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Radiative-convective equilibrium simulations with ICON using climate ("ECHAM") physics

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Abstract

The basic structure of the atmosphere is determined by radiative cooling of the atmosphere and heating mainly through the net release of latent heat through precipitation. In radiative-convective equilibrium experiments this balance is explored on a global scale and needs spherically symmetric irradiation and switching off all effects coming from the rotation of the Earth. The corresponding namelist settings are explained in this document for icon-2.4.0.
Keywords: radiative-convection equilibrium, test case, ICON

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1. Introduction

The radiative–convective equilibrium (RCE) offers a possibility to improve our fundamental understanding of processes in the atmosphere and their impact on climate change (e.g. Manabe and Strickler (1964)). The idea behind this simplified modeling of the atmosphere is that the basic atmospheric structure, especially in the tropics, is determined by the balance between cooling of the atmosphere through radiative processes and a commensurate heating through convection, mainly by the net release of latent heat through precipitation.

The RCE has been investigated in models of different complexity, ranging from simple energy balance, 1–dimensional column models to high resolution LES simulations. The RCE is also implemented into the general circulation model ICON by creating a model configuration, where the resulting climate is given merely through the balance of radiative processes and convection. Columns can interact with each other and thus create a mean three–dimensional circulation which develops interactively, although it is very different from the general circulation we know from the real Earth. E.g., the RCE results in slowly moving convective clusters of sometimes continental extension (Popke et al. (2013)).

To inhibit net energy transport from the tropics to the poles, homogeneous boundary conditions are specified, where every gridpoint of the sphere receives the same incoming solar radiation (e.g. about 340 W/m^2). A diurnal cycle may be switched on, but is kept exactly the same for each column representing a pulsating light source shining from all directions equally. The Earth's rotation velocity is set to zero. In the standard RCE configuration, land–sea contrasts are removed and an underlying mixed–layer ocean with a constant ocean albedo should be switched on. The surface temperature calculation of the mixed layer ocean is based on the vertical energy budget only and meant for RCE simulations. Sea ice formation is excluded and there is no heat flux correction. Land–sea contrasts may be included in idealized form for special studies (Becker and Stevens (2014)). This model version has not been tested for possible equilibria dependence on the initial boundary conditions yet, nor for complete isotropy of variables expected from the homogeneous boundary conditions.

2. Setting initial and boundary conditions and parameters for the RCE

We describe the settings in the standard example script `exp.atm_rce_test` here. The mixed layer ocean is switched on by

Listing 1: Mixed-layer-ocean switch in `exp.atm_rce_test`

```
&echam_phy_nml
...
echam_phy_config(n)%lmlo=.TRUE.[.FALSE.]
...
/
```

where `n` is the domain number (e.g. `n=1`) for domain number 1, the global domain. We will use the symbol `n` for the domain index from here on.

For the initialization of the RCE configuration, we use the `nh_testcase_nml` namelist of Listing 2.

Listing 2: Testcase namelist for RCE in `exp.atm_rce_test`

```
&nh_testcase_nml
 nh_test_name      = 'RCE_glb'
 ape_sst_case      = 'sst_const'
 ape_sst_val       = 25.
 tpe_temp          = 298.15
 tpe_psfc          = 1013.25e2
/
```

In the namelist `nh_testcase_nml` (Listing 2), the variable `nh_test_name` set to `'RCE_glb'` has the effect to initialize a global model with all values not depending on the geographical position. The primary initialization is performed by the subroutine `init_nh_state_rce_glb` of module `mo_nh_rce_exp.f90`. After this primary initialization, a random noise is added to the variables. The variable `ape_sst_case` is used to initialize the ocean surface temperature by a constant throughout the globe whereas `ape_sst_val` gives the value of the sea surface temperature in degrees centigrade. The variable `tpe_temp` determines the temperature of the atmosphere in Kelvin that is independent of altitude at the beginning. The variable `tpe_psfc` gives the surface pressure in Pascal.

The RCE model can be run in a configuration with the climate ("ECHAM") physics only, since the use of the PSRAD radiation is essential for the special radiation settings of the RCE. A uniform irradiation of the globe that may undergo a daily cycle is switched on by setting `echam_rad_config(n)%l_sph_symm_irr` to `.TRUE.` in namelist `echam_rad_nml` (see Listing 3). However, a Kepler orbit with no eccentricity has to be used to warrant a sun–earth distance that is constant in time. This is assured by the three first variables of the namelist `echam_rad_nml` as shown in Listing 3. The obliquity is set to zero for convenience.

Listing 3: Orbit namelist `echam_rad_nml` for RCE in `exp.atm_rce_test`

```
&echam_rad_nml
echam_rad_config(n)%cecc            = 0.0
echam_rad_config(n)%cobld           = 0.0
echam_rad_config(n)%l_orbvsop87     = .FALSE.
echam_rad_config(n)%l_sph_symm_irr  = .TRUE.
echam_rad_config(n)%ldiur           = .FALSE.
echam_rad_config(n)%isolrad         = 5
/
```

The angular velocity of the earth is set to zero in order to exclude any quantity that depends on latitude as the Coriolis force. To this end, `grid_angular_velocity` is set to zero in namelist `grid_nml` (see Listing 4).

Listing 4: Grid namelist `grid_nml` for RCE in `exp.atm_rce_test`

```
&grid_nml
 grid_angular_velocity = 0.
/
```

The diurnal cycle can be switched on (`.TRUE.`) and off (`.FALSE.`) with the variable `echam_rad_config(n)%ldiur` of namelist `echam_rad_nml` (see Listing 3).

If a circular orbit with no obliquity is used, a year with months of a different number of days does not make sense. Instead, a 360-day year should be used. The calendar must be set at the beginning of the `exp.atm_rce_test` script (Listing 5).

Listing 5: Calendar for APE (`exp.atm_rce_test`)

```
  calendar="360␣day␣year"
```

The solar irradiation has to be set to an average value that corresponds to the actual energy flux into the atmosphere of the real earth. If spherically symmetric irradiation without diurnal cycle is chosen, `echam_rad_config(n)%isolrad` has to be set to 5. If the diurnal cycle is switched on, `echam_rad_config(n)%isolrad` has to be set to 4, (see Listing 3). These settings result in a global mean insolation of $340.3\,\mathrm{W/m^2}$. However, the sum of the 14 solar wavelength bands is higher ($433.3371\,\mathrm{W/m^2}$ and $1069.315\,\mathrm{W/m^2}$ for `isolrad` $= 5, 4$, respectively), due to the applied solar zenith angles and the eventual diurnal cycle.

The composition of the atmosphere used in the RCE model is determined by the corresponding switches of namelist `echam_rad_nml` (see Listing 6). The O_3 concentration is read from a special file `bc_ozone_rce.nc` that exists in various resolutions in a special directory containing the input data of ICON. Prognostic water vapour and prognostic liquid and ice cloud water is used together with constant CO_2 in space and time, and no aerosols. All other greenhouse gases are set to zero (see Listing 6).

Listing 6: Radiation namelist `echam_rad_nml` for RCE in `exp.atm_rce_test`

```
&echam_rad_nml

 echam_rad_config(n)%irad_h2o   = 1 ! prognostic vapor, liquid and ice
 echam_rad_config(n)%irad_co2   = 2 ! constant co2
 echam_rad_config(n)%irad_ch4   = 0 ! no ch4
 echam_rad_config(n)%irad_n2o   = 0 ! no n2o
 echam_rad_config(n)%irad_o3    = 4 ! perpetual january of used o3 file
 echam_rad_config(n)%irad_o2    = 0 ! no o2
 echam_rad_config(n)%irad_cfc11= 0 ! no cfc11
 echam_rad_config(n)%irad_cfc12= 0 ! no cfc12
 echam_rad_config(n)%irad_aero = 0 ! no aerosol
 echam_rad_config(n)%isolrad    = 5 ! 4 if diurnal cycle is active
 echam_rad_config(n)%ldiur      = .FALSE. ! no diurnal cycle, .TRUE. otherwise
/
```

References

Becker, T. and B. Stevens, 2014: Climate and climate sensitivity to changing CO_2 on an idealized land planet. *J. Adv. Model. Earth Syst.*, **6**, 1205–1223.

Manabe, S. and R. Strickler, 1964: Thermal equilibrium of the atmosphere with a convective adjustment. *J. Atmos. Sci.*, **21**, 361–385.

Popke, D., B. Stevens, and A. Voigt, 2013: Climate and climate change in a radiative–convective equilibrium version of ECHAM6. *J. Adv. Model. Earth Syst.*, **5**(1), 1–14.

Aqua planet experiments with ICON using climate ("ECHAM") physics

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Abstract

Aqua Planet Experiments (APEs) simulate the general circulation of the atmosphere with a bottom boundary consisting of water only. They serve as a test–bed for model intercomparisons but provide also an idealized setup for studies focusing on basic atmospheric phenomena as (tropical) convection for example. The standard namelist settings and analytical forms of surface temperature that are available in ICON are described here for icon-2.4.0.
Keywords: aqua planet, test case, ICON

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The Aqua Planet Experiment (APE) is incorporated in ICON as a set of testcases, all of them having in common that the bottom boundary consists of water only, with all land surface and orography being removed. Originally, APEs were constructed as a test–bed for model intercomparison regarding the interaction of dynamics and physical parameterizations in atmospheric General Circulation Models (GCMs) (Neale and Hoskins (2001a,b)). However, this idealized setup is also well suited for studies focusing on the interaction of basic atmospheric phenomena and the ocean surface, e.g. tropical convection, when a realistic representation of the atmosphere and ocean is secondary.

The APE is one of the test cases of ICON and can be switched on by setting the respective `nh_test_name` variable to `'APE_echam'` in the `nh_testcase_nml` namelist, see Listing 7.

Sea Surface Temperatures (SSTs) can either be prescribed by one of several analytical functions and kept constant in time, or alternatively SSTs may interact with the atmosphere by the use of a mixed layer ocean like the one used in radiative–convective equilibrium simulations. The analytical functions for the sea surface temperatures T_{surf} which are available in `mo_ape_params.f90` are listed under their respective keywords in Figure 1. The symbol T_{m} in these equations represents the standard freezing temperature of fresh water ($T_{\text{m}} = 273.15\,\text{K}$).

The various SSTs can be set in the namelist `nh_testcase_nml` by attributing the corresponding keyword to the variable `ape_sst_case`. For an example see Listing 7.

Listing 7: Testcase namelist for APE (`exp.atm_ape_test`)

```
&nh_testcase_nml
```

```
 nh_test_name      = 'APE_echam'
 ape_sst_case      = 'sst_qobs'
/
```

The APE can be conducted with the ECHAM (climate) physics only since the use of the PSRAD radiation is essential for the APE. A standard example script `exp.atm_ape_test` is provided. In this standard version, a Kepler orbit with no eccentricity and zero obliquity is used. The orbit parameters are set in the `echam_rad_nml` namelist (Listing 8). They have to be specified for every domain `n`.

Listing 8: Orbit parameters in the `echam_rad_nml` namelist for APE (`exp.atm_ape_test`)

```
&echam_rad_nml
echam_rad_config(n)%cecc        = 0.0     ! zero excentricity
echam_rad_config(n)%cobld       = 0.0     ! zero obliquity
echam_rad_config(n)%l_orbvsop87= .FALSE. ! use Kepler orbit instead of historic one
/
```

If a circular orbit with no obliquity is used, a year with months of a different number of days does not make sense. Instead, a 360-day year should be used. The corresponding calendar must be set at the beginning of the `exp.atm_ape_test` script (Listing 9).

Listing 9: Calendar for APE (`exp.atm_ape_test`)

```
  calendar="360␣day␣year"
```

The solar irradiation is set to the pre-industrial value, i.e. to a value of 1360.875 W/m^2. The APE uses a composition of the atmosphere the O_3 concentration of which is read from a special file. Prognostic water vapour and prognostic liquid and ice cloud water is used together with constant CO_2 in space and time, and no aerosols. All other greenhouse gases are set to zero (Listing 10). All these variables have to be specified for every domain `n`.

Listing 10: Solar irradiation and composition of atmosphere (`exp.atm_ape_test`)

```
&echam_rad_nml
 echam_rad_config(n)%isolrad    = 2 ! pre-industrial solar constant
                                    ! of 1360.875 W/m^ at 1 AE
 echam_rad_config(n)%irad_h2o   = 1 ! prognostic vapor, liquid and ice
 echam_rad_config(n)%irad_co2   = 2 ! constant co2
 echam_rad_config(n)%irad_o3    = 4 ! perpetual january of used ozone file
 echam_rad_config(n)%irad_ch4   = 0 ! no ch4
 echam_rad_config(n)%irad_n2o   = 0 ! no n2o
 echam_rad_config(n)%irad_o2    = 0 ! no o2
 echam_rad_config(n)%irad_cfc11 = 0 ! no cfc11
 echam_rad_config(n)%irad_cfc12 = 0 ! no cfc12
 echam_rad_config(n)%irad_aero  = 0 ! no aerosol
 echam_rad_config(n)%ighg       = 0 ! no greenhouse gas scenario
/
```

The O_3 concentrations are read from the file `bc_ozone_ape.nc`.

Figure 1: Analytic SSTs as provided by `mo_ape_params.f90`

keyword `sst1`**:**

$$T_{\text{surf}} = \begin{cases} T_{\text{m}} + 27\,\text{K}\left(1 - (\sin(3\phi/2))^2\right) & \text{for all} \quad -\pi/3 < \phi < \pi/3 \\ T_{\text{m}} & \text{otherwise} \end{cases} \tag{1}$$

keyword `sst2`**:**

$$T_{\text{surf}} = \begin{cases} T_{\text{m}} + 27\,\text{K}\left(1 - \frac{3}{\pi}|\phi|\right) & \text{for all} \quad -\pi/3 < \phi < \pi/3 \\ T_{\text{m}} & \text{otherwise} \end{cases} \tag{2}$$

keyword `sst3`**:**

$$T_{\text{surf}} = \begin{cases} T_{\text{m}} + 27\,\text{K}\left(1 - (\sin(3\phi/2))^4\right) & \text{for all} \quad -\pi/3 < \phi < \pi/3 \\ T_{\text{m}} & \text{otherwise} \end{cases} \tag{3}$$

keyword `sst4`**:** This distribution has its temperature peak at 5°N:

$$T_{\text{surf}} = \begin{cases} T_{\text{m}} + 27\,\text{K}\left(1 - \left(\sin(1.6363(\phi - \frac{\pi}{36}))\right)^2\right) & \text{for all} \quad \pi/36 < \phi < \pi/3 \\ T_{\text{m}} + 27\,\text{K}\left(1 - \left(\sin(1.3846(\phi - \frac{\pi}{36}))\right)^2\right) & \text{for all} \quad -\pi/3 < \phi \leq \pi/36 \\ T_{\text{m}} & \text{otherwise} \end{cases} \tag{4}$$

keyword `sst_qobs`**:**

$$T_{\text{surf}} = \begin{cases} T_{\text{m}} + \frac{27}{2}\,\text{K}\left(2 - (\sin(3\phi/2))^2\left(1 + (\sin(3\phi/2))^2\right)\right) & \text{for all} \quad -\pi/3 < \phi < \pi/3 \\ T_{\text{m}} & \text{otherwise} \end{cases} \tag{5}$$

keyword `sst_ice`**:**

$$T_{\text{surf}} = \begin{cases} T_{\text{m}} - 1.9\,\text{K} + 27\,\text{K}\left(1 - (\sin(3\phi/2))^2\right) & \text{for all} \quad -\pi/3 < \phi < \pi/3 \\ T_{\text{m}} - 1.9\,\text{K} & \text{otherwise} \end{cases} \tag{6}$$

keyword `sst_const`**:**

$$T_{\text{surf}} = T_{\text{m}} + 29\,\text{K} \tag{7}$$

References

Neale, R. and B. Hoskins, 2001a: A standard test for AGCMs including their physical parametrizations. I: The proposal. *Atmos. Sci. Lett.*, **1**, doi:10.1006/asle.2000.0019.

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