Progress on ecRad radiation in Météo-France and ACCORD models

Sophia Schäfer [1], Robin Hogan [2,3], Marie-Adèle Magnaldo [1],
Ole Lindberg[4], Emily Gleeson[5]

1 Centre National de Recherches Météorologiques CNRM (Météo-France, CNRS),

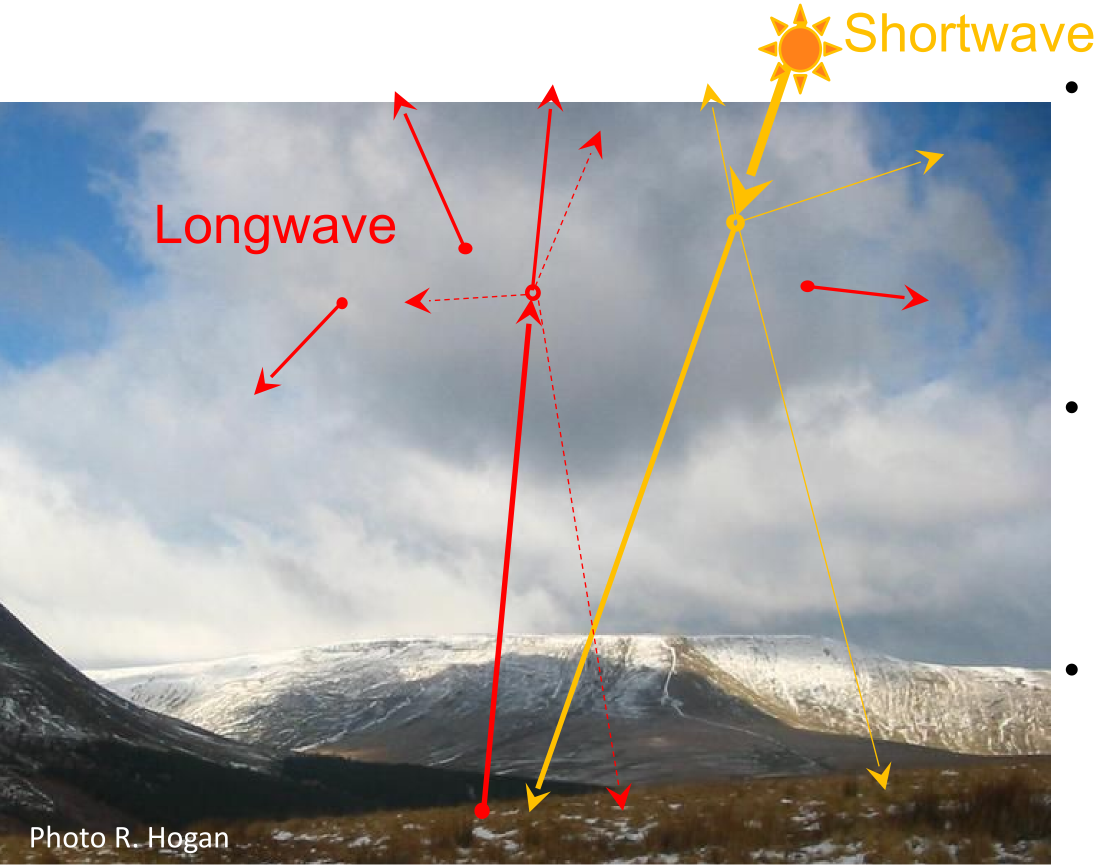
2 European Centre for Medium-Range Weather Forecasts, 3 University of Reading, 4 Danish Meteorological Institute

5 Met Éireann

Overview

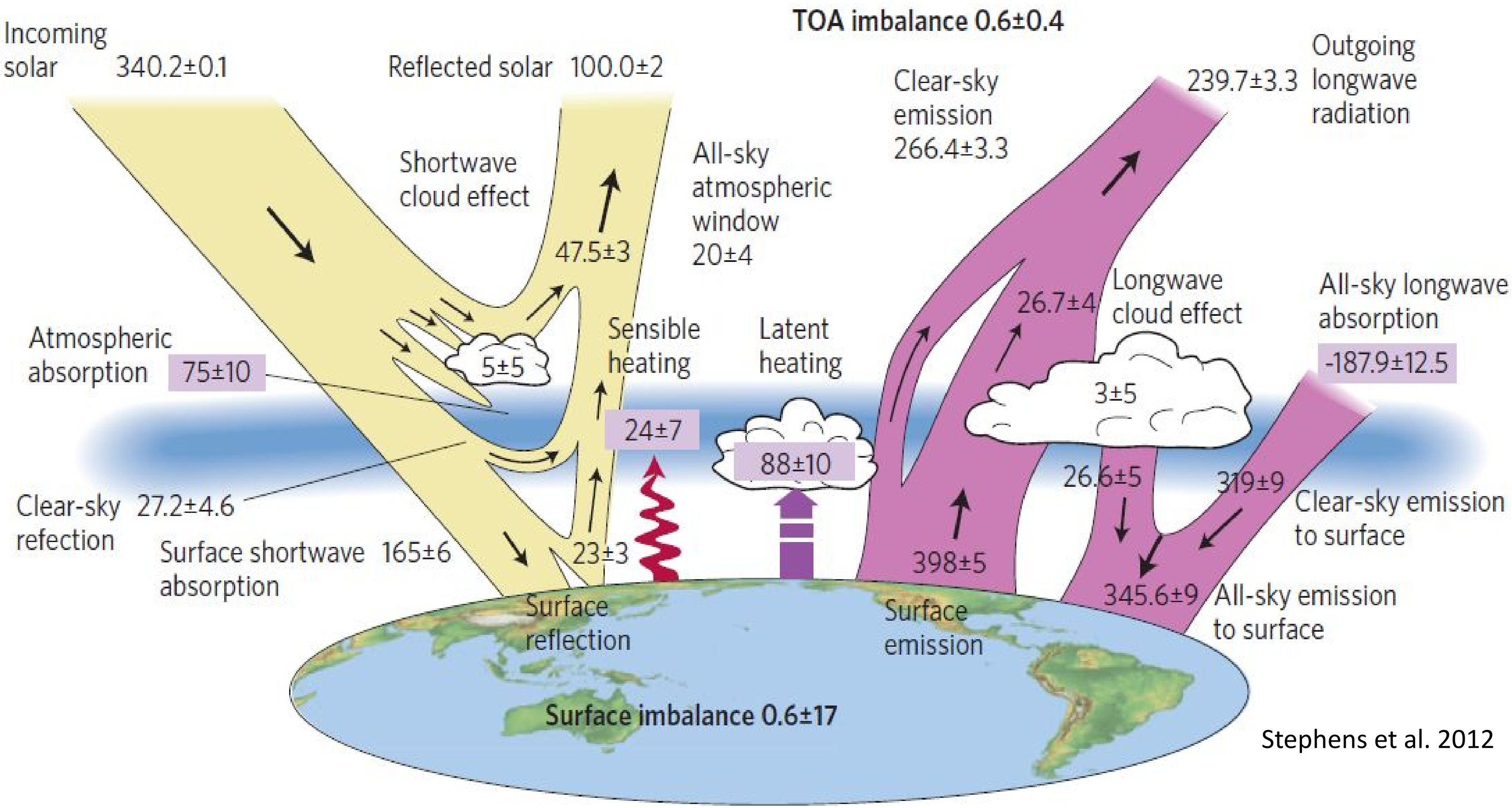
- Radiation: sources and impact
- Radiation scheme ecRad
- Status of ecRad in AROME, HARMONIE-AROME
- Options: cloud geometry and 3D effects
- Previous sensitivity tests on radiation options
- Case study: missing cloud, 04.02.2025
- Research project on 3D effects in mountains
- Summary

Radiation sources



- Photons emitted by sun (visible/shortwave) and Earth system (infrared/longwave) interact with surface, atmospheric gases, aerosol, cloud water or ice particles
- Described by electromagnetic **Maxwell equations** and quantum mechanics, BUT can‘t treat every photon and atmospheric particle!
- Have to capture bulk effect of each component - simplifications for practical calculation

Radiation budget drives climate and weather



Stephens et al. 2012

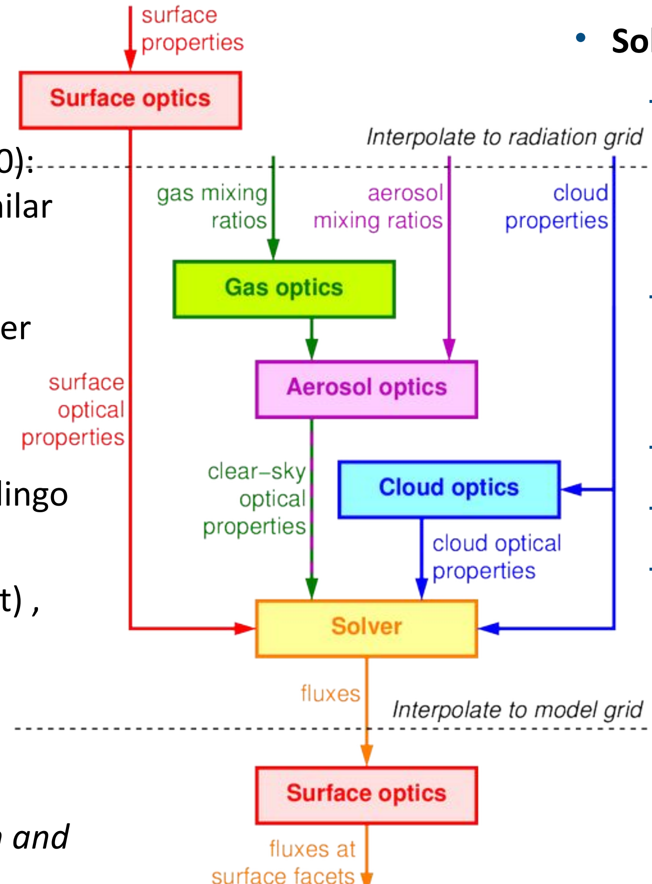
Models tuned to top-of-atmosphere radiative fluxes (directly observable), ideally bias < 1W/m²

New modular radiation scheme ecRad (Hogan & Bozzo 2018)

- **Gas optics:**
  - RRTMG (Iacono et al. 2008)
  - ecCKD (Hogan & Matricardi 2020): Fewer spectral intervals but similar precision
- **Aerosol optics:** variable species number and properties (set at run-time)
- **Cloud optics:**
  - **liquid:** SOCRATES (MetOffice), Slingo (1989), Mie calculation
  - **ice:** Fu 1996, 1997, 1998 (default) , Yi et al. 2013, Baran et al. 2014, Baum et al. 2014

From ecRad 1.6: user can choose hydrometeor number + add optics

- *Surface: Consistent treatment of urban and forest canopies*



- **Solvers** for radiative transfer equations:
  - **McICA** (Pincus et al. 2003), **Tripleclouds** (Shonk & Hogan, 2008) or **SPARTACUS** (Schäfer et al. 2016, Hogan et al. 2016)
  - SPARTACUS makes ecRad the only global radiation scheme that can do sub-grid **3D** radiative effects
  - Longwave scattering optional
  - Can configure **cloud overlap**
  - **Cloud inhomogeneity**: can configure width and shape of PDF

ecRad 1.6 operational in ARPEGE, AROME Meso-NH: update in progress

Namelist parameters for ecRad in AROME

All ecRad parameters are explained in the user guide:
https://confluence.ecmwf.int/download/attachments/70945505/ecrad_documentation.pdf?version=4&modificationDate=1584914933898&api=v2

&NAERAD #radiation parameters for all schemes, still being tested

Needed for ecRad (?):

LAER3D=.TRUE., # => using 3D or real-time aerosols? Might be important?

LUSEPRE2017RAD=.FALSE., # => To use ecRad

LRRTM=.TRUE., # => To use ecRad

LSRTM=.TRUE.,# => To use ecRad

NAER=0, # Aerosol option, used, 1 by default, 0=no aerosols

NRADFR=18, # Variable for intermittent

NAERMACC=1, # CAMS aerosol, needed

NOZOCL=4, # Ozon climatology choice

NSW=6, # No. of shortwave bands, somethingg funny happening...

RRE2DE=0.64952, # Geometrical factor for hexagonal particles, not sure if needed

Not used in ecRad ?:

NDUMPBADINPUTS=0, ??

NICEOPT=3, # Ice option, Internal for old scheme

NLIQOPT=2, # Liquid option, Internal for old scheme

NMCICA=1, # old scheme, hopefully

NOVLP=1, # Overlap - not needed

NRADIP=3, # effective radius size ice particle, probl. not used

NRADLP=2, # effective radius size liquid particle, prob. not used

RLWINHF=1, # Longwave inhomogenity, old scheme, spp-patterns ensemble

RSWINHF=1, # Shortwave inhomogenity, old scheme, spp-patterns ensemble

&RADIATION # ecRad parameters

Iverbose=1, # from 1 to 5

Iverbosesetup=3, # highest is 5

directory_name=".", # can change

do_clear=.TRUE., # clear sky and all sky calculations if TRUE

do_save_radiative_properties =.FALSE., # default FALSE

do_save_spectral_flux =.FALSE., # goes into seperate file, for debugging...

do_save_gpoint_flux=.FALSE., # as above, a lot of data

do_surface_sw_spectral_flux =.TRUE., # for spectral coupling to the surface

use_aerosols=.TRUE., # FALSE: all aerosol input ignored, should always be TRUE?!

do_lw_derivatives=.TRUE., # Diagnostic, set to FALSE?

gas_model_name='RRTMG-IFS', # Other options in user guide, only in offline ecRad

cloud_mixing_ratio_threshold=.100E-08, # less water than this then considered no cloud

cloud_inhom_decorr_scaling= 1.00, # same vertical decorrelation scale for cloud edges and cloud internal inhomogenity

cloud_fraction_threshold= .100E-05, # if less than this then no cloud

use_beta_overlap= .FALSE., # not using beta -> then using alpha overlap, default

liquid_model_name='Nielsen', #needs the .nc file provided in data folder

ice_model_name='Fu-IFS', # Operational option, other might be better

do_fu_lw_ice_optics_bug=.FALSE., # There was a bug in the IFS, can be reproduced if you want

overlap_scheme_name='Exp-Ran', # Most sensible choice, IFS used a different one

sw_solver_name='McICA', # Shortwave solver , McICA is the operational one

lw_solver_name='McICA', # Longwave solver, possible to use different from SW but need a reason

do_sw_delta_scaling_with_gases=.FALSE., # FALSE: only cloud particles, TRUE: also with gases

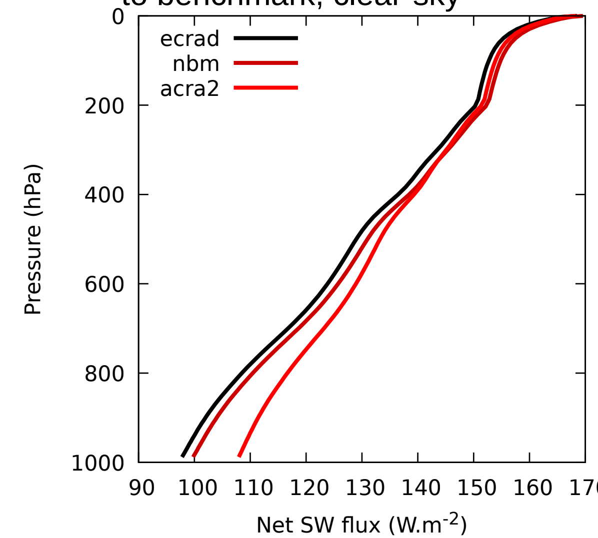
do_lw_cloud_scattering=.FALSE., # TRUE: more expensive, better, but more cost for small benefit

do_lw_aerosol_scattering=.FALSE., # benefit of TRUE is even smaller than for the cloud scattering

ecRad radiation + aerosol status in AROME/ARPEGE, tests in ALARO

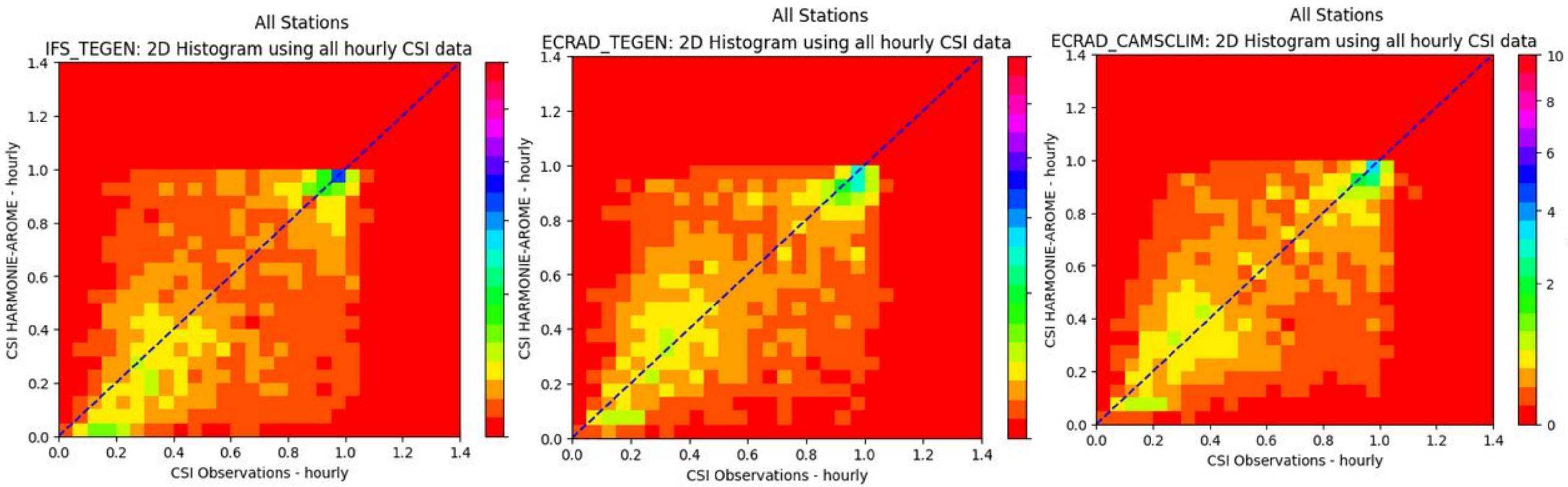
<table>
<tr><td></td><td colspan="3">OPER (CY48T1)</td><td colspan="3">E-SUITE (CY49T1)</td></tr>
<tr><td></td><td>SW</td><td>LW</td><td>Aerosols</td><td>SW</td><td>LW</td><td>Aerosols</td></tr>
<tr><td>AROME</td><td rowspan="2">ecRad (SRTM McICA)</td><td rowspan="2">ecRad (RRTM McICA)</td><td>CAMS 3D clims (11 var)</td><td rowspan="2">ecRad (SRTM McICA)</td><td rowspan="2">ecRad (RRTM McICA)</td><td rowspan="2">CAMS 3D clims (11 var)</td></tr>
<tr><td>ARPEGE</td><td>Tegen 2D clims (6 var)</td></tr>
</table>

Comparison ecRad, ACRANEB2 to benchmark, clear-sky



- Tests of near-real-time CAMS aerosol for CY49T1_op : improvements for dust outbreaks, ongoing work by Salomé Antoine
- Tested ecRad versus ACRANEB2 in ALARO (with Ján Mašek, CHMI, visit October 2024): ecRad much better for clear-sky (better gas optics), ACRANEB2 frequent cloud-only updates might be an interesting idea
- Ongoing work on reduced radiation grid (with Ole Lindberg, DMI, Balthasar Reuter, ECMWF, Fabrice Voitus, MF) and on ecRad GPU port (with MF and ECMWF colleagues)

Radiation tests in HARMONIE-AROME (Emily Gleeson, Met Éireann)



Comparison of clear-sky index $=F/F_{clear}$ PDF in HARMONIE-AROME to observations with old IFS radiation scheme and ecRad, Tegen / CAMS aerosols (Emily Gleeson)

- First test: ecRad improves CSI PDF agreement with observations, using CAMS might further improve it; Agreement at CSI = 1 gets a bit worse

- → Further tests with ecRad, ecRad options, cloud and aerosol options in AROME and HARMONIE-AROME,
- Evaluate more meteorological variables

Options: Radiation solvers and sub-grid cloud geometry

Simplify by treating **only vertical** dimension explicitly.

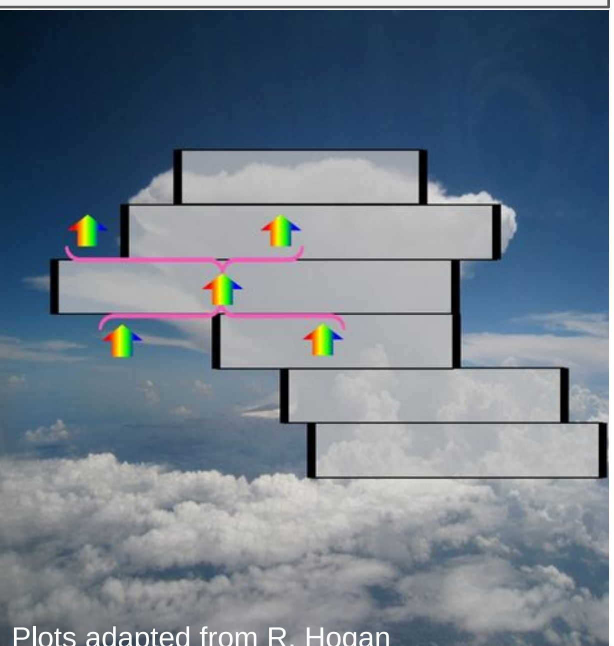
Deterministic:

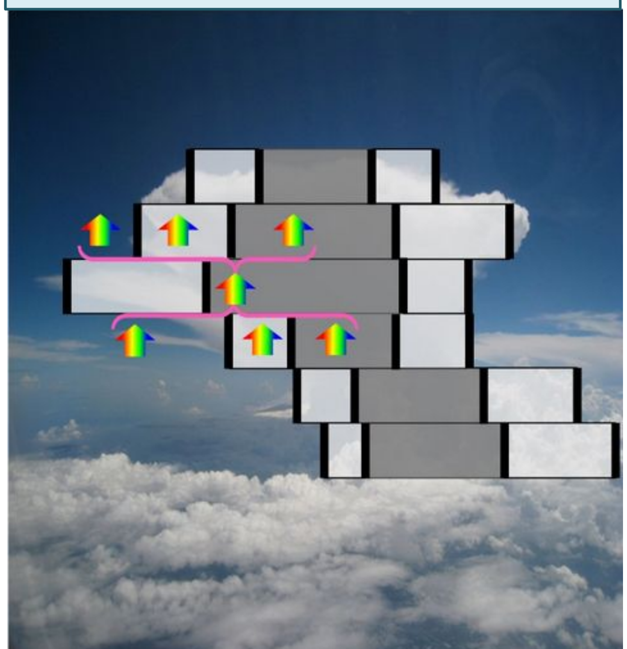
Two-stream solver: solve in **cloudy / clear regions**, partition at layer boundaries according to **overlap**

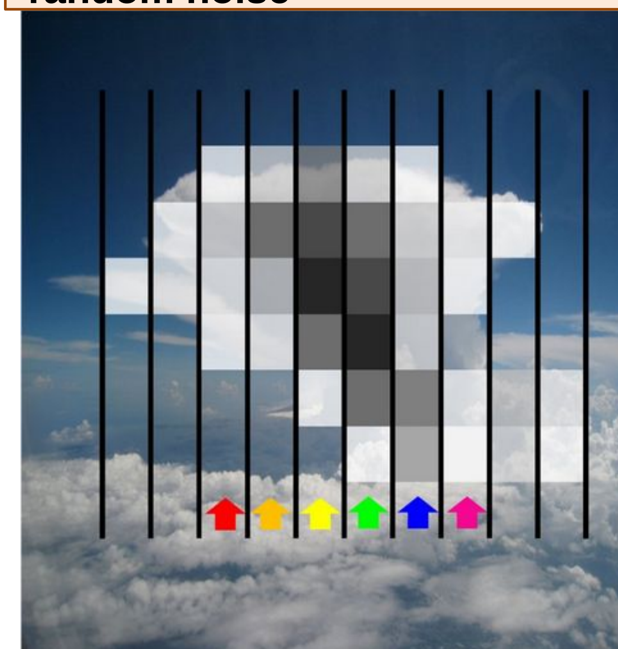
Tripleclouds/SPARTACUS (ecRad)**:** similar; 3 regions: **clear, thin cloud, thick cloud** cloud **inhomogeneity**

Stochastic:

McICA (ecRad)**:** draw **random clouds in sub-columns** for overlap + inhomogeneity; **distribute spectral intervals** in 1 sub-column each **fast, random noise**

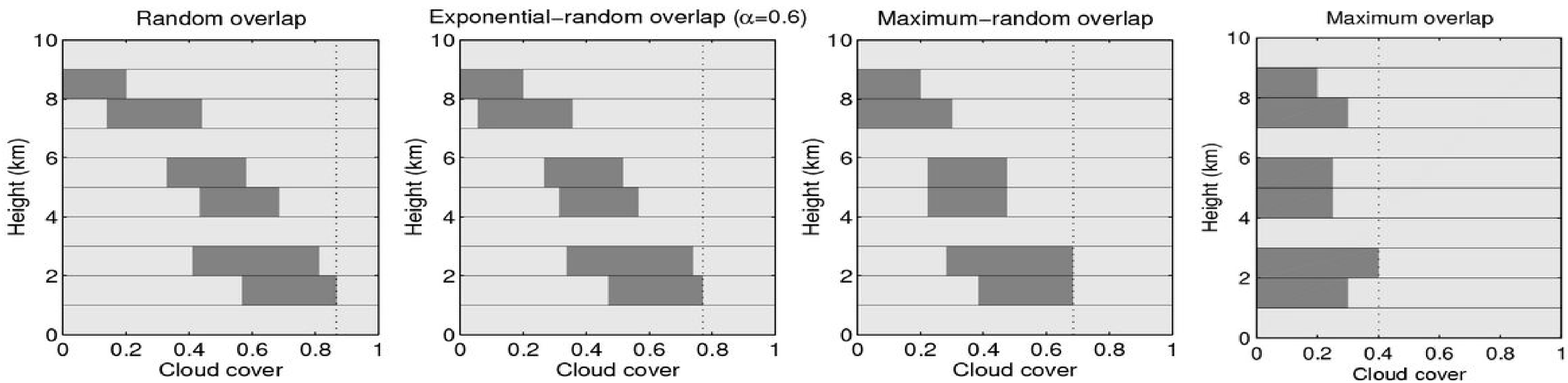






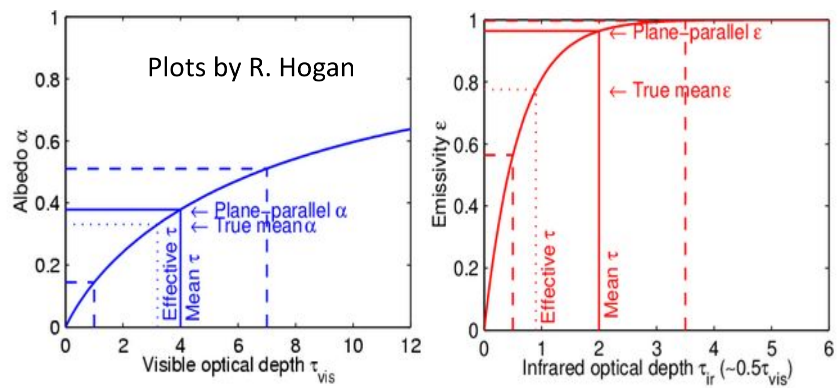
Plots adapted from R. Hogan

Cloud geometry uncertainties

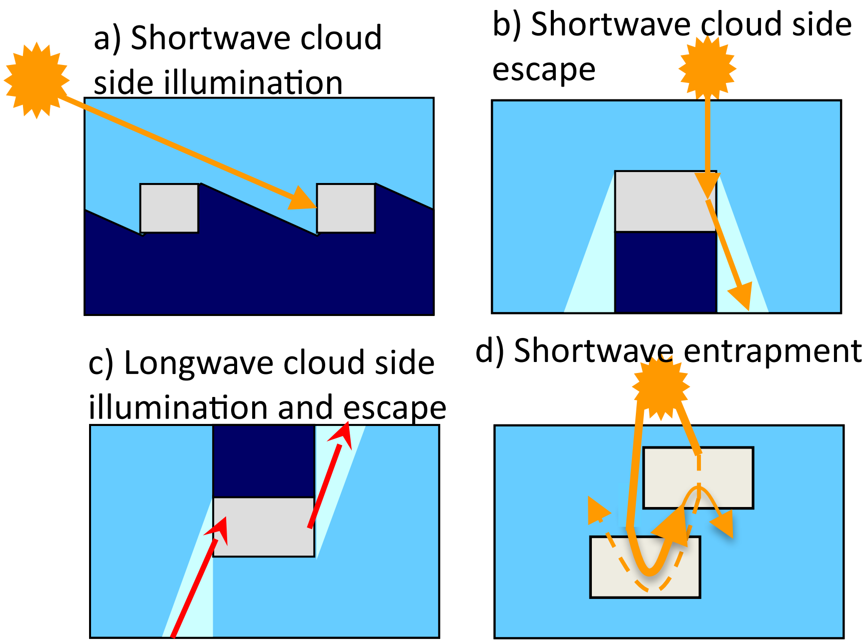


Adapted from Hogan & Illingworth 2000

- For given layer clouds, **cloud overlap** decides total cloud cover
- Observations: **exponential-random overlap,** decorrelation length 2 km (Hogan & Illingworth 2000) to 100-600 m (Neggers et al. 2011) - **Should depend** on cloud type
- Reflectivity and longwave emissivity **non-linear functions** of optical depth: need **horizontal cloud variability** (fractional standard deviation FSD = standard deviation / mean optical depth)
- Should also depend on cloud type, resolution



3D cloud effects



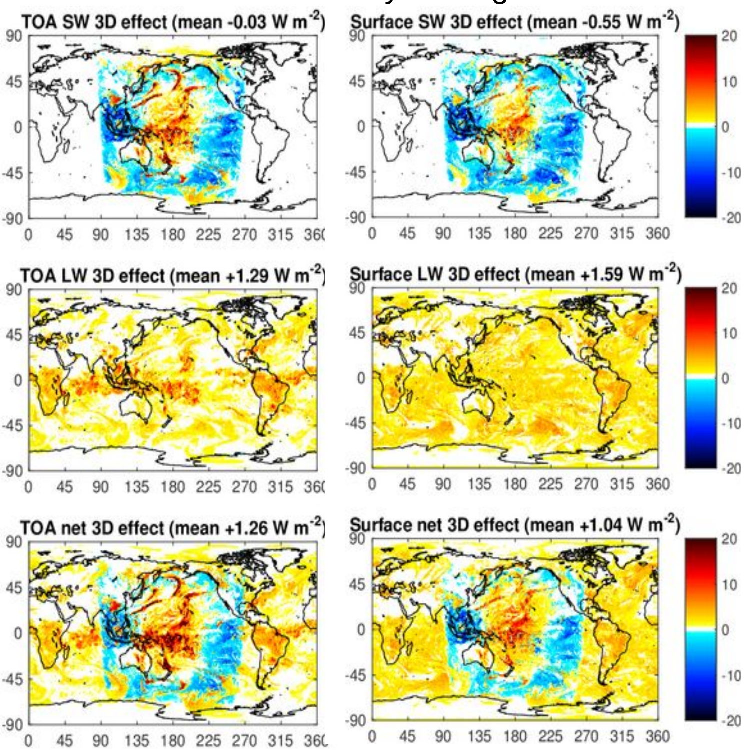
- **Shortwave cloud side illumination** increases cloud reflectivity, **cloud side escape** decreases cloud reflectivity
- **Longwave cloud side illumination and escape** increase cloud effect
- **Shortwave entrapment** decreases cloud reflectivity
- Similar effects at complex surfaces (trees / mountains / buildings)
- **Usually neglected, SPARTACUS** solver in ecRad can treat them (Schäfer et al. 2016, Hogan et al. 2016, 2019), cost x4

Further uncertainties: cloud optics (especially ice), surface coupling: albedo, emissivity, one- or multi-level
Cloud and aerosol input

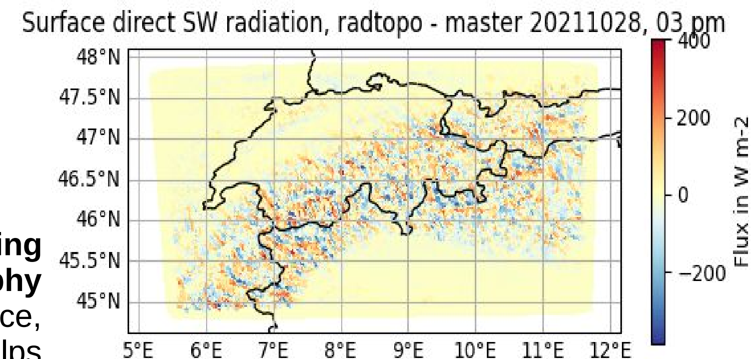
3D radiation in NWP / climate models

- Current AROME: cloud and vegetation 3D effects ignored; ORORAD corrections for 3D orography slope angle, shadowing, longwave skyview switched of due to bias (Rontu et al. 2016)

Instantaneous 3D cloud effects in Era5 field, 01.04.2000 0 UTC. Plots by R. Hogan



3D effects of **including shadowing by orography** on SW direct flux at surface, in ICON model, western Alps



- SURFEX: Mountain treatment with slopes for skyview (M.Lafaysse, I. Gouttevin et al.), NOT energy conserving when coupled to atmosphere; Buildings / vegetation: SPARTACUS coupled to TEB urban scheme (Schoetter et al 2024)
- In ecRad: SPARTACUS (Schäfer et al. 2016, Hogan et al. 2016, 2019) approximates sub-grid; depends on good geometry estimates
- Global 3D cloud effects: 1 W/m² (Hogan et al. 2019), partial compensations; some SPARTACUS biases in LW (ongoing work)
- Resolved 3D approximation POMART3D (R. Hogan, ECMWF, ongoing): tilted column + layerwise diffusion, ready for first testing

Impact of radiation options on radiation fluxes

Global ICON, Δx=40 km, 1y, TOA net down;
Each cell mean bias, RMSE vs. CERES-EBAF

	1y 2020, SW	1y 2020, LW	1y 2020, clc (uncertain)
rrtm	1.78, 11.7	2.9, 6.51	-5.12, 9.15
ecrad	-0.0261, 9.18	-1.27, 5.65	-6.61, 9.95
lwscat	-0.11, 9.0	0.735, 5.41	-6.65, 10.0
tripleclouds	1.29, 8.92	-1.26, 5.38	-6.57, 9.84
SPARTACUS 3D	7.0, 11.3	2.48, 7.54	-5.86, 9.49
Slingo liquid	-0.452, 9.41	-0.341, 5.29	-6.07, 9.54
Baran 2016 ice	-1.4, 9.31	-1.04, 5.12	-6.69, 9.93
max-ran	1.61, 9.06	-1.87, 5.77	-6.69, 10.0
decorr 1000m	-1.89, 9.61	-0.575, 5.24	-6.67, 9.93
decorr param	0.538, 8.74	-1.39, 5.66	-6.68, 10.0
FSD 0.7	-3.16, 10.2	-0.0685, 5.44	-6.31, 9.81
FSD 1.4	4.52, 10.1	-3.1, 6.43	-7.05, 10.4
FSD param	1.26, 8.64	-1.4, 5.53	-6.66, 10.0

- Most radiation parameters only have small impact – larger uncertainty due to clouds
- Sensitivities fairly robust between models / height / runtimes, but errors vary wildly over cloud types

	ecRad	+Exp	+Max	+FSD	+Slingo	+SOCRATES
Biais	22.2/29.3	22.5/29.7	22.5/29.8	18.6/26.0	22.1/29.1	21.9/28.9
RMSE	71.8/109.3	71.9/109.4	71.9/109.5	71.7/109.4	71.8/109.5	71.6/109.1
SDE	68.2/105.3	68.3/105.3	68.3/105.3	69.2/106.2	68.4/105.3	68.2/105.2

	+Yi	+Tripleclouds	+SPARTACUS	+ k
Biais	20.7/28.1	23.6/30.7	23.6/30.6	29.5/37.2
RMSE	70.5/108.7	72.7/110.2	72.7/110.2	73.7/111.2
SDE	67.4/105.0	68.7/105.7	68.7/105.8	67.5/104.8

SW downward flux errors at surface in AROME Cy48t1 24h-forecasts for February / August 2020 (above) and February bias (SDE) by cloud type (below); Magnaldo (2024)

	CR0	CR1	CR2	CR3	CR4	CR5	CR6	CR7
ecRad	-18 (46)	-18 (64)	43 (91)	29 (58)	-4 (61)	38 (71)	18 (79)	21 (66)
+Exp	-18 (49)	-16 (63)	45 (66)	29 (59)	-2 (62)	38 (72)	17 (79)	21 (66)
+Max	-19 (49)	-16 (63)	47 (73)	29 (59)	-3 (62)	38 (71)	18 (79)	21 (67)
+FSD	-25 (50)	-25 (66)	46 (80)	28 (59)	-9 (65)	35 (71)	11 (80)	16 (67)
+Slingo	-20 (51)	-16 (63)	48 (96)	29 (60)	-1 (62)	37 (71)	17 (78)	21 (67)
+SOCRATES	-18 (47)	-19 (64)	36 (88)	29 (59)	-4 (61)	37 (70)	17 (78)	21 (67)
+Yi	-18 (47)	-18 (61)	36 (64)	31 (60)	-7 (60)	36 (70)	18 (79)	17 (63)
Tripleclouds	-16 (47)	-16 (64)	46 (74)	29 (59)	-1 (62)	37 (72)	20 (80)	24 (67)
SPARTACUS	-16 (48)	-16 (65)	45 (74)	29 (59)	-0 (62)	36 (71)	20 (80)	24 (67)
+k	-2 (40)	2 (64)	52 (77)	30 (60)	10 (61)	38 (71)	32 (77)	31 (66)

RÉPUBLIQUE FRANÇAISE

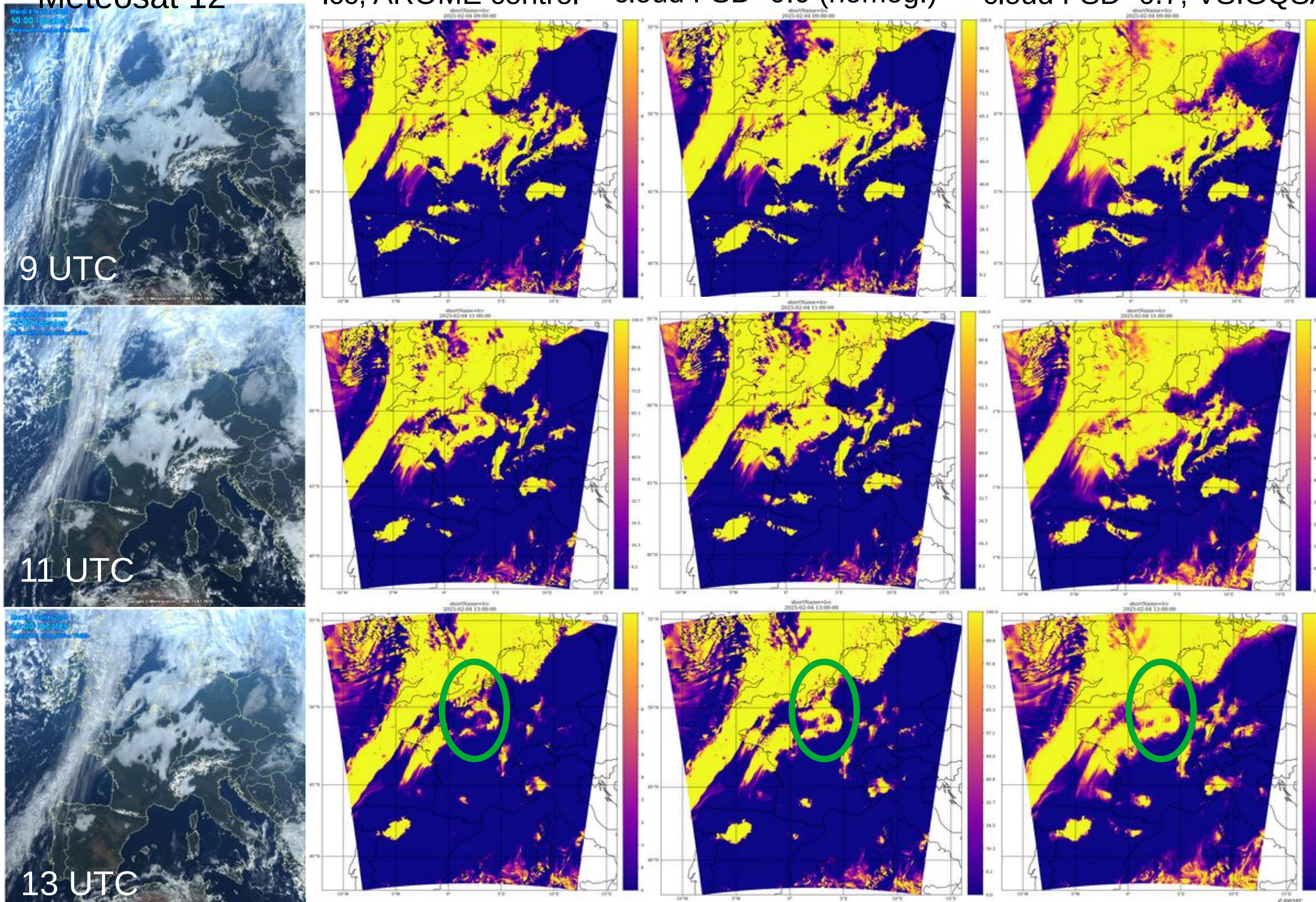
METEO FRANCE

cnrs

CNRM

Case study: missing low cloud in AROME, 04.02.2025

Meteosat 12 | lcc, AROME control | cloud FSD=0.0 (homog.) | cloud FSD=0.7, VSIGQSAT=0.05

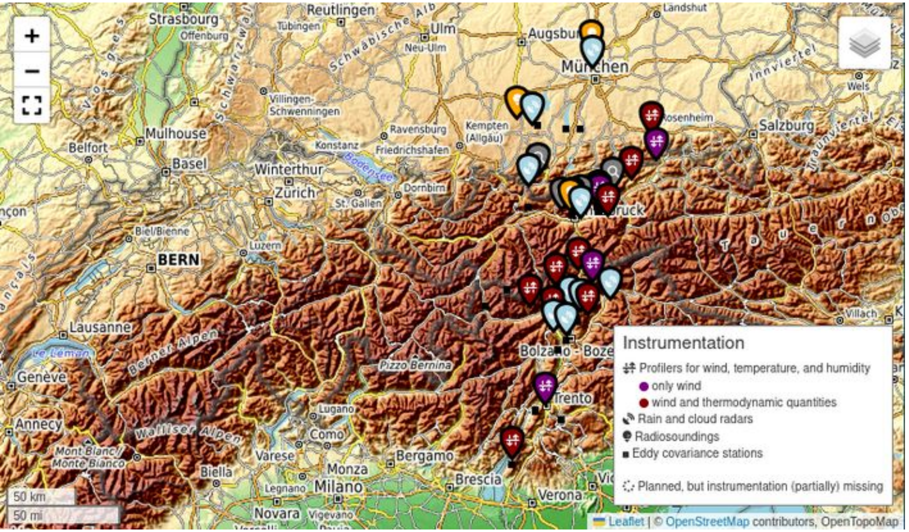


- Reducing cloud fractional standard deviation (FSD) increases the cloud radiative effect, delays afternoon cloud dispersal a bit
- Even with FSD=0, clouds still disperse too quickly
- Best : FSD 0.7 + VSIGQSAT=0.05 (from Sébastien Riette, increases cloud PDF width, de Rooy et al. 2010)

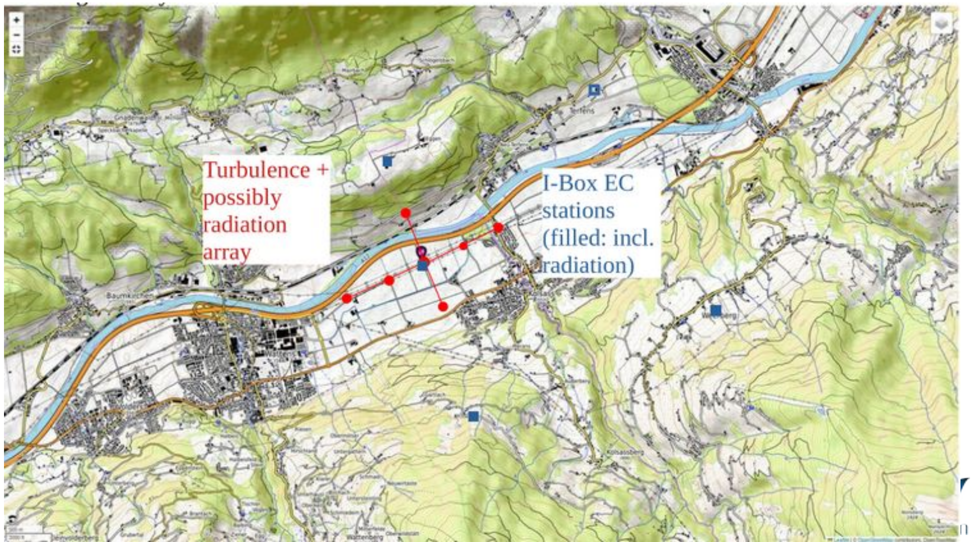
Planned AMCoM project on 3D physics in mountains

- Investigate 3D versus 1D model physics (radiation, turbulence, surface interactions) at high resolution in complex terrain, with Geosphere Austria, Uni Innsbruck, LEGI
- Use and develop 1D and 3D physics options in AROME and Meso-NH
- In TEAMx project (https://www.teamx-programme.org): Sept. 2024 – Sept 2025 with focus on complex terrain, energy fluxes, boundary layer, summer EOP 16 June – 25 July 2025: radiation obs array planned in Inn Valley (incl. CNRM instruments from CNRM)
- Improve current treatment for 3D mountains, test 3D cloud schemes in AROME / Meso-NH

Planned instrument locations in TEAMx campaign



Planned array in Inn Valley



Summary

- ecRad operational in AROME, available in HARMONIE-AROME and ALARO
- Sensitivity tests: some uncertainty in cloud geometry, ice, even more in cloud input
- In HARMONIE-AROME, ecRad improves CSI, so do CAMS aerosols
- 3D radiation: mountains: ORORAD (AROME); clouds / vegetation: SPARTACUS sub-grid 3D, ongoing work on POMART3D for resolved 3D

- Ongoing: evaluation, optimisation of settings, consistency with other parametrisations (e.g. microphysics with ICCARE project), reduced radiation grid for AROME
- Planned project: AMCoM 3D physics in mountains
- Planned PhD project (with Dominique Bouniol, CNES): tropical cloud-radiation evaluation in AROME-Climat with EarthCARE data

Thank you for your attention!

Contact: sophia.schaefer@meteo.fr

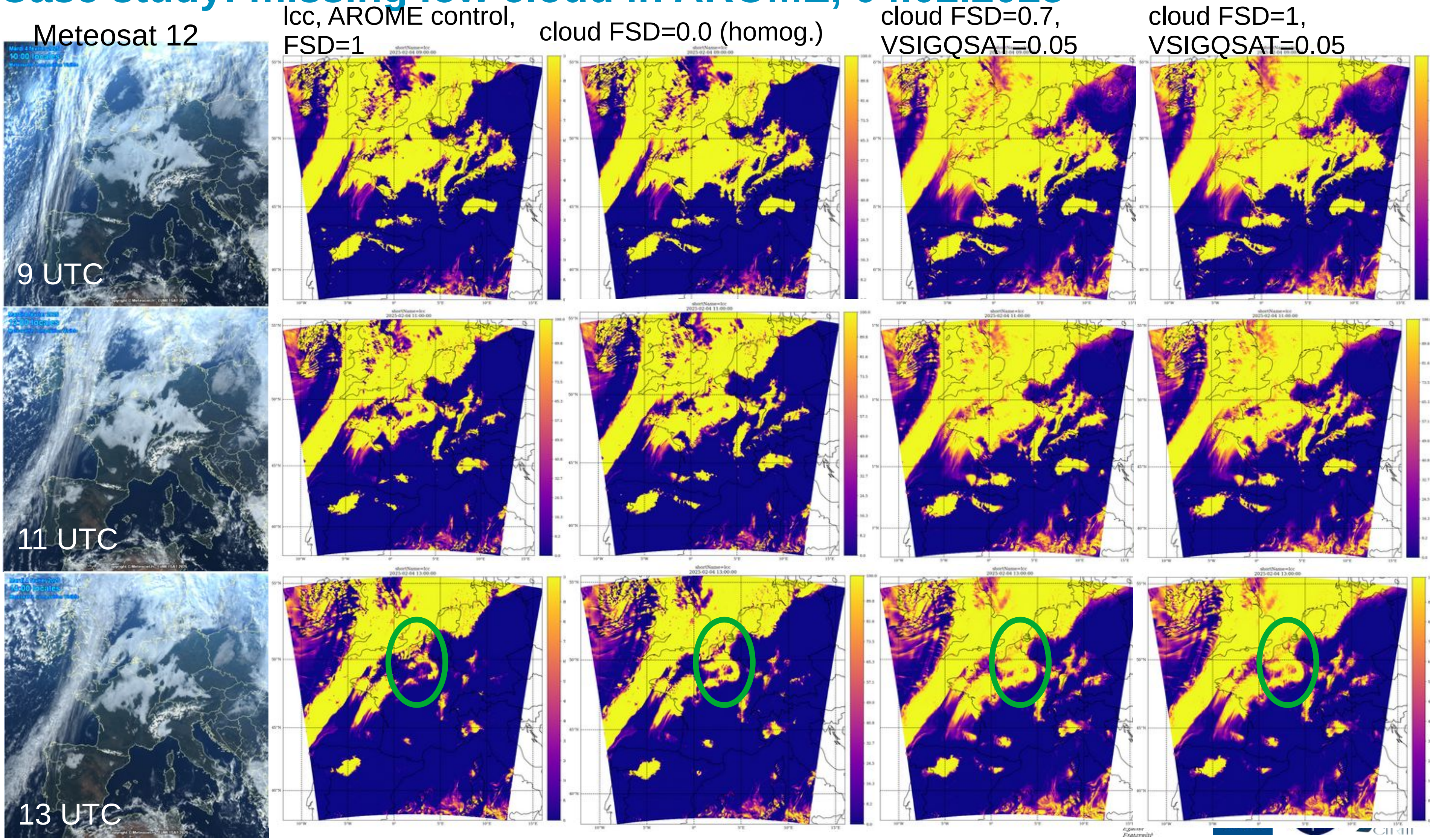
RÉPUBLIQUE FRANÇAISE

METEO FRANCE

cnrs

CNRM

Case study: missing low cloud in AROME, 04.02.2025



Implementation of ecRad 1.6.1 in Meso-NH (consistent with ARPEGE/AROME, IFS)

- New cleaner implementation of ecRad and finished except for error with aerosols (with Quentin Rodier), will be available in Meso-NH 6.0 (summer 2025)

- Includes update to ecRad 1.6.1: new options for gas optics (ecckd), general cloud optics: user-defined number and type of cloud hydrometeors, general aerosol optics

- Plan to include ecRad in Meso-NH as external library (also at ECMWF for IFS): easier, cleaner code, automated conversion offline ↔ online versions of ecRad (implementation ongoing at ECMWF)

- Evaluation planned using Adèle Magnaldo's methodology

Scientific options:

- Cloud optical properties accounting for particle shape distribution, (liquid E. Jahangir, ice M. Taufour) is being combined with new ecRad version by collaboration with Christelle Barthe and Samira el-Gdachi (project ICCARE, LAERO)

- Reduced radiation grid (implemented by V. Masson)

Namelist Meso-NH: From MesoNH 6.0, all ecRad namelist parameters will be available (see src/MNH/modn_param_ecradn.F90, https://confluence.ecmwf.int/download/attachments/70945505/ecrad_documentation.pdf?version=4&modificationDate=1584914933898&api=v2)

NAMELIST/NAM_PARAM_ECRADn/

IVERBOSESETUP, IVERBOSE, & # How much is written in output?

output fluxes, solver

LDO_SW, LDO_LW, LDO_SW_DIRECT, LDO_CLEAR, LDO_SURFACE_SW_SPECTRAL_FLUX, LDO_CANOPY_FLUXES_SW, LDO_CANOPY_FLUXES_LW & #which fluxes?

LDO_SAVE_SPECTRAL_FLUX, LDO_SAVE_GPOINT_FLUX, LDO_LW_DERIVATIVES, LDO_SAVE_RADIATIVE_PROPERTIES, &# save intermediate properties?

CSW_SOLVER_NAME, CLW_SOLVER_NAME, LDO_LW_CLOUD_SCATTERING, LDO_LW_AEROSOL_SCATTERING, & # Radiation solver, Do LW cloud / aerosol scattering?

gas / cloud optics

CGAS_MODEL_NAME, NRADLP, NRADIP, **CLIQUID_MODEL_NAME, CICE_MODEL_NAME**, LDO_FU_LW_ICE_OPTICS_BUG, & # gas, liquid, ice optics, do IFS ice bug?

CGAS_OPTICS_SW_OVERRIDE_FILE_NAME, CGAS_OPTICS_LW_OVERRIDE_FILE_NAME& # use gas optics from specified file ?

LDO_SW_DELTA_SCALING_WITH_GASES, LUSE_THICK_CLOUD_SPECTRAL_AVERAGING & # Do Delta-Eddington scaling with gases/ thick cloud spectral averaging?

XMAX_GAS_OD_3D, XMAX_CLOUD_OD, **LUSE_GENERAL_CLOUD_OPTICS**, & # max. gas / cloud optical depth, General cloud types method?

CCLOUD_TYPE_NAME, CCLIQ_OPTICS_OVERRIDE_FILE_NAME, CICE_OPTICS_OVERRIDE_FILE_NAME, & # Vector of cloud types, liquid / ice optics from specified file?

aerosols

LUSE_AEROSOLS, LUSE_GENERAL_AEROSOL_OPTICS, & # Do aerosols? Use general aerosol method?

LDO_CLOUD_AEROSOL_PER_SW_G_POINT, LDO_CLOUD_AEROSOL_PER_LW_G_POINT, & # do aerosols per band or per g-point?

NAEROSOL_TYPES , NI_AEROSOL_TYPE_MAP, CAEROSOL_OPTICS_OVERRIDE_FILE_NAME, & number + type of aerosols, use aerosol optics from file?

Surface

SURF_TYPE, LDO_WEIGHTED_SURFACE_MAPPING, & # Surface type / mapping

LSPEC_ALB, LSPEC_EMISS, LDO_NEAREST_SPECTRAL_SW_ALBEDO, LDO_NEAREST_SPECTRAL_LW_EMISS, & # spectral albedo / emissivity / mapping method

ISW_ALBEDO_INDEX, ILW_EMISS_INDEX, XSW_ALBEDO_WAVELENGTH_BOUND, XLW_EMISS_WAVELENGTH_BOUND, & # Albedo / emissivity index / bands

cloud geometry

XCLOUD_FRACTION_THRESHOLD, XCLOUD_MIXING_RATIO_THRESHOLD, & minimum thresholds for cloud

OVERLAP_SCHEME_NAME, LUSE_BETA_OVERLAP, NREG, **XCLOUD_FRAC_STD**, & # vertical overlap scheme, beta overlap? number of regions, fractional stand. dev.

XCLOUD_INHOM_DECORR_SCALING, XCLEAR_TO_THICK_FRACTION & # cloud inhomogeneity overlap compared to region overlap, ratio of thick cloud next to clear

CCLOUD_PDF_SHAPE_NAME, CCLOUD_PDF_OVERRIDE_FILE_NAME, & # name of horizontal cloud distribution PDF / Use PDF from file?

SPARTACUS solver: 3D effects

LDO_3D_EFFECTS, LDO_LW_SIDE_EMISSIVITY, LDO_3D_LW_MULTILAYER_EFFECTS, XMAX_3D_TRANSFER_RATE, & #Do 3D effects? / Which ones? Maximum 3D flux

CSW_ENTRAPMENT_NAME, LUSE_EXPM_EVERYWHERE, XOVERHANG_FACTOR, XOVERHEAD_SUN_FACTOR, & # method entrapment, matrix exponential, min SZA, 3D

References

Overview radiation: Petty, Grant William, 2006. *A first course in atmospheric radiation*. Sundog Pub.

- Ahlgrimm, M., & Forbes, R. M. (2017). Regime dependence of ice cloud heterogeneity—A convective life-cycle effect. *Q. J. R. Meteorol. Soc.*
- Baran, A. J., Hill, P., Furtado, K., Field, P., & Manners, J. (2014). A coupled cloud physics–radiation parameterization of the bulk optical properties of cirrus and its impact on the Met Office unified model global atmosphere 5.0 configuration. *J.Clim.*
- Baum, B. A., P. Yang, A. J. Heymsfield, A. Bansemer, A. Merrelli, C. Schmitt, and C. Wang (2014). Ice cloud bulk single-scattering property models with the full phase matrix at wavelengths from 0.2 to 100 um. J. Quant. Spectrosc. Radiat. Transfer, 146, 123-139
- Buzzi, M., (2008). Challenges in operational numerical weather prediction at high resolution in complex terrain, PhD thesis, ETH Zürich
- Caliot, C., R. Schoetter, V. Forest, V. Eymet, and T.-Y. Chung (2022). Model of spectral and directional radiative transfer in complex urban canopies with participating atmospheres. Boundary-Layer Meteorology, 186, 145-175.
- Coddington, O.; Lean, J.; Pilewskie, P.; Snow, M.; Lindholm, D. (2016). A solar irradiance climate data record. *Bull. Am. Meteorol. Soc.*
- Corbetta, G., Orlandi, E., Heus, T., Neggers, R., & Crewell, S. (2015). Overlap statistics of shallow boundary layer clouds: Comparing ground-based observations with large-eddy simulations. *Geophys. Res. Lett.*
- Delanoë, J., Protat, A., Testud, J., Bouniol, D., Heymsfield, A. J., Bansemer, A., Brown, P. R. A., and Forbes, R. M. (2005), Statistical properties of the normalized ice particle size distribution, *J. Geophys. Res*., doi:10.1029/2004JD005405.
- Fu, Q. (1996). An accurate parameterization of the solar radiative properties of cirrus clouds. *J. Clim.*
- Fu, Q., Liou, K. N., Cribb, M. C., Charlock, T. & Grossman, A. (1997). Multiple scattering parameterization in thermal infrared radiative transfer, *J. Atm. Sci*.
- Fu, Q., Yang, P., & Sun, W. B. (1998). An accurate parametrization of the infrared radiative properties of cirrus clouds of climate models. *J. Clim.*
- Hogan, R. J., & Illingworth, A. J. (2000). Deriving cloud overlap statistics from radar. *Q. J. R. Meteorol. Soc.*
- Hogan, R. J., Schäfer, S. A. K., Klinger, C., Chiu, J.-C., & Mayer, B. (2016). Representing 3-D cloud-radiation effects in two-stream schemes: 2. Matrix formulation and broadband evaluation, *J. Geophys. Res.*
- Hogan, R. J., & Bozzo, A. (2018). A flexible and efficient radiation scheme for the ECMWF model. *J. Adv. Modeling Earth Sys*., https://doi.org/10.1029/2018MS001364
- Hogan, R. J., M. D. Fielding, H. W. Barker, N. Villefranque and S. A. K. Schäfer (2019). Entrapment: An important mechanism to explain the shortwave 3D radiative effect of clouds. *J. Atmos. Sci.*
- Hogan, R. J. and Matricardi, M. (2020). Evaluating and improving the treatment of gases in radiation schemes: the Correlated K-Distribution Model Intercomparison Project (CKDMIP), *Geosci. Model Dev.*

RÉPUBLIQUE FRANÇAISE METEO FRANCE cnrs CNRM

References

- Iacono, M. J., J. S. Delamere, E. J. Mlawer, M. W. Shephard, S. A. Clough and W. D. Collins (2008), Radiative forcing by long-lived greenhouse gases: Calculations with the AER radiative transfer models, *J. Geophys. Res.*, doi:10.1029/2008JD009944
- Loeb, N. G., Doelling, D. R., Wang, H., Su, W., Nguyen, C., Corbetta, J. G., et al. (2018). Clouds and the Earth's radiant energy system (CERES) energy balanced and filled (EBAF) top-of-atmosphere (TOA) edition-4.0 data product. *J. Clim.*
- Mlawer, Eli J. et al., (1997). Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave, *J. Geophys. Res.*
- Neggers, R. A. J., Heus, T., & Siebesma, A. P. (2011). Overlap statistics of cumuliform boundary-layer cloud fields in large-eddy simulations, *J. Geophys. Res.*
- Pincus, R., Barker, H. W., & Morcrette, J.-J. (2003). A fast, flexible, approximate technique for computing radiative transfer in inhomogeneous clouds, *J. Geophys. Res.*
- Schäfer, S. A. K., Hogan, R. J., Klinger, C., Chiu, J.-C., & Mayer, B. (2016). Representing 3D cloud-radiation effects in two-stream schemes: 1. Longwave considerations and effective cloud edge length, *J. Geophys. Res.*
- Schäfer, S. A. K. (2017), What is the global impact of 3D cloud-radiation interactions? *PhD thesis, University of Reading.* https://centaur.reading.ac.uk/view/creators/90004951.html
- Schoetter, R., R.J. Hogan, C. Caliot, and V. Masson (2024). Coupling the urban canopy model TEB (SURFEXv9.0) with the radiation model SPARTACUS-Urbanv0.6.1 for more realistic urban radiative exchange calculation. Under discussion at EGUsphere.
- Shonk, J. K. & Hogan, R. J. (2008). Tripleclouds: An efficient method for representing horizontal cloud inhomogeneity in 1D radiation schemes by using three regions at each height, *J. Clim.*
- Slingo, A. (1989). A GCM parametrization for the shortwave radiative properties of water *J. Atm. Sci.*
- Sulak, A. M., Calabrase, W. J., Ryan, S. & Heus, T. (2020). The contributions of shear and turbulence to cloud overlap for cumulus clouds, *J. Geophys. Res.*
- Villefranque, N., R. Fournier, F. Couvreux, S. Blanco, C. Cornet, V. Eymet, V. Forest, and J.-M. Tregan, 2019: A path-tracing Monte Carlo library for 3-D radiative transfer in highly resolved cloudy atmospheres. Journal of Advances in Modelling Earth Systems, 11, 2449-2473.
- Yi, B., Yang, P., Baum, B. A., L'Ecuyer, T., Oreopoulos, L., Mlawer, E. J., et al. (2013). Influence of ice particle surface roughening on the global cloud radiative effect. *J. Atm. Sci.*