Introduction to Physical Processes in the IFS

"A hands-on introduction to Numerical Weather Prediction Models"
ECMWF, 13-17 Nov 2023

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Thanks to contributions from Gianpaolo Balsamo, Peter Bechtold, Anton Beljaars, Mark Fielding, Robin Hogan, Irina Sandu

European Centre for Medium-range Weather Forecasts

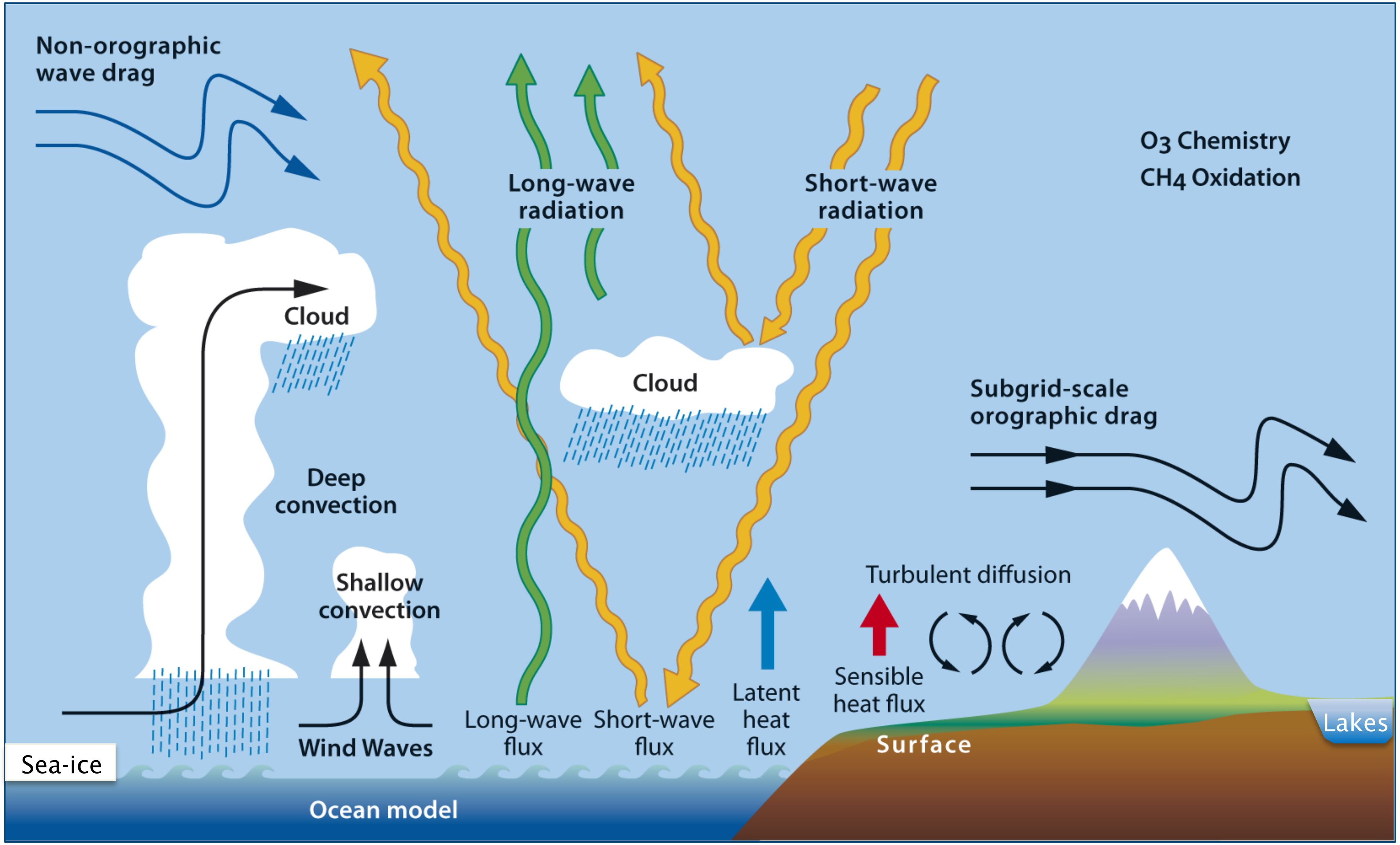
ECMWF

Outline

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

Overview 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 development
  - Diabatic heating and friction influence synoptic development

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

- Data assimilation
  - Forward operators are needed for observations

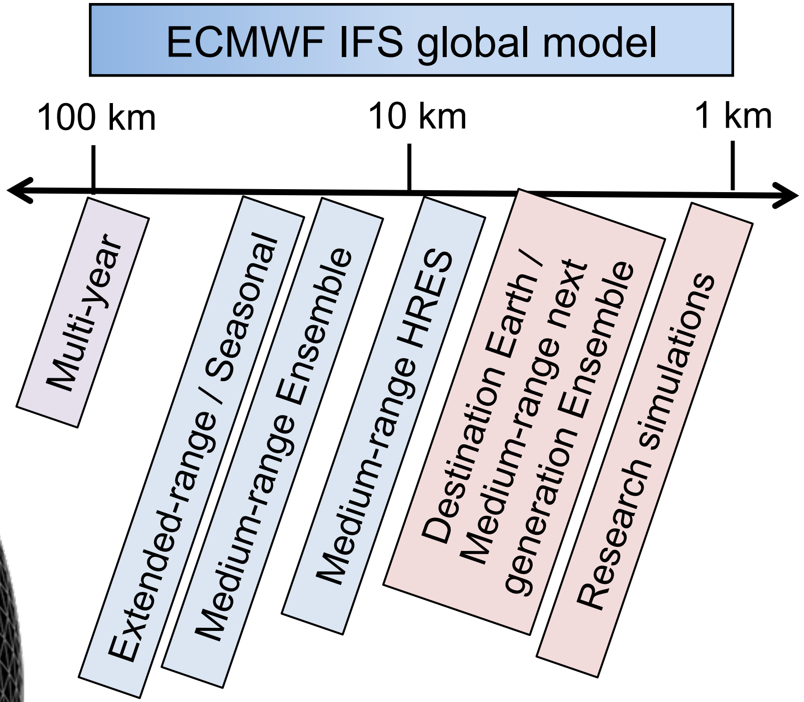
Global modelling across space and time scales

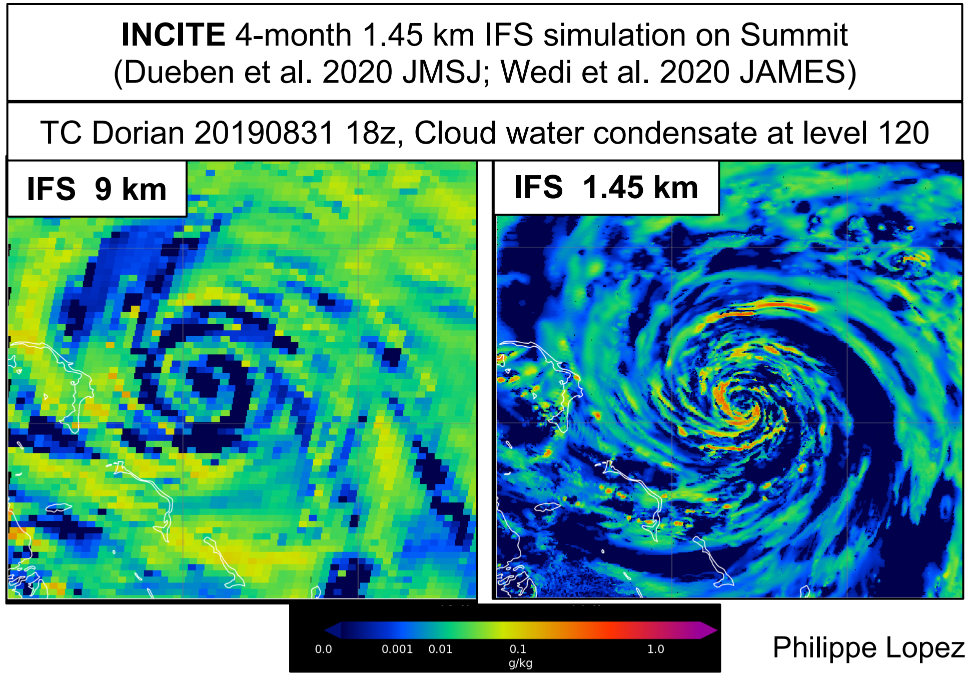
- Increasing computational power and advances in computational science
  → higher resolution
  → more components of the Earth System (e.g. ocean, sea-ice, chemistry, hydrology)
  → potential for more realistic physical parametrizations (e.g. radiation, microphysics)

- 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…

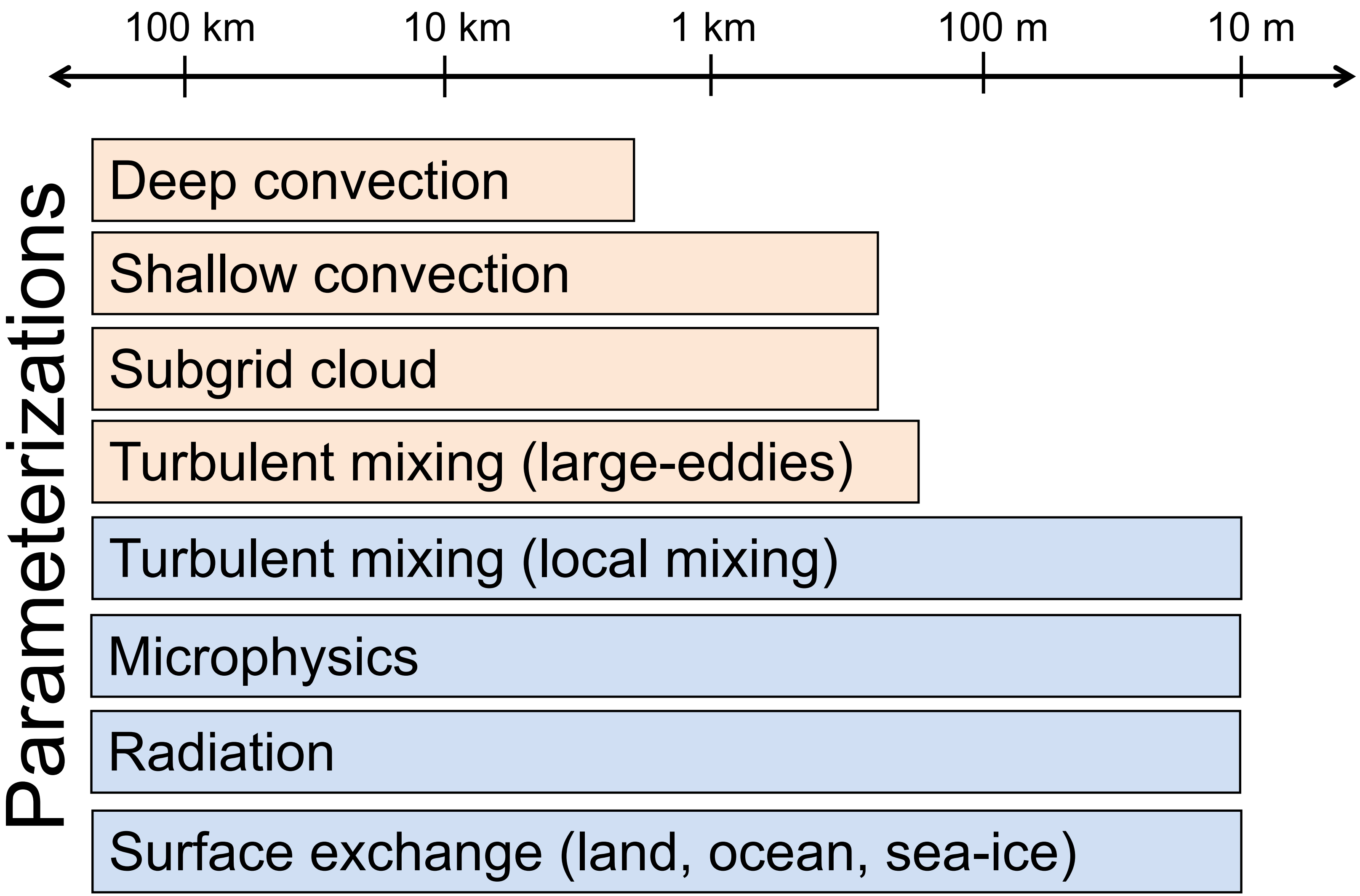
New! Machine Learning/AI models also now a reality!





Philippe Lopez

Parametrization of atmospheric physical processes – Model resolution



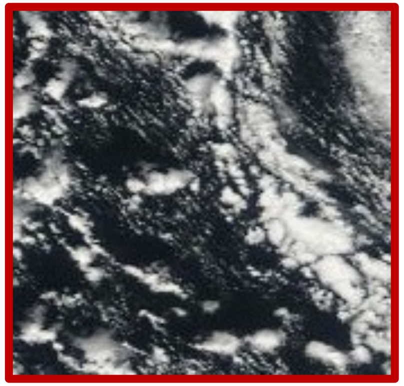
Parametrization of physical processes - Impacts

Temperature

Vertical velocity

Wind

Humidity



Precipitation

Cloud particle size

Ozone

Aerosols

Cloud fraction

Cloud condensate

Cloud phase

Radiative Impacts

Heating, cooling…

Hydrological Impacts

Precipitation, surface hydrology…

Thermodynamical Impacts

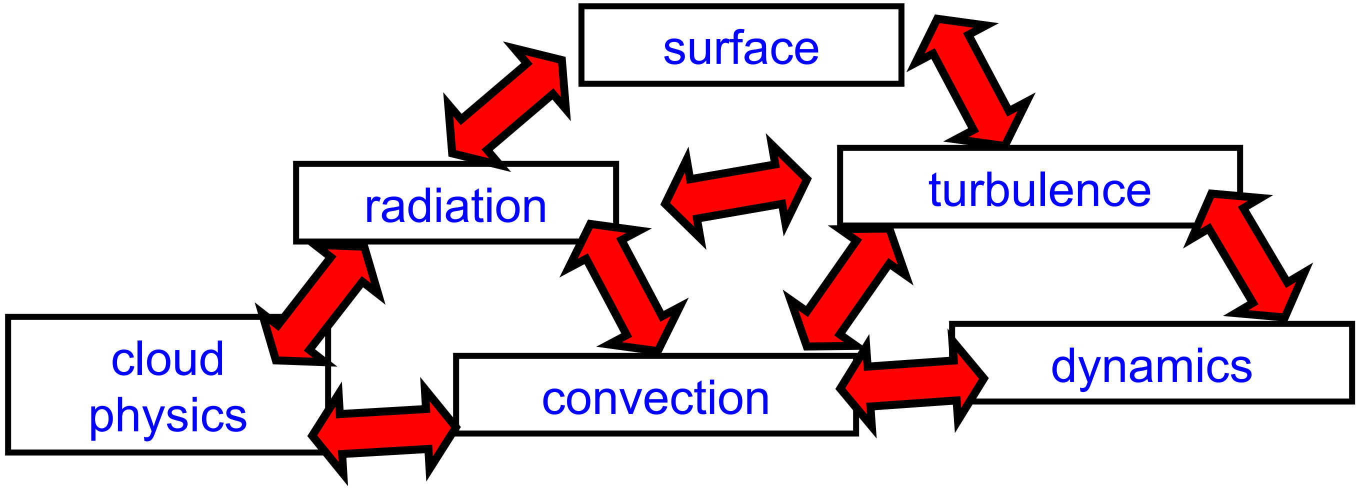
Condensation, evaporation, deposition, sublimation…

Momentum Transport

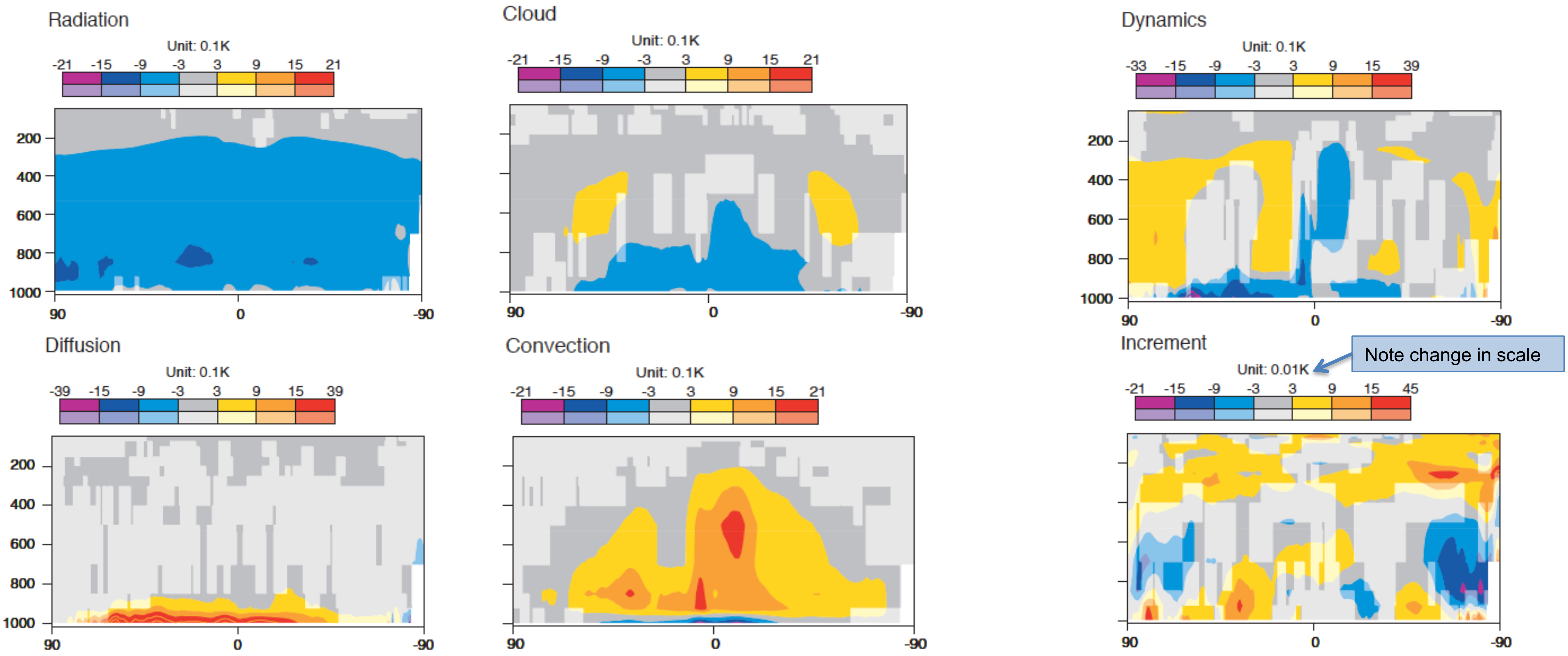
Turbulent mixing, convection, advection…

Parametrization of physical processes - Interactions

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

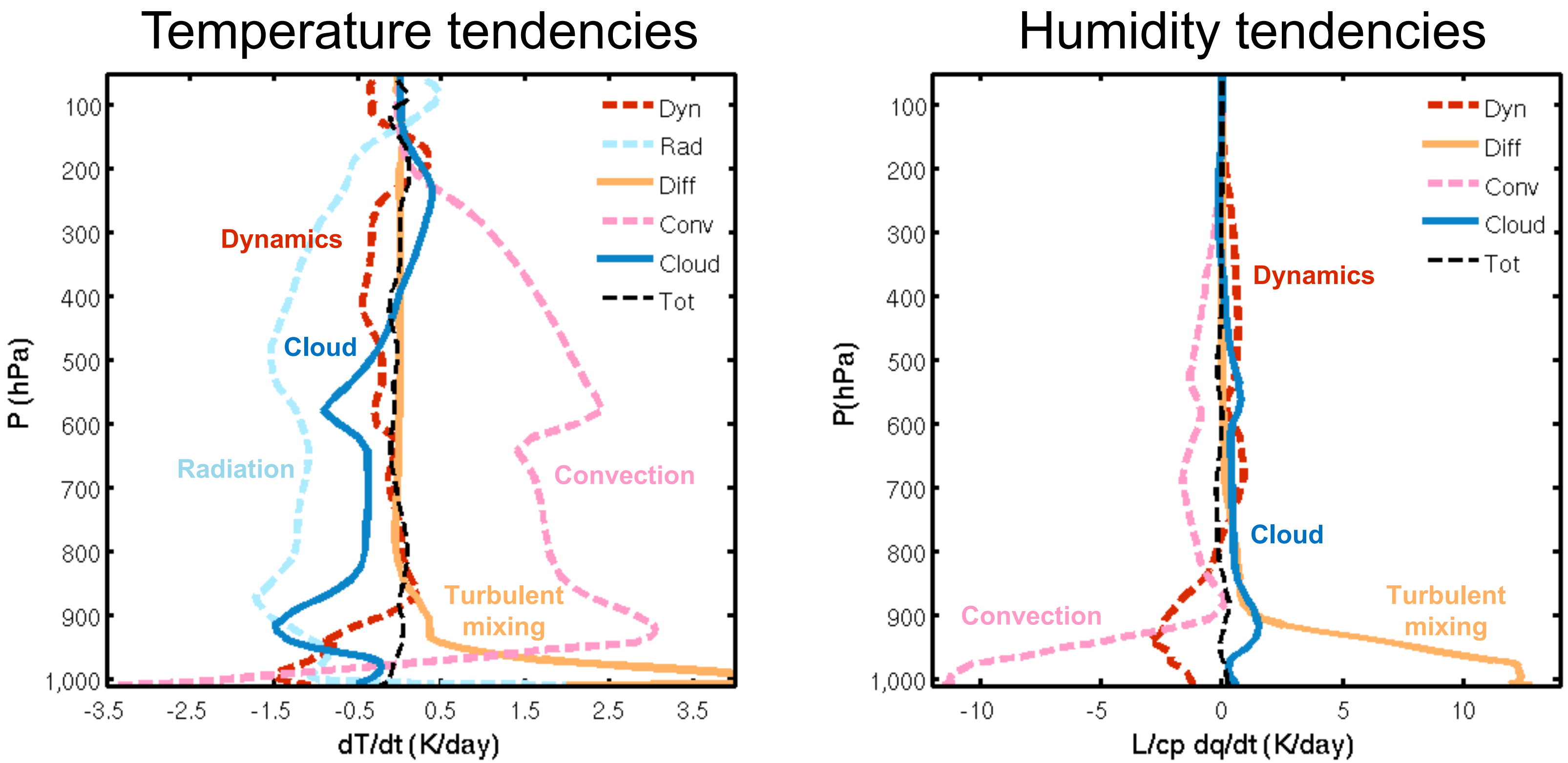


Temperature tendencies (12-hour data assimilation window). Mean DJF 2014.



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

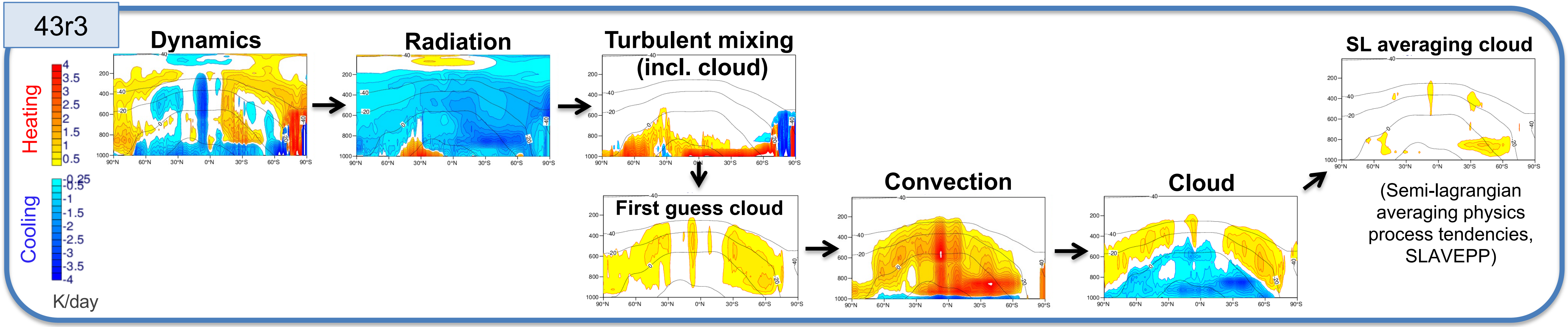
Model Tendencies – Tropics Equilibrium



- 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

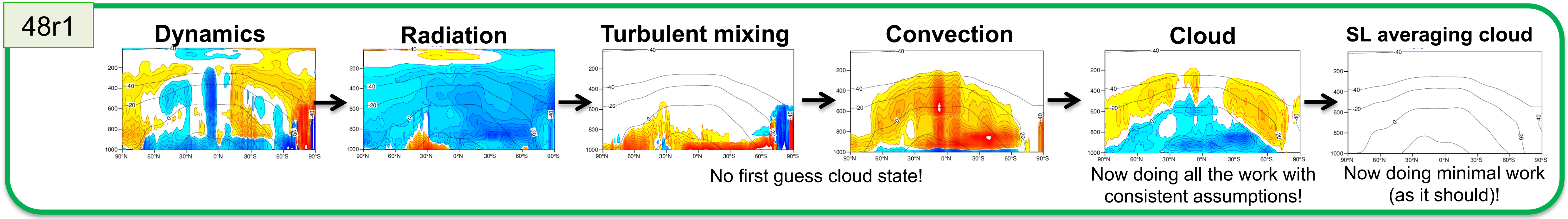
Order of calling physics parametrizations in the IFS

In 43r3, there is a complicated parametrization sequence in the IFS



Process temperature tendencies (day 1 average over June 2017)

In 48r1, there is a simplified parametrization sequence in the IFS



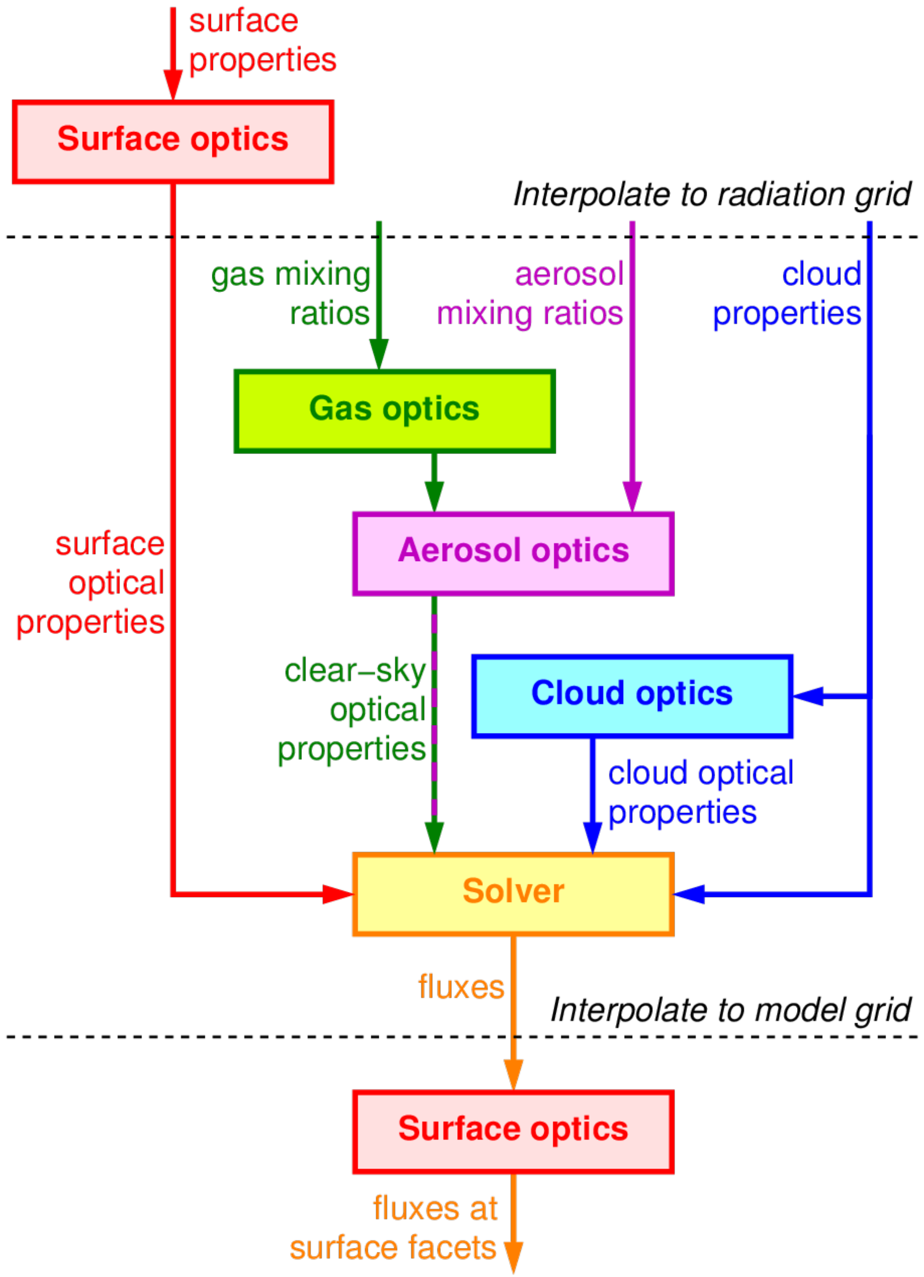
Parametrizations in the IFS

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

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

ılsamo 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

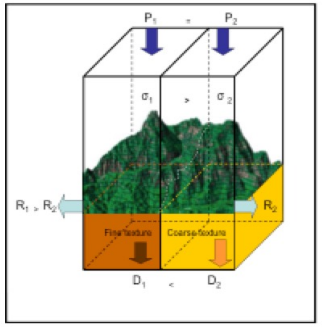
Mironov et al (2010),

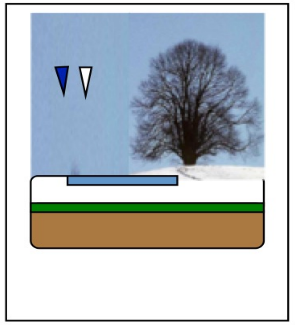
Dutra et al. (2010),

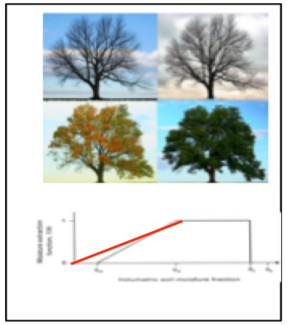
Balsamo et al. (2012, 2010)

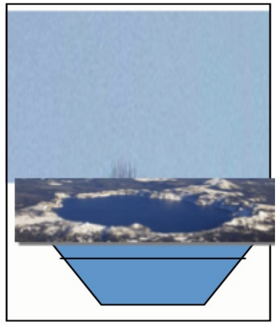
Extra tile (9) to for sub-grid lakes and ice

LW tiling (Dutra)

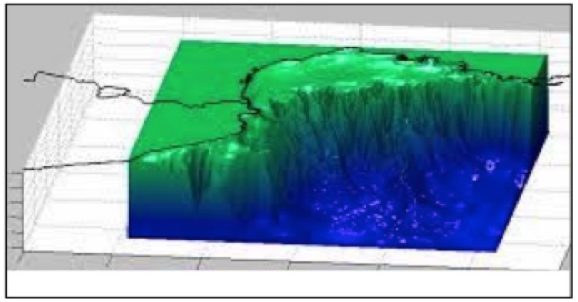




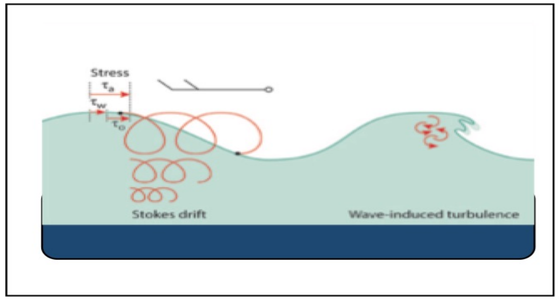




Ocean model (NEMO)



Ocean-Waves (EC-Wam)



Sea-ice (LIM2)

OpenIFS

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

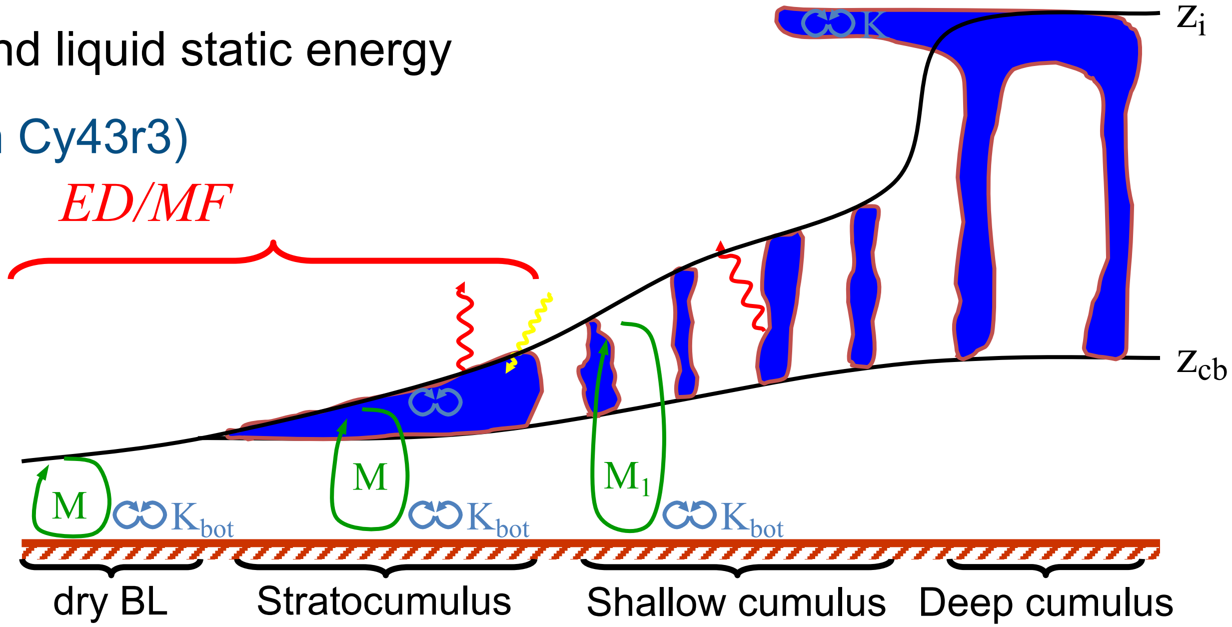
- Surface waves and currents (EC-WAM)

Ocean and sea-ice models are separate

Turbulent transport

Eddy Diffusivity Mass Flux (EDMF) approach in the PBL

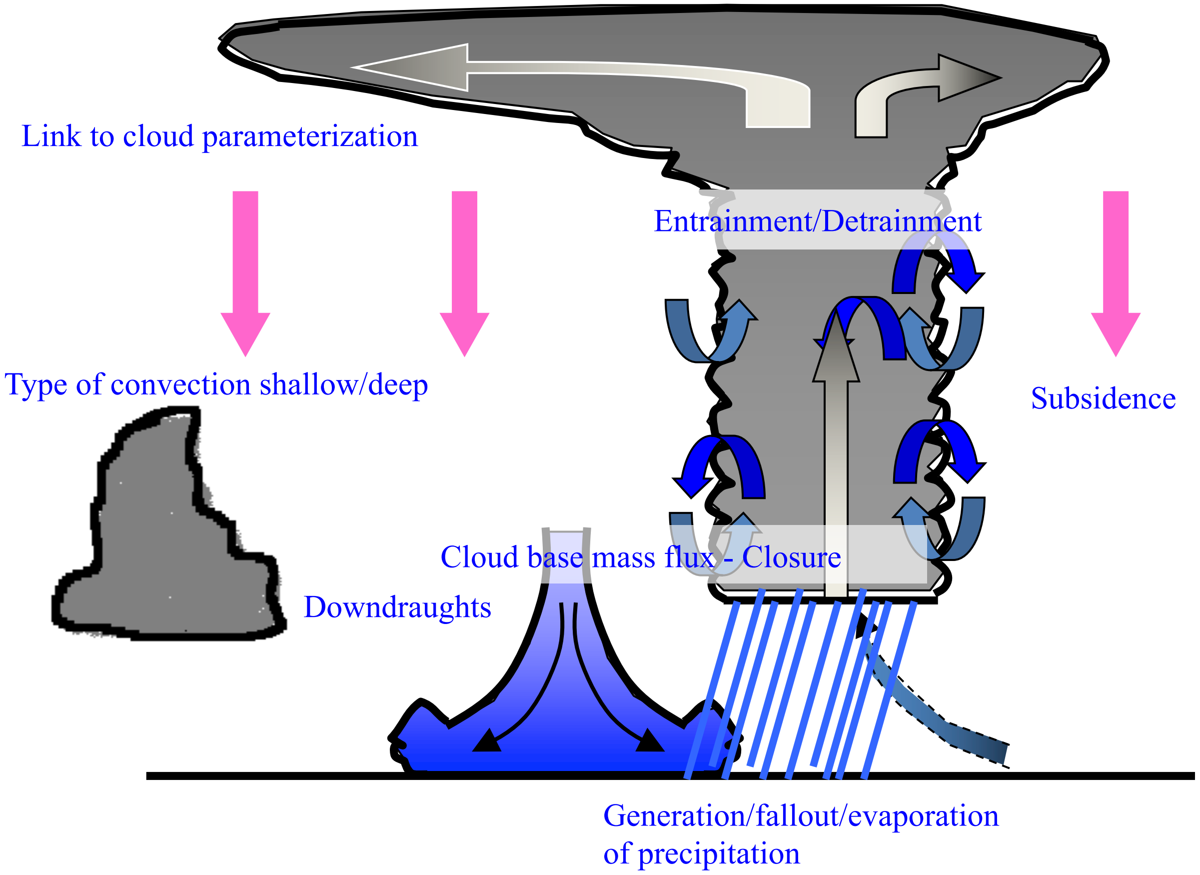
- Vertical exchange of heat, momentum and moisture through sub-grid scale turbulence
- Surface layer – K-diffusion closure based on Monin-Obukhov similarity theory
- Local turbulent mixing (K-diffusion - Eddy Diffusivity) $\overline{\phi' w'} \approx -K \frac{\partial \overline{\phi}}{\partial z}$ $\overline{\varphi' w'} \approx M(\varphi^{up} - \overline{\varphi})$
  Non-local turbulent mixing in unstable conditions = large-eddies in convective boundary layer (Mass-Flux)
- EDMF (Köhler et al., 2011)
- Uses moist conserved variables; total water and liquid static energy
- Diagnostic cloud scheme for stratocumulus (in Cy43r3)
- 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

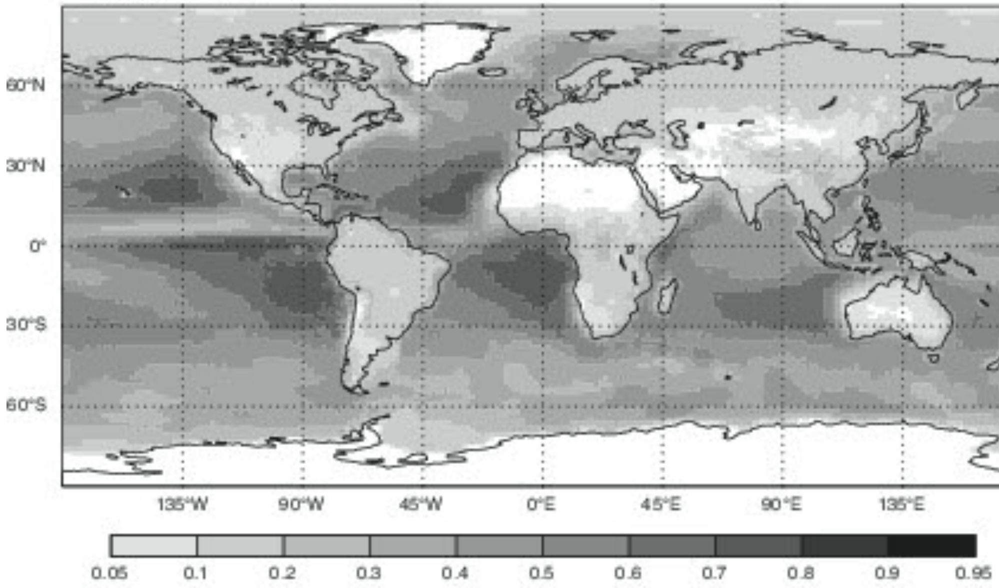
- Mass-flux entraining-detraining plume scheme (Tiedtke 1989; Bechtold et al. 2008)
- Convective types
  (1) Deep (including congestus)
  (2) Shallow
  (3) Mid-level (elevated moist layers)
- Modified CAPE closure to improve the diurnal cycle (equilibrium assumed between the large-scale and boundary-layer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



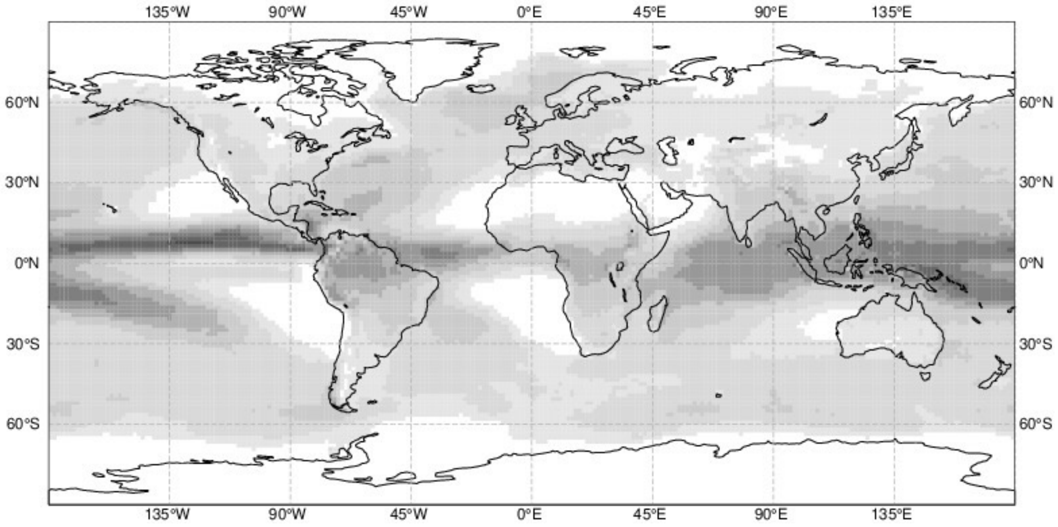
Convection

Frequency distribution of shallow and deep convection in IFS

Shallow convection



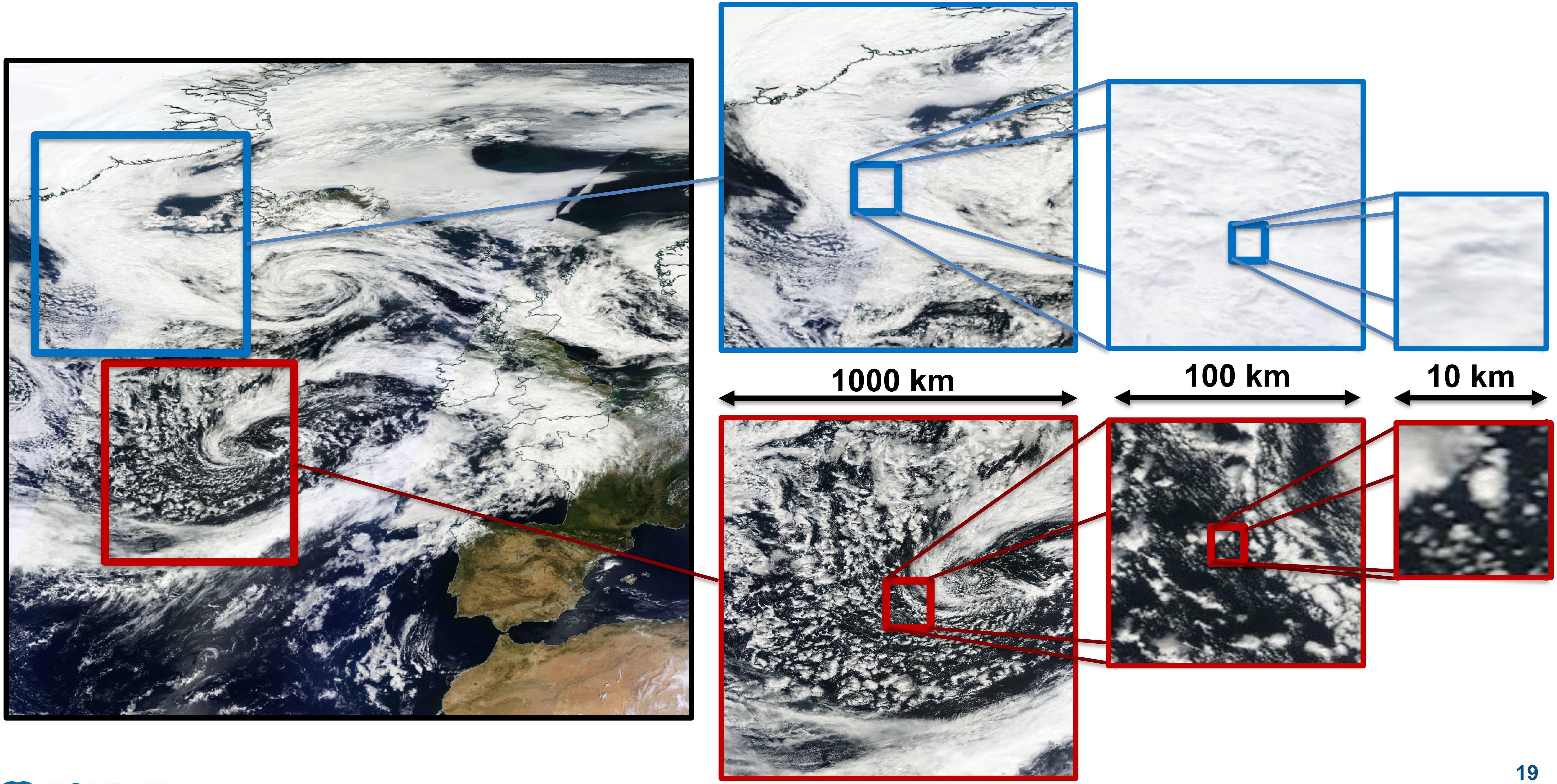
Deep convection including congestus



ECMWF

Sub-grid cloud scheme

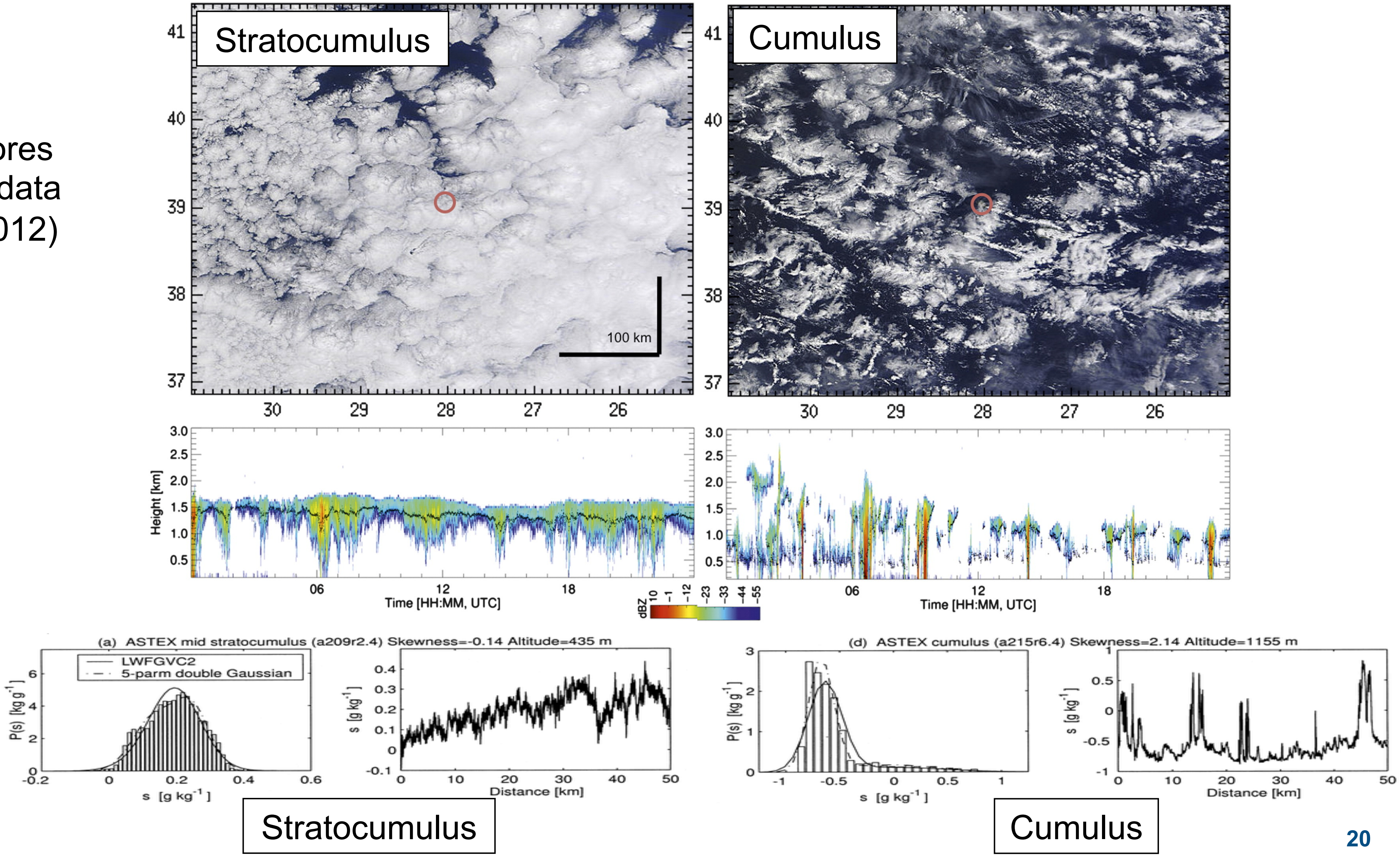
Observations of cloud heterogeneity



Sub-grid cloud scheme

Observations of cloud heterogeneity

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

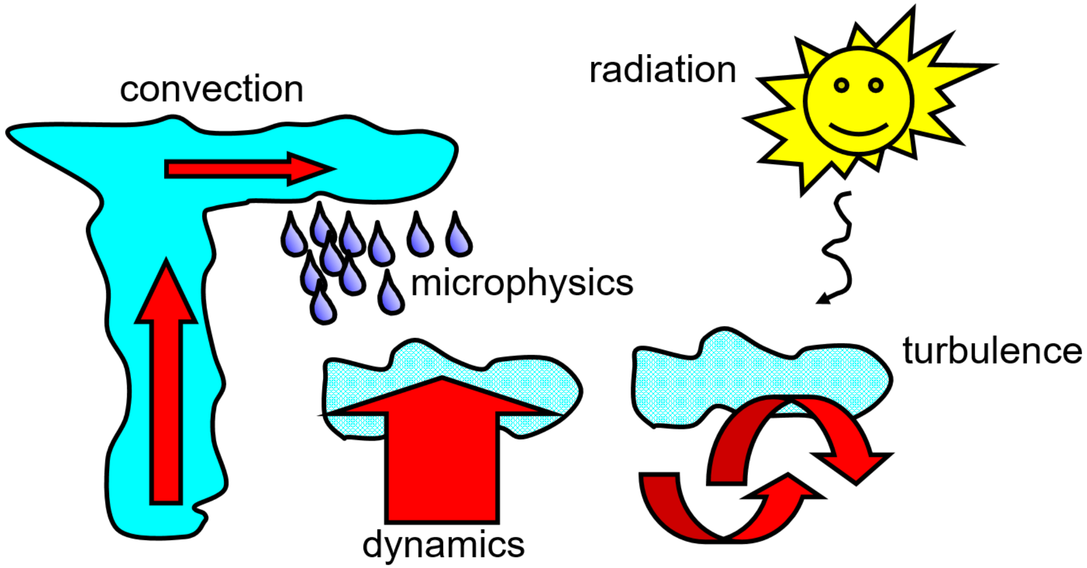


ASTEX aircraft data
(Larson et al. 2001)

Sub-grid cloud scheme

Subgrid condensation/evaporation

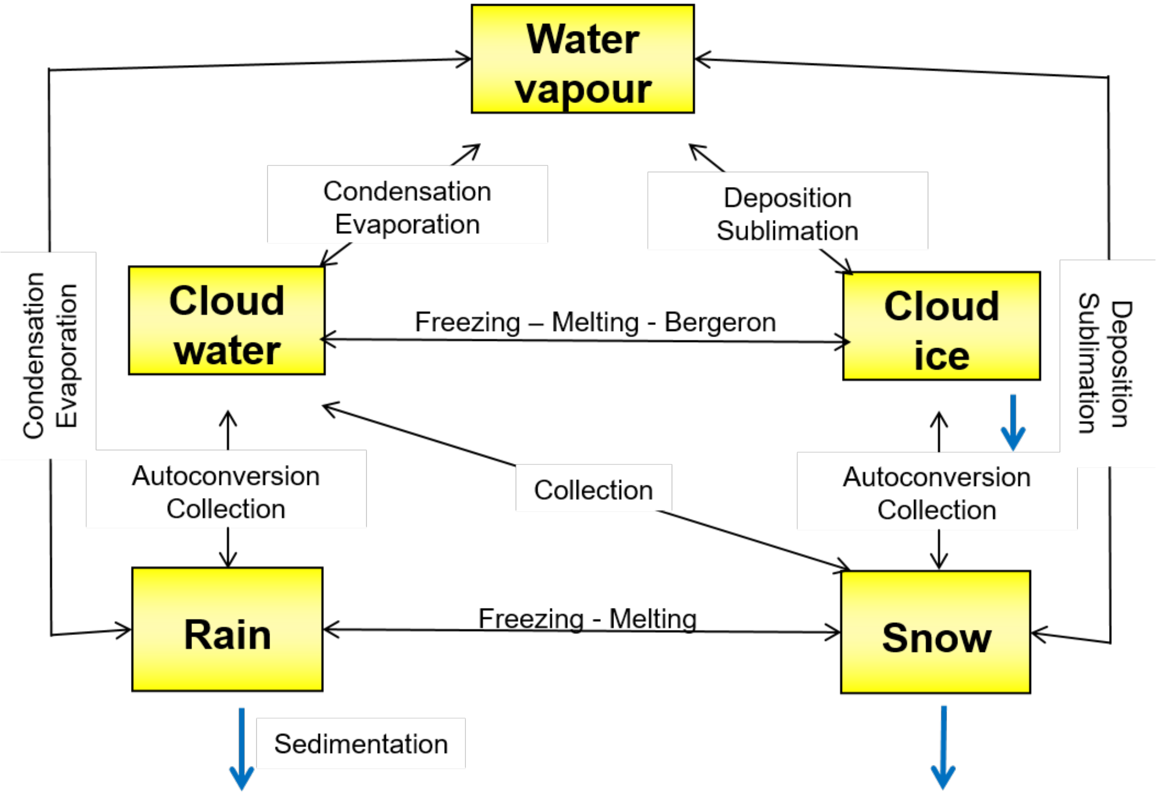
- Prognostic cloud fraction (Tiedtke 1993) for cloud liquid and cloud ice
- Allows skewed pdf of total water to represent e.g. high condensate/small fraction cloud cover from convection in a low humidity environment
- Source of cloud cover/condensate from top-hat subgrid humidity distribution for condensation 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

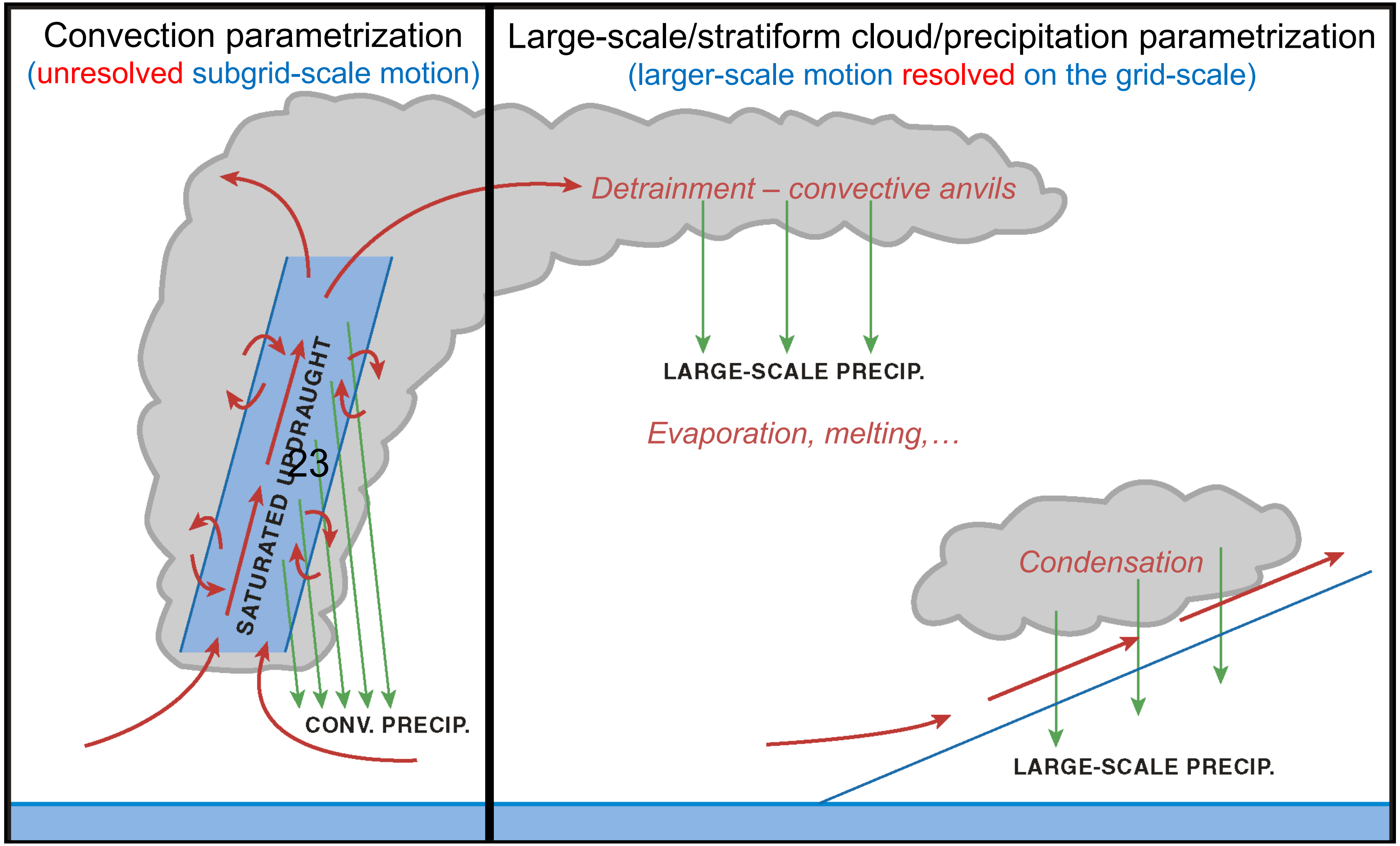
Single-moment bulk scheme

- 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



Convective surface precip Rain and Snow (CP)

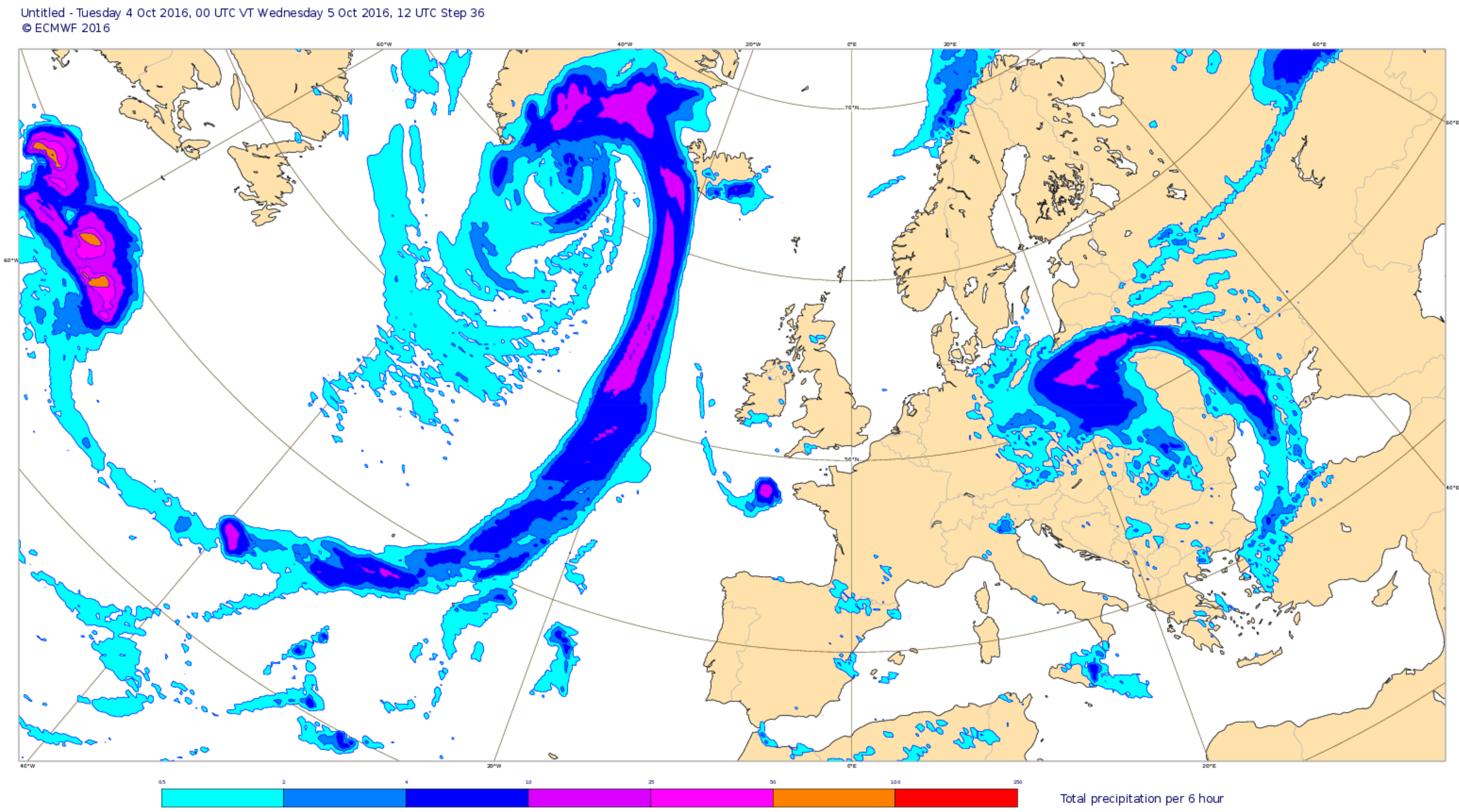
"Large-scale" surface precip Rain and Snow (LSP)
Cloud cover (TCC, HCC, MCC, LCC)

One grid box

Cloud and convection

Example 6 hour precipitation accumulation

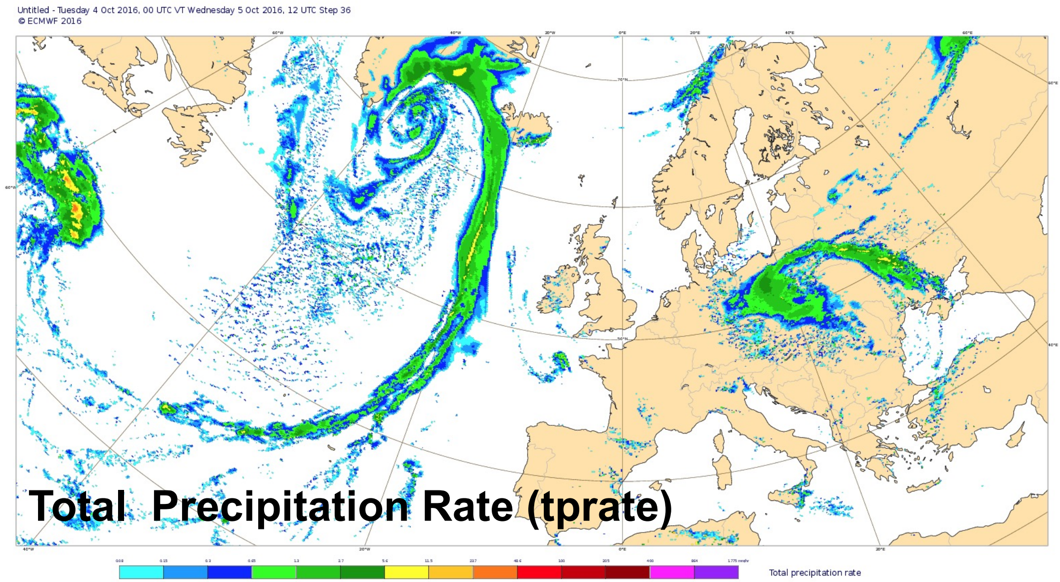
Forecast for Wed 5 October 2016

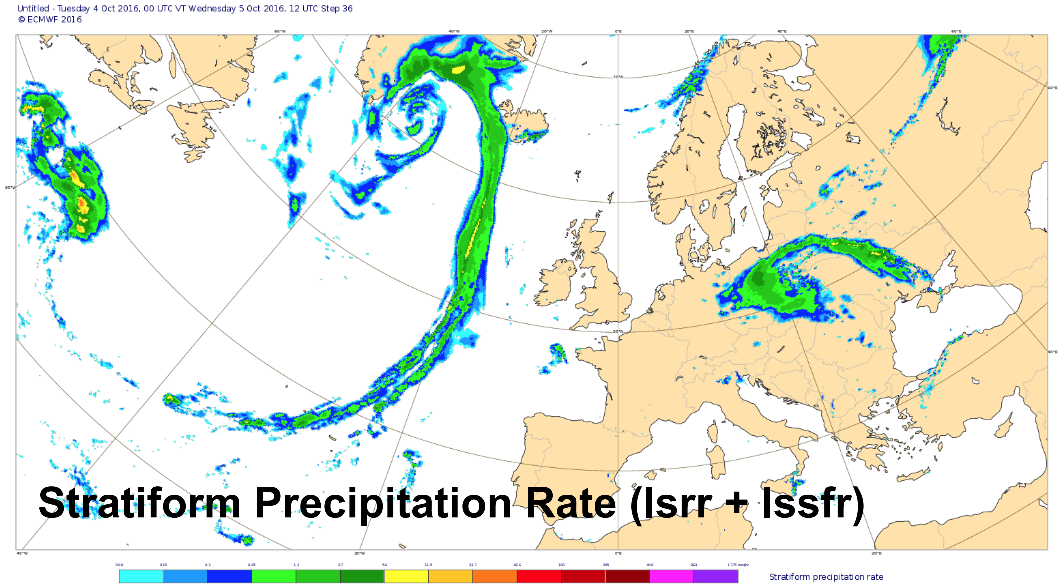


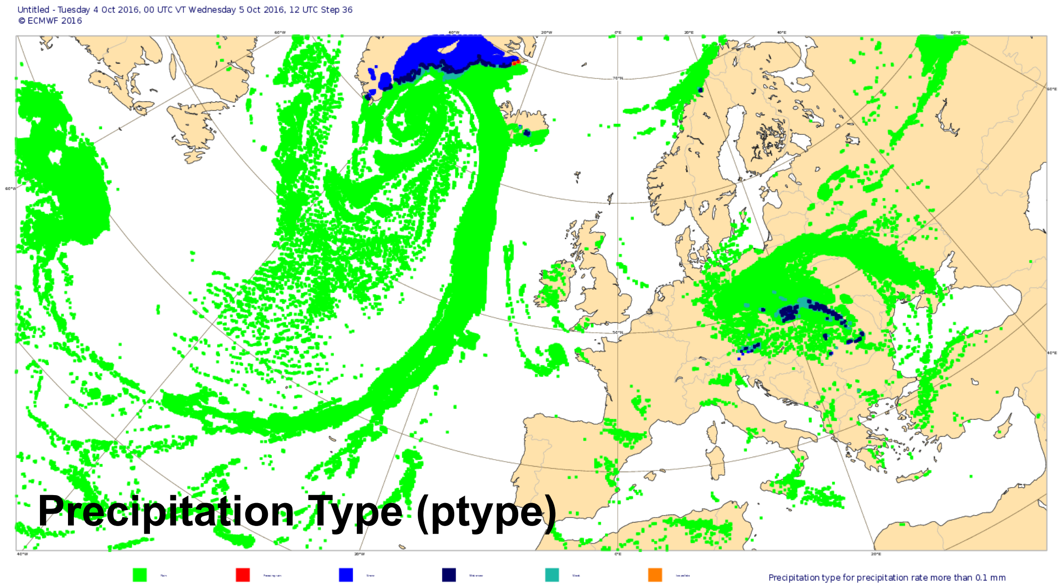
Precipitation Accumulation: Large-scale rain + convective rain + large-scale snow + convective snow

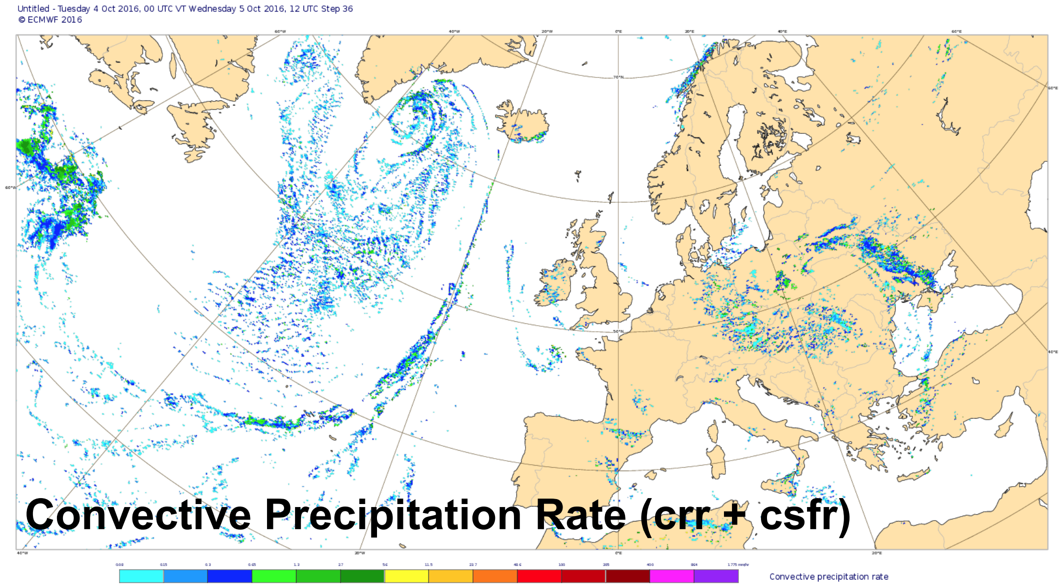
Cloud and convection

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









Orographic drag

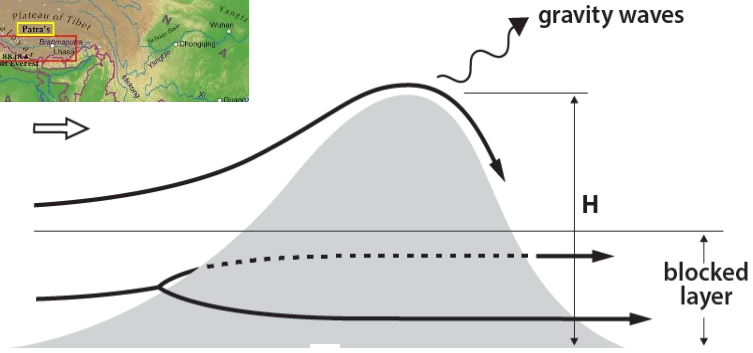
Subgrid drag (stress) mechanisms in the ECMWF model

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.

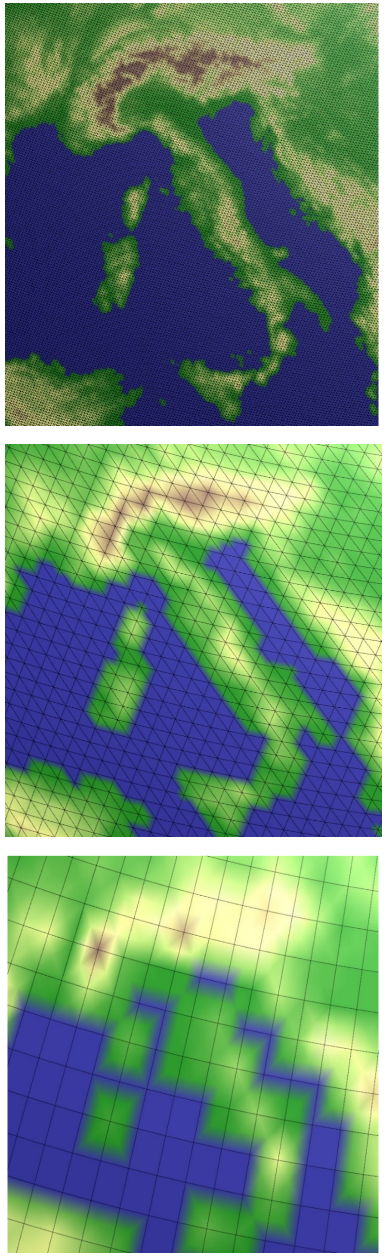
Scales larger than 5 km



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

Orography



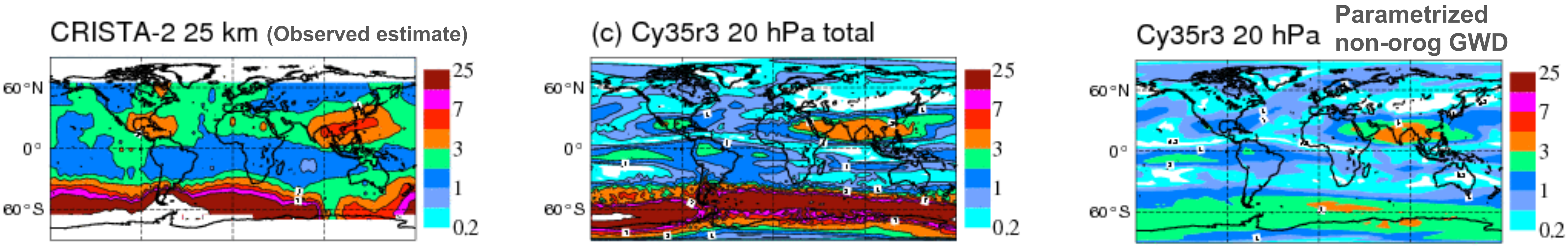
9 km

50 km

125 km

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)



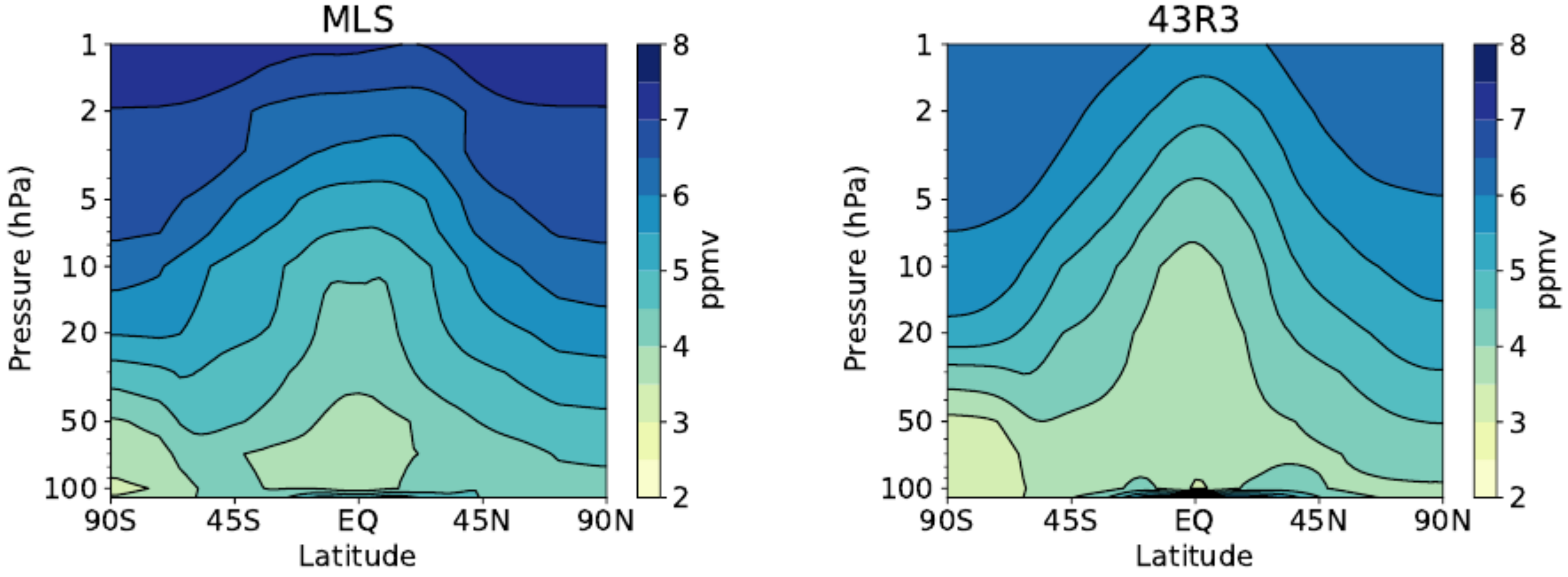
Comparison of observed (left), total resolved+parametrized orog+non-orog (centre) and parametrized non-orog (right) gravity wave momentum flux (mPa) for 8-14 August 1997. Observed values are for CRISTA-2 (Ern et al. 2006).

Methane Oxidation

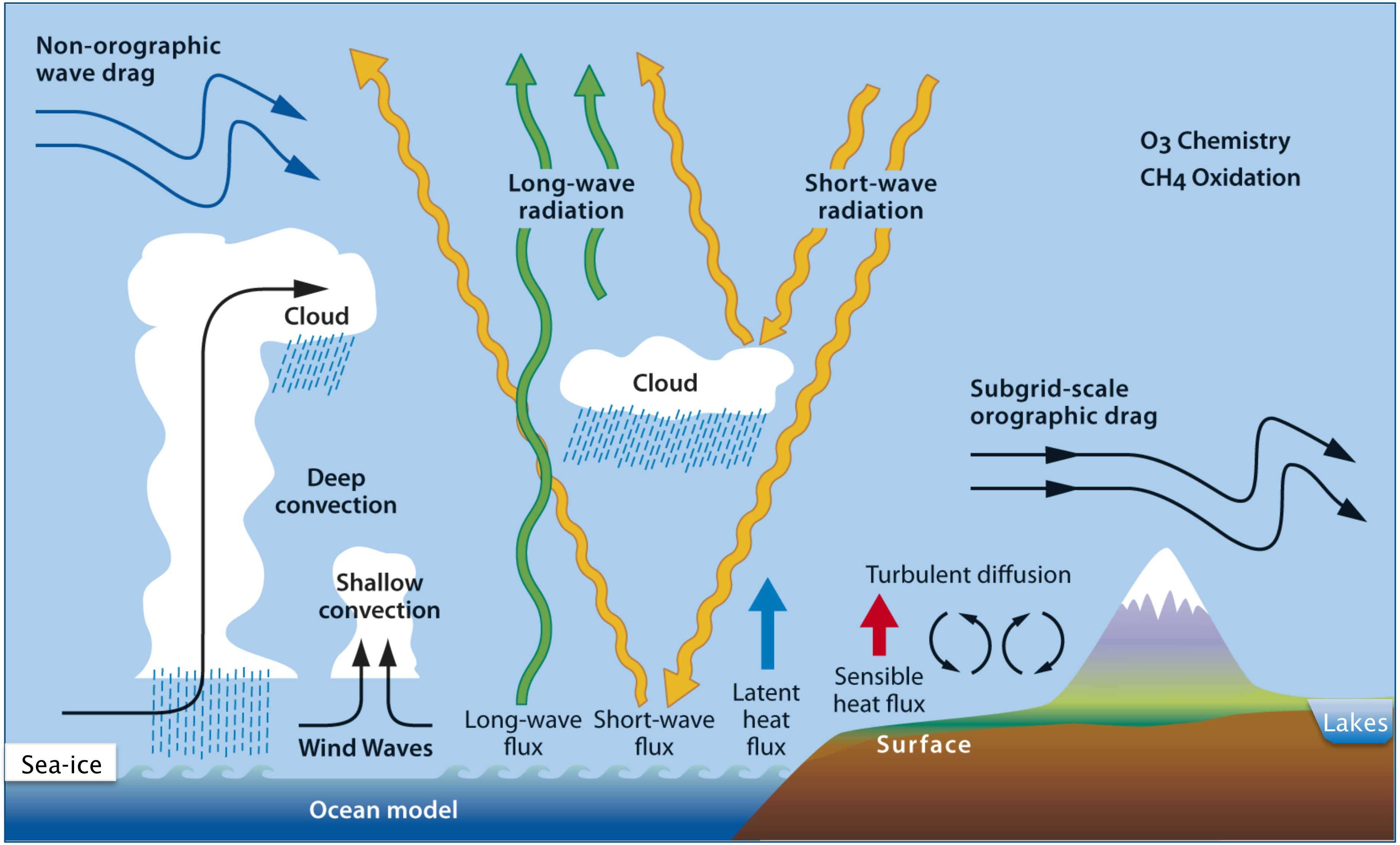
Stratospheric water vapour and methane oxidation

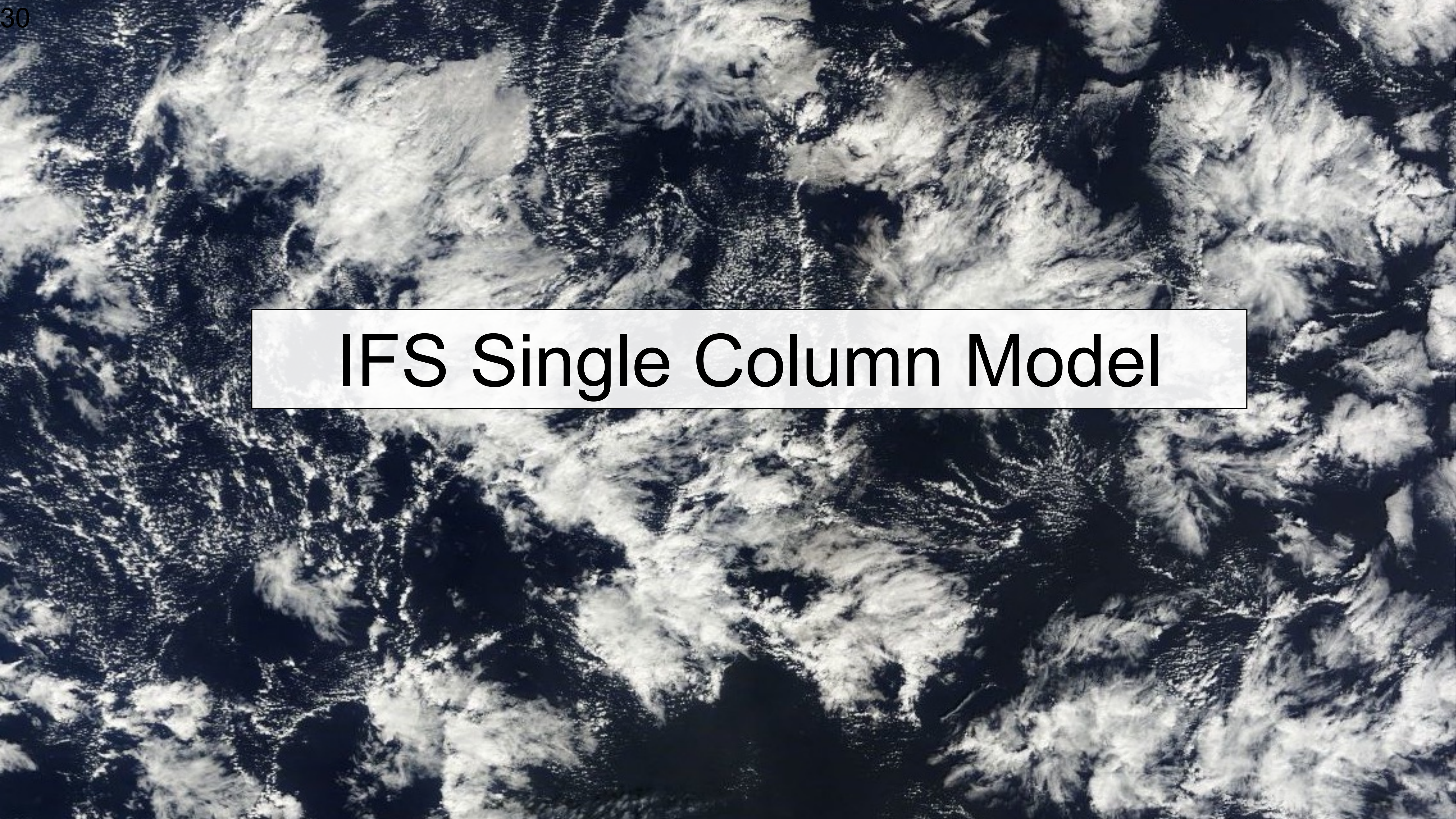
- Source of water vapour in the mid-to-upper stratosphere, transported by Brewer-Dobson circulation
- Parametrized based on the assumption that methane+water vapour is approximately constant at these altitudes
- Methane, and therefore water vapour, in the stratosphere have been gradually increasing over recent decades
- IFS Cy43r3 has a 15% underestimate compared to recent observations (increased in Cy45r1 & later)

Zonal mean annual mean cross section of stratospheric water vapour from the Microwave Limb Sounder (MLS and IFS Cycle 43r3)



Parameterized processes in the ECMWF model

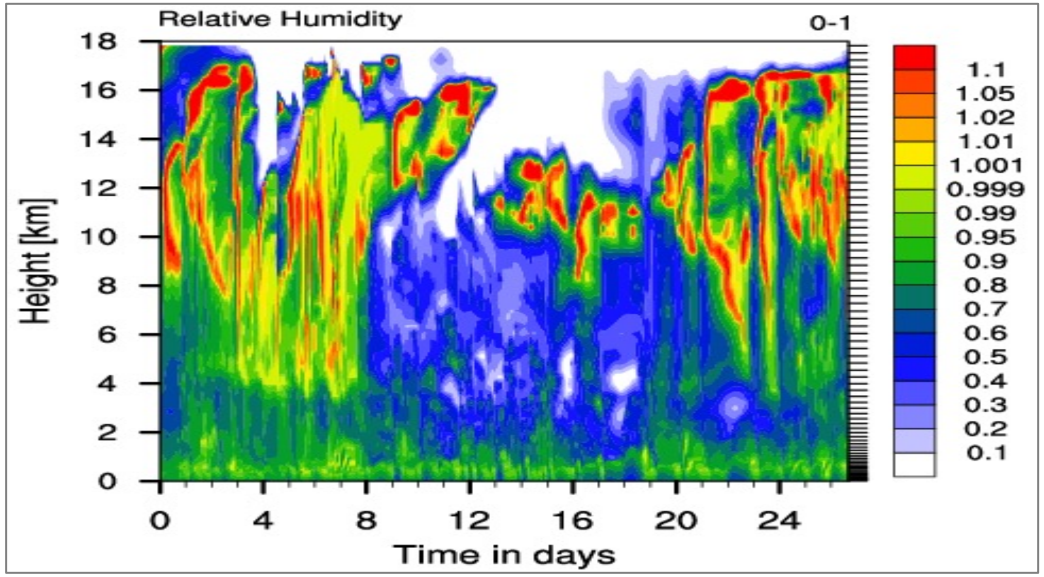




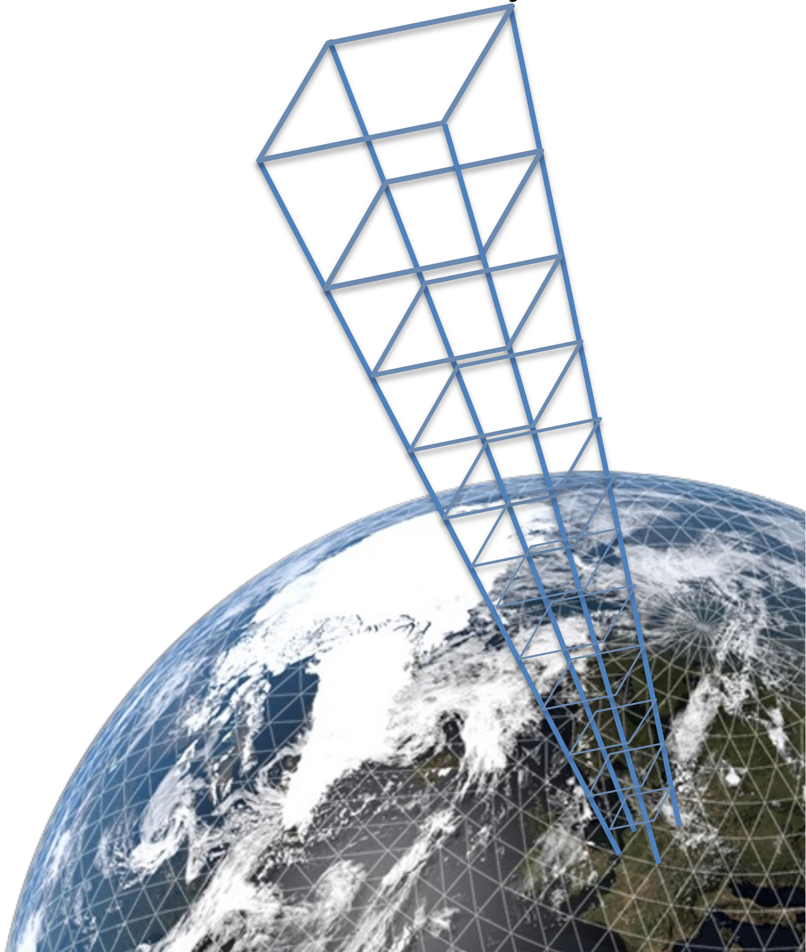
IFS Single Column Model

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
- Last OpenIFS SCM release was Cy43r3. Now updated to Cy48r1



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

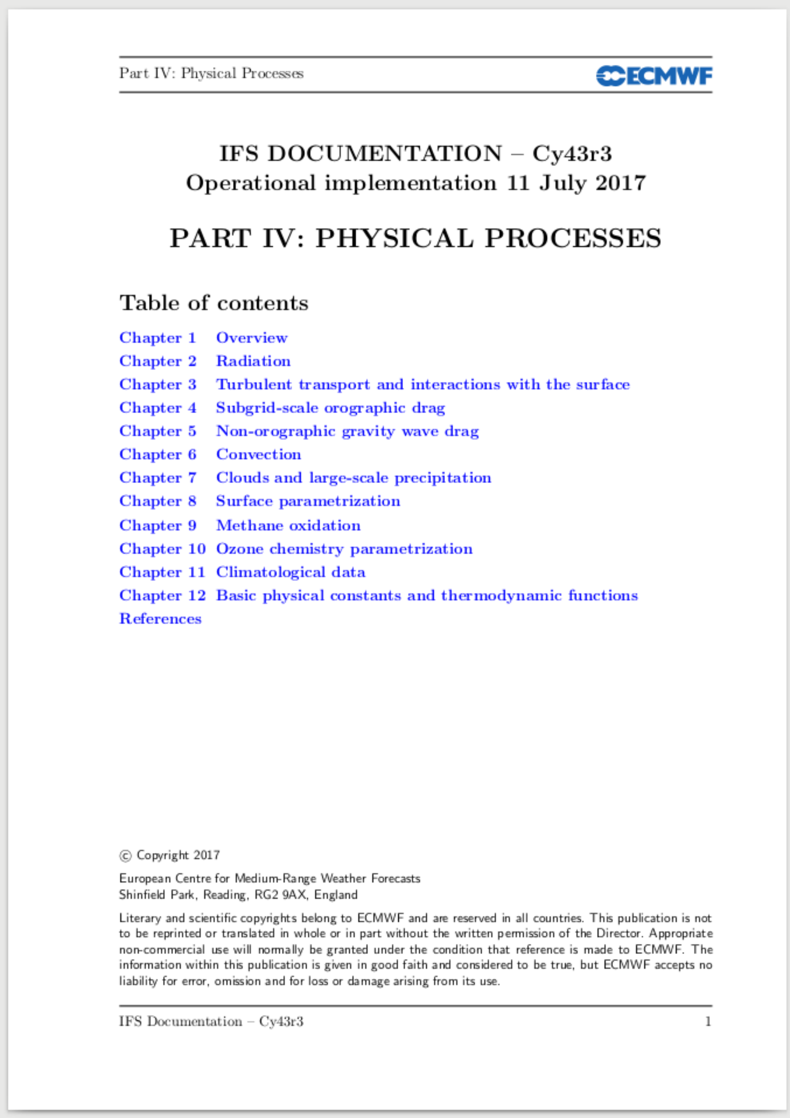
- Overview description of IFS model
  https://www.ecmwf.int/en/research/modelling-and-prediction
  https://confluence.ecmwf.int/display/OIFS/OpenIFS+User+Guide

- IFS Documentation (Cy43r3 & Cy48r1– 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

Table of contents

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