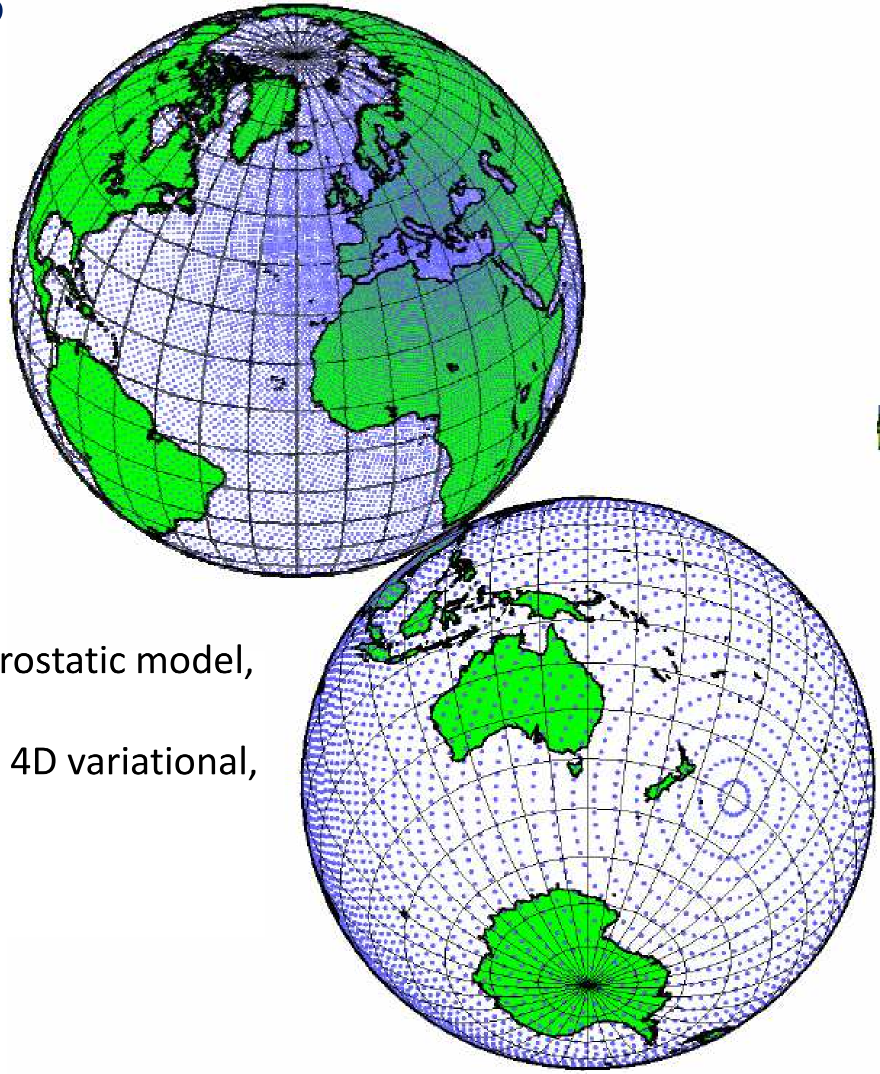
ARPEGE & IFS

ARPEGE: Action de Recherche Petite Échèlle Grande Échèlle,
operationally used at Météo-France

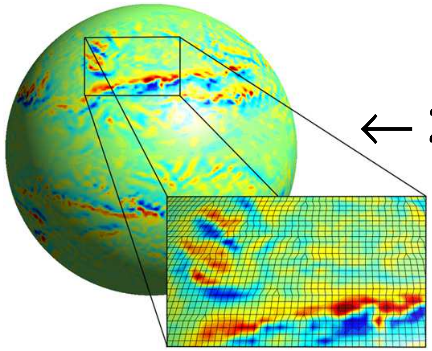
IFS: Integrated Forecasting system, operationally used at ECMWF



- global spectral model,
- Gaussian grid for grid-point calculations,
- terrain-following pressure hybrid vertical coordinates,
- option for a horizontally variable mesh: change of horizontal representation is defined by a change of pole.
- contains different models: 3D primitive-equation model, 3D non-hydrostatic model, 2D shallow-water model),
- different assimilation schemes: optimal interpolation, 3D variational, 4D variational,
- different physics packages: weather at different scales, climate.

Both systems are regularly synchronized!

IFS cycle 41r2 (since March 2016)

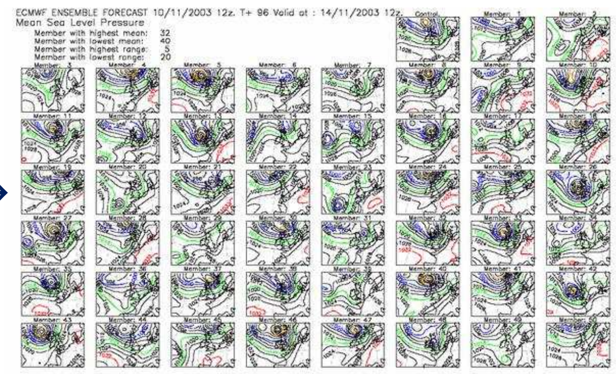


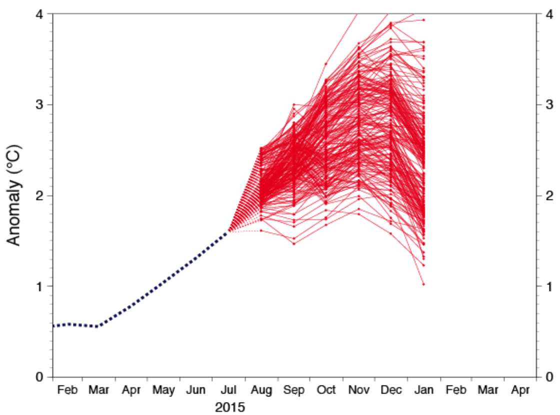
← **2x 9-km global high-resolution 10-day forecasts per day**

(4x ARPEGE 7.5 km over France, 37 km opposite, 3-4.5 days)

51x 18-km global lower-resolution 15-day forecasts per day… →

… extended to 46 days twice per week at 36 km

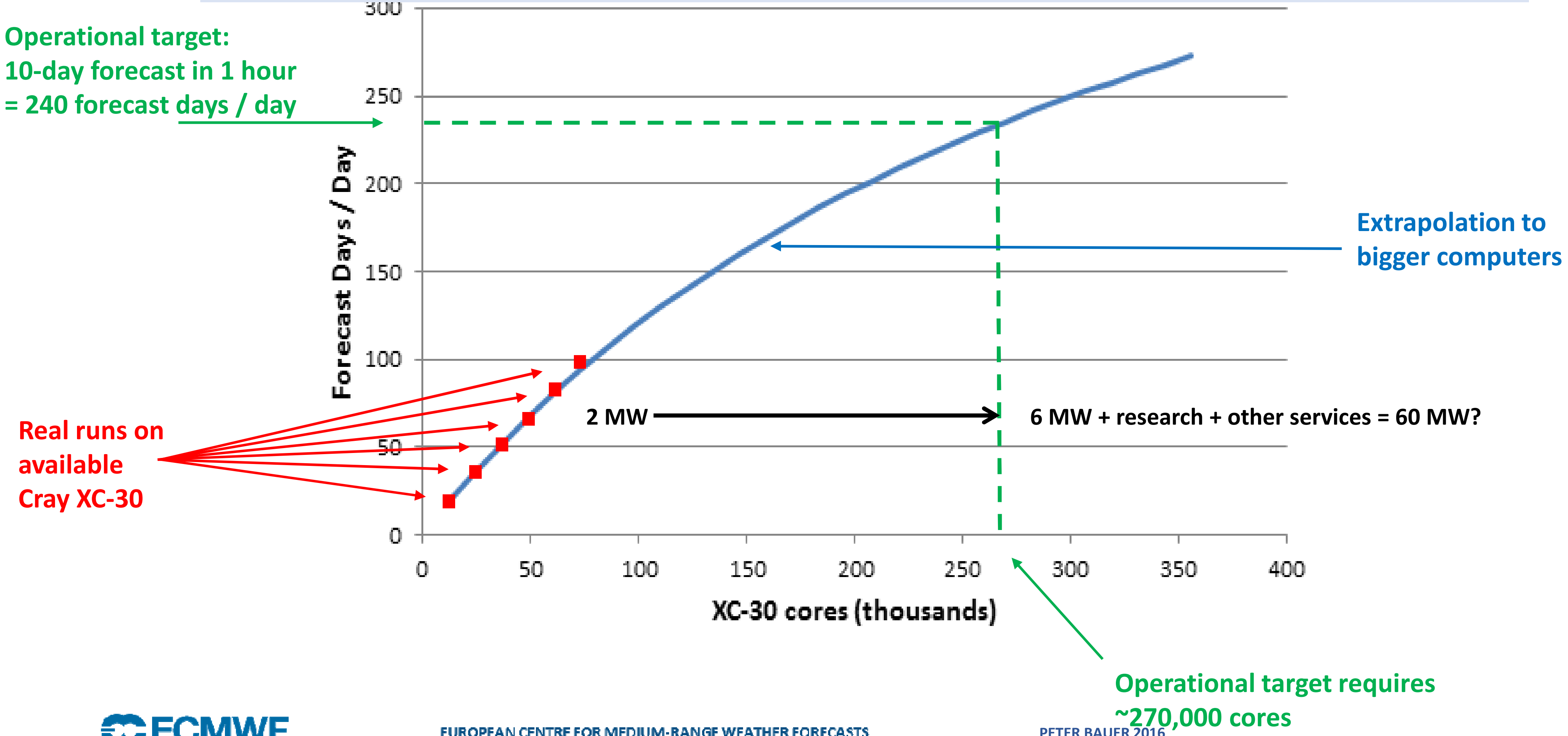




← **51x 64-km global low resolution 7-month forecast per month**

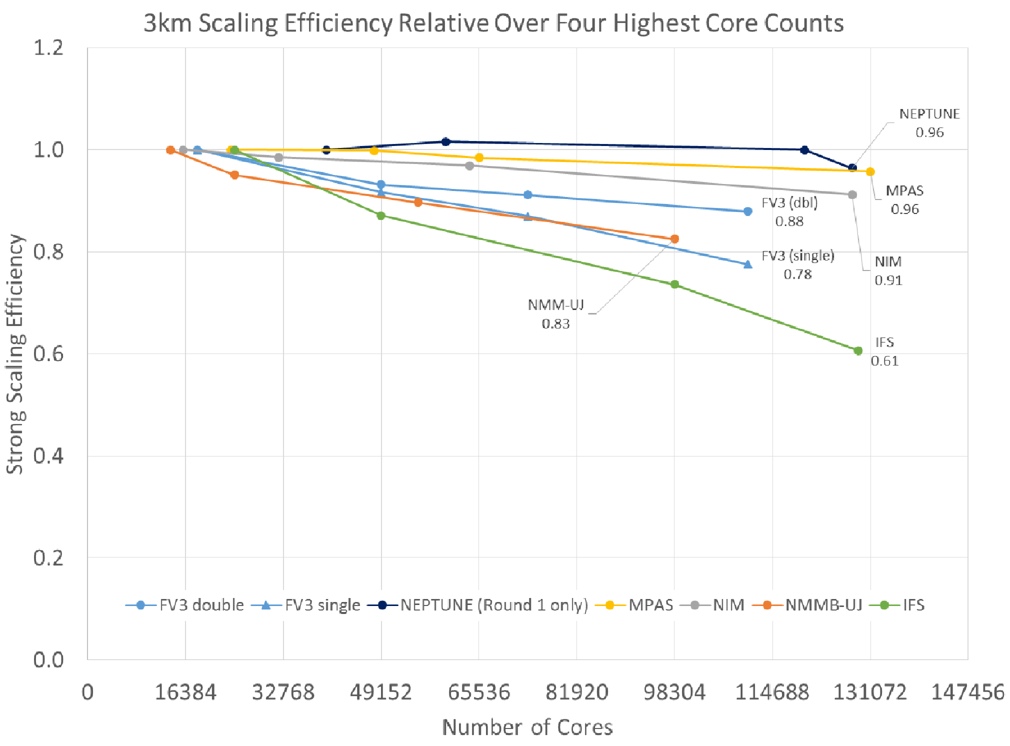
What is the challenge?

Global forecast experiments with ECMWF's IFS at 2.5 km (today's resolution is 9 km) – still far away from targeted 1 km resolution

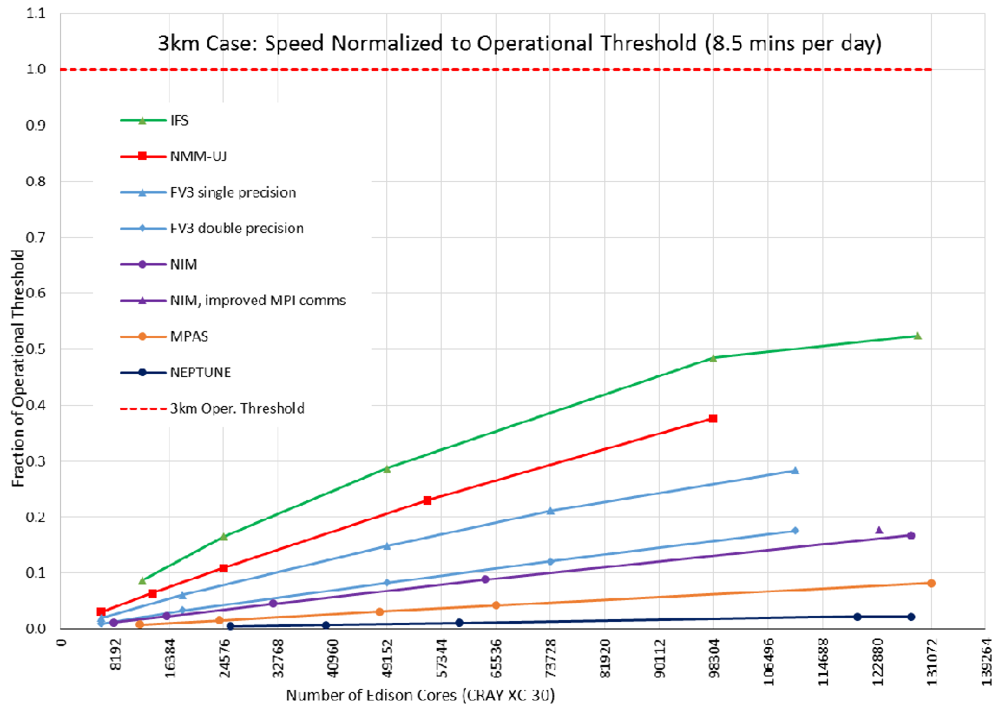


AVEC forecast model intercomparison: 3 km

Scalability:

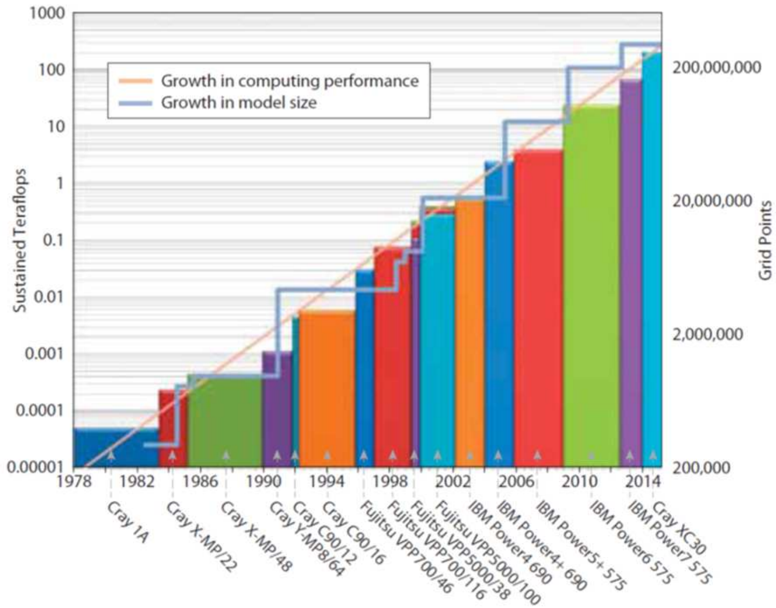


Efficiency:



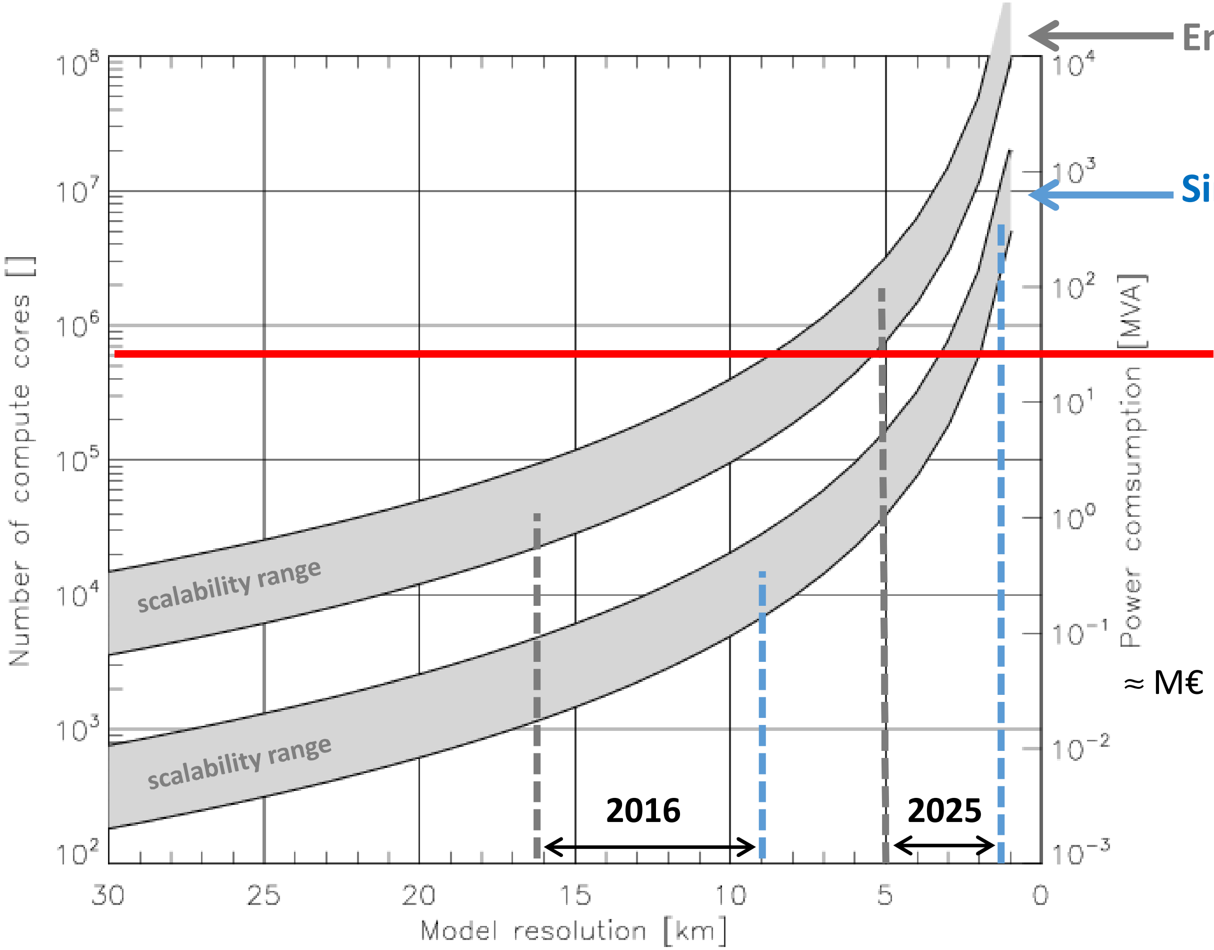
[Michalakes et al. 2015: AVEC-Report: NGGPS level-1 benchmarks and software evaluation]

ECMWF HPC



	Phase 1 (Ivybridge) – 2014-2016	Phase 2 (Broadwell) – 2016-2020
CPU	24 cores (2 x 12 core) @ 2.7GHz	36 cores (2 x 18 core) @ 2.1 GHz
Memory/Node	64 Gb (1866 MHz DDR3)	128Gb (2400 MHz DDR4)
Memory/Core	2.6 Gb	3.5Gb (+35% cf Phase 1)
Parallel Nodes (per cluster)	3,400	3,513 (+3% cf Phase 1)
Total Cores (per cluster)	84,096	130,212 (+55% cf Phase 1)
Tf sustained (both clusters)	200	320 (+60% cf Phase 1)

Simple compute projection (only resolution)



[Bauer et al. 2015]
nature

Four-year plan: Projected HPC cost

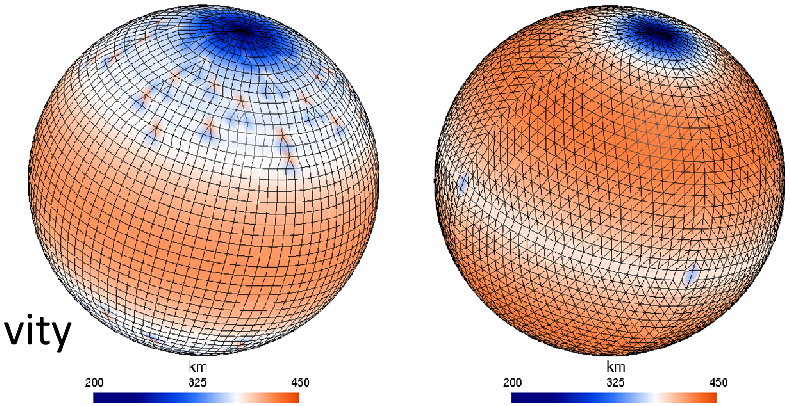
Strategic target:
Global 5km, seamless analysis-forecast ensemble in 2025

EDA:		2016		2017	2018	2019	2020
	H resolution o/l	TCo639					TCo1279
	H resolution i/l	TL191	TCo191				
	V resolution	L137					
	Coupling				orca025l75		
	Ensemble size	M25		M50			
	Window length	2x12h	4x6h				
	Efficiency gains						
	Nodes:	1600	2560	5120	5632	5632	28160
	Factor:	1	1.6	2.0	1.1	1.0	5.0
	Acc. factor:	1	1.6	3.2	3.5	**3.5**	**17.6**

ENS/legA:		2016		2017	2018	2019	2020
	H resolution	TCo639					TCo1279
	V resolution	L91			L137		
	Coupling	orca100l42	orca025l75				
	Forecast range	d10		d15			
	Ensemble size	M51					
	Reforecast ensemble size	M11				M15	
	Efficiency gains						
	Nodes:	1530	1683	2525	3787	4355	21774
	Factor:	1	1.1	1.5	1.5	1.2	5.0
	Acc. factor:	1	1.1	1.7	2.5	**2.8**	**14.2**

IFS/ARPEGE: Old assets and new features

Retain:
- Semi-implicit, semi-Lagrangian (SISL) solution procedure of the hydrostatic primitive equations
- Fast spectral transforms
- Effective and load-balanced combinations of MPI and OpenMP
- A fully-compressible, non-hydrostatic, deep-atmosphere option (from ALADIN to IFS/ARPEGE)
- Spectral transform efficiency at large hydrostatic scales



N24 reduced Gaussian grid

N24 octahedral Gaussian grid

Add:
- Flexibility in data structure design and numerical methods
- Small-scale simulation capability and nearest-neighbour connectivity
- Local mass conservation of tracers and moist species
- Steep slope orography capabilities
- Increased resolution (by re-thinking the spectral wavenumber truncation to grid point number ratio (Wedi 2014; by introducing the cubic-octahedral grid (TCo1279) at ECMWF (Wedi et al. 2015)).

The future of the spectral model

Horizontal discretization of a variable, e.g. temperature:

$$X(\lambda,\mu,\eta,t) = \sum_{m=-N}^{N} \sum_{n=|m|}^{N} X_n^m(\eta,t) Y_n^m(\lambda,\mu)$$

Triangular truncation (isotropic)

Spherical harmonics

$$X_n^m(\eta,t) = \frac{1}{4\pi} \int_{-1}^{1} \int_{0}^{2\pi} X(\lambda,\mu,\eta,t) P_n^m(\mu) e^{-im\lambda} d\lambda d\mu$$

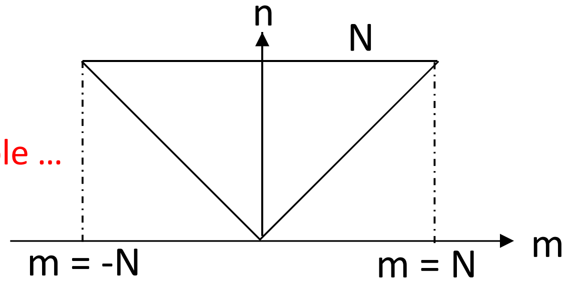
Fourier functions

associated Legendre polynomials

Legendre transform
by Gaussian quadrature
using $N_L \geq (2N+1)/2$
"Gaussian" latitudes (linear grid)
((3N+1)/2 if quadratic grid)
"fast" algorithm desirable ...

FFT (fast Fourier transform)
using
$N_F \geq 2N+1$
points (linear grid)
(3N+1 if quadratic grid)
"fast" algorithm available ...

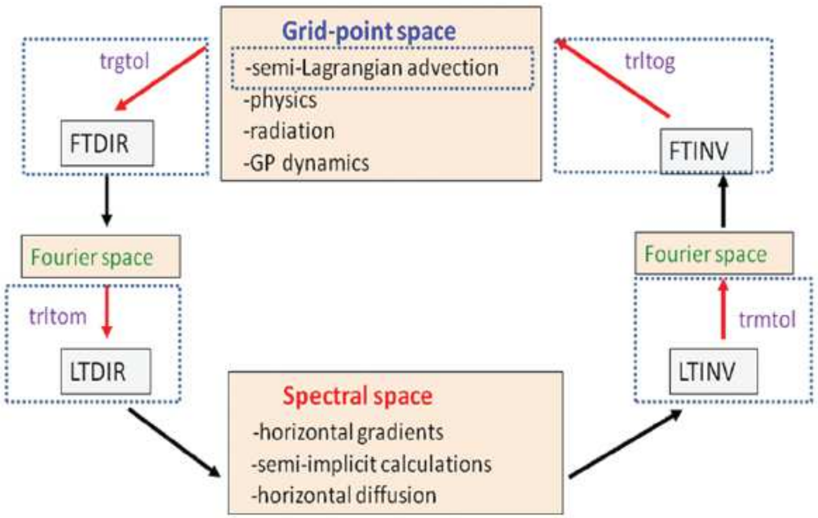
Triangular truncation:



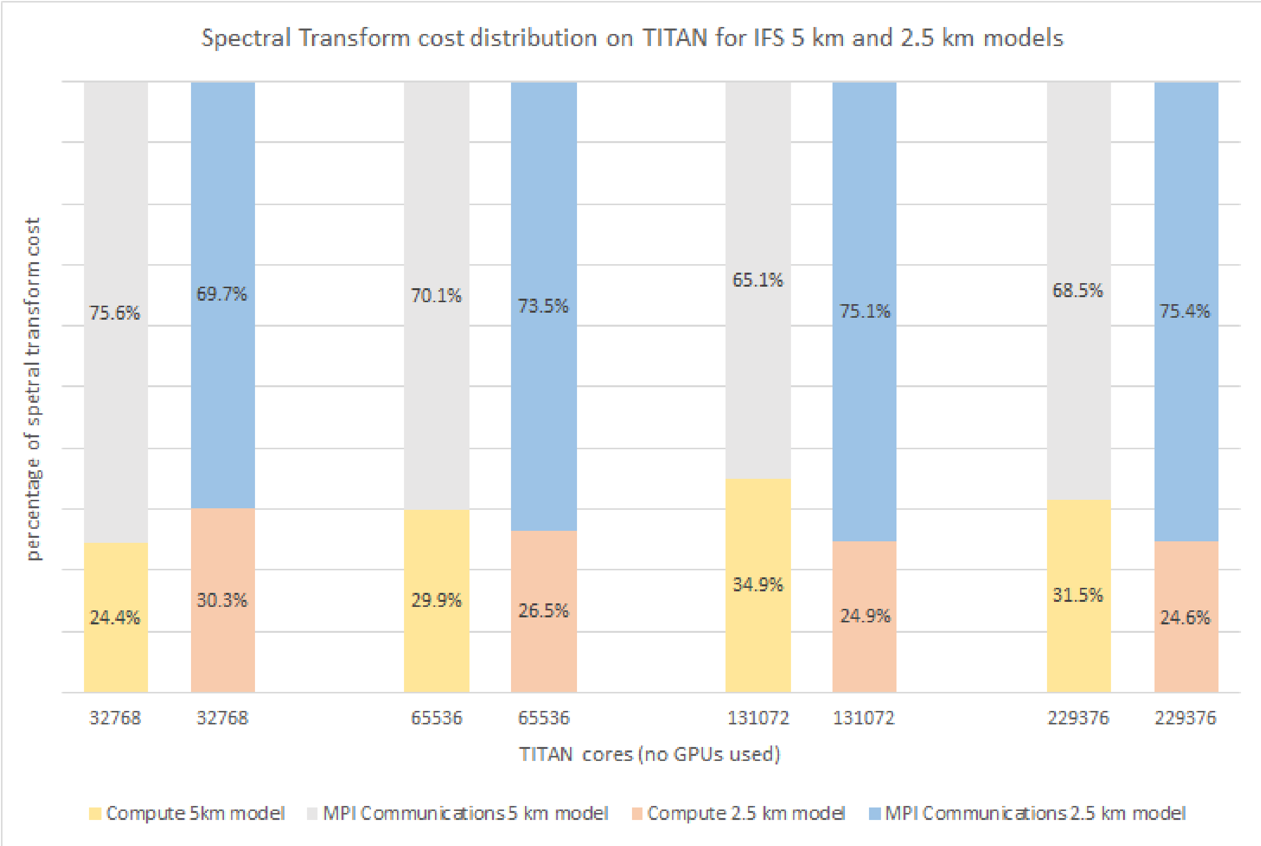
[Courtesy Nils Wedi]

The future of the spectral model

Once per time step:



Communication vs computation cost:



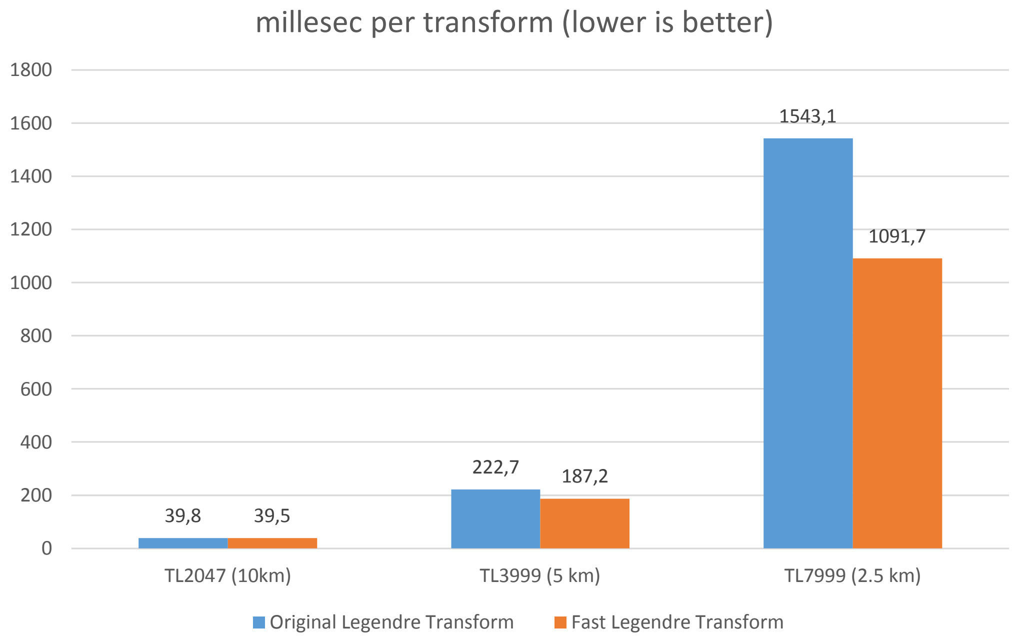
→ **Spectral transforms ~ 30% of total model cost (physics + waves 40%, SL-scheme 10% etc.) at globally 9 km resolution**

[Courtesy George Mozdzynski]

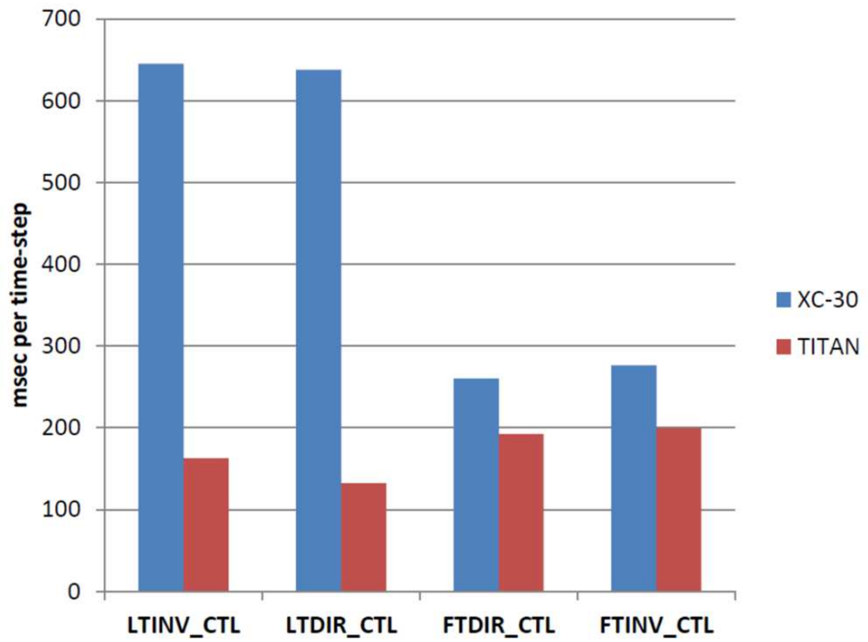
The future of the spectral model

Use of fast Legendre transform:

Nils P. Wedi, Mats Hamrud, and George Mozdzynski, 2013: A Fast Spherical Harmonics Transform for Global NWP and Climate Models. Mon. Wea. Rev., 141, 3450–3461.



Transforms on GPUs:

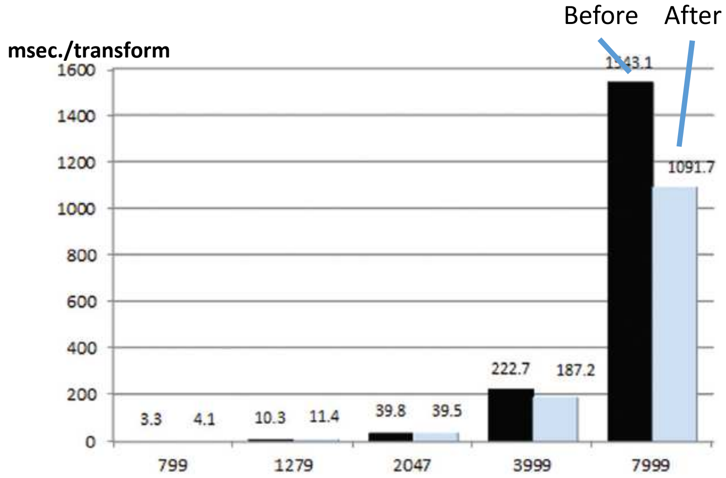


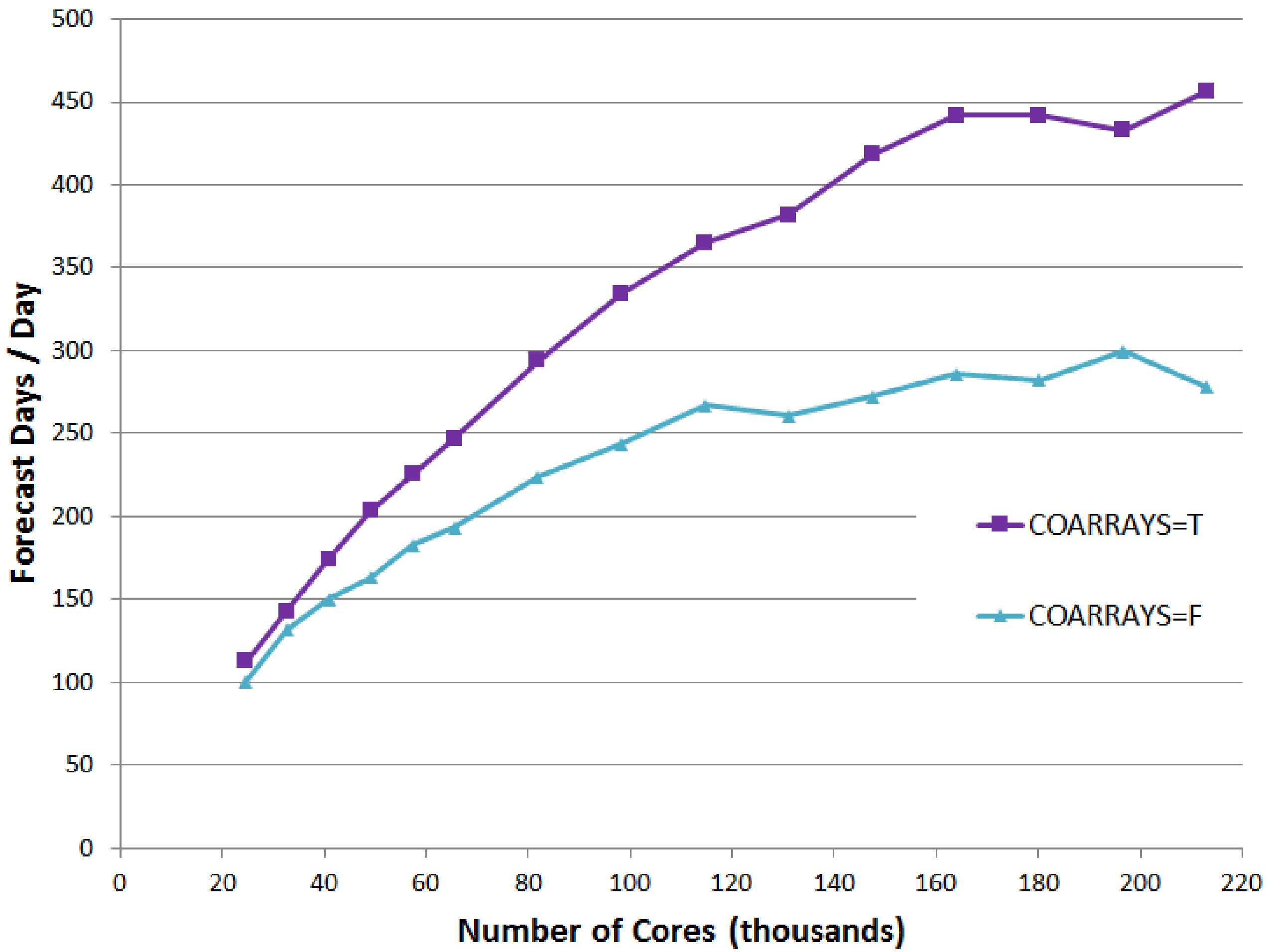
[Courtesy George Mozdzynski]

The future of the spectral model

Overlap of communication and computation:

Mozdzynski et al. 2015: A PGAS implementation of the ECMWF IFS. Int. J. High-Perf. Comp. App.

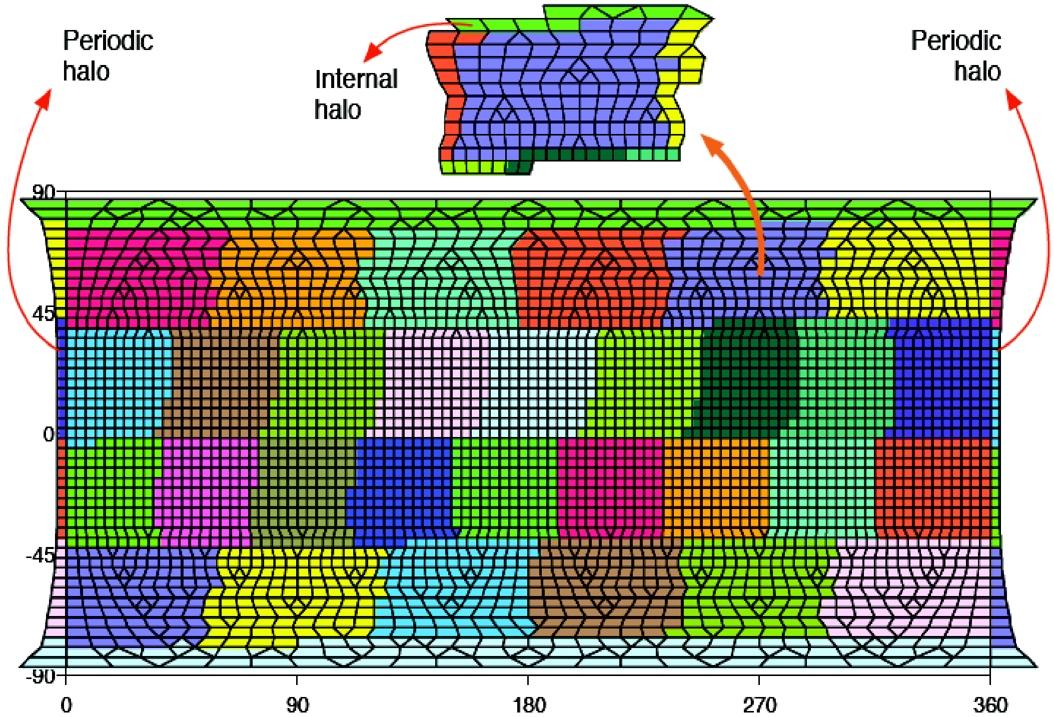




[Courtesy George Mozdzynski]

ATLAS: A flexible data structure

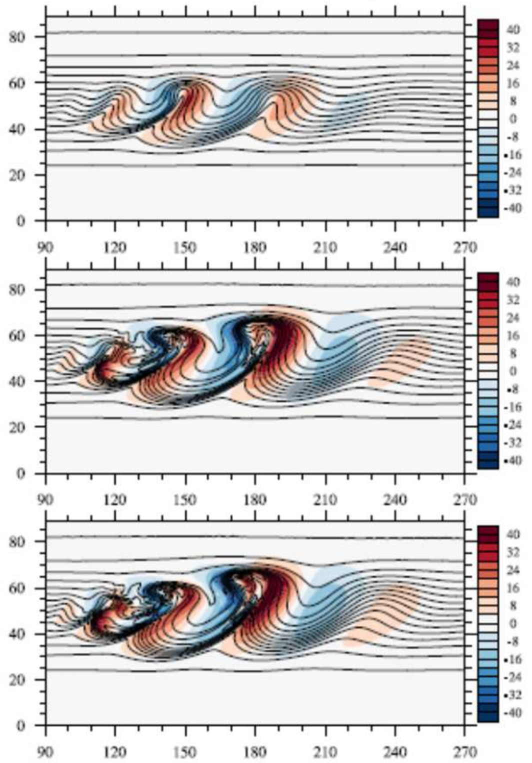
At 9 km: 6,599,680 grid points x 137 levels x 10 variables = 9 billion points
→ Equal area (MPI) parallel decomposition (1600 tasks)



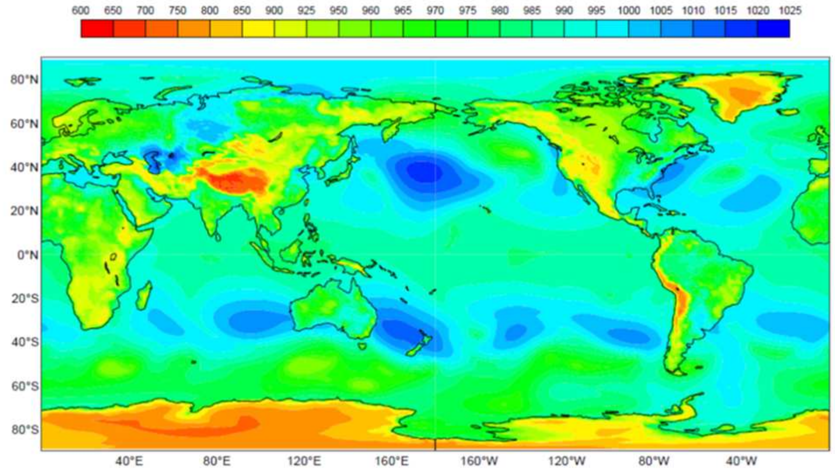
[Courtesy Willem Deconinck]

Finite-volume module (FVM)

Baroclinic instability benchmark with the FVM (anelastic, pseudo-incompressible, compressible)



O640 - Held-Suarez with real orography: surface pressure after 50 days of simulation



→ Compressible equations provide the most efficient solution as well as flexibility on the solution procedure in time

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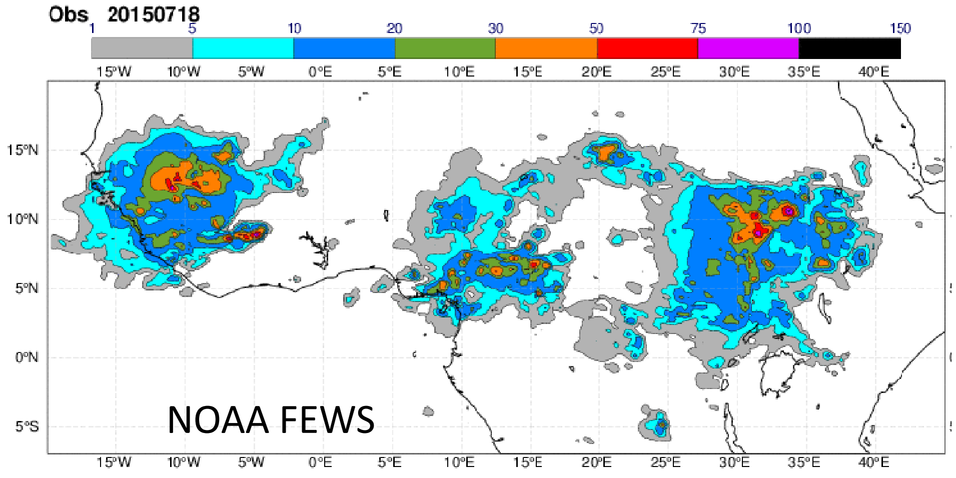
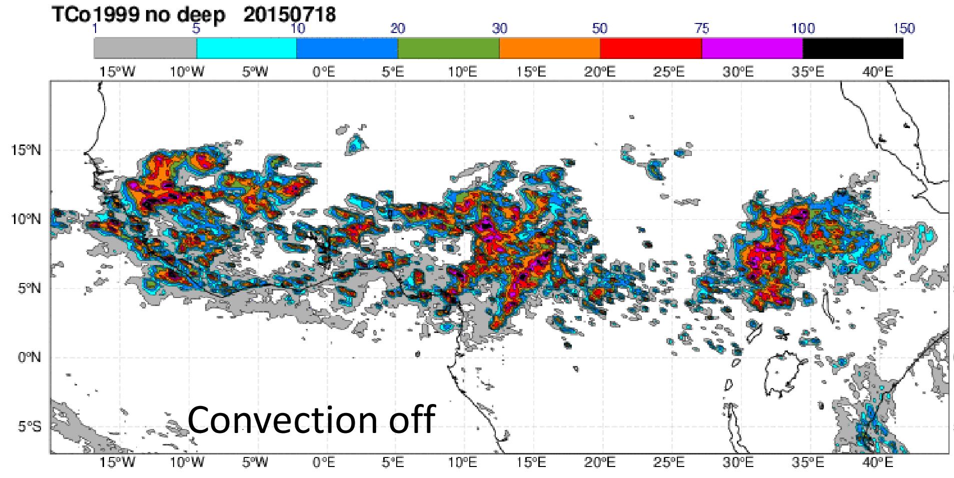
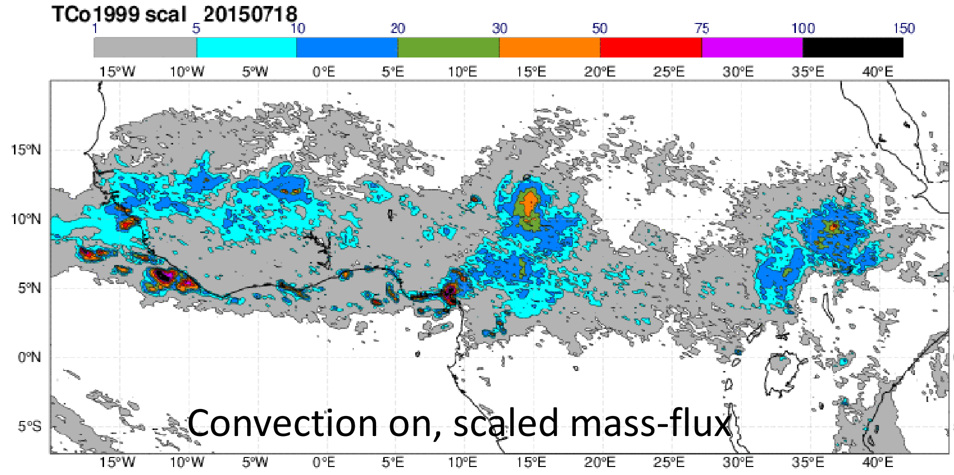
[Courtesy Piotr Smolarkiewicz, Christian Kühnlein]

The future of the parameterized convection

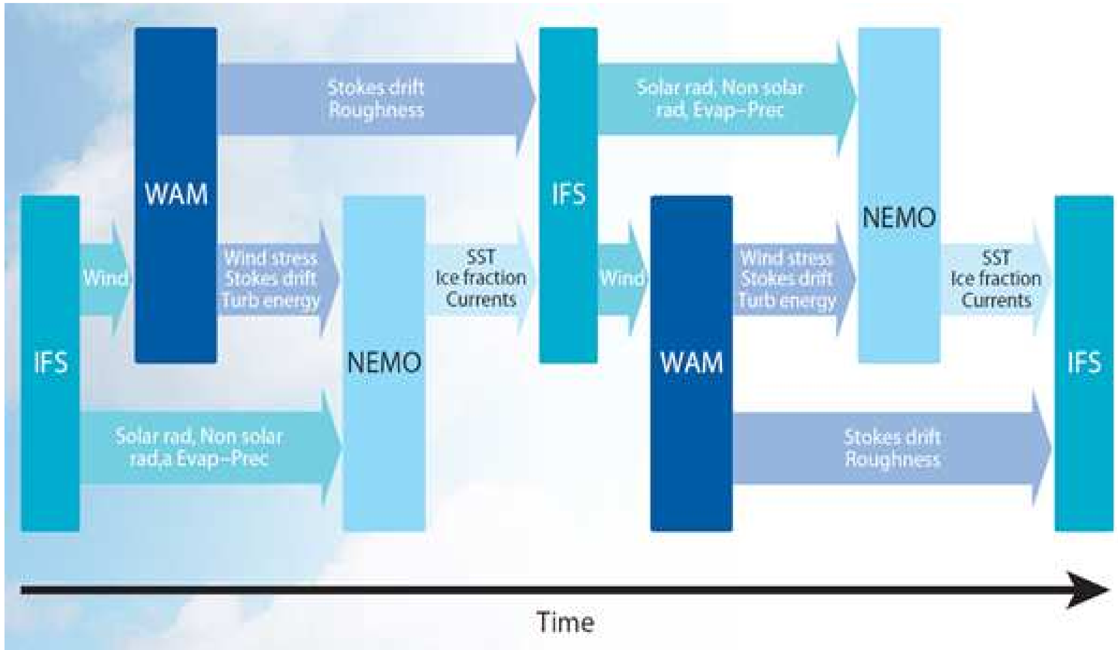




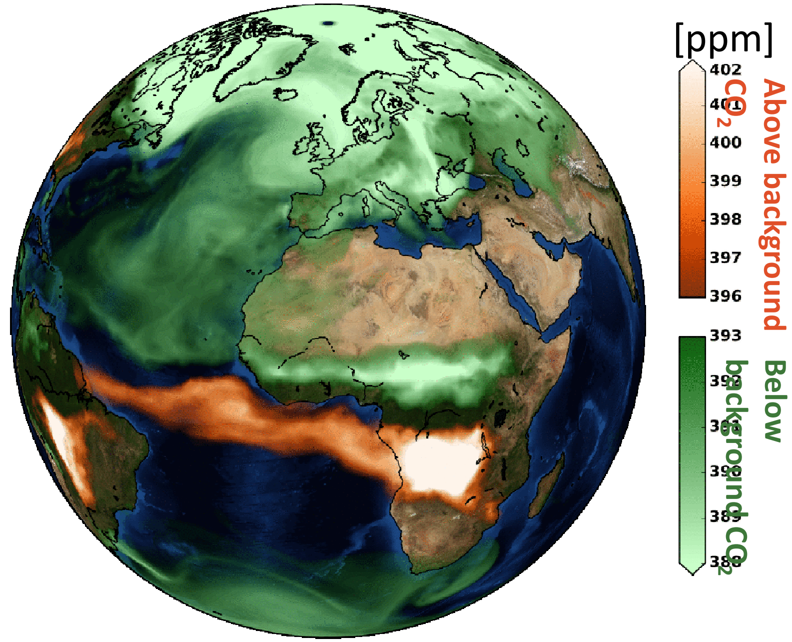


[Courtesy Peter Bechtold]

ESM coupling



[Courtesy Kristian Mogensen]



[Courtesy Anna Agusti-Panareda]

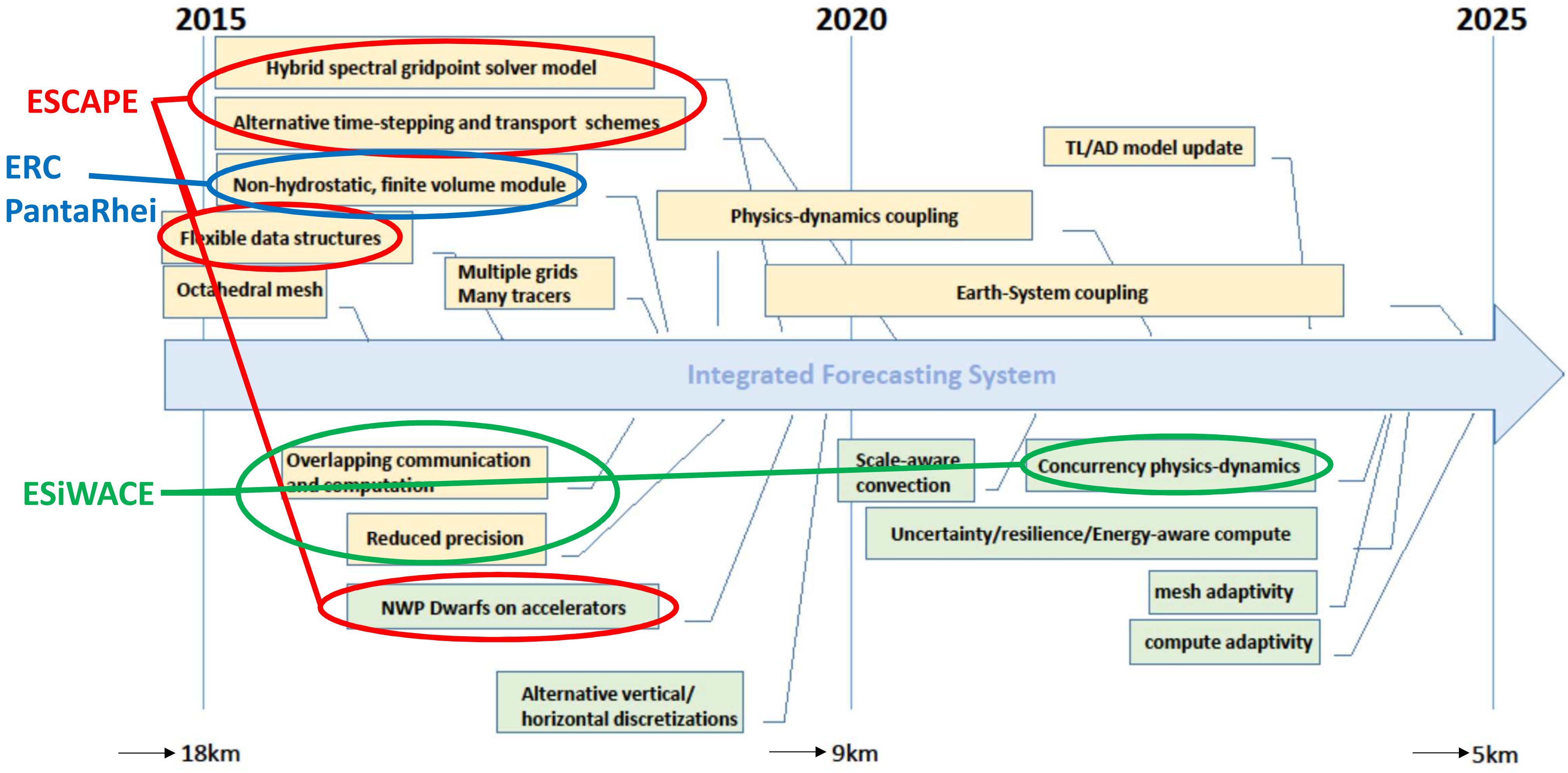
Issues with ESM initialization, and trading off model complexity and potential increase in predictive skill

Key challenges

- Extract *predictive skill* from a complete description of the *Earth-System*
- Optimize *time-to-solution*, *energy-to-solution* and *information density*
- Provide *computational efficiency to enhance forecast reliability*
- Apply *adaptive numerical techniques and tools* for forecast reliability but also for application resilience in a computing environment that itself may be subject to (partial) failure

[Wedi et al. 2015]

IFS/ARPEGE roadmap



[Wedi et al. 2015]