Is there a positive feedback between Arctic stratus and diminishing sea ice?
Master thesis

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Abstract

This will be my abstract.
Write it later....
No more than a page and should contain:
- main findings - how it compares to others - a conclusion?

Acknowledgements

First of all I want to thank my main supervisor Jón Egill Kristjánsson for an interesting project and for the opprtunity to come and work at NCAR for a couple of weeks. I also want to thank my other supervisor Kari Alterskjær for her "poking" and setting deadlines and pushing me for the last six months. I greatly appreciate their guidance and critisism throughout this project, and the doors that were always safe to knock on. Thank you so much to Anne Claire Fuillioux for helping me with setting up and getting started with WRF, and to both her and Kjell Andresen for help with technical problems during my work with this thesis. Thanks also to Gregory Thompson whom Jón Egill and I met with in Boulder, for meeting with us and answering all my e-mails about running the new aerosol-aware microphysics scheme in WRF. These past two years have been very enjoyable in all their stress thanks to Marta and Helle especially, for all their positiveness. Last, but not least, I would like to thank Henrik, for great technical help and moral support.

Contents

Chapter 1

Introduction

Here I will write my introduction. Something about how low clouds in the Arctic have a warming affect as opposed to the cooling effect they have on lower latitudes. This warming is due to the lack of SW radiation flux to reflect, and the emission of LW radiation flux to the ground therefore makes a greater difference.

(Something citing the IPCC report 2013 on the ice conditions in the Arctic, and something about Arctic clouds and radiation?)

Clouds are an important regulator of the Earth's radiation budget. They cover approximately 60% of the Earth's surface Lohmann2005. It is well know that low clouds have a cooling effect at the surface due to their reflecting of incoming solar radiation. However, the effect is opposite in the Arctic, which I will elaborate on in the theory section. Therefore it is important to investigate the changes in low clouds and their properties in the Arctic.

1.1 Main goal

1.2 My contribution

The findings in my thesis have been achived with some of the most recently developed code (by Greg Thompson) for cloud microphysics and their effects on radiation, in modelling. The results build further on the work of many researchers @name-some-and-cite and contribute and may raise some questions for further research within the field.

1.3 Structore of the thesis

In the following chapter 2 Background I will present the background for my thesis; what work I hope to compare with and relate my thesis to. Also I will touch upon why the subject of my thesis is important. In chapter 3 Theory the most important theory and basic knowledge needed to understand some of the processes in clouds and their possible effect on the sea ice. Chapter 4 Model and methods is where I explain how I have worked with different tools to get the results presented in chapter **??** which are further discussed in chapter **??**. A summary of main findings and conclusions are presented in the last chapter **??** Summary and conclusions, before the lists of figures and references at the very end.

1.4 Area description

Here I should describe the area I have studied, and why it was chosen. Shown in figure **??** in Chapter 4 Model and methods. The area was chosen because it had some ice in september, and because there have been research campaigns over the area with focus on clouds in the arctic (which is what I am studying). (show a map..?) Know the correct names of the seas and the land!!

Chapter 2

Background

In this chapter I shall present some recent literature on the subject. Some new (and older) research that makes my thesis interesting and relevant to the field. No one has done this study with a weather forecasting model, it is interesting to look at changes in parameters in similar meteorological conditions, the same initial and boundary conditions in every run. Describe some of the work done by Palm2010? WuLee2012 and others on autumn low clouds in the Arctic to emphasize the importance of my work.

Is my work new thinking and does it seem to be very extensive?

Should this whole chapter be a part of introduction..?

Chapter 3

Theory

3.1 Arctic clouds

The Arctic cloud cover is dominated by low clouds @cite. Most high amounts of stratus clouds are over the oceans Klein1993. The Arctic is the only region where the season of maximum stratus does not correspond to the season of greatest lower troposphere static stability Klein1993, which could be due to lack of evaporation during the cold winter months. According to [2] stratus in the Arctic basin peaks during summer at nearly 62%, while during the winter season the stratus only accounts for 18% of the cloud cover. This leads them to conclude that the seasonal cycle of stratus in the Arctic is driven by the temperature cycle, thereby moisture content in the atmosphere, rather than the static stability.(, as opposed to other areas.)

Are there any typical cloud properties special to the arctic? CURRY!

The air in the Arctic is very stable in winter (polar night) and clean as there are not many sources for pollution. In Autumn the sea ice extent reaches a minimum after the summer melting and leave open water to influence low clouds and their properties.

Low clouds have bases below 2000 m. Stratus (St) are layered clouds that form when extensive areas of stable air are lifted. Stratus clouds are normally between 0.5 and 1 km thick, whereas they can be several km wide (@citeAguadoBurtpage188?).

3.2 Radiation and clouds

The cloud microphysical properties that determine the cloud radiative properties include: the amount of condensed water, the size and shape of the

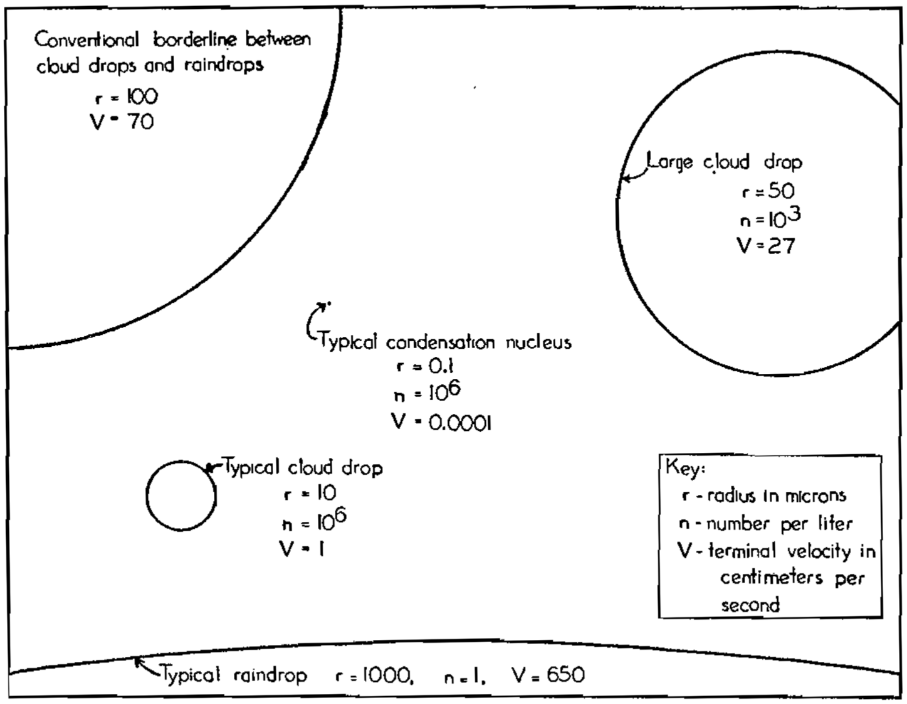

Figure 3.1: Size of CCN, typical cloud droplet, large cloud droplet, boarderline between cloud droplets and raindrops and typical size of raindrop. Adapted from McDonald1958.

cloud particles, and the phase of the particles/and if the particles are liquid or ice Curry1996. The amount of condensed water can be expressed by the liquid water content (LWC) in the cloud, often presented with units $g\ m^{-3}$, and is proportional to the cloud droplet number consentrations when we use the median volume radius, $\bar{r}$, m. From [?] we can express the number of droplets with radius r by

$$N = \int n(r)dr \tag{3.1}$$

where N is the cloud droplet number concentration cm^{-3}, and $n(r)$ is the number of droplets with radius r. @isit? The LWC can be written

$$\begin{aligned} LWC &= \int \rho_L \frac{4}{3}\pi r^3 n(r) dr && (3.2) \\ &= \frac{4}{3}\pi \rho_L \int r^3 n(r) dr && (3.3) \\ &= \frac{4}{3}\pi \rho_L \overline{r}^3 \int n(r) dr && (3.4) \\ &= \frac{4}{3}\pi \rho_L \overline{r}^3 N && (3.5) \end{aligned}$$

where the last equation shows the proportionality of LWC to the cloud droplet number concentration N, and ρ_L is the density of liquid water.

If the LWC is integrated over the height of the cloud, or any layer with chosen base and top in the atmosphere, we find the liquid water path (LWP) of that layer.

$$LWP = \int_{base}^{top} LWC dz \tag{3.6}$$

The LWP is the column of liquid water in a cloud and is usually expressed by $g\ m^{-2}$.

The cloud droplet effective radius determines many important radiative properties of a cloud and is therefore of particular interest. For example it determines the cloud albedo Hansen1974, which I will go more into when describing the first indirect effect.

Cloud consist of droplets that absorb and scatter SW radiation and absorb, scatter and emit LW radiation.. (introduction@)In this thesis shortwave (SW) radiation means solar radiation and longwave (LW) radiation covers the terrestrial infrared radiation. How clouds scatter and absorb SW and LW radiation. Explain something about blackbodies, clouds and blackbodies? Stefan–Boltzmanns law states that the flux density emitted by a blackbody is proportional to the fourth power of the absolute temperature @citeLiou2002page12. For a greybody, like a cloud, the equation can be written

$$F = \epsilon \sigma T^4 \tag{3.7}$$

where the emissivity of the greybody, ϵ, is included. $F[W\ m^{-2}]$ is the flux density emitted by the greybody, and $\sigma = 5.67 \cdot 10^{-8} Jm^{-2} sec^{-1} deg^{-4}$ is the Stefan–Boltzmann constant.

Write about optical depth from Wallace and Hobbs: Normal optical depth or optical thickness, τ_λ is a measure of the cumulative depletion that a beam of radiation directed straight downward (zenith angle $\theta = 0$) would experience in passing through a defined layer WallaceHobbs2006. The optical depth can be expressed as

$$\tau_\lambda = \int_z^\infty k_\lambda \rho r dz \tag{3.8}$$

where k_λ is the mass absorption coefficient, which has units of $m^2\ kg^{-1}$, ρ is the density of air, which has units of $kg\ m^{-3}$, and r is the mass of the absorbing gas per unit mass of air.

As mentioned in Chapter 1 Introduction there is no solar radiation to reflect during winter and the polar night in the Arctic, where as in the summer the zenith angle is so high that even though there is sunlight 24 hours a day the cooling effect in summer does not average out the heating effect the clouds have in winter. The low clouds' ability to absorb and emit terrestrial radiation domiantes over their reflective effect on the solar radiation. @cite?

How do clouds reflect radiation? What is the effect of more water? Or more ice? What about the droplet size? (effective radius)
How do clouds absorb and emit radiation? Effect of more or less water or ice? Droplet size?

Ice is more effective in reflecting SW than water. Snow has a higher albedo than rain. Is there any use in presenting some albedo values for water, snow, ice? Or open water versus sea ice? New ice versus old sea ice?

Make sure to include something on how LWC/LWP and effective radii plays in, if this is to be mentioned in the results or discussion!!

3.3 Aerosol effects on clouds

Aerosols affect clouds in numerous ways. They have a direct effect on the climate by scattering and absorbing SW radiation. acting as CCNs og INs. elaborate? If there are few CCNs a cloud in the area would be a clean cloud with few, but large droplets and therefore have a low albedo and precipitate easily. If the area had high aerosol concentration, the cloud would be polluted and have more numerous but smaller droplet, which means it would have a higher albedo and precipitation woul be suppressed.

Not only the aerosol burden is important, if it is the same for two areas with different meteorological forcing that would also affect the cloud properties. Say an area has weaker updraft than another area, a cloud formed due to the weaker updraft will have lower LWC, lower albedo and little precipitation. The cloud formed in a stronger updraft will have higher LWC, higher albedo and be more precipitating.

@introduction?— Diminishing sea ice could lead to an increase in the aerosol number concentrations in the area where ice has retreated. The open sea surface it self would lead to an increase in release of sea salt to the lower atmosphere @cite. The lack of sea ice would also increase the likelyhood that the sea could be used for shipping, which would pollute the area @cite. —- There are two known indirect effects that aerosols have on radiation, through clouds. The first indirect effect was proposed by [7] and is often referred to as the Twomey effect. The second indirect effect was proposed by [1] and is also known as the lifetime effect.

3.3.1 The first indirect effect

(Maybe just call it all indirect effects and refer to Lohmann and Feichter) The first indirect effect, suggested by [7], describes the enhancement of cloud albedo as a consequence of an increase in aerosol content and thereby available CCNs. In short, the first indirect effect is a cloud albedo enhancement. By increasing droplet concentration and hence the optical thickness of a cloud, pollution acts to increase the reflectance of clouds Twomey1977. The optical thickness is increased when the number of CCN is increased. Although the changes are small, the long term effects on climate can be profound Twomey1974.

Meg: The optical depth will change with changes in aerosol number concentrations and changes in clouds and their properties. For instance if a cloud has many small droplets, the optical depth will be higher. Where as fewer cloud droplets will yield a lower optical depth, resulting in more SW radiation reaching the ground — possibly having a warming effect on the area.

3.3.2 The second indirect effect

Albrecht 1989 The second indirect effect, or the cloud lifetime effect, suggests more numerous but smaller droplets reduce the precipitation efficiency and by that enhances the cloud lifetime and hence the cloud reflectivity Albrecht1989. This effect has been estimated to be of roughly as large as the first indirect effect Lohmann2005.

Production of DMS by phytoplankton Charlson 1987

Chapter 4

Model and methods

4.1 Modeling System description

(What did Johanne and Kjetil think was important enough to write about in their thesees?)

To produce results for the thesis, a formulation of the Weather Research and Forecasting (WRF) Model called the Advanced Research WRF (ARW) has been used, Version 3.6.1, released in April 2014. The model is developed at the National Centre for Atmospheric Research (NCAR) in Boulder, Colorado. The ARW model is the first fully compressible conservative form nonhydrostatic model designed for both research and operational numerical weather prediction (NWP) applications Skamarock2008.

As can be seen from figure 4.1 the WRF Modeling System consists of four major programs Wang2012:

- The WRF Prepocessing System (WPS)
- WRF-Data Assimilation (WRF-DA)
- ARW solver
- Post-processing & Visualization tools

WPS is used primarily for real data simulations Wang2015, like the study presented in this thesis. Its functions include defining simulation domains, interpolating terrestrial data and degribbing and interpolating meteorological data from another model to this simulation domain Wang2015. WRF-DA is optional and can be used to ingest observations into the interpolated analyses created by WPS Wang2015, but was not used in this study. The ARW

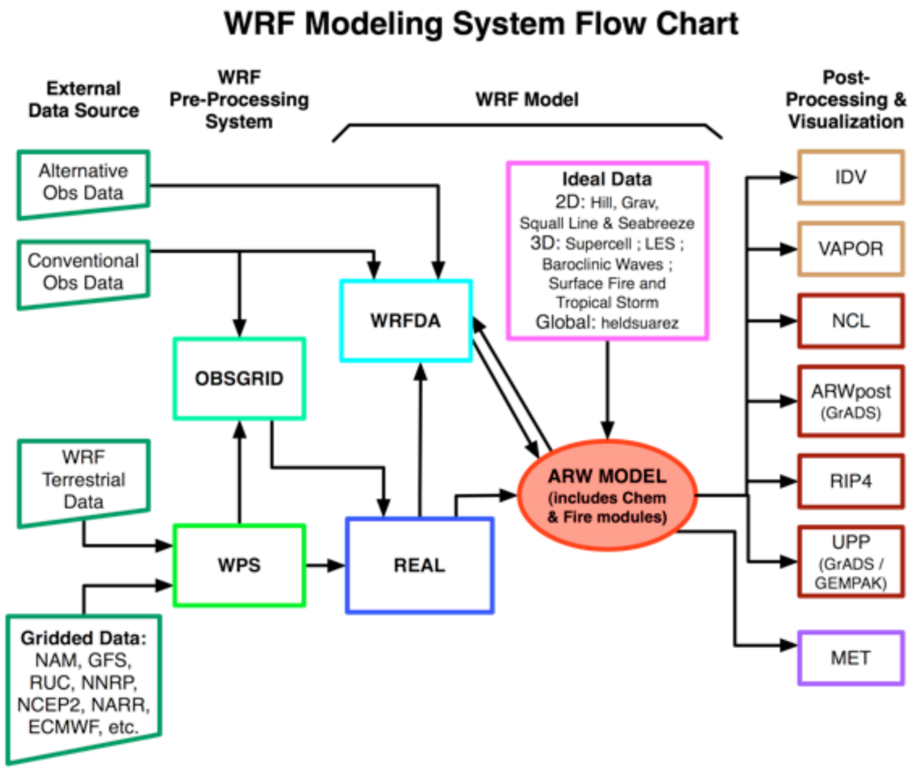

Figure 4.1: Flowchart for the WRF ARW Modeling System Version 3. From [8].

solver is the key component of the modeling system, which is composed of several intialization programs for idealized, and real-data simulations, and the numerical integration program Wang2015. Fully compressible nonhydrostatic equations with hydrostatic options, regional and global applications, complete coriolis and curvature terms and that vertical grid-spacing can vary with height are among the WRF models key features according to [8].

The continuous equations solved in the ARW model are the Euler equations cast in a flux form where the vertical coordinate, η, is defined by a normalized hydrostatic pressure,

$$\eta = (p_h - p_{ht})/ \tag{4.1}$$

where $= (p_{hs} - p_{ht})$ Skamarock2008. p_h is the hydrostatic component of the pressure and p_{hs} and p_{ht} are the values of the hydrostatic pressure in a dry

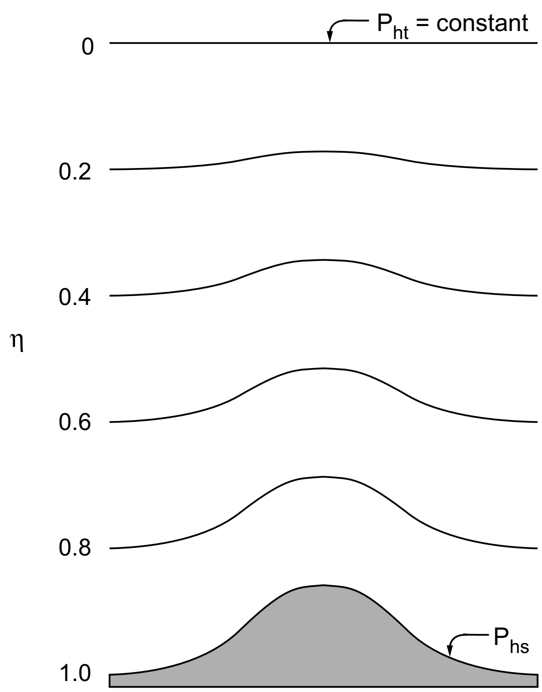

Figure 4.2: This figure is shown as presented in [4], and is a schematic of the terrain following a σ coordinate. P_{hs} and P_{ht} is the hydrostatic pressure at the surface and the top respectively.

atmosphere at the surface and top boundaries respectively Skamarock2008.

The vertical coordinate is the traditional σ coordinate used in many hydrostatic atmospheric models, shown in a diagram in figure 4.2.

4.2 Schemes

The ARW model offers a wide selection of schemes to treat different physics that one wants represented in the model. The schemes treat the physics slightly differently and some schemes are better for certain horisontal and vertical resolutions than others, so one needs to be careful when choosing how the model is to treat the physics. For my thesis, the especially relevant scheme to mention is the cloud microphysics scheme that I chose, which is the aerosol-aware scheme described in [5] which is a development of the bulk microphysisc scheme described in [6], to include aerosols and scavenging of them. The scheme is a true double moment scheme and therefore treats cloud water, cloud ice, rain and snow in a complex and detailed way(@???litt vagt og rart å skrive) [5]. At the time of writing, the only radiation schemes that make use of the effective radii are the Rapid Radiative Tranfer Model (RRTM) for General Circulation Models (GCMs) (RRTMG) radiation schemes [?] for both SW and LW. These were therefore used in combination with the aerosol-aware cloud microphysics scheme.

4.2.1 The aerosol-aware scheme

The microphysics option 28 Thompson2014 is built on the schematic shown in figure 4.3. It is a double moment scheme, which means it computes both mixing ratios and number concentrations for the same water species (hydrometeors).

Write more about this figure!

4.3 Model setup

@Area description. Sea names: Beaufort and ??. By Canada and Alaska, this is because data from the area has been used for research by others @citations. The area is not ice free any part of the year @cite, and provides a good place to simulate cloud and sea ice interaction.
I ran ARW with a horisontal resolution of 4 km, and 72 vertical layers. This resolution is sufficient to resolve clouds @citation. 300$\cdot$ 300 gridpoints, with 4 km spacing, between .
I call the vertical layers in the ARW model eta levels, because of the choice of η as the vertical coordinate. These levels have uneven vertical spacing. Since the level height is dependent on pressure, the height varies in both time and space. Consequently the levels in the lower troposphere are closer to each other than higher up in the troposphere. Therefore the low clouds in the area can be resolved. (@How close? what heights??)
The sea ice in the area was removed by editing the input file constructed? built? by WPS and real.exe, to get results to compare with results from runs with ice.
From diminishing sea ice we might experience an increase in sea traffic, which would lead to an increase in aerosol content in otherwise clean air @citation. To include increase in aerosol concentrations due to lack of sea ice I used the microphysics scheme developed by Greg Thompson and Trude Eidhammer described in [5].

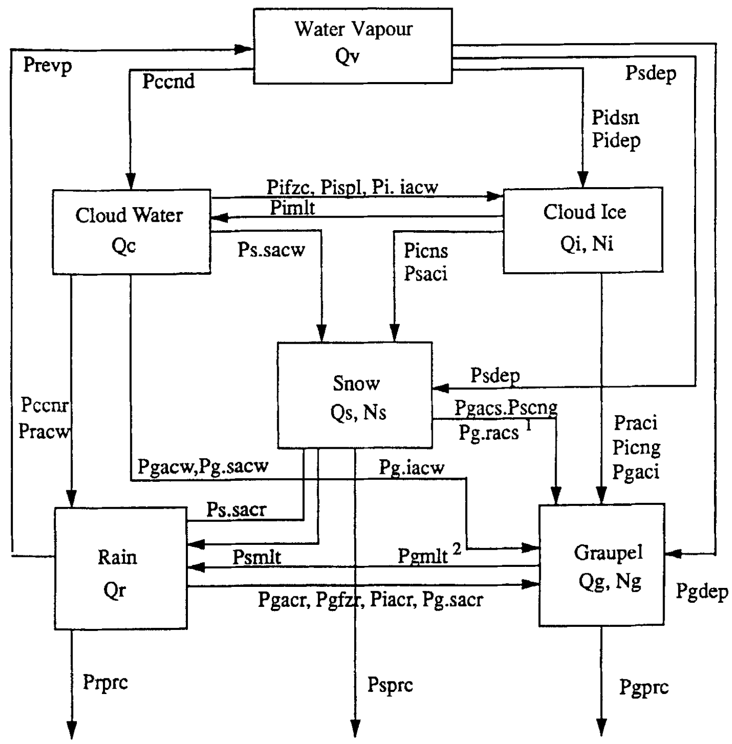

Figure 4.3: Cloud microphysical parameterization scheme typically used i NWP models as shown in [3]. A full list of the acronyms used in the schematic can be found in [3].

The scheme uses a monthly mean for aerosol number concentrations derived from multi-year (2001-2007) global model simulations @citationColarco2010??(det har de cita) in which particles and their precursors are emitted by natural and anthropogenic sources and are explicitly modeled with multiple size bins for multiple species of aerosols by the Goddard Chemistry Aerosol Radiation and Transport (GOCART) model (@desiterteGinoux2001) Thompson2014.
Choice of schemes and reasons should be presented. As should hos WPS and real.exe and wrf.exe works. At least short about what they do and contribute with to get to the end results. Explain some of the improvements in the micro physics scheme in combination with the revised radiation schemes (RRTMG for SW and LW).

4.4 Model runs

Table 4.1: Table showing the name of the runs and what is included

Name	Horisontal resolution	Dimensions	Vertical layers	Δt	Sea ice	Aerosol concentration
control	4 km x 4 km	300 x 300	72	24 s	initial	control
NoIce	4 km x 4 km	300 x 300	72	24 s	removed	control
IncAero	4 km x 4 km	300 x 300	72	24 s	initial	control x 100
IncAeroNoIce	4 km x 4 km	300 x 300	72	24 s	removed	control x 100

Which table?

Table 4.2: Caption could say: Table showing the names of the runs and if they have sea ice or not, and if the aerosol concentration has been increased. All the runs have the same horisontal resolution of 4kmx4km, dimensons 300x300, vertical layers 72 and time step 24 s.

Name	Sea ice	Aerosol concentration
control	initial	control
NoIce	removed	control
IncAero	initial	control x 100
IncAeroNoIce	removed	control x 100

4.4.1 Manipulation of input files

To run the model without ice and with an increased number of aerosols I manipulated the input files for WRF. I used a netCDF Operator (NCO) tool, ncap2. This allowed me do manipulate the netCDF files from my terminal window in the folder where they were located. Elaborate on removal or placing of sea ice. Elaborate on multiplying the aerosol number concentration with a factor 10. By use of ncap2 from NetCDF (NCO).

4.4.2 Changed ice run

The seaice variable was simply multiplied by 0 in every gridpoint and by that removed. Removed ice from the input file for the model run by using NCO and ncap2. The point of this is to compare the run with no ice to the control run, and see if there are any changes to the cloud properties.

4.4.3 Changed aerosols run

The increase in aerosol concentration was a bit more complicated, but the same method. The number of water and ice friendly aerosols were multiplied by 100 and so were their tendencies and respective concentrations at the boundaries of the area. Multiplied the aerosol number concentration fields at all levels with a factor of 10 by using NCOs ncap2, using the same tool I also changed the belonging..? (tilhørende..) variables in the bdy input file (is this a building file.. or what?). The goal is to find changes in cloud properties compared to those in the control run.

4.5 Input data

ERA-Interim reanalysis from European Centre for Medium-Range Weather Forecasts (ECMWF) used as input for initial and boundary?? conditions. (Downloaded by python scripts provided by Anne (more names) at the IT-help ??? at section for Meteorology and Oceanography at the University of Oslo.) The data from ERA-Interim was interpolated over a the grid with a 2 degree minute spacing between the points, to be used to initialize the model.

4.6 Processing of the results

Figures presented in my thesis, I made (unless other is stated) by use of National Centre for Atmospheric Research (NCAR) Command Language (NCL) and MatLab. For the NCL scripts I found a lot of help and inspiration from the example scripts for WRF-users available at (URL for examples).

I made some figures with NCL, but most with MatLab provided by the University. Most figures that are not over a map were made with MatLab. MathWorks, it is very useful and easy to use.

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