. 11 July 2017 (CY43R3) - improved humidity analysis
   b. June 2018 (CY45R1) - Ocean coupling to the HRES forecast
2. On-going R&D activities and challenges (CY46R1 and beyond….)

Cycle 45r1 content: highlights

1. An increased number of observations is assimilated (Infrared data over land, all-sky microwave over coastlines)
2. **Ocean and sea-ice models coupled in HRES forecast** (now consistent with ENS/SEAS5 setup)
3. **Radiosondes drift** and improved aircraft obs bias correction
4. Atmospheric model changes (**warm-rain**, convection)
5. The **model uncertainty** SPPT scheme simulation becomes more ‘physical’, and the SKEB deactivation brings 2.5% cost savings
6. Changes to SPPT makes the **EDA more reliable** and consistent with ENS setup
7. A new product, **lightning and probability of lightning**, can be generated
8. Operational production is expected to be faster (~ 15%)
9. Impact on scores: positive over the tropics, neutral over extra-tropics

Atmosphere-Ocean coupling: Ocean surface currents at various resolutions



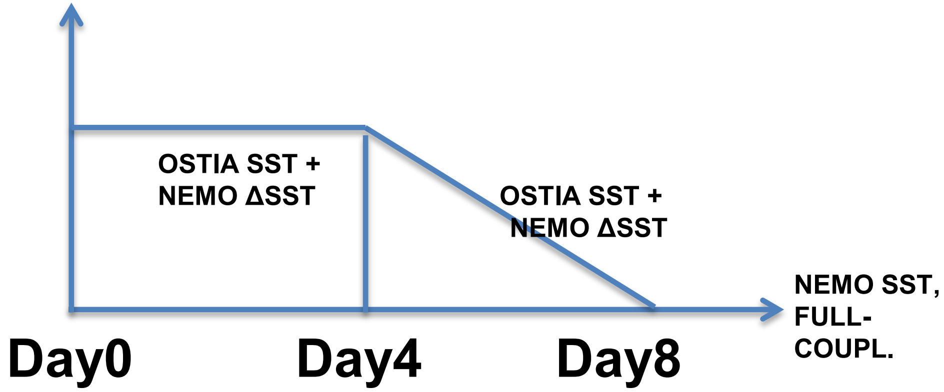
Eddy resolving | Eddy permitting | Eddy parameterising

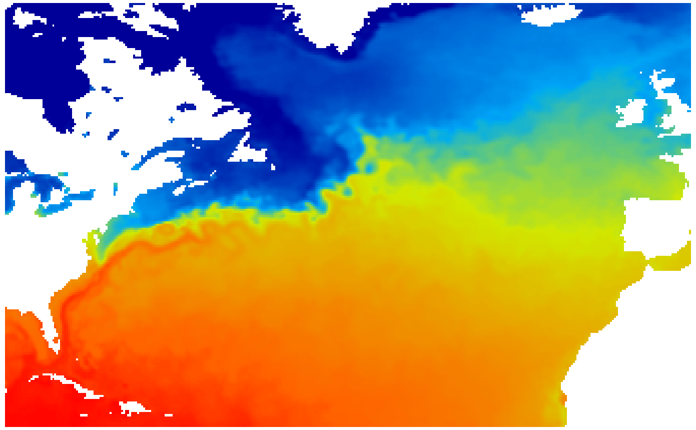
Ocean-Atmosphere coupling

Coupled ocean-atmosphere forecasts are exposed to the problem of initial shock as the atmosphere and the rest of earth surface is not yet in balance with the ocean.

PARTIAL COUPLING:

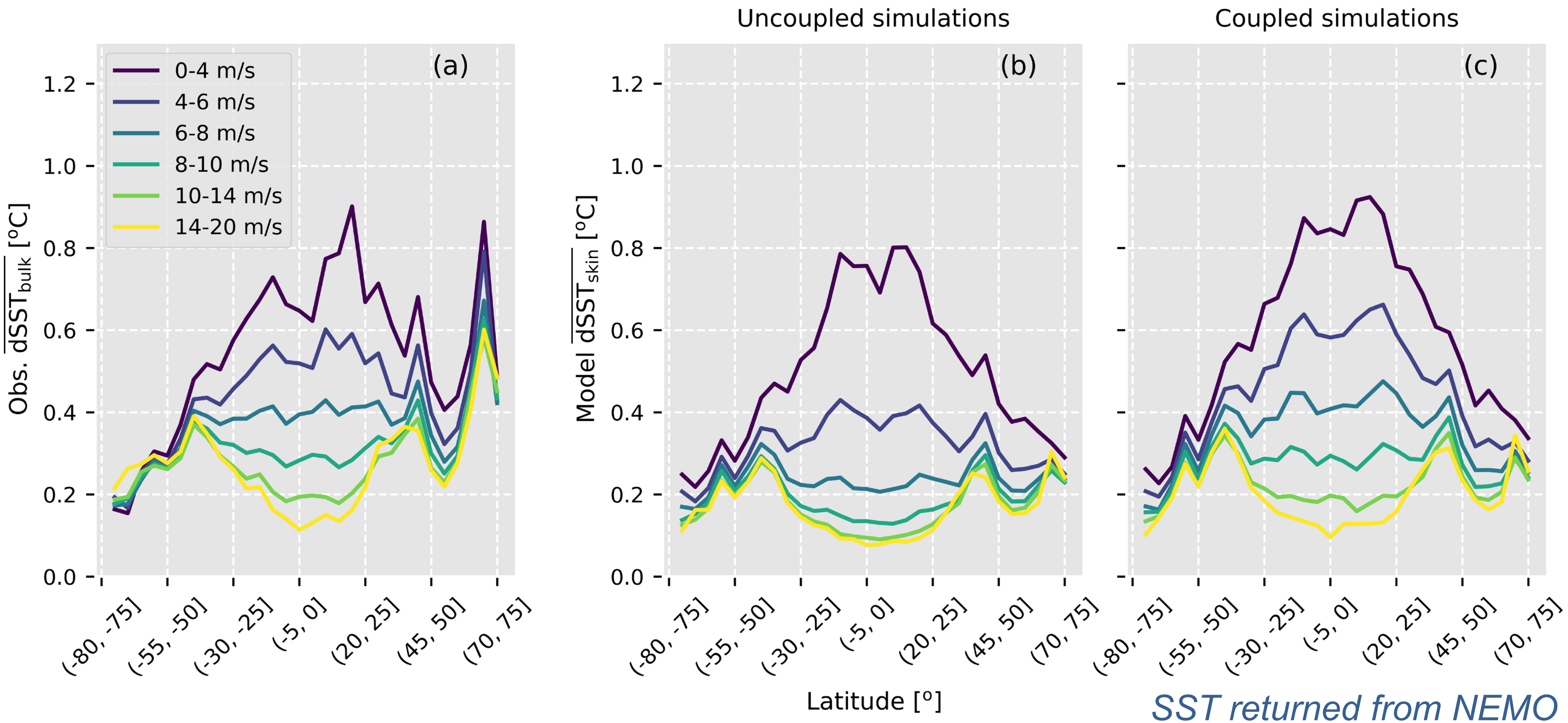
The change of SST from the Ocean NRT analysis (OCEAN5) is added to the initial OSTIA SST 1/20 degree for 4-days and then relaxed to 0 gradually from day 4 to day 8. After day 8 full coupling





OSTIA 1/20 deg (5km) SST field has details of the eddies not resolved by ocean models (at 0.25 degrees)

Diurnal cycle of SST for different wind regimes



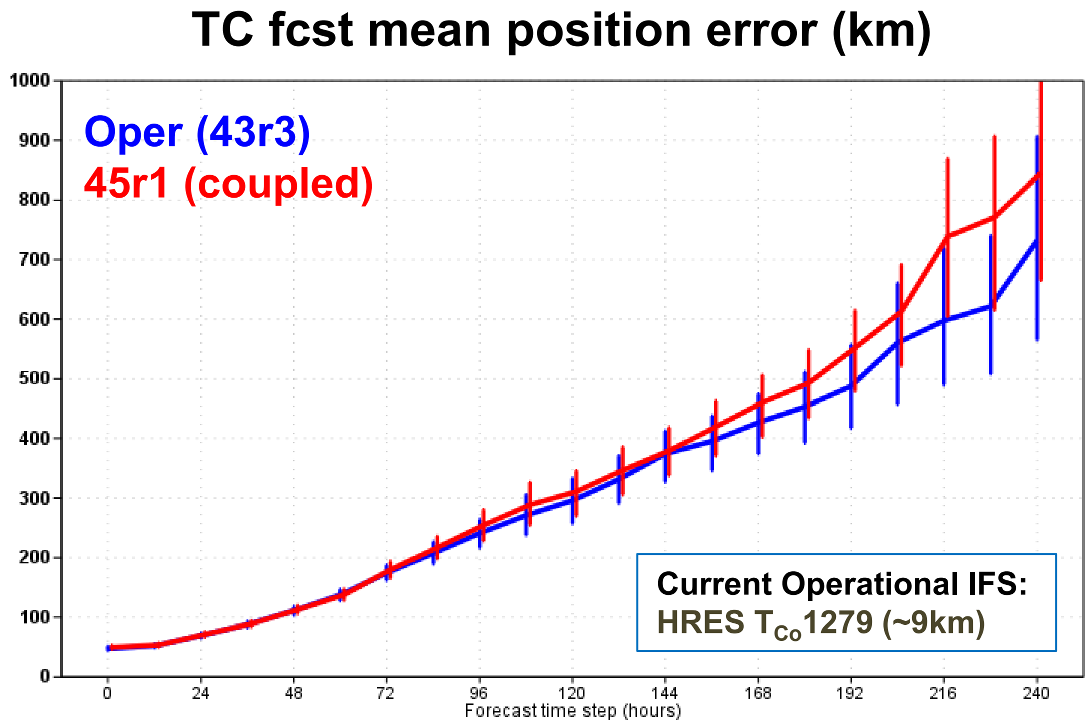
Progn equation for SST
(Zeng and Beljaars, 2005)

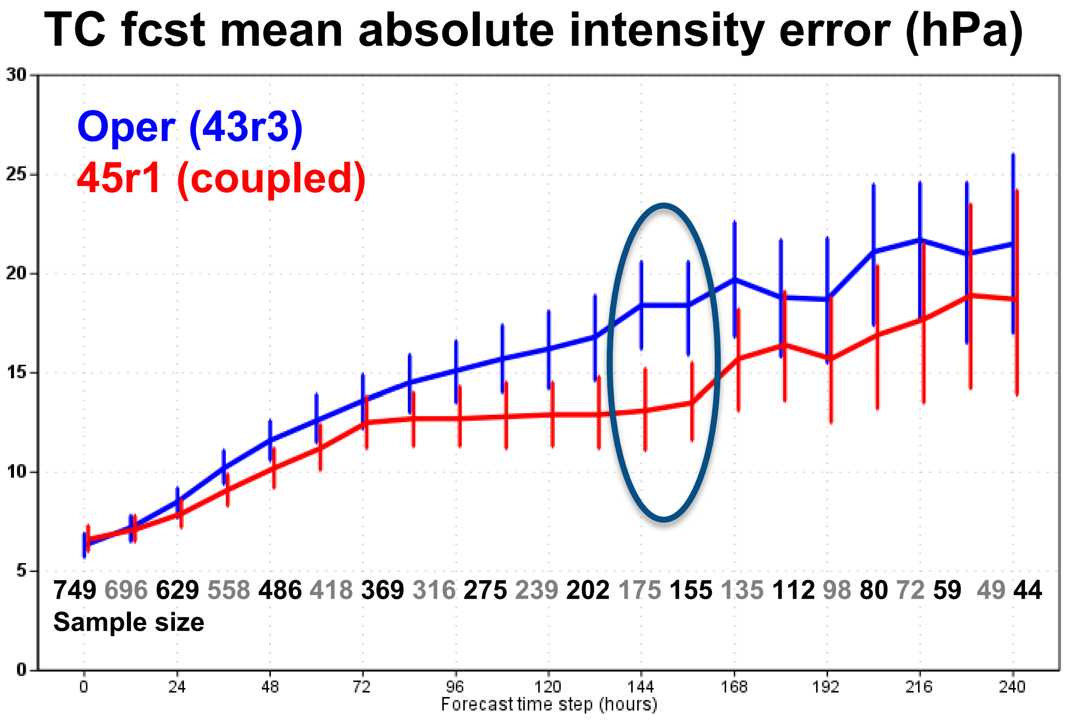
SST returned from NEMO
1m top layer
(Salisbury et al, TechMemo 826)

ECMWF

45r1 HRES TC forecasts improvements

Results indicate small differences in TC forecasts, with a small statistically-significant improvement in the intensity error in the medium-range. Earlier experiments indicated that this can be linked to the introduction in the HRES of the ocean coupling.

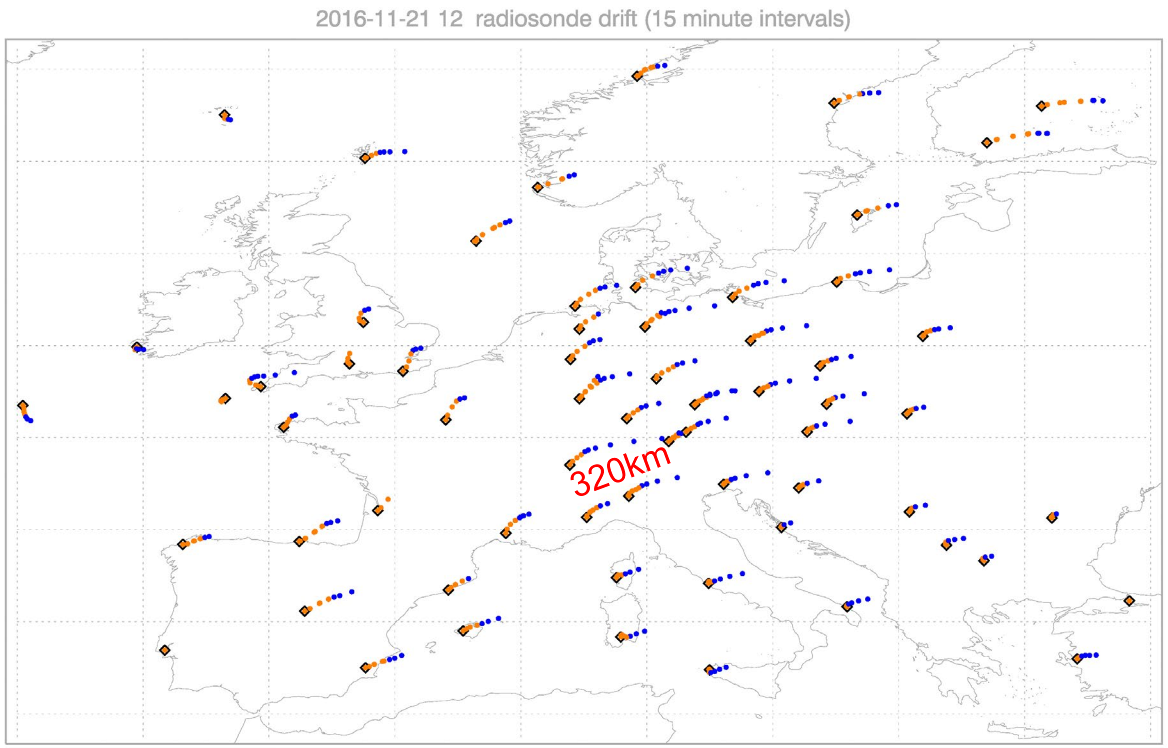




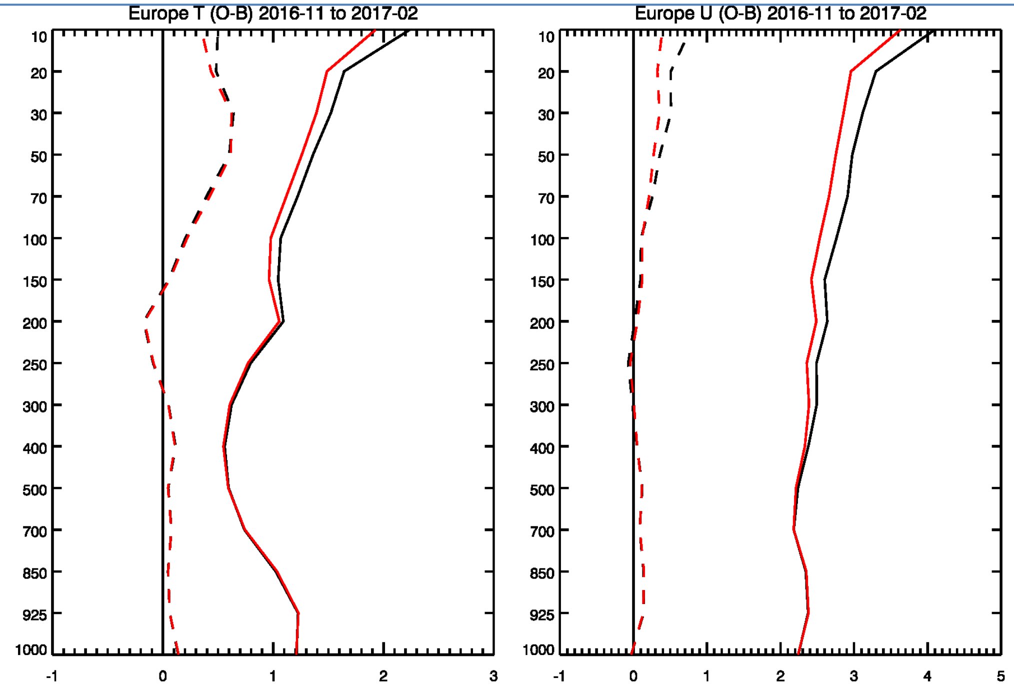
ECMWF

In 45r1 the radio-sondes' drift is taken into account

For radiosondes reporting their position at each level in **This enables more accurate computation of innovations**



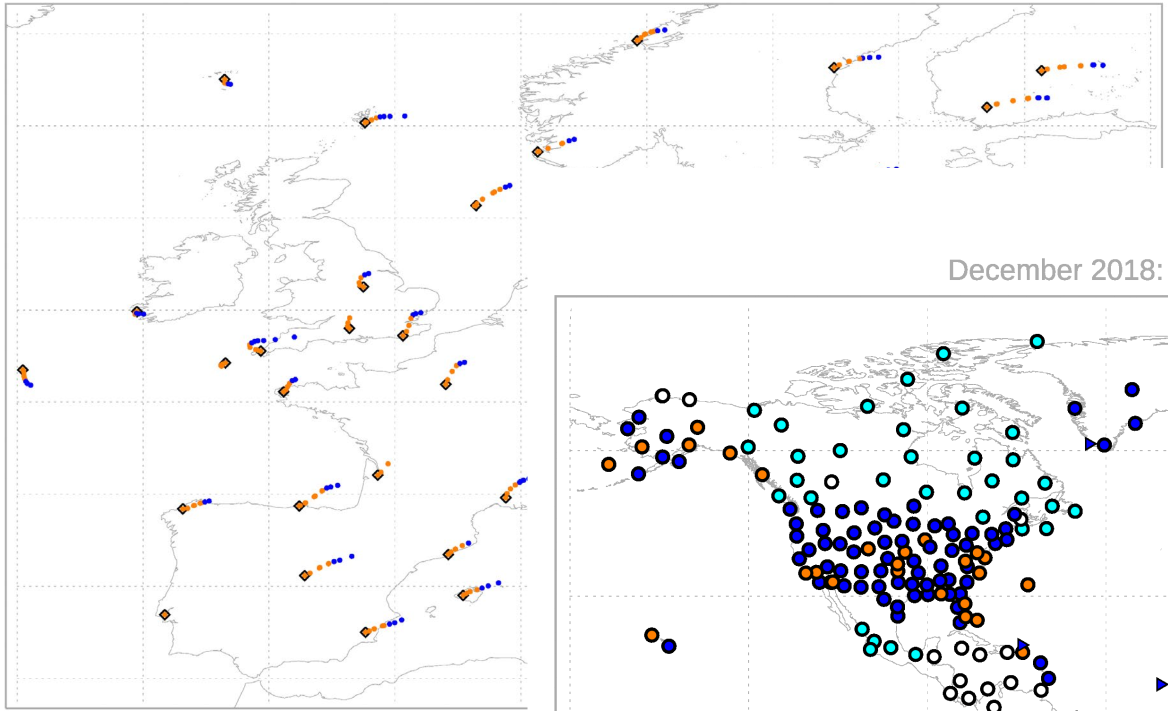
RAOB O-B departures, Europe, Nov. 2016 – Feb. 2017



In 45r1 the radio-sondes' drift is taken into account

For radiosondes reporting their position at each level in **This enables more accurate computation of innovations**

2016-11-21 12 radiosonde drift (15 minute intervals)



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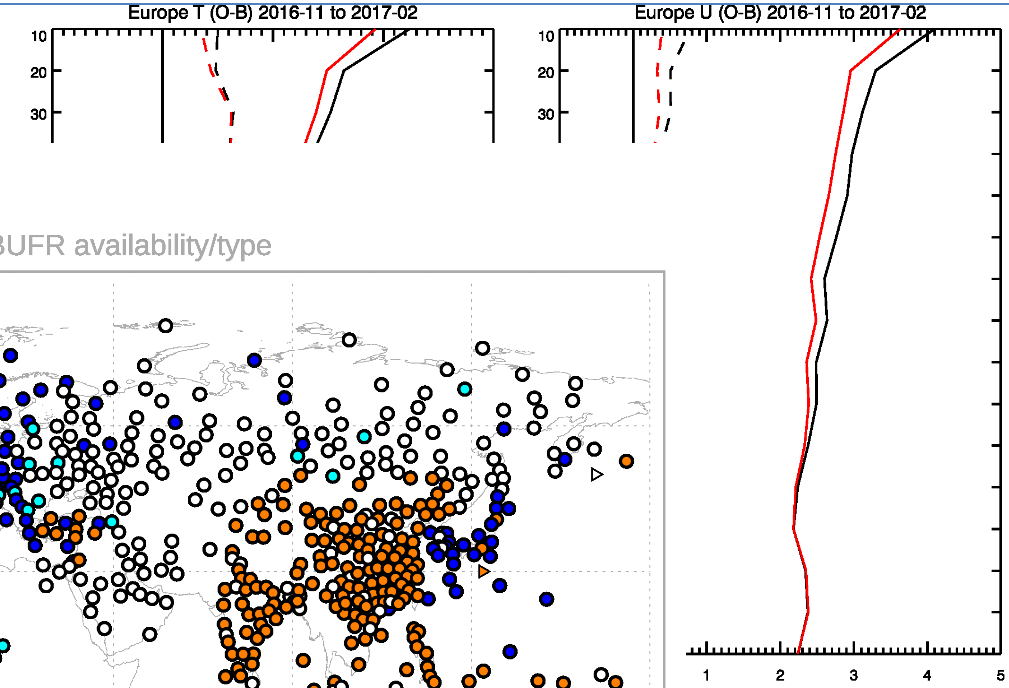
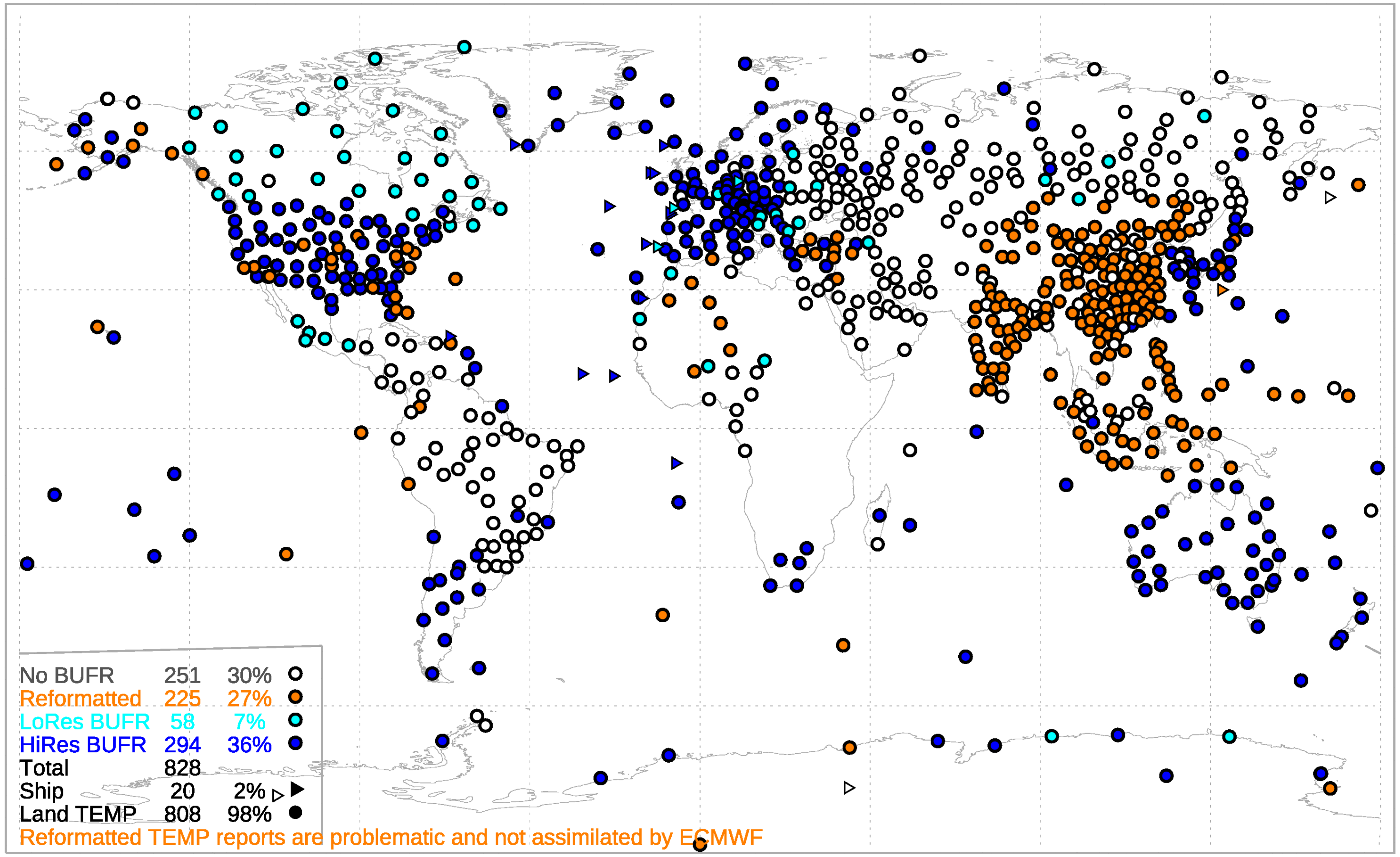


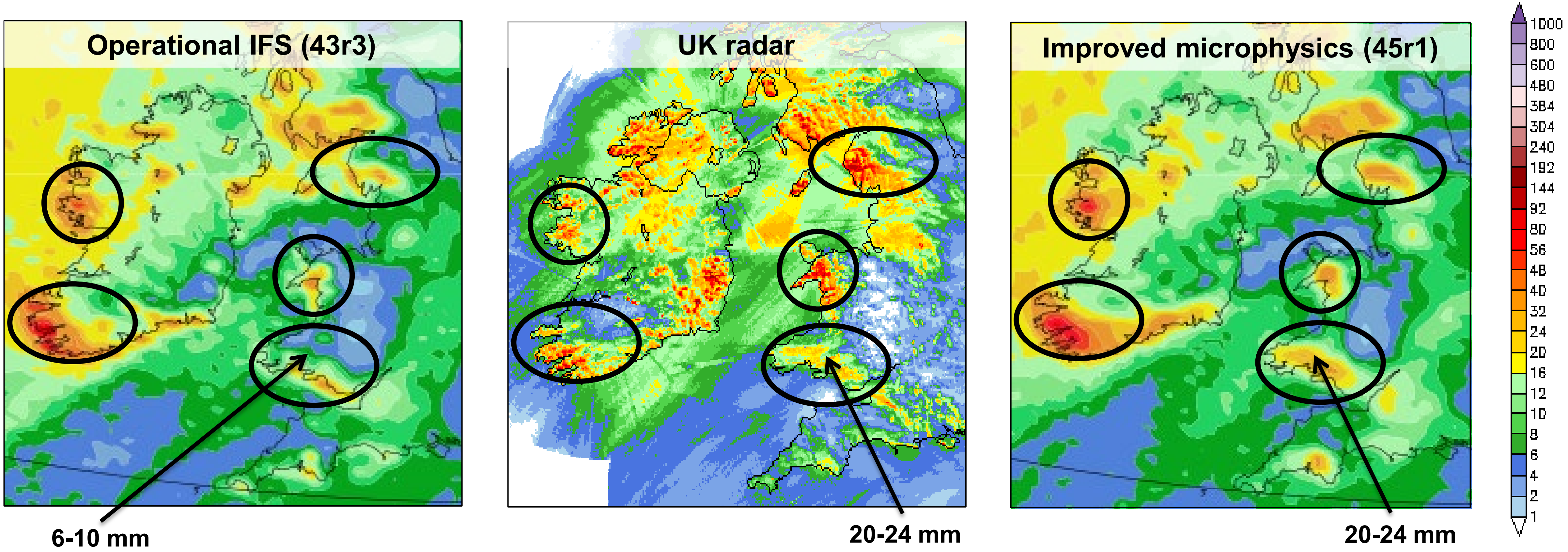
December 2018: Radiosonde BUFR availability/type



45r1 changes to micro-physics improve precipitation

In **warm-rain dominated situations** the 45r1 precipitation is no longer off the coast, but inland with maxima over orography, in much **better agreement with the observations.**

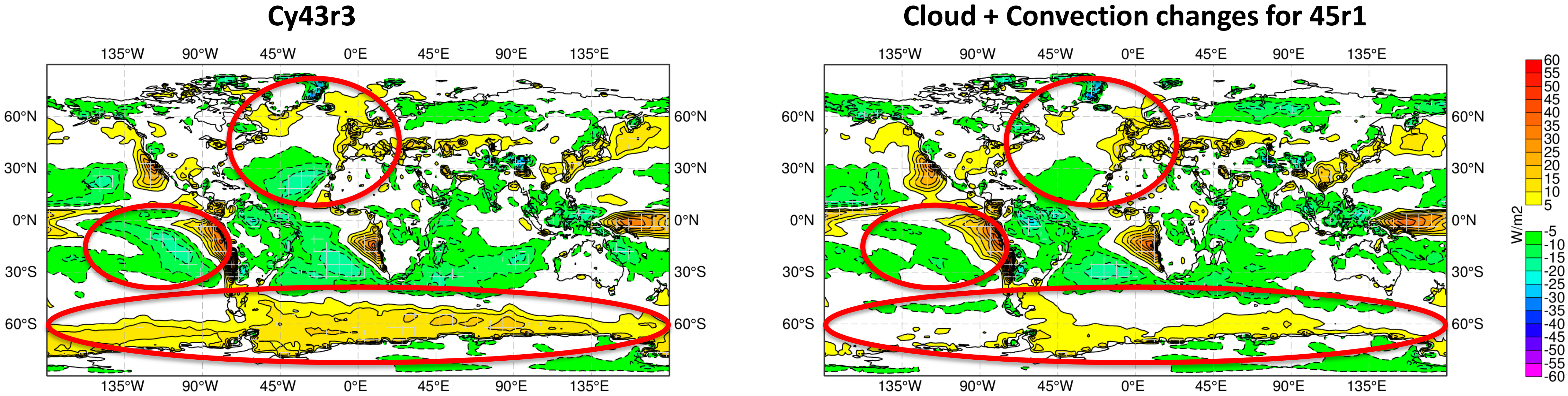
Example case study 14 May 2017 00Z 48hr forecast accumulated precipitation (mm)



45r1 changes to short-wave radiation reduce errors

Reduction in systematic shortwave radiation errors from warm-rain microphysics upgrade and convection changes.

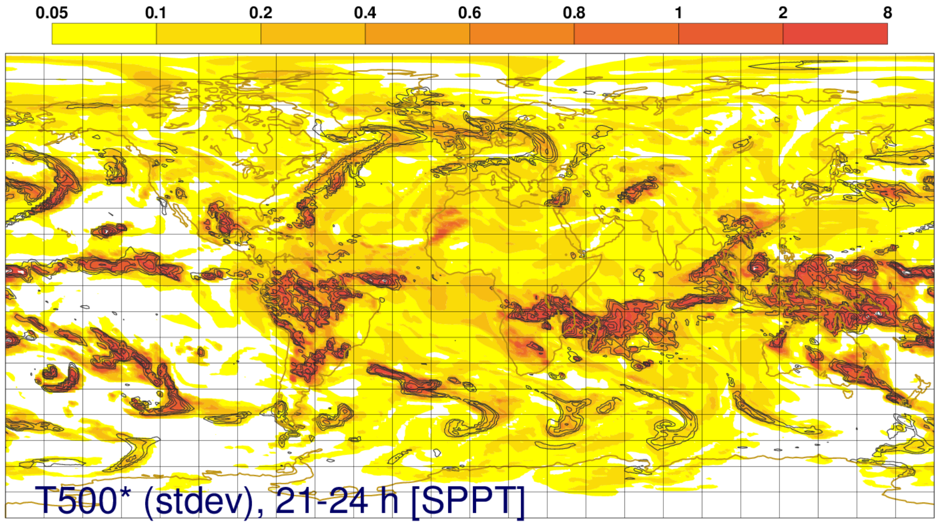
- Too much reflection (green) in subtropics (due to too much cloud cover?)
- Too little reflection (yellow) in mid-high latitudes, due to too little super-cooled liquid (SLW) in convection
- Convection and cloud changes reduce cloud cover in sub-tropics and increase SLW in cold air outbreaks – reduction in SW radiation error

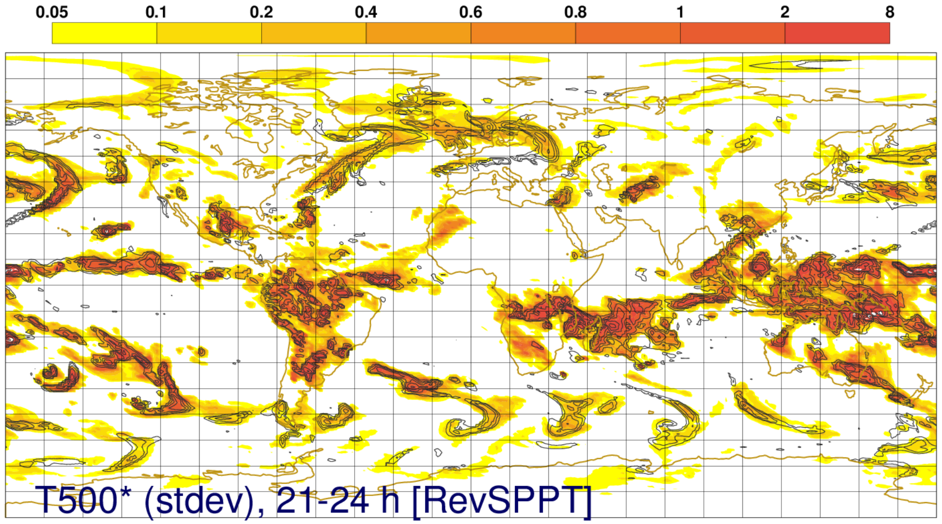


1 year annual mean top-of-atmosphere SW error versus CERES

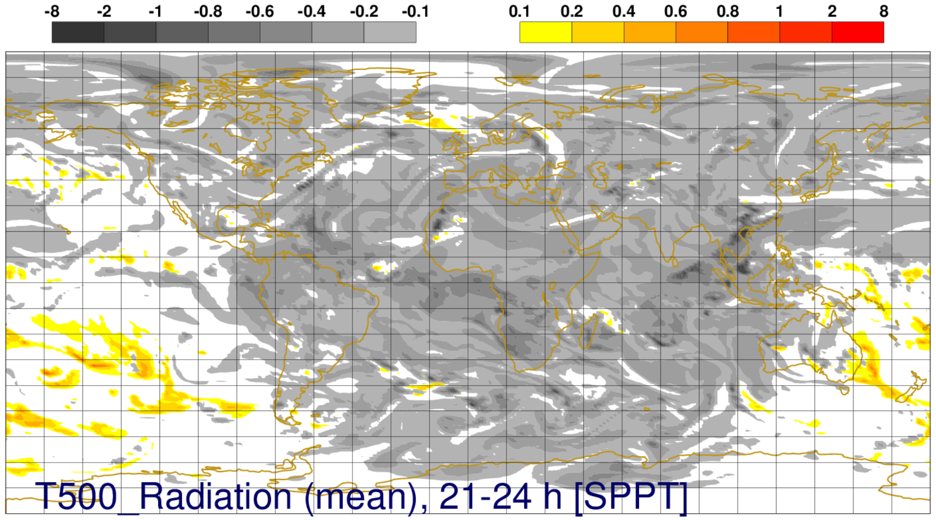
ECMWF

45r1 includes more realistic model uncertainty schemes





temperature tendency perturbations due to SPPT only (K/3h, shading)
precipitation (ens. mean, .5/1/2/4/8/... mm, black contours)
2015011000, t=+21–24 h

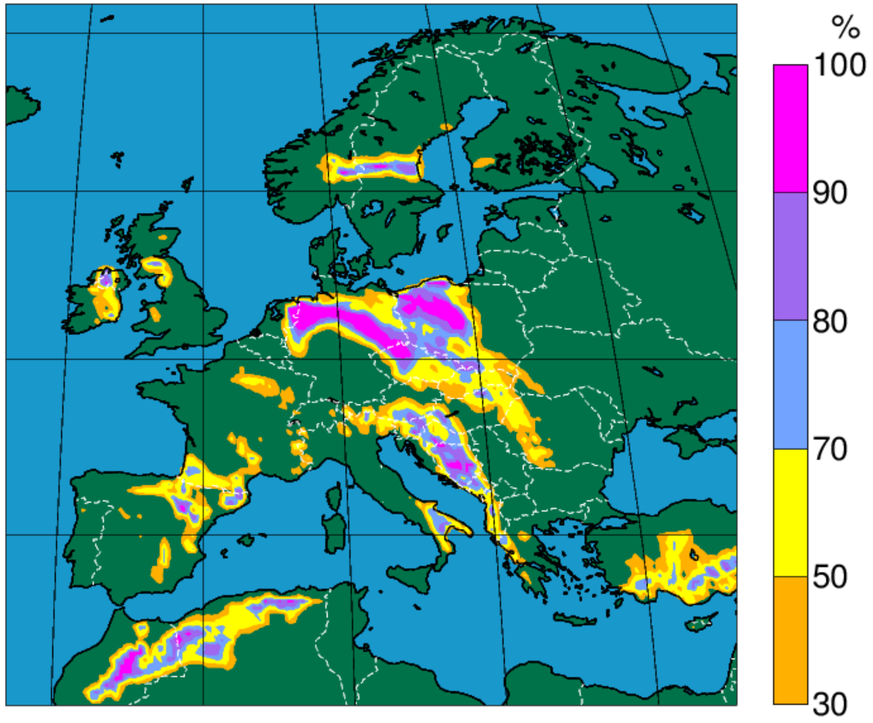


- **More realistic diurnal cycle of tendency perturbations in SPPT** by not perturbing the clear-sky radiative tendency;
- Perturbations in stratosphere and weaker tapering of perturbations in boundary layer
- Same SPPT in ENS and EDA, and cycling of random fields in EDA
- 20% reduced SPPT amplitude
- **SKEB deactivation** (2.5% saving)

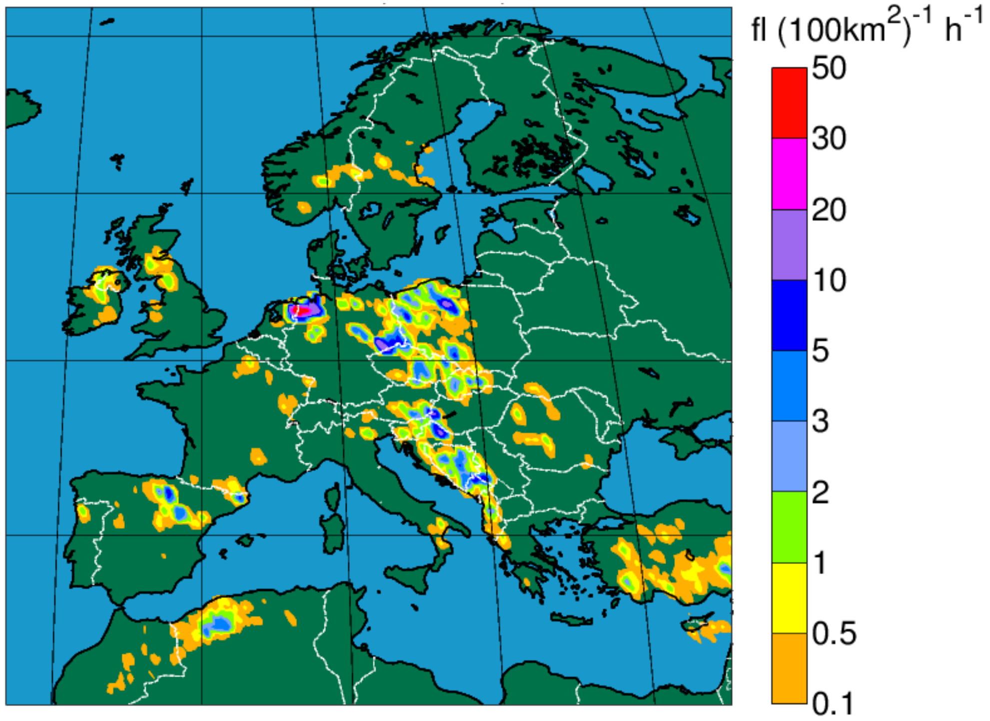
ECMWF

Probabilistic lightning prediction from ensemble forecasts

Ensemble forecast from oper 45r1 esuite
Probability[flash density > 0.1 fl/100km^2/h]
Base: 1 June 2018 00Z, range: **T+12 to T+15h**



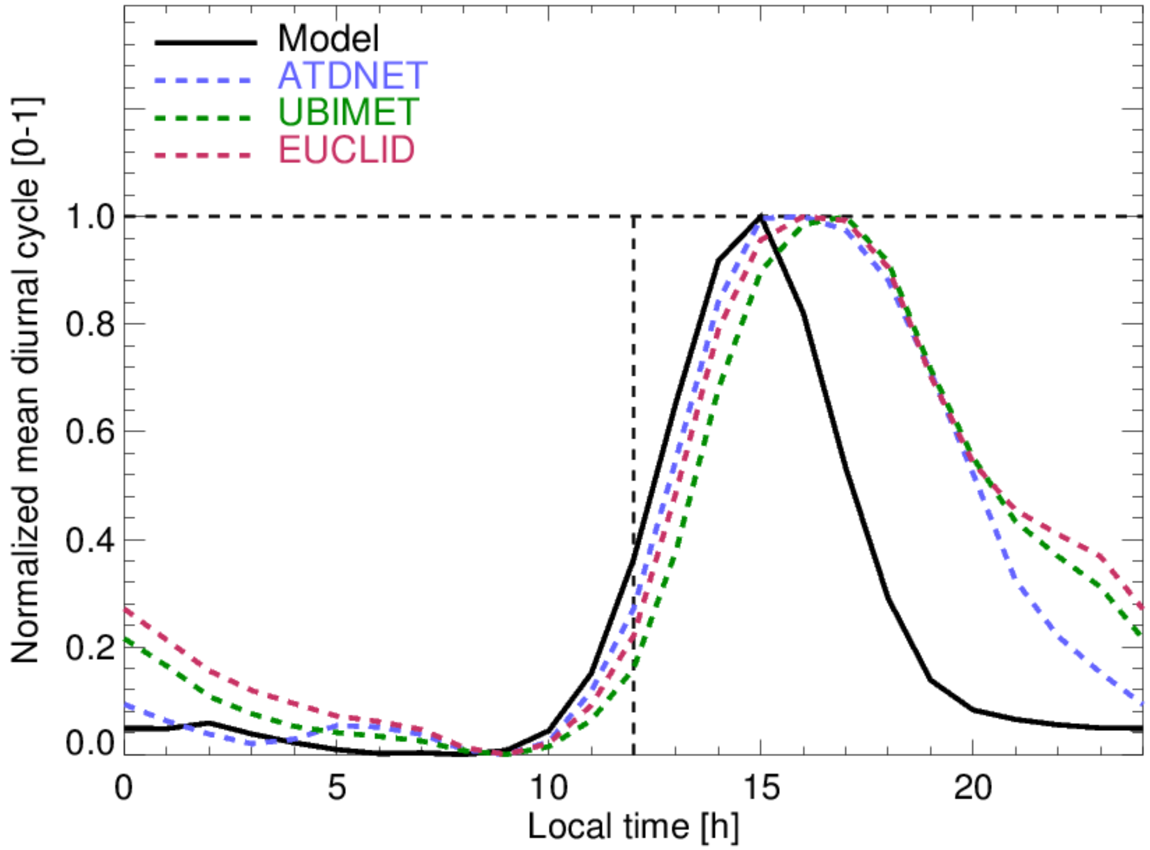
Observations:
ATDnet lightning flash densities
1 June 2018 from 12Z to 15Z

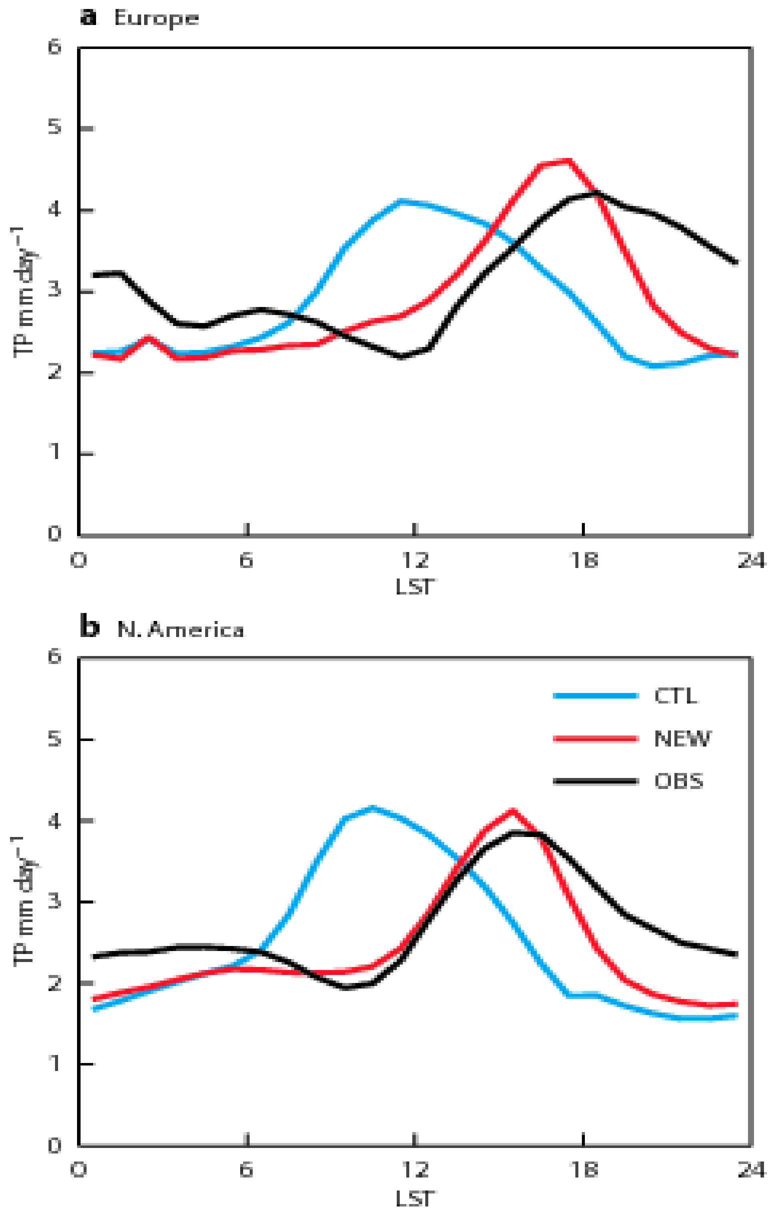


The lightning parametrisation strongly depends on the convection parametrisation as it takes as input: CAPE, convective cloud base height and frozen water content (P. Lopez, MWR, 2016)

ECMWF model vs various ground-based lightning networks.

Diurnal cycle of mean flash densities (normalized by amplitude).
Based on 0-24h forecasts (16 km res.) over Europe in summer 2015.





Model lightning declines too early in the afternoon.
→ Consistent with previous studies based on precipitation.

See ECMWF Newsletter No 136 Summer 2013
Bechtold et al., 2014, J. Atmos. Sci.

Outline

1. Highlights of recent and forthcoming IFS upgrades
    a. 11 July 2017 (CY43R3) - improved humidity analysis
    b. June 2018 (CY45R1) - Ocean coupling to the HRES forecast
2. CY46R1 and beyond….

Cycle 46r1 content: highlights

At the end of May, we will start merging all RD contributions in a controlled, step-wise approach, to identify potential negative interactions. Contributions are expected in many areas, including:

1. DA: **continuous DA**, **50 member EDA**; OOPS contributions;
2. Upgraded use of observations (surface pressure bias-correction, aircraft obs, Huber norm, use of new OSTIA product, ..);
3. Surface assimilation using 50-member EDA Jacobians;
4. Wave model physics improvements; ocean model upgrade (NEMO 3.6)
5. Atmospheric model changes: **convection, radiation**, new snow scheme, changes to allow more testing of single-precision, aerosols (full 3D climatology and revised optical properties)
6. ENS radiation time step from 3 to 1 hour; initial perturbations’ re-tuning following EDA upgrade
7. …..

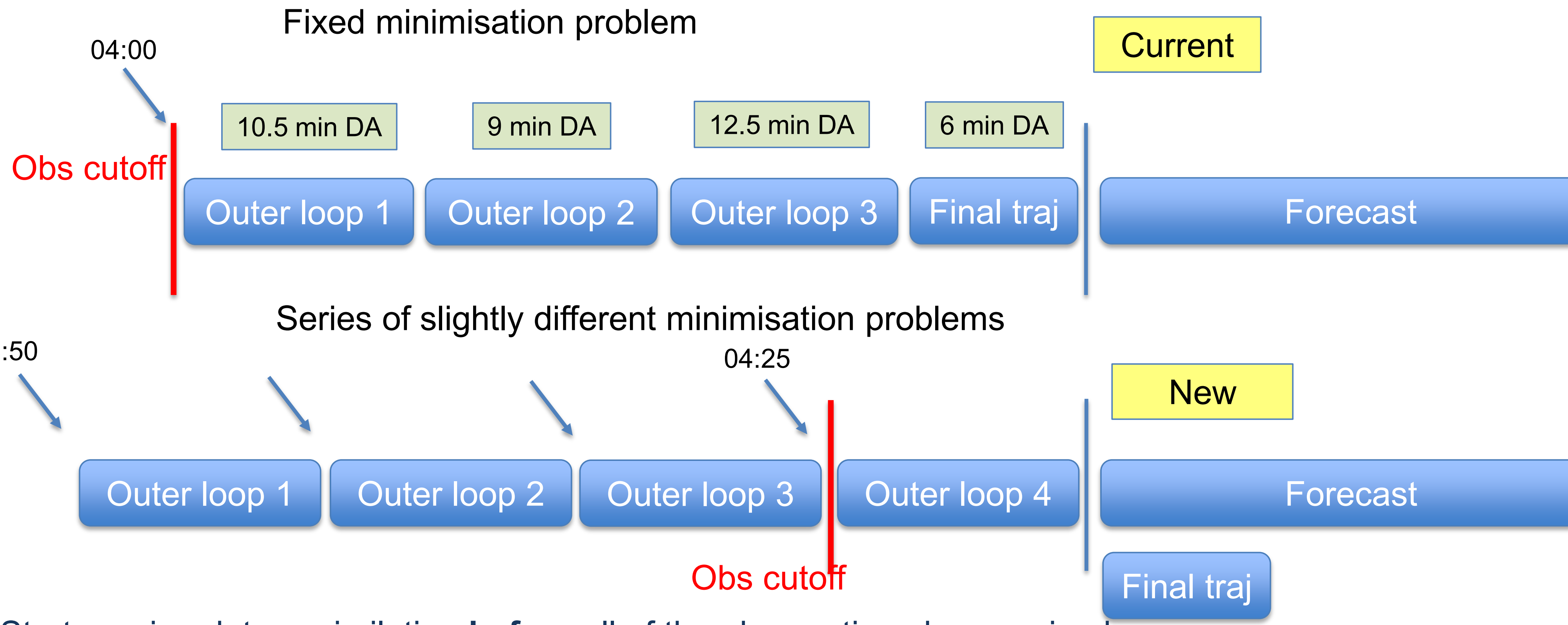
Continuous data assimilation: ~~Trade-off~~

Continuous DA configuration allows **both**:

- Later cut-off to collect **more observations**
- A longer assimilation window
- **More time to perform DA computations**

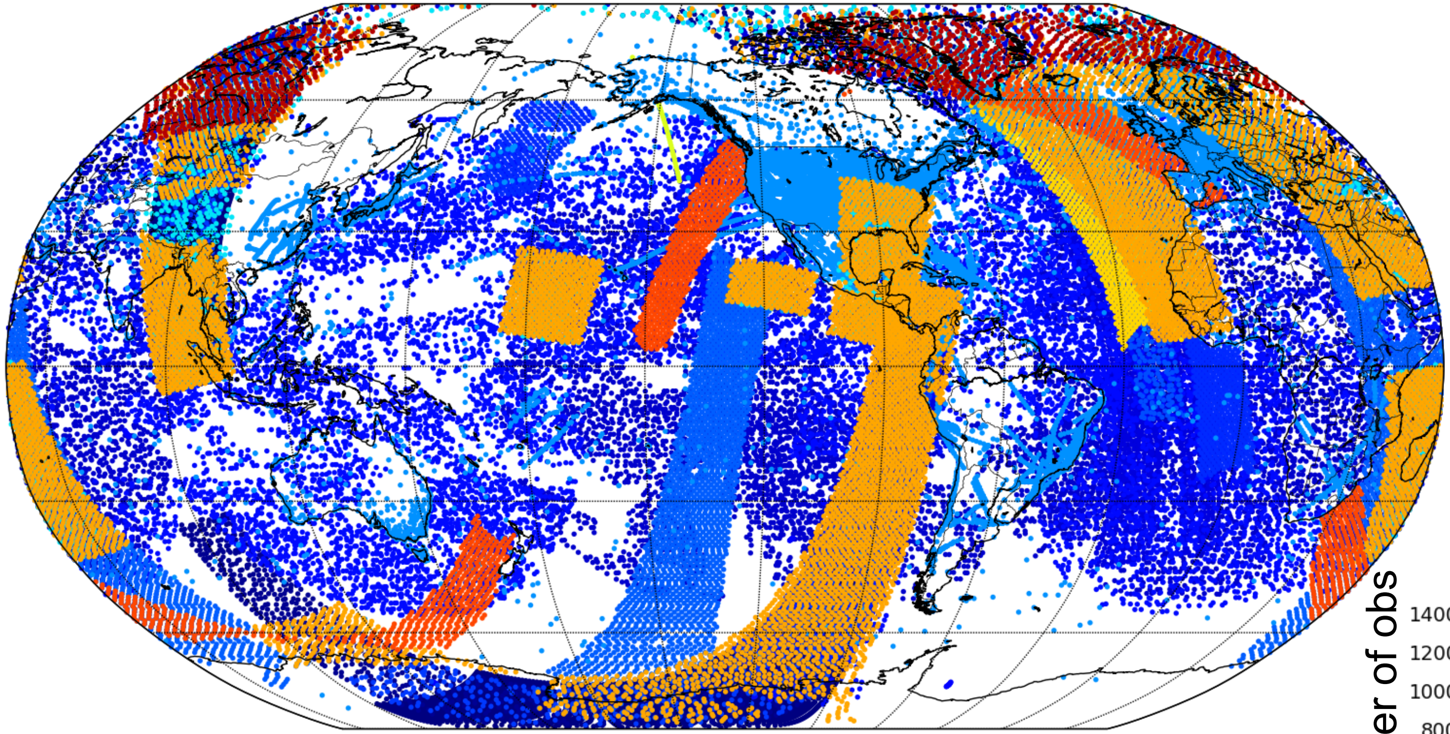
Continuous Data Assimilation Configuration

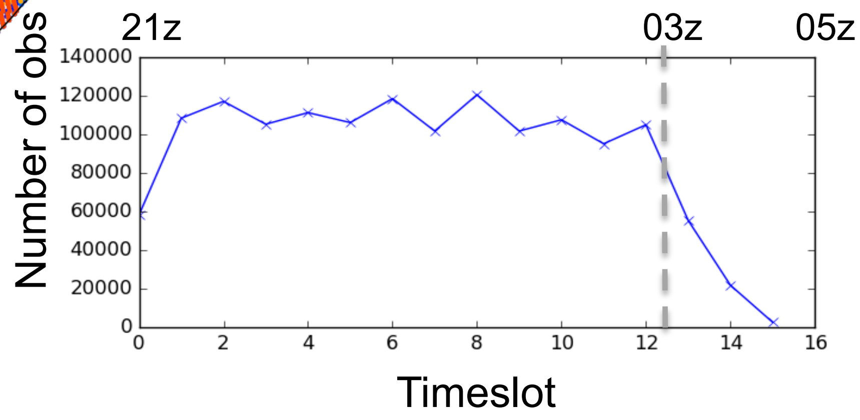
DA analysis



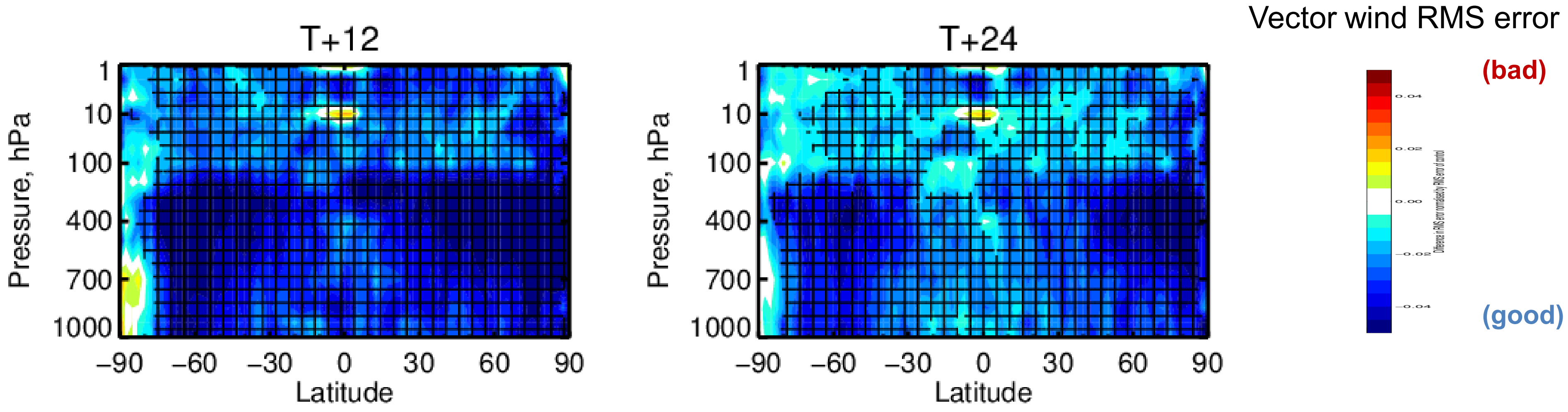
- Key point: Start running data assimilation **before** all of the observations have arrived
  - Most of the assimilation is removed from the time critical path
  - Configurations which were previously unaffordable can now be considered.
- Opens the possibility of a fully continuous assimilation system.

Extra observations assimilated in Continuous DA configuration

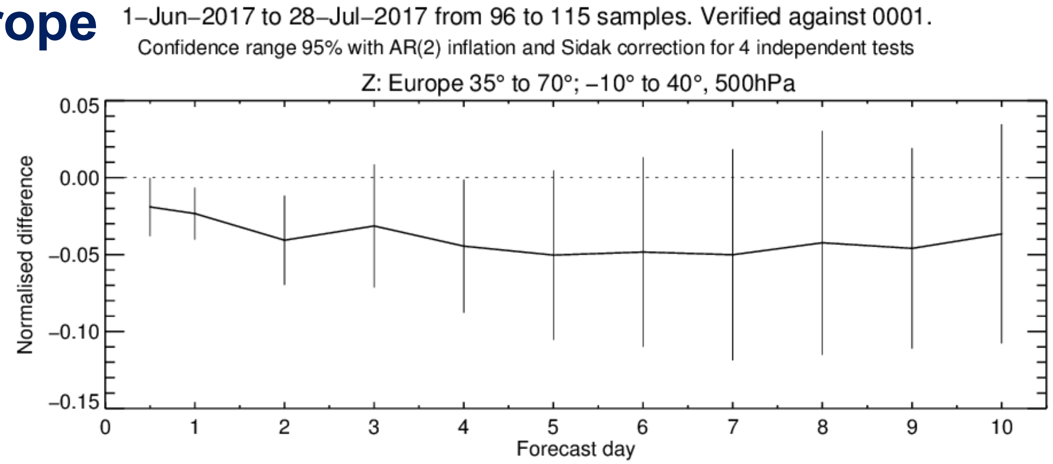




Improvements at all forecast ranges

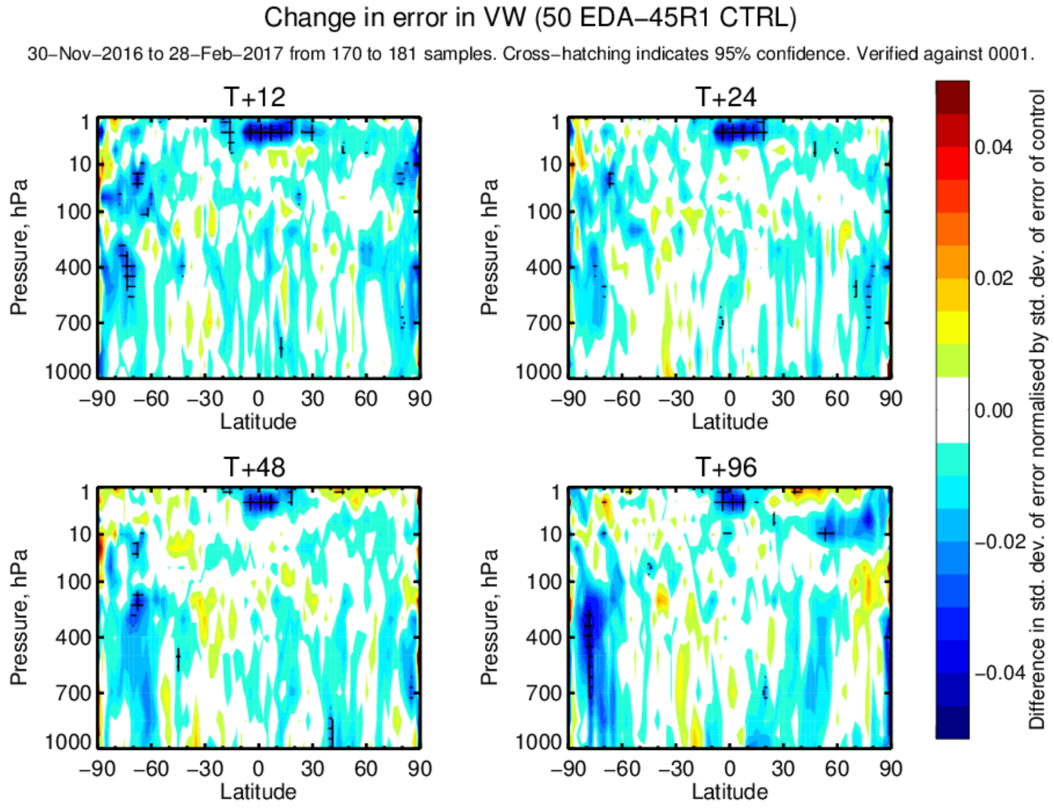


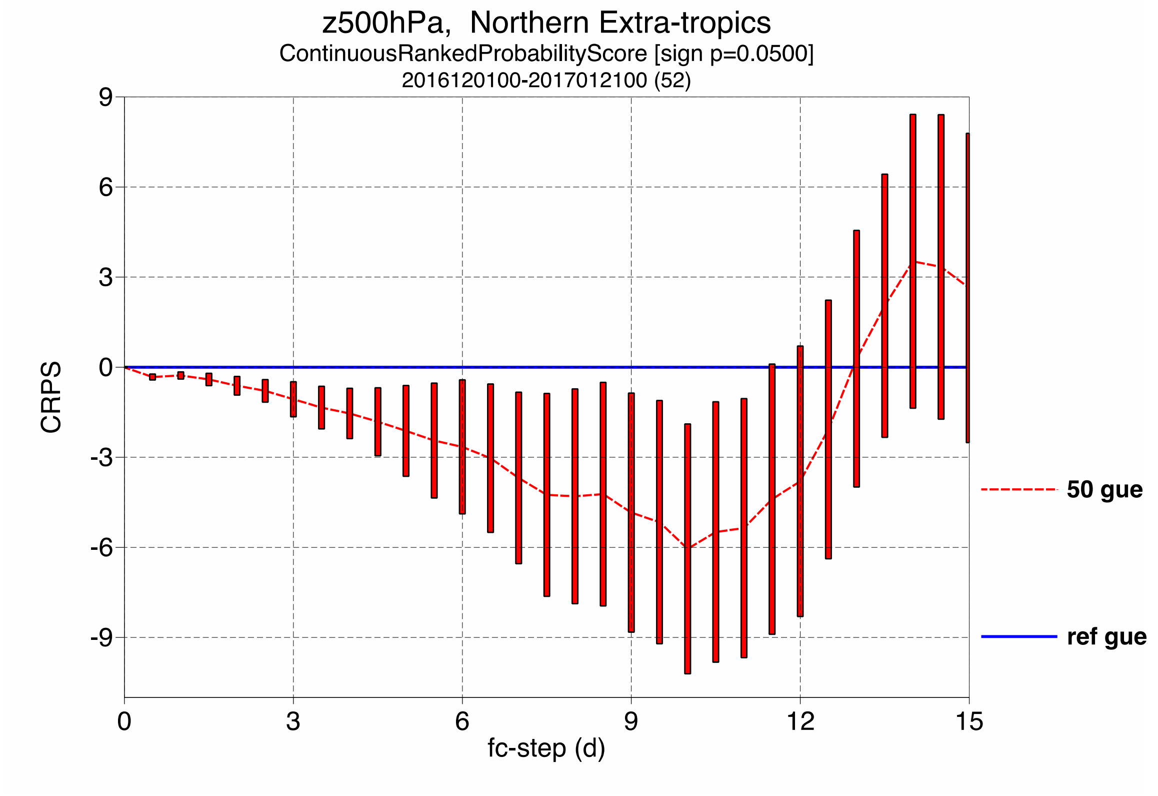
Europe



46r1: EDA from 25 to 50 members

- Optimization of EDA configuration allows doubling (25->50) ensemble size with marginal increase in computational cost
- Positive impact on forecast skill from larger ensemble apparent for both HRES (left) and ENS (right) test configurations





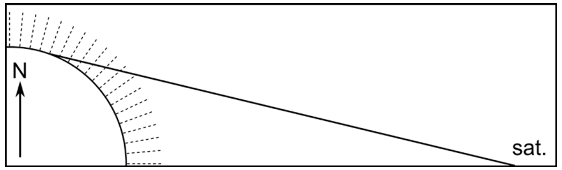
ECMWF

Geostationary radiances …. peaking around 300-500 hPa (these are complemented by AMVs)

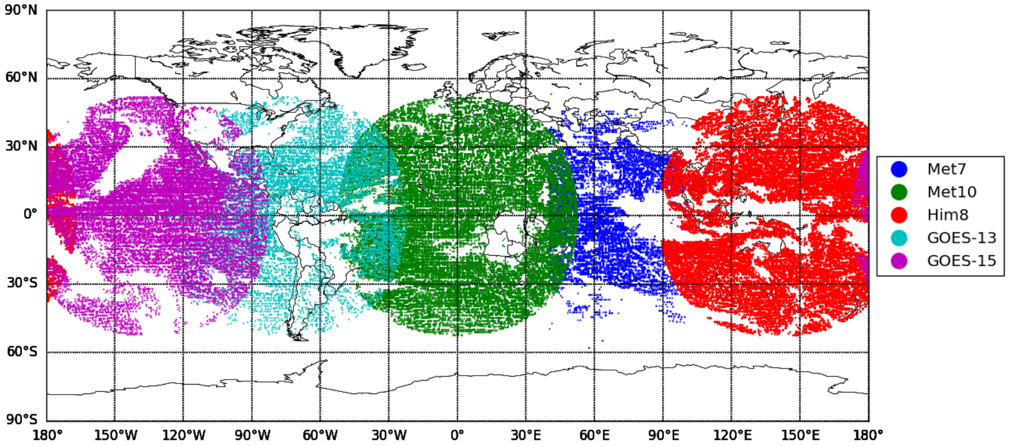
Diagnosed inter-channel error correlations for the water vapour channels on SEVIRI, AHI and ABI. E.g.

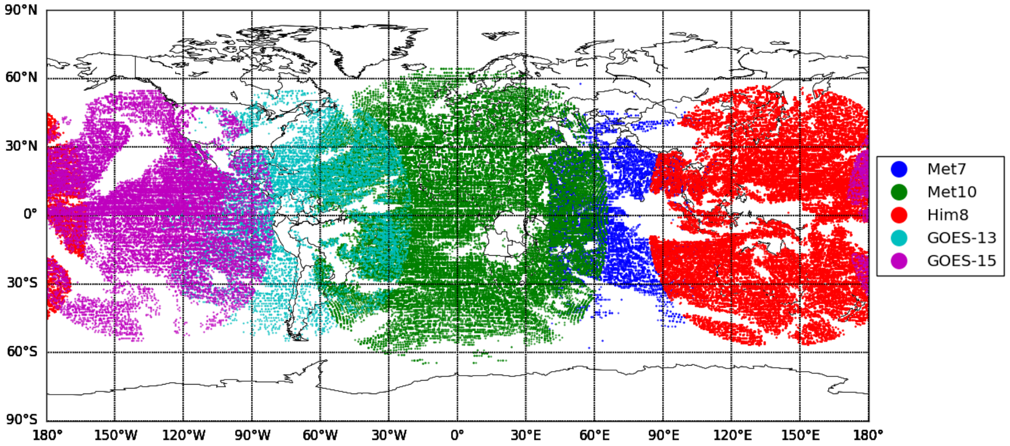
$$\mathbf{R}_{SEVIRI} = \begin{pmatrix} 0.46 & 0.20 \\ 0.20 & 0.30 \end{pmatrix} \qquad \mathbf{R}_{AHI} = \begin{pmatrix} 0.55 & 0.43 & 0.22 \\ 0.43 & 0.46 & 0.31 \\ 0.22 & 0.31 & 0.35 \end{pmatrix}$$

Slant path radiative transfer – this improves forward-modelling at high zenith angles:



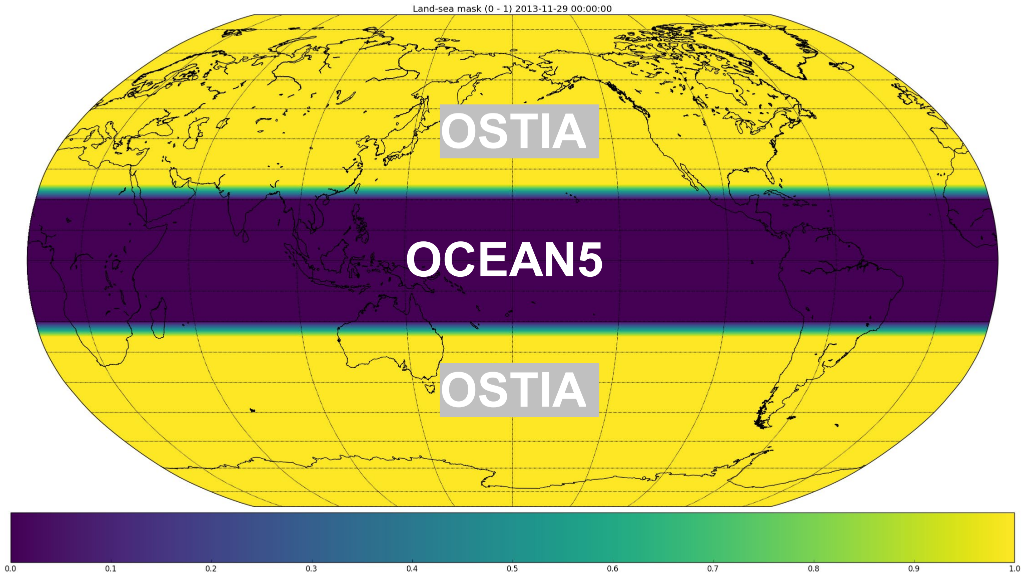
Increased use of data at high zenith angles beyond 60° (assisted by the slant path processing):



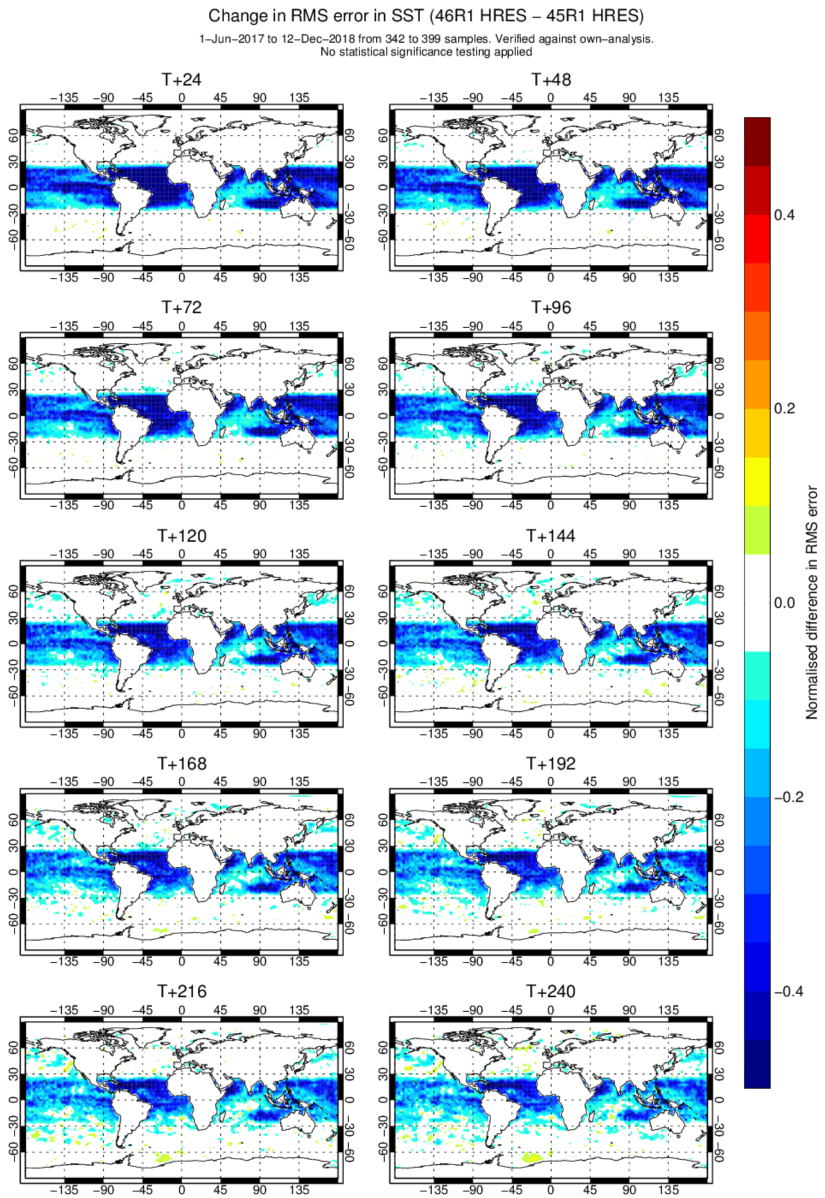


Weakly coupled SST assimilation

- At 45R1: $SST_{AN} \neq SST_{step\ 0}$
- From 46R1: $SST_{AN} = SST_{step\ 0}$



No extra cost/complexity – same as WCDA sea ice in 45R1



ESM physics + ENS contributions with active meteorological impact

Physics and numerics contributions

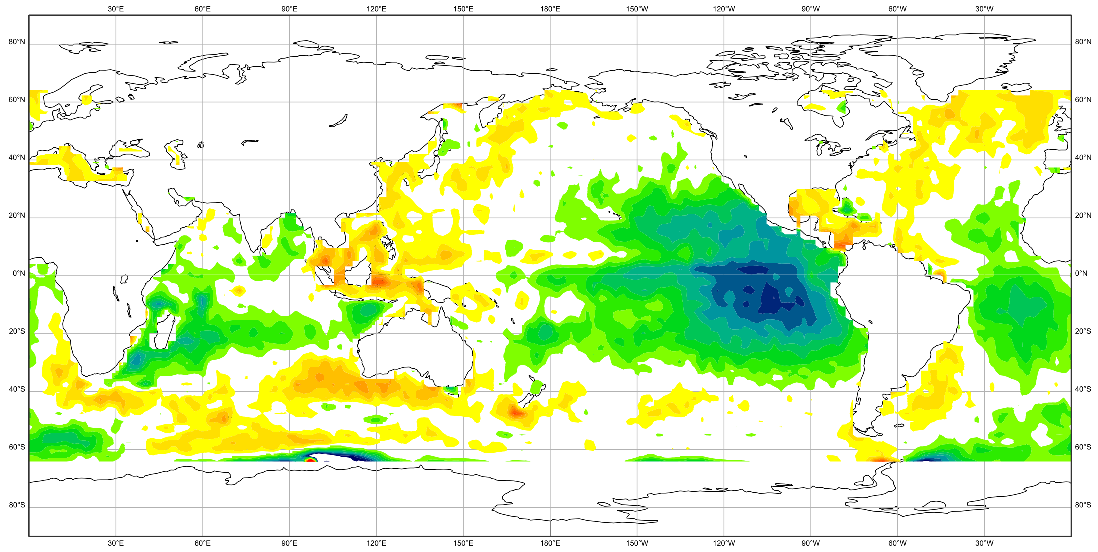
- Convection revisions (perturbations, evaporation, scaling) + corresponding TL/AD revisions
- LW scattering radiation changes
- More realistic 3D aerosol climatology
- Fix instability and diagnostic T2m issue related to wet tile
- Remove wrong scaling of dry mass flux in diffusion scheme
- TL/AD bug (CRAY feature) fix for the semi-Lagrangian departure point scheme + missing vectorization
- New wave mode physics

Ensemble

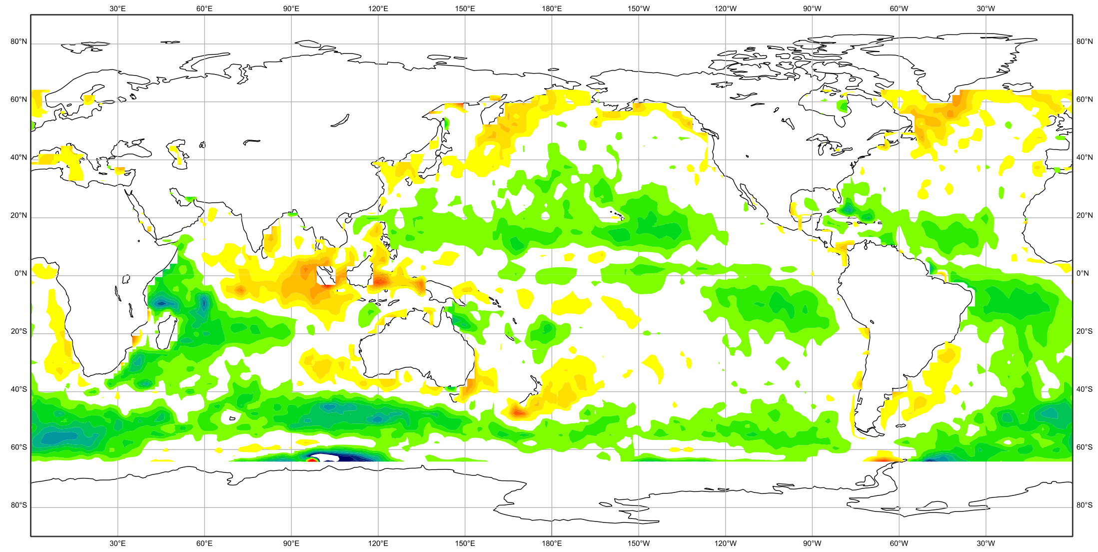
- 1-hour radiation timestep (Simon, Robin)

Standalone wave model **hindcast: much improved !**

with default physics



with Ardhuin et al. 2010 physics



-0.4 -0.36 -0.32 -0.28 -0.24 -0.2 -0.16 -0.12 -0.08 -0.04

0.04 0.08 0.12 0.16 0.2 0.24 0.28 0.32 0.36 0.4

Model overestimates

Bias = Alt. - Mod.

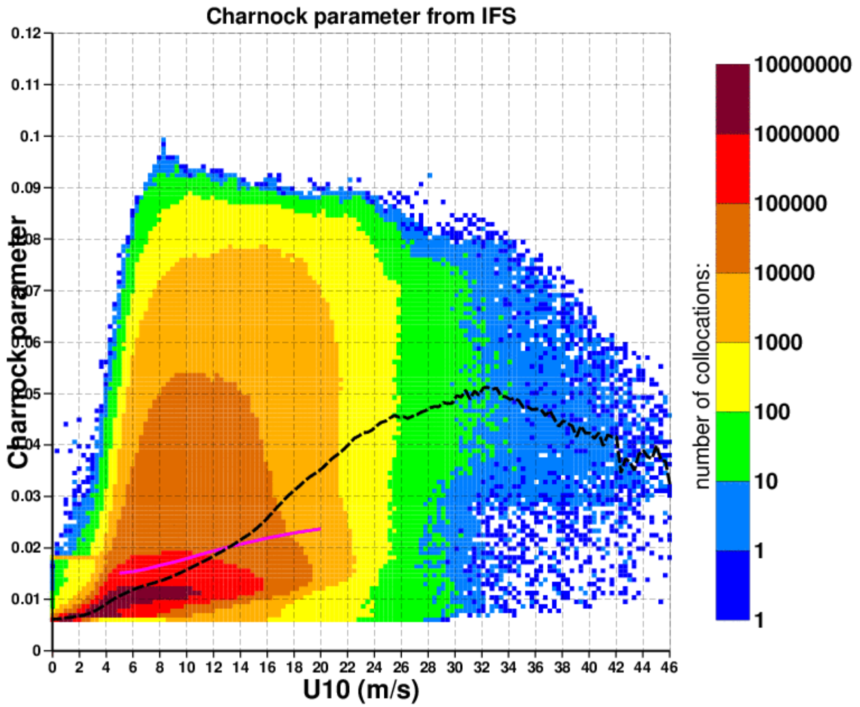
Jason-2

Model underestimates

ECMWF

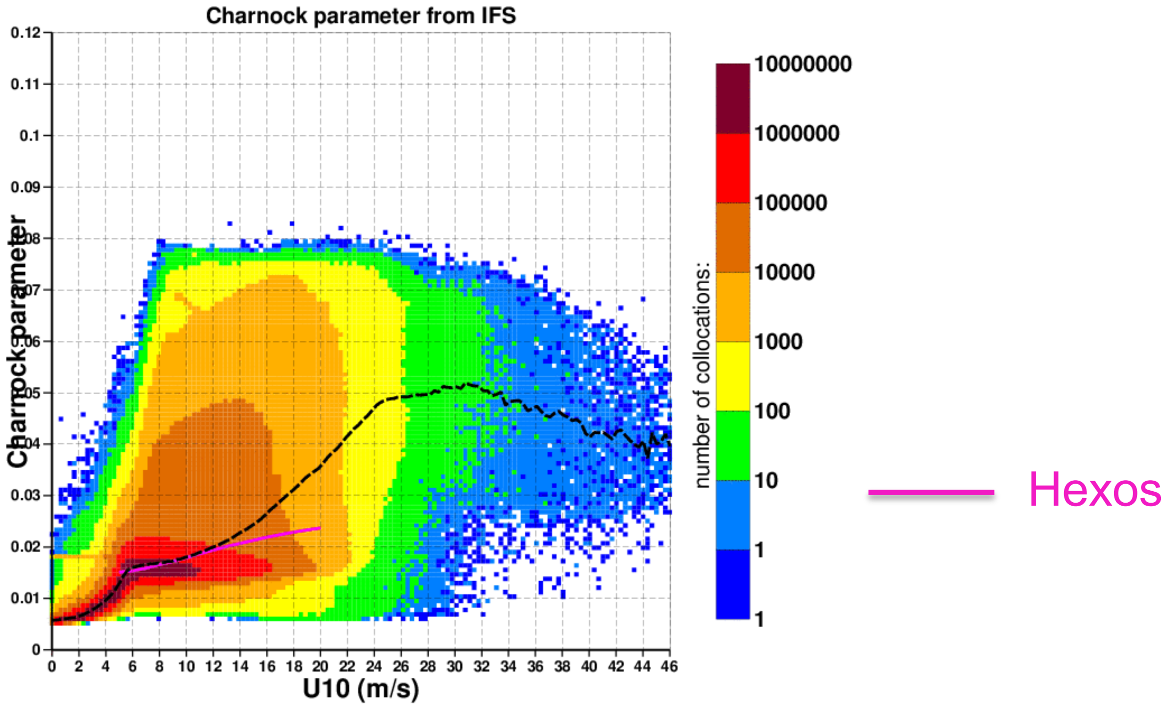
Feedback to the atmosphere: Charnock parameter α

with default physics (CY45R1)



Forecast data from stream oper, class rd, expver gqcv, all Sea points with sea ice cover <= 0.3
from 20150310 00UTC, for steps from 3 to 240 by 3

with Ardhuin et al. 2010 physics



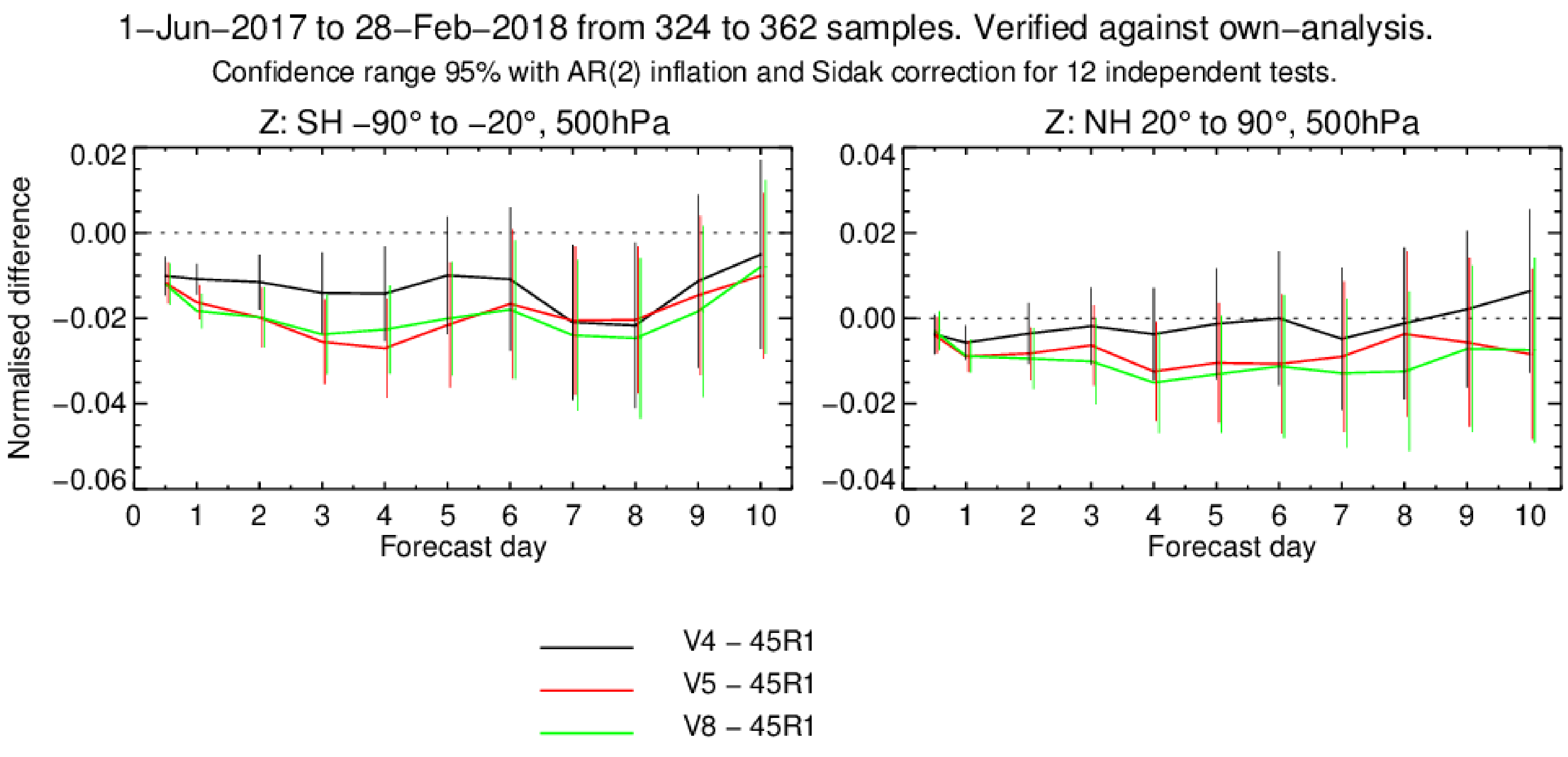
Forecast data from stream oper, class rd, expver gtyx, all Sea points with sea ice cover <= 0.3
from 20150310 00UTC, for steps from 3 to 240 by 3

TCo1279 coupled forecast from 2015-03-10 0 UTC, step 3 to 240 by 3 hours

The new system yields a slightly tighter distribution for Charnock and potentially address the problem of too low drag in tropical winds conditions (~ 6-10 m/s) (slightly higher Charnock)

ECMWF

Headline scores – 500hPa Geop height

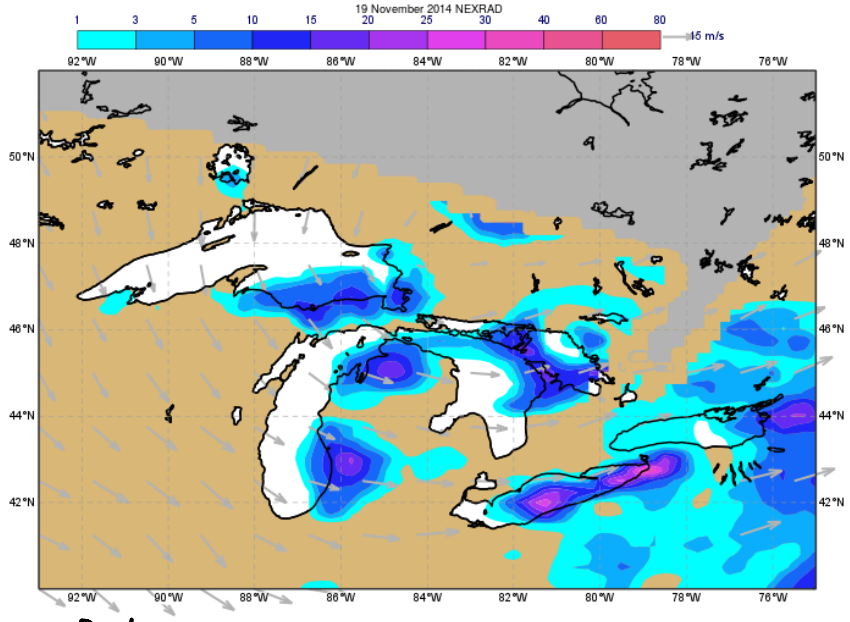


v4: obs + DA changes - cont DA - new EDA
v5: all changes - wave - cont DA - new EDA
v8: all changes - cont DA - new EDA

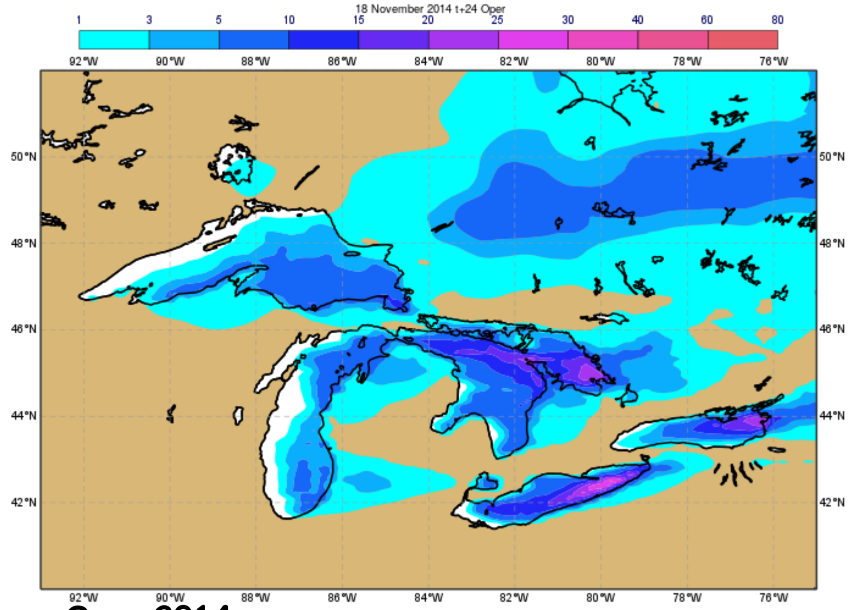
Just some of the forthcoming challenges...

- DA science (oper & reanalysis; maximize use of in situ and satellite obs, algorithms, EDA, higher res inner loops)
- Physical processes (resolved and unresolved)
- Increased coupling (land/ocean/atmospheric composition/meteorology)
- Uncertainty – parameter perturbations, ENS, EDA
- Predictability and seamless ensembles (EDA/ENS/monthly/seasonal)
- New dynamical core (FVM)
- Climate monitoring, ERA-Interim replacement: ERA5
- Scalability
- Aeolus !!!!! Finally up in space and laser switched on

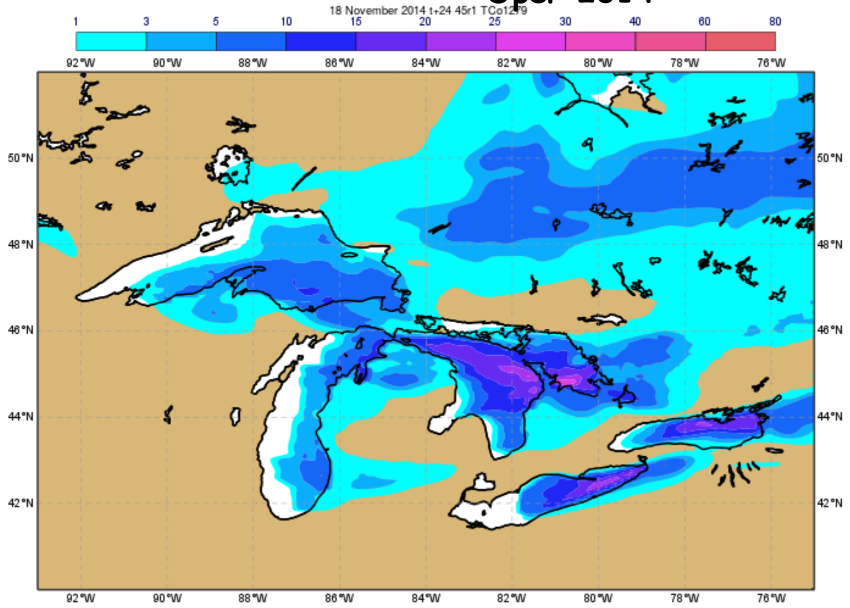
Outstanding issues: Wintery lake convection -snow



Radar



Oper 2014



45r1

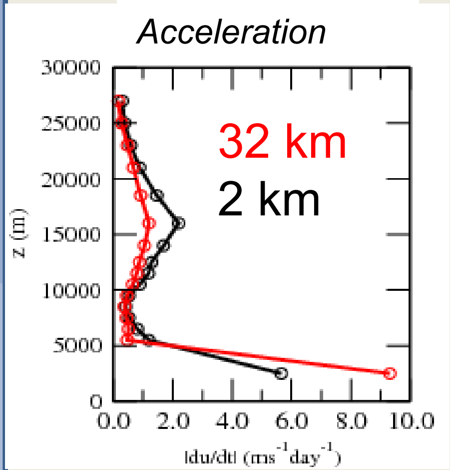
ECMWF

Working on the grey zone in collaboration with our member states

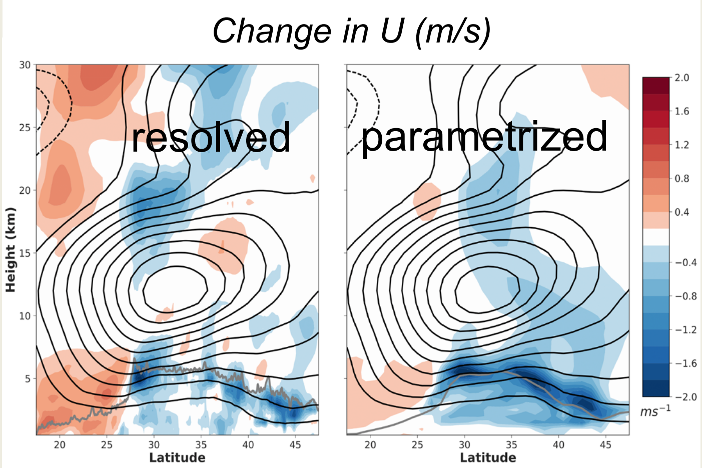
Orographic drag - Metoffice

2 - 5 km simulations of Rockies and Himalayas, used to evaluate parametrized drag in UM & IFS

Rockies (UM)



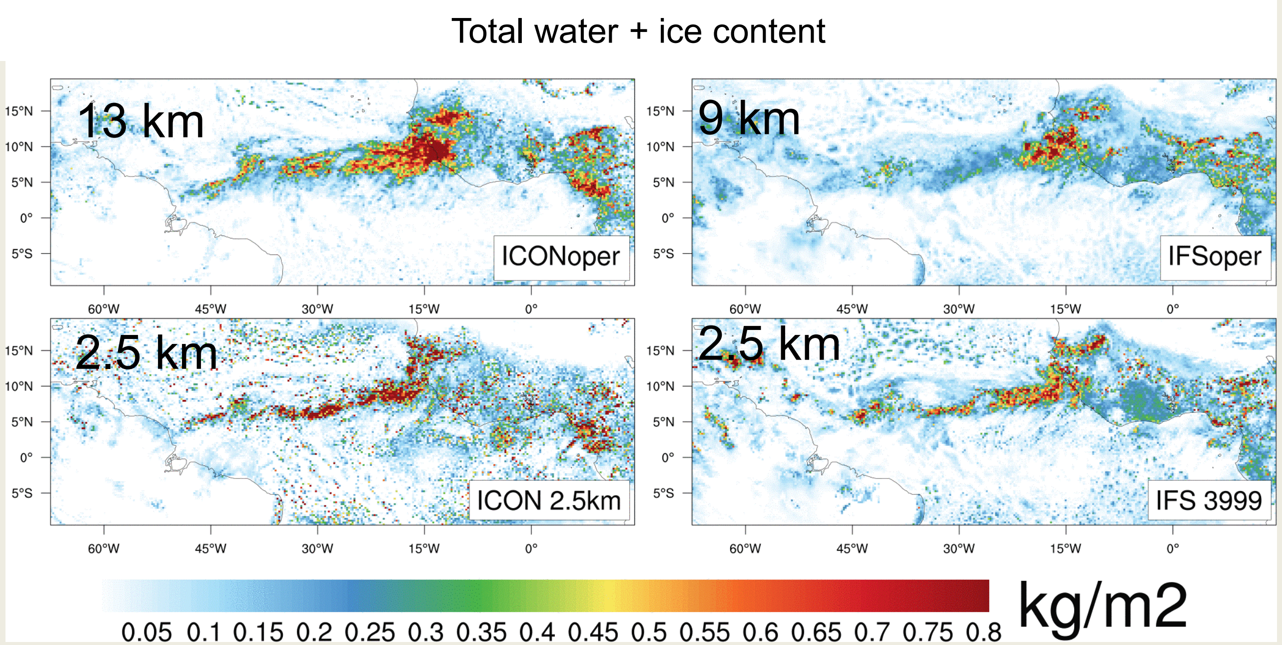
Himalayas (UM)



Vosper et al., Van Niekerk et al., in preparation

Convection - DWD

1, 2.5, 5, ~ 9 km of Tropical Atlantic with ICON & IFS

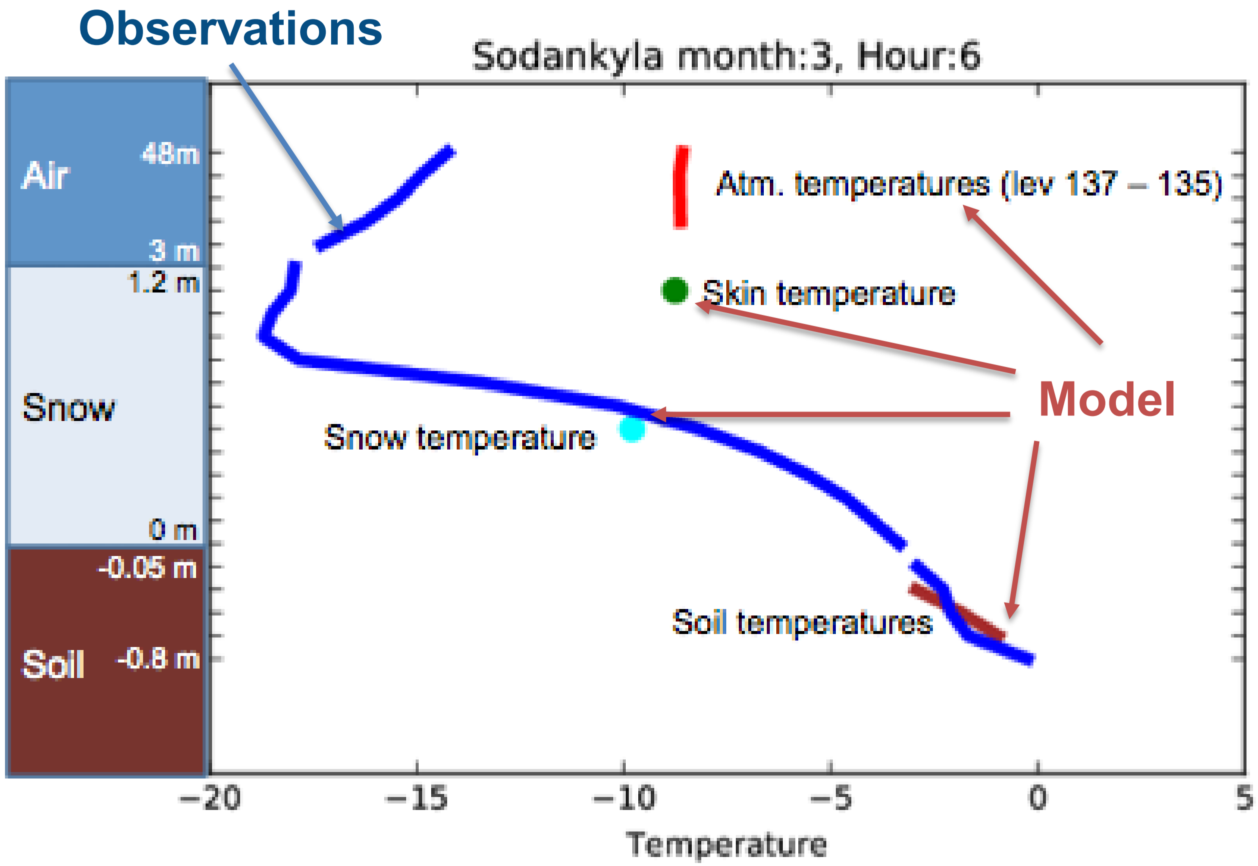


Courtesy Daniel Klocke and Nils Wedi

Workshop held in autumn 2017

Exploring the benefits of more vertical layers for the snow

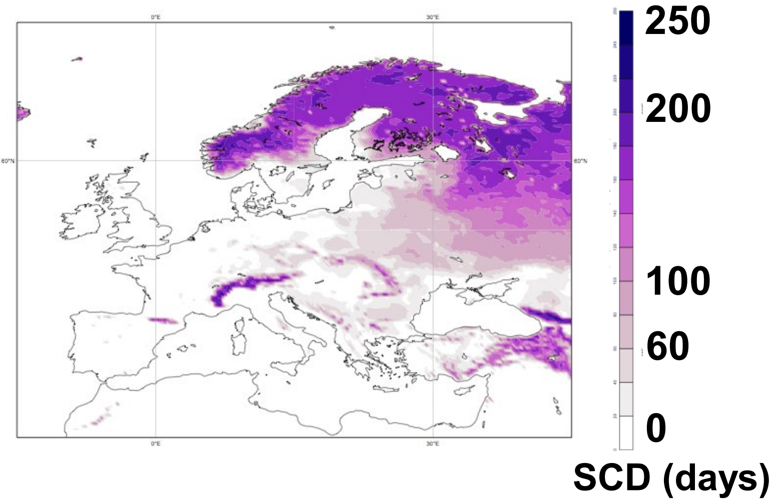
Comparison of temperature profile from observations (Sodankyla) and the operational model



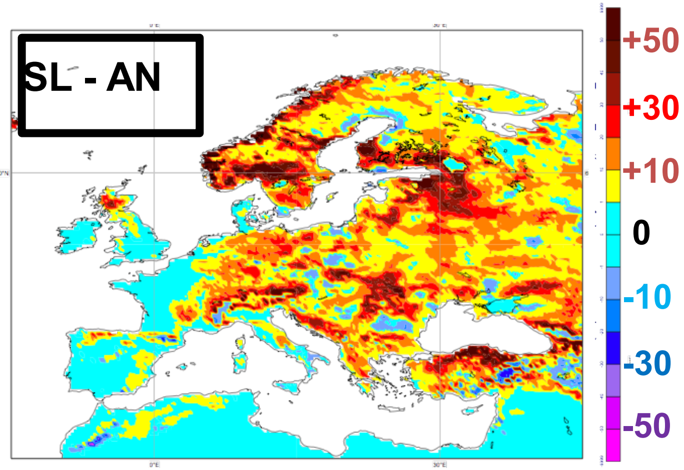
Thanks to Finnish Meteorological Institute's Arctic Research Centre (FMI-ARC) for observations and Linus for the figure.

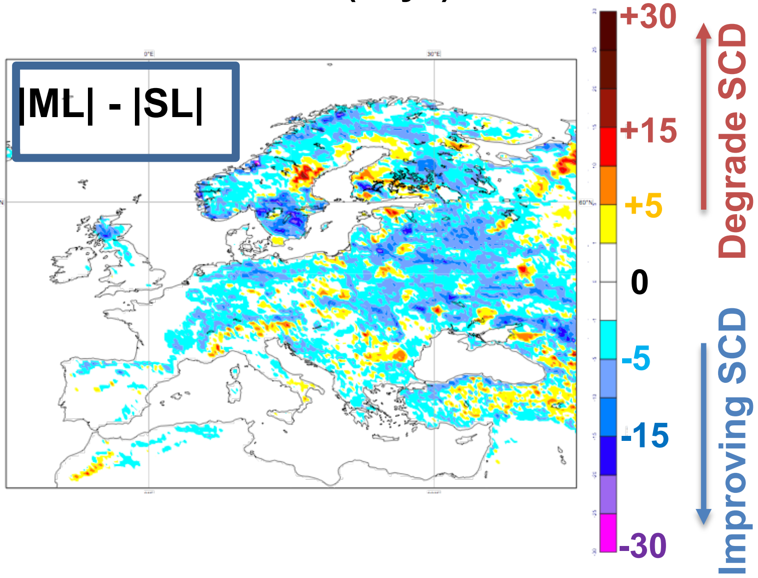
Snow cover duration (SCD) over Europe

SCD = Number of days snow cover > 0.5; 201610 — 201704



Operational analysis





AN: Operational analysis

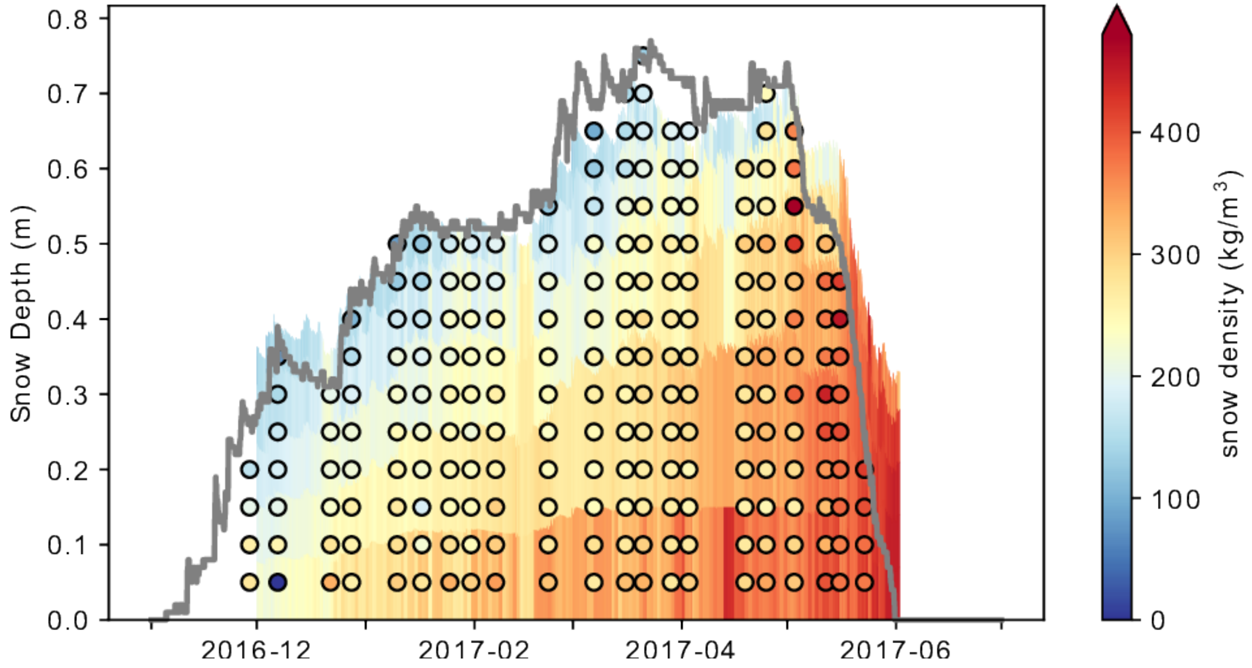
SL: Single-layer exp

ML: Multi-layer exp

Sodankyla, Finland: time-height plots of snow multi-layer fields (t+24 to t+47)

- Concatenated forecasts from t+24 to t+47 to create a continuous time-series
- Comparison with observed **snow density** (snow pit)

Snow density

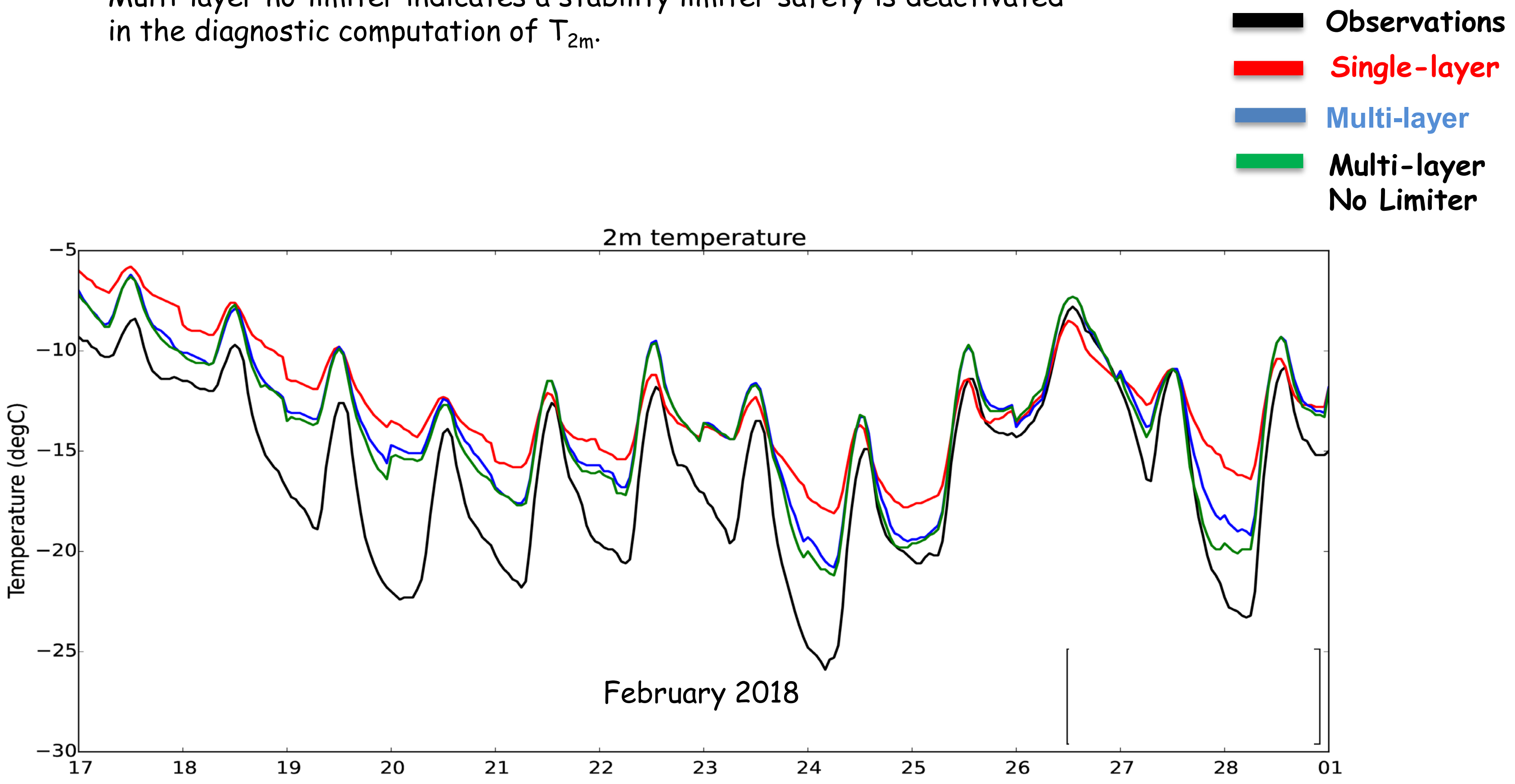


- Qualitative good agreement of snow density, in particular upper layers
- Issues with densification at the end of the season

ECMWF

Possible future improvements of Scandinavian warm bias with a multi-layer snow scheme

- Concatenated forecasts from t+24 to t+47 to form a continuous time-series
- Multi-layer no-limiter indicates a stability limiter safety is deactivated in the diagnostic computation of T_{2m}.

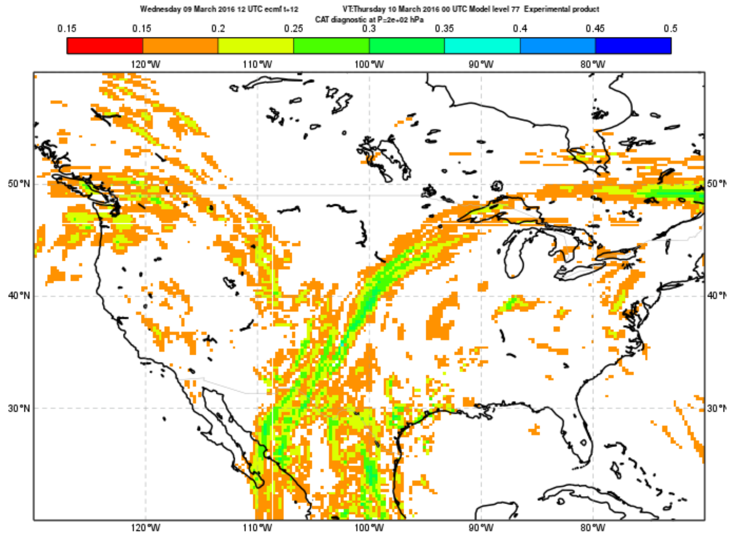


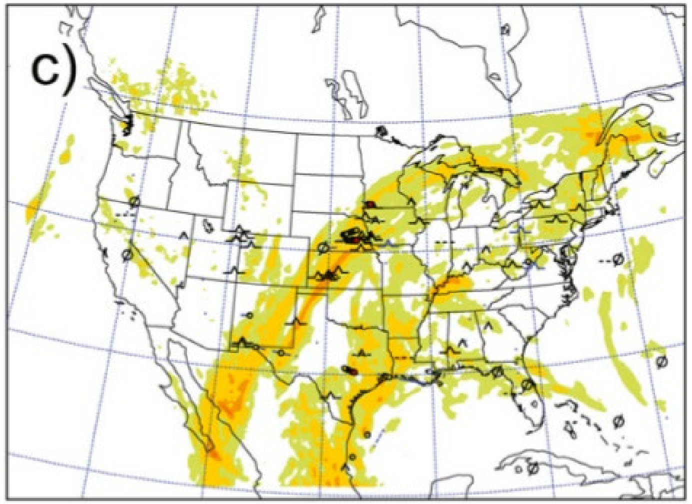
Experiments (T+24 to T+47)

ECMWF

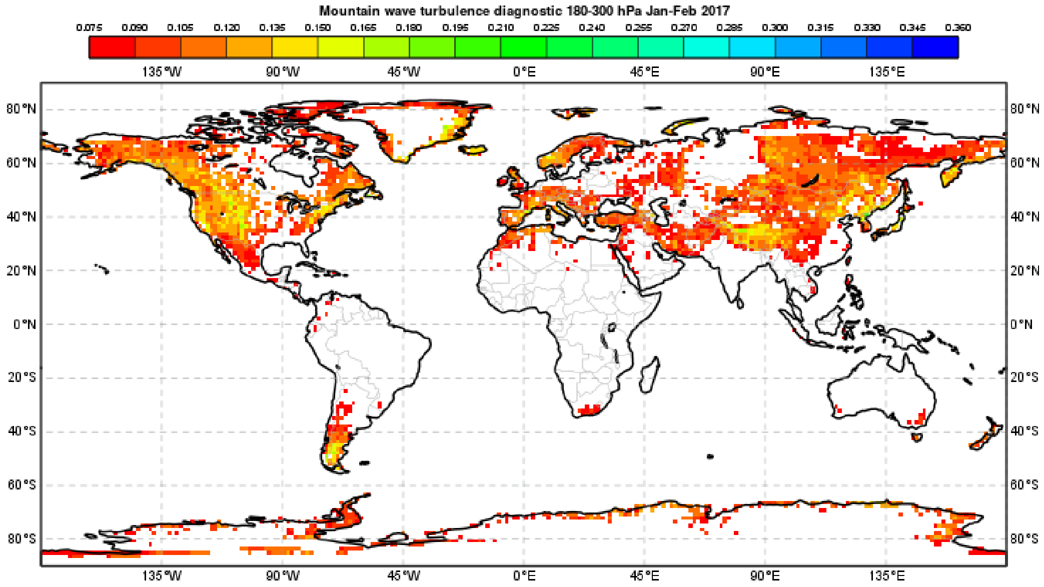
Example of CAT and MWT diagnostics

Based on Ellrod index, 3D Frontogenetic index, etc projecetd onto climatology of Eddy dissipation rate following Sharman and Pearson (2017)





Example CAT from IFS and article



IFS climatology of Mountain Wave Turbulence Jan-Feb 2017

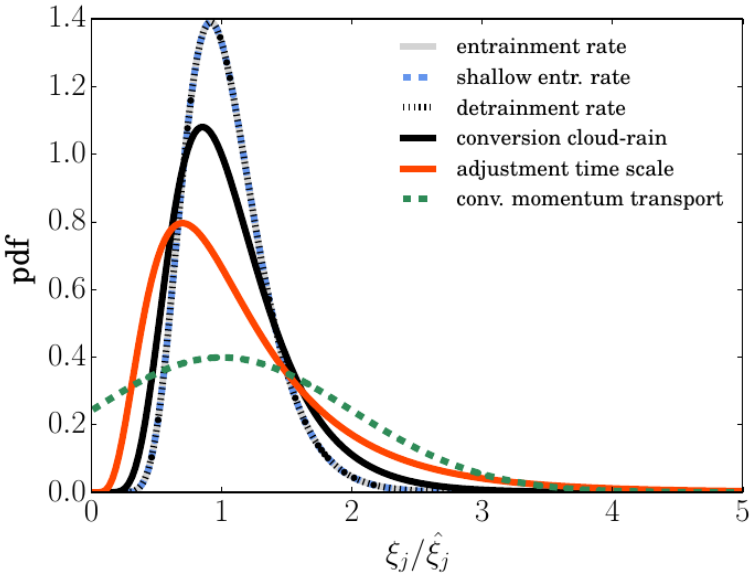
Work to improve the representation of model uncertainties

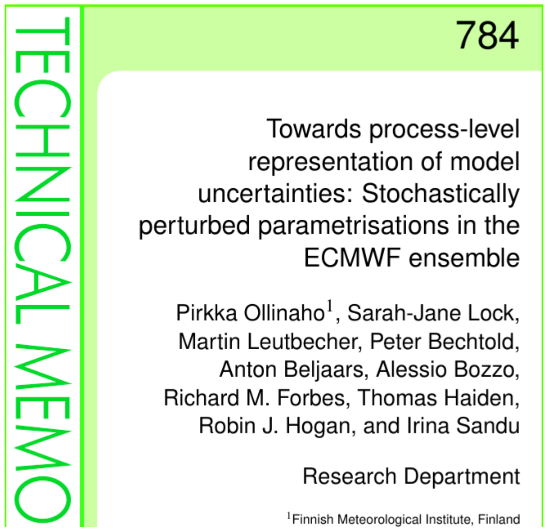
SPP scheme

Towards process-based representation of model uncertainties

e.g. parameters in convection are sampled from distributions on the right

x-axis: ratio of perturbed parameter value to unperturbed parameter value





TECHNICAL MEMO

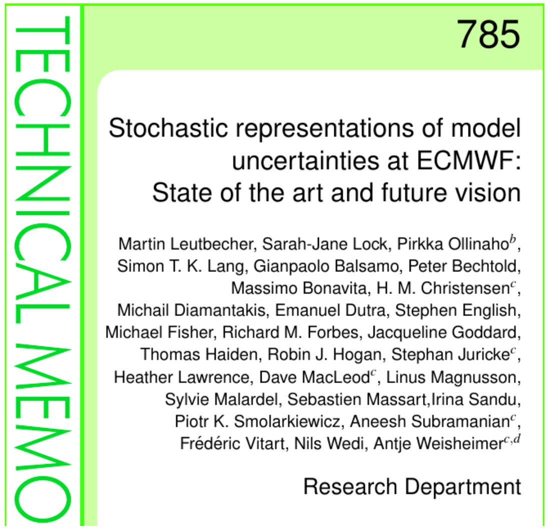
784

Towards process-level representation of model uncertainties: Stochastically perturbed parametrisations in the ECMWF ensemble

Pirkka Ollinaho[1], Sarah-Jane Lock, Martin Leutbecher, Peter Bechtold, Anton Beljaars, Alessio Bozzo, Richard M. Forbes, Thomas Haiden, Robin J. Hogan, and Irina Sandu

Research Department

[1]Finnish Meteorological Institute, Finland



TECHNICAL MEMO

785

Stochastic representations of model uncertainties at ECMWF: State of the art and future vision

Martin Leutbecher, Sarah-Jane Lock, Pirkka Ollinaho[b], Simon T. K. Lang, Gianpaolo Balsamo, Peter Bechtold, Massimo Bonavita, H. M. Christensen[c], Michail Diamantakis, Emanuel Dutra, Stephen English, Michael Fisher, Richard M. Forbes, Jacqueline Goddard, Thomas Haiden, Robin J. Hogan, Stephan Juricke[c], Heather Lawrence, Dave MacLeod[c], Linus Magnusson, Sylvie Malardel, Sebastien Massart, Irina Sandu, Piotr K. Smolarkiewicz, Aneesh Subramanian[c], Frédéric Vitart, Nils Wedi, Antje Weisheimer[c,d]

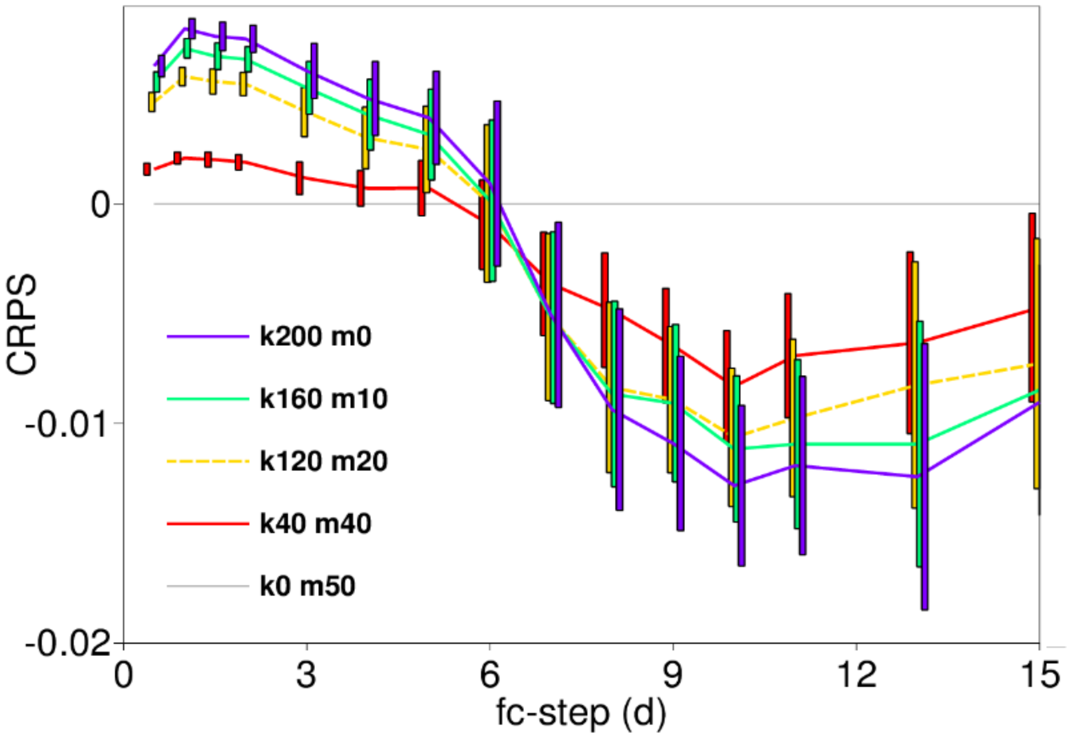
Research Department

- stochastic parameter perturbations that vary in space and time (2000 km, 3 d)
- up to 20 independent perturbations in parametrisation of subgrid orography and vertical mixing, radiation, large-scale cloud and precipitation and **convection**
- Ollinaho et al. (2016, Quarterly Journal, in press; ECMWF TM784)

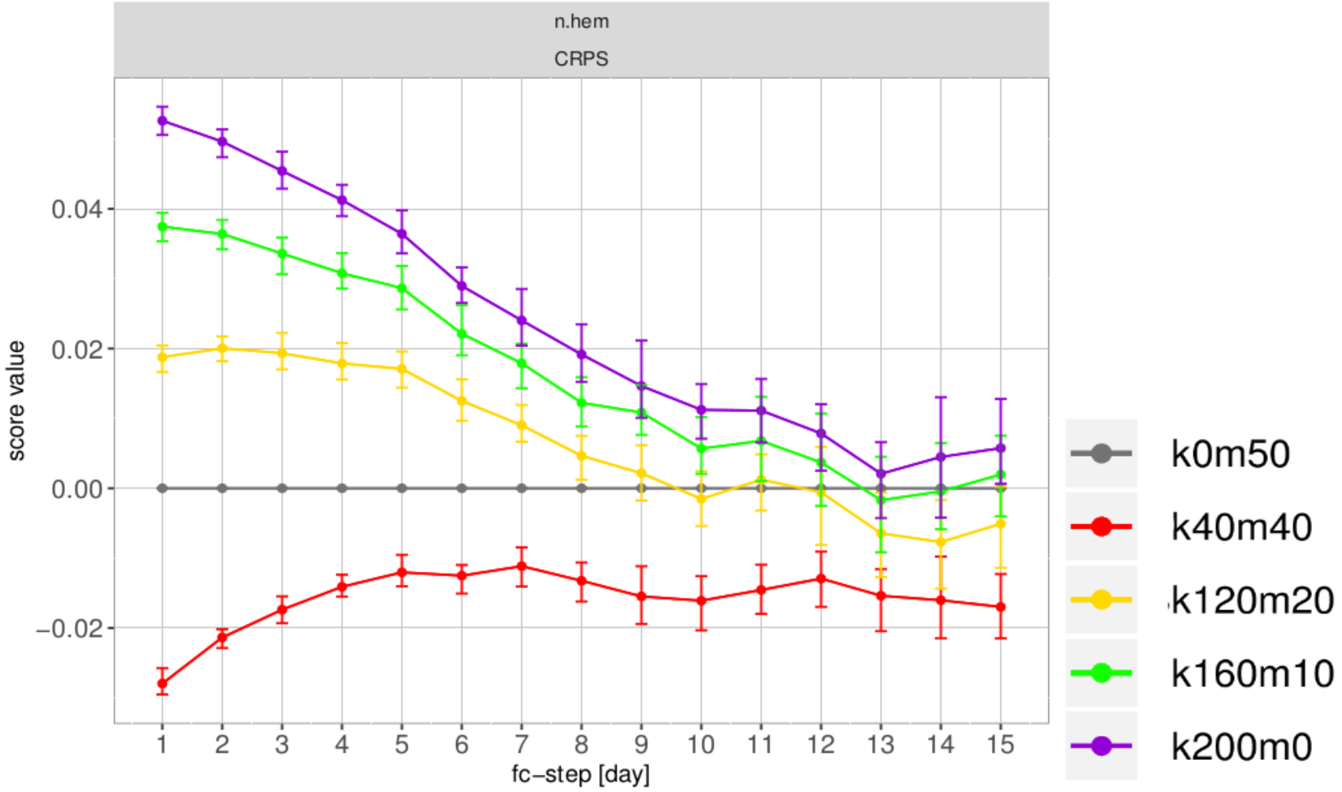
www.ecmwf.int/en/elibrary/technical-memoranda

Pooling k TCo399 members and m TCo639 members

850 hPa temperature vs. AN



2-metre temperature vs. OBS

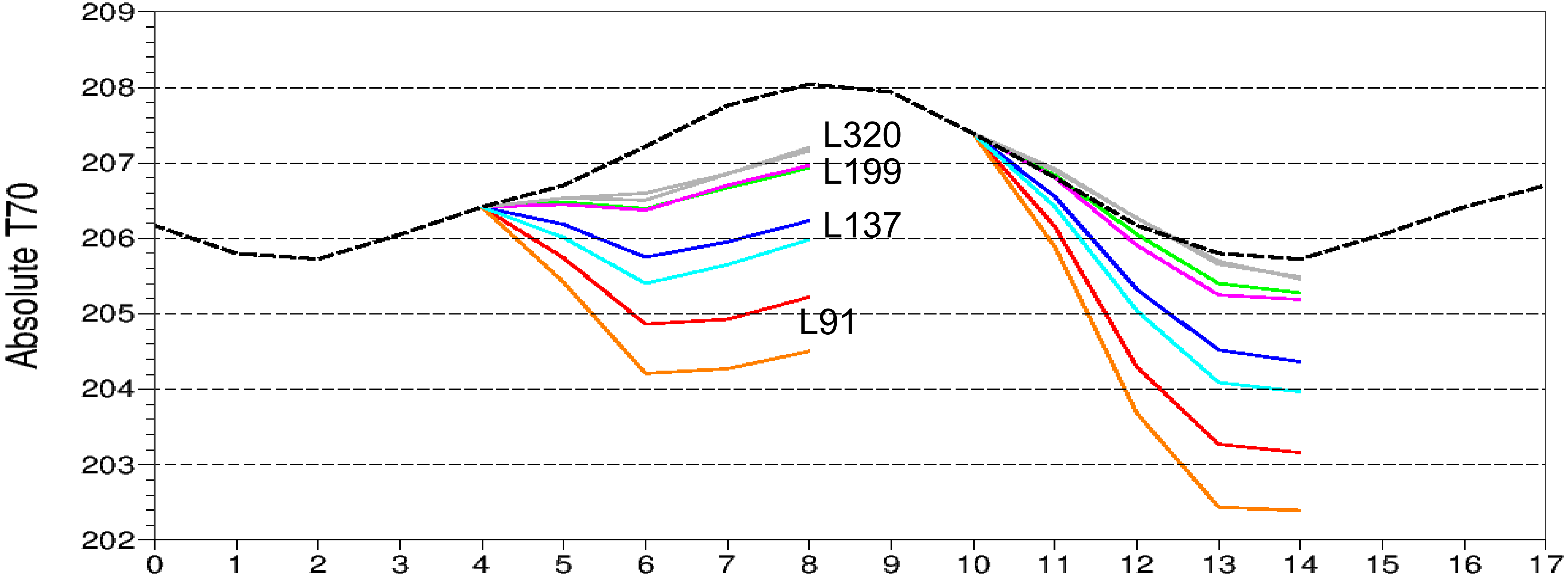


- CRPS difference relative to higher-resolution only (negative: better than higher-resolution only)
- Equal computational cost

ECMWF

M. Leutbecher, Z. Ben Bouallegue, in preparation
Baran et al.,arXiv:1811.05821

Impact of horizontal and vertical resolution changes



Red and orange =
TCo199L91 and TCo319L91

Dark blue and light blue =
TCo199L137 and TCo319L137

Green and pink =
TCo199L198 and TCo319L198

Grey and grey =
TCo199L320 and TCo319L320

ECMWF

Activities using OpenIFS

- Ongoing researches: surface processes, reduced precision, large eddy simulations, predictability of specific weather phenomena (MJO, typhoons etc.)
- New research & development areas, collaborations:
  - **EC-Earth** towards decadal predictions & climate projections: effective I/O handling, coupling interface, atmospheric composition with the next OpenIFS cycle
  - **climate*prediction*.net**: weather & climate experiments with OpenIFS@home
- OpenIFS in the education:
  - Meteorological & computing trainings based on a **complex, state-of-the-art NWP model**
  - Special tools & configurations: single column model, Metview macro system, idealized configurations
- Next OpenIFS cycle will be **cy43r3** (it was operational until June):
- Introduction of a new, more general **ECMWF training course on IFS**
- **5th OpenIFS user meeting, June 2019** (University of Reading, UK):
  Atmospheric rivers and their impact on forecasts

ECMWF

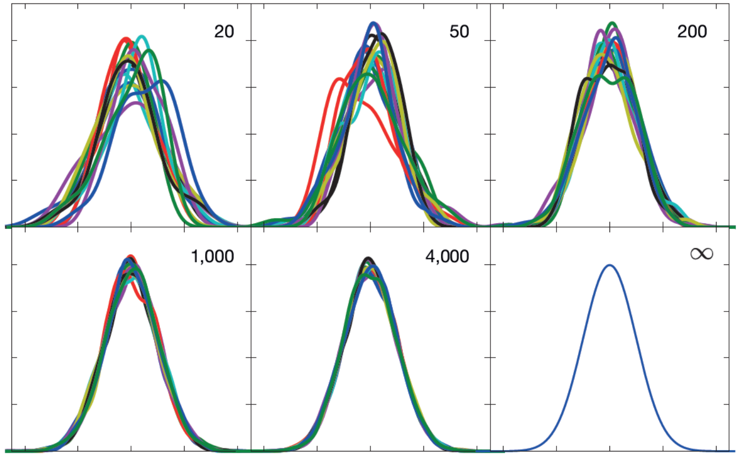
OpenIFS Meteorological Evaluation: https://software.ecmwf.int/wiki/x/jxwXBQ

Szépszó & Carver, 2018: New forecast evaluation tool for OpenIFS. *ECMWF Newsletter 156*, 14–15

Do less or do the same but cheaper

Single precision (Vana et al. 2017, MWR; Dueben et al. 2018, MWR):
- running IFS with single precision arithmetics saves **40%** of runtime,
- storing ensemble model output at even more reduced precision can save 67% of data volume:

→ to be implemented in **operations**



Less optimal ensemble (Leutbecher 2018, QJ):
- reduce ensemble size for research experimentation (ensemble skill scales with $C_M/C_\infty = 1 + 1/M$)

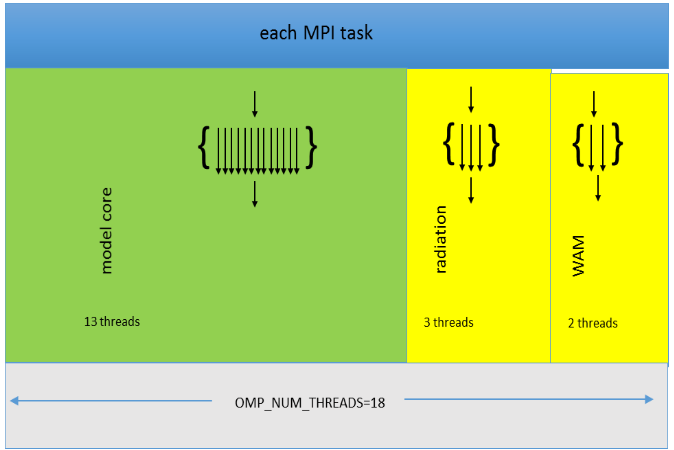
→ to be implemented for **research**

Concurrency:
- allocating threads/task (/across tasks) to model components like radiation or waves can save **20%**

→ to be implemented in **operations**

Overlapping communication & computation:
- through programming models (Fortran co-array vs GPI2 vs MPI) could save **15%**

→ to be explored further

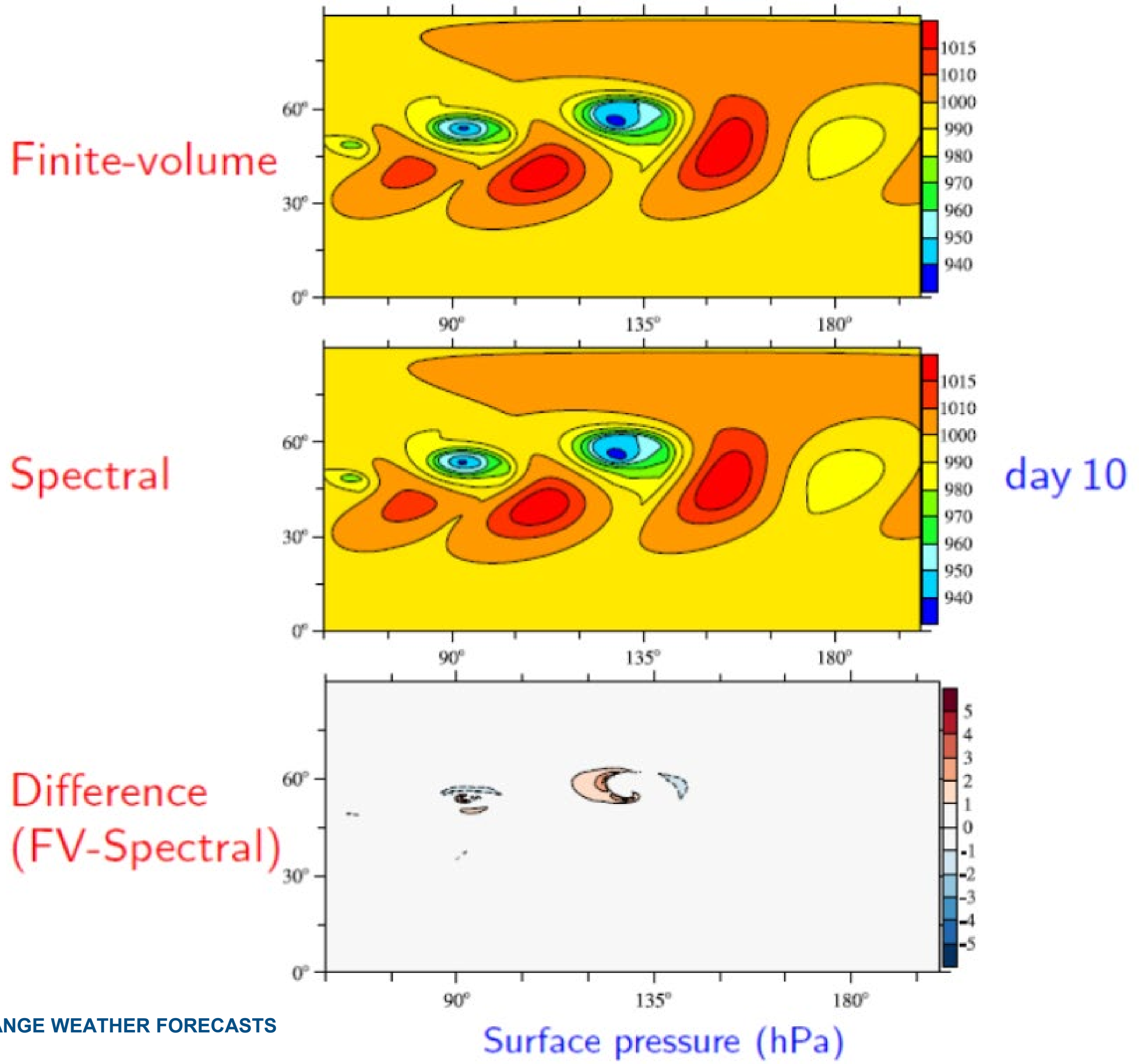


ECMWF

Finite-Volume dynamical core protoype

See Kűhnlein&Smolarkiewicz, 2017, for comparison with FV3 see Zarzycki et al. 2018

Dry baroclinic instability, FVM (O640) versus the spectral IFS ($T_{co}639$):

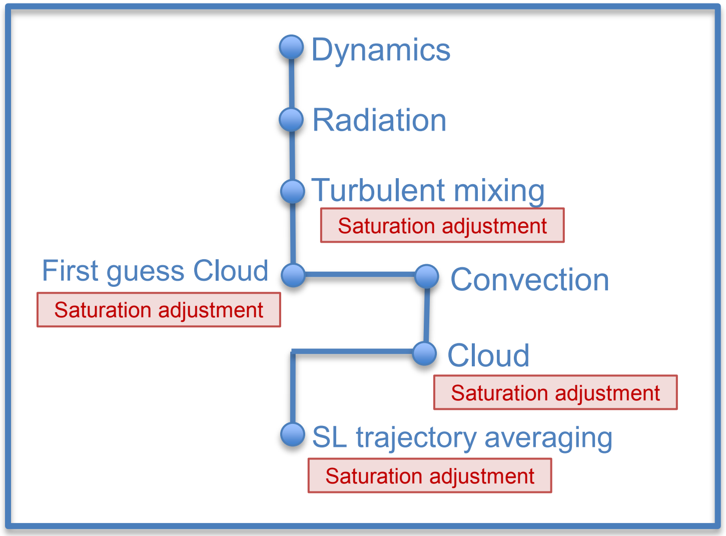


Progress IFS revised moist physics interactions

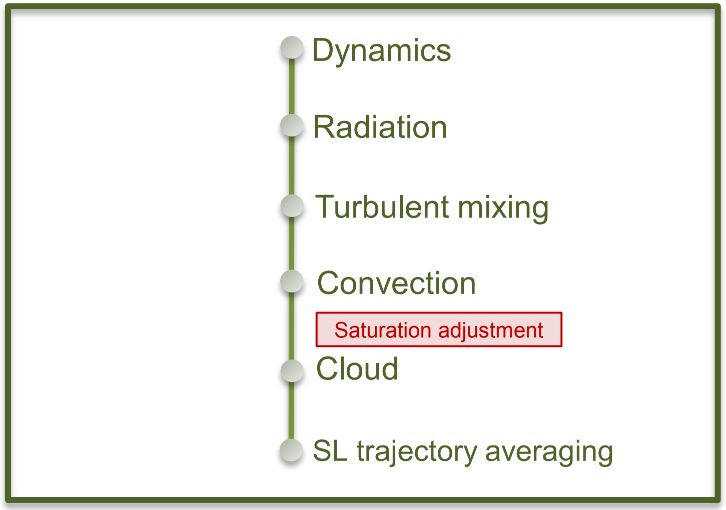
Good progress being made for the revised moist physics interactions:

- Correction of long-standing saturation adjustment bug
- Simplified calling sequence for moist physics
- Consistent treatment of mixed-phase saturation
- Correct SL physics averaging supersaturation check
- Improved convection – cloud scheme interaction
- Improved turbulent mixing – cloud scheme interaction

Current IFS



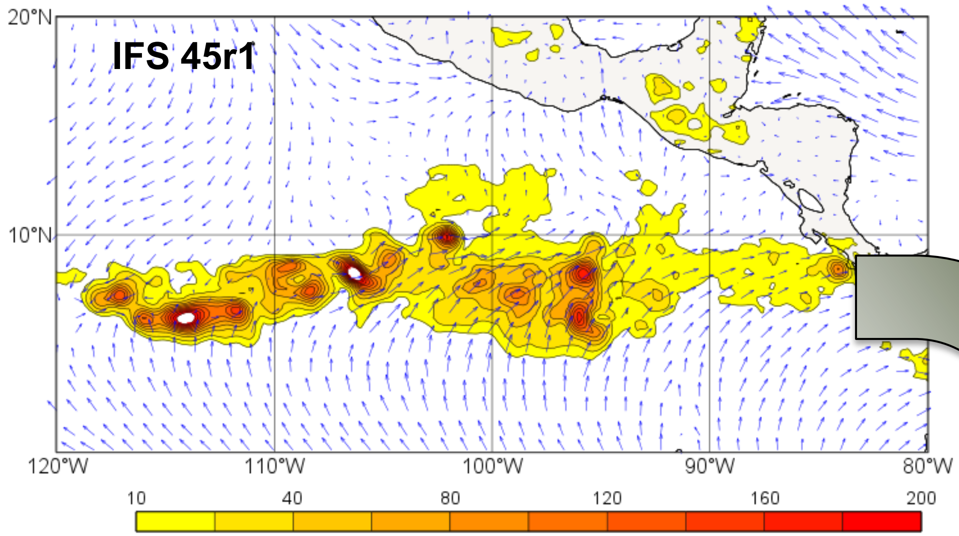
Future IFS



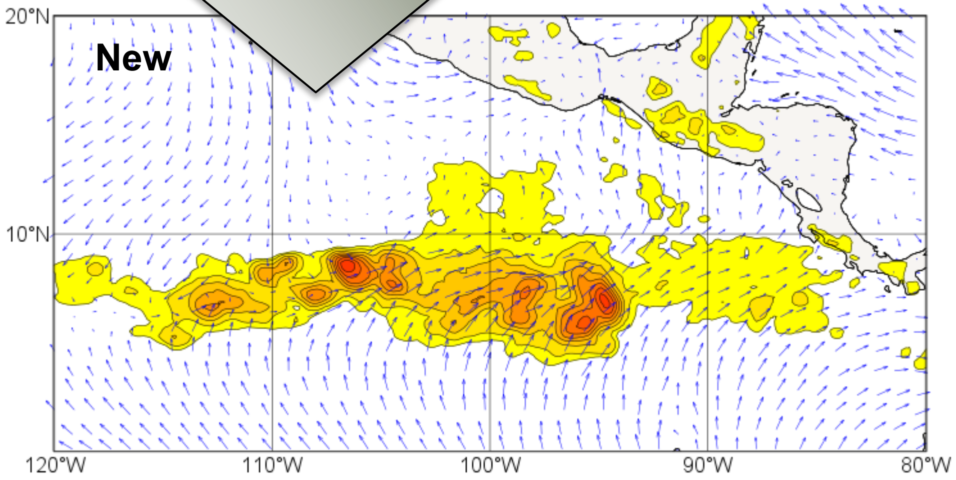
ECMWF

Improved IFS physics calling sequence and saturation adjustment bug fix

IFS now: Overactive precipitation cells in the Tropics

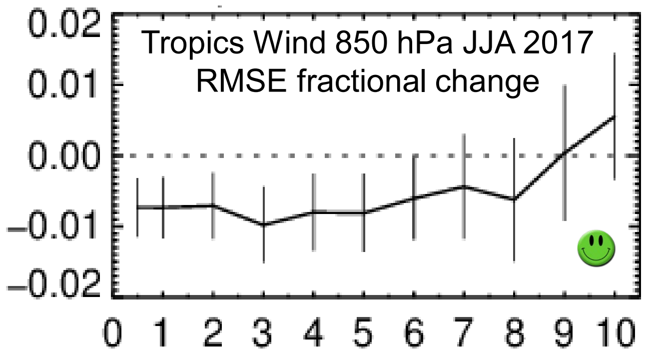


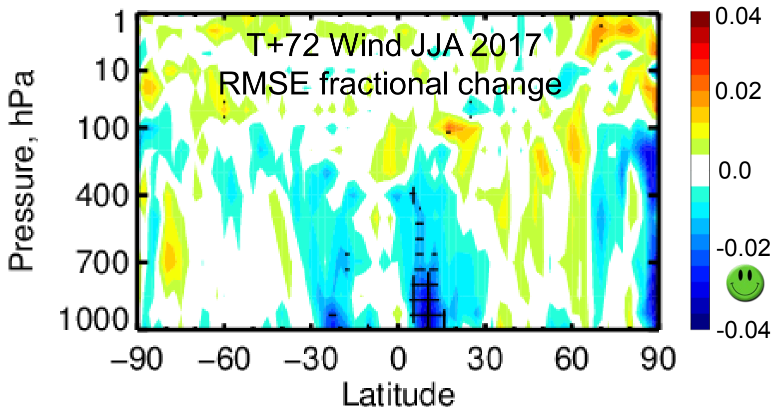
2017-06-05 00UTC T+24 Accumulated Precipitation (mm)



New saturation adjustment:

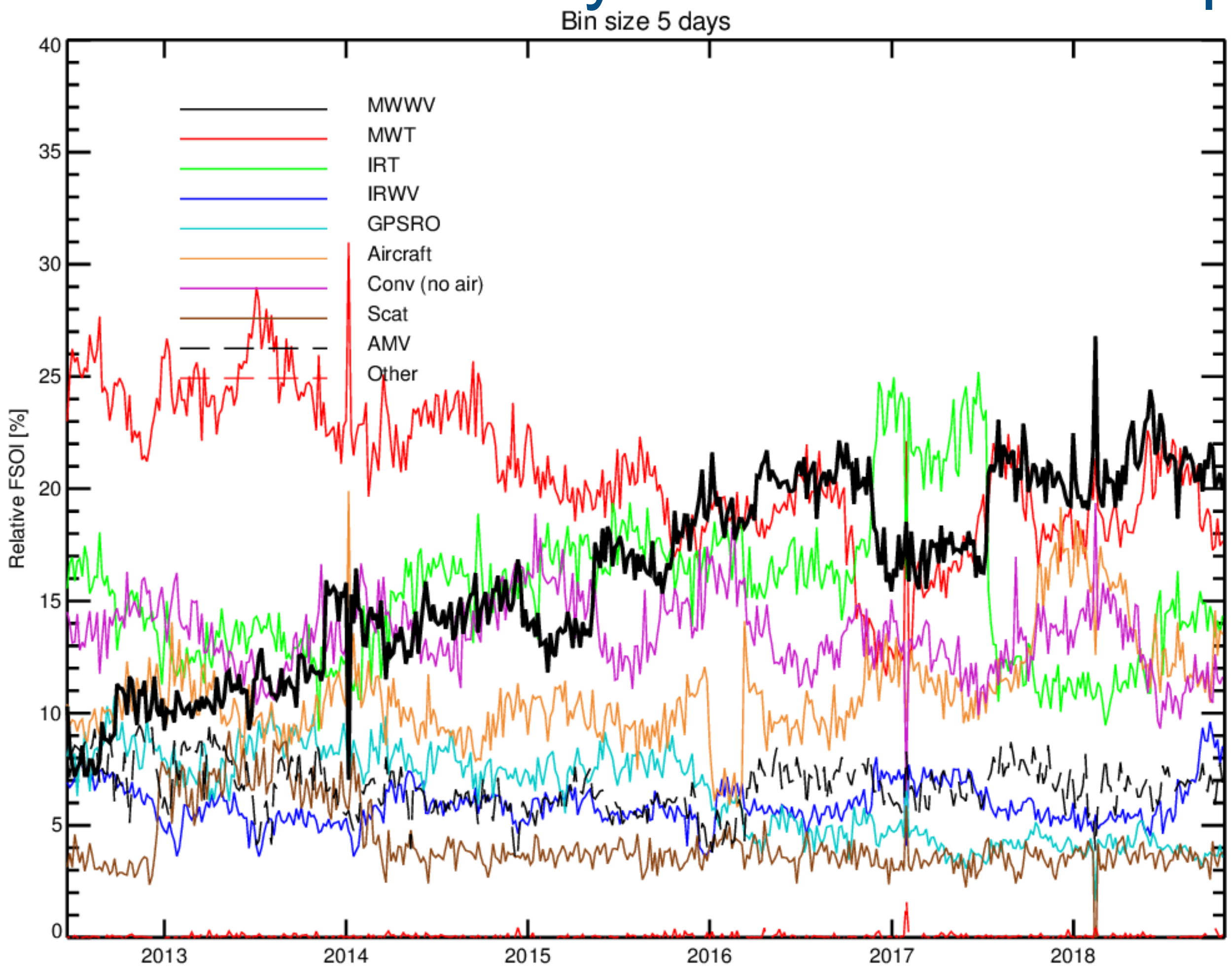
- Reduces overly strong resolved-scale updraughts
- Reduces overestimate of precipitation along ITCZ
- Improves tropical winds

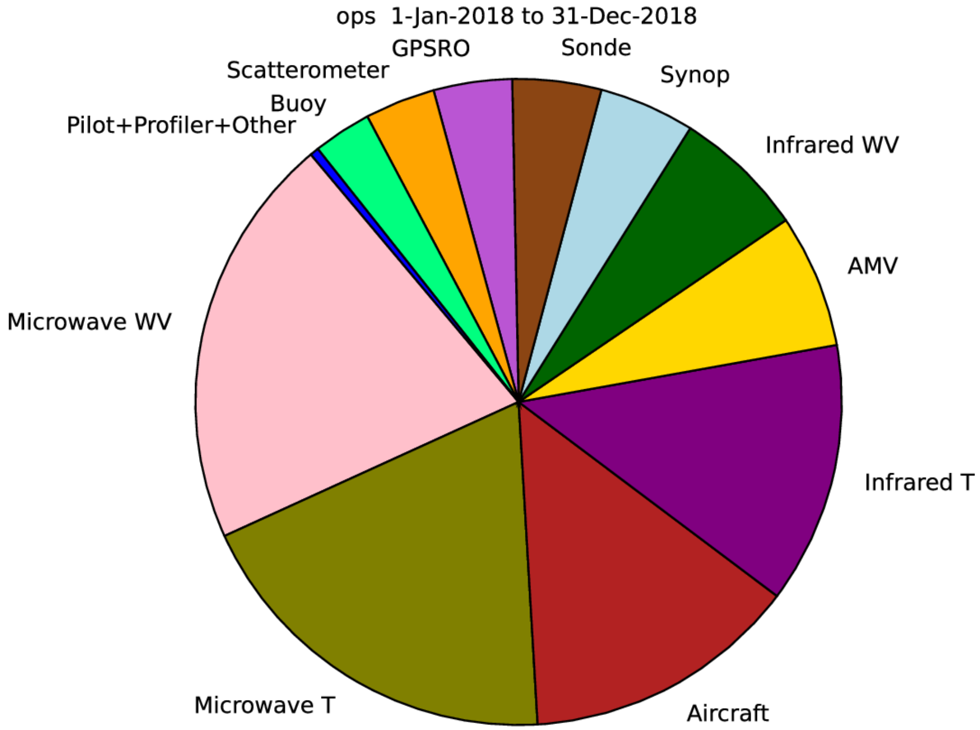




ECMWF

Forecast sensitivity of observation impact





Caution It is possible to improve FSOI just by reducing Obs error, but forecast scores degrade vice versa changes to observation usage that improve forecast can decrease FSOI

Aeolus

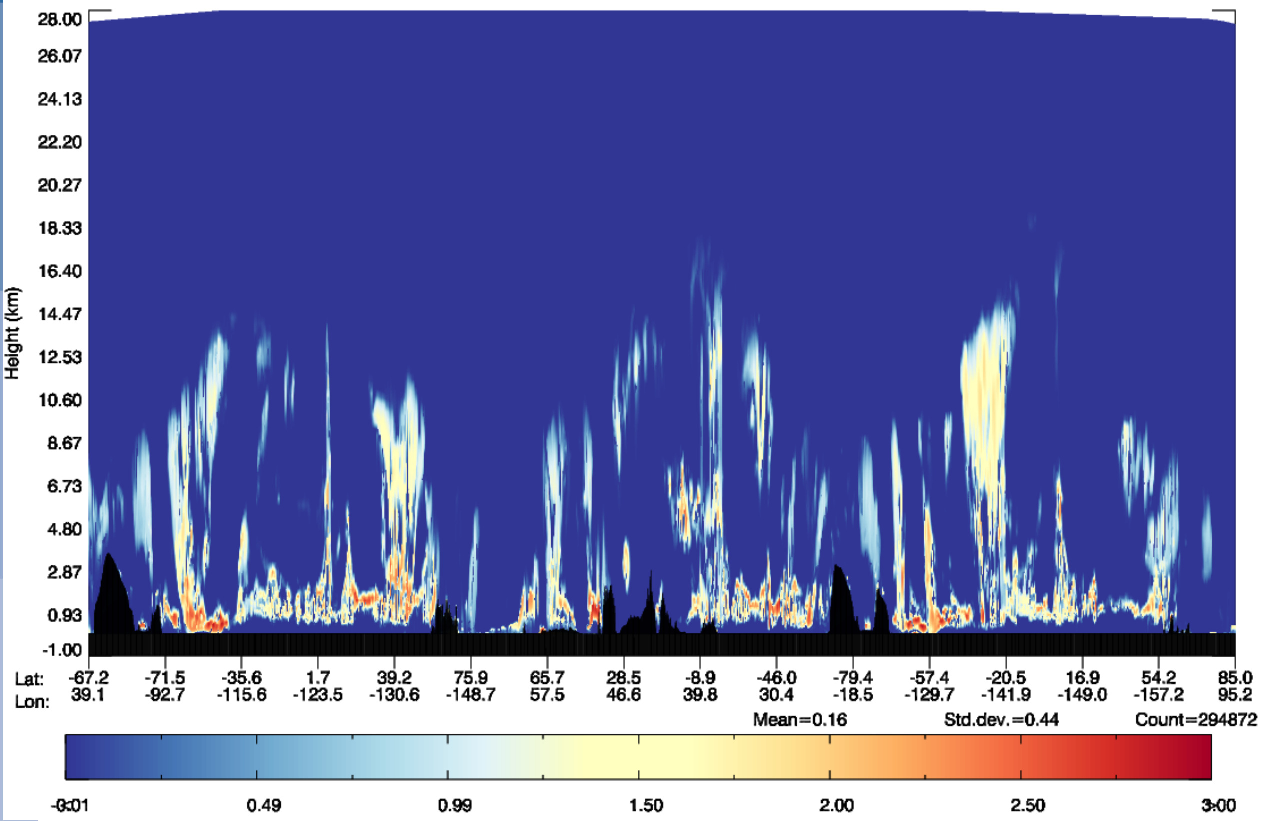
- ESA Earth Explorer Core Mission
  - Chosen in 1999
  - Part of ESA's Living Planet Programme
- Doppler wind lidar (DWL) payload
- Technology demonstration; designed to be a 3 year mission

Mission status

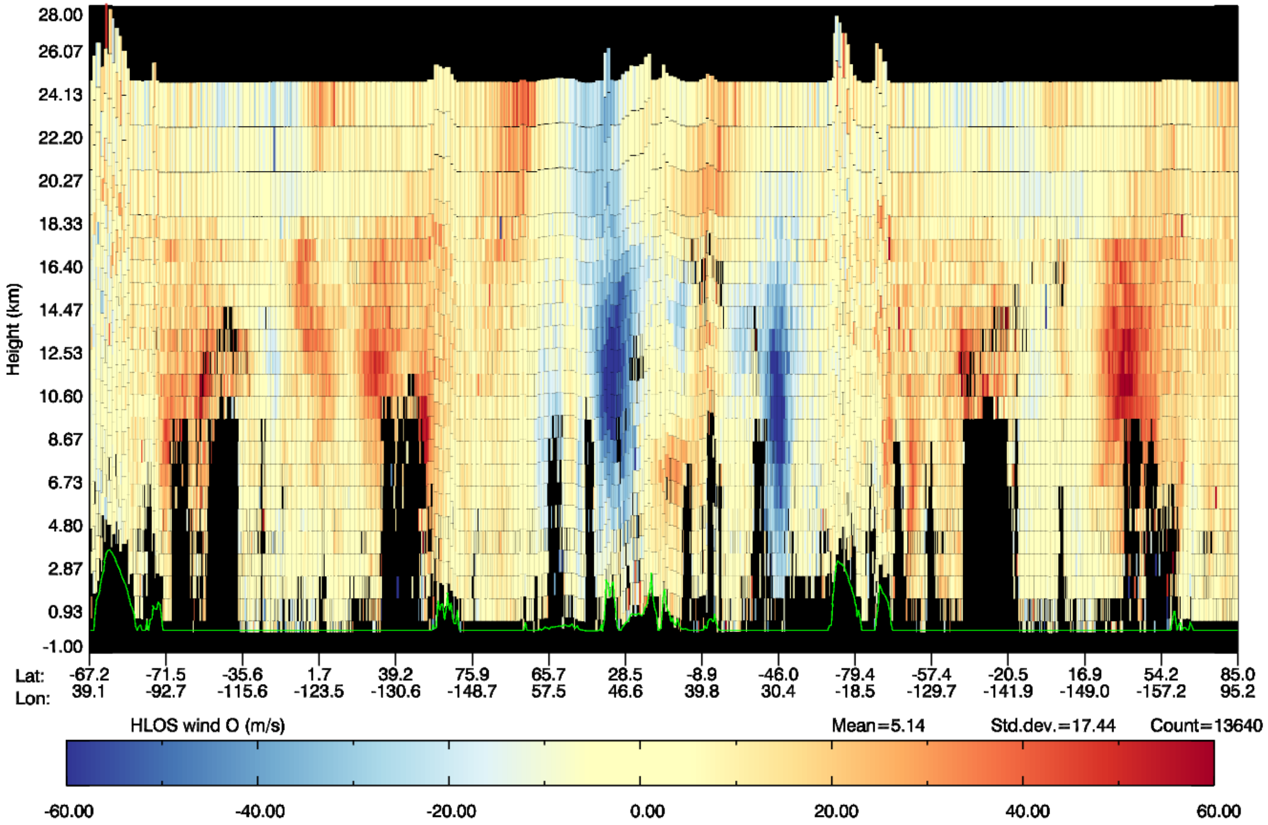
- **Launched on 22/8/2018!** *delayed by a decade*
  - *First* European lidar in space, after 20 years of development challenges
  - *First* wind lidar in space
  - *First* high-power UV lidar in space, with stringent frequency stability requirements
- **Aeolus has been technically proven to work as the first wind lidar in space**
  - Over 4 months of winds data

Rayleigh and Mie winds are complimentary

ECMWF model cloud



Rayleigh-clear L2B HLOS winds

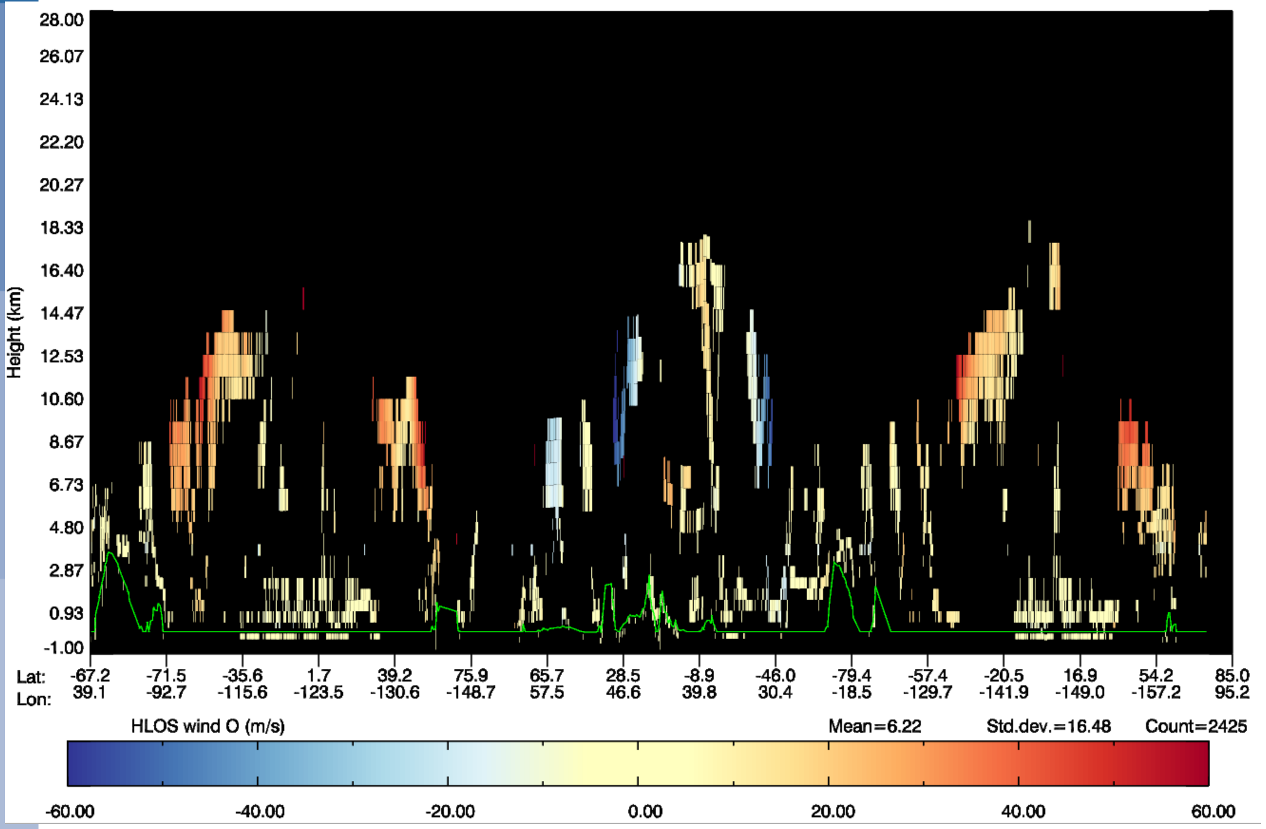


~5.5 times more Rayleigh than Mie winds

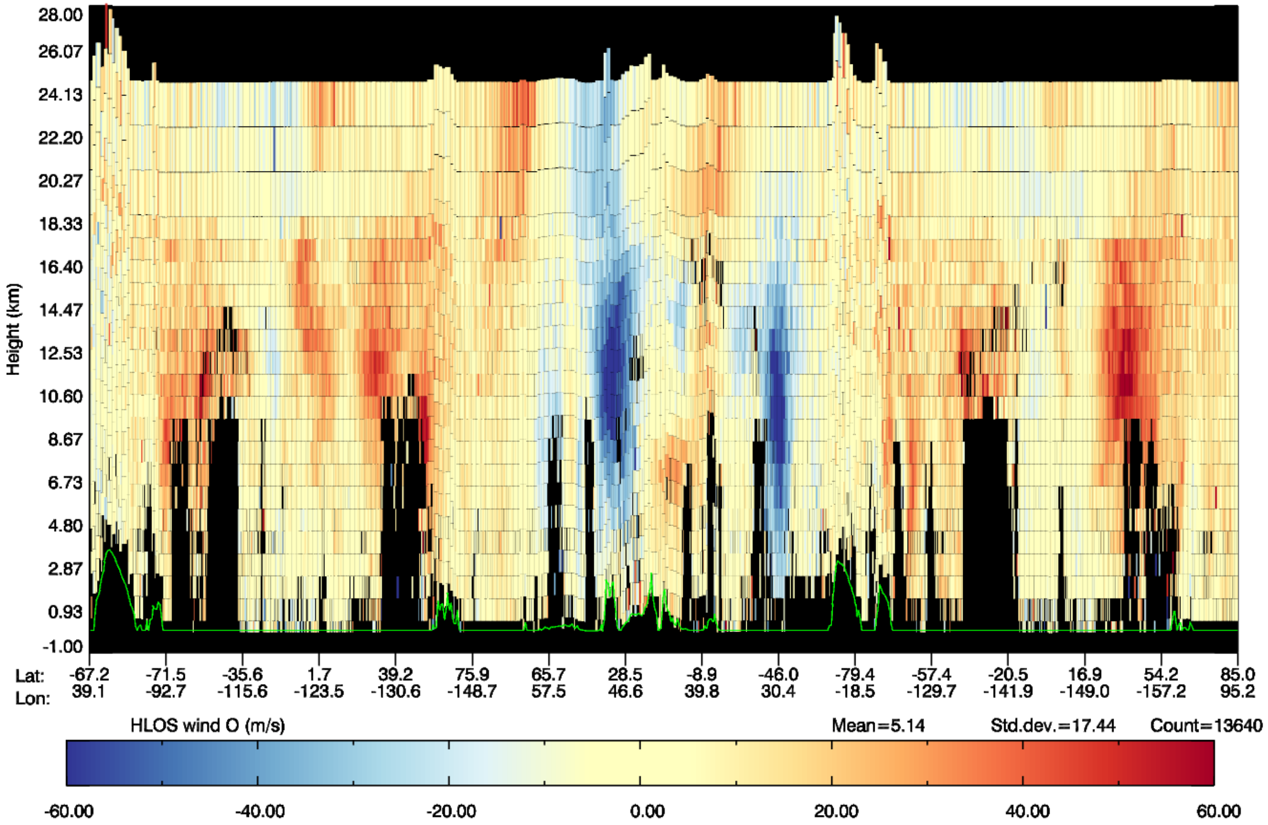
This example has range-bin settings more suited to NWP

Rayleigh and Mie winds are complimentary

Mie-cloudy L2B HLOS winds



Rayleigh-clear L2B HLOS winds

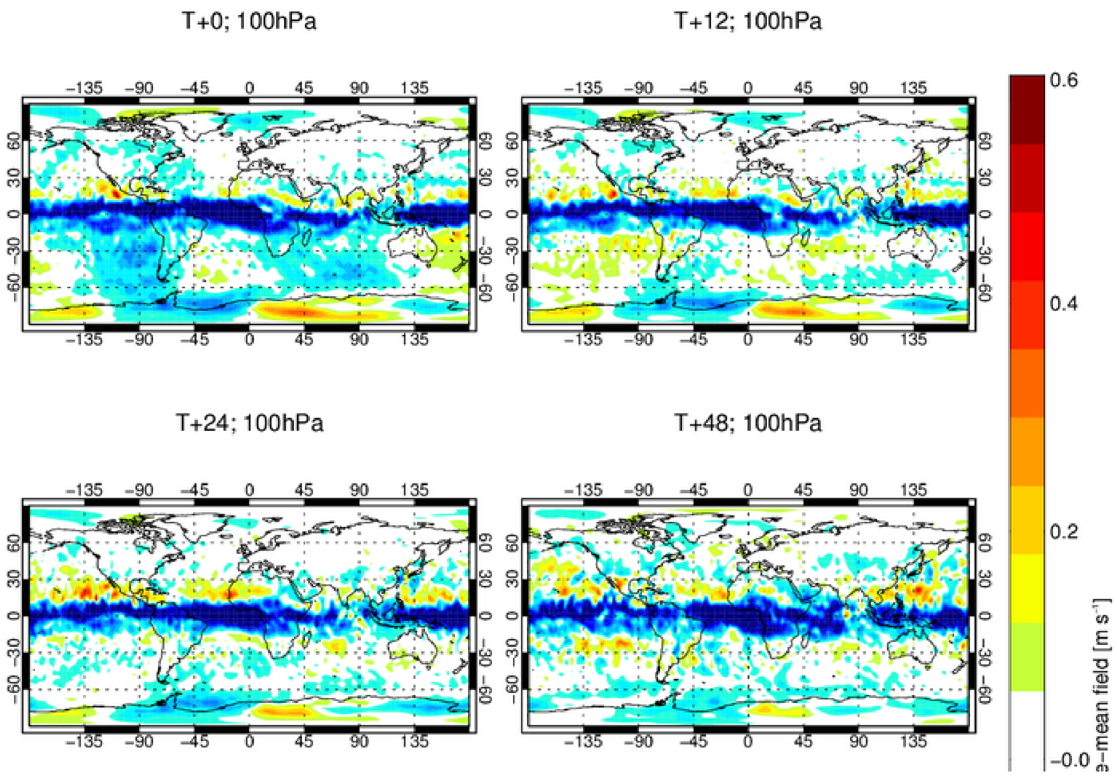


~5.5 times more Rayleigh than Mie winds

This example has range-bin settings more suited to NWP

Overall impression of the Aeolus winds (so far) from an NWP perspective

- Random errors are larger than hoped for, but still very useful for NWP
  - Obs error std. dev. is ~4 m/s for Rayleigh and ~2.3 m/s for Mie
- Significant time varying biases have been observed. Characteristics/probable causes:
- The laser energy drop off with time is a major concern for the lifetime of Aeolus
  - However, ESA and industry believe that the second laser (FM-B) will be much more controllable
- Preliminary NWP impact assessment shows Aeolus **improves short-range forecasts** of tropospheric wind, humidity and temperature verified against observations



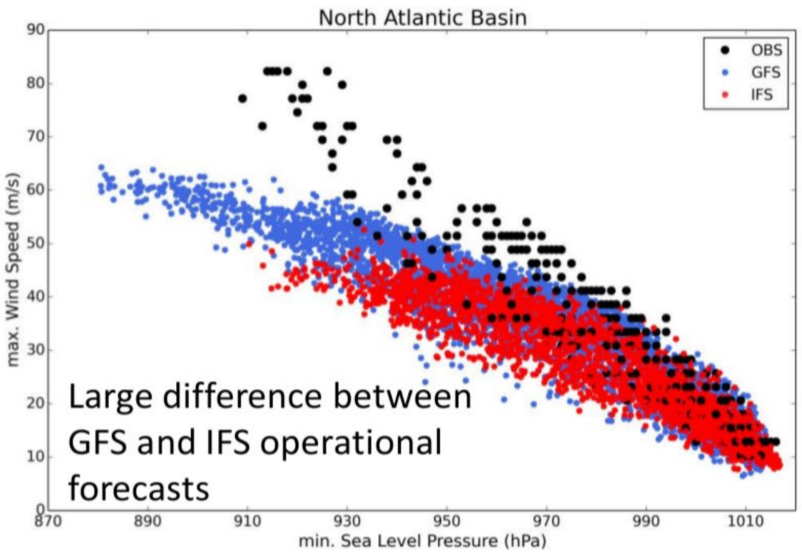
Increasing tropical easterlies by 0.5 m/s

Wind/pressure relation

Linus Magnusson and Jan-Huey
for internal use ONLY

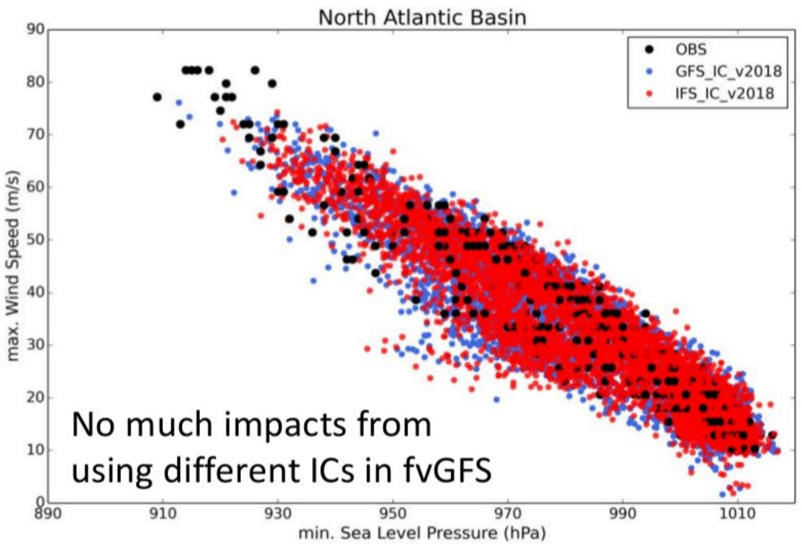
GFS (blue) and IFS (red)

Wind speed



Pressure

FV3



FV3 much better relation than IFS and GFS