SPECIAL PROJECT PROGRESS REPORT

All the following mandatory information needs to be provided. The length should *reflect the complexity and duration* of the project.

Reporting year	2021-2022
Project Title:	Mesoscale Organisation of Shallow Cumulus Convection
Computer Project Account:	SPNLSIEB
Principal Investigator(s):	Pier Siebesma, Fredrik Jansson, Frans Liqui-Lung & Allesandro Savazzi
Affiliation:	Delft University of Technology
Name of ECMWF scientist(s) collaborating to the project (if applicable)	……………………………………………………….…… ……………………………………………………….……
Start date of the project:	2021
Expected end date:	2023

Computer resources allocated/used for the current year and the previous one

(if applicable)

Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	10.000.000		10.000.000	10.000.000
Data storage capacity	(Gbytes)	2000		4000	

Summary of project objectives (10 lines max)

The main questions we want to address in this project are:

- Are high resolution simulations capable of reproducing realistically the different modes of mesoscalecloud organisation such as observed during the EUREC4A field campaign?
- Can we explain and predict the the physical origin of the different modes of cloud organisation?
- Do the different modes of cloud organisation influence the cloud-radiation interaction?
- Is the strength of the cloud feedback of shallow clouds different for organised shallow cumulus clouds than for unorganised shallow cumulus cloud fields.

Summary of problems encountered (10 lines max)

A number of challenges were encountered during the project. Most importantly:

- The Dutch Atmospheric Large Eddy Simulation model (DALES) that is used within this project is designed to simulate using periodic lateral boundary conditions. In order to allow more realistic simulations especially for large domains we developed the options to run DALES with open boundary conditions. This was a mathematically and numerically challenging task because the model has a non-hydrostatic anelastic formulation, so as a consequence we had to introduce a iterative Poisson solver for the pressure fluctuations.

- Earlier simulations that are using the same sea surface flux parameterizations as in the IFS gave a strong overestimation of the surface latent heat fluxes when compared with observed fluxes. At present it is unknown what the cause is of this overestimation and this will be further investigated within this project as it might also signal a problem with the IFS sea surface flux parameterization. As a temporary fix we use at present a smaller roughness length as to have realistic values for the surface evaporation.

Summary of plans for the continuation of the project (10 lines max)

At the moment we have finished a 10 day simulation with DALES on a 150 x 150 km2 domain with a resolution of 150 m . In the attached report we show further results of this simulation. For the last 1.5 year it is planned:

- to extend the domain to 300 x 400 km.
- to add simulations with open boundary conditions
- to make pseudo-global warming simulations to assess the cloud feedback strength for the simulation cloud mesoscale structures.
- To skip the anticipated super-parameterized (SP) simulations as recent research demonstrated that SP simulations are not capable of representing the observed cloud mesoscale structures.

List of publications/reports from the project with complete references

- No accepted publications yet

Summary of results

See the attached document progress_spnlsieb-2022.pdf for the summary

Supplement of Progress Report on
Modeling Mesoscale Organisation of Shallow Cumulus Convection

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1. Introduction and Context

Shallow Cumulus over the subtropical oceans is the most abundant cloud type in our climate system and its radiative response to global warming is highly uncertain. Previous Model Intercomparison Projects (BOMEX, ATEX, ARM) on shallow cumulus convection have explored the representation of spatially unorganised shallow cumulus convection and their response to climate warming.

It has become clear over the last decade that marine shallow cumulus convection has a natural strong tendency to develop into mesoscale organised cloud structures and that unorganised shallow cumulus convection is rather the exception than the rule.

It is particular challenging to realistically simulate these mesoscale cloud patterns. On the one hand, this requires turbulence resolving resolutions to represent the vertical convective mixing processes while at the same time domains of several hundreds of kilometres are needed to represent the observed mesoscale cloud structures. It is only recently that the computational capability is allowing us to simulate these rich structures.

It is for this reason that we propose a MIP on shallow cumulus convection over the Northern Atlantic subtropical ocean such as observed during the EUREC4A field campaign in January-February 2020.

The three main objectives of this MIP are:

- Assessing simulation capability of the observed shallow cloud mesoscale organisation
- Understanding the underlying dynamical processes leading to the organisational patterns
- Assessing the radiative response of this weather regime to climate warming using the Pseudo-Global Warming (PGW) framework for the limited area models (LAM’s).

Ideally this requires models that simulate the atmosphere at turbulent resolving resolutions of 100 meter on domains of several thousands of kilometres. At present this is not yet a numerically feasible configuration. We therefore propose to have threedifferent model approaches in this MIP that concentrate on different spatiotemporal domains and resolution:

- Global Storm Resolving Model (SRM) simulations with resolutions of 2.5-5 km for the whole EUREC4A period of Jan-Feb 2022.
- Storm Resolving Model (SRM) simulations with resolutions of 0.5-2.5 km over a domain of typical 2000 X 2000 km^2 for the whole EUREC4A period of Jan-Feb 2022.
- Large Eddy Model (LEM) simulations with resolutions of 50~500 meter over a domain of 300 X 300 km for the period February 1-11 2020.

The present special project SPNLSIEB deals with the preparation of the MIP of the Large Eddy Model (LEM) simulations and the initial analyses of these simulations.

2. Set up of the LEM simulations

In preparation of the LEM MIP we have set up a LEM simulation on a 150 x 150 km^2 domain centered around 57.5 W, 13.3 N which was the central point around which most of the flights of the EUREC4A field campaign were executed. The used horizontal resolution was 100 meter and a stretched vertical grid was used with a resolution that was 20 meter near the surface and around 100 meter near 8 km near the top of the model domain.

Periodic boundary conditions were used. Daily varying Sea surface Temperature (SST) were used as a lower boundary condition. The large scale forcing is derived from the operational mesoscale NWP model HARMONIE from which the dynamical tendencies are derived. So therefore these tendencies contain the averaged large scale advection and horizontal diffusion terms of a HARMONIE hindcast simulation over the Carribean area. More precisely the total tendencies for the prognostic variables ϕ in $\{q_v, q_l, T, u, v, w\}$ from HARMONIE can be decomposed in a dynamical part and a part due to the physical parameterizations in HARMONIE

$$\left(\frac{\partial \phi}{\partial t}\right)_{\mathrm{tot}} = \left(\frac{\partial \phi}{\partial t}\right)_{\mathrm{phys}} + \left(\frac{\partial \phi}{\partial t}\right)_{\mathrm{dyn}} \quad (1)$$

The left hand side can be obtained from diagnosing the change in the prognostic HARMONIE fields, the parameterized tendencies are standard output fields so that the dynamical tendencies can be obtained as a residual from one and subsequently spatially averaged over an area twice the size of the LEM domain as to suppress noise. The tendencies were also averaged over periods of 1 hour so that in the end we have hourly large scale tendencies for all the prognostic variables of the LEM that are applied uniformly over all the grid boxes during the LEM simulations.

Two main 10-day experiments (Feb 02 – Feb11 2020) were conducted with DALES:

1. A free LES run forced with a (hindcast) regional climate model (HARMONIE) without nudging.
2. A free LES run forced with a climate HARMONIE simulation and with nudging to the mean profiles of the forcing model.

Two sensitivity experiment were also conducted on one of the days to investigate the effect of a more realistic surface representation:

1. Using a different roughness length parametrization.
2. Using a spatially distributed sea surface temperature (SST).

From these experiments several non-standard outputs were saved every 15 minutes and 3D fields every 30 minutes. Tendency terms were also saved to reconstruct the budgets of momentum, humidity and temperature. In addition to the domain-mean tendencies, these terms were also conditionally sampled on updrafts, downdrafts and cloud core, sensibly affecting the runtime

3. Results

We will present here a couple of preliminary results. More comprehensive analyses basd on the simulations are on the way. We also reached some conclusions how to improve the setup of the LEM simulations before opening the MIP up to other models.

3.1 Cloud Structures

Figure 1 gives a flavour of the cloud structures that are being resolved by the 100 m LEM simulation as compared with the more traditional mesoscale simulations at 2.5 km. The figure shows the liquid water path (LWP): outside the orange box the LLWP as simulated by the 2.5 km resolution HARMONIE model and inside the orange box a snapshot of the 100 meter resolution simulation of DALES.

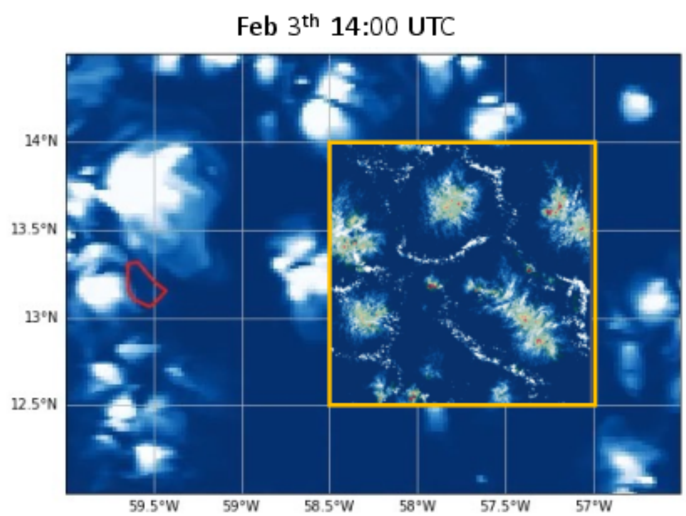

Figure 1: Snapshot of the simulated liquid water path (LWp) of the mesoscale 2.5km resolution model HARMONIE (outside the orange box) along with the embedded snapshot of LWP simulated by DALES on 1a 100 meter resolution (inside the box). The red contours indicate the island of Barbados with a typical scale of around 50 km.

An eyeball comparison of the reflectivity on February 5th between MODIS and DALES is shown in Fig 2. The top row contains 4 snapshots of the HARMONIE run. At 0:00 UTC most of the cumulus clouds are subgrid in HARMONIE so they show up as a smeared out LWP field with no internal structure. Later on the day from 9:00 UTC onwards distinct cloud structures become visible with sizes of tens of kilometers, resembling so called “flower” structures that are often observed by satellite. The orange box indicates the 150 by 150 km^2 domain which is simulated by DALES at a 100 meter resolution. At 0:00 UTC, small individual cumulus clouds can be observed, but not randomly distributed but rather clustered at the surrounding edges of cold pools that are characterized by clear air. As time progresses the cold pool structures become more pronounced larger in size and accompanied with cloudy outflows, similar to cloud anvils of deep convection but much shallower in the present case. MODIS images are only available at 10:30 and 12:30 UTC but the structures have a remarkable statistical resemblance with the DALES simulations. A more quantitative comparison of the simulated versus the observed cloud structure will provide more definite answer on the capability of LEM simulations to simulate the observed mesoscale cloud structures.

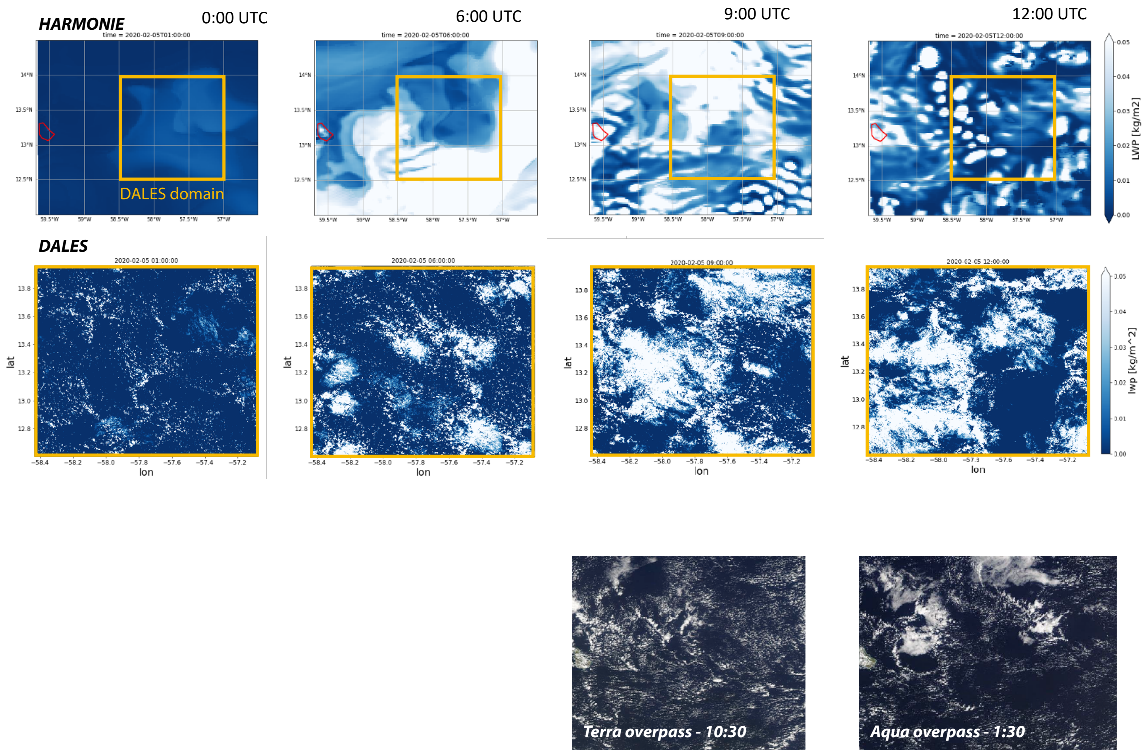

Figure 2: Snapshots of HARMONIE and DALES simulations on February 5th along with MODIS observations of the same area.

3.2 Time Development of the Vertical Extent of the cloud structures.

In Figure 2 we show a time-height development of the cloud fraction during the first 7 days of the simulation without nudging. It shows a steady growth of the cloud top height from around 2 km on the first day to 5 km at day 7. Observations from the Barbados Cloud Observatory (BCO) and MODIS clearly show that cloud top does not extend beyond 3 km during this period. This unrealistic growth is probably due to the strong cooling and moistening from the prescribed large scale forcings (Figure 3). This also demonstrates that if simulations are only forced by external large scale tendencies, there is no mechanism present that prevents runaway effects, such as the unbounded growth of the cloud top height. It is for this reason that we also included simulation where nudging to the mean state is added in order to prevent the runaway affects. Using open boundary conditions is another way to prevent runaway effects.

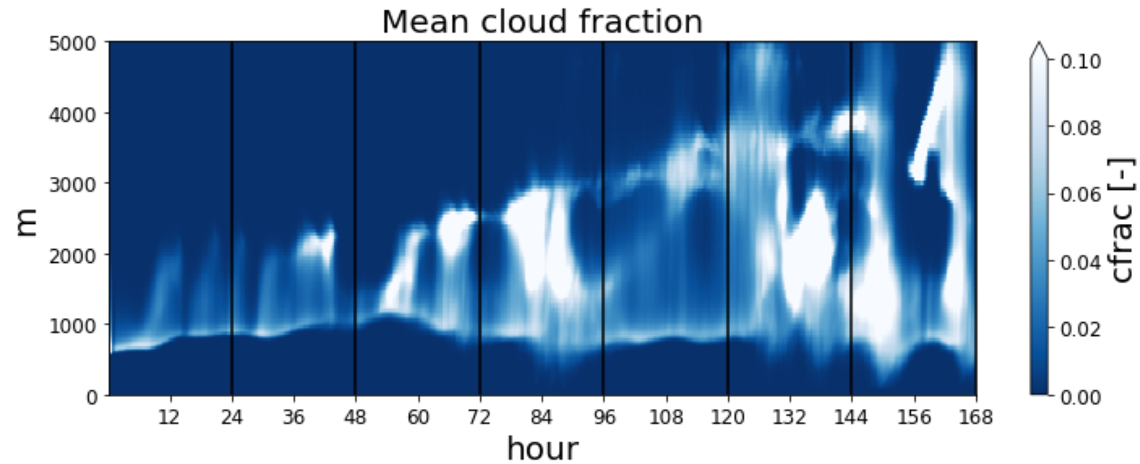

Figure 3: Time development of the cloud fraction of the DALES run without nudging. Note the unrealistic growth of the vertical extent of the cumulus convection

3.3 Surface Fluxes

Initially we made the simulations with the same surface flux parameterization as used in the ECMWF's IFS. However this resulted in an overestimation of the surface latent heat flux of more than 50 W/m^2 . It is not clear whether this is due the observed dry bias in the subcloud layer inherited from the IFS analysis or due to the drag formulation. At present we use a more simplified surface flux parameterization (in blue in Figure 4) that compares well with the observations. It is in the planning to look more carefully in the behaviour of the various surface flux parameterization and how they compare with the observed fluxes.

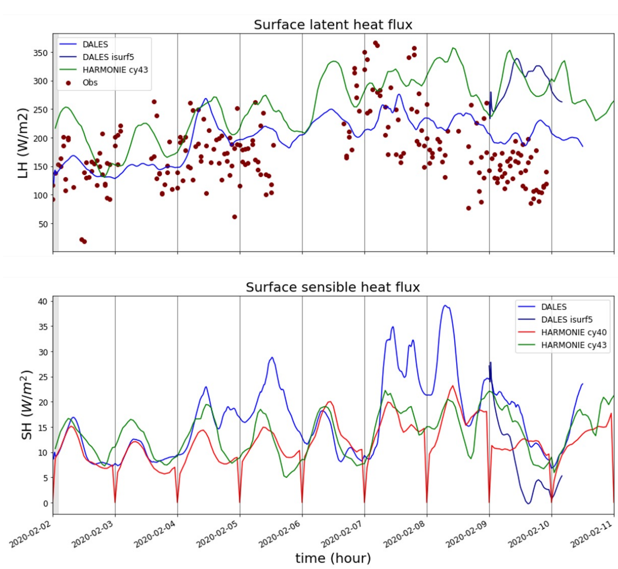

Figure 4 Time development of the surface fluxes of the mesoscale model HARMONIE (green), DALES with the IFS surface parameterization (dark blue , only on 10-02) and a simplified surface parameterization (blue).

3.4 Wind Fields

Besides the cloud organisation we are also interested in evaluating the convective momentum transport. At present the effect of convective momentum transport and its effect on the wind profiles is highly uncertain.

In Figure 5 we show the time development of the wind speed at 300 meter for HARMONIE, DALES, ERA5 and observations from radio- and dropsondes. These results show that the simulated wind fields from HARMONIE en DALES are in good agreement with ERA5 and the insitu observations. Only DALES shows a 1 to 2 meter positive bias over the last 3 days.

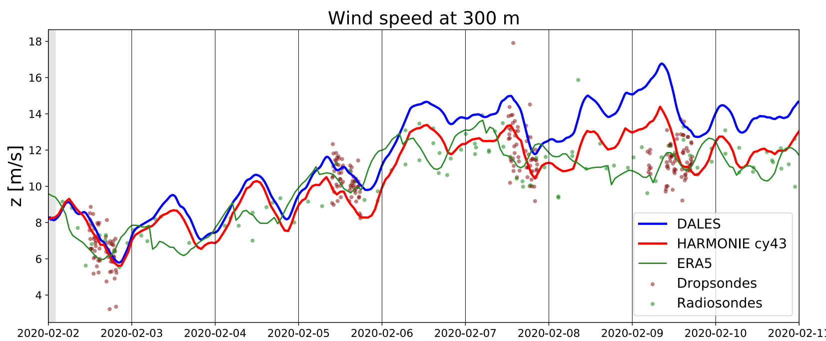

Figure 5 : Time series of the wind speed at 300m. blue: nudged DALES simulation, red: Harmonie simulation, green: ERA5.

In Figure 6 we show the mean zonal wind tendencies of HARMONIE and DALES between 0 and 750m. For HARMONIE these tendencies are further subdivided into the total tendency (net), the physical tendency (Phy) (see also eq. 1). A few observations can be made:

- The dynamical tendency of HARMONIE is equal to the prescribed large scale forcing of DALES. This should not be a surprise because this is how the large scale forcing of DALES is derived.
- The net tendencies of HARMONIE and DALES are similar. This demonstrates that the simulated development of the zonal wind is comparable between the two models.
- The physical tendencies of HARMONIE are very similar to the dynamical tendencies of DALES. In other words the parameterized tendencies in HARMONIE are equall to the explicitly resolved dynamics of DALES. This makes DALES a perfect instrument to futher flesh

out the intricate dynamics of the convective momentum transfer and to test and develop momentum transport parameterizations.

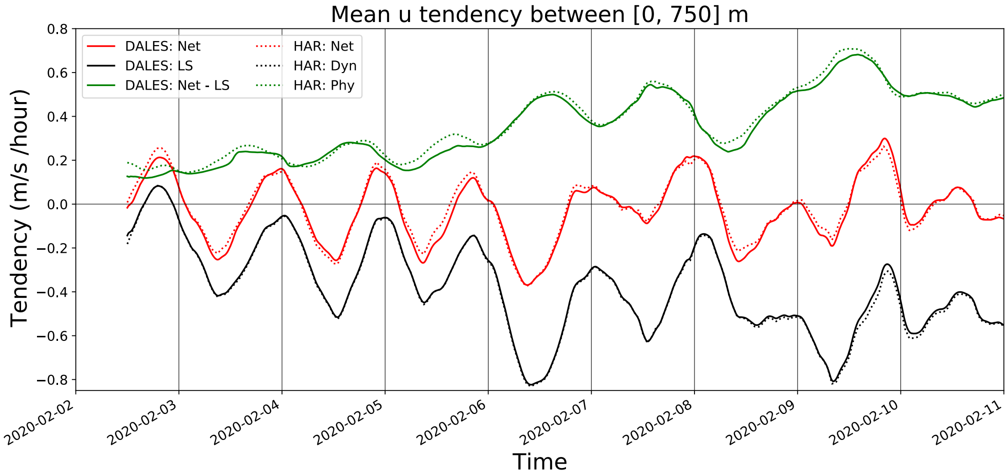

Figure 6: : Time series of the zonal momentum tendencies.

4. **Planned Simulations for the remainder of the Project**

A couple of simulations are foreseen in the remainder of the project:

- Simulations with periodic boundary conditions on a larger 400x300 km domain
- Simulations with open boundary conditions on a larger 400x300 km domain
- Simulations with a Pseudo-Global Warming Perturbations with open boundary conditions on a larger 400x300 km domain

These runs will require more than the requested 10^6 SBU's. DALES has already been ported to the new ATOS machine in Bologna.