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THE SENSITIVITY OF NORTHERN GROUNDWATER RECHARGE TO CLIMATE CHANGE: A CASE STUDY IN NORTHWEST ALASKA[1]

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ABSTRACT: The potential impacts of climate change on northern groundwater supplies were examined at a fractured-marble mountain aquifer near Nome, Alaska. Well water surface elevations (WSE) were monitored from 2004-2009 and analyzed with local meteorological data. Future aquifer response was simulated with the Pan-Arctic Water Balance Model (PWBM) using forcings (air temperature and precipitation) derived from fifth-generation European Centre Hamburg Model (ECHAM5) global circulation model climate scenarios for extreme and modest increases in greenhouse gases. We observed changes in WSE due to the onset of spring snowmelt, low intensity and high intensity rainfall events, and aquifer head recession during the winter freeze period. Observed WSE and snow depth compared well with PWBM-simulated groundwater recharge and snow storage. Using ECHAM5-simulated increases in mean annual temperature of 4-8°C by 2099, the PWBM predicted that by 2099 later freeze-up and earlier snowmelt will decrease seasonal snow cover by one to two months. Annual evapotranspiration and precipitation are predicted to increase 27-40% (55-81 mm) and 33-42% (81-102 mm), respectively, with the proportion of snowfall in annual precipitation decreasing on average 9-25% ($p < 0.05$). The amount of snowmelt is not predicted to change significantly by 2099; however, a decreasing trend is evident from 2060 in the extreme ECHAM5 greenhouse gas scenario. Increases in effective precipitation were predicted to be great enough to sustain sufficient groundwater recharge.

(KEY TERMS: climate variability/change; arctic/antarctic; groundwater hydrology; recharge; snowmelt; Pan-Arctic Water Balance Model.)

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INTRODUCTION

At high latitudes, recent climatic warming has occurred more rapidly than many other regions on earth (Manabe *et al.*, 1991; Serreze *et al.*, 2000; Ramaswamy *et al.*, 2001). As a result, major changes in the arctic and subarctic hydrological cycle have been observed in the last few decades, such as later freeze-up and earlier snowmelt, as well as increased precipitation and runoff (Magnuson *et al.*, 2000; Hinzman *et al.*, 2005; White *et al.*, 2007; Rawlins *et al.*, 2010). This likely has important consequences for groundwater recharge, which is dependent upon

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the amount and duration of winter precipitation and spring snowmelt.

In Alaska and the circumpolar north, where groundwater aquifers are primarily recharged by snowmelt, climate change is poised to affect the sustainability of northern water supplies (Schindler, 1997; White *et al.*, 2007; Alessa *et al.*, 2008). Despite this, there have been very few studies that predict the sensitivity of arctic or subarctic groundwater resources to changing climate.

The effects of climatic warming on groundwater recharge are likely to be diverse and complex. Earlier snowmelt and later freeze-up will reduce the period of snow accumulation resulting in a longer summer season, which, even with more annual precipitation and runoff, could mean more water lost through evaporation and evapotranspiration, and a potential net loss in groundwater recharge (Hinzman *et al.*, 2005; Hamlet *et al.*, 2007). Understanding these complex interactions is critical for making predictions about how subarctic freshwater systems will respond to climate change and, in turn, how this will affect human societies.

Water balance models are increasingly being used to assess the importance of different hydrologic parameters on water storage and demand under a variety of hydrologic conditions, and to predict hydrologic conditions under a range of future climate scenarios (Rouse, 1998; Xu and Singh, 1998; Jasper *et al.*, 2006). Hydrological models that adequately capture the arctic and subarctic water cycle are needed to understand the current and future relationship between climate and water resources. There are major limitations, however, in the availability and quality of arctic climate and physiographic data (e.g., precipitation, river discharge, soil properties, and vegetation characteristics) needed to parameterize and drive these models that must be taken into account (Lammers *et al.*, 2001; Shiklomanov *et al.*, 2002; Rawlins *et al.*, 2003). Given these restrictions, Rawlins *et al.* (2003) presented a Pan-Arctic Water Balance Model (PWBM) that is simplified and scaled suitably to fit the spatial resolution of available input data in arctic regions.

The PWBM is a terrestrial hydrological model driven by daily air temperature and precipitation, and by gridded fields of vegetation cover, rooting depth, and soil characteristics (soil texture and organic content). For application at high-latitudes, Rawlins *et al.* (2003) modified the water balance model presented by Vörösmarty *et al.* (1996, 1998) to include a simple thaw-freeze model that allows daily changes in the amount of liquid and frozen water in soil to be calculated for large spatial scales (Rawlins *et al.*, 2003). Soil moisture is estimated in the PWBM using a simple "bucket" model of soil moisture, a model where predicted soil water is analogous to that determined for the rise (when precipitation > evapotranspiration) and drop (evapotranspiration > precipitation) of water in a bucket, which has been shown to perform comparably to finer resolution water balance models that incorporate the effects of vegetation on soil-moisture fluxes (e.g., Robock *et al.*, 1995). In a sensitivity analysis, Rawlins *et al.* (2003) reported that, similar to other large-scale hydrology models (e.g., Nijssen *et al.*, 2001), the PWBM-simulated runoff is more responsive to climatic forcings (precipitation and air temperature) with less effects noted when land cover specifications or model parameters are altered. This appropriately reflects the type of data that is available in this project.

This project used the PWBM to address the potential impacts of climate change on northern groundwater supplies. We used five years of groundwater height and meteorological data to investigate the sensitivity of northern aquifers to climate data, and the PWBM was used to understand how water resources in the circumpolar north may change under different future climate scenarios. We addressed the following research questions at a fractured-marble mountain aquifer: (1) How responsive is groundwater level to observed changes in snowmelt and precipitation? (2) How is future groundwater recharge likely to change with projected climate-change scenarios?

METHODS

Study Site

To understand the sensitivity of northern groundwater supplies to climate change we studied Moonlight Springs aquifer, which is located approximately 6 km north of Nome, Alaska (64°33′N, 165°24′W; elevation ca. 46 m), and is the sole municipal water source for the City of Nome (Figure 1). Mean daily air temperature for Nome ranges from −15°C in January to +11°C in July (Figure 2). Total annual precipitation averages 438 mm, with most winter precipitation falling as snow (National Climatic Data Center, http://www.ncdc.noaa.gov, *accessed* September 1, 2009). Vegetation in the Nome region is characterized by low shrub arctic tundra communities, with areas of open and closed canopies of willows or shrub birch, or open alder (Raynolds *et al.*, 2006).

Moonlight Springs exists in a fractured marble formation at the base of Anvil Mountain, in a region of discontinuous permafrost. Nearby Anvil Creek is separated from Moonlight Springs by a fault system to the east of the creek. The assumption that

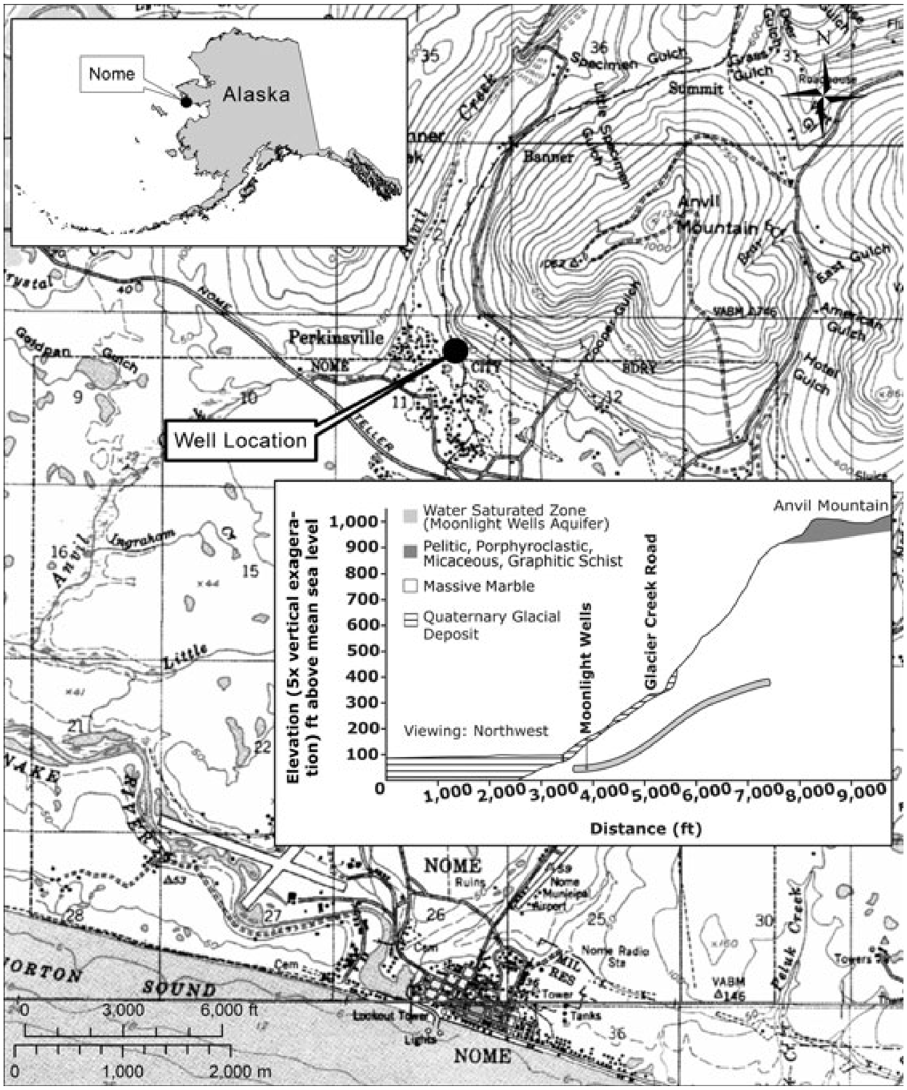

FIGURE 1. Location of Moonlight Wells on the Seward Peninsula, Alaska. Cross-section of Moonlight Wells Geology (Inset) Modified after Bristol Environmental and Engineering Services Corporation, "Technical Memorandum Moonlight Wells Protection Area Nome, Alaska", Unpublished Report for City of Nome, 2005. Subsurface Contacts Between Geologic Units are Approximate, and the Lateral and Vertical Extent of the Aquifer is Unknown.

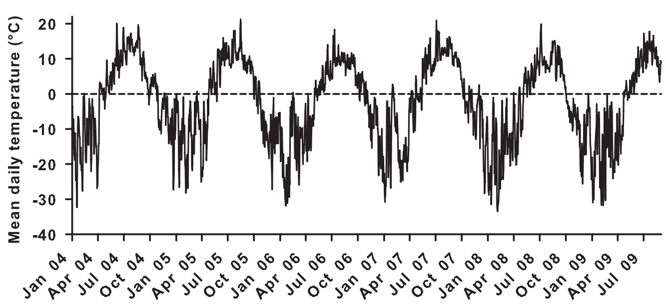

FIGURE 2. Temporal Variation in Mean Daily Air Temperature at Nome Airport, Alaska, for the Five Study Years.

groundwater flow does not cross this fault is supported by surface water gauging and analysis of spring water chemistry (Alaska DNR, 1992; Stevens, 2005). For instance, Anvil Creek is found to lose flow to groundwater at a site below the Moonlight Springs elevation, indicating that Moonlight Springs is not the receiving body for this flow. Furthermore, spring water chemistry exhibits characteristics consistent with flow through the highly fractured marble formation that outcrops above Moonlight Springs on the hillside of Anvil Mountain rather than schist, which is present below the aquifer (Alaska DNR, 1992).

Well WSE and Climate Data

Pressure transducers were installed in all three wells at Moonlight Springs in July 2004 to measure changes in well water surface elevations (WSEs).

The WSE data were recorded at 15-min intervals from 2004 to 2009. The well casings were steel, with aluminum sanitary caps. The bottoms of the wells were approximately 25-37 m below ground surface (BGS), and the well casings ranged in length from 23 to 28 m BGS. The wells were unscreened, hence below the well casing the bore hole was open and in the water-bearing marble fracture. Two of the three wells were actively pumped, which is evident in the WSE data. In addition to well data, the City of Nome provided monthly pumping volumes for the years 1981 to 2008. The data represent the combined withdrawals from the three Moonlight wells. Annual pumping volumes differed very little during the study period, averaging approximately 534,000 ± 17,000 m^3. Water extractions differed on average <10,000 m^3 between winter and summer seasons.

Climate data used in this study include daily total precipitation, snowfall, snow depth, maximum temperature, minimum temperature, and average temperature. The data were obtained from the National Climatic Data Center website (http://www.ncdc.noaa.gov) and represent measurements taken at the Nome airport.

Filtering Well Data

The Moonlight wells were actively pumped, which introduced two important effects: (1) intermittent drawdown associated with direct pumping, and (2) changes in aquifer storage and gradients associated with water withdrawals. Due to the high flow velocities in this fractured bedrock aquifer, transient effects from pumping were largely removed by filtering out periods that exhibited abrupt WSE drops followed by a short recovery period. To this end, the original 15-min data were initially filtered by selecting the maximum daily WSEs. A second data pass used graphical analysis to identify and remove additional points that clearly showed the effects of pumping, usually because a well had been pumped for most or all of a day, thus passing the initial filter undetected.

The justification for the data processing employed here follows from the observation that, when a well pump was turned off, WSEs in the well showed rapid increases that stabilized within a few hours. As the wells were generally pumped intermittently throughout the day, maximum daily water levels tended to represent nonpumping conditions. This procedure, however, did not address the effect of aquifer withdrawals. Total monthly withdrawals may help to understand how withdrawals modify overall aquifer trends. Without knowing details of the aquifer properties, the influence is restricted to a qualitative assessment.

The city's primary production wells (Wells 2 and 3) were removed from the analysis, as pumping made data filtering less effective due to numerous gaps in the data. The well least frequently pumped (Well 1) was therefore best suited for further analysis. Although the behavior of all wells was considered, the similar temporal trends in well WSE and the close proximity of all of the wells (<100 m) meant that the primary production wells (Wells 2 and 3) were generally considered as replicates of the least pumped well (Well 1). From here onward, all references to well WSE refer to Moonlight Well 1.

Pan-Arctic Water Balance Model

Future changes in the groundwater hydrology of Moonlight Springs aquifer were examined using the PWBM (Rawlins *et al.*, 2003). All simulated water fluxes and storages were drawn from a simulation for a single point centered on the Nome region. The PWBM is capable of simulating the effects of frozen soil on soil thermal and hydrological dynamics. For this study, we disabled the model's frozen (permafrost) soil scheme, as the recharge area of the Moonlight Springs site is not underlain by permafrost. We simulated, at an implicit daily time step, key components of the surface and subsurface hydrology such as snow storage, groundwater recharge, and surface runoff associated with seasonal precipitation and snowmelt. The model accounts for daily changes in soil water within two layers (Figure 3). The top layer is a rooting zone, parameterized as 40 cm thick given the low shrub tundra in the area. The lower model layer (deep zone) accounts for slow delays in water movement from the soil column to streams and rivers. Given current configuration of the model, we found that setting this lower zone to 10 cm thick resulted in closest agreement with the observed responses seen in the well data. Both layers were subject to horizontal drainage, but in contrast to the rooting zone, the deeper soil zone was not subject to vertical draw from evapotranspiration, and lost water only to runoff (Figure 3). The deeper soil zone represents all slow processes related to groundwater recharge and discharge and is analogous to the storage in a well. Thus, aquifer recharge was estimated by the flux of water from the root zone to the deep soil zone.

The PWBM incorporates spatially varying soil textures from the Food and Agriculture Organization/UNESCO data set. In order to account for typical hydrological responses from the Moonlight Springs fractured marble formation, and based on field observations that characterized the soil as a large rubble crop, a representative published porosity value of 0.15 was used in each zone, with a field capacity of 0.05. This gave a pore space in rooting zone (water equivalent) of 60 mm.

For simulations over the period 2004-2009, temperature and precipitation were drawn from Nome airport records. Our simulation for the period 1902-1999 incorporated outputs from the fifth-generation European Centre Hamburg Model (ECHAM5) general circulation model (GCM) forced by the Special Report on Emissions Scenarios (SRES) version A1B. Future hydrologic fluxes (2010-2099) were produced using the ECHAM5 model and the A2 and B1 scenarios, respectively, for extreme and modest increases in greenhouse gas (GHG) concentrations. ECHAM5, like most GCMs, is biased cold and wet. The data were adjusted to be more consistent with contemporary climate. This was accomplished by determining the mean monthly bias (1961-1990) between ECHAM 5 precipitation and the precipitation value in the NCEP/NCAR reanalysis (Kalnay *et al.*, 1996). The offset was then applied to the ECHAM5 precipitation data for the future (2010-2099) period. A similar approach was used to reduce the bias in the future ECHAM5 air temperatures.

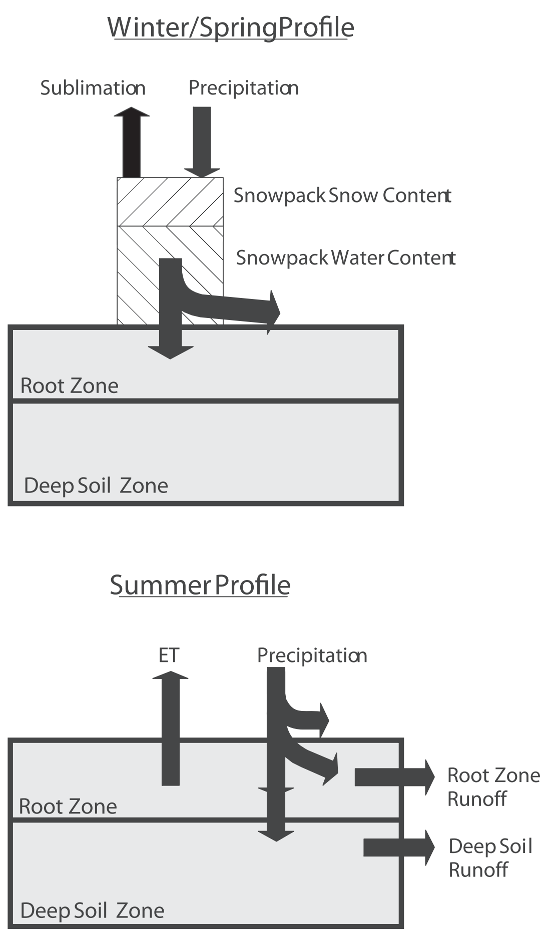

FIGURE 3. Diagram of the PWBM Setup Showing the Two Soil Zones, and Water Fluxes in Winter/Spring and Summer. Water in Root and Deep Soil Zones were Frozen in the Winter, Disabling Runoff.

RESULTS

Climate and Hydrology

Snowmelt had a distinct influence on WSEs. The abrupt loss of snow pack in April marked the spring melt and was followed in early May by a period of increasing water level of 1-2 m, representing snowmelt recharge to the aquifer (Figure 4). Aquifer response to nonwinter precipitation, on the other hand, was not readily apparent (Figure 4). Although some very wet periods appeared to affect aquifer response (e.g., September-October 2005), the correlation did not seem to hold for all rain events or even for all wet periods. This suggests that the relevant scales for rainfall recharge were longer than daily. Accordingly, aquifer response to precipitation was separated by seasons of nonwinter rainfall (May-October) and winter snowfall (November-April); the aggregated precipitation peaks appear to correspond well to changes in water levels (Figure 4).

Precipitation was compared with changes in water level for a range of averaging periods. The strongest correlation (r^2 = 0.61) was found between the 15-day moving average precipitation and the centered eight-day water-level slope (i.e., the change in water level over an eight-day period) (Figure 5). The relationship suggests that when the total daily precipitation (averaged over 15 days) was above 2 mm, aquifer recharge was greater than depletion. On the other hand, aquifer drainage exceeded recharge when the 15-day

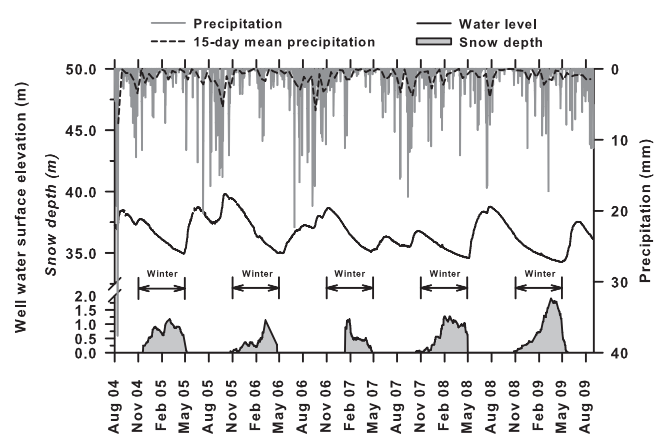

FIGURE 4. Well Water Levels With Meteorological Data, Including 15-Day Average Precipitation. Snow Depth Data were Missing for Early Winter in 2007.

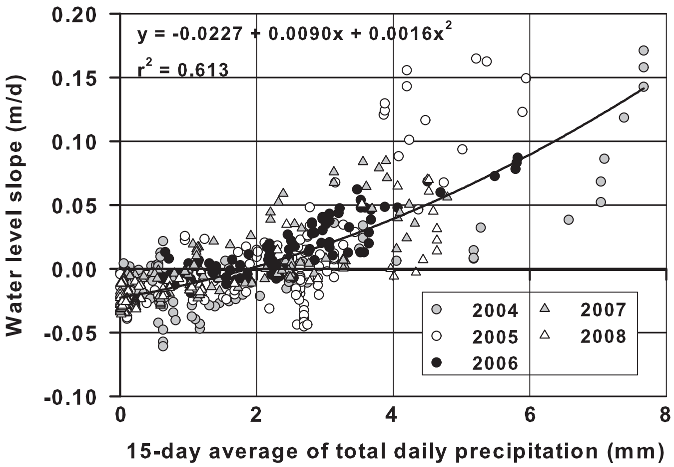

FIGURE 5. Well Water-Level Slope *Vs.* 15-Day Average Precipitation for Periods That Exclude Winter and Spring Melt (July-October, 2004-2008).

average precipitation fell below this threshold. Additionally, the rate of water-level decline began to level off as the average precipitation approached 0 mm. Conceptually, it is expected that, in the prolonged absence of recharge, the aquifer should approach its natural drainage rate. WSEs for winter periods were used to further investigate this hypothesis.

As the precipitation was stored at the surface as snow and ice during the winter season, the data should represent aquifer response in the absence of recharge. Groundwater levels declined steadily throughout the winters (Figure 6). A similar rate of water-level decline was observed for all the wells. The slopes of each plot in Figure 6 represent the water-level time rate of change. These winter slopes corresponded well with the minimum slopes found from the precipitation-water-level analysis (Figure 5). Depending on whether the data were fit with a linear or quadratic trend, the minimum rate of water-level decline from Figure 5 (y-intercept) was between 0.02 and 0.03 m/day, respectively. The rate decline during winter was between 0.01 and 0.03 m/day (Figure 6).

Pan-Arctic Water Balance Model

Snowmelt. For all five study years, there was excellent agreement between the model-estimated and measured onset of snow accumulation (Figure 7a). Furthermore, predicted increases in snow water equivalent (SWE) fit well with the measured increases in snow depth (Figure 7a). Comparisons between the decline in model-estimated SWE and measured snow depth indicate that snowmelt occurred slightly earlier than the model predicted, particularly in years when snowmelt was more gradual (e.g., 2005 and 2007) (Figure 7a). Model-estimated snow storage did not capture the abrupt decline in mid-winter snowpack that occurred in some years. Although modeled snowmelt occurred more rapidly than measured snowmelt, the timing of complete snowmelt, that is, when SWE and snow depth were equal to zero, compared very well (Figure 7a). As snow depth rather than SWE was measured at the site, it should be noted that a direct comparison of measured and modeled SWE could not accurately be conducted.

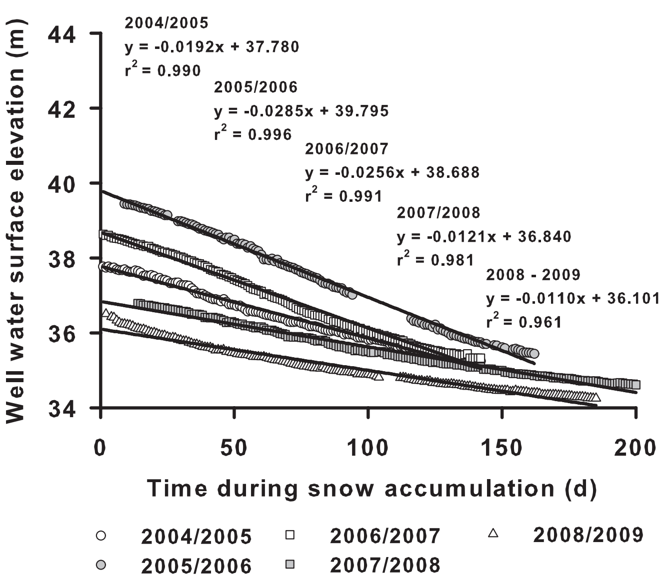

FIGURE 6. Decline in Well Water Levels During Five Winter Seasons (2004/2005-2008/2009).

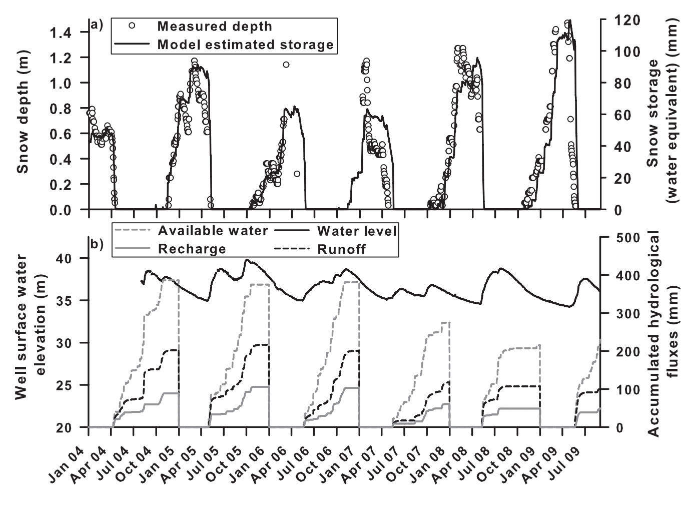

FIGURE 7. Time Series of Measured Snow Depth, and PWBM-Simulated Snow Water Equivalent (a), and Measured Well Surface Water Elevation and PWBM-Simulated Accumulated Soil Available Water (From Rainfall and Snowmelt), Runoff, and Recharge (Estimated by Soil Water Down-Flux) (b) From 2004-2009.

Groundwater Recharge. Increases in measured WSE correlated well with the modeled hydrological fluxes (Figure 7b). The PWBM-simulated hydrologic fluxes captured the abrupt seasonal increase in aquifer recharge following snowmelt, as well as the increases in recharge associated with late summer-fall precipitation (Figure 7b). Differences in groundwater recharge among years were also predicted fairly well by the model, for example, the large rapid snowmelt and subsequent groundwater recharge in May 2005, with the exception of 2008 where measured groundwater recharge was higher than predicted (Figure 7b). Modeled recharge in 2008 was the lowest of the five year study period, and was similar to 2007 (Figure 7b), with total runoff values of 107 and 118 mm, respectively (Table 1). Contrary to this, 2008 and 2007 WSEs were very different, with maximum summer WSEs of 38.8 and 36.8 m, respectively (Figure 7b). Interestingly, 2008 was the coolest and driest year of the study period, with respective annual air temperature, precipitation, and evapotranspiration values of −4.0°C, 273 mm, and 179 mm (Table 1). It may be that reduced evapotranspiration in 2008 can account for the greater than predicted well recharge. Alternatively, this discrepancy may be associated with the higher than predicted snow accumulation in late January 2008 (Figure 7a).

Well WSEs in summer 2007 were approximately 2 m lower than levels measured during the other study years (Figures 4 and 7b). The reduced WSEs were in part due to lower spring melt associated with a late January/early February 2007 thaw (Figures 2 and 7a) that would have reduced the snow pack. Although the model did not capture the abrupt decline in mid-winter snowpack, reduced summer hydrological fluxes were predicted effectively for infiltration and runoff (Figure 7b).

Future Simulations. Mean annual air temperature in Nome Alaska increased steadily over the past century in ECHAM5 A1B scenario, from an average of −4°C in the 1900s to −2.2°C in the 2000s ($p < 0.05$) (Figure 8a). Further increases in air temperature were predicted, but vary depending on the estimated increases in GHG emissions. By 2090, the ECHAM5 GCM predicted an increase in mean annual air temperature of approximately 4°C ($p < 0.05$) for the modest GHG scenario (SRES B1) and approximately 8°C ($p < 0.05$) for the extreme GHG scenario (SRES A1) (Figure 8a).

Similarly, total annual precipitation and evapotranspiration increased slightly ($p = 0.05$ and <0.05, respectively) over the last century (ECHAM5 A1B scenario), and were predicted to increase by 33-42% (81-102 mm) and 27-40% (55-81 mm), respectively, by 2090 ($p < 0.05$) (Figures 8b and 8c). Predicted increases in precipitation were lower during nonwinter months (May-October) than in the winter (November-April), which resulted in a slight decrease (<4% in the B1 scenario, $p > 0.05$; and <10% in the A2 scenario, $p < 0.05$) in the proportion of summer to annual precipitation (Figure 9).

TABLE 1. Key Annual Fluxes (precipitation, evapotranspiration, snowmelt, available water, infiltration water, root zone to deep zone (recharge) base flow, and total runoff) and Annual Air Temperature.

	Annual Fluxes (mm)							
Year	**Precipitation**	**Evapotranspiration**	**Snowmelt**	**Available Water**	**Infiltration Water**	**Root to Deep Zone**	**Total Runoff**	**Annual Air Temperature (°C)**
1990	591	268	67	487	415	119	294	−3.1
1991	407	245	77	398	336	92	222	−1.7
1992	346	183	10	212	190	53	106	−4.3
1993	494	237	107	406	360	114	263	−0.9
1994	495	222	70	407	363	104	250	−2.8
1995	391	237	145	369	301	79	222	−1.7
1996	438	235	61	307	274	70	155	−2.6
1997	475	223	69	393	355	113	243	−1.9
1998	670	292	155	591	461	144	412	−1.7
1999	389	214	55	344	288	79	198	−5.3
2000	528	250	72	406	387	133	257	−1.2
2001	362	240	70	276	229	54	137	−3.2
2002	369	220	84	296	275	79	161	−0.6
2003	413	227	15	325	314	79	146	−1.3
2004	455	233	35	386	339	89	203	−0.6
2005	402	227	69	375	359	106	217	−1.8
2006	458	254	34	381	367	103	201	−3.2
2007	362	235	32	274	259	61	118	−1.2
2008	273	179	68	215	204	49	107	−4.0

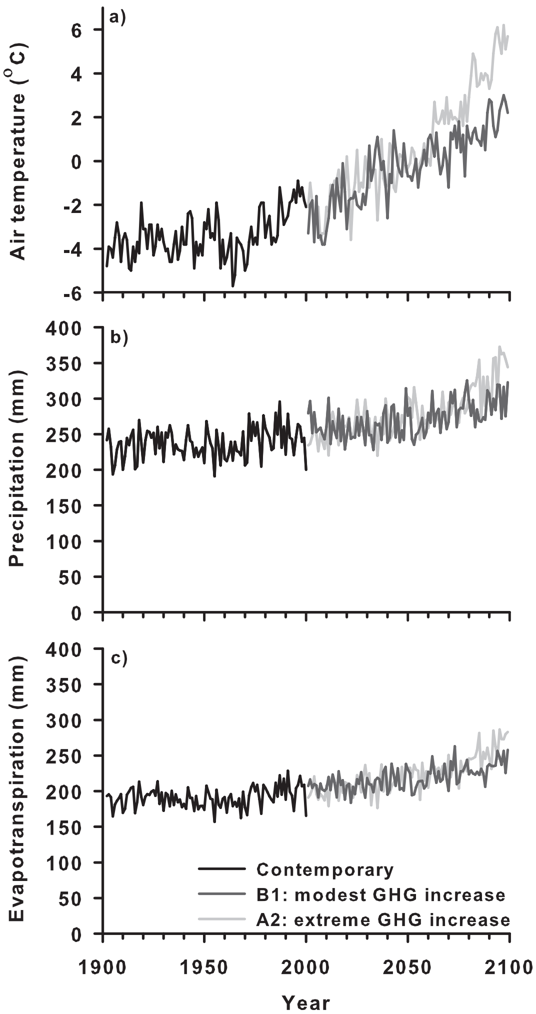

FIGURE 8. Predicted Trends in Mean Annual Air Temperature for Nome, Alaska. Simulations are from the ECHAM5 GCM, Forced by Contemporary and Future Anthropogenic GHG Scenarios from the Special Report on Emissions Scenarios (SRES).

Using the ECHAM5 GCM temperature data discussed above, the PWBM predicted that, over the next century, snow accumulation in the Nome region will increasingly begin later in the year (Figure 10a), and snowmelt will progressively begin earlier (Figure 10b). Rather than snow accumulation beginning in late-October/early-November, snow will not begin to accumulate until mid-November/mid-December, whereas the onset of snowmelt will shift from mid-May to early/mid-April (Figures 10a and 10b). Collectively, this means that, over the next century, the length of seasonal snow cover is predicted to decrease from between approximately 187 and 199 days of snow cover in 2009/2010 to between approximately 128 and 167 days of snow cover by 2098/2099 (Figures 10a and 10b). This equates to a decrease in seasonal snow cover of approximately one to two months (depending on the GHG scenario used) (Figures 10a and 10b).

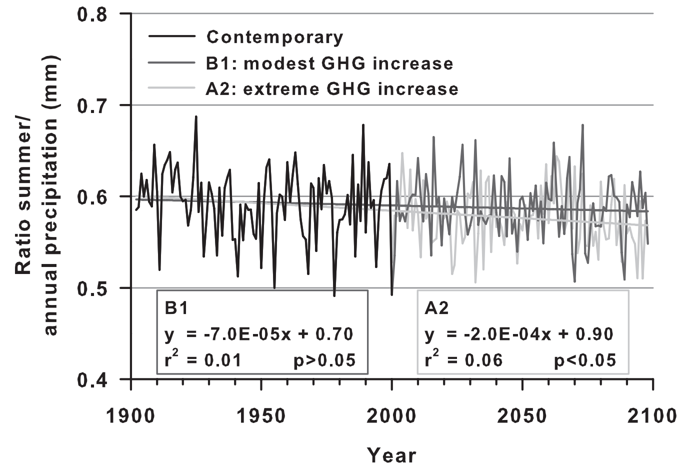

FIGURE 9. Linear Regressions Between Year and the Ratio of Modeled "Summer" (May to October) to Annual Precipitation (snow + rain) From 1902 to 2098.

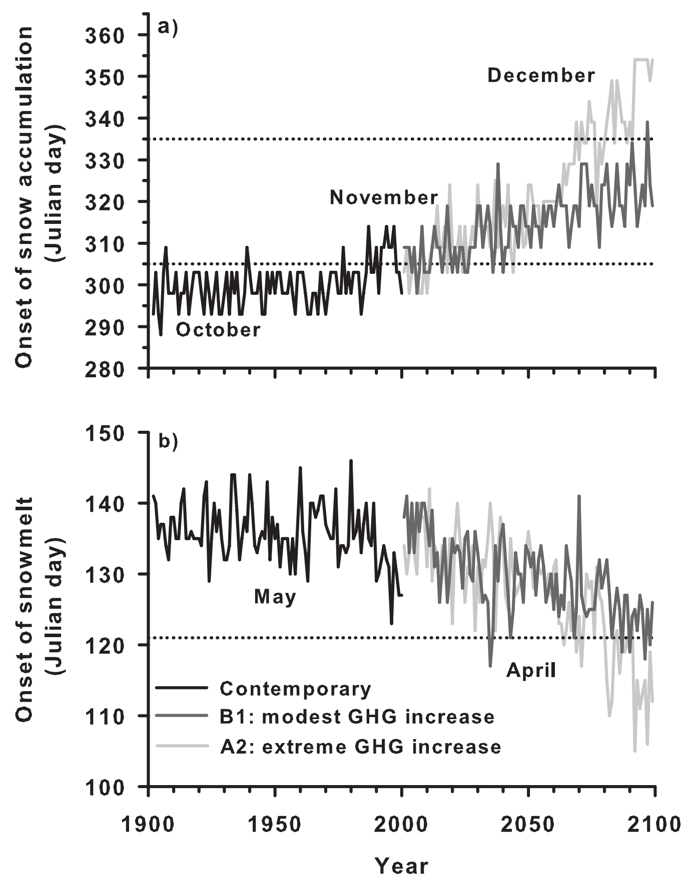

FIGURE 10. Comparison of PWBM-Simulated Onset of Snow Accumulation (a) and Onset of Snowmelt (b) for Contemporary ECHAM5 GCM Climate (1902-1999), and Two Future ECHAM5 GCM Scenarios (2000-2099).

The snowpack melt process, the period with liquid water present in snowpack, occurred approximately over two weeks for all simulations. The snowmelt output occurred over five to seven days. Due to increases in annual precipitation (Figure 8b), the PWBM predicted that the amount of snowmelt in the Nome region will not change significantly over the next 100 years ($p > 0.05$) despite the shorter winter season (Figures 11a, 11b, and 11c). The proportion of snowfall in annual precipitation, however, was predicted to decline significantly ($p < 0.05$) in both GHG scenarios, particularly from 2061 to 2099 in the extreme GHG scenario (Figure 11e).

Despite concurrent increases in mean annual temperature and evapotranspiration ($p < 0.05$) (Figures 8a and 8c), the annual root to deep zone flux (aquifer recharge) increased 50-100% ($p < 0.05$), from approximately 21 mm/year in the late 1990s to 30-42 mm/year (depending on the GHG scenario used) by 2099 (Figure 12b). This was due to increases in annual precipitation of between 80 and 100 mm (Figure 8b).

DISCUSSION

Climatic Controls on Aquifer Recharge

Groundwater hydrology in the subarctic is strongly governed by extreme climatic conditions that prolong seasonal snow cover (Rouse *et al.*, 1997). As a consequence, spring snowmelt is a major hydrological event, replenishing aquifers, rivers, and lakes by releasing water that has been stored in the snowpack for up to six months (Kane *et al.*, 1991). Spring snowmelt in arctic regions is changing as the climate warms (Hinzman *et al.*, 2005), and is likely to be sensitive to recent observed shortening of the snow season (Stone *et al.*, 2002; Yang *et al.*, 2003). Understanding how changes in snowmelt will affect groundwater recharge is necessary to be able to predict the possible restrictions on water availability.

The sensitivity of northern groundwaters to climate change largely depends on the following variables: (1) the effective recharge for rainfall *vs.* snowmelt (Winograd *et al.*, 1998; Earman *et al.*, 2006), (2) dependence of effective rainfall recharge on temperature and evapotranspiration (Eckhardt and Ulbrich, 2003), and (3) how evaporation and direct runoff are affected by wetting and drying episodes (Rouse *et al.*, 1997; Rawlins *et al.*, 2003).

At Nome, the Moonlight wells aquifer showed signs of climate forcing at scales from a few weeks (spring-fall precipitation) to seasonal (winter snow accumulation). Evidence includes the immediate increase of well water levels following spring melt, water level increases following prolonged wet periods on the order of two weeks or longer, and aquifer depletion during mild rainfall or dry periods (Figure 4). A period of decreasing WSE typically occurred in the summer from late June-July, until the aquifer was recharged by autumnal precipitation. For aquifer recharge to occur, average 15-day precipitation in the Nome region must be >2 mm (Figure 5). In the event

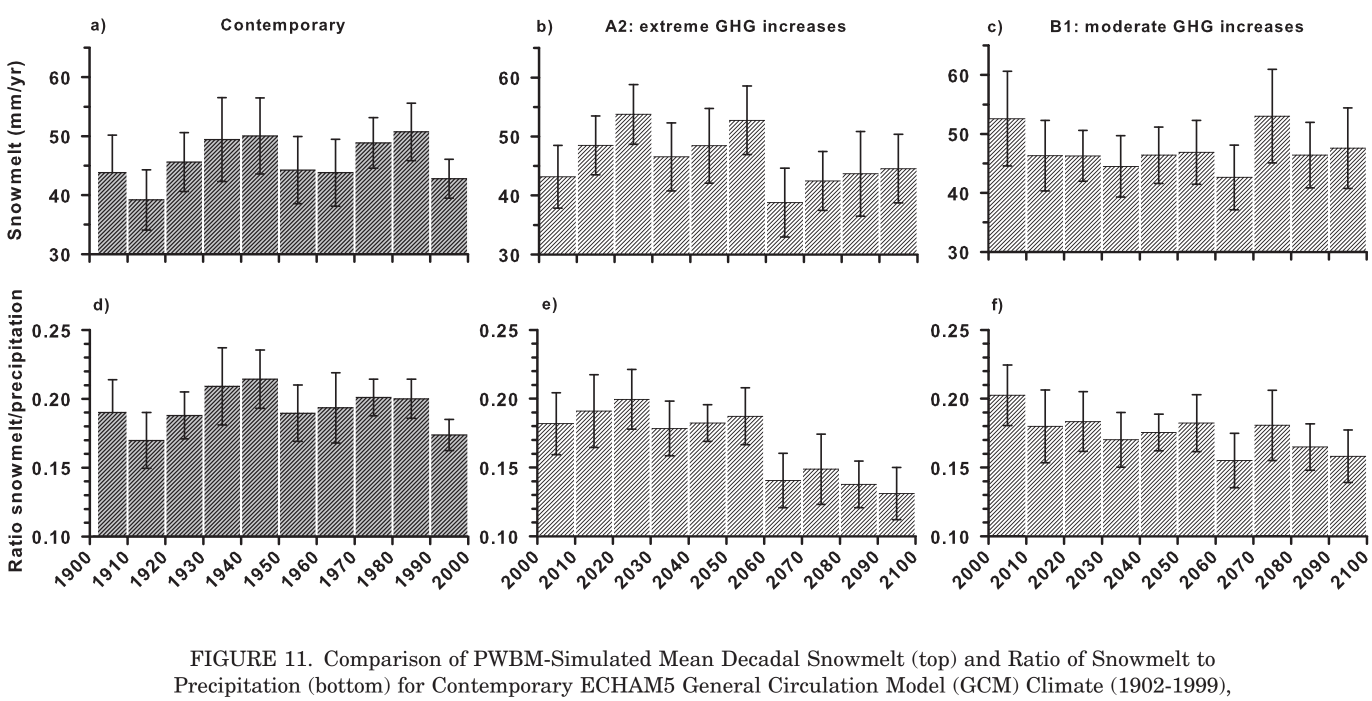

FIGURE 11. Comparison of PWBM-Simulated Mean Decadal Snowmelt (top) and Ratio of Snowmelt to Precipitation (bottom) for Contemporary ECHAM5 General Circulation Model (GCM) Climate (1902-1999), and Two Future ECHAM5 GCM Scenarios (2000-2099). Error Bars Denote ± 95% Confidence.

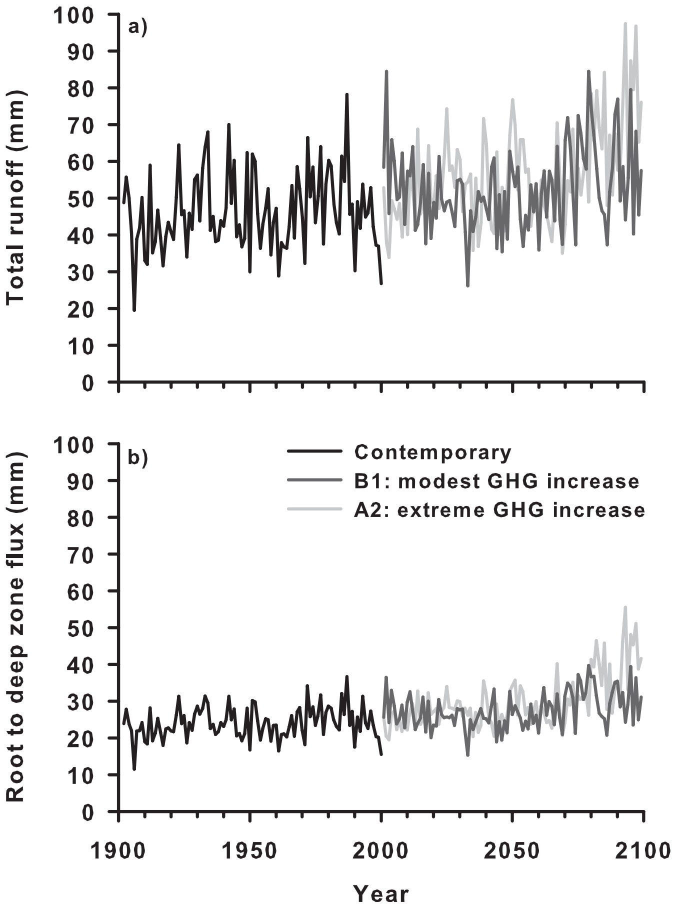

FIGURE 12. Comparisons of Annual Total Runoff (a) and Annual Root to Deep Soil Zone Flux (Aquifer Recharge) (b) Simulated by the PWBM Using Contemporary ECHAM5 GCM Climate Data (1902 - 1999), and Two Future ECHAM5 GCM Scenarios (2000 - 2099).

of prolonged absence of precipitation and subsequent recharge, groundwater levels at Nome aquifer are expected to decline at a rate of between 0.01 and 0.03 m/day (Figure 6).

The influence of water abstractions was not quantified in this study; however, the effects of current pumping levels are expected to be negligible. Following pumping, the WSEs stabilized rapidly (within a few hours) to pre-pumped levels and data filtering successfully removed the drawdown effects. The sensitivity of Moonlight Springs to differing pumping levels will become important with changes in demand.

Modeled Hydrological Fluxes

Groundwater models are essential to our understanding of the impacts that climate change may have on the hydrological cycle, and have been employed in a number of climate-impact studies (e.g., Younger *et al.*, 2002; Eckhardt and Ulbrich, 2003; Herrera-Pantoja and Hiscock, 2008). In regions where groundwater aquifers constitute a major municipal water source, such as in Nome, the ability to predict the range of change to groundwater storage that is likely to occur is important for water resource management. In this study we validated the PWBM for Nome with observed groundwater data, and then used the model to simulate future hydrological fluxes under two differing GHG scenarios (modest and extreme increases in GHG). This allowed us to account for some of the uncertainty concerning future GHG emissions and associated climatic warming. Ideally, streamflow measurements would have been used to validate the PWBM-simulated fluxes. However, surface runoff from Anvil Mountain in the area of the wells collects in a marshy area where it interacts with spring water in a series of ponds. The lack of streamflow data and the characteristics of surface runoff from areas around Anvil Mountain preclude a direct comparison of model simulated runoff with commensurate observed data in that area.

Observed changes in snow accumulation were successfully simulated by the PWBM. Similarly, increases in measured WSE correlated well with modeled increases in recharge. Model-estimated snow storage for 2007 did not capture the abrupt decline in mid-winter snowpack that occurred in January. This may be due to either a bias in the air temperature at Nome airport relative to the area near the well, or the PWBM snowmelt function did not adequately melt the snow early enough. Rawlins *et al.* (2003) report that PWBM runoff estimates are near zero in winter (also see Figure 7b), and generally provide a conservative estimate. Regardless, the PWBM was able to adequately predict temporal changes in water storage, capturing intra-annual patterns of hydrological flux, that is, groundwater fluxes associated with spring/winter snowmelt and nonwinter precipitation, and interannual variability in recharge.

Hydrological outputs from the PWBM indicate that if climatic warming occurs on the order predicted by the ECHAM5 model and associated scenarios, then substantial seasonal shifts in the hydrological cycle at Nome can be expected by the end of the century. Snow accumulation typically begins in late-October/-early-November, but increases in mean annual air temperature of up to 8°C over the next century are predicted to delay snow accumulation until late-November/mid-December (Figure 10a). Furthermore, the onset of snowmelt is predicted to shift from mid-May to early/mid-April (Figure 10b). Overall snow cover is predicted to decrease by one month for the modest GHG scenario and two months for the extreme GHG scenario.

Interestingly, despite a substantial shortening of the winter season, the PWBM does not predict significant declines in spring snowmelt (Figures 11b and 11c). Although snowfall is a declining proportion of annual precipitation ($p < 0.05$) in the extreme GHG scenario (SRES A2) (Figure 11e), this shift is largely attributed to increases in rainfall rather than decreases in snowfall.

A groundwater-climate sensitivity study spanning west-central Canada that observed significant shifts in the hydrological cycle (from 1960 to 2000), such as earlier occurrence of snowmelt (see Westmacott and Burn, 1997), also reported less substantial changes in the size of hydrologic fluxes. They concluded that climatic change may initially have more of an influence on the timing of hydrologic events, for example, spring snowmelt, than on the magnitude of hydrologic events. Indeed, it is not until towards the end of the century (post-2060), as the mean annual air temperature increases beyond 0°C, then the amount of snowmelt predicted by the PWBM begins to decline. How will this affect groundwater recharge depends on the balance between predicted increases in winter rainfall and evapotranspiration.

A similar climate-impact study (Eckhardt and Ulbrich, 2003) that used the SRES B1 and A2 ECHAM scenarios for European mountain groundwaters predicted little change in annual mean groundwater recharge in a region of decreasing precipitation. Eckhardt and Ulbrich (2003) did, however, find large seasonal changes in groundwater recharge, in particular a substantial reduction (up to 50%) in summer recharge. Similarly, using equivalent future GHG emissions scenarios from the UK Climate Impacts Programme (UKCIP02) and the UK Meteorological Office GCM (HadCM3), Herrera-Pantoja and Hiscock (2008) predicted that the main effect of climate change on aquifer recharge in the UK was evident in the dry season. Overall, they predicted decreases in groundwater recharge of up 20-40% in areas of decreasing precipitation in England, and 4% in southern Scotland by the end of the century.

In our study, predicted increases in annual precipitation and evapotranspiration from 2000-2099 were also mirrored by increases in root to deep zone flux in both climate scenarios (Figures 8b and 8c, and 12b), indicating that the effective precipitation is predicted to be great enough to sustain groundwater recharge. Although the ratio of winter to annual flows are likely to increase at Moonlight Springs, substantial increases in summer precipitation are predicted in the Nome region by 2099, thus water availability in the summer is not expected to decrease.

Future increases in summer aquifer-recharge are likely to be due to water vapor feedbacks associated with increased evapotranspiration and availability of water vapor for cloud formation (Stocker *et al.*, 2001). Where this moisture will be redistributed is unknown, but it is possible that a proportion of the evapotranspired water will fall as convective storm precipitation on Anvil Mountain within the Moonlight springs recharge area.

It is also worth noting that we defined the winter precipitation by month (November-April) rather than temperature or period of snow accumulation. As the period of snow accumulation decreases, precipitation during these months may in fact decrease relative to non snow-accumulation months.

Changes in Growing Season and the Effects on Climate

Later snow accumulation and earlier snowmelt will increase the snow free period resulting in a decrease in surface albedo and extension of the growing season. Collectively, this may lead to changes in vegetation cover. Tape *et al.* (2006) reported increases in shrub abundance in response to recent climate warming in northern Alaska, and consequently increases in the interception of precipitation, and increases in evaporation and plant transpiration (Keyser *et al.*, 2000; Oechel *et al.*, 2000). In contrast, increases in shrub abundance, such as willow, alder, and dwarf birch, may serve as a trap for snow, which would increase the potential recharge. Furthermore, Eckhardt and Ulbrich (2003) found that increases in CO_2 levels lead to a reduction in plant stomatal conductance and thus a lower demand for water. These effects were not addressed in the PWBM simulations. Further analysis could include altering the evapotranspiration equation to include changing vegetation types and associated increases in water demands (Sturm *et al.*, 2001; Tape *et al.*, 2006), as well as applying the counteracting effects of decreased stomatal conductance (Eckhardt and Ulbrich, 2003). Further studies at the aquifer could also test more complex groundwater models, such as SUTRA (see Voss and Provost, 2002) or MIKE SHE (see Boeggild *et al.*, 1999) capable of operating in cold climates. The performance of a series of GCMs could also be evaluated for the Nome region, similar to the study conducted by Walsh *et al.* (2008), in order to select an ensemble of GCMs that perform the best and from which a particular field (e.g., precipitation) could be averaged.

CONCLUSIONS

The key factors controlling well WSEs were the length of the winter freeze season and aquifer head recession, the magnitude of winter snow accumulation and spring snowmelt, and the intensity of summer rainfall. Simulations from the PWBM indicate that these hydrologic processes will be altered if the mean annual air temperature increases on the order predicted by ECHAM5 and the associated emissions scenarios. Our study suggests that climatic warming in the subarctic will result in later freeze-up and earlier snowmelt, decreasing the amount of snowfall by the end of the century. Despite a lengthening of the frost-free season and increases in evapotranspiration, substantial increases in annual liquid precipitation are predicted to be sufficient to sustain the groundwater recharge necessary for the maintenance of some northern freshwater supplies.

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