The KNMI Parameterization Testbed

User's Guide

Version 2.0

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1. Introduction

The objective of the KNMI Parameterization Testbed (KPT) is to generate continuous series of Single Column Model (SCM) simulations at various operational supersites that cover long (i.e. multi-year) periods of time, and to subsequently evaluate these simulations at multiple time-scales against the many continuous observational datastreams that are available at these locations. Currently included locations are Cabauw (see Fig.1), various other sites involved in the European CloudNet project (e.g. Chilbolton, Lindenberg), the Southern Great Plains (SGP) site of the Atmospheric Radiation Measurement (ARM) program, and Schiphol International Airport. For a detailed description and discussion of the strategy behind KPT, as well as an illustrating example of a model evaluation exercise, we refer to a forth-coming paper on KPT that is currently to be submitted to BAMS (available online at *http://www.knmi.nl/~neggers/index_publ.html*). The purpose of this document is to provide a user's guide to KPT, including a detailed description of i) the SCM input requirements, ii) the configuration of the simulations, and iii) the output requirements. This should allow the user to prepare an SCM for participation in KPT. Also, the available observational datastreams from the Cabauw site are shortly described, as well as some evaluation techniques that are applied in the tested.

FIGURE 1: The 213m tower at the Cabauw site in The Netherlands, with the Baseline Surface Radiation Network (BSRN) station in the foreground.

2. Strategy

The strategy is to keep the number of specifications for the SCM configuration as low as possible, in order to allow the simulation of any preferred model setting. The motivation for this choice is twofold;

- different SCMs may represent the physics of larger-scale models of very different type, requiring different settings.

- during model development it might be of interest to switch off components, to perform sensitivity tests, or to be able to study a simplified model setting.

Among the settings to be chosen by the user are the following;

- The time-integration step;
- The duration of the simulation;
- The vertical extent of the column;
- The interactivity of the land model;
- The interactivity of the surface turbulent fluxes;
- The model-internal configuration;
- etcetera.

The interpretation of the SCM results is therefore entirely up to the user; in the subsequent model intercomparison the results are taken "as is".

The stand-alone codes of the participating SCMs can be simulated either internally at KNMI or remotely at other locations. In the last case the results can be uploaded through ftp (contact the author to obtain an account). A LINUX workstation has been designated for the "in-house" codes. All SCM results are archived, as well as all available observational datastreams. The archive will be fully accessible through the internet, through an interactive website at a dedicated server (*http://www.knmi.nl/~neggers/KPT*, under construction).

3. SCM input

In KPT so-called "driver file" are constructed and provided for the various locations of interest. These driver files contain all input fields required to simulate an SCM. Different driver files are available in KPT, obtained from different sources;

- the most recent 3D RACMO forecast (operational);
- the ECMWF Re-Analysis (ERA Interim) (operational);
- the ARM Constrained Variational Analysis (operational);
- an Integrated Profiling Technique (IPT; future option).

The first "a-priori" option reflects a short-range *forecast* by a Numerical Weather Prediction (NWP) model, in this case the Regional Atmospheric Climate Model (RACMO) of the KNMI that is run daily in forecast mode. RACMO is initialized with the ECMWF analysis and forced by ECMWF boundaries. The driver file obtained from RACMO is used for generating daily SCM forecasts; i.e. the time integration of the SCMs *into the future*. In this mode the duration of the SCM simulation is only a few (i.e. three) days, in order to remain close to the analysis state with which the 3D RACMO forecast was initialized. As NWP forecasts can be expected to gradually deteriorate over time, the evaluation against measurements only makes sense on the first full day of simulation; only then can the evaluation profit from the proximity in time of the analysis. In the KPT the a-priori forecast mode is fully automated, which means that every day simulations are generated as soon as the RACMO forecasts become available. Normally this takes place at about 22-23 UTC.

The other options in the list above represent “a-posteriori” modes. In principle these driver files should be closer to the “true” state at a supersite throughout their duration, as they are (at least partially) based on local measurements (through assimilation). Naturally, the a-posteriori driver files only become available when the period of integration is past. They can also vary in length, for example the driver files from the ARM Constrained Variational Analysis typically cover one month.

The driver file, which has the format of the ECMWF SCM, contains time-series and time-height fields for a specific location. The period and vertical extent covered by the driver file set the outer limits of the SCM simulation. The format of the driver file is NetCDF. The time-resolution of the supplied fields is high enough to capture diurnal variation of forcings and boundary conditions; typically 1 hour is used. The default vertical discretization is that of the currently operational Integrated Forecasting System (IFS) of the ECMWF, consisting of 91 levels and 92 half levels. Half level k is the lower boundary of layer k, while full level k is its exact middle. Full level 91 is closest to the surface, while full level 1 is the highest. The extra half level 0 is the ceiling of the top model layer. The pressure heights of these levels are defined by the a and b coefficients, predefined at each level,

$$p_h^k = a^k + p_s\, b^k \tag{1}$$

$$p_f^k = \frac{1}{2}\left(p_h^k + p_h^{k-1}\right) \tag{2}$$

where p_s is the surface pressure. These coefficients are supplied as general attributes with the driver file. A complete overview of all variables, their units, and a short description, is supplied in Appendix A.

Note: different SCMs require different input variables, concerning both definition and format. Accordingly, an interface program has to be constructed that translates the supplied driver file (which has the ECMWF SCM format) into a driver file that can be digested by the SCM of interest. This may involve the formulation of different variables, changes in units, and vertical interpolation between the L91 levels. The construction of this interface is entirely the responsibility of the user, as he/she has most detailed knowledge of the SCM of interest.

4. Simulation setup

a. Budget equations

Suppose variable ϕ represents one of the following state variables of thermodynamics and momentum,

$$\phi = \{\theta, q_v, U, V\}. \tag{3}$$

The total tendency of ϕ can be written as

$$\frac{\partial \phi}{\partial t} = \left(\frac{\partial \phi}{\partial t}\right)_{ph} + \left(\frac{\partial \phi}{\partial t}\right)_{LS} + \left(\frac{\partial \phi}{\partial t}\right)_{rel}, \tag{4}$$

where subscript ph indicates model physics, subscript LS indicates the larger scale forcings, and subscript rel indicates a relaxation term (to be described later).

b. Large-scale forcings

The forcing of the column by the larger-scale circulation is prescribed; no interaction exists between model physics and the larger scale circulation. The forcing term in (4) is decomposed into a horizontal component and a vertical component,

$$\left(\frac{\partial \phi}{\partial t}\right)_{LS} = \left(\frac{\partial \phi}{\partial t}\right)_{LS,h} - \omega\frac{\partial \phi}{\partial p}, \tag{5}$$

where ω is the prescribed large scale subsidence. Accordingly, the vertical advection is interactive with the vertical gradient in the model. For thermodynamics the horizontal component purely represents horizontal advection, specified as a tendency in the driver file,

$$\left(\frac{\partial \phi}{\partial t}\right)_{LS,h} = \left(\frac{\partial \phi}{\partial t}\right)_{adv,h} \qquad \text{for} \qquad \phi \in \{\theta, q_v\}. \tag{6}$$

For momentum the Coriolis force also has to be included in the forcing,

$$\left(\frac{\partial U}{\partial t}\right)_{LS,h} = \left(\frac{\partial U}{\partial t}\right)_{adv,h} - f\left(V_g - V\right), \tag{7}$$

$$\left(\frac{\partial V}{\partial t}\right)_{LS,h} = \left(\frac{\partial V}{\partial t}\right)_{adv,h} + f\left(U_g - U\right). \tag{8}$$

The departure from geostrophy thus also drives the model wind. The geostrophic wind (U_g, V_g) is specified in the driver file.

Note that the radiative forcing is considered part of the physics term ph, and is therefore not specified in the driver file; it is assumed that a radiation scheme is included in the SCM.

c. Continuous relaxation

During the simulation, the SCM state is continuously (i.e. at every time-step) relaxed towards a certain background state,

$$\left(\frac{\partial \phi}{\partial t}\right)_{rel} = \frac{\phi_{bg} - \phi}{\tau}, \tag{9}$$

where τ is the associated timescale. The default value in the automated a-priori simulations is 6 hours, a value that was arrived at after an experimental stage; in our experience this intensity of relaxation is sufficiently tight to make the SCM simulation follow the larger-scale weather

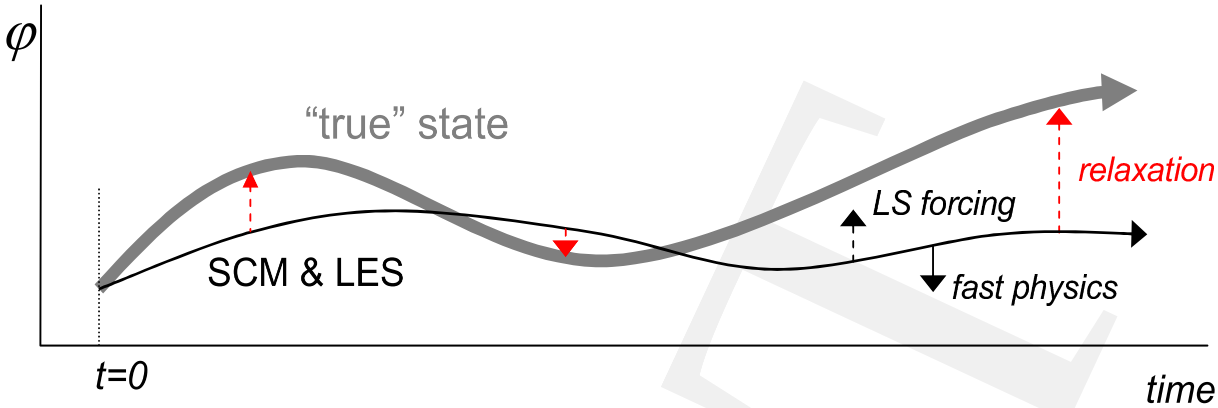

FIGURE 2: Schematic illustration of the SCM relaxation method, as described in the text.

(such as fronts), while at the same time being loose enough to allow the fast PBL physics to set their own preferred state. The background or "true" state for the whole period is included in the driver file. The relaxation method is schematically illustrated in Fig. 2.

The motivation for including this nudging term, and for choosing this particular value of τ, is the following. When the weather is dominated by the larger-scale forcings (for example in case of a passing front), the physics term is relatively small compared to the other two terms in (4). Also, giving τ the synoptic value of 6 hours makes the relaxation term of the same order of magnitude as the large-scale forcing term. As a result, the SCM state will always stay close to the background state in such situations. In contrast, when the weather is locally driven (for example by the surface buoyancy flux), the SCM physics can start to create their own unique state. In such situations, SCMs with different physics will start to give different results; at this point conclusions might be drawn on which code performs best.

5. SCM output

When the SCM simulations have been generated the model results can be i) evaluated against observational datastreams, and ii) inter-compared among each other. In Appendix B a list of output variables is given that can be viewed in the KPT interface (*http://www.knmi.nl/˜neggers/KPT*). This list only acts as a guideline; it is not required to supply all mentioned variables, any selection however small would already be sufficient. The reason is that some variables may simply not be part of the SCM. Also, it should be possible to run trial SCM versions in the testbed, in which some model components are simply not yet present.

All output has to be supplied in one single file, the format of which is again NetCDF. The time and height discretization of the output is that at which the run is performed; the averaging is applied during the preparation of the results for visualization. One output requirement that has to be strictly followed is the naming convention of the variables and their units, as documented in Appendix B. The reason is that otherwise the processing of model output would become needlessly complicated, time-consuming, and fragile; also, the KPT interface is programmed to recognize only this pre-defined list of variables in the NetCDF files.

6. Cabauw observational datastreams

A list of all Cabauw observational datastreams currently accessible in the KPT interface for model evaluation is given in Appendix C. The current set of datastreams covers surface meteorology, the vertical structure of the lowest 200m, the surface turbulent and radiative fluxes, and various cloud properties. The instruments used are only shortly mentioned; for any further details we can refer to the scientist at KNMI responsible for its daily operation.

The Cabauw datastreams are all obtained from the database of the Cabauw Experimental Site for Atmopsheric Research (CESAR, see *http://www.cesar-observatory.nl/*). All included datastreams are as continuous as possible, i.e. we strive to create uninterrupted time-series of measurements. Naturally, in reality this is not always the case. Many of the observational datastreams are available at two data-levels, i.e. both quality-checked and near-real-time. For the automated SCM simulations in forecast mode prefabricated plots of various model variables are generated that include relevant observational data; during the subsequent three days these plots are refreshed on an hourly basis. This allows detailed assessment of current, developing weather at physics level.

At the moment of writing this documentation we are in the process of acquiring observational datasets for the other sites for which forcings are available in KPT. This includes the CloudNet products for the other CloudNet sites, and the observational datasets for the ARM SGP site that are part of the ARM Constrained Variational Analysis.

7. Large-eddy simulation (LES) datastreams

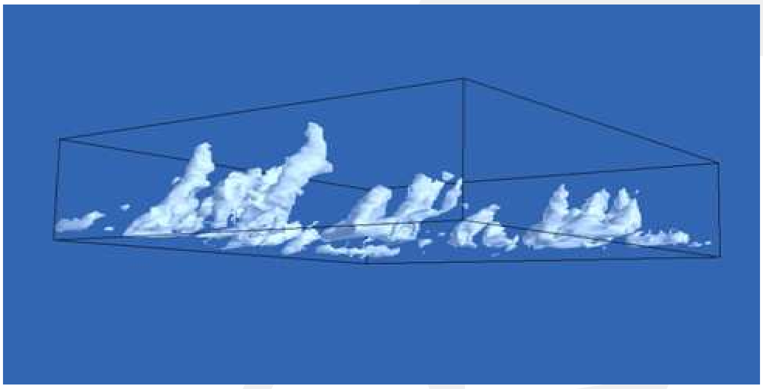

FIGURE 3: A visualization of a three-dimensional snapshot of a cloud field as generated by DALES for the GCSS ARM shallow cumulus case.

In January 2010 we have commenced with the automated daily generation of Large-Eddy Simulation (LES) forecasts for the Cabauw location. To this purpose we use the Dutch Atmospheric Large-Eddy Simulation (DALES) code, driven by RACMO forcings. The LES is initialized and forced in exactly the same way as the SCMs; this makes their inter-comparison meaningful. The LES simulation can be interpreted as a three-dimensional downscaling of the RACMO forecast for Cabauw at high-resolutions. The LES can thus serve to provide information on three-dimensional variability that the current instrumentation at the Cabauw point can not yet measure, such as the turbulent fluxes and variances, cloud heterogeneity, characteristics of convection, and so forth.

The LES covers a domain of 6.4x6.4x6km, at a resolution of 100x100x40m. The high computational cost of LES makes this relatively crude discretization for present-day standards a necessity when used in daily simulation. In addition, the simulated code does not yet contain interactive radiation, nor an interactive land scheme, nor complex microphysics. However, simulations at higher resolutions with a more complex code can be generated on a case-by-case basis, if needed. Also, we plan to expand computational capacity for the daily LES at Cabauw in the near future. The currently simulated period covers 12 daytime hours on day-1 of the RACMO forecasts, starting at 06:00 UTC and ending at 18:UTC. This simulation takes 4 hours on our designated KPT workstation at KNMI; as a result, the LES forecasts for each day typically become available at about 02:00 UTC. A list of all LES datastreams currently available in the KPT interface for model evaluation is given in Appendix D.

8. Evaluation techniques

a. Direct comparison

The most straightforward evaluation method is to plot the various models next to observations in one frame.

b. RMS scores

A more advanced way of evaluating models is to calculate the root-mean-square value of the differences between a model-generated signal (superscript m) and an observed signal(superscript o),

$$RMS = \left(\frac{1}{N_t} \sum_{i=1}^{N_i} (\phi_i^m - \phi_i^o)^2 \right)^{\frac{1}{2}} \tag{10}$$

where i indicates the step in the sequence and N_i the number of steps in the sequence. For each SCM simulation, (10) can be applied to both

- 3-day time-series, and
- vertical profiles at 3-hour intervals,

of various model variables. This assigns a unique RMS value (or score) to each model on each day. Time-series of these RMS scores for various participating models can be intercompared for long periods of time. This quantifies the long-term performance of a model, and might reveal structural problems.

c. Indices

One step beyond the RMS of a single variable is the *index*, representing the cumulative RMS scores of a group of variables,

$$\mathrm{CI} \;=\; \sum_{v=1}^{N_v} \frac{\mathrm{RMS}_v}{\mathrm{RMS}_v^{ref}} \tag{11}$$

where CI stands for the Cabauw index, v indicates a variable with N_v the number of variables in the index group, and ref indicates a reference RMS value. For the reference RMS values we use those of April 2008, the month in which this technique became operational in the testbed.

The various index groups are defined by a certain themes;

- surface meteorology (2m T and q; 10m wind; surface turbulent and radiative fluxes)
- vertical structure (profiles of T; q; U; fluxes)
- cloud location (cloud base height; cloud top height)
- bulk cloud properties (liquid water path; ice water path; total cloud cover)
- bulk humidity budget variables (total column water vapour; P-E)

For all variables mentioned an observational datastream is available. The primary role of these indices is to give quick insight into the model performance per variable category.

d. Scatterplots

To diagnose effective parametric relations in models.

e. Mixing diagram vectors

Using bulk mixed layer arguments to visualize top-entrainment mixing in models Betts (1992).

SCM driver file contents (NetCDF)

Dimension name	Value	Description
time	73	Number of time steps
nlev	91	Number of model full levels
nlevp1	92	Number of model half levels
nlevs	4	Number of soil levels

Variable name	Array dimensions	Unit	Description
date	(time)	yyyymmdd	Date
time	(time)	seconds	Time since Initialization
second	(time)	seconds	UTC Time
lat	(time)	deg N	Latitude
lon	(time)	deg E	Longitude
ps	(time)	Pascal	Surface Pressure
u	(time, nlev)	m s^{-1}	Zonal Wind
v	(time, nlev)	m s^{-1}	Meridional Wind
t	(time, nlev)	K	Temperature
q	(time, nlev)	kg kg^{-1}	Water Vapor Mixing Ratio
ql	(time, nlev)	kg kg^{-1}	Liquid Water Mixing Ratio
qi	(time, nlev)	kg kg^{-1}	Ice Water Mixing Ratio
cloud_fraction	(time, nlev)	0-1	Cloud Fraction
uadv	(time, nlev)	m s^{-2}	LS Advective U Tendency
vadv	(time, nlev)	m s^{-2}	LS Advective V Tendency
tadv	(time, nlev)	K s^{-1}	LS Advective T Tendency
qadv	(time, nlev)	kg kg^{-1} s^{-1}	LS Advective Q Tendency
aadv	(time, nlev)	1 s^{-1}	LS Advective Cloud Fraction Tendency
ladv	(time, nlev)	kg kg^{-1} s^{-1}	LS Advective Liquid Water Tendency
iadv	(time, nlev)	kg kg^{-1} s^{-1}	LS Advective Ice Water Tendency
ug	(time, nlev)	m s^{-1}	Geostrophic U Wind
vg	(time, nlev)	m s^{-1}	Geostrophic V Wind
omega	(time, nlev)	Pa s^{-1}	Vertical Pressure Velocity

Variable name	Array dimensions	Unit	Description
high_veg_type	(time)	-	High Vegetation Type
low_veg_type	(time)	-	Low Vegetation Type
high_veg_cover	(time)	-	High Vegetation Cover
low_veg_cover	(time)	-	Low Vegetation Cover
mom_rough	(time)	m	Momentum Roughness Length
heat_rough	(time)	m	Heat Roughness Length
t_skin	(time)	K	Skin Temperature
q_skin	(time)	m of water	Skin Reservoir Content
t_snow	(time)	K	Snow Temperature
albedo_snow	(time)	0-1	Snow Albedo
density_snow	(time)	kg m^{-3}	Snow Density
sfc_sens_flx	(time)	W m^{-2}	Surface Sensible Heat Flux (+ down)
sfc_lat_flx	(time)	W m^{-2}	Surface Latent Heat Flux (+ down)
h_soil	(nlevs)	m	Soil layer thickness (1st is top layer)
t_soil	(time, nlevs)	K	Soil Temperature
q_soil	(time, nlevs)	m^3 m^{-3}	Soil Moisture
lsm	(time)	0 or 1	Land-Sea Mask
sea_ice_frct	(time)	0-1	Sea Ice Fraction
t_sea_ice	(time, nlevs)	K	Sea Ice Temperature
open_sst	(time)	K	Open SST
sdor	(time)	m	Subgrid-scale orography - Standard deviation
isor	(time)	1	Subgrid-scale orography - Anisotropy
anor	(time)	degree	Subgrid-scale orography - Orientation
slor	(time)	m m^{-1}	Subgrid-scale orography - Mean slope
orog	(time)	m^2 s^{-2}	Orography (surface geopotential)
snow	(time)	m	Snow Depth
albedo	(time)	0-1	Surface Albedo

attribute name			Description
coor_par_a	(nlevp1)		Pressure height discretization coefficient
coor_par_b	(nlevp1)		Pressure height discretization coefficient

List of SCM output variables (NetCDF)

Variable Name	Dimensions	Unit	Description
time	(time)	s	Time since initialization
date	(time)	s	Date
ps	(time)	Pa	Surface pressure
height_f	(time,nlev)	m	Full level height
height_h	(time,nlevp1)	m	Half level height
pressure_f	(time,nlev)	Pa	Full level pressure
pressure_h	(time,nlevp1)	Pa	Half level pressure
qadv	(time,nlev)	kg kg^{-1} s^{-1}	LS Advective Q Tendency
tadv	(time,nlev)	K s^{-1}	LS Advective T Tendency
uadv	(time,nlev)	m s^{-2}	LS Advective U Tendency
vadv	(time,nlev)	m s^{-2}	LS Advective V Tendency
aadv	(time,nlev)	kg kg^{-1} s^{-1}	LS Advective Cloud Fraction Tendency
ladv	(time,nlev)	kg kg^{-1} s^{-1}	LS Advective Liquid Water Tendency
iadv	(time,nlev)	kg kg^{-1} s^{-1}	LS Advective Ice Water Tendency
omega	(time,nlev)	Pa s^{-1}	LS Subsidence
ug	(time,nlev)	m s^{-1}	LS Zonal Geostrophic Wind
vg	(time,nlev)	m s^{-1}	LS Meridional Geostrophic Wind
tau_nudg	(nlev)	s	Nudging timescale
t	(time,nlev)	K	Temperature
theta	(time,nlev)	K	Potential Temperature
thl	(time,nlev)	K	Liquid Water Potential Temperature
thv	(time,nlev)	K	Virtual Potential Temperature
qt	(time,nlev)	kg kg^{-1}	Total Water Specific Humidity
qv	(time,nlev)	kg kg^{-1}	Water Vapour Specific Humidity
ql	(time,nlev)	kg kg^{-1}	Liquid Water Specific Humidity
qi	(time,nlev)	kg kg^{-1}	Ice Water Specific Humidity
u	(time,nlev)	m s^{-1}	Zonal wind
v	(time,nlev)	m s^{-1}	Meridional Wind
Vamp	(time,nlev)	m s^{-1}	Wind speed
Vdir	(time,nlev)	degrees from N	Wind direction
rh	(time,nlev)	%	Relative humidity
cc_a, cc	(time,nlev)	%	Cloud fraction, defined by area[1]
cc_v	(time,nlev)	%	Cloud fraction, defined by volume[2]

[1]Including subgrid-scale vertical overlap, i.e. the cloud fraction as seen by the radiative transfer scheme.
[2]Excluding subgrid-scale vertical overlap. See Brooks et al. (2004) for a detailed description.

Variable Name	Dimensions	Unit	Description
t2m	(time)	K	Temperature at 2m
theta2m	(time)	K	Potential temperature at 2m
td2m	(time)	K	Dewpoint temperature at 2m
qv2m	(time)	kg kg	Specific humidity at 2m
qs2m	(time)	kg kg	Saturation specific humidity at 2m
rh2m	(time)	%	Relative humidity at 2m
u10m	(time)	m s^{-1}	Zonal wind speed at 10m
v10m	(time)	m s^{-1}	Meridional wind speed at 10m
Vamp10m	(time)	m s^{-1}	Wind speed at 10m
Vdir10m	(time)	degrees from N	Wind direction at 10m

... and subsequently the above variables at the heights of 20m, 40m, 80m, 140m and 200m, for evaluation against sensors on the Cabauw tower.
Naming convection: <variable name><height in meters>m,
e.g. theta140m, qv200m, rh40m, Vamp80m, ...
These datastreams can be obtained from their time-height counterparts through linear interpolation.

E	(time)	W m^{-2}	Surface latent heat flux (+ upw.)
H	(time)	W m^{-2}	Surface sensible heat flux (+ upw.)
WTV	(time)	W m^{-2}	Surface virtual temperature flux (+ upw.)
rBowen	(time)	-	Surface Bowen ratio
SWu	(time)	W m^{-2}	Surface upward SW rad. flux (+ upw.)
SWd	(time)	W m^{-2}	Surface downward SW rad. flux (+ downw.)
SWnet	(time)	W m^{-2}	Surface net SW rad. flux (+ downw.)
SWnetc	(time)	W m^{-2}	Surface net SW rad. flux (clear sky)(+ downw)
LWu	(time)	W m^{-2}	Surface upward LW rad. flux (+ upw.)
LWd	(time)	W m^{-2}	Surface downward LW rad. flux (+ downw.)
LWnet	(time)	W m^{-2}	Surface net LW rad. flux (+ downw.)
LWnetc	(time)	W m^{-2}	Surface net LW rad. flux (clear sky)(+ downw)
RADnet	(time)	W m^{-2}	Surface net radiation(+ downw)
G0	(time)	W m^{-2}	Ground heat flux
SWrad_flx	(time,nlevp1)	W m^{-2}	net SW radiative flux (+ downw)
LWrad_flx	(time,nlevp1)	W m^{-2}	net LW radiative flux (+ downw)
Pflux	(time,nlevp1)	mm day^{-1}	Total Precipitation Flux
Pfluxs	(time,nlevp1)	mm day^{-1}	Total Snow Flux

Variable Name	Dimensions	Unit	Description
tcc	(time)	%	Total cloud cover
lcc	(time)	%	Low cloud cover
mcc	(time)	%	Medium cloud cover
tcc	(time)	%	High cloud cover
wvp	(time)	kg m^{-2}	Water vapour path
lwp	(time)	mm	Liquid water path
iwp	(time)	mm	Ice water path
zccbase	(time)	m	Cloud base height
zccmax	(time)	m	Height of maximum cloud fraction
ccmax	(time)	%	Maximum cloud fraction
roverlap	(time)	-	Cloud overlap ratio: ccmax/tcc
P	(time)	mm day^{-1}	Surface precipitation rate
Psnow	(time)	mm day^{-1}	Surface snowfall rate
Pacc	(time)	mm	Accumulated P (since initialization)
Psnowacc	(time)	mm	Accumulated Psnow (since initialization)
ustress	(time)	m^2 s^{-2}	Surface U stress
vstress	(time)	m^2 s^{-2}	Surface V stress
mfsfc	(time)	m^2 s^{-2}	Surface Momentum flux
t_skin	(time)	K	Skin temperature
q_skin	(time)	m	Skin humidity (a.k.a. interception reservoir)
t_soil_top	(time)	K	Temperature of top soil level
q_soil_top	(time)	m^3 m^{-3}	Moisture in top soil level
albedo	(time)	-	Surface albedo
rough_mom	(time)	m	Surface roughness length for momentum
rough_heat	(time)	m	Surface roughness length for heat

Variable Name	Dimensions	Unit	Description
wthl	(time,nlevp1)	$W\ m^{-2}$	Turbulent Flux of Liq Wat Potential Temperature
wth	(time,nlevp1)	$W\ m^{-2}$	Turbulent Flux of Potential Temperature
wqt	(time,nlevp1)	$W\ m^{-2}$	Turbulent Flux of Total Specific Humidity
wqv	(time,nlevp1)	$W\ m^{-2}$	Turbulent Flux of Specific Humidity
wql	(time,nlevp1)	$W\ m^{-2}$	Turbulent Flux of Liquid Water
wqi	(time,nlevp1)	$W\ m^{-2}$	Turbulent Flux of Ice Water
wu	(time,nlevp1)	$m^2\ s^{-2}$	Turbulent Flux of Zonal Momentum
wv	(time,nlevp1)	$m^2\ s^{-2}$	Turbulent Flux of Meridional Momentum
mf	(time,nlevp1)	$m^2\ s^{-2}$	Turbulent Flux of Momentum
wth_c	(time,nlevp1)	$W\ m^{-2}$	Convective Flux of Potential Temperature
wqv_c	(time,nlevp1)	$W\ m^{-2}$	Convective Flux of Specific Humidity
wu_c	(time,nlevp1)	$m^2\ s^{-2}$	Convective Flux of Zonal Momentum
wv_c	(time,nlevp1)	$m^2\ s^{-2}$	Convective Flux of Meridional Momentum
mf_c	(time,nlevp1)	$m^2\ s^{-2}$	Convective Flux of Momentum
wth_tot	(time,nlevp1)	$W\ m^{-2}$	Total Flux of Potential Temperature
wqv_tot	(time,nlevp1)	$W\ m^{-2}$	Total Flux of Specific Humidity
wu_tot	(time,nlevp1)	$m^2\ s^{-2}$	Total Flux of Zonal Momentum
wv_tot	(time,nlevp1)	$m^2\ s^{-2}$	Total Flux of Meridional Momentum
mf_tot	(time,nlevp1)	$m^2\ s^{-2}$	Total Flux of Momentum
uplcl	(time)	m	Updraft lifting condensation level
uptop	(time)	m	Updraft termination height
upfrac	(time,nlevp1)	%	Updraft area fraction
upw	(time,nlevp1)	$m\ s^{-1}$	Updraft vertical velocity
upM	(time,nlevp1)	$m\ s^{-1}$	Updraft mass flux
upB	(time,nlevp1)	$m\ s^{-2}$	Updraft buoyancy
upql	(time,nlevp1)	$kg\ kg^{-1}$	Updraft liquid condensate
upqi	(time,nlevp1)	$kg\ kg^{-1}$	Updraft ice condensate
upthlex	(time,nlevp1)	K	Updraft thl excess
upqtex	(time,nlevp1)	$kg\ kg^{-1}$	Updraft qt excess
Kh	(time,nlevp1)	$m^2\ s^{-1}$	Eddy diffusivity coefficient for Heat
Km	(time,nlevp1)	$m^2\ s^{-1}$	Eddy diffusivity coefficient for Momentum
TKE	(time,nlevp1)	$m^2\ s^{-2}$	Turbulent kinetic energy (TKE)
sigthl2	(time,nlev)	K^2	Variance of Liquid water potential temperature
sigqt2	(time,nlev)	$kg^2\ kg^{-2}$	Variance of Total water specific humidity
sigw2	(time,nlev)	$m^2\ s^{-2}$	Variance of Vertical velocity

APPENDIX C

Observational datastreams

Class	Instrument	Datastream	Unit	Status
Surface meteorology		Surface pressure	Pa	$\surd$
		2m T	K	$\surd$
		2m Td	K	$\surd$
		2m qv	K	$\surd$
		2m rh	K	$\surd$
		10m wind	m s^{-1}	$\surd$
		Surface precip	mm day^{-1}	$\surd$
Surface turbulent fluxes		Latent heat	W m^{-2}	$\surd$
		Sensible heat	W m^{-2}	$\surd$
		Bowen ratio	-	$\surd$
		Virtual temperature flux	W m^{-2}	$\surd$
		Ground heat flux	W m^{-2}	$\surd$
Surface radiative fluxes		LW down	W m^{-2}	$\surd$
		LW up	W m^{-2}	$\surd$
		LW net	W m^{-2}	$\surd$
		SW down	W m^{-2}	$\surd$
		SW up	W m^{-2}	$\surd$
		SW net	W m^{-2}	$\surd$
		Total net	W m^{-2}	$\surd$
		Surface albedo	-	$\surd$
	BSRN	LW down	W m^{-2}	$\surd$
		SW down	W m^{-2}	$\surd$
Vertical structure	Cabauw Tower (lowest 200m)	T	K	$\surd$
		q_v	kg kg^{-1}	$\surd$
		U	m s^{-1}	$\surd$
		wT	K m s^{-1}	X
		wq	kg kg^{-1} m s^{-1}	X
		wU	m^2 s^{-2}	X
	Profiler			X

Class	Instrument	Datastream	Unit	Status
Clouds	CT75 ceilometer	Cloud base height	m	$\surd$
		Total cloud cover	%	$\surd$
	LD40 ceilometer	Cloud base height	m	X
		Total cloud cover	%	X
	Leosphere lidar	Cloud base height	m	X
		Total cloud cover	%	X
	Nubiscope	Cloud base height	m	X
		Total cloud cover	%	X
	HATPRO MWR	LWP	mm	$\surd$
		WVP	kg m^{-2}	$\surd$
	CloudNet	Cloud fraction profile	%	$\surd$
		Total cloud cover	%	$\surd$
		target classification		X

LES datastreams

Variable Name	Dimensions	Unit	Description
t	(time,nlev)	K	Temperature
theta	(time,nlev)	K	Potential Temperature
thl	(time,nlev)	K	Liquid Water Potential Temperature
thv	(time,nlev)	K	Virtual Potential Temperature
qt	(time,nlev)	kg kg^{-1}	Total Water Specific Humidity
qv	(time,nlev)	kg kg^{-1}	Water Vapour Specific Humidity
ql	(time,nlev)	kg kg^{-1}	Liquid Water Specific Humidity
qi	(time,nlev)	kg kg^{-1}	Ice Water Specific Humidity
rh	(time,nlev)	%	Relative humidity
u	(time,nlev)	m s^{-1}	Zonal wind
v	(time,nlev)	m s^{-1}	Meridional Wind
Vamp	(time,nlev)	m s^{-1}	Wind speed
Vdir	(time,nlev)	degrees from N	Wind direction
cc	(time,nlev)	%	Cloud fraction
wcc	(time,nlev)	m s^{-1}	Cloud vertical velocity
Mcc	(time,nlev)	m s^{-1}	Cloud mass flux
Bcc	(time,nlev)	m s^{-2}	Cloud buoyancy
qlcc	(time,nlev)	kg kg^{-1}	Cloud liquid condensate
qicc	(time,nlev)	kg kg^{-1}	Cloud ice condensate
qtexcc	(time,nlev)	kg kg^{-1}	Cloud qt excess
thlexcc	(time,nlev)	K	Cloud thl excess
cco	(time,nlev)	%	Cloud core fraction
wco	(time,nlev)	m s^{-1}	Cloud core vertical velocity
Mco	(time,nlev)	m s^{-1}	Cloud core mass flux
Bco	(time,nlev)	m s^{-2}	Cloud core buoyancy
qlco	(time,nlev)	kg kg^{-1}	Cloud core liquid condensate
qico	(time,nlev)	kg kg^{-1}	Cloud core ice condensate
qtexco	(time,nlev)	kg kg^{-1}	Cloud core qt excess
thlexco	(time,nlev)	K	Cloud core thl excess

Variable Name	Dimensions	Unit	Description
t20m	(time)	K	Temperature at 20m
theta20m	(time)	K	Potential temperature at 20m
td20m	(time)	K	Dewpoint temperature at 20m
qv20m	(time)	kg kg	Specific humidity at 20m
rh20m	(time)	%	Relative humidity at 20m
u20m	(time)	m s^{-1}	Zonal wind speed at 20m
v20m	(time)	m s^{-1}	Meridional wind speed at 20m
Vamp20m	(time)	m s^{-1}	Wind speed at 20m
Vdir20m	(time)	degrees from N	Wind direction at 20m

... and subsequently the above variables at the heights of 40m, 80m, 140m and 200m, for evaluation against sensors on the Cabauw tower.

tcc	(time)	%	Total cloud cover
wvp	(time)	kg m^{-2}	Water vapour path
lwp	(time)	mm	Liquid water path
iwp	(time)	mm	Ice water path
zccbase	(time)	m	Cloud base height
zcctop	(time)	m	Cloud top height
zccmax	(time)	m	Height of maximum cloud fraction
ccmax	(time)	%	Maximum cloud fraction
roverlap	(time)	-	Cloud overlap ratio: ccmax/tcc
E	(time)	W m^{-2}	Surface latent heat flux (+ upw.)
H	(time)	W m^{-2}	Surface sensible heat flux (+ upw.)
WTV	(time)	W m^{-2}	Surface virtual temperature flux (+ upw.)
rBowen	(time)	-	Surface Bowen ratio
ustress	(time)	m^2 s^{-2}	Surface U stress
vstress	(time)	m^2 s^{-2}	Surface V stress
mfsfc	(time)	m^2 s^{-2}	Surface Momentum flux

Variable Name	Dimensions	Unit	Description
wthl	(time,nlev)	W m^{-2}	Turbulent Flux of Liq Wat Potential Temperature
wth	(time,nlev)	W m^{-2}	Turbulent Flux of Potential Temperature
wthv	(time,nlev)	W m^{-2}	Turbulent Flux of Virtual Potential Temperature
wqt	(time,nlev)	W m^{-2}	Turbulent Flux of Total Specific Humidity
wqv	(time,nlev)	W m^{-2}	Turbulent Flux of Specific Humidity
wql	(time,nlev)	W m^{-2}	Turbulent Flux of Liquid Water
wqi	(time,nlev)	W m^{-2}	Turbulent Flux of Ice Water
wu	(time,nlev)	m^2 s^{-2}	Turbulent Flux of Zonal Momentum
wv	(time,nlev)	m^2 s^{-2}	Turbulent Flux of Meridional Momentum
mf	(time,nlev)	m^2 s^{-2}	Turbulent Flux of Momentum
TKE	(time,nlev)	m^2 s^{-2}	Turbulent kinetic energy (TKE)
TKEint	(time)	m^3 s^{-2}	Vertically integrated TKE
sigthl2	(time,nlev)	K^2	Variance of Liquid water potential temperature
sigthv2	(time,nlev)	K^2	Variance of Virtual potential temperature
sigthl2	(time,nlev)	K^2	Variance of Potential temperature
sigqt2	(time,nlev)	kg^2 kg^{-2}	Variance of Total water specific humidity
sigu2	(time,nlev)	m^2 s^{-2}	Variance of Zonal wind
sigv2	(time,nlev)	m^2 s^{-2}	Variance of Meridional wind
sigw2	(time,nlev)	m^2 s^{-2}	Variance of Vertical velocity

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