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 2016-2025 strategy: overview

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## Horizontal resolution upgrade (March 2016 – CY41R2)

<table>
<thead>
<tr>
<th>Grid res.</th>
<th>HRES</th>
<th>ENS LegA LegB/M’ly</th>
<th>4DV inner loops 1&lt;sup&gt;st&lt;/sup&gt; 2&lt;sup&gt;nd&lt;/sup&gt; 3&lt;sup&gt;rd&lt;/sup&gt;</th>
<th>EDA Outer 1&lt;sup&gt;st&lt;/sup&gt; 2&lt;sup&gt;nd&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>128 km</td>
<td>41r1</td>
<td>TL255 TL255 TL255</td>
<td>TL159 TL159</td>
<td>TL191 TL191</td>
</tr>
<tr>
<td>64 km</td>
<td>41r2</td>
<td>TL319 TL399 TL399</td>
<td>TL399</td>
<td>TL399</td>
</tr>
<tr>
<td>32 km</td>
<td></td>
<td>TL639 TCo319</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 km</td>
<td></td>
<td>TL1279 TCo639</td>
<td></td>
<td>TCo639</td>
</tr>
<tr>
<td>9 km</td>
<td></td>
<td>TCo1279</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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
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

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?
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.

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.

**PARTIAL 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

Uncoupled simulations

Coupled simulations

Progn equation for SST
(Zeng and Beljaars, 2005)

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

<table>
<thead>
<tr>
<th>TC fcst mean position error (km)</th>
<th>TC fcst mean absolute intensity error (hPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Oper (43r3)</strong></td>
<td><strong>Oper (43r3)</strong></td>
</tr>
<tr>
<td>45r1 (coupled)</td>
<td>45r1 (coupled)</td>
</tr>
</tbody>
</table>

Current Operational IFS: HRES T_co1279 (~9km)

Sample size:

749 696 629 558 486 418 369 316 275 239 202 175 155 135 112 98 80 72 59 49 44
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

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

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
45r1 includes more realistic model uncertainty schemes

- 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)
Probabilistic lightning prediction from ensemble forecasts

Ensemble forecast from oper 45r1 esuite
Probability[flash density > 0.1 fl/100km²/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.

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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**

Users expect all products are available

Allow more time for computations (earlier cut-off)

Collect more observations (later cut-off)

04z

06:55z
Continuous Data Assimilation Configuration

DA analysis

Fixed minimisation problem

- 10.5 min DA
- 9 min DA
- 12.5 min DA
- 6 min DA

Outer loop 1
Outer loop 2
Outer loop 3
Final traj

Current

Forecast

Series of slightly different minimisation problems

- 03:50
- 04:00
- 04:25

Outer loop 1
Outer loop 2
Outer loop 3
Outer loop 4
Final traj

New

Forecast

- 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.

ECMWF

- Opens the possibility of a fully continuous assimilation system.
Extra observations assimilated in Continuous DA configuration
Improvements at all forecast ranges

Europe


Confidence range 95% with AR(2) inflation and Sidak correction for 4 independent tests

Z: Europe 35° to 70°; −10° to 40°; 500 hPa

Vector wind RMS error

(good)

(bad)
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
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.

\[ R_{SEVIRI} = \begin{pmatrix} 0.46 & 0.20 \\ 0.20 & 0.30 \end{pmatrix} \quad R_{AHI} = \begin{pmatrix} 0.55 & 0.43 & 0.22 \\ 0.43 & 0.46 & 0.31 \\ 0.22 & 0.31 & 0.35 \end{pmatrix} \]

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: \( \text{SST}_{\text{AN}} \neq \text{SST}_{\text{step 0}} \)

• From 46R1: \( \text{SST}_{\text{AN}} = \text{SST}_{\text{step 0}} \)

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

**Jason-2**

**Bias = Alt. - Mod.**

Model overestimates

Model underestimates
Feedback to the atmosphere: Charnock parameter $\alpha$

with default physics (CY45R1)

with Ardhuin et al. 2010 physics

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)
Headline scores – 500hPa Geop height


Z: SH –90° to –20°, 500hPa

Z: NH 20° to 90°, 500hPa

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
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)

Change in U (m/s)

resolved  parametrized

13 km  9 km
2.5 km  2.5 km

Courtesy Daniel Klocke and Nils Wedi

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

Convection - DWD

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

Total water + ice content

kg/m2

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

Observations

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)

- Qualitative good agreement of snow density, in particular upper layers
- Issues with densification at the end of the season
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 $T_{2m}$.
Example of CAT and MWT diagnostics

Based on Ellrod index, 3D Frontogenetic index, etc projected 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

- 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

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

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
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
  - **climateprediction.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

OpenIFS Meteorological Evaluation: [https://software.ecmwf.int/wiki/x/jxwXBQ](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
Finite-Volume dynamical core protoype

See Kühnlein & Smolarkiewicz, 2017, for comparison with FV3 see Zarzycki et al. 2018
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
Improved IFS physics calling sequence and saturation adjustment bug fix

**IFS now:** Overactive precipitation cells in the Tropics

**New saturation adjustment:**
- Reduces overly strong resolved-scale updraughts
- Reduces overestimate of precipitation along ITCZ
- Improves tropical winds
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

GFS (blue) and IFS (red)

FV3

GFS (blue) and IFS (red)

FV3 much better relation than IFS and GFS

Large difference between GFS and IFS operational forecasts

No much impacts from using different ICs in fvGFS