# Introduction to Physical Processes in the IFS

"A hands-on introduction to NWP Models"
ECMWF, 10-14 Nov 2025

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With thanks to contributions from ECMWF colleagues

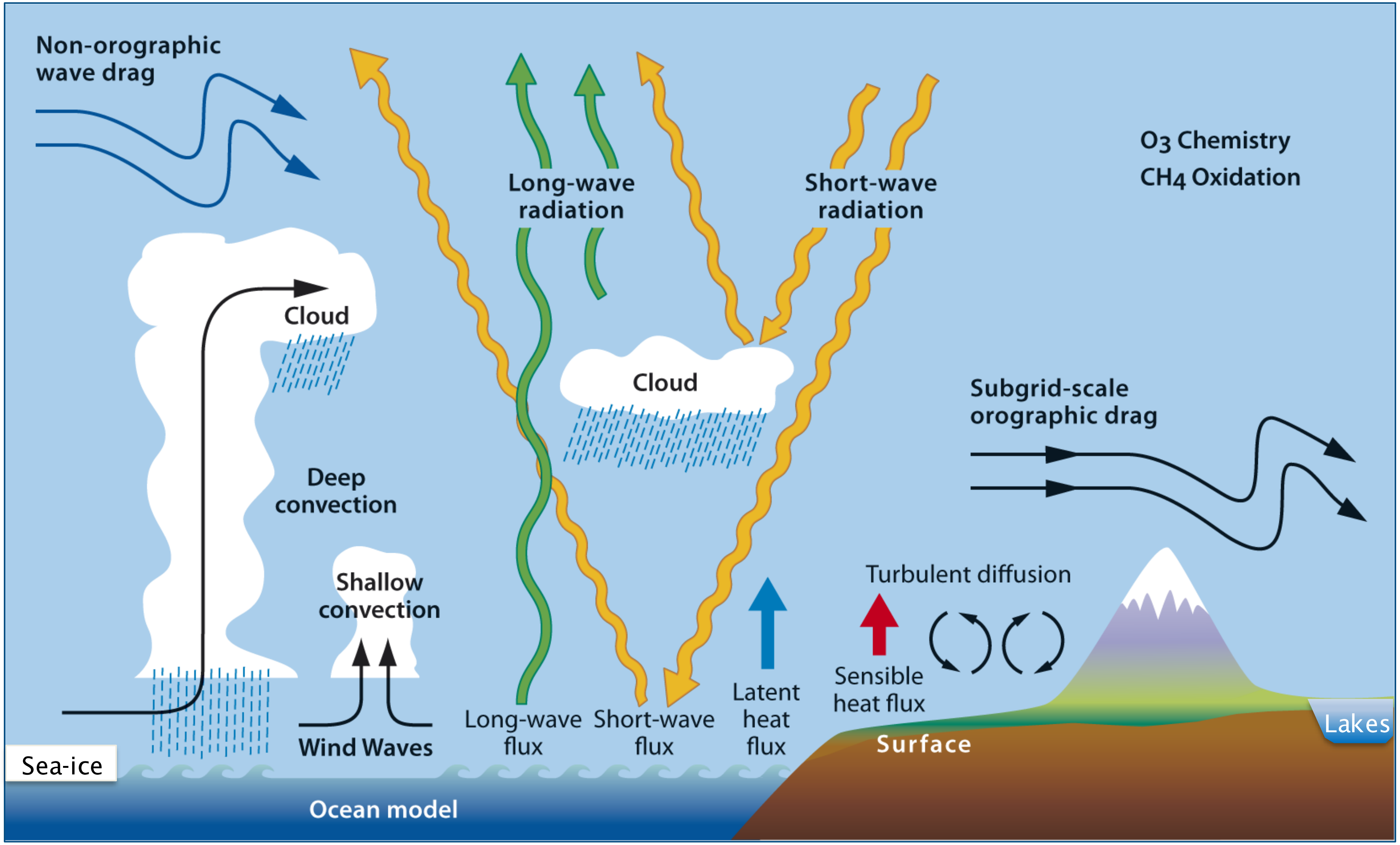
European Centre for Medium-range Weather Forecasts

# Outline

- An overview of the parametrization of atmospheric physical processes and their impacts in the IFS
- Brief description of each parametrization
- The OpenIFS Single Column Model

# Overview of the parametrization of physical processes and their impacts in the IFS

# Parameterized processes in the ECMWF model



# Parametrization of physical processes – Importance

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

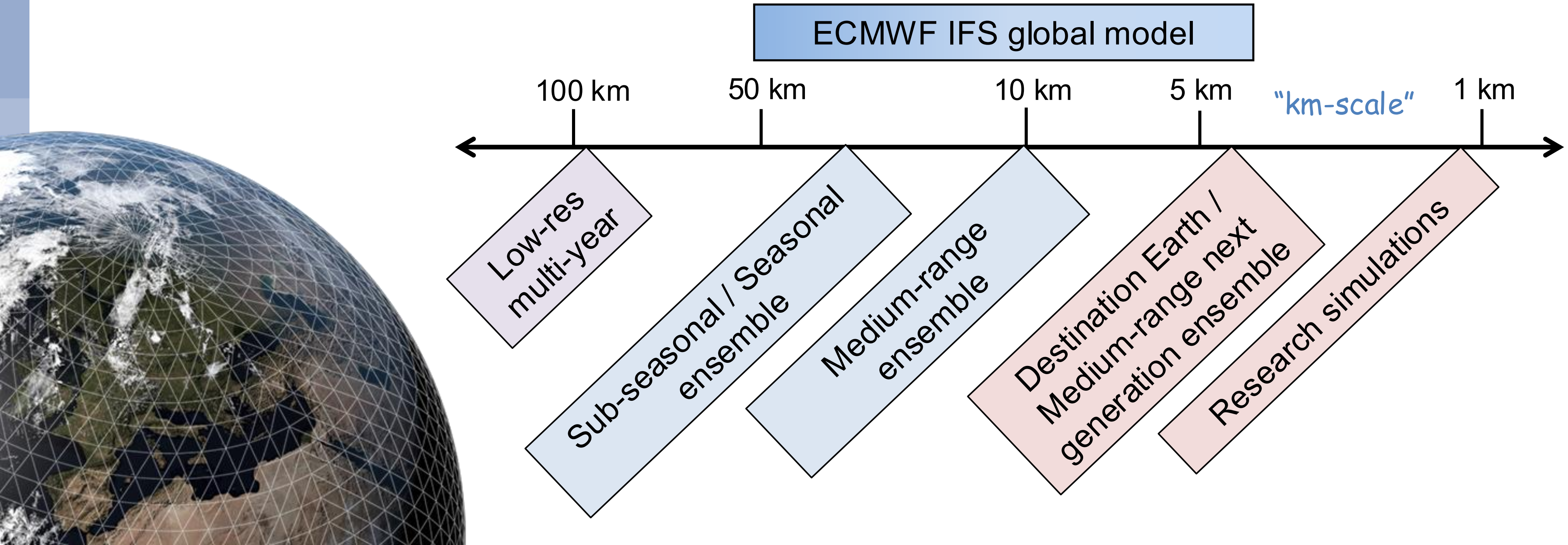
- Synoptic and mesoscale developments
    - Diabatic heating and friction influence synoptic development and mesoscale phenomena

- Weather parameters
    - Clouds, precipitation, fog, visibility
    - Wind, gusts
    - Near-surface (2m) temperature and humidity

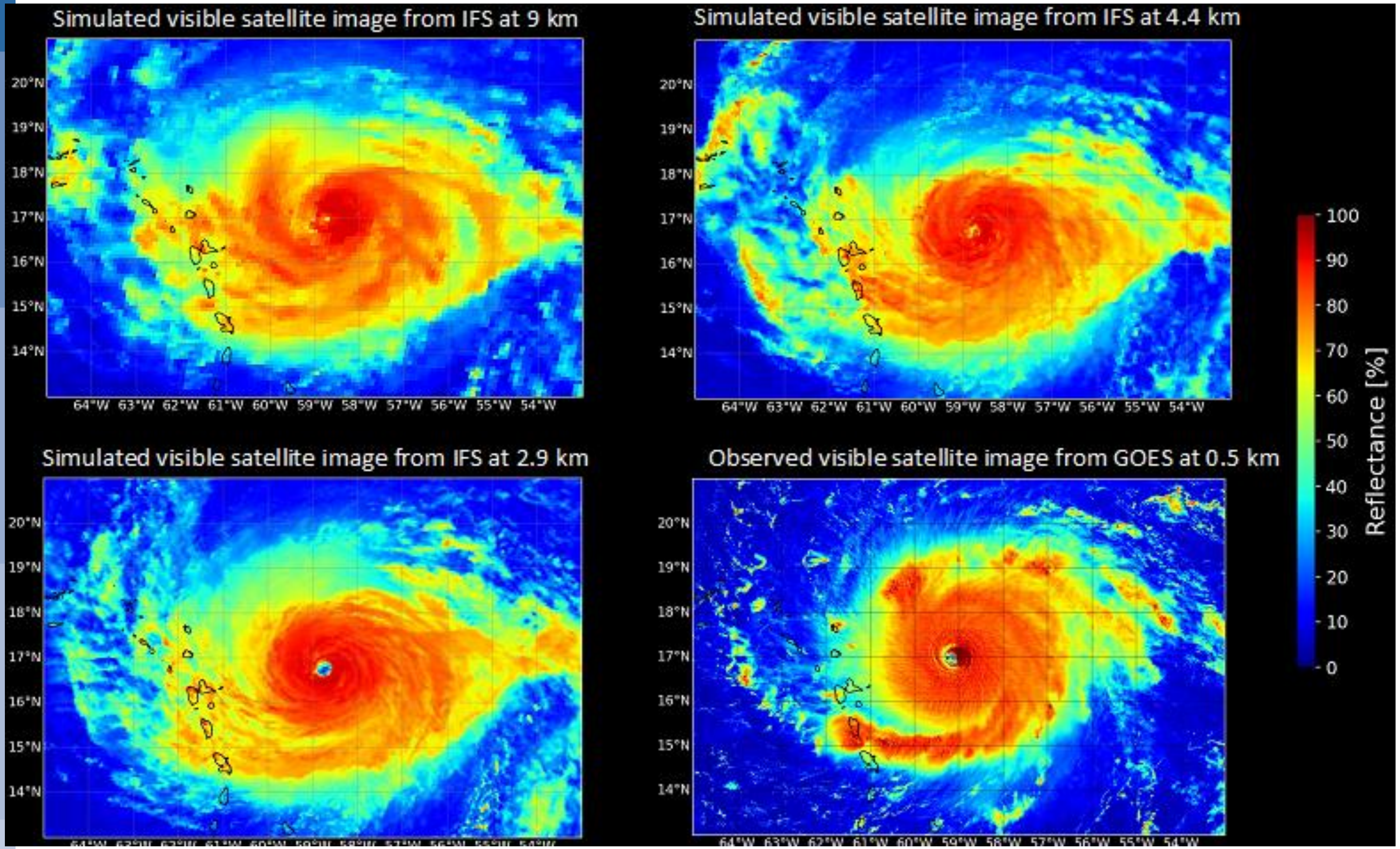
- Data assimilation
    - Forward operators are needed for observations

# Global modelling across space and time scales

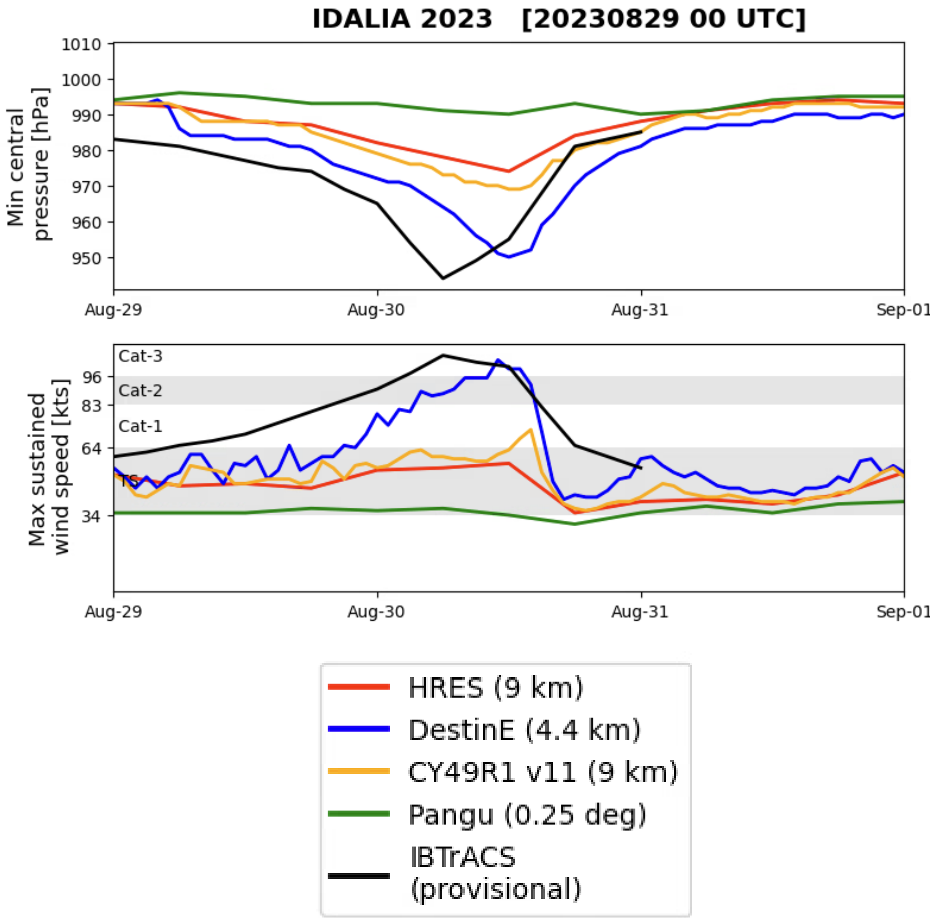
- Increasing computational power and advances in computational science
  → higher resolution
  → more components of the Earth System (e.g. ocean, sea-ice, chemistry, hydrology)
  → potential for more realistic physical parametrizations (e.g. radiation, microphysics)
- Global models need parametrizations appropriate for resolutions from O(100 km) to O(1 km) and forecast lead times from O(days) to O(years)
- Accurate, numerically robust (long timesteps), computationally efficient, scale-aware…



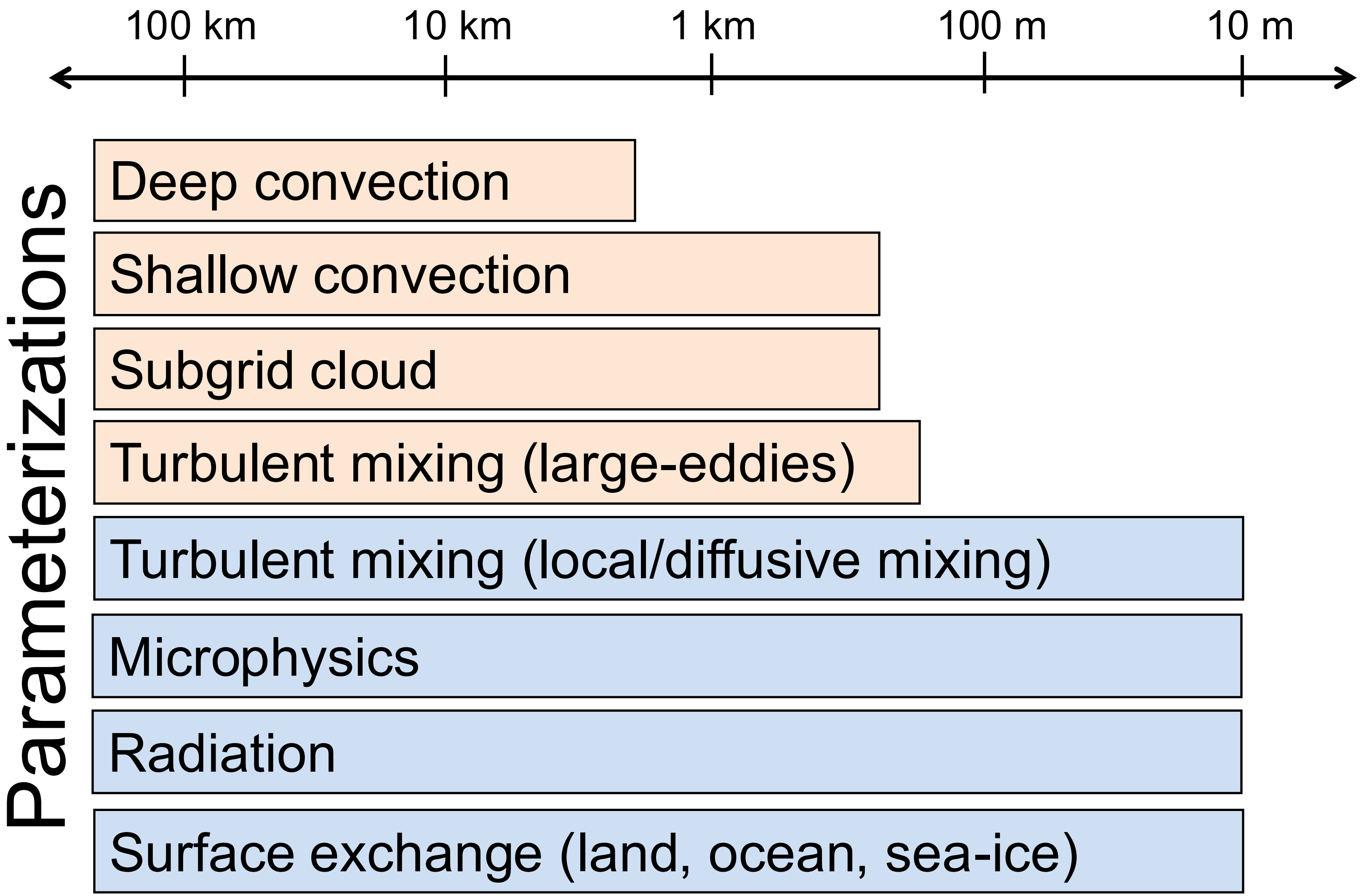
# High-resolution – improved prediction of extreme weather



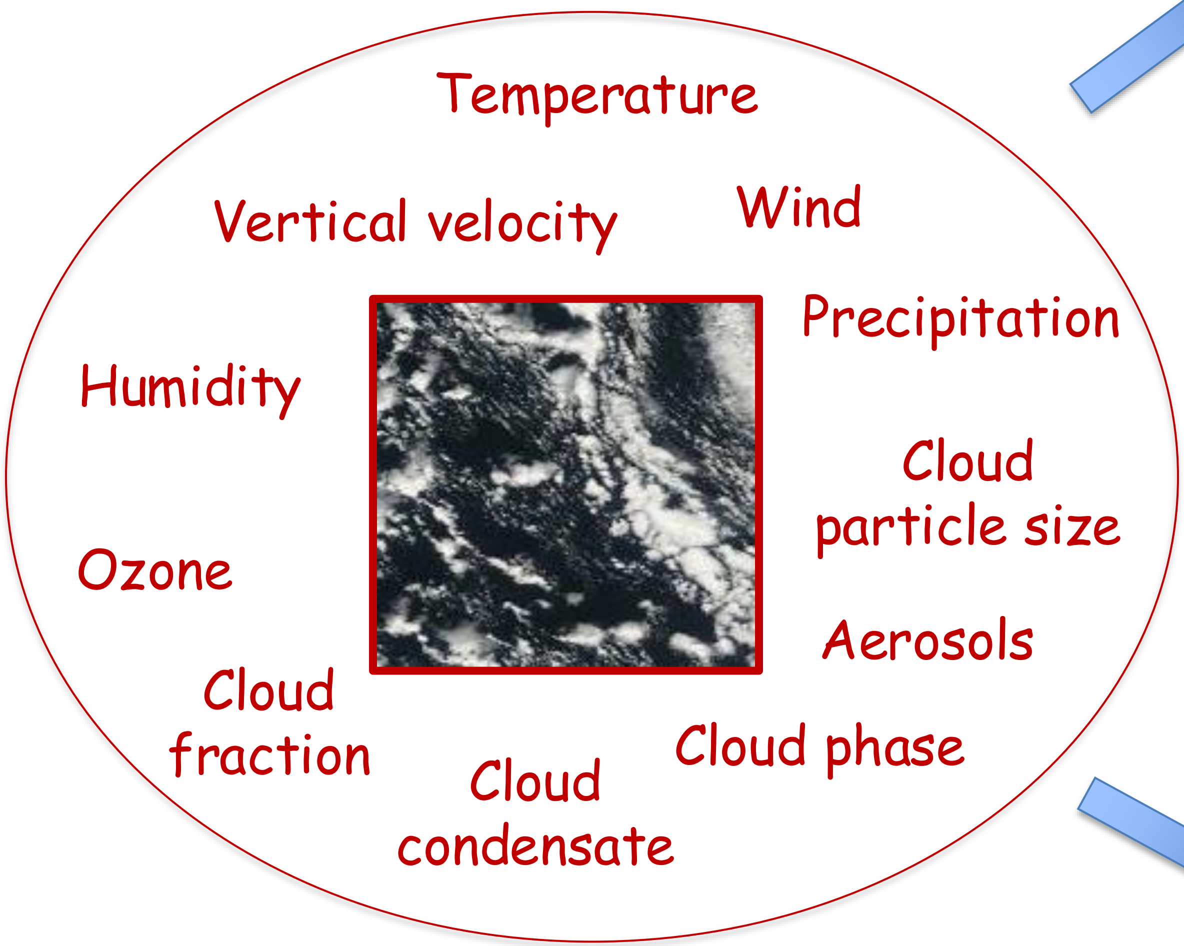

*Hurricane Irma (2017-09-05 00 UTC T+18)*



# Parametrization of atmospheric physical processes – Model resolution



# Parametrization of physical processes - Impacts




## Radiative Impacts

Heating, cooling…

## Hydrological Impacts

Precipitation, surface hydrology…

## Thermodynamical Impacts

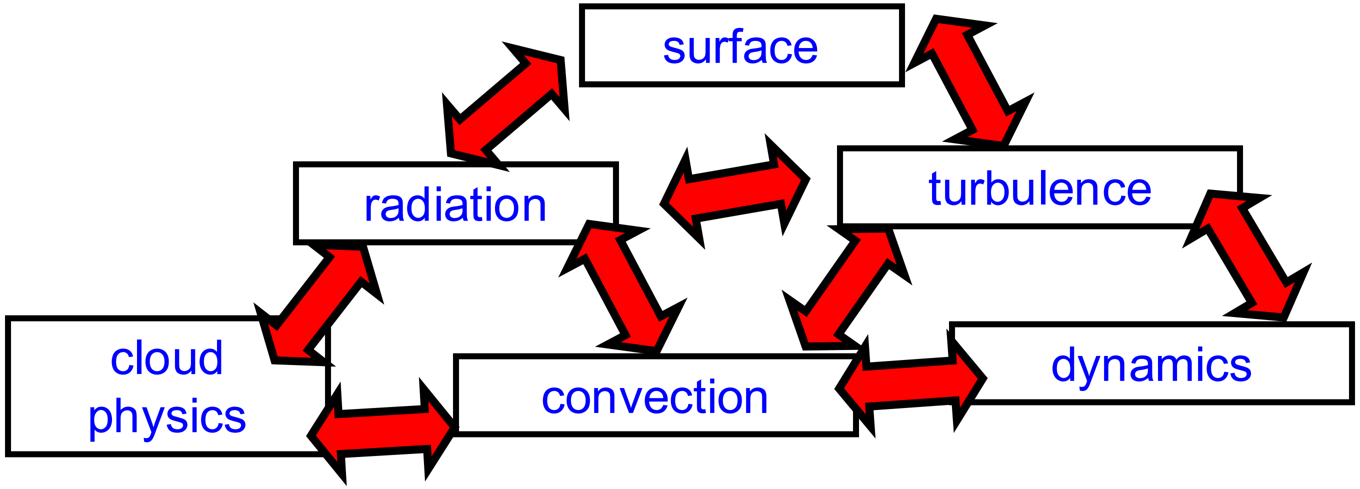
Condensation, evaporation, deposition, sublimation…

## Transport

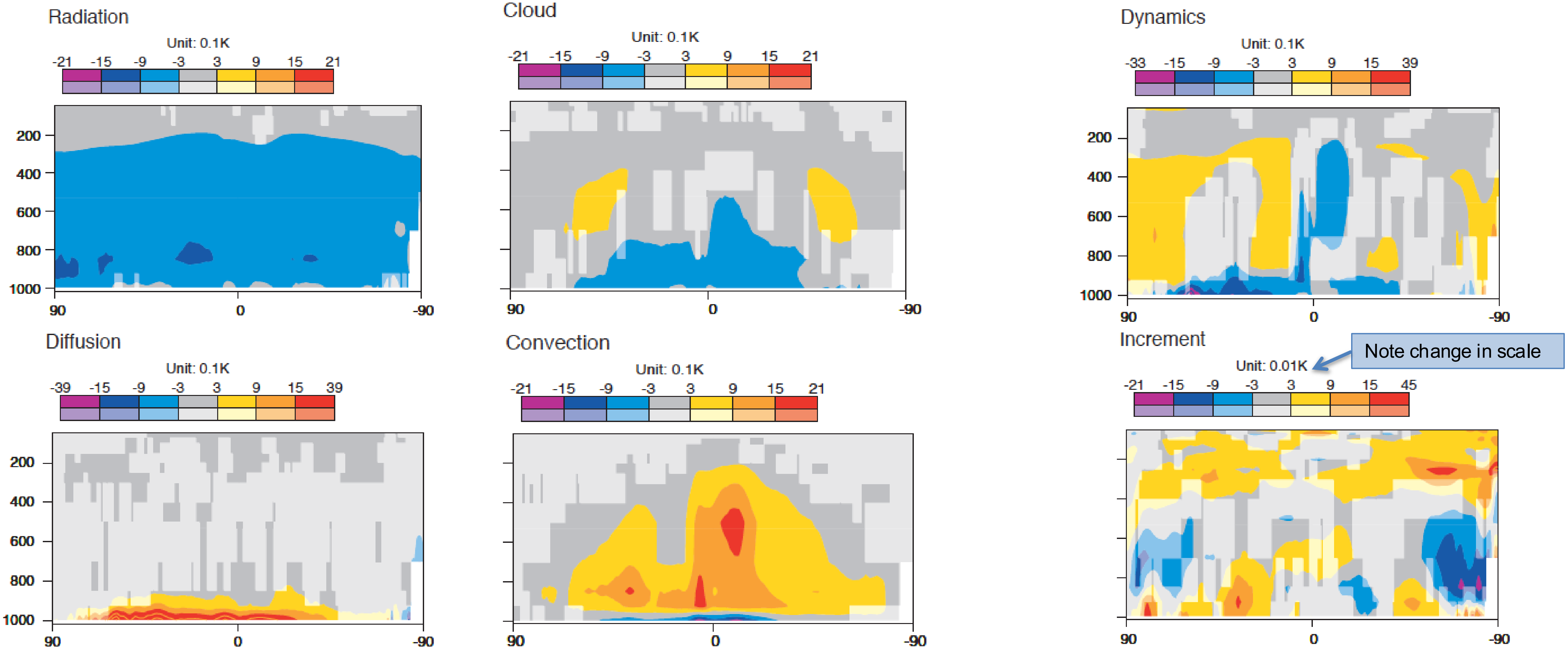
Turbulent mixing, convection, advection…

# Parametrization of physical processes - Interactions

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

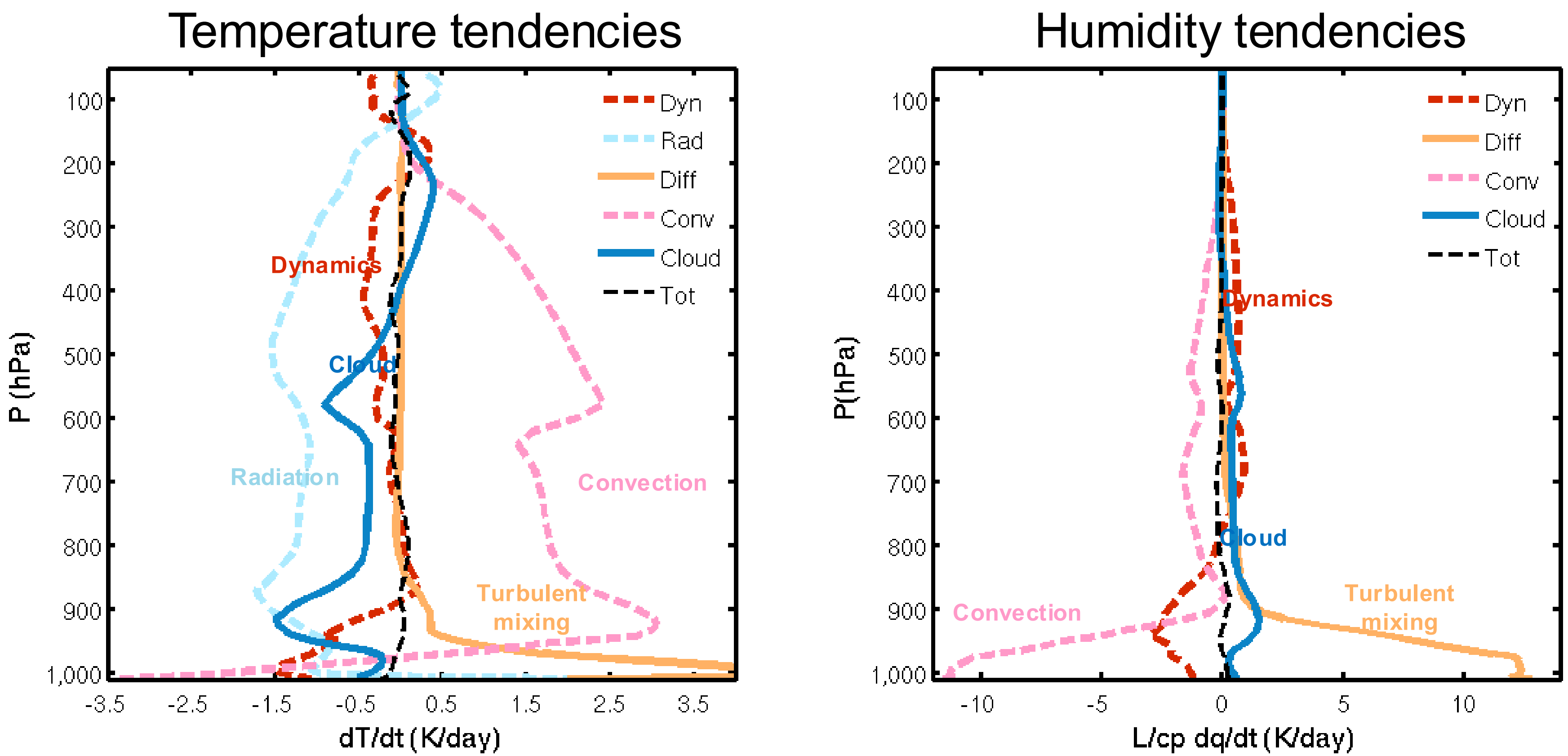


# Temperature tendencies (12-hour data assimilation window). Mean DJF 2014.




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

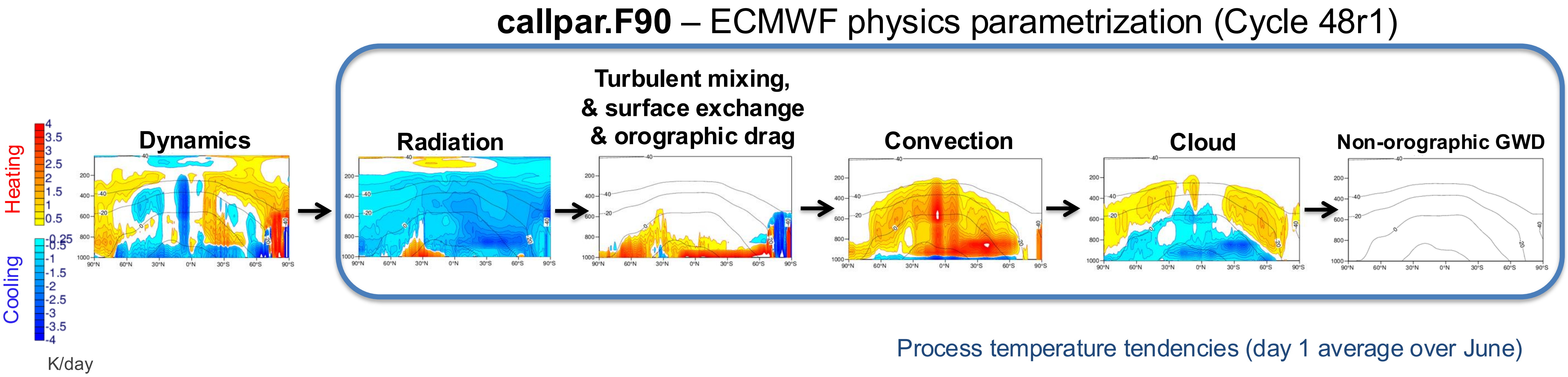
# Model Tendencies – Tropics Equilibrium




- For temperature there is on average radiative-convective equilibrium (above the boundary layer)
- For moisture there is roughly an equilibrium between **moistening** from dynamical transport (resolved motion and subgrid turbulence), and convection **drying** (condensation and precipitation formation).
- Global budgets are dominated by the tropics and are therefore similar

# Order of calling physics parametrizations in the IFS in 48r1

- Main routine that calls the ECMWF parametrizations is “CALLPAR”
- Process parametrizations called sequentially after the dynamics
- Radiation, turbulent mixing, surface exchange, orographic drag, convection, cloud, non-orographic gravity wave drag (GWD)




Process temperature tendencies (day 1 average over June)

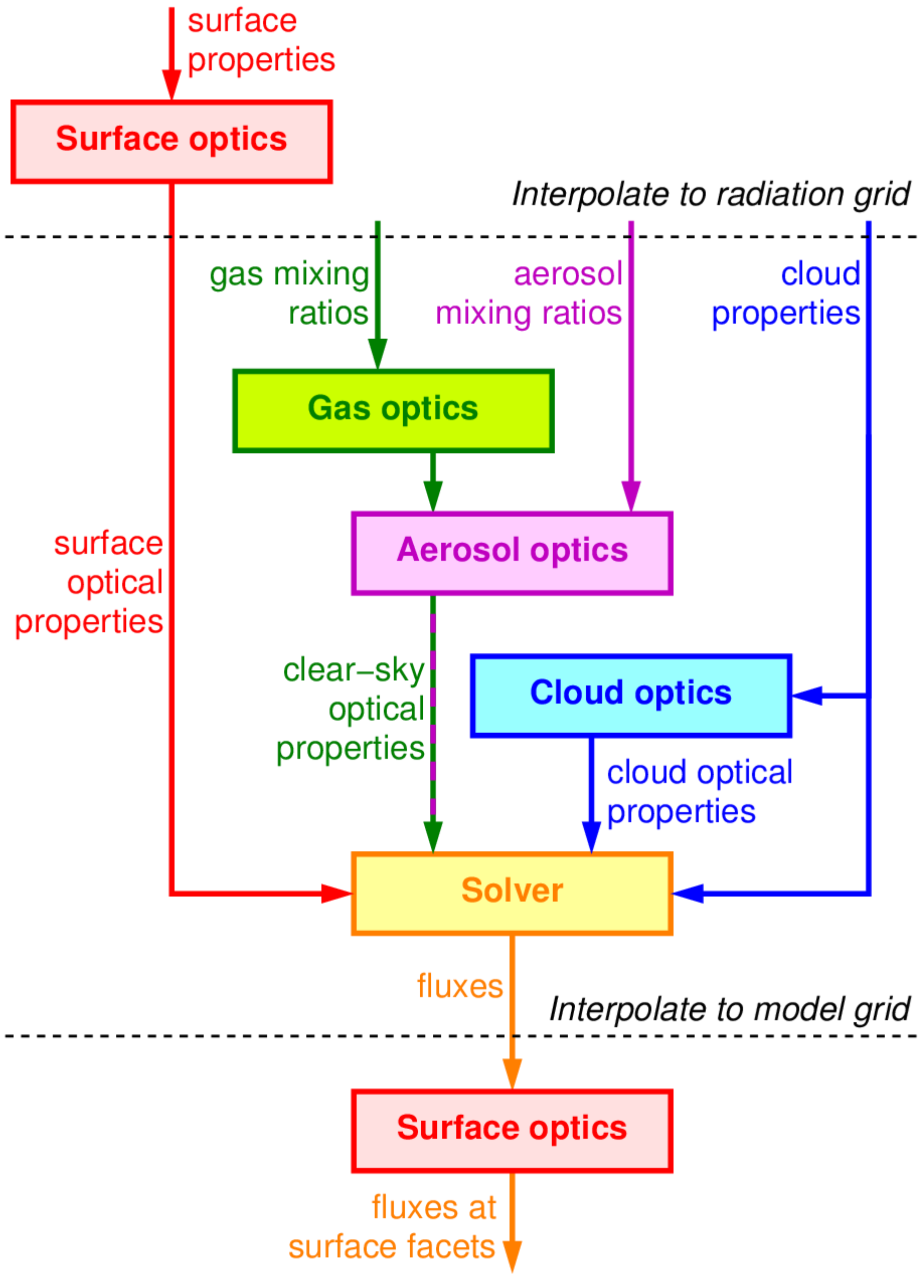
# Parametrizations in the IFS

- Radiation
- Surface
- Turbulent transport
- Convection
- Clouds and precipitation
- Orographic and non-orographic drag

# Radiation

## ecRad – modular design

- Gas optics
  - RRTM-G
- Aerosol optics
  - Number of species set at run time and optical properties configured by NetCDF file
  - Supports Tegen and CAMS (prognostic & diagnostic)
- Cloud optics
  - Liquid clouds: more accurate SOCRATES scheme
  - Ice clouds: Fu by default, Baran and Yi available




- Solver
  - McICA, Tripleclouds or SPARTACUS (3D) solvers
  - Longwave scattering optional
  - Can configure cloud overlap, width and shape of PDF
- Surface *(under development)*
  - *Rigorous and consistent treatment of radiative transfer in urban and forest canopies*
- Offline version available for non-commercial use under OpenIFS license

# Surface

## Earth surface modelling components @ECMWF

### Land surface and lake model

**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

**Surface snow**

Dutra et al. (2010)

Revised snow density

Liquid water reservoir

Revision of Albedo and sub-grid snow cover

(48r1 = multi-level snow)

**Leaf Area-Index**

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

**Lakes/ coastal water**

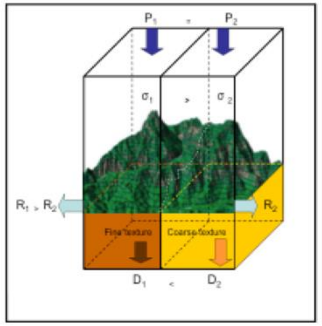
Mironov et al (2010),

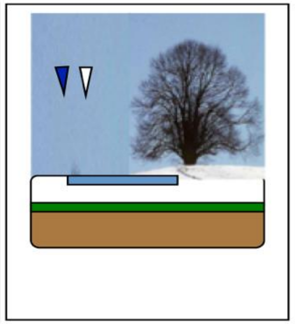
Dutra et al. (2010),

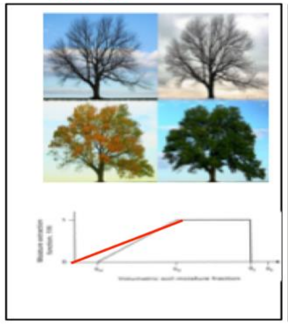
Balsamo et al. (2012, 2010)

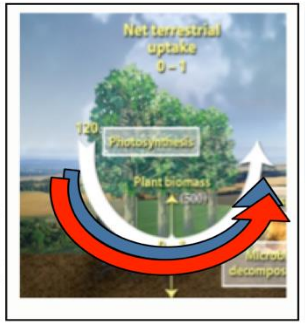
Extra tile (9) to for sub-grid lakes and ice

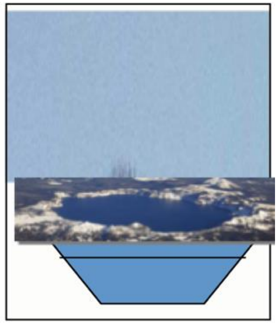
LW tiling (Dutra)



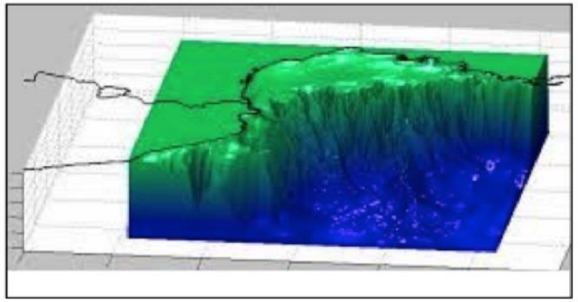




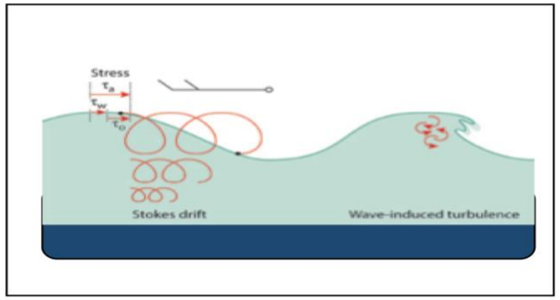


**Ocean model (NEMO)**



**Ocean-Waves (EC-Wam)**




**Sea-ice**

**OpenIFS**

- Land surface 1D-model
- Soil (4-layers)
- Vegetation
- Hydrology
- Snow (multi-level in 48r1)
- Lakes / coastal water
- Same resol. as atmos.

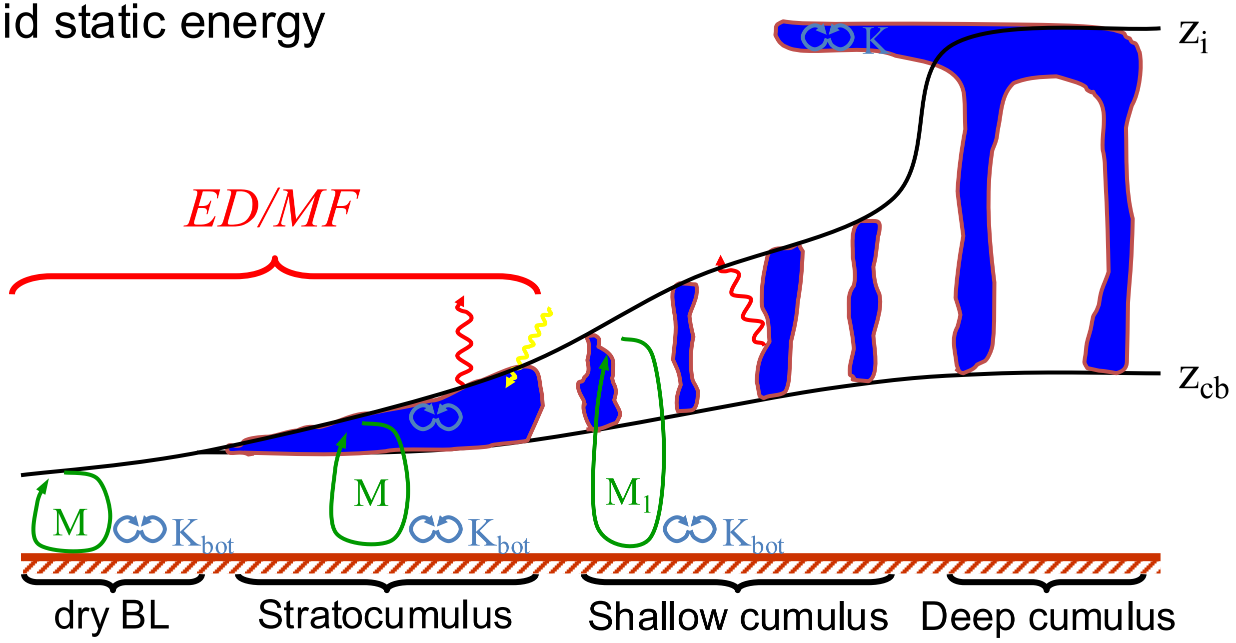
- Surface waves and currents (EC-WAM)

Ocean and sea-ice models are separate

# Turbulent transport

## Eddy Diffusivity Mass Flux (EDMF) approach in the PBL

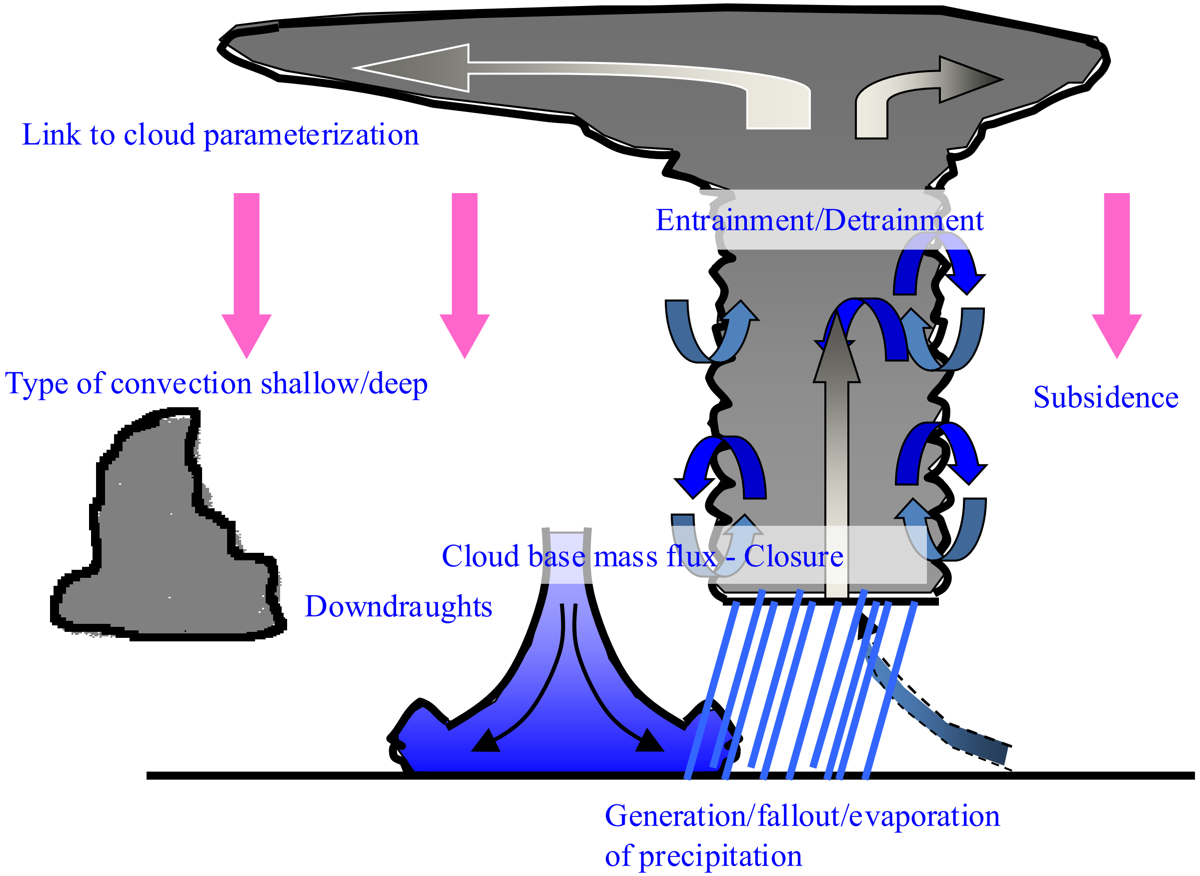
- Vertical exchange of heat, momentum and moisture through sub-grid scale turbulence
- Surface layer – K-diffusion closure based on Monin-Obukhov similarity theory
- Local turbulent mixing (K-diffusion - Eddy Diffusivity)
  Non-local turbulent mixing in unstable conditions = large-eddies in convective boundary layer (Mass-Flux)
- Eddy-Diffusivity Mass-Flux scheme (EDMF) (Köhler et al., 2011)
- Uses moist conserved variables; total water and liquid static energy
- In unstable convective regime, clouds are treated with shallow convection scheme
- Close interaction between the EDMF, convection and cloud schemes



Convection

# Parametrization of subgrid convection

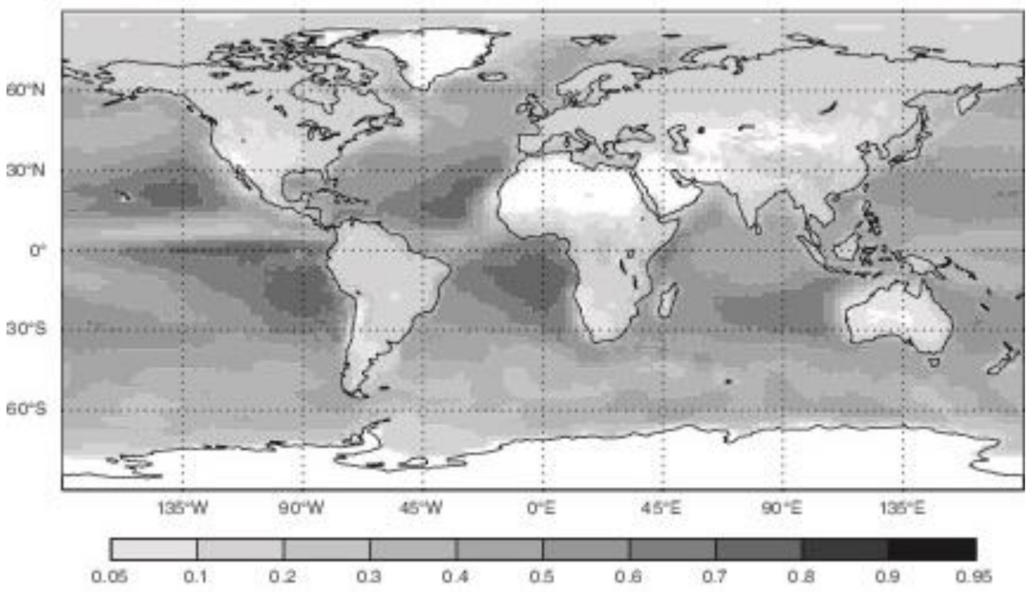
- Mass-flux entraining-detraining plume scheme (Tiedtke 1989; Bechtold et al. 2008)
- Convective types
  (1) Deep (including congestus)
  (2) Shallow
  (3) Mid-level (elevated moist layers)
- Modified CAPE closure to improve the diurnal cycle (equilibrium assumed between the large-scale and boundary-layer forcing for source/sink of CAPE) (Bechtold et al. 2014)
- Includes downdraught parametrization
- Generates precipitation (rain/snow)
- Detrains cloud fraction/condensate to cloud scheme



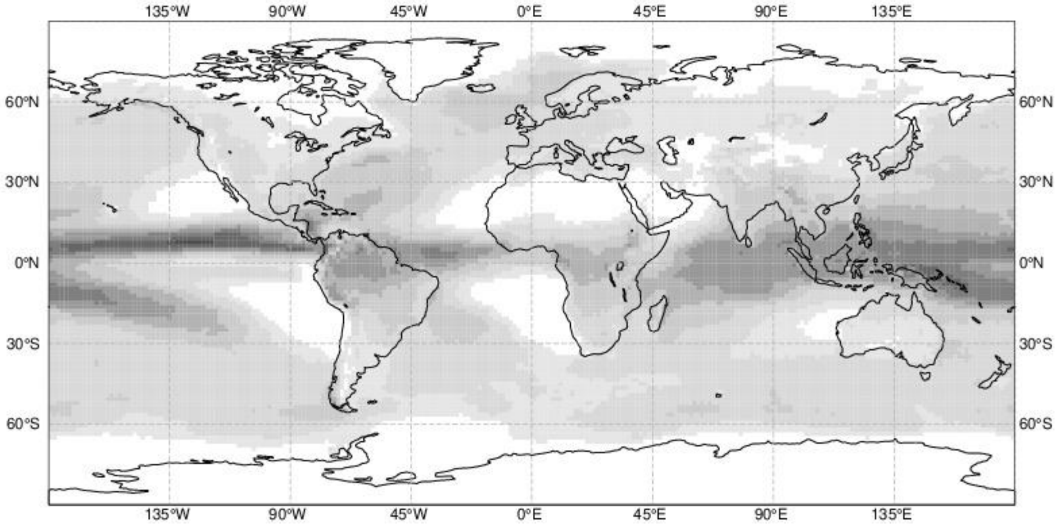
Convection

# Frequency distribution of shallow and deep convection in IFS

Shallow convection

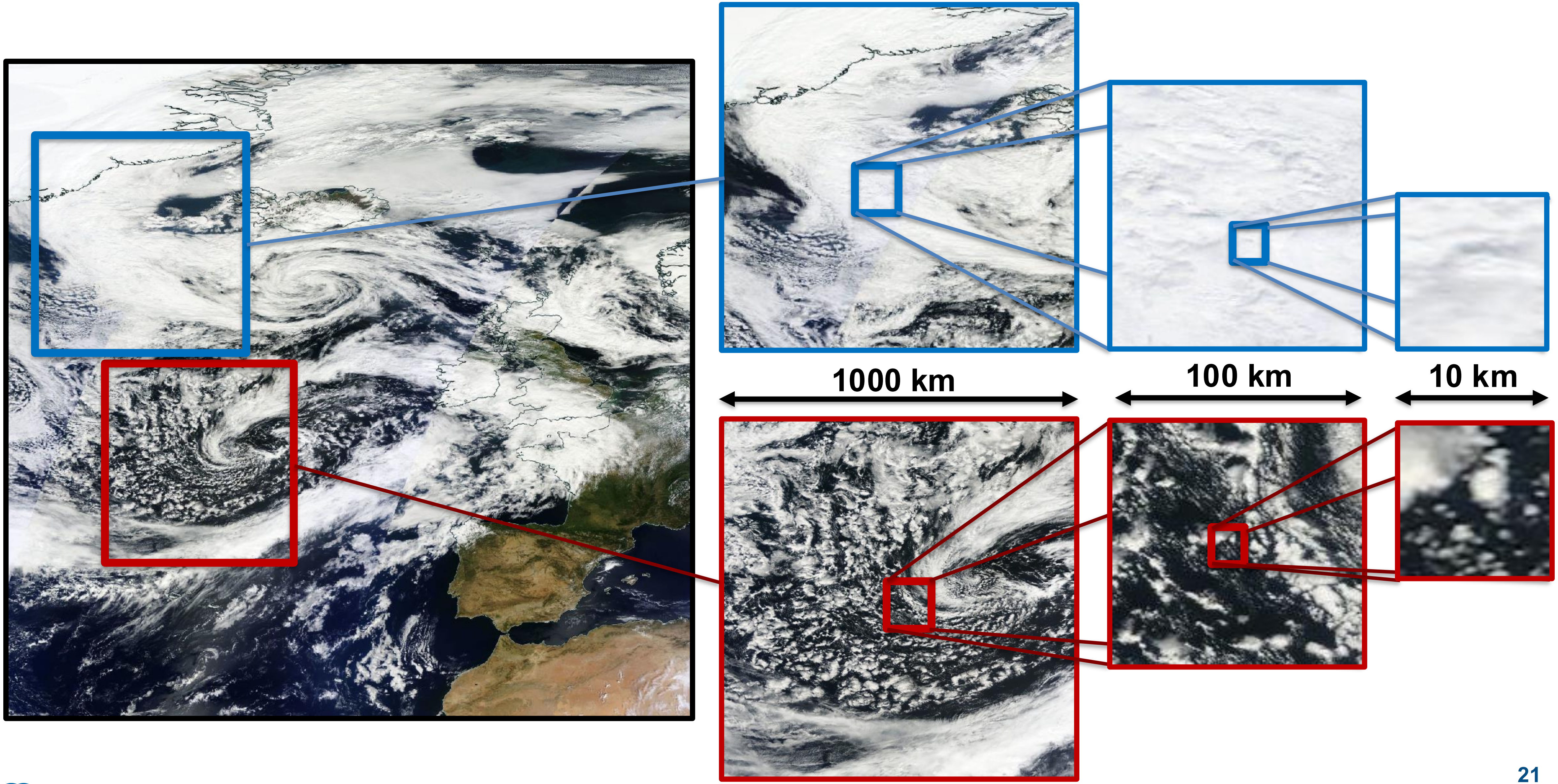



Deep convection including congestus



# Sub-grid cloud scheme

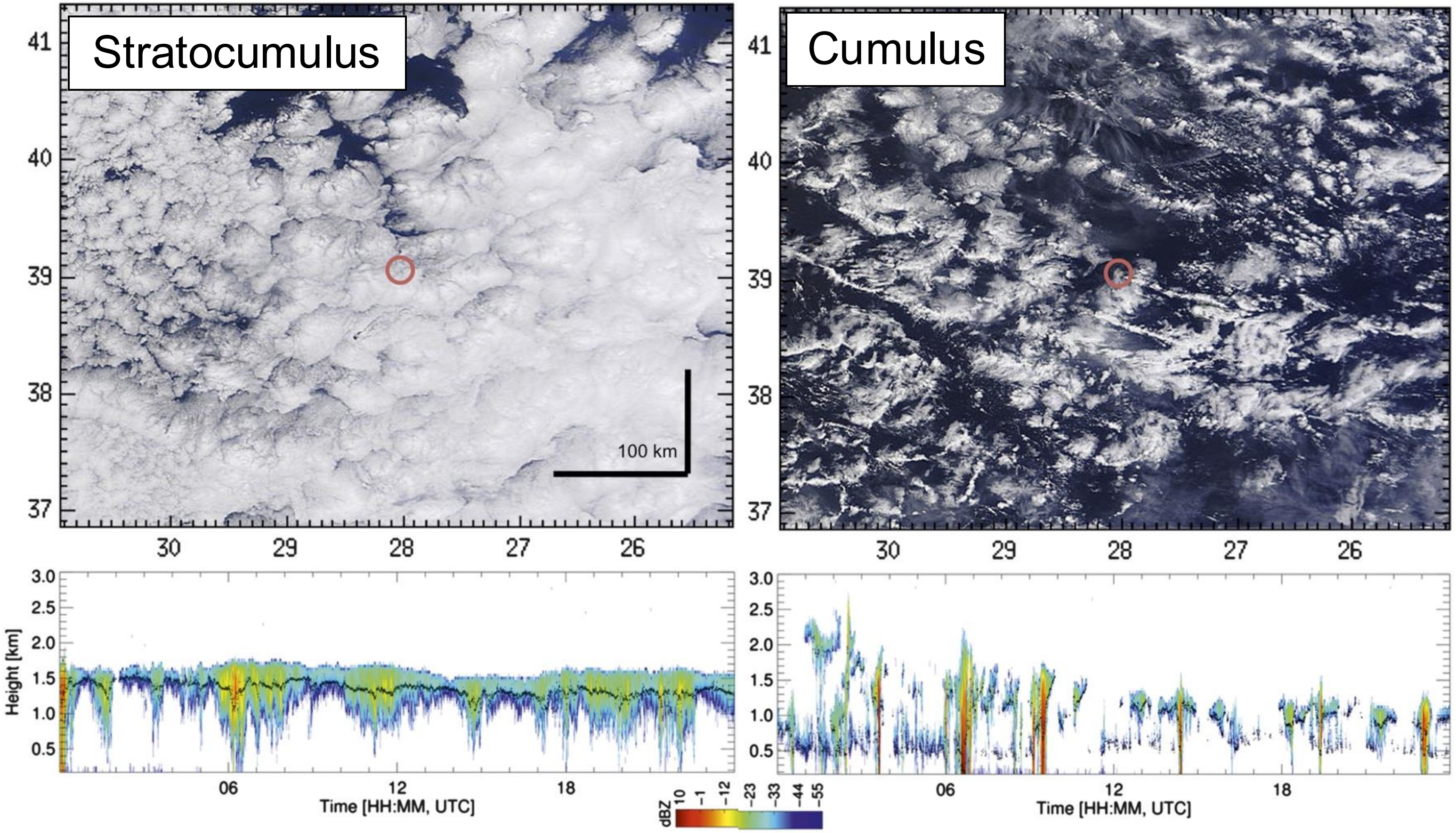
## Observations of cloud heterogeneity



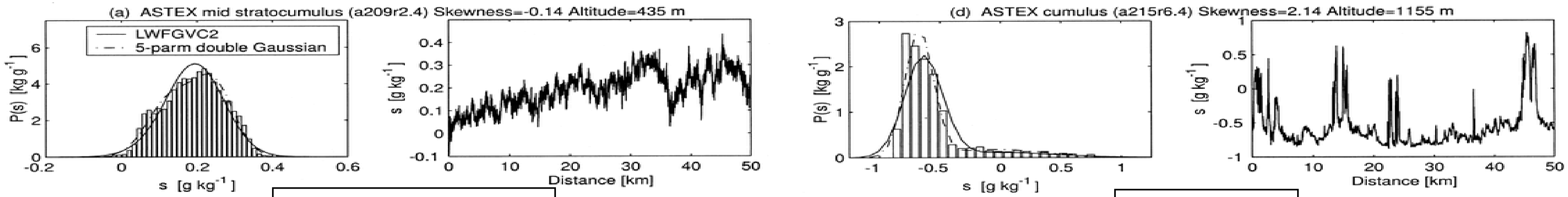
# Sub-grid cloud scheme

## Observations of cloud heterogeneity

North Atlantic, Azores
MODIS and radar data
Rémillard et al. (2012)




ASTEX aircraft data
(Larson et al. 2001)



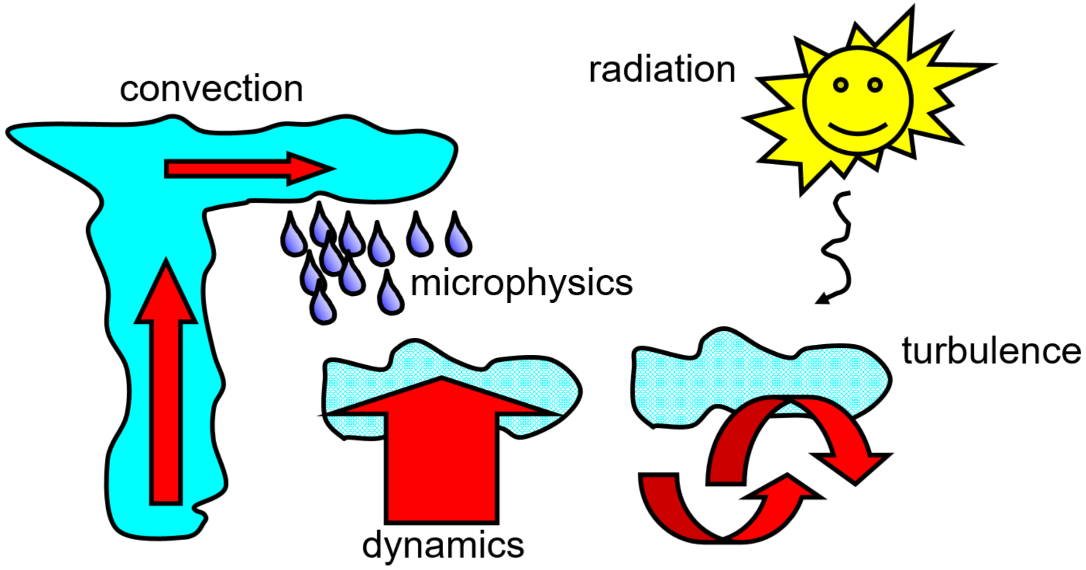

Stratocumulus

Cumulus

# Sub-grid cloud scheme

## Subgrid condensation/evaporation

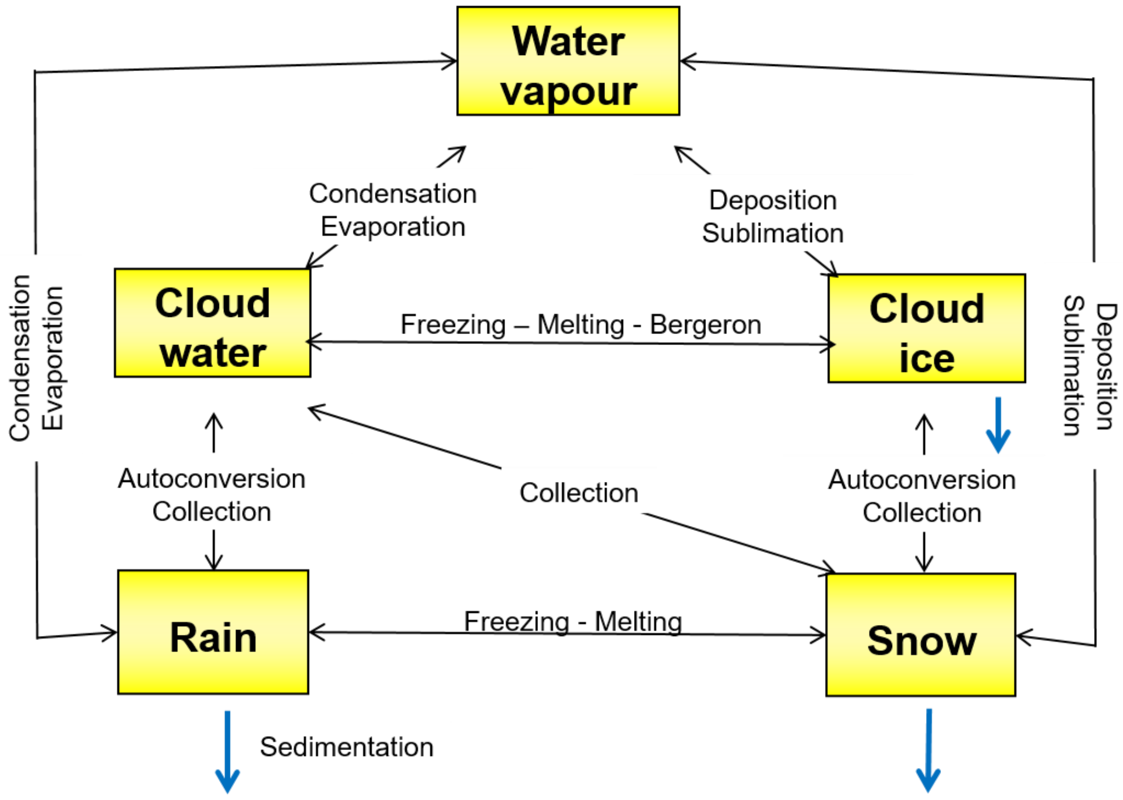
- Prognostic cloud fraction (Tiedtke 1993) for cloud liquid and cloud ice
- Allows skewed pdf of total water to represent e.g. high condensate/small fraction cloud cover from convection in a low humidity environment
- Source of cloud cover/condensate from top-hat subgrid humidity distribution for condensation from adiabatic cooling, radiative cooling/warming
- Direct detrainment of cloud fraction/condensate from convection scheme, represents anvils
- Evaporation of condensate from convective subsidence and cloud edge turbulence
- Diagnostic precipitation fraction for rain and snow
- Supersaturation over ice allowed in clear sky part of the grid box (Tompkins et al. 2007)



# Cloud and precipitation microphysics

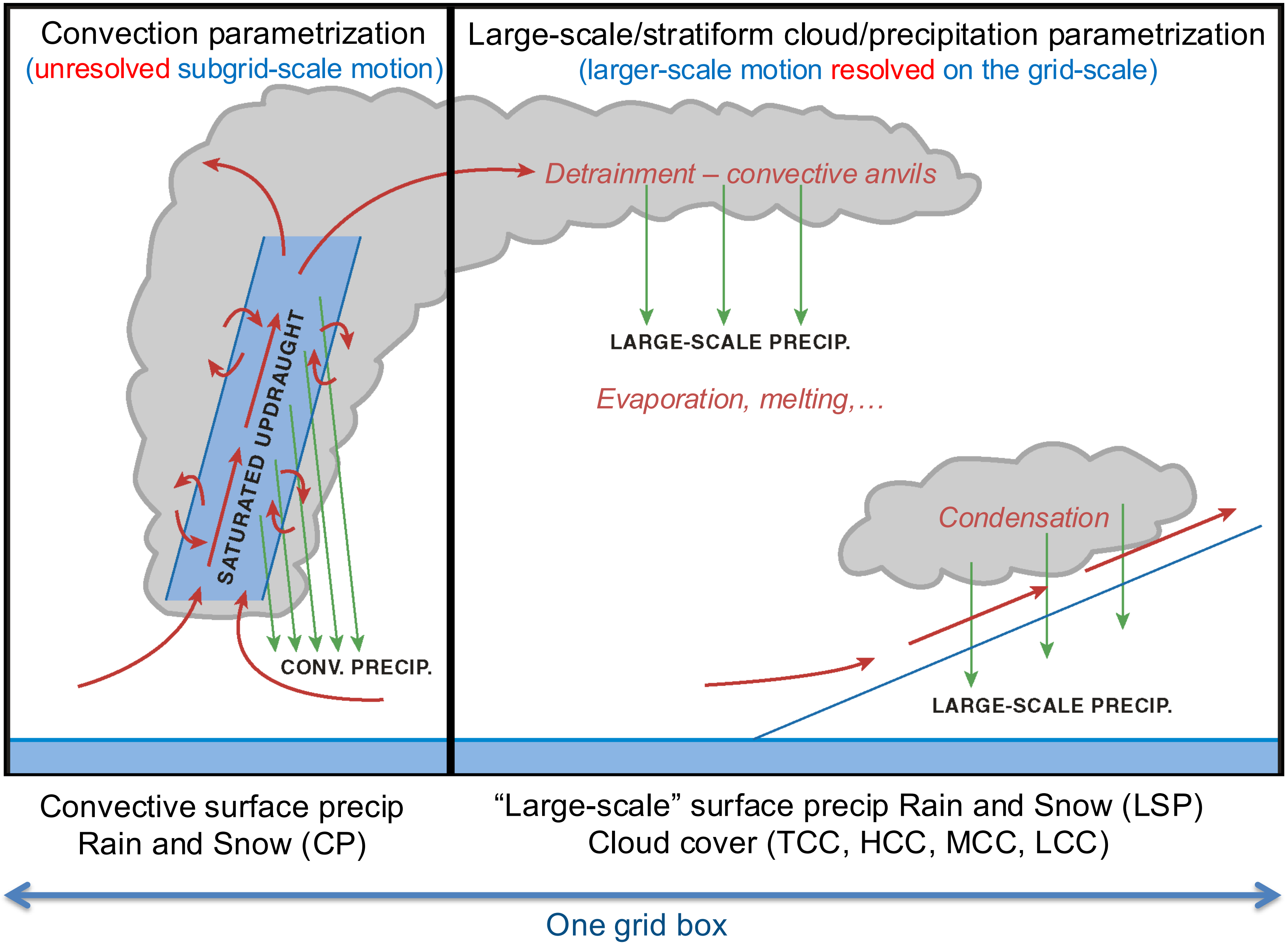
## Single-moment bulk scheme

- Prognostic variables: grid-box mean specific mass of water vapour, cloud liquid droplets, cloud ice particles, rain and snow
- Tiedtke (1993); Forbes and Tompkins (2011); Forbes et al. (2011)
- Assumed (exponential) particle size distributions
- Parametrized microphysical processes (using in-cloud water contents)
- Simple ice nucleation assumptions (Meyers et al 1992)
- Rain, snow and cloud ice precipitate
- Diagnostic winter precipitation type (freezing rain, ice pellets, wet snow, dry snow)



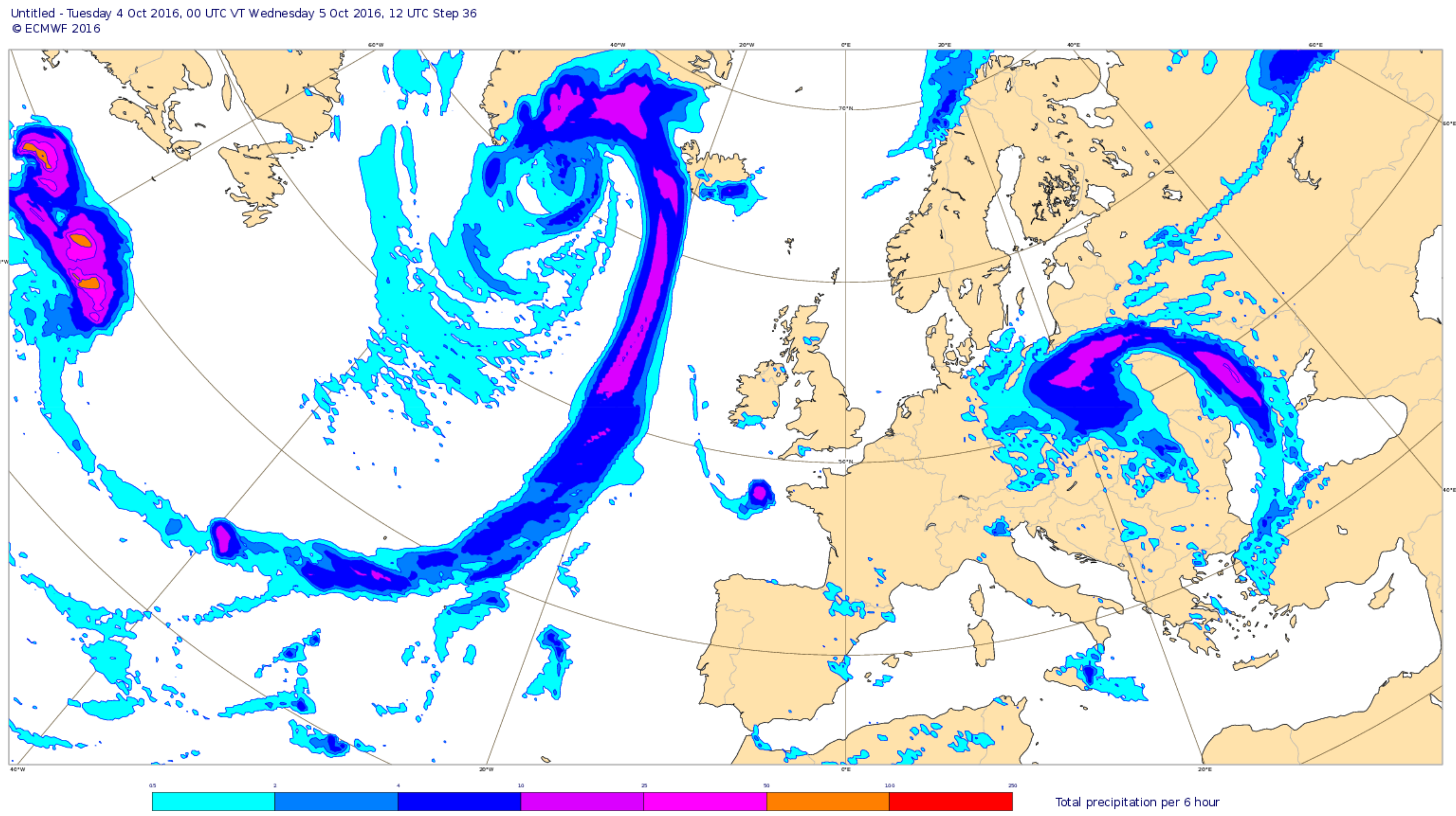
# Cloud and convection

## Convective and stratiform precipitation and clouds



# Cloud and convection

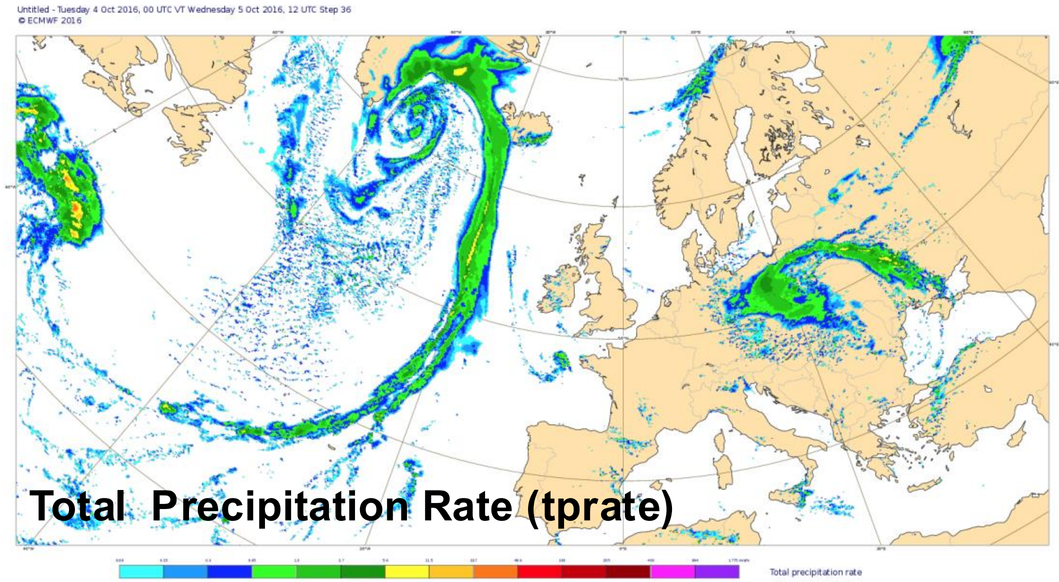
## Example 6 hour precipitation accumulation
Forecast for Wed 5 October 2016

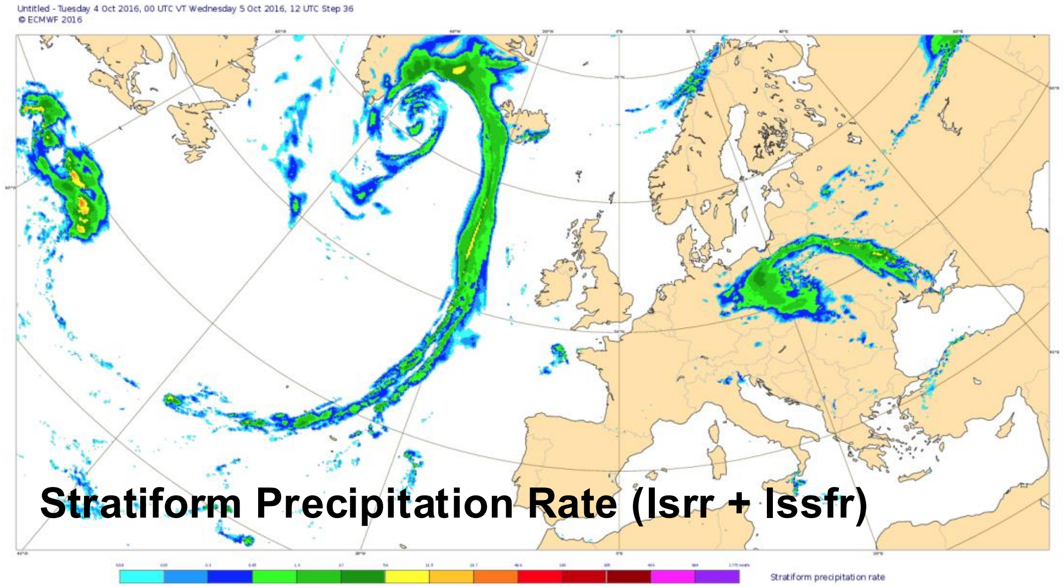


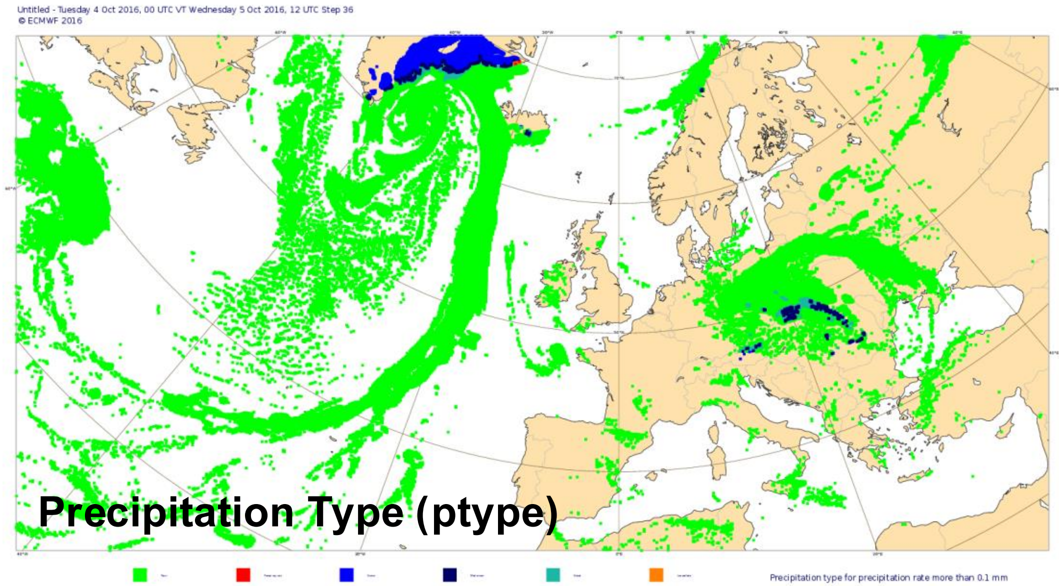

Precipitation Accumulation: Large-scale rain + convective rain + large-scale snow + convective snow

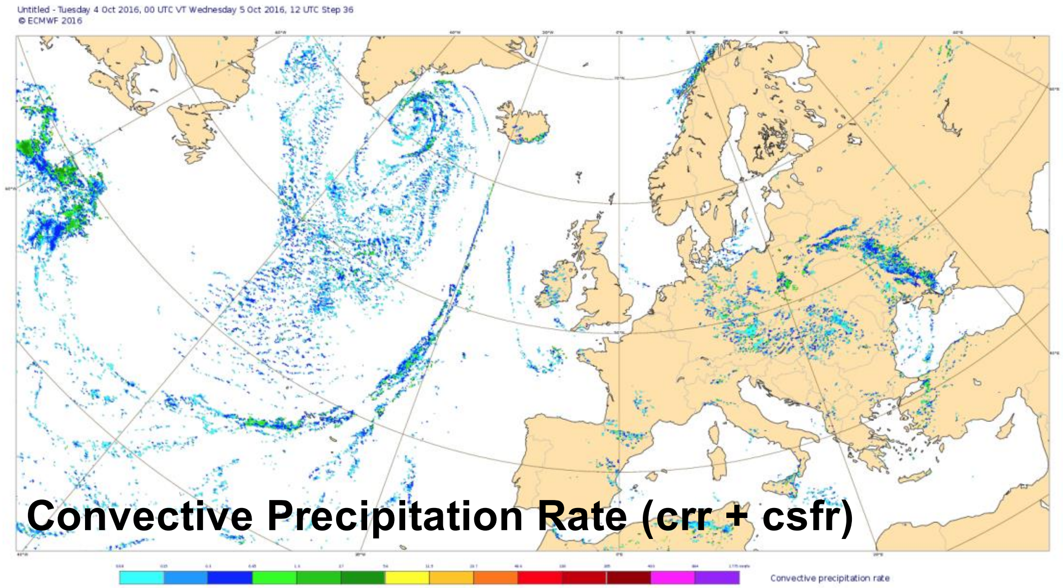
# Cloud and convection

## Precipitation rate/type example (12 UTC Wed 5 Oct)



# Orographic drag

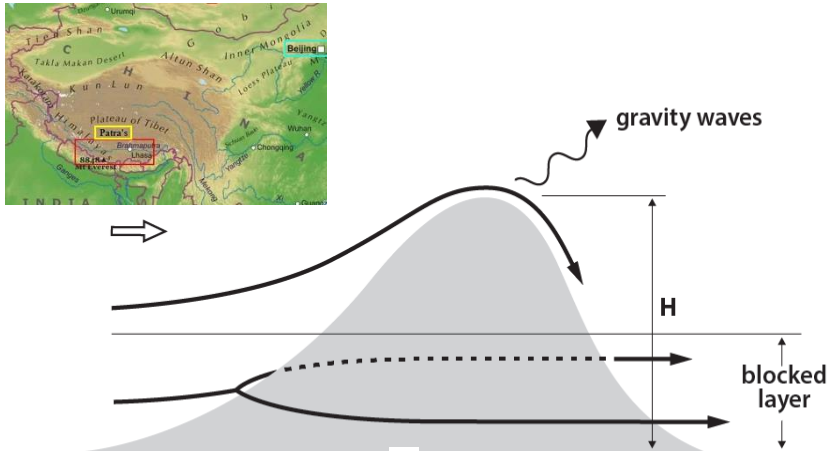
## Subgrid drag (stress) mechanisms in the ECMWF model

### Scales smaller than 5 km

**a) Turbulent Drag - TURB**: Traditional Monin-Obukhov transfer law with roughness for land use and vegetation

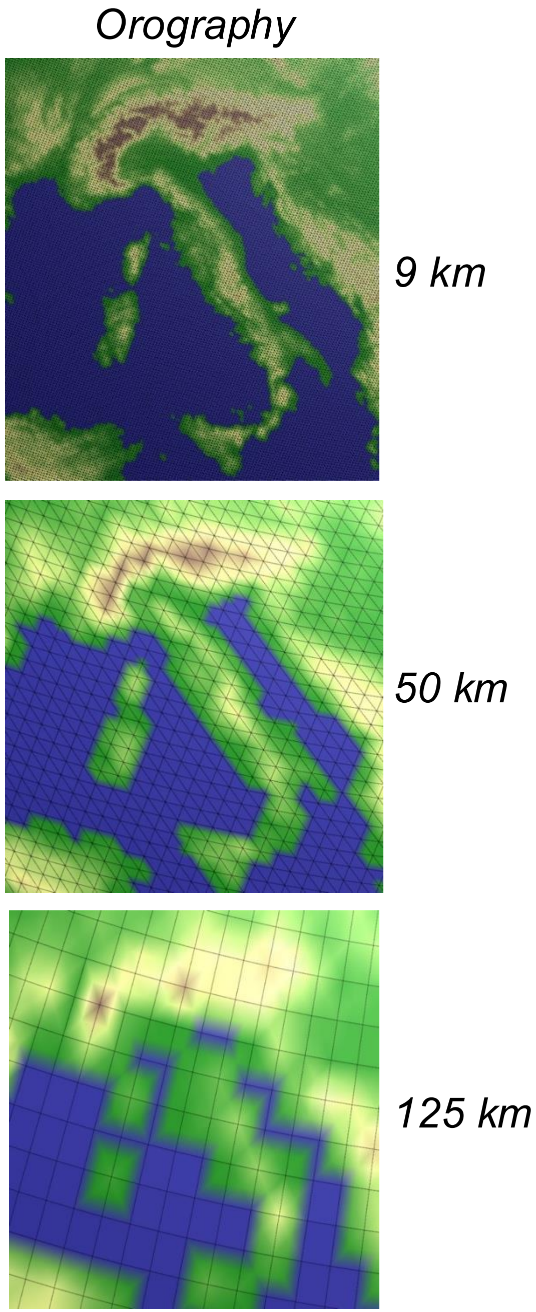
**b) Turbulent Orographic Form Drag - TOFD**: drag from small scale orography (Beljaars et al. 2004); Other models use orographic enhancement of roughness.

### Scales larger than 5 km



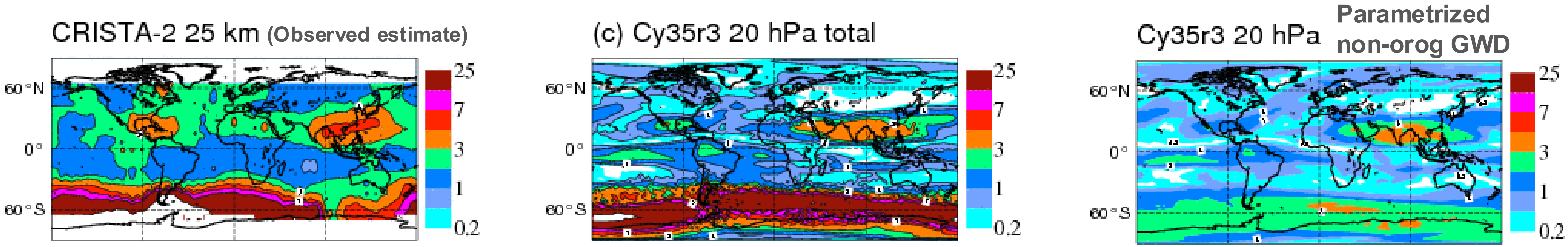

**a) Gravity Wave Drag - GWD** : gravity waves are excited by the "effective" sub-grid mountain height, i.e. height where the flow has enough momentum to go over the mountain (Lott and Miller 1997)

**b) Orographic low level blocking - BLOCK** : strong drag at lower levels where the flow is forced around the mountain



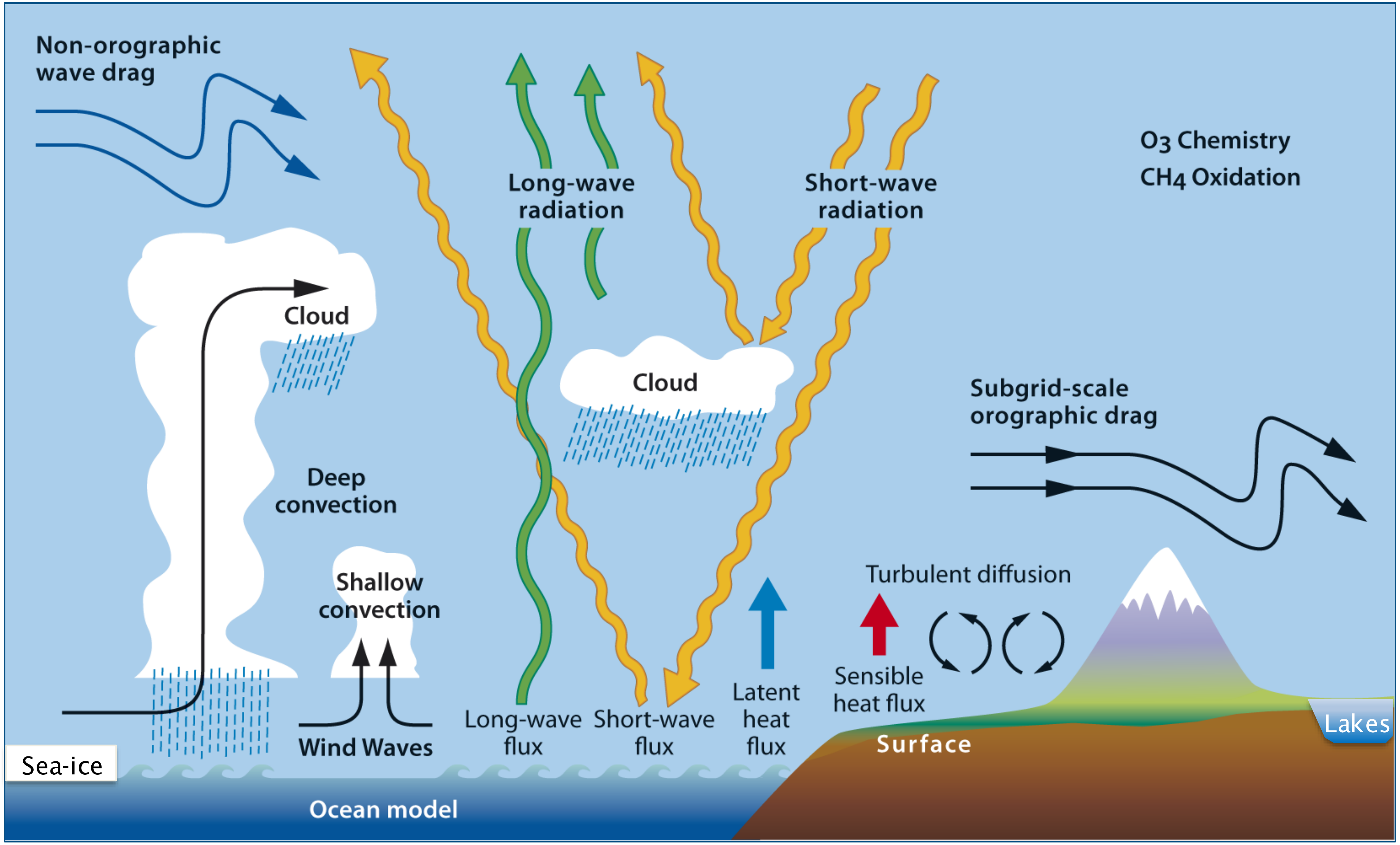
# Non-orographic gravity wave drag

- Accounts for effects of **unresolved** gravity waves from sources such as convection, fronts, jet-stream
- Waves propagate upward from the troposphere (wavelengths: vertical O(1-10 km), horizontal O(10-1000 km)
- Waves break in the stratosphere/mesosphere exerting a drag on the flow
- Parametrization uses a globally uniform wave spectrum and propagates it vertically through changing winds and air density
- Represents wave breaking due to critical level filtering and non-linear dissipation (Orr et al. 2010)




Comparison of observed (left), total resolved+parametrized orog+non-orog (centre) and parametrized non-orog (right) gravity wave momentum flux (mPa) for 8-14 August 1997. Observed values are for CRISTA-2 (Ern et al. 2006).

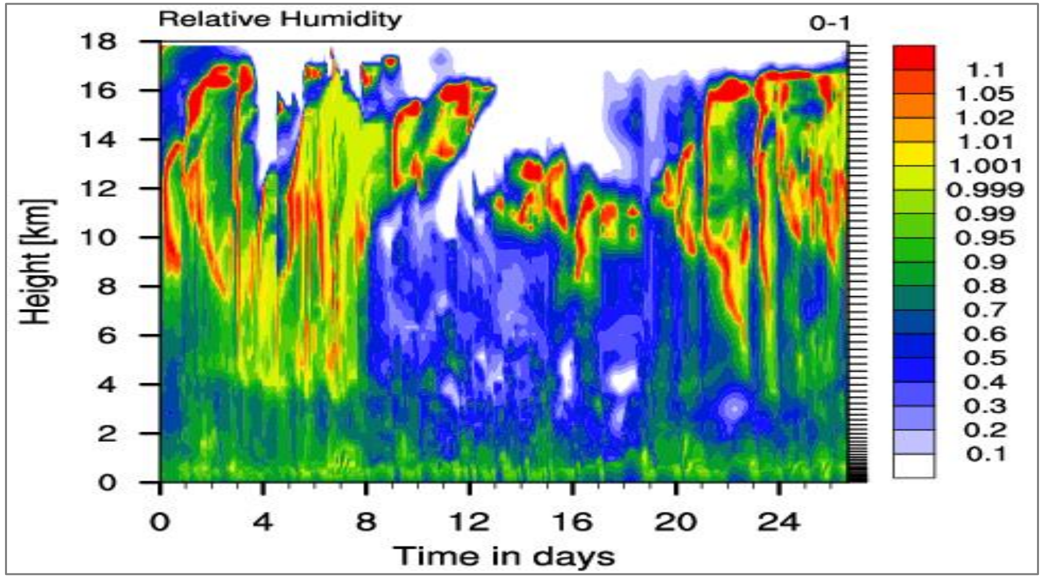
# Parameterized processes in the ECMWF model



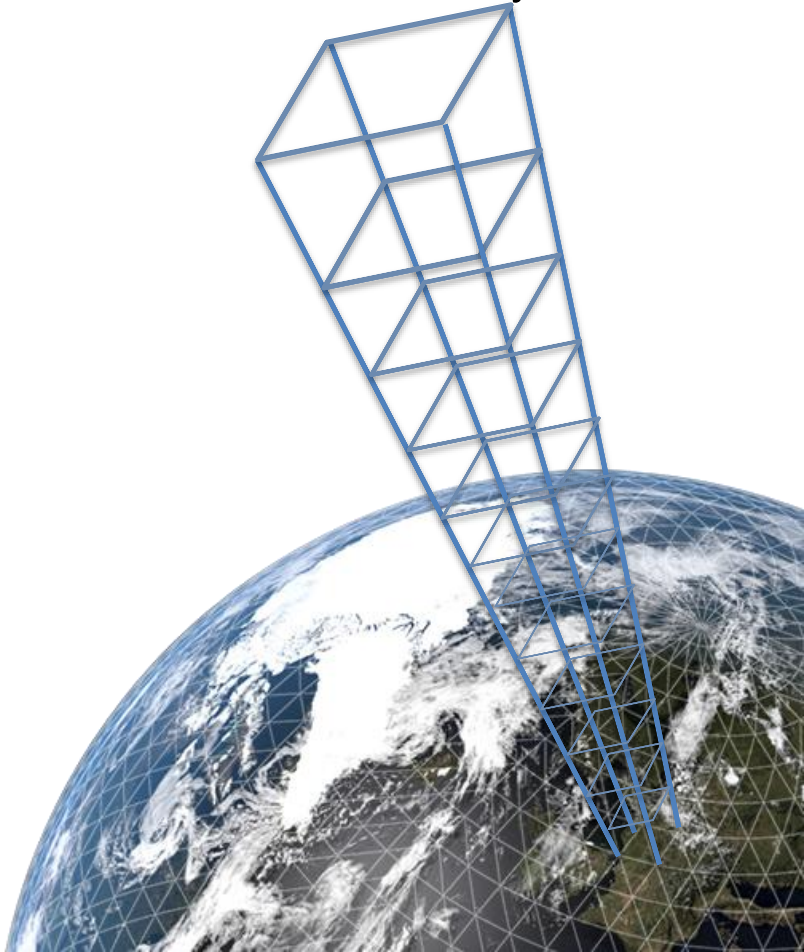
# IFS Single Column Model

# OpenIFS/IFS Single Column Model – a tool for development and collaboration

- The IFS SCM used for **efficient code development**, **testing new ideas**, **collaboration**
- Single column physics (the same as in 3D), vertical advection, forcing of T, Q, UV (advective or relaxation)
- Quick to run on workstation, many different options
- Case studies based on observations, idealised, or from grid column extracted from the IFS/reanalysis
- SCM is available as part of the OpenIFS SCM release




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



# Further information on IFS physical parametrizations

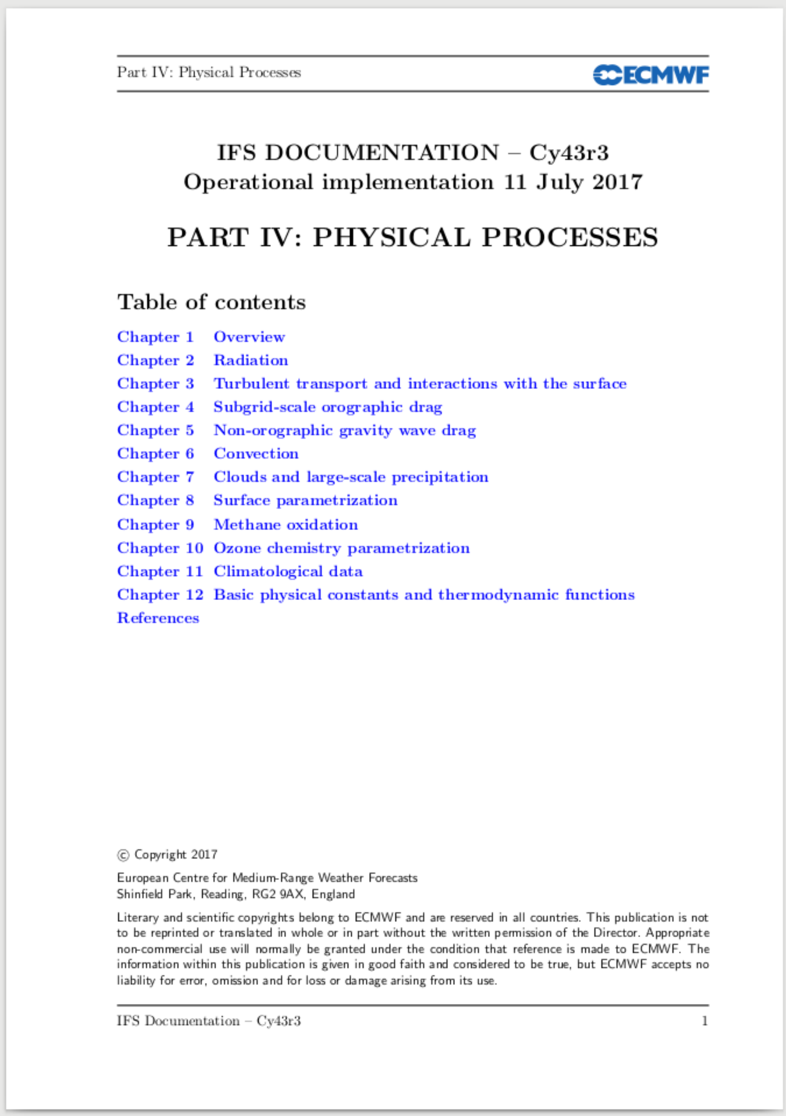
- Overview description of IFS model
  https://www.ecmwf.int/en/research/modelling-and-prediction
  https://confluence.ecmwf.int/display/OIFS/OpenIFS+User+Guide

- 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

# Summary

- A comprehensive set of physically based parametrizations in the IFS
- Each parametrization is a part of the whole – important to understand their impacts and interactions
- Parametrizations need to represent physical processes across space and time scales, from high-impact weather a few days ahead (T2m, fog, freezing rain, CAT,…) to longer-term global impacts (convective tropical heating, MJO, radiation balance,…)
- Accurate, numerically robust, computationally efficient, scale-independent
- OpenIFS/IFS Single Column Model (SCM) useful for understanding and development

# Questions?

# Tendencies – how to output extra diagnostics

- T/Q/U/V dynamics/physics tendency budget
- Set LBUD23=T in namelist &NAEPHY (default = false)
- In CALLPAR, PSURF%PSD_XA( : , : , 1-25 )
- Need to specify grib codes 91,92,…,115 in NVEXTRAGB(:) in &NAMPHYDS and add to MFP3DFS(:) in &NAMFPC
- Can use this mechanism to get other 3D/2D variables out
- Note: not all cloud/precip budget terms present

## Physics+Dynamics tendency budget (LBUD23)

| Field (3D on model levels) | Unit (fluxes and tendencies are accumulated) | Grib Code Currently in this order from 91 to 114 (Table 128) |
|---|---|---|
| **dU/dt** dynamics | $m/s^2$ *s | 91 |
| **dV/dt** " | $m/s^2$ *s | 92 |
| **dT/dt** " | K/s *s | 93 |
| **dq/dt** " | kg/kg/s *s | 94 |
| **dT/dt** radiation | K/s *s | 95 |
| **dU/dt** vertical diff.+grav.wave | $m/s^2$ *s | 96 |
| **dV/dt** " | $m/s^2$ *s | 97 |
| **dT/dt** " | K/s *s | 98 |
| **dq/dt** " | kg/kg/s *s | 99 |
| **dU/dt** gravity wave drag | $m/s^2$ *s | 100 |
| **dV/dt** " (orog+non-orog) | $m/s^2$ *s | 101 |
| **dT/dt** " **(=dissip wave break)** | K/s *s | 102 |
| **dU/dt** convection | $m/s^2$ *s | 103 |
| **dV/dt** " | $m/s^2$ *s | 104 |
| **dT/dt** " | K/s *s | 105 |
| **dq/dt** " | kg/kg/s *s | 106 |
| **Prflux conv liquid** | $kg/(m^2\ s)$ *s | 107 |
| **Prflux conv ice** | $kg/(m^2\ s)$ *s | 108 |
| **dT/dt** cloud | K/s *s | 109 |
| **dq/dt** " + methox | kg/kg/s *s | 110 |
| **dql/dt** cloud | kg/kg/s *s | 111 |
| **dqi/dt** " | kg/kg/s *s | 112 |
| **Prflux strat liquid** | $kg/(m^2\ s)$ *s | 113 |
| **Prflux strat ice** | $kg/(m^2\ s)$ *s | 114 |
| **2D fields in a 3D array** | | **115** |

| 2D fields contained in a single 3D model level field | Unit | Grib Code 115 |
|---|---|---|
| **Convective cloud top** | Model level number | Model level 1 |
| **Convective cloud base** | Model level number | level 2 |
| **Convection type** | (1=deep, 2=shallow, 3=mid-level) | level 3 |
| **Occurrence of deep convection** | Counts (maximum count= number of time steps) | level 4 |
| **Occurrence shallow conveect** | counts | level 5 |
| **Occurrence mid-level convect** | counts | level 6 |
| **PBL top height** | m | level 7 |
| **PBL type** | (0, 1 , 2, 3) | level 8 |
| **Occurrence PBL type 0** | counts | level 9 |
| **Occurrence PBL type 1** | counts | level 10 |
| **Occurrence PBL type 2** | counts | level 11 |
| **Occurrence PBL type 3** | counts | level 12 |

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