Role of air-mass transformations in exchange between the Arctic and mid-latitudes

Felix Pithan[1], Gunilla Svensson[2], Rodrigo Caballero[2], Dmitry Chechin[1,3], Timothy W. Cronin[4], Annica M. L. Ekman[2], Roel Neggers[5], Matthew D. Shupe[6], Amy Solomon[6], Michael Tjernström[2], and Manfred Wendisch[7]

[1]Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany
[2]Department of Meteorology and Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden
[3]A.M. Obukhov Institute of Atmospheric Physics of the Russian Academy of Sciences, Moscow, Russia
[4]Department of Earth, Atmospheric, and Planetary Science, MIT, Cambridge, MA, USA
[5]Institute for Geophysics and Meteorology, University of Cologne, Cologne, Germany
[6]Cooperative Institute for Research in Environmental Science, University of Colorado and NOAA Earth System Research Laboratory Physical Science Division, Boulder, Colorado, USA
[7]Institute for Meteorology, University of Leipzig, Leipzig, Germany

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Pulses of warm and moist air from lower latitudes provide energy to the Arctic and form its main energy source outside of the summer months. These pulses can cause substantial surface warming and trigger ice melt. Air-mass transport in the opposite direction, away from the Arctic, leads to cold-air outbreaks. They are often associated with cold extremes over continents, and extreme surface heat fluxes and occasional polar lows over oceans. Air masses advected across the strong Arctic-to-mid-latitude temperature gradient are rapidly transformed into colder and dryer or warmer and moister air masses by

clouds, radiative and turbulent processes, particularly in the boundary layer. Phase changes from liquid to ice within boundary-layer clouds are critical in these air-mass transformations. The presence of liquid water determines the radiative effects of these clouds, whereas the presence of ice is crucial for subsequent cloud decay or dissipation, processes that are poorly represented in weather and climate models. We argue that a better understanding of how air masses are transformed on their way into and out of the Arctic is essential for improved prediction of weather and climate in the Arctic and midlatitudes. Observational and modelling exercises should take an air-mass-following Lagrangian approach to attain these goals.

The atmospheric general circulation can be viewed as a global heat engine (1): air is strongly heated and moistened in the Tropics, carried poleward and then rapidly cooled and dried at high latitudes before returning equatorwards (2). Here, we review the understanding of how air is transformed as it cools and dries while entering the Arctic in the northward branch of this circulation, or is warmed and moistened on its way south, out of the Arctic.

By controlling the radiative heat loss and vertical temperature structure in the Arctic, air mass transformation processes are also crucial for the Arctic amplificaton (3) of climate change, which is found in observations, reconstructions of past climates, and climate model experiments (4; 5; 6).

Most of the heat and moisture import into the Arctic occurs as pulses of anomalously warm and moist air that penetrate into the region from lower latitudes. We refer to these events as intrusions throughout this paper. Intrusions occur throughout the year (7; 8; 9; 10) and they are important for extreme Arctic weather and climate in all seasons (11; 12; 13; 14). When warm, moist air intrudes into the Arctic, radiative cooling in winter or turbulent fluxes towards the melting surface in summer lead to the formation of low-level liquid clouds. These liquid-containing clouds warm the surface, except late in the summer season. As radiative cooling continues in wintertime intrusions, frozen precipitation gradually dries the air, and the clouds glaciate or dissipate in the cold and dry final stage of the air mass transformation (15; 16; 17; 18).

Conversely, cold and dry Arctic air is transformed as it is transported southward in cold-air outbreaks. During such outbreaks over the ocean in winter, the ice-free surface releases large amounts of heat and moisture to the much colder air. Clouds develop at the top of a convective boundary layer, which progressively deepens (19; 20). The clouds often arrange themselves in streets roughly along the wind direction, breaking up into cellular structures at larger distances from the sea-ice edge (21). Cold-air outbreaks over continents cause extreme cold weather and may lead to severe disruption in populated areas of lower latitudes (22). In this paper, we focus primarily on marine outbreaks, in which the transformation process is faster and more intense than in continental outbreaks.

Both intrusions and cold-air outbreaks typically occur when the prevailing large-scale wind has a meridional orientation, often in association with a blocking-like high-pressure system. How likely such configurations are to occur depends on the state of the tropical atmosphere (9) and on stratospheric dynamics (23). Changes in their frequency of occurrence would potentially have important impacts on the weather and climate of mid and high latitudes (24).

The observational record of Arctic weather and climate is short and includes both large trends and large internal variability (25). Models have problems capturing many processes specific to Arctic air mass transformations (3; 26). Over the next few years, ongoing and planned concerted observational and modelling efforts to improve the understanding of Arctic weather and climate and the multi-scale processes controlling it (27), including studies on intrusions and cold-air outbreaks, will provide unprecedented opportunities to further our understanding of Arctic air-mass transformations.

In this paper, we first condense the state of understanding of the boundary layer dynamics triggered by the strong vertical temperature gradients between the surface and atmosphere in both types of air-mass transformation. We then review the roles of these features in the global climate system. The final outlook section is intended to set the stage for, and guide, upcoming activities based on the synthesis of current knowledge and crucial open questions.

1 Intrusions of warm, moist air into the Arctic

In intrusions, mid-latitude air masses penetrate into the Arctic basin, mostly in filamentary structures (7; 30) akin to atmospheric rivers (Figure 1, (31)). Intrusions occur throughout the year (32). They are initiated by large-scale flow anomalies typically featuring a blocking-like high centered near the Arctic Circle with a low-pressure system to its west (Figure 1). This dipole generates strong poleward flow that injects mid-latitude air across the Arctic Circle and guides it into the Arctic basin (8; 30). The injection point can occur at any longitude, but in winter, there is a marked preference for intrusions originating in the North Atlantic and North Pacific, the two sectors where mid-latitude marine air lies in closest proximity to the Arctic. Such intrusions occur roughly once a week on average and they take about five days to cross the Arctic (30). In summer, intrusions commonly originate over the warm Siberian land mass (33; 10).

Over 60% of the total moisture flux into the Arctic occurs during events occupying only 10% of the time (9), and more than one third of the total flux occurs during spatially and temporally coherent intrusion events (8). The intrusions cause strong, locally concentrated positive anomalies of column water vapour, usually accompanied by clouds, which lead to positive surface temperature anomalies in excess of 6 K over land or sea ice (16; 34; 35; 12; 36; 30; 32). The surface warming results mostly from increased downward terrestrial radiation and can limit sea-ice growth by reducing the ocean's conductive heat loss through the ice (37) and may trigger an earlier onset of the spring melt (12; 38; 13). On longer time scales, nearly half of the 1979-2011 sea-ice decline in the Barents-Kara Seas can be attributed to an increased flux of heat and moisture from lower latitudes (36). Individual events are important, for example an intrusion caused melt over more than 90 % of the Greenland ice sheet surface in summer 2012 (39; 40; 14), and warm air from Siberia was advected northward over the Arctic Ocean causing rapid sea-ice melt in August 2014 (33).

It is useful to take a Lagrangian view of the air-mass transformation (15; 16; 41), following a column of warm and moist air as it intrudes over the Arctic ice pack (see inset in Figure 1). The lowermost part of the atmosphere cools rapidly until it reaches saturation and cloud droplets form. As liquid-water clouds are largely opaque to terrestrial radiation, the strongest cooling is displaced to the cloud top (Figure 1b, (34)). The downward motion generated by this cloud-top cooling drives turbulence, which can extend all the way to the surface or form a separate turbulent layer (18; 42). Ice particles appear as the cloud continues to cool radiatively. In spite of moisture losses due to precipitating ice crystals and latent heat release due to condensation, this mixed-phase state is often very long-lived (43; 17), as radiative cooling and cloud-top entrainment of moist air across the elevated inversion sustain the cloud (44). In the cold season, these coupled radiative, dynamical, and microphysical processes eventually consume most of the available moisture, and the cloud glaciates and/or dissipates, (45; 46; 47) leaving a state where radiative surface cooling forms a surface-based temperature inversion (Figure 1c).

Arctic air can also be formed over high-latitude continents, where it reaches even colder temperatures than over the Arctic ocean. In addition to radiative cooling, evaporative cooling caused by precipitation falling into dry layers of air contributes to this air-mass transformation. Over Canada, Arctic air formation is often associated with cold-air damming in the lee of the Rocky Mountains (48).

The interaction between the small-scale processes in shallow layers, with cold temperatures, weak turbulence and a rapidly responding surface, is challenging not only for global weather and climate models, but also for smaller-scale cloud resolving models (49). Models struggle to represent both the cloudy and cloud-free states and the transition between the two in a Lagrangian transformation (35), and generate a range of different vertical structures and surface energy exchanges. Maintaining super-cooled liquid water in the presence of ice particles, which ultimately determines the cloud radiative effect on the surface (50), is a particular challenge. This problem seems to be less pronounced in models that separately compute the temporal evolution of cloud ice and liquid water (35; 51; 47).

The partitioning between liquid water and ice is particularly sensitive to the number of cloud condensation nuclei and ice nucleating particles (46; 47), yet there are few obvious local sources of these particles in the Arctic. Relatively weak precipitation and sedimentation rates are important for sustaining liquid water over several days. Ice nucleating particles from ice crystal sublimating below the cloud can be recycled and contribute to sustaining the ice processes (45; 47). Intrusions may also supply cloud condensation nuclei and ice nucleating particles as these are usually more abundant at lower latitudes. Relatively aerosol-rich free tropospheric air could be an important source of such particles, particularly for clouds that extend into the inversion (52; 53). Collectively representing these processes is essential for properly capturing the time-scale of the air mass transformation and thereby the spatial extent of the cloudy state, which provides substantial energy to the surface and maintains a higher surface temperature.

2 Fast warming and moistening in marine cold-air outbreaks

Cold-air outbreaks occur when cold Arctic air is advected into much warmer regions by the large-scale flow, with the strongest events produced by a pressure dipole with a high on the western and a low on the eastern side (Figure 2, (20)). Cold-air outbreaks most frequently occur in bands stretching from the North Pacific to western North America and from the North Atlantic towards Europe (55). Over the warm currents in the western Atlantic and Pacific, cold air masses advected off the continents are mostly transformed in baroclinic processes that drive the storm tracks. We here discuss the canonical, more vertically uniform cold-air outbreaks that occur over the ice-free or partly freezing seas in the Arctic and develop most frequently in the cold sectors of cyclones. The extent and impact region of a cold-air outbreak is defined not only by the scale of the synoptic eddy, but also by the along-stream horizontal scale of the air mass transformation (56), which is proportional to the temperature difference between the open water surface and cold air mass and can extend to about 500-1000 km. Thus, colder outbreaks or those reaching warmer sea-surface temperatures have larger horizontal extent (55).

The temperature difference between the ocean surface and the advected cold air can exceed 30 K and generate surface fluxes of heat and moisture of 500 $\mathrm{W\,m^{-2}}$ (57) close to the coastline or sea-ice edge. The associated instability of the boundary layer results in intense shallow convection, which can be clearly identified on satellite imagery as cloud streets close to the sea-ice edge and open cells further downstream (Figure 2, (21; 26)). Cloud streets associated with roll circulations in the boundary layer are typically found over the first several hundred kilometers downwind of the sea-ice edge or coastline (Figure 2). Large-eddy simulations (58) show that the organization into rolls is triggered by surface temperature heterogeneities in the marginal ice zone. The transition from rolls to open cells is often accompanied by a transition from thin, elongated stratocumulus to deeper, dispersed cumulus clouds (59). Traditionally, the roll-to-cell transition is explained as a shift towards a more convective state of the boundary layer and thereby increasing latent heat release in clouds relative to surface heating (60). A recent study (61) concluded that mixed-phase microphysical processes and, in particular, an enhancement of precipitation due to cloud ice formation, play an important role in the stratocumulus-to-cumulus transition.

Intense snow showers are observed at downstream coastlines. These convective snowstorms are well-studied for some regions (e.g. the densely populated Great Lakes region (62)), but less investigated for the Arctic coast (63). Marine cold-air outbreaks account for 60-80% of the ocean heat loss over the Norwegian and Irminger seas during the cold season (57), and play a key role in deep-water formation (64) and ocean vertical mixing (65). Moreover, marine cold-air outbreaks strongly influence new sea-ice formation and ice and ocean dynamics of the marginal ice zone (65; 66).

While strong winds are common during marine cold-air outbreaks, they are even further enhanced when the flow is organized in orographic jets (67), low-level baroclinic jets (68), fronts (69) and Polar Lows (70; 71). Such enhanced wind speeds further intensify the surface heat flux and thus ocean heat loss (72; 73).

The representation of convection and clouds in marine cold-air outbreaks in weather prediction and climate models remains problematic, although models generally simulate the transition from a well-mixed stratocumulus boundary-layer to a partly decoupled cumulus boundary layer (26). Models tend to underestimate cloud liquid water and ice in these conditions (74; 59), which also leads to an underestimation of solar radiation reflected by clouds in the cold sectors of cyclones (75). The lack of cloud water is possibly related to an underestimation of surface fluxes and vertical mixing in the presence of strong wind shear (26).

3 Slow air-mass transformation over continents

Continental cold-air outbreaks often occur in anticyclonic conditions (76) that advect Arctic air southward from Canada or westward into Europe from Siberia. With a typical size of several thousand kilometers, continental cold-air outbreaks have a larger spatial scale than their marine counterparts (22). These large spatial scales and timescales of several days (77) are due to a slower warming and moistening of cold air over the continents. Most research on continental cold-air outbreaks has been focused on the dynamics and predictability of such events, and little is known about their thermodynamics. Estimates for typical heat and moisture fluxes in cold-air outbreaks over Asia are below 100 Wm^{-2} (78), and substantially smaller values have been reported for snow-covered continents (77). Snow reflects much of the solar radiation that reaches the surface, which is an important effect in continental cold-air outbreaks that reach far outside the Arctic. Adiabatic warming due to downward motion in high-pressure systems can play an important role in the energy budget of continental cold-air outbreaks

(76).

4 Connections to the global climate system

Mid-latitude air cools and dries in an intrusion, whereas Arctic air moistens and warms in a marine cold-air outbreak. These air masses typically have well-defined boundaries over which little lateral mixing occurs (41), so air mass transformations are essential pathways of communication between the Arctic and mid-latitudes. From the global heat engine perspective, cooling and drying of warm, moist air is the dominant situation in the polar branch of the mass circulation, whereas the regionally important rapid warming and moistening in outbreaks is small compared to the warming and moistening of air in the deep Tropics (2). When the circulation is averaged on surfaces of constant potential temperature, mean inflow into the Arctic occurs at heights above 700 hPa (79). The episodic and extreme intrusions that carry much of the poleward moisture flux occur below 850 hPa (8). Most Arctic air flows southward across the continents and fuels the baroclinic storm-track processes when it reaches the ocean. Only a smaller fraction of Arctic air is transformed in marine cold-air outbreaks (79).

4.1 Thermodynamic controls

Assuming fixed advection, the along-wind horizontal scale of an air-mass transformation depends on the timescale of the transformation, which largely depends on the thermodynamic processes in the boundary-layer and clouds discussed in the previous sections. This timescale is substantially shorter for marine cold-air outbreaks (hours up to a day) than for continental cold-air outbreaks and intrusions (several days), with implications on the climate impacts of air-mass transformations. The longer an intruding moist air mass remains in the cloudy state with substantially increased downward radiation, the greater its effect on the surface energy budget and sea ice will be (30). How the timescale of air-mass transformation depends on the air-mass properties, surface conditions and the large-scale circulation is therefore an important research question.

The thermodynamics of air-mass transformations are changing in a warming climate. Assuming fixed relative humidity and no major changes in circulation, the Clausius-Clapeyron relation (80) implies that the amount of moisture injected into the Arctic in intrusions will increase in a warming world. Higher initial moisture content in intrusions could contribute to longer lifetimes of liquid clouds during the air mass cooling process, contributing to surface-amplified warming over the Arctic and high-latitude continents (81) and thereby to the positive Arctic lapse-rate feedback. The reduction of sea-ice area will shrink the domain over which air masses cool following an intrusion, also increasing the relative importance of the cloudy state of the boundary layer. Reduced sea-ice and snow thickness will increase the ocean heat release and thus surface temperatures especially in the clear state. We expect that this will further increase the timescale of air-mass transformation.

Arctic amplification implies that the source regions of cold-air outbreaks warm more than the regions affected by the outbreaks, reducing the severity of continental cold-air outbreaks and thus cold extremes in mid-latitudes more than implied by the local increase in average winter temperatures (82; 83). Furthermore, the marine cold-air outbreak source regions will move poleward with the retreating sea-ice edge. Over the North Atlantic, this leads to a weakening of cold-air outbreaks as their location shifts away from the warm Atlantic surface currents, while no major change is seen in the Sea of Okhotsk (84). Changes in ocean currents and thereby in sea surface temperatures could additionally impact the strength of marine cold-air outbreaks. The observed increase of open ocean north of Svalbard and also in the north-eastern Barents Sea makes these newly ice-free areas prone to strong heat loss and ice production during outbreaks both leading to increased mixing in the ocean. This contributes to the observed 'atlantification' of the Eurasian Basin of the Arctic Ocean (85). Another consequence is that warmer temperatures and a thicker and moister boundary layer are observed over Svalbard during outbreaks (86). Polar lows in the North Atlantic are projected to become less frequent because warming aloft is stronger than at the surface, which suppresses their formation (87).

While the thermodynamic changes in the properties of intrusions in a warming climate follow first principles, analogous dynamical theory to explain their interaction with large-scale dynamics is lacking. This issue relates to the World Climate Research Program's grand challenge of clouds, circulation and climate sensitivity (88).

4.2 Dynamical response and forcing

In idealized simulations of Arctic air-mass formation, low-level radiative cooling causes a dynamic response: Cold and dense outflow near the surface leads to convergence into the air mass aloft that is balanced by downward motion in the center of the air mass (89). This leads to high pressure in the center and the development of anticyclonic motion, in agreement with observations showing that cold, dry air tends to be associated with higher surface pressure (17). In numerical experiments without subsidence, cloudy layers in intrusions rise rapidly by entrainment (35; 49), while observed clouds remain much closer to the surface (90). Downward motion above the clouds could maintain clouds at low levels while they entrain moist air from aloft. However, real-world intrusions are driven by a pressure dipole with a cyclone to the west and an anticyclone to the east (Figure 1), and reanalysis composites suggest that upward motion initially dominates on the cyclonic side of this dipole, and subsidence only prevails after about five days, when the air mass has largely crossed the Arctic (11). Tropopause polar vortices also generate both ascent and descent over different areas, and are generally associated with cold anomalies in the troposphere (91). The evolution of large-scale vertical motion during an intrusion is a key observational challenge both for process understanding and model improvement (92).

The strong meridional advection patterns that drive intrusions and outbreaks are often associated with blocking-like high pressure systems that can remain stagnant for several days. Mid-latitude cyclones also play an important role, but often they do not enter into the Arctic. Blocking events that enhance the meridional flow may have precursors in the stratosphere or far from the region of interest. If the strong zonal winds in the stratospheric polar vortex are weakened or reversed in sudden stratospheric warming events, strong meridional advection patterns are more likely to occur in the troposphere (93; 23). Intrusions often follow Rossby-wave breaking events, which cause a local reversal of the climatological temperature gradient, disturb the westerly flow and can lead to blocking and stronger meridional transport (9). Localized tropical convection over the Pacific Ocean can generate planetary-scale Rossby-wave trains that propagate poleward, where they interact with the climatological stationary waves to generate meridional flow and moisture advection into the Arctic (94; 95).

If disturbances of the westerlies at high latitudes became more or less frequent or persistent in a warming climate, this would also change the frequency or characteristics of intrusions and outbreaks, with substantial impacts on weather and climate. To what extent and by what mechanisms Arctic amplification could lead to an increased frequency of such disturbances is still under discussion (24).

5 The pathway forward

Improved understanding of Arctic air-mass transformations and their role in the climate system requires a new holistic and coupled view that incorporates both observations and models. Air-mass transformations are more than merely a flux of heat or moisture to or from the Arctic. Their rich multi-scale physics provide an opportunity to better understand both local-scale processes (e.g., cloud microphysics, boundary-layer turbulence) and the feedbacks between these processes and larger-scale circulations, as well as the coupling among atmosphere, ocean, and sea ice. Models are key tools for understanding such linkages, and their failure to adequately represent important aspects of the air-mass transformations impedes our understanding of the Arctic and global systems in a changing climate.

Most of the observational basis for understanding, especially at process level, has been developed through an Eulerian framework. Air-mass transformation, however, occurs over Lagrangian pathways (15; 16; 41; 60). Therefore, an alternative conceptual thinking is required when planning observations and improving models that better targets air-mass transformation processes across surface temperature gradients, coastlines or the marginal ice zone. Such a concept was pioneered for stratocumulus to cumulus transformation (96).

This Lagrangian perspective can be applied to existing observations to improve the understanding of, for example, the spatial variation in processes and the timescales involved in the transformations (97). Using trajectory analysis, cases can be identified that leverage consecutive observations from several locations along an air-mass trajectory, allowing for a characterization of up- and down-stream conditions during air-mass transformation events. Key examples would be combining icebreaker-based observations from within the icepack (e.g., SHEBA, ASCOS, PASCAL, see Table 1) with coastal land-based observatories, ideally with supporting aircraft observations (e.g. FIRE-ACE, AMISA, ACLOUD) to provide spatial linking and context.

The ongoing Polar Prediction Project (PPP, 2013-2022) and the Year of Polar Prediction (YOPP) provide additional observational, model and coupled reanalysis data to the community (98; 27). The MOSAiC initiative will offer a full year perspective on the Arctic atmosphere and coupled climate system from the central Arctic sea ice directly within a major transport pathway for intrusions. At the same time, the COMBLE campaign will focus on cold air outbreaks in the North Atlantic Arctic. Advances in observatories at locations like Ny Ålesund and Barrow provide additional continuous atmospheric profiling along important transport pathways. While many of these observations are still primarily Eulerian in concept, there are now opportunities to engage mobile observation systems that can target and follow air masses as they move into or out of the Arctic. Long-range aircraft systems such as HALO and HIAPER, along with other key airborne assets, can play a central role in linking fixed observatories. Autonomous aircraft, like the Global Hawk and other drones or airships, also offer the ability to track air masses as they evolve and provide near-instantaneous transects along and across the primary direction of large-scale flow. Satellite products provide larger areal coverage and the data can be organized along calculated trajectories for air-mass transformation. In particular, new satellite opportunities (e.g. EarthCARE) will allow for enhanced observations of the spatial structure of air-mass transformation events, including exciting insight into the associated clouds.

Modeling air-mass transformations correctly is essential to improve forecast capabilities and to represent feedback mechanisms important for climate change. Particular focus is needed on how models handle transitions between cloudy and cloud-free states, the evolution of cloud phase partitioning and air mass moisture sources and sinks (i.e. precipitation efficiency), all of which impact the spatio-temporal scales for transformations. The representation of exchange processes between the transforming air and the underlying surface also requires improvement, to consider complexities related to strong contrasts in e.g. temperature, roughness and albedo between land, variable sea ice cover, and open ocean. To improve our scientific understanding, it is essential to employ a hierarchy of model perspectives ranging from tools that resolve boundary-layer turbulent eddies and cloud-scale processes, up to regional and global-scale models that can represent large-scale forcing and responses. In the Arctic, with the rapidly changing surface, it is important to develop models within a coupled framework (99). Omitting surface interactions in model development, by forcing sub-models with observations or reanalysis, leads to severe biases when models are ultimately coupled.

We suggest that the path forward is to focus on advancing the understanding of processes important for air-mass transformation. With the additional observational efforts, now is an opportune time for the broader community to engage in implementing new knowledge in models that is necessary to understand the connections between the Arctic and mid-latitude weather and climate. This could be supported by process-oriented model intercomparisons (35) focusing on air-mass water budgets, cloud longevity, surface energy budgets, entrainment and turbulence, and cloud/air-mass structural organization for both cold air outbreaks and warm air intrusions.

6 Essential lessons

Air masses that are exchanged between lower latitudes and the Arctic undergo key transformations that involve the boundary layer, clouds, and thermodynamic and dynamical interactions with the larger-scale environment. The transformations occur over hours to days and across hundreds to thousands of kilometres and are unique at high latitudes. The thermodynamics of the transformations are affected by climate change and its amplification in the Arctic, and affect Arctic climate feedbacks. Current models do not adequately represent the underlying processes, and classical observations that are fixed in space only provide one snapshot of an ongoing transformation. We suggest that observations and model experiments that follow air masses on their paths to and from the Arctic will substantially advance our understanding of the transformation processes.

7 Data Availability

ERA-Interim data for Figure 1 have been obtained from the European Centre for Medium-range Weather Forecasts' (ECMWF) data server. The satellite image in Figure 2 is from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Aqua satellite, provided by the National Aeronautics and Space Administration (NASA) via https://earthdata.nasa.gov/.

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Correspondance and requests for material should be addressed to F.P. (felix.pithan@awi.de).

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Author contributions

All authors wrote the paper, which was coordinated by F.P. and G.S.. T.W.C. and D.C. produced the figures.

Tables

Table 1: Campaign and instrument acronyms used in the outlook section

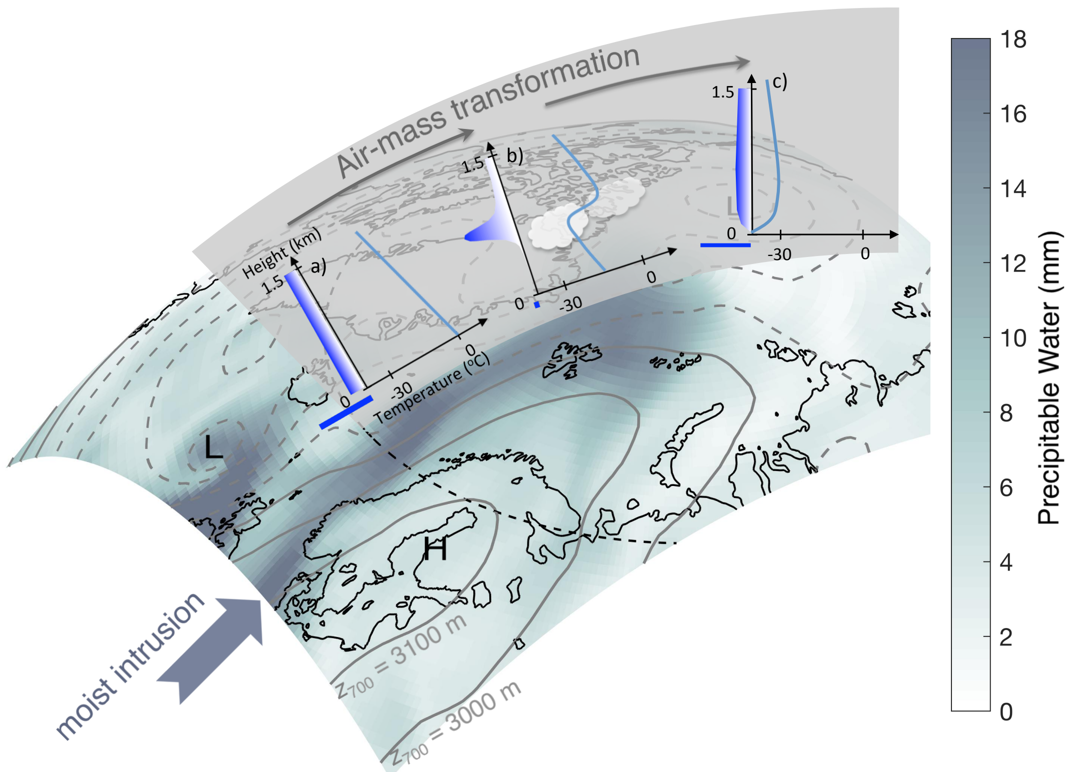
acronym	campaign or instrument	reference
SHEBA	Surface Heat Budget of the Arctic	(100)
ASCOS	Arctic Summer Cloud Ocean Study	(101)
PASCAL	Physical feedback of Arctic PBL, Sea ice, Cloud And AerosoL	(102)
FIRE-ACE	First ISCCP Regional Experiment - Arctic Cloud Experiment	(103)
AMISA	Arctic Mechanisms of Interaction between the Surface and Atmosphere	(104)
ACLOUD	Arctic CLoud Observations Using airborne measurements during polar Day	(105)
MOSAiC	Multidisciplinary drifting Observatory for the Study of Arctic Climate	(106)
COMBLE	Cold-air Outbreak in the Marine Boundary Layer Experiment	(107)
HALO	High Altitude and Long Range Research Aircraft	(108)
HIAPER	High-Performance Instrumented Airborne Platform for Environmental Research	(109)
EarthCARE	Earth Clouds, Aerosol and Radiation Explorer	(110)

Figure Captions

Figure 1. **A filament of moist air is channeled poleward and transformed to Arctic air in an intrusion event (28)**. map: precipitable water and 700 hPa geopotential height on 29 Dec 2015, 18 Z from ERA-Interim (29). curtain: air-mass transformation from (a) a well-mixed marine state to (b) an elevated inversion within and above low-level liquid clouds and (c) a surface-based inversion under cloud-free skies. White-blue shading to the left of the temperature profiles shows radiative cooling rates in the atmosphere and blue bars illustrate surface radiative cooling.

Figure 2. **Air-mass transformation and the associated boundary-layer and cloud structures during a marine cold-air outbreak.** a) Schematic representation of the evolution of the organized convective structures during marine cold-air outbreaks; and the evolution of boundary layer height, temperature and surface fluxes of heat and moisture up to about one day downwind the ice edge, adopted from (54) b) Satellite image of a cold-air outbreak on 7 Apr 2013 over the Greenland, Norwegian and Barents Seas

Figures



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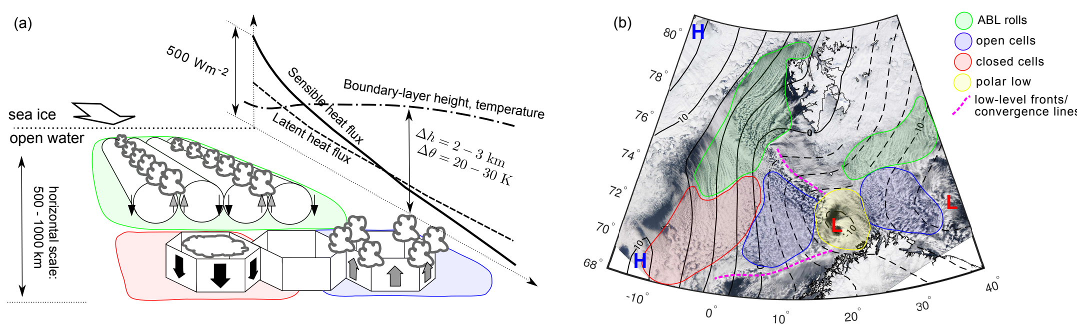

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