Resilience of persistent Arctic mixed-phase clouds

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Hugh Morrison[1]*, Gijs de Boer[2,5], Graham Feingold[3], Jerry Harrington[4], Matthew D. Shupe[5] and Kara Sulia[4]

Affiliations:

[1]Mesoscale and Microscale Meteorology Division, NCAR Earth System Laboratory, National Center for Atmospheric Research, 3450 Mitchell Lane, Boulder, CO 80307

[2]Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, MS90KR121, 1 Cyclotron Road, Berkeley, CA 94720

[3]Earth System Research Laboratory, Chemical Sciences Division, National Oceanic and Atmospheric Administration, 325 Broadway, Boulder, CO 80305

[4]Department of Meteorology, Pennsylvania State University, 517 Walker Building, University Park, PA 16802

[5]University of Colorado Cooperative Institute for Research in Environmental Sciences, NOAA Earth System Research Laboratory, Physical Sciences Division, R/PSD3, 325 Broadway, Boulder, CO 80305

*Corresponding author (morrison@ucar.edu)

The Arctic is particularly sensitive to climate change, with potentially dramatic consequences for the regional ecosystem. Arctic mixed-phase clouds, comprising both ice and supercooled liquid water, have been observed to occur frequently in all seasons and persist for many days at a time. They have a large impact on the shortwave and longwave radiative transfer, and consequently play an important role in regulating the flow of energy in the system. Due to the inherent instability of ice-liquid coexistence, the persistence of these clouds is remarkable. We review the literature on Arctic mixed-phase clouds and develop a conceptual model of their existence. Complex feedbacks between various local processes related to supercooled liquid water, radiation, turbulence, entrainment, surface heat and moisture fluxes, aerosol, and ice microphysics collude to create a resilient cloud system. Despite this complexity, the mixed-phase cloud state exhibits distinct emergent properties, likely related to interactions with the large-scale meteorological environment. It is inferred that changes in the frequency of mixed-phase cloud occurrence caused by an altered large-scale environment could have a large impact on surface radiative fluxes and hence the energy budget and evolution of sea ice.

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 hypothesised 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]. Since clouds impact downwelling solar and longwave radiative fluxes, cloud-radiation feedbacks are inextricably linked with 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 last 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 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 cloud 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 due to their longevity[18]. They persist under a variety of conditions, including weak synoptic-scale forcing and large-scale subsidence[18,21,23,25] (i.e., 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 vapor pressure than liquid, meaning that when ice and water coexist at subfreezing temperatures, liquid droplets evaporate and release water vapor allowing ice crystals to grow by vapor deposition, unless there is enough cooling or moistening to maintain liquid saturation. The growth of ice by vapor 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 at 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

Modeling and theoretical studies have attempted to explain the counterintuitive persistence of Arctic mixed-phase clouds despite microphysical instability arising from the WBF mechanism. Turbulence and cloud-scale upward air motion appear 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 day^{-1} near 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 liquid water-radiative-turbulence feedback pathway (Fig. 2, pathway A).

Further sustenance for these mixed-phase cloud layers is gained by moisture associated with large-scale advection which results in frequent moisture inversions near 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 due to ice precipitation[48]. As a result, local feedbacks between cloud droplets, radiation, and turbulence, in conjunction with moisture inversions near 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 surface sensible heat and moisture fluxes[51,52]. These fluxes, whose magnitude depends upon surface type, in turn provide energy and moisture that can help to maintain the cloud layer (Fig. 2, pathway B). 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 the aerosol

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^{o} to 0^{o} C) involves a subset of aerosol particles with heterogeneous ice-nucleating properties (ice nuclei, or IN). Although many details of ice nucleation are poorly understood, enough knowledge exists to draw first-order conclusions[36,54-57]. Cloud condensation nuclei (CCN; aerosol particles that nucleate liquid cloud droplets) concentrations range from about 10-1000 cm^{-3}, while IN concentrations are typically much lower (10^{-5} – 0.1 cm^{-3}), meaning that only about 1 in a million particles acts as an IN[57]. The concentration of ice particles and hence IN is critical for mixed-phase clouds because it impacts the WBF process[21,32,33,36,42,45,46]. Modeling 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 the presence of large drops and ice concentration are not only correlated[22,58-60], but also that ice particles typically form only after supercooled liquid water is present, despite highly ice-supersaturated conditions prior to 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[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 supercooled water loss from ice growth (Fig. 2, pathway C). In addition, maintenance of supercooled water depends on gravitational fallout of ice, which removes ice from the cloud layer and hence restricts the ability of ice to compete with liquid droplets for available water vapor[32,40,62].

Other aerosol influences occur through changes in CCN concentration and impacts on cloud droplet concentration and size (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 the collection (and subsequent freezing) by falling ice particles[65,66]. Modeling studies of sub-tropical, 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 synthesised in the conceptual model shown in Fig. 3. These interactions tend to organise 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 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, cloud top[49,50]. Resilience of these clouds also depends on resupply of water vapor 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 (e.g., surface coupling, presence of moisture inversions, relatively weak solar heating), likely explaining at least in part the longevity of Arctic mixed-phase clouds compared to their lower-latitude, mid-level 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 organisation of these clouds, and it remains a major task to understand and quantify this intricate web of process interactions.

Given the multiple, 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 numerous ways, poor understanding of any one process or its interactions may have important consequences for understanding 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,* i.e., 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 the inherent microphysical instability is suggestive of emergent qualities. It also evokes properties of "self-organisation", defined as "internal, local process interactions giving rise to global order"[70]. The distributed nature of these interactions results in a system that is robust, i.e., it is resilient to perturbation.

Self-organisation prevails in a range of natural and man-made systems. Examples include oscillating chemical reactions[71], flock behaviour amongst bird populations, predator-prey behaviour in the fields of ecology[72] and cloud physics[73], light amplification by stimulated emission of radiation, and computer network theory[74]. In the sub-tropics 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-organised systems often have a number of preferred states or attractors[77]. The sub-tropical 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, inter alia, on environmental conditions or external forcing. Small perturbations often strengthen state robustness by allowing further phase-space exploration in the vicinity of the attractor, while large perturbations may cause the system to transition from one preferred state to another[73].

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 10-14 days[82]. To further illustrate these two states, data from the Surface Heat Budget of the Arctic Ocean experiment (SHEBA)[83,84] are analyzed for the period Nov. 1, 1997, to May 26, 1998, similar to ref. 82. Figure 4a shows a joint probability density function of net surface longwave radiation (LW) (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 3 km 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 LW. Points near -40 W m^{-2}

correspond to the radiatively-clear state, while 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 LW 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 this opaquely-cloudy, mixed-phase cloud state? While this state 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 1-5 day time trajectories 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 LW versus surface pressure, similar to ref. 82. These trajectories show the system slowly evolving within either the mixed-phase state (with net LW near 0 W m^{-2}) or radiatively-clear state (with net LW near -40 W m^{-2}), until it rapidly transitions to the other state. Thus, system evolution appears to be influenced by both slow and fast timescale processes. Slow timescale processes are generally associated with the large-scale meteorological environment (e.g., large-scale advection of water vapor 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. While 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 sub-tropical marine boundary layer clouds[85,86]. These interactions tend to occur along slowly-evolving surfaces in phase space, or "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 LW and surface pressure from SHEBA[82] evolve along slow manifolds corresponding to either the mixed-phase state 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 hypothesise that local process interactions, as depicted in Fig. 2 for the mixed-phase 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 sub-tropical marine environment when cloud water and hence radiative cooling are sufficiently reduced[86].

Remaining uncertainties, outlook, and implications for climate

The past decades of research reviewed here provide evidence of significant progress in our understanding of Arctic mixed-phase clouds but expose a number of unresolved issues. As in other geographical regions, the primary concern is one of relating statistical properties of clouds to the larger-scale meteorological environment[87,88]. A recent review[53] proposed a regime-based approach to help constrain the meteorological context of aerosol-cloud interactions. In this regard, the Arctic represents a regime with distinct meteorological characteristics, and given its sensitivity to climate change, one that requires special attention.

Characterisation of the relationship between cloud properties and thermodynamic structure of the Arctic environment is hampered by remoteness and inaccessibility. Regional model reanalyses suffer from a lack of observational constraints[89]. Cloud properties retrieved from ground-based radars, lidars and radiometers at long-term monitoring sites and experiments (e.g., Barrow, Alaska; Eureka, Nunavut, Canada; SHEBA), along with radiosonde thermodynamic profiles, have provided statistical data sets upon which many of the ideas presented here are based. Unfortunately, limitations to these observations still lead to a relatively poor characterisation of crucial properties such as the liquid water profile near cloud-top[90] which is responsible for cloud maintenance through radiatively–driven turbulence. Further insight into cloud microphysical properties has been gleaned from aircraft campaigns[21,25,27,34]. However, even sophisticated in-situ cloud probes flown during these campaigns carry large uncertainties in counting and sizing particles[21,23,56]. Ice nucleus concentrations and details of active freezing mechanisms are perhaps the most significant uncertainty. There exist only a handful of instruments capable of making IN measurements[57] and relating their data to in-cloud conditions and specific ice nucleation mechanisms is challenging. More laboratory experiments on ice nucleation[91,92] that explore links between aerosol composition and droplet freezing are sorely needed.

In spite of the process-level complexity (Fig. 2) and often limited observational constraints, the persistence of distinct Arctic states[82] indicates that the problem may be more tractable than the complexity suggests. To the extent that we can observe distinct emergent properties of the system using phase diagrams such as Fig. 4, a key question is how these states are selected. Given the correlation of these states with surface pressure[82], parameters related to synoptic-scale circulation, such as large-scale vertical velocity (or subsidence) and heat and moisture transport, are likely to be important. However, relating these preferred states to the large-scale Arctic environment has proven challenging, plausibly because of the interaction of fast and slow timescale processes. Large differences between open-ocean and sea ice surface heat and moisture fluxes may also play a role in selecting these states. For example, negative correlation between cloud and sea ice coverage in satellite observations supports the idea that increased surface heat and moisture fluxes during ice-free periods result in increased cloud cover[93].

State selection in the context of the systems-based approach is complicated by potential feedbacks between the large-scale environment, surface, and clouds. For example, changes in the surface type induced by clouds[12,94] may in turn alter cloud and boundary layer characteristics[9], representing either a positive or negative feedback depending in part on whether longwave or shortwave cloud radiative forcing is dominant (leading to either surface warming or cooling, respectively). Increased upper ocean heat content resulting from greater absorption of solar radiation during longer periods of ice-free conditions[95] may further alter interactions between the surface and clouds. Additional feedbacks between clouds and large-scale atmospheric circulation may occur, for example, through changes in low-level radiative cooling caused by increased precipitation and subsequent drying (i.e., the Arctic “dehydration-greenhouse” feedback[96]). Multiscale models that address scale interactions from 100s of km down to 10s of m (ref. 48), together with detailed statistical analyses of the relationship of these states to the large-scale environment and surface, are likely to be of great value in quantifying the importance of these interactions. Such modeling could also address the role of mesoscale circulations (with scales of roughly a few km to 100 km) and their impact on mixed-phase cloud resilience, which remains largely unexplored.

For reasons articulated above, it has proven challenging for climate models to correctly simulate Arctic mixed-phase clouds. Misrepresentation of these clouds results in errors in surface and top-of-the-atmosphere radiation, impacting surface and atmospheric energy budgets[34,36,38]. This reduces confidence in the ability of these models to predict future climate and changes to other components of the Arctic system. Model predictive capability is particularly important for understanding Arctic climate because of the significant difference in net surface radiation between the radiatively-clear and opaquely-cloudy, mixed-phase states. For example, net LW radiation differs by roughly 30-40 W m^{-2} between these states based on the SHEBA dataset shown in Fig. 4. Thus, only a 5% shift in frequency of occurrence from the radiatively-clear state to the mixed-phase state would result in an overall increase in net surface LW of about 1.5-2 W m^{-2}, all else being equal. Such a shift would influence the surface energy budget and likely reduce winter sea-ice thickness[15]. Furthermore, changes in mixed-phase cloud occurrence in summer could influence surface shortwave radiation, thereby impacting melt of sea ice[12] and permafrost[97,98], freshwater run-off through rivers, and productivity and diversity of the oceanic and terrestrial biospheres[99,100]. These examples reinforce the need for improved understanding of how the mixed-phase cloud state is related to the large-scale environment so that we can better understand the role of these clouds in a changing environment.

Given the sensitivity of the Arctic system to climate change, it is imperative that we continue to pursue this problem with both existing and new observational strategies, numerical modeling efforts, and conceptual approaches that have proven successful in predicting the characteristics of other complex systems. In particular, a merging of reductionist and systems-based approaches[69] may prove useful.

Author contributions

The ideas herein were jointly conceived at multiple roundtable discussions. All authors participated in the writing of the paper and drafting of figures, with HM coordinating the effort. Other authors are listed alphabetically.

Additional information

The authors declare no competing financial interests.

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Author to whom correspondence should be addressed: Hugh Morrison

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Figure legends.

Figure 1 | Cloud radar and lidar indicate 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 due to ice precipitation. Cloud radar reflectivity (top), Z_e, 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.

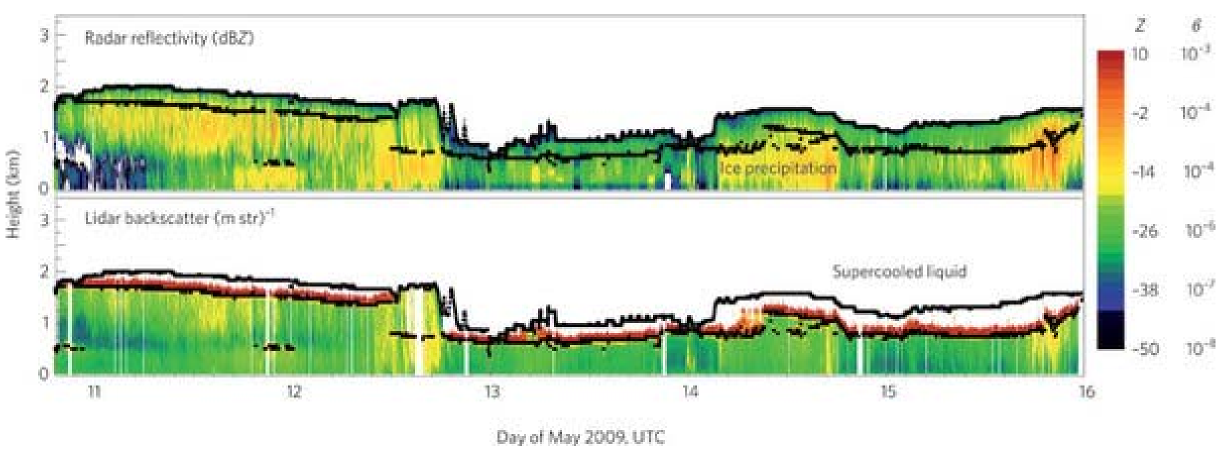

Figure 2 | Processes associated with Arctic mixed-phase clouds are linked through a complex web of interactions and feedbacks. In this diagram, arrows signify the direction of influence of interactions between various physical quantities (boxes) and processes (ovals). Signs (+ or -) indicate the expected response (increase or decrease) of the receiving element. Colour-coding relates to the type of process or quantity involved and is consistent with the colours and descriptions in Fig. 3. Not all important associations are included in this diagram, while three specific interaction pathways (labeled **A**, **B**, and **C**) are highlighted and discussed in greater depth in the text.

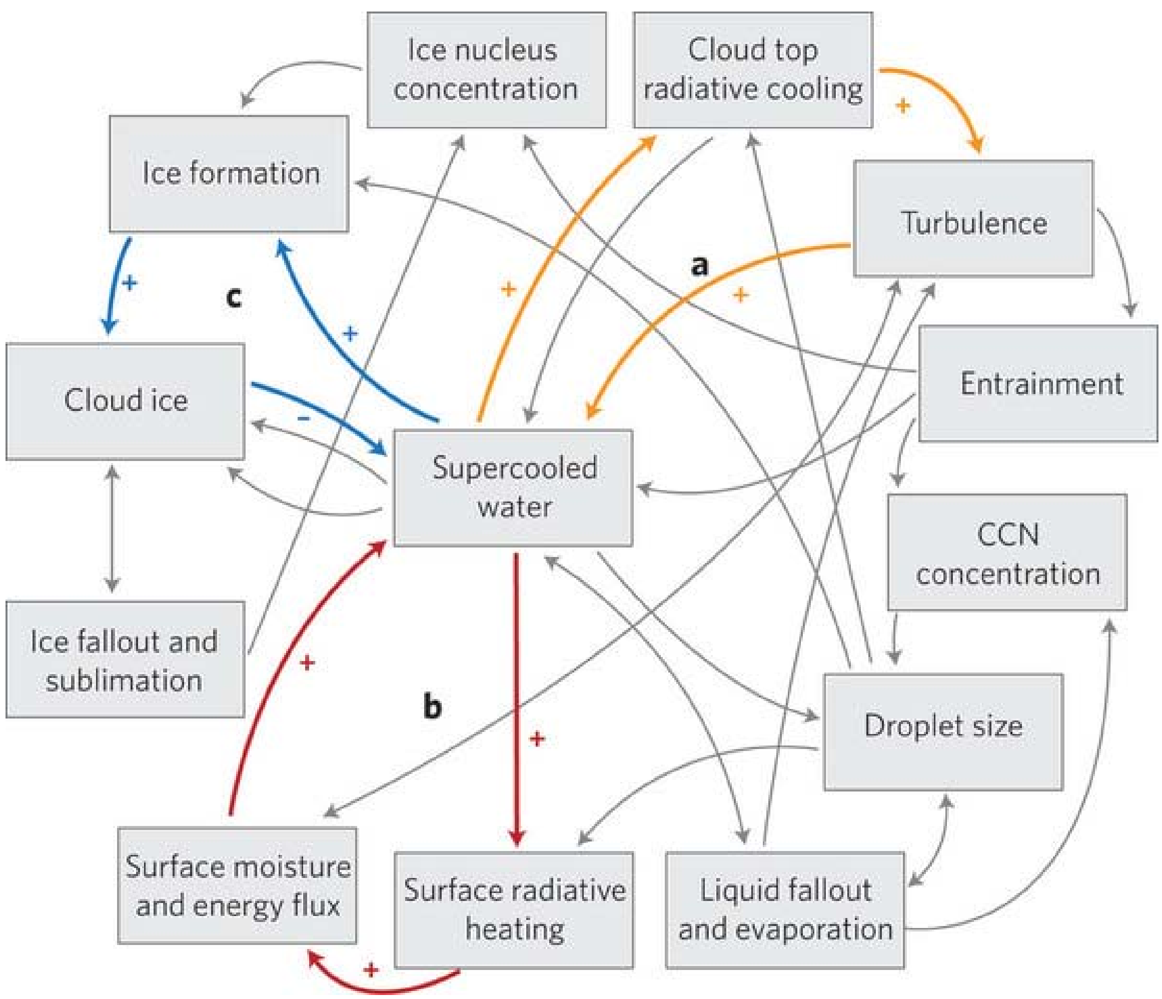

Figure 3 |A conceptual model illustrates the primary processes and basic physical structure of persistent Arctic mixed-phase clouds. The main schematic elements are described in text boxes colour-coded for consistency with Fig. 2 (e.g., microphysical quantities are in blue). Characteristic profiles are provided of cloud liquid (q_{liquid}), ice (q_{ice}), and water vapor (q_{vapor}) mixing ratios, and equivalent potential temperature (θ_E). These profiles may differ depending upon local conditions (e.g., dry vs. moist layers/moisture inversions above cloud top or surface coupling vs. decoupling). While this diagram illustrates many features, it does not fully represent all manifestations of these clouds.

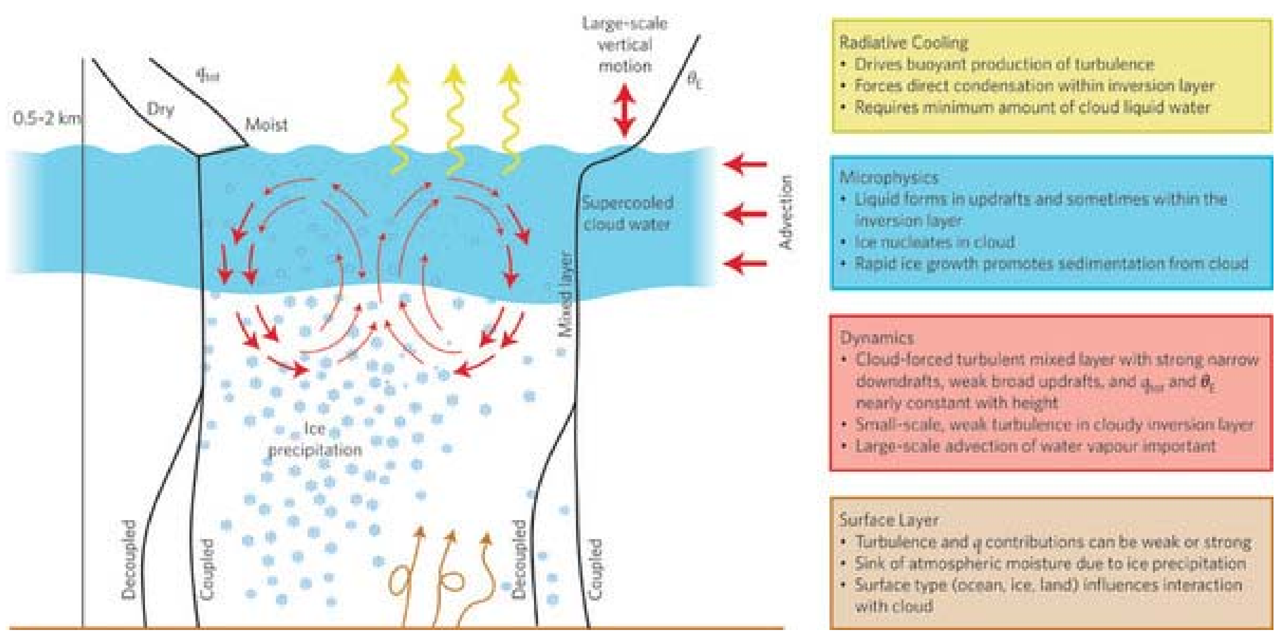

Figure 4 | Preferred Arctic states are evident from observations of net surface longwave radiation (LW). a: A normalised joint probability density function (PDF) of LW and surface pressure is derived from hourly SHEBA measurements[84] over the period Nov. 1, 1997 to May 26, 1998, excluding periods with clouds above 3 km. The two preferred states[82] correspond with PDF maxima indicated by **A** (radiatively-clear) and **B** (opaquely-cloudy). **b:** The PDF in the left panel superimposed with five different timeseries of LW versus surface pressure over 1-5 day periods (coloured lines) illustrates transition between the states. Triangles (squares) indicate start (end) of the timeseries.