REQUEST FOR A SPECIAL PROJECT 2021–2023

MEMBER STATE: The Netherlands

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Project Title: Mesoscale Organisation of Shallow Cumulus Convection

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP** ________________	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2021	
Would you accept support for 1 year only, if necessary?	YES X	NO ☐

Computer resources required for 2021-2023: (To make changes to an existing project please submit an amended version of the original form.)		**2021**	**2022**	**2023**
High Performance Computing Facility	(SBU)	10.000.000	10.000.000	10.000.000
Accumulated data storage (total archive volume)[2]	(GB)	10.000	20.000	30.000

Continue overleaf

[1] The Principal Investigator will act as contact person for this Special Project and, in particular, will be asked to register the project, provide annual progress reports of the project's activities, etc.

[2] These figures refer to data archived in ECFS and MARS. If e.g. you archive x GB in year one and y GB in year two and don't delete anything you need to request x + y GB for the second project year etc.

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Extended abstract

Summary

Marine shallow cumulus is the most abundant cloud type on our planet and a prime source of climate feedback uncertainty, due to our lack of knowledge how this cloud type responds to global warming. From satellite observations it has become clear that these clouds often organised in clusters of various sizes and shapes. Yet, the precise physical mechanisms that create these various organisation modes remain unclear. Furthermore, the relevance of cloud organisation for cloud-radiation interaction and cloud-feedback strength is unknown. The high resolution simulations, as proposed in the project, on large domains based on the recent field campaign EUREC4A will be essential in answering these questions.

Motivation

Over the last twenty years there have been a number of high resolution model intercomparison studies of marine shallow cumulus convection based on observational field campaigns such as BOMEX (Siebesma et al 2003), ATEX (Stevens et al. 2001) and RICO (van Zanten at al. 2011). Large Eddy Simulations (LES) based on these observations have been highly instructive in elucidating the cloud dynamics and cloud microphysics of this most abundant cloud type. In addition, these simulations have also provided useful bounds for parameterised descriptions of cumulus convection in terms of mass flux, entrainment, detrainment rates, cloud fraction profiles and precipitation rates. LES have also been used to quantify the response of shallow cumulus clouds to warming by subjecting them to a warmer Sea Surface Temperature (SST) and a warmer atmosphere under constant relative humidity conditions (Blossey et al. 2013). These studies showed that shallow cumulus clouds are resilient to perturbations, hence suggesting a small, but nevertheless positive cloud feedback.

However, none of the above cited simulations cited did show any sign of spatial cloud clustering, despite the fact that mesoscale organisation is rather the rule than the exception for marine subtropical cumulus clouds (Stevens et al. 2020). At least two reasons are responsible for the absence of clustering in these “early generation” of large eddy simulations of shallow cumulus convection:

1. ***Too small domains:*** More recent simulations (Seifert et al. 2013) do show that there is a tendency for cumulus convection to cluster, provided that the domains are sufficiently large (at least 50 km) and the simulation time is long enough (days). This tendency of clustering, aka mesoscale organisation, is strongly accelerated by precipitation (Vogel et al. 2016). In the presence of precipitation, saturated downdrafts create cold pools. Cloud formation is suppressed within the cold pools while it is triggered at the outflow edges of the cold pools. Cloud organisation induced by cold pools is a frequent observed mode of organisation over the subtropical oceans.

2. ***Oversimplified large scale forcings:*** Traditionally, large eddy simulations use idealised periodic boundary conditions and simplified large scale forcings that are fixed in time and space. More realistic simulations that are forced by temporally varying forcings derived from the operational numerical weather prediction (NWP) models do show substantially more cloud clustering (Schalkwijk et al. 2014)

In short, it is possible to simulate mesoscale organisation of shallow cumulus convection, provided that the numerical domain size is large enough, through bottom-up processes, through top-down processes (realistic large scale forcings) or through a combination of these processes.

Recent analyses of satellite observations show a wide variety of modes of cloud organisation over the subtropical oceans for which exotic names have been coined such as: "sugar", "gravel", "flowers" and "fish" (Stevens et al. 2020) . At present it is unknown under which atmospheric conditions these different organisation modes develop and which dynamical processes are responsible for creating these structures.

Recently, a new large observational field campaign EUREC4A was conducted near Barbados (20 January – 20 February 2020) (Bony et al. 2017). Key objectives of EUREC4A are i) to understand the mechanisms that create the various modes of cloud organisation over the subtropical Atlantic ocean and ii) to quantify the relevance of these organisation modes for vertical transport and cloud-radiation interaction in present and future climate. EUREC4A has been a unique field experiment, because for the first time both the large scale conditions as well as the small scale cloud dynamics and cloud microphysics have been carefully monitored. Previous campaigns either only observed the large scale conditions (BOMEX) or only the small scale cloud dynamics and microphysics (RICO).

In short, this project will allow the execution of a series of high resolution large eddy simulation runs over large domains in various configurations, based on the EUREC4A observations. These simulations will be a key ingredient in the process of understanding the mechanisms of the spatial organisation of shallow cumulus convection and the relevance for weather and climate.

Main Research Questions

With the simulations we aim to answer the following research questions:

- Are high-resolution simulations capable of realistically reproducing the different modes of mesoscale organisation such as observed during EUREC4A?
- 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?

The last two research questions are especially relevant for global climate and NWP models that usually operate at resolutions not (yet) sufficient to resolve these mesoscale cloud structures.

Methods

Designing realistic simulations that can reproduce the observed mesoscale cloud structures is a highly nontrivial task. On the one hand, the resolution needs to be fine enough to resolve the turbulent structures that shape the resulting clouds. This requires a minimum resolution of ~100~200 metres. On the other hand, the domain size has to be large enough to capture the observed mesoscale structures. These structures vary almost on a daily basis between unorganised cumulus fields ('sugar'), cold pool structures ('gravel'), circular outflow structures ('flowers'), and elongated cloud clusters ('fish'). The sizes of these structures differ strongly: unorganized sugar (O(1 km), gravel O(10~100km), flowers O(50~500km) and fish O(100~1000km) (See Fig. 1).

Within this project, our aim is to run a number of simulations with the Dutch Atmospheric Large Eddy Simulation (DALES) model on large domains (Heus et al. 2010) . DALES is a state of the art LES model that is well suited to run efficiently on a massive parallel machine. DALES was the first model that was capable of producing realistic simulations of weather on the scale of a country, which makes it a suitable modelling tool for creating the simulation envisioned in this project.

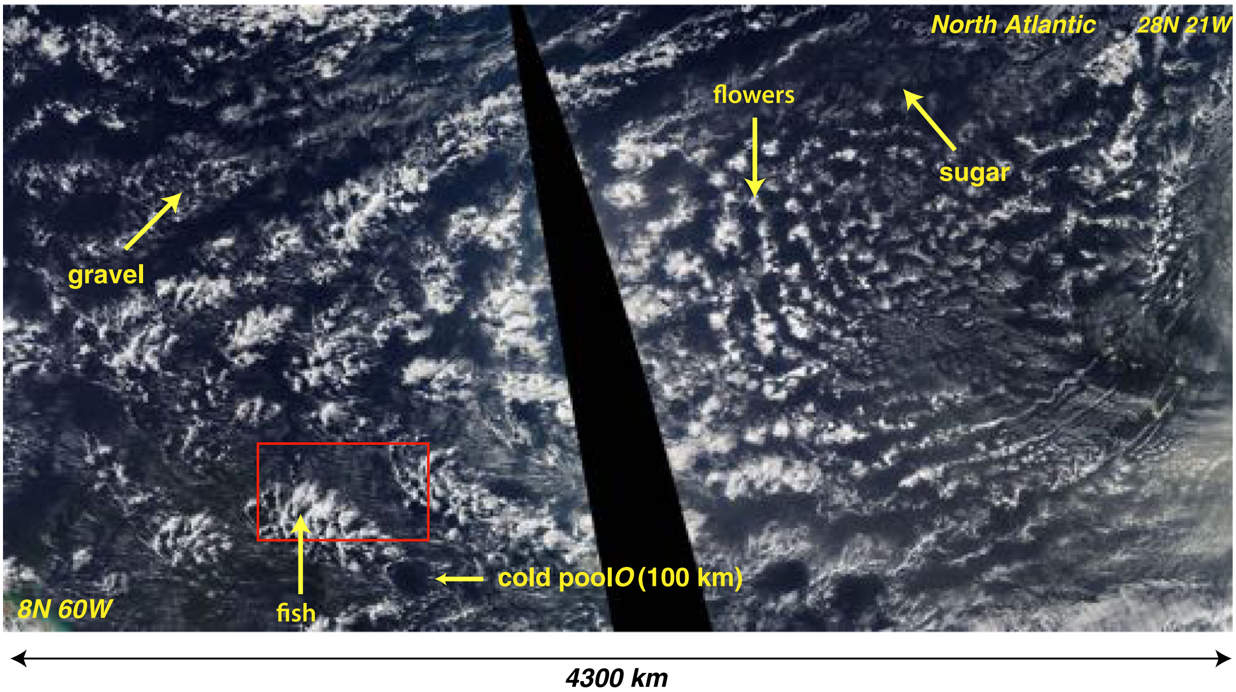

Figure 1: Shallow cumulus convection over the Atlantic Ocean as viewed by MODIS Aqua at 13:30 local time on December 12, 2013 (Figure copied from Nuijens and Siebesma 2019).

In the 1st phase (year 1), a number of days (O(10)) will be simulated using DALES on domains of a size 150~300 km and a resolution of 100~200 m. For the large scale forcing we will use two flavors: i) observational large scale forcings derived from the dropsondes during the campaign and ii) large scale forcings from the operational NWP model HARMONIE. HARMONIE runs operationally over the Caribbean and the dynamical tendencies have been extracted and can be used to force DALES. These domains should be sufficiently large to represent sugar and gravel. The larger 'flower' and 'fish' structures might be too large to capture. To this purpose also high-resolution simulations of global and storm-resolving mesoscale models will be analysed (see Section on embedding). This phase will address research question 1 and 2. For more information on the precise analyses we refer to a recently published overview paper by two of the applicants of this proposal on this topic (Nuijens & Siebesma 2019)

In the 2nd phase (year 2) we will perturb a small number of simulations that are representative for the various modes of organisation. This will be done in the same spirit as was done during the CGILS intercomparison (Blossey et al. 2013) , i.e. the SST is raised by 4K, the atmosphere is warmed accordingly following a moist adiabat while the relative humidity is kept constant. In this manner a plausible future climate simulation will be recreated. The change in cloud radiative forcing will show to what extent organised cloud clusters (i.e. gravel) respond differently to warming than unorganised cloud fields (i.e. sugar).

In the 3rd phase (year 3) we will explore how well the IFS can represent the modes of cloud organisation in a super-parameterized setting. In a previous project we have developed the possibility of replacing the parameterization in the IFS by a DALES instance for a pre-selected number of grid boxes (Jansson et al. 2019). For these selected grid boxes, the subgrid contributions are provided by a DALES instance. In return the IFS provides the large scale forcing at each time step to the DALES instances. We will produce a series of simulations in which the resolution of the IFS is increasingly refined and simultaneously the domain sizes of the LES instance reduced. This way we can explore the influence of the scale break on the cloud organisation as a function of the used resolution. At the same time ideas will be developed on how to communicate humidity variability from DALES (or a parameterisation) to the resolved scales of the IFS and vice versa.

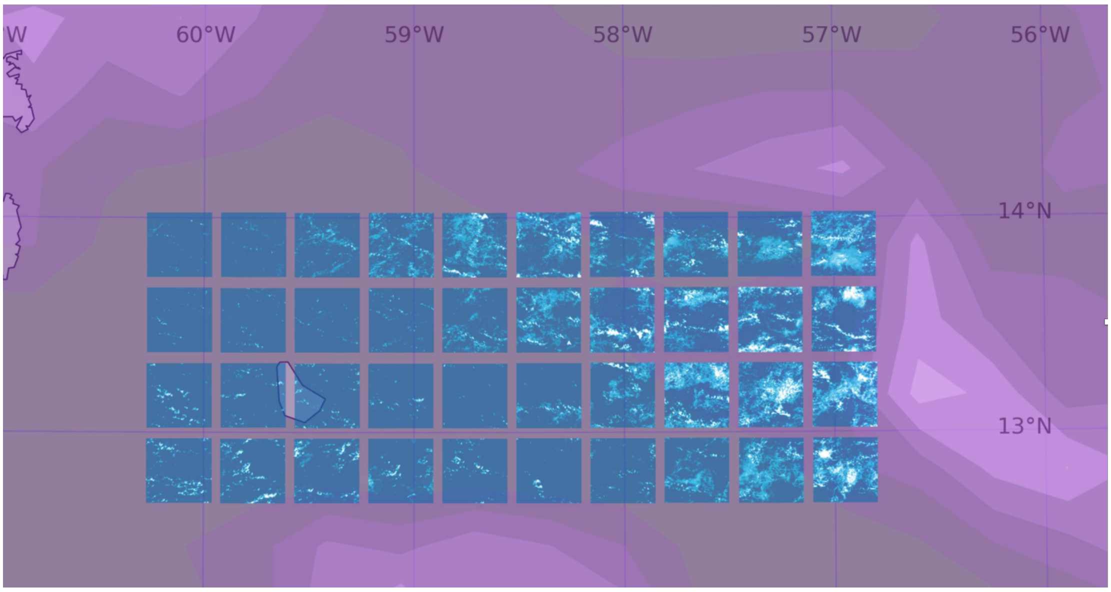

Figure 2. Snapshot of an IFS simulation where 40 grid boxes are superparameterized with 40 DALES instances. The different colors correspond to different values of the liquid water path.

Justification of the Computer Resources

Dales simulations have been executed as the HPC of the ECMWF for a long time and the model exhibits a perfect weak scaling behaviour on one node. The computational behaviour is slightly deteriorating for multiple nodes but this issue is currently being addressed as part of an ECiWACE project. The typical DALES run requires 2.5 10^{-6} sec per grid point per time step per core on the Cray machine of ECMWF. The typical time step of the model is 1 sec.

For the runs in phase 1 this implies that a simulation of 1 day on a domain of 300 by 300 km with a resolution of 200 m requires 330 000 SBU's. For phase one we anticipate one month (30 days) of simulations which amounts to 10^6 SBU's.

In phase 2 we will only perturb a subset (~ 5 days) to future climate situations, but we will use different perturbation scenario's. For instance we will also explore what the effect of the perturbed climate runs is if the subsidence is weakened. So our estimate is that we will also need simulation time for 30 days which amount roughly for the same amount of 10^6 SBU's.

In phase 3 we will simulate a super-parameterised versions of the IFS. Our ambition is to super-parameterise an area of at least 1000 by 200 km, which amounts 600000 SBU per day. We anticipate a series of 2 day simulations, for a range of IFS resolutions (5km, 50km, 200km).

Embedding

The proposed model runs are of crucial importance for the modelling efforts of EUREC4A to investigate our simulation capability of the rich observed modes of cloud organisation. It is part of a larger modelling effort. A number of institutes (ECMWF, MetO, DWD, MeteoFrance) will provide high resolution global simulations for the EUREC4A period as well as simulations with their operational storm resolving models. The simulations in this project will complement these simulations with high resolution large eddy simulations as part of the H2020 CONSTRAIN project.

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