Heterogeneous water table response to climate revealed by 60 years of ground water data

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Received 27 September 2010; revised 18 October 2010; accepted 26 October 2010; published 21 December 2010.

[1] Recent findings suggest that climate change will lead to modifications in the timing and nature of precipitation, giving rise to an altered hydrologic cycle. The response of subsurface hydrology to decadal climate and longer-term climate change to date has been investigated via site specific analyses, modeling studies, and proxy analysis. Here we present the first instrumental long-term regional compilation and analysis of the water table response to the last 60 years of climate in New England. Ground water trends are calculated as normalized anomalies and analyzed with respect to regional compiled precipitation, temperature, and streamflow. The time-series display decadal patterns with ground water levels being more variable and lagging that of precipitation and streamflow pointing to site specific and non-linear response to changes in climate. Recent trends (i.e., last 10 years) suggest statistically significant increasing water tables, which could lead to a higher risk for flooding in New England. **Citation:** Weider, K., and D. F. Boutt (2010), Heterogeneous water table response to climate revealed by 60 years of ground water data, *Geophys. Res. Lett.*, *37*, L24405, doi:10.1029/2010GL045561.

1. Introduction

[2] The scientific evidence that humans are directly influencing the Earth's natural climate is increasingly compelling. Numerous studies suggest that this climate change will lead to changes in the seasonality of surface water availability thereby altering the hydrologic cycle [*Anderson and Emanuel*, 2008; *Allen and Ingram*, 2002; *Hayhoe et al.*, 2007; *Hodgkins and Dudley*, 2006; *Huntington et al.*, 2004]. Research shows that the Northeast region of the U.S. is experiencing major changes to its natural climate [*Hayhoe et al.*, 2007; *Bradbury et al.*, 2002]. However, research on how climate change affects ground water systems is lacking at the regional scale and are necessary due to the fact that projected changes in meteorological variables vary regionally with different hydrological systems reacting in different ways to the changes.

[3] Rising temperatures and the increase and timing of New England precipitation are changing the character of the seasons and the hydrologic cycle [*Hodgkins et al.*, 2002, 2005; *New England Regional Assessment Group*, 2001]. The amount and timing of precipitation has potential implications for ground water as it affects the total amount of water available as contributions to streamflow, ground water, lake levels, and the timing of peak and low flows as extreme events [*Hayhoe et al.*, 2007]. Ground water flow and storage, often viewed as static reservoirs, are dynamic and continually changing in response to human and climatic stress [*Alley et al.*, 2002; *Gleeson et al.*, 2010]. Although few observational studies on ground water and climate exist [*Eltahir and Yeh*, 1999; *Anderson and Emanuel*, 2008], the majority of research has been directed at forecasting the potential impacts to surface water hydrology [*Eckhardt and Ulbrich*, 2003; *Hodgkins et al.*, 2002, 2005; *Hodgkins and Dudley*, 2006; *Hodgkins et al.*, 2003; *Roosmalen et al.*, 2007]. More frequently numerical and theoretical studies of the potential impact of climate change on ground water have been popular [*Chen et al.*, 2002; *Allen and Ingram*, 2002; *Jyrama and Sykes*, 2007; *Bouraoui et al.*, 1999; *Croley and Luukkonen*, 2003; *Eckhardt and Ulbrich*, 2003; *Kirshen*, 2002; *Roosmalen et al.*, 2007]. This investigation will evaluate the physical mechanisms, natural variability and response of aquifers in New England. No studies, to date, document the relationship between ground water conditions and climate at a regional scale using instrumental records. The goal of this paper is to document the response of the sub-surface hydrological cycle to decadal climate patterns using instrumental records of surface air temperature, precipitation, streamflow and ground water table elevation.

2. Data Sources and Methods

[4] The instrumental data used in this analysis are from various sources. Ground water sites are taken from the Climate Response Network for this analysis with care to avoid any significant data inequalities. A station's ground water level data must contain 20 years or more of continuous monthly data with minimal omissions (less than 10%); sites with significant amounts of missing data were not used in the analysis. One hundred percent of the wells used in this analysis contain 20 or more years of data with 83%, 78%, 17% and 7% of the sites containing 30, 40, 50 and 60 years of data respectively (Figure 2d). Care is taken to find data that spans across the New England region with well sites selected to be within differing geologic, watershed, and climatic environments. Monthly streamflow observational data are collected from the U.S. Geological Survey (USGS) National Streamflow Information Program using the same site selection criteria as ground water. Monthly precipitation and temperature data are taken from two sources; the National Oceanic Atmospheric Administration's National Climatic Data Center (NCDC) and the U.S. Historical Climatology Network (USHCN) [*Easterling et al.*, 1996]. Similar site selection criteria are used to find precipitation stations as ground water and streamflow for this analysis from NCDC and USHCN. Figure 1 displays all selected sites, which include 43 temperature sites, 75 precipitation stations, 67 stream gages and 100 ground water sites.

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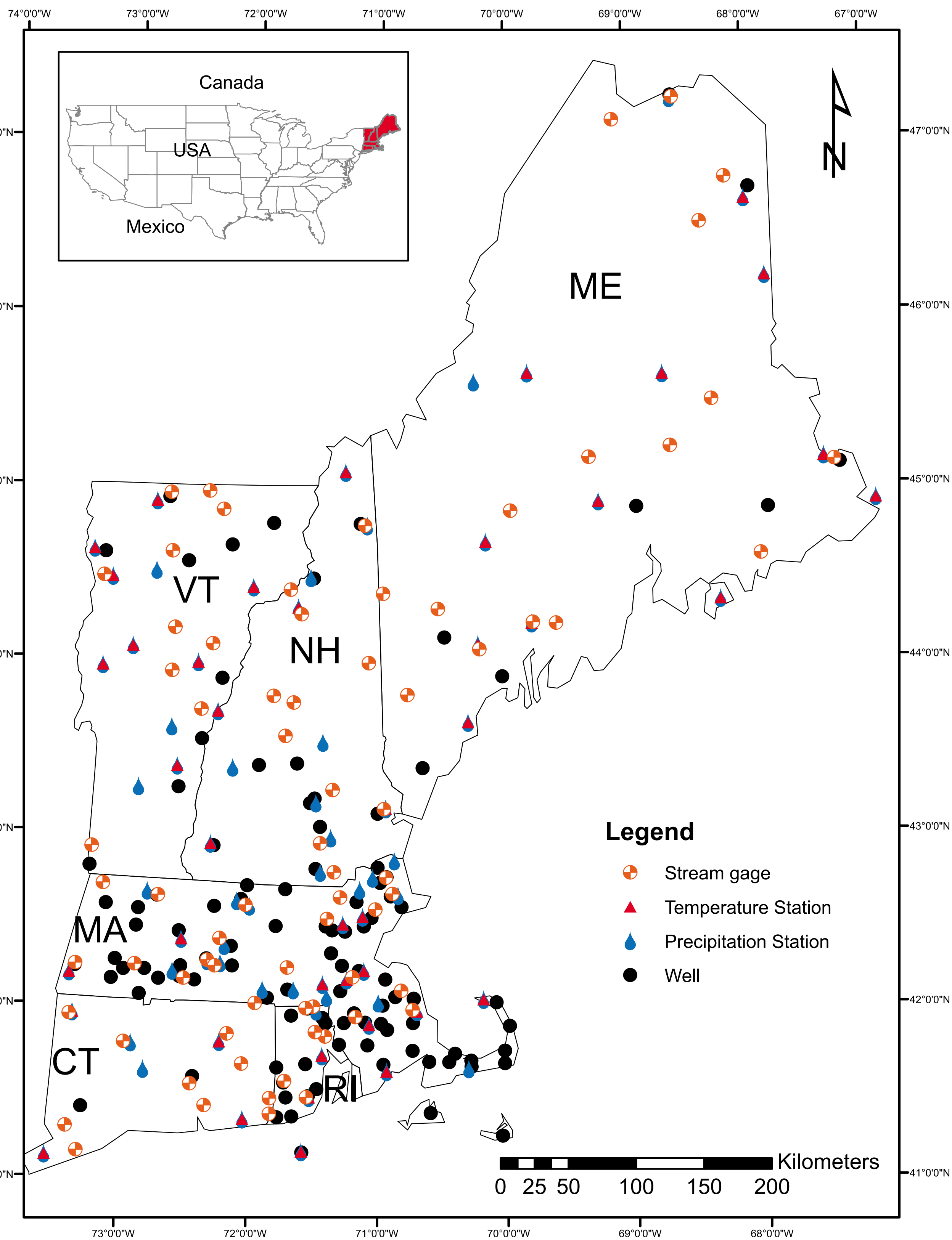

Figure 1. Location of New England measurement sites of hydrologic variables: stream gages (orange and white circle), temperature (red triangles), precipitation (blue droplets), and wells (black circles).

[5] Observational data is used to create temperature, precipitation, streamflow and ground water anomalies. Normalized anomalies (A_i) are defined as

$$A_i = \frac{m_i - \overline{m}}{\sigma_m} \quad (1)$$

where m_i is the monthly value, $\overline{m}$ is the average for an individual month over the whole time series, and σ_m is the standard deviation for the individual month over the whole time series. A 12 month-moving average is fit through monthly anomaly values. This windowing technique removes short-term fluctuations and highlights long term (i.e., multi-month) trends within the data.

3. Results and Discussion

[6] Calculations of New England anomalies from 1940–2010 depict intriguing relationships between climate variables and ground water levels (Figure 2). Twelve month moving average lines for the anomaly data are created for each of the four variables for every instrumental site and plotted together (red lines). The site-wide average of all 12 month moving average lines or the average of all raw anomaly data are calculated for each variable and is denoted by the black lines in Figure 2.

[7] Temperature anomalies show (Figure 2a) higher than normal temperature change, starting in 1983 and continuously staying above normal through present day. Overall, precipitation and streamflow anomalies (Figures 2b and 2c) remain relatively stable and homogeneous throughout their records until the last 10 years (2000–2010) where we see consistently above normal precipitation and streamflows. These results parallel the modeled and projected increases in precipitation and temperature for the New England region [*Hayhoe et al.*, 2007], which is contemporaneous with higher than normal ground water levels (Figure 2d). Plots in Figure 2 also reveal that ground water levels in New England have higher variability in their response than streamflow, precipitation, or temperature seen by the more pronounced positive and negative anomaly values (red lines) and the higher standard deviations values for ground water (Figure 3b).

[8] The average of the 12 month moving average lines are then compared qualitatively and quantitatively in Figure 3a. New England averaged ground water, streamflow, precipitation and temperature anomalies are tested for statistically significant trends and is performed by using the seasonal Mann-Kendall Test. Results show that all variables are producing significant increasing trends for the New England region (details in the auxiliary material).[1] During wet periods (positive anomalies) ground water levels follow closely with streamflow and precipitation, however an asymmetric response of the water levels occurs during drought periods. We propose that aquifers respond differently to floods and droughts [*Eltahir and Yeh*, 1999], which results in a disconnect of dry (more negative) anomalies and a dissipation of wet (more positive) anomalies in the ground water levels (Figure 3a) compared to streamflow. During drought periods a lag is observed from the climate variables to the ground water levels that are not seen during wet periods. This observation can be attributed to the fact that during wet anomalies the water table is already high and as ground water levels continue to rise they intersect with more stream networks. During dry periods, the opposite occurs, less intersection of stream networks occur as water level becomes more and more disconnected from surface water features.

[9] When all sites are averaged together, consistency and correlation between precipitation, streamflow, and ground water exist (Figure 3a). Cross-correlations between the New England averaged ground water and precipitation, ground water and streamflow and ground water and temperature reveal that streamflow and precipitation are highly correlated to ground water levels in New England (see auxiliary material). These raw correlations fail to account for the mutual correlation of both ground water and streamflow to precipitation. When removing the mutual correlation of precipitation the correlation between streamflow and ground water becomes smaller, $R^2 = 0.37$, compared to a raw correlation of $R^2 = 0.76$, but is still significant ($P < 0.000$). In humid regions with permeable surficial materials, the stream network effectively acts as drain on the ground water system causing ground water and streamflow to be correlated [*Allen and Ingram*, 2002].

[10] A close examination of Figure 3a indicates that during times of negative anomalies a consistent progression from low to highly negative anomaly magnitude is apparent when comparing precipitation to streamflow and then to ground water anomalies, for example, during the mid 1960s and early 1980s. During periods of positive anomalies these trends are also apparent but the difference in magnitude between streamflow and ground water is not significant for reasons discussed above. The trend of increasing negative and positive anomaly magnitudes is puzzling, as climate drivers (such as precipitation) often show larger magnitude anomalies than ground water due to precipitations' highly non-autocorrelated nature [*Eltahir and Yeh*, 1999]. Ground water systems are often called upon to moderate climate forcing, acting as a low-pass filter. Yet, this data suggests that ground water is being amplified compared to both temperature and precipitation.

[11] Through use of a linear representation of ground water level, *Knotters and Bierkens* [2000] show that the response time of ground water systems to precipitation anomalies is large for aquifers with low permeabilities and at large distances from connected surface water features. The amplitude (A) can also be shown [*Knotters and Bierkens*, 2000; *Alley et al.*, 2002] to be proportional to $\frac{L^2}{T}$ where L is this distance from the nearest stream and T is the transmissivity of the aquifer. The relationship between A and the time lag can be a good proxy for the transmissivity of the aquifer system. The relationship between the time lag between ground water and precipitation and the amplitude of the ground water anomaly at fifty precipitation-ground water sites was investigated. A strong positive correlation using a linear regression model with a large variation in slope was observed (see auxiliary material), indicating variability in the response time characteristics of the aquifer system. These results support other work [*Allen and Ingram*, 2002; *Roosmalen et al.*, 2007], suggesting that the geology of the region plays a major role in the magnitude of the hydrologic response to climate change.

[12] Analysis of the site to site variability, expressed as the standard deviation of all sites, of anomalies produces

[1] Auxiliary materials are available in the HTML. doi:10.1029/2010GL045561.

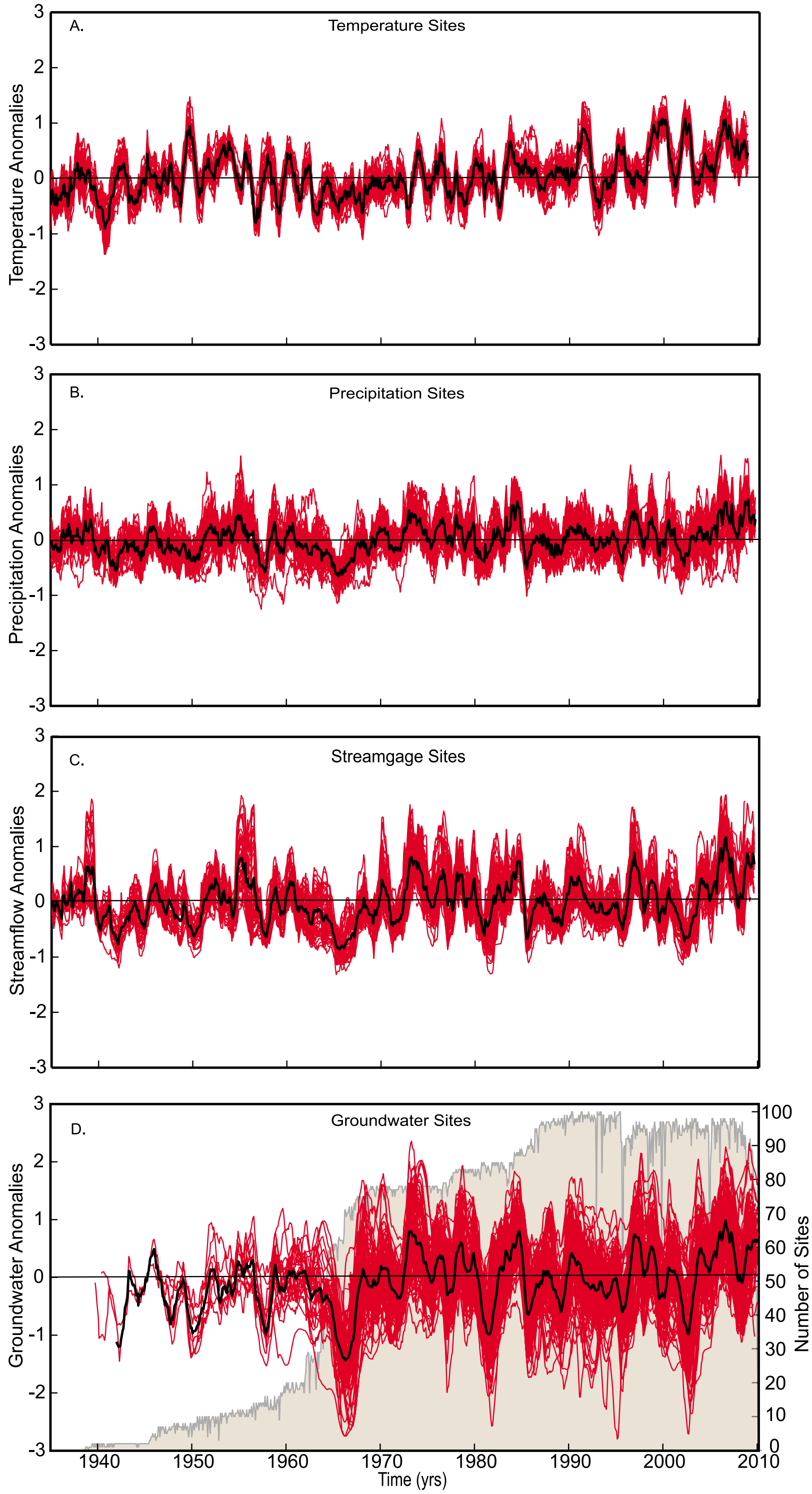

Figure 2. Time series of the normalized monthly anomalies for all sites (red lines) (a) temperature, (b) precipitation, (c) streamflow, and (d) ground water. The black line through the data is average of all 12-month moving averages or the average of all anomaly data. The shaded region in Figure 2d is the Monthly cumulative distribution of the number of sites that have data in a certain year.

some interesting trends (Figure 3b). By calculating a standard deviation of anomalies for all sites a measure of the variation (see scatter in individual site response in Figure 2) of a site for a given time period is obtained. In general the ground water sites statistically display the most variation about the mean, with having almost twice as much variability (~0.5 for ground water) compared to temperature and precipitation (~0.2). Streamflow sites show less variation than ground water but on average display more erratic variability compared to precipitation and temperature records.

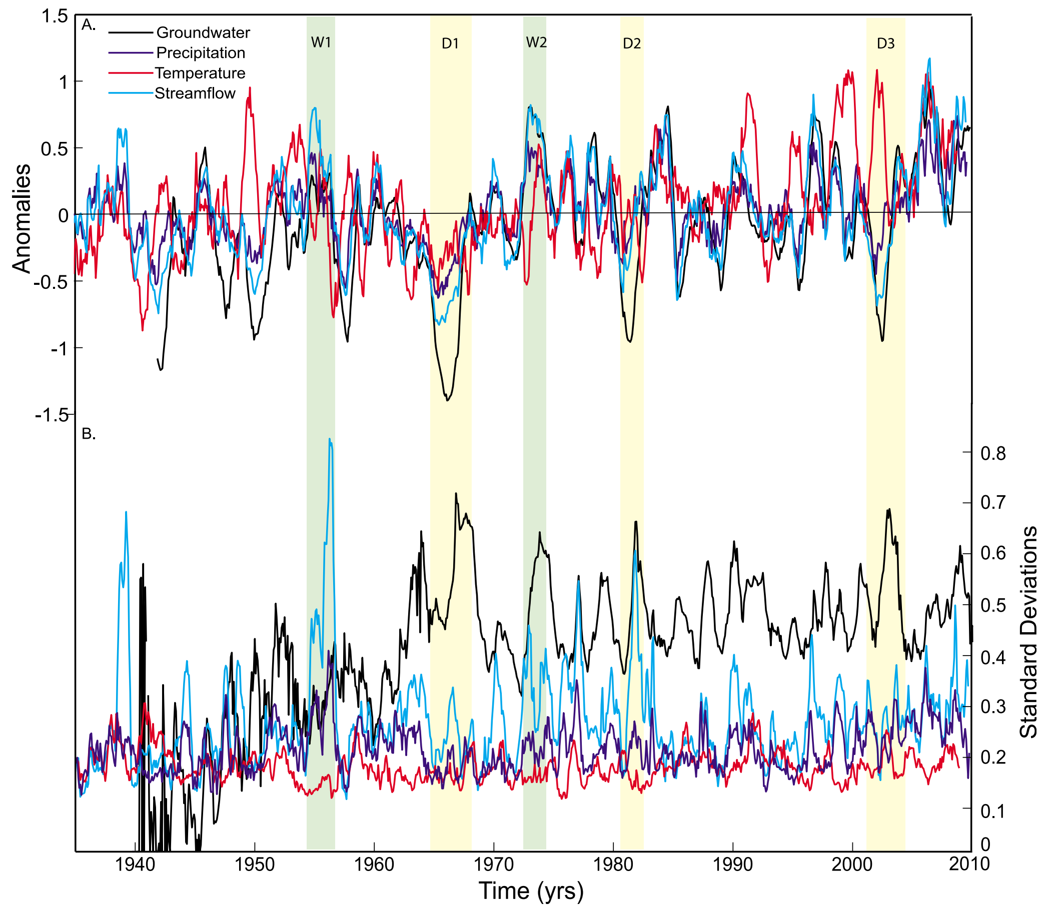

Figure 3. Combination anomalies: (a) Average of all 12-month moving averages for ground water (black), precipitation (dark blue), temperature (red), and streamflow (light blue). (b) Standard deviations of anomaly data for ground water, precipitation, temperature and streamflow. Shaded regions (D1, D2 and D3) reflect dry periods within the record while shaded regions (W1 and W2) reflect wet periods.

Both ground water and streamflow records have time periods where they show significantly more variability compared to the average variability of the dataset such as during the late 1960s to early 1980s. These peaks in variability for ground water are always greater than streamflow, excluding the mid 1950s streamflow peak, and often are more variable (wider peaks) for greater amounts of time. Wider peaks in ground water can be attributed to the response time of ground water versus streamflow. Even under natural conditions, the travel time of ground water from areas of recharge to discharge can range tremendously creating a delay or extension of the signal in response to the perturbation. These peaks in both streamflow and ground water appear to correlate with either highly positive or negative anomalies in the composite dataset. The largest ground water variations (Figure 3b) are strongly correlated with negative anomalies (Figure 3a), these are represented by the shaded regions (D1, D2 and D3) where ground water minimums are recorded in the composite anomalies as highly anomalous times seen by the high standard deviation values in Figure 3b. Highly anomalous or high standard deviations also occur during more positive anomalies (wet times W1 and W2), where ground water and streamflow values are above normal. Not all peaks in variability in ground water display a peak in the streamflow variability as it does around 1982. Ultimately, results suggest that the subsurface or geologic material has a strong influence on the amplification and dissipation of anomalies creating the ambiguities visible between different ground water sites.

4. Summary and Conclusions

[13] The analysis of New England climate anomalies from 1940–2010 depict a strong relationship between climate variables and ground water levels displaying intriguing decadal patterns that reveal information about the sensitivity of aquifers to climate perturbations. Ground water levels in New England have higher variability in their response than streamflow, precipitation, or temperature seen by the more pronounced positive and negative anomaly values. Minima in ground water anomalies lag that of corresponding precipitation anomalies (and streamflow anomalies) by as much as 2 years. These lags are well correlated with the magnitude of the anomaly and are potentially a manifestation of the hydrogeologic characteristics of the local aquifer. Understanding the relationship between the size of the time lag and aquifer characteristics is important for understanding the timing and nature of ground water response to climate.

[14] Additionally, the temperature, precipitation, streamflow and ground water anomalies show a statistically significant increasing trend over time that is more pronounced in the last 10 years. Higher water tables could lead to increased baseflow in streams and higher soil moisture

content potentially leading to the higher probability for increased risks to flooding in the New England region. More water and higher water tables will potentially lead to increased water levels in reservoirs acting as public water supplies. Statistical analysis, such as this one, with free and easily accessible data can be performed in regions with climate response networks to understand the physical mechanisms dominating the hydrologic cycle.

[15] **Acknowledgments.** Discussion with members of the hydrogeology group at UMass-Amherst significantly improved the content of this manuscript. The authors acknowledge the thoughtful and constructive comments of two anonymous reviewers.

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