Why modellers should care about field projects

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Abstract

In this paper we discuss the utility of field observations for model development from an Arctic standpoint. Models have to be true to reality as far as is possible, and when it comes to developing model physics, which is crucial for model climate and hence for model performance on all time scales, there are many processes that can only be studied with the dedicated detailed observations that comes from field projects. We argue that field observations can be of use for model developments in three different ways: 1) To discover phenomena and aspects of processes that have not been covered previously; 2) To explore process or variable relationships that are needed either to develop new parameterizations, to evaluate assumptions that lie behind all parameterisations or to determine closure constants in parameterisations; 3) To evaluate models either straightforward, where regular observations are unavailable, or process oriented which is the method we encourage since it is the only means by which compensating errors can be avoided and random errors separated from systematic errors.

1. Introduction

In atmospheric sciences exists a sometimes unhealthy subdivision of activities into “modelling” and “experimental”. While it is probably true to some degree that the two activities require different slightly skill sets and different approaches, the gap between the two leads to fundamental deficiencies in the “final outcome” of the science; the results that one way or another are important either to society directly, or to the scientific community and hence to society at a later time or at least in a different way.

Field projects aim at studying, often in great detail, processes that are important to the system; as such they are most assuredly needed in models. There is an obvious inherent utility to such work; curiosity can never be satisfied and the implied need to explore something further and further is a vital and necessary motivator in science. However, the observations all by themselves are nothing more than numbers in a data base and without a link to some kind of modelling there is risk that important processes are picked apart in ever more detail, without ever setting results into context.

This can become a “self-playing piano” in the sense that while more knowledge is generated it is only used to motivate new proposals for new field projects, where the results are evaluated by fellow experimentalists, leading to even more field projects, but without safeguard neither that the most relevant issues are pursued nor that the results are ever used. Of course, no one scientist can alone claim to know what knowledge is most relevant; this can however come about in an active communication between experimentalists and modellers. Without that communication, modelling and the detailed process knowledge risks diverging. As a consequence, processes important in modelling, whether of the climate or of next day’s weather, becomes sub-optimally explored. Knowledge that we do have about important processes does not make it into new models simply because those developing the models are unaware of new knowledge, while those who do have that understanding spend their time splitting the same hair over and over again.

However, by itself a model is only lines of code, sometimes quite a few, and it is in confronting the model with observations that hypotheses can be tested. There is an obvious linkage here that is often overlooked. Randall and Wielicki (1997) suggest: *"The models by themselves are "stories" about the atmosphere. In making up these stories, however, modellers must strive to satisfy a very special and rather daunting requirement: the stories must be true, as far as we can tell; in other words, the models must be consistent with all of the relevant measurements."* In other words, a model must conform to the observations, not just some of them but to *all the relevant ones*. They go on to state: *"Models are conceptual constructs that can be used to make predictions about the outcomes of measurements. Hypotheses can be expressed in terms of model results. The most fundamental use of measurements is to falsify such hypotheses, and thereby to falsify models, not to validate them."*

Hence models are hypotheses; a prediction of the outcome of a measurement and hypotheses need observations for testing. Another, more loose, way to express this is "*Data without a model is chaos; a model without data is guesswork"* (Patrick Crill, personal communication 2011). The bottom line here is that modellers cannot – or at least should not – be without observations while experimentalists need a hypothesis to know what they are looking for - a model. Sometimes experimentalists do not even realize that they used a model when exploring their experimental data, or at least do not think of their tool as a model; this need not always be a numerical model, but is a model nevertheless. Conceptual models is an underutilized concept that falls within this category, but also other more formals hypotheses, such as for example, predictions following the Monin-Obukhov similarity theory when analysing micrometeorological observations.

Hence, this paper could stop right here; the utility of observations to modelling is clear and inherent in all scientific work. Still we will go on to provide a few examples. For the purpose of this paper, we will divide the utility of field experiment data for modelling into three different categories:

- *Expanding our knowledge* – reveal things we didn't know before
- *Reveal process relationships* – understanding the system to improve model formulations
- *Evaluate models* – this can off course be done in different ways

Observations can tell us things we did not already know; this is obvious. Before we can describe sub-grid scale processes in a model, we need to understand how they work and what they depend on. And before we can trust the predictions of a model we need to know that it is not a false hypothesis (see above); that requires observations. But model evaluation can (should?) also be done by comparing process relationships in the model, such as when developing parameterizations, with those from the observations; in that sense the two last points are somewhat interlinked. We will attempt to consider them separately; the separation will simply be based on whether (a) model(s) were involved.

In the following sections we will discuss and give examples of these categories briefly, with a focus on conditions in the Arctic Ocean and on clouds and boundary layer processes.

2. Utility of field experiments

Before discussing the utility of field observations for model development and testing, there is need for an additional comment on observations in the Arctic in general, and about the Arctic Ocean in particular. The Arctic Ocean is an ocean surrounded by continents and this ocean is covered by drifting sea ice; in the winter the whole basin is covered while in the summer increasingly less ice cover remains at the end of summer. This means that there is nowhere to locate permanent observation stations; on the surface of the ice, buoys are frequently deployed that measures properties of the ice and the ocean, and to some minimal extent the near-surface atmosphere severely restricted by the unfriendly environment where the ice is subject to ridging and formation of leads and riming and frost are severe problems, not to mention the problem of power supply. In the winter, the sun is essentially absent and it is cold and dark. In the summer the ice melts and breaks more easily. Sounding stations, that could provide information of the vertical structure of the whole troposphere, are almost entirely absent; only soundings from the Russian drifting "ice islands" are available.

As a consequence, there are very few regular observations in the Arctic Ocean and almost none of the vertical structure of the atmosphere. Hence field experiment data, often from ice-breaker borne expeditions, are even more important than field experiments in many other locations on Earth, simply because they are so sparse. However, there is a considerable summer bias in such observations, when the Arctic Ocean is comparably accessible, and even less data available from winter conditions.

This lack of observations is to some degree compensated by satellite observations. Because the track of polar orbiting satellites converges on the poles, there are multitudes of satellite data; more than at most other locations on Earth. However, the retrieval of this data is complicated by the environmental conditions; visual wavelengths are useless in winter and because of the sea ice satellites have difficulties to separate clouds from the surface using only infrared wavelengths. Also here field experiment data plays an important role, in providing "ground truth" for retrieval development, but that is a separate issue which we will not comment on further here, except to say that environmental monitoring in the central Arctic will have to rely largely in satellite data in conjunction with atmospheric and oceanic data assimilation. Also in this last sense model development is crucial, and hence here comes the field experiment data again.

2.1. Expanding knowledge

The Arctic is a very cloudy place; estimates of cloudiness from several sources, including satellite data, indicate that the cloud cover in winter is 50-70% while in summer it is >90% (e.g. Wang and Key 2005, Shupe et al. 2011). Clouds have a marked effect on the climate and also on weather forecasting; however, in the Arctic the aerosol climate is different from most other locations on Earth, with generally less aerosols available for the formation of cloud condensation or ice forming nuclei (CCN or IN). Hence it is not obvious that Arctic clouds have the same optical properties as similar clouds would have, say, in the sub-tropics. Observations that to some degree cover these aspects in the central Arctic were essentially absent before 1997, when the Surface Heat and Energy Balance of the Arctic (SHEBA; Uttal et al. 2002) was launched; a full year of observations on the ice based on the Canadian icebreaker *des Glouciers*. Today, one and a half decade later, the dataset from SHEBA is still a major source for understanding the Arctic climate system, although the latter has changed substantially since then.

A major unexpected result from the cloud radar and lidar observations from SHEBA was the presence of super-cooled liquid water at very low temperatures; models at the time (including the ECMWF/IFS) typically diagnosed the amount of ice and liquid in clouds based only on temperature (Figure 1), indicating only ice below about -20°C. As an immediate action, the diagnosis in IFS

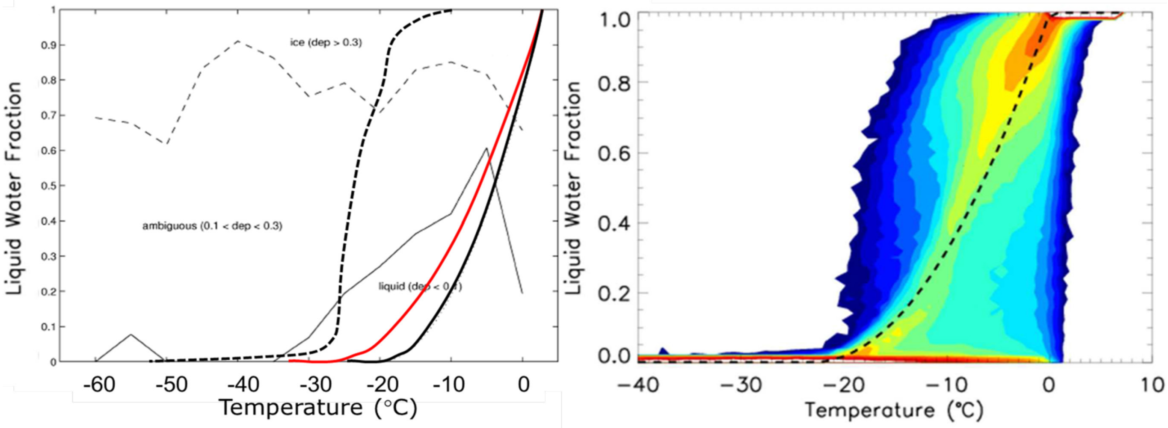

Figure 1. Partitioning of cloud water into liquid and ice as a function of temperature. The left panel shows two versions of this from IFS (from Beesley et al. 2000) along with the observed liquid water fraction, using the lidar depolarization. The right panel shows the probability of this partitioning as evaluated from the new cloud scheme in the IFS (Richard Forbes 2013, personal communication) , with prognostic cloud liquid and ice; the dashed line in the left panel is approximately the demarcation when there is never liquid water in this model

curves was adjusted; today the IFS has a more advanced prognostic functionality separately forecasting cloud liquid and ice. Still, even the envelop of results from this formulation does not fully capture the amounts of liquid water in clouds at low temperatures in the Arctic.

This may seem like a small detail in the greater scheme of things, but is very important for the surface temperature due to the different optical properties of clouds containing liquid or ice. Liquid clouds more often appear act as "black bodies", hence down-welling longwave radiation at the surface is much larger when liquid is present than for ice clouds. This effect is compounded by precipitation formation; ice in a mixed-phase cloud is supersaturated with respect to ice and hence ice crystals grow at the expense of the liquid water and precipitate out. Allowing clouds to completely glaciate in models, clouds essentially falls out of the sky and cloudiness is underestimated (e.g. Prenni et al. 2007), resulting in even less down-welling longwave radiation at the surface. But the story doesn't end here; this also dehydrates the atmosphere which in winter is already extremely dry due to the very low temperature, hence reducing the longwave radiation at the surface even further.

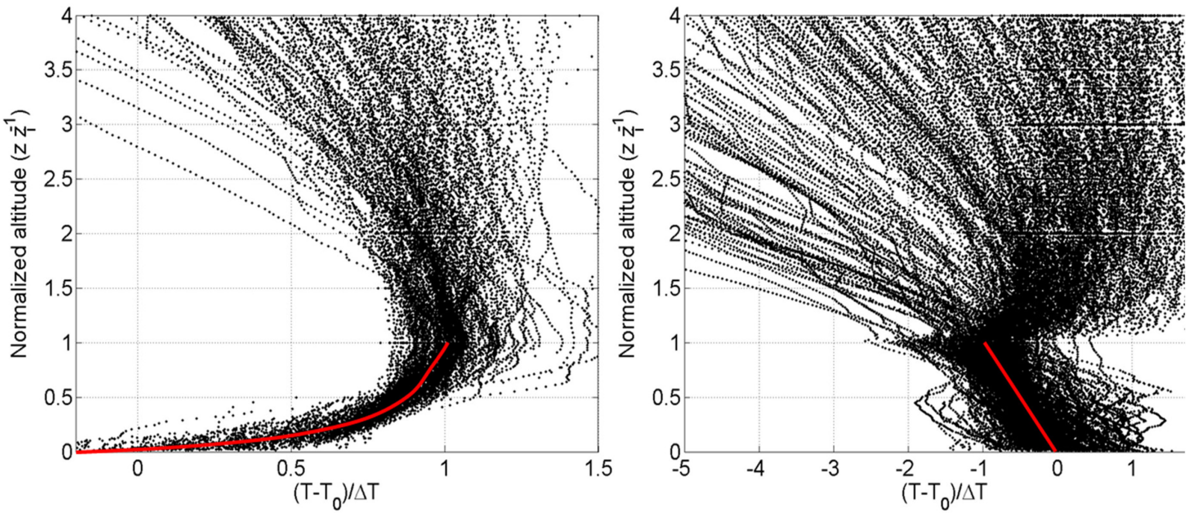

Figure 2. Vertical structure of SHEBA soundings showing surface inversion (left) and elevated inversion (right) and both the height and temperature axes are normalized (Tjernström and Graversen 2009). All soundings are used and the cases are separated simply by requiring that the first inversion base is below (left) or above (right) 15 m above the surface.

Without high resolution soundings of the atmosphere (as opposed to satellite profiling) it is also difficult to understand the linkages between the persistent clouds and boundary layer mixing. One of the most common and persistent misconceptions of near-surface conditions over the Arctic Ocean sea ice, is that the boundary-layer is dominated by large static stability and surface inversions even in summer. Again, the soundings from SHEBA tells a different story; Tjernström and Graversen (2009) analysed all the soundings from SHEBA and found that they could essentially group all profiles into two distinct categories; surface inversion or a well-mixed boundary layer under a capping inversion (Figure 2). There is a distinct annual cycle; surface inversion were common in autumn and winter, with 61 and 53% occurrence respectively, but in spring and summer these numbers drop to 15 and 9%, respectively. Inversion strengths and depths also have an annual cycle. But still, seen over the whole year surface, inversions occurs only about a third of the time, both because of the total dominance of well-mixed and neutral conditions in spring and summer but also the frequent occurrences of those conditions in winter. Winter inversions are surely substantially stronger than summer inversions, but the variability is also larger in winter; this variability in links directly to the clouds.

Figure 3, from Tjernström et al. (2012), illustrates another peculiarity in the Arctic low troposphere that would like remain unknown, or at least poorly known, without *in situ* observations. The upper panels in this figures shows the probability of equivalent potential temperature and relative humidity

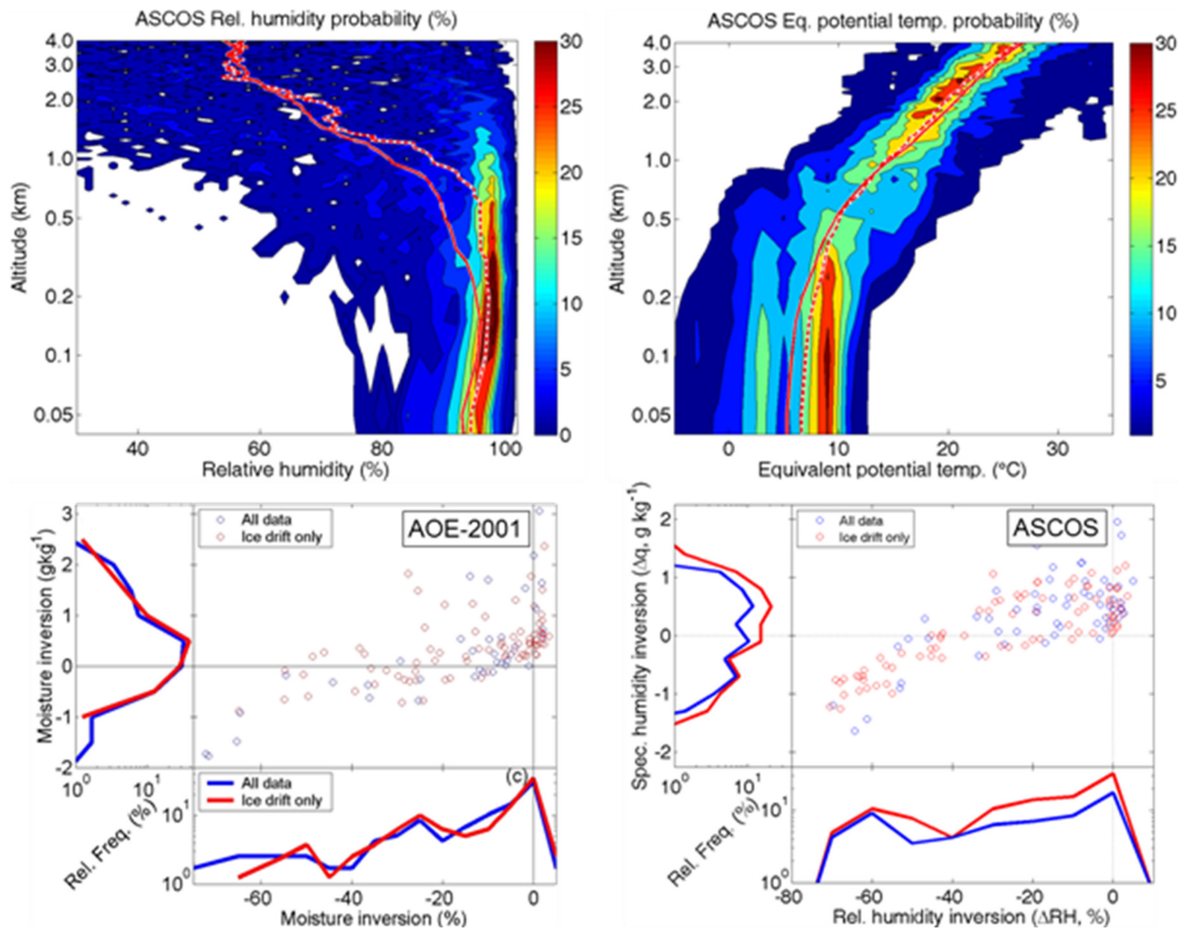

Figure 2. Illustration of the vertical structure of the summer Arctic boundary layer (Tjernström et al. 2004, 2012). Upper panels shows the probability of the (left) relative humidity and (right) equivalent potential temperature; note the difference in the lower layer depth. Lowe panels show the PDFs of the jump in specific humidity and in relative humidity across the capping inversion, from (left) AOE-2001 and (right) ASCOS.

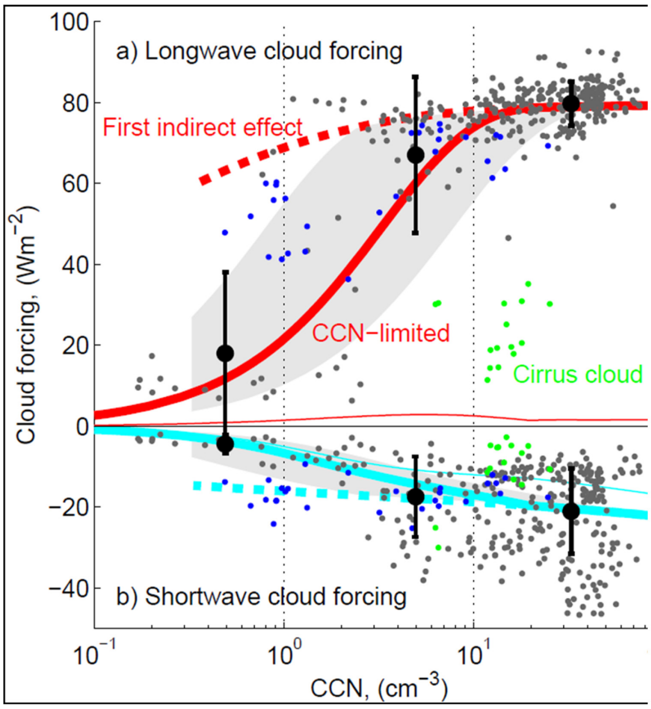

Figure 4. Surface (a) longwave and (b) shortwave cloud radiative effect as a function of CCN number concentration, from Mauritsen et al. (2011). Lines are from idealized radiative transfer calculations where the dashed lines represent the first aerosol indirect effect alone and solid thick lines correspond to cloud liquid content being limited by an effective radius Re < 15 µm.

from 145 soundings during the 40 days of the Arctic Summer Cloud Ocean Study (ASCOS; Tjernström et al. 2013). While the well mixed structure is obvious, one can also see how the depth of the moist layer is deeper than that of the well mixed structure. Since this means that a constant high relative humidity penetrates into the lower part of the capping inversion, where the temperature increases with height, this implies an increasing specific humidity with height, contrary to what is typically found in stratocumulus clouds in other regions. This is confirmed in the lower two panels, showing the statistics for the jump in relative humidity and specific humidity from ASCOS and from the Arctic Ocean Experiment 2001 (AOE-2001; Tjernström et al. 2004), another summer experiment. This layer of moist air is likely "fossil humidity" left over from the upstream moist and warm deeper boundary-layer structure over open ocean surface south of the sea-ice edge.

One last example of comes from observations of so-called optically thin clouds can be found in Figure 4. Here, the surface-radiative cloud effect (CRE; the difference in net surface radiation with and without clouds, everything else being the same) is plotted for short- and longwave radiation as a function of the concentration of cloud condensation nuclei (CCN). The CRE is calculated as the difference between the observed surface radiation and the calculated surface radiation from a model based on soundings but removing the clouds. The lower panel shows the expected so-called Twomey effect (Twomey 1997); decreasing solar radiation with increasing optical depth. The interesting feature is in the upper panel, showing the transition from optically thin (grey body) to optically thick (black body) clouds as the CCN concentration goes up. To explain the observations, a second indirect effect has to be assumed; as CCN concentration decreases, cloud droplets grow in size beyond a critical limit and are removed by gravitational settling. Although there is no dynamics in this analysis, it can be further speculated that each settling droplet will also remove CCN, hence causing a positive feedback on the CCN concentration. Using the CCN concentration as a proxy, Mauritsen et al. (2011) and Tjernström et al. (2013) estimate this regime to be present about 30% of the time in summer.

2.2. Exploring the parameter space

Parameterizations, or "model physics" as it is also sometimes referred to (although this raises the question on if the model dynamics is not physics), are relationships that often are a mixture of insight that can be derived from theory and hypotheses and what comes out from observations. In the first case there are usually closure relationships or constants that can only be derived from observations.

Such relationships also often encompass understanding that can be assembled into conceptual models that may be an intermediate step in parameterization development.

Figure 5 explores the parameter space of the wintertime surface energy budget, from the SHEBA experiment (Persson 2011). Exploring the net longwave radiation in winter, the probability density function (PDF) is clearly bimodal (left panel). One mode is due to cloudy conditions and the other for (essentially) clear conditions; see above. When clouds are absent (or optically thin), the loss of radiative energy from the surface is roughly compensated in about equal parts by sensible heat flux from the atmosphere and heat transfer from the warm ocean below the ice. When low clouds are present, however, the longwave cooling to space instead occurs at the cloud top, rather than at the surface. In the absence of solar forcing, this generates a near zero net-radiation balance at the surface. But the near-surface air temperature is still substantially lower that the ocean temperatures beneath the ice, which remain slightly below zero (the freezing point of the ocean is ~ -2°C). Hence there remains a substantial heat transfer from the ocean through the ice and to the atmosphere. With a near-zero net radiation, the consequence must be an upward sensible heat flux at the surface and slightly unstable surface layer; the boundary layer is therefore mixed from below, and from the top by negative buoyancy from the cloud-top cooling. This forms the shallow well-mixed inversion capped boundary layer. This structure would not exist unless there was substantial liquid water in the clouds; see above. Consequently the energy balance is balanced even when spring and autumn sub-zero temperature conditions are added (upper right panel), with some hysteresis due to the surface temperature adjusting to changing conditions. In summer (lower right panel) the situation is completely different; except radiation, all heat fluxes are small and do not respond to changes in the radiative forcing. This

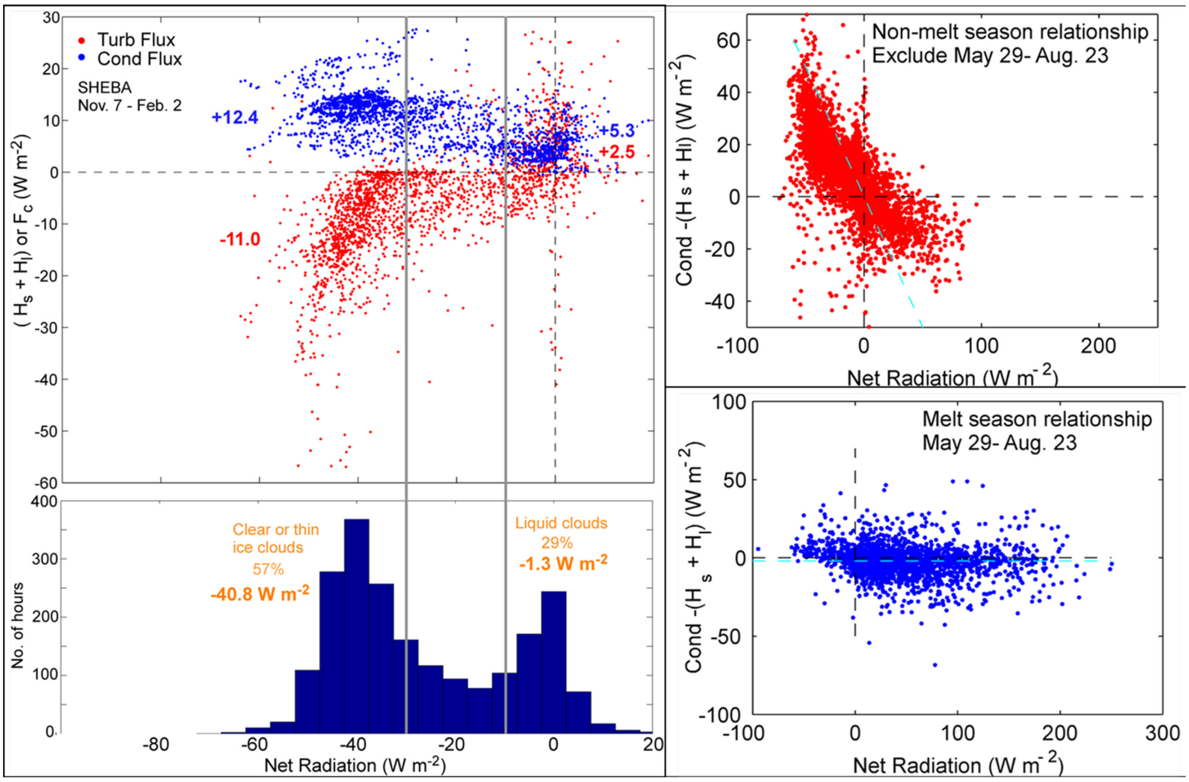

Figure 3. Illustrations of the relationships between different terms in the surface energy budget from Persson (2011). Left two panels show the sensible heat flux and the thermal conduction through the ice as a function of net longwave radiation at the surface and it's PDF. The two panels to the right show the sum of the turbulent surface heat fluxes and the thermal conduction as a function of net radiation, for (upper panel) the freezing and (lower panel) the melt season.

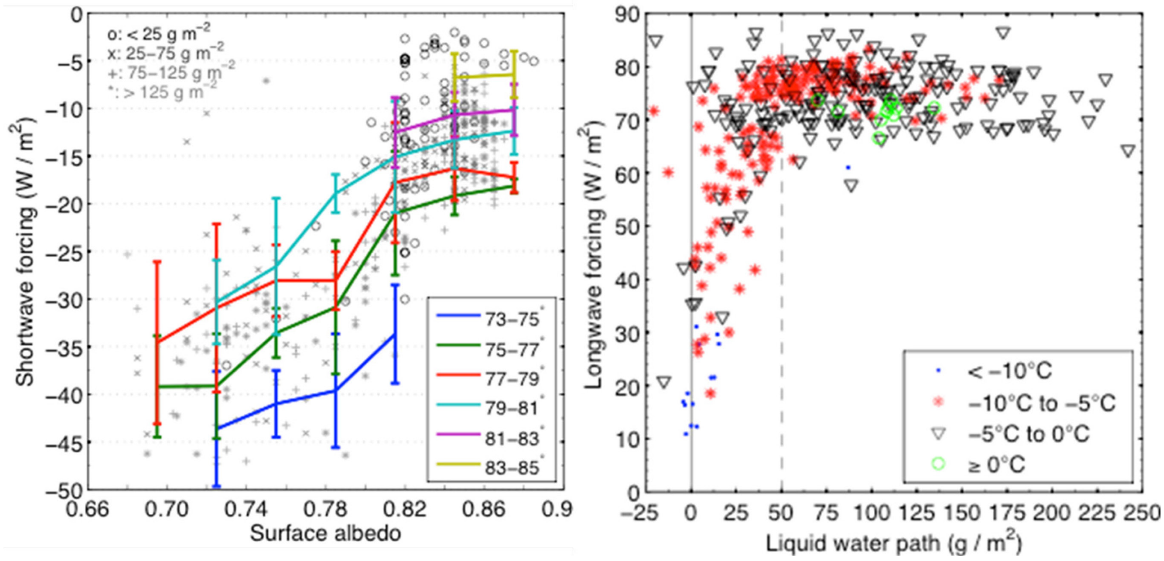

Figure 4. Dependences of surface radiative effects on different ambient parameters, from Sedlar et al. (2011). Left: Shortwave effects as a function of surface albedo, with symbols and shading for different LWP (g m^{-2}) and colored lines for bin-averaged solar zenith angle (SZA). Right: One-hour LWF (W m-2) as a function of cloud LWP (g m^{-2}), separated by cloud base temperature ranges from below -10 °C to above 0 °C. All effects are given in W m^{-2}.

is simply because the surface is melting and the temperature is "locked" near 0 °C and all excess/deficit heat goes into surface melt/freeze.

The cloud forcing depends critically on several the environmental parameters (Figure 6). The main contributors to the magnitude of the solar effect are surface albedo, solar zenith angle and liquid water path (left panel). The (negative) solar cloud effect increases with decreasing surface albedo and solar zenith angle, and with an increasing liquid water path. The total magnitude if this is however only half of the longwave surface radiation cloud effect, but this on the other hand saturates rapidly; optically thick clouds seems never to be the coldest while optically thin clouds are rarely very warm; this is sort of intuitively expected, but there is a no super-clear trends here and the data from ASCOS is from a limited time period in summer. The cloud effects are hence probably even more important in winter than in summer.

2.3. Evaluating models

As alluded to in the introduction, there is a sliding scale between this subsection and the previous; model evaluations can either be straightforward, comparing observations and model predictions for certain variables in isolation, or process oriented in the sense it explores a model's ability to reproduce realistic parameter combinations. Here we will start with an example of a more simple evaluation and then move on to more complex evaluations.

Figure 7 shows a comparison of vertical profiles from two regional reanalyses (Arctic System Reanalysis, ASR, two versions; Bromwhich et al. 2010) and ERA-Interim (Dee et al. 2011; ASR is forced by ERA-Interim) with ASCOS soundings (Wesslén et al. 2013). For all the reanalyses the low-level wind speed is higher than observed, while in the free troposphere the wind speeds are slightly on the low side. They are also slightly too cold in the lower free troposphere (~1-4 km), but while ASR is close to the observations in the boundary layer (< 1km) ERA-Interim has a systematic warm bias larger than 1°C. This is peculiar since this is from the summer, and the temperatures are usually close

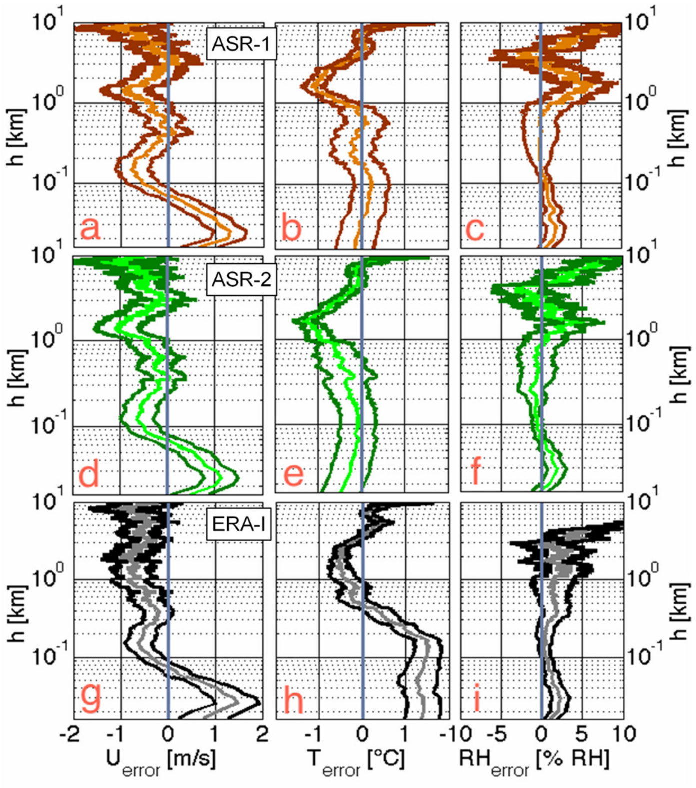

Figure 5. The mean error as a function of altitude (km), comparing reanalyzes from (a-c) ASR1, (d-f) ASR2 and (g-i) ERA-Interim to ASCOS soundings. The panels show (a, d, g) scalar wind speed in ms^{-1}, (b, e, h) temperature in °C, and (c, f, i) relative humidity in %. The lighter-colored middle line is the median error while the darker lines are the ± 95% significance interval. Note the logarithmic vertical scale.

to zero due to melting snow on the ice (e.g. Tjernström et al. 2004; Tjernström 2005, Tjernström et al. 2012). All models are slightly too moist and both temperature and moisture profiles indicates a problem with the height to the tropopause.

The two upper panels in Figure 8 explore the relationship between incoming surface radiation and integrated cloud water, from SHEBA and a set of regional models (Tjernström et al. 2008). Note that while exploring this relationship, we can effectively ignore the ability of any of the models to describe the actual presence and character of clouds at any given time; we only explore the statistical relationship between the clouds and the radiation. In the left panel incoming longwave radiation is expressed as an "effective emissivity" using the near surface air temperature as a norm; the clouds are very often low clouds, and hence a high emissivity indicates thick clouds that emit radiation as black bodies at a temperature near the surface temperature, in essence a near-zero net radiation. The effective emissivity increases with cloud water path, as expected, but a majority of the models of have lower median values, compared to the observations. Similarly, the right upper panel shows illustrate cloud effects on incoming solar radiation, here expressed as the amount of radiation that theoretically would reach the surface had the sun been in zenith rather than at the zenith angle that was observed; this situation is more complex. As expected, more cloud water gives less radiation at the surface. But here some models do a decent job of reproducing the observations for thicker clouds; however, for thinner clouds also here many models underestimate the incoming radiation.

Hence one might draw the conclusion that "thinner clouds" are to optically think for solar and all clouds are to optically thick for longwave radiation; sounds like a contradiction. We hypothesized in Tjernström et al. (2008), that the error is a split in time; the solar radiation problems is obviously mostly a summer problem and means that the modelled cloud albedo is too high, while the longwave radiation problem is more of a winter problem but may exist also in summer, and is mainly a consequence of having too little liquid water in cold winter clouds. In fact, none of the models in this study has any significant cloud ice at all during winter (not shown). The two lower panels show the PDFs for the error in incoming short- and longwave radiation for the whole year; the spread is substantial and is due to the models' ability to describe the presence and character of the clouds at any given time; the part of an error "hidden" in the upper panels. The peaks in the PDF illustrate the model biases; this can now be understood in terms of the upper panels. The conclusion is that the

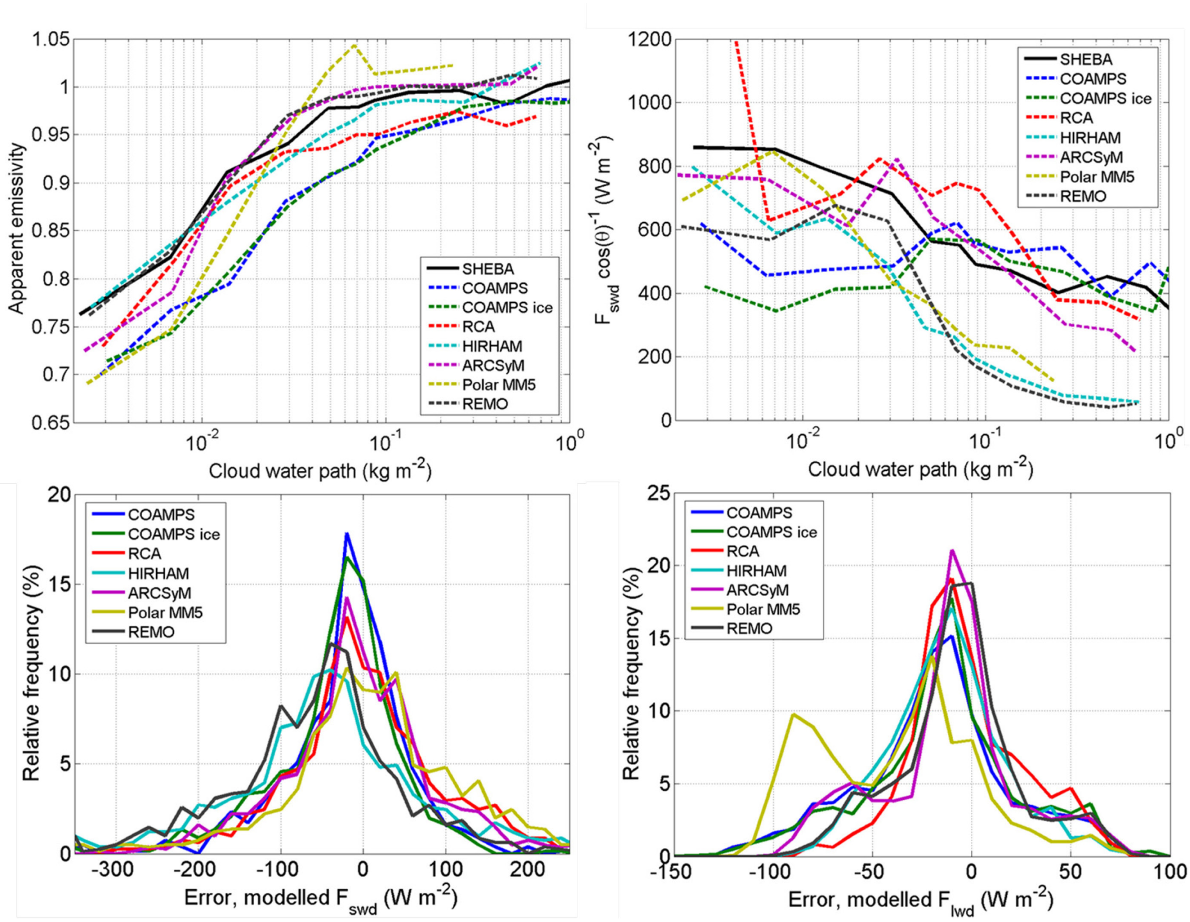

Figure 6. Upper panels show the relationship between incoming (left) longwave and (right) shortwave radiation at the surface and vertically integrated cloud water; only cases with clouds present are used. Longwave

models lack about 10-20 Wm^{-2} surface radiation because of limitations in the cloud parameterizations.This may be of little consequence for a weather-forecast model, where the spread of the error might be worse, but is huge in terms of climate. Couple any of these results to an interactive ice/ocean model and things will go seriously bad.

Tjernström et al. (2005) concluded that the actual correlation between observed and modelled fluxes was very low and that accumulated systematic errors in the sensible and latent heat fluxes approximately cancel on an annual basis. By instead estimating the PDFs of the turbulent heat fluxes, from SHEBA and from several regional models runs one can explore the “climate” of the models separately from the random model error. The PDFs shows (Figure 9) that all the models overestimate the turbulent heat fluxes by anywhere from a factor two to four or five, regardless of the sign. The modelled friction velocity (momentum flux, not shown) agrees better with the observations, but its PDF shows an underestimation of cases with low values and an overestimation of high values; the cross-over occurs at about $u_* \sim 0.3$ ms^{-1}. Hence the models are over diffusive; this is a common feature for many models, especially for stably stratified conditions. This problem then carries over to the heat fluxes, due to the way the turbulent fluxes are interdependent in most surface-layer schemes making these also to large.

3. Conclusions

The quality of an atmospheric numerical model, for weather forecasting or climate, is intimately related to how the model climate compares to the real climate; especially for climate models, but increasingly also for weather forecasting as more and more advanced data assimilation methods are employed. The model climate is critically dependent on how sub-grid scale processes are handled. To parameterize something, there has to be a basic understanding of the process; that understanding comes from or has to be anchored in field experiment data. One cannot parameterize a process when there is no proper understanding of how it works.

Models have to be evaluated before they can gain credibility. Some evaluations can use standard observations, but in an area like the Arctic where for example soundings are essentially absent, only field observation data is available. Some evaluations also needs to be on the process level, especially when developing new parameterisations that may additionally require estimations of closure parameters or functions that can only come from field observations. The physics package in most models is a maze of compensating errors, some there just because we lack a fundamental understanding. Hence the model climate may be correct but for the wrong reasons. Or this may be the case for many areas on Erath, but not in the Arctic, which may be dominated by a different set of processes. To get into such schemes and improves them requires an analysis of process relationships, that can often only come from field experiment data; for the Arctic Ocean field experiment data is the only source of such data. This is why modellers should care about field experiments!

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