Delft University of Technology

Additional Thesis

A validation of subtropical marine low clouds in the HARMONIE regional weather model

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Abstract

One of the areas of major importance when it comes to weather prediction are clouds, due to their significant impact on the climate and because they are major source of the spread in climate sensitivity in climate models. This paper will focus on the main numerical weather prediction model, HARMONIE, used by the Royal Netherlands Meteorological Institute, with the objective to determine whether this model is able to accurately simulate the meso-scale organization and structures of subtropical low marine clouds. This is done by comparing various HARMONIE simulation outputs with the observed variables obtained from the Barbados Cloud Observatory. To determine how the different processes within HARMONIE are affecting the simulation outputs, several experimental runs are analyzed. Based on the results it can be seen that HARMONIE cycle 43 does produce a higher amount of low cloud cover compared to HARMONIE cycle 40. This is expected as HARMONIE cycle 43 does contain the additional height variance which was added in order for the model to produce more low clouds. However, it is overestimating the total low cloud cover, in contrast to the underestimation by HARMONIE cycle 40. It can be seen that when the additional height variance is removed the simulation of the low cloud cover is significantly improved and is comparable to the observational low cloud cover. Furthermore, when the additional height variance and shallow convection are both removed the amount of low cloud cover produced by HARMONIE cycle 43 also closely resembles the observed low cloud cover amount. When it comes to cloud fraction in the atmosphere, all of the experimental runs are not able to produce clouds that are present above 3000 m. This result was also obtained from simulation outputs of HARMONIE cycle 40. Besides this, also the specific humidity and potential temperature from the simulation outputs of HARMONIE cycle 43 are not accurately modelled. All of the experiments seem to have a dry BIAS near the surface and a cold BIAS throughout the whole entirety of the atmosphere. Based on these findings it can be concluded that HARMONIE cycle 43 is able to produce meso-scale subtropical marine clouds, however it does not do this accurately but is overestimating at all times. Moreover, it can be seen that the additional height variance has significant impact on the cloud production and it is recommended it be removed as the simulation outputs more accurately describe the observational data when it is not present. Furthermore there is no major improvement between cycle 40 and 43 in the cloud formation above 3000m. Both cycles are not able to produce any clouds in the simulation outputs. Based on this new understanding of what is the major source affecting the cloud production in HARMONIE, it is possible to further look into them with the aim to improve the overall weather prediction of HARMONIE.

Contents

1 Introduction

1.1 Introduction to Topic

It is of major importance that weather prediction models accurately describe and predict the current weather and climate. This is necessary for the day to day life, as well as to predict and determine what the future climate will be. One of the areas of major importance when it comes to weather prediction are clouds. Clouds play an important role in radiation budget of the atmosphere. Not only due to their reflectivity but also due to their ability to absorb and re-emit long-wave radiation. Even with the current technological advancements, cloud feedbacks remain the largest source of the inter-model spread in climate sensitivity [2]. The reason for this is that the physics of clouds are still not completely understood and it becomes hard to model and predict current cloud formations.

1.2 Research Aim

This paper is a continuation of the thesis, '*Evaluation of the representation of subtropical marine clouds in the numerical weather prediction model HARMONIE*' by F. van der Voort [9], which focused on HARMONIE cycle 40, with the aim to compare various cloud properties from HARMONIE simulation outputs with observations and determine whether HARMONIE is able to simulate meso-scale cloud structures that occur in the Caribbean area [9].

In contrast to the paper mentioned above, this research will focus on HARMONIE cycle 43. The main objective of this research is to validate the HARMONIE numerical weather prediction model cycle 43, by using real life observations with the aim to determine whether HARMONIE can accurately simulate the meso-scale subtropical low marine clouds. This research will not be focused on the ability of HARMONIE to simulate the meso-scale cloud structures.

1.3 Research Domain

Clouds have the property to reflect incoming solar radiation due to their high albedo. As a result, the presence of clouds over the dark sub-tropical oceans increases the albedo of the oceans, making tropical oceans absorb less radiation and influencing the overall radiation budget of the world. As a result, subtropical marine clouds have a substantial influence on the climate. Furthermore, shallow cumulus, such as those found in the trade-winds of the North Atlantic, can be considered the predominant cloud type on the planet [4]. Based on the points previously mentioned, it is of major importance to understand the clouds in this region.

Due to the importance of understanding and modelling low marine subtropical clouds accurately, the area of study for this evaluation is located in the tropical belt, specifically the Barbados Cloud Observatory , hereafter referred to as BCO, located on the island of Barbados ($13°5'52''N, 59°37'6''W$), seen in figure 1.1. BCO is located on the windward coast of Barbados, and is well situated to observe undisturbed air masses carried by the trade winds over the Atlantic Ocean [4].

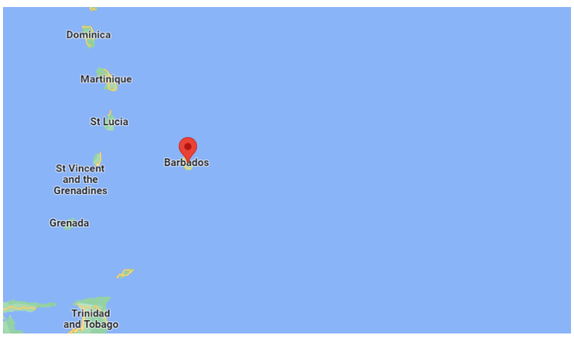
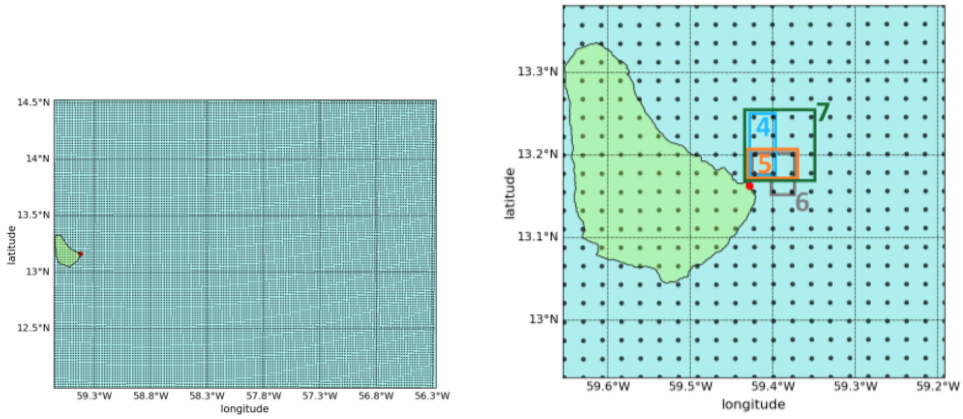


Figure 1.1: Barbados Location. Retrieved from: Google Maps.

The research period used to conduct this evaluation is the same as the ElUcidating the RolE of Cloud-Circulation Coupling in ClimAte (EUREC4A) field campaign period, which ran from the 20th of January 2020 - 22nd of February 2020. Lastly, all of the observations obtained from the BCO will be compared to HARMONIE simulations. Results from the HARMONIE numerical weather prediction model are obtained from gridpoints, as seen in figure 1.2a. To be able to compare the observations with the simulated results, only a part of the domain of HARMONIE will be used for this research, namely gridcell 7, as shown in figure 1.2b. Based on the paper: *Evaluation of the representation of subtropical marine clouds in the numerical weather prediction model HARMONIE*, by F.van der Voort, this gridcell was chosen due to its large sea fraction and close proximity to the BCO.



(a) HARMONIE simulation domain

(b) HARMONIE gridcell 7

Figure 1.2: HARMONIE domain. Retrieved from: *Evaluation of the representation of subtropical marine clouds in the numerical weather prediction model HARMONIE*, by F. van der Voort.

An in depth explanation for the choice of the research area, HARMONIE domain and choice of gridcell can be found in *Evaluation of the representation of subtropical marine clouds in the numerical weather prediction model HARMONIE* [9].

1.4 Report Structure

The structure of the report will be as follows: Chapter 1 discusses the subject, aim of research and domain. This is followed by a description of the model versions and updates in chapter 2. Chapter 3 describes the various comparisons that will be made. The results are presented in chapter 4 and lastly chapter 5 contains conclusions and recommendations.

2 Model

The HARMONIE numerical weather prediction model used by The Royal Dutch Meteorological Institute, in Dutch; Koninklijk Nederlands Meteorologisch Instituut (KNMI), has been developed specifically for short-term weather forecasts [1]. It is a regional high-resolution meso-scale model with a non-hydrostatic dynamical core and has a resolution of 2.5x2.5 km, contains 65 levels in the vertical and has a model time step of 75 seconds [8]. The model has the ability to solve various equations as well as use parametrizations for all of the physical properties that are happening within the gridbox that cannot be explicitly solved. The HARMONIE model can be run with different settings. Switches can be turned off or on, in this manner different experiments are conducted to determine the effects of the various variables.

An overview of the different experiments that will be used and discussed in this paper are presented in table 1. These will be further discussed in the following sections.

Nr.	Name	Cycle	Model Type	Description	Comparison Name
1	EUREC4A_harm40_hindcast	40	Hindcast	ECUME height QS = FALSE	HAcy40 HINDCAST
2	EUREC4A_harm43h22tg3_hindcast	43	Hindcast	ECUME 6 height QS = TRUE	HAcy43 HINDCAST
3	BES_harm43h22tg3_fERA5_exp0	43	Climate run	ECUME 6 height QS = TRUE	HAcy43 climate run
4	HA43h22tg3_clim_noHGTQS_ECUME	43	Climate run	ECUME height QS = FALSE	HAcy43 climate run + no height variance + ECUME
5	HA43h22tg3_clim_noHGTQS	43	Climate run	ECUME 6 height QS = FALSE	HAcy43 climate run + no height variance
6	HA43h22tg3_clim_noHGTQS_noSHAL	43	Climate run	ECUME 6 height QS = FALSE shallow convection = FALSE	HAcy43 climate run + no height variance + no shallow convection
7	HA43h22tg3_clim_noSHAL	43	Climate run	ECUME 6 height QS = TRUE shallow convection = FALSE	HAcy43 climate run + no shallow convenction
8	HA43h22tg3_clim_noUVmix	43	Climate run	ECUME 6 height QS = TRUE wind mixing = FALSE	HAcy43 climate run + no wind mixing

Table 1: Overview of model cycles and experiments.

2.1 HARMONIE Versions and Updates

Based on the results obtained from the paper; *Evaluation of the representation of subtropical marine clouds in the numerical weather prediction model HARMONIE*, it can be observed that HARMONIE cycle 40 has an underestimation of low clouds during the day and an overestimation of low clouds during the night. Furthermore, in the vertical, the clouds below 1 km are underestimated, the clouds between 1 - 2 km are pretty accurately represented, and the clouds above 2 km are underestimated again. For the whole entirety of the EUREC4A period there is underestimation of clouds above 3 km.

To resolve the underestimation of the clouds in HARMONIE cycle 40, an additional variance term was added on top of the already existing variance term, also referred to as height QS or LHGHT QS. This additional variance is dependent on the level layer depth. Because HARMONIE level thicknesses increase with height, the variance is low at the surface, and increases with height, reaching its maximum value at the top level. With this additional variance it was expected that HARMONIE would produce more clouds.

An in depth explanation of the physics and dynamics of cycle 40 and in depth information on the different updates for cycle 43 can be found in “The HARMONIE-AROME model configuration in the ALADIN-HIRLAM NWP system” [8] and “Model development in practice: A comprehensive update to the boundary layer schemes in HARMONIE-AROME cycle 40” [5] respectively.

3 Methodology

To get a clear understanding of which components of the model are affecting the simulation outputs, 2 main comparisons will be conducted, one comparison which determines the sensitivity to the model setup and another comparison which determines the sensitivity to the model physics. The comparisons are as follows:

- **Comparison 1. Model Setup Sensitivity.**
  HARMONIE hindcast cycle 40
  HARMONIE hindcast cycle 43
  HARMONIE climaterun cycle 43
  HARMONIE climaterun cycle 43 + no height variance
  HARMONIE climaterun cycle 43 + no height variance + ECUME

- **Comparison 2. Model Physics Sensitivity.**
  HARMONIE climaterun cycle 43 + no height variance
  HARMONIE climaterun cycle 43 + no height variance + no shallow convection
  HARMONIE climaterun cycle 43 + no shallow convection
  HARMONIE climaterun cycle 43 + no wind mixing

4 Results

4.1 Comparison of Low Cloud Cover

The overall cloud cover is the percentage of the surface on earth that is covered with clouds. To determine whether HARMONIE correctly simulates the total amount of cloud cover, all of the simulation outputs will be compared to observed cloud amount under 2500 m.

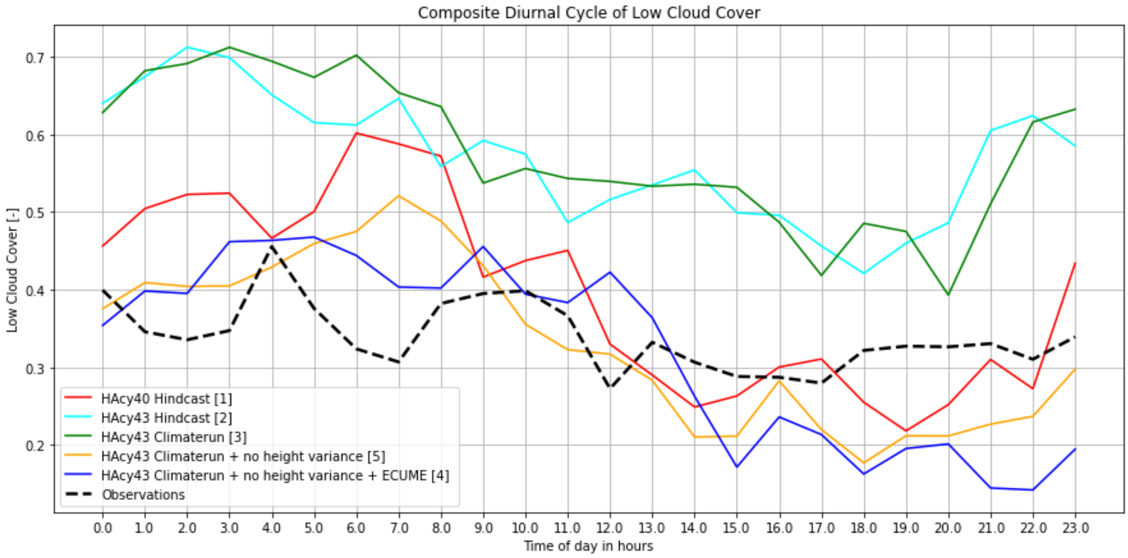


Figure 4.1: Low Cloud Cover Comparison 1

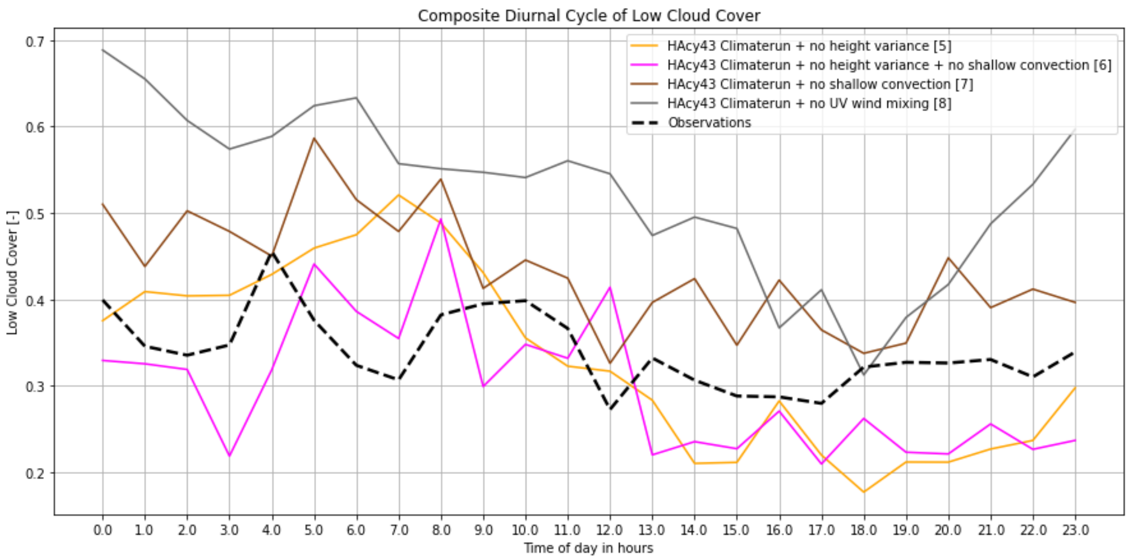


Figure 4.2: Low Cloud Cover Comparison 2

Name	**Mean Low Cloud Cover**
Observations	**0.34**
HAcy40 HINDCAST	0.40
HAcy43 HINDCAST	0.57
HAcy43 climate run	0.58
HAcy43 climate run + no height variance	0.33
HAcy43 climate run + no height variance + ECUME	0.32
HAcy43 climate run + no height variance + no shallow convection	0.30
HAcy43 climate run + no shallow convection	0.43
HAcy43 climate run + no wind mixing	0.53

Table 2: Mean Low Cloud Cover.

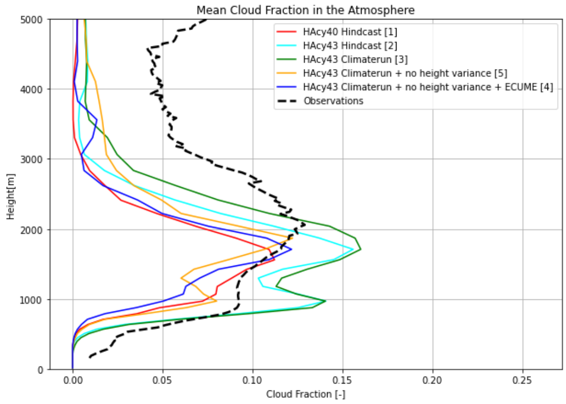
First of all, from figure 4.1 and table 2, it can be observed that both HARMONIE cycle 43 hindcast and climate run, which contain the additional height variance, have a higher cloud cover amount compared to HARMONIE cycle 40 runs and HARMONIE cycle 43 where no additional height variance is used. This is an expected result, as the additional height variance was added to resolve the problem of underestimation of clouds by HARMONIE cycle 40. Even though the additional height variance did produce more cloud amount, it did not produce the *correct* cloud cover amount. It is overestimating the cloud amount throughout the whole diurnal cycle. There is not much difference in the simulated outputs of cycle 43 hindcast and climaterun, whereas it is usually expected that hindcast runs are better at simulating the observations due to the re-initialization of the model. This can also be attributed to the additional height variance added within HARMONIE cycle 43.

From figure 4.1 it can be seen that HARMONIE cycle 43 climaterun + no height variance is the best at simulating the observed low cloud cover. With a low cloud cover mean of approximately 0.33, it is the closest to the observational mean of 0.34. It can be seen that HARMONIE cycle 43 climate run + no shallow convection still overestimates the cloud cover amount, due to the presence of the additional height variance. When the additional height variance is also removed, figure 4.2, the simulated diurnal cycle of the low cloud cover amount is significantly improved and resembles the observations more accurately. Lastly the low cloud cover is not drastically influenced when ECUME is used. This is expected as ECUME/ECUME 6 are the schemes that describe the surface fluxes within the model, and have little impact on the cloud production.

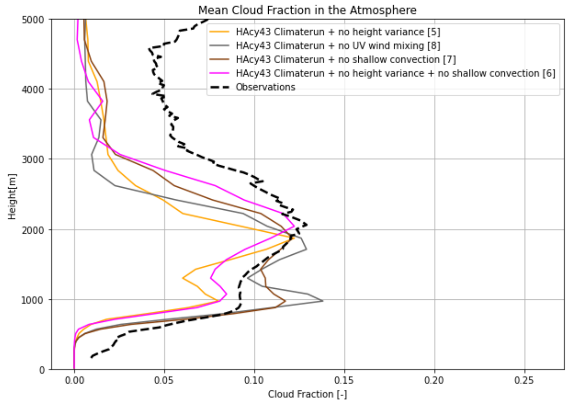
A contourplot of the diurnal cycles of low cloud cover can be found in appendix A.

4.2 Comparison of Cloud Fraction in the Atmosphere

Cloud fraction, here on after referred to as CF, is the percentage of an area that is covered by clouds at a specific height. The type of clouds being studied in this research typically have tops near 2-3 km, therefore the analysis is restricted to 5km [9].Furthermore, besides the simulated output of the CF, also the BIAS of the CF are graphically presented.

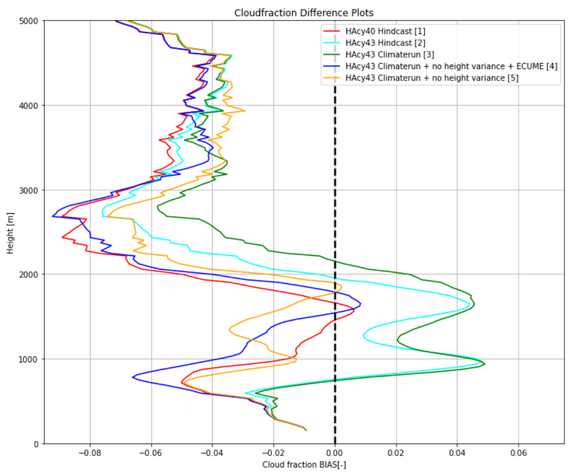


(a) Comparison 1

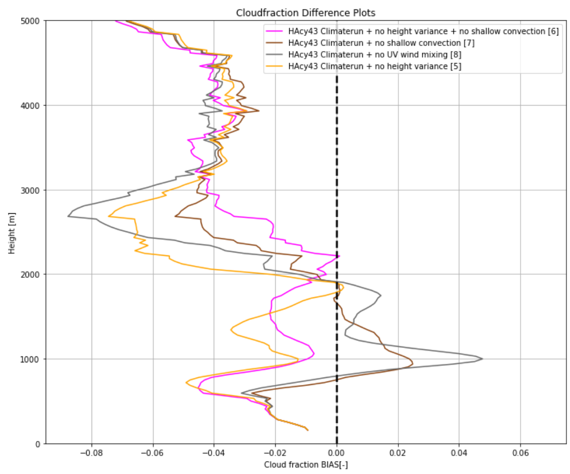


(b) Comparison 2

Figure 4.3: Cloud fraction.



(a) Comparison 1



(b) Comparison 2

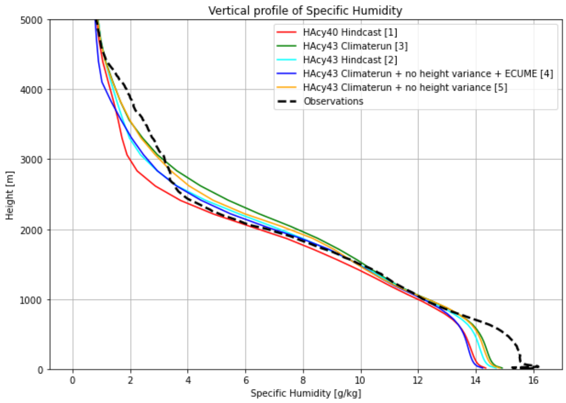
Figure 4.4: Cloud fraction BIAS.

It is important to note that CF is not only determined by the variance but also by the convection and turbulence. It can be seen that HARMONIE cycle 43 is unable to produce the clouds above 3km. From this height upward the CF from all simulation outputs is approximately 0. This is also present in HARMONIE cycle 40, as described in *Evaluation of the representation of subtropical marine clouds in the numerical weather prediction model HARMONIE.*Moreover, every run containing the additional height variance has the tendency to overestimate CF in the lower layers (1km - 2km). However, even these runs encounter an underestimation of the CF higher up in the atmosphere. The runs without the additional height variance, mostly underestimate the CF not only in this specific area, but also throughout the whole entirety of the atmosphere.

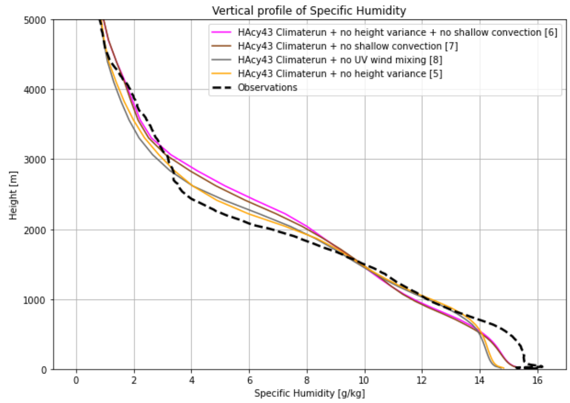
Based on figure 4.4b, it can be seen that when the additional variance is removed and there is no shallow convection, the simulation output somewhat resembles the observed CF near the surface, up to 2km. However, there is still underestimation of the CF throughout the whole atmosphere.

4.3 Comparison of Specific Humidity, Relative Humidity and Potential Temperature

4.3.1 Specific Humidity

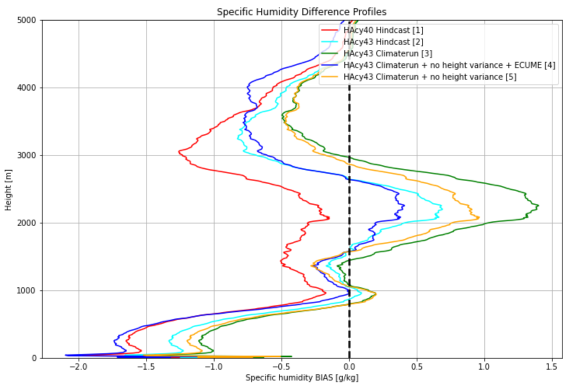


(a) Comparison 1

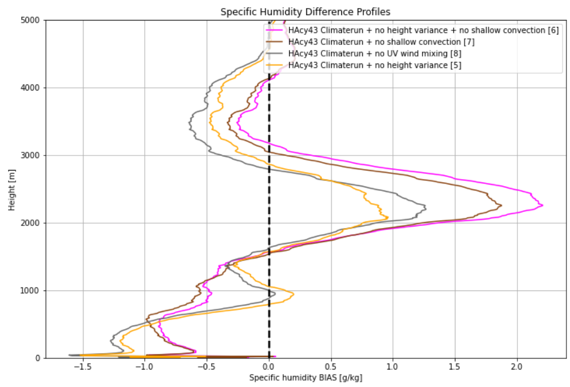


(b) Comparison 2

Figure 4.5: Specific Humidity.



(a) Comparison 1



(b) Comparison 2

Figure 4.6: Specific Humidity BIAS

All of the simulation outputs present a dry bias near the surface. This result is in accordance with the underestimation of cloud fraction in the same area, as presented in section 4.2. It can be seen that between 800m and 1500m the HARMONIE cycle 43 climaterun and the hindcast pretty accurately simulate the observed specific humidity. This is contradicting based on the fact that both of these runs overestimate the total cloud fraction, as presented in section 4.2. This will be further analyzed by looking at the potential temperature in section 4.3.3.

From the simulation outputs of the experiments without shallow convection, it can be seen that the dry BIAS near the surface is slightly diminished. For both of the experiments without shallow convection the gradient of the specific humidity graph is larger compared to the other experiments. Because there is no shallow convection, there is less mixing in the atmosphere, causing a less homogeneously mixed atmosphere as seen in figure 4.5b. In order to determine the cause for the dry bias within the HARMONIE simulation outputs, it is relevant to analyze the boundary conditions received from the ERA5 model, as presented in figure 4.7.

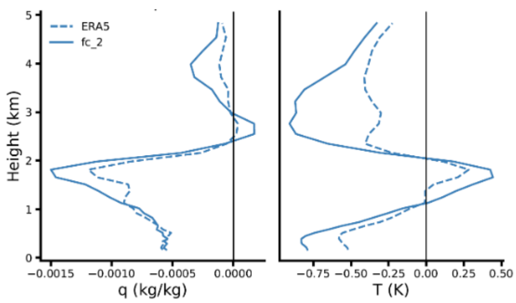
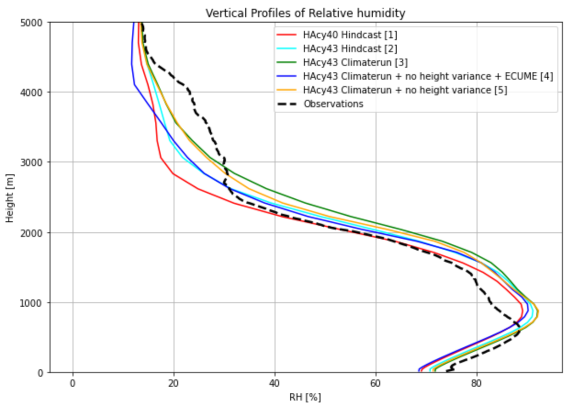


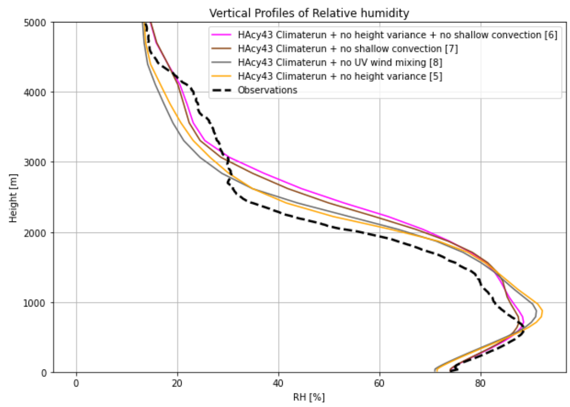
Figure 4.7: Mean bias with respect to radio profiles for IFS forecast (fc_2, solid line) and IFS analyses (ERA5, dashed line) from 2020-01-18 to 2020-02-15. The bias is calculated on a domain of about 300 x 300 km2 . The zero line is the line of the observations. Retrieved from: Evaluation of the representation of subtropical marine clouds in the numerical weather prediction model HARMONIE, by F. van der Voort. Image produced by: Alessandro Savazzi.

From the figure it is clear that the model output from the ERA5 simulation also contains a dry bias. Near the surface this dry bias reaches a maximum of about 1.5 g/ kg, which is also in the same order of magnitude as the HARMONIE cycle 43 simulation outputs. One cannot conclude that HARMONIE itself produces produces inaccurate results, based on the fact that the model is initialized with a dry bias.

4.3.2 Relative Humidity

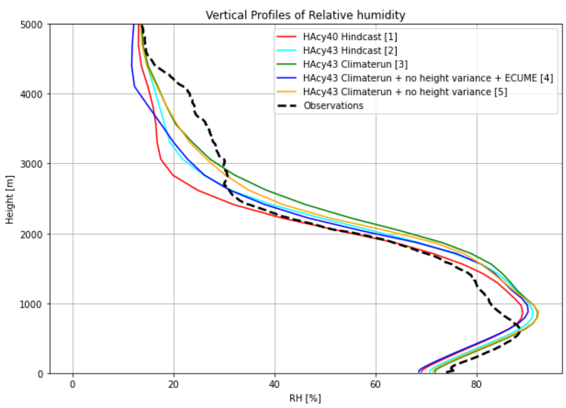


(a) Comparison 1

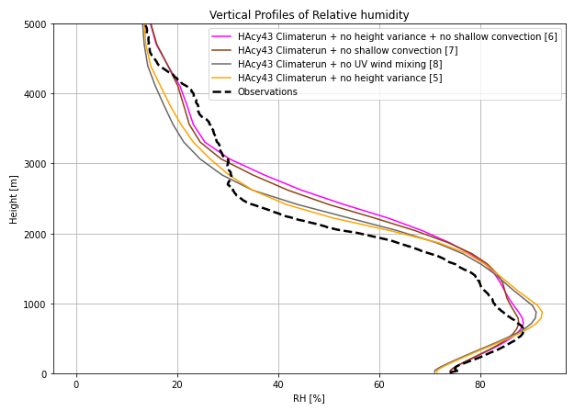


(b) Comparison 2

Figure 4.8: Relative Humidity



(a) Comparison 1

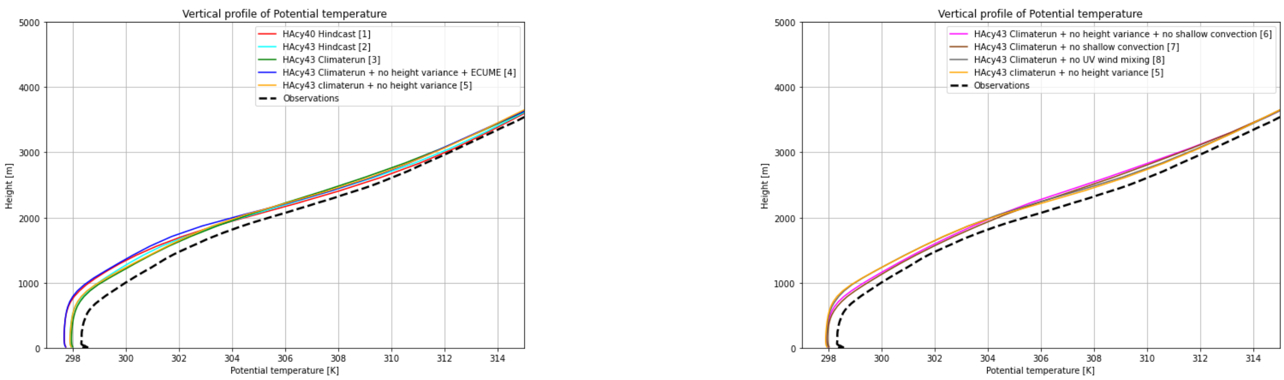


(b) Comparison 2

Figure 4.9: Relative Humidity BIAS

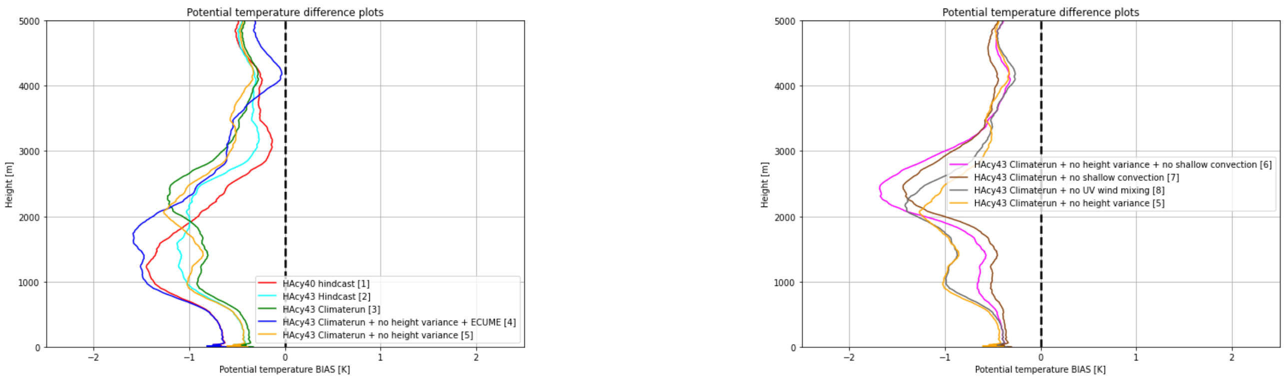
Near the surface, up to approximately 700m, all simulation runs have a dry bias. From figure 4.8a it can be seen that the additional height variance does not have much effect on the RH. Between 1000m-3500m the wet BIAS is very slightly diminished, but there still is a wet BIAS present. However, shallow convection does have an impact on the RH profile, especially near the surface, which is expected. When shallow convection is not present the lower layers of the atmosphere are less dry. Lastly, in the last meters, from 3000m up to 5000m, all of the simulation outputs seem to have a dry BIAS. From this one is inclined to assume that the underestimation of clouds in this area is due to the dryness of the model.

4.3.3 Potential Temperature



(a) Comparison 1 (b) Comparison 2

Figure 4.10: Potential Temperature



(a) Comparison 1 (b) Comparison 2

Figure 4.11: Potential Temperature BIAS

First thing that can be noted from the potential temperature is that the cold BIAS from HARMONIE cycle 40, near the surface, is reduced with HARMONIE cycle 43. This can be seen in figure 4.10a. However, further up in the atmosphere, at 1500m, both cycles have similar profiles. From the figures it can be seen that all simulations seem to have a cold bias, of about 1-1.5 degrees Kelvin, throughout the whole entirety of the atmosphere, up to 5000m.

Furthermore the use of ECUME instead of ECUME 6 has a visible impact on the potential temperature near the surface, seen in figure 4.10a. ECUME/ECUME6 are the schemes that define the surface fluxes present within the model. As a result, it is expected that with a change in the surface flux scheme that is used, the potential temperature near the surface also changes. By using ECUME instead of the default ECUME 6 the cold BIAS near the surface is increased with about 0.25-0.5 degrees Kelvin. This enhancement of the cold BIAS is eliminated at about 3000m, where it can be seen that both simulations have the same vertical profile of potential temperature.

To further analyze the overestimation of clouds between 1000 - 2000m as presented in section 4.2, the potential temperature and specific humidity in this area are looked into. As already presented in section 4.3.1, between 800m and 1500m HARMONIE cycle 43 pretty accurately simulates the specific humidity however, in this same area HARMONIE cycle 43 presents a cold BIAS of about 1 degree Kelvin. The presence of the cold BIAS creates a favourable environment for cloud formation. Even though the specific humidity may be correctly modelled, the presence of the cold BIAS produces inaccurate cloud amounts.

4.4 Comparison of Stability of the Atmosphere

Stability is an important topic for cloud formation and the various states of stability are classified as [3]:

$$\textbf{unstable}: \frac{d\theta}{dz} < 0, \textbf{neutral}: \frac{d\theta}{dz} = 0, \textbf{stable}: \frac{d\theta}{dz} > 0 \tag{4.1}$$

The mean stability profiles for day and night time are presented in figures 4.12 and 4.13 respectively.

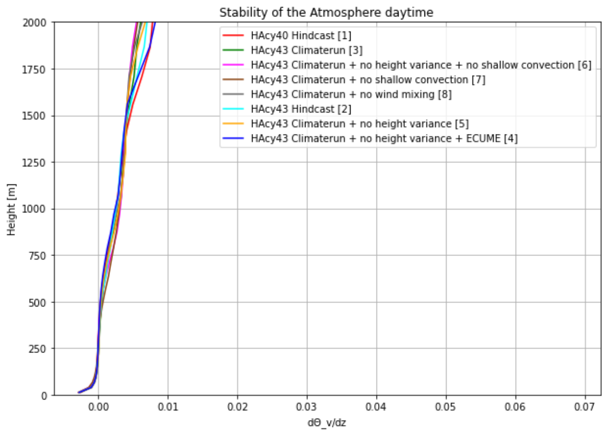


Figure 4.12: Stability of the Atmosphere during daytime

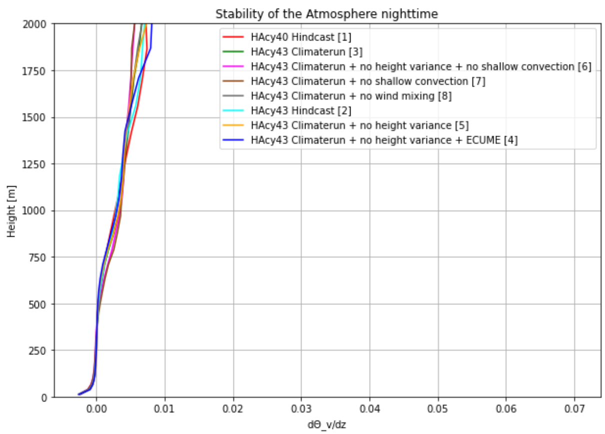
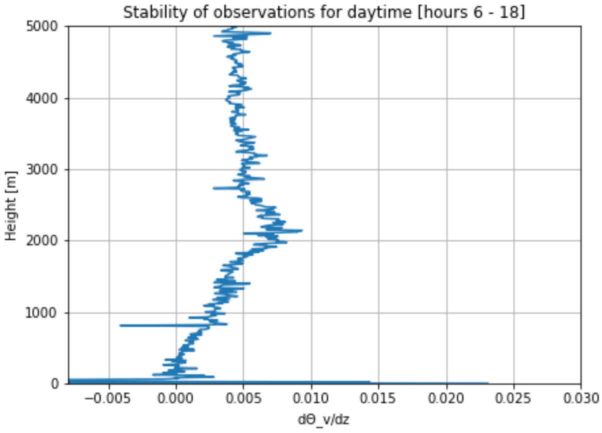
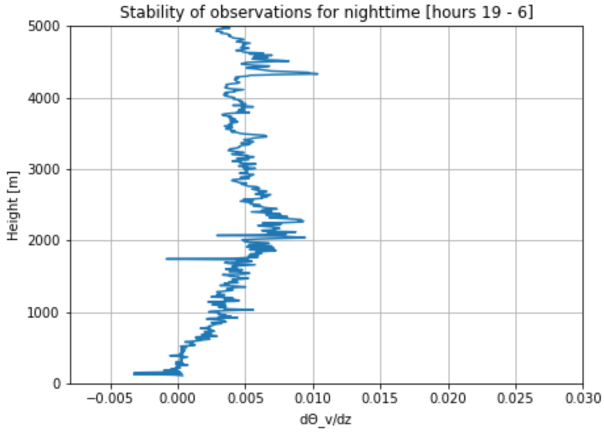


Figure 4.13: Stability of the Atmosphere during nighttime



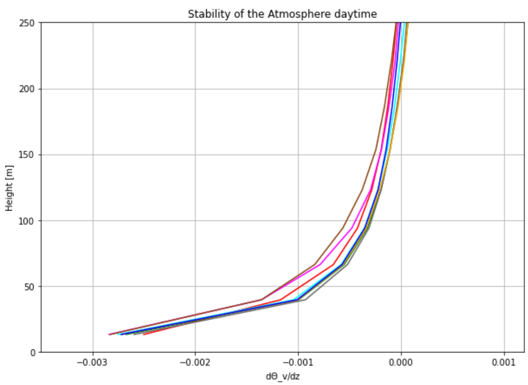
(a) Stability of observations during daytime.



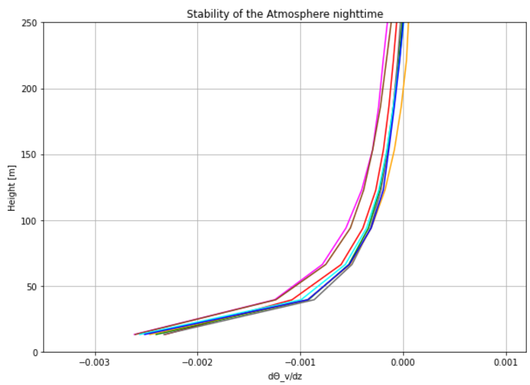
(b) Stability of observations during nighttime.

Figure 4.14: Stability of observations

What can be noted from the stability profiles, is the unstable layer very close to the surface. A zoomed in version of the stability profile can be seen below, in figures 4.15a and 4.15b.



(a)



(b)

Figure 4.15: Lowest 250 m of Stability during daytime [left] and nighttime [right].

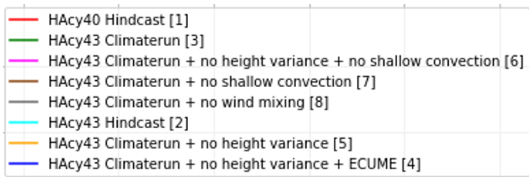


Figure 4.16: Legend

This unstable layer is present in all of the simulation outputs. As the earth's surface absorbs short-wave radiation coming from the sun during the day, it gets heated and becomes hotter than its surrounding environment, producing an unstable atmosphere very close to the surface.
It is observed that the runs without shallow convection are more unstable near the surface and this unstable layer is slightly deeper compared to the other simulation outputs. This is an expected result based on the the way the convection scheme is described within the HARMONIE model. The overall convective scheme can be briefly summarized using equation 4.2 [6]. It is split into two parts, the diffusivity part and the mass flux part. When shallow convection is turned off, there will be no mass flux present. As a result of this, the convective scheme is only driven by diffusivity and can be described as presented in equation 4.3.

$$\overline{w'\phi'} = -K\frac{\partial \phi}{\partial z} + M(\phi_u - \bar{\phi}) \tag{4.2}$$

$$w\bar{'}\phi' = -K\frac{\partial \phi}{\partial z} \tag{4.3}$$

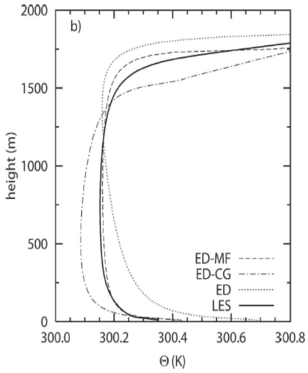


Figure 4.17: The mean potential temperature profiles after 10 h of simulation. Retrieved from: "A combined eddy-diffusivity mass-flux approach for the convective boundary layer".

From the figure it can be seen that when diffusivity and mass flux are both present [ED-MF], the atmosphere is unstable in the layers very close to the surface and becomes nearly neutral very quickly at around 250m, whereas when mass flux is not present [ED], in the case when shallow convection is turned off, the atmosphere is very unstable near the surface and clearly remains unstable up until 1500m.

Besides all of the comparison discussed above, a comparison of precipitation and organization of cloud structures can be found in appendix B and C respectively.

5 Conclusions & Recommendations

HARMONIE cycle 40 was updated in order to resolve the problem of underestimation of cloud amount. This was done by adding an additional height dependent variance term, LHGTQS, to the newest cycle, HARMONIE cycle 43. From the results presented in this paper it can be concluded that the addition of the extra height dependent variance did increase the amount of cloud produced by HARMONIE. However, with this additional variance the HARMONIE model overestimated the total cloud amount, producing a mean cloud cover of approximately 0.58 compared to the true value of approximately 0.34. When the additional height variance is removed from the simulation run, the mean cloud cover is significantly reduced to about 0.32. which is the closest to the observational mean value. Furthermore it can be seen that shallow convection and wind mixing alone do not have much influence on the simulation outputs. The mean low cloud cover is reduced from 0.58 to 0.43 and 0.53 respectively.

When analyzing the vertical profile of cloud fraction in the atmosphere it can be seen that there is no major improvement between cycle 40 and cycle 43. Above 3000m none of the experiments are able to produce any clouds. This can be attributed to the mainly dry bias in the top, that can be observed from the specific humidity profiles. Besides this there is also a dry bias near the surface. It is likely that these dry biases are due to the cold bias from the ERA5 simulation output. The HARMONIE simulation is initialized using these outputs, as a result the whole HARMONIE model is initialized with data already containing a dry bias.

The same can be said for the temperature. All of the HARMONIE simulation outputs have a cold bias of approximately 1 degree throughout the whole entirety of the atmosphere. A probable cause for this can also be attributed to the ERA5 simulation outputs. It is observed that the ERA5 produces a cold bias of approximately 0.75 K, which is comparable with the cold bias produced by the HARMONIE simulation outputs.

Moreover, it is visible that the stability of the various runs are pretty similar to each other. Every run has a very shallow layer of instability near the surface. For most of the runs this instability turns into stability moving higher into the atmosphere. For the runs without shallow convection it is noticeable that the instability is much deeper compared to the other runs. This can be attributed to way the convection scheme is presented within the model.

To conclude it can be said that the addition of the additional height variance within HARMONIE cycle 43 did produce more clouds, as was expected. However it still did not produce the correct cloud amounts. HARMONIE cycle 43 is still unable to accurately reproduce the meso-scale marine clouds. However, it is recommended that the additional height variance be removed as this results in a more accurate representation of the observed low cloud cover. Another recommendation is to determine whether convection is reaching high enough in the atmosphere in order to determine whether this is the cause for the underestimation of clouds above 3000m. This can be done by looking at the momentum fluxes.

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Appendix A Composite Diurnal Cycle of Cloud Fraction.

To get an even better view of the simulated CF in the atmosphere, some contour plots of the CF are presented.

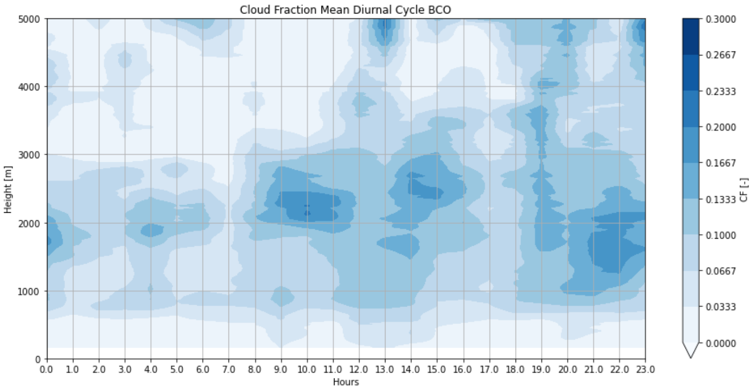
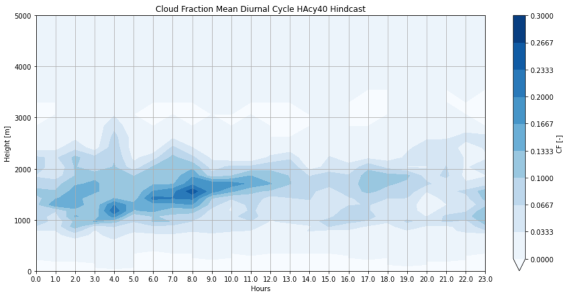
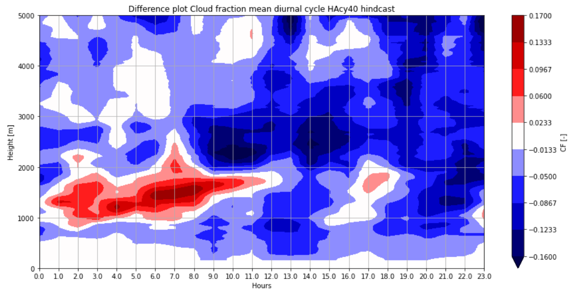


Figure A.1: Observed contour plot of the diurnal cycle of the cloud fraction.

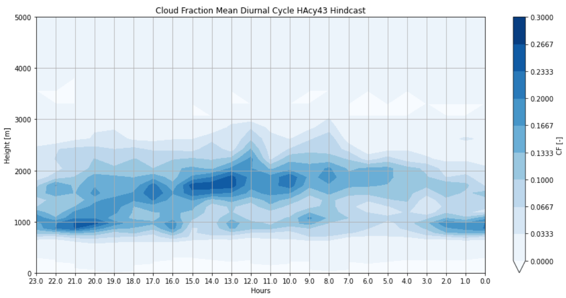


(a)

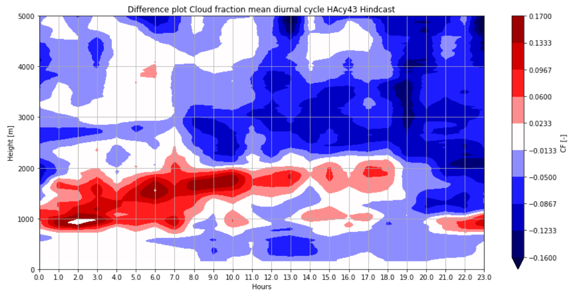


(b)

Figure A.2: Contout plot of the mean Diurnal Cycle HARMONIE cycle 40 hindcast.

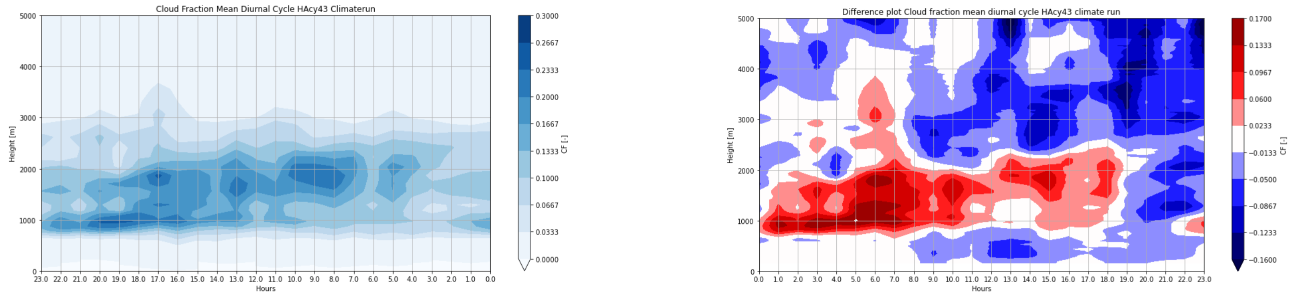


(a)



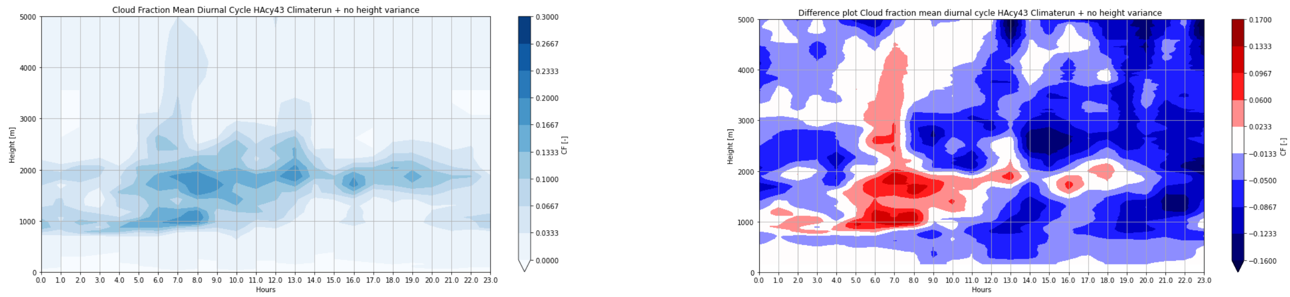
(b)

Figure A.3: Contour plot of the mean Diurnal Cycle HARMONIE cycle 43 hindcast.



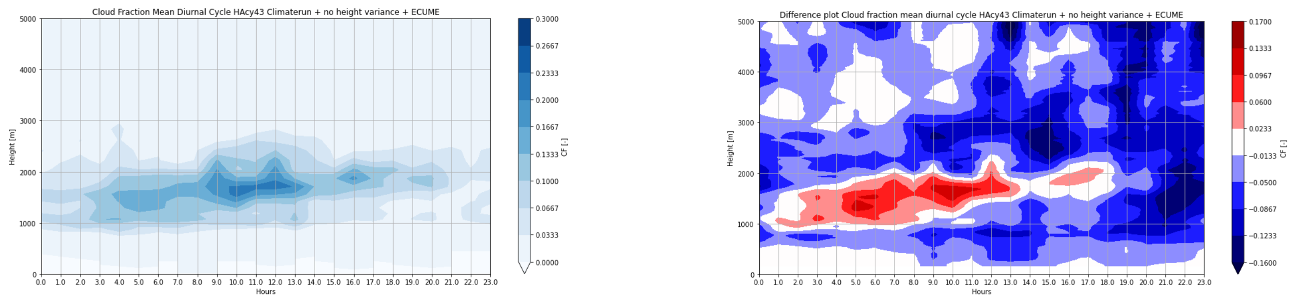
(a) (b)

Figure A.4: Contour plot of the mean Diurnal Cycle HARMONIE cycle 43 climaterun.



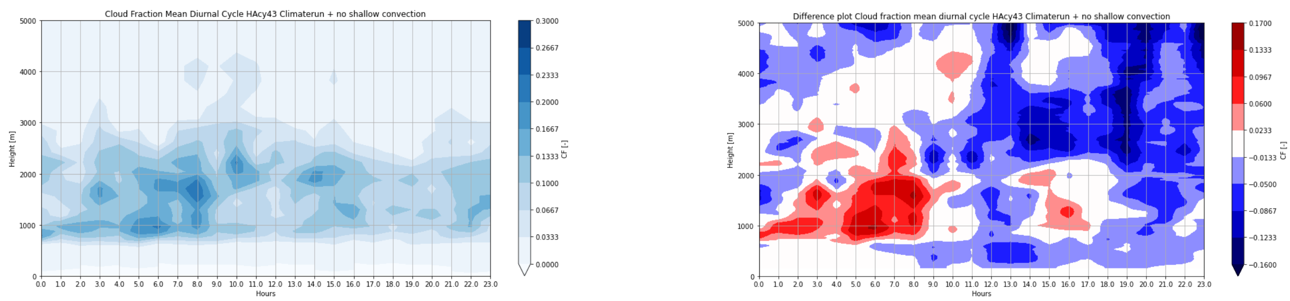
(a) (b)

Figure A.5: Contour plot of the mean Diurnal Cycle HARMONIE cycle 43 climaterun with no additional height variance.



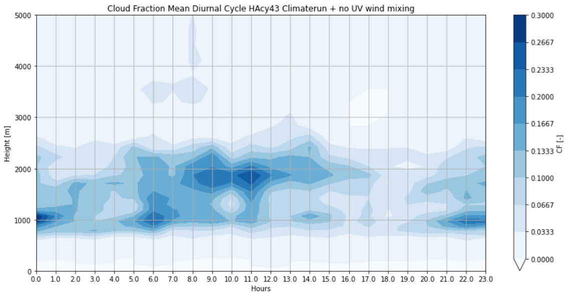
(a) (b)

Figure A.6: Contour plot of the mean Diurnal Cycle HARMONIE cycle 43 climaterun with no additional height variance and using ECUME.

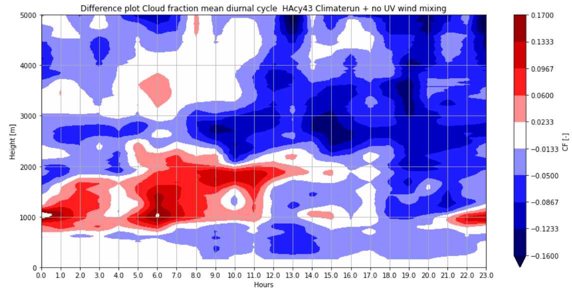


(a) (b)

Figure A.7: Contour plot of the mean Diurnal Cycle HARMONIE cycle 43 climaterun with no shallow convection.

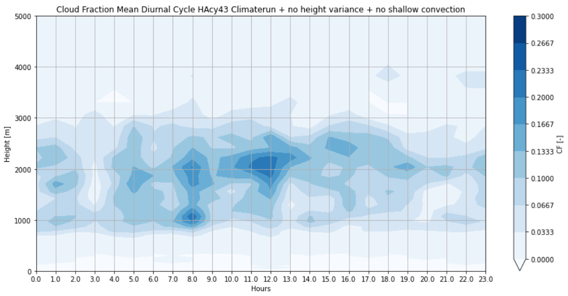


(a)

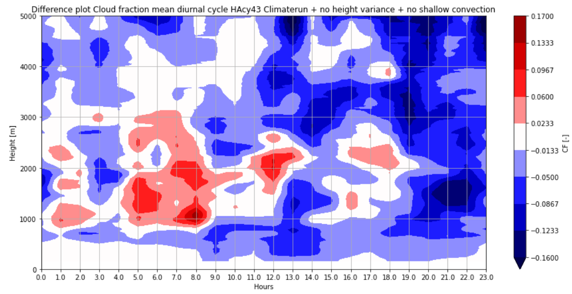


(b)

Figure A.8: Contour plot of the mean Diurnal Cycle HARMONIE cycle 43 climaterun with no wind mixing from U and V wind direction.



(a)



(b)

Figure A.9: Contour plot of the mean Diurnal Cycle HARMONIE cycle 43 climaterun with no additional height variance and no shallow convection.

Appendix B Comparison of Precipitation

A time series plot of precipitation is presented in figure B.1.

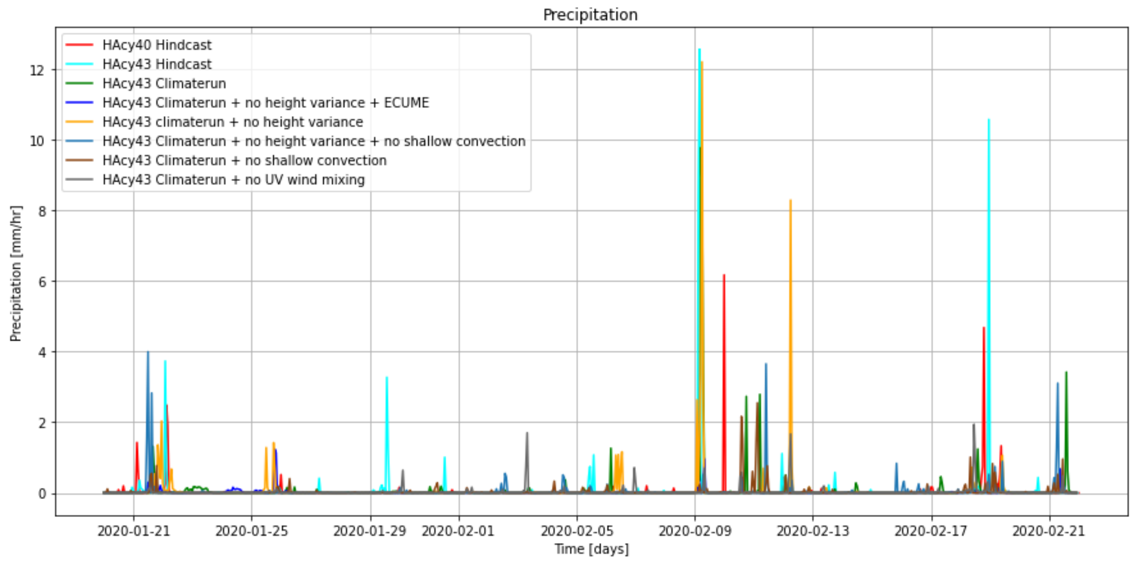


Figure B.1: Timeseries of Precipitation.

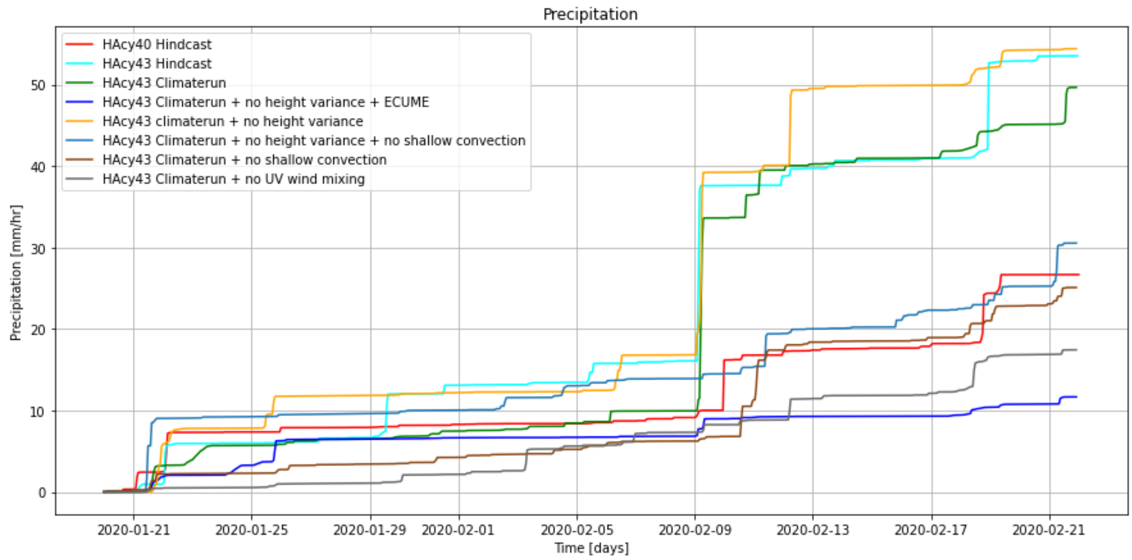


Figure B.2: Timeseries of Accumulated Precipitation.

Appendix C Comparison of Cloud Organization

One of the most important properties of HARMONIE is the ability to reproduce the various meso-scale cloud structures that exist. A first attempt has been made to categorize the different cloud structures [7]. These are:

- Fish structure
- Flower structure
- Gravel structure
- Sugar structure

The following section will analyze the cloud structures produced by HARMONIE and compare them with satellite observations, with the aim to determine whether HARMONIE can accurately reproduce the same organization of clouds.

C.1 Fish Structure

To get an overview of the fish structure produced by HARMONIE day 2020-01-22 at time 14:00 is used.

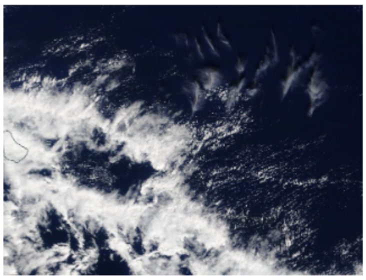
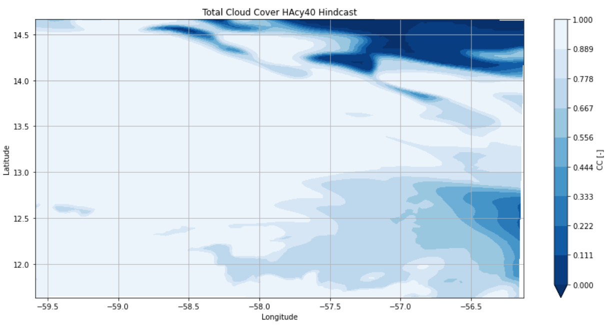
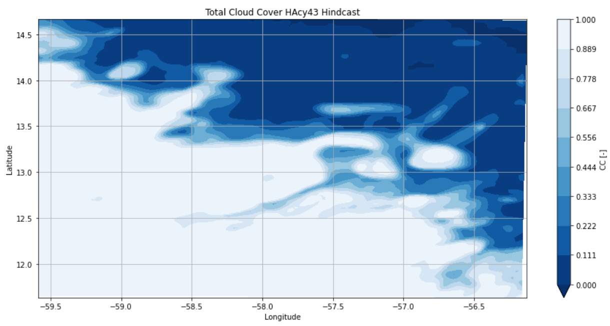


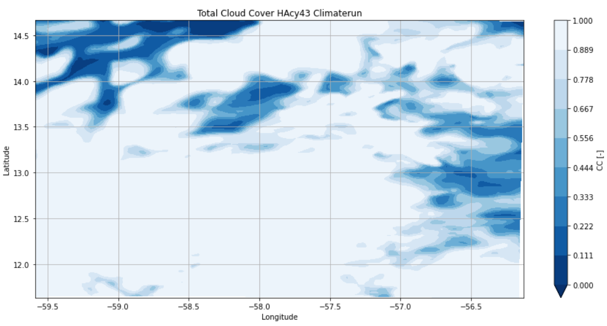
Figure C.1: Terra satellite cloud cover overview at 14:14. Retrieved from: Evaluation of the representation of subtropical marine clouds in the numerical weather prediction model HARMONIE, by F. van der Voort.



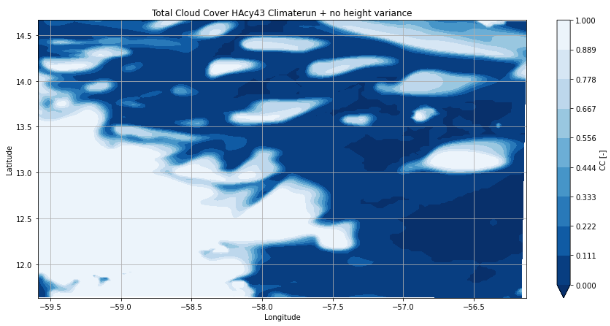
(a) Cloud Cover overview HARMONIE cycle 40 hindcast.



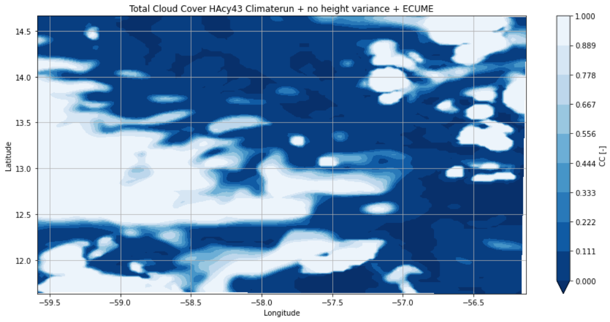
(b) Cloud Cover overview HARMONIE cycle 43 hindcast.



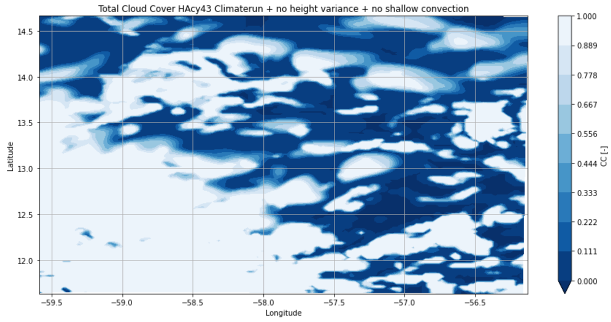
(c) Cloud cover overview HARMONIE cycle 43 climaterun



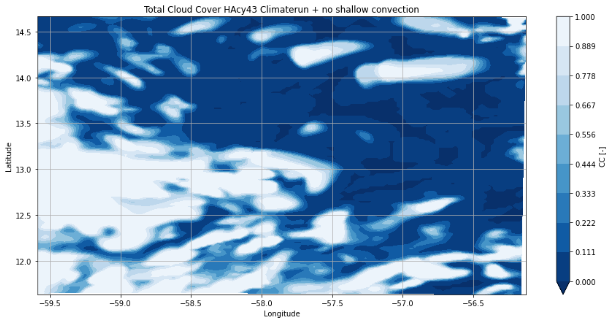
(d) Cloud cover overview HARMONIE cycle 43 climaterun with no additional height variance.



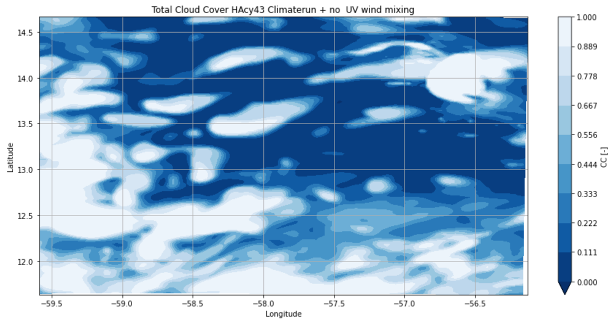
(e) Cloud cover overview HARMONIE cycle 43 climate run with no additional height variance and using ECUME.



(f) Cloud cover overview HARMONIE cycle 43 climaterun with no additional height variance and no shallow convection.



(g) Cloud cover overview HARMONIE cycle 43 climaterun with no shallow convection.



(h) Cloud cover overview HARMONIE cycle 43 climaterun with no UV wind mixing.

Figure C.2: Fish cloud structures.

C.2 Flower Structure

To get an overview of the flower structure produced by HARMONIE day 2020-02-02 at time 14:00 is used.

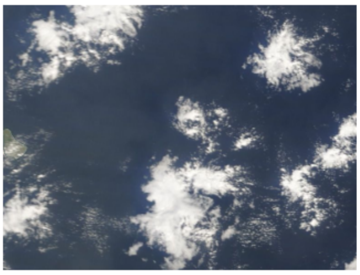
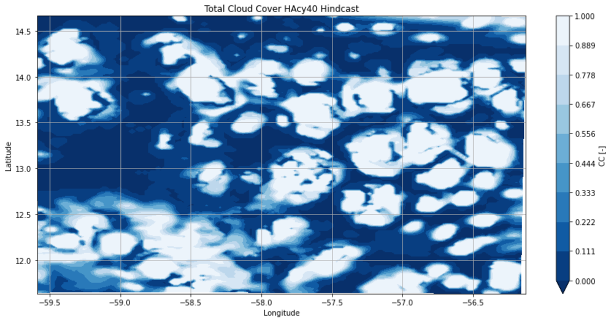
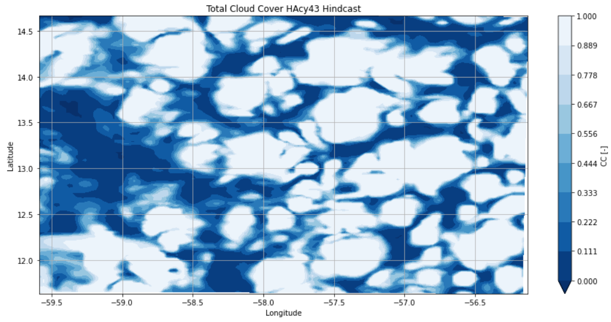


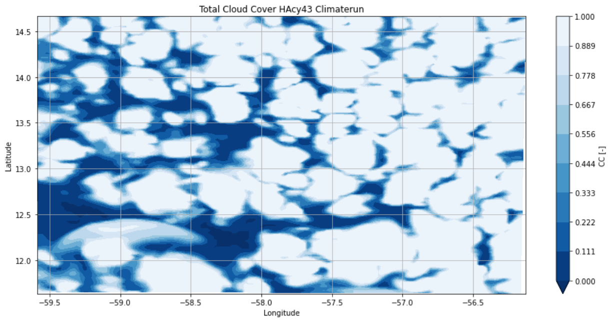
Figure C.3: Terra satellite cloud cover overview at 13:56. Retrieved from: Evaluation of the representation of subtropical marine clouds in the numerical weather prediction model HARMONIE, by F. van der Voort.



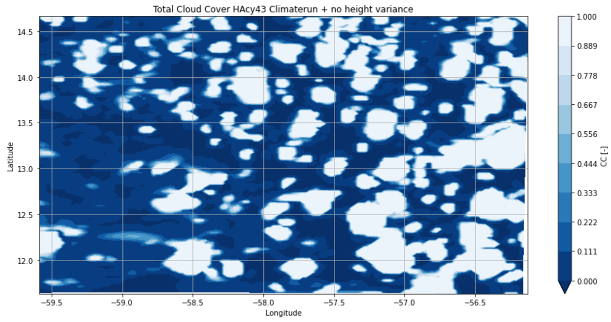
(a) Cloud Cover overview HARMONIE cycle 40 hindcast.



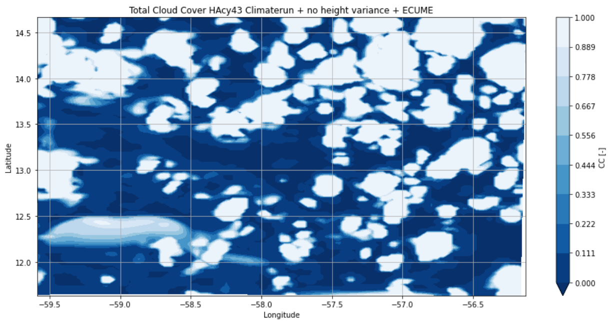
(b) Cloud Cover overview HARMONIE cycle 43 hindcast.



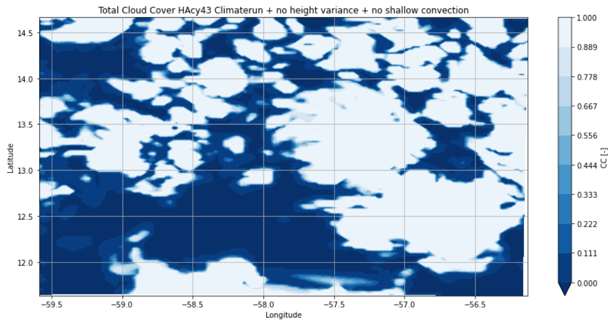
(c) Cloud Cover overview HARMONIE cycle 43 climaterun.



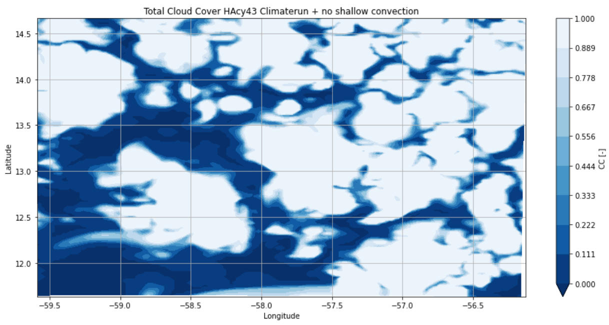
(d) Cloud Cover overview HARMONIE cycle 43 climate run with no additional height variance.



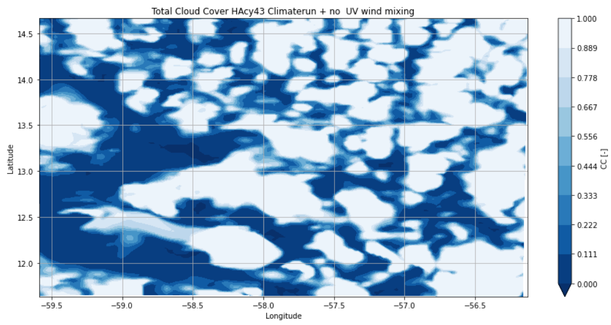
(e) Cloud cover overview HARMONIE cycle 43 climaterun with no additional height variance and using ECUME.



(f) Cloud cover overview HARMONIE cycle 43 climaterun with no additional height variance and no shallow convection.



(g) Cloud cover overview HARMONIE cycle 43 climaterun with no shallow convection.



(h) Cloud cover overview HARMONIE cycle 43 climaterun with no U and V wind mixing.

Figure C.4: Flower cloud structures.

C.3 Gravel Structure

To get an overview of the gravel structure produced by HARMONIE day 2020-02-05 at time 14:00 is used.

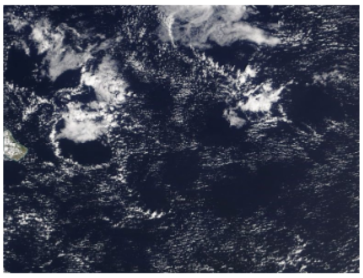
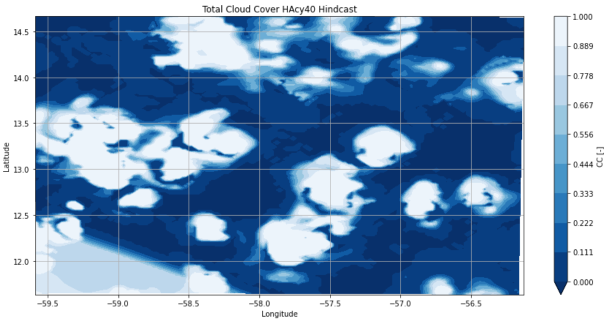
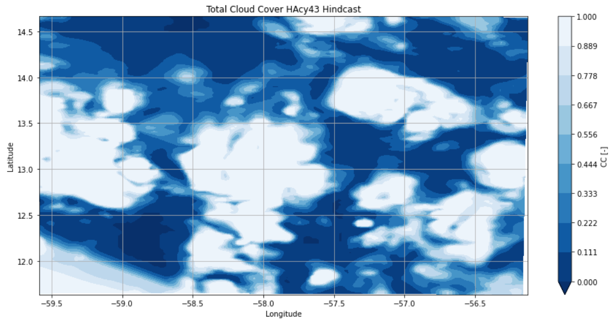


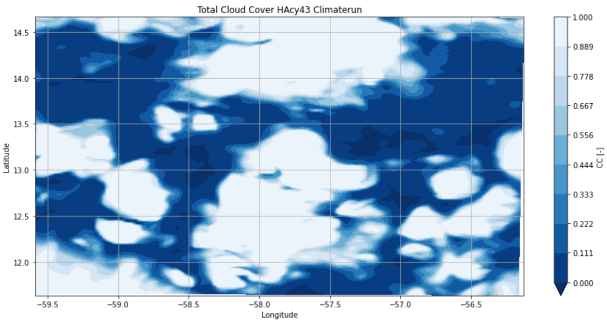
Figure C.5: Terra satellite cloud cover overview at 14:26. Retrieved from: Evaluation of the representation of subtropical marine clouds in the numerical weather prediction model HARMONIE, by F. van der Voort.



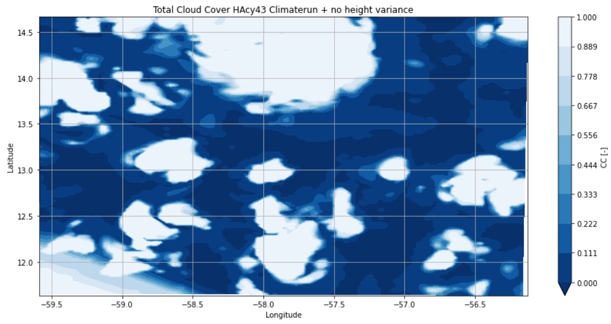
(a) Cloud cover overview HARMONIE cycle 40 hindcast.



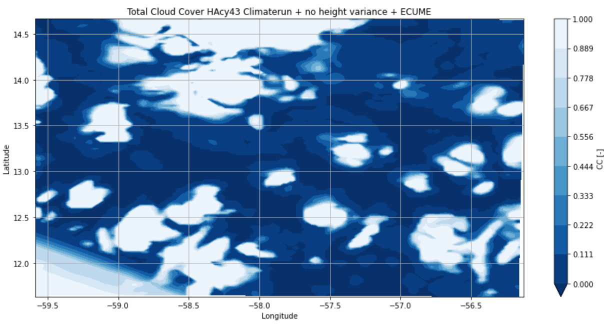
(b) Cloud Cover overview HARMONIE cycle 43 hindcast.



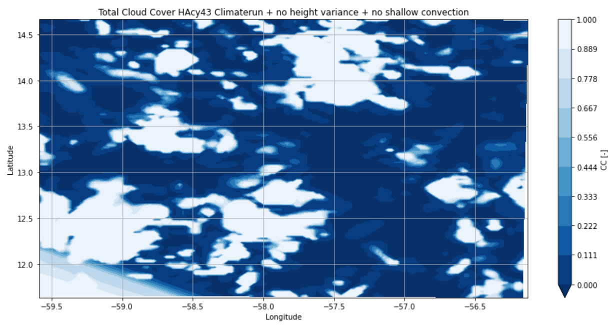
(c) Cloud cover overview HARMONIE cycle 43 climaterun.



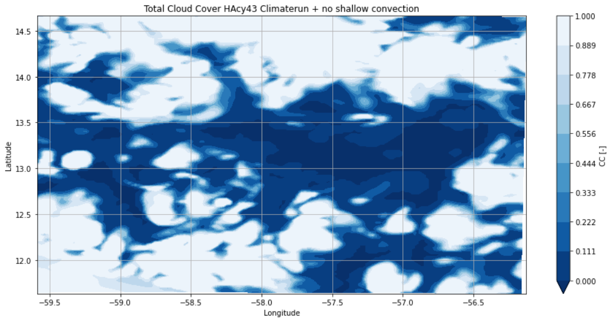
(d) Cloud cover overview HARMONIE cycle 43 climaterun with no additional height variance.



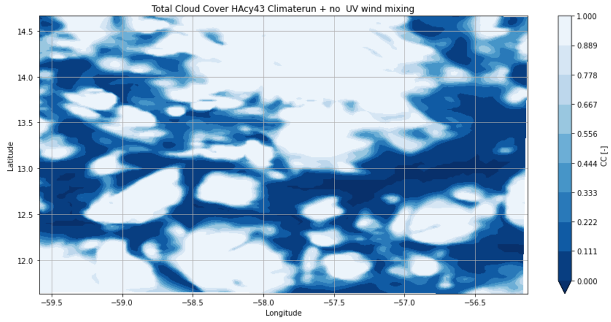
(e) Cloud cover overview HARMONIE cycle 43 climaterun with no additional height variance and using ECUME.



(f) Cloud cover overview HARMONIE cycle 43 with no additional height variance and no shallow convection.



(g) Cloud cover overview HARMONIE cycle 43 climaterun with no shallow convection.



(h) Cloud cover overview HARMONIE cycle 43 climaterun with no U and V wind mixing.

Figure C.6: Gravel cloud structures.

C.4 Sugar Structure

To get an overview of the fish structure produced by HARMONIE day 2020-02-11 at time 17:00 is used.

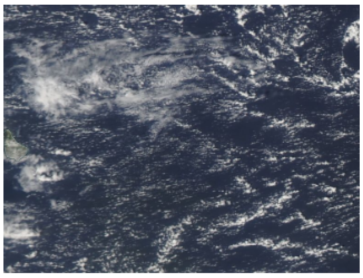
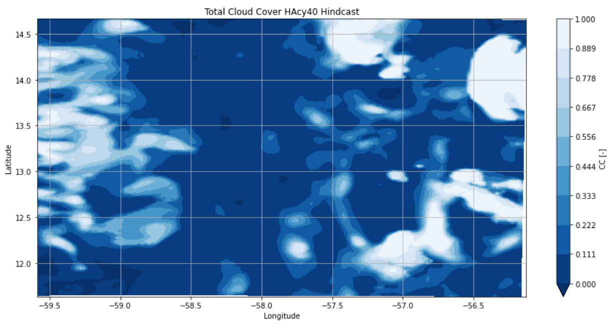
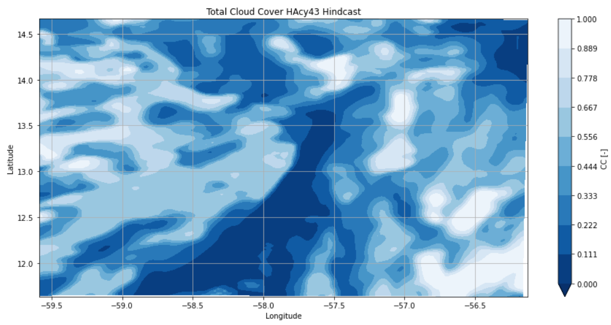


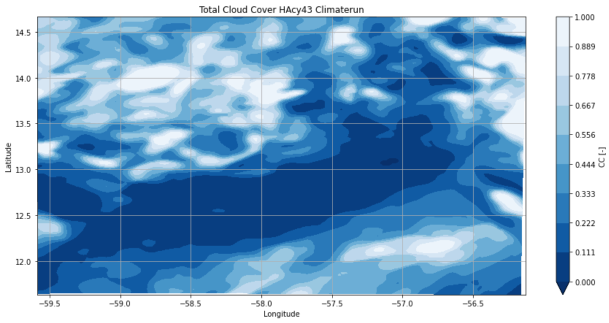
Figure C.7: Terra satellite cloud cover overview at 16:53. Retrieved from: Evaluation of the representation of subtropical marine clouds in the numerical weather prediction model HARMONIE, by F. van der Voort.



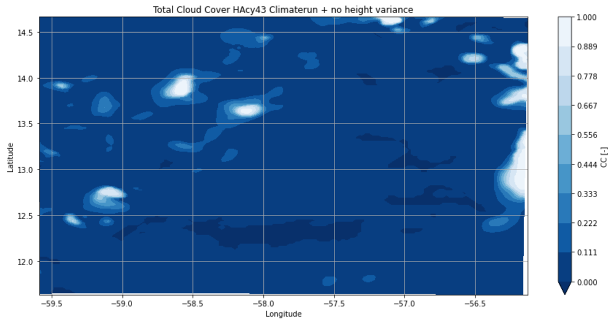
(a) Cloud cover overview HARMONIE cycle 40 hindcast.



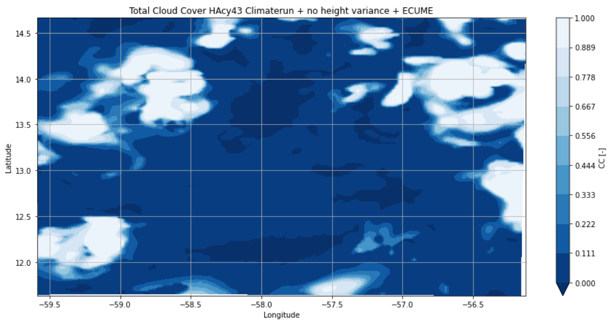
(b) Cloud cover overview HARMONIE cycle 43 hindcast.



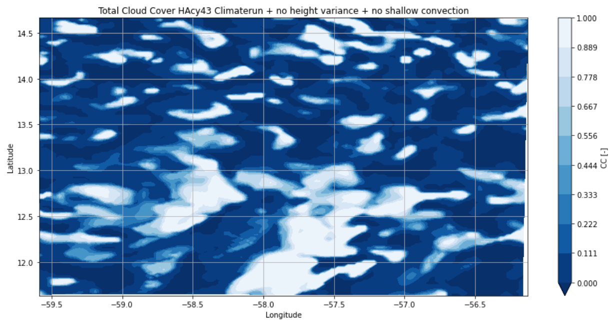
(c) Cloud cover overview HARMONIE cycle 43 climaterun.



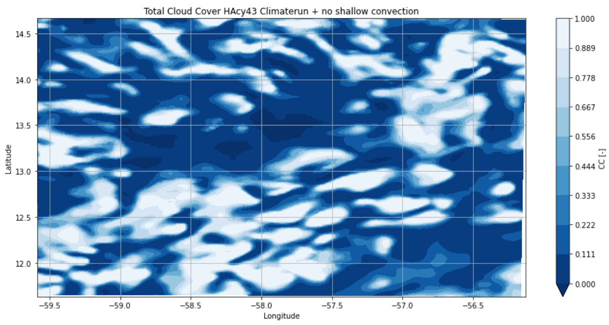
(d) Cloud cover overview HARMONIE cycle 43 climaterun with no additional height variance.



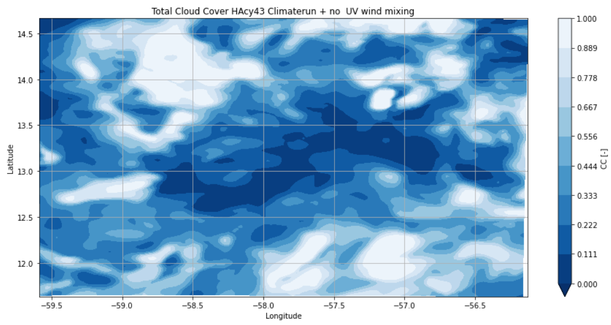
(e) Cloud cover overview HARMONIE cycle 43 climaterun with no additional height variance and using ECUME.



(f) Cloud cover overview HARMONIE cycle 43 climaterun with no additional height variance and no shallow convection.



(g) Cloud cover overview HARMONIE cycle 43 climaterun with no shallow convection.



(h) Cloud cover overview HARMONIE cycle 43 climaterun with no U and V wind mixing.

Figure C.8: Sugar cloud structures.

C.5 Overcast

To get an overview of an overcast day produced by HARMONIE day 2020-02-15 at time 15:00 is used.

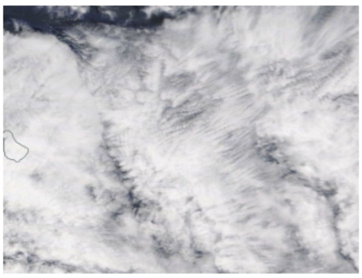
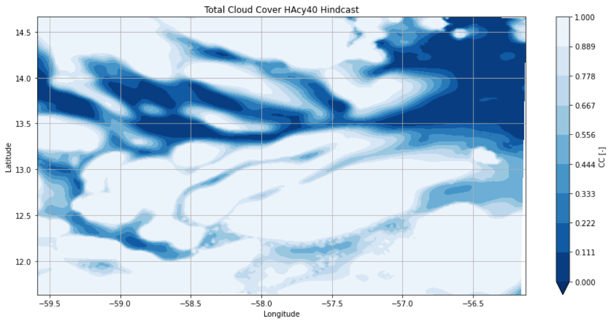
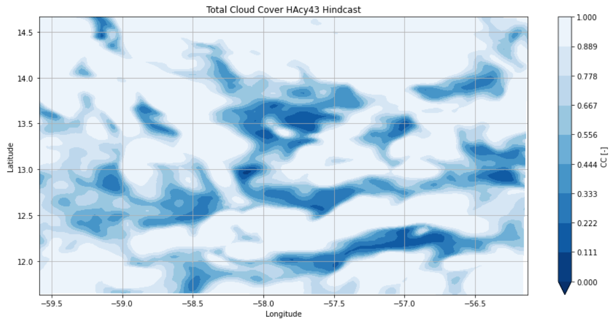


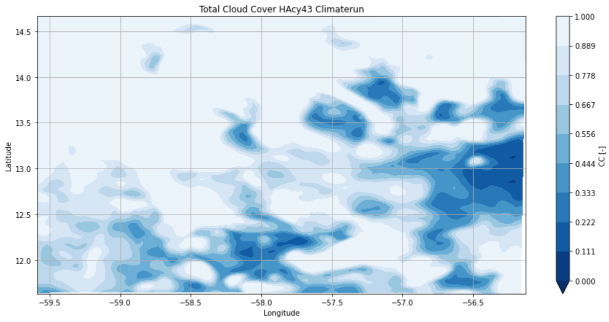
Figure C.9: Terra satellite cloud cover overview at 15:03. Retrieved from: Evaluation of the representation of subtropical marine clouds in the numerical weather prediction model HARMONIE, by F. van der Voort.



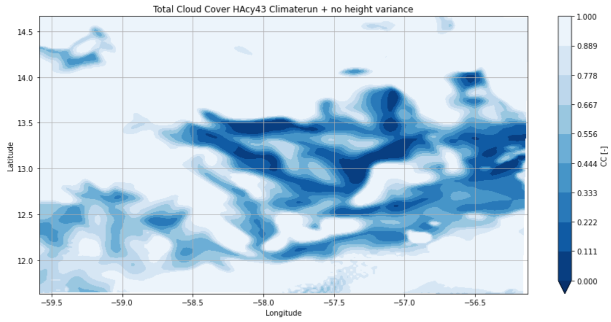
(a) Cloud cover overview HARMONIE cycle 40 hindcast.



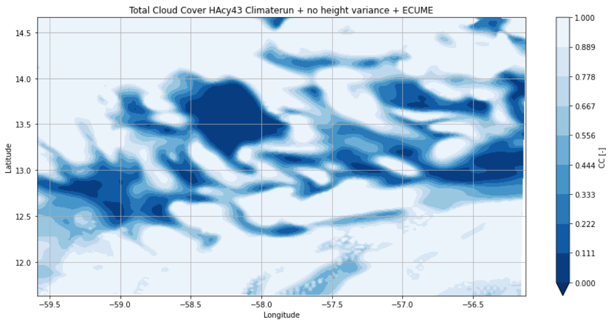
(b) Cloud cover HARMONIE cycle 43 hindcast.



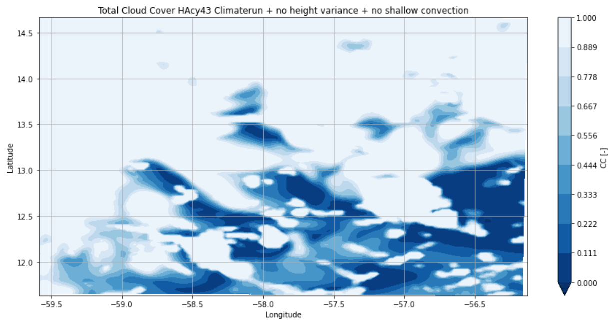
(c) Cloud cover overview HARMONIE cycle 43 climaterun.



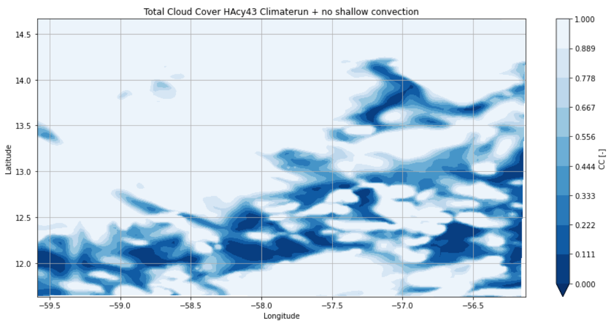
(d) Cloud cover overview HARMONIE cycle 43 climaterun with no additional height variance.



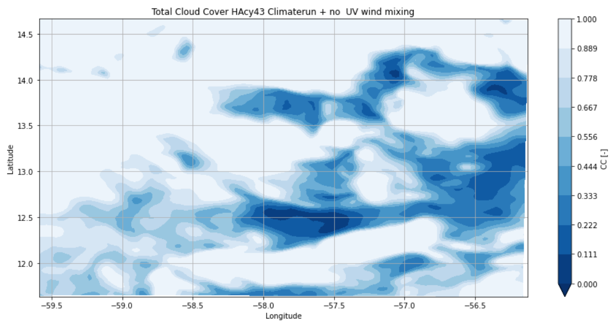
(e) Cloud cover overview HARMONIE cycle 43 climaterun with no additional height variance and using ECUME



(f) Cloud cover overview HARMONIE cycle 43 climaterun with no additional height variance and with no shallow convection.



(g) Cloud cover overview HARMONIE cycle 43 climaterun with no shallow convection.



(h) Cloud cover overview HARMONIE cycle 43 climaterun with no U and V wind mixing.

Figure C.10: Overcast days