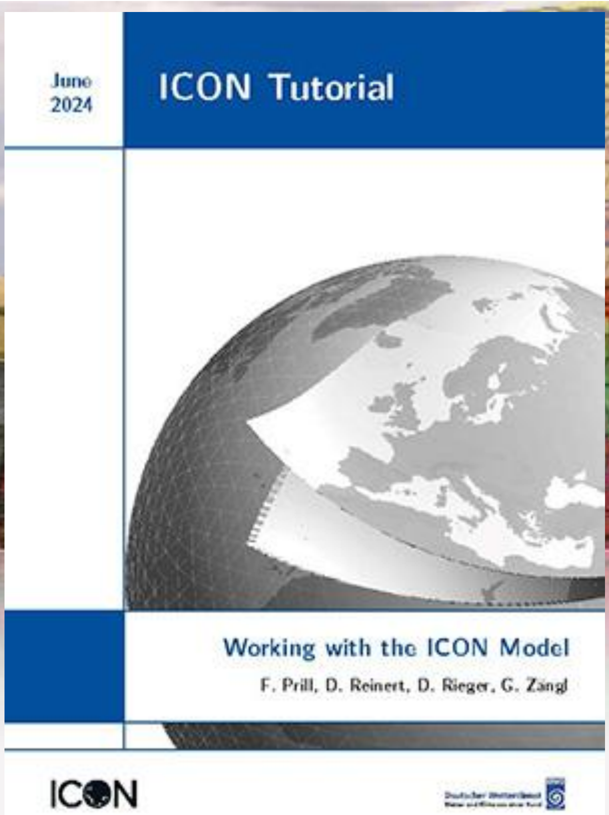
ICON land-surface processes and physiographic data

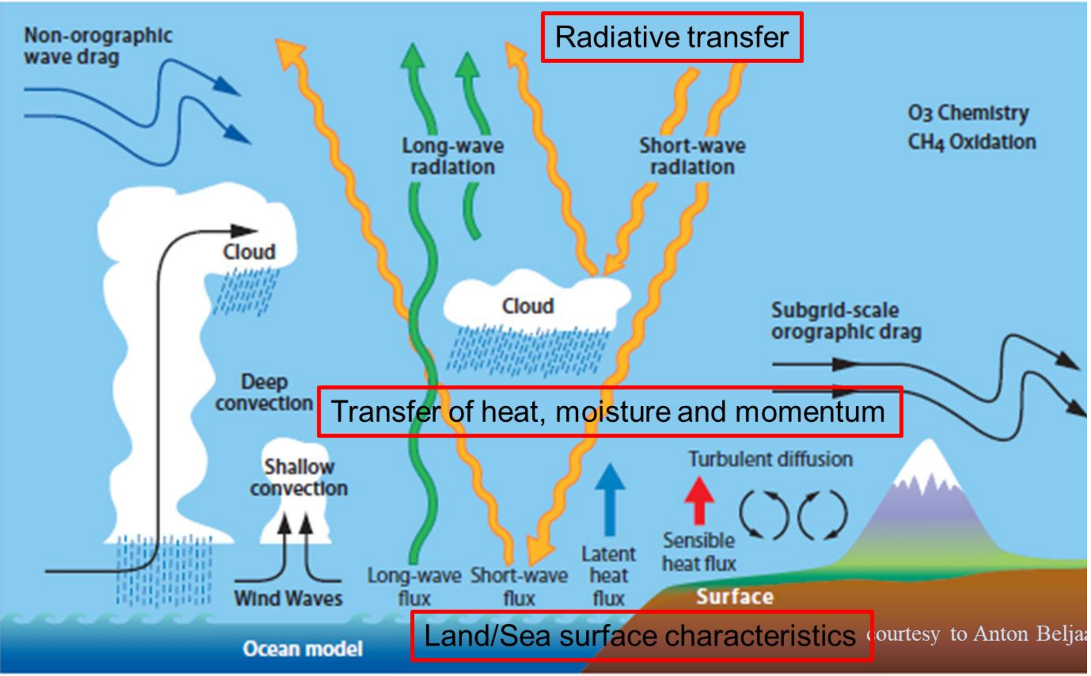
J. Helmert et al. | Numerical Model Training | May 2025

Motivation


June
2024
ICON Tutorial
Working with the ICON Model
F. Prill, D. Reinert, D. Rieger, G. Zängl
ICON


Numerical
Model Training Course
2025

- Parametrization schemes express the effect of subgrid/subscale processes on resolved variables – solving the closure problem



3.8.11. Land-Soil Model TERRA

Section author

J. Helmert, DWD Physical Processes Division

The soil-vegetation-atmosphere-transfer component TERRA (Schrodin and Heise, 2001, Heise et al., 2006, Schulz et al., 2016) in the ICON model is responsible for the exchange of fluxes of heat, moisture, and momentum between land surface and atmosphere. It establishes the lower boundary-condition for the atmospheric circulation model and considers the energy and water budget at the land surface fractions of grid points. Based on a multi-layer concept for the soil, TERRA considers the following physical processes at each of the tiled land-surface columns, where an uniform soil type with physical properties is assumed:

Radiation

- Photosynthetically active radiation (PAR) is used for plant evapotranspiration
- Solar and thermal radiation budget is considered in the surface energy budget

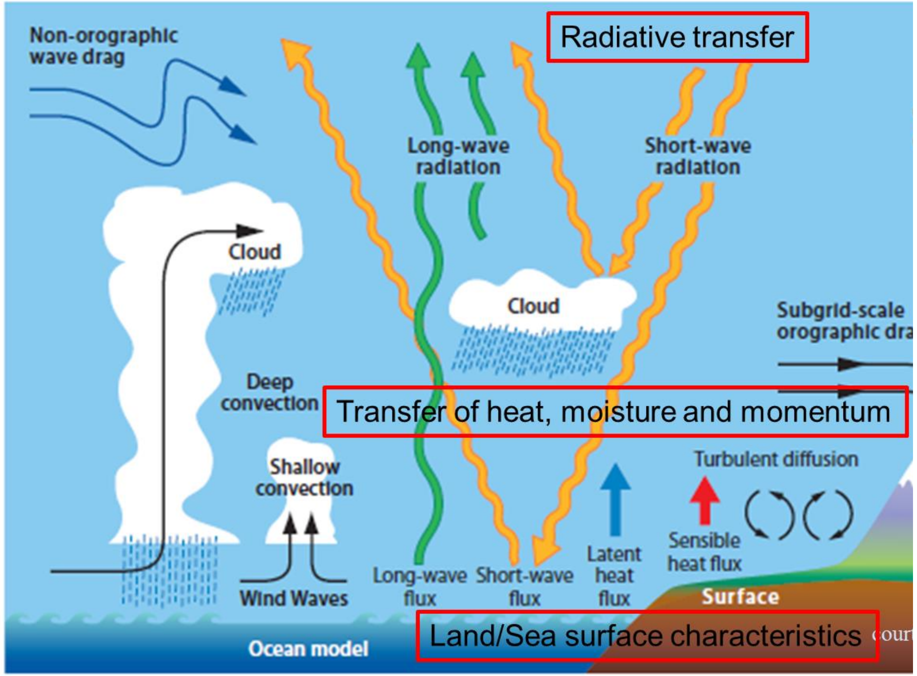
Biophysical control of evapotranspiration

- Stomatal resistance concept controls the interchange of water between the atmosphere and the plant
- One-layer vegetation intercepts and hold precipitation and dew, which lowers water input to the soil and enhances evaporation
- Roots with root-density profile determines the amount of water available for evapotranspiration in the soil
- Bare-soil evaporation is considered for land-surface fractions without plants.

Heat and soil-water transport

- Implicit numerical methods are used to solve the vertical soil water transport and soil heat transfer between the non-equidistant layers.
- In the operational model version seven layers are used in the soil.

- Parametrization schemes express the effect of subgrid/subscale processes on resolved variables – solving the closure problem



- The lower boundary condition for the heat conduction equation is provided by the climatological mean temperature.
- Surface and sub-surface runoff of water is considered.
- The lower boundary condition is given by a free-drainage formulation.
- A rise of groundwater into the simulated soil column is not represented.
- Soil heat conductivity depends on soil-water content.
- Freezing of soil water and melting of soil ice is considered in hydraulic active soil layers.

Snow

- TERRA offers a one-layer snow model (operational in ICON-NWP) and a multi-layer snow model option (for experiments).
- A prognostic snow density, and snow melting process as well as the time dependent snow albedo are considered
- Surface fractions partly covered with snow are divided in snow-free and snow-covered parts (snow tiles)

Coupling to the atmosphere

- Application of the turbulence scheme at the lower model boundary
- Roughness length for scalars implicitly considered by calculation of an additional transport resistance throughout the turbulent and laminar roughness layer.

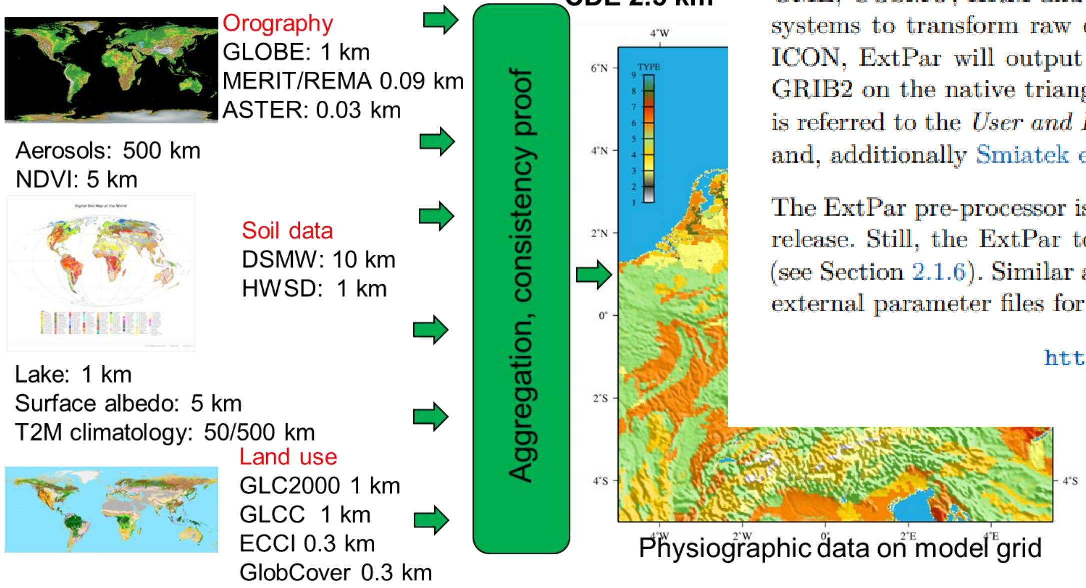
TERRA requires a number of external parameter fields, see Section 2.4 for details.

EXTPAR

Physiographic data

Physiographic data

NWP and Climate models: e.g. ICON R02B07 13 k CDE 2.5 km



Physiographic data on model grid

2.4.1. ExtPar Software

The ExtPar software (ExtPar – External Parameters for numerical weather prediction and climate application) is able to generate external parameters for the different models GME, COSMO, HRM and ICON. Experienced users can run ExtPar on UNIX or Linux systems to transform raw data from various sources into domain-specific data files. For ICON, ExtPar will output the fields given in Table 2.3 in the NetCDF file format and GRIB2 on the native triangular grid. For a more detailed overview of ExtPar, the reader is referred to the *User and Implementation Guide* of ExtPar, Asensio and Messmer (2014), and, additionally Smiatek et al. (2008, 2016).

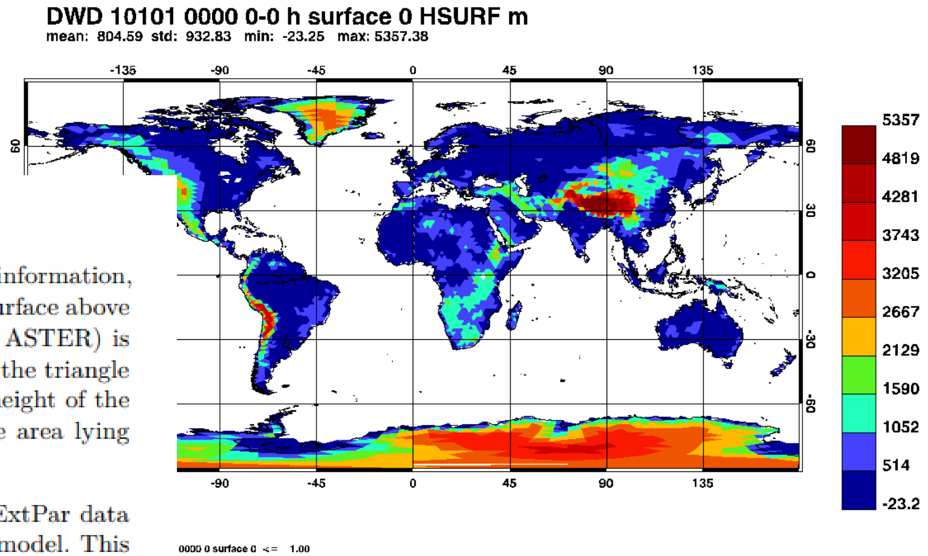
The ExtPar pre-processor is a COSMO software and not part of the ICON training course release. Still, the ExtPar tool can be accessed via the ICON grid generator web service (see Section 2.1.6). Similar as for the grid files, for fixed domain sizes and resolutions some external parameter files for the ICON model are available for download via

`http://icon-downloads.mpimet.mpg.de`

2.4.2. Topography Information

Among various other fields, the external parameter files provide topography information, see Table 2.3. The HSURF dataset contains the geometric height of the earths surface above sea level (unit: m), where the raw data of the terrain model used (GLOBE, ASTER) is aggregated over the grid box/triangle and the aggregated value is assigned to the triangle center point. Therefore, HSURF is *not* identical to the specific mean sea level height of the point lying under the center of the triangle or the maximum altitude of the area lying under the triangle (as e.g. in aeronautical charts).

Besides, please note the following remark: The topography contained in the ExtPar data files is in general *not identical* to the topography data which is used by the model. This is because at start-up, after reading the ExtPar data, the topography field is optionally filtered by a smoothing operator (`n_iter_smooth_topo >0` in `extpar_nml`). Therefore, for post-processing purposes it is necessary to specify and use the topography height `topography_c` (GRIB2 short name HSURF) from the model output (cf. Section 7 and Appendix B). The same applies to the fields DEPTH_LK, FR_LAND, FR_LAKE, and Z0, which are unconditionally modified by ICON.



2.4.3. Additional Information for Surface Tiles

ExtPar data files are available for download with and without additional information for surface tiles. See Section 3.8.11 for details on the tile approach.

ExtPar files suitable for the tile approach are indicated by the suffix `_tiles`. They are also applicable when running the model without tiles. ExtPar files without the suffix "`_tiles`", however, must only be used when running the model without tiles (`ntiles` = 1, namelist `lnd_nml`).

The data files do not differ in the number or type of fields, but rather in the way some fields are defined near coastal regions. Without the `_tiles` suffix, various surface parameters (e.g. `SOILTYP`, `NDVI_MAX`) are only defined at so-called dominant land points, i. e. at grid elements where the land fraction exceeds 50%. With the `_tiles` suffix, however, these parameters are additionally defined at cells where the land fraction is below 50%. By this, we allow for mixed water-land points. The same holds for the lake depth (`DEPTH_LK`) which is required by the lake parameterization scheme FLake. For files without the `_tiles` suffix, `DEPTH_LK` is only defined at dominant lake points.

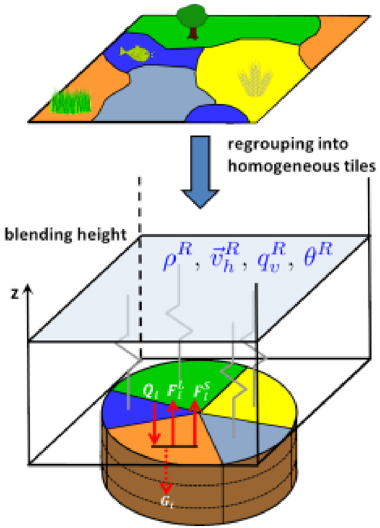
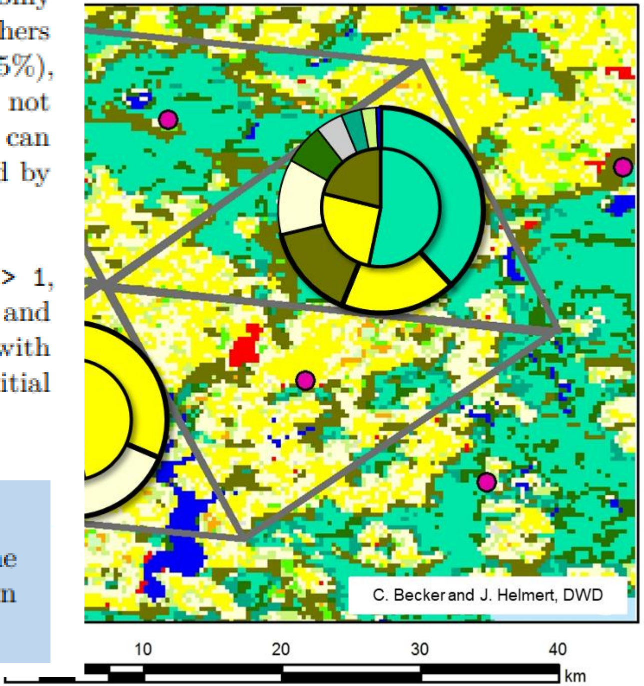


Figure 3.11.: Tile approach for a grid cell containing various surface types. Patches of the same surface type within a grid box are regrouped into homogeneous classes (tiles) for which the soil and surface parameterizations are run separately.

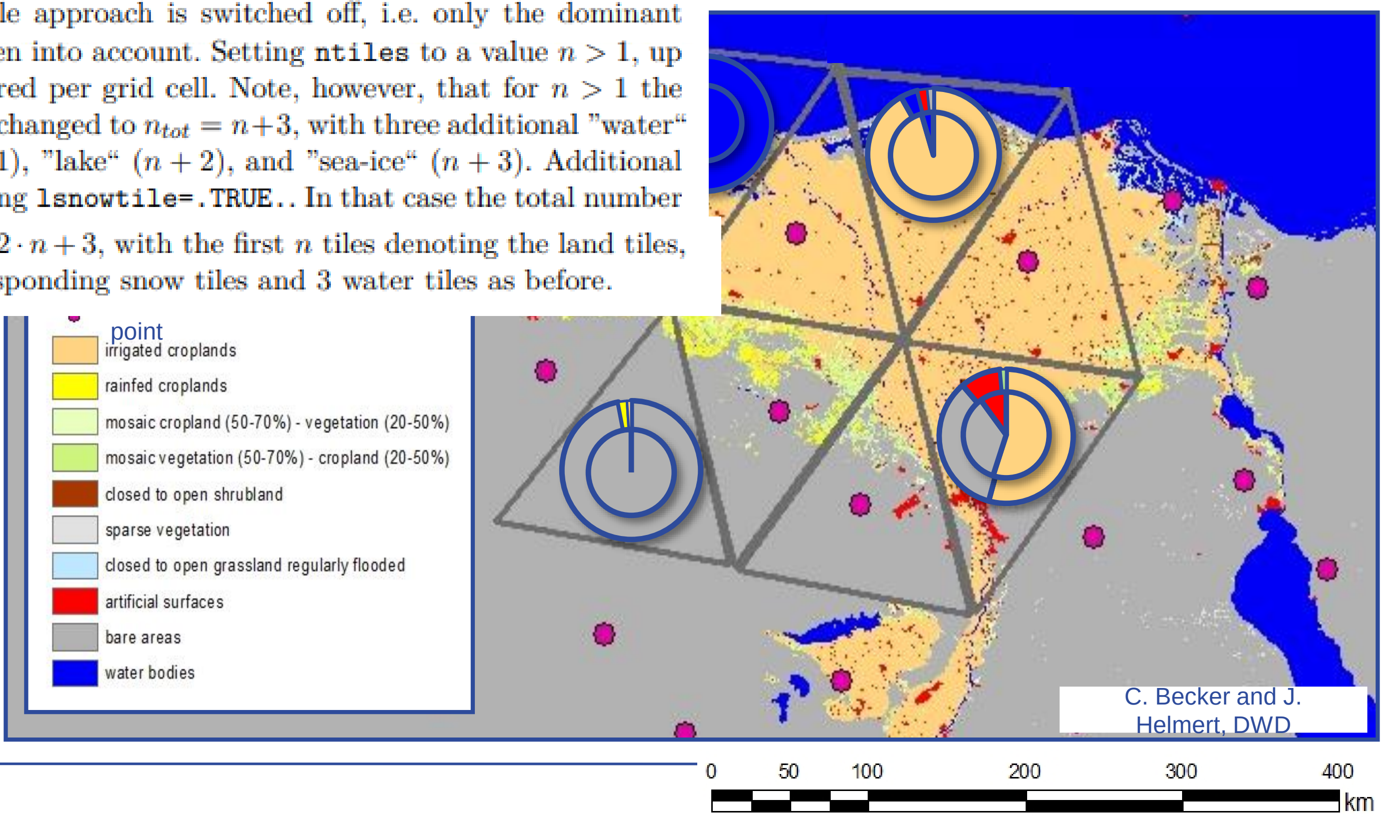
The process of tile generation in ICON works as follows:
During the setup phase, all land-surface types within a grid box are ranked according to the fractional area f they cover (see Figure 3.12, outer ring). For efficiency reasons, only the `ntiles` (typically about 3) dominating ones are represented by tiles, with the others being discarded (inner ring). If a grid cell contains non-negligible water bodies ($f > 5\%$), up to 3 more tiles are created (i.e. open water, lake, and sea-ice) even if they are not among the dominating ones. By this approach, the surface types represented by tiles can differ from grid cell to grid cell such that the full spectrum of surface types provided by the land cover data set is retained.

If the model is initialized from horizontally interpolated initial data and `ntiles > 1`, a tile coldstart becomes necessary. This can be done by setting `ltile_init=.TRUE.` and `ltile_coldstart=.TRUE.` in the namelist `initicon_nml`. Each tile is then initialized with the same cell averaged value. Note that `ltile_init=.TRUE.` is only necessary, if the initial data come from a model run without tiles.

> *Important note:*
> Naive horizontal interpolation of tile-based variables is incorrect, since the dominant tiles and/or their internal ranking will most likely differ between source and target cell. Only aggregated fields can be interpolated!



In ICON, the number of surface tiles is specified by the parameter `ntiles` (`lnd_nml`). Setting `ntiles=1` means that the tile approach is switched off, i.e. only the dominant land-surface type in a grid cell is taken into account. Setting `ntiles` to a value $n > 1$, up to n dominant land tiles are considered per grid cell. Note, however, that for $n > 1$ the total number of tiles n_{tot} is implicitly changed to $n_{tot} = n+3$, with three additional "water" tiles classified as "open water" $(n+1)$, "lake" $(n+2)$, and "sea-ice" $(n+3)$. Additional snow-tiles can be switched on by setting `lsnowtile=.TRUE.`. In that case the total number of tiles is further expanded to $n_{tot} = 2 \cdot n + 3$, with the first n tiles denoting the land tiles, the second n tiles denoting the corresponding snow tiles and 3 water tiles as before.

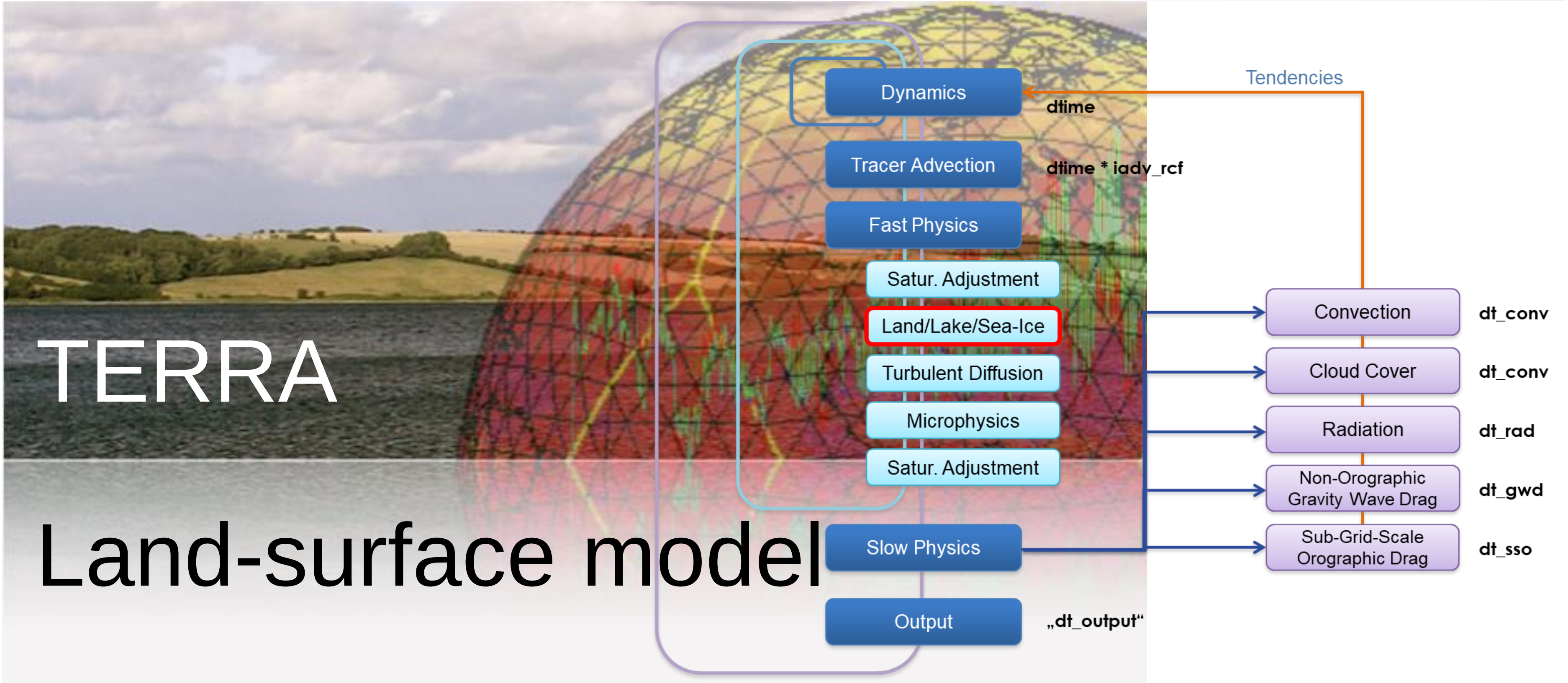


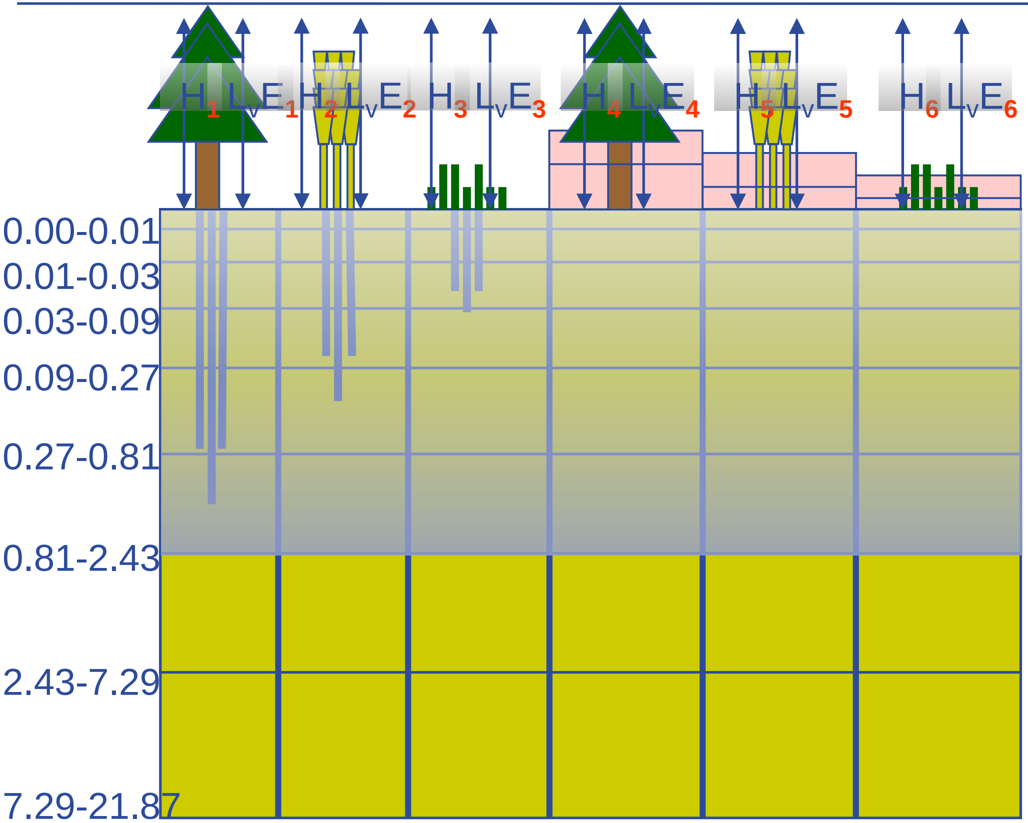
Summary - EXTPAR

- ExtPar software generates external parameters for weather and climate models COSMO, HRM, and ICON.
- It can transform raw data into domain-specific data files on UNIX or Linux systems.
- For ICON, ExtPar outputs specific fields in the NetCDF and GRIB2 formats on the native triangular grid.
- The tool can be accessed via the ICON grid generator web service, and some external parameter files for the ICON model are available for download.
- The HSURF dataset in the external parameter files provides topography information, but it is not identical to the topography data used by the model because it is optionally filtered by a smoothing operator at start-up.
- For post-processing purposes, it is necessary to use the topography height from the model output and some other fields, which are unconditionally modified by ICON.

TERRA

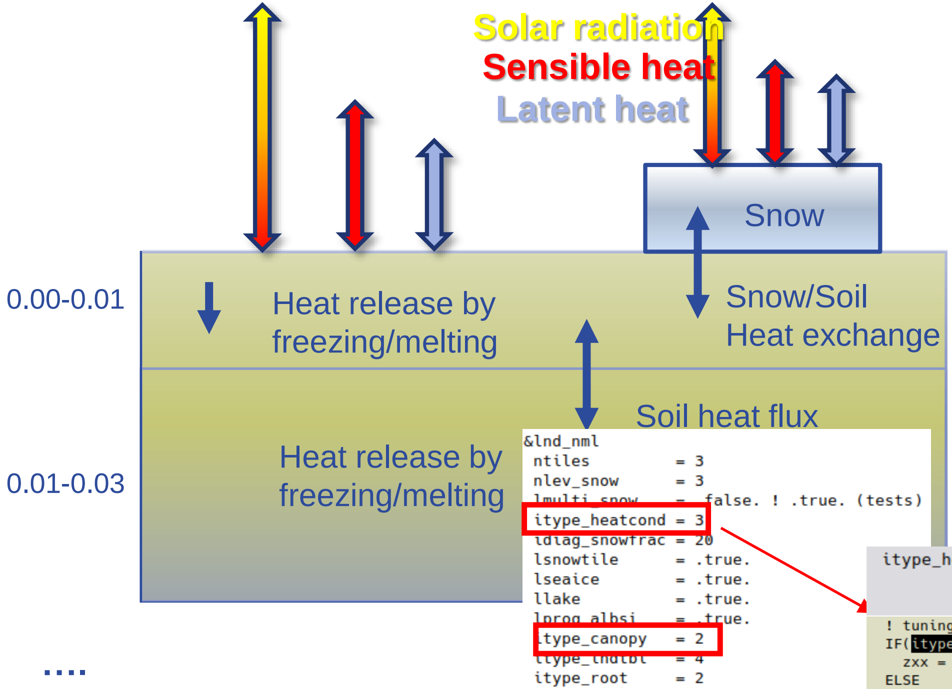
Land-surface model






```
&lnd_nml
 ntiles          = 3
 nlev_snow       = 3
 lmulti_snow     = .false. ! .true. (tests)
 itype_heatcond  = 3
 idiag_snowfrac  = 20
 lsnowtile       = .true.
 lseaice         = .true.
 llake           = .true.
 lprog_albsi     = .true.
 itype_canopy    = 2
 itype_lndtbl    = 4
 itype_root      = 2
 itype_evsl      = 4
 itype_trvg      = 3
 cwimax_ml       = 5.e-4
 c_soil          = 1.25
 c_soil_urb      = 0.5
 sstice_mode     = 2
 lbottom_hflux   = .true.
 itype_snowevap  = 3
/
```

TERRA – Energy budget




```
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 itype_trvg      = 3
 cwimax_ml       = 5.e-4
 c_soil          = 1.25
 c_soil_urb      = 0.5
 sstice_mode     = 2
 lbottom_hflux   = .true.
 itype_snowevap = 3
/
```

Thermal processes

$$\frac{\partial T_{so}}{\partial t} = \frac{1}{(\rho c)} \frac{\partial}{\partial z} \left(\lambda \frac{\partial T_{so}}{\partial z} \right)$$

Evolution of the soil temperature

$$\left(\frac{\partial T_{so}}{\partial t} \right)_{k=1} = \frac{1}{\rho c \Delta z_1} \left[\boxed{\lambda} \frac{(T_{so})_{k=2} - (T_{so})_{k=1}}{z_{m,2} - z_{m,1}} + G_{sfc} \right]$$

Evolution of the soil temperature layer 1

$$G_{sfc} = c_p \hat{H}^3_{sfc} + L(F^3_{q^v})_{sfc} + Q_{rad,net} + G_P + G_{snow,melt}$$

Surface forcing

```
itype_heatcond = 2        ! type of soil thermal conductivity (see Schulz et al. 2016)
                          !  1: vertically constant, representing a mean soil water content
                          !  2: dependent on soil water content in each layer (Johansen 1975)
```

```
! tuning factor to indirectly account for the impact of vegetation, which does not depend on soil moisture
IF(itype_heatcond == 3 .AND. zmls(kso) < 0.075_wp) THEN
  zxx = 12.5_wp*(0.075_wp-zmls(kso))*zzz
ELSE
  zxx = 0.0_wp
ENDIF
hzalam(i,kso) = heatcond_fac(i)*(zKe*(zlamsat - zlamdry) + zlamdry)*(1._wp-zxx) + zxx*0.06_wp

! heat conductivity is also artificially reduced on snow-free forest-covered tiles generated
! by the melting-rate parameterization
IF (tsnred(i) < -1.0_wp .AND. z0(i) >= 0.2_wp) THEN
  zxx = MAX(0.0_wp,2.0_wp - ABS(tsnred(i)))
  hzalam(i,kso) = zxx*hzalam(i,kso) + (1.0_wp-zxx)*0.06_wp
ENDIF
```

- Skin temperature formulation (Viterbo and Beljaars, 1995) was implemented (Schulz and Vogel, 2020) in TERRA to improve systematic model deficiencies (underestimated diurnal temperature range at the surface)
- Skin temperature formulation comprises a canopy description of intermediate level of complexity

$$\Lambda_{\mathrm{sk}}(T_{\mathrm{sk}} - T_{\mathrm{s}}) = R_{\mathrm{SW}} + R_{\mathrm{LW}} + LE + H$$

The behavior of an equation is determined by the parameter Λ_{sk}, the skin layer conductivity.

- Small values of Λ_{sk} describe a weak coupling, allowing for T_{sk} to have a considerably larger diurnal cycle than Ts. This can cause leaves to become warmer during the day and cooler at night
- In the current implementation of the skin temperature formulation in TERRA, grid elements covered with snow are excluded

```
itype_canopy          ! type of canopy parameterisation with respect to the surface energy balance
                      !  1: surface energy balance equation solved at the ground surface,
                      !     canopy energetically not represented
                      !  2: skin temperature formulation by Schulz and Vogel (2020),
                      !     based on Viterbo and Beljaars (1995)
```

References:

Schulz, J.-P. and G. Vogel, 2020: Improving the processes in the land surface scheme TERRA: Bare soil evaporation and skin temperature. *Atmosphere*

Viterbo, P. and A. C. M. Beljaars, 1995: An improved land surface parameterization scheme in the ECMWF model and its validation. *J. Climate*, **8**, 2716–2748.

Änderungsmitteilung operationelles NWV-System 2020-05-19

Snow

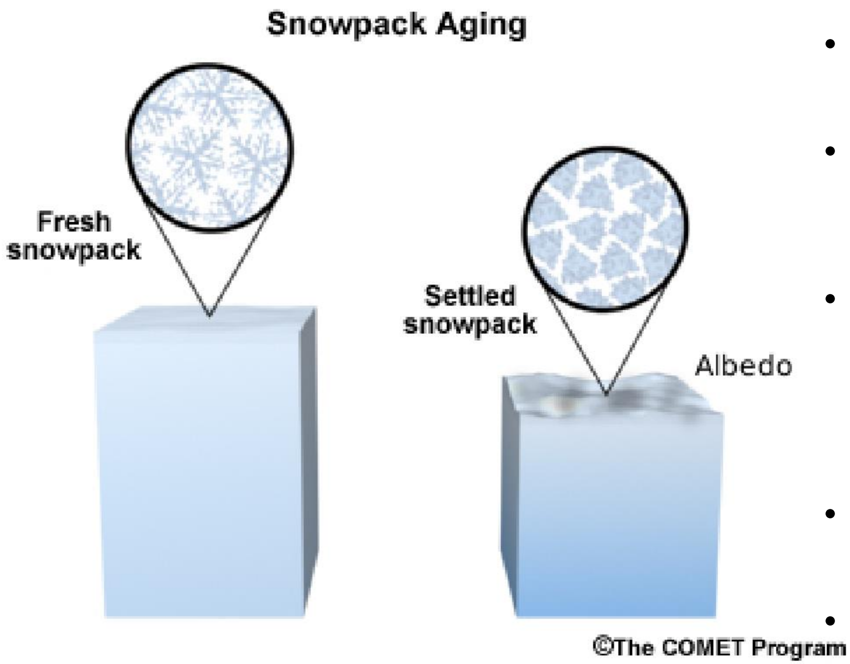


Figure: Snow Processes (COMET® Website at http://meted.ucar.edu/)

- Insulation effect: Decoupling of soil from atmosphere (30%-90% of the snow mantle is air)
- Albedo Effect: Higher albedo than any other natural surface (0.4-0.85 for bare ground/low vegetation, 0.2-0.33 for snow in forests)
- Snow melting prevents rise of surface temperature above 0°C for a long period in spring – impact on hydrological cycle and energy budget at surface

Snow Model

- One layer – prognostic variables : snow temperature, snow water equivalent, snow density, snow albedo
- Multi-layer – Vertical profiles in snow pack; considers equations for the snow albedo, snow temperature, density, *total* water content and content of *liquid* water. Therefore phase transitions in the snow pack are included.

Thermal processes for snow

$$\frac{\partial T_{snow}}{\partial t} = \frac{1}{(\rho c \Delta z)_{snow}} \left(G_{snow,sfc} - G_{snow} + G_{melt}\right)$$

Evolution of the snow temperature

$$G_{snow} = \lambda_{snow} \frac{T_{snow,sfc} - T_{sfc}}{\Delta z_{snow}}$$

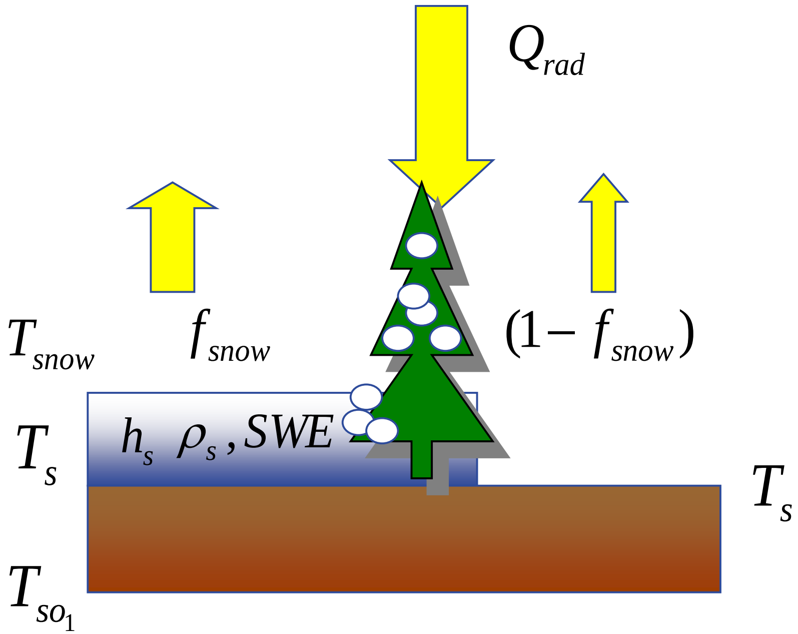
$$\lambda_{snow} = \lambda_{ice} \frac{\rho_{snow}}{\rho_w}^{1.88}$$

Heatflux through the snow

$$G_{sfc} = (1 - f_{snow}) \cdot \left(c_p \hat{H}^3_{sfc} + L(F^3_{q^v})_{sfc} + Q_{rad,net}\right) + f_{snow} \cdot G_{snow}$$

Surface forcing

Snow



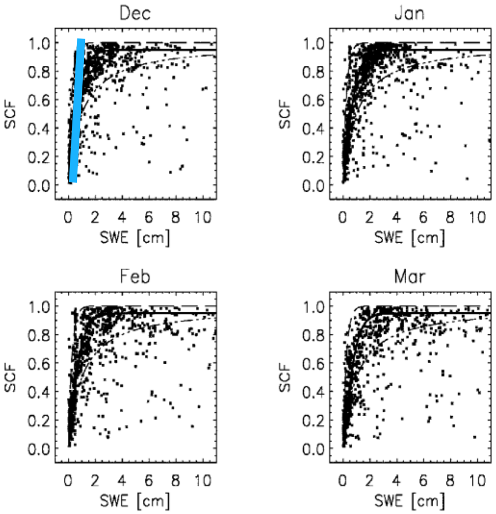


Fig. 3 SCF as a function of SWE in flat, non-forested T106 grid cells. SWE interpolated from USAF snow depth climatology; SCF from NOAA data (1973–1996). Curves are displayed for the new parametrization (*solid thick line*, Eq. 6), "Europa-Modell" (EM, *long-dashed*) and ECHAM (*dash-dotted*, Eq. 2)

$$f_{snow} = \frac{SWE}{0.015m}$$

$$f_{snow} = f(h_{snow}, SSO, landuse, freshsnow)$$

Roesch et al., 2001

Snow


```
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 itype_trvg      = 3
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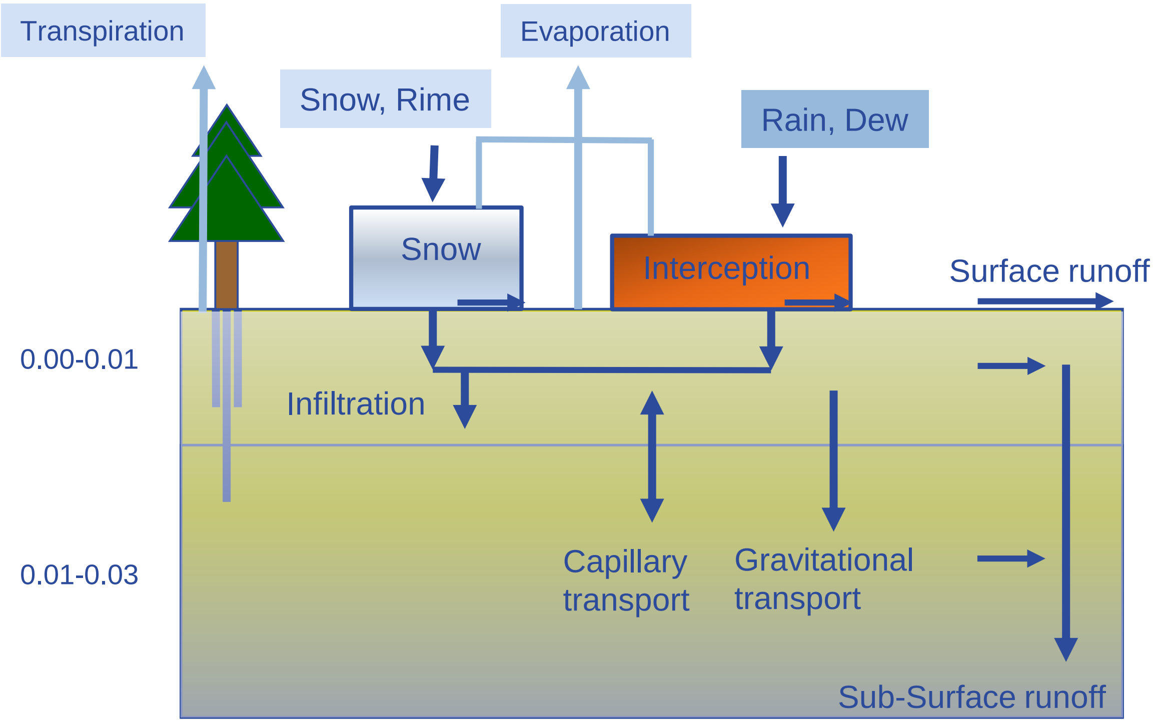
 c_soil          = 1.25
 c_soil_urb      = 0.5
 sstice_mode     = 2
 lbottom_hflux   = .true.
 itype_snowevap  = 3
/
```

- ‘Old’ tuning measure introduced several years ago: Artificial reduction of snow-cover fraction of melting snow, creating a snow-free tile or enhancing its fractional area
- New: Parameterization of temperature difference between snow and dark vegetation elements depending on differential radiation absorption and saturation deficit
- Further developed variant of evaporation tuning using (in addition) snow age and maximum snow depth during snow accumulation period to parameterize the difference between the accumulation phase and the melting phase

G. Zängl, ICCARUS, 2019

TERRA – Water budget



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 lbottom_hflux   = .true.
 itype_snowevap  = 3
/
```

Hydrological processes

W_i, W_{snow}	water content of interception and snow store, resp. $[m\ H_2O]$
$W_{l,k}$	liquid water content of soil layers $[m\ H_2O]$
$W_{ice,k}$	ice content of soil layers $[m\ H_2O]$
E_i, E_{snow}	evaporation from interception and snow store, resp. $[kg/(m^2 s)]$
E_b	evaporation from bare soil $[kg/(m^2 s)]$
Tr_k	water extraction by roots $[kg/(m^2 s)]$
P_r, P_{snow}	precipitation rate of rain and snow, resp. $[kg/(m^2 s)]$
α	factor for distributing rain between interception store and infiltration $[-]$
I_{perc}, I_{snow}	infiltration contributions from percolation and from melting snow, resp. $[kg/(m^2 s)]$
$R_{inter}, R_{infil}, R_{snow}$	runoff from interception store, from limited infiltration rate and from snow store, resp. $[kg/(m^2 s)]$
R_1, R_k	runoff from soil layers $[kg/(m^2 s)]$
$F_{k,k+1}$	gravitational and capillary flux of water between layers $k+1$ and k $[kg/(m^2 s)]$
S_k	source term of liquid water by melting soil ice

Hydrological processes

$$\rho_w \frac{\partial W_i}{\partial t} = \alpha \cdot P_r + E_i - I_{perc} - R_{inter},$$

Interception store

$$\rho_w \frac{\partial W_{snow}}{\partial t} = P_{snow} + E_{snow} - R_{snow} - I_{snow},$$

Snow store

$$\begin{aligned}\rho_w \frac{\partial W_{l,k}}{\partial t} &= \delta_{1,k}[E_b + I_{snow} + I_{perc} + (1-\alpha)P_r - R_{infil}] \\ &+ F_{k,k+1} - (1-\delta_{1,k})F_{k-1,k} + Tr_k - R_k + S_k,\end{aligned}$$

Soil water

$$\rho_w \frac{\partial W_{ice,k}}{\partial t} = -S_k,$$

Soil ice

TERRA – Water budget

$$\frac{\partial w_l}{\partial t} = \frac{1}{\rho_w} \frac{\partial F}{\partial z}$$

Evolution of the soil liquid water fraction

$$F = -\rho_w \left[-D_w(w_l) \frac{\partial w_l}{\partial z} + K_w(w_l) \right]$$

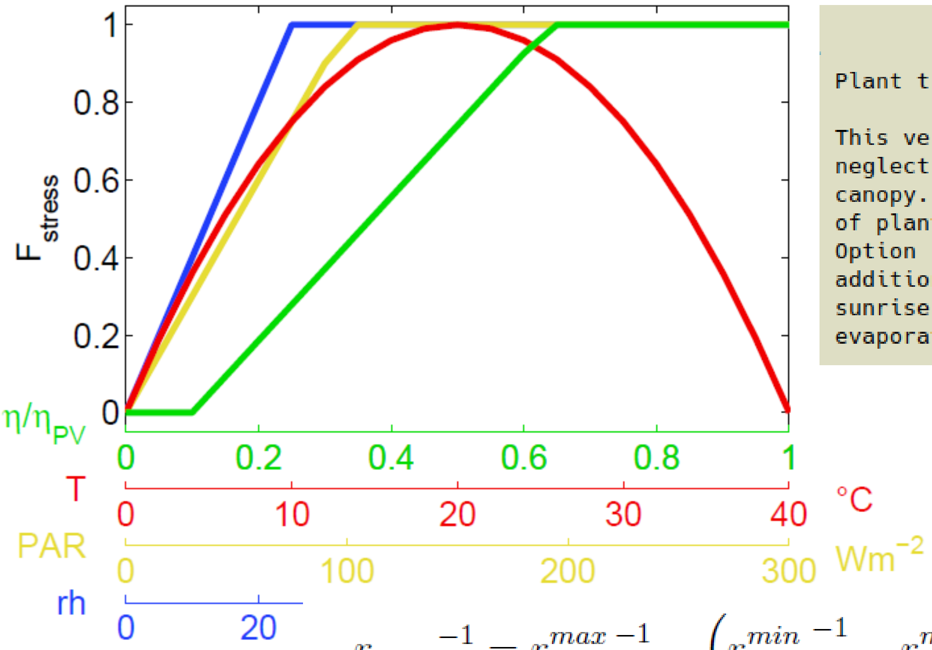
Richards equation
for the water flux

$$D_w(w_l) = D_0 \;\; exp \;\; \left[D_1 (w_{PV} - \bar{w}_l)/(w_{PV} - w_{ADP}) \right]$$

$$K_w(w_l) = K_0 \;\; exp \;\; \left[K_1 (w_{PV} - \bar{w}_l)/(w_{PV} - w_{ADP}) \right]$$

Hydraulic diffusivity and conductivity are soil type dependent

TERRA – Water budget



Plant transpiration, BATS version.

This version is based on Dickinson's (1984) BATS scheme, simplified by neglecting the water and energy transports between the soil and the plant canopy. This leads to a Monteith combination formula for the computation of plant transpiration.
Option itype_trvg=TRVG_BATS_EXT (=3) is an extended variant with an additional diagnostic variable for accumulated plant evaporation since sunrise, allowing for a better representation of the diurnal cycle of plant evaporation (in particular trees). (G. Zängl, 2017)

$$r_{stom}^{-1} = r_{stom}^{max\ -1} - \left(r_{stom}^{min\ -1} - r_{stom}^{max\ -1}\right) F_{rad} F_{\eta} F_{tem} \boxed{F_{hum}}$$

(Ament, 2006)

```
itype_interception        ! type of plant interception
cwimax_ml                 ! scaling parameter for maximum interception storage. Almost turned off by default;
                          ! the recommended value to activate interception storage is 5.e-4
c_soil                    ! surface area density of the (evaporative) soil surface
c_soil_urb                ! surface area density of the (evaporative) soil surface, urban areas
```

Summary - TERRA

- TERRA is a component of the ICON model responsible for the exchange of heat, moisture, and momentum between land surface and atmosphere.
- It establishes the lower boundary condition for the atmospheric circulation model and considers the energy and water budget at the land surface.
- TERRA uses a multi-layer concept for the soil and considers physical processes such as radiation, biophysical control of evapotranspiration, and heat and soil-water transport.
- It also offers a one-layer snow model and a multi-layer snow model option.
- The tile approach is used to calculate proper cell-averaged surface fluxes in the case of large subgrid variations in surface characteristics.

ICON

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Jürgen Helmert
FE14
juergen.helmert@dwd.de

Questions?