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Exploring the decision-making process in model development: focus on the Arctic snowpack

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Abstract. The Arctic poses many challenges to Earth System and snow physics models, which are unable to simulate crucial Arctic snowpack processes, such as vapour gradients and rain-on-snow-induced ice layers. These limitations raise concerns about the current understanding of Arctic warming and its impact on biodiversity, livelihoods, permafrost and the global carbon budget. Recognizing that models are shaped by human choices, eighteen Arctic researchers were interviewed to delve into the decision-making process behind model construction. Although data availability, issues of scale, internal model consistency, and historical and numerical model legacies were cited as obstacles to developing an Arctic snowpack model, no opinion was unanimous. Divergences were not merely scientific disagreements about the Arctic snowpack, but reflected the broader research context. Inadequate and insufficient resources partly driven by short-term priorities dominating research landscapes, impeded progress. Nevertheless, modellers were found to be both adaptable to shifting strategic research priorities - an adaptability demonstrated by the fact that interdisciplinary collaborations were the key motivation for model development - and anchored in the past. This anchoring led to diverging opinions about whether existing models are "good enough" and whether investing time and effort to build a new model was a useful strategy when addressing pressing research challenges. Moving forward, we recommend that both stakeholders and modellers be involved in future snow model intercomparison projects in order to drive developments that address snow model limitations that currently impede progress in various disciplines. We also argue for more transparency about the contextual factors that shape research decisions. Otherwise, the reality of our scientific process will remain hidden, limiting the changes necessary to our research practice.

1 Introduction

If the number of mentions in Intergovernmental Panel on Climate Change Assessment Reports (IPCC AR) can be used as a proxy to quantify the importance of a component in the climate system, then our understanding of the key role played by the cryosphere can be dated to the mid-2000s. Cryosphere processes and feedback covered just 5 pages in the IPCC Working Group 1 (WG1) AR3 (IPCC, 2001), but a 48-page dedicated chapter in the IPCC WG1 AR4 (IPCC, 2007). By the Sixth Assessment Cycle, an IPCC Special Report focused on the role of changing oceans and cryosphere under a changing climate (IPCC, 2019). The average number of mentions per page of the words "Arctic" and "snow" in thirty-one years of IPCC WG1 AR trebled (Fig. 1). Meanwhile, the Arctic as a whole has warmed at twice, with some regions almost four times, the global rate (e.g. Serreze et al., 2000; ACIA, 2005; Walsh, 2014; Rantanen et al., 2022).

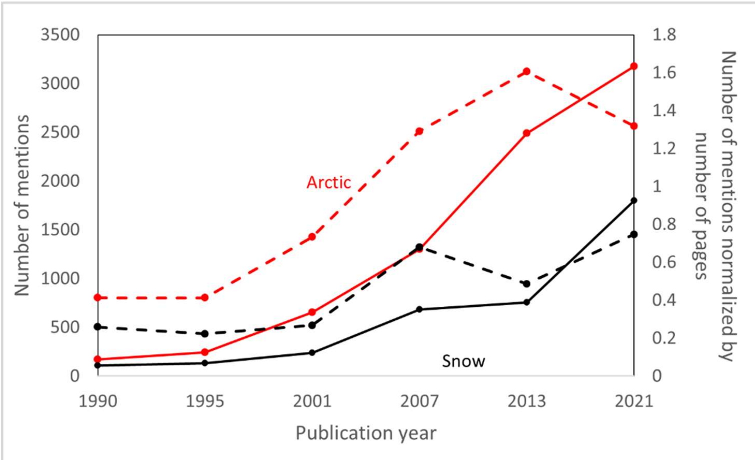

Figure 1: Number of mentions of the words "arctic" (red) and "snow" (black) in each IPCC WG1 AR (IPCC, 1990; IPCC, 1995; IPCC, 2001; IPCC, 2007; IPCC, 2013; IPCC, 2021) (solid line) and number of mentions normalized by the number of pages in each report (dashed line).

The attribution and quantification of climate change by the IPCC WG1 is partly based upon simulations provided by Earth System models (ESMs), which are lines of code, written over time by multiple scientists, that describe processes relevant to life on Earth. Other types of models are dedicated to investigating specific components of the Earth system e.g snow physics models. In both types of models, the “real world” must be translated into a numerical language, requiring modellers to make decisions at every stage of the model development. Given limited computing capabilities, modellers must decide which processes matter enough to be represented, which parametrization of the chosen processes best suits the purpose of their model, which language to use, how to select or tune parameter values, how to solve the equations, which input data are used, which decisions to leave to users, which metrics to evaluate their model against; the list of “*the choreography of coded procedures*” (Gramelsberger, 2011) goes on.

The representation of snow in ESMs and snow physics models (hereafter, when combined, referred to as “snow models”) can take on various levels of complexity (here meaning incorporating increasing number of processes) (see e.g. Slater et al., 2001; Largeron et al., 2020). The simplest representation is a soil-snow composite layer in which the top soil layer “becomes” snow by adopting some of its attributes when present e.g. albedo, thermal conductivity. The next complexity level represents a single snow layer where bulk snowpack properties e.g., snow water equivalent (SWE), depth and density, are simulated. Finally, multi-layer snow models usually allow a pre-determined maximum number of snow layers, although some models add snow layers corresponding to each snowfall, with their specific thickness, density and other attributes.

Most multi-layer snow models use a densification model first developed by Anderson (1976), itself based on measurements made by Kojima (1967) in Sapporo and Moshiri, Hokkaido, Japan (hereafter the Anderson-Kojima scheme). The model parameters account for compaction due to the weight of the overlying snow, as

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well as destructive, constructive and melt metamorphism; as such, each layer increases in density with depth. This snow profile broadly resembles the properties associated with montane forest and maritime snow (Sturm and Liston, 2021), but is not appropriate to simulate wind-packed snow and depth-hoar, i.e. what Arctic tundra snowpacks are often almost entirely composed of (Fig. 2). Some snow physics models attempt to simulate explicitly the vapour diffusion that leads to depth hoar formation or the internal snowpack ice layers that commonly occur after rain-on-snow events or the thick ice crust that forms at the surface of the snowpack following freezing rain (e.g. SNOWPACK in Wever et al., 2016 and Jafari et al., 2020; SnowModel in Liston et al., 2020; Crocus in Quéno et al., 2018, Touzeau et al., 2018 and Royer et al., 2021). No ESM, so far, simulates these Arctic snowpack processes, although many in the climate change scientific community consider them critical for understanding changes in Arctic biodiversity, livelihood, permafrost and the global carbon budget (e.g. Zhang et al., 1996; Rennert et al., 2009; Descamps, et a., 2016; Domine et al., 2018; Serreze et al., 2021).

The aim of this study is to understand why decisions made by modellers all over the world and over the past decades have not led to more (or is it "any"?) progress in Arctic snowpack modelling, i.e. in the part of the planet that warms faster than anywhere else. While a systematic literature review would provide some answers, this study takes a different approach, borrowed from Science and Technology Studies (STS), whereby the modellers themselves are part of the investigation into understanding science in the making. We start with the premise that humans are central to the decision-making process when determining model developments and our focus is on understanding the factors that influence these decisions. Therefore, to address our aim, we will investigate the construction of snow models through interviews with the individuals who shape their content and present the results of this investigation in their own words.

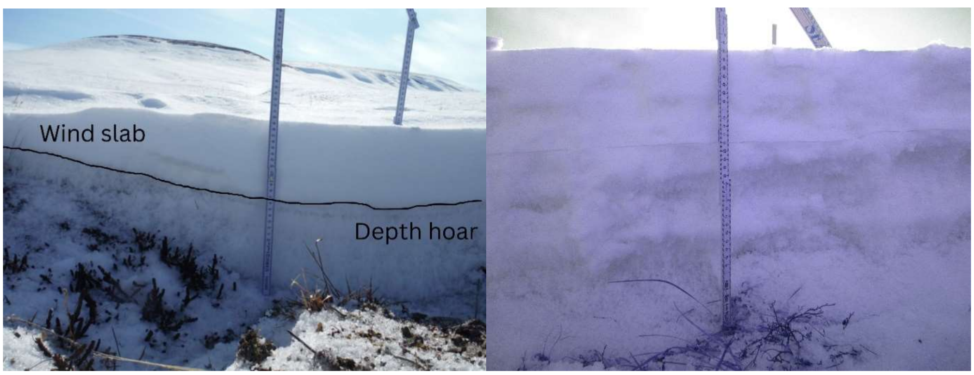

Fig 2. High Arctic snowpack with wind slab over depth hoar, taken on Bylot island on 18 May 2015 by Florent Dominé (left) and near-infrared picture showing a 2 mm ice layer at 26 cm on 16 March 2018 (right). The ice layer on the right was the result of rain on snow on 15 January. Taken at Trail Valley Creek, Canada, by Nick Rutter.

2 Methods

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This study originated from discussions between the first three authors (CM, SR, and IM) who are collaborators on the interdisciplinary project CHARTER, which aims at enhancing the adaptive capacity of Arctic communities to climatic and biodiversity changes (CHARTER, 2023). In these discussions, it became clear that the current snow models fell short in representing all the Arctic snowpack processes needed by project collaborators. CM, SR and IM compiled a shortlist of participants, both within and outside CHARTER, who consider the snowpack structure important for their research. The shortlist initially included three participants in each of the five so-called "expert" groups:

1. Snow modeller collaborators (SMC). Participants with research expertise in Arctic fauna and flora biodiversity.
2. Field scientists (FS). Participants whose field campaigns focus on snow-related processes and whose field work supports the development of remote sensing and snow physics models.
3. Remote sensing scientists (RSS). Participants involved in the development of satellite products or of remote sensing models for snow.
4. Snow physics modellers (SPM). Participants who have developed a snow physics model.
5. Large scale modellers (LSM). Participants with expertise in ESMs, in the land surface component of ESMS, and/or in numerical weather prediction (NWP).

Potential participants were emailed with a request for participation that included a participant information sheet and consent form (see supplementary material); all those contacted accepted to participate. Although the groups were broadly split between stakeholders (SMC, FS and RSS) and snow model developers (SPM and LSM), the expertise classification was somewhat artificial and, as we discovered during some interviews, distinctions between groups were sometimes negligible. For example, all but LSM had extensive field experience. One FS had expertise in Arctic biodiversity, one RSS had been involved in the development of a snow physics model, one SPM had contributed to the development of a land surface model and so on. These overlaps prompted the addition of four more participants to the shortlist for a more comprehensive expertise.

In total, nineteen one-to-one interviews lasting between 40 and 65 minutes took place on Microsoft Teams or Zoom between August 2022 and January 2023. One SMC withdrew from the study shortly after the interview and their data are not used. All interviews, which were conducted by CM, were individual in-depth semi-structured interviews (DiCicco-Bloom and Crabtree, 2006), which means that a set of specific questions and themes were systematically addressed, but other themes that emerged during individual interviews were also discussed. All participants were questioned about why the structure of the snowpack was important in their research and about the representation of Arctic snowpacks in snow models, but the questions differed somewhat between groups to reflect the expertise of the participants. SMC, FS, and RSS were interviewed to understand the diverse applications of Arctic snow (e.g. snow as a habitat, snow as an insulating medium, snow as water resource, snow as a complex microstructure etc) and to evaluate if limitations in snow models constrained their research. Interviews with individual group members followed in sequence (i.e. group 3 after 2 after 1 etc) so that SMC, FS and RSS could suggest questions to SPM and LSM. SPM and LSM were then asked about their decision-making process e.g. how do they prioritise model developments? What are the limitations of their model and how do they affect our understanding of Arctic snow processes? All interviews were video recorded and transcribed. The transcripts were analysed by conducting a thematic analysis (Braun and Clark, 2006;

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Rapley, 2011), which consists in identifying codes (semantic content or latent features in interviews) and collating them into overarching themes. Iterative coding was conducted in NVivo, a qualitative data analysis software that facilitates the classification and analysis of unstructured data. Three iterations were necessary to identify all codes and to classify codes into themes.

Quotes from the interviews are used throughout the paper. As such, a number of editing decisions were made for readability: 1/ speech dysfluency was edited 2/ punctuation was used to replace non-verbal communication 3/ quotes were not attributed to specific groups unless necessary to improve understanding of the context within which they were cited.

Qualitative researchers must declare "*the position they adopt about a research task and its social and political context*" (Holmes, 2020) because it influences both how research is conducted and evaluated (Rowe, 2014). Positionality statements are part of the practice of social researchers and partly serve the purpose of establishing whether they are "insiders" or "outsiders" to the culture under investigation (Holmes, 2020). As qualitative methods were employed to comprehend decision-making processes within a quantitative field, the positions of CM, SR, and IM as either insiders or outsiders in relation to the expertise of the five groups is presented here: CM has been a model developer on snow physics and large scale models. SR and IM have been users of snow physics models. All have conducted winter and summer field work in the Arctic. All have collaborated or currently collaborate closely with all groups represented.

3 Results: Separating the content from context

The working title of this study in the participant information sheet was "*A multi-perspective approach to snow model developments*", thus implicitly alluding to the fact that, by approaching a single issue from multiple angles, this study sought to elicit diverse responses. This certainly turned out to be the case. Most significantly, no opinion was unanimous; every statement made by each participant was contradicted by a statement made by another participant.

By opting for the semi-structured interview format, our aim was to use a medium, the conversation, in which using "I" was natural. While all participants provided important information related to their field – information that is presented in Section 3.1– they also ventured where few scientists do, at least in their publications: they offered opinions. Many were offered cautiously and were grounded in their experience and expertise, others were more personal: *"I'm sick of modelers who think the world is a computer screen", "the scientific community is very conservative, so as soon as you try to change the paradigm, you have outcry and everyone hits each other", "The[se] models spend so much time doing things that aren't very important for lots of applications that they're kind of worthless", "other groups have said we're going to start over, and that is also totally fraught"*. Such open and candid comments do not (usually) make it to publications, but we argue that such statements are a manifestation of the researcher's sense of identity i.e., they "*signal the dynamic interplay over time of personal narratives, values and processes of identification with diverse groups and communities*" (McCune, 2019). These processes of identification are clear in the participants' choice of words which echo McCune's

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(2019) definition: the participant who qualifies the scientific "community" as conservative, distances themselves from this community, as does the other one from "groups" whose strategy they reject. The participants' identity also manifested itself in their interpretation of the Arctic under discussion. There are many definitions of Arctic, some of which are based on the Arctic circle, treeline, climate, permafrost and so on (ACIA, 2005). CM began each interview by describing Arctic snowpack processes absent in existing models, but did not define "Arctic" beyond land snow processes, causing varied interpretations. SMC, FS and RSS, all of whom had extensive field experience, generally defined the type of Arctic they meant when describing a process, even if their description was at times itself open to interpretation: "*proper Arctic*", "*entire Arctic*", "*high Arctic*", "*Canadian Arctic*", "*tundra*", "*sub and low Arctic*", "*Scandinavian Arctic*", "*polar snowpack*", "*Finnish snowpack but not high Arctic*", "*pan Arctic*". Only two SPM and one LSM (out of four in each group) specified what Arctic they meant. We will not attempt to provide a retrospective definition because, despite these different interpretations, all participants knew of processes that snow models cannot represent in "their" Arctic. Examples include rain-on-snow-induced ice layers, which predominantly occur in Fennoscandian oroarctic tundra, or internal snowpack thermal gradients and vapour fluxes, which are more relevant in the high Arctic.

In Section 3.1, we will outline the scientific reasons given by the participants for the lack of development of an Arctic snowpack based on the content of the interviews. In Section 3.2 we will examine the statements that deal with the context in which the participants' research is undertaken. By content we refer to the actual information being communicated, while context refers to the circumstances that help interpreting that content. We will also consider how this context contributes to shaping the participants' research identity, thereby "*bridg[ing] the somewhat artificial dichotomy between the 'professional' and the 'personal'*" (Staddon, 2017).

3.1 Content

3.1.1 Scale, heterogeneity and internal consistency

The most often cited challenges impeding the implementation of an Arctic snowpack in large scale models were related to scale, sub-grid heterogeneity and the interplay of processes within the models. The difficulty in reconciling this triad when prioritizing model developments was captured by one participant: *"[large scale models] try to represent all land processes that are relevant to all around the world for all different problems and snow, of course, is just one of however many processes that we need to be considering*." Therefore, "b*y necessity, you have to make some trade-offs".*

These "*trade-offs*" vary in nature. One trade-off is to rank errors according to the perceived importance of the missing process as per this example: "*the spatial variability of snow depth is so high that with respect to the energy exchange with the soil below, the error that you make if you get your snow depths wrong by a few centimetres is much larger than if you miss an ice layer*". Another trade-off aims to maintain internal consistency in terms of complexity between the modelled processes: "W*hy would I have the perfect snow model and, at the same time, I would simplify clouds?", "I want the model to be of the same degree of complexity in all its domains".* Related to this is the opinion that "*it is undesirable in global models to have regionally specific parameterizations*", as the inclusion of Arctic-specific processes was seen to be by some participants. This argument was countered by others who argued that, in models, solving the Arctic snowpack was not a geographical issue but a physical one: "*the physics doesn't care where it is. [Getting the physics right] should make the model work wherever"*. Finally, the last identified trade-off, which all LSM mentioned, is error compensation. Sometimes modellers know that a parameter *"is completely wrong, but it helps compensate an error in [another process. So] you have that resistance against improving a parametrization because you know that you have the error compensation".*

Issues of scale are further complicated by the fact that some models are being repurposed and operate at scales that they were not intended to. Examples include context-specific models being used at large scale ("*a lot of snow models are being used now in land surface schemes as broadly applicable snow models for all snow climate classes. But, I mean Crocus, it's an avalanche model, right?")* and large scale models increasing their resolution even though *"the physics may not be anymore realistic. It's just a little sexier to be able to say you can run an earth system model globally at 25 kilometers compared to what you used to run so".* Although increasing resolution means that "*processes that were before negligible in are not so much so now*", LSM ranked improving the representation of albedo or of sub-grid heterogeneity due to shading and orography was higher in the priority list than e.g. vapour fluxes.

3.1.2 Data availability

Model developments are supported by and evaluated against observations: "*Everything always start at field site level in terms of testing a new model parameterization*". Participants from all groups (which isn't to say all participants) mentioned that more data were needed to understand the processes typical of an Arctic snowpack formation before being able to implement them in a model: "*we need to be out there when it's really happening*", "*we have very few sites across the Arctic*" so "*it's not easy with the available data. We're looking to the observations people to provide the information on the Arctic snow*".

While the scale at which the models of the participants operate differed, all but one participant identified data gaps as being a limit to model developments. *"If you don't have site data to attribute a process to, it is difficult to defend its implementation. For example, I'm not aware of sites that we could use to tackle wind compaction*". Other participants highlighted the difficulty in parametrizing ice layer formation: "w*hen you find an ice crust in the snow pit, you don't know whether it is from rain on snow or wind compaction*" so "*for starters, you need the precipitation to be right*". While some snow physics models attempt to simulate depth hoar formation (e.g. Crocus in Vionnet et al., 2012; SnowModel in Liston and Elder, 2006; SNOWPACK in Jafari et al. 2020), data against which to evaluate the thermal gradients and vapour transport that contribute to depth hoar formation are limited; to the authors' knowledge only one such dataset, which provides both driving and evaluation data, at a single site exists (Domine et al, 2021 at Bylot Island, Canada). However, "*it's a pretty high bar before something changes in* [large scale models] *based on a bit of experimental work. So, just because we get to show it at one site, that's not going to be good enough. You've got to show it over multiple sites, multiple regions*".

However, there is one area where snow physics models were judged to be lagging behind data availability. Five participants mentioned that the Micro-CT (Heggli et al., 2011), which allows measurements of the 3-D

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snowpack architecture, was a "*step-change*" in understanding internal snowpack properties. "*model[s are trying] to catch up with [the available data] because they now have something which is higher resolution and more objective than people looking through the microscopes handle lenses and trying to measure snow crystals on the grid, which was hugely subjective to compare to*".

3.1.3 The historical development of snow models

Ten participants began the interview by providing some background about snow model developments, using this as a historical justification for Arctic snowpack properties not being included in snow models. For "*the first 30 years,* [snow physics models were] *driven by climate system processes and hydrology, snow for water resources applications*" or *"were designed to understand and predict avalanches*". As for large scale models *"what [they] want to know about polar climate is when it influences where people live. There are people living, of course, in the high latitude, but most of the people live in the mid latitudes*" so "*every parameterization in every [large scale] model was developed for mid latitudes. And some of them work in the Arctic and some of them don't*". The historical legacy of model development impedes the implementation of Arctic-specific processes because the stratigraphy used in the Anderson-Kojima scheme makes it numerically challenging to adapt existing models. *"[Models] are limiting the number of [snow] layers for computational stability and efficiency so they are not respecting the way in which the snow pack is actually built up i.e. in episodic snowfall events, which will form different layers (…) That structure couldn't represent ice layers; it would refreeze meltwater or rain on snow, but in layers that are thicker than you'd observe. With numerical diffusion, these layers would spread out so there won't be a strong density contrast"*. "*Numerically, it's just messy [to simulate the formation of an ice layer] because all of a sudden you have a new layer in the middle of other layers*"

3.2 Context

3.2.1 The scale of needed resources

With the exception of error compensation, which is a numerical exercise, the trade-offs discussed in Section 3.1.1 are only necessary because developments perceived to be most important needed to be prioritized. Prioritisation is only necessary because human, financial and computational resources are limited. "*When I speak to large scale modellers about rain on snow, the feedback is usually 'we are aware that something needs to be done, but we have other priorities and we don't have resources for this'. It's not straightforward.*"

The "*few people called 'academic scientists' [are but] a tiny group among the armies of people who do science"* (Latour, 1979). These "armies" include stakeholders, research government agencies, funders, taxpayers, and others, all capable of influencing funding decisions. While participants generally accepted the competitive nature of funding stoically ("*really good and important science will not always be funded because there's not enough money to go around*"), participants from all groups voiced concerns about the inadequate resources allocated to modelling centers given the high expectations placed on them: "*we have two groups*

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running two different land surface schemes within the same government department on a small budget. That makes no sense", "that just means we're distributing our resources way too thin. Every group is tasked with doing everything - and there's a huge number of things to do in land modelling. (…) *I don't think we're that far off from having a crisis situation. These models desperately need to be modernized."*

Short-termism was also perceived to hinder progress. "*[This government agency] has lots of short term goals. 'I need results for this project in six months'. Developing new tools is not part of the strategy*". In addition, there was a recognition that short-term funding could not support the type of scientific expertise required for model developments "*You need that longevity of funding within one area. I mean, the idea that you're going to create an arctic snow model in a PhD is...?!*". National modelling capabilities *"need a lot more software engineering support to be able to rebuild these models, make them sleek and flexible enough that we actually have the ability to make changes more quickly without causing bugs."*

Limited resources are also the reason why data are not available although they are not the only reason. Most Arctic research is conducted by researchers who are not based in the Arctic, which is a logistical reason why "*the number of detailed measurements in the Arctic during the entire winter season is close to 0*". "*If you want to study alpine snow* [e.g Col de Porte, France, and Davos, Switzerland, which were set-up to support the local tourism industry], *you get out of your home, walk in the field or take your car, drive 15 minutes and you see it. If you want to look at arctic snow, it's more complex".* The nature of this complexity is manifold. Firstly, although no participant mentioned that meteorological instruments are prone to malfunctioning at low temperatures (see e.g. Fig. 3), it was understood to be the implicit reason why some measurements were not available. Secondly, "*we need to find people willing to do this work in total darkness*"; polar nights and harsh winter meteorological conditions make access to Arctic sites difficult, which is why field campaigns often take place in Spring and Summer time. However, "*we need to observe how this happens in the real world. I mean, we certainly have snow pits and we see ice lenses there, but we need to be out there when it's really happening*".

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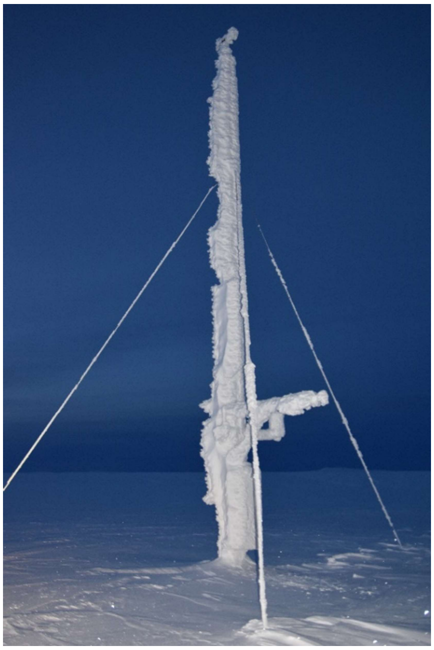

Figure 3: Meteorological station covered with rime before maintenance in Reinhauger, Varanger peninsula, Norway. Photo taken on 23 January 2020 by Jan Erik Knutsen.

3.2.2 Adaptability

Public funding is granted to projects that fall within the strategic objectives and research priorities of government funding agencies. As such, "the right to research" (Henkel, 2005) is conditional upon scientists adapting and responding to an evolving funding landscape. Although much literature argues that there is a conflict between academic freedom and solution-based or applied science (e.g. Henkel, 2005; Winter, 2009; Skea, 2019 etc), we found instead that adaptability and shifting priorities was integral to the participants' identities. "*To some degree, we follow what is being hyped, you know, if something is being hyped in Nature*". Model developments were presented as being responsive and at the service of others: "*There is no master plan. It's opportunity driven, it depends on projects that come in, (…) on what some of the users want to do. It's kind of nice*". When questioned about what the priorities for snow model developments are, one SPM answered "*It's not just the snow modellers who can answer that. It is the people who want to use the snow models".* Arguably, performance-based research funding systems like the UK Research Excellence Framework have been in place long enough in some countries for researchers to have adapted to the constraints of the "publish or perish", "be funded or fade out" and "impact or pack in" culture.

In fact, interdisciplinary collaborations were the key motivation for model development, demonstrating the participants' adaptability. The reasons for interdisciplinary collaborations driving snow model developments were manifold. First, they are necessary to address research questions: "*Permafrost, snow, wildlife biology (…)*

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These fields have evolved independently over the last 30 or 40 years or whatever (...) [Now] we're working together to do a better job of answering all these interdisciplinary questions". Second, they drive innovations in all fields involved: "*if you don't have a good physical snow modelling capability, you can't maximize the value of new [satellite data] retrieval algorithms*". Third, they allow model developments to be relevant to a wide range of stakeholders, as is, for example, the case with progress on the many sectors that rely on numerical weather predictions. Fourth, they generate funding: "*We wouldn't have enough base funding to pay for a master plan [for model developments] so we are depending on projects that come in and on the interest of individual people". Finally, they provide human resources, especially when models are open-source. From the developers' perspective, open-source means that "*the majority of the development work is done external[ly. For example,] for the most recent release, we had 50 people involved from 16 different institutions*"; for the users, it makes models "*easy to use. You can just pick up examples and test the model for yourself (...)*" and "*if something doesn't work or if you have questions, you always find support".*

3.2.3 The anchoring bias

Despite limited or poor Arctic snow process representation, existing snow models serve as a reference point or "anchor" against which to evaluate the potential benefits of investing resources into new developments. Such anchoring is a widely used cognitive strategy that uses "*subjective probability distributions*" to judge uncertainty (Tversky and Kahneman, 1974). Although this strategy is economical, it can lead to systematic errors even amongst experts. We argue that this anchoring contributes largely to the absence of Arctic snow processes in existing models.

Some participants in all but the SMC group argued that many developers misjudged or did not understand the importance of snow when modelling Arctic processes. Four participants stressed the need to design and to implement a long-planned snow model intercomparison project (SnowMIP) focusing on tundra (in both Arctic and Antarctic) snow processes because "*the first thing it would do is alert the modelers to the difficulties that they have in the Arctic that, in the absence of these evaluations, they wouldn't even know about… In my sense, large scale climate modellers aren't sufficiently aware of snow. (...) There are so many people who don't care about that".* At the root of this issue is the modeller's impression of their existing models. A "*model is never perfect, but is it good enough for what is being done with it*?" What is "good enough" is contextual. It depends on the research question to be addressed, on the data, time and funding available, on the extent to which what is expected of the model measures against the anchor. As such, what is "good enough" evolves as the anchor shifts. For one participant, the anchor shifted during the interview: "*I understand now what you [CM] have been talking about, how far we are from what people who live in the Arctic really care about*". Generally, the anchor shifts as a result of community efforts such as model intercomparison projects, which motivate developments because they "*distil the information and tell [modellers] what are the priorities and what are the sites good for. (...) [SnowMIP] brings together observation experts and other models and modellers. We all learn enormously*"; "*the community does a reasonably good job of trying to develop, incrementally, through different research groups*". Nevertheless, as "*models are not [currently] very well tested for the Arctic, it is not easy to*

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know what they do well", anchoring bias plays an important part in the assessment of whether models are *"*good enough" or not.

Anchoring also explains why historical and logistical legacies (as outlined in Section 3.2.1) from models developed over forty to fifty years ago still serve as reasons for not pursuing innovation. Of the ten participants who mentioned historical legacies, only one nuanced this background information by acknowledging that these developments happened *"quite a long time ago"*. One participant reflected that "*you can't change humans as fast as models or techniques*" and because models are developed by humans, models evolve slowly.

Finally, anchoring is at the root of divided opinions about the benefit of starting models from scratch or not, "*but taking into account all the knowledge we had before*", a topic eight participants spontaneously discussed in view of some modelling groups undertaking this task (e.g. IVORI, 2023 and CliMA, 2023, which are ongoing projects developing a novel type of snow and climate model respectively). While the time and effort of such an undertaking were the main causes for concern ("W*ith respect to the new model, what I see is that this quest for purity (...) makes things extremely slow"*; "*the effort of rewriting a climate model [is huge]. I'm not saying it's not worth it (...) but I can understand why people don't do it*"), it is specifically because the participants were weighing the benefit against a reference or anchor point – the existing models – that one concluded that starting from scratch was *"totally fraught because you're probably talking about a five year project to get even close to the capability of what the current models have. And at the moment, who wants to give up their capabilities?*". On the other side of the argument, another participant argued that "*trying to improve the candle did not invent electricity. [For tundra snow], existing snow models, there's one thing to do with them. Trash*". Somewhere in the middle, more nuanced opinions were presented: "*The community should be endorsing IVORI, but there is such a lag between activities like this and the current suite of models, which people use in high impact papers, that we also need to spend time understanding what the limitations are and how we can get some improvement out of these models*".

4 Moving forward

So, what is next? The premise of this study was rooted in the belief that comprehending the cause of a problem– if indeed the absence of an Arctic snowpack is one – provides a foundation for addressing it and recommending ways to move forward. The premise found echoes in this participant's quote:*"[You] should never keep doing what you're doing because that's the way it's always been done. (...) What are the priorities? What do we need to learn? What do we need to do that's new?*". In this study, continuing the use of snow models originally developed for alpine snow represents "*doing what you're doing because that's the way it's always been done*", while creating code suitable for Arctic snowpack processes embodies "*what we need to do that is new*." Sections 3.1. and 3.2 showed that the answers to "*What are the priorities?"* and *"What do we need to learn?"* depended on the participants' disciplinary expertise as well as many, sometimes conflicting, opinions and perspectives. In this section, we aim not to reconcile these opinions, but to identify what we *should keep doing* and propose what we *should start doing.*

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4.1 Opening-up research

As mentioned in Section 2, SMC, FS, and RSS were interviewed to provide a broad picture of the range of Arctic snow applications and to understand how the absence of an Arctic snow model constrained their own research. We argue that efforts to represent Arctic snowpack processes would pave the way in the research areas highlighted below for new interdisciplinary collaborations, yielding benefits such as innovation, stakeholder involvement and funding (as per Section 3.2.2):

<u>Permafrost-carbon feedback</u>. "*Snow is a kind of blind spot in the international climate modelling community. We know that snow is wrong, but people are not coordinated, people are not really working together*". "*At the moment, snow structure is not considered for permafrost modelling. It's only how thick the snow is and whether the temperature decouples from the ground or not*". Participants from all groups highlighted the importance of snowpack structure to understand soil winter processes. "*It's clear that the winter climate is changing even more than the summer climate*". For example, "*when there is rain-on-snow, the short-term warming to the ground influences the entire following winter history. What is the magnitude of the impact? Knowing the temperature at the base of the snow is the really crucial information*". One participant stressed the importance of upscaling the many *in situ* soil experiments with the help of suitable snow models: "*What manipulation experiments show is that whether we have less snow, or shorter winters or we have ice layers or something else will have very different, even opposite, effects on soil processes, gas exchanges, plant and soil ecology. (…) For example, when you have ice layers, the ice is disturbing the gas exchange between the soil and atmosphere, but it's still active (…) [so] you get carbon dioxide accumulation. We also found that soil microbes are resilient to late snowpack formation and earlier melt, but the growing season started earlier than usual. (…) [What we now need] is to translate the results of that experiment to larger landscape level.*"

<u>Arctic food webs</u> Upscaling is also needed to translate local scale findings to ecosystem scale when investigating fauna biodiversity. "*When the snow gets very hard [e.g. after a ROS event or refreezing], lemmings don't move as well through the snow; they cannot access their food anymore and then they starve (…) [Many] specialized Arctic predators depend on lemmings to survive (…) or to reproduce successfully [e.g. snowy owls, pomarine skuas, Arctic foxes]. (…) They also eat a lot and influence the vegetation (…) If a snow model could reconstitute the snowpack in a reliable way, we could see if there a relationship at the large scale between cyclic lemming populations and snow conditions? (…) and address a row of other ecological hypotheses*".

<u>Reindeer husbandry</u> For reindeer herders, obtaining near real time spatial information on the structure of the snowpack could save their livelihood and their lifestyle: "*During the winters of 2020 and 2021, we had thawing, raining and refreezing in January and there was already a lot of moisture at the ground from the previous Fall. So the reindeer have to dig through all that and then there's a layer of ice on the ground. The lichens, blueberries, everything is encased in ice. So there's two options. They starve or they short circuit their digestive system because they eat the ice-encrusted vegetation get too much of water in their rumen. The Sami herders say that kills the animal anyway. (…) If the herders could get a heads up (…) Can I go move my herd? East. West. Where is soft snow?*"

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Remote sensing applications Remote sensing products are used to tackle many environmental issues, including the three described in this section and their development is intrinsically linked with physically-based models. "*Remote sensing doesn't work everywhere all the time so we need to combine information from a model and from satellite data. We need to improve the physical snow models, but in step with developing the remote sensing. If you do one without the other then you're not gonna be able to maximize the value of both*". For example, "*snow has a confusing effect on retrieval estimates. Some of the signal comes from the atmosphere [e.g. clouds], some comes from the snow, and if you can't disentangle what comes from what then you just throw away millions of satellite data that could potentially be used for numerical weather prediction, better weather forecasts*".

4.2 Snow model intercomparison projects

The Earth System Modelling – SnowMIP (ESM-SnowMIP; Krinner et al, 2018), the fourth snow model intercomparison in 24 years (Slater et al, 2001; Etchevers et, 2004; Essery et al., 2004; Rutter et al, 2009; Essery et al., 2009) is a community effort that aims to evaluate snow schemes in ESMs and to improve our understanding of snow-related feedback in the Earth System. Out of the ten planned exercises, the evaluation of models against in situ data is the only one to have taken place so far. During the first exercise, little progress in snow models was found to have occurred since the previous snow MIPs (Menard et al., 2021) because of scientific reasons as well as contextual circumstances that resonate with the findings in this study. In addition, the next planned phase, which aims to test models in the tundra, has suffered a number of setbacks, not least because *"the models are not very well tested for the Arctic so it is not easy to know what they do well and it's not easy to ask that question with the available data"*. In line with discussions about responsible modelling in other sectors (e.g. Saltelli et al., 2020; Nabavi, 2022), we argue that by involving stakeholders (e.g as represented here by SMC, FS and RSS) in future snow MIPs, the models would be better prepared to tackle research questions that currently remain unanswered (although there have been attempts to do so with the existing models), thereby unlocking opportunities in new research domains and motivate the collection of the new type of data needed to test models in the Arctic. The research questions identified in Section 4.1 should contribute to determining the focus of the next snow MIP rather than the next snow MIP determining what questions can be answered given the current modelling constraints, the latter approach failing to challenge the notion that existing models are "good enough".

Another consideration would be the type of output expected from a tundra SnowMIP. In the past, SnowMIP participants were required to provide model results. However, if a tundra SnowMIP is to advance snow modelling, the obstacles described in Section 3.1 that limit the implementation of Artic tundra snow processes, e.g. the numerical legacies of the Anderson-Kojima scheme, should be directly addressed. Although modularisation was not mentioned by participants within a SnowMIP context, two participants suggested that, moving forward, "*shareable modules would be strategies that would allow us to make better progress"* because *"it will be easier for people to take your parameterization, take your model compartment and put it in their model to see what it does*". Therefore, we argue that future snow MIPs should endorse sharing of code, results

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and configuration files, to avoid duplication of efforts and to accelerate the model developments required to tackle Arctic snow challenges.

Nevertheless, Menard et al. (2021) identified contextual factors (e.g. poor model documentation, lack of motivation, workload) that hindered the first ESM-SnowMIP exercise. Unless the context in which MIPs, SnowMIP and otherwise, operate is not reconsidered, the same factors will continue hindering community efforts. "*A modelling center doesn't get money to do a MIP, but they want to do it because it's important to them. So, they end up being involved, but they get MIP-saturated and that's when the errors arise (…) At the very least, future SnowMIP-like projects need dedicated people whose main responsibility is to take this on, to say 'I have funding to do it, I can dedicate time to it*'".

4.3 Values and positionality

Models are not only the representation of a situation, but also the product of many socio-political interactions (Nabavi, 2022). Even when models lack core government funding, their ability to secure competitive funding underscores their alignment with strategic research priorities that often reflect political agendas. Heymann and Dahan Dalmedico (2019) argued that the IPCC ushered in a new era of expertise in which scientists are conditioned and formalized by politically relevant issues. As architects of ESMs, this implies that modellers become vehicles for political agendas. The IPCC WG1 AR6 Ch. 1 (Chen et al., 2021) recognises that values, defined as "*fundamental attitudes about what is important, good, and right*", play a critical role in climate science by influencing the construction and assessment of, and communication throughout the research process. Values are another construct to a researcher's identity, but the prevailing notion linking value-free science with objectivity and impartiality (Pulkkinen et al., 2021) presents obstacles to achieving greater transparency in bridging the gap between our personal identities and our professional decisions.

Participants in this study have provided various reasons for not having prioritised the development of an Arctic snowpack model: data availability, historical context, human resources, lack of funding, competing research priorities, strategic priorities of government agencies and so on. This undeniably places their decision-making within a social and political context that warrants more transparency in revealing their position within these contexts. Following Bourdieu (2001) who argued that scientists should not take a position without acknowledging that they are doing so, we argue that natural scientists should, as do social scientists (see Section 2), position themselves as "insiders" and "outsiders" within the context of the research they conduct and publish. "Coming clean" (Lincoln, 1995) about our positionality in our publications would contribute to responsible research and to the ongoing discussion about the role of values in climate science. We also believe that it would improve the reviewing process and help avoid the type of bad practice describe by these participants: "*Some papers will say in just one or two sentences 'well the snow profile is probably uncertain but' etc... They don't make the effort to quantify what the sensitivity of their key result is to how snow is characterized by the model. It's a flaw in the review system that these papers don't go to somebody who has real expertise in snow. (…) And they often don't because if you're talking about carbon budgets across the Arctic for over 12 months seasonal cycle, it always goes towards the growing season community (…). So [these papers]*

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don't get scrutinized the way they should so"; "*Some users of [our model], they probably don't know what they're doing, and sometimes a paper comes where I say ???"*

Finally, a "*unique practice of sensitive wording*" (Gramelsberger et al., 2020) was developed in climate science to describe the information produced by climate models. This practice satisfies the socio-political expectations of climate science to produce trusted information in decision-making, as well as acting as a barrier to accidental or intentional misinterpretation of the same information by climate deniers. An example of such sensitive wording is the "likelihood language" to describe scientific uncertainties (Landström, 2017; Moss & Schneider, 2000). We suggest that another instance of sensitive wording is the separation between the model and the modeller, which contributes to presenting the information produced as objective and impartial. For example, the IPCC WG1 AR6 mentions "*model(s)*" 12666 times, but "*modeller(s)*" three times. Such wording is invisibilising the role of modellers in the decision-making process of model development and evaluation, and arguably, in some of the information produced in climate science.

Yet, models are a product of one or multiple modelers' vision. This was reflected in the interviews during which many participants often mentioned the name of the model creator or lead developer instead of, or as well as, the model's name. The research identity of many modellers is, whether they want it or not, intertwined with their model; inviting authors to reflect about their positionality would allow modelers to regain control over their own narrative and research identity.

5 Conclusion

As per more conventional review papers, the novelty in this paper is not in its content, but in the medium it chooses to present that content. What participants said, they had said, but not necessarily written, it before. Conferences, workshops, meetings and end-of-day visits to more informal venues are places where disagreements about the limits and motivations to model development *are* debated. But while the written history narrated by our publications does record the arguments presented here in the content section, it does not record what is presented in the context section.

In fact, the medium is not novel either. Science and technology studies examine the context within which science is constructed and much of what is non-Arctic snowpack-specific could probably be found in Genesis and Development of a Scientific Fact (Fleck, 1935) and in The Structure of Scientific Revolutions (Kuhn, 1962), two of the seminal books in STS. However, although one of the participants directly quotes one of Kuhn's concepts when they advocate for a change in paradigm, STS is practiced by outsiders looking in on a field. This position hinders the dissemination of their findings to, and the acceptance of their recommendation by, insiders.

Therefore, the novelty here is that it is an insider's job. It is a reflective exercise which, we hope, will be the start rather than the end point of the conversation. The comments of the participants-turned-co-authors at the paper writing stage certainly suggested so much: '"*it's interesting that nobody commented on the conventional wisdom that modelling tundra snow is "too hard"?*'; "*discussions about digital Earth twins are shaking the [LSM] community. Some suggest that many resources, on continental or even global level, should be bundled to*

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create the *one big model. Others think this is a recipe for disaster, and some that is "scientific colonialism'"*; "*the next step in modelling should be an evolutionary one: we should take the best of each*".

The participants were interviewed in their role (or identity) as researchers, but all will have been reviewers of papers and grants, some (co-)editors of journals and some will have influenced policy-makers. We argue that it is our role as insiders to motivate the change to our own practice. We also argue that it is our role as researchers to be more transparent about the contextual factors that influence and restrict our decisions. More importantly, it is our role as reviewers, editors and policy-makers to allow for such transparency to happen and to challenge openly the idea that short-term funding can lead to ground-breaking science, that Arctic data can be collected without engaging the people who live there, that 40-year old models are good enough to tackle challenges we knew nothing about ten years ago. If we fail to take on these roles, the reality of our scientific process will remain invisible and silent, and by virtue of it being hidden, unchanged.

6 Code / data availability

The transcripts are not available as they contain sensitive and personal information.

7 Author contribution

CM, SR and IM conceptualised the research. CM conducted the interviews and analysed the data. CM prepared the original draft with contributions from SR and IM. All other co-authors were interviewed for the research and contributed to the final version of the manuscript.

8 Competing interests

At least one of the (co-)authors is a member of the editorial board of The Cryosphere.

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