Introduction to parametrization of sub-grid physical processes in the IFS

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Thanks to many ECMWF colleagues

Numerical Weather Prediction Training Course:
Parametrization of Subgrid Physical Processes

Outline

- Global NWP at ECMWF - the Integrated Forecasting System (IFS)
- An overview of physical process parametrization
- Development & evaluation
- Kilometre-scale modelling
- Machine Learning
- Summary

ECMWF operational global ensemble forecasting and monitoring (Nov 2023)

Development: Destination Earth – km-scale

NEW: Machine Learning model AIFS

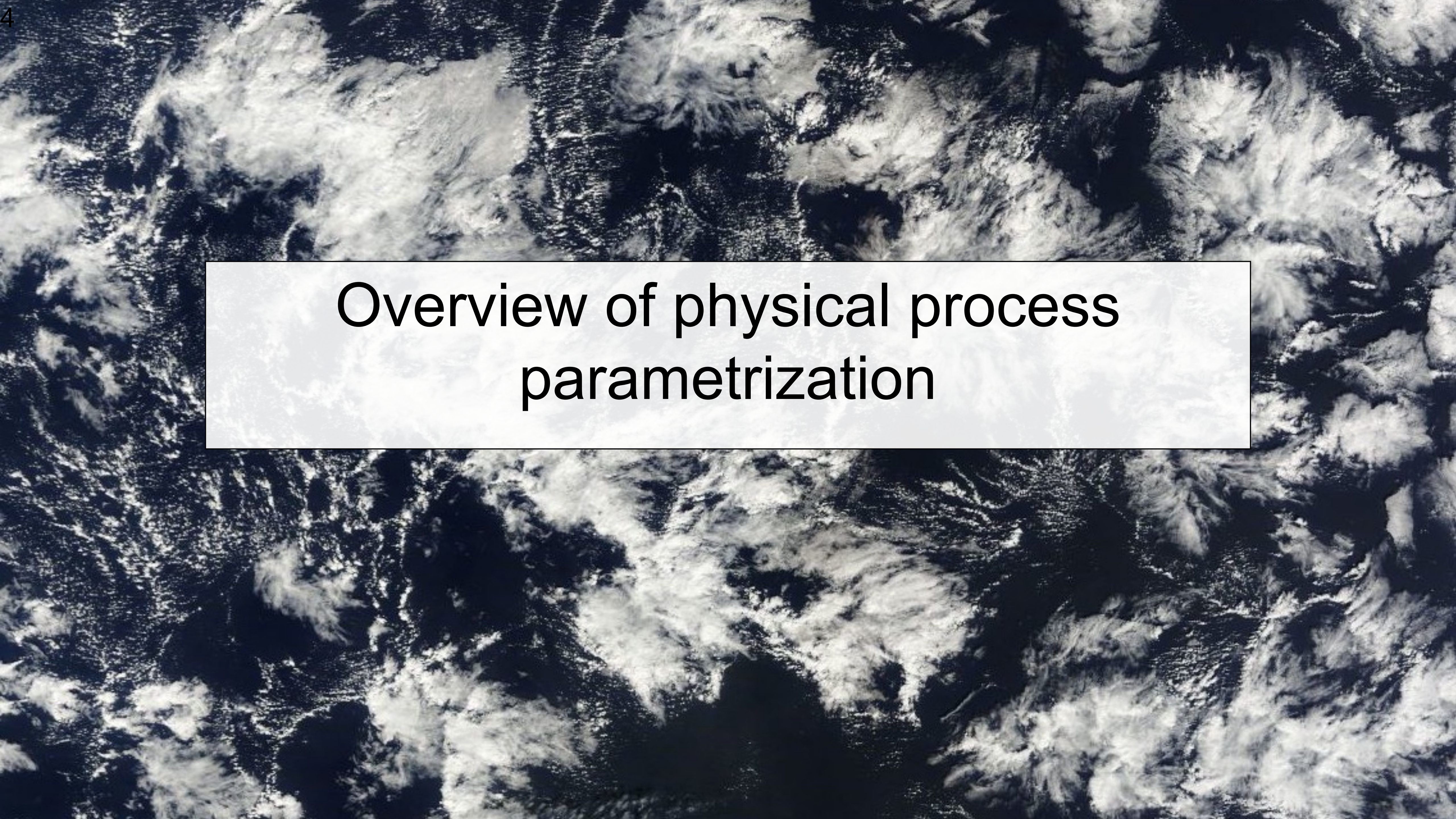
Analysis	Forecast (atmos-land-wave-ocean-seaice)
HRES 4DVAR T_{CO}1279 L137 (9km) (atmos-land-wave)	**Control forecast (“HRES”)** T_{CO}1279 L137 (9km) 2x daily
EDA 50 members T_{CO}1279 L137 (9km) (atmos-land-wave)	**ENS 51 member ensemble** T_{CO}1279 L137 (9km), 2x daily **Sub-seasonal 101 member ensemble** T_{CO}319 L137 (36km), daily
Ocean5/ORAS5-5 0.25 deg z75 ORCA (ocean-seaice)	**Seasonal (SEAS5)** T_{CO}319 L91 (36km) Cy43r1, 51 member (7month) 15 members (13 months) 1x monthly

Forecast Day: 0, 10, 15, 46, 210, 365

CAMS: Copernicus Atmospheric Monitoring Service: Global atmospheric composition analysis and forecasts

C3S: Copernicus Climate Change Service: ERA5 (hourly, 31km), ERA5T (near real time), ERA5L (hourly 9km, land only)

CEMS-Flood: GLOFAS/EFAS **CEMS-Fire**



Overview of physical process parametrization

Why parametrization

Processes to be parametrized:

- Processes that contribute to the subgrid fluxes (e.g. subgrid turbulent motions)
- Diabatic processes that lead to diabatic heating/cooling (*Q*)
- The effect of the sub-grid processes on the grid-scale are represented statistically
- In an ensemble forecasting system, we want to also represent uncertainty

e.g. equation for potential temperature:

$$\frac{\partial\Theta}{\partial t}+\underbrace{u\frac{\partial\Theta}{\partial x}+v\frac{\partial\Theta}{\partial y}+w\frac{\partial\Theta}{\partial x}}_{\text{advection}}=\underbrace{Q}_{\text{source}}+\underbrace{\lambda\left(\frac{\partial^2\Theta}{\partial x^2}+\frac{\partial^2\Theta}{\partial y^2}+\frac{\partial^2\Theta}{\partial z^2}\right)}_{\text{molecular diffusion}}$$

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Reynolds decomposition

e.g. equation for potential temperature:

$$\frac{\partial \Theta}{\partial t} + \underbrace{u\frac{\partial \Theta}{\partial x} + v\frac{\partial \Theta}{\partial y} + w\frac{\partial \Theta}{\partial x}}_{\text{advection}} = \underbrace{Q}_{\text{source}} + \underbrace{\lambda\left(\frac{\partial^2 \Theta}{\partial x^2} + \frac{\partial^2 \Theta}{\partial y^2} + \frac{\partial^2 \Theta}{\partial z^2}\right)}_{\text{molecular diffusion}}$$

Reynolds decomposition: $U = u + u', \quad V = v + v',$
$W = w + w', \quad \Theta = \theta + \theta'.$

Averaged (e.g. over grid box):

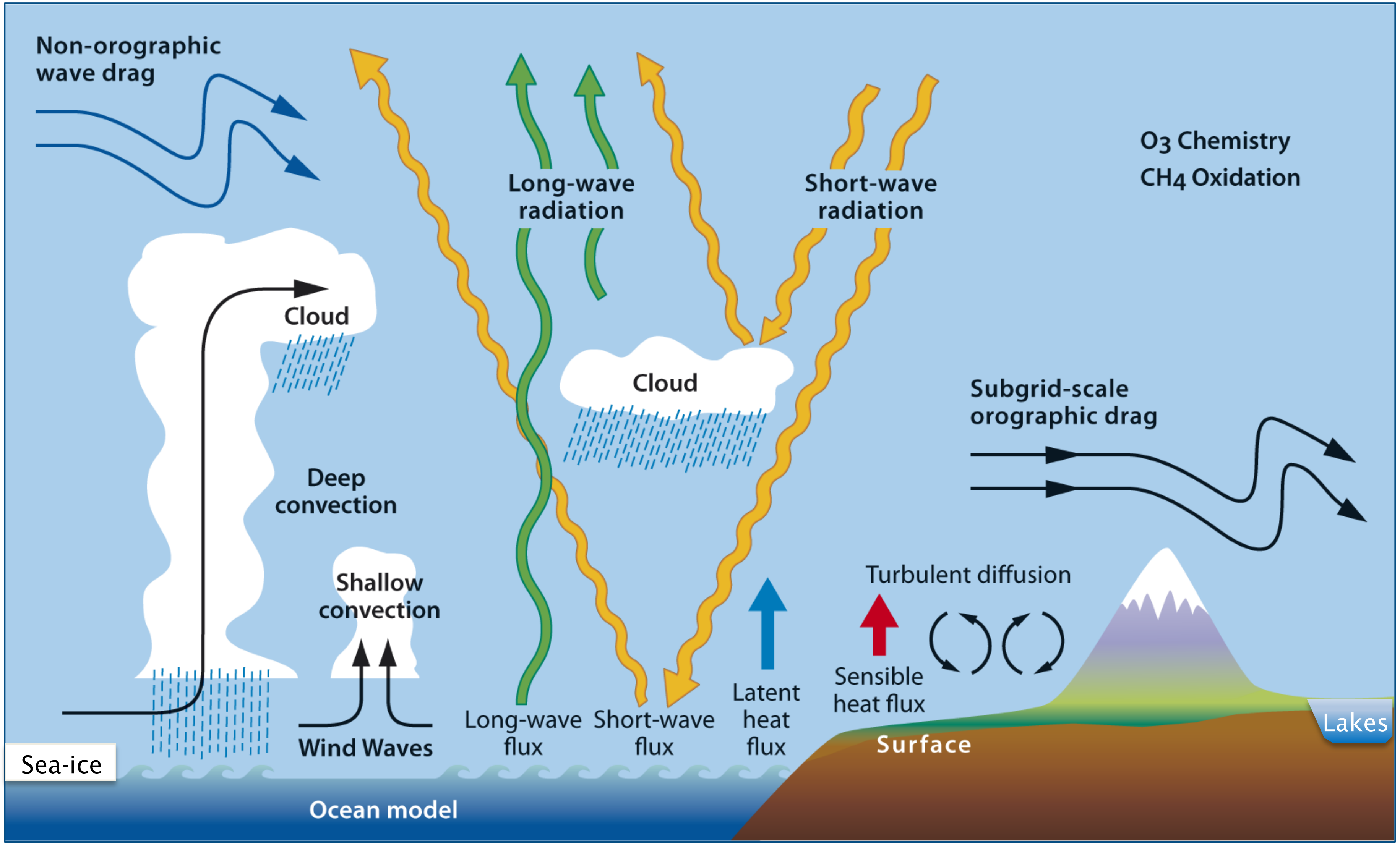
$$\frac{\partial \theta}{\partial t} + u\frac{\partial \theta}{\partial x} + v\frac{\partial \theta}{\partial y} + w\frac{\partial \theta}{\partial x} =$$

$$Q + \frac{\partial}{\partial x}\left(-\overline{u'\theta'} + \lambda\frac{\partial \theta}{\partial x}\right) + \frac{\partial}{\partial y}\left(-\overline{v'\theta'} + \lambda\frac{\partial \theta}{\partial y}\right) + \frac{\partial}{\partial z}\left(-\overline{w'\theta'} + \lambda\frac{\partial \theta}{\partial z}\right)$$

Q : source term (e.g. radiation absorption/emission or condensation)

$\overline{w'\theta'}$: subgrid (Reynolds) transport term (e.g. due to turbulence, convection)

Parameterized processes in the ECMWF model



Parametrization of physical processes – Importance

Impact on the atmosphere

- Sub-grid physical processes have substantial impacts on the atmosphere
- Diabatic processes drive the general circulation

“Weather” products

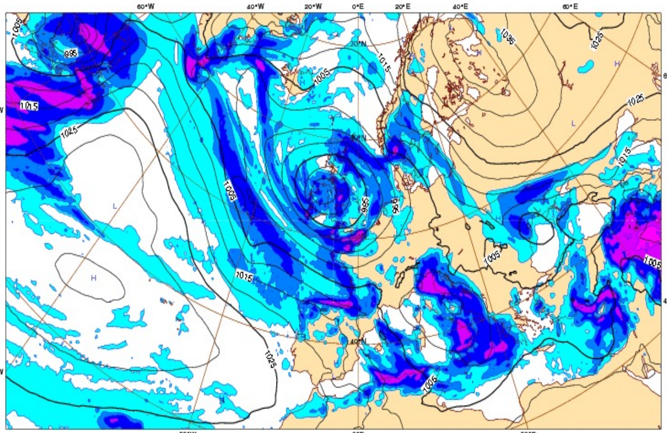
- Clouds, precipitation, fog, visibility, 10m wind, gustiness, 2m T, lightning, CAT

Data assimilation

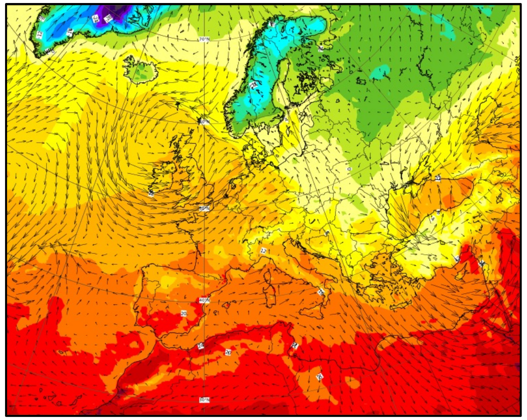
- The tangent linear/adjoint are required for 4D-Var assimilation
- Forward operators (with sub-grid physical assumptions) are needed for observations

“Weather” product examples

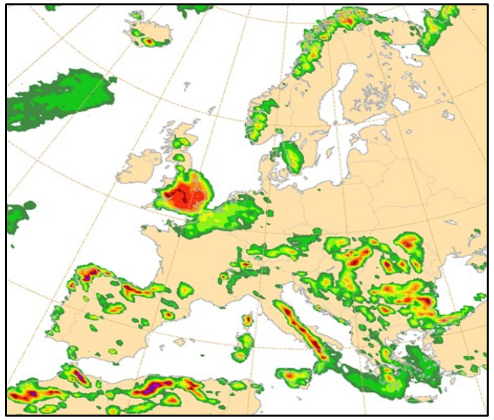
Precipitation



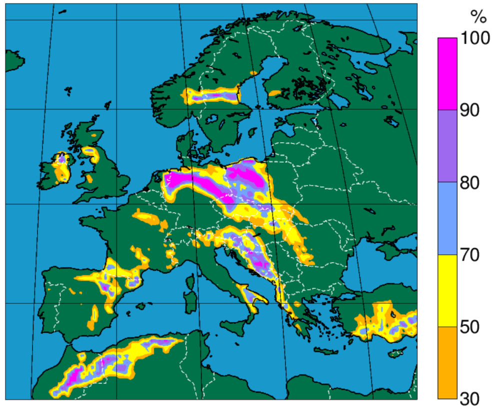
2m temperature



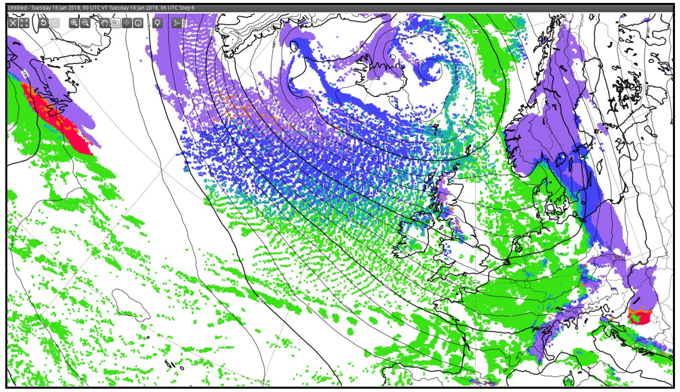
Visibility / fog



Lightning

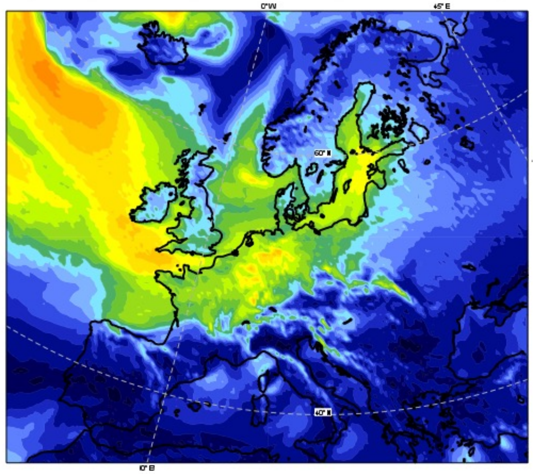


Winter precipitation-type

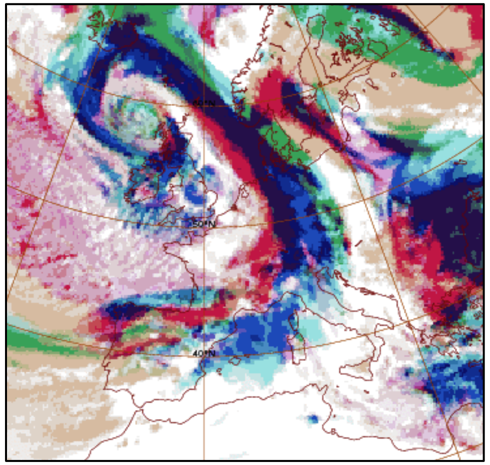


rain / mix rain-snow / wet snow
snow / ice pellets / freezing rain

10m wind & gustiness

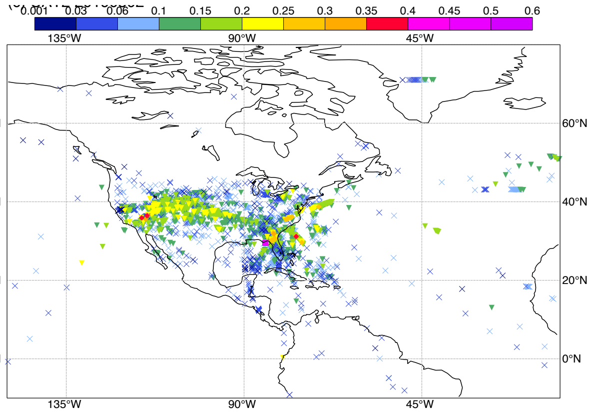


Cloud cover



high/mid-level/low

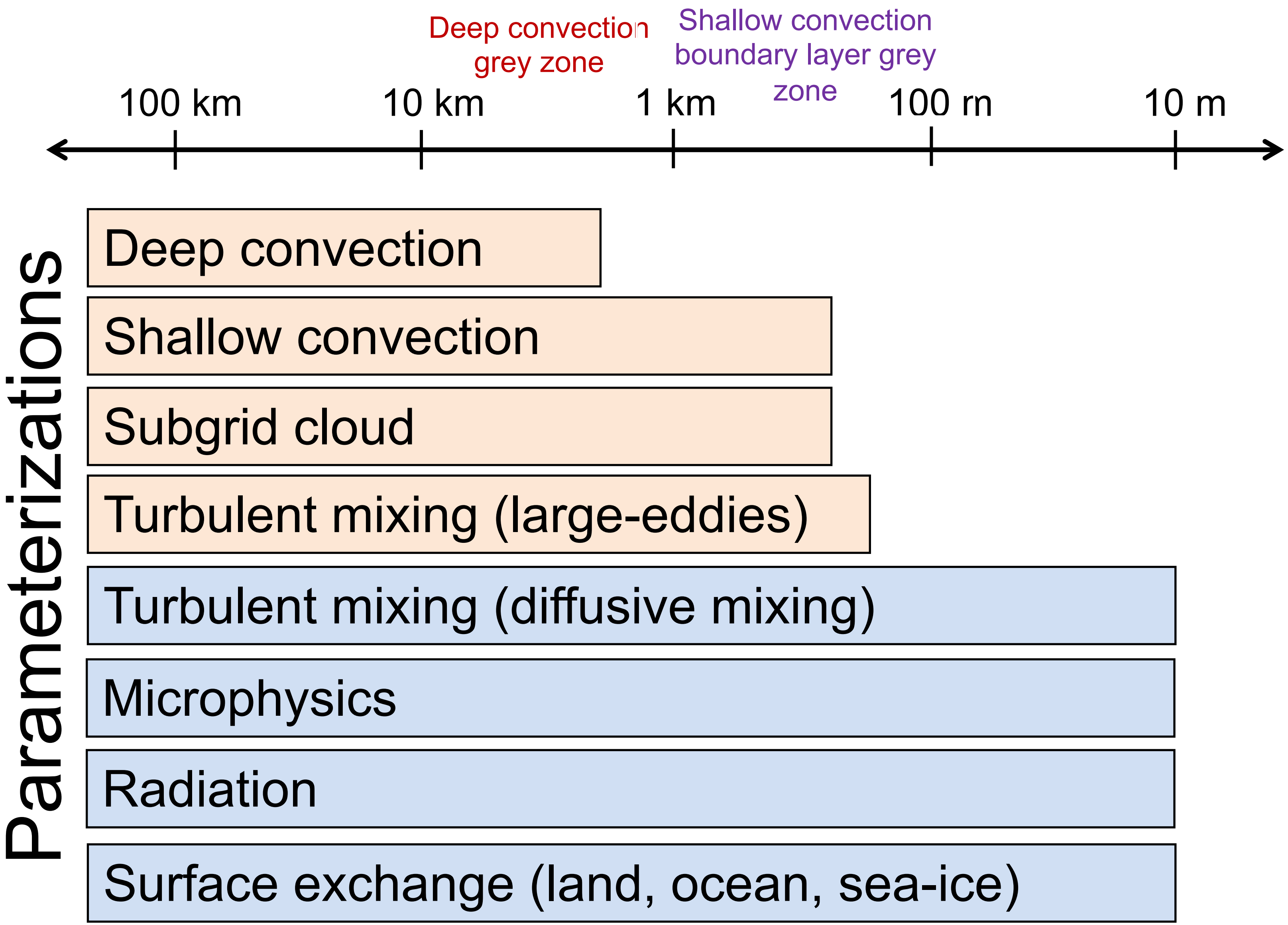
Clear Air Turbulence



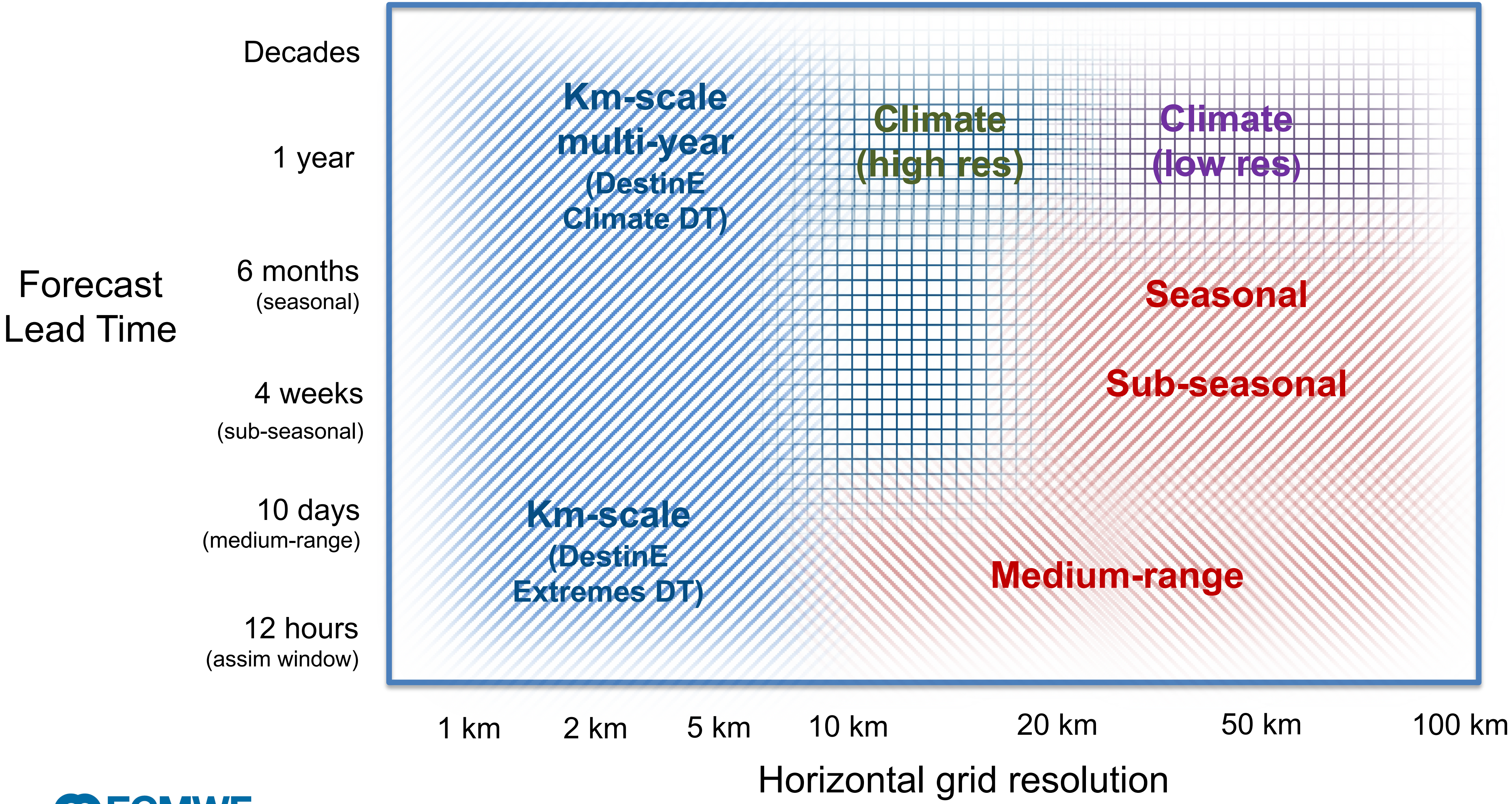
Parametrizations in the IFS

- Radiation (SW, LW)
- Turbulent transport (boundary layer & above)
- Surface exchange (land, snow, lakes, ocean , sea-ice)
- Convection (shallow, mid-level, deep)
- Sub-grid cloud (cloud fraction, sub-grid heterogeneity)
- Cloud and precipitation microphysics
- Orographic drag (roughness, hills, mountains)
- Non-orographic gravity wave drag (front, convection)
- Methane oxidation (stratospheric water vapour)
- Ozone chemistry (stratosphere)

Parametrization of atmospheric physical processes – Model resolution



Seamless prediction across time & space scales – a modelling challenge for the IFS!



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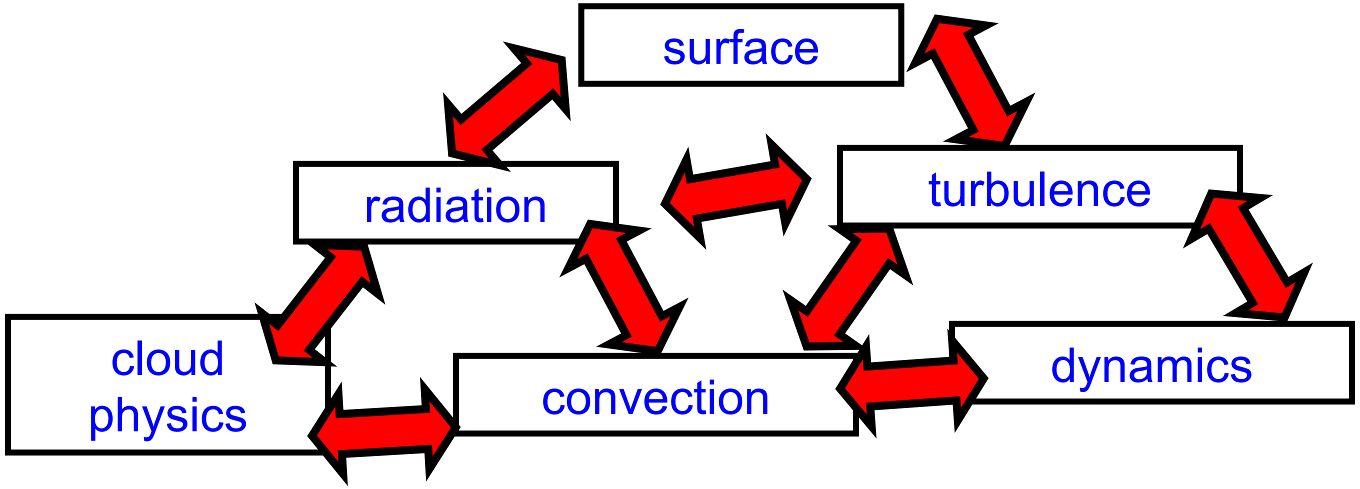
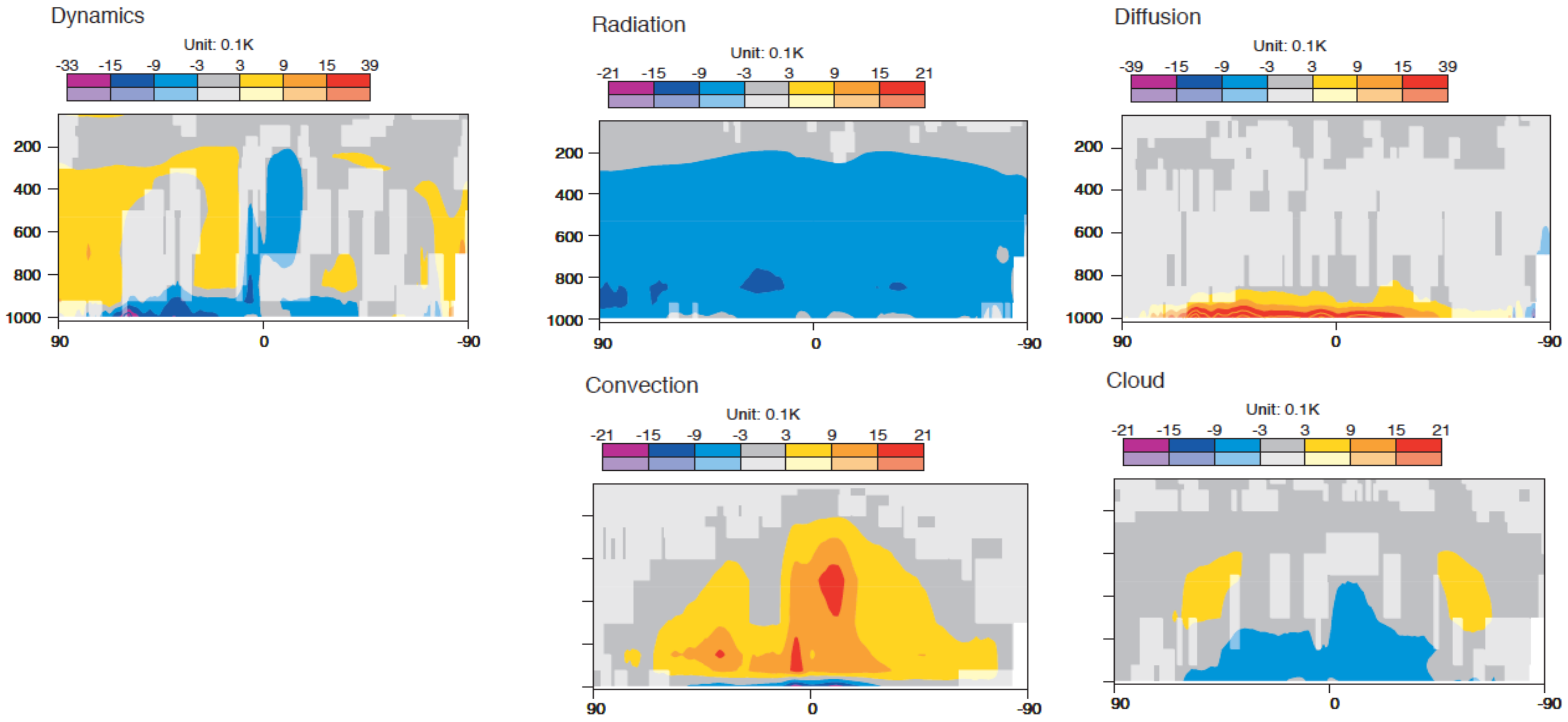
Parametrization of physical processes - Interactions

The interactions between schemes can be as important as the details of the individual parametrizations

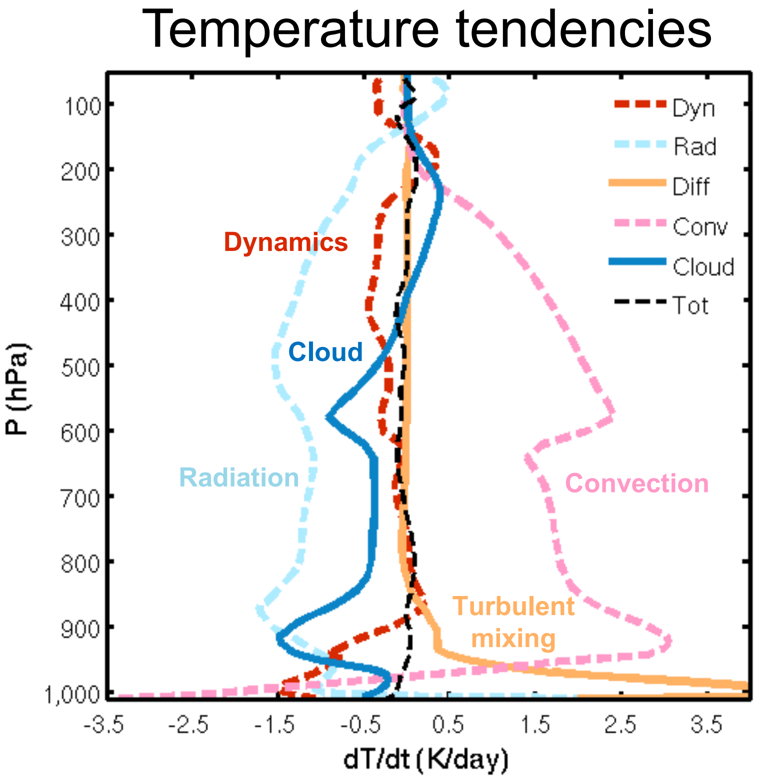


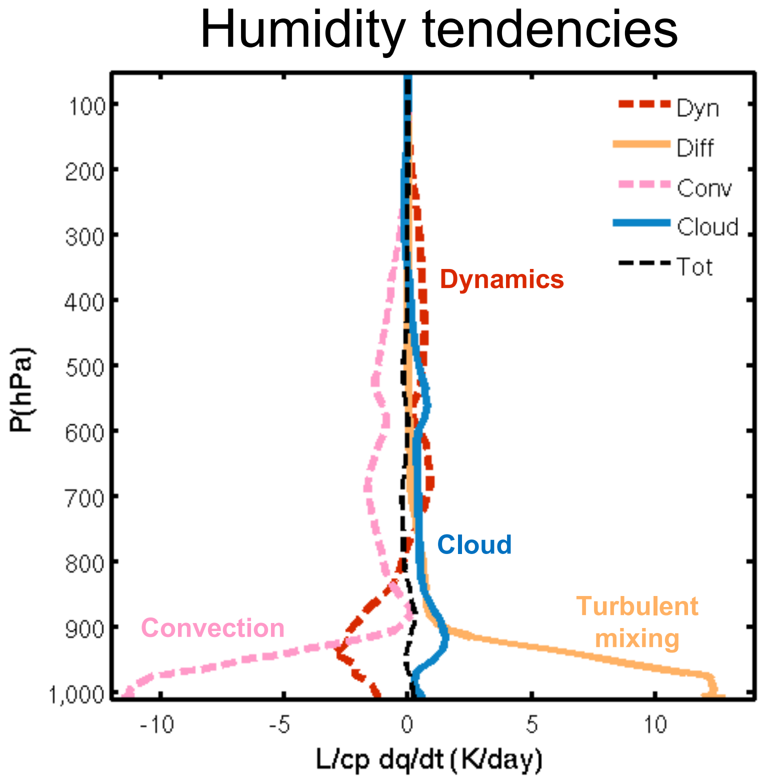
Temperature tendencies (12-hour data assimilation window). Mean DJF 2014.



Deep colours = 5% significant.
(Diagnostics Mark Rodwell)

Model Tendencies – Tropics Equilibrium (global similar)





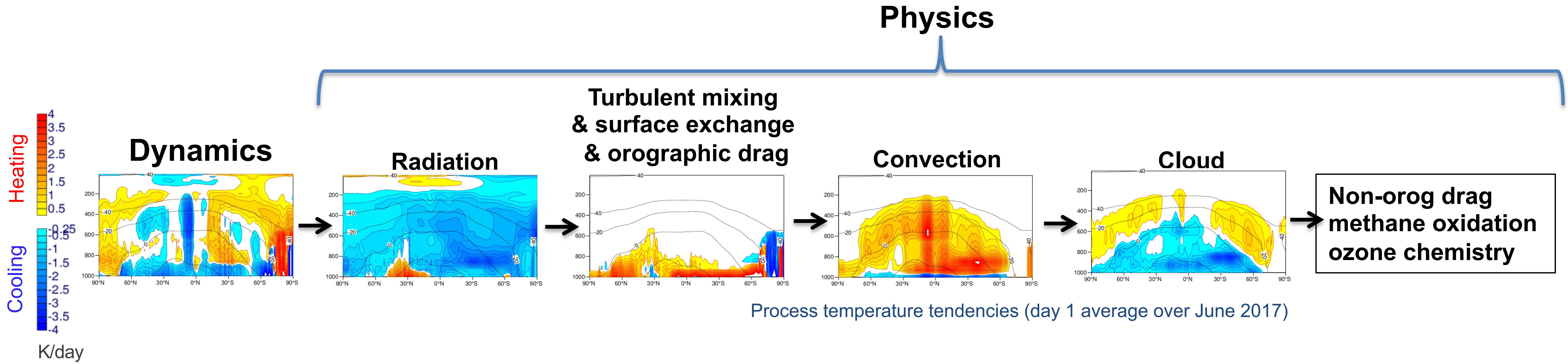
ABOVE THE BL:
Radiative-convective equilibrium; **radiative cooling** and **convective heating**

ABOVE THE BL: equilibrium between **moistening from dynamical transport** (resolved motion and subgrid turbulence), and **convection drying** (condensation and precipitation formation).

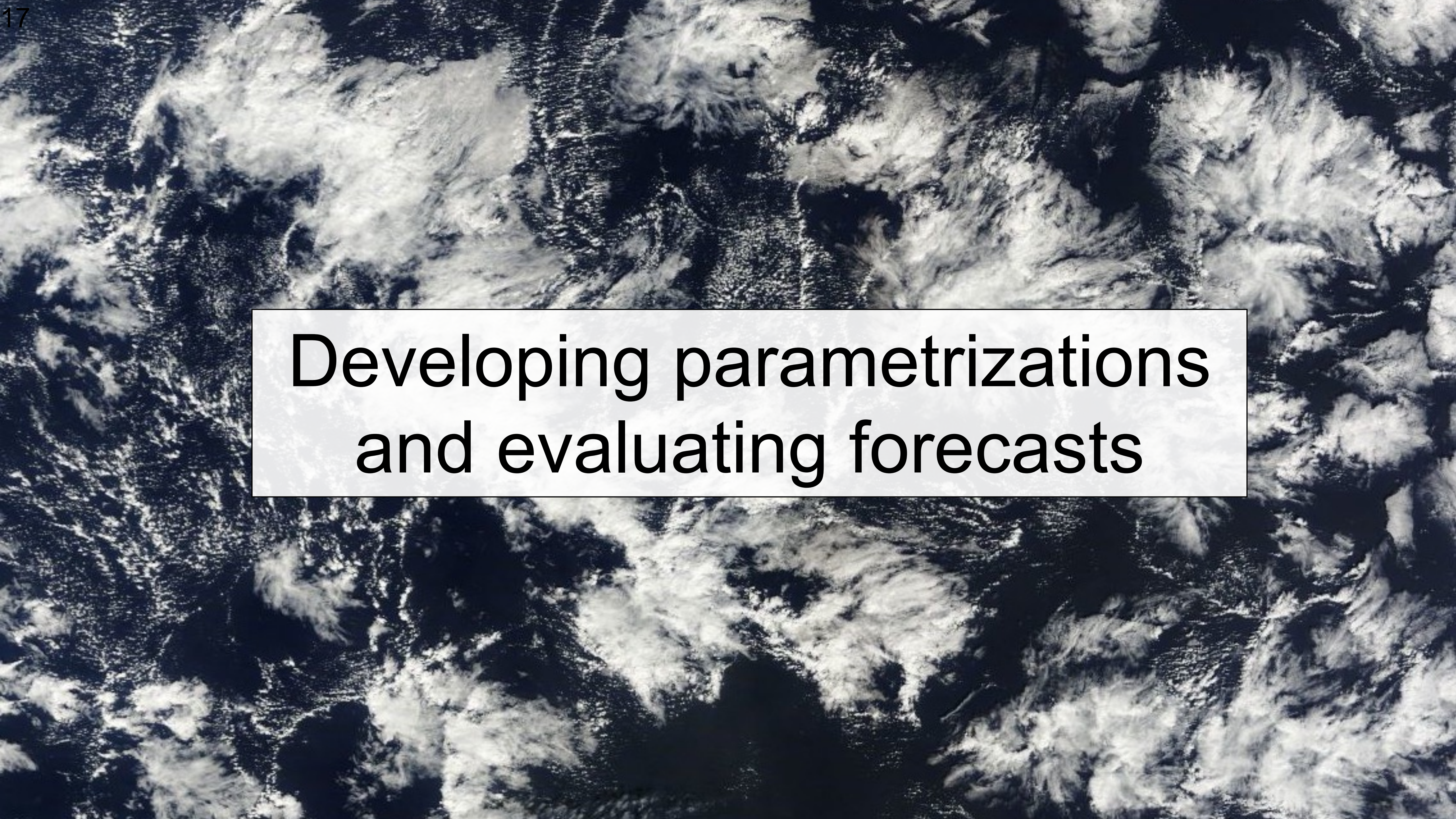
IN THE BL: Balance between heating/moistening from surface via turbulent mixing and dynamical/convective drying/cooling

Order of calling dynamics and physics parametrizations in the IFS

- In the IFS, physics is called sequentially after the dynamics
- Other models have different calling sequence
- Slow processes vs. fast processes?



Process temperature tendencies (day 1 average over June 2017)



Developing parametrizations and evaluating forecasts

Parametrization of physical processes - Impacts

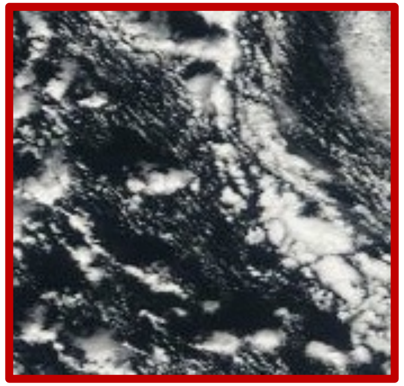
Temperature

Vertical velocity

Wind

Precipitation

Humidity



Cloud particle size

Ozone

Aerosols

Cloud fraction

Cloud phase

Cloud condensate

Radiative Impacts

Heating, cooling…

Hydrological Impacts

Precipitation, surface hydrology…

Thermodynamical Impacts

Condensation, evaporation, deposition, sublimation…

Momentum Transport

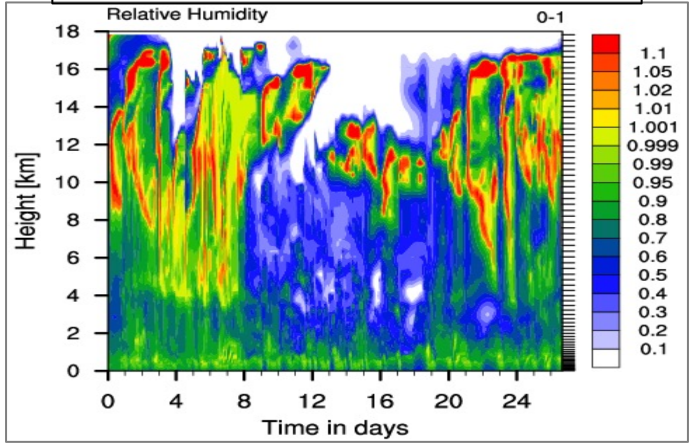
Turbulent mixing, convection, advection…

Parametrization development strategy

- Determine empirical relations (e.g. based on theory, similarity arguments or physical insight)

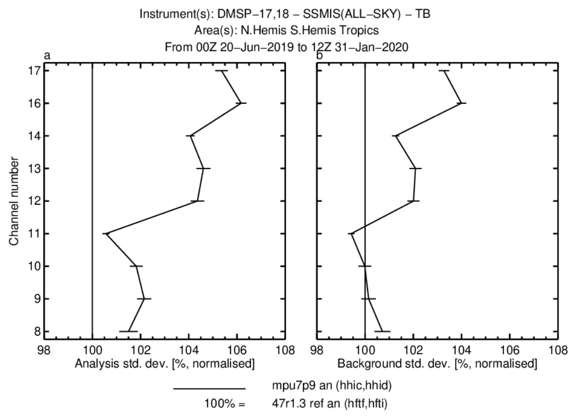
  To find parameters use:
  - Theory (e.g. radiation)
  - Field data
  - Cloud resolving models (e.g. for clouds/convection)
  - Mesoscale models (e.g. for subgrid orography)
  - Large eddy simulation (turbulence)
- Test in stand alone or single column model (SCM) →
- Test in 3D mode with short range forecasts
- Test in long integrations (model climate)
- Consider interactions

Example: Time-height plot of relative humidity from an IFS SCM simulation for the TWPICE deep convection case study

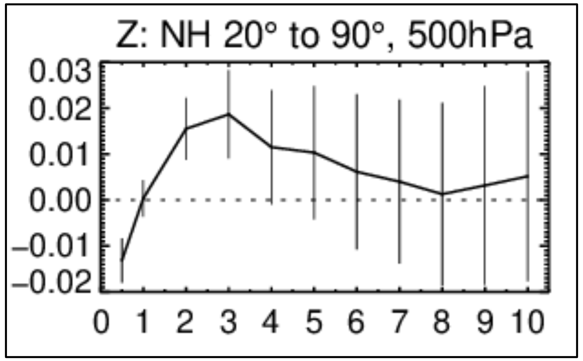


Validation and diagnostics

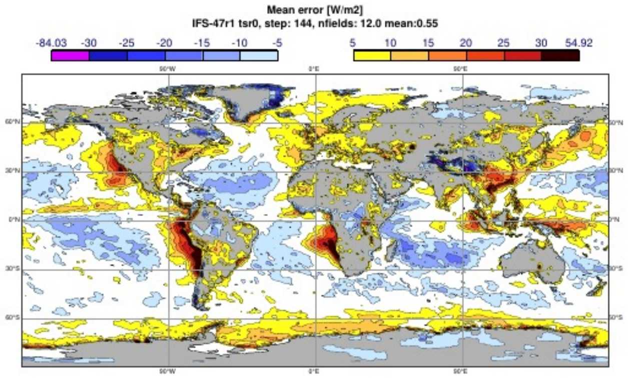
- Compare with analysis
  - daily verification
  - systematic errors e.g. from monthly averages
  - initial tendency diagnostics
- Compare with operational observations
  - SYNOPs
  - radio sondes
  - satellite
- Climatological data
  - CERES, ISCCP
  - ocean fluxes
- Field experiments
  - TOGA/COARE, PYREX, ARM, FIFE, ...



Obs – model departure std dev in the assimilation



Z500 forecast – analysis relative RMS error (%/100)



Annual mean TOA net SW radiation bias, forecast – CERES

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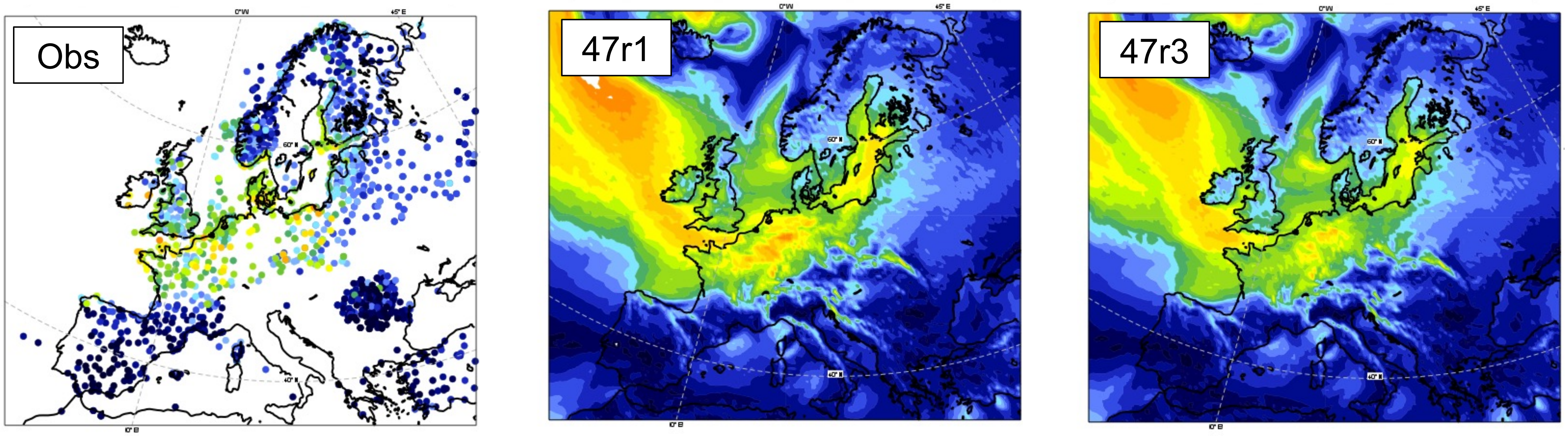
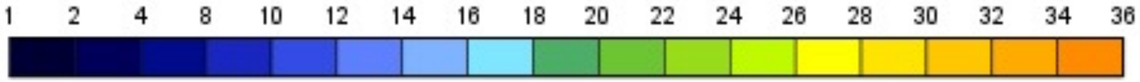
Example: 10m wind gusts in the IFS

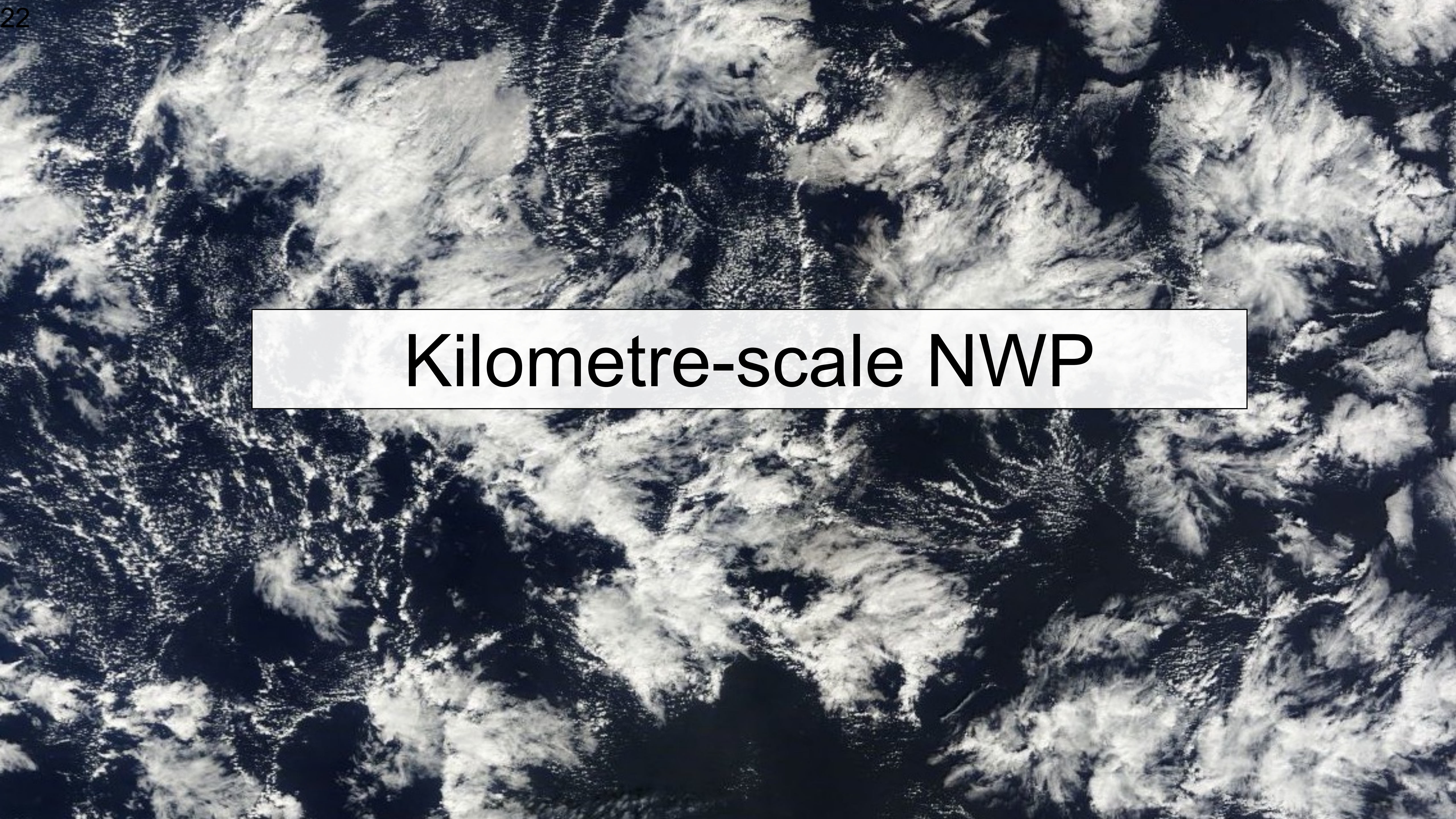
- Wind gusts too strong in unstable conditions in IFS Cycle 47r1 compared to SYNOP station obs
- Revision of gust parametrization in IFS Cycle 47r3
- Snapshot shown here, statistics from several months show 47r3 is in closer agreement to observations



Case study: 10 Feb 2020 00z
HRES 24 hour forecast



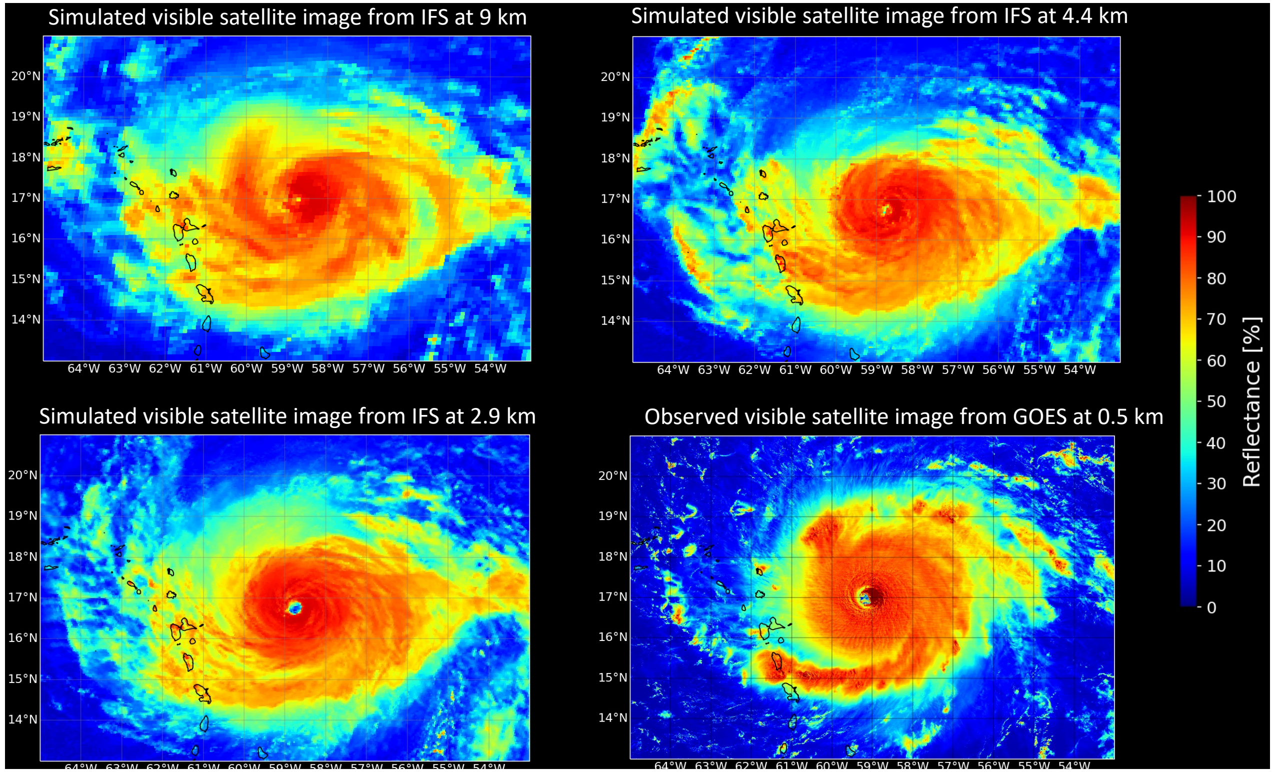
Maximum 10m wind gust in 24 hours (m/s)



Kilometre-scale NWP

Kilometre-scale weather forecasting

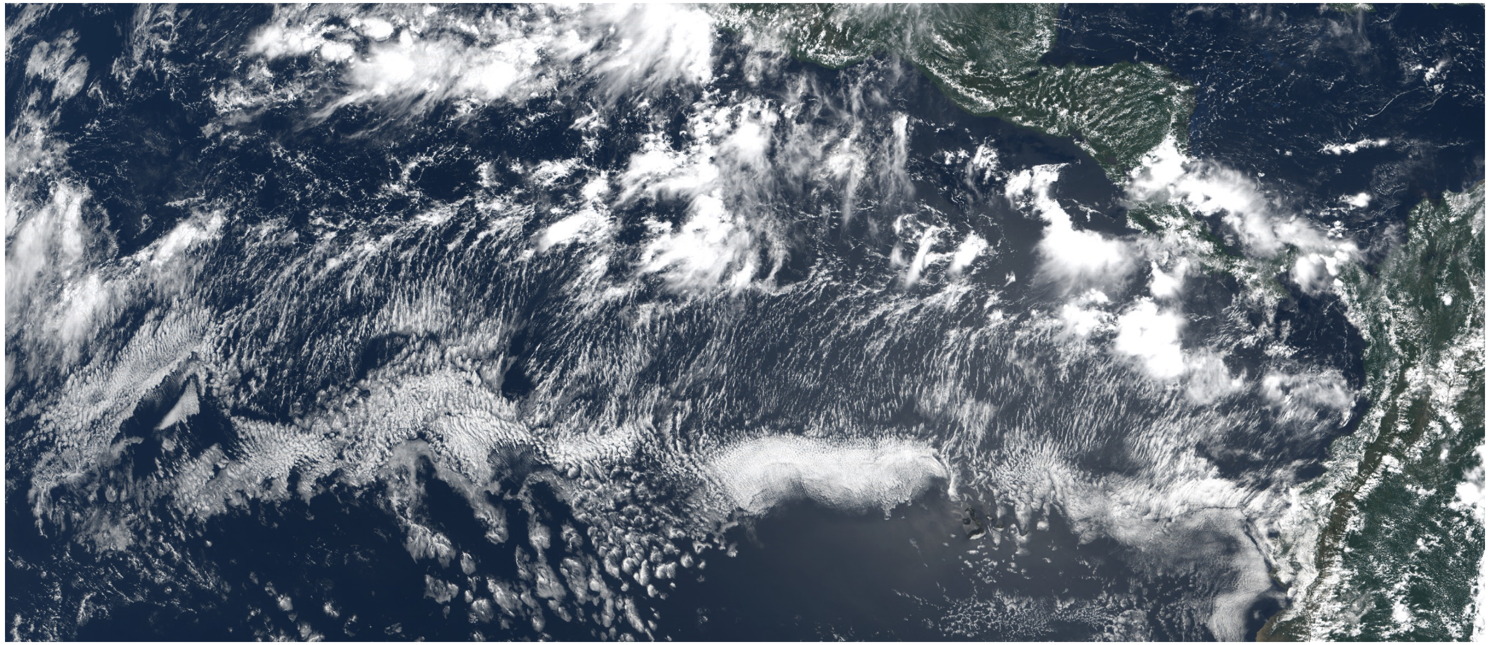
- Increasing computational resources allows higher resolution grids
- Kilometre-scale grid resolutions now possible (1 to 5 km)
- Improved representation or orography/coastlines/land surface
- Improved resolution of dynamical processes and extreme weather (e.g. tropical cyclones)
- Towards explicit representation of deep convection and convective organisation

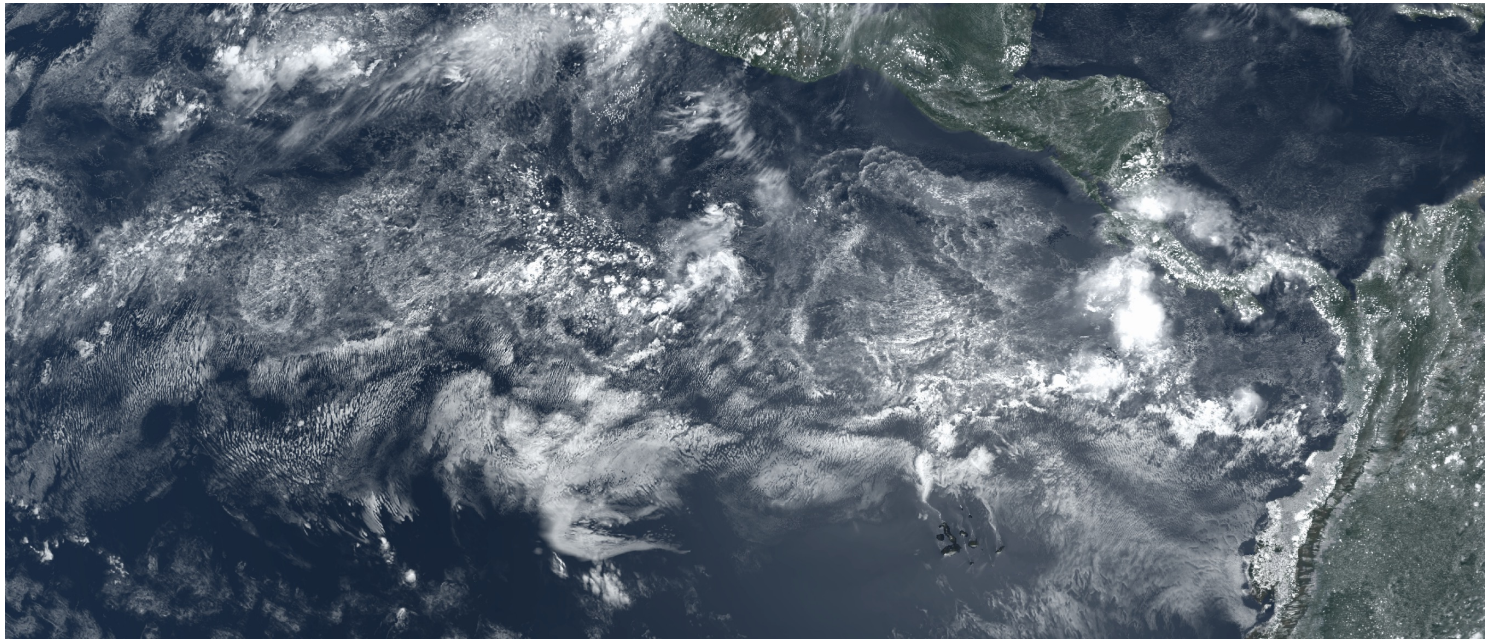


Simulated reflectance of TC Irma at 18 UTC on 5 Sep 2017 for IFS at 9 km, 4.4 km and 2.8 km atmospheric grid-spacing, and observed reflectance from the GOES-16 satellite.

Eastern equatorial Pacific

- 500m GOES-16 satellite image
- 1.4km IFS simulation T+18





Both natural colour (0.47, 0.64 and 0.86-um wavelengths combined) images are valid at 18:00Z 5 September 2017.

Forecast range: 18h.
Deep convection on.
Resolutions: 500m for GOES-16 satellite image; 1.4 km for IFS forecast.

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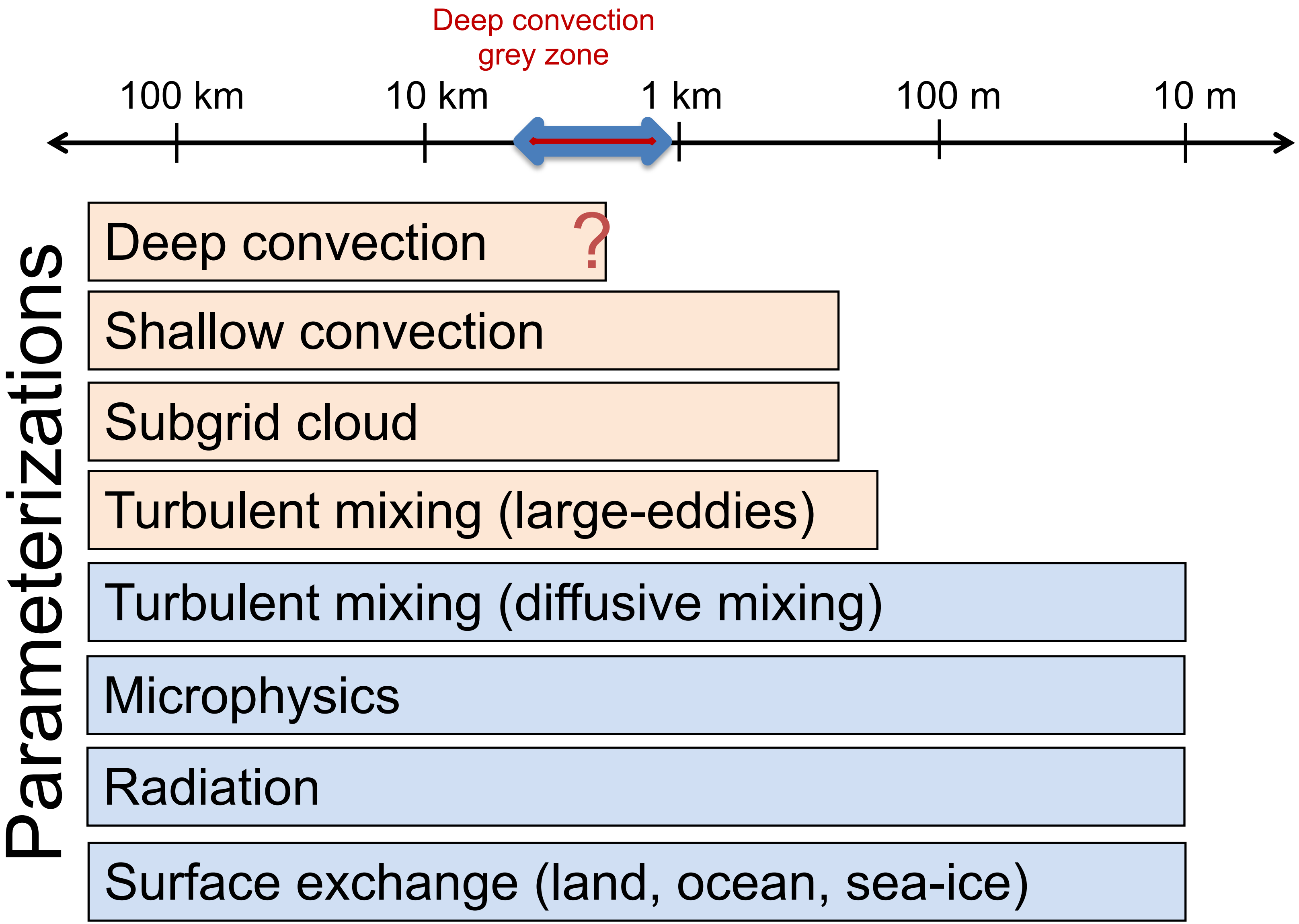
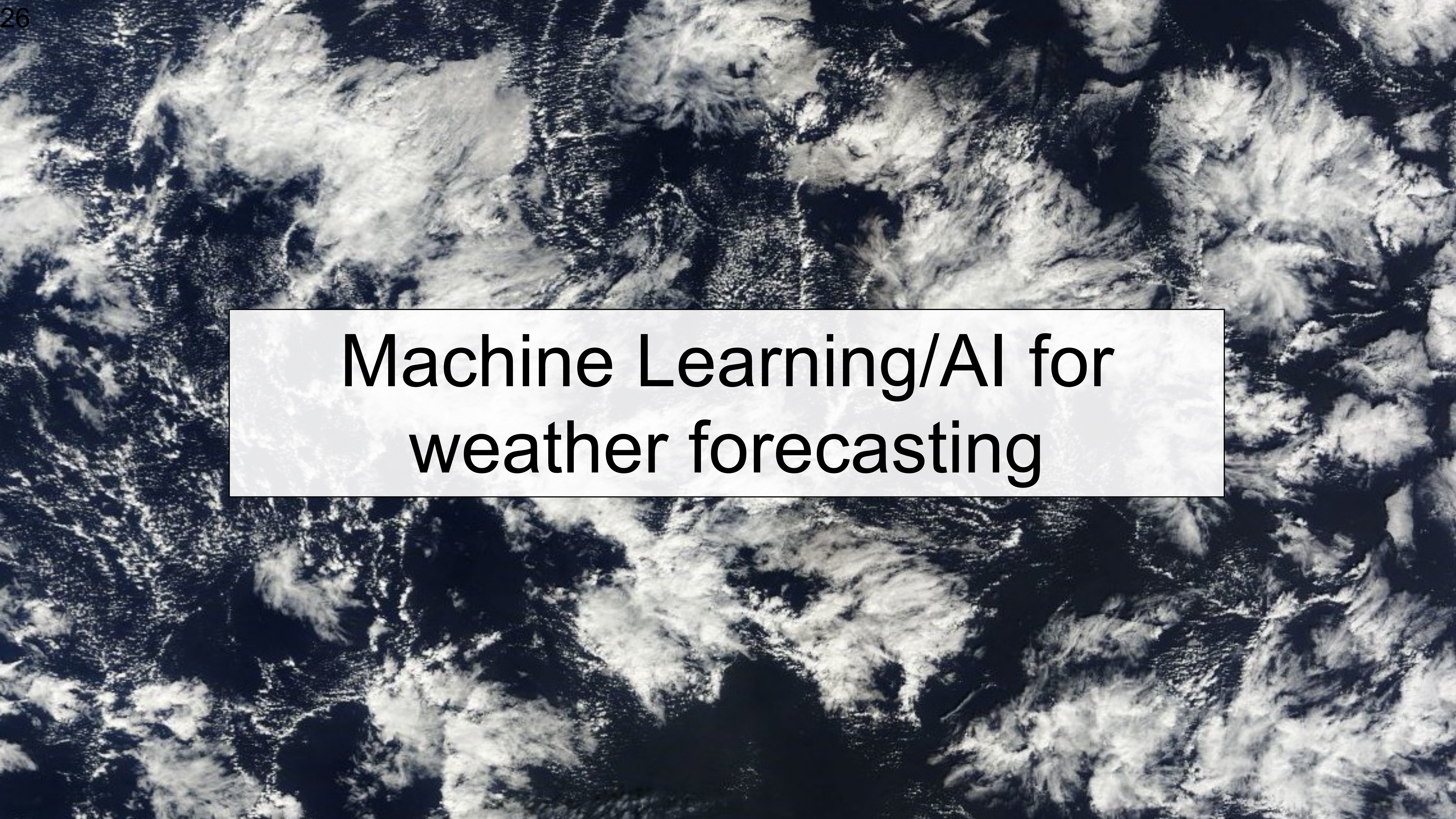
Kilometre-scale models – deep convective “grey zone”





Machine Learning/AI for weather forecasting

Machine Learning/AI for Weather Forecasting

ML/AI methods / computations now able to run efficiently to emulate complex problems

Possible approaches for parametrizations/NWP:

1. ML replaces individual parametrized processes, trained on better physical models (higher resolution, more complex/realistic, more computationally expensive?)

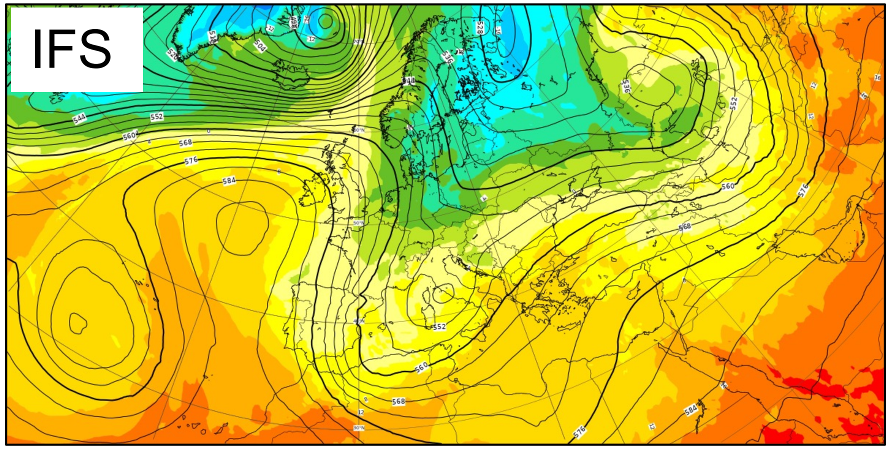
2. ML emulates individual parametrizations to gain computational speed

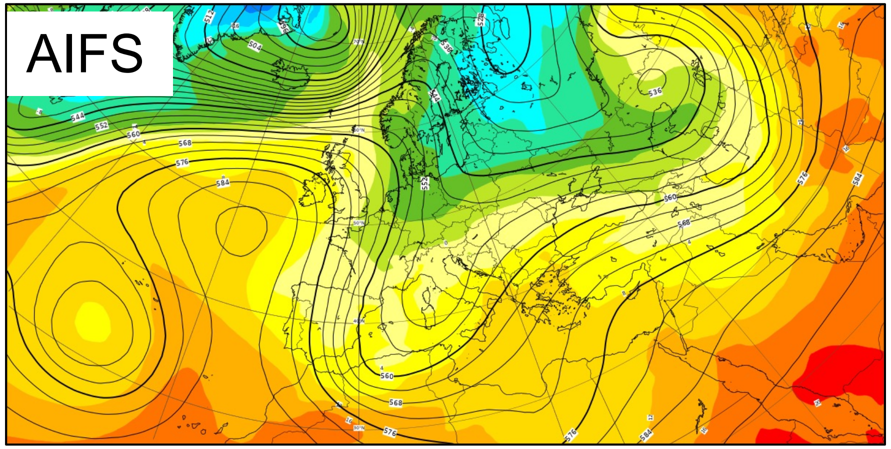
3. ML emulates the whole physics from inputs and outputs

4. ML learns from reanalysis to be a full forecast model

Machine Learning/AI models for Weather Forecasting

- Rapidly evolving field of research and development
- Huawei PanguWeather, NVIDIA FourCastNet, Google Deepmind Graphcast,…
- ECMWF has recently (last few months) developed AIFS based on Graph Neural Networks
- Competitive forecast skill
- But still lower resolution and only a few variables /levels e.g. 500hPa geop. height / T850hPa / T2m
- Representation of uncertainty? Precipitation and other more physically-based variables? Physical constraints?

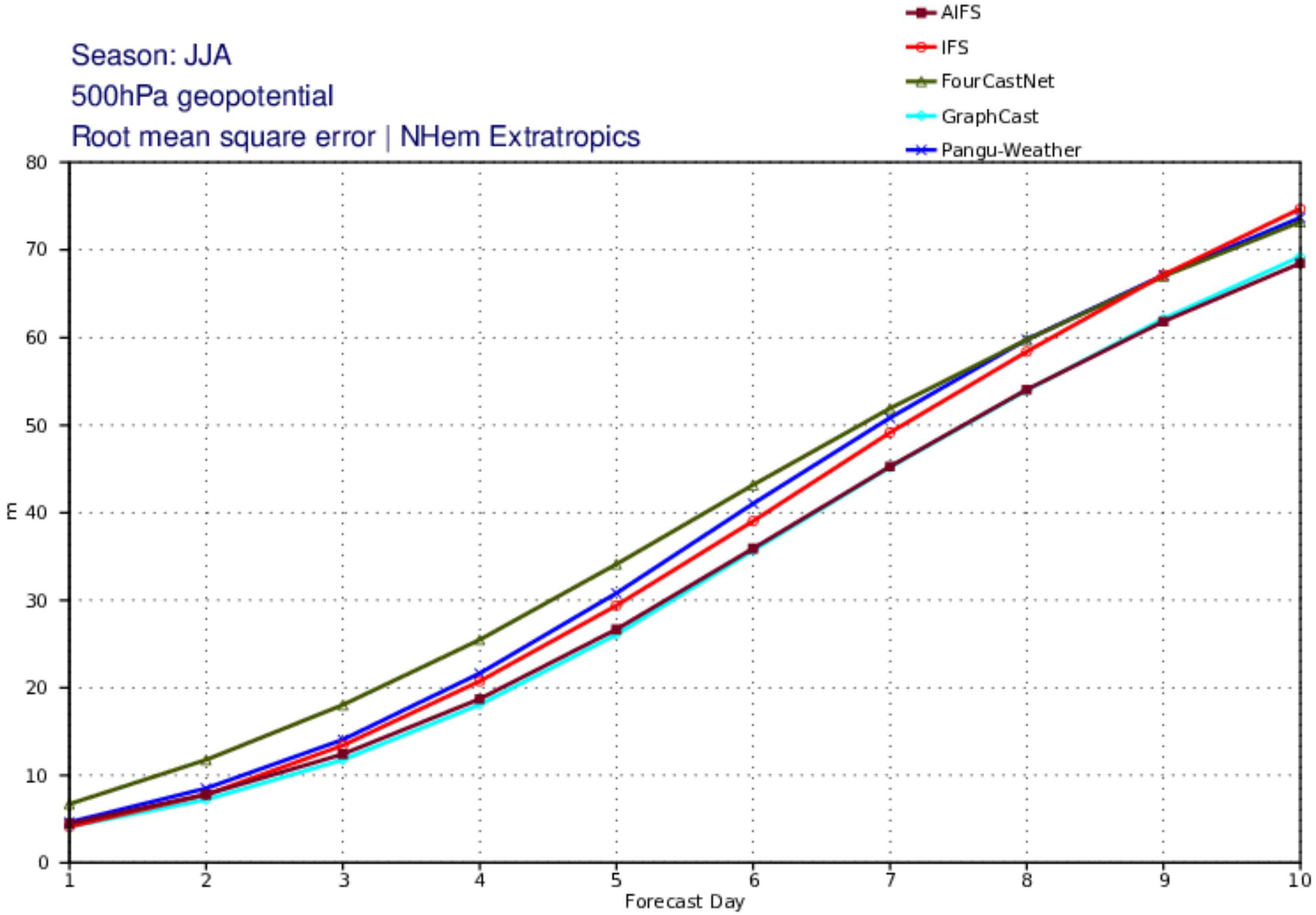




3-day forecast of Z500 and T850
for Wed 23 Nov 2023 00 UTC

See ECMWF AIFS blog on the ECMWF website (ecmwf.int)

Machine Learning/AI models for Weather Forecasting



Root-mean-square error in geopotential height at 500 hPa for the IFS, AIFS and other ML models for June–July–August 2023 in the northern hemisphere extratropics.

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Summary

Summary

- NWP models require a comprehensive set of physically based parametrizations
- Required: accurate, numerically robust, computationally efficient, scale-aware
- Each parametrization is a part of the whole – important to understand impacts and interactions
- Need to represent across space and time scales (1-100km, days-to-decades)
- Need to represent uncertainty
- Continual improvement through range of evaluation / observations / testing
- ML is changing the way we do things, but dynamical/physical understanding is still at the heart of weather forecasting

Further information on IFS physical parametrizations

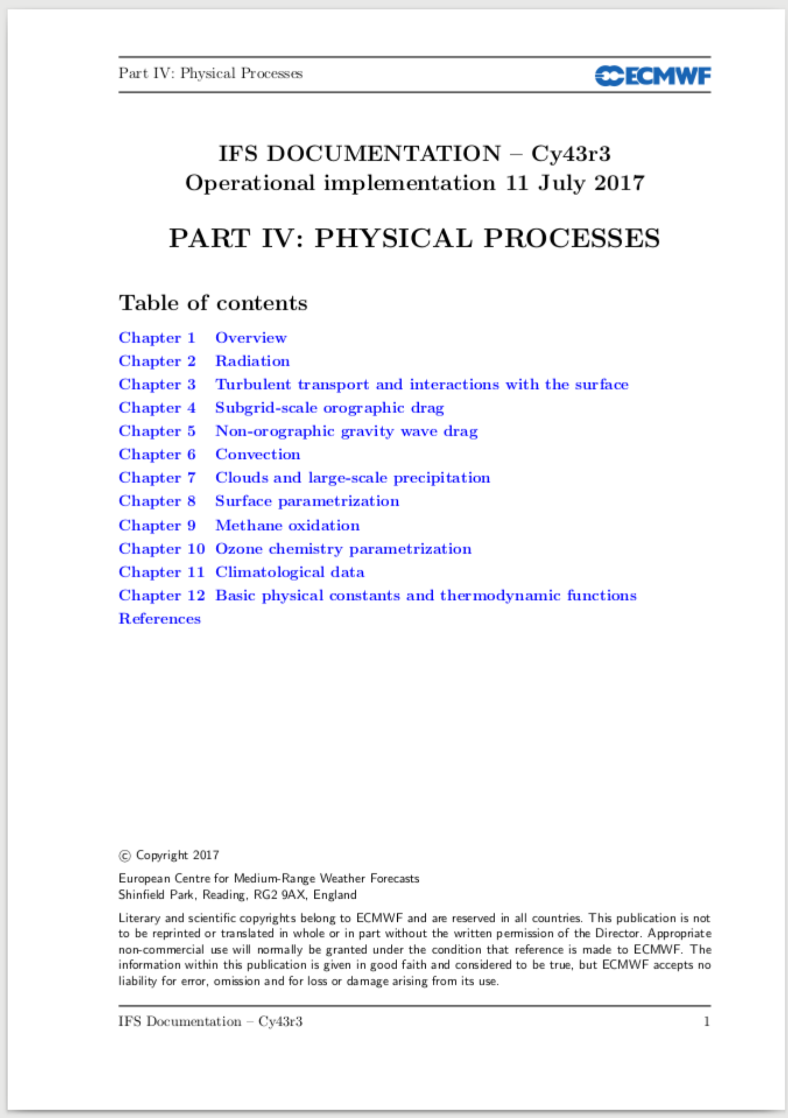
- Overview description of IFS model
  https://www.ecmwf.int/en/research/modelling-and-prediction
  https://confluence.ecmwf.int/display/OIFS/OpenIFS+User+Guide

- IFS Documentation (Part IV: Physical processes):
  https://www.ecmwf.int/en/publications/ifs-documentation

- Details of changes to the operational IFS:
  https://www.ecmwf.int/en/forecasts/documentation-and-support/changes-ecmwf-model

- Online resources – eLearning modules
  https://learning.ecmwf.int/

- IFS model "climate" quicklook plots (4-member ensemble 1-year forecasts versus satellite obs)
  https://charts.ecmwf.int/catalogue/packages/physics/products/physics_clim2000


Part IV: Physical Processes ECMWF

IFS DOCUMENTATION – Cy43r3
Operational implementation 11 July 2017

PART IV: PHYSICAL PROCESSES

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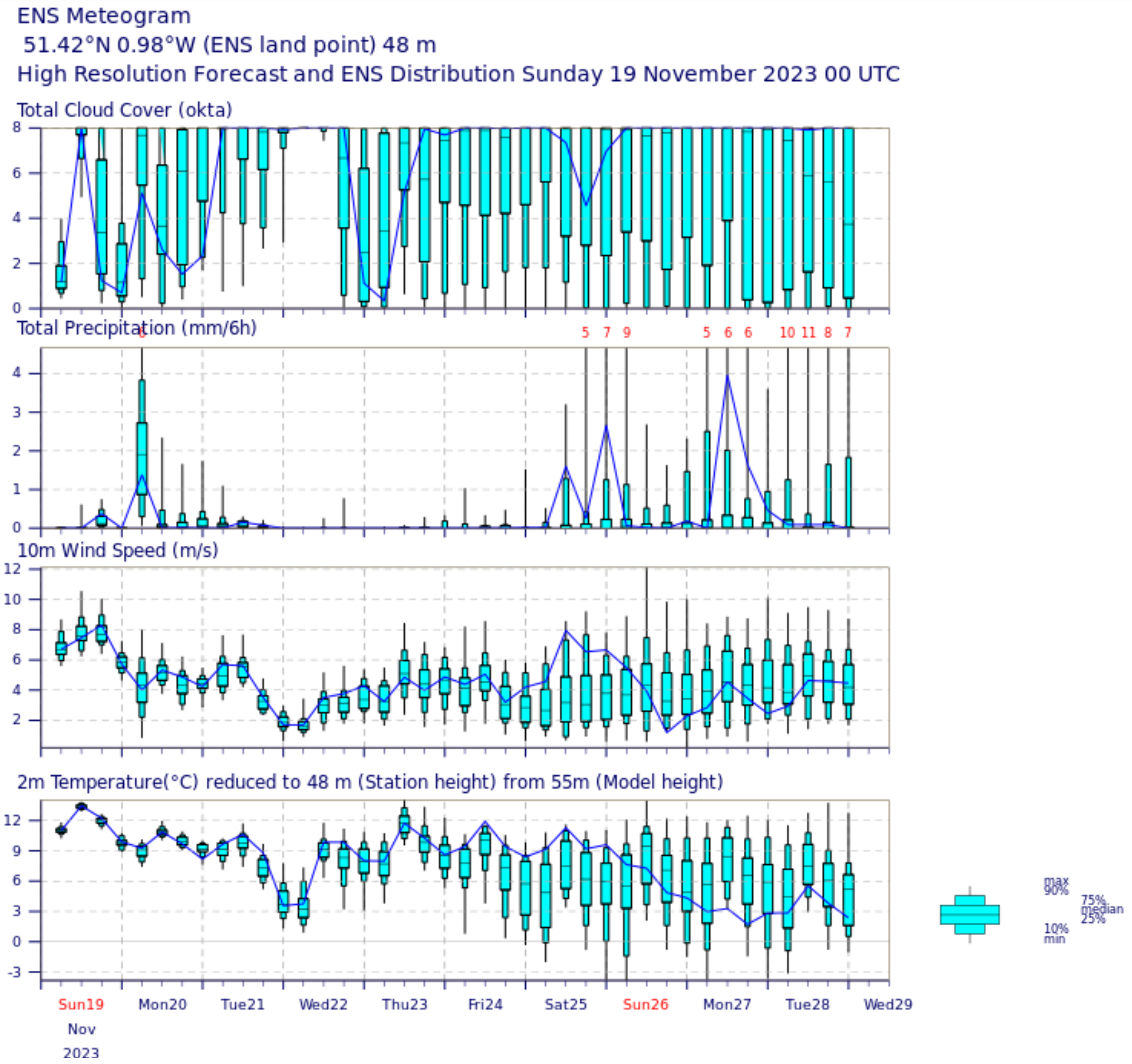
IFS Documentation – Cy43r3 1

Forecast for Reading for the week



Concluding remarks

- Ask questions
- Make the most of being here
- Enjoy the course!

Questions?