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An arctic hydrologic system in transition: Feedbacks and impacts on terrestrial, marine, and human life

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[1] The pace of change in the arctic system during recent decades has captured the world's attention. Observations and model simulations both indicate that the arctic experiences an amplified response to climate forcing relative to that at lower latitudes. At the core of these changes is the arctic hydrologic system, which includes ice, gaseous vapor in the atmosphere, liquid water in soils and fluvial networks on land, and the freshwater content of the ocean. The changes in stores and fluxes of freshwater have a direct impact on biological systems, not only of the arctic region itself, but also well beyond its bounds. In this investigation, we used a heuristic, graphical approach to distill the system into its fundamental parts, documented the key relationships between those parts as best we know them, and identified the feedback loops within the system. The analysis illustrates relationships that are well understood, but also reveals others that are either unfamiliar, uncertain, or unexplored. The graphical approach was used to provide a visual assessment of the arctic hydrologic system in one possible future state in which the Arctic Ocean is seasonally ice free.

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1. Introduction

1.1. Global Relevance of the Arctic Hydrologic Cycle

[2] The hydrologic cycle is woven throughout the arctic's climate system, integrating physical, biological, and human elements. The influence of the arctic freshwater cycle spreads far beyond the boundaries of the region. Approximately 11% of the world's river runoff flows into the Arctic Ocean [*Gleick*, 2000]. Because ocean stratification is controlled primarily by salinity, the Arctic Ocean's vertical structure is governed by drainage from surrounding continents, exchanges with the saltier Atlantic and Pacific Oceans, and net precipitation onto its surface. Changes in sea-ice area affect, for example, the amount of insolation that is absorbed by the Earth. Variability in ice thickness modulates the amount of heat exchanged between the ocean and atmosphere. The freshwater flux into the North Atlantic, along with the formation of dense, salty water resulting from freezing, influences deepwater formation and thus the strength of ocean circulation around the globe. The nutrient-rich waters of the Arctic's peripheral seas are some of the most biologically productive on Earth; this productivity is affected by the delicate balance of near-surface stratification. Net precipitation is governed by moisture transport into the region by the atmosphere, which along with the permeability (or lack thereof) of the high-latitude soils, determines river runoff. This complex set of interactions between the atmosphere, land surface, ice, snow, and ocean determines the state of the freshwater cycle in the Arctic as well as the ultimate role it plays in the global climate. Figure 1 presents a schematic illustrating the main components and fluxes that compose the arctic freshwater system.

1.2. Sensitivity of Freshwater in the Arctic

[3] Water exists in all three phases in all seasons of the year in the Arctic. At interfaces between liquid and frozen states, the temperature hovers near the melting point, making the area's physical characteristics especially sensitive to changes in temperature. This sensitivity has been demonstrated in recent decades by large-scale changes in many aspects of the arctic climate system [e.g., *Overland et al.*, 2004; *White et al.*, 2007; *Hinzman et al.*, 2005; *Peterson et al.*, 2006; *Arctic Climate Impact Assessment* (*ACIA*),

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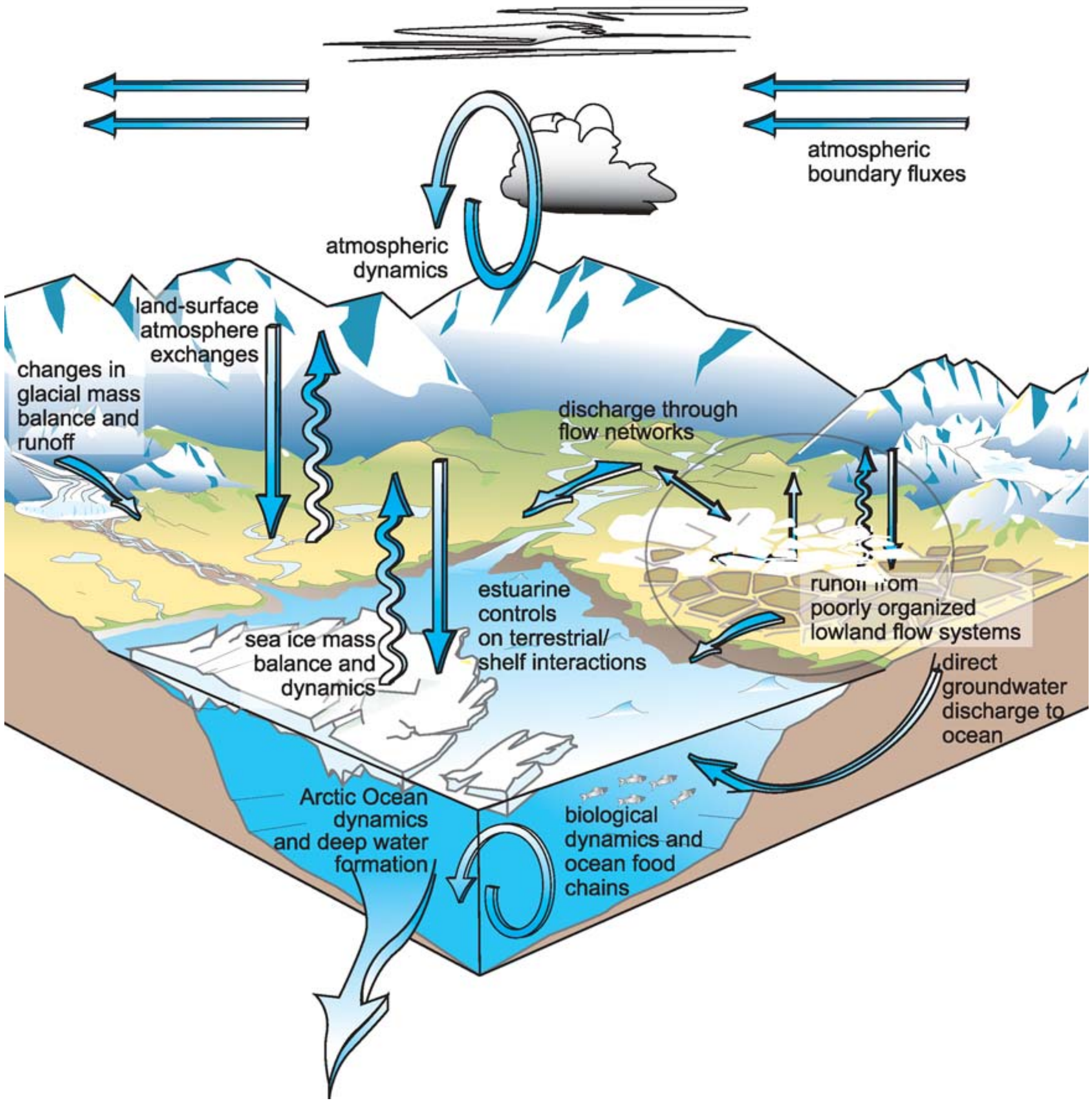

Figure 1. Schematic of the Arctic hydrologic system, including primary linkages among the atmosphere, ocean, ice, and land [from *Vörösmarty et al.*, 2001].

2005]. Warming in the arctic region is approximately double that of the globe, on average, during the past few decades [*Serreze and Francis*, 2006]. This so-called arctic amplification is believed to result from a number of mainly positive feedbacks in polar regions that are tied to phase changes of water. The best measured of these is the rapid loss of sea ice over the past several decades [e.g., *Serreze et al.*, 2007; *Maslanik et al.*, 2007; *Stroeve et al.*, 2007], along with retreating glaciers [e.g., *Oerlemans*, 2005], shrinking ice caps [e.g., *Rignot and Kanagaratnam*, 2006], warming and thinning permafrost [e.g., *Osterkamp*, 2005; *Romanovsky et al.*, 2002], and decreased snow cover [e.g., *Yang et al.*, 2003]. Runoff has increased from rivers that empty into the Arctic Ocean as has the export of freshwater out of the Arctic and into the North Atlantic [*McClelland et al.*, 2006; *Peterson et al.*, 2002; *Steele and Ermold*, 2007]. Changes in arctic vegetation have also been observed, likely resulting from the combined effects of temperature and precipitation changes along with altered storage and transport of water within tundra soil [e.g., *Sturm et al.*, 2001].

1.3. Study Objectives

[4] The freshwater system in the Arctic consists of many elements linked together in a myriad of ways, some of which are difficult to observe and are thus poorly understood. The objective of this study was to simplify the system into its essential pieces and interactions to help visualize how changes in observable parts of the system are likely to affect others. To narrow the scope, the analysis focuses on the primary physical elements of the system that drive changes in arctic biological systems, namely marine productivity, the terrestrial ecosystem, and the well-being of humans who live in the region. We seek a better understanding of fundamental linkages and feedbacks; at this time we are not searching for numerical predictability but rather the unveiling of basic system architecture. In this respect we

rely on an inductive rather than deductive approach. We take this tack as a precursor to the community's ability to address these complex and intertwined issues, which still awaits the deductive approach.

[5] Our approach is to investigate these interactions using the graphical, heuristic method of *Overpeck et al.* [2005]. In this method, primary components or "hubs" of the system were connected to other hubs with arrows depicting the sign and strength of the relationship according to knowledge of system behavior during recent decades. As the *Overpeck et al.* [2005] approach offered new insight into the trajectory for the entire Arctic, expectations for the present effort were to do the same for the hydrologic system but in greater depth and with underpinnings of documented relationships. Moreover, feedback loops within these collections of hubs and arrows were identified as either positive or negative feedbacks, depending on the nature of relationships defining the loop. Some of the feedbacks identified this way were familiar and documented in the literature. Others were not, however, and could perhaps be the subject of new research activities. We ascertained qualitatively how each of these feedback loops affects the living parts of the system by exacerbating or reducing changes in terrestrial, marine, and human life. In the first part of the analysis, we considered the freshwater system in its present form and the likely decadal-scale changes. We went on to use the same approach applied to a scenario in which perennial sea ice, land ice, and permafrost are markedly diminished.

[6] This paper is the fourth in a sequence of synthesis publications supported by the Freshwater Integration study. *Serreze et al.* [2006] updated present knowledge of the arctic freshwater budget; *White et al.* [2007] summarized observed changes in the arctic freshwater system; and *Holland et al.* [2007] explored future projections by coupled climate models. In this paper, we hope to shed light on the myriad of interactions among the main elements of the arctic hydrologic system, including the biological components affected by change.

2. Methods

[7] The method used herewith was adapted from *Overpeck et al.* [2005], who used a system of "hubs" to describe the arctic climate system. By applying general knowledge of system behavior, they linked hubs together with arrows that indicated the direction of the interaction as well as its sign, i.e., whether a change in one component would produce a change of the same or opposite sense in the other. An expanded version of this approach is used here to diagnose primary components of the Arctic hydrologic system and the interactions among them.

2.1. Dividing the Arctic Hydrologic System

[8] The system was first divided into subsystems emphasizing interactions that occur primarily within the atmospheric, oceanic, and terrestrial systems, and that also include linkages to the global system. The primary components, or hubs, within each of these subsystems were then selected from among the many possible variables depending on the satisfaction of three criteria: (1) the variable captures essential characteristics of the system that are not captured by other hubs, (2) strong connections exist to other hubs in the system, and (3) the variable can be described as increasing or decreasing in a pan-arctic sense. Each hub was then evaluated to determine whether it plays a role in the atmospheric, terrestrial, and/or oceanic subsystems of the overall arctic hydrologic system. Some hubs are present in more than one subsystem, such as precipitation, while others appear only in one, such as permafrost in the terrestrial system. Within each of the subsystem diagrams, the hubs were grouped according to their physical provenance. In the representation for the atmosphere, for example (Figure 2), certain hubs were grouped as "atmosphere" hubs and others as biological, or "life" hubs. The groupings within subsystems served as a convenient way of organizing the hubs that could be consistently applied across the subsystems. Each hub was then evaluated to determine whether it had teleconnections to the global environment, as this would have broader ranging impacts and attributions.

[9] While the set of hubs in the system diagrams represent the major components and interactions in the arctic hydrologic system, a slightly different combination may also accomplish the objectives of this study.

2.2. Identification and Characterization of Linkages

[10] Once the hubs were identified, grouped into subsystems, and classified within subsystems, information from published literature was used to determine the direction and sense of connections between hubs in the present-day system. Referring again to the example for the atmosphere in Figure 2, there are several types of arrows. Red arrows were used to indicate that a change in one hub would lead to a change of the same sign in another, blue arrows to denote interactions with opposite signs, and black arrows to represent interactions that have competing effects. Weak interactions were designated with thin arrows. Thick gray arrows were used to indicate major linkages with the global system, and therefore pathways through which the arctic hydrologic system affects and is affected by changes outside of the Arctic. Short statements describing the rationale for each arrow, both its existence and sign, were presented for each subsystem in Figures 3, 6, and 9, followed by the references supporting the statements.

[11] Based on the arrows entering and leaving a hub, the hub was identified as either a driver or recipient depending on whether it had more arrows leaving it (driver) or pointing toward it (recipient). In the case of cloud cover, for example, 4 arrows pointed away from it and 2 toward it (note arrows may be double-ended); thus it was considered a driver hub. The arrows also indicate which of the physical hubs have important influences on the biological part of the system, which are denoted with red asterisks.

2.3. Identification of Feedback Loops

[12] The next step in our analysis was to identify feedback loops that served to enhance or lessen changes in those hubs identified as primary biological drivers. Feedback loops were indentified where a path could be traced from an initial hub, through the system, and back to the starting point. The strength in this approach is the ability to identify relationships that may be obscured in the full complexity of the complete system. A hub was selected as the lead in the feedback if observations during recent decades exhibited a distinct trend, allowing its effects through the system to be

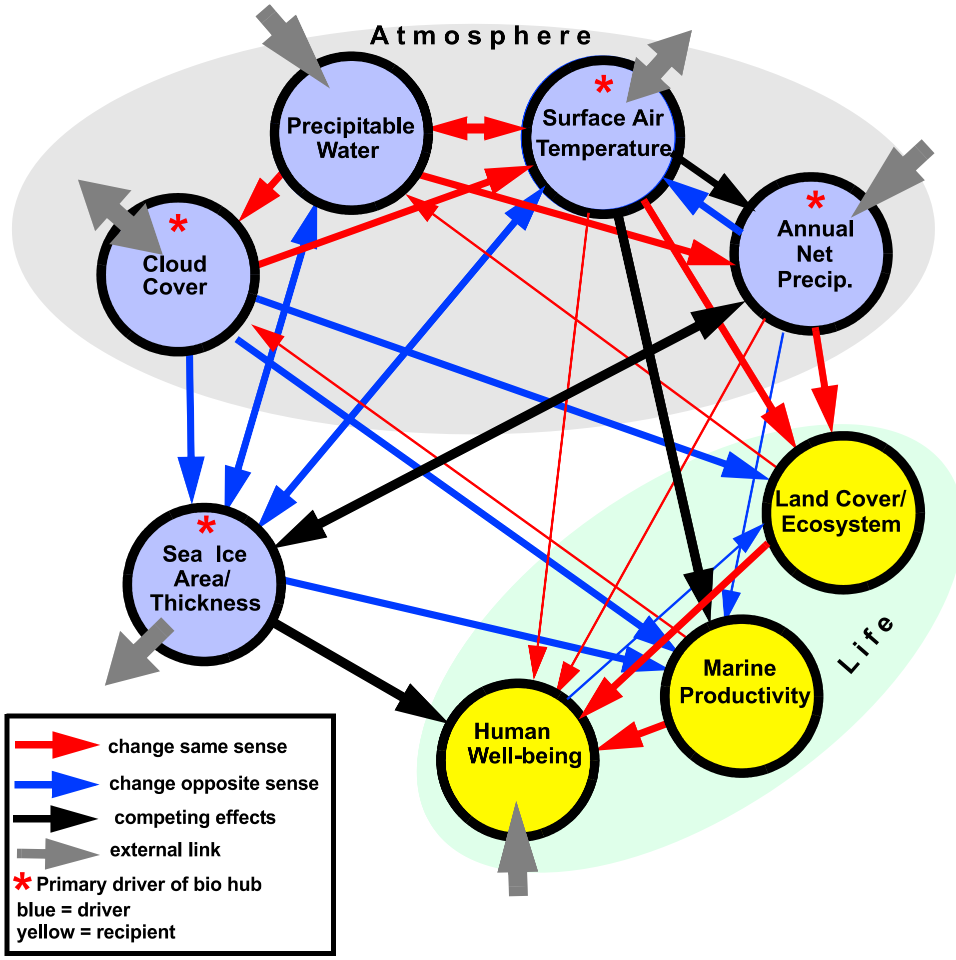

Figure 2. Wiring diagram for the atmospheric component of the Arctic hydrologic system. Blue (yellow) hubs are drivers (recipients), red (blue, black) arrows denote interactions of the same (opposite, competing) sign, thick (thin) arrows are strong (weak) influences, and red asterisks identify the physical hubs that directly influence living components of the system. Thick gray arrows denote direct connections with the global system.

ascertained with greater confidence. While some of the feedbacks that emerged from the diagrams were recognizable and understood at some level (literature references are provided when available), others were less familiar. Each loop that emerged from the diagrams has been graphically isolated to clarify its mechanism. Verifying the realism of each feedback was beyond the scope of this paper, but we illustrated in each subsystem how observations and/or models could be used to ascertain the existence, sign, strength, and potential influence of one of the feedbacks on the biological parts of the system.

2.4. Hypothetical Future State

[13] In the last section we considered how the approach might be used in the analysis of a hypothetical future state of the arctic hydrologic system in which the summer sea ice,

Figure 3. Rationale for arrows shown in the atmospheric subsystem, and references cited in each cell: 1, *Francis et al.* [2009] and *Andreas et al.* [2002]; 2, *Sewall and Sloan* [2004], *Alexander et al.* [2004], and *Magnusdottir et al.* [2004]; 3, *Hinzman et al.* [2005]; 4, *Perovich et al.* [2007a, 2007b]; 5, *Arrigo et al.* [2008]; 6, *ACIA* [2005]; 7, *Dorn et al.* [2007], *Dunlap et al.* [2007], and *Eisenman et al.* [2007]; 8, *Tuomenvirta et al.* [2000] and *Wang and Key* [2005]; 9, *Olofsson et al.* [2007]; 10, *Nemesure et al.* [1994] and *Wang and Key* [2005]; 11, *Francis and Hunter* [2006, 2007]; 12, *McGuire et al.* [2006] and *Wang and Key* [2005]; 13, *Stramler* [2006]; 14, *Groves and Francis* [2002] and *Curry et al.* [1995]; 15, *Eriksson et al.* [2007] and *Johannessen et al.* [2004]; 16, *Isaac and Stuart* [1992], *Cassano et al.* [2007], and *Hanssen-Bauer and Førland* [1998]; 17, *Furgal et al.* [2002]; 18, *Kutzbach et al.* [2007] and *Simpson et al.* [2002]; 19, *Serreze and Francis* [2006]; 20, *Maykut* [1982]; 21, *Ellis and Leathers* [1998] and *Walsh et al.* [1985]; 22, *Berner and Furgal* [2005]; 23, *Prokushkin et al.* [2005] and *Kharuk et al.* [2005]; 24, *Rosentrater and Ogden* [2003]; 25, *Lohmann and Leck* [2005]; 26, *Eugster et al.* [2000] and *Lynch et al.* [1999]; 27, *Diaz et al.* [2006]; 28, *Lubin and Vogelmann* [2006]; 29, *Katlov and Walsh* [2000]; 30, *Serreze et al.* [2007]; 31, *Cassano et al.* [2007].

	Ice area/ Thickness	Cloud Cover	Precipitable Water	Surface Air Temp.	Annual Net Precip.	Human Well-being	Marine Productivity	Land Cover/ Ecosystem	Global System
Ice area/ Thickness			Less ice cover leads to increased evaporation, more PW. (1)	Less ice increases sensible, latent, and conductive heat fluxes, leading to increased air temp. (1)	Sea ice loss leads to enhanced precip in area where ice lost, but reduced precip in areas downstream. (2)	Less ice makes ship transportation easier and improves access to natural resources, aiding the local economy, but traditional hunting becomes more difficult. (3)	Less ice allows increased solar radiation, enhancing photosynthesis and marine productivity. (4, 5)		Decreased ice area leads to decreased planetary albedo, augmenting anthropogenic warming, and also increases access by ships and to natural resources. (6)
Cloud Cover	Increased cloud cover blocks more solar radiation, but increases emission of longwave more, melting more ice. (7)			Increased cloud blocks solar radiation but increases longwave emission to surface more, warming surface. (8)			Increased cloud cover blocks solar radiation, less light for photosynthesis. (5)	Increased cloud cover blocks solar radiation, less light for photosynthesis. (9)	Increased cloud cover raises planetary albedo, offsets anthropogenic warming. (10)
Precip-itable Water	More PW increases longwave emission from atmosphere, melts ice. (11)	More PW leads to increased condensation into cloud droplets. (12)		More PW increases longwave emission and warmer sfc temps. (13)	More PW leads to increased condensation and precipitation. (14)				
Surface Air Temp.	Increased air temp melts more ice. (15)		Warmer air temps allow higher PW. (14)		Warmer air temps increases evaporation, reduces P-E, and decreases total precip in summer over land. Warming in winter leads to increased precip. (16)	Warmer air temps make it more comfortable for humans to live. (17)	Warmer air temps will benefit some species of phyto/zooplank-ton and reduce others. (5)	Warmer air temps increase plant growth, increase plant diversity, and promote transition from tundra to shrubs. (18)	Increased surface temperatures reduce poleward temperature gradient in low levels, reducing sensible heat advection from lower latitudes, slowing warming. (19)
Annual Net Precip.	Increased precip leads to additional snow cover on ice, which helps insulate it from winter			Increased snowfall increases albedo, leading to reduced air temp (21)		Increased precip provides freshwater for human use. (22)	Increased precip increases stratification of the surface layer, which prevents upwelling of	Increased precip provides additional water for plants, increases plant density and diversity. (23)	

Figure 3

	atmosphere (slows growth), but it also increases the surface albedo in spring (slows melt). (20)						nutrients from deeper waters. (5)		
Human Well-being								Increased human well-being leads to more intensified use of land to the detriment of the ecosystem. (24)	
Marine Produc-tivity		Increased marine productivity leads to increased emission of DMS, which transforms into cloud condensation nuclei and increased cloud. (25)				Increased marine productivity provides additional food sources for humans. (6)			
Land Cover/ Ecosystem			Increased vegetation leads to increased evaop-transpiration and increased PW. (26)			Greater species diversity increases human well-being. (27)			
Global System		Increased aerosols from lower latitudes leads to increased Arctic cloud cover. (28)	Increased moisture advection from lower latitudes increases PW. (14)	Increased moisture advection from lower latitudes increases PW, longwave emission, and surface temperature. (11, 14)	Global warming leads to poleward migration of jet stream and increased storminess in Arctic, increased precipitation (29, 31)	Increased global interest in Arctic resources has both beneficial and adverse effects on Arctic native populations. (25, 30)			

Arrows begin at hub named in row (left) and end at hub named at top of column. Cells are colored according to arrow color (white cell = black arrow, gray cell is no arrow). Colored cells with hub names correspond to whether they are net drivers or recipients in the system.

Figure 3. (continued)

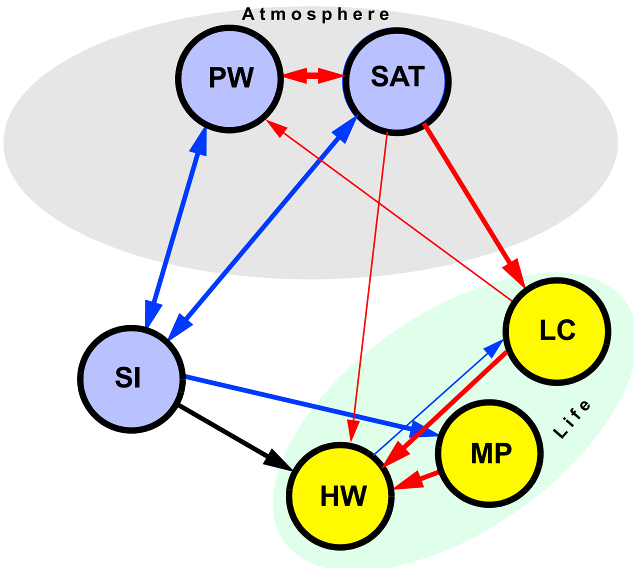

Figure 4a. Feedback loops in the atmospheric hydrologic system. Hub names are abbreviated: cloud cover (CLD), total-column precipitable water vapor (PW), surface air temperature (SAT), annual net precipitation (P-E), sea ice area/thickness (SI), human well-being (HW), marine productivity (MP), and land cover/ecosystem (LC). Feedback number 1: the sea ice/temperature/water vapor feedback is positive and operates in both directions. SI => SAT => PW => SI and SI => PW => SAT => SI.

permafrost, and glaciers were greatly diminished, analogous to that presented by *Overpeck et al.* [2005] and consistent with the trajectory of observed change in recent decades. To understand the impacts of a seasonally ice-free Arctic Ocean as well as greatly diminished permafrost and terrestrial ice, we repeated an assessment of the diagrams in the absence of hubs for multiyear sea ice, glaciers and ice sheets, and permafrost. One could also assess a different scenario that assumed a reversal in the present trajectory and an increase in these components.

3. Results Part 1: Present Arctic Hydrologic System

3.1. Atmospheric Subsystem

[14] The hydrologic subsystem for the atmosphere is presented in Figure 2. This depiction consists of five physical hubs: cloud cover (CLD), total-column water vapor or precipitable water (PW), surface air temperature (SAT), annual-mean net precipitation (P-E), and sea-ice area/thickness (SI). Completing the representation are three biological or "life" hubs: human well-being (HW), which is defined as the success and health of arctic communities; marine primary productivity (MP); and land cover/ecosystem/vegetation (LC). Based on the relative numbers of incoming and outgoing arrows to and from each hub, we found that all of the atmospheric hubs emerge as net drivers of the system. This analysis is consistent with *Serreze et al.* [2006] and earlier studies in suggesting that the atmosphere drives much of the arctic hydrological cycle, both directly through net precipitation and indirectly through energy transfer processes that affect the surface. All of the physical hubs and one life hub in the atmospheric diagram are linked with the global system (denoted with thick gray arrows). For example, sea ice is exported to lower-latitude oceans by winds and ocean currents where it affects the thermohaline circulation in the Nordic and Labrador Seas; water vapor and clouds are affected by large-scale dynamics and, in turn, influence the global system through their effect on the planetary albedo and longwave emission; surface air temperature responds to changes in heat advection from lower latitudes; and P-E is driven by water vapor availability and storm systems. These linkages underscore the multiple conduits through which atmospheric moisture processes are connected with the global climate system. The diagram also provides new insight into linkages between physical hubs and life hubs. Three physical hubs exhibit marked changes in recent decades: surface air temperature (increase), water vapor (increase), and sea ice area/thickness (decrease). Evidence suggests that clouds and net precipitation have also changed, but the seasonal and spatial variability in the trends renders a general conclusion less certain. Because atmospheric hubs are key drivers of the system, effects of their changes are felt throughout, including direct influences on arctic life.

3.1.1. Feedbacks in the Atmospheric Subsystem

[15] To focus the analysis, we identified feedbacks involving hubs that directly affect the biological parts of the system and that contain at most four arrows. Figures 4a–4g illustrate simplified diagrams of the seven feedbacks identified within the atmospheric subsystem. Each feedback diagram includes only those hubs and arrows that participate in that feedback and/or are linked to a life hub. Table 1 presents a summary of the overall effect of each physical feedback on the change in a life hub, i.e., whether a feedback acts to produce an overall positive or negative change in a living component given the observed change in the lead hub. Figure 3 includes accompanying references for documentation of the relationships described in the text.

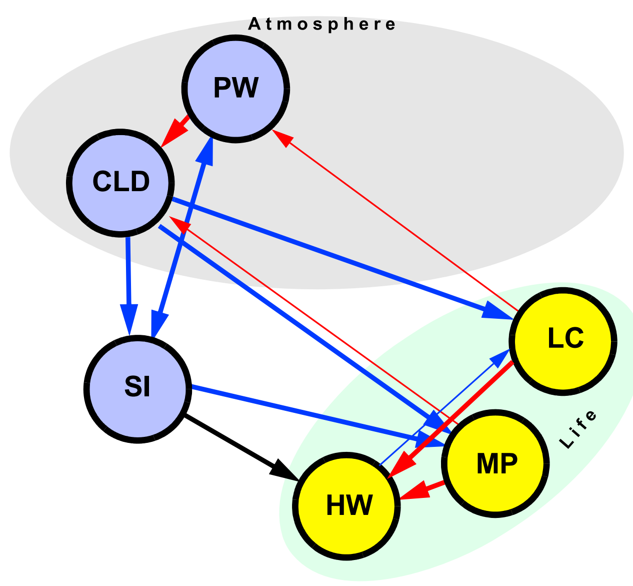

Figure 4b. Feedback number 2: sea ice/water vapor/cloud feedback, positive. SI => PW => CLD => SI.

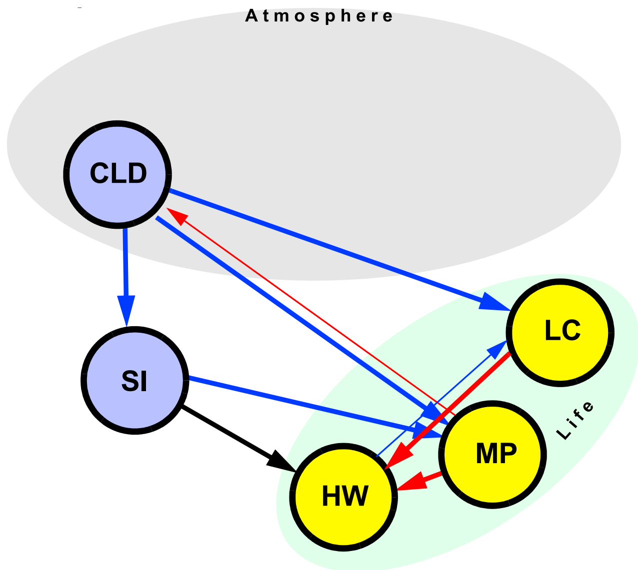

Figure 4c. Feedback number 3: sea ice/DMS/cloud feedback, positive. SI => MP => CLD => SI.

Each feedback and its influence on the biological part of the system are discussed briefly below.

3.1.1.1. Feedback Number 1: Sea Ice/Temperature/Water Vapor Feedback

[16] This simple, well recognized feedback [e.g., *Curry et al.*, 1996] begins with sea ice (SI), the summer minimum of which has declined by approximately 40% during recent decades [*Stroeve et al.*, 2007]. Because double-headed arrows (two-way interactions) link sea ice with both PW and SAT, the loop can be followed in either direction; both are positive feedbacks. The loss of sea ice leads to increased evaporation and thus increased PW. Through increased longwave emission to the surface by a moister atmosphere, the SAT also increases, thereby melting additional sea ice.

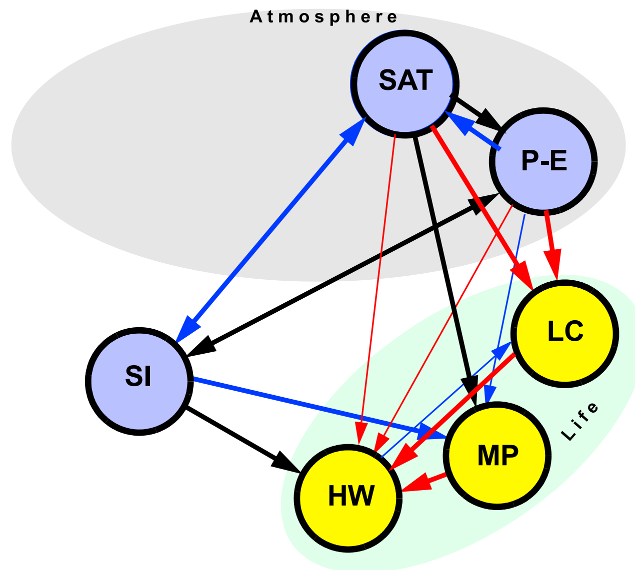

Figure 4e. Feedback number 5: sea ice/temperature/net precipitation feedback, sign uncertain. SI => SAT => P-E => SI.

In the other direction, reduced sea ice results in higher surface temperatures as open water absorbs more insolation (known as the ice-albedo feedback). Through the Clausius-Clapeyron equation, which relates atmospheric temperature to the maximum water vapor content, and assuming a near-constant relative humidity (consistent with observations), an increase in PW occurs, again leading to a decrease in sea ice owing to increased atmospheric emission of infrared radiation to the surface. The stronger of these two feedbacks appears to be in the direction of SI = > SAT = > PW = > SI according to observations and analysis reported by *Francis and Hunter* [2007], in which the change in PW is implicated as a stronger factor than SAT in increasing infrared emission

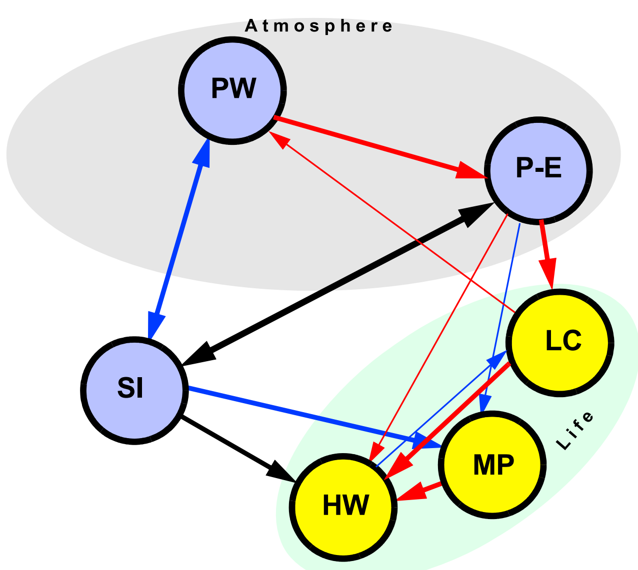

Figure 4d. Feedback number 4: sea ice/water vapor/net precipitation feedback, sign uncertain. SI => PW => P-E => SI.

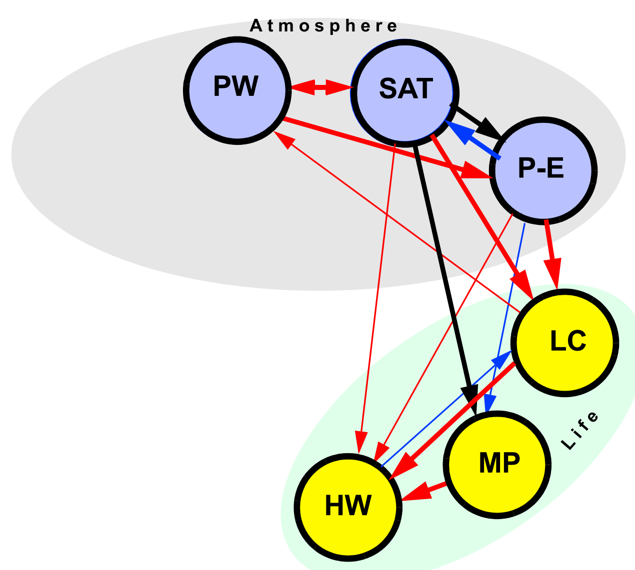

Figure 4f. Feedback number 6: water vapor/net precipitation/temperature feedback, negative. PW => P-E => SAT => PW.

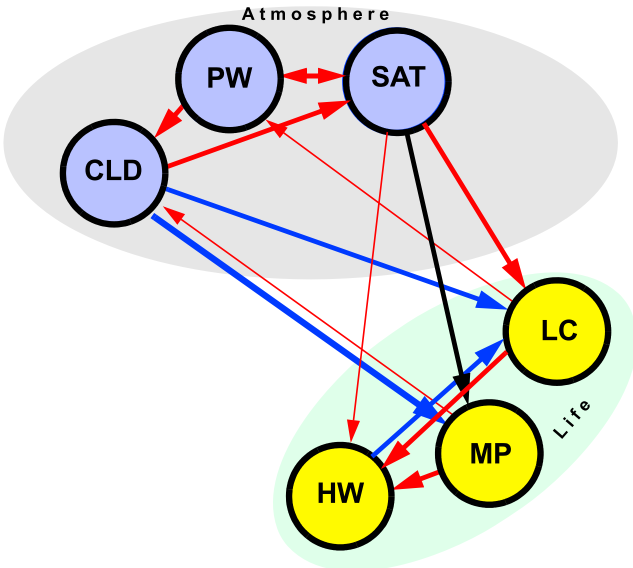

Figure 4g. Feedback number 7: water vapor/cloud/temperature feedback, positive. PW => CLD => SAT => PW.

from the atmosphere. Through the linkages between SAT and the life hubs, vegetation on land is enhanced by warming and thawing of the soil, along with conditions generally more conducive to plant growth. Human well-being is also improved, as life in the Arctic is generally easier in warmer conditions. Decreased sea ice will enhance marine productivity, as additional insolation is available to photosynthetic algae, building the base of the marine food web. Sea ice loss has competing effects on human well-being through improved conditions for travel by sea and resulting new opportunities for the local economy, but it also deteriorates conditions for subsistence hunters and their prey. Note that references for these relationships are listed in conjunction with Table 1.

3.1.1.2. Feedback Number 2: Sea Ice/Water Vapor/Cloud Feedback

[17] As sea ice declines, evaporation increases, leading to increased PW. Increased availability of moisture enhances condensation and cloud formation, which leads to an increased blockage of incoming solar radiation but a larger increase in longwave emission toward the surface [*Francis and Hunter*, 2006]. The net effect is increased net radiation, which leads to a further decline of sea ice: a positive feedback [*Curry et al.*, 1996]. As in the previous case, there are competing influences on human well-being. Increased cloud cover is detrimental to both terrestrial and marine plants [*Sakshaug and Slagstad*, 1991], as less light is available for photosynthesis.

3.1.1.3. Feedback Number 3: Sea Ice/DMS/Cloud Feedback

[18] This feedback has been previously recognized [e.g., *Hegg et al.*, 1991], although its existence is difficult to verify in the Arctic [*Hegg et al.*, 1995]. As noted above, reduced sea ice allows additional insolation to enter the open water. Marine primary productivity likely increases as a result, leading to increased production of dimethyl sulfide (DMS), which transforms to sulfate particles in the atmosphere. These particles act as cloud condensation nuclei, which tend to produce more but smaller cloud droplets and optically thicker clouds that block more solar radiation. As previously described, the net effect of increased cloud amount is to enhance longwave emission and further reduce sea ice, thus creating a positive feedback. The more abundant cloud cover resulting from this feedback likely has a net detrimental effect on land vegetation, but through the sea-ice connection, it will be beneficial to marine primary productivity. Resulting effects on humans are mixed, as reduced vegetation and enhanced marine productivity offset each other, while the sea-ice loss directly affects humans in competing ways, as explained above.

3.1.1.4. Feedback Number 4: Sea Ice/Water Vapor/Net Precipitation Feedback

[19] A decline in sea ice leads to a larger water vapor concentration because of increased evaporation from a larger area of unfrozen Arctic Ocean and also through higher air temperatures that allow a higher vapor pressure. Increased PW likely leads to more annual net precipitation, although this effect is difficult to verify, as a mechanism to initiate condensation is required. The influences of increased snowfall on sea ice are competing. On one hand it will enhance sea-ice loss by adding insulation, resulting in reduced ice growth during freezing months. On the other hand, it may also lessen sea-ice loss by augmenting ice mass directly and by increasing the albedo of the snow-on-ice surface, which decreases the amount of solar radiation absorbed by the ice and ocean. The melt season is lengthened, as the snow must melt away before the ice melts. This feedback is fraught with uncertainty and should be the focus of additional research as new relevant data become available, particularly techniques to measure snow amount on sea ice. Increases in precipitation alone will have direct interactions with the life hubs: it will enhance plant growth

Table 1. What Effect Does a Feedback in the Atmospheric Subsystem Have on the "Life Hubs" in Response to the Observed Trend in a Feedback's Lead Variable?[a]

Feedback	Feedback Name (Sign)	Land Cover/Ecosystem	Marine Primary Productivity	Human Well-Being
1	sea ice/temperature/water vapor (positive)	positive	positive	unknown
2	sea ice/water vapor/cloud (positive)	negative	negative	unknown
3	sea ice/DMS/cloud (positive)	negative	negative	unknown
4	sea ice/water vapor/net precipitation (unknown)	unknown	unknown	unknown
5	sea ice/temperature/net precipitation (unknown)	unknown	unknown	unknown
6	water vapor/net precipitation/temperature (negative)	negative	unknown	negative
7	water vapor/cloud/temperature (positive)	unknown	negative	unknown

[a]Sign of feedback indicated by positive, negative, or unknown.

and diversity on land and provide additional freshwater to support human inhabitants. Effects on MP are likely detrimental owing to increased stratification of the ocean surface, which deters mixing with nutrient-richer waters below. The uncertainty in the influence of the feedback involving the link between P-E and sea ice, however, leaves in doubt the overall impact of this feedback on the living system.

3.1.1.5. Feedback Number 5: Sea Ice/Temperature/Net Precipitation Feedback

[20] While this feedback loop includes large uncertainties owing to the existence of competing effects in two of the relationships, it may also hold great importance, as both sea ice and surface air temperature have changed dramatically in recent decades. Both of these hubs also have direct links with biological components. As sea ice declines, surface air temperature increases. The effects of warming on net annual precipitation vary with season and whether land or ocean areas are considered. Over land in summer, warming generally leads to increased evapotranspiration, which would contribute to a decrease in P-E. As winters warm, however, an increase in precipitation on land has been observed. Over the Arctic Ocean the temperature-precipitation relationship is less certain, but warming would likely lead to increased precipitation as the potential water vapor content is larger. The connection back to sea ice also involves competing effects as described in feedback number 4. Clearly the direct linkages between declining sea ice and precipitation represent an important uncertainty that could be investigated through experiments with a coupled model or perhaps using observations. As already described, the effects of warming on the living parts of the system are generally positive for terrestrial vegetation and human well-being, but uncertain for marine organisms. Increased MP may also decrease the open-water albedo, thereby enhancing absorption of insolation and sea-ice melt [*Lengaigne et al.*, 2009]. Because the sign of change in P-E resulting from this feedback is uncertain, its effects on the living system are uncertain, as well.

3.1.1.6. Feedback Number 6: Water Vapor/Net Precipitation/Temperature Feedback

[21] Increased water vapor leads to increased precipitation in all seasons. As explained in feedback number 4, increased snowfall leads to decreased surface air temperature owing to its low conductivity of heat from the surface, be it ice or land. Increased snowfall also raises the surface albedo and delays exposure of the darker surface beneath the snow, thereby reducing the amount of solar radiation absorbed by the system. If precipitation falls as rain on land, however, there may be a warming effect in early spring if the snow cover has not yet begun to melt. The overall effect of increased moisture in soil is likely to be cooling owing to increased evaporation and heat capacity. Cooling leads to reduced water vapor in the atmosphere, hence completing this negative feedback loop, the only one identified in this subsystem. This feedback is discussed further below in an example of a verification analysis.

[22] The damping effect is offset to some extent by a subloop that involves influences of increasing precipitation on land cover, and its subsequent link back to water vapor. Increased precipitation enhances land vegetation, both density and diversity, which increases evapotranspiration and augments atmospheric water vapor. Assuming the land cover loop is weaker than the link through surface temperature, the effect of this feedback on the life hubs is generally detrimental. If increases in PW and SAT are damped through this negative feedback, the benefits to land vegetation and human well-being are reduced, with uncertain effects on marine productivity.

3.1.1.7. Feedback Number 7: Water Vapor/Cloud/Temperature Feedback

[23] There is much more to this feedback than the simple arrows depicted in this diagram, as it encompasses cloud-radiation interactions and the roles they play in driving the hydrologic arctic system. The well documented increase in water vapor during the past few decades in the Arctic provides additional moisture for cloud formation and thickening. While more numerous and/or optically thicker clouds block additional insolation from reaching the surface (cooling effect), they also enhance the emission of infrared radiation to the surface (warming effect). Because the blocking effect only occurs during a few months of the year and its impact is reduced by the high surface albedo, the infrared enhancement dominates on an annual basis, and thus leads to an overall increase in SAT. As already explained, this leads to an increased atmospheric capacity for vapor, and hence a positive feedback [*Curry et al.*, 1996]. The impact of this physical feedback on the living hubs, however, may not be positive overall. Cloud cover has two direct linkages with living hubs: enhanced cloud cover adversely affects both marine and terrestrial plant life by blocking sunlight and reducing photosynthesis. This effect on land cover is offset to some degree by beneficial effects of increased SAT, thus uncertainty obscures the net effect on terrestrial plants. As already mentioned, warmer air will benefit some marine species and harm others. Humans are not strongly affected by changes in any of these hubs, but the net effects on marine and terrestrial ecosystems will indirectly have an impact on arctic inhabitants.

[24] In summary, there is clearly much to learn not only about the physical feedbacks in the arctic hydrologic system, particularly those involving precipitation, clouds, and radiation, but also the relative strengths of the interactions that compose each feedback, the relative influence of the feedbacks on each of the living parts of the system, and in many cases, even the sign of the net effects. One of the primary objectives of this investigation is to reveal gaps in our knowledge of the arctic hydrologic system and the effects of those gaps on understanding arctic life, thus highlighting areas in need of focused, interdisciplinary research. From this analysis, it is clear that uncertainties involving the effects of changing precipitation, both quantity and phase, are critical links in several feedbacks that affect life in the Arctic. In particular, the links between precipitation and sea ice, marine primary productivity, and terrestrial vegetation stand out as obstacles to understanding the trajectory of change in the arctic system.

3.1.2. Example Verification

[25] Some of the feedback loops identified through these diagrams have been discussed in literature, and to varying degrees, their importance as amplifiers or moderating influences in the system has been tested using either models or observations. Other feedbacks that emerge from this analysis may not be familiar, thus their importance and very existence requires evaluation, providing possible new direc-

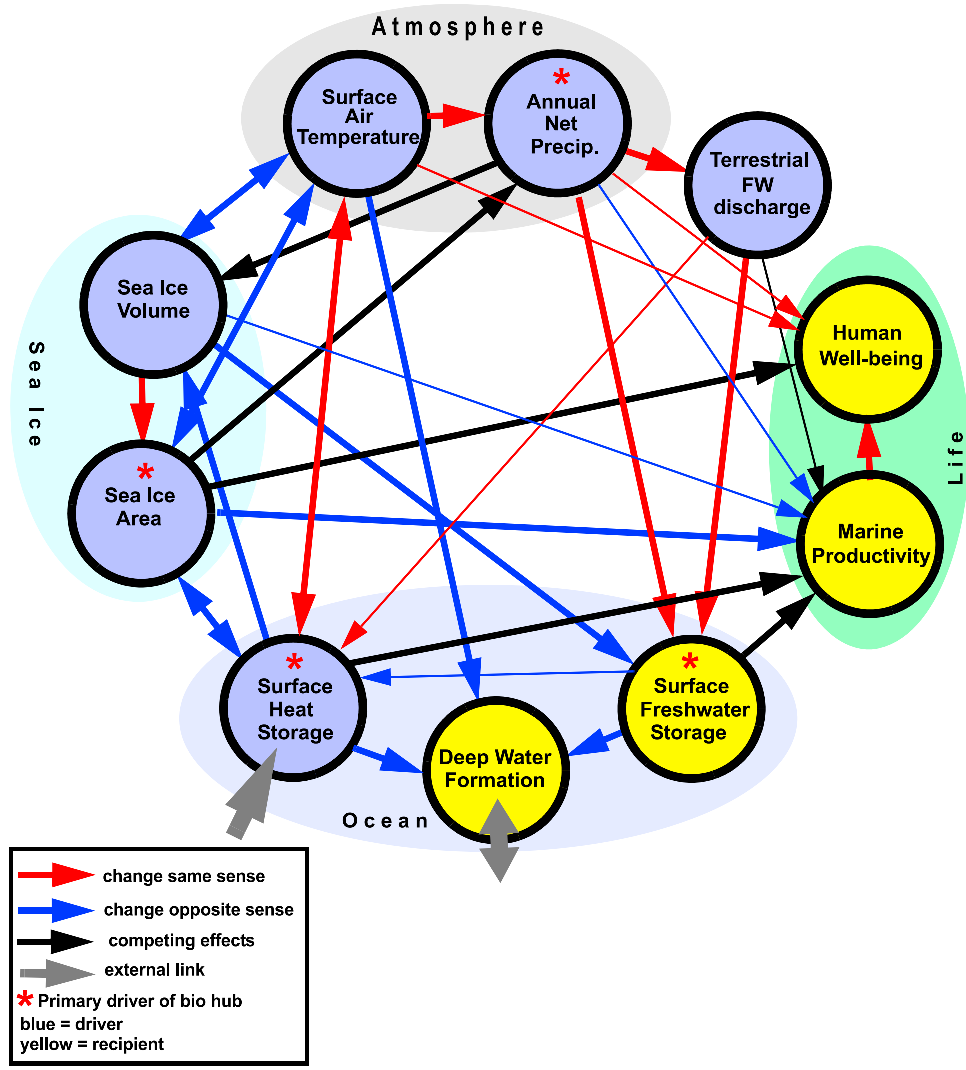

Figure 5. Same as Figure 2 but for the oceanic component of the Arctic hydrologic system.

tions for future research. Evaluating each feedback that emerges from this analysis is beyond the scope of this paper, so instead we investigate one of the lesser known feedbacks in each subsystem in an attempt to illustrate how others might be investigated.

[26] For the atmospheric subsystem, we use information from recent studies to investigate feedback number 6 in Figure 4f, the water vapor/net precipitation/temperature feedback. This is the only negative feedback to emerge from the wiring diagram of the atmospheric subsystem. It may also represent a critical set of relationships in the arctic hydrologic system because it involves two physical drivers that are water (PW and P-E), and all three physical fields in the feedback have direct linkages with life hubs.

[27] An analysis of both reanalysis data and output from 15 of the global climate models that participated in the fourth Intergovernmental Panel on Climate Change (IPCC) assessment was conducted by *Cassano et al.* [2007] to evaluate the magnitudes and causes of net precipitation changes in the Arctic under increasing anthropogenic forcing. Sea level pressure patterns were used to assess which models were able to realistically simulate atmospheric patterns in comparison with those from reanalyses. Only four of them were able to reasonably reproduce observed sea level pressure patterns. These four were then used to investigate changes in net precipitation later in the 21st century. *Cassano et al.* [2007] showed that over 80% of the projected increase in arctic net precipitation was caused by thermodynamic processes, the increased availability of water vapor being a key factor. This represents a quantitative assessment of the red arrow from PW to P-E in feedback number 6. The link between net precipitation, snow cover in particular, and surface air temperature is documented by *Groisman et al.* [1994], *Brown* [2000], and *Ye et al.* [2008]. If it is assumed that precipitation falls as snow, any additional snow cover would increase surface albedo so less insolation is absorbed by the surface. Snow also adds thermal inertia to the system, as the soil temperature cannot rise above the freezing point until the snow has melted or sublimated. The final link in the feedback loop is explained by the Clausius-Clapeyron relationship, in which warmer air can support a higher vapor pressure, and thus a higher mass of water molecules. This negative feedback, therefore, represents an important damping on arctic warming. If arctic temperatures increased sufficiently so that a substantial fraction of the precipitation fell as rain, the

damping effect of this feedback would be greatly diminished. The sign of the feedback could even change if the snow cover decreased or if rain fell earlier on existing snow thereby lowering its albedo, both of which would allow air temperatures to rise more quickly than they would otherwise.

3.2. Oceanic Subsystem

[28] The diagram representing the oceanic component of the arctic hydrologic system (Figure 5) consists of 10 hubs that represent the key freshwater components of the sea ice, unfrozen ocean, atmosphere, input of freshwater from the land, and biological elements. Two hubs were used to represent sea ice: area (SIA) and volume (SIV). The state of the unfrozen ocean was captured in three hubs: surface-layer heat storage (HS), deepwater formation in the Arctic Ocean and Nordic Seas (DW), and surface-layer freshwater storage (FW). The atmosphere was represented by surface air temperature (SAT) and annual net precipitation (P-E). Freshwater input from the terrestrial component (TFW) and two life hubs, human well-being (HW) and marine primary productivity (MP), completed the system. Note that only variables that play important roles in the Arctic Ocean's hydrologic system were included. As in the atmospheric diagram, primary linkages with the global system were indicated with thick gray arrows, and hubs that directly affect the living parts of the system were indicated with a red asterisk. Colors and line styles of arrows and hub colors have the same definitions as those depicted in the atmospheric system. The rationale for the existence and characterization of the arrows are presented in Figure 6, along with references supporting each relationship.

[29] Based on the relative numbers of incoming and outgoing arrows from each hub (note that some arrows are double-headed), we found that the atmospheric hubs to be drivers of the subsystem. The two sea-ice hubs and one of the unfrozen-ocean hubs were also found to be drivers. This suggests that hydrologic changes in the Arctic Ocean are driven primarily by a combination of atmospheric and sea-ice changes, along with the heat content in the upper ocean and effects external to the Arctic. Linkages with the global system occur primarily through the exchange of heat with other oceans (via heat storage) and deepwater formation.

[30] As was the case in the atmospheric diagram, the two living hubs were found to be recipients, affected most directly by changes in sea-ice area, surface heat storage, and surface freshwater storage. Three of the drivers exhibited significant and unambiguous change in recent decades: air temperature (2 to 3°C/decade increase during spring and winter since ~1960), sea-ice cover (~10%/decade loss in summer), and ice volume (~3%/decade loss). The direct effect of warming is probably weak, but may represent a net benefit to humans, as a warmer environment is less hostile to human activities. Reduced ice area has competing effects on HW, as industrial development and marine transportation are enhanced, but subsistence hunting practices and over-ice travel are hampered. A reduction in ice area has mixed effects on marine primary productivity: more open water allows additional photosynthetic activity, but surface-layer warming increases stratification, which reduces nutrient circulation. Higher temperatures will also alter the mix of plankton that can thrive. Nevertheless, recent studies suggest an overall increase in marine primary production that is attributed to the shrinking summer ice cover.

[31] The diagram could also be used to qualitatively assess the effect of an observed change in one component on other parts of the system. For example, evidence suggests that sea-ice volume has declined dramatically in recent decades [*Maslanik et al.*, 2007; *Rothrock et al.*, 2008]. Combined with an observed increase in terrestrial runoff [*McClelland et al.*, 2006; *Peterson et al.*, 2002], this leads to increased storage of freshwater in the ocean, which in turn decreases downstream formation of deepwater. Reduced ice volume also affects marine productivity by increasing the surface stratification and hampering mixing that provides nutrients for phytoplankton. It should be noted, however, that some of the linkages with marine and human well-being outlined here are based on regionally specific or case studies, and additional research is needed to determine the spatial variations and to quantify the net interactions on a pan-arctic scale.

[32] As with the atmospheric component, feedback loops were identified that directly affect the living constituents and that include a physical hub that has exhibited significant recent change. We excluded loops that involve a large number of interactions, as with each interaction, additional uncertainty was introduced. Figures 7a–7e and Table 2 present the diagrams and a summary of the overall effect of each feedback on the changes in the life hubs. Each feedback and its influence on the biological part of the system is discussed below.

3.2.1. Feedbacks in the Oceanic Subsystem

3.2.1.1. Feedback Number 1: Ice Area/Surface Heat Storage/Ice Volume Feedback

[33] The first feedback is actually a family of three straightforward positive feedbacks that begin with the observed decrease in multiyear sea ice area during recent decades [e.g., *Serreze et al.*, 2007; *Stroeve et al.*, 2005] and is commonly known as the ice-albedo feedback. An increase in open water contributes to warming of the ocean surface layer and overlying SAT owing to increased absorp-

Figure 6. Rationale for arrows shown in the oceanic subsystem, and references cited in each cell: 1, *Manabe and Stouffer* [1980]; 2, *Maykut* [1982]; 3, *Andreas et al.* [2002]; 4, *Groves and Francis* [2002]; 5, *Instanes* [2006]; 6, *Arrigo et al.* [2008], *Wang et al.* [2005], *Booth and Horner* [1997], *Gosselin et al.* [1997], *Pabi et al.* [2008], and *Walsh et al.* [2005]; 7, *Perovich et al.* [2007a, 2007b], *Hall* [2004], *Budyko* [1969], *Sellers* [1969], and *Steele et al.* [2008]; 8, *Holland et al.* [2006] and *Maslanik et al.* [2007]; 9, *Holland et al.* [2007] and *Steele and Ermold* [2007]; 10, *Groves and Francis* [2002]; 11, *Furgal et al.* [2002]; 12, *Gregory et al.* [2005]; 13, *Karcher et al.* [2003]; 14, *Maykut and Untersteiner* [1971]; 15, *White et al.* [2007]; 16, *Berner and Furgal* [2005]; 17, *Serreze et al.* [2006] and *Peterson et al.* [2006]; 18, *Cooper et al.* [2005] and *Loeng et al.* [2005]; 19, *Lammers et al.* [2007]; 20, *Manabe and Stouffer* [1980], *Rennermalm et al.* [2007], and *Dickson et al.* [1996]; 21, *Steele and Boyd* [1998]; 22, *Shimada et al.* [2006]; 23, *Zhang et al.* [2004] and *Gnanadesikan et al.* [2005]; 24, *Stommel* [1961]; 25, *Rahmstorf* [2003].

	Ice area	Ice volume	Surface Air Temper-ature	Annual net precipita-tion	FW runoff from land	Human well-being	Marine productivity	Surface layer FW storage (Arctic, GIN, & Labrador Seas)	Deep water formation	Surface layer heat storage (Arctic, GIN, and Labrador Seas)	Global system
Ice Area			Reduced ice area leads to increased turbulent heat loss to atmosphere in fall through spring. (1,2)	Less ice cover leads to increased evaporation, reducing P-E, but more PW leads to increased precipitation. (3,4)		Competing effects. Reduced ice cover increases accessibility for shipping and resource extraction that could have beneficial economic impacts but may also negatively affect coastal erosion, pollution risk, and indigenous cultures. **(5)**	Less ice increases sunlight for photosynthesis. (6)			Reduced ice area allows increased SW absorption and increased heat storage. (7)	
Ice Volume	**Thinner ice can more easily melt out leading to a decrease in ice area. (8)**		Reduced ice volume leads to increased air temperature via increased upward heat transfer. (2)				Decreased ice volume allows more light to penetrate ice to organisms below. (6)	Decreased ice volume via melt or low growth adds FW to ocean, while volume loss via export has no effect on FW. (9)			
Surface air temper-ature	Warmer temperatures increase melting and reduce ice area. (2)	Warmer temperatures increase melting and reduce ice volume. (2)		Warmer air leads to increased water vapor, resulting in increased precip. over the ocean. (10)		**Warmer temperatures enhance human well-being. (11)**	Warmer air temps will benefit some species of phyto/zooplank-ton and reduce others. (6)		Warmer temperatures stabilize surface layer, decrease deep water formation. (12)	Warmer temperatures increase heat input to surface layer. (13)	

Figure 6

Annual net precipita-tion		Competing effects. Increased snowfall on ice increases albedo (enhances growth) and also insulates ice from cold air (reduces growth). (14)			Increased P-E causes increased river runoff to ocean. (15)	**Increased precip provides freshwater for human use. (16)**	Increased snowfall prevents light from penetrating into organisms below. (6)	Increased net precip freshens surface layer (17)			
FW runoff from land							Increased river discharge brings more nutrients to coastal waters, increasing marine productivity, but it also increases surface stratification, which reducies mixing of nutrients from below. (18)	Increased river discharge leads to larger FW ocean storage. (17)		Increased river discharge adds small amount of heat to surface layer. (19)	
Human well-being											
Marine produc-tivity						Increased marine productivity leads to more abundant marine food resources for humans.					
Surface layer freshwater storage (Arctic, GIN, and Labrador Seas)							Increased surface FW increases stratification, which keeps organisms near light source but blocks upwelling of nutrients from deeper layers. (6)		Increased surface FW storage increases FW flux out of Arctic, stabilizies water column and reduces deep-water formation. (20)	Increased surface FW increases stratification, leading to suppressed upward heat flux from Atlantic and Pacific Water layers below. (21,22)	

Figure 6. (continued)

Deep water formation										Increased MOC brings additional heat to the surface layer of the Eurasian sector. (23)	Decreased deep-water formation reduces the MOC and global ocean circulation. (24)
Surface layer heat storage (Arctic, GIN, and Labrador Seas)	Increased heat storage leads to larger ocean-ice heat flux and reduced ice area. (22)	Increased heat storage leads to larger ocean-ice heat flux and reduced ice volume. (23)	Increased heat storage leads to increased ocean-air heat flux and higher surface air temperatures.				Warmer air temps will benefit some species of phyto/zooplankton and reduce others. (6)		Warmer surface waters stabilize water column and decrease deep-water formation. (11)		
Global system									Changing global ocean circulation and large-scale wind patterns affects deep-water formation.(25)	Increased influx warmer water from lower latitudes increases surface heat storage.(23)	

Arrows begin at hub named in row (left) and end at hub named at top of column.
Cells are colored according to arrow color (white cell = black arrow, gray cell is no arrow).
Colored cells with hub names correspond to whether they are net drivers or recipients in the system.

Figure 6. (continued)

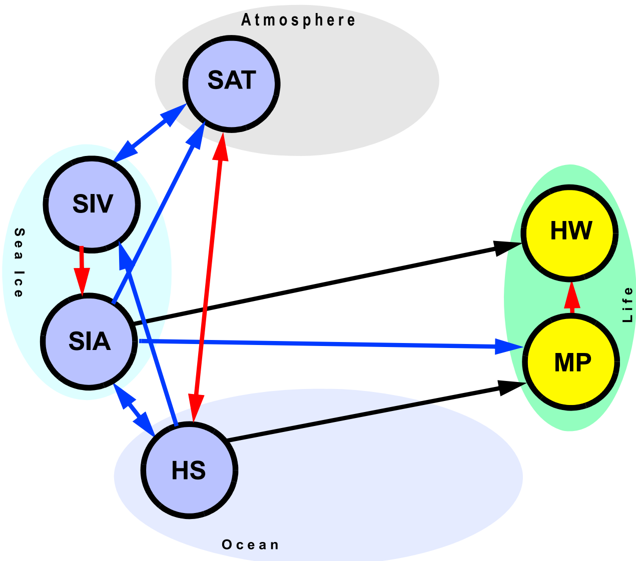

Figure 7a. Feedback loops in the oceanic hydrologic system. Hub names are abbreviated: sea-ice volume (SIV), sea-ice area (SIA), surface heat storage (HS), deep-water formation (DW), surface freshwater storage (FW), human well-being (HW), marine productivity (MP), terrestrial freshwater input (TFW), annual net precipitation (P-E), and surface air temperature (SAT). Feedback number 1 is actually a family of three similar feedbacks: the ice area/heat storage/air temperature/ice volume feedback is positive: SIA => HS => SIV => SIA (or SIA => SAT => SIV => SIA or SIA => HS => SAT => SIV => SIA).

tion of solar radiation. This heat leads to enhanced ice melt, a delay in the fall ice growth, and a reduced sea ice volume. Thinner sea ice, which is tantamount to sequestering heat in the system, leads to a higher probability of a further reduction of ice cover the following summer. The existence of this feedback has competing effects on human well-being: the region is more habitable in warmer conditions, and opportunities for economic development are enhanced in an Arctic with less summer sea ice. Ice-based subsistence

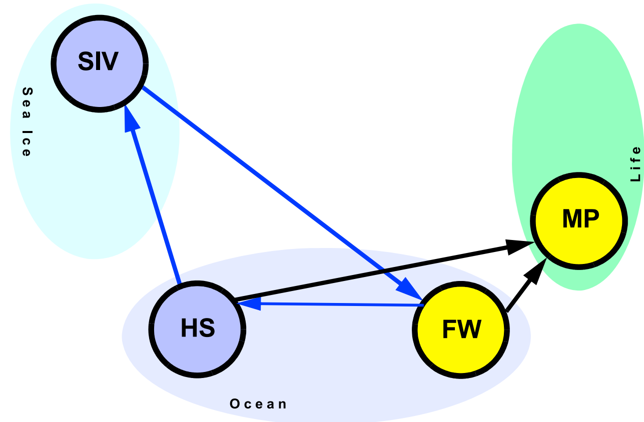

Figure 7c. Feedback number 3: ice volume/surface freshwater/heat storage feedback, negative. SIV => FW => HS => SIV.

hunting, however, will be more difficult. Ice loss leads to increased marine productivity, as larger areas of open water during summer allows more sunlight into the ocean for photosynthesis. Warming of the surface layer may have an offsetting effect owing to increased surface stratification leading to reduced upwelling of nutrients. Both light and nutrients are implicated in limiting marine primary production in the Arctic.

3.2.1.2. Feedback Number 2: Air Temperature/Net Precipitation/Ice Volume Feedback

[34] This feedback links rising arctic temperatures to changes in net precipitation and the ice cover. As SAT increases, net precipitation is also expected to increase owing to higher water vapor content in a warmer atmosphere. Assuming most of the additional precipitation falls as snow, the primary effects on ice volume will compete: a thicker snow cover in spring and summer will increase surface albedo, which will delay and reduce ice melt. During the ice-growth season, however, additional snow will insulate the ice from the cold atmosphere and slow the freezing process, leading to reduced ice thickness. A thinner ice cover will tend to augment near-surface warming. If,

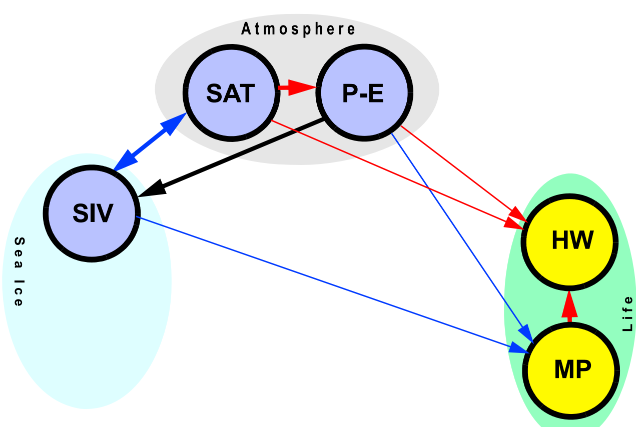

Figure 7b. Feedback number 2: air temperature/precipitation/ice volume feedback, uncertain sign. SAT => P-E => SIV => SAT.

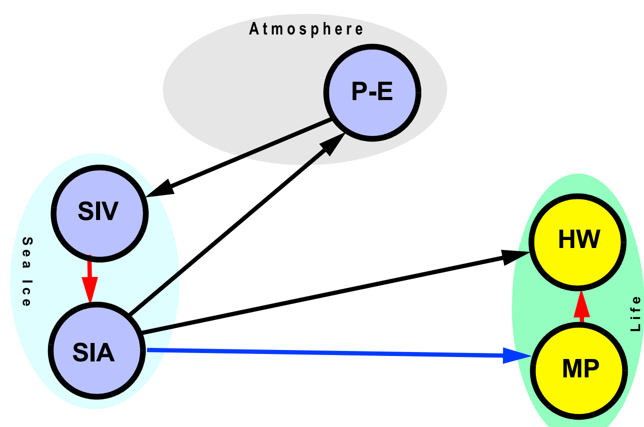

Figure 7d. Feedback number 4: ice area/net precipitation/ice volume feedback, uncertain sign. SIA => P-E => SIV => SIA.

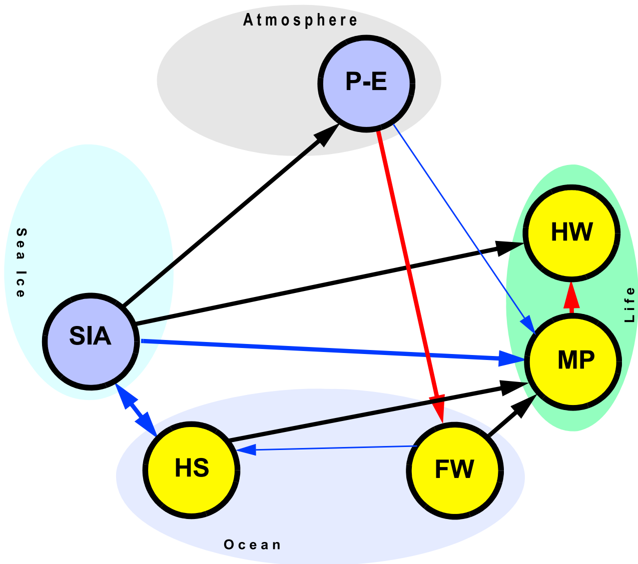

Figure 7e. Feedback number 5: ice area/net precipitation/freshwater/heat storage feedback, uncertain sign. SIA => P-E => FW => HS => SIA.

however, the additional precipitation increases the frequency of rain, the surface albedo generally will be reduced, and this feedback is most likely positive. The linkages between these physical hubs and the living constituents are believed to be relatively weak. The competing effects of increased P-E on ice volume lead to a feedback of unknown sign, and consequently, an unknown effect on human well-being and marine productivity.

3.2.1.3. Feedback Number 3: Ice Volume/Surface Freshwater/Surface Heat Storage Feedback

[35] This loop identifies direct linkages between the ocean surface layer and ice volume; the only negative feedback identified in the ocean system. Ice meltwater increases the freshwater content of the surface layer, which enhances stratification and prevents mixing of heat from warmer layers below, thus leading to increased ice volume. While the sign of the physical feedback loop appears to be negative, it is likely not an important feedback owing to the weak influence of changes in the freshwater content of the mixed layer on vertical mixing. Moreover, the effects on the living hubs are competing and not at all clear. As explained in number 4, marine productivity is expected to change as the heat and freshwater content of the surface layer change, but some species likely benefit and others suffer. The seasonality of these changes also affects the overall impact of this feedback.

3.2.1.4. Feedback Number 4: Ice Area/Net Precipitation/Ice Volume Feedback

[36] Related to number 2, this feedback links changes in net precipitation with sea ice. A decline in ice area will have competing effects on P-E. Additional open water will enhance surface evaporation but will also provide additional water vapor that is likely to enhance precipitation in regions well downwind of the open water. Which effect dominates in a pan-arctic sense is uncertain, albeit GCM simulations suggest that arctic P-E will increase in the future [*Holland et al.*, 2007]. If P-E increases, there are also competing effects on ice thickness, as described in number 2. An addition of freshwater to the Arctic Ocean, directly from precipitation and also from river discharge, will increase the stratification of the mixed layer, allowing ice to reform more easily. Offsetting this effect is the larger area of open water, which will enhance wind-driven mixing and reduce stratification. Net precipitation in the Arctic is notoriously difficult to measure and model, thus the potentially important ramifications of this feedback highlight an area ripe for further research. The effects of this feedback on the living constituents are also unknown.

3.2.1.5. Feedback Number 5: Ice Area/Net Precipitation/Surface Freshwater/Surface Heat Storage Feedback

[37] This is a highly uncertain feedback owing to the number of links, competing effects, and a likely weak relationship. Nevertheless, it emerges from the diagram, and because there are several direct links to the living system, its existence may be significant. This loop introduces the positive connection between net precipitation and freshwater storage in the surface layer of the Arctic Ocean. An increase in the FW will tend to reduce heat storage in this layer owing to the increased stratification and reduced mixing with warm Atlantic water below. Obviously, increased heat storage further reduces the ice cover. The linkages with living hubs are also uncertain. In addition to those already discussed with respect to ice area changes, any alterations in either the freshwater or heat storage in the surface layer have varying effects on different species of plankton, thus the pan-arctic ramifications of this feedback are unknown.

[38] In summary, the abundance of black arrows, indicative of competing effects of one hub on another, highlights that the ocean's role in the hydrologic cycle of the Arctic is extremely uncertain, and thus the changes that will result from continued anthropogenic influences on the system are even more uncertain. This analysis raises questions about relationships that are important for understanding the implications of change in the hydrologic system: (1) As ice melts

Table 2. What Effect Does a Feedback in the Oceanic Subsystem Have on the "Life Hubs" in Response to the Observed Trend in a Feedback's Lead Variable?[a]

Feedback	Feedback Name (Sign)	Marine Primary Productivity	Human Well-Being
1	ice area/heat storage/air temperature/ice volume (positive)	positive	unknown
2	air temperature/net precipitation/ice volume (unknown)	unknown	unknown
3	ice volume/surface freshwater/heat storage (negative)	unknown	unknown
4	ice area/net precipitation/ice volume (unknown)	unknown	unknown
5	ice area/net precipitation/freshwater/heat storage (unknown)	unknown	unknown

[a]Sign of feedback indicated by positive, negative, or unknown.

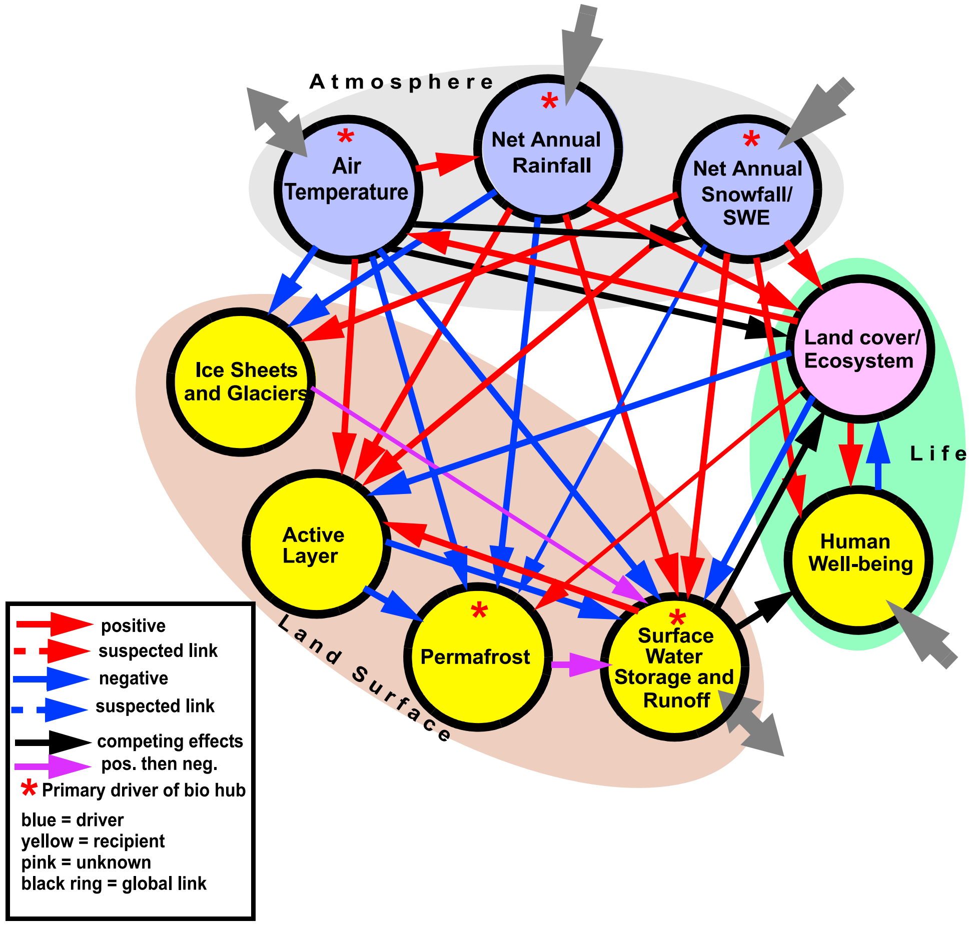

Figure 8. Same as Figure 2 but for the terrestrial component of the Arctic hydrologic system.

and net precipitation increases, will the addition of heat and freshwater to the Arctic Ocean result in a net increase or decrease in mixed-layer stratification, how will that feed back to the ice cover, and how will these relationships vary regionally and seasonally? (2) How will phytoplankton be affected by changes in temperature, salinity, stratification, and nutrient availability that result from changes in the ice cover, precipitation, and runoff? (3) What will be the net effect of projected changes in the oceanic system on coastal communities? These uncertainties point to topics ripe for focused research so that the impacts of projected changes in the physical characteristics of the Arctic Ocean on the global system and living constituents can be understood and anticipated.

3.3. Example Verification

[39] Encapsulated in oceanic feedback number 1 is the positive surface ice-albedo feedback mechanism that is thought to play a dominant role in arctic sea-ice loss and projections of amplified arctic warming [e.g., *Manabe and Stouffer*, 1980; *Holland and Bitz*, 2003]. Coupled numerical models explicitly represent the interactions that lead to this (and other) feedbacks, and thus can be a powerful tool for examining the magnitude, character, and relative roles of

Figure 9. Rationale for arrows shown in the terrestrial subsystem, and references cited in each cell: 1, *Brown and Grave* [1979], *Hinkel and Nicholas* [1995], *Brown* [1963], *Douglas et al.* [2008], and *Prowse et al.* [2006]; 2, *Yoshikawa and Hinzman* [2003] and *Prowse et al.* [2006]; 3, *Kodial et al.* [2005], *Yoshikawa and Hinzman* [2003], *Woo and Guan* [2006], and *Lloyd et al.* [2003]; 4, *Hinzman et al.* [1991]; 5, *Lynch et al.* [1998] and *Mendez et al.* [1998]; 6, *Linell and Tedrow* [1983], *Kane et al.* [2003], and *Kasischke et al.* [2006]; 7, *Callaghan et al.* [2005], *Juday et al.* [2005], *Jorgenson and Osterkamp* [2005], *Prowse et al.* [2006], and *Walker et al.* [2003]; 8, *Kane et al.* [1991]; 9, *Isaac and Stuart* [1992], *Ye et al.* [2008], *Brown* [2000], *Groves and Francis* [2002], *Stone et al.* [2002]; 10, *Dyurgerov and Meier* [1997] and *Shiyin et al.* [2006]; 11, *Alexeev* [2003]; 12, *Woo et al.* [1994] and *Kane and Stein* [1983]; 13, *Berezovskaya et al.* [2004]; 14, *Yari and Van Cleve* [2006]; 15, *Hanna et al.* [2006]; 16, *Stieglitz et al.* [2003], *Henry* [2008], and *Stieglitz et al.* [2003]; 17, *Kane and Yang* [2004]; 18, *Vlassova* [2002], *Diaz et al.* [2006], and *Kazantseva* [2008]; 19, *Sturm et al.* [2005], *Brown* [1963], *Prowse et al.* [2006], *Brown and Grave* [1979], and *Foley et al.* [2003]; 20, *Chapin et al.* [2005]; 21, *Dyurgerov* [2003] and *Peterson et al.* [2006]; 22, *IPCC* [2007]; 23, *Graversen et al.* [2008]; 24, *Groves and Francis* [2002]; 25, *Law and Stohl* [2007].

	Active layer	Perma-frost	Surface water storage and runoff	Surface air temp.	Net annual rainfall	Net annual SWE	Human well-being	Land cover	Ice sheets, glaciers	Global system
Active Layer		Increasing active layer leads to permafrost degradation. (1).	Increasing active layer improves drainage. (2)							
Permafrost			Permafrost degradation initially causes surface subsidence and ponding, followed by improved drainage and drying. (3)							
Soil water storage and runoff	Decreasing surface water contributes to thinning active layer. (3,4)			Decreased soil moisture allows surface to warm and increase air temperature. (5)			Drier soils lead to more habitable land but also greater fire potential and less usable water. (6)	Decreased surface moisture leads to greater species diversity. (7)		
Surface Air Temperature	Warming leads to thicker active layer. (8)	Warming causes permafrost degradation. (8)			Warming causes greater percentage of precipitation to fall as rain as well as increased moisture in atmosphere. (9).	Warming causes smaller percentage of precip to fall as snow, but also increases water vapor, increasing precipitation. (9)		Warming benefits some ecosystems, but is detrimental to others. (7)	Warming causes decrease in ice sheets and glaciers. (10)	Warming reduces poleward temperature gradient, reduces poleward heat advection. (11)
Net annual precip: Rain	More rain increases active layer. (12)	Increased rainfall causes permafrost thawing. (12)	More rain leads to more surface water storage and runoff (13).					Increased rain increases land cover. (14)	Increased rain melts ice sheets and glaciers. (15)	

Figure 9

Net annual precip: SWE	More snow, greater insulation. (16)	More snow, greater insulation, thicker active layer, i.e., less permafrost. (16)	Reduced snowpack leads to less surface water storage and runoff. (15)				Decreased snowpack reduces water resources. (17)	Decreased snowpack decreases land cover. (14)	Decreased snow, reduces ice sheets. (15)	
Human Well Being								Increased human population decreases diversity. (18)		
Land Cover	Increased vegetation density leads to thinner active layer.. (19)	Increased vegetation density protects permafrost. (1).	Increased landcover, increases ET, decreases surface water and runoff. (19)	Increasing landcover density, decreases albedo, causes increased solar absorption, which warms air. (20)			Reduced species diversity decreases human well being. (18).			
Ice Sheets Glaciers			Increased melt on glaciers increases river runoff until glaciers are gone. (21)							
Global system			Increased FW input to drainage basins that extend south of Arctic increase discharge. (22)	Increased heat advection increases temperature. (23)	Increased moisture advection increases precipitation. (24)	Increased moisture advection increases precipitation. (24)	Increased greenhouse gases and pollutants have detrimental effects on Arctic inhabitants. (25)			

Arrows begin at hub named in row (left) and end at hub named at top of column. Cells are colored according to arrow color (white cell = black arrow, gray cell is no arrow). Colored cells with hub names correspond to whether they are net drivers or recipients in the system.

Figure 9. (continued)

different feedback mechanisms. The ice-albedo feedback has been assessed using single column ice-ocean models [*Curry et al.*, 1995; *Holland and Curry*, 1999], coupled models of intermediate complexity [*Holland et al.*, 2001], and fully coupled climate models [*Hall*, 2004; *Graversen and Wang*, 2009]. In these studies, the feedback was investigated using a control climate simulation (i.e., no anthropogenic forcing) compared with two experiments that incorporate perturbed forcing. In the first experiment, processes in the model are fully active, and a perturbation to the forcing is applied either as a surface heat flux anomaly or a change in atmospheric CO_2 concentration. The effects of varying atmospheric forcing are represented by the blue arrows between SAT and ice hubs, as well as the red arrow between SAT and surface heat storage. Varying surface albedo is implicit in these linkages. The second experiment applies an identical forcing anomaly, but the surface albedo feedback is suppressed by prescribing the surface albedo to remain at control-climate values. A comparison of the climate response between the two experiments allows an explicit quantification of the albedo feedback and its role in the climate system response.

[40] Using this method, *Hall* [2004] showed that the global surface albedo feedback explained only a small fraction of the intrinsic variability in the simulated climate system, accounting for at most 20% of the variability in some isolated regions and seasons. In the climate change experiments with a doubling of CO_2, however, the surface albedo feedback accounted for about 50% of the high-latitude climate warming and had far-reaching effects. In response to doubled CO_2 levels, over 30% of the Northern Hemisphere sea-ice area and volume reductions were associated with this feedback [*Holland et al.*, 2001]. Additionally, *Curry et al.* [1995] pointed out that the albedo feedback is active within the perennial ice pack even in the absence of changes in open water owing to changing ice-surface properties, such as the length of the snow-free season and evolution of melt-pond (pools of meltwater that form on sea ice) conditions. While the strength of this feedback does vary among different climate models [*Winton*, 2006], it is clear that across models it has an important effect on the simulated response of the arctic climate system to increasing greenhouse gases.

3.4. Terrestrial Subsystem

[41] The terrestrial subsystem is presented in Figure 8. This depiction consists of seven physical hubs: active layer (AL), permafrost (PF), surface water storage and runoff (SW), surface air temperature (SAT), net annual rainfall (RF), net annual snowfall (SF), and ice sheets and glaciers/land ice (LI). Groundwater was not included because so little information is available to describe regional trends. Two life hubs, land cover/ecosystem/vegetation (LC) and human well-being (HW), were used to represent the living part of the system. The hubs were grouped according to their involvement in processes on the land surface, in the atmosphere, and with living organisms. The relative number of arrows in and out of the hubs reveals that the atmospheric hubs are principally drivers in this subsystem while all others are recipients. The LC hub has an equal number of arrows entering and exiting, thus it is unclear whether it is an overall driver or responder in the system. The SW, HW, and all the atmospheric hubs have substantial global links, underscoring the multiple conduits through which atmospheric moisture and freshwater processes are connected with the global climate system. The diagram also provides new insight into the connections between five of the seven physical hubs that have a direct influence on life hubs. The primary drivers of the life hubs are permafrost, SW, and all of the atmosphere hubs, all of which have exhibited marked change in recent decades. Most of these changes are expected to have predominantly beneficial effects on human well-being, e.g., increased vegetative mass and less harsh living conditions for humans.

[42] The terrestrial system is unique in that some arrows change sign with time, particularly those related to permafrost. A thawing of permafrost, for example, generally results in a wetter surface as thermokarst forms, particularly in areas of continuous permafrost. Thermokarst areas are initially wet as the depressed surface first fills with water that is retained by the permafrost underneath. As permafrost continues to thaw, however, and ultimately allows water to drain through to the permafrost-free subsurface, the surface will dry. Even though permafrost is a net recipient in the system, it is a unique characteristic of the arctic terrestrial system and plays a key role in the freshwater cycle of the Arctic. A summary of the rationale for the existence and sign of each arrow is described in Figure 9 and accompanying references. The relationships described in the following discussion are documented in Figure 9.

3.4.1. Feedbacks in the Terrestrial Subsystem

[43] As in the other two subsystems, isolated feedbacks in the terrestrial subsystem were identified and are presented in Figures 10a–10d. Table 3 includes a summary of the overall effect of each feedback on the change in a life hub. Each feedback and its influence on the biological part of the system is discussed below.

3.4.1.1. Feedback Number 1: Permafrost/Surface Water/Land Cover/Active Layer Feedback

[44] This feedback starts with permafrost (PF), which has warmed during recent decades and has decreased in extent and thickness in some areas. Initially, a thawing of near-surface permafrost results in thermokarst formation, subsidence, and an increase in surface water storage and runoff (SW). Increasing SW reduces surface albedo and increases the absorption of solar radiation. Consequently the depth of the active layer increases (the layer of soil above permafrost that seasonally experiences thawing and freezing), which coincides with the degradation of permafrost. The PF linkage is positive then negative, indicating that while a decrease in PF initially increases SW, the SW ultimately decreases once the permafrost degrades sufficiently to allow good drainage. The complete loss of permafrost results in a generally drier environment. Plant growth is initially enhanced by warming and thawing of the soil, but soil saturation or excessive drying has varying effects on different plant species. If vegetation (LC) increases, its insulating effect leads to a reduction in the active-layer thickness and preservation or even growth of permafrost. Human well-being likely benefits from a decrease in permafrost, as infrastructure is more stable and agriculture is more practical in a permafrost free environment [*Chapin et al.*, 2005;

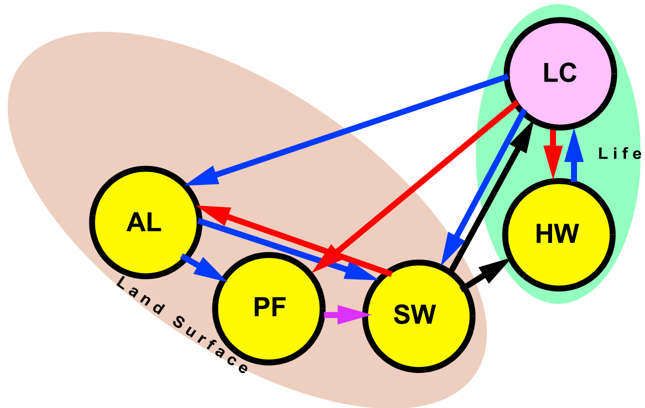

Figure 10a. Feedback loops in the terrestrial hydrologic system. Hub names are abbreviated: ice sheets and glaciers/land ice (LI), active layer (AL), permafrost (PF), surface water storage and runoff (SW), human well-being (HW), marine productivity (MP), land cover/ecosystem (LC), net annual snowfall (SF), net annual rainfall (RF), and surface air temperature (SAT). Feedback number 1: the permafrost/surface water/land cover/active layer feedback, sign is uncertain: PF => SW => LC => AL => PF.

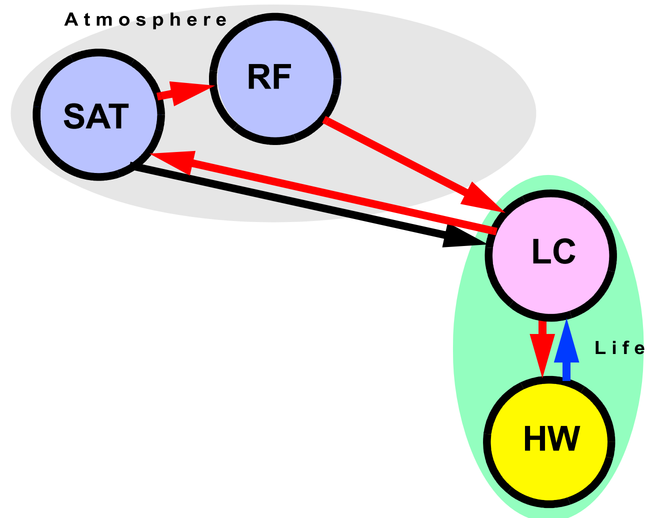

Figure 10c. Feedback number 3: air temperature/rainfall/land cover feedback, positive. SAT => RF => LC => SAT.

McGuire et al., 2002]. The signs for feedback number 1 in Table 3 reflects the ultimate drying of the environment.

3.4.1.2. Feedback Number 2: Air Temperature/Active Layer/Surface Water/Land Cover Feedback

[45] This feedback is related to the previous one, but highlights the important role played by the active layer in the arctic hydrologic system. Warming leads to a thicker active layer, which initially causes the soil to become wetter. This has competing effects on land cover: where soils are dry, vegetation will increase, but where soils become inundated, there will be a detrimental impact on species productivity and diversity. This is a complicated feedback, as some impacts compete with our primary assessment of the overall feedback result. For example, we believe that the increase in vegetation will ultimately increase the active layer thickness through its relationship with surface air temperature. It is well known, however, that in areas with thick vegetation or that are shaded, the active layer generally thins. In addition, an increase in vegetation will generally increase the evapotranspiration rate, thereby decreasing the surface water storage. It is difficult to determine which of the various responses will dominate as the outcome will vary under differing slope aspect, terrain, substrate, and topography. Observations over recent decades suggest that the tundra surface has been generally drying [e.g., *Oechel et al.*, 2000; *Smith et al.*, 2005].

3.4.1.3. Feedback Number 3: Surface Air Temperature/Rainfall/Land Cover Feedback

[46] In another simple feedback, we start with the air temperature hub (T), which has been observed to increase in

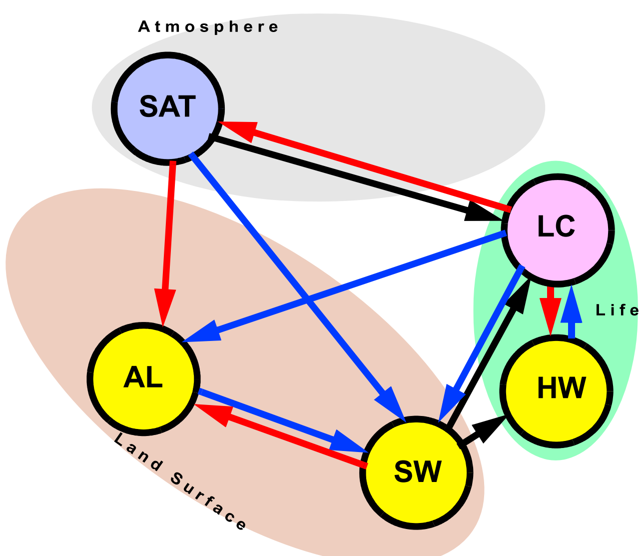

Figure 10b. Feedback number 2: air temperature/active layer/surface water/land cover feedback, sign uncertain. SAT => AL => SW => LC => SAT.

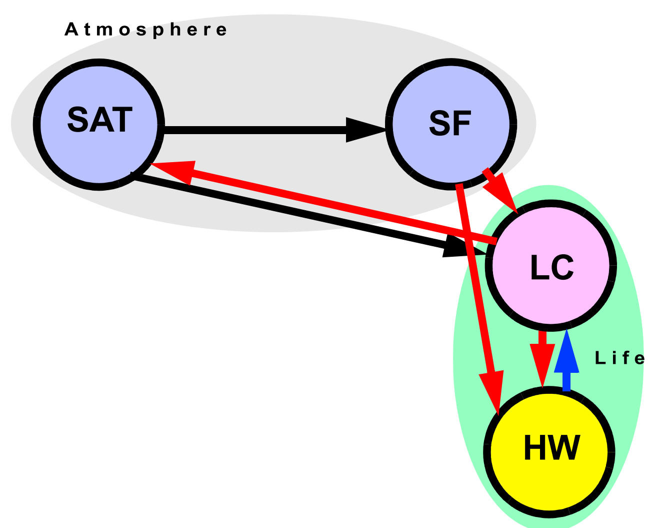

Figure 10d. Feedback number 4: air temperature/snowfall/land cover feedback, uncertain sign. SAT => SF => LC => SAT.

Table 3. What Effect Does a Feedback in the Terrestrial Subsystem Have on the "Life Hubs" in Response to the Observed Trend in a Feedback's Lead Variable?[a]

Feedback	Feedback Name (Sign)	Land Cover/Ecosystem	Human Well-Being
1	permafrost/surface water/land cover/active layer (unknown)	unknown	unknown
2	air temperature/active layer/surface water/land cover (unknown)	unknown	unknown
3	air temperature/rainfall/land cover (positive)	positive	positive
4	air temperature/snowfall/land cover (unknown)	unknown	unknown

[a]Sign of feedback indicated by positive, negative, or unknown.

the Arctic during recent decades [e.g., *Hinzman et al.*, 2005]. An increase in temperature leads to a general increase in net precipitation through more abundant water vapor, although the relationship is seasonally varying and will be offset by increasing evapotranspiration. Warmer air and less ice also contribute to a higher frequency of precipitation falling as rain, which generally benefits land cover productivity and diversity. Likewise an increase in air temperature is expected to increase land cover productivity unless desiccation occurs. Increased vegetation decreases albedo, leading to further warming. In combination with increased diversity, this generally improves human well-being, but this may have a detrimental impact on land cover diversity as the demand for agriculture, housing, and infrastructure increases. A higher net annual rainfall augments the surface and groundwater supplies that people depend upon.

3.4.1.4. Feedback Number 4: Surface Air Temperature/Snowfall/Land Cover Feedback

[47] Increasing temperature has competing impacts on net snowfall. The snow-free season will be longer and a smaller percentage of the mean annual precipitation may fall as snow. In contrast, warmer air and less sea ice lead to increased atmospheric water vapor and terrestrial precipitation, which in winter would lead to a greater snowfall. A higher snow-water equivalent promotes land cover productivity and an increase in the abundance of shrubs, trees and other vascular plants, lowering albedo and furthering warming. Taller species tend to provide some shading, which results in soil cooling. Taller plant species also allow the snowpack to persist longer in the springtime, however, insulating the ground and retaining heat in the active layer and permafrost. This effect could lead to further increases in plant cover and diversity.

[48] An important result emerging from this analysis is the critical role played by the land cover hub in the terrestrial hydrologic system. This element is involved in every feedback loop identified from the diagrams. Uncertainties surrounding its relationships with other hubs, however, highlight areas in need of research. One of these is the linkage between precipitation and vegetation: whether precipitation increases or decreases and whether it falls as snow or rain has important implications for the response of vegetation. In general, the impacts and feedbacks associated with a lengthening growing season needs additional research as we expect that rain on snow events, rainfall frequency and intensity, and extended and intensified evapotranspiration all effect the distribution of water, flora, and fauna across the landscape. An increase in snow cover also effects soil temperature, and thus the permafrost/active layer, in competing ways. Additional snow will cool the soil through a higher albedo, but the insulating processes may prevent cooling during winter. Another topic in need of further research is the relationship between vegetation and the active layer/permafrost, i.e., how changes in the types and distribution of tundra plants affect the response of the active layer. Whether permafrost is continuous or discontinuous is another important factor that affects the timing of change in soil moisture, and thus the vegetation that can grow there. All of these uncertainties, as well as how changes in these elements affect human well-being, emerge as topics requiring further study.

3.5. Example Verification

[49] Observations of changes in tundra regions of the Arctic provide evidence to verify feedback number 1 (Figure 10a), and related feedback number 2. The defining element in local hydrological processes operating in arctic land regions is the presence or absence of permafrost, and whether it is continuous or discontinuous. The thickness of the active layer and the total thickness of the underlying permafrost are also important factors. As permafrost becomes thinner or decreases in areal extent, the interaction with surface and subpermafrost groundwater processes becomes more important. The inability of near-surface soil moisture to penetrate ice-rich permafrost and infiltrate to deeper groundwater zones maintains the very wet soils characteristic of arctic regions. In the slightly warmer regions of the subarctic, however, the permafrost is thinner or discontinuous. In permafrost-free areas where infiltration is not restricted, surface soils can be quite dry, affecting ecosystem dynamics, fire frequency, and latent and sensible heat fluxes. Other hydrologic processes influenced by degrading permafrost include increased streamflow during winter, decreased peak flow during summer, changes in stream water chemistry, and other fluvial geomorphological processes [*McNamara et al.*, 1999]. Hydrologic changes observed at various study sites where permafrost has declined include drying of thermokarst ponds, increased active layer thickness, increased importance of groundwater in the local water balance, and differences in the surface energy balance.

[50] The most significant hydrologic changes occur in response to changing permafrost extent or thickness. As permafrost becomes thinner, the subpermafrost groundwater can contribute more readily to streamflow, or can promote surface drainage. Thermokarst topography forms as ice-rich permafrost thaws, and the ground surface subsides into the resulting voids. The important and dynamic processes involved in thermokarsting include thaw, ponding, surface and subsurface drainage, surface subsidence, and related erosion [*Toniolo et al.*, 2008], which can lead to rapid and extensive modification of the landscape. Prevention of or adaptation to recent thermokarsting is a major challenge for northern development. The depth to which the active layer thaws each summer season depends upon many local

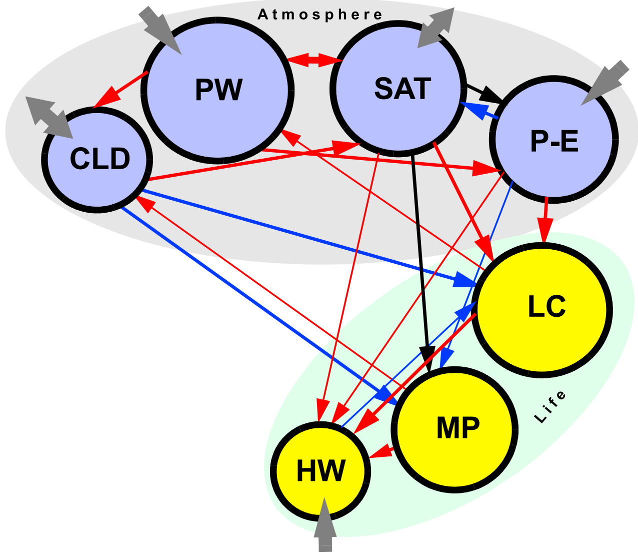

Figure 11. Atmospheric hydrologic system of the future Arctic with greatly reduced permanent ice. Differences in the size of hubs relative to present-day condition (Figure 2) are a qualitative indication of change in those components of the system.

factors, including site hydrology, temperature, and levels of soil moisture due to variation in precipitation and evapotranspiration.

[51] In response to some imposed disturbance, such as a tundra fire or climatic warming, massive-ice permafrost (permafrost consisting of nearly 100% ice) may differentially thaw, creating irregular surface topography [*Hinzman et al.*, 2003]. Depressions on the surface then form ponds, accelerating subsurface thaw through lower albedo and heat advected into the pond through runoff. Eventually a talik (layer of unfrozen soil above the permafrost and below the seasonally frozen soil) may form below these ponds as the depth of water becomes greater than the amount that can refreeze during the winter. If the talik grows to a size that completely penetrates the underlying soil or connects to a subsurface layer that allows drainage, the pond may then begin to drain. The implications of this process are that in regions over thin permafrost (less than approximately 20 m), surface ponds may shrink and surface soils may become drier as the permafrost degrades. This process depends upon regional hydrologic gradients, i.e., whether the region is a groundwater upwelling or downwelling zone. The same mechanisms that allow drying of the ponds may also cause dry soil, with significant impacts on latent and sensible heat fluxes as well as vegetation abundance and diversity.

4. Results Part 2: An Arctic Hydrologic System With Diminished Permanent Ice

[52] According to *Wang and Overland* [2009] and others, the Arctic system appears to be on a trajectory toward a state in which the Arctic Ocean is virtually ice free in summer and other permanent ice forms are greatly reduced. Clearly a change of this magnitude would have a large impact on the arctic hydrologic system. In this section we use the diagrams to assess in a general way how the present-day interactions would be altered and how changes in the physical system may affect the biological organisms of the Arctic that have adapted to the presence of perennial ice.

[53] The diagram for an atmospheric system in a seasonally ice-free scenario is shown in Figure 11. Clearly the new system is much simpler because sea ice is involved in many of the linkages in present-day conditions, and most of the feedbacks have disappeared. Warmer temperatures occur in tandem with increases in water vapor, cloud cover, net precipitation, land vegetation, and marine productivity. While the sea ice hub disappears in this analysis, all other hubs increase in size, except for human well-being, and all hubs retain their character as either a driver or recipient in the system. Elimination of thick, multiyear sea ice would open the Arctic to transportation and access to energy and raw materials during summer months. Increased availability of natural resources and newly open shipping routes would bring economic opportunities to arctic inhabitants. Indigenous cultures whose ice-centric activities define their traditions and hunting practices will be negatively affected. Migrations of animals and plants will likely lead to losses of certain sensitive species but will result in new population distributions [*ACIA*, 2005]. In the event that a seasonally ice-free Arctic Ocean does become a reality, the winters will continue to be cold and dark, ultimately limiting the migration of many species and human activities on a year-round basis.

[54] The changes in the seasonally ice-free ocean system (Figure 12) are even more striking, albeit less certain, as two of the sea-ice hubs are lost that take with them many of the linkages within the system. As temperature and net precipitation increase, so would the terrestrial freshwater discharge, leading to increased freshwater entering the Arctic Ocean. This would strengthen the stratification of the surface layer and increase the discharge of liquid freshwater into the North Atlantic Ocean. The discharge of ice, however, would occur only through the transport of sea-

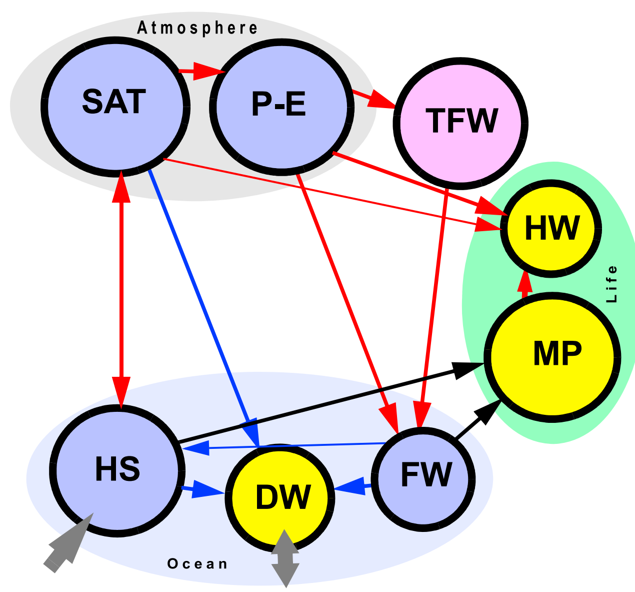

Figure 12. Same as Figure 11 but for the future oceanic hydrologic system. Compare to present-day diagram in Figures 7a–7e.

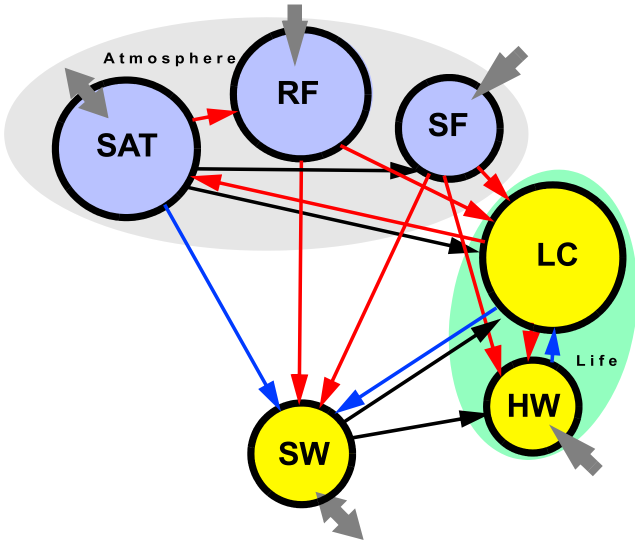

Figure 13. Same as Figure 11 but for the future terrestrial hydrologic system. Compare to present-day diagram in Figure 8.

sonal ice. While the additional stratification along with increased heat storage in the North Atlantic Ocean would have a damping effect on deepwater formation, the reduction in ice export into the convection regions would reduce the stratification and enhance deepwater formation in the Nordic and Labrador Seas. Which effect would dominate in this case is unknown, but it will have important ramifications for the strength of the global thermohaline circulation. Interestingly, the loss of summer sea ice would also change the classification of two of the hubs: terrestrial FW discharge shifts from a driver to neutral influence (same number of arrows in and out), while the surface FW hub switches from a recipient to a driver. Every one of the five feedbacks in the present-day system involves sea ice, thus none of them exists in the future seasonally ice-free scenario. Other feedbacks that are more typical of a midlatitude environment, however, will assume greater importance. It is likely that marine organisms will become more abundant and perhaps more similar in species to those now found in subarctic areas. Humans will have to adapt to a world in which improved access will translate to greater resource development and increased immigration, both of which are likely to provide new economic opportunities but challenge the preservation of native cultures.

[55] The terrestrial hydrologic system loses the influence of three hubs representing permafrost, glaciers and ice sheets, and the active layer (Figure 13). The active layer does not actually disappear, but it becomes irrelevant when permafrost exists only at great depths. Once again, a much simpler system emerges. Approximately 32 arrows are reduced to 14, with only two of four feedbacks remaining.

5. Conclusions

[56] The arctic hydrologic system is complex and intricately entwined with life in the region. Changes occurring in the global climate system have direct and indirect effects on the Arctic and vice versa. A variety of feedbacks involving phase transformations of water exacerbate or reduce these changes. Much is uncertain about the ramifications of global change on the hydrologic system; in the Arctic this is particularly true owing to the complicating effects of diminished permanent ice in its various forms. Global climate models are not yet able to simulate all the processes and interactions that link components of the physical system, and they are even farther from simulating effects on the biological and societal connections. In this study we attempted to assess the myriad of hydrologic interactions and feedbacks within the arctic system, both physical and biological, using a heuristic approach. This analysis has yielded the following conclusions:

[57] 1. The atmospheric hubs in each subsystem are net drivers, i.e., they primarily force rather than respond to changes in the other components. The life hubs in each subsystem are net recipients.

[58] 2. The atmospheric hydrologic subsystem consists of 5 physical components or hubs, all of which are drivers, all have direct linkages with the global climate system, and all but one have direct interactions with the life hubs.

[59] 3. Based on our criteria for identifying feedback loops (see section 2), seven feedbacks exist in the atmospheric subsystem, four of which are positive, one is negative, and the signs are uncertain in the remaining two. All but two of these feedbacks involve sea ice. The effects of these physical feedbacks on the biological components are varying and often competing.

[60] 4. The oceanic subsystem consists of ten hubs, half of which are drivers: two are atmospheric, two represent sea ice, and one is terrestrial freshwater discharge. All three of the "wet ocean" hubs are recipients, as are the two life hubs.

[61] 5. Five feedback loops are identified in the oceanic subsystem: one is positive, one is negative, and three are uncertain as to their signs.

[62] 6. All of the feedbacks in the oceanic system involve sea ice. The influence of these feedbacks on the life hubs is highly uncertain owing to competing factors in the relationships between changes in the physical system and the well-being of marine organisms and human society.

[63] 7. The terrestrial subsystem is represented by nine components. The three atmospheric hubs are the only drivers of the system, and they involve precipitation and temperature. The land surface consists of four components, two of which are forms of permanent ice. The connections between these hubs are numerous and complex, but most can be assigned a definite sign based on previous studies.

[64] 8. Four feedbacks emerge from this diagram: one is negative, and three have uncertain signs. In the one negative feedback, the effect on the two life hubs is unanimously positive, suggesting that recent observed changes in the system are enhancing the increase in vegetative biomass and benefiting humans overall, but that uncertainties in the other three feedbacks need further investigation.

[65] 9. Surprisingly, all four of the terrestrial subsystem feedbacks include the land cover/ecosystem/vegetation hub, underscoring the essential role played by the changing tundra in the arctic hydrologic system.

[66] This analysis was extended to depict a future Arctic with greatly reduced permanent ice (multiyear sea ice, permafrost, and glaciers/ice sheets). Because permanent ice plays pivotal roles in all three systems and in many of

the feedbacks, the diagrams representing the future differ dramatically from those of the present day. From this exercise we found that:

[67] 1. In the seasonally ice-free scenario, the diagram for the atmospheric subsystem is much simpler. All the components except human well-being increase. Of the seven feedbacks in the present-day system, only two remain. The physical and biological characteristics are more sub-Arctic-like, and certain aspects of indigenous cultures could suffer without sea ice, which is integral to many of their traditions and subsistence hunting practices. Prosperity may increase, however, as new economic opportunities emerge in a seasonally ice-free Arctic Ocean.

[68] 2. The future oceanic system minus its two sea-ice hubs is greatly simplified. Half of the interactions represented by arrows disappear, and all five of the feedback loops are gone. All of the hubs except human well-being and deepwater formation increase in a seasonally ice-free scenario, although the expected change in deepwater formation is uncertain owing to competing effects.

[69] 3. The terrestrial subsystem loses three hubs in the depiction of the future: permafrost, glaciers/ice sheets, and the active layer. All remaining components increase except for human well-being, and the number of interactions among hubs drops from 32 to 14. As the landscape becomes more midlatitude-like in terms of its hydrologic cycle, the traditional way of life for arctic peoples will likely become more difficult to preserve. Again, however, there may be many more economic opportunities in the warmer Arctic.

[70] The simplified, ‘‘big-picture’’ approach used in this study provides a framework for identifying the important relationships and feedbacks in the arctic hydrologic system. It also allows for identification of the key gaps in knowledge that frustrate efforts to understand and anticipate how the changing system will affect life on land and in the ocean. The most important of these gaps or uncertainties are summarized here, and represent issues that require further research:

[71] The primary source of uncertainty related to atmospheric drivers revolves around net precipitation in the Arctic. Observations, models, and logic suggest that it will generally increase as greenhouse gases continue to accumulate, but the spatial and seasonal details are unclear. Even less certain are the effects of changing quantities and type (rain or snow) on the sea ice mass budget, which in turn affects many other feedback loops in the oceanic and atmospheric subsystems. Changing precipitation is also expected to affect marine primary productivity through a change in the freshwater content, and thus stratification of the ocean mixed layer. Stronger stratification will reduce mixing and enhance warming in the mixed layer, but will also hamper vertical transport of nutrients. None of these effects are well understood. Finally the relationships and feedbacks that connect changing precipitation with arctic vegetation are also uncertain, as some tundra plants may benefit from additional moisture while others will be displaced by species adapted to warmer conditions.

[72] In addition to linkages between precipitation and marine productivity described above, the effects of sea-ice change on marine productivity are also highly uncertain. There is evidence that the additional light penetrating the ocean as ice retreats will generally increase phytoplankton abundance, but the secondary effects of a fresher mixed layer along with stronger vertical mixing by winds over larger areas of open water are competing. Increased solar energy in the ocean will also warm the mixed layer, which will likely affect the diversity of plankton populations. How all these relationships will affect the lives of humans living in the Arctic is also an open question, as food sources on land and in the ocean will change, new economic opportunities will emerge, and traditional ways of life will be increasingly influenced by external pressures.

[73] Terrestrial vegetation emerges from this study as a key participant in the arctic hydrologic system, as it plays a role in every feedback loop that was identified. While the atmosphere drives changes in the land cover, the vegetation is an important driver for permafrost and the active layer, which in turn effects soil moisture and the feedback to vegetation. Moreover, these relationships differ depending on the mix of vegetation species.

[74] These results highlight relationships in the arctic hydrologic system that are poorly understood, or for which competing influences leave open questions as to the cumulative impact on marine productivity, terrestrial plants, and the well-being of humans living in the region. Many of these open questions provide ripe opportunities for research using data sets emerging from new satellite instruments, observations from recently deployed surface-based observing networks such as the Arctic Observing Network [*Interagency Arctic Research Policy Committee* (*IARPC*), 2008], a wealth of state-of-the-art GCM output [*Walsh et al.*, 2002], and the flurry of field campaigns conducted as a part of the International Polar Year [*Polar Research Board* (*PRB*), 2004]. If the Arctic continues along its trajectory toward ever-decreasing stores of permanent ice, the analysis presented here depicts a hypothetical and highly simplified projection for how this system, whose behavior is now defined by the presence of permanent ice and all the processes in which it participates, may evolve into a climate with predominantly seasonal ice. The fundamental shift in the physical realm, based on this graphical projection and the changes already being observed, would have substantial implications for all plants and animals living in the region, not the least of which will be the native peoples and their way of life.

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