ECMWF: modelling and data assimilation

Christian Kühnlein for ECMWF colleagues

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ECMWF 2016-2025 strategy: overview

Forecast targets by 2025:

- Ensemble predictions of **high impact weather** up to two weeks ahead
- Seamless approach, aiming towards predictions of **large scale patterns and regime transitions** up to four weeks ahead and **global-scale anomalies** up to a year ahead

Research goals by 2025:

- Research at frontiers of knowledge
- 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 National Met Services, universities and research institutes (OpenIFS)
- Pooling expertise to improve scalability

Continued support:

Dedicated HPC, software, and data resources for Member States
Advanced training

Outline

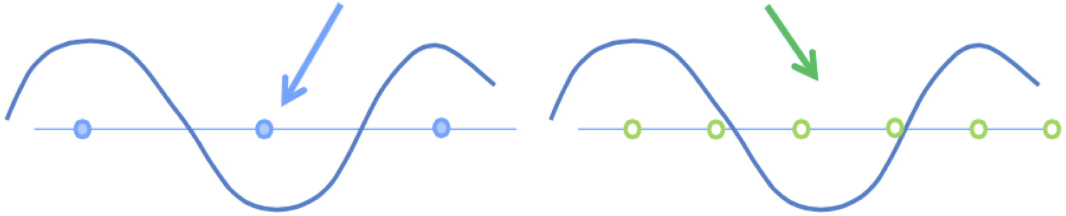
1. Highlights of recent model upgrades
    a. 8 March 2016 (CY41R2) - increased horizontal resolution of atmospheric models
    b. 22 Nov 2016 (CY43R1) - increased ocean resolution
    c. 11 July 2017 (CY43R3) - humidity background errors from EDA, TC structure, new radiation scheme, aerosol climatologies
    d. 5 June 2018 (CY45R1) - ocean and sea-ice coupled in HRES, ENS, SEAS:
       increased number of obs assimilated;
       radiosondes drift and improved aircraft obs biascorrection;
       atmospheric model changes (warm-rain, convection);
       mod. uncertainty SPPT scheme more physical, SKEP off
       new product for lightning and its probability
2. Selected R&D activities and challenges (CY46R1 and beyond….)

Resolution upgrade: cubic octahedral reduced Gaussian grid

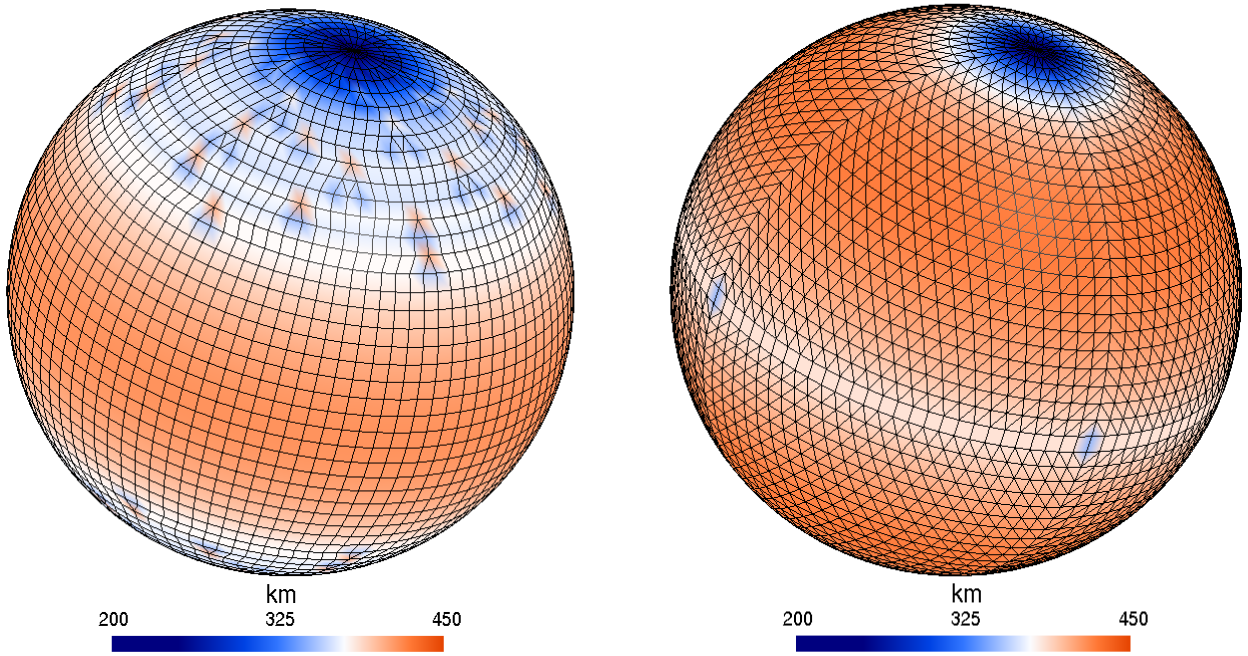
2N+1 gridpoints to N waves : T_L linear truncation
4N+1 gridpoints to N waves : T_c cubic truncation

- Mathematically more correct in the presence of nonlinear terms in governing equations
- Less numerical filtering – almost no numerical diffusion, no dealiasing
- Better mass conservation
- Less expensive than the equivalent linear truncation
- Naming convection for cubic reduced Gaussian grid ”TCo”

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

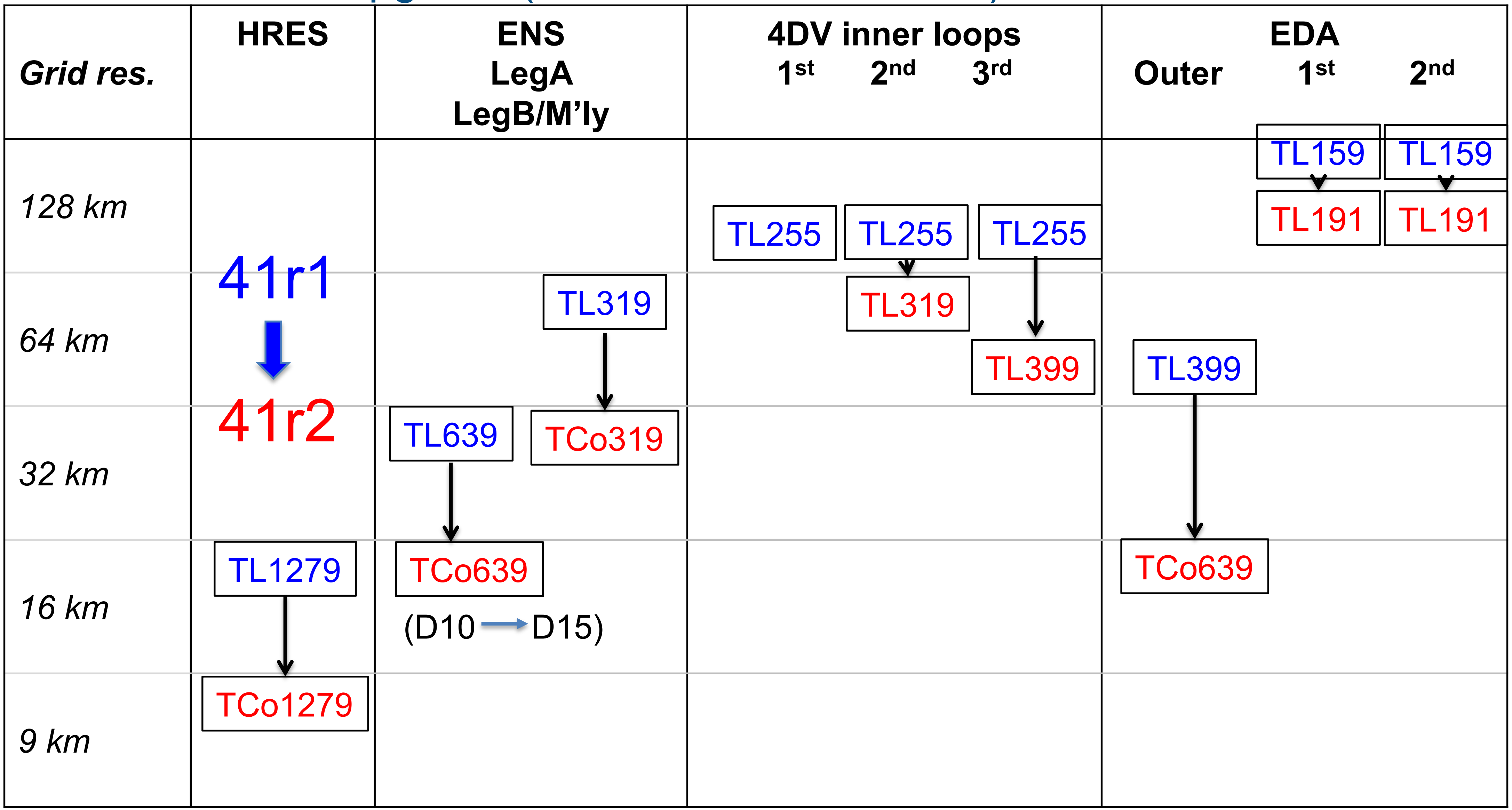


“N24 Reduced Gaussian” “O24 Octahedral reduced Gaussian”

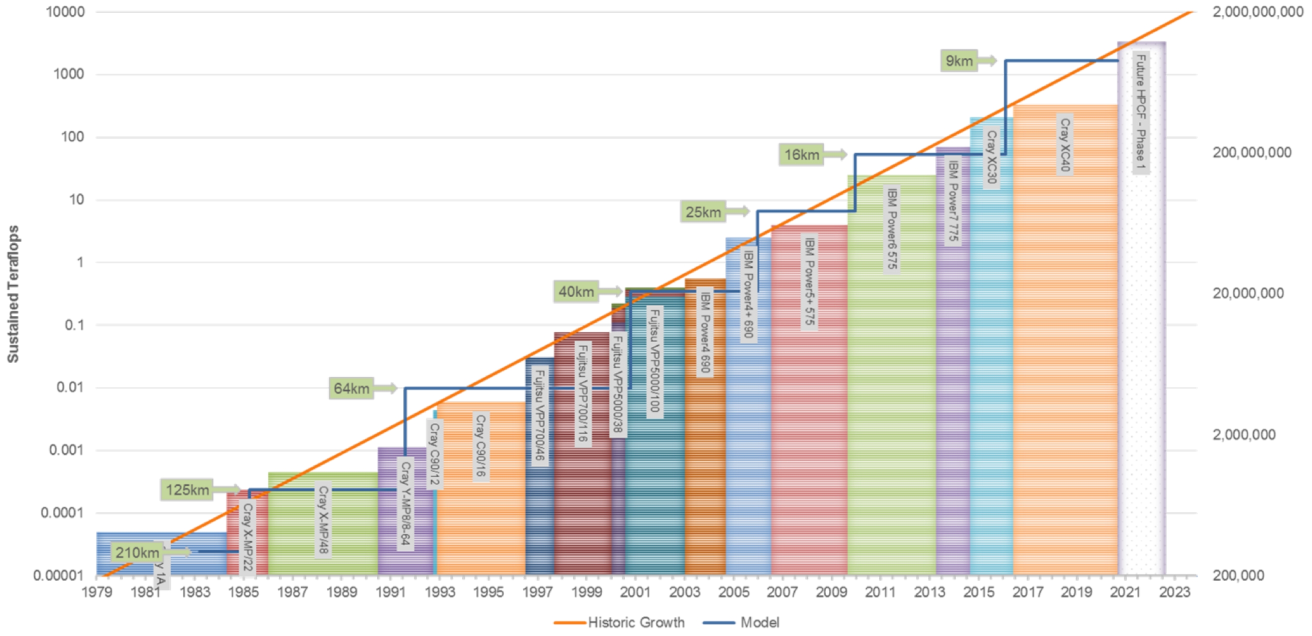


Malardel et al., ECMWF Newsletter 146

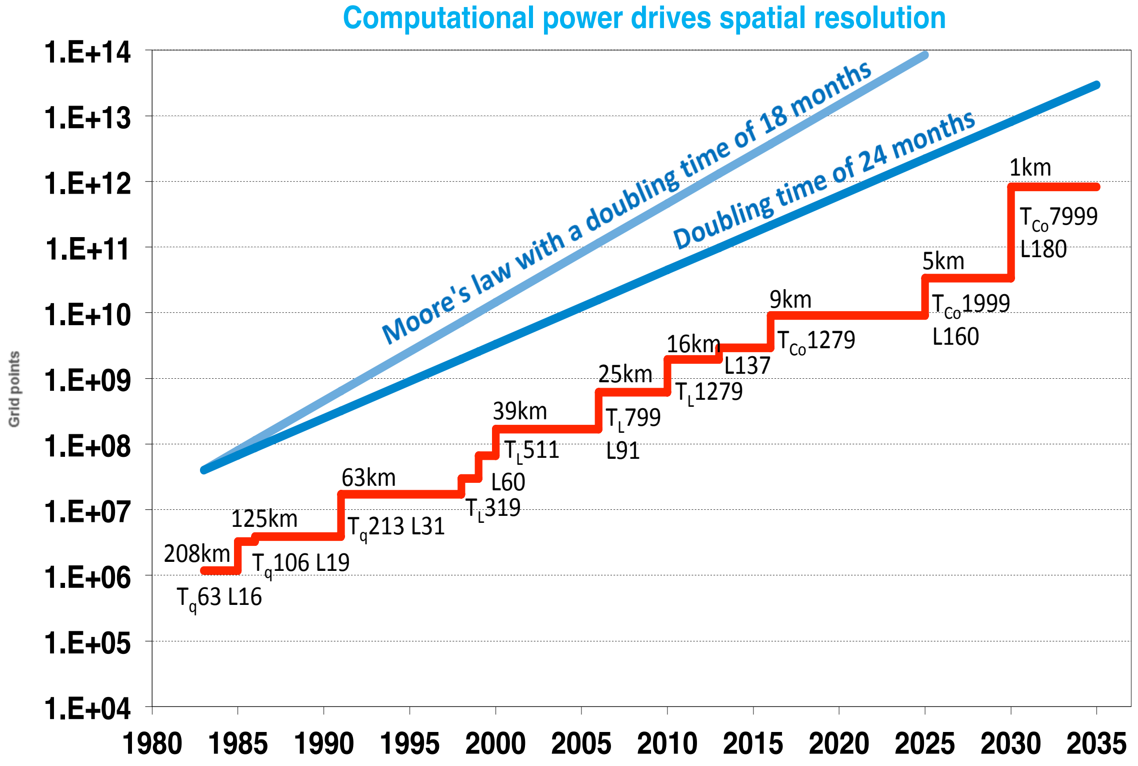
Horizontal resolution upgrade (March 2016 – CY41R2)



Holm et al., ECMWF Newsletter 147



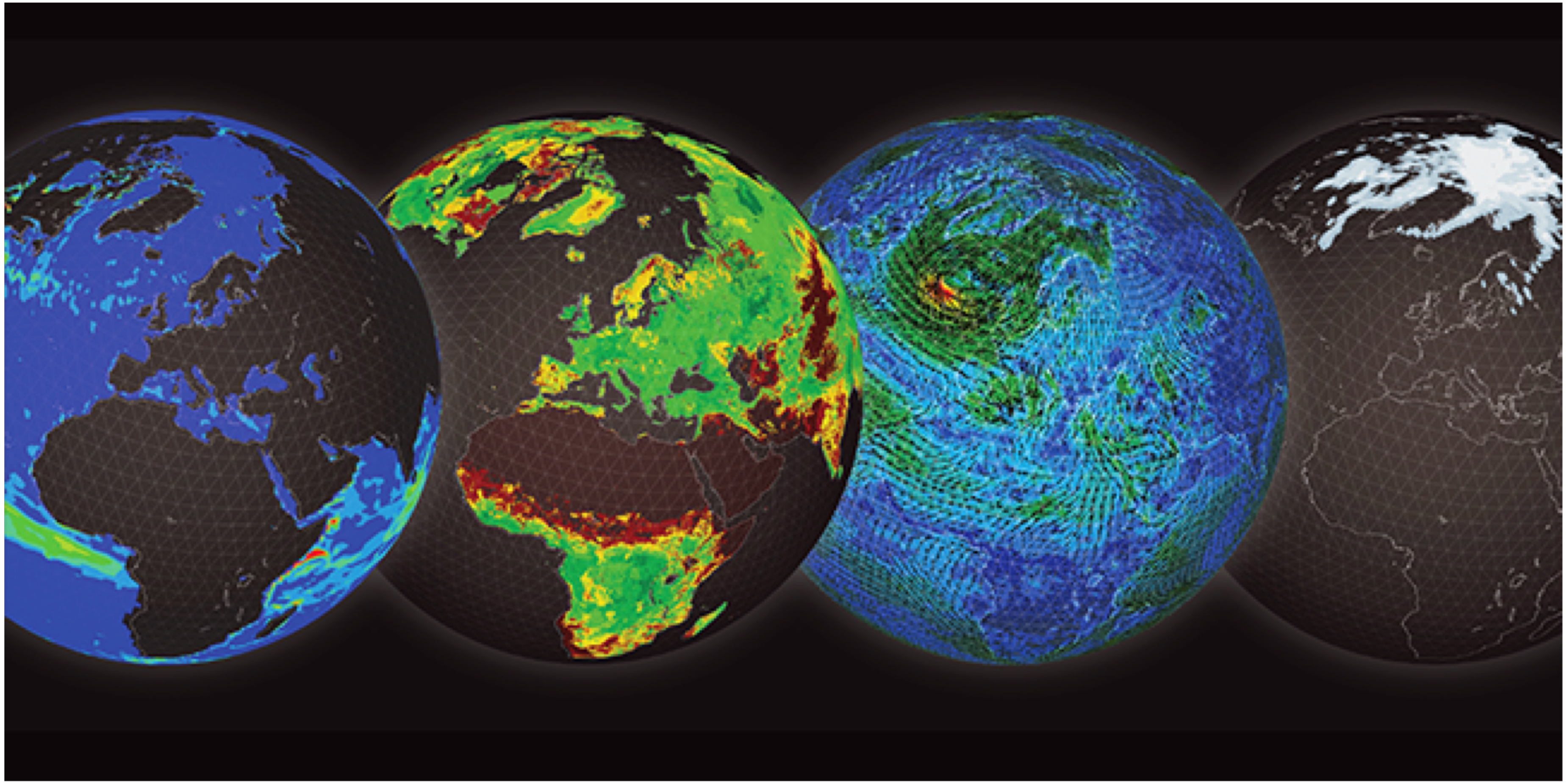
Sustained HPC performance



ECMWF's progress in degrees of freedom
(levels x grid columns x prognostic variables)

(Schulthess et al, 2018)

Ocean – Land – Atmosphere – Sea ice



Earth surface modelling components @ECMWF in 2018

- **NEMO3.4**

  NEMO3.4 (Nucleus for European Modelling of the Ocean)

  Madec et al. (2008)

  Mogensen et al. (2012)

  ORCA1_Z42: 1.0° x 1.0°

  ORCA025_Z75 : 0.25° x 0.25°

- **EC-WAM**

  ECMWF Wave Model

  Janssen, (2004)

  Janssen et al. (2013)

  ENS-WAM : 0.25° x 0.25°

  HRES-WAM: 0.125° x 0.125°

- **LIM2**

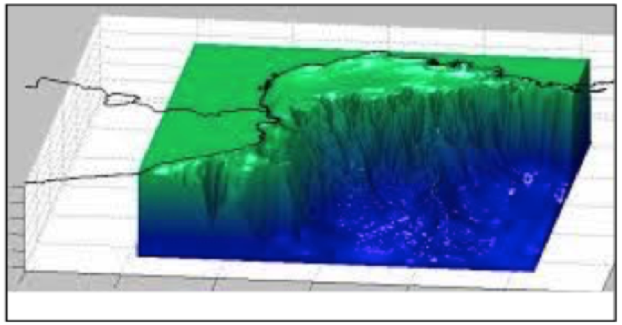
  The Louvain-la-Neuve Sea Ice Model

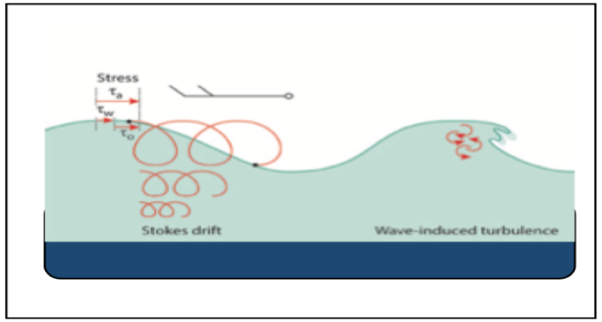
  Fichefet and Morales Maqueda (1997)

  Bouillon et al. (2009)

  Vancoppenolle et al. (2009)

  ORCA025_Z75 : 0.25° x 0.25°





- **Hydrology-TESSEL**

  Balsamo et al. (2009)
  van den Hurk and Viterbo (2003)

  Global Soil Texture (FAO)

  New hydraulic properties

  Variable Infiltration capacity & surface runoff revision

- **NEW SNOW**

  Dutra et al. (2010)

  Revised snow density

  Liquid water reservoir

  Revision of Albedo and sub-grid snow cover

- **NEW LAI**

  Boussetta et al. (2013)

  New satellite-based

  Leaf-Area-Index

- **SOIL Evaporation**

  Balsamo et al. (2011),

  Albergel et al. (2012)

- **H_2O / E / CO_2**

  Integration of

  Carbon/Energy/Water

  Boussetta et al. 2013

  Agusti-Panareda et al. 2015

- **Lake & Coastal area**

  Mironov et al (2010),

  Dutra et al. (2010),

  Balsamo et al. (2012, 2010)

  Extra tile (9) to for sub-grid lakes and ice

  LW tiling (Dutra)

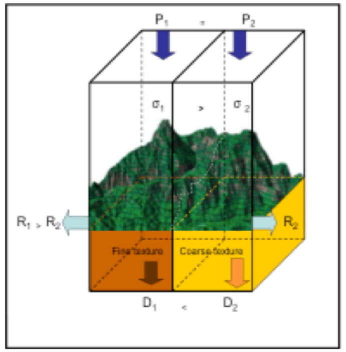
- **Enhance ML**

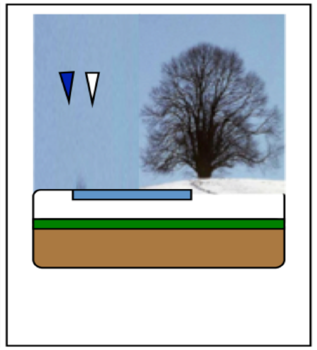
  Snow ML5

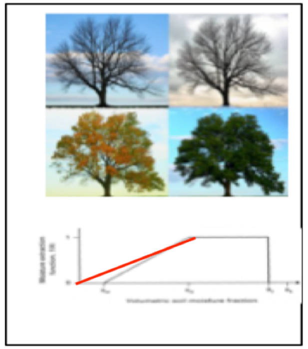
  Soil ML9

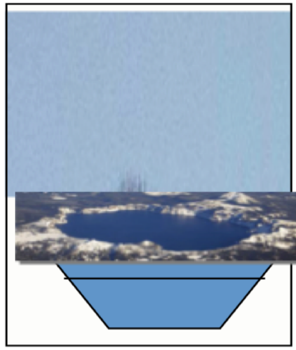
  Dutra et al. (2012, 2016)

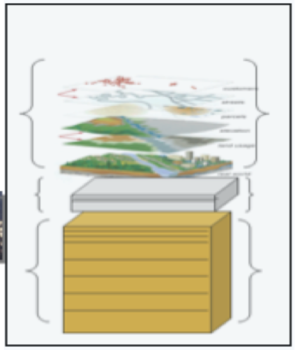
  Balsamo et al. (2016)











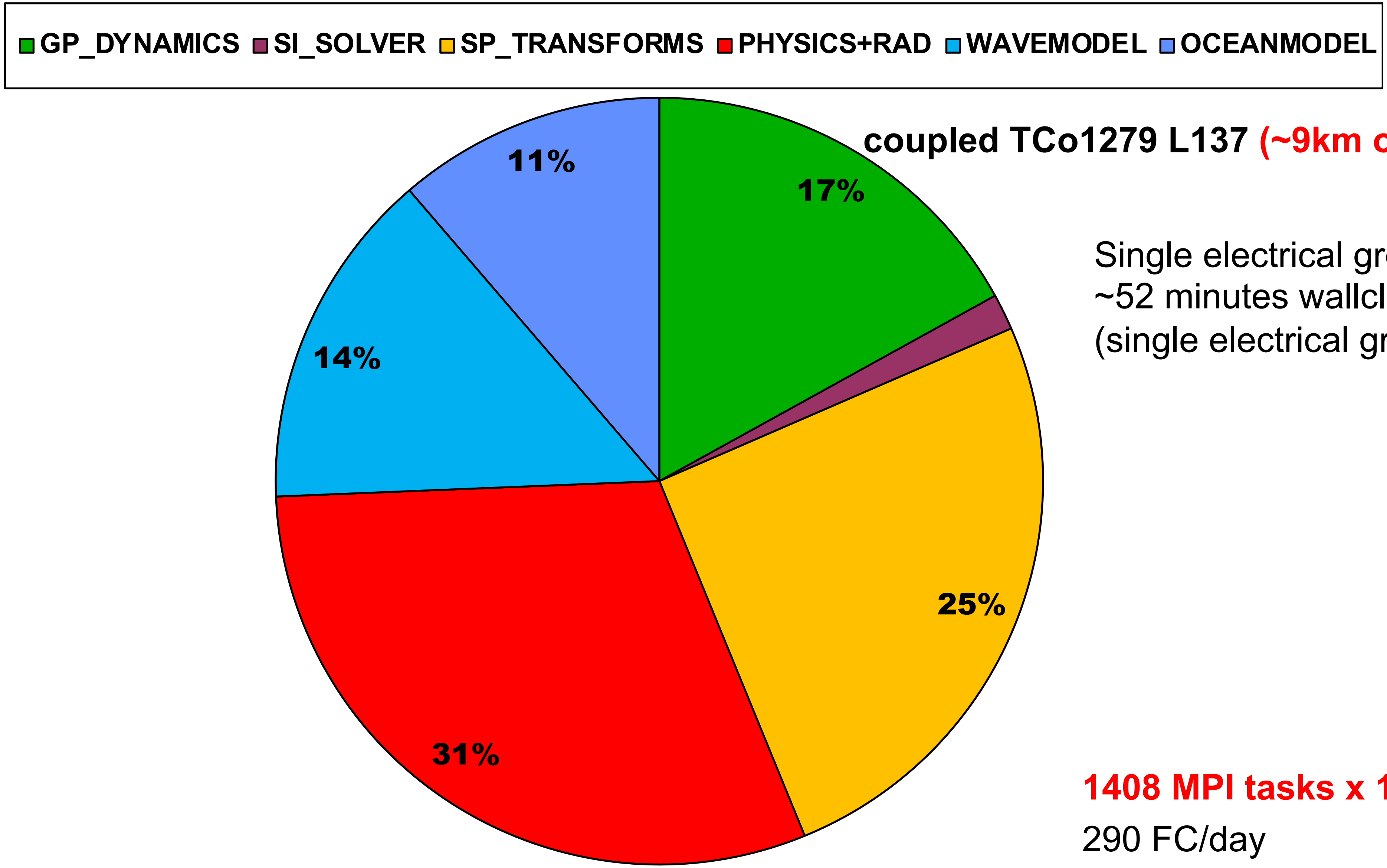
Atmos Land Resol.	ECMWF in 2018
80 km	ERAI
32 km	ERA5⁺ SEAS5⁺*
18 km	ENS⁺*
9 km	HRES⁺*

**Ocean*
used across forecast systems and in Ocean reanalysis

(*migration completed with HRES-coupled operational from the 5th June 2018)

+Land
used across forecast systems and new Climate reanalysis

Where do we spend the time ? Cycle 45r1 operations



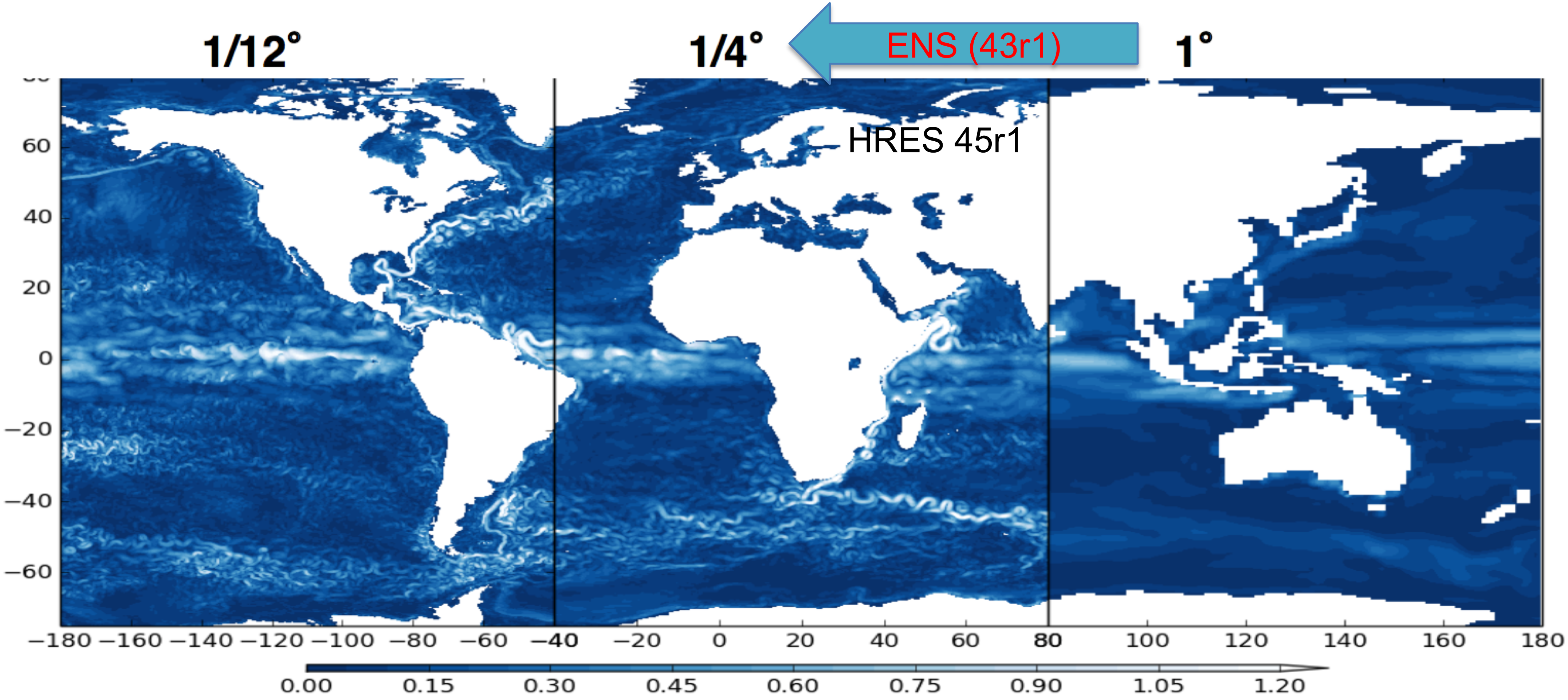
coupled TCo1279 L137 (~9km operational) run

Single electrical group:
~52 minutes wallclock time
(single electrical group==384 nodes)

1408 MPI tasks x 18 threads

290 FC/day

Atmosphere-Ocean coupling: Ocean surface currents at various resolutions



Eddy resolving

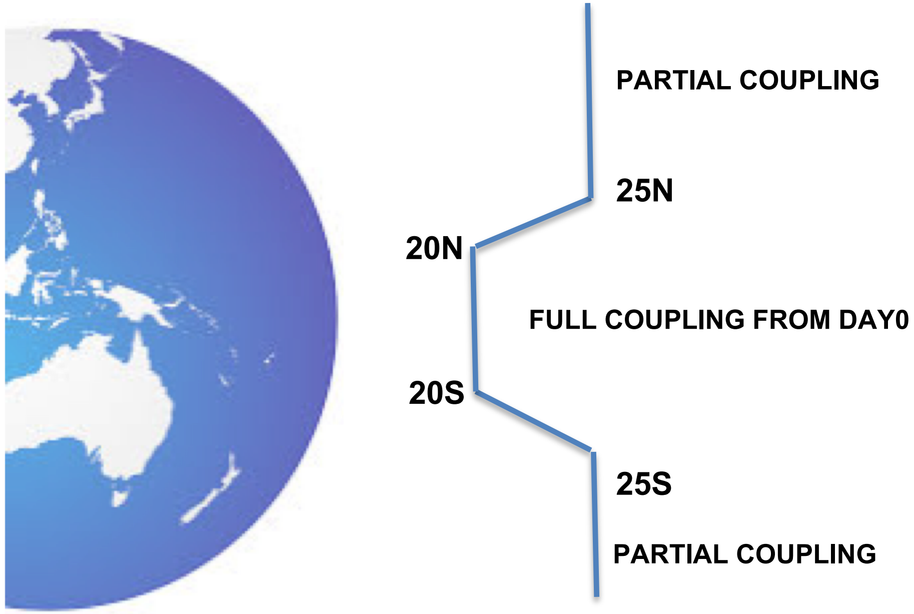
Eddy permitting

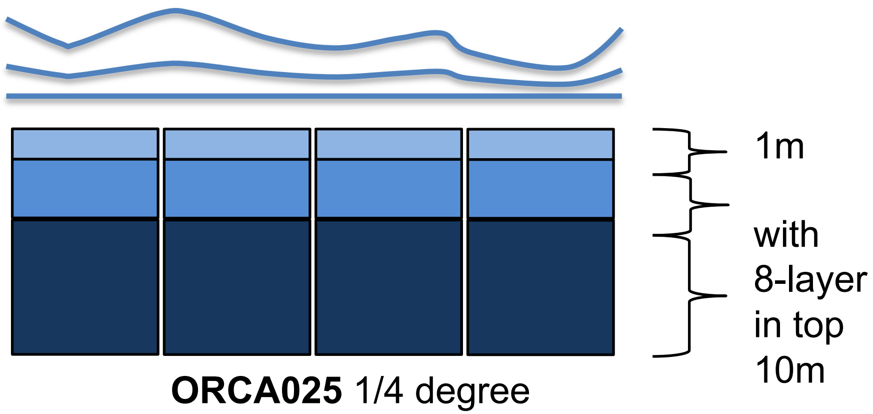
Eddy parameterising

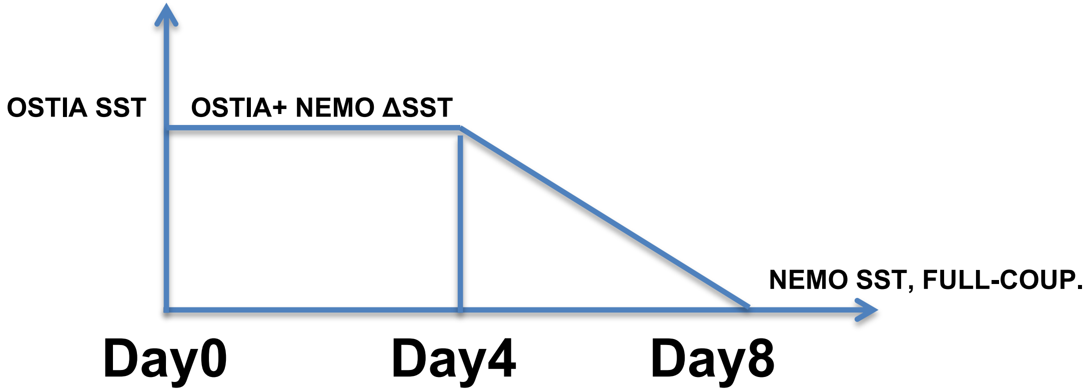
Partial-coupling-in-extratropics in 45r1 ENS/HRES: Method

- OCEAN5 and NEMO Tropical Oceans are best performing (ENS/SEAS5 testing)
- Extra-Tropics do benefit from OSTIA-SST initialization (Especially Gulf Stream)

Since **PARTIAL COUPLING** essentially corrects extratropical SST errors, a **PARTIAL COUPLING EXTRA-TROPICS** Is proposed and tested

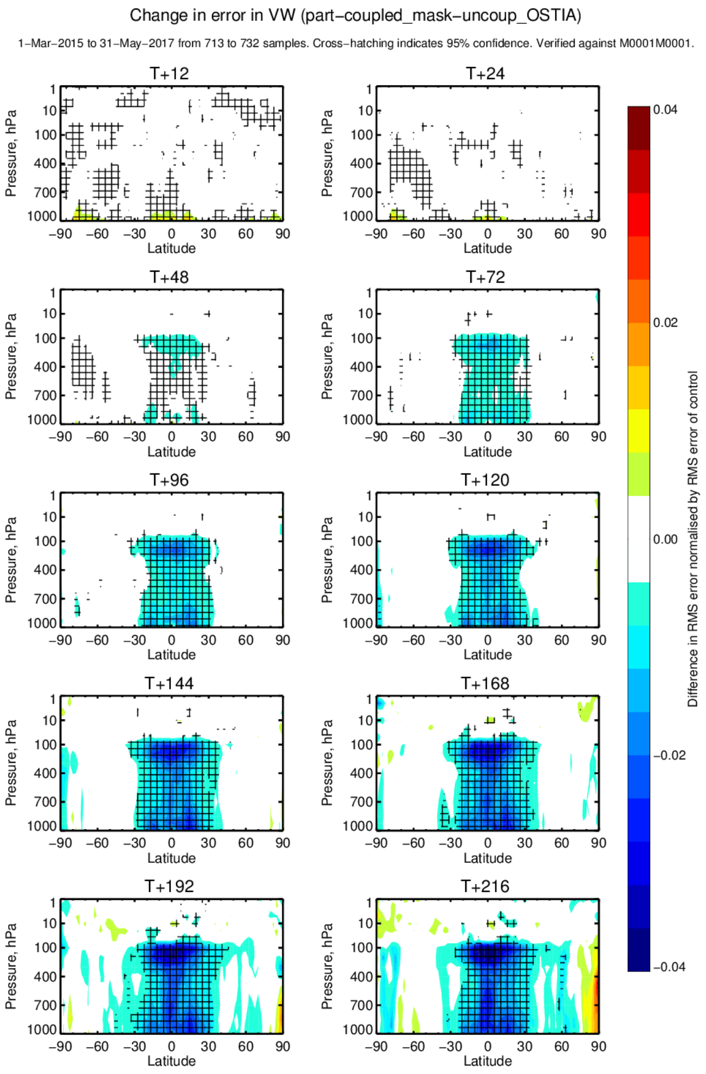


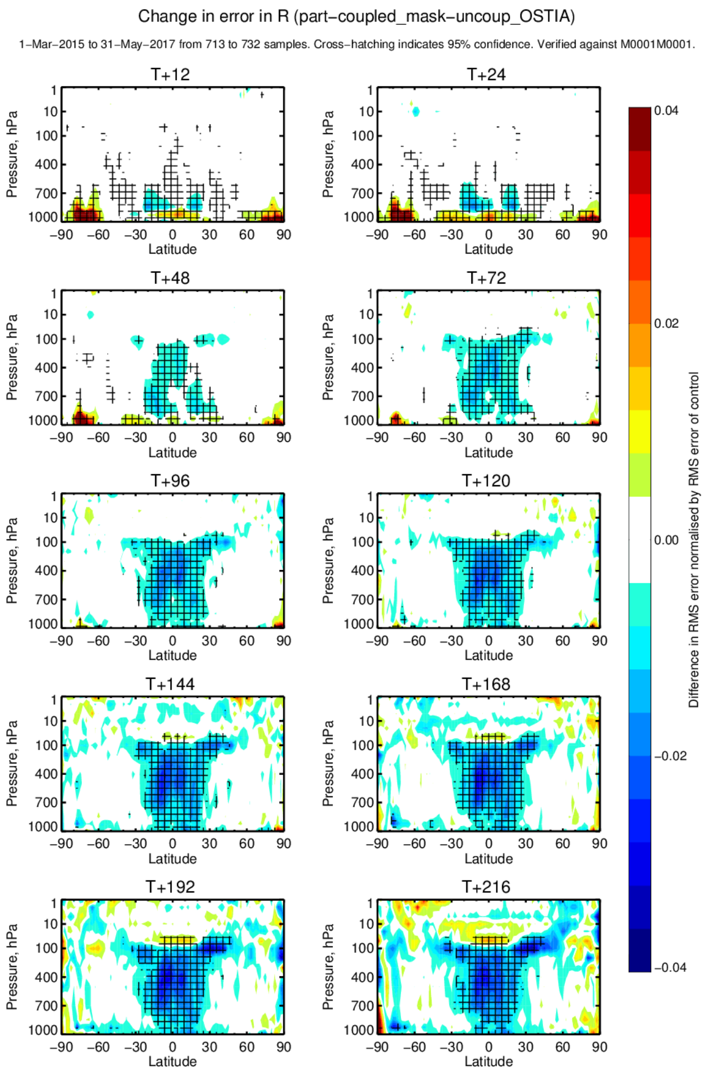




Impact of coupling (2 years combined scores. TCo1279)

Wind

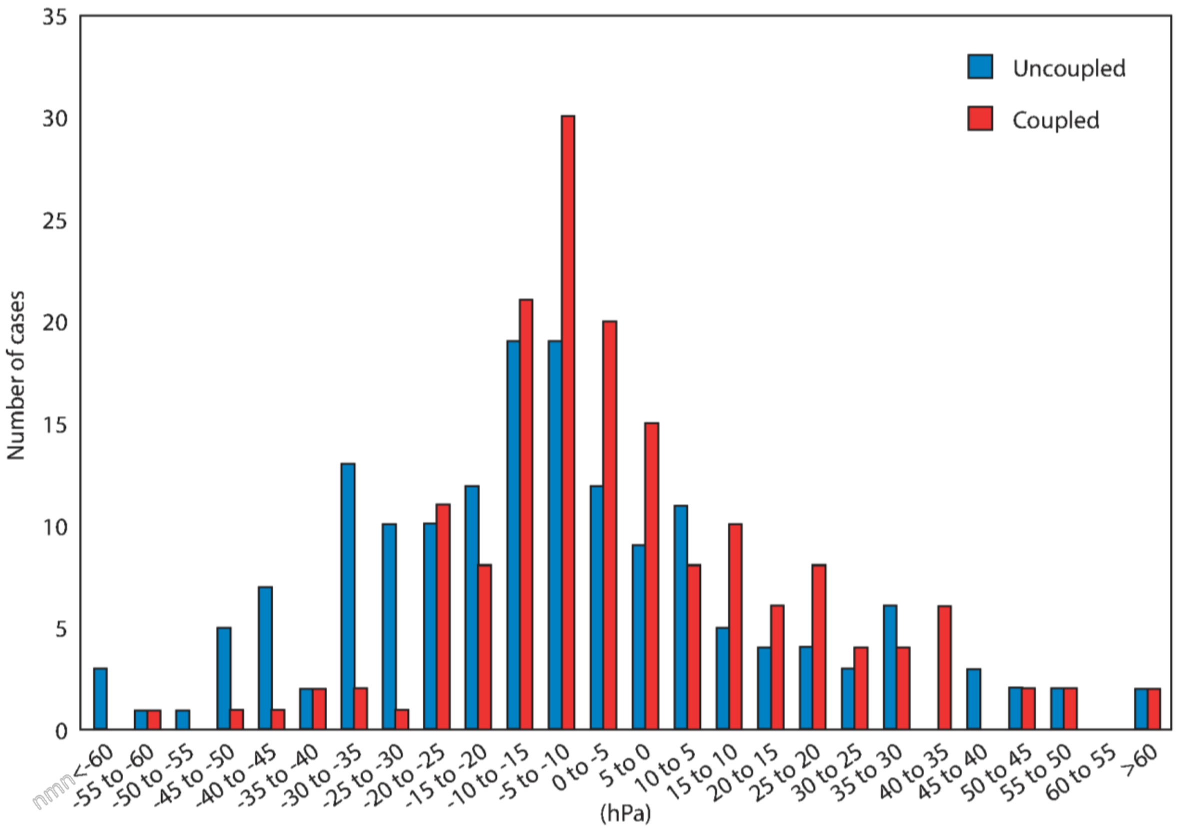




Humidit

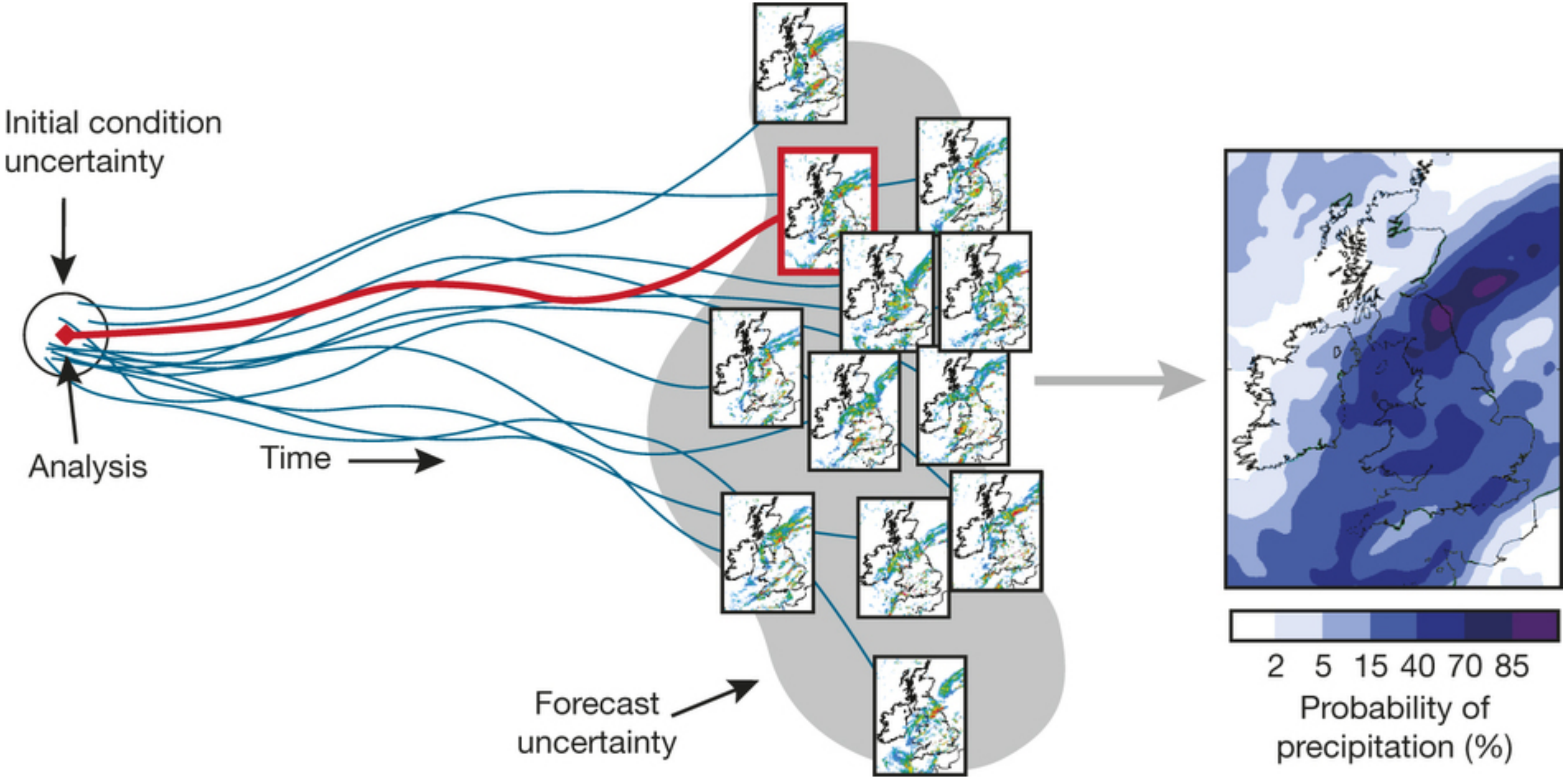
EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS

Does the ocean coupling actually matter for a large sample of TC's?



- Distribution of 7-day TC intensity forecast errors for coupled and uncoupled high-resolution forecast experiments.
- The experiments cover the period of March 2015 to June 2017 and were carried out over all basins for a total of 163 TCs.
- The number of over predictions is reduced in the coupled forecasts compared to the uncoupled forecasts.

Ensemble of assimilations and forecasts

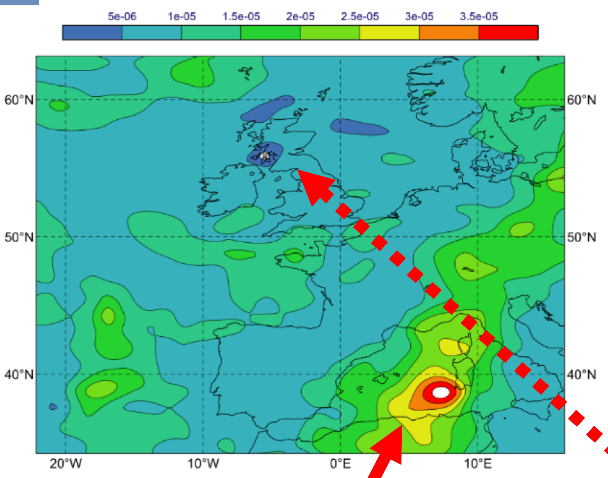


From 25 to 50 EDA Members in 46r1

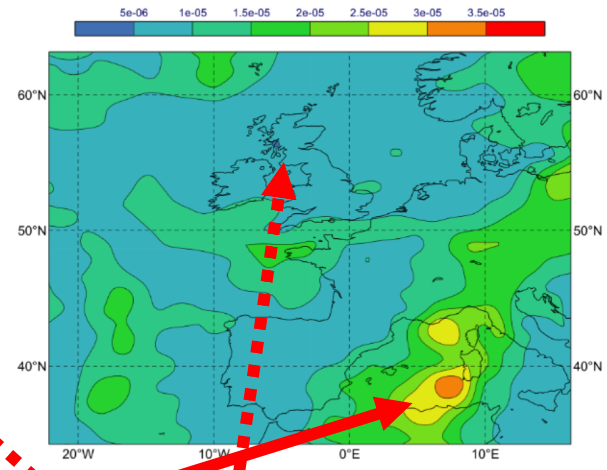
4D-Var:

EDA Ensemble Standard deviation of relative vorticity (s^{-1}) at model level 100, 3 h background forecasts, initial date 31-08-2017 18 UTC

25 -Member



50 -Member



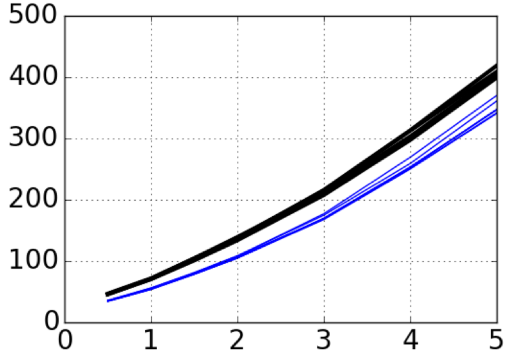
Maxima reduced

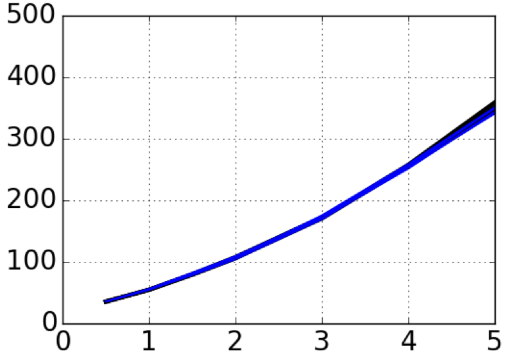
Less points with very low values

Reduced sampling uncertainty -> smoother fields

-> moreover, ENS radiation time step to 1h consistent with HRES in 46r1

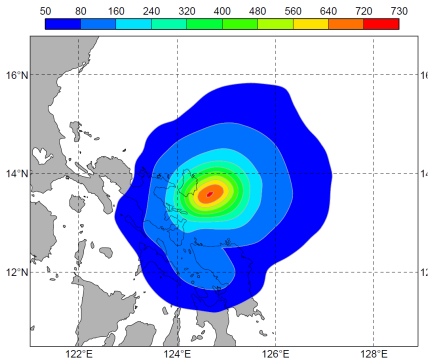
ENS, 25 +- pert (EDA + SV) -> 50 pert (EDA + SV)



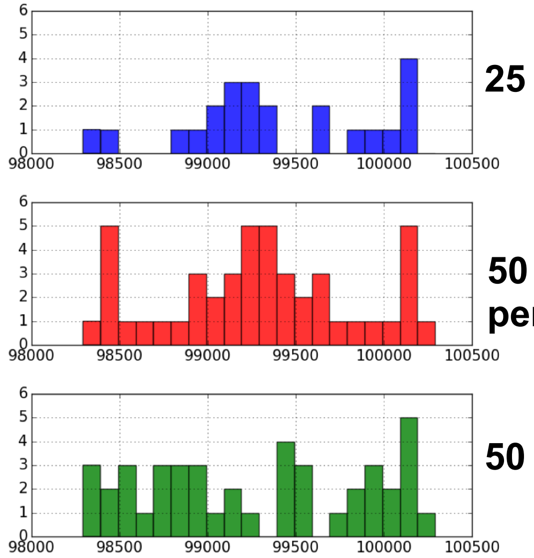


Mean absolute difference of 500 hPa geopotential in the northern extratropics between consecutive pairs of members (black lines) and non-consecutive pairs (blue lines) for (left) an ENS experiment with plus-minus symmetry of the initial perturbations and (right) an ENS experiment without. The differences are averaged over a period of 41 days.

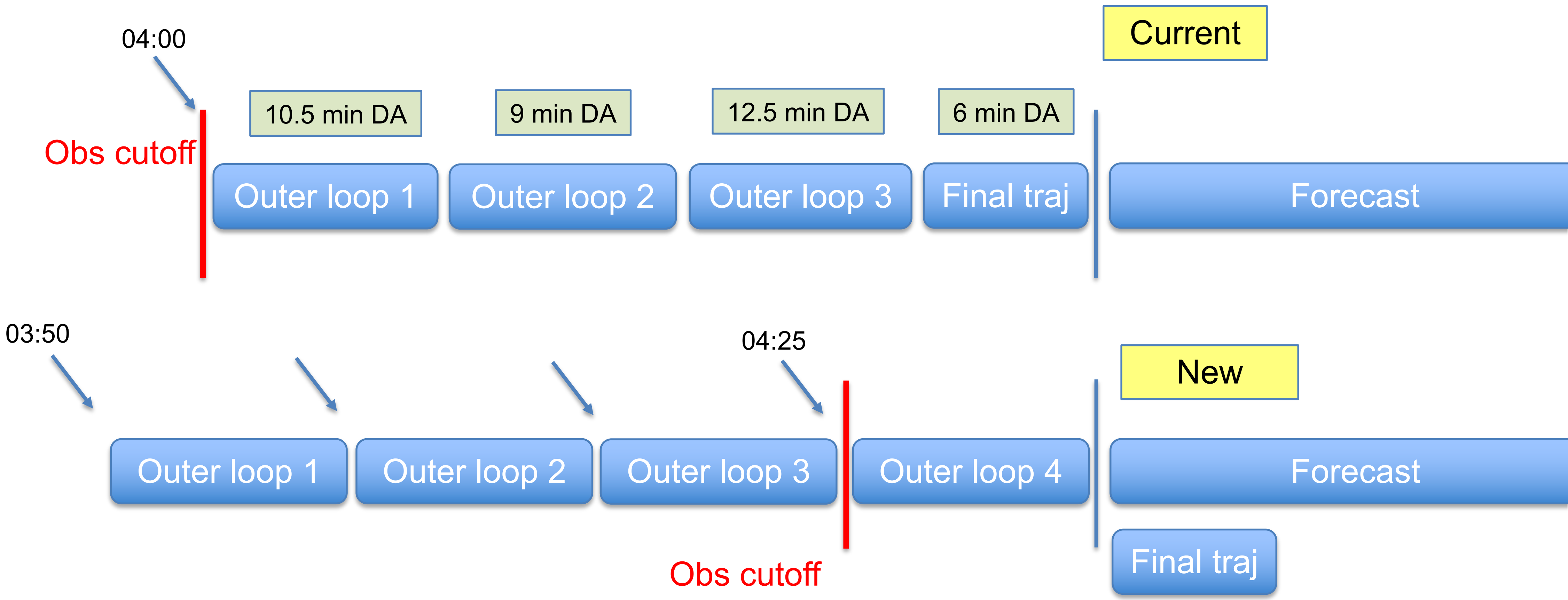
Ensemble Distribution at LAT 13.57, LON=124.65 (Core)



Mean Sea Level Pressure Ensemble Standard Deviation from 50 Member EDA

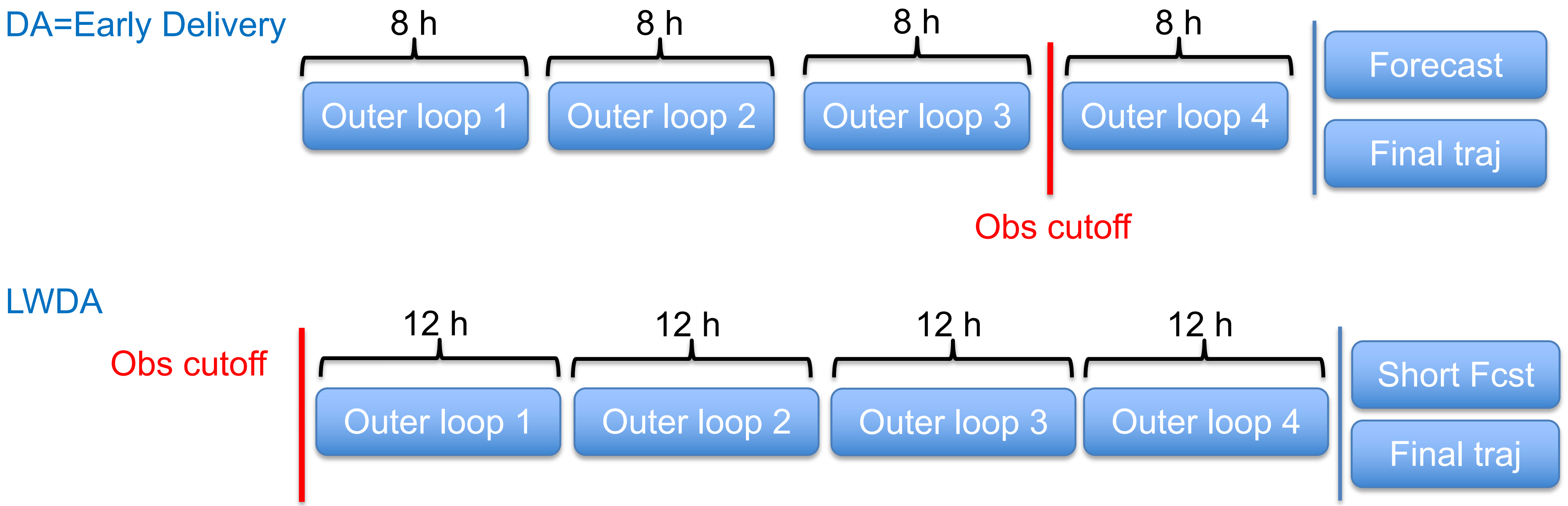


Continuous Data Assimilation: Changes to Early Delivery=DA in 46R1

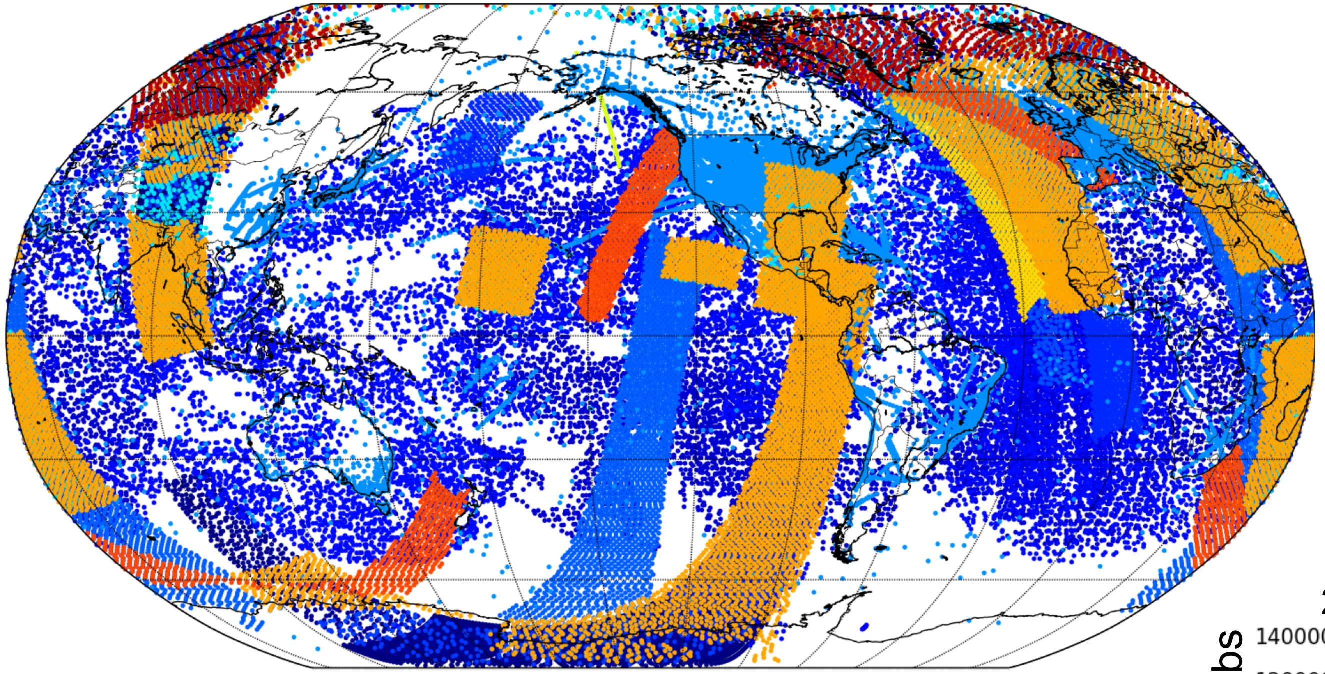


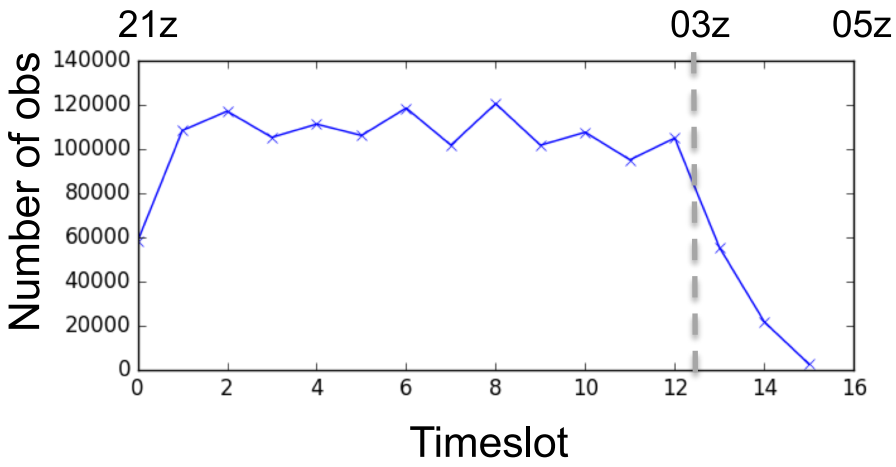
Continuous DA in 46R1

1) **Later observation cut-off (DA only)**: New observations added in each outer loop, “re-screening” the observations in each trajectory
2) **Early Delivery assimilation window** from 6h to 8h, ensures **all** observations that have arrived can be assimilated (LWDA unchanged at 12h)
3) **Outer loops from 3 to 4 (DA+LWDA)**: Inner loops TL255-319-399 to TL255-255-319-399



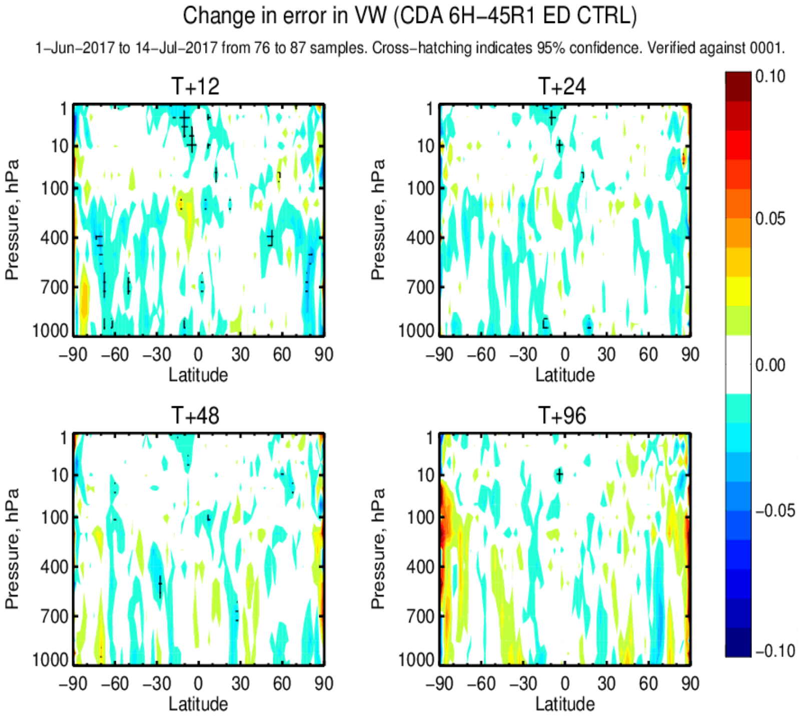
Extra observations assimilated in Continuous DA configuration



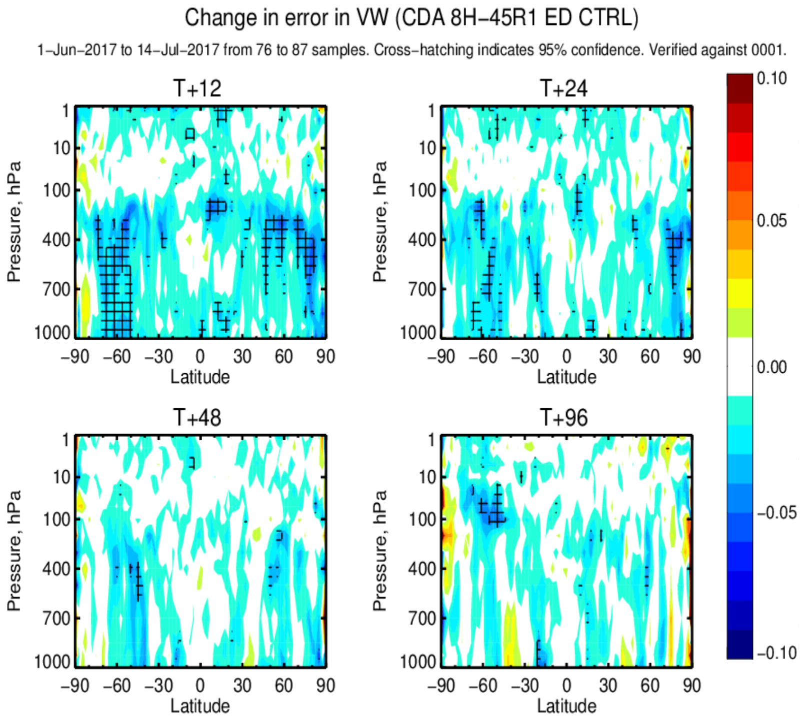


Continuous DA

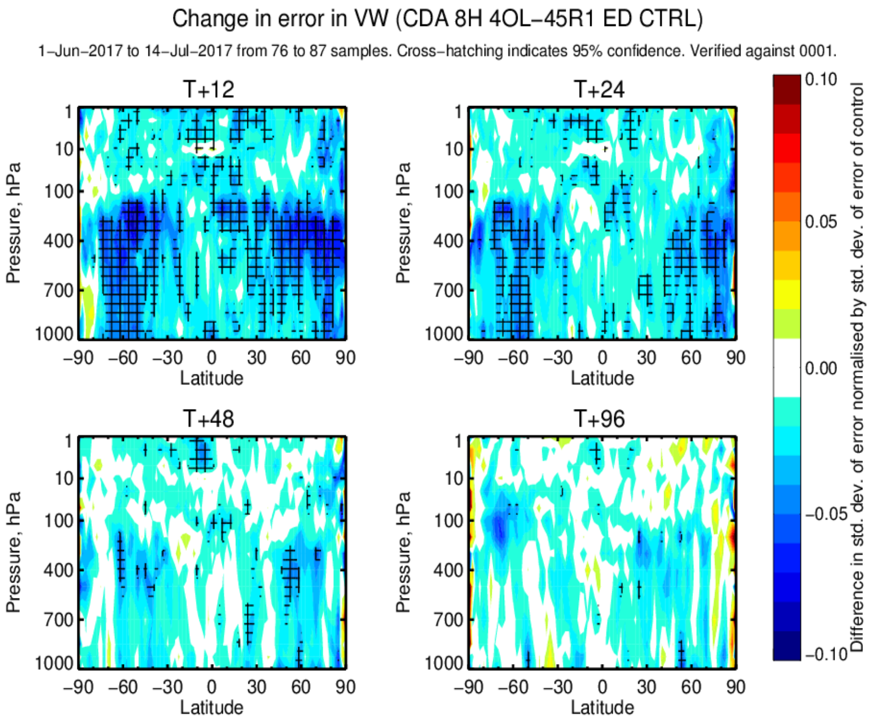
- **Preliminary results (Wind Vector error stdev, 1/6/17 – 14/7/17)**



A: Late obs – 6h window



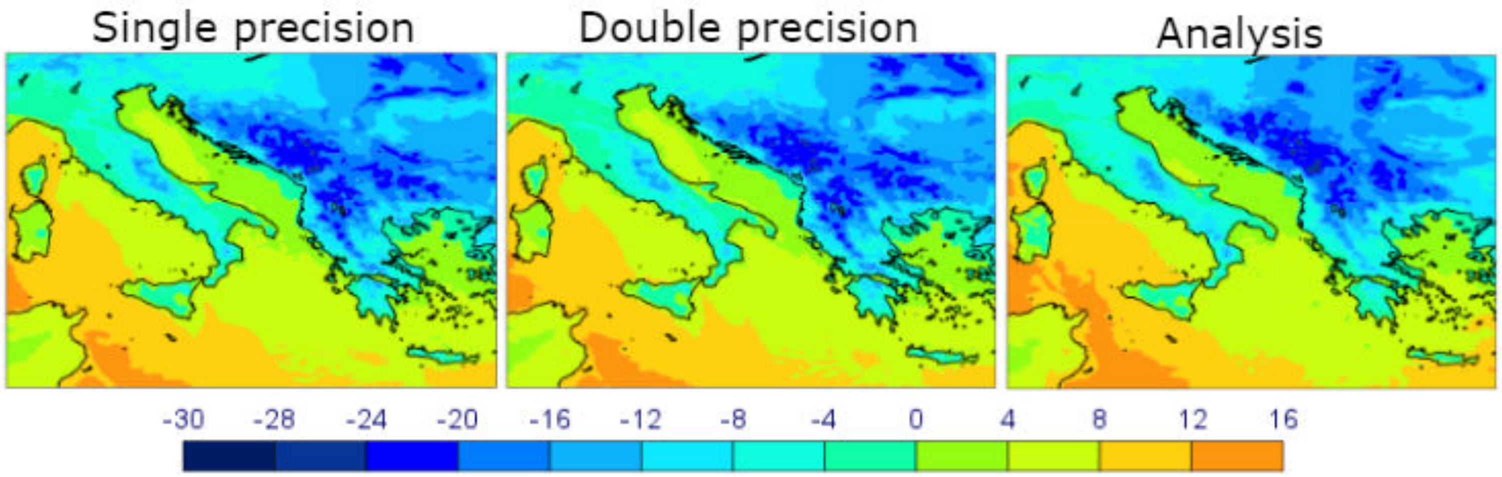
B: Late obs – 8h window



C: B + 4 outer loops

Single precision IFS

Surface temperature in degree Celsius of five day forecasts for 8th January 2017 0:00 UTC

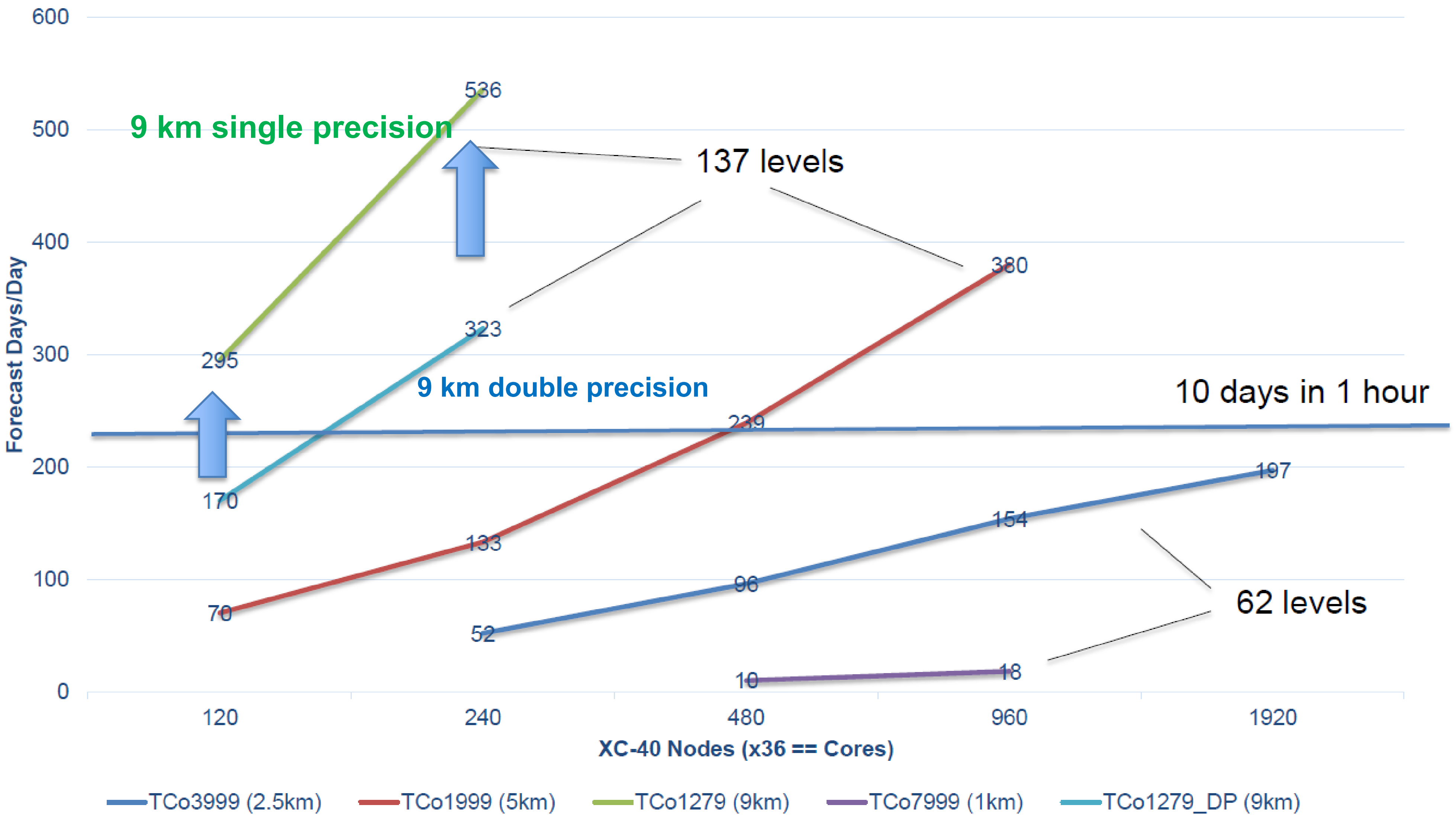


- Forecast quality in double and single precision is almost identical.
- 40% speed-up.
- Benefit for global simulations at 1.0 km resolution.

Düben and Palmer MWR 2014; Váňa, Düben et al. MWR 2017

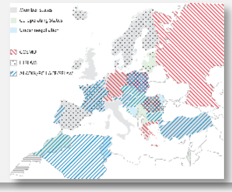
Single precision IFS

Funded by the European Union



ECMWF Scalability Programme

Governance: ECMWF, Member states, Regional consortia



Projects:

Observation processing:
- Lean workflow in critical path
- Object based data store
- Screening/bias correction

Data assimilation:
- Flexible algorithms (C++)
- IFS integration
- Coupling with ocean and sea-ice
- Parallel minimization

Numerical methods:
- Numerical methods
- h/v/t-discretization, multiple grids
- Prognostic variables, coupling

Model output processing:
- Broker-worker workflow
- Near-memory processing
- Data compression

Code adaptation:
- Benchmarking
- Vectorization
- Programming models
- Precision
- DSL/libraries
- Transition to operations

Computer architecture support:
- Benchmarking
- Novel architectures
- Compilers
- Vendor support
- Transition to operations

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

Together - More collaboration:

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- Pooling expertise to improve scalability

Continued support:

Dedicated HPC, software, and data resources for Member States
Advanced training

Future directions...

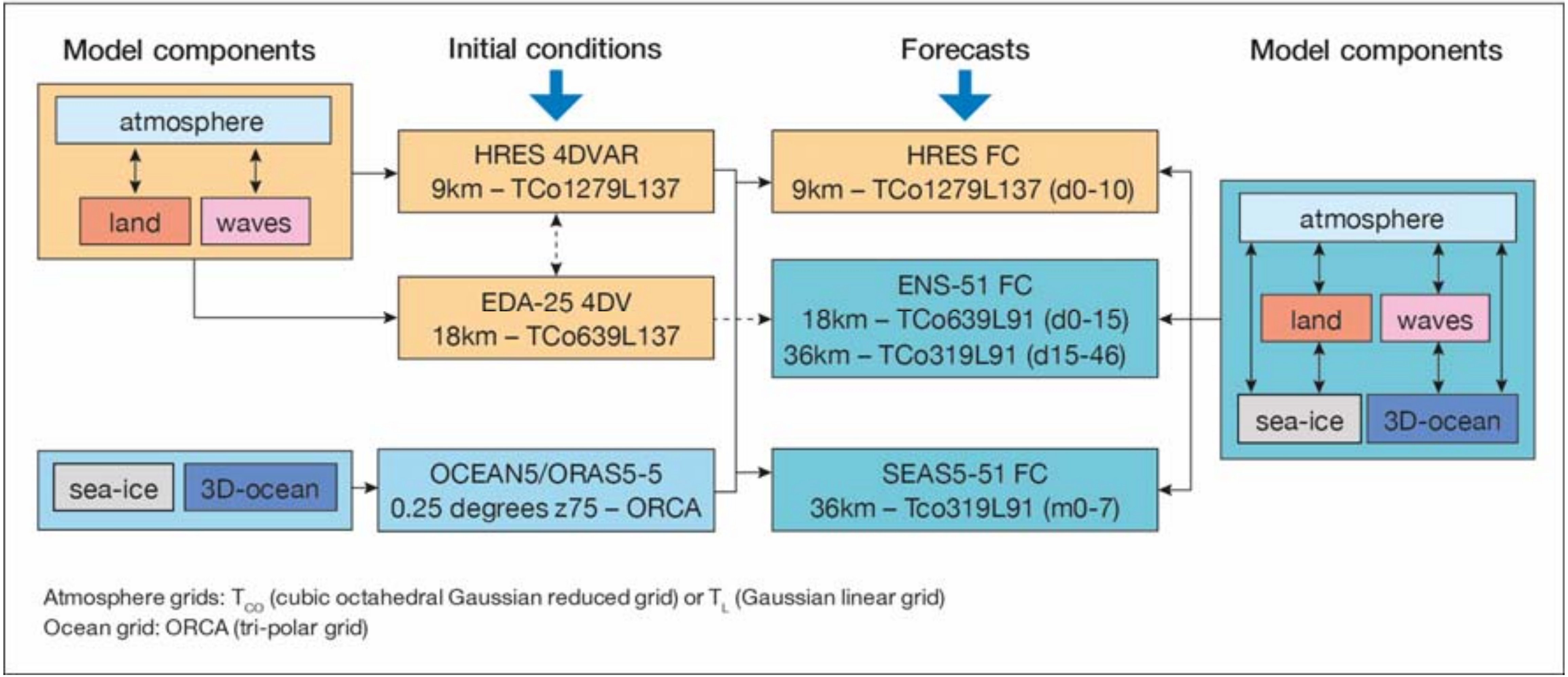
- DA science (oper & reanalysis; maximize use of in situ and satellite obs, algorithms, EDA, higher res inner loops)
- Physical processes (resolved and unresolved)
- Increased coupling (land/ocean/atmospheric composition/meteorology)
- Uncertainty – parameter perturbations, ENS, EDA
- Predictability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

Representation of model uncertainties revised in 2018

Revision in medium-range and extended range ensemble forecasts and EDA implemented in June 2018 (cycle 45r1):

- SKEB has been switched off due to marginal impact of current configuration
- SPPT revised (cf. last year's WGNE slides)
  - Perturbations to (total phys. ten.)−(clear-sky rad. ten.) instead of (total phys. tendency)
  - Boundary layer tapering closer to surface
  - No tapering in stratosphere
  - 20% reduction of stdev of random fields
- Consistent model uncertainty representation in ensemble of data assimilation and ensemble forecasts

The ECMWF suites (July 2018)



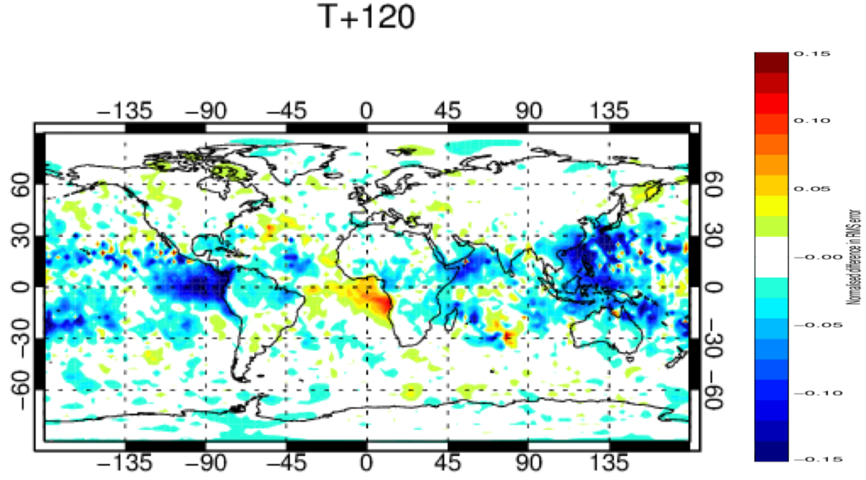
CY45R1 Ocean Coupling in HRES
(full coupling tropics; partial coupling extra-tropics)

Forecast improvements at Day+5 (**1 year**) (blue colors indicate RMSE reduction) due to the HRES coupling of the NEMO+LIM Ocean and sea-ice model to the atmospheric model integrations

Evaluated on one full year of TCo1279 daily forecasts (April 2015-March 2016).

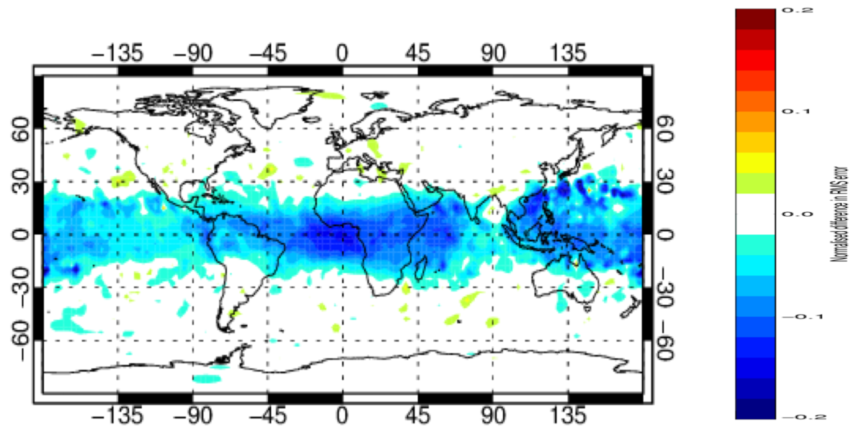
Largely positive in Tropical regions. Guinea Gulf demands attention (feedback w. stratocumulus region *)

HRES MSLP
improvement from Ocean-coupling



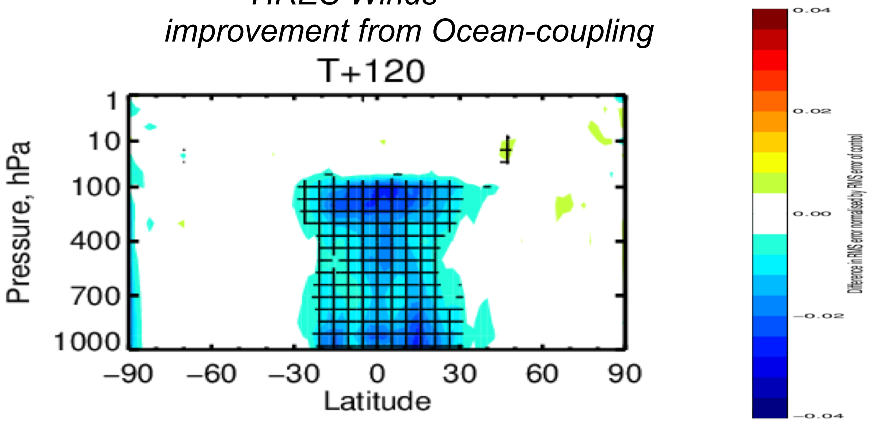
Tropics pressure about 5-10 % (*)

HRES Z500
improvement from Ocean-coupling
T+120; 500hPa



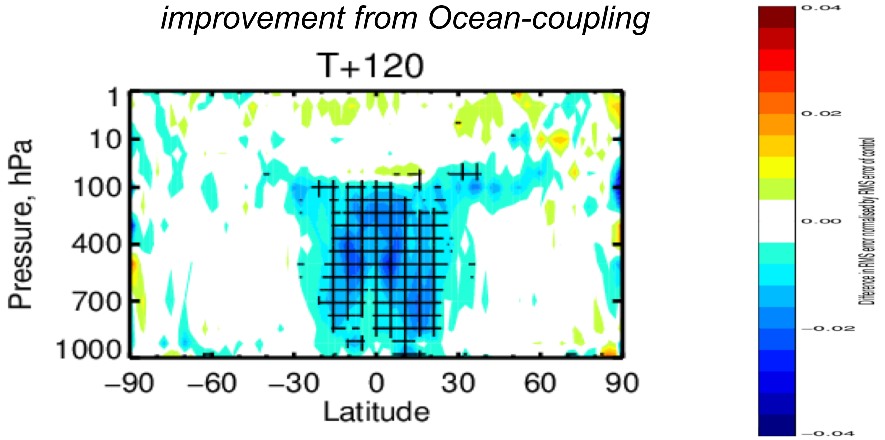
Tropics Z500 about 5-10 %

HRES Winds
improvement from Ocean-coupling



Tropics winds 2-4 %

HRES Relative Humidity
improvement from Ocean-coupling



Tropics humidity 2 %

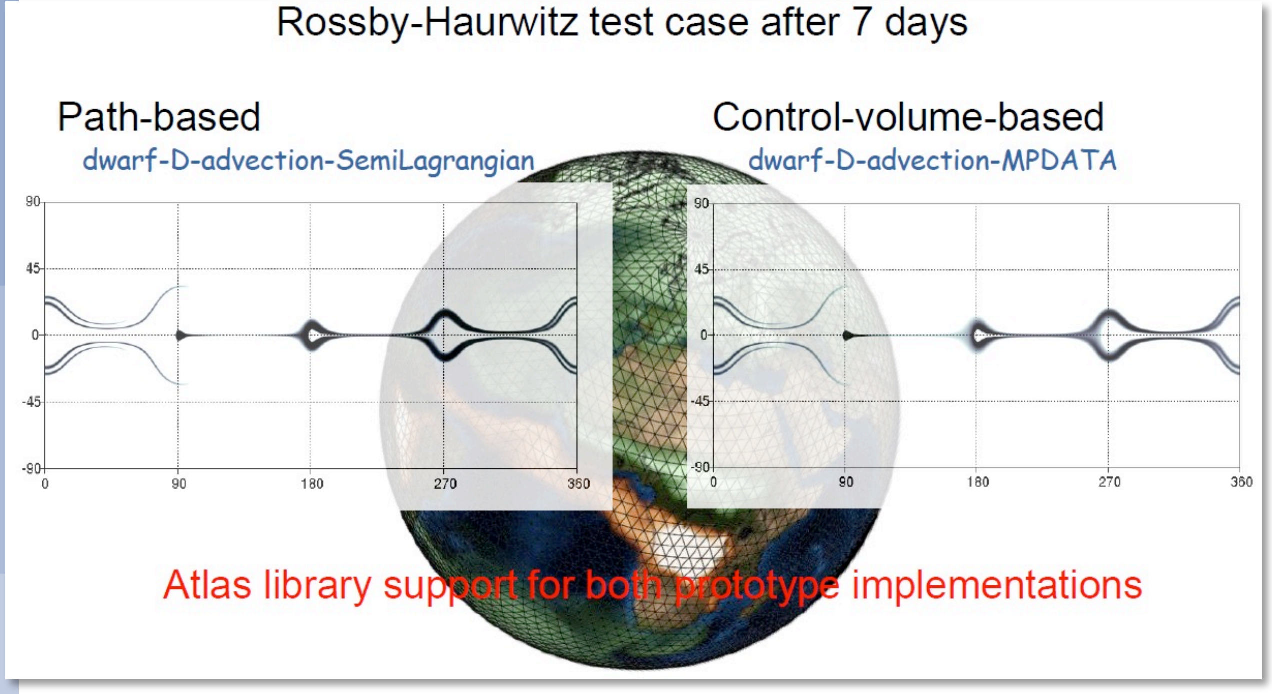
ECMWF
Kristian Mogensen & CP

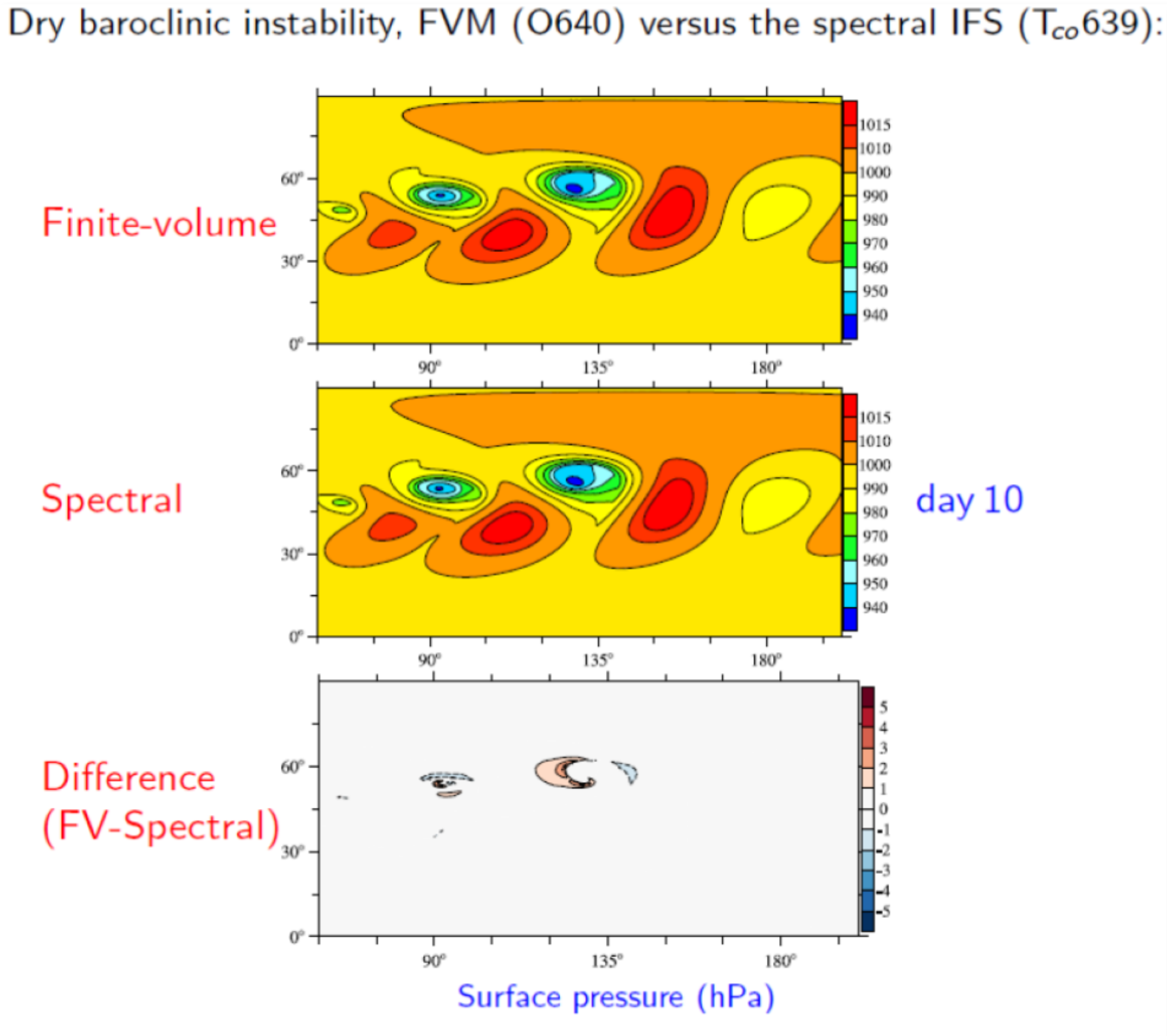
ESCAPE: Dwarfs

Funded by the European Union

ESCAPE dwarf concept:

- Extract key functional components, adapt to new processors
- Build in algorithmic flexibility for future IFS





Atlas for LAM grids

- Grid coordinates are called (x,y), and are not necessarily same as (lon,lat) !!!

- It is up to a Projection to translate between (x,y) and (lon,lat). This is a member of the Grid object.

- Rotation is implemented by a Projection!

- Currently implemented projections:
  - “lonlat” (a.k.a. no projection)
  - “rotated_lonlat”
  - “lambert”
  - “mercator”
  - “rotated_mercator”
  - “schmidt”
  - “rotated_schmidt” (as used in ARPEGE)

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Atlas: A library for numerical weather prediction and climate modelling

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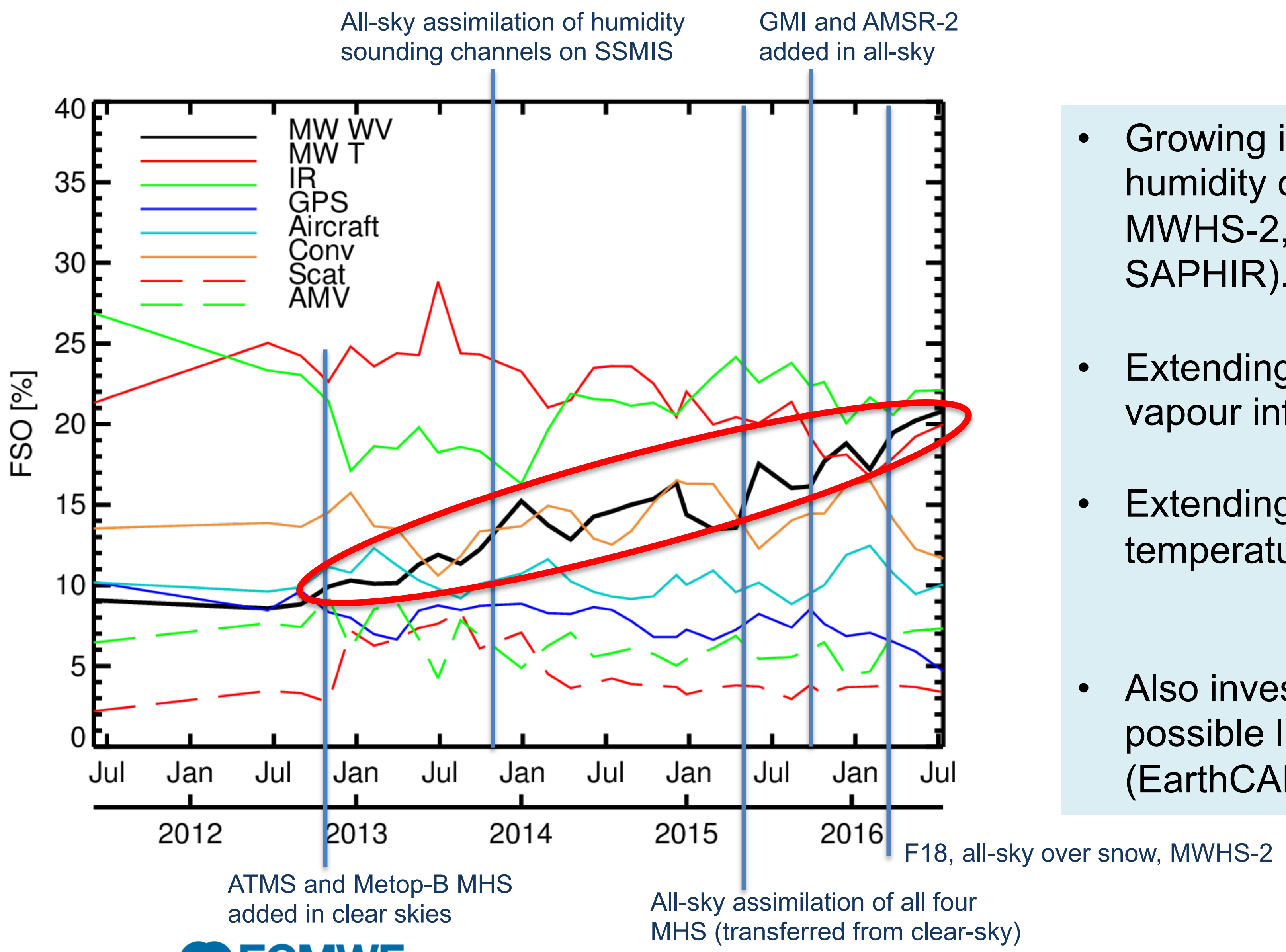
```
void print_gridpoints( Grid grid ) {

  for( PointXY& p : grid.xy() ) {
    Log::info() << p.x() << “ ” << p.y() << std::endl;
  }

  for( PointLonLat& p : grid.lonlat() ) {
    Log::info() << p.lon() << “ ” << p.lat() << std::endl;
  }
}
```

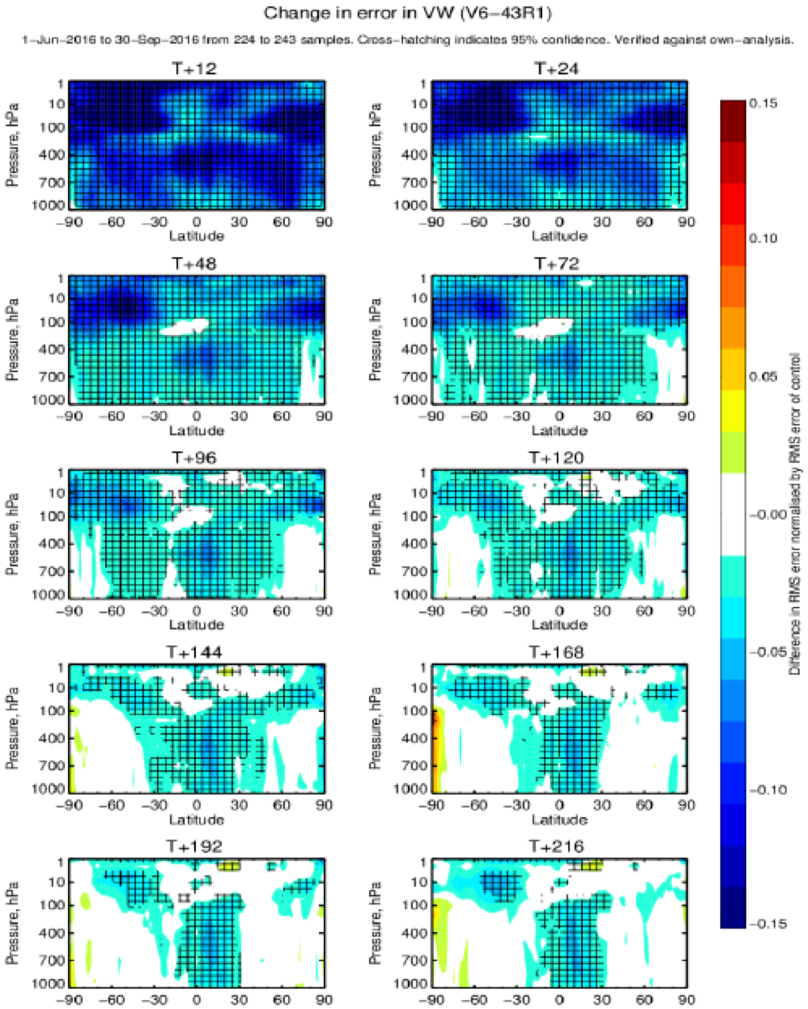
Observation changes: the rise of all-sky!



- Growing importance of microwave humidity observations (MHS, ATMS, MWHS-2, SSMIS, AMSR2, GMI, SAPHIR).
- Extending this to infrared water vapour information.
- Extending to all-sky microwave temperature observations.
- Also investigating radar, lidar, and possible lightning observations (EarthCARE, Aeolus, GOES-R, MTG).

4DVar Development

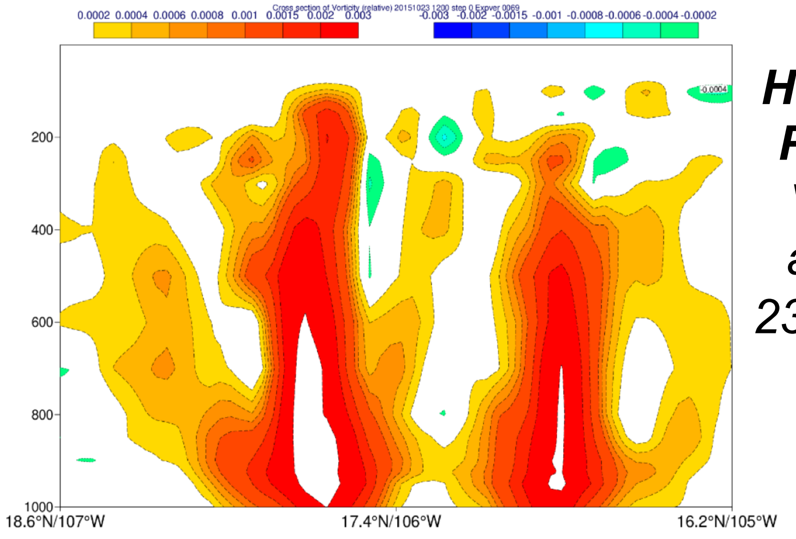
- Hybrid **B** modelling: introduction of EDA estimated humidity errors (CY43R3; previously fixed statistical functions of background state)
  - Change in RMSE of wind vector forecast
  - Largest improvement in tropical winds since…
  - Confirmed against observations (SATOB winds)
  - Humidity tracer advection is believed to be the main driver
  - To be extended to cloud condensate (Q1/Q2 2018)



Tropical Cyclone Initialization

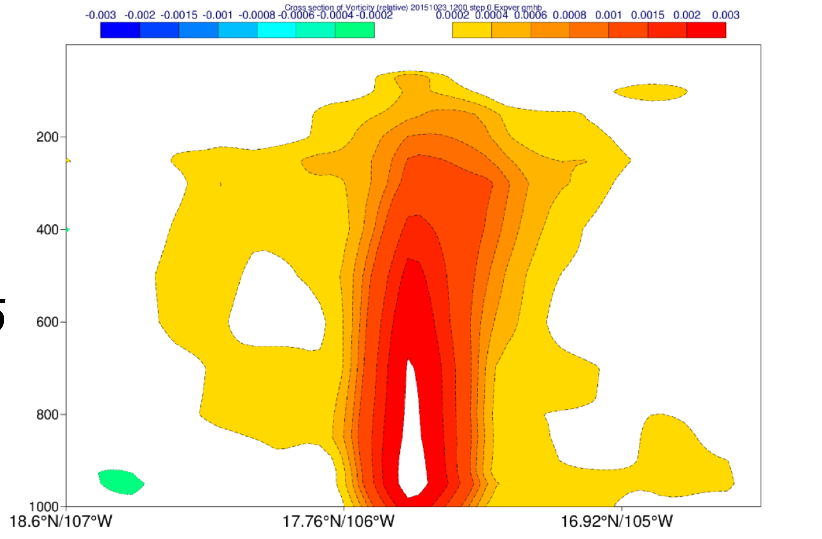
- **Adaptive observation error for dropsonde winds** leading to more cautious observation use.
- **Smoother filtering of EDA background error variances** through spectral truncation to T159 followed by **a new wavelet signal-to-noise filter**.

Before…



Hurricane Patricia:
Vorticity analysis
23/10/2015
12 UTC

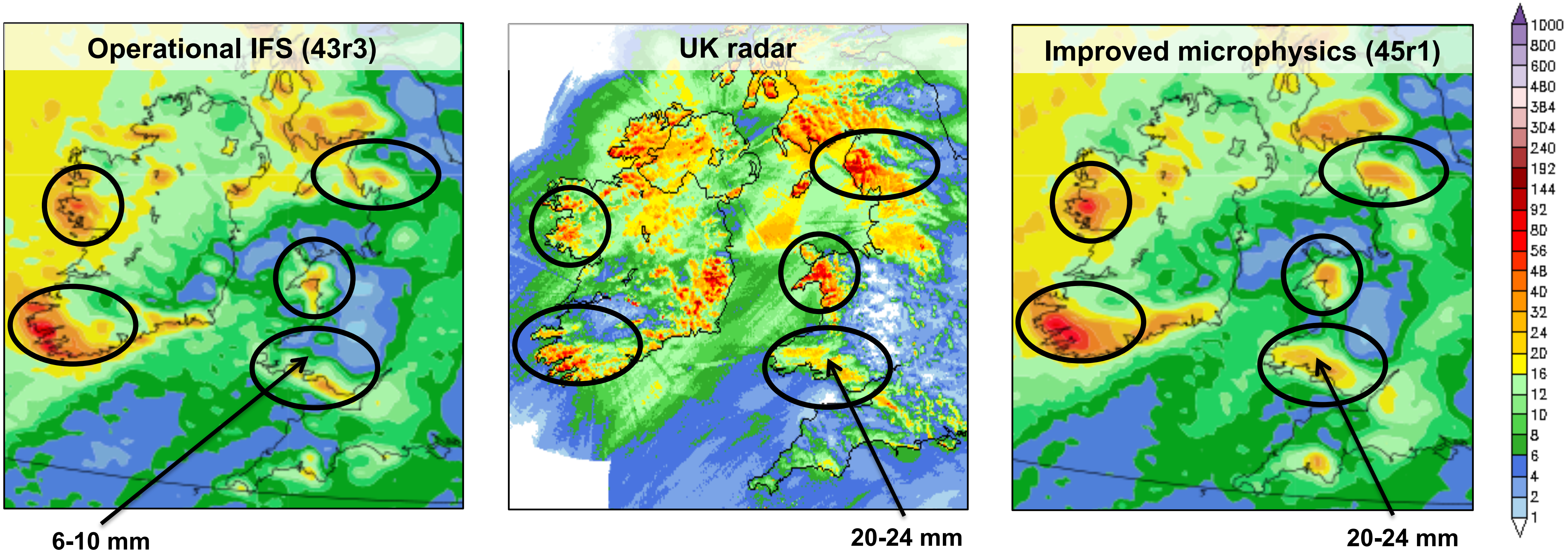
…after



Warm-rain microphysics numerics package (45r1)

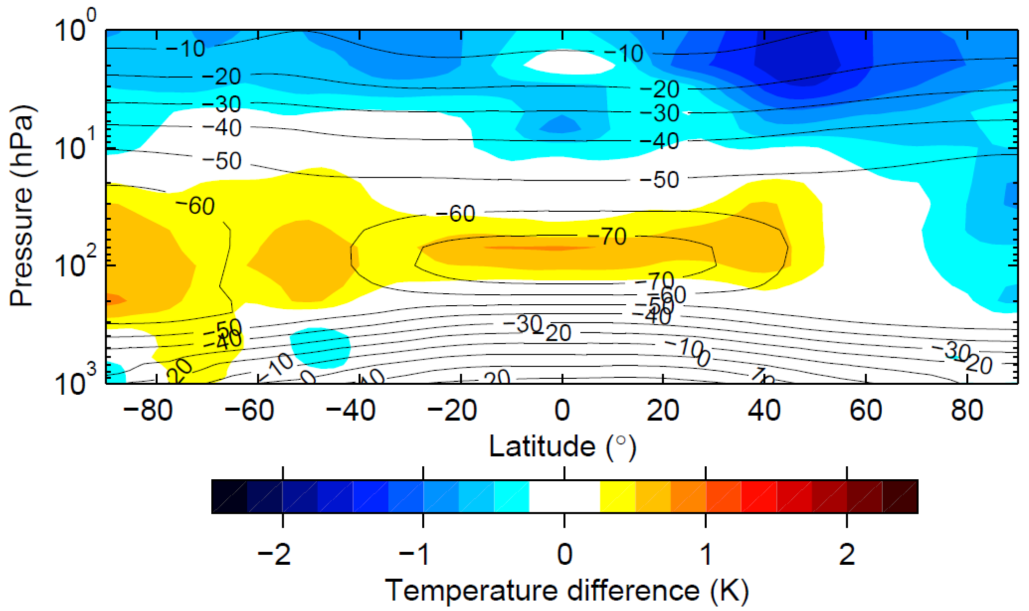
Improvements in precipitation along coast lines/lakes and over orography

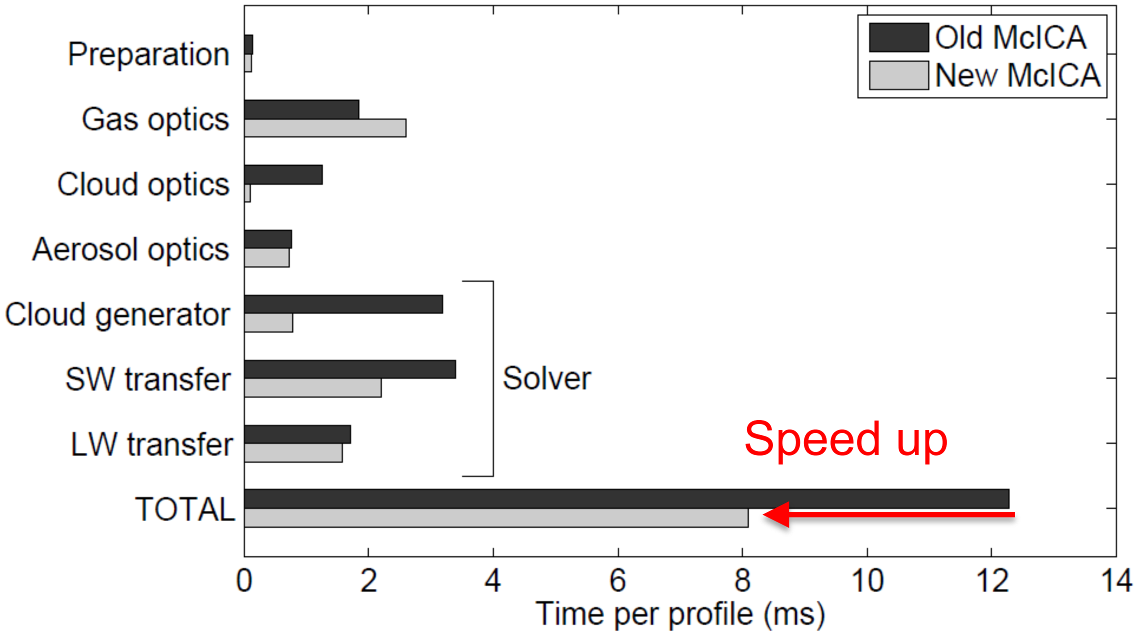
Example case study 14 May 2017 00Z 48hr forecast accumulated precipitation (mm)



New radiation scheme (ECRAD)

- Flexible and modular: easy to test future changes (16000 lines of code)
- Better solution to longwave equations improves stratosphere
- 31-34% faster
- Reduction in McICA noise leads to slight reduction in temperature errors





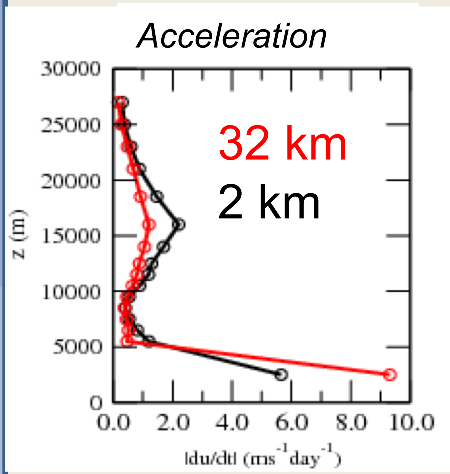
Hogan and Bozzo, TM787, 2017

Advancing science in partnership (grey-zone)

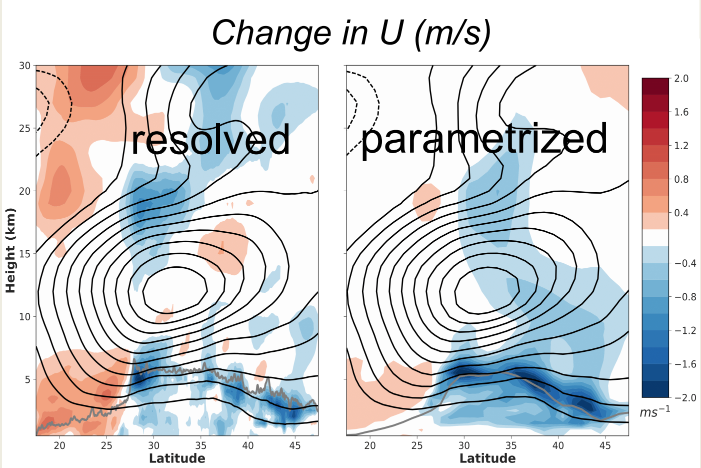
Orographic drag - Metoffice

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

Rockies (UM)



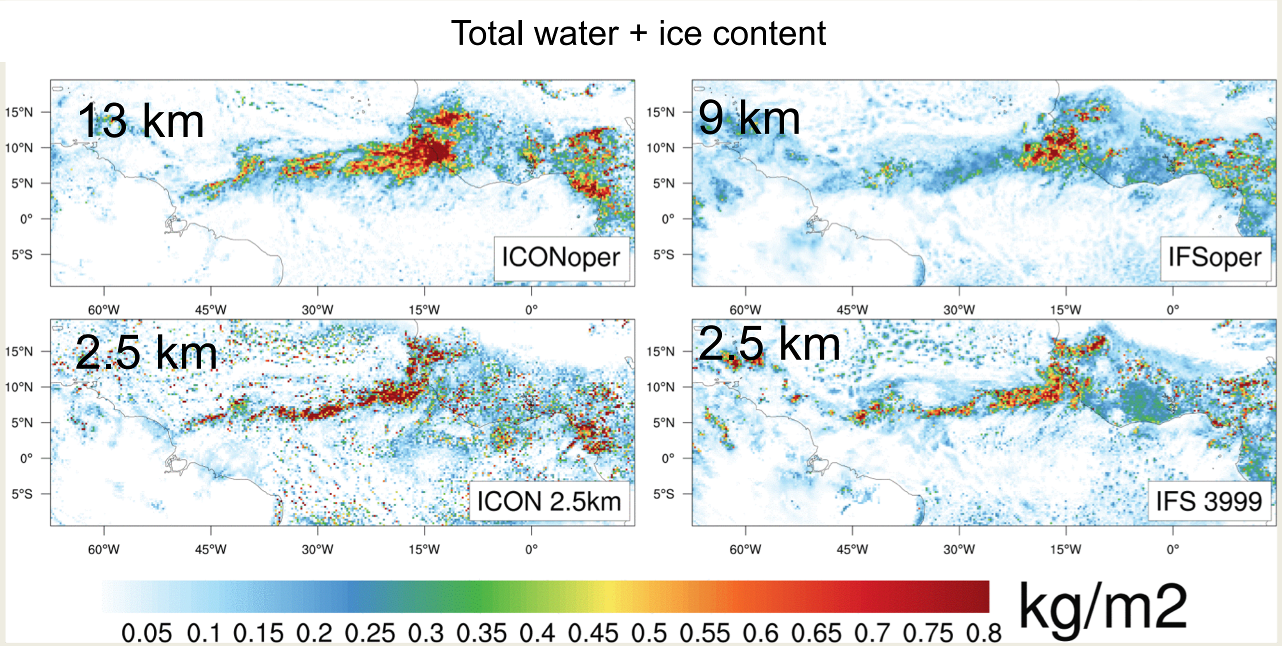
Himalayas (UM)



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

Convection - DWD

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

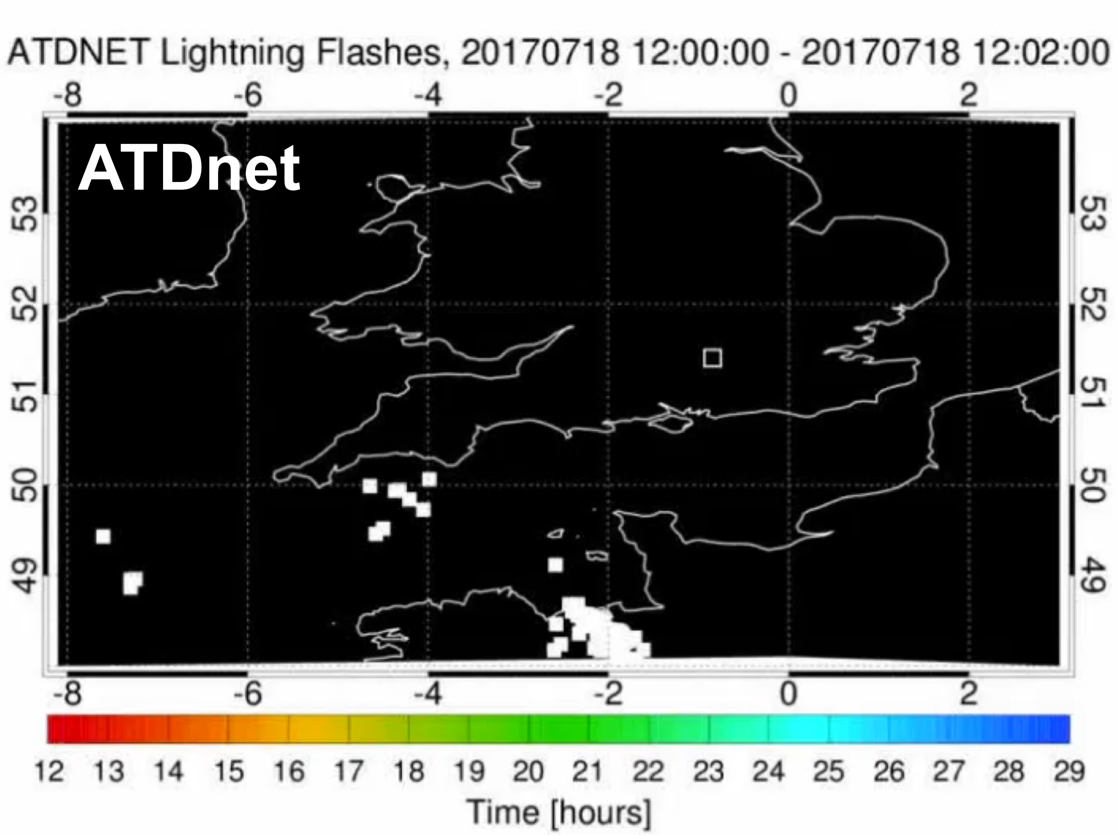


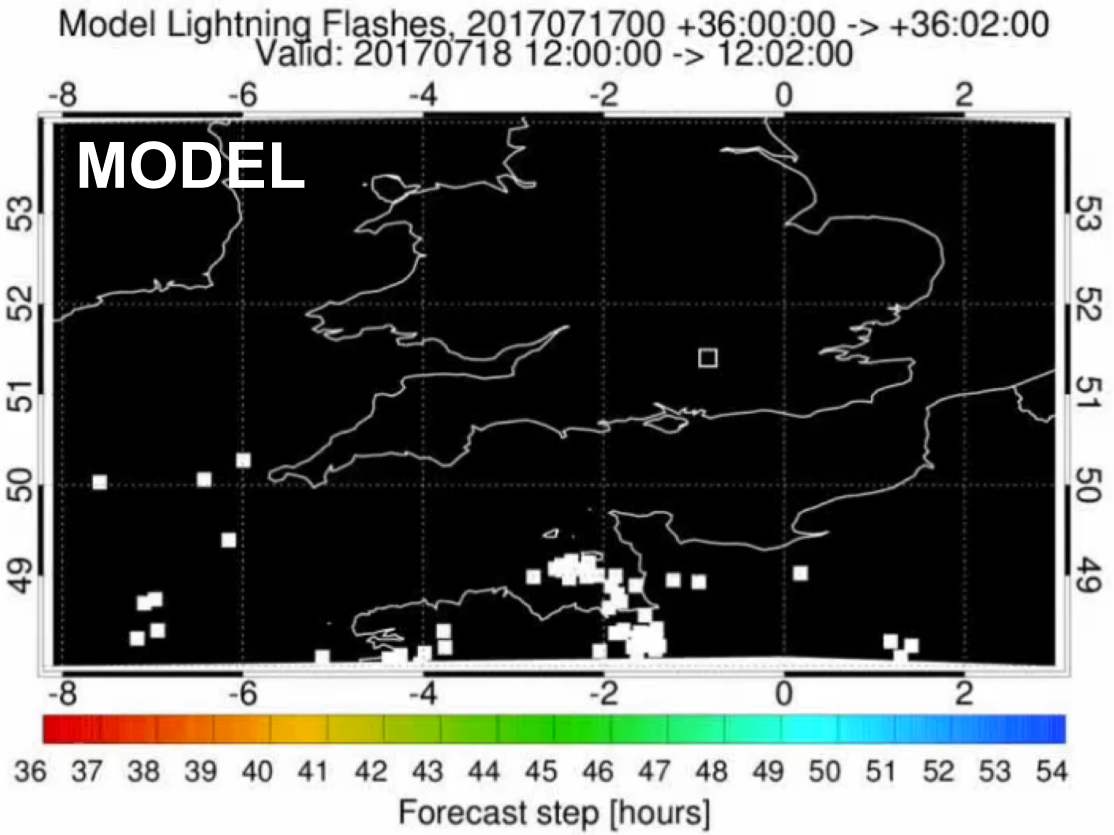
Courtesy Daniel Klocke and Nils Wedi

ECMWF

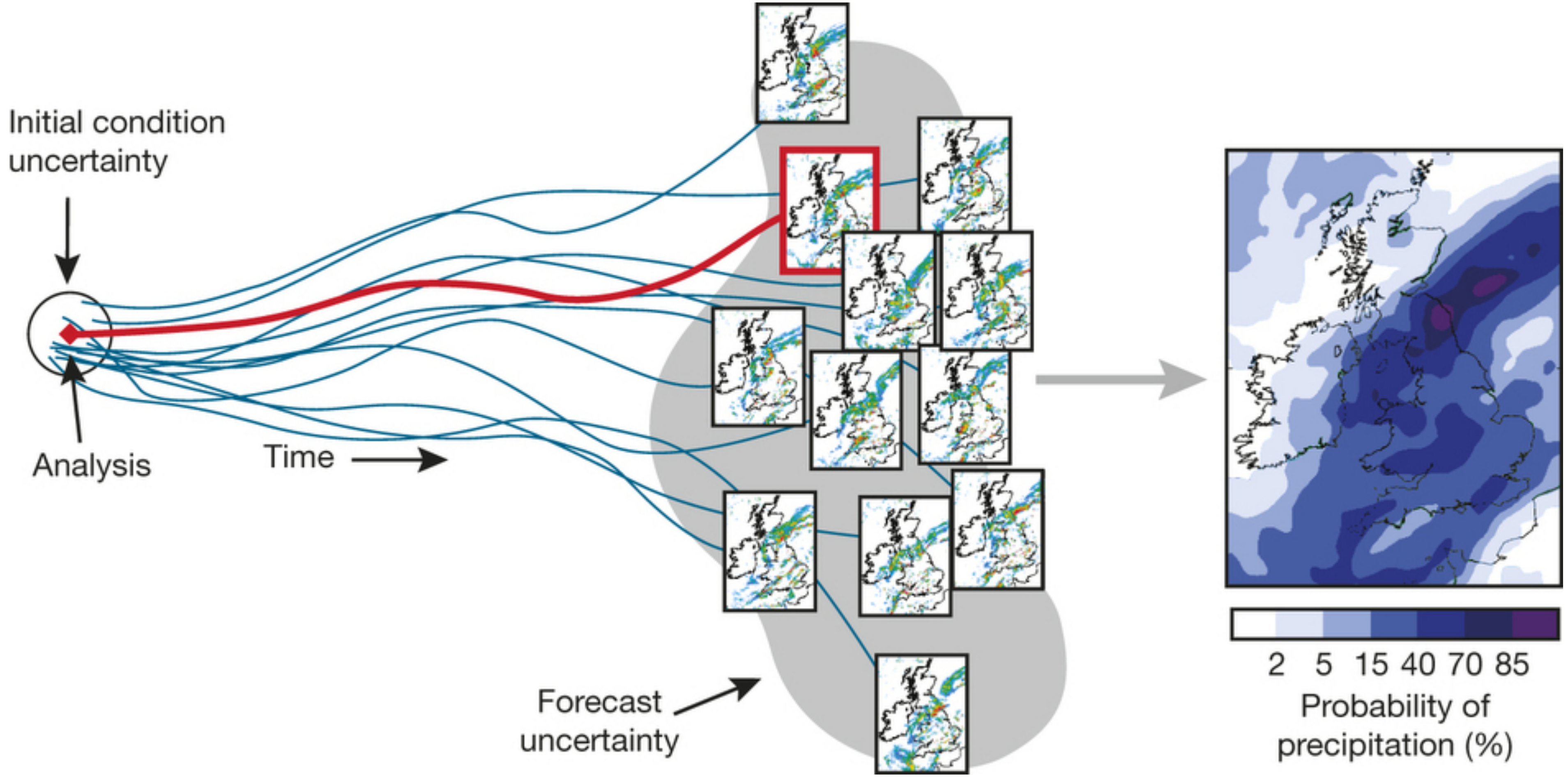
Comparison of model with ATDnet (Met Office) lightning flashes.

18h animation of 2-mn flash data starting from 18 July 2017 at 1200 UTC. TCo1279 L137 model forecast +36h → +54h.

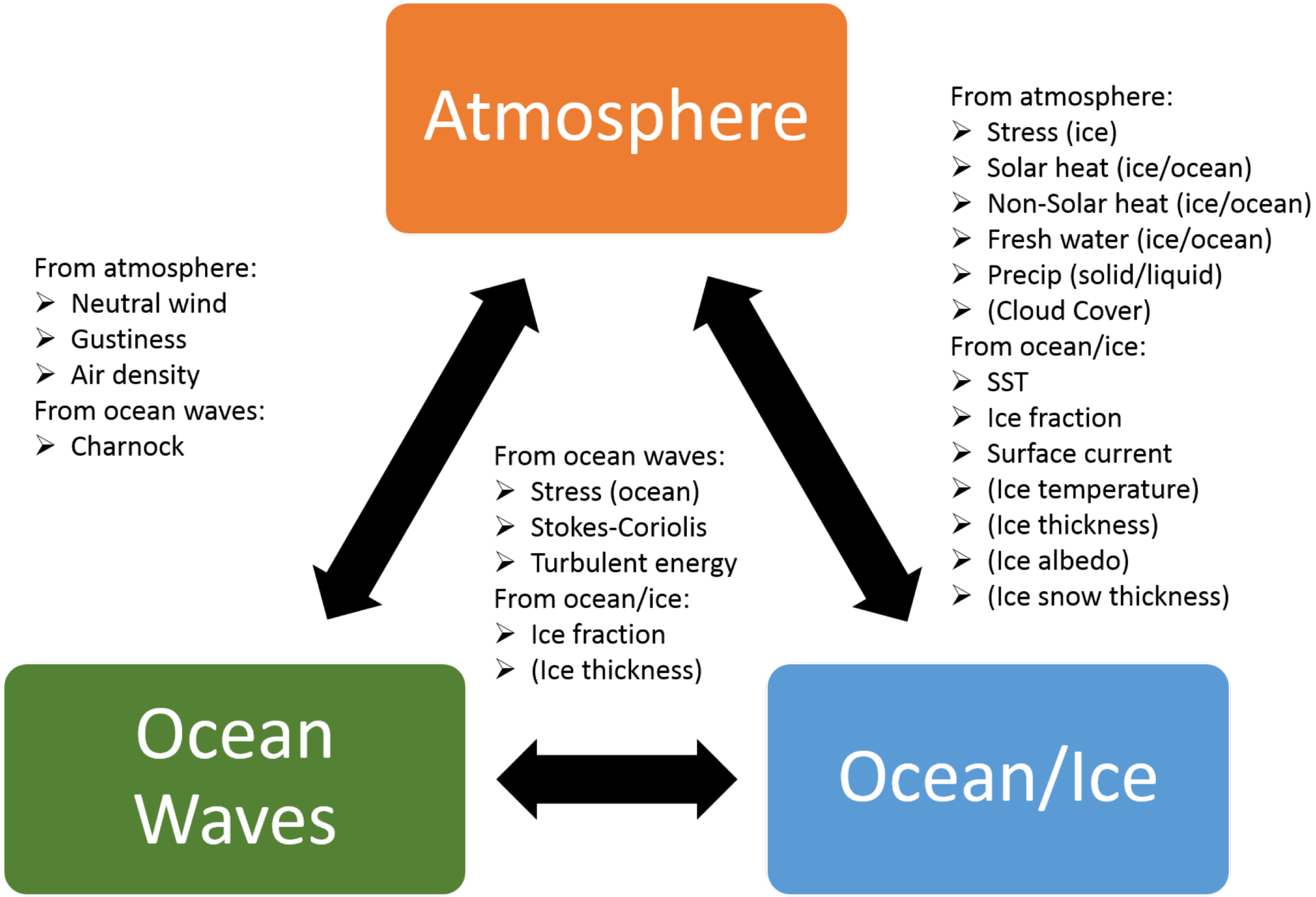




Ensemble of assimilations and forecasts



Data exchanges in the ECMWF coupled model



Fields in () are not currently used in operations