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Supplement of

A new radiation infrastructure for the Modular Earth Submodel System (MESSy, based on version 2.51)

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1 Introduction

This document describes in detail the technical infrastructure of the new radiation related submodels including the submodel RAD (with sub-submodel RAD_FUBRAD), the submodel AEROPT (calculation of aerosol optical properties), the submodel CLOUDOPT (calculation of cloud optical properties) and the submodel ORBIT (calculation of orbital parameters). All these submodels are part of MESSy (Jöckel et al., 2005, 2010) and provide a very easy way of controlling and specifying different radiation setups without re-compilation.

As the previous MESSy submodel RAD4ALL, RAD is partly based on the radiation routines of ECHAM5 (Roeckner et al., 2006). Its submodel core layer (SMCL) consists of the following Fortran95 modules (the relationship between the different Fortran95 modules of RAD are shown in Fig. 1 of the main paper):

- messy_rad.f90
- messy_rad_fubrad.f90
- messy_rad_short_v1.f90 and messy_rad_short_v2.f90
- messy_rad_long.f90
- messy_rad_albedo.f90

The submodel interface layer (SMIL), which provides the connection to the superordinate model infrastructure, consists of 2 Fortran95 modules:

- messy_rad_e5.f90
- messy_rad_fubrad_e5.f90

In the following sections the description of the user interface, i.e., the Fortran95 namelists, is given for the new radiation related submodels RAD, AEROPT, CLOUDOPT and ORBIT. According to the MESSy standard (Jöckel et al., 2005), the namelist files contain a control namelist (CTRL), a coupling namelist (CPL) and, if required, additional specific namelists.

2 RAD namelist user interface

The user interface of the submodel RAD is the namelist file *rad.nml* (see example namelist in Table 2). It contains the RAD CPL namelist, the RAD CTRL_FUBRAD namelist and the CPL_FUBRAD namelist.

2.1 RAD CPL namelist

The CPL namelist comprises switches and selectors for input data to the submodel RAD:

- The logical switch `lfubrad` enables (`.TRUE.`)/disables (`.FALSE.`) the extension of the high resolution shortwave radiation scheme FUBRAD (Nissen et al., 2007).
- With the namelist entry `trigrad` (an *event*, see documentation of submodel TIMER, Jöckel et al., 2010) the frequency of the radiation calculation is controlled. The `trigrad` event comprises four comma-separated entries: the time interval (integer), the unit of the time interval (e.g. 'days', 'month', 'years', or 'steps'), the adjustment inside the time interval (e.g. 'first', 'last'), and the offset of the time interval to the initial date (in seconds).
- The possibility to modify the solar constant is given with `rset_solc`. `rset_solc` consists of a logical, which indicates whether the solar constant is changed (`.TRUE.`) or not (`.FALSE.`), and the value of the corresponding solar constant (in W/m^2), if `.TRUE.`.
- The logical `l_switch(n)` is used to enable the *n*th diagnostic call of the radiation scheme. This logical switch must be set `.TRUE.` for radiative forcing calculations. The first switch (`l_switch(1)`) must always be set to `.TRUE.`, as the first call provides the temperature feedback.

- `i_rad(n)` has entry 1 or 2. With the integer 1 the instantaneous radiative forcing, and with the integer 2 the stratosphere adjusted radiative forcing is selected, respectively. For the first call entry 1 is always required (`i_rad(1)=1`). The entry `i_rad(n)` has only an effect, if the corresponding `l_switch(n) = .TRUE..`
- The switch `i_sw(n)` determines, whether the default shortwave radiation scheme (`i_sw(n)=1`), or the shortwave radiation scheme according to Thomas (2008) (`i_sw(n)=2`) is used for the n th radiation call. This entry has only an effect, if the corresponding `l_switch(n) = .TRUE..`
- Online or offline variables needed for the radiation calculation are selected with the namelist entries `r_inp(m,n)`. An individual selection of the $m = 1 \dots 18$ radiation related input variables
 1. water vapour,
 2. CO₂,
 3. CH₄,
 4. O₃,
 5. N₂O,
 6. CFC-11,
 7. CFC-12,
 8. longwave optical thickness of aerosol,
 9. shortwave optical thickness of aerosol,
 10. aerosol asymmetry factor,
 11. aerosol single scattering albedo,
 12. cloud cover,
 13. longwave optical depth of clouds,
 14. shortwave optical depth of clouds,
 15. cloud asymmetry factor,
 16. cloud single scattering albedo,
 17. total cloud cover, and
 18. clear/cloudy index

is possible for each of the n radiation calls. Three possibilities of selecting input are possible:

- If calculated online, the input field `r_inp(m,n)` is indicated by the respective comma separated list of the channel name (which contains the channel object to be referenced) and the channel object name to be referenced.
Example: `r_inp(1,4) = 'tracer_gp', '03'`
- The offline import of radiation related variables (e.g., external climatologies) can be achieved with the submodel IMPORT, in case the variables are available on a geographical grid (Kerkweg and Jöckel, 2015). The namelist entry `r_inp(m,n)` then contains the channel name 'import_grid' and the channel object name of the regridded input variable. This input variable is composed of the event name (set in import.nml), followed by an underscore and by the name of the imported variable (e.g. 'RADC02_CO2').
Example: `r_inp(1,2) = 'import_grid', 'RADC02_CO2'`
- In addition, for greenhouse gases there are two other possibilities: For uniform volume mixing ratios the namelist entry `r_inp(m,n)` is the string '#const', comma separated by the name of the variable and the value of the variable in mol/mol (e.g., 'CO2=367.E-06'). Alternatively for CH₄, N₂O, CFC-11 and CFC-12, volume mixing ratios decaying with altitude can similarly be specified with '#vgrad' instead of '#const'. Here, the vertical gradient of the GHG volume mixing ratio (vmr) is calculated as:

$$0.5 * (vmr + c1 * vmr) * \left(1 - \frac{vmr + c1 * vmr}{vmr - c1 * vmr} * \tanh\left(\frac{\log\left(\frac{p}{c2}\right)}{c3}\right)\right), \quad (1)$$

with vmr (in mol/mol) from namelist. The constants c1, c2 and c3 differ for the different GHGs and are given in Table 1.

Example: `r_inp(1,2) = '#vgrad', 'CH4=1.75E-06'`

Table 1: Constants c_1 , c_2 and c_3 for calculating the vertical gradient of the GHGs CH_4 , N_2O , CFC-11 and CFC-12 (see equation 1).

	c_1	c_2	c_3
CH_4	0.125	683	-1.43
N_2O	0.012	1395	-1.43
CFC-11	0.0001	4159	-0.73
CFC-12	0.0001	3177.4	-0.73

2.2 CTRL_FUBRAD and CPL_FUBRAD namelist

The namelist file *rad.nml* contains two namelists for the high resolution shortwave radiation scheme FUBRAD, CTRL_FUBRAD and CPL_FUBRAD:

- With the namelist parameter `solfac` in CTRL_FUBRAD the solar cycle condition can be set. It can vary between 0 and 1, where the value 0 indicates solar minimum and the value 1 solar maximum conditions, respectively. This parameter is obsolete, if `fubrad_solar` in CPL_FUBRAD is activated.
- The second parameter in CTRL_FUBRAD, `nbands`, sets the spectral resolution of FUBRAD. Possible are 55 (default), 106, and 49 bands. However the old version of 49 bands is not recommended, as it leads to an inconsistent flux profile and misleading flux diagnostics.
- In CPL_FUBRAD the channel object providing an external solar cycle time series can be chosen with `fubrad_solar`. If such a time series is, for instance, imported with the submodel IMPORT_TS (Kerkweg and Jöckel, 2015), the channel name (first string) is `'import_ts'` followed by the channel object name (second string), e.g. `'solact'`, or `'solspec'`. The time series may consist of either one parameter (the F10.7 cm flux), or of `nbands + 1` parameters for spectrally resolved data. If `fubrad_solar` is commented (or empty), `solfac` in CTRL_FUBRAD is used instead.

2.3 RAD CPL namelist settings for radiative forcing calculations

The RAD submodel can be called several times with different radiation settings, as the calculation is fully diagnostic, besides the first call, which provides the temperature feedback. As mentioned above, `l_switch(n)` switches the n th radiation calculation. With this new feature in the radiation submodel RAD the user can calculate instantaneous and stratosphere adjusted radiative forcing during a model simulation. The namelist file *rad.nml* in Table 2 shows an example of one additional diagnostic call ($n = 2$) for calculating stratosphere adjusted radiative forcing of enhanced CO_2 mixing ratios (`r_inp(2,2) = '#const', 'CO2=416.E-6',`). In the second call, radiation is diagnostically calculated (without temperature feedback) for the changed CO_2 mixing ratios. The empty strings (see Table 2) for the second call are automatically replaced by the corresponding entries of the first call, such that only modifications need to be listed.

With the submodel VISO, which is mapping 3-D scalar fields in grid-point representation on surfaces defined by a level index (Jöckel et al., 2010), it is possible to map the simulated radiative forcing onto arbitrary horizontally oriented surfaces, e.g., onto the tropopause. Here, it is highly recommended to use a fixed annual mean tropopause to define the domain for stratospheric temperature adjustment and to ensure that the new flux balance above the tropopause is reached rapidly.

3 AEROPT namelist user interface

The selection of the input data sets for AEROPT is entirely managed via its namelists (see example namelist file *aeropt.nml* in Table 3).

In CTRL the user can specify

- the desired lookup-tables for both spectra (longwave and shortwave), including the path where the data sets are located. It is also possible to allow multiple specifications, i.e. different data sets for different calculations.

Table 2: Example for the RAD namelist file *rad.nml*, displaying a possible radiation setup with FUBRAD, and with one additional diagnostic call ($n = 2$). The first part of the CPL namelist file contains switches and selections for the radiation setup. The second part of the CPL namelist contains the input variables for the 2nd radiation calculation (with different CO₂ mixing ratio as input for this diagnostic call). FUBRAD namelist entries in CTRL_FUBRAD and CPL_FUBRAD are required.

CPL	
lfubrad = T	
trigrad = 3,'steps','first',0	
rset_solc = F, 1366.04,	
<i>TRUE for calculating radiation; first call always provides temperature feedback</i>	
l_switch(1) = T	! TRUE for radiation calculation
l_switch(2) = T	
i_rad(1) = 1,	
i_rad(2) = 2,	! stratosphere adjustment
i_sw(1) = 1,	
i_sw(2) = 1,	
<i>1. call of radiation (always required)</i>	
r_inp(1,1) = 'ECHAM5', 'qm1',	! H2O [mol/mol] or [kg/kg]
r_inp(2,1) = 'import_rgt', 'RADCO2_CO2',	! CO2 [mol/mol]
r_inp(3,1) = 'import_rgt', 'RADCH4_CH4',	! CH4 [mol/mol]
r_inp(4,1) = 'tracer_gp', 'O3',	! O3 [mol/mol]
r_inp(5,1) = 'import_rgt', 'RADN2O_N2O',	! N2O [mol/mol]
r_inp(6,1) = 'import_rgt', 'RADCF13_CFC13',	! CFC11 [mol/mol]
r_inp(7,1) = 'import_rgt', 'RADCF2C12_CFC12',	! CFC12 [mol/mol]
r_inp(8,1) = 'aeropt_TANRE_STD', 'aot_lw',	! lw aerosol optical thickness
r_inp(9,1) = 'aeropt_TANRE_STD', 'aot_sw',	! sw aerosol optical thickness
r_inp(10,1) = 'aeropt_TANRE_STD', 'gamma_sw',	! aerosol asymmetry factor
r_inp(11,1) = 'aeropt_TANRE_STD', 'omega_sw',	! aerosol single scat. albedo
r_inp(12,1) = 'cloudopt01', 'sum_cov',	! cloud cover
r_inp(13,1) = 'cloudopt01', 'tau_cld_lw',	! lw optical depth clouds
r_inp(14,1) = 'cloudopt01', 'tau_cld_sw',	! sw optical depth clouds
r_inp(15,1) = 'cloudopt01', 'gamma_cld_sw',	! cloud asymmetry factor
r_inp(16,1) = 'cloudopt01', 'omega_cld_sw',	! cloud single scattering albedo
r_inp(17,1) = 'cloudopt01', 'clcv',	! total cloud cover
r_inp(18,1) = 'cloudopt01', 'idx_cld',	! clear/cloudy index
<i>2. call of radiation</i>	
r_inp(1,2) = '', '',	
r_inp(2,2) = '#const', 'CO2=416.E-6',	!CO2 pert[mol/mol]
r_inp(3,2) = '', '',	
...	
r_inp(18,2) = '', '',	
CTRL_FUBRAD	
solfac = 0.5	! 0: solar minimum, 1: solar maximum
nbands = 55	
CPL_FUBRAD	
fubrad_solar = 'import_ts', 'solact',	! F10.7 cm (1 parameter)

In CPL the user can specify

- the number of the sets of aerosol radiative properties to be provided (defined by the index),
- names for these sets (e.g. "TANRE_STD" for the first example in Table 3),
- a logical switch, whether prognostic tracers shall be used, or the internal climatology is applied (the climatology is used for TANRE only, otherwise interactive tracers are mandatory),

- whether certain aerosol species shall be excluded (such as diagnostic tracers, or for sensitivity tests); two types of entries are possible (each internally separated by ';' for more than one tracer): the first entry string represents individual specific tracers, the second all tracers with this tracer *basename*. Alternatively, also an index can be used for the TANRE climatology (in the given example (Table 3) the index 4, which represents volcanic aerosol).
- the channel name for the coupling to the respective aerosol module,
- the names for the dry and ambient aerosol radius channel objects, respectively,
- the name for the channel object containing aerosol numbers. (Note, that if this entry is empty, this information is extracted from the aerosol number tracer; however, it should be defined for an aerosol model, which does not use prognostic number tracers.)
- the number of the respective lookup-table set (which must be defined in the CTRL namelist), that shall be used for this optical property set,
- a logical switch whether the calculation of sea salt concentrations shall be performed from the sea salt tracer alone or from Na^+ and Cl^- and a potential sea salt tracer,
- a logical switch whether an internal or an external mixture shall be used for the hydrophobic modes,
- a logical switch whether a channel shall be constructed including aerosol optical information as required by the photolysis scheme, including the corresponding calculations
- an optional set of specific wavelengths, for which diagnostically the aerosol optical thickness (e.g., AOD at 550 nm) for improved comparison with satellite data, are calculated.

Note, that for the TANRE climatology not all these switches and entries are required, as there is no coupling to tracers or an aerosol module. Furthermore, note, that the entries (except for the optional additional wavelengths) must always exist in the namelist, but they might be empty.

In CPL_IMP the user optionally specifies

- a set of aerosol radiative properties provided by an external source, e.g., via the MESSy submodel IMPORT, including the dimensionality of the objects. The entries include always the channel name and the channel object name. The order of the variables is
 1. longwave extinction
 2. shortwave extinction
 3. shortwave asymmetry factor
 4. shortwave single scattering albedo

In CPL_MERGE the user specifies

- a name for each merged data set,
- the name of the two data sets to merge, including weighting factors,
- the merging (pressure) altitude in Pa (if both values are set to zero, the data sets are simply added including their weighting factors). Two different values can be provided (one for each data set). In case the values are not identical a zone with linear interpolation between the two data sets is constructed.

4 CLOUDOPT namelist user interface

The namelist file *cloudopt.nml* (see example in Table 4) consists of a CTRL namelist and a CPL namelist.

The CTRL namelist has four entries controlling the parameter `rset_asic` (asymmetry factor of ice particles) and the model resolution dependent parameters `rset_zinhomi` (cloud inhomogeneity factor of ice), `rset_zinhoml` (cloud inhomogeneity factor of liquid water) and `rset_zinpar` (parameter to correct the asymmetry factor of ice clouds). The default values of these parameters (which are hard-wired in the model code) can be overwritten without re-compilation of the code. These parameters consist of two entries: a logical switch, which is `.TRUE.` for overwriting the default value and a new value, respectively. The user can specify:

Table 3: Example for an AEROPT namelist file (*aeropt.nml*): The CTRL namelist contains desired lookup-tables. The CPL namelist (including CPL, CPL_IMP and CPL_MERGE) contains information about the aerosol radiative properties.

```

CTRL
READ_LUT_SETS(1) = 1, '$INPUTDIR_MESSY/aeropt/aeropt_sw_1.59_1.59_2.00.nc', \
'$INPUTDIR_MESSY/aeropt/aeropt_lw_1.59_1.59_2.00.nc'
READ_LUT_SETS(1) = 2, '$INPUTDIR_MESSY/aeropt/aeropt_sw_1.59_1.59_1.70.nc', \
'$INPUTDIR_MESSY/aeropt/aeropt_lw_1.59_1.59_1.70.nc'
CPL
READ_AERO_SETS(1)='TANRE_STD' , F, '', '4', '', T, T, '', '', '', '', 0, F
READ_AERO_SETS(2)='GMXE' , T, '', 'RGM;PASSAER01;Pb210', '', T, F, 'gmxe_gp', 'wetradius', \
'dryradius', '', 1, T, 0.55, 1.0
CPL_IMP
READ_INPUT_SETS(1) = 'CCMI_CLIM', 'import_rgt', 'OPT-LW_AOD_LW', 'import_rgt', 'OPT-SW_AOD_SW', \
'import_rgt', 'OPT-SW_GAMMA_SW', 'import_rgt', 'OPT-SW_OMEGA_SW', 3
CPL_MERGE
READ_MERGE_SETS(1) = 'MERGED', 'TANRE_STD', 1.0, 'CCMI_CLIM', 1.0, 50000.0, 30000.0
READ_MERGE_SETS(2) = 'MERGED2', 'GMXE', 1.0, 'CCMI_CLIM', 1.0, 50000.0, 30000.0

```

- the asymmetry factor of ice particles (`rset_asic`),
- the cloud inhomogeneity factor of ice water (`rset_zinhomi`),
- the cloud inhomogeneity factor of liquid water (`rset_zinhoml`), and
- the parameter to correct the asymmetry factor of ice clouds (`rset_zinpar`). Note that this parameter can be set to influence `zinhoml`,

The CPL namelist contains entries controlling the input data provided for the submodel CLOUDOPT:

- With the integer `NCALL` the submodel CLOUDOPT can be called `NCALL` times in each model time step with different input for the diagnostic calculations. All calls of CLOUDOPT can be combined with all calls of RAD.
- Six ($m = 1 \dots 6$) input variables `cld_inp(m,n)`, required for calculating cloud optical properties, need to be specified for each (n th) call of CLOUDOPT. These are specified as channel and channel object name pairs:
 1. cloud cover,
 2. cloud liquid water,
 3. cloud ice,
 4. cloud nuclei concentration,
 5. effective radii of liquid droplets, and
 6. effective radii of ice droplets.

Items 1 to 4 can be determined by calculating them online, for instance in the submodel CLOUD, or by importing them from an external data source via the submodel IMPORT. The effective radii (items 5 and 6) can be

- calculated internally by setting `#std` as channel name,
 - set to a constant value by setting `#const` as channel name and the corresponding value as object name,
 - imported via channel object selection from another submodel (including external data fields via IMPORT).
- Cloud perturbations can be added as shown in the example in Table 4 and their optical properties can be calculated separately and cumulatively. In this example, which represents a benchmark test for the radiative effect of thin ice clouds (Myhre et al. , 2009), a 1% homogeneous contrail cover is added in one model level (level 19 in the example). When using the option `#const_tau`, a fixed amount of ice or liquid water as given in the namelist, yielding a constant optical depth.

Table 4: Example of a CLOUDOPT namelist file (*cloudopt.nml*). The namelist settings show a possible setup with default parameters (CTRL) and input for calculating cloud optical properties for the reference case (CPL). In addition, an example is given for a second diagnostic call with additional perturbation coverage according to Myhre et al. (2009).

CTRL	
rset_asic = F, 0.80,	! asymmetry factor of ice particles
rset_zinhomi = F, 0.96,	! cloud inhomogeneity factor of ice water
rset_zinhoml = F, 0.7,	! cloud inhomogeneity factor of liquid water
rset_zinpar = F, 0.96,	! parameter to correct the asymmetry factor of ice clouds
CPL	
NCALL = 2	! number of calls
cld_inp(1,1)='ECHAM5','aclc',	! cloud cover from ECHAM5 channel
cld_inp(2,1)='ECHAM5','xlm1',	! cloud liquid water from ECHAM5 channel
cld_inp(3,1)='ECHAM5','xim1',	! cloud ice from ECHAM5 channel
cld_inp(4,1)='ECHAM5','acdnc',	! cloud nuclei concentration from ECHAM5 channel
cld_inp(5,1)='#std', 'radlp',	! effective raddii or liquid droplets calculated internally
cld_inp(6,1)='#std', 'radip',	! effective raddii or ice droplets calculated internally
cld_inp(1,2)='ECHAM5;#const_cov','aclc;bench_cov=19=0.01',	! additional constant cloud cover in given model level
cld_inp(2,2)='ECHAM5;#const_tau','xlm1;bench_liq=19=0.0',	! no perturbation of cloud liquid water
cld_inp(3,2)='ECHAM5;#const_tau','xim1;bench_ice=19=1.99211',	! additional ice water, yielding constant optical depth
cld_inp(4,2)='ECHAM5','acdnc',	! no perturbation of cloud nuclei concentration
cld_inp(5,2)='#std;#const', 'radlp;radlp_1=20.',	! perturbation has constant liquid droplet radius
cld_inp(6,2)='#std;#const', 'radip;radip_1=12.',	! perturbation has constant ice particle radius

5 ORBIT namelist user interface

The namelist file of the submodel ORBIT (*orbit.nml*) contains a CTRL and a CPL namelist. An example of *orbit.nml* is shown in Table 5.

The CTRL namelist has four entries for the orbital parameters:

- `cecc` is the eccentric anomaly,
- `cobl` is the inclination,
- `clonp` is the longitude of the Perihelion, and
- `l_orbvsop87` switches between the computation of an annual cycle (`.TRUE.`) or a perpetual month setup (`.FALSE.`).

In the CPL namelist the user can specify

- the parameter providing the radiation calculation time offset Δt_{rad} . The namelist entry `c_rad_offset` comprises two strings denoting the channel name (e.g. `'rad'`) and the channel object name (`'dt_offset'`) of the offset.
- a second parameter of the same type (`c_offset`) for an additional offset calculation.

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Table 5: Example of an ORBIT namelist file (*orbit.nml*). The CTRL namelist contains the selection of orbital parameters. The CPL namelist selects the channel object containing the time offset for the radiation calculation.

```

CTRL
cecc = 0.016715
cobld = 23.441
clonp = 282.7
l_orbvsop87 = T                ! T for annual cycle, F for perpetual month experiments
CPL
c_rad_offset = 'rad','dt_offset',

```

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