

MODIS-simulator for process-oriented climate model evaluation

Johannes Quaas, Max Planck Institute for Meteorology
johannes.quaas@zmaw.de

Deliverable D1.2: Final version of MODIS simulator

The MODIS-simulator is publicly available at

http://wiki.esipfed.org/index.php/Indirect_forcing#.E2.80.9CSatellite_simulator.E2.80.9D

Abstract

A tool is presented that allows for a comparison of climate-model simulated cloud and aerosol fields with retrievals by MODIS and other spaceborne passive radiometers. The tool considers three steps: (i) the sampling of cloud-top quantities using the model's cloud overlap hypothesis, (ii) the satellite instrument sensitivity by discarding clouds with little cloud fraction or optical depth, and (iii) the diurnal sampling by taking into account the satellite overpass time for polar-orbiting satellites. The tool is easy to implement and easy to use, and has been tested widely.

Introduction

A major problem in general circulation models (GCMs) is the need to parameterise diabatic subgrid-scale processes such as cloud processes. Such statistical descriptions of non-linear processes are frequently derived as empirical formulations from process-scale observations, or high-resolved models, and need further evaluation when implemented in a large-scale model (e.g., Lohmann et al., 2007). Satellite data are well suited for such an evaluation since they cover large space and time scales. However, it has been recognised since long that satellite-retrieved physical quantities may be defined slightly differently than the corresponding quantities in a GCM, and that characteristics of the satellite instrument have to be taken into account (e.g., Klein and Jacob, 1999). For this purpose, "satellite simulators" have been introduced, which reprocess model fields to generate physical quantities fully consistent with the satellite retrievals. A prominent example is the "International Satellite Cloud Climatology Project (ISCCP) simulator" (Klein and Webb, 2009).

Since several years, the problem of aerosol indirect effects, or the radiative forcing by anthropogenic aerosols by modifying cloud properties, has emerged as a major uncertainty in simulating global climate change (e.g., Lohmann et al., 2007). In order to evaluate the parameterisation of aerosol indirect effects in GCMs, satellite data are useful, and for such evaluations, a satellite simulator is needed considering cloud microphysical quantities and aerosols (e.g., Quaas et al., 2004). A tool fulfilling this purpose at little cost is presented here. The tool has been used widely, and is implemented in ten GCMs for an intercomparison study on aerosol indirect effects (Quaas et al., 2009).

The MODIS simulator

The tool follows three steps to render modelled cloud fields comparable to the satellite retrievals. Firstly, cloud-top quantities are sampled, secondly, the instrument sensitivity is taken into account, and thirdly, the overpass time of the polar-orbiting satellite is simulated.

1. Sampling cloud-top fields

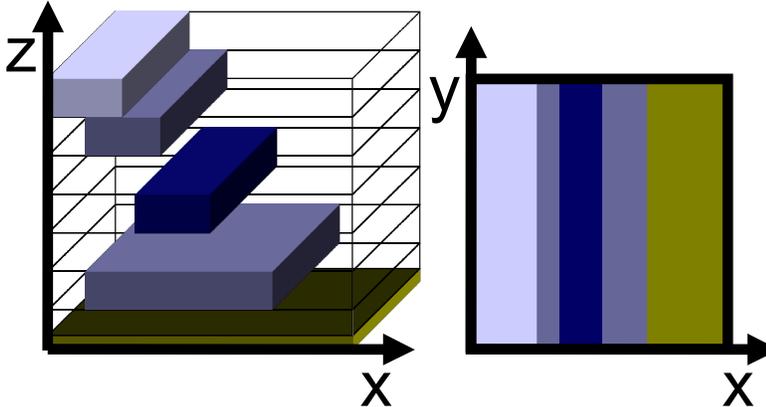


Fig. 1: Projection of cloud-top quantities, here for a random-maximum overlap assumption.

In many satellite simulators, in order to sample cloud-top quantities, each grid column is divided into sub-columns which in each layer are either completely clear or overcast. These subcolumns can be generated from any subgrid-scale information available, yet, usually, just the cloud overlap assumption for fractional cloudiness in each layer is used. In the MODIS simulator presented here, the overlap assumption is applied directly in an analytical way, where a division into subcolumns is not necessary. Thus, the

sampling is more efficient. If $k=1,2,\dots,n_z$ is an index for the discrete vertical levels, from 1 at the top-of-the-atmosphere to n_z the surface level, x_k any cloud quantity to be sampled at cloud top, f_k the cloud fraction in layer k and F_l the projected cloud fraction (in case of random or maximum-random, the projected clear-sky fraction, or the complement to the cloud fraction) between the top-of-the-atmosphere and layer l , then, assuming the uppermost model level is cloud-free, the cloud-top quantity X is defined for

(i) a maximum-overlap assumption (i.e., two clouds in adjacent layers overlap as much as possible):

$$F_l = \max_{k=1}^l f_k$$

$$X = \sum_{k=2}^{n_z} [(F_k - F_{k-1}) \cdot x_k]$$

(ii) a random-overlap assumption (i.e., the probability of overlap for clouds in adjacent layers is given by the product of the two cloud fractions):

$$F_l = \prod_{k=1}^l (1 - f_k)$$

$$X = \sum_{k=2}^{n_z} [(F_{k-1} - F_k) \cdot x_k]$$

(iii) a maximum-random-overlap assumption (i.e., maximum overlap for clouds in adjacent layers, and random overlap for (blocks of) clouds separated by at least one completely clear layer):

$$F_l = \prod_{k=1}^l \frac{1 - \max(f_k, f_{k-1})}{1 - \min(f_{k-1}, 1 - \epsilon_f)}$$

$$X = \sum_{k=2}^{n_z} [(F_{k-1} - F_k) \cdot x_k]$$

2. Accounting for satellite instrument sensitivity

A passive satellite radiometer, identifying clouds by (i) a reflectance larger and (ii) an infrared brightness temperature colder than what would be expected for a clear-sky column, is unable to detect clouds which are either very small or optically very thin. A GCM, on the other hand, defines a cloud wherever any condensate is simulated. Very small or optically very thin clouds, thus, may not be

considered in the satellite simulator. In the MODIS simulator presented here, this is taken into account by defining each grid layer as clear, where either (i) cloud fraction is smaller than a threshold value, $f_k < \epsilon_f$ or (ii) cloud optical thickness, τ_c , is smaller than a threshold, $\tau_{c,k} < \epsilon_\tau$

with a choice of $\epsilon_f=0.001$ (0.1% cloudiness) and $\epsilon_\tau=0.3$ (Platnick et al., 2003).

3. Sampling the satellite overpass time

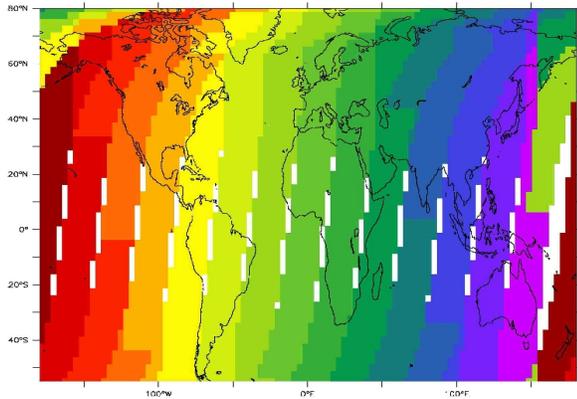


Fig. 2: Sampling the satellite overpass swath. In the MODIS simulator presented here, a simplified version is applied where the approximate local overpass time is taken into account rather than sampling the actual satellite instrument swath as depicted in this figure.

A polar-orbiting satellite like Aqua or Terra, on board of which spacecraft the MODIS instrument is operated, observes each point at the Earth's surface only at distinct intervals. For the swath of the scanning MODIS instrument, this is about once per day, except for high latitudes, where swaths overlap. Sensitivity studies show that a simulation of the exact orbit is unnecessary. As an approximation, here, it is chosen to select the longitudes of the model grid, where the local solar time is the approximate local overpass time of the respective satellite (10.30 a.m. for Terra, and 1.30 p.m. for Aqua, respectively) plus or minus one half of the model time step. A mask is created with which the fields generated by the MODIS simulator are weighted. The model output is then post-processed to take into account this masking.

Pseudo-Code

(1) Sampling of cloud-top quantities

- let $i=1,2,\dots,n_x$ be the index for the horizontal grid-points
- let $k=1,2,\dots,n_z$ be the index for the vertical levels, with 1 being the uppermost level, and n_z the surface level

naming convention for the 3D input fields:

- $iovl$ is the flag to select the overlap hypothesis
- $cod3d(n_x,n_z)$ cloud optical thickness
- $f3d(n_x,n_z)$ cloud fraction
- $t3d(n_x,n_z)$ temperature
- $phase3d(n_x,n_z)$ cloud thermodynamic phase (0: entire cloud consists of ice, 1: entire cloud consists of liquid water, between 0 and 1: mixed-phase)
- $cdr3d(n_x,n_z)$ cloud droplet effective radius
- $icr3d(n_x,n_z)$ ice crystal effective radius
- $cdnc3d(n_x,n_z)$ cloud droplet number concentration

`thres_cld = 0.001`

```

thres_cod = 0.3
IF ( iovl = random OR iovl = maximum-random ) THEN
  tcc(i) = 1.
ELSE
  tcc(:) = 0
ENDIF
icc(:) = 0
lcc(:) = 0
ttop(:) = 0
cdr(:) = 0
icr(:) = 0
cdnc(:) = 0

DO i=1,nx
  DO k=2,nz ! assumption: uppermost layer is cloud-free (k=1)
    IF ( cod3d(i,k) > thres_cod and f3d(i,k) > thres_cld ) THEN ! visible, not-too-small cloud
      ! flag_max is needed since the vertical integration for maximum overlap is different from the
      two others: for maximum, tcc is the actual cloud cover in the level, for the two others, the actual
      cloud cover is 1 - tcc
      ! ftmp is total cloud cover seen from above down to the current level
      ! tcc is ftmp from the level just above
      ! ftmp - tcc is thus the additional cloud fraction seen from above in this level

      IF ( iovl = maximum ) THEN
        flag_max = -1.
        ftmp(i) = MAX( tcc(i), f3d(i,k) ) ! maximum overlap
      ELSEIF ( iovl = random ) THEN
        flag_max = 1.
        ftmp(i) = tcc(i) * ( 1 - f3d(i,k) ) ! random overlap
      ELSEIF ( iovl = maximum-random ) THEN
        flag_max = 1.
        ftmp(i) = tcc(i) * ( 1 - MAX( f3d(i,k), f3d(i,k-1) ) ) / &
          ( 1 - MIN( f3d(i,k-1), 1 - thres_cld ) ) ! maximum-random overlap
      ENDIF
      ttop(i) = ttop(i) + t3d(i,k) * ( tcc(i) - ftmp(i) ) * flag_max
      ! ice clouds
      icr(i) = icr(i) + icr3d(i,k) * ( 1 - phase3d(i,k) ) * ( tcc(i) - ftmp(i) ) * flag_max
      icc(i) = icc(i) + ( 1 - phase3d(i,k) ) * ( tcc(i) - ftmp(i) ) * flag_max

      ! liquid water clouds
      cdr(i) = cdr(i) + cdr3d(i,j) * phase3d(i,k) * ( tcc(i) - ftmp(i) ) * flag_max
      cdnc(i) = cdnc(i) + cdnc3d(i,j) * phase3d(i,k) * ( tcc(i) - ftmp(i) ) * flag_max
      lcc(i) = lcc(i) + phase3d(i,k) * ( tcc(i) - ftmp(i) ) * flag_max

      tcc(i) = ftmp(i)
    ENDIF ! is there a visible, not-too-small cloud?
  ENDDO ! loop over k

  IF ( iovl = random OR iovl = maximum-random ) THEN
    tcc(i) = 1. - tcc(i)
  ENDIF
ENDDO ! loop over I

```

(2) Sampling of the satellite-overpass-time

To sample the overpass time of the satellite (13.30 h local time for the Aqua satellite), the idea is to create a mask (satmask) indicating whether or not at the grid-box the local time is $13.30 \text{ h} \pm \frac{1}{2}$ model-timestep. Then, all output fields are weighted with this mask (field * satmask), and in the output, the diurnal mean is taken. The physical fields at 13.30 h local time are obtained in post-processing by dividing each field by the mask (field / satmask). So, the diurnal mean of satmask must be stored as well!

naming convention for the input variables:

- utctime current time of the day in UTC in seconds
- time_step_len length of model time-step
- lon(nx) longitude in degrees from 0 to 360°

```

sat_mask(:) = 0
overpasstime = 48600 ! 13.30 p.m. local time

DO i=1,nx
  localtime(i) = utctime + 240 * lon ! for each degree of longitude east, 4 min
  earlier local time
  IF ( localtime(i) > 86400 ) THEN ! this is still the previous day
    localtime(i) = localtime(i) - 86400
  ENDIF

  ! Select 10.30 a.m. ± dt/2
  IF ( ABS( localtime(i) - overpasstime ) <= time_step_len/2 )
    sat_mask(i) = 1
  ENDIF

  ! Weight the output fields with this mask
  aod(i) = aod(i) * sat_mask(i)
  cdr(i) = cdr(i) * sat_mask(i)
  cdnc(i) = cdnc(i) * sat_mask(i)
  tcc(i) = tcc(i) * sat_mask(i)
  lcc(i) = lcc(i) * sat_mask(i)
  lwp(i) = lwp(i) * sat_mask(i)
  albs(i) = albs(i) * sat_mask(i)
  ssw(i) = ssw(i) * sat_mask(i)
  sswclr(i) = sswclr(i) * sat_mask(i)
  slw(i) = slw(i) * sat_mask(i)
  slwclr(i) = slwclr(i) * sat_mask(i)
  ttop(i) = ttop(i) * sat_mask(i)
  lts(i) = lts(i) * sat_mask(i)
  iwp(i) = iwp(i) * sat_mask(i)
  icr(i) = icr(i) * sat_mask(i)
  icc(i) = icc(i) * sat_mask(i)
  cod(i) = cod(i) * sat_mask(i)
  ccn(i) = ccn(i) * sat_mask(i)
ENDDO

```

In the diurnal-mean output files, the actual in-cloud fields are derived by

```

cdr' = cdr / lcc
cdnc' = cdnc / lcc
lwp' = lwp / lcc

ttop' = ttop / tcc

iwp' = iwp / icc
icr' = icr / icc

```

For all other fields, the actual values are derived by

```

aod' = aod / sat_mask

```

etc.

References

Klein, S. and C. Jacob, Validation and sensitivities of frontal clouds simulated by the ECMWF model. Mon. Wea. Rev., 127, 2514–2531, 1999.

Klein, S. and M. Webb, ISCCP simulator implementation instructions: Readme.

<http://cfmip.metoffice.com/README>, 2009.

Lohmann, U., J. Quaas, S. Kinne, and J. Feichter, Different approaches for constraining global climate models of the anthropogenic indirect aerosol effect, *Bull. Am. Meteorol. Soc.*, 88, 243–249, 2007.

Platnick, S., M. D. King, S. A. Ackerman, W. P. Menzel, B. A. Baum, J. C. Riédi, and R. A. Frey: The MODIS cloud products: Algorithms and examples from Terra, *IEEE Transactions on Geoscience and Remote Sensing*, 41, 459-473, 2003.

Quaas, J., O. Boucher, and F.-M. Bréon: Aerosol indirect effects in POLDER satellite data and in the LMDZ GCM, *J. Geophys. Res.* 109, D08205, doi:10.1029/2003JD004317, 2004.

Quaas, J., Y. Ming, S. Menon, T. Takemura, M. Wang, J. Penner, A. Gettelman, U. Lohmann, N. Bellouin, O. Boucher, A. M. Sayer, G. E. Thomas, A. McComiskey, G. Feingold, C. Hoose, J. E. Kristjánsson, X. Liu, Y. Balkanski, L. J. Donner, P. A. Ginoux, P. Stier, B. Grandey, J. Feichter, I. Sednev, S. E. Bauer, D. Koch, R. G. Grainger, A. Kirkevåg, T. Iversen, Ø. Seland, R. Easter, S. J. Ghan, P. J. Rasch, H. Morrison, J.-F. Lamarque, M. J. Iacono, S. Kinne, and M. Schulz, Aerosol indirect effects - general circulation model intercomparison and evaluation with satellite data, *Atmos. Chem. Phys.*, 9, 8697-8717, 2009.