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CLIMATE FORCINGS ON GROUNDWATER  
VARIATIONS IN UTAH AND THE GREAT BASIN

by

Kirsti A. Hakala

A thesis submitted in partial fulfillment  
of the requirements for the degree

of

MASTER OF SCIENCE

in

Climate Science

Approved:

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Shih-Yu Wang  
Major Professor

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UTAH STATE UNIVERSITY  
Logan, Utah  
2014

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## ABSTRACT

Climate Forcings on Groundwater  
Variations in Utah and the Great Basin

by

Kirsti Hakala, Master of Science

Utah State University, 2014

Major Professor: Shih-Yu Wang  
Department: Plants, Soils, and Climate

Within Utah, the second driest state in the U.S., the declining trend of groundwater levels exacerbated by rapid growth of urban population and associated water withdrawal is already a concern for water managers and users. Human-induced depletion of groundwater resources is complicated by natural climate variability, which affects both the amount and form of precipitation. Previous research has identified a close link between the Great Basin hydroclimate and sea surface temperature anomalies (SSTA) of the Pacific Ocean. Based on this link, groundwater simulations produced by the Community Earth System Model version 1 (CESM1) are utilized for both historical simulation and future projection of groundwater in Utah, as well as the attribution study for climate change impact. The CESM1 projects a further reduction in groundwater levels due to changes in climate forcing. The implication is that groundwater resources in Utah may decline further in the future regardless of additional human withdrawal.

(41 pages)

## PUBLIC ABSTRACT

Climate Forcings on Groundwater  
Variations in Utah and the Great Basin

Groundwater levels over northern Utah have undergone a declining trend since the 1960's. This trend has made apparent the need to understand the relationship between climate and groundwater resources. Such necessary information is already in dire need in places such as California. At the close of 2013, California had experienced its driest year in recorded history, with severe drought continuing for the foreseeable future. Utah is the second driest state in the U.S., and therefore has been paying close attention to California's current water crises. Water resource projections may prove to be one of the most vital pieces of information toward securing adequate water for those who are currently enduring such water shortages.

In order to accomplish the initial research necessary for developing a fundable proposal, we requested support from the Utah State University Research Catalyst Grant to (a) evaluate a state-of-the-art climate model (its ability to assess groundwater) against statewide groundwater wells and operational groundwater models, (b) reduce climate model uncertainties, (c) conduct a study in the form of observational well site evaluations, and (d) develop strategies to effectively disseminate information on Utah's future groundwater budget to water managers and policy makers. This research is now fully funded externally by the Bureau of Reclamation.

Kirsti Hakala

## DEDICATION

I would like to dedicate this thesis to my father. He has been a constant source of inspiration throughout my life – his work ethic, love of nature and history, and passion for understanding inevitably molded my desire to study water resources. I thought of him as a legendary man who fished the Bering Sea, hunted and hiked the mountains of Alaska, and in the end lived quietly by the lakes in northern Minnesota. His endless effort to spend as much time as possible with me – exploring and visiting nature, are the simple beginnings of all my scientific curiosities. Thank you for the loving guidance.

Miss you and Love you Dad

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# CHAPTER 1

## GENERAL INTRODUCTION

### 1.1 Introduction

Globally, groundwater is the source of one third of all freshwater withdrawals. Despite the vital contributions to human welfare, there are a limited number of studies on the relationship between climate and groundwater [Treyens, 2005]. In the past half-century, the role of groundwater has increased dramatically. So much so, that in places such as in California [Wang *et al.*, 2014], groundwater reserves have been depleted to the extent that well yields have decreased, pumping costs have risen, and water quality has deteriorated [Smith, 2014]. The Intergovernmental Panel on Climate Change (IPCC) has provided limited assessments on interactions between groundwater and climate change within both its third and fourth assessment report. Groundwater is also not an output from the Coupled Model Intercomparison Project (CMIP5). However, by applying global-scale modeling, as well as observational and satellite monitoring, all of which are employed herein, we may considerably enhance our understanding of interactions between groundwater and climate.

Semi-arid valleys in northern Utah, home to the majority of the state's population, are heavily dependent on the springtime melt of snowpack [Gillies *et al.*, 2012]. In addition, Utah's valleys are undergoing rapid population growth, which have already surpassed 2 million people according to the recent figures contained in the 2010 census [U.S. Census Bureau, 2011]. Such population growth correlates with a substantive increase in groundwater withdrawal, which is expected to continue well into the future [Burden *et al.*, 2013]. Measurements taken from groundwater reservoirs in northern Utah

since the 1960's show that levels have been declining [*Burden et al.*, 2013]; these declining trends are understandably of concern to water managers throughout the state. The magnitude of groundwater depletion was further realized when, in 2012, drought conditions lead to depleted groundwater reserves in Toole County (located in northwestern Utah) and well yields were reduced substantively. In fact, the U.S. Department of Agriculture had to handle more than the normal number of rancher requests statewide for disaster assistance [*Fahys*, 2012].

In Utah, groundwater is the source of 58 percent of the public water supply. Groundwater is vital for irrigation when surface water resources are depleted late in the growing season; this becomes particularly important during the onset of drought. Three factors are now in play when it comes to water supplies in Utah: (1) population increase, (2) a variable water supply that arises due to natural climate variability, and (3) long-term trends due to global warming. As to point (1), noted earlier was its correlation with groundwater withdrawal. Point (2) is a result of natural climate oscillations, examples of which are the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) [e.g. *Wang et al.*, 2010; *Wang et al.*, 2012], while point (3) is linked to the longer-term climate change cause by a combination of natural variation and greenhouse gases [*Gillies et al.*, 2012]. Therefore, appreciating and understanding the climate factors that modulate hydroclimate variability (seasonal to decadal timescales) and extremes (e.g. drought) will inevitably assist water managers in their decision and planning practices regarding the maintenance, allocation and development of future water resources.

## 1.2 Background Review of Groundwater and Hydroclimate over Northern Utah

Groundwater is vastly surveyed in northern Utah – in both the past and the present. The first groundwater investigations over Utah were conducted in the early 1900's [Richardson, 1906]. Published data became more plentiful in the 1940's and 50's, as was exemplified by *Taylor and Leggette* [1949], who investigated groundwater recharge and chemical quality. *Lofgren* [1952] examined Salt Lake Valley's groundwater development as of 1951. Later, *Hely et al.* [1967, 1968, and 1969] compiled a series of hydrological and climatological data and produced a summary of Salt Lake Valley's groundwater hydrology [i.e., *Hely et al.*, 1971]. Further work by *Arnou and Mattick* [1968] studied groundwater discharge toward Great Salt Lake in basin-fill deposits. In the 1980's, on the subject of the effects of increased groundwater withdrawal, *Waddell et al.* [1987a] predicted the effects of increased withdrawals from wells in the Salt Lake Valley. In the 90's *Anderson et al.* [1994] and *Anderson and Susong* [1995] mapped groundwater recharge and discharge areas for the principal aquifers along the Wasatch Front: At this time, computer models were being designed for various monitoring purposes, for example, *Lambert* [1995a] produced a three-dimensional, finite-difference numerical groundwater flow model for the basin-fill aquifer; such models were subsequently used to simulate capture zones for selected public supply wells [*Lambert*, 1995b].

However, the relationship between groundwater and climate forcing in Utah is somewhat new: *Sandow et al.* [2010] were instrumental in connecting groundwater to drought in the Salt Lake Valley when they assessed the effects on groundwater levels of different pumping rates and precipitation rates. More recently, *Wang et al.* [2010] and *Gillies et al.* [2011] identified a link between northern Utah's hydroclimate with Pacific

Ocean sea surface temperature anomalies (SSTA) at a unique timescale of 10-15 years, referred to as the Pacific Quasi-Decadal Oscillation (QDO), the signal of which is recorded in the lake level change of the Great Salt Lake. The QDO is described and referenced in a number of articles that focused on low-frequency variability in the Pacific SST [*Allan, 2000; Tourre et al., 2001; White and Tourre, 2003; White and Liu, 2008; Wang et al., 2011*]. The Pacific QDO alternates between warm and cool temperature in the central equatorial Pacific defined as the NINO4 region (160°E-150°W, 5°S-5°N) and features distinctive phases of atmospheric circulation perturbations that induces a teleconnection that modulates the intermountain West precipitation [*Wang et al., 2009, 2010, 2011*].

Given the fact that various climate oscillations control the magnitude of Northern Utah's precipitation [*Gillies et al., 2012*], it is crucial to investigate their linkage with groundwater reservoirs. The potential interference caused by anthropogenic climate change is likely to pose a great challenge. Yet, managing water resources in response to climate oscillations provides a practical guide for future risk management practices. Therefore, we undertook a scientific study of Utah's groundwater reserves not only to establish the hydroclimate connections but correspondingly to gauge the prospects of future groundwater levels in Utah's changing climate.

CHAPTER 2

DATA SOURCES AND METHODOLOGY

2.1 Data and Methods

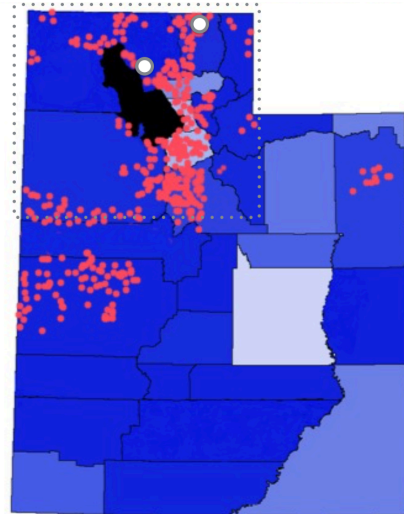
Groundwater level records in Utah became consistent after 1960. We used 400 active wells over northern Utah, obtained from the U.S. Geological Survey (USGS) Active Groundwater Level Network (<http://groundwaterwatch.usgs.gov/default.asp>). Well locations and groundwater dependence for public supply use per county are plotted in Figure 1.



Utah Groundwater Dependence

(color = % dependence on groundwater for public supply for 2005)

County	% Dependence
Beaver	100
Box Elder	100
Cache	98.92
Carbon	69.07
Daggett	53.85
Davis	36.42
Duchene	57.17
Emery	22.83
Garfield	100
Grand	100
Iron	100
Juab	100
Kane	100
Millard	100
Morgan	100
Plute	100
Rich	100
Salt Lake	29.03
San Juan	54.75
Sanpete	100
Sevier	98.83
Summit	99.3
Tooele	98.92
Uintah	89.76
Utah	82.83
Wasatch	99.23
Washington	75.5
Wayne	100
Weber	47.86



Dependence= 0% 100%

- Location of observational groundwater wells
- Box Elder and Cache County groundwater wells utilized in Figure 3a
- ... Denotes area utilized in Figure 2

Figure 1. Utah’s dependence on groundwater for public supply for 2005 with darker shades showing greater dependence and lighter shades showing less dependence. Groundwater levels over northern Utah were recorded by 400 active wells. Well locations are shown by red circles.

Springtime groundwater levels were standardized prior to averaging among the 400 wells. Other datasets utilized include: (a) the station-derived monthly Global Precipitation Climatology Centre (GPCC) grid at a 1° horizontal resolution [Schneider *et al.*, 2013], (b) monthly tropospheric winds acquired from the NCEP Reanalysis at a resolution of 2.5° long. x 2.5° lat., (c) monthly National Climatic Data Center (NCDC) reconstructed sea surface temperature (ERSST) at a resolution of 2° long. x 2° lat. [Smith *et al.*, 2014] , and (d) the Great Salt Lake (GSL) surface elevation (<http://waterdata.usgs.gov/nwis>). GHCN (Global Historical Climate Network) rainfall and, maximum and minimum daily air temperatures were downloaded from the Utah Climate Center's website (<http://climate.usu.edu>). Reference evapotranspiration (ET<sub>o</sub>) was calculated using maximum and minimum daily temperatures according to Hargreaves *et al.* [2003].

## **2.2 CESM1 and CLM4**

The Community Earth System Model version 1 (CESM1) is a powerful compilation of computer models, which were designed for meeting the intellectual challenge of understanding the climate and the Earth system, and they are the only scientific tool capable of integrating the myriad physical, chemical, and biological processes that determine past, present, and future climate. The CESM1 is an essential tool for testing and confirming understanding for making predictions that can be beneficial to society and policy makers. Changes in climate, whether anthropogenic or natural, involve a complex interplay of physical, chemical, and biological processes of the atmosphere, ocean, and land surface. Output from the CESM1 were generated by the Pacific Northwest National Laboratory (PNNL) at a resolution of 2.5° long. x 1.875° lat.

Changes in climate, whether anthropogenic or natural, involve a complex interplay of physical, chemical, and biological processes of the atmosphere, ocean, and land surface. This work focuses on the specific output of groundwater from CESM1. More specifically, groundwater is a direct output from the CESM1's Community Land Model (CLM) [Hurrell *et al.*, 2013]. The CLM version 4 (CLM4) represents several aspects of the land surface and consists of soil hydrology components such as: surface runoff, infiltration, redistribution of water within the column, subsurface drainage, and groundwater. These processes are configured within the model through simulated canopy drip, snow accumulation and melt, water transfer between snow layers, infiltration, evaporation, surface runoff, sub-surface drainage, redistribution within the soil column, and groundwater discharge and recharge to simulate changes in canopy water  $\Delta W_{can}$ , surface water  $\Delta W_{sfc}$ , snow water  $\Delta W_{sno}$ , soil water  $\Delta W_{liq,i}$ , soil ice  $\Delta W_{ice,i}$ , and water in the unconfined aquifer  $\Delta W_a$ . The total water balance of the system is

$$\begin{aligned} \Delta W_{can} + \Delta W_{sfc} + \Delta W_{sno} + \sum (\Delta w_{liq,i} + \Delta W_{ice,i}) + \Delta W_a = \\ (q_{rain} + q_{sno} - E_v - E_g - q_{over} - q_{h2osfc} - q_{drai} - q_{rgwl} - \\ q_{snwcp,ice}) \Delta t. \end{aligned} \quad (2.1)$$

where  $q_{rain}$  is the liquid part of precipitation,  $q_{sno}$  is the solid part of precipitation,  $E_v$  is ET from vegetation,  $E_g$  is ground evaporation,  $q_{over}$  is surface runoff,  $q_{h2osfc}$  is runoff from surface water storage,  $q_{drai}$  is sub-surface drainage,  $q_{rgwl}$  and  $q_{snwcp,ice}$  are liquid and solid runoff from glaciers, wetlands, and lakes, and runoff from other surface types due to snow capping,  $N_{levsoi}$  is the number of soil layers and  $\Delta t$  is the time step (s) [Oleson *et al.*, 2010].

The CESM1 was chosen not just because it produces groundwater directly but also because it depicts the El Niño Southern Oscillation (ENSO) evolution well along with associated teleconnections and precipitation impacts over western North America [Wang *et al.*, 2014]. The CESM1 simulations employed Historical Experiments that were initialized at 1850 (i.e. under pre-industrial conditions) with the following external forcings: (i) Natural (NAT) – consisting of volcanic eruptions and solar cycle; (ii) Anthropogenic aerosols (AERO); (iii) Greenhouse gases (GHG); and, (iv) All forcings (ALL) that include (i), (ii), and (iii) plus land use change and ozone. Each CESM1 ensemble is comprised of two members with the exception of the ALL ensemble; which is comprised of four members. Additionally, we utilized CESM1 representative concentration pathways (RCP) [Meinshausen *et al.*, 2011] simulations to depict groundwater outcomes. The RCP simulations were conducted for the period 2006 to 2100.

### 2.2.1 Groundwater in the CLM4

Within the CLM4, the determination of water table depth  $z_v$  is based on the work of Niu *et al.* [2007]. In this approach, a groundwater component is added in the form of an unconfined aquifer lying below the soil column. The groundwater solution is dependent on whether the water table is within or below the soil column. Two water stores are used to account for these solutions. The first,  $W_a$ , is the water stored in the unconfined aquifer (mm) and is proportional to the change in water table depth when the water table is below the lower boundary of the hydrologically-active soil column. The second,  $W_t$ , is the actual groundwater, which can include water within the soil column. When the water table is below the soil column  $W_t = W_a$ . When the water table is within



the soil column,  $W_a$  is constant because there is no water exchange between the soil column and underlying aquifer, while  $W_t$  varies with soil moisture conditions [Oleson *et al.*, 2010].

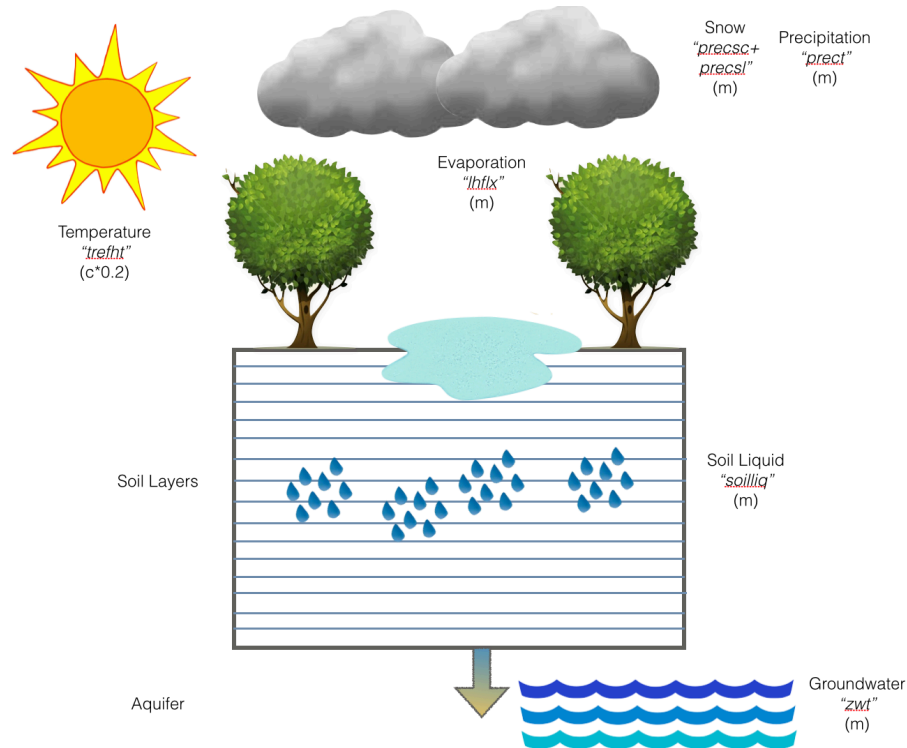


Figure 2. CLM4's hydrologic processes. An unconfined aquifer is added to the bottom of the soil column. Changes in aquifer water content are controlled by the balance between drainage from the aquifer water and the aquifer recharge rate.

## 2.2.2 Groundwater Projections

The CESM1 is able to simulate the temporal evolution of CO<sub>2</sub> sources, which are manifested in the representative concentration pathways (RCP) experiments: RCP4.5, RCP6.5, and RCP8.5. We specifically utilized CESM1's RCP4.5 and RCP8.5 simulations to depict the outcome of groundwater behavior. The RCP simulations begin in year 2006 and projections are carried out to year 2100. RCP4.5 represents a specific concentration of CO<sub>2</sub> in the atmosphere defined as stabilization without overshoot

pathway to  $4.5 \text{ W/m}^2$  ( $\sim 650 \text{ ppm CO}_2$ ), reaching stabilization after year 2100. RCP8.5 represents a higher concentration of  $\text{CO}_2$ , defined as rising radiative forcing pathway leading to  $8.5 \text{ W/m}^2$  ( $\sim 130 \text{ ppm CO}_2$ ) by year 2100.

## CHAPTER 3

## CESM1 GROUNDWATER – CLIMATE RELATIONSHIP

**3.1 Observation Data**

To understand the hydrological forcing that leads to the variation of groundwater levels, the monthly time series of  $\Delta\text{SST}(\text{Niño-4})$ , the precipitation averaged over the Great Basin, and the GSL elevation are displayed in Figure 3a, originally from *Wang et al.* [2010], which were all filtered with a 10–15-yr frequency band. The major phases of a Pacific QDO revolution are evident in all three elements, comprising of the warm, cool, rising, and falling transition, where precipitation specifically follows the transition of the QDO. Expanding upon previous studies [*Wang et al.*, 2009, 2010, 2011], we plotted observed precipitation over northern Utah (Figure 3b) alongside the tendency of the GSL level (Figure 3c), and the tendency of groundwater level over northern Utah (Figure 3d). Tendency here was defined as the derivative of the original field. The tendency was plotted here, rather than using the original groundwater and GSL level signal, in order to align the phase relationship between the three variables following the hydrologic equation: climate forcing, precipitation forcing, and GSL level/groundwater response. Fluctuations in precipitation are in good agreement with the tendency of GSL level and groundwater. Moreover, Figure 3 shows clearly a pronounced quasi-decadal frequency within these variables (10-15 year time period). This 10-15 year variability in precipitation, reflected by the alternating dry and wet spells, is particularly pronounced after the 1960s [*Wang et al.*, 2009]. This documented quasi-decadal variability will be used as a metric to evaluate CESM1 output, which is next.

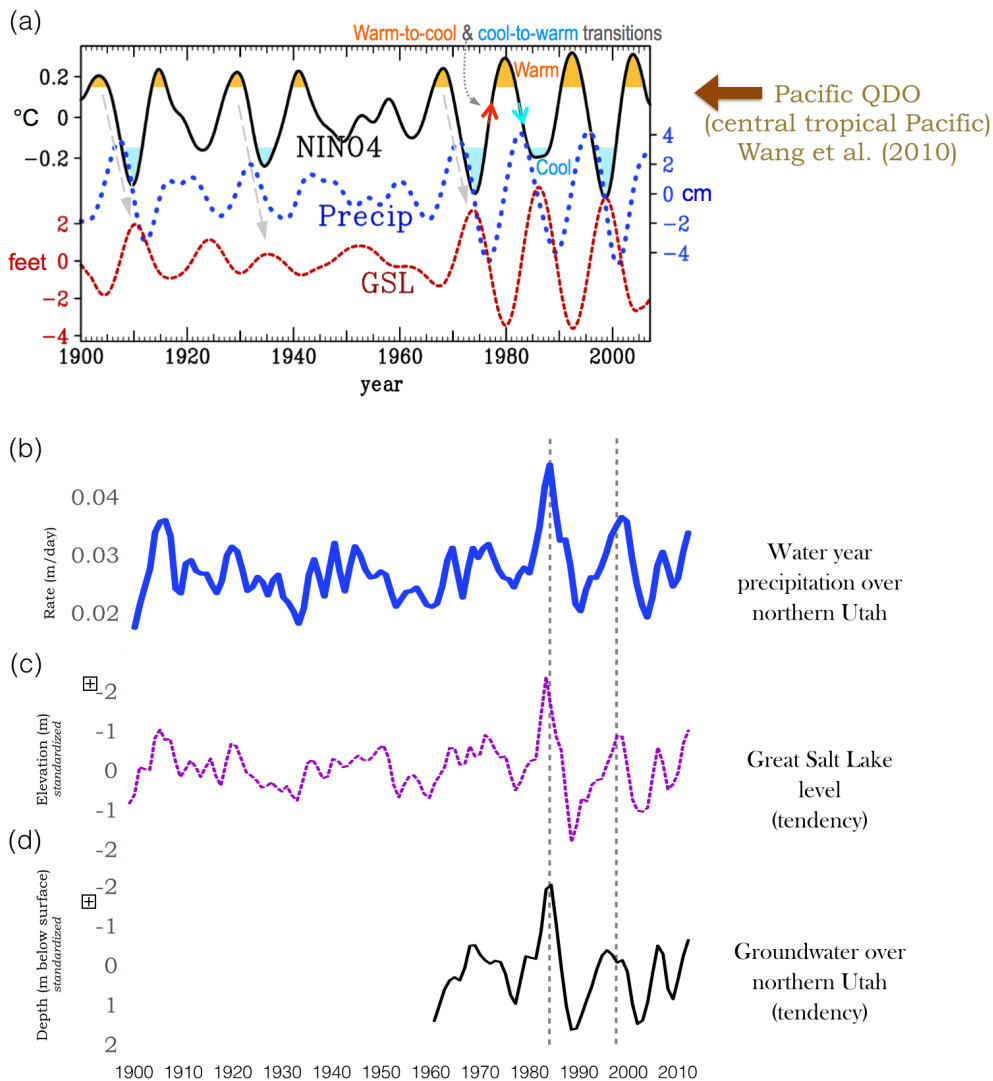


Figure 3. (a) Monthly SST (Nino-4), plotted alongside precipitation, and GSL elevation – filtered with a 10-15 frequency band (figure provided by *Wang et al.* [2010]). The major phases of the QDO can be seen in all three elements. A 3-year phase relationship exists between each variable with a total phase lag of 6-8 years between Nino-4 and GSL. (b) Observed precipitation plotted on top, oscillates in tandem with (c) GSL level (tendency) and (d) northern Utah groundwater (tendency). Dashed lines were provided to highlight the consistency in oscillations.

### 3.2 Evaluation of CESM1's Historical Simulation

First, the seasonal cycle of groundwater was evaluated in CESM1's historical simulation (Figure 4a). The domain chosen for this analysis is focused over northern Utah (114°W-111°W, 40°N-42°N as outlined in Figure 1). Individual members of CESM1 groundwater outputs from the GHG, AERO, NAT, and ALL experiments were plotted against observational groundwater from two counties: Box Elder and Cache County (depicted with white dots in Figure 1). Figure 4a shows that groundwater levels increase from spring into summer and subside into fall and winter, following the typical revolution from snowmelt (recharge) to summer evaporation and withdrawal. Groundwater depth simulated by CESM1 shows a similar pattern (i.e. seasonal timing) with a steady increase in groundwater depth from January to May and a decrease from June to December. This correspondence indicates that CESM1 can capture the region's seasonal groundwater recharge and discharge cycle.

Because all CESM1 simulations are fully coupled experiments, in which the model years cannot be directly compared to observational years, the power spectrum of simulated groundwater level is compared with that of observational data. Figure 4b shows that a spectral peak around the 10-16 years of frequency is revealed in the observational GSL and groundwater depth as well as CESM1 simulated precipitation and groundwater depth. Such coherence between CESM1 output and observational data alludes to the model's capability to recreate the predominant decade-scale climate oscillations in the region, and this result adds confidence in using the model.

The Pacific QDO affects northern Utah's precipitation with a 3-year lag owing to a unique teleconnection induced in the transition phase from the western Pacific [*Wang et al.*,

2010, 2011]. To evaluate whether CESM1 can simulate such a lagged relation, the 3-year lag correlation between annual (water year) SSTA and precipitation over northern Utah

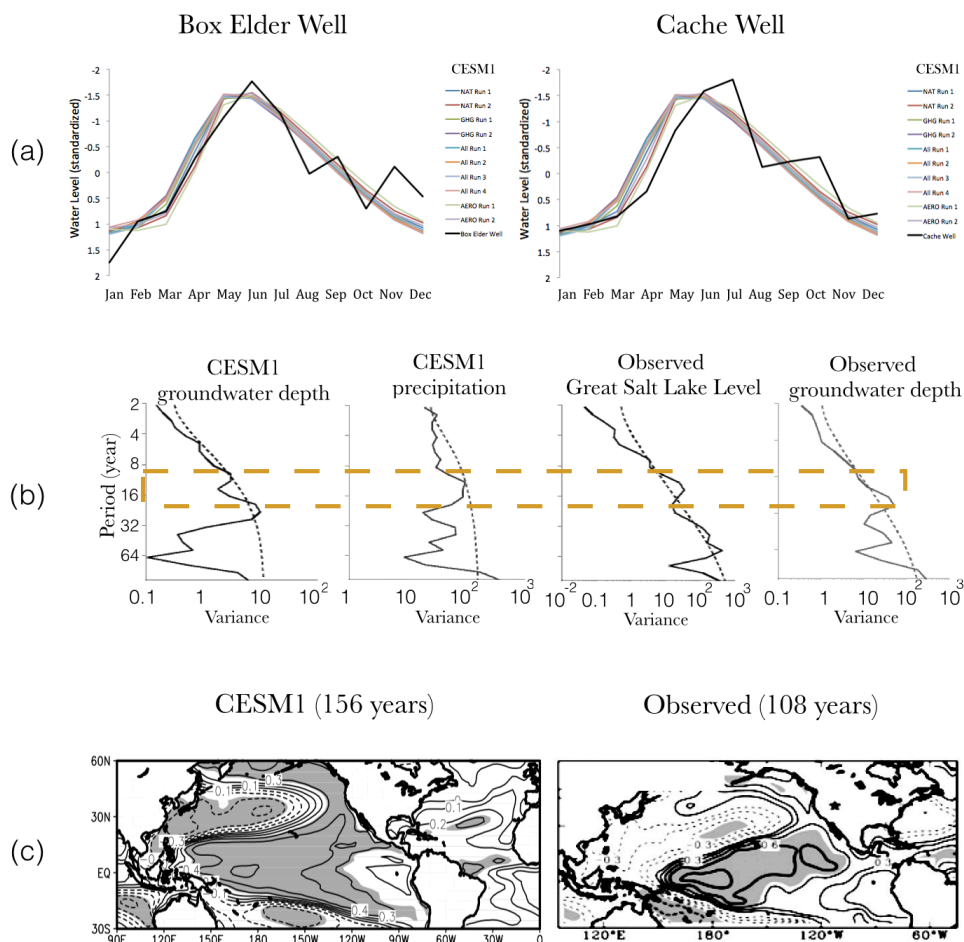


Figure 4. (a) Observational groundwater is plotted alongside CESM1 modeled groundwater for long-term seasonality. (b) Power spectrum analysis was performed on modeled versus observational data: modeled groundwater depth and modeled precipitation are compared here to observational GSL elevation and observed groundwater depth. Across the board, both modeled and observational data contain a peak 10-15 years, which is reminiscent of the QDO's behavior. (c) *Wang et al.* [2010] performed a 3-year lag correlation between observed SST and observed precipitation over the Great Basin for 108 years of data. The CESM1 is able to recreate the 3-year lag correlation between modeled SST and modeled precipitation over northern Utah for 156 years of data.

was computed. The data was smoothed by taking a 7-year running mean to eliminate interannual signals. Figure 4c shows, on the left, a correlation map of modeled SSTA with modeled precipitation for a 156-year period with the precipitating lagging 3 years. To the right, observed data depicted an equivalent 3-year lag correlation map for a 108-year period obtained from *Wang et al.* [2010]. Their consistent geographical distribution of the SST patterns that form during the transition phases of the Pacific QDO lends confidence in the model's performance; this feature about the relationship between the Pacific QDO and the Great Basin precipitation is also shown in [*Smith et al.*, 2014]. In summary, the CESM1 robustly simulates the seasonal cycle of groundwater level. More pronouncedly, its historical simulation captures the QDO related changes and lagged relationship between SSTA and precipitation over northern Utah.

### **3.3 Impact of Greenhouse Gases on Utah's Groundwater Resources**

Figure 5a depicts CESM1 ensembles for groundwater depth for the time period of 1850 to 2005. Results show that groundwater depth produced from all forcings is highly oscillatory, and without discernable long-term trends prior to 1970. After 1970, groundwater simulated only by GHG undergoes a declining trend. This is consistent with a general concept that the vast majority of the increase in GHG within the atmosphere has occurred since 1960 [*IPCC*, 2013], thus these simulations suggest that a rampant and sudden increase in GHG can have a noticeable effect on groundwater in Utah after the 1970's. It is also noteworthy that ALL forcing runs do not show clear decreasing trends, which is likely due to cancellation by each model member's random internal climate variability.

To examine the robustness of the decrease in groundwater depth from the GHG simulations, Figure 5b shows individual members for GHG (hereafter referred to as GHG1 and GHG2) for the time period of 1960-2005. Both members reveal a steady decrease in groundwater depth beginning around 1980, and both are significant at  $p < 0.05$  per t-test (the null hypothesis was set with the mean of 1980 and later to be different than the previous increments). Specifically, the mean of GHG1 after 1980 is significantly lower than all of the other time periods at the 95% significance level. The decreasing trend in GHG2 is significant against 1880-1904 and 1905-1929 at the 95% significance level. Also worth noting is that none of the other single-forcing model members revealed any significant decline in groundwater depth after 1980 (not shown), further suggesting the role of GHG in reducing groundwater in Utah.

To examine the robustness of the decrease in groundwater depth from the GHG simulations, Figure 5b shows individual members for GHG (hereafter referred to as GHG1 and GHG2) for the time period of 1960-2005. Both members reveal a steady decrease in groundwater depth beginning around 1980, and both are significant at  $p < 0.05$  per t-test (the null hypothesis was set with the mean of 1980 and later to be different than the previous increments). Specifically, the mean of GHG1 after 1980 is significantly lower than all of the other time periods at the 95% significance level. The decreasing trend in GHG2 is significant against 1880-1904 and 1905-1929 at the 95% significance level. Also worth noting is that none of the other single-forcing model members revealed any significant decline in groundwater depth after 1980 (not shown), further suggesting the role of GHG in reducing groundwater in Utah.



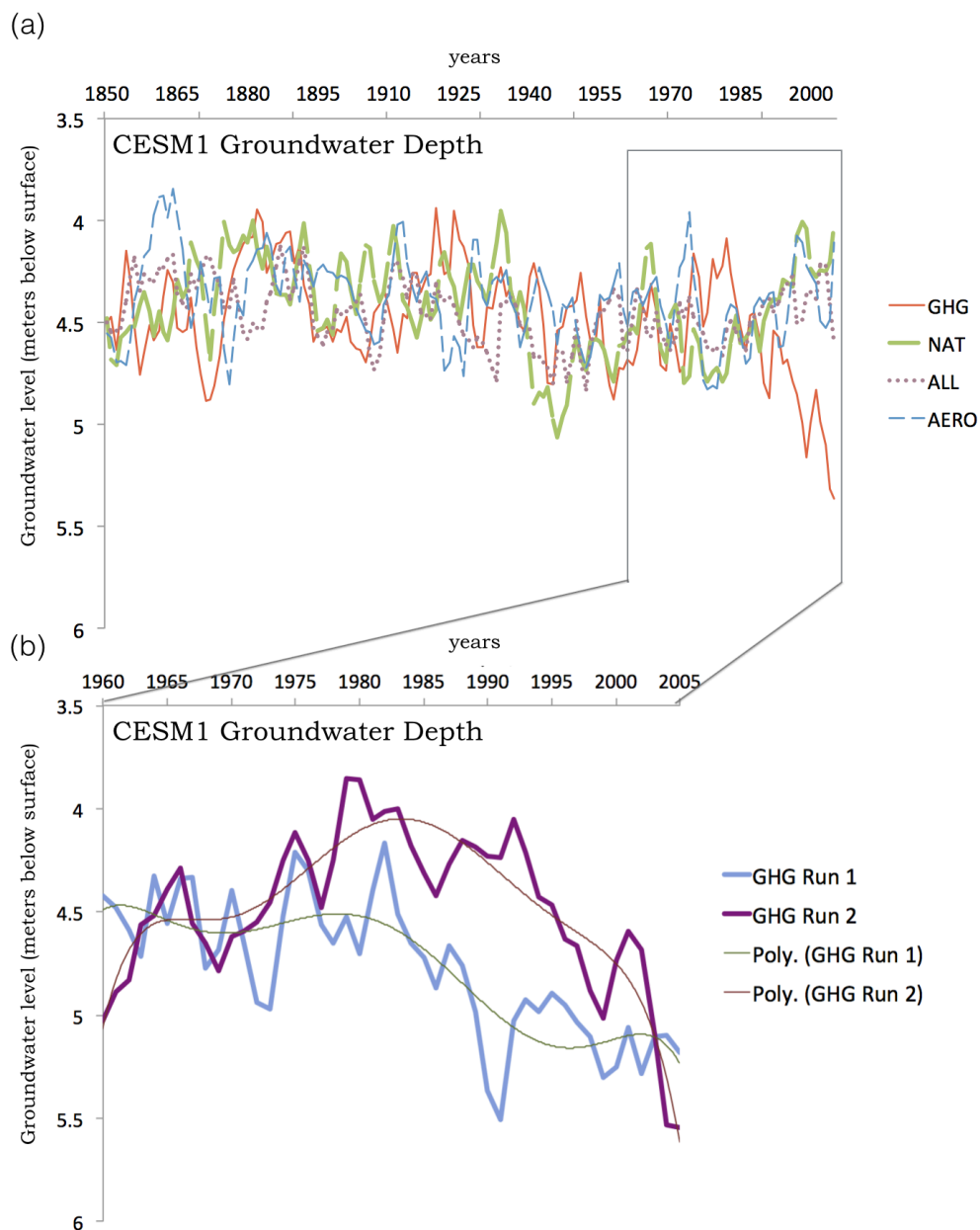


Figure 5. (a) CESM1 modeled groundwater ensembles for all experiments: GHG, NAT, ALL, and AERO. All forcings are highly oscillatory and relatively flat prior to 1970. After 1970, the GHG experiment diverges downward from the other experiments as GHG in the atmosphere causes groundwater to undergo a drying trend. (b) Individual GHG members are plotted alongside each other to reveal a significant decrease in groundwater beginning around 1980.

This result fueled the question as to what processes led the GHG forcing in the atmosphere to influence the hydrological cycle and eventually reduce groundwater. To understand this question, we selected two periods with the same declining slopes in annual precipitation from the GHG and NAT ensemble simulations and analyzed their difference in hydrological processes (with and without GHG). The same declining trend in annual precipitation occurs in the time period of 1870 – 1920 for the NAT and 1955 – 2005 for the GHG, based on the ensemble means (Figure 6a). Next, the trends of the following hydrologic variables were analyzed for the same periods: precipitation, groundwater, water in the unconfined aquifer, total water in storage, evaporation, snow, temperature, soil liquid, and soil ice – all of which comprise of the total water balance within the model. Figure 6b shows the trends (slopes) for the annual mean hydrologic variables derived from the GHG experiment. In comparison, Figure 6c shows the same variables with the NAT experiment. One can see that groundwater is reduced to a greater degree within the GHG simulation, but not as much in NAT, even though both experiments feature the same precipitation declines. Temperature change within the GHG simulation is much higher than in the NAT simulation, as expected, but evaporation is lower in the GHG simulation. This means that the analysis of annual changes alone may not be adequate to attribute the cause of groundwater depletion.

To examine further, the slopes of values were computed for each individual month for the same variables and results are shown in Figure 7. The monthly dissection of precipitation in NAT (Figure 7a) shows that change in precipitation each month throughout the year is highly variable and seemingly random. In contrast, the GHG simulation shows rather persistent precipitation declines in every month with the

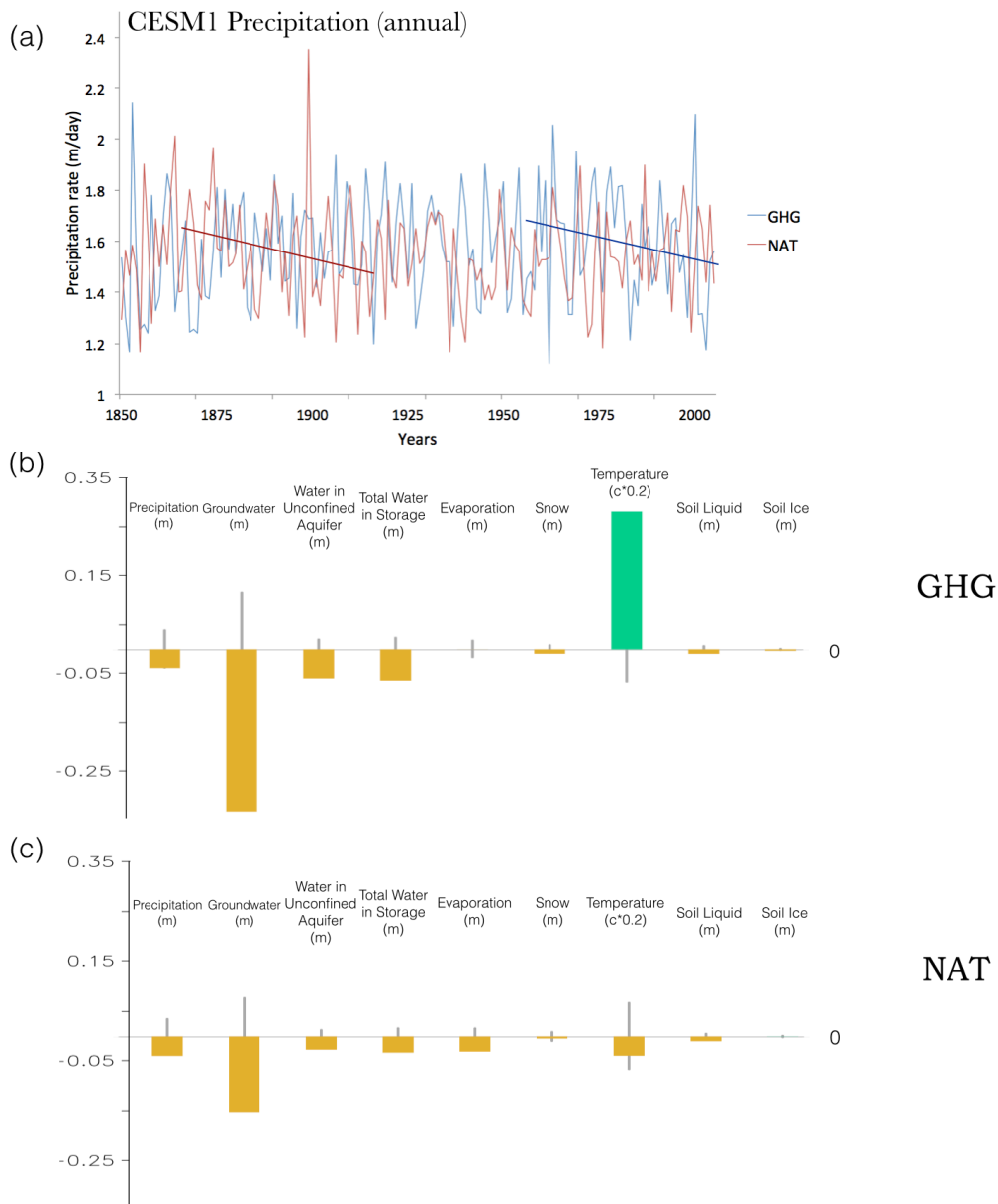


Figure 6. (a) CESM1 modeled precipitation from 1850 to 2005, with GHG trend: 1870-1920 and NAT precipitation trend: 1955-2005. These trends were selected to isolate the same declining pattern in both experiments ( $\sim -2.2e-06$ ). (b) GHG experiment: trends of the hydrologic variables within the water balance were analyzed for the same time periods as indicated by the trends within part a. (c) Same analysis was performed as in part b, with NAT experiment.

exception of October and December. Although the 50-year trend of annual precipitation was held constant for this analysis, these monthly dissections demonstrate how greenhouse gases and natural variability could cause precipitation to change differently throughout the year. Also, GHG induced year-round temperature increases (Figure 7b) while NAT in this case show increased temperatures primarily for January and slight increases for June, August, and September. However, decreasing temperature for all other months offsets these increasing trends.

We note in Figure 7c that evaporation change under the GHG forcing increases in the colder months of January through May and October through December. Evaporation then decreases throughout the warmer months of June through September. These monthly dissections of evaporation show that, within the GHG simulation, evaporation increases during critically colder and rainier months, resulting in less soil liquid (Figure 7d) to be evaporated in the warmer months, leading to no overall annual trend for evaporation. Soil liquid was plotted to include only the top three modeled soil layers (~ top 2 inches of soil). Thus we note that once soil liquid within the topsoil is reduced, less water is available to percolate through soil layers and become groundwater. To this extent, these experiments show that within the GHG experiment, groundwater level (Figure 7e) is reduced to a greater degree than in the NAT experiment, despite undergoing the same reduction in annual precipitation.

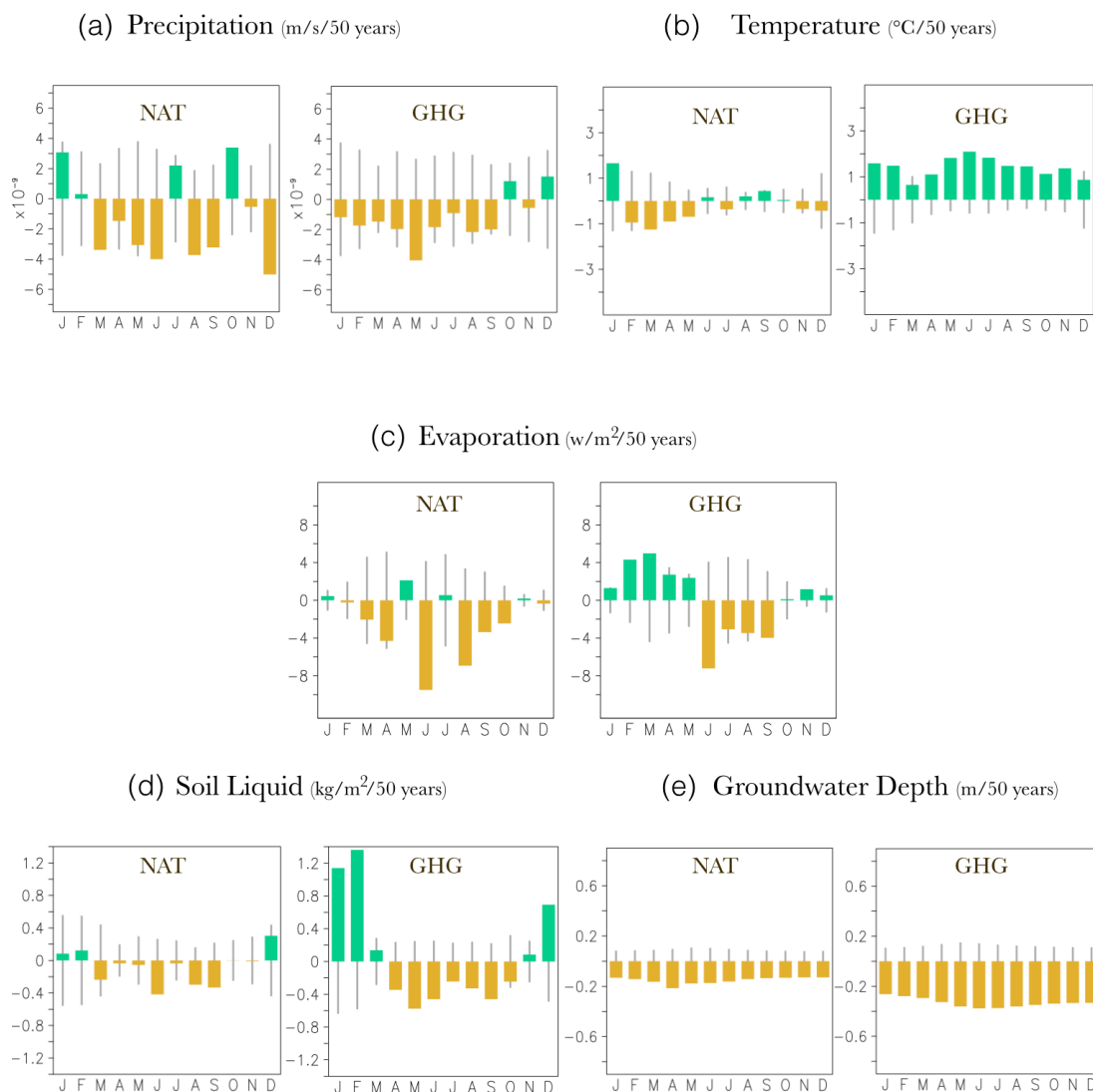


Figure 7. The slope of monthly long-term averages for each variable are analyzed here for the same time periods as in Figure 6 (GHG trend: 1870 to 1920; NAT trend: 1955 to 2005). A comparison of NAT experiment to GHG experiment shows that groundwater depletion within the GHG experiment stems from extended months of low (a) precipitation (NAT experiment offers intermittent dry/ wet months), (b) higher temperatures, and (c) greater evaporation in the historically cooler months. These effects trickle down the system and eventually impact (d) soil liquid and cause (e) groundwater level to decrease.

Next we analyzed SST, wind fields, and precipitation trends over a larger region including the entirety of the Great Basin and western U.S. in order to examine the role of large-scale, climatic forcings in the changing precipitation over northern Utah under the GHG forcing. Figure 8a depicts the observed changes of precipitation over land, SST and associated 850 mb winds for the January-March season over the 1975-2005 period (to be consistent with CESM1 which only goes until 2005). The result illustrates the decadal variability in the North Pacific Ocean and its vicinity, accompanied by an anticyclonic anomaly in the central North Pacific and a weak cyclonic anomaly off the coast of the western U.S.; this circulation setting led to an overall increase in precipitation along the West Coast accompanied by slight drying in the intermountain West [e.g., *Gutzler et al.*, 2002]. By comparison, the CESM1 GHG and NAT simulations reveal a drastic difference in SST between the two simulations: while GHG simulations produce a much warmer SST, NAT simulations produce mostly cooler SST patterns (Figures 8b and 8c). However, the change in 850-mb winds depicts anticyclonic anomalies in the central North Pacific by both NAT and GHG experiments, though cyclonic activity is evident near the western U.S. by the NAT, which is closer to the observed Pacific Decadal Oscillation influence [*Brown*, 2011]. In the GHG simulations, the anticyclonic flow is situated further east and covers the western U.S. These distinctions between the two simulations translate into vastly different hydrologic regimes over Utah and the Great Basin. As a result, precipitation simulated by the NAT (as well as groundwater in Figure 5a) shows a discernibly wetter climate for the same region. The GHG experiment shows a stark contrasting condition, in which much of the western U.S. north of the Gulf of Mexico experiences a much drier climate. The geographical extent of historical groundwater decline is shown in Figures 10a for NAT and

10b for GHG over 1975-2005. The NAT experiment shows increased groundwater levels for this time period, whereas GHG shows an overarching decreasing tendency; this is consistent with Figure 5a.

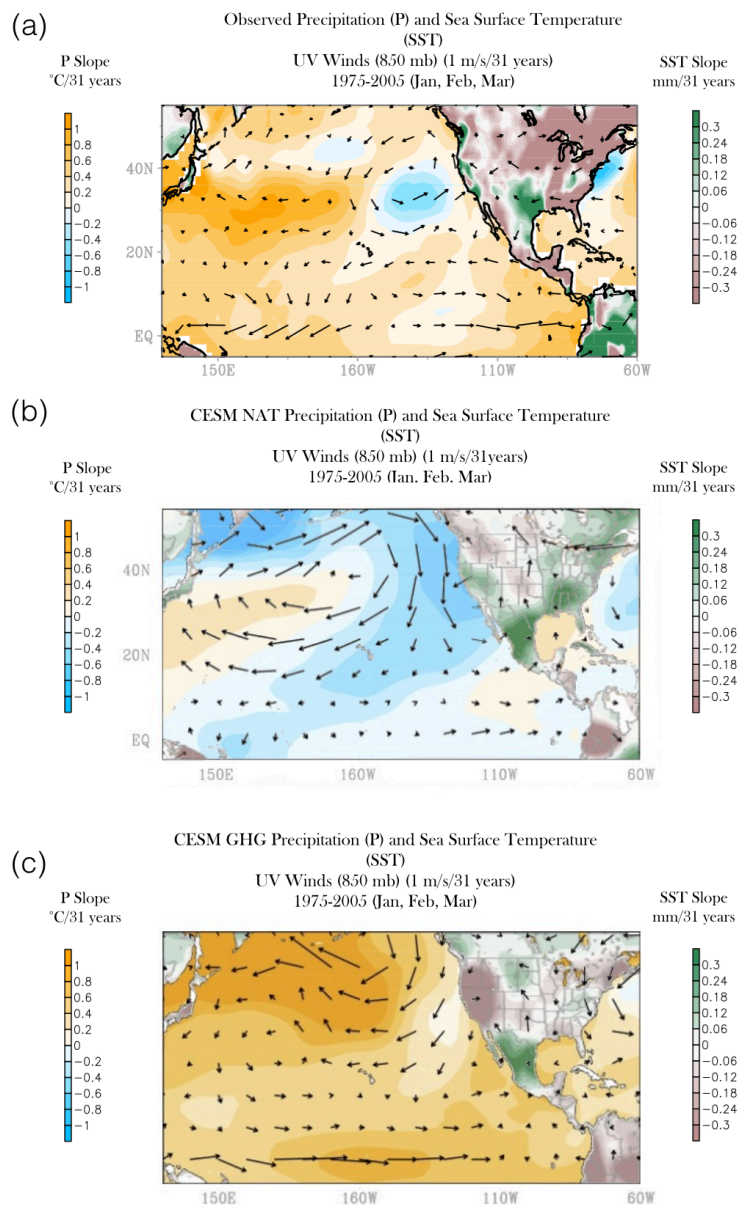


Figure 8. (a) A comparison of observational precipitation over land with sea surface temperature (850 mb) for a long-term trend analysis of the January-March seasonal mean for 1975-2010. (b) 1960-2005. (c) CESM1 NAT and GHG experiments are compared using their respective modeled precipitation over land and modeled sea surface temperature for a long-term trend analysis of the January-March seasonal mean for 1975-2005.

### 3.4 Projection of groundwater resources in Utah

Regarding future projections, the RCP-driven CESM1 simulations indicate a robust reduction in groundwater over Utah (Figure 9) compared to the historical simulations; this future reduction of groundwater is present in both scenario of RCP4.5 and RCP8.5. It appears that the higher levels of CO<sub>2</sub> in RCP8.5 cause a greater decrease in groundwater level over time, resulting in an approximate 1.5-meter drop in groundwater level by year 2100 for northern Utah.

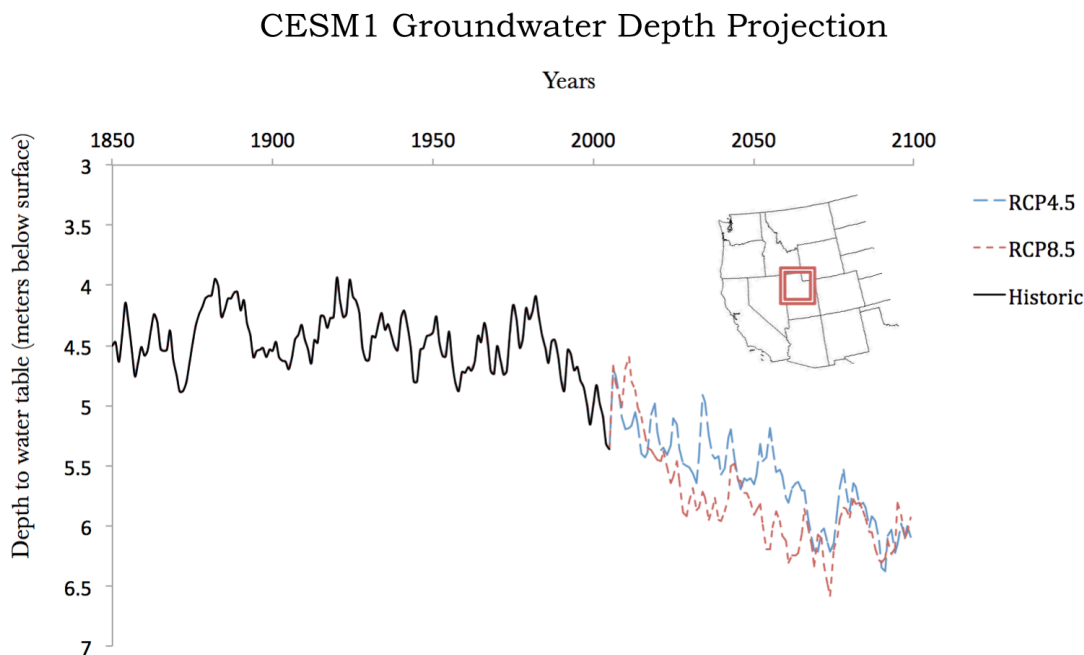


Figure 9. CESM1 – The historical ensemble of GHG forcing on groundwater level over northern Utah (shown in red square over map) is plotted on top (black) with ensemble 4.5 (blue) and RCP ensemble 8.5 (red). The RCP ensembles show the projections of groundwater out to 2100. Each ensemble is the average of two members.



The geographical extent of such groundwater decline in the future is shown in Figures 10a and 10b, which reveal historical groundwater trends from the NAT and GHG experiments for the time period of 1975-2005. The NAT experiments shows increasing

### Linear Trend (slope) in Groundwater Depth

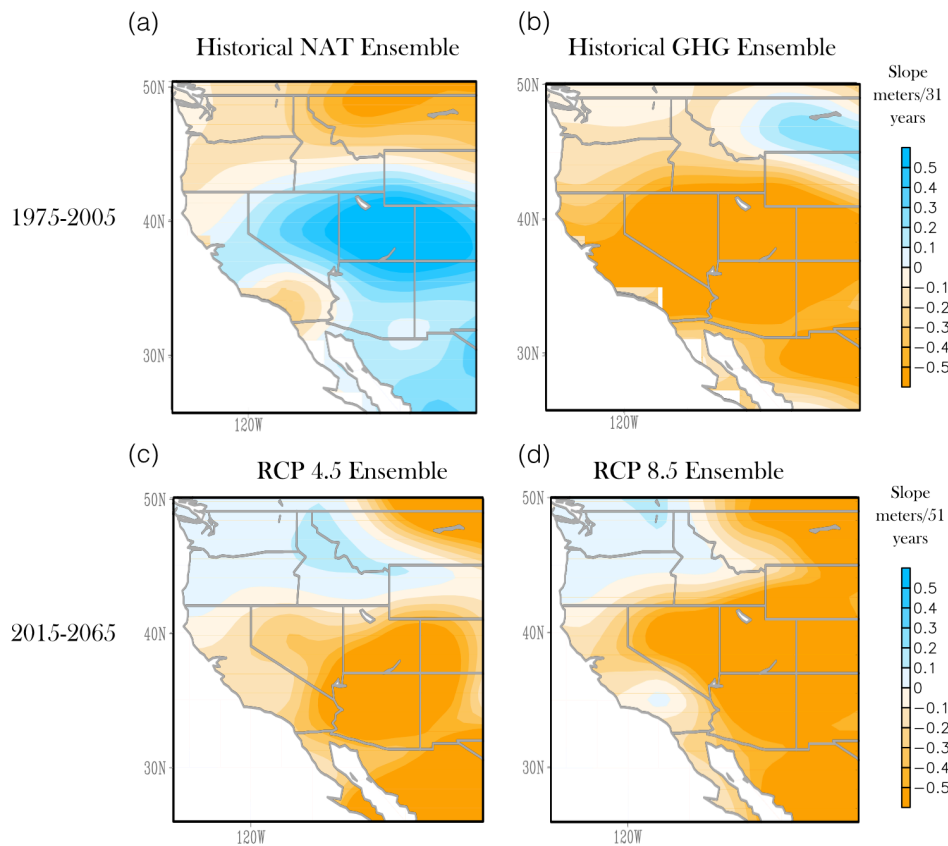


Figure 10. CESM1's historical simulation of groundwater is shown for the time period of 1975-2005. The NAT experiment is compared to the GHG experiment, showing stark differences. The NAT experiment is shown to have intermittent wet/ dry periods; GHG shows an overarching drying effect. Projections of groundwater are depicted by RCP4.5 and RCP8.5 trend maps for the time period 2015-2065. Trends for both RCP4.5 and RCP8.5 show greater trends decrease drastically over Utah and the Great Basin with a greater decrease of groundwater experienced in RCP8.5 ensemble.

groundwater levels for this time period, whereas GHG shows an overarching decreasing tendency. Projections of groundwater in RCP4.5 and RCP8.5 for the time period of 2015-2065 (Figures 10c and 10d) reveal groundwater trends that indicate a drastic decrease in Utah and the Great Basin, with a greater decrease in groundwater for RCP8.5. Both the historical and projected declines in groundwater are coincident with a recent study [Castle *et al.*, 2014] that indicated similar declining trends in groundwater storage over the Colorado River Basin using the Gravity Recovery and Climate Experiment (GRACE) data.

## CHAPTER 4

### GENERAL CONCLUSIONS

#### 4.1 Implications for Groundwater and Policy

Within Utah, total precipitation is projected to increase; yet the form of precipitation is expected to shift from snow to rain [Gillies *et al.*, 2012]. This will dramatically affect agriculture and irrigation water supply since the majority of the state heavily relies upon a slow spring runoff brought on by the melting of snowpack during spring season. With continually less snow in the future, the state will have to consider how to capture adequate rainwater and a much faster runoff that is already occurring two to three weeks ahead of historical average [Gillies *et al.*, 2012]. Such a change in the climate regime can influence growing seasons, water rights, field rotation, and etc. Higher summer temperatures speed up the drying of the soil through evaporation and plant transpiration. As groundwater levels drop, wells could go dry, as has already been reported statewide [e.g. Fahys, 2012; Higley, 2014]. As people deepen their wells, pumping costs go up. Demands for senior water rights and new water rights could escalate. These issues can also be expected to manifest themselves in industry.

Utah is the second driest state in the U.S., yet water consumption per capita is the highest. Irrigated landscapes account for 60 percent of Utah's culinary water use, much of which is due to over-irrigation [Kjelgren *et al.*, 2000]. However, the U.S. bases its traditional gardening aesthetic on the English gardening style of landscaping that was imported by European settlers and does not translate to the arid climate of Utah. Thus, a further implication of these results may be illustrated further in Figure 11, which was provided by Kjelgren *et al.* [2000]. Figure 11 shows a comparison of rain, reference

evaporation (ET), and air temperature between Salt Lake City and South East England. South East England lies within a maritime climate characterized by lush, green vegetation that thrives on high summer rainfall, high humidity, mild temperatures, and infrequent drought (Figure 11a). On the other hand, Salt Lake City lies within a climatic zone with comparatively much lower rainfall and humidity and higher summer temperatures (Figure 11b). As a result, ET is higher in Salt Lake City than in England. ET determines the baseline for water withdrawals for outdoor systems [Kjelgren *et al.*, 2000]; from this baseline 20-30 percent greater withdrawal is expected due to inefficiencies in water usage. As discussed within this paper, CESM1 groundwater projections show a declining trend for groundwater when subjected to increased amounts of GHG in the atmosphere (increasing levels of ET). This result highlights the apparent vulnerability of groundwater in Utah.

Several meetings (3/19/2013, 8/20/2013, 3/5/2014) with water managers from Salt Lake Public Utilities and Jordan River Valley Conservancy District have shown an expressed need for groundwater and surface water projections. As discussed within this paper, CESM1 groundwater projections show a declining trend for groundwater when subjected to increased amounts of greenhouse gases in the atmosphere. These groundwater projections in conjunction with the reconstruction of historical surface water using tree ring data can be used to decipher the past and future behavior of water resources in Utah. Current projects are underway, which will make available these projections to water management agencies in the Salt Lake City area.

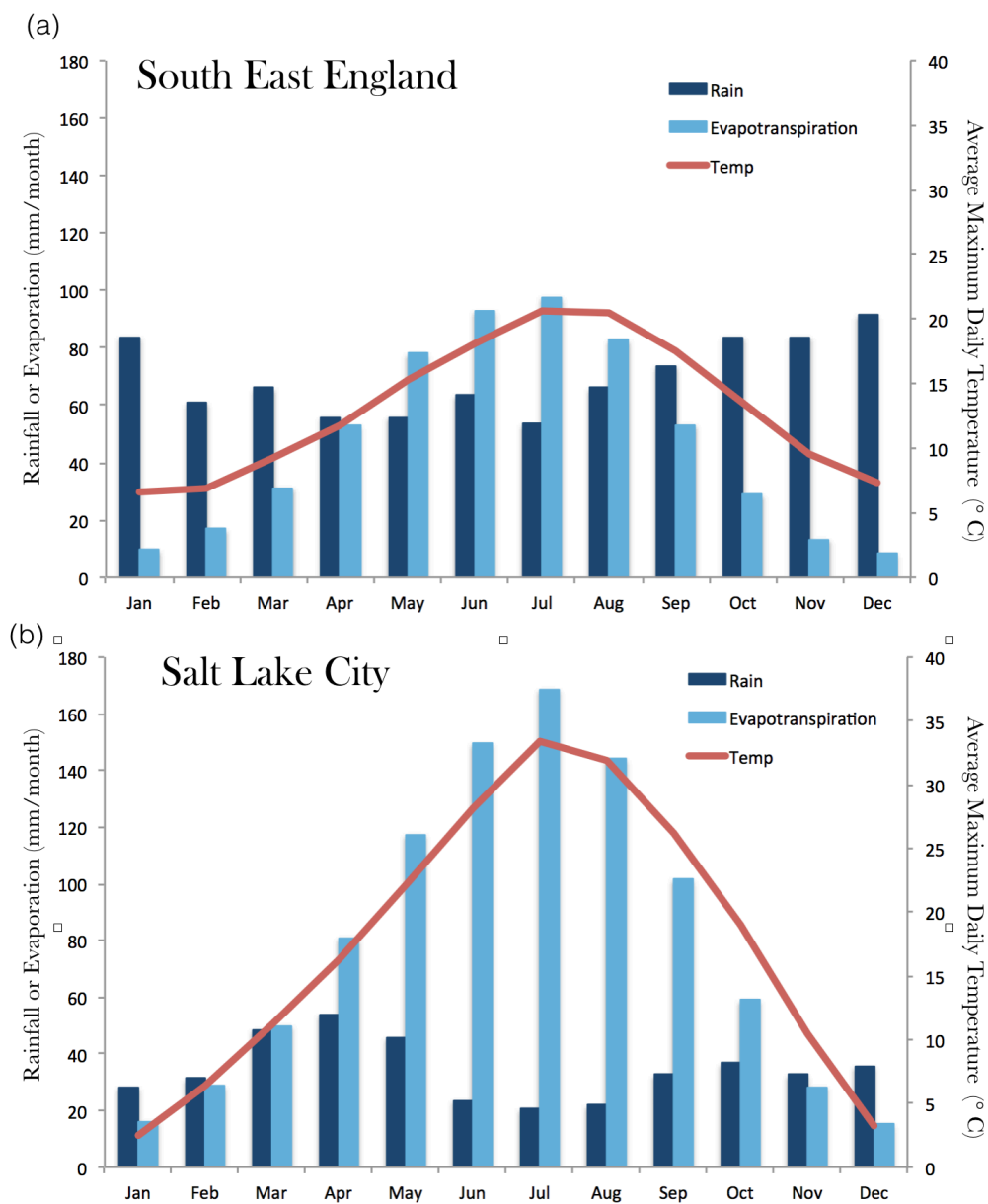


Figure 11. A comparison of rain, evapotranspiration, and air temperatures for Salt Lake City and South East England. Utah is the second driest state in the country, yet their water consumption per capita is the highest in the nation. The U.S. bases its traditional gardening aesthetic on the English gardening style of landscaping. Figure provided by *Kjelgren et al.*, [2000].

## 4.2 Concluding Remarks

As shown earlier, groundwater resources in Utah and the Great Basin are already susceptible to depletion under the changing climate regimes of precipitation and temperature and subsequent ET. This issue is then exacerbated by the increasing trend in water withdrawal for irrigational and public-supply purposes. The realization of such implications to groundwater resources have already come to fruition during California's ongoing (2014) drought [*Wang et al.*, 2014], which has spawned a well drilling boom due to the scarcity of irrigation water. For instance, in some regions of California, such as Tulare County, the number of permits to drill for groundwater has tripled. Prices for this dwindling resource have skyrocketed, which can currently cost a farmer in California anywhere between \$50,000 to \$500,000 to drill a well, prior to installing pumps [*Smith*, 2014]. Utah may be two states away, but the current crises experienced in California may be taken as an early warning and an analogy to Utahans regarding groundwater resources.

Due to these concerns, research on the predictive nature of groundwater resources is increasingly important given the present evidence that the increase of GHG in the atmosphere can have a direct influence on this drought-prone region. Our study has a potential limit due to relatively small number of ensembles. However, the findings in this study, such as the GHG driven groundwater reduction, are robust. This research hopes to pave the way for the utilization of coupled global climate modeling for the prediction of groundwater and strives to inspire the need for better water management in light of the changing climate.

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