Aerosol-Cloud-Precipitation-Climate (ACPC) Initiative:
Deep Convective Cloud Group Roadmap
Updated: October 2017

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Uncertainties in aerosol-cloud-precipitation interactions continue to limit the ability to predict and assess the impacts of aerosols on weather and climate on both short-term and long-term temporal scales (Tao et al., 2012; Fan et al., 2016). The goals of the ACPC initiative, and in particular the deep convective cloud group, are to increase our understanding of the impacts of aerosols on deep convective storms and to enhance the representation of these impacts in cloud-resolving models (CRMs) through global climate models (GCMs) through the utilization of a unique combination of observations and numerical experiments. A recent ACPC meeting held in April 2016 at the University of Oxford identified specific case studies of isolated deep convective clouds near Houston, Texas that will serve as the focal point of the deep convective cloud group's endeavor to address the short-term and long-term prognosis of aerosol impacts on convection.

The key science questions that will be addressed under this deep convective cloud (DCC) roadmap include:

- **SQ1:** What is the variability of the atmospheric response, both locally and regionally, to aerosol perturbations among different state-of-the-art CRMs?
- **SQ2:** What physical processes are the most significant contributors to aerosol-induced uncertainties in current CRMs, in terms of representing aerosol-cloud-precipitation-climate interactions?
- **SQ3:** What are the spatial and temporal observations required to calculate accurate estimates of energy, moisture, and aerosol fluxes on the scales of a GCM grid box?

Part I: Multi-Model Case Study Simulations

Some of the uncertainties in aerosol-cloud interactions can be attributed to the range of models that are used to study such interactions. Understanding the spread of responses (e.g., precipitation, cloud cover, radiative fluxes) to the same aerosol perturbation among a range of CRMs in a highly constrained experiment will assist in quantifying this uncertainty. Furthermore, inter-model comparisons along with model comparisons with observations will be used to determine biases in individual models, which in turn will be used to further the development of aerosol-cloud representations in CRMs.

The chosen case study focuses on isolated deep convection near Houston, Texas that occurred on 19-20 June 2013. The case is favorable for the study of aerosol interactions with deep convective clouds due to the isolated nature of deep convection on this day as well as the localized sources of aerosol particles evident in the region on this day. Case study simulations with clean and polluted aerosol conditions will be evaluated across an ensemble of CRMs. These proposed simulations are described in detail in the appendix. The simulations will be used to quantify the spread in the response to aerosol perturbations among the range of state-of-the-art CRMs (SQ1). In-depth analysis of individual convective cells and microphysical processes will provide the physical reasons for these results (SQ2). For example, convective cell tracking will be used to create composites of cloud lifecycles in relatively clean and polluted conditions to determine how different aerosol concentrations change the properties of the isolated deep convective clouds simulated. The methodology used and developed for this first case study could be extended to other cases should this be deemed desirable. Additional cases could include convective events in the same region, such as those observed during the SEAC4RS and Discover-AQ field campaigns in August - September 2013 (e.g., Toon et al. 2016), and convective events in other world regions developing under different large-scale conditions.

Part II: Observational Analysis

Observations will be used both in conjunction with the case study simulations, as described above, and separately as another tool to study aerosol-cloud interactions (SQ2). The chief objective will be to systematically establish observable differences in isolated convective microphysics where there is a substantial aerosol perturbation within a relatively uniform thermodynamical environment, and to evaluate to the best degree possible whether CRMs reproduce basic aspects of such signatures in simulations of clean and polluted conditions. Observational sources that will be utilized are the NEXRAD radar network, the Lightning Mapping Array (LMA), and various satellite instruments. These sources provide direct observations of variables that can be forward-simulated from CRM outputs, such as polarimetric variables available from the NEXRAD network, as well as derived microphysical quantities. The promise of the radar data in particular to address substantial uncertainties in CRM microphysics schemes of every type may motivate field campaign efforts to deploy mobile polarimetric radars capable of rapid scanning for updraft evolution studies. Satellite, LMA, and other measurements will be used to the degree possible to support analyses of radar observables. For instance, preliminary analysis of LMA measurements supports substantial differences in updraft evolution between polluted and clean areas in the Houston region.

Observations will be the limiting factor in evaluating CRM simulations. Our approach is therefore to bring simulations as close as possible to the narrow list of well-observed quantities. Our central focus will be on properties within or near updrafts where radars will provide the most quantitative data. First, we will compare 3D fields of precipitation rate and raindrop size distribution parameters retrieved from NEXRAD observations with those simulated. These analyses will be focused sufficiently below the melting level to avoid complications presented by ice. Focus throughout will be on the evolution of these variables during observed and simulated isolated convection evolution. Retrievals will be used at all elevations available to yield 3D structure of precipitation evolution to the maximum extent possible, allowing analysis of such factors as cell size as evidenced in the precipitation footprint. Second, we will compare 3D fields of reflectivity, differential reflectivity, and specific differential phase from NEXRAD observations with values forward calculated from simulations. It is expected that large uncertainties will remain in precise forward calculations but this approach will allow mining of extensive additional information about the 3D evolution of the liquid phase and cell structure that will be uniquely valuable for assessing the ability of CRMs to well simulate isolated convection under clean versus polluted conditions. We note that observations will contain updrafts within polluted and clean regions of a single observational domain, whereas simulations will contain clean or polluted conditions domain-wide in simulations that differ only in aerosol field. Initial analysis of NEXRAD observations indicates that aerosol differences do yield substantial differences in polarimetric radar signatures. Analysis of simulations will help to establish whether surface conditions, boundary layer depth associated with distance from shoreline, or other factors could contribute to such signatures downwind of the Houston urban region versus cleaner locations established from satellite retrievals of aerosol conditions. Whereas simulations may provide many cells to analyze over a relatively large model domain, the area within 100 km of a NEXRAD radar is a factor that limits observational statistics. Observational analysis will therefore also include radar, LMA, satellite data obtained on 8 June and 7 July 2013, which exhibited conditions similar to 19 June 2013. The latter was selected for the modeling case study owing to the most favorable conditions for simulating primarily isolated cells.

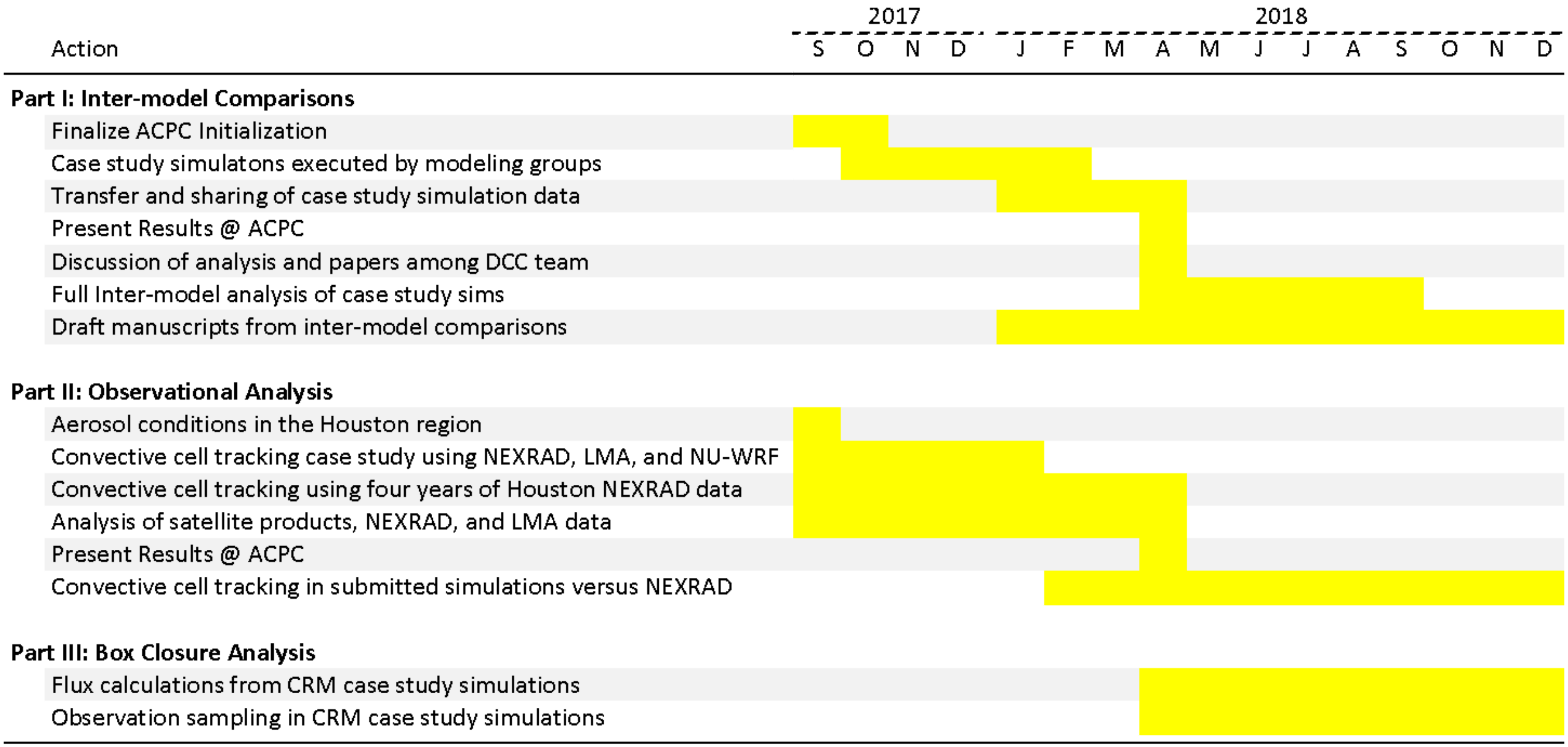
Part III: Box Closure Study

The case study simulations will also provide high spatial and temporal resolution data that will be used to address the feasibility of conducting a box closure study for a GCM grid box, as outlined in Rosenfeld et al. (2014). The simulation data will be used to calculate precise energy, moisture, momentum, and aerosol fluxes across a region representing a GCM grid box (~100 x 100km in horizontal extent and to the top of the tropopause in vertical extent). Hypothetical field campaign sampling techniques will be applied to the simulation data to determine the temporal frequency and spatial resolution of observations necessary to calculate synthetic flux measurements (SQ3). If feasible, such a study would motivate a proposal to conduct a field campaign to carry out these observations. The large-scale GCM box flux measurements will be calculated for all of the CRM simulations in order to quantify the variability in the energy, moisture, momentum and aerosol fluxes to aerosol perturbations across the different CRMs (SQ1).

Data Storage and Timeline

The simulation and observation data will be archived within an ACPC workspace on JASMIN, a data center funded by the Natural Environment Research Council (NERC) and the UK Space Agency (UKSA). Please see the JASMIN instructions document for information on how to access JASMIN.

The following timeline will assist in successfully achieving the stated science objectives of this proposed deep convective roadmap. This timeline will be adjusted as appropriate throughout the collaboration. As is evident from the timeline, several manuscripts will be submitted for review outlining the results and findings of the proposed experiments.



Appendix: Simulation Overview

Introduction

Based on the deep convective cloud roadmap developed during the most recent ACPC initiative meetings, we invite all modeling groups interested in participating in achieving the ACPC goals to conduct case study simulations of a convective event that occurred near Houston, Texas on 19-20 June 2013. These simulations will assist in addressing two of the science goals of this roadmap: (SQ1) assessing the inter-model variability of aerosol effects in a deep convective regime and (SQ3) testing the potential to conduct a box-closure experiment as outlined in Rosenfeld et al. (2014).

Model configuration	Setup
Simulation period	1200 UTC 19 June 2013 to 1500 UTC 20 June 2013
Total run hours	27
Initialization and boundary data	NCEP Global Data Assimilation System (GDAS)/FNL ***(download link)***
Number of model nests	3, one-way nesting only (no interactive nests), all nests share same center lat / lon
Horizontal grid length of each nest	4.5km, 1.5km, 500m
Number of horizontal grid points in each nest (Approximate size of each nest)	4.5km nest: 400 x 400 grid points (~1800 x 1800 km), 1.5km nest: 547 x 547 grid points (~820 x 820 km), 500m nest: 500 x 500 grid points (~250 x 250 km) (or closest numbers of grid points that your model will allow)
Vertical levels	95, please use level spacings (in either height or pressure) specified at this link
Model top	Approx. 22km / 50hPa; please use provided specified levels
Center lat of domain	29.4719
Center lon of domain	-95.0792
Map projection	Lambert preferred, otherwise use best option for your model
Geographical / topography data	Please use highest resolution data available
Coriolis	On
Model time step, outer nest	3 s
Time step ratio per nest	1:1:2

Frequency of radiation calling	1 minute
Frequency of model output (each nest)	4.5km nest: 60 min for entire simulation 1.5km nest: 60 min for entire simulation 500m nest: 60 min for entire simulation, 5 min between 1600 UTC 19 June and 0400 UTC 20 June 2013 1 min between 2100 UTC 19 June and 0000 UTC 20 June 2013 Please refer to table of required output variables.

Physics parameterizations	Setup
Land-Surface model	Please use an interactive land-surface model if available
Convection	No convection or cumulus scheme in any of the 3 grids
Cloud Microphysics	Two-moment bulk or bin scheme preferable, interactive aerosol processing optional. Please use specified initial aerosol profiles below
Aerosol - radiation coupling	Radiatively inactive aerosols
Diffusion / PBL	Please use best option for your model; please call every time step
LW radiation	Please use best option for your model; please call every 1 minute
SW radiation	Please use best option for your model; please call every 1 minute

We ask that each modeling team initially conduct two simulations. Simulation details are listed below. We have constrained the model setup as much as possible such that comparisons of simulations can be more directly attributed to the different models and parameterizations utilized. We therefore ask all participants to follow the instructions below.

In the event of any questions pertaining to the details below, please contact Max Heikenfeld (max.heikenfeld@physics.ox.ac.uk) and Peter Marinescu (peter.marinescu@colostate.edu).

Model Set-Up

We ask all contributors to use the following model configurations:

At a minimum, we ask that two simulations (Base Simulations) be performed, one using the clean aerosol conditions and the other with the polluted aerosol conditions shown below. The simulations should otherwise be identical in configuration (see next section). We ask each modeling team upload a file containing a description of their model, descriptions of the parameterizations (i.e., microphysics, turbulence) used with relevant references, and an overview of output variable names and units.

WRF users may use the linked WPS pre-processing file and WRF namelist file and edit the physics section as necessary.

Aerosol Initialization

Simulation participants can be involved at several levels. At a minimum, all modeling teams should perform the Base Simulations: (CLN and POL). If resources are available, we also ask simulation participants to complete the Additional Simulations (CLN-2Mode and POL-2Mode) below, which includes a second aerosol mode with larger concentrations of smaller aerosol particles.

Aerosol Mode Specifications

The Base Simulations include only one aerosol mode. This aerosol mode follows a log-normal distribution with a geometric mean diameter of 100nm. Additional Simulations while include the Base Simulation aerosol mode, with the addition of a second aerosol mode at smaller aerosol particle sizes (geometric mean diameter of 20 nm). Additional specifications of these modes can be found in the table below.

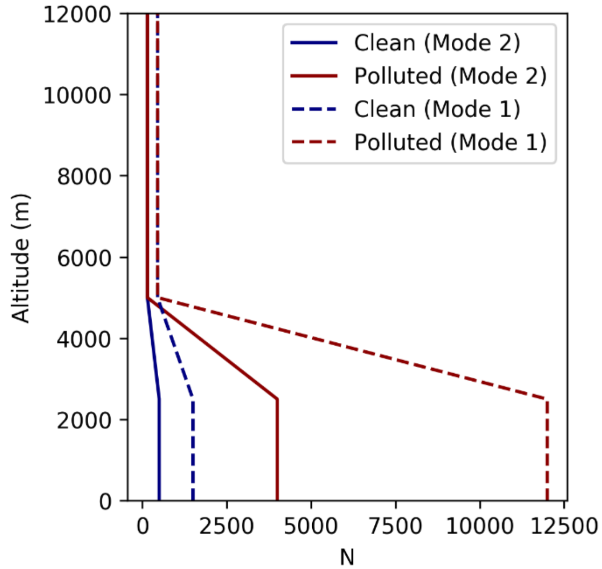
Aerosol Vertical Profiles

Horizontally homogeneous vertical profiles of aerosol particle number concentration (N) are to be specified in all three grids/nests. The number concentrations of each aerosol mode will follow a specified vertical profile. The profiles feature constant values in the boundary layer up to 2.5km and in the free troposphere over 5km with a linear transition between these heights. The height of the constant profile up to 2.5km includes the expected cloud bases of the deep convective clouds in the simulations and serves to eliminate of possibly different aerosol processing and different cloud base heights in the models.

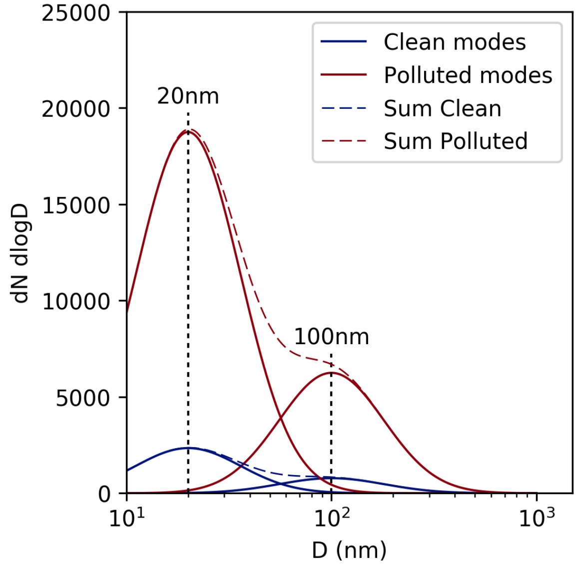
Aerosol Initialization Specifications

	Base Simulations			Additional Simulations			
Simulations (4)	CLN	POL		CLN-2Mode		POL-2Mode	
Aerosol mode(s) in each simulation	Mode 1	Mode 1		Mode 1	Mode 2	Mode 1	Mode 2
Vertical Profiles of Concentrations							
Number concentrations of aerosol particles in the boundary layer (N_{BL}, # cm^{-3})	500	4000		500	1500	4000	12000
Number concentrations in the free troposphere (N_{FT}, # cm^{-3})	150	150		150	450	150	450
Depth of the linear transition layer between the boundary layer and the free troposphere (d_{tran}, m)	2500	2500		2500	2500	2500	2500
Vertical profile of aerosol number concentrations (N_{aer}, # cm^{-3})	$N_{aer}(z) = \begin{cases} N_{BL} & for \quad 0 < z \leq 2.5km \\ N_{BL} - \frac{N_{BL} - N_{FT}}{d_{tran}} (z - d_{tran}) & for\ 2.5km < z \leq 5.0\ km \\ N_{FT} & for \quad z > 5.0\ km \end{cases}$						
Aerosol Mode Specifications							
Lognormal geometric mean diameter (D_{pg}, nm)	100	100		100	20	100	20
Lognormal distribution width (σ_g)	1.8	1.8		1.8	1.8	1.8	1.8
Hygroscopicity parameter (κ)	0.2	0.2		0.2	0.1	0.2	0.1

Aerosol Vertical Profiles



Aerosol Size Distributions



These aerosol specifications are based on convective cloud base cloud droplet number concentrations estimated via a satellite algorithm from data on 19 June 2013 near Houston, Texas (Details of this algorithm can be found in Rosenfeld et al. (2014)) and aircraft measurements from the Discover-AQ campaign over the Houston area in September 2013 (Discover-AQ Science Team).

For groups that use models that represent aerosol sources and/or atmospheric chemistry (i.e., WRF-CHEM), please contact Peter Marinescu and Max Heikenfeld, so that we can ensure that the aerosol initializations are comparable to other simulations.

Model Output

As stated above, we request that model output from all of the simulations is provided at the following spatial and temporal frequency:

- Every hour for the entire 27 hour simulation period for all 3 model domains

We also request the following higher frequency output, *in addition to* the hourly output. Producing these data will likely require restart simulations to be performed for each sub-period of higher frequency output.

- 5 minute model output for the 500 m domain between times of 1600 UTC on 19 June 2013 and 0400 UTC on 20 June 2013 to allow microphysical process analysis (SQ2), and
- 1 minute model output for the 3 hour period between 2100 UTC on 19 June 2013 and 0000 UTC on 20 June 2013 to allow convective cell tracking (SQ1).

We ask contributors to provide at a minimum the following variables for all of their simulations. Data should be provided separately for each grid, as one file per model output time. Contributors should provide in a separate file the assumptions and parameters that define the hydrometeors/aerosol distributions, including ice properties. This information is necessary to reconstruct the hydrometeor and particle distributions for analyses, including running an offline radar simulator.
The simulation data will be archived within an ACPC workspace on JASMIN, a data center funded by the Natural Environment Research Council (NERC) and the UK Space Agency (UKSA). One member of each modeling group is asked to make an account on the JASMIN system and upload their data to the shared group space. The detailed procedure of creating the account and getting access to the group workspace is outlined in a separate document (link). For questions regarding the data storage, get in touch with Max Heikenfeld (max.heikenfeld@physics.ox.ac.uk) or Philip Stier (philip.stier@physics.ox.ac.uk).

3D - Variables

Atmospheric State		
P	hPa	Pressure
Z	m	Height
T	K	air temperature
u	m s^{-1}	zonal wind velocity (eastward is positive)
v	m s^{-1}	meridional wind velocity (northward is positive)

w	m s^{-1}	vertical wind velocity (upward is positive)
ρ	kg m^{-3}	dry air density
Water Variables		
qv	kg kg^{-1}	water vapor mixing ratio
qc	kg kg^{-1}	cloud water mixing ratio
nc	# kg^{-1}	cloud droplet number concentration
qr	kg kg^{-1}	rain water mixing ratio
nr	# kg^{-1}	rain drop number concentration
qX, nX	kg kg^{-1}, # kg^{-1}	*Provide hydrometeor mass mixing ratios and number concentrations for each X hydrometeor class in your model*
Aerosol/CCN Variables		
ma	kg kg^{-1}	aerosol mass mixing ratio (separately for all available aerosol types)
na	# kg^{-1}	aerosol number density (separately for all available aerosol types)
ma_h	kg kg^{-1}	aerosol mass mixing ratio in hydrometeors (if available)
na_h	# kg^{-1}	aerosol number density in hydrometeors (if available)
ra	m	effective radius (separately for all available aerosol types)
Process Rates		
LH_rate	K s^{-1}	Latent heating rate
CE	kg kg^{-1} s^{-1}	condensation/evaporation rate (if possible time-integrated)
DS	kg kg^{-1} s^{-1}	deposition/sublimation rate (if possible time-integrated)

Melt	kg kg^{-1} s^{-1}	Ice melting rate (if possible time-integrated)
Frz	kg kg^{-1} s^{-1}	Liquid freezing rate (if possible time-integrated)
CldNuc	kg kg^{-1} s^{-1}	cloud nucleation rate (if possible time-integrated)
IceNuc	kg kg^{-1} s^{-1}	ice nucleation rate (if possible time-integrated)

2D - Variables

lon	degree	geographic longitude
lon	degree	geographic latitude
top	m	Topography
pcp_rate	kg s^{-1} m^{-2}	instantaneous surface precipitation
pcp_accum	kg s^{-1} m^{-2}	accumulated surface precipitation
SLP	hPa	sea-level pressure
SHF	W m^{-2}	surface sensible heat flux
LHF	W m^{-2}	surface latent heat flux
SWdn_sfc	W m^{-2}	shortwave downwelling radiative flux at the surface
SWup_sfc	W m^{-2}	shortwave upwelling radiative flux at the surface
LWdn_sfc	W m^{-2}	longwave downwelling radiative flux at the surface
LWup_sfc	W m^{-2}	longwave upwelling radiative flux at the surface
SWdn_TOA	W m^{-2}	shortwave downwelling radiative flux at the TOA
SWup_TOA	W m^{-2}	shortwave upwelling radiative flux at the TOA
LWdn_TOA	W m^{-2}	longwave downwelling radiative flux at the TOA
LWup_TOA	W m^{-2}	longwave upwelling radiative flux at the TOA
Albedo	fraction	surface albedo

References

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