Introduction of the Transregional Collaborative Research Center TR 172: Arctic Amplification

M. Wendisch[+)], M. Brückner[+)], J. P. Burrows[*)], S. Crewell[#)], K. Dethloff[-)], K. Ebell[#)], Ch. Lüpkes[--)], A. Macke[°)], J. Notholt[*)], J. Quaas[+)], A. Rinke[-)], I. Tegen[°)]

[+)] Leipzig Institute for Meteorology, Stephanstr. 3, 04103 Leipzig, E-Mail: mbrueck@rz.uni-leipzig.de
[*)] Institute of Environmental Physics, Otto-Hahn-Allee 1, 28359 Bremen)
[#)] Institute for Geophysics and Meteorology, Pohligstr. 3, 50969 Cologne)
[-)] Alfred-Wegener-Institute for Polar and Marine Research – Potsdam, Telegrafenberg A43, 14473 Potsdam)
[--)] Alfred-Wegener-Institute for Polar and Marine Research – Bremerhaven, Am Handelshafen 12, 27570 Bremerhaven)
[°)] Leibniz Institute for Tropospheric Research, Permoserstr. 15, 04318 Leipzig)

Summary: A new German research consortium is investigating the causes and effects of the rapid rise of near-surface air temperatures in the Artic. Within the last 25 years a remarkable increase of the Arctic near-surface air temperature exceeding the global warming by a factor of two to three has been observed. The phenomenon is commonly referred to as Arctic Amplification. The warming results in rather drastic changes of a variety of climate parameters. For example, the Arctic sea ice has declined significantly. This ice retreat has been well identified by satellite measurements. However, coupled regional and global climate models still fail to reproduce it adequately; they tend to systematically underestimate the observed sea ice decline. This model-observation difference implies that the underlying physical processes and feedback mechanisms are not appropriately represented in Arctic climate models. Thus, the predictions of these models are also likely to be inadequate. It is mandatory to identify the origin of this disagreement.

Zusammenfassung: Ein neu geschaffenes deutsches Forschungskonsortium untersucht die Ursachen und Effekte des rapiden Anstiegs der bodennahen Lufttemperatur in der Arktis. Innerhalb der letzten 25 Jahre wurde ein bemerkenswerter Anstieg der Bodenlufttemperatur in der Arktis beobachtet, welcher die globale Erwärmung um den Faktor 2 bis 3 übersteigt. Dieses Phänomen wird als arktische Verstärkung bezeichnet. Diese Erwärmung resultiert vielmehr in einer drastischen Änderung einer Vielzahl von Klimarparametern. Beispielsweise ist das arktische Meereis deutlich zurückgegangen. Dieser Eisrückgang wurde durch Satellitenbeobachtungen gut beobachtet. Dagegen haben regionale und globale Klimamodelle immer noch Probleme, den Rückgang entsprechend zu reproduzieren. Sie tendieren dazu, den Meereisrückgang systematisch zu unterschätzen. Die Unterschiede zwischen Modell und Beobachtungen legen nahe, dass die grundlegenden physikalischen Prozesse und Rückkopplungsmechanismen nicht

entsprechend in arktischen Klimamodellen repräsentiert werden. Somit sind wahrscheinlich auch die Vorhersagen der Modelle unzureichend. Es ist notwendig, den Ursprung dieser Unstimmigkeit zu identifizieren.

1. Introduction

Parts of this paper were published in *Wendisch et al., 2017*. For meteorologists and climate scientists, the Arctic is one of the most interesting regions on Earth. Here, climate changes currently take place at an unprecedented pace and intensity, and the reported dramatic changes have not been completely anticipated. The Arctic is warming more rapidly than the rest of the world, a process referred to as the Arctic Amplification.

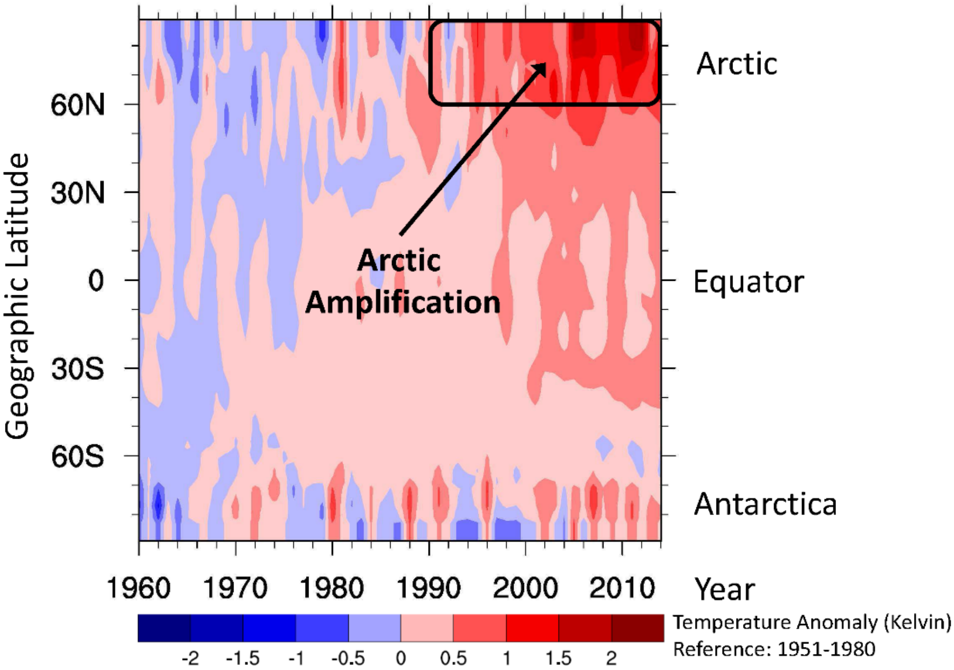

Fig. 1: Mean temperatures (by location and year, measured in Kelvins), shown as deviations from 1951–1980 mean temperatures. The increase in red areas in more recent years indicates global warming. The area inside the black box shows how this warming is amplified in the Arctic. The data have been provided by the NASA Goddard Institute for Space Studies.

Over the past 25 years, scientists have observed a remarkable increase of near-surface air temperatures, which exceeds the global warming by a factor of 2 to 3 (Figure 1). To find out why this is happening, in January 2016 the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) launched a new Transregional Collaborative Research Center (TR 172) called "Arctic Amplification: Climate Relevant Atmospheric and Surface Processes, and Feedback Mechanisms."

This effort, known by the abbreviation $(AC)^3$, has as its overarching scientific objectives the identification, investigation, and evaluation of key processes involved in Arctic Amplification; improving the understanding of the major feedback mechanisms; and quantifying the relative importance of these mechanisms.

Our current understanding of the rapid changes in the Arctic climate implies that atmospheric processes likely dominate the short-term warming mechanisms involved. Thus, research in (AC)³ has an atmospheric focus during its Phase I, which was approved to obtain funding by DFG from January 2016 to December 2019. In Phases II and III the researchers of TR 172 plan to investigate the interactions between oceanic and atmospheric components more thoroughly.

The project is organized in 5 project Cluster. Project Cluster A characterizes the fluxes of energy in the Arctic boundary layer, while Cluster B investigates clouds, aerosol particles, and water vapour. Cluster C addresses surface-atmosphere interactions and processes. Large-scale atmospheric circulation patterns and transport are investigated in Cluster D. Project Cluster E aims to synthesizing and synergistically combining the observation analyses of Clusters A-D by linking the results of observations and simulations. Altogether, the project consists of 19 individual sub-projects..

2. Recent Arctic Climate Changes

As a consequence of the recent drastic warming in the Arctic, other climate variables will also be affected dramatically [*Serreze and Barry*, 2011]. For example, routine satellite measurements have documented an enormous decline in the extent of the Arctic sea ice, which is even more than models predicted [*Stroeve et al.*, 2012; *Jeffries et al.*, 2013]. The past nine years of satellite data have revealed the six smallest annual minima of sea ice extent since appropriate and reliable satellite observations began in 1979. The recent decline is larger than any observed in more than 1400 years [*Kinnard et al.*, 2011]. Climate models predict that the summer Arctic sea ice may completely vanish by the end of the 21st century or earlier.

Not only is the Arctic sea ice extent shrinking, but so is its thickness [*Lindsay and Schweiger*, 2015]. The reduced summer sea ice in the Arctic results in larger areas of thinner first-year ice forming during the subsequent winters. The average thinning of the Arctic sea ice causes a higher transmission of solar radiation into the ocean and enhanced heat energy fluxes from the ocean to the atmosphere. It also accelerates transpolar ice drift, a migration of ice from Russia's Siberian coast across the Arctic basin, resulting in an increased export of sea ice into the North Atlantic off the eastern coast of Greenland. The thinner sea ice is also more vulnerable to storms like the major Arctic cyclone in summer 2012.

The extent of the summer snow cover in both Eurasia and North America reached a record low in June 2012 [*Shi et al.*, 2013]. In contrast, autumn snow cover over Eurasia has tended to increase in recent years, enhancing the strength of the Siberian high-pressure system during winter. This change in snow cover strongly affected the surface albedo of the Arctic land areas, the length of the growing season, the timing and dynamics of spring river runoff, the thawing of permafrost, and the wildlife population.

A continued amplified warming in the Arctic is also expected to decrease the temperature gradient between the Arctic and midlatitudes, which is supposed to influence the meandering of the polar jet stream and wind patterns [*Walsh*, 2014]. Consequently, this might increase the probability of extreme weather events in the midlatitudes, including colder winters and summer heat waves.

3. Models have Room for Improvement

Unfortunately, coupled regional and global climate models do not yet unambiguously reproduce the recent drastic changes of Arctic climate parameters. For example, they systematically underestimate the decline of observed sea ice extent. These significant differences between models and observations imply that the climate models do not adequately describe the underlying physical processes and feedback mechanisms in the Arctic. As a result, the projections from these models are also likely to be inadequate and not yet fit for use.

As human influence on climate increases, more significant and potentially drastic climate changes in the Arctic are likely, although the accuracy of current projections is uncertain. These changes will have perceptible socioeconomic and ecological consequences for marine transportation, fisheries, ecosystems and ecosystem services, and tourism, as well as for oil, gas, and mineral exploration. It is thus a matter of urgency to qualitatively and quantitatively improve our knowledge of the Arctic climate system and the accuracy of its prediction.

4. How the Arctic is Unusual

The Arctic climate exhibits many unique features. For example, the sun does not rise high over the horizon, and seasonal variations in daylight are extreme (polar day and night). Bright ice and snow cover provide a highly reflective surface, low-level mixed-phase (water and ice) clouds are quite frequent, and the prevailing atmospheric boundary layer is specially shallow in the Arctic. These special characteristics profoundly influence physical and biogeochemical processes and atmospheric composition, as well as meteorological and surface parameters in the Arctic.

Several feedback mechanisms are particularly effective in the Arctic, and these generally increase the sensitivity of the Arctic climate system (Figure 2). The most famous and already well-studied feedback mechanism is the surface albedo effect, which reinforces warming over highly reflecting surfaces worldwide but is amplified even more in the Arctic. The increased near-surface air temperature causes a melting of the sea ice and snow cover. This reduced coverage, in turn, exposes less reflective surfaces, including open seawater, bare ground, and vegetated land. The less reflective surfaces absorb more solar radiation, which warm the land surface and the upper oceanic mixing layer, enhancing the energy fluxes from the surface to the atmosphere, which increases the near-surface air temperature even further.

The surface albedo effect amplifies global warming in the Arctic, and other changes might intensify this warming even further. Such changes include meridional (north–south, or vice versa) atmospheric and oceanic mass transport processes and related modifications of vertical turbulent exchange of energy between the ocean and the atmosphere. A warmer ocean surface could increase the atmospheric water vapor amount and enhance the occurrence of clouds in the atmosphere, which warm the lower atmosphere by radiating heat downward. An increase in the abundance of soot aerosol particles could enhance the absorption of solar radiation both in the atmosphere and on snow or ice surfaces, further intensifying the warming effect. Biological activity changes in the ice-free ocean could increase the amounts of phytoplankton, which would also absorb more solar radiation.

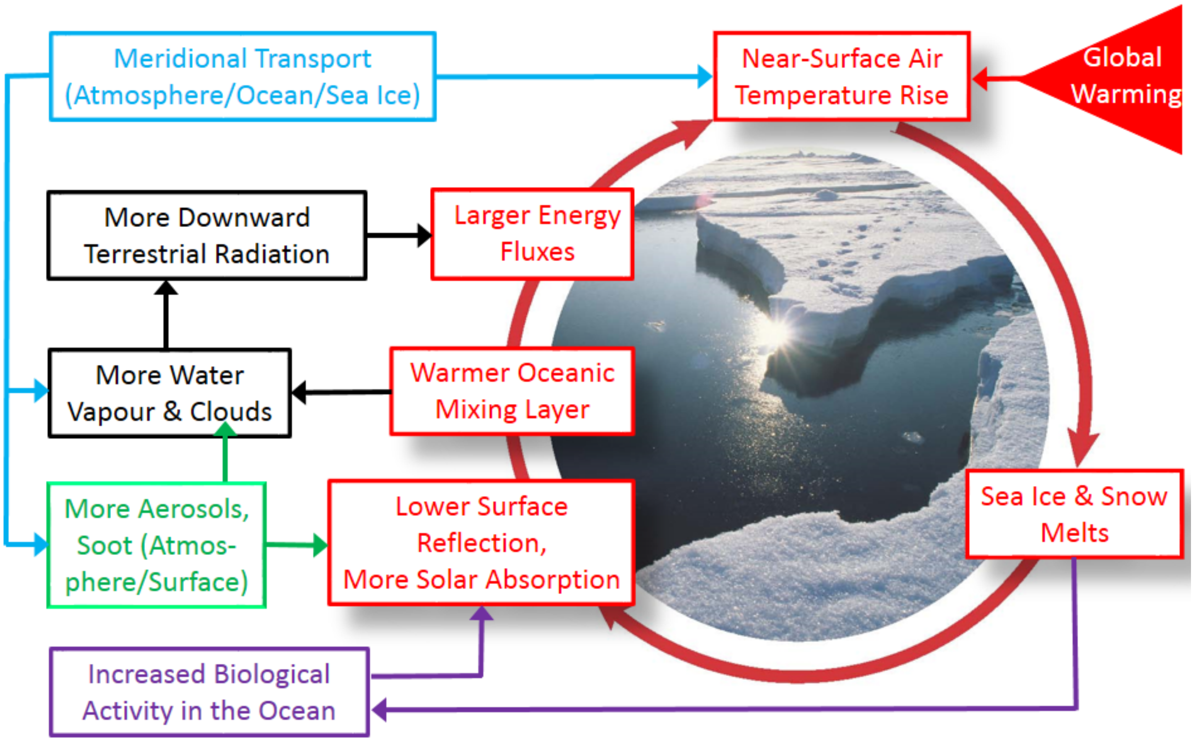

Fig. 2: Examples of feedback processes that amplify an initial near-surface air temperature rise caused by global warming.

These changes will have an impact on the unique atmospheric chemical processes taking place at high latitudes, removing short-lived climate pollutants and toxic heavy metals in the troposphere and controlling the stratospheric ozone layer. In addition, algae and phytoplankton production depend on these processes and their modifications, and the organohalogens they release into the atmosphere will also change.

Although many individual consequences of changes in these Arctic climate parameters are known, their combined influence and relative importance for Arctic Amplification are complicated to quantify and difficult to disentangle. As a result, there is not yet a consensus in the Arctic research community about the dominant mechanisms leading to the phenomenon of Arctic Amplification.

5. Planned Observations and Modelling Studies

In the framework of $(AC)^3$, we will use campaign-based and continuous observations to establish consistent shorter- and longer-term measurements and data product records. These observations will be collected by instrumentation carried on aircraft, tethered balloons, research vessels, and satellites and from instruments at a selected set of ground-based sites. We will conduct field studies in different seasons and meteorological conditions, covering a suitably wide range of spatial and temporal scales (Figure 3).

The shorter-term intensive campaigns are embedded in longer-term data sampling programs (i.e., the past 30 years), which aim to identify trends in the spatiotemporal variability of Arctic climate parameters. We will carry out this observational strategy in an international context and in close collaboration with modeling activities.
Modelers will use a hierarchy of process, regional, and global models to bridge the spatiotemporal scales, from local processes to appropriate global and long-term climate indicators (Figure 4). The models will serve several purposes. They will guide the planning and performance of field campaigns, assist in the interpretation of the local measurements, serve as test beds to evaluate process parameterizations, quantify feedback mechanisms, and help researchers determine the origins of observed Arctic climate changes. The observations, in turn, will be used to evaluate the predictive skills of the models.

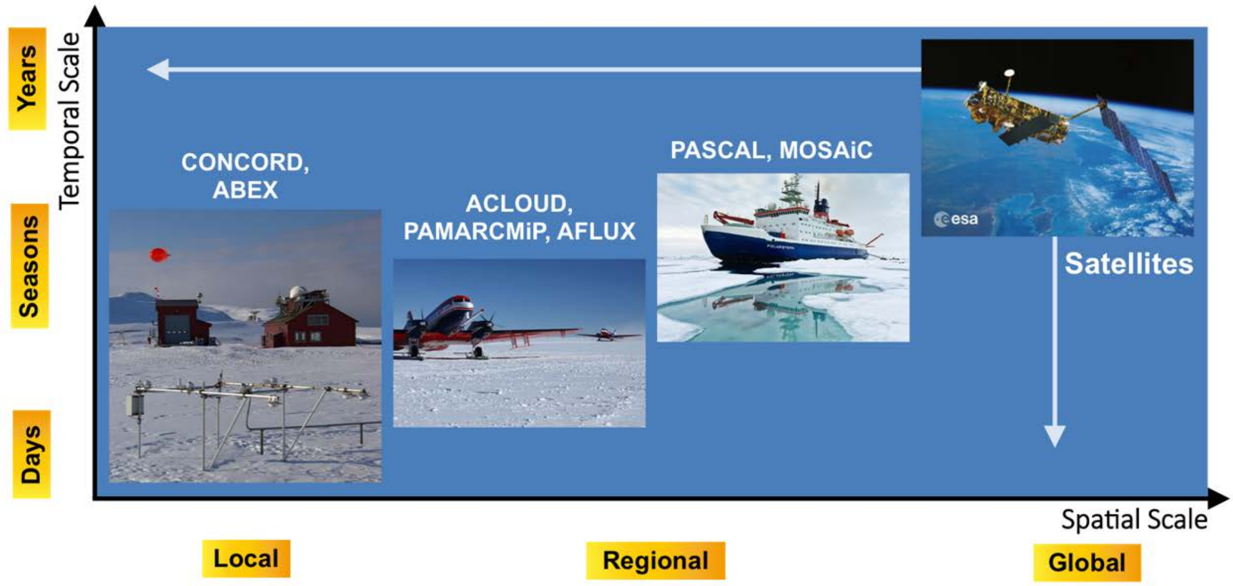

Fig. 3: Field observations within the framework of (AC)^3. CONCORD, continuous characterization of the Ny-Ålesund/Spitsbergen column and radiative effects from ground-based remote sensing; ABEX, Arctic Balloon-borne profiling Experiment (May–June 2017); ACLOUD, Arctic Clouds–Characterization of Ice, aerosol Particles and Energy fluxes (May–June 2017); PAMARCMiP, Polar Airborne Measurements and Arctic Regional Climate Model Simulation Project (spring 2018); AFLUX, Arctic Amplification: Fluxes in the Cloudy Atmospheric Boundary Layer (spring 2019); PASCAL, Physical feedback of Arctic Atmospheric Boundary Layer, Sea ice, Cloud and Aerosol (May–June 2017); MOSAiC, Multidisciplinary drifting Observatory for the Study of Arctic Climate (2019–2020).

We will place particular emphasis on evaluating different parameterizations, analyzing and quantifying feedback mechanisms in sensitivity studies, and assessing the importance of processes for Arctic climate and their interaction with the global dynamics and climate change.

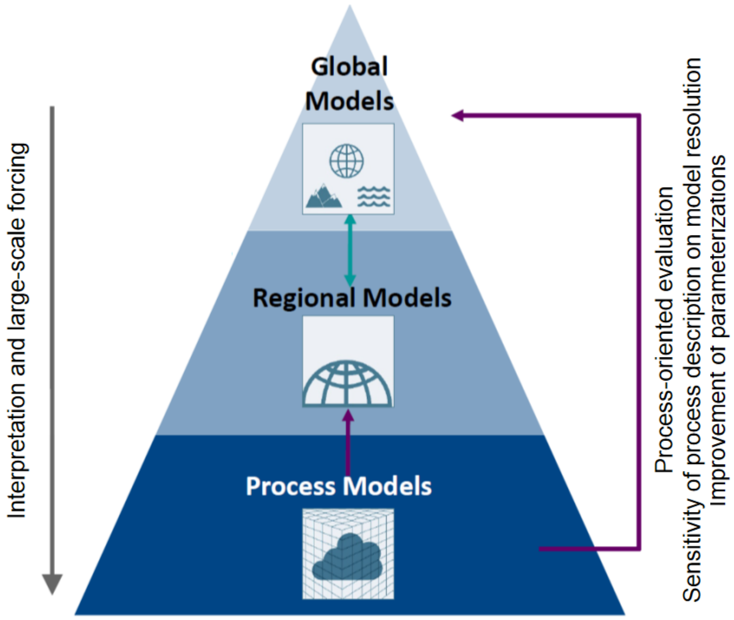

Fig. 4: The (AC)³ consortium will use a hierarchy of models covering a wide range of spatial and temporal scales to study Arctic Amplification.

6. Plans for the Coming Year

We have made preparations for a major observational campaign using the R/V *Polarstern*, tethered balloon measurements from an ice floe camp, and the research aircraft Polar 5 and Polar 6 (based in Longyearbyen, Svalbard) during May and June 2017. In particular, we will investigate the coupling of sea ice, clouds, and aerosol in the transition zone between open ocean and sea ice.
The instrumentation on board R/V *Polarstern* will provide standard observations and additional spectral radiation measurements to determine the surface energy budget and a detailed characterization of surface, cloud, and aerosol properties. A continuous ground-based measurement site at Svalbard, close to the open ocean, will provide similar measurements.
Polar 5 and Polar 6 will operate between Svalbard and the actual location of R/V *Polarstern* along the sea ice edge. The airborne observations will be supplemented by measurements of the boundary layer structure (turbulent and radiative energy fluxes) from a tethered balloon. The campaign will be the basis for extended modeling efforts to improve our understanding of Arctic climate changes.

The Leipzig Institute for Meteorology (LIM) is represented with altogether 8 individual sub-projects and is the coordinating speaker university. The main focus of airborne measurements in sub-projects A02 and A03 is on turbulent fluxes of momentum, sensible and latent heat, and radiation, and their vertical distribution for different meteorological situations, cloud cover, aerosol content, and sea ice coverage. Sub-project B03 investigates the importance of mixed-phase Arctic clouds for the cooling/warming of the near-surface air by means of aircraft-based measurements. Sub-project C01 deals with the radiative warming (or cooling) due to Arctic clouds and how sensitive it is to the heterogeneity of surface reflection properties like ice/snow and open water, while in sub-project C02 the extent of the darkening of snow/ice surface by soot depositions is investigated and the issue of the near-surface air warming by atmospheric soot is studied. Sub-project D01 hypothesizes that regional Arctic climate change and Arctic Amplification is modulated by large-scale tropospheric and stratospheric circulation patterns. Sub-project D02 will quantify the role of aerosol particles, their impact on clouds, as well as its transport and radiative/dynamical effects on Arctic Amplification from a modelling perspective. Sub-project E01 will quantitatively identify the important physical climate feedback mechanisms in the Arctic using state-of-the-art global circulation models.

7. Acknowledgment

We gratefully acknowledge the support from the German Research Foundation (Deutsche Forschungsgemeinschaft) within the Transregional Collaborative Research Center (TR 172) "Arctic Amplification: Climate Relevant Atmospheric and Surface Processes, and Feedback Mechanisms $(AC)^3$."

8. References

Wendisch, M., M. Brückner, J. P. Burrows, S. Crewell, K. Dethloff, K. Ebell, Ch. Lüpkes, A. Macke, J. Notholt, J. Quaas, A. Rinke and I. Tegen, 2017: Understanding causes and effects of rapid warming in the Arctic. *Eos*, 98, doi:10.1029/2017EO064803. Published on 17 January 2017.

Jeffries, M. O., J. E. Overland and D. K. Perovich (2013), The Arctic shifts to a new normal, *Phys. Today*, *66*(10), 35–40.

Kinnard, C., et al. (2011), Reconstructed changes in Arctic sea ice over the past 1,450 years, *Nature, 479*, 509–512, doi:10.1038/nature10581.

Lindsay, R. and A. Schweiger (2015), Arctic sea ice thickness loss determined using subsurface, aircraft, and satellite observations, *Cryosphere, 9*, 269–283, doi:10.5194/tc-9-269-2015.

Serreze, M. C. and R. C. Barry (2011), Processes and impacts of Arctic amplification: A research synthesis, *Global Planet. Change*, *77*, 85–96, doi:10.1016/j.gloplacha.2011.03.004.

Shi, X., et al. (2013), Relationships between recent pan-Arctic snow cover and hydroclimate trends, *J. Clim., 26*, 2048–2064, doi:10.1175/JCLI-D-12-00044.1.

Stroeve, J. C. et al., (2012), Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations, *Geophys. Res. Lett.*, *39*, L16502, doi:10.1029/2012GL052676.

Walsh, J. E. (2014), Intensified warming of the Arctic: Causes and impacts on middle latitudes, *Global Planet. Change*, *117*, 52–63, doi:10.1016/j.gloplacha.2014.03.003.