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Resilience of persistent Arctic mixed-phase clouds

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The Arctic region is particularly sensitive to climate change. Mixed-phase clouds, comprising both ice and supercooled liquid water, have a large impact on radiative fluxes in the Arctic. These clouds occur frequently during all seasons in the region, where they often persist for many days at a time. This persistence is remarkable given the inherent instability of ice–liquid mixtures. In recent years it has emerged that feedbacks between numerous local processes, including the formation and growth of ice and cloud droplets, radiative cooling, turbulence, entrainment and surface fluxes of heat and moisture, interact to create a resilient mixed-phase cloud system. As well as the persistent mixed-phase cloud state there is another distinct Arctic state, characterized by radiatively clear conditions. The occurrence of either state seems to be related, in part, to large-scale environmental conditions. We suggest that shifts in the large-scale environment could alter the prevalence of mixed-phase clouds, potentially affecting surface radiative fluxes and the Arctic energy budget.

Global and regional climate models have highlighted the Arctic as a region of particular sensitivity to climate change[1]. These model results are supported by observations showing rapid environmental change and accelerated warming relative to lower latitudes[2–6]. This sensitivity has been hypothesized to result from myriad feedbacks operating in the region. Central to these feedbacks are changes in cloud fraction, water content, phase, particle size and temperature[7–9]. Because clouds impact downwelling solar and longwave radiative fluxes, cloud-radiation feedbacks are inextricably linked to surface processes and feedbacks[7,10,11]. Cloud-related processes have been implicated as a major factor in recent summertime sea-ice loss[12], which has accelerated over the past decade at a rate much higher than predicted by most climate models[12–14]. The challenge of attribution becomes apparent when considering that Arctic sea-ice loss over the past 30 years can be explained by an energy surplus of just 1 W m^{-2} (ref. 15).

Mixed-phase clouds are composed of a mixture of supercooled liquid droplets and ice crystals. At lower latitudes, these conditions typically occur in conjunction with deep convection or as mid-level altostratus or altocumulus clouds associated with tropical or synoptic-scale mid-latitude weather systems[16,17]. More commonly found in the Arctic, mixed-phase clouds cover large swaths of the region throughout the year[18] and occur as extensive single or multiple stratiform layers of supercooled liquid water from which ice crystals form and precipitate with regularity, producing a characteristic structure of liquid near the cloud top and ice within and below the liquid layer(s)[19–27]. The liquid water they comprise has a large impact on surface radiative fluxes and energy balance[23,28], and is therefore critical to climate. In contrast to lower-latitude mixed-phase clouds, this structure is often long-lived and can persist for several days; an example from Eureka, Nunavut (Canada) is shown in Fig. 1. The high frequency of occurrence of Arctic mixed-phase clouds is largely owing to their longevity[18]. They persist under a variety of conditions, including weak synoptic-scale forcing and large-scale subsidence[18,21,23,25] (that is, they do not require synoptic-scale upward air motion associated with cyclones and fronts). This persistence is surprising when one considers that the mixture of supercooled liquid droplets and ice is microphysically unstable. Ice has a lower equilibrium vapour pressure than liquid, meaning that when ice and water coexist at subfreezing temperatures, liquid droplets evaporate and release water vapour, allowing ice crystals to grow by vapour deposition, unless there is enough cooling or moistening to maintain liquid saturation. The growth of ice by vapour deposition at the expense of liquid is referred to as the Wegener–Bergeron–Findeisen (WBF) mechanism[29–31]. This microphysical instability can transform mixed-phase clouds to ice-only clouds within a few hours or less[21,22,32,33]. Consequently, the persistence of these clouds for periods of days to weeks[18,23,25] (Fig. 1) is unexpected.

A complex web of interactions between various physical processes has made it difficult to assemble an overall picture of how Arctic mixed-phase clouds persist. This uncertainty is reflected in the poor simulation of these clouds by numerical models on all scales[34–38], which erodes confidence in model estimates of Arctic cloud–climate feedbacks and climate sensitivity. Moreover, process complexity has made it difficult to identify key parameters that inhibit our ability to understand and simulate these clouds. We will argue that a lack of sufficient progress indicates a need for a more integrated, systems-based methodology that complements existing strategies relying primarily on a process-level, reductionist approach. We will show that such a systems-dynamics perspective helps identify some critical aspects of these clouds, and provides a natural framework for interpreting their persistence and understanding their role in climate.

Local process interactions in Arctic mixed-phase clouds

Modelling and theoretical studies have attempted to explain the counterintuitive persistence of Arctic mixed-phase clouds despite microphysical instability arising from the WBF mechanism.

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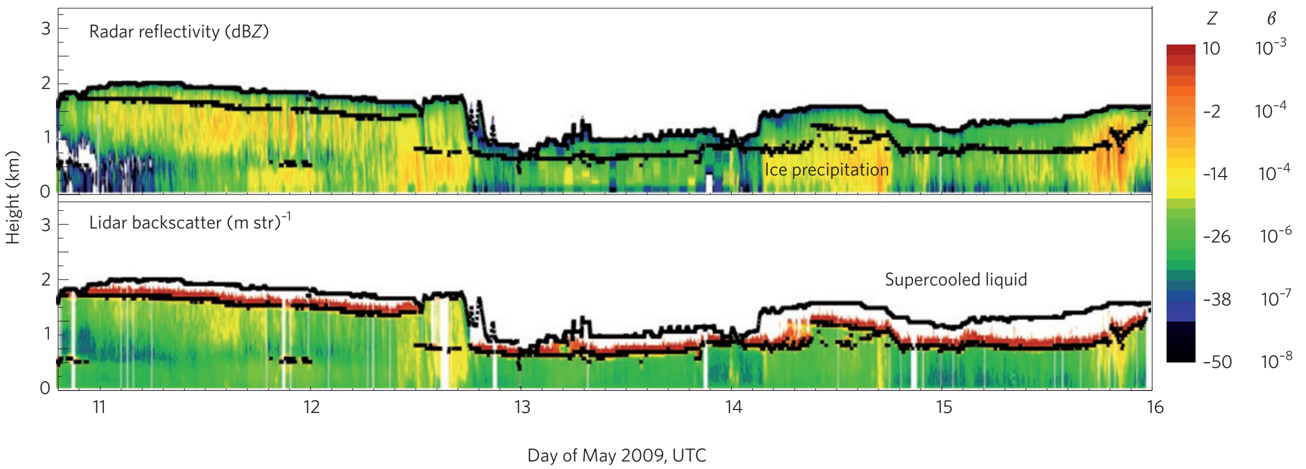

Figure 1 | Cloud radar and lidar indicating the characteristic structure of long-lived Arctic mixed-phase stratiform clouds. In this example, supercooled liquid water perseveres for more than 5 days despite a near-continual loss of mass owing to ice precipitation. Cloud radar reflectivity (top), Z, is dominated by the relatively large ice crystals that form in, and fall from, supercooled liquid cloud layers. Lidar backscatter (bottom), β, is dominated by the much smaller, yet more numerous, droplets found in liquid layers. The lidar signal is attenuated within the supercooled liquid layer, whose boundaries are defined by the black contour. UTC, coordinated universal time.

Turbulence and cloud-scale upward air motion seem to be critical in maintaining mixed-phase clouds under weak synoptic-scale forcing[39–43]. In updrafts, relative humidity increases through expansion and cooling of air. If the updrafts are strong enough, conditions can become supersaturated with respect to liquid water, leading to simultaneous growth of ice particles and supercooled liquid droplets, rather than ice growing at the expense of liquid[44]. Turbulence itself is driven by local process interactions that simultaneously depend on, and help maintain, liquid water[32,45]. In particular, supercooled liquid water leads to strong longwave radiative cooling, with cooling rates that can exceed 60 K per day near the cloud top[21,32,33,45,46]. This cooling leads to decreased static stability, buoyant production of turbulent updrafts, and condensational growth of droplets[32,45,47,48]; these processes constitute a self-maintaining feedback pathway between liquid water, radiation and turbulence (Fig. 2a).

Further sustenance for these mixed-phase cloud layers is gained by large-scale advection that results in frequent moisture inversions near the cloud top[49,50], in contrast to warm stratocumulus and mixed-phase clouds at lower latitudes that typically have dry air above the cloud[48]. In the presence of a moisture inversion, turbulent entrainment of air from above the cloud actually moistens the cloud layer and helps to sustain it against the near-continual mass loss resulting from ice precipitation[48]. As a result, local feedbacks between cloud droplets, radiation and turbulence, in conjunction with moisture inversions near the cloud top, can lead to persistence of Arctic mixed-phase clouds even in cases when the cloud layer is decoupled from surface energy and moisture sources[48]. For mixed-phase clouds that are dynamically coupled to the surface, feedbacks between clouds and the surface can also lead to resilience[51]. Supercooled liquid water can induce surface longwave radiative warming and atmospheric cooling, decreasing static stability and increasing fluxes of surface sensible heat and moisture[51,52]. These fluxes, whose magnitude depends on surface type, in turn provide energy and moisture that can help to maintain the cloud layer (Fig. 2b). This source of moisture also helps to balance the loss of water from ice precipitation for clouds that persist in the absence of humidity inversions[23,45].

Impact of aerosols

Atmospheric aerosol particles can influence the persistence of Arctic mixed-phase clouds by affecting cloud microphysical characteristics. These aerosol-related feedbacks further complicate the web of process interactions, perhaps much more so than in warm liquid-phase clouds[53]. Ice formation at mixed-phase cloud temperatures (−40° to 0° C) involves a subset of aerosol particles with heterogeneous ice-nucleating properties (ice nuclei). Although many details of ice nucleation are poorly understood, enough knowledge exists to draw first-order conclusions[36,54–57]. Concentrations of cloud condensation nuclei (CCN; aerosol particles that nucleate liquid cloud droplets) range from about 10 to 1,000 cm^{-3}, whereas concentrations of ice nuclei are typically much lower (10^{-5} to 0.1 cm^{-3}), meaning that only about one in a million particles acts as an ice nucleus[57]. The concentration of ice particles and hence ice nuclei is critical for mixed-phase clouds because it impacts the WBF process[21,32,33,36,42,45,46]. Modelling studies have shown that even modest increases in the concentration of ice can lead to rapid conversion of mixed-phase clouds to all-ice clouds[21,32,33,36,45].

The liquid phase itself may play a self-regulating role in the production of ice particles. Observations indicate that not only are ice concentration and the presence of large drops correlated[22,58–60], but ice particles typically form only after supercooled liquid water is present, despite highly ice-supersaturated conditions before the appearance of liquid[61]. Indeed, ice-only clouds occur much less frequently than mixed-phase clouds at temperatures higher than about −25° to −15 °C (refs 18,61). If ice formation is indeed initiated by the presence of liquid droplets, this represents a negative feedback that helps to maintain the clouds. Specifically, as ice formation ensues, liquid water is depleted, which then suppresses ice formation and prevents excessive loss of supercooled water from ice growth (Fig. 2c). Furthermore, maintenance of supercooled water depends on the gravitational fallout of ice, which removes ice from the cloud layer and hence restricts its ability to compete with liquid droplets for available water vapour[32,40,62].

Other aerosol influences occur through changes in CCN concentration and impacts on the concentration and size of cloud droplets (Fig. 2). For example, increased aerosol loading associated with transport from mid-latitudes increases cloud-droplet concentration and hence longwave radiative emissivity of thin clouds (all else being equal)[8,63,64]. The subsequent increase in downwelling longwave radiation can result in surface warming[63,64], which may increase surface turbulent fluxes and provide a greater source of moisture. More recent work[8] suggests that increased aerosol concentration, by enhancing cloud emissivity, accelerates the positive feedback loop between cloud-top radiative cooling, turbulence and condensation of cloud liquid. Moreover, cloud-droplet size and concentration also affect the rate at which liquid is removed through collection (and subsequent freezing) by falling ice particles[65,66]. Modelling studies of subtropical, liquid-phase stratocumulus clouds have shown the influence of droplet size on gravitational fallout of liquid, which impacts cloud-top radiative cooling and entrainment[67,68]. Although there has been less focus on these interaction pathways in Arctic mixed-phase clouds, it is reasonable to assume that they might be important[48].

Dynamics of the system

Various process interactions and their roles in shaping the emergent behaviour of persistent Arctic mixed-phase clouds are synthesized in the conceptual model shown in Fig. 3. These interactions tend to organize the cloud system into a distinct, quasi-steady structure consisting of one or more fairly thin layers containing supercooled water droplets and ice crystals, with larger ice crystals falling below the liquid-containing layer. Supercooled water near the cloud top drives radiative cooling and production of turbulence, maintaining the cloud in a well-mixed layer capped by temperature and often moisture inversions at, or just above, the cloud top[49,50]. Resilience of these clouds also depends on resupply of water vapour from the surface and/or from entrainment of moisture above the inversion[48], which balances the loss of moisture from ice precipitation and keeps the cloud system in a quasi-steady state. Several features contrast with lower-latitude, mid-level mixed-phase clouds (for example, surface coupling, presence of moisture inversions and relatively weak solar heating), probably explaining at least in part the longevity of Arctic mixed-phase clouds compared with their mid-latitude counterparts, which tend to dissipate rapidly in the presence of large-scale subsidence[17]. Additional pathways, some of which appear in Fig. 2, play a role in the maintenance and organization of Arctic mixed-phase clouds, and it remains a major task to understand and quantify this intricate web of process interactions.

Given the numerous, tightly coupled process interactions depicted in Fig. 2, it is particularly difficult to predict how the cloud system will behave. Because these interactions are nonlinear and interlinked in many ways, poor understanding of any one process or its interactions may have important consequences for comprehending the overall system behaviour. Two scientific lines of enquiry can be applied to complex systems of this kind. In the reductionist approach, the system is reduced to the sum of the interactions between its parts. However, when a complex system manifests emergence, that is, general behaviour that cannot be described by the sum of the component interactions of the system, a systems-based approach may prove fruitful[69]. The tendency for mixed-phase Arctic clouds to maintain themselves in spite of their inherent microphysical instability is suggestive of emergent qualities. It also evokes properties of self-organization, defined as "internal, local process interactions giving rise to global order"[70]. The distributed nature of these interactions results in a robust system that is resilient to perturbation.

Self-organization prevails in a range of natural and man-made systems. Examples include oscillating chemical reactions[71], flock behaviour among bird populations, predator–prey interactions in the fields of ecology[72] and cloud physics[73], light amplification by stimulated emission of radiation, and computer network theory[74]. In the subtropics and mid-latitudes, cloud fields associated with mesoscale convection often present themselves as closed- or open-cellular patterns[75,76], exhibiting system-wide order emerging from local interactions. Self-organized systems often have a number of preferred states or attractors[77]. The subtropical marine boundary layer provides a vivid example of self-organization around two distinct states: the high-albedo, closed-cell cloud state and the precipitating, low-albedo, open-cell cloud state[76,78–81]. The system selects the preferred state based, among other things, on environmental conditions or external forcing. Small perturbations often strengthen state robustness by allowing further phase-space exploration in the vicinity of the attractor, whereas large perturbations may cause the system to transition from one preferred state to another[73].

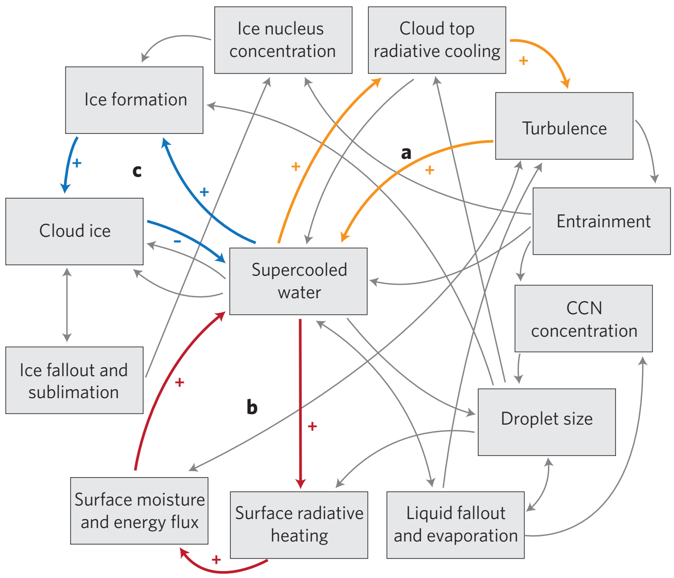

Figure 2 | Processes associated with Arctic mixed-phase clouds are linked through a complex web of interactions and feedbacks. In this diagram, the arrows signify the direction of influence of interactions between various physical quantities and processes. Not all important associations are included. Three specific interaction pathways (labelled a, b and c) are highlighted by coloured arrows and discussed in greater depth in the text. Signs (+ or -) indicate the expected response (increase or decrease) of the receiving element.

In the central Arctic, observations provide evidence for the existence of two preferred, quasi-steady states corresponding to radiatively clear (clear sky or radiatively thin clouds) or opaquely cloudy conditions that persist for up to 10 to 14 days[82]. To further illustrate these two states, data from the Surface Heat Budget of the Arctic Ocean (SHEBA) experiment[83,84] are analysed for the period from 1 November 1997 to 26 May 1998, similar to ref. 82. Figure 4a shows a joint probability density function of net surface longwave radiation (downwelling minus upwelling) and surface pressure based on hourly measurements[84]. We are primarily concerned here with persistent mixed-phase clouds under relatively weak synoptic-scale forcing. Therefore, our analysis excludes times when there is cloud cover above three kilometres in altitude, to minimize the impact of deep clouds driven by strong but short-lived forcing associated with the passage of cyclones and fronts. This diagram indicates a distinct clustering of points around two regions of the phase space: near $0\,W\,m^{-2}$ and near $-40\,W\,m^{-2}$ net surface longwave radiation. Points near $-40\,W\,m^{-2}$ correspond to the radiatively clear state, whereas those near $0\,W\,m^{-2}$ correspond to the opaquely cloudy state[82]. Although the opaquely cloudy state in Fig. 4a includes instances of all-ice clouds, it is dominated by mixed-phase clouds; for this dataset, supercooled liquid water occurred 84% of the time when the net surface longwave radiation was greater than $-20\,W\,m^{-2}$, with ice usually but not always present. The two preferred states are also apparent in distributions of surface temperature, sensible heat fluxes, and atmospheric humidity and temperature structure[82].

State stability and selection

The key question, then, is what conditions select the occurrence of the opaquely cloudy, mixed-phase cloud state? Although this state

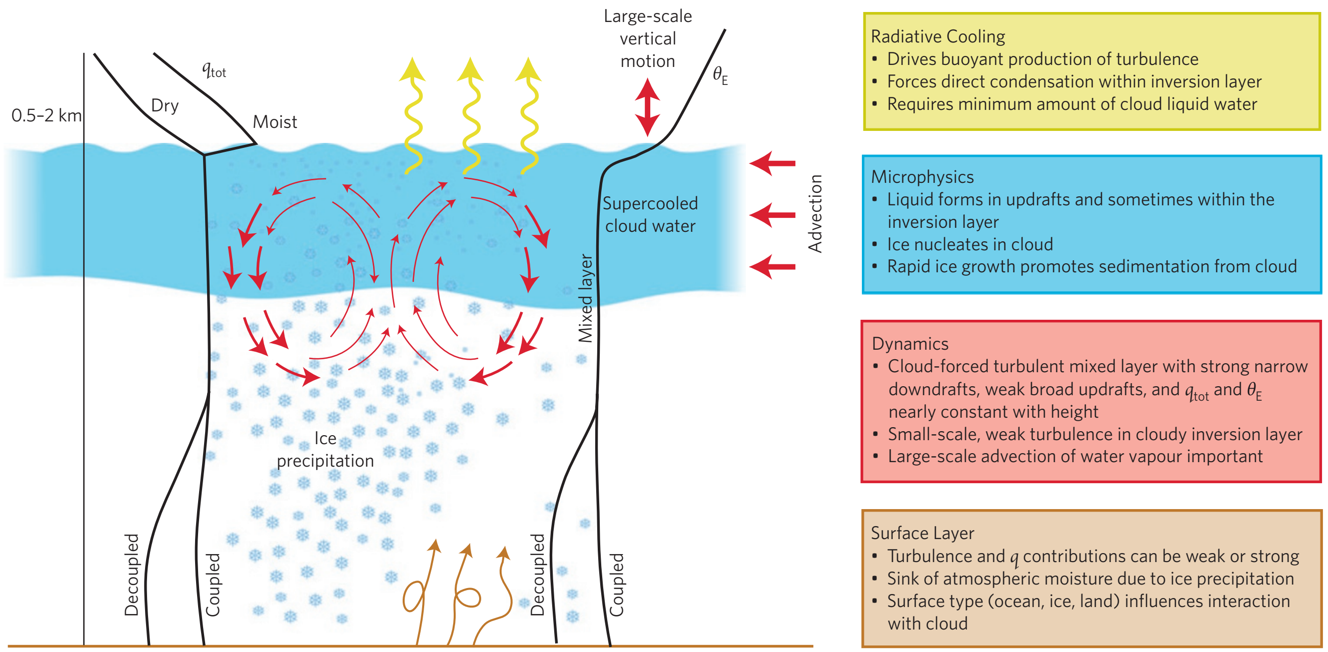

Figure 3 | A conceptual model that illustrates the primary processes and basic physical structure of persistent Arctic mixed-phase clouds. The main features are described in text boxes, which are colour-coded for consistency with elements shown in the diagram. Characteristic profiles are provided of total water (vapour, liquid and ice) mixing ratio (q_{tot}) and equivalent potential temperature (θ_E). These profiles may differ depending on local conditions, with dry versus moist layers/moisture inversions above the cloud top, or coupling versus decoupling of the cloud mixed layer with the surface. Cloud-top height is 0.5–2 km. Although this diagram illustrates many features, it does not fully represent all manifestations of these clouds.

is resilient and often lasts for several days[18,23–26], transitions between it and the radiatively clear state typically occur over timescales of hours or less[52]. These transitions are accompanied by sharp changes in clouds, turbulence, radiation, surface energy budget and atmospheric thermodynamic profiles. Observed time trajectories of one to five days from SHEBA (Fig. 4b) provide examples of transitions between radiatively clear conditions and low-level mixed-phase clouds (or vice versa) in the phase space of net surface longwave radiation versus surface pressure, similar to ref. 82. These trajectories show the system slowly evolving within either the mixed-phase state (with net longwave radiation near $0\,\mathrm{W\,m^{-2}}$) or radiatively clear state (with net longwave radiation near $-40\,\mathrm{W\,m^{-2}}$), until it rapidly transitions to the other state. Thus, system evolution seems to be influenced both by slow- and fast-timescale processes. Slow-timescale processes are generally associated with the large-scale meteorological environment (for example, large-scale advection of water vapour shown in the conceptual model; Fig. 3), with a characteristic timescale on the order of a day or longer. Fast-timescale processes are associated with local process interactions between clouds, radiation, aerosol, turbulence and the surface as depicted in Fig. 2, with characteristic timescales on the order of one hour or less. Although fast processes typically interact in ways that lead to resilience of the state, they can drive rapid evolution and transition between states if these interaction pathways are disrupted[45]. The importance of both fast- and slow-timescale processes may explain why it has been difficult to clearly relate these Arctic states to large-scale environmental conditions. For example, despite being able to correlate the opaquely cloudy and radiatively clear states with surface pressure, the authors[82] were unable to identify specific processes or mechanisms that explain this relationship.

Interactions between fast-timescale, local processes and slow-timescale, large-scale environmental processes have been described for subtropical marine boundary layer clouds[85,86]. These interactions tend to occur along slowly evolving surfaces in phase space, called slow manifolds[86]. Slow manifolds may also be a helpful way to understand interaction of the persistent mixed-phase cloud state with the large-scale Arctic environment. In the examples shown in Fig. 4b, individual time trajectories of observed net surface longwave radiation and surface pressure from SHEBA[82] evolve along slow manifolds corresponding to either the mixed-phase or radiatively clear state as the large-scale environment (in this illustration, surface pressure) changes. This slow evolution is punctuated by sudden transition from one state to the other, followed again by slow evolution along the other manifold. (Note, however, that not all transitions between these two states follow such clear paths.) We hypothesize that local process interactions, as depicted in Fig. 2 for the mixed-phase cloud state, tend to keep trajectories 'slaved' to the slow manifolds[86], leading to resilience and persistence of the states. However, if changes to the large-scale environment are significant enough to disrupt these local process interactions, then transition between the manifolds may occur.

Large eddy simulations of the Arctic boundary layer[45,48] provide support for this hypothesis. For example, the mixed-phase state can be maintained by local process interactions even when there is a drying of the large-scale environment through advection and precipitation[48], but if the drying is large enough and supercooled water is reduced below the amount required to maintain sufficient cloud-top radiative cooling and production of turbulence, rapid transition to the radiatively clear state occurs[45]. Similar transition from a well-mixed, stratocumulus-topped boundary layer to a partly cloudy, decoupled boundary layer occurs in the subtropical marine environment when cloud water and hence radiative cooling are sufficiently reduced[86].

Limitations

Our understanding of Arctic mixed-phase clouds has progressed significantly over the past few decades, but a number of unresolved issues remain. As in other geographical regions, the primary concern is that of relating the statistical properties of clouds to the larger-scale meteorological environment[87,88].

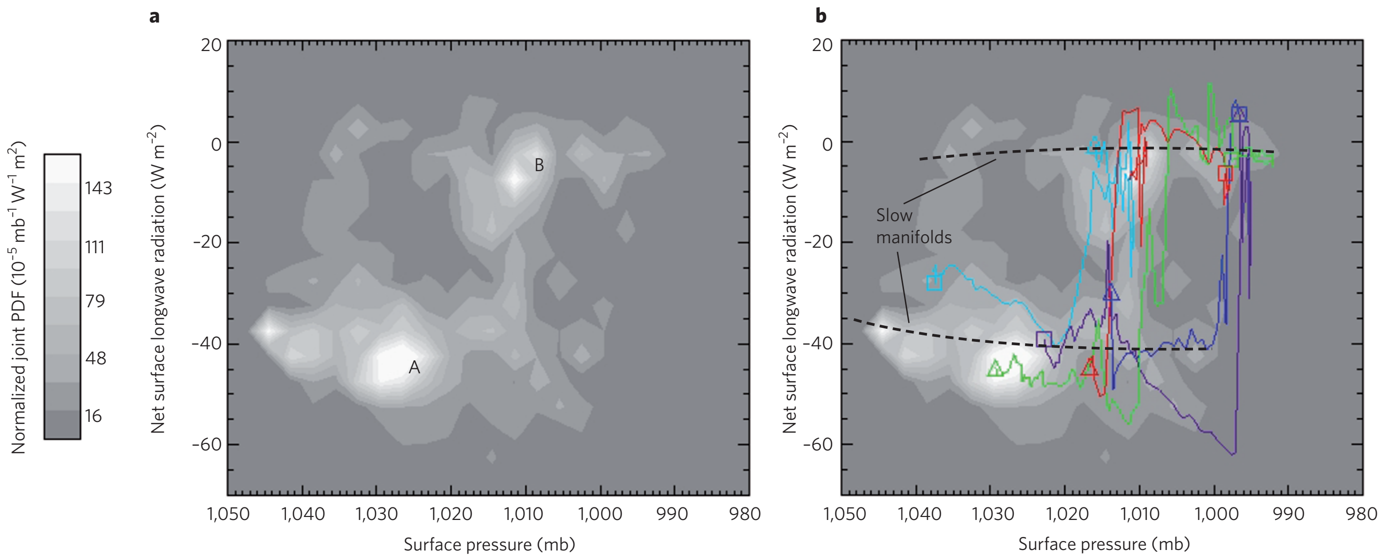

Figure 4 | Preferred Arctic states evident from observations of net surface longwave radiation. a, A normalized joint probability density function (PDF) of longwave radiation and surface pressure is derived from hourly SHEBA measurements[84] over the period from 1 November 1997 to 26 May 1998, excluding periods with clouds above three kilometres in altitude. The two preferred states[82] correspond to PDF maxima indicated by A (radiatively clear) and B (opaquely cloudy). **b**, The PDF in the left panel superimposed with five different time series of longwave radiation versus surface pressure over periods of one to five days (coloured lines) illustrates transition between the states. Triangles and squares indicate the start and end of the time series, repectively.

Relationships between cloud properties and the thermodynamic structure of the Arctic environment are difficult to characterize owing to the remoteness and inaccessibility of the region. Cloud properties retrieved from ground-based radars, lidars and radiometers, along with radiosonde thermodynamic profiles, were used to generate the statistical datasets on which many of the ideas presented in this Review are based. Unfortunately, crucial properties, such as the cloud-top liquid water profile[89] are poorly characterized owing to limitations of these observations.

Further insight into cloud microphysical properties has been gleaned from aircraft campaigns[21,25,27,34]. However, instruments flown during these campaigns carry large uncertainty when it comes to the counting and sizing of particles[21,23,56]. Ice nucleus concentrations and details of active freezing mechanisms are perhaps the greatest source of uncertainty. Laboratory experiments on ice nucleation[90,91] that explore links between aerosol composition and cloud-droplet freezing are sorely needed.

Despite the system complexity and observational limitations, there is evidence for the existence of two distinct, persistent Arctic states corresponding to radiatively clear and opaquely cloudy mixed-phase conditions (Fig. 4). The specific meteorological conditions that favour each state are uncertain. However, parameters related to synoptic-scale circulation — such as large-scale vertical velocity (or subsidence), and heat and moisture transport — are likely to be important. Relating these two states to the large-scale Arctic environment has proved challenging[82], possibly owing to interactions between fast processes associated with local interactions, and slow processes associated with the wider meteorological environment. Large differences in the heat and moisture fluxes over the open ocean and sea ice may also play a role in selecting these states. For example, negative correlations between cloud and sea-ice coverage in satellite observations support the idea that increased surface heat and moisture fluxes during ice-free periods result in increased cloud cover[92].

State selection is further complicated by potential feedbacks between the large-scale environment, surface and clouds. For example, cloud-induced changes in surface properties such as sea-ice extent[12,93] can result in either a positive or negative feedback on cloud occurrence. Changes in upper-ocean heat content caused by changes in ice extent, and resultant changes in the absorption of solar radiation[94], may further alter interactions between the surface and clouds. Additional feedbacks between clouds and the large-scale atmospheric circulation may result, for example, from changes in precipitation and subsequent impacts on atmospheric moisture content and radiative cooling[95]. Multiscale models that address interactions on scales of hundreds of kilometres down to tens of metres[48], together with detailed statistical analyses of the relationship between the two states, the large-scale environment and the surface, are likely to be of great value in quantifying the importance of these various interactions.

Outlook

It has proved challenging to correctly simulate Arctic mixed-phase clouds in climate models. Misrepresentation of these clouds results in errors in surface and top-of-the-atmosphere radiation in model simulations, impacting surface and atmospheric energy budgets[34,36,38]. This reduces confidence in the ability of these models to predict future climate and changes in other components of the Arctic system. It is particularly important to simulate cloud occurrence accurately in assessments of Arctic climate, given the significant difference in net surface radiation between the radiatively clear and opaquely cloudy mixed-phase states. For example, net longwave radiation differs by roughly 30–40 $\mathrm{W\,m^{-2}}$ between these two states, based on the SHEBA dataset shown in Fig. 4. Thus, only a 5% shift in the frequency of occurrence from the radiatively clear state to the opaquely cloudy mixed-phase state would result in an overall increase in net surface longwave radiation of about 1.5–2 $\mathrm{W\,m^{-2}}$, all else being equal. A shift of this magnitude would influence the surface energy budget and probably reduce winter sea-ice thickness[15]. Furthermore, changes in the occurrence of mixed-phase clouds in summer could influence surface shortwave radiation, thereby impacting sea-ice[12] and permafrost[96,97] stability, freshwater runoff through rivers, and productivity and diversity in marine and terrestrial environments[98,99]. These examples reinforce the need for improved understanding of how the large-scale environment influences the mixed-phase cloud state, so that we can better understand the role of these clouds in a changing Arctic setting.

Given the sensitivity of the Arctic system to climate change, it is imperative that we continue to pursue the factors regulating and sustaining mixed-phase clouds using a range of observational, modelling and conceptual approaches that have proved successful in predicting the characteristics of other complex systems. In particular, a merging of reductionist and systems-based approaches[69] may prove useful.

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Additional information

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