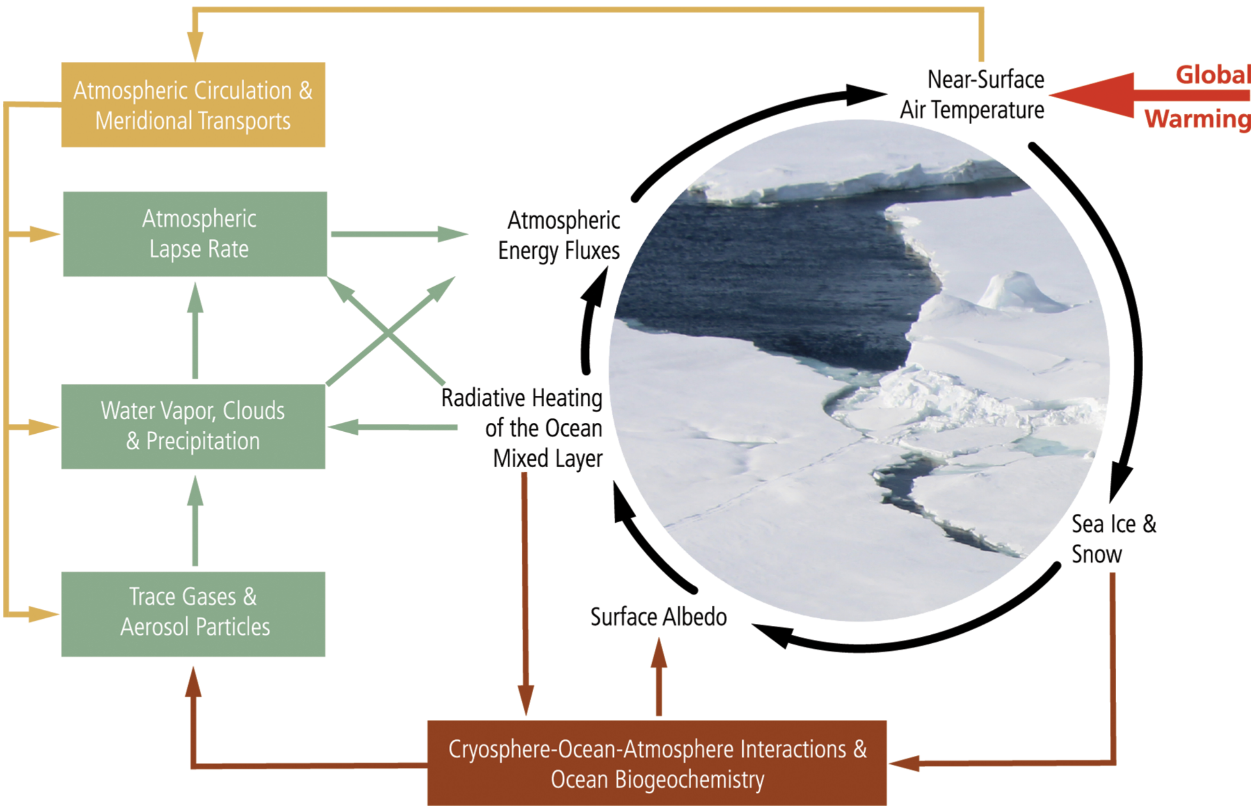
Key messages from "Atmospheric and Surface Processes, and Feedback Mechanisms Determining Arctic Amplification: A Review of First Results and Prospects of the (AC)^3 Project," by **M. Wendisch (Universität Leipzig), M. Brückner, S. Crewell, A. Ehrlich, J. Notholt, C. Lüpkes, A. Macke, J. P. Burrows, A. Rinke, J. Quaas, M. Maturilli, V. Schemann, M. D. Shupe, E. F. Akansu, C. Barrientos-Velasco, K. Bärfuss, A.-M. Blechschmidt, K. Block, I. Bougoudis, H. Bozem, C. Böckmann, A. Bracher, H. Bresson, L. Bretschneider, M. Buschmann, D. G. Chechin, J. Chylik, S. Dahlke, H. Deneke, K. Dethloff, T. Donth, W. Dorn, R. Dupuy, K. Ebell, U. Egerer, R. Engelmann, O. Eppers, R. Gerdes, R. Gierens, I. V. Gorodetskaya, M. Gottschalk, H. Griesche, V. M. Gryanik, D. Handorf, B. Harm-Altstädter, J. Hartmann, M. Hartmann, B. Heinold, A. Herber, H. Herrmann, G. Heygster, I. Höschel, Z. Hofmann, J. Hölemann, A. Hünerbein, S. Jafariserajehlou, E. Jäkel, C. Jacobi, M. Janout, F. Jansen, O. Jourdan, Z. Jurányi, H. Kalesse-Los, T. Kanzow, R. Käthner, L. L. Kliesch, M. Klingebiel, E. M. Knudsen, T. Kovács, W. Körtke, D. Krampe, J. Kretzschmar, D. Kreyling, B. Kulla, D. Kunkel, A. Lampert, M. Lauer, L. Lelli, A. von Lerber, O. Linke, U. Löhnert, M. Lonardi, S. N. Losa, M. Losch, M. Maahn, M. Mech, L. Mei, S. Mertes, E. Metzner, D. Mewes, J. Michaelis, G. Mioche, M. Moser, K. Nakoudi, R. Neggers, R. Neuber, T. Nomokonova, J. Oelker, I. Papakonstantinou-Presvelou, F. Pätzold, V. Pefanis, C. Pohl, M. van Pinxteren, A. Radovan, M. Rhein, M. Rex, A. Richter, N. Risse, C. Ritter, P. Rostosky, V. V. Rozanov, E. Ruiz Donoso, P. Saavedra Garfias, M. Salzmann, J. Schacht, M. Schäfer, J. Schneider, N. Schnierstein, P. Seifert, S. Seo, H. Siebert, M. A. Soppa, G. Spreen, I. S. Stachlewska, J. Stapf, F. Stratmann, I. Tegen, C. Viceto, C. Voigt, M. Vountas, A. Walbröl, M. Walter, B. Wehner, H. Wex, S. Willmes, M. Zanatta, and S. Zeppenfeld**. Published online in *BAMS*, January 2023. For the full, citable article, see **https://doi.org/10.1175/BAMS-D-21-0218.1**.

Climate Change Amplified

Unraveling Intertwined Processes and Feedbacks in the Arctic's Sensitive Climate System

Human-induced global warming reached approximately 1 K above preindustrial levels in 2017. However, the Arctic stands out as a real "hot spot" of the global climate. Observations have shown a particularly enhanced increase of the near-surface air temperature in the Arctic progressing almost four times faster than the global warming of the last 40–50 years. Unfortunately, this excessive warming is mostly underestimated by state-of-the-art climate models. Another prominent sign of currently ongoing drastic Arctic climate changes is the unprecedented decline of Arctic sea ice observed since about 1970, which appeared greater than expected from simulations. Arctic sea ice cover at the end of summer has halved over the last 40 years. In addition, it is believed that Arctic climate changes intensify midlatitude weather extremes, such



The (AC)³ simplified schematic of important local and remote processes and feedback mechanisms driving Arctic amplification. The figure illustrates the initial trigger by global warming (red), and shows examples of processes/feedback mechanisms such as surface albedo feedback (black), upper-ocean effects (brown), local atmospheric processes (green), and Arctic–midlatitude linkages (yellow).

as extended and severe cold spells and heat waves in North America and Europe. Overall, these and further observed Arctic climate changes indicate amplifying effects caused by Arctic-specific local and remote processes and feedback mechanisms, which are referred to as Arctic amplification.

Mechanisms behind Arctic amplification are widely explored and discussed in the literature, but typically through a piecemeal approach of individual research studies. Instead, the (AC)³ project, which was established in 2016, uniquely aims at a comprehensive and cross-cutting approach to unravel the details of Arctic amplification. The project is intended as a 12-year effort and comprises extensive observational and data analysis work, closely combined with modeling elements. The research within (AC)³ is based on a new, simplified scheme exemplifying intertwined processes contributing significantly to Arctic amplification. Key elements of the scheme include the initial triggering by global warming, surface albedo feedback, upper-ocean effects, and atmospheric processes as well as Arctic—midlatitude linkages.

So far, (AC)³ has assembled a wealth of high-quality ground-based, airborne, shipborne, and satellite data on physical and chemical properties of the Arctic atmosphere, cryosphere, and upper ocean. The international Arctic research community is invited to use these freely accessible data.

Within (AC)³, several short-term changes and indications of long-term trends in Arctic climate parameters have been revealed. For example, a distinct atmospheric moistening, an increase of regional storm activity, an amplified winter warming in the Svalbard and North Pole regions, a multidecadal trend toward brighter and more liquid water clouds, a decrease of sea ice thickness in the Fram Strait, and a decrease of snow depth on sea ice have been detected. Local marine/biogenic sources of cloud condensation nuclei (CCN) and ice nucleating particles (INPs) were found.

Furthermore, an enhanced process understanding has been achieved. For example, surface albedo–cloud interactions were identified as an influential component driving cloud radiative effects. A four-mode structure—instead of the common two modes—of the surface radiative energy budget was revealed based on observations, and this structure was sufficiently reproduced by the Icosahedral nonhydrostatic (ICON) weather forecast model of the German Weather Service. The presence of cloud layers above the dominant boundary layer clouds was found to significantly impact the lower cloud by damping cloud top cooling and turbulent fluxes. The quantitative impact of black carbon (BC) on radiative forcing in the Arctic during polar daytime has been quantified. A seasonal variation of INP and BC concentrations and indications for both terrestrial and marine/biogenic INP sources have been found. Marine/biological particles within the upper ocean have been shown to significantly absorb solar radiation and, thus, to contribute to warming of the ocean mixed layer. The vertical atmospheric stability has been shown to determine the coupling of the surface with cloud processes, while humidity may feed clouds from below and/or above. A quasi-Lagrangian observational strategy to investigate air mass transformations during meridional transport has been applied successfully during the HALO–(AC)³ airborne campaign.

The exploitation of observational data has led to improved parameterizations that have been implemented in various models. To improve the model representation of the surface albedo feedback, models have been equipped with new sea ice albedo parameterizations derived from field measurements, which also consider the dependence of surface albedo on cloud properties. Furthermore, revised parameterizations of convective plumes and related processes over leads of different widths have been established. Turbulent energy flux parameterizations for very stable surface layers using Monin-Obukhov similarity theory stability functions have led to an improved reproduction of transfer coefficients in the very stable surface layer. Systematic comparisons of simulations with measurements have revealed further open issues in models. For example, the cloud droplet activation scheme of ICON was revised, scaling the default CCN profile, representative for a more polluted atmosphere, to be in better agreement with actually observed CCN concentrations and, furthermore, by using a representation of the turbulence impact on cloud-scale updraft speeds.

For the next four years we are planning three dedicated observational campaigns for very specific topics. Apart from that, we will concentrate on the analysis of existing data. In particular, we will focus on the detailed analysis of the international Multi-disciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition and the HALO–(AC)³ campaign. These two field studies have employed unique measurement systems and, thus, have extended spatial and temporal scales beyond previous levels. We will continue to analyze the collected ground-based, ship-based, and airborne measurements in close collaboration with satellite and modeling activities building mostly on the ICON model family. We will use a hierarchy of ICON configurations that covers a broad range of scales, including micro-, meso-, regional, and up to global scales. The model results will allow us to gain insight into the processes driving Arctic amplification at multiple levels, from individual processes to global responses. In parallel, satellite studies will continue to provide local-to-regional-scale observations of the Arctic. This will deliver data for comparison with the higher (but still sparse) spatial resolution of the aircraft measurements. Putting more and more pieces of the Arctic climate puzzle together will enable $(AC)^3$ to achieve major advances in our understanding of the causes and effects of Arctic amplification, and in projecting its future development.

METADATA

BAMS: What would you like readers to learn from this article?

M. Wendisch (Universität Leipzig): *The Arctic is a special place. On the one hand, effects of global warming are strongly amplified in the Arctic compared to the rest of the globe, and therefore appear more distinct and obvious in observations. Thus, we would be inclined to assume the Arctic as kind of an easy-to-handle natural laboratory, where we can simply try out different cause–effect scenarios. However, this hope is not fulfilled because numerous processes and feedback mechanisms that are closely intertwined take place in parallel in the Arctic, which makes it very hard to clearly disentangle the individual causal chains. Everything is influenced by everything. The only chance to sort out individual processes is to combine measurements and simulations, which are both equally important. Without models, we cannot project the future evolution of Arctic amplification, which is our ultimate goal. Without measurements, we cannot control and check if the model results appropriately reproduce reality. Therefore, we need to go out into the field, into the Arctic. This is challenging and costly, but there is no way around it. And you need to involve the modelers in the planning and actual performing of the field observations. They should realize what is possible to do in the harsh conditions of the Arctic, and then they will know what observations they can actually make use of in the models. Teamwork between observational people and modelers is crucial!*

BAMS: How did you become interested in the topic of this article?

MW: *Our research group at Leipzig University has been involved in Arctic research for almost 20 years. We were (and still are) fascinated by the exciting and gorgeous landscape of the Arctic and are impressed by the power and drama of the currently ongoing Arctic climate changes. There are so many secrets still to be solved up there in the North, a dream for a scientist. As a small group, we focused on airborne measurements and accompanying radiative transfer simulations. We soon realized that this approach is way too narrow. To reveal the reasons for Arctic amplification, which started to become an obvious sign of Arctic climate changes around 2000, it became more and more evident that we would need a much broader approach and a much larger team with experienced scientists in several branches of Arctic research. Therefore, roughly 10 years ago, we decided to form a group of smart Arctic researchers within Germany and jointly applied for the $(AC)^3$ project. $(AC)^3$ became a Transregional Collaborative Research Center funded by our German Research Foundation (DFG) that includes a powerful team of three universities (Cologne, Bremen, Leipzig) and two non-university institutes (Alfred Wegener Institute Bremerhaven/Potsdam and Leibniz Institute for Tropospheric Research in Leipzig) to tackle the issue of Arctic amplification. The group includes both observational specialists and modelers. After approval of the proposal, we started in 2016. Currently, we are in the process of submitting the proposal for phase III of $(AC)^3$ that, if funded, would enable us to continue our research for four more years (2024–27). Our article describes what we did so far and intend to do in the years to come in the framework of $(AC)^3$.*

BAMS: What surprised you the most about the work you document in this article?

MW: *The fact that the surface (sea ice or open-ocean water) plays such a prominent role in most of the processes and feedbacks determining the Arctic climate system. It is the surface albedo, emissivity, and numerous interactions between the upper ocean layer and the atmosphere that are decisive for many processes.*

BAMS: What was the biggest challenge you encountered while doing this work?

MW: *Covid complicated our field work in the Arctic and the cooperation of the project collaborators heavily. The $(AC)^3$ consortium consists of 30–35 Ph.D. students, about 10 postdocs, and 35 principle investigators. For such a big crowd, communication is key. And this was greatly hampered during the pandemic.*