A conceptual model for climatic teleconnection signal control on groundwater variability in Europe

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Abstract

The ability to predict future variability of groundwater resources in time and space is of critical importance to drought management. Periodic control on groundwater levels from oscillatory climatic systems (such as the North Atlantic Oscillation) offers a potentially valuable source of longer term forecasting capability. While some studies have found evidence of the influence of such climatic oscillations within groundwater records, there is little information on how periodic signals propagate between a climatic system and a groundwater resource. This paper develops a conceptual model of this relationship for groundwater resources in Europe, based on a review of current research. The studies reviewed here reveal key spatial and temporal signal modulations between climatic oscillations, precipitation, groundwater recharge and groundwater discharge. Generally positive correlations are found between the NAO (as a dominant influence) and precipitation in northern Europe indicating a strong control on water available for groundwater recharge. These periodic signals in precipitation are transformed by the unsaturated and saturated zones, such that signals are damped and lagged. This modulation has been identified to varying degrees, and is dependent on the shape, storage and transmissivity of an aquifer system. This goes part way towards explaining the differences in periodic signal strength found across many groundwater systems in current research. So that an

understanding of these relationships can be used by water managers in building resilience to drought, several research gaps have been identified. Among these are improved quantification of spatial groundwater sensitivity to periodic control, and better identification of the hydrogeological controls on signal lagging and damping. Principally, research needs to move towards developing improved predictive capability for the use of periodic climate oscillations as indicators of longer term groundwater variability.

Keywords: teleconnection; hydroclimatology; groundwater; water management; climate

1. Introduction

A number of studies have identified significant extra-annual periodic signals in long-term groundwater records (Holman et al. 2011; Holman 2006; Kuss & Gurdak 2014; Velasco et al. 2015; Cao et al. 2016; Dickinson et al. 2014). Such signals are understood to be ultimately driven by oscillatory climatic systems, such as the El-Niño Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) (Kingston et al. 2006). Currently there is no conceptual model that describes how these extra-annual periodic signals are propagated and transformed by meteorological and hydrogeological processes. Thus the spatial and temporal variability of low-frequency signal strength found in groundwater data cannot be systematically explained at present. These long-period signals offer a source of improved forecasting capability for hydrogeological response, thereby representing a potentially valuable area of development for systematic understanding of groundwater variability (Kingston et al. 2007; Kuss & Gurdak 2014; Water UK 2016; Kingston et al. 2006; Loon 2013; Tallaksen et al. 2006).

Many operational assessments of hydrogeological resilience to drought are based on the premise that describing response to annual fluctuation in groundwater recharge is sufficient for resource management (Environment Agency 2013; Kingston et al. 2006). Annual variability typically represents a large proportion of the total variance observed in long-term groundwater records (Holman et al.

2011). As such it a useful component in identifying groundwater sensitivity to catchment characteristics (Rust et al. 2014). However, as a requirement of the predictive modelling used for many water resource investigations (Van Loon 2015), statistical assessments of groundwater records often assume variance and autocorrelation are stationarity at extra-annual scales (Milly et al. 2008). Therefore, the systematic periodic controls on groundwater resources at extra-annual scales have not traditionally been considered (Kingston et al. 2006; Currell et al. 2014; Alexander et al. 2005; Folland et al. 2015; Hanson et al. 2006; Kuss & Gurdak 2014; Bloomfield et al. 2003).

While parts of the systematic linkage between climate and groundwater have been assessed in isolation by previous studies, the current lack of a unifying model means that existing information on these periodic controls cannot be readily used to inform groundwater management decisions. Given the potential for improved prediction of groundwater variability, this information should allow for more effective planning for social, ecosystem, and infrastructure resilience to drought (Kingston et al. 2006; Van Loon 2013; Van Loon 2015). This is of particular importance in Europe, which has received little focus in groundwater teleconnection literature to date. In this paper we review existing research on hydroclimatological linkages and signal propagation through the water cycle to produce a conceptual model of how periodic climatic variability drives sympathetic signals in groundwater systems in Europe.

2. Generalised conceptual model of periodic climatic signal propagation to groundwater resources

A generalised conceptual model of the control linkages within the water cycle between periodic climate systems and groundwater response is shown in Figure 1. The first two stages of this figure conceptualise the generation and propagation of low-frequency climate and weather signals, while the last two stages conceptualise how those signals propagate through the land surface and groundwater system via groundwater recharge and discharge. By assessing the current evidence base in each of these four stages, here we develop a conceptual model for spatiotemporal signal propagation between climate and groundwater systems in Europe, and identify knowledge gaps. In the following sections we assess the spatial distribution of climatic systems in the North Atlantic region (Section 3), the evidence for signal generation and spatial propagation through coupled climate and weather systems (Section 4) and finally signal transformations through the groundwater system (Section 5 & 6).

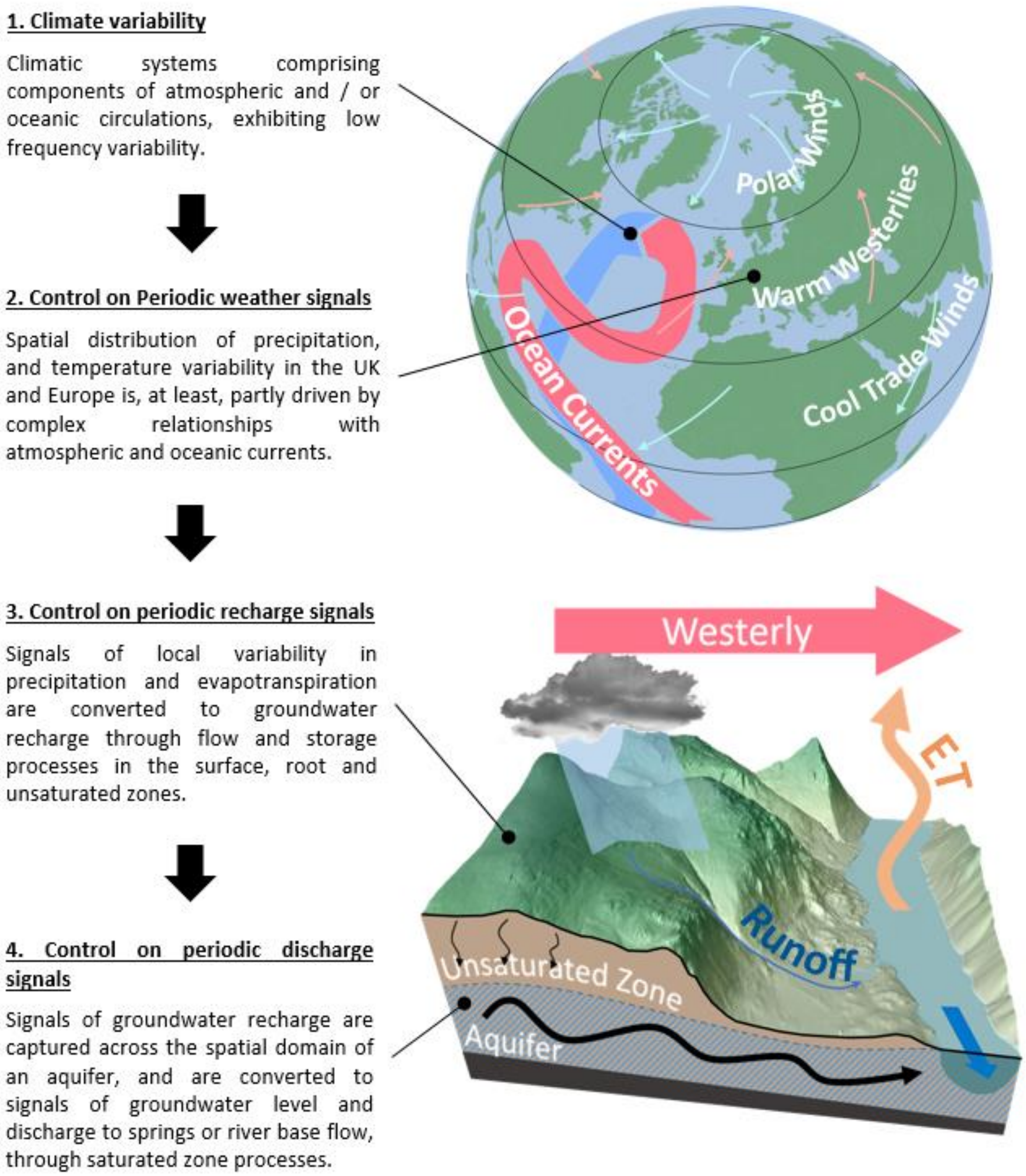

Figure 1 – Generalised conceptual model of low frequency signal propagation between climatic systems and groundwater level and discharge

3. Climatic Variability and Teleconnections

3.1. Measures of Climatic Variability

Research into hydroclimatology often relies on statistical assessments between climatic anomalies and hydrological datasets. Anomalies are defined as the difference between a measured climate variable (for instance sea level pressure (SLP)) and the normal state, usually the temporal mean, of that variable. They are therefore useful metrics for comparing measurements at different locations within a climate system (Hurrell et al. 2003).

Teleconnection (TC) indices are constructed from anomalies at different locations within a system of atmospheric or oceanic variability (such as the NAO), giving a spatial picture as to the state of the system. TC indices are often described in terms of their phase as departures from the mean, either a positive or negative phase. This indicates which anomaly is most dominant and therefore which mode the system is in. For instance the El Niño or La Niña mode in the case of the El Niño Southern Oscillation (ENSO). TC indices often exhibit multiscale periodic variability as a result of complex non-linear processes within atmospheric and oceanic dynamics (Hauser et al. 2015; Hurrell et al. 1997). These indices are therefore favoured by hydroclimatologists as a tool to measure hydrological sensitivity to climatic circulations. (Kingston et al. 2006; Loboda et al. 2006).

A broad range of TCs have been studied in the past such as NAO (Hurrell 1995), ENSO (Wang & Kumar 2015), Pacific Decadal Oscillation (Routson et al. 2016; Kuss & Gurdak 2014), Atlantic Multidecadal Oscillation (Wyatt et al. 2012), and Arctic and Antarctic Oscillation (Tabari et al. 2014), as well as other indicators of climate and oceanic variability such as sea surface temperature (SST) (Wilby et al. 1997). While it is not the intention of this paper to provide an exhaustive review of TCs, here we focus on recent TC research of potential relevance to groundwater systems in Europe. Such circulations are described in the following sections.

3.1.1. North Atlantic Oscillation (NAO)

The NAO is a dipole of SLP anomalies between semi-permanent centres of action in the North Atlantic: the Azores (Sub Tropical) High and the Icelandic (Sub Polar) Low (Hurrell et al. 2003). The oscillation exhibits a principle periodicity of 8 - 9 years, and a secondary periodicity of 3 - 5 years, which are seen principally in winter index values (Hurrell & Deser 2010). Its variability is understood to be partially driven by quasi-stationary planetary waves (Hurrell 1995, Trenberth 1993).

The NAO is the dominant mode of atmospheric behaviour throughout the year in the North Atlantic region (Dickson et al 1999). It can account for up to 30% of the variability in SST (Shabbar et al. 2001) and 50% of winter weather variability in Europe (Cassou 2003; Hurrell and Van Loon, 1997; Fritier et al 2012). Although the NAO is principally influential on European regional climate, its influence extends, to a lesser extent, to Africa, China and the USA (López-Moreno et al. 2011; Lee & Zhang 2011; Wang et al. 2015; Magilligan & Graber 1996).

3.1.2. East Atlantic Pattern (EA)

The East Atlantic (EA) pattern has a similar spatiotemporal structure to the NAO, but shifted southwest within the Atlantic region. The EA exhibits a strong multi-decadal mode of variability (Holman et al. 2011) and is the second most prominent mode of low frequency variability in the North Atlantic Region (Wallace & Gutzler 1981). The effect of the EA on regional climate closely mirrors that of the NAO, however it has been shown to exhibit internal variability (Hauser et al. 2015; Tošić et al. 2016).

3.1.3. Arctic Oscillation (AO)

The Arctic Oscillation (AO) is also known as the Northern Hemisphere Annual Mode (CPC, 2016). It is characterised by pressure anomalies over the Arctic, with other anomalies centred on latitudes of 37-45° N (Givati 2013). The temporal variability of the AO is similar to that of the NAO, with a November-

April correlation of 0.95 (Deser 2000). As a result of this, the AO exhibits a similar modulation on moisture and heat exchange in Europe to the NAO. Wallace (2002) suggests that the NAO is a regional expression of the larger AO, however the majority of research accepts that the NAO and AO are internally variable, in some instances influencing each other (Dickson et al. 2000).

3.1.4. Scandinavia Pattern / Polar – Eurasian Pattern (POL)

The Scandinavia pattern (SCAND), also referred to as the Eurasia-1 Pattern (Barnston & Livezey 1987) or the Polar-Eurasian Pattern (POL), consists of a primary circulation centre over Scandinavia with weaker centres of opposite phase over Western Europe and eastern Russia/ western Mongolia (CPC, 2016, Saunders et al. 2012, Wedgbrow, et al 2002). Although no strong periodicity is given is the literature, Holman et al. (2011) suggest that the Scandinavia pattern exhibits relatively large inter-seasonal, inter-annual and inter-decadal variability.

3.1.5. Teleconnection Independency

Wyatt et al (2012) and Water & Frag (2005) found significant co-variances between all North Atlantic indices, suggesting that most individual TC systems are not internally variable and are driven by a wider system. Despite these findings, Lavers et al. (2010) and Cooper (2009) argue that any attempt to confine such complex non-linear systems to univariate or bivariate measures will always fail to account for true variability. Given this, they are still useful tools so long as their assumptions are well understood throughout their analysis (Hurrell et al. 2003).

4. Teleconnection controls on periodic weather signals

The amount of recharge to a given groundwater store is related to the amount of precipitation (PPT) and evapotranspiration (ET) received. These two processes are therefore critical carriers of periodic signals between climatic systems and groundwater response. In order to explain the character of extra-annual periodic signals found in groundwater stores, it is first necessary to assess the role of weather systems. In the following section we firstly review the causal relationships between climatic systems and moisture and thermal exchange, and secondly the subsequent impacts on PPT and ET across Europe.

4.1. Atmospheric currents and storm generation

North Atlantic westerlies and the Arctic Polar Jetstream affect the distribution of storm activity and wider thermal and moisture exchange over Europe (Joyce et al. 2000; Alexander et al. 2005; Feser et al. 2015). For example, the strength and location of the Polar Jetstream has been shown to account for approximately a third of winter storm variability in Western Europe (Alexander et al. 2005).

Since the NAO represents a system of pressure distribution in the North Atlantic, it can directly modulate transatlantic pressure gradients and therefore westerly strength (Feser et al. 2015). Strong westerlies enhance the advection of warm moist air from the Atlantic, creating stronger and more frequent cyclones along the North Atlantic storm track (Trigo et al. 2002). Additionally, decreased atmospheric pressure over Iceland, seen in the NAO+, is associated with an increase in the meridional tilt of the North Atlantic storm track (Walter & Graf 2005). Thereby, there is an increased likelihood of larger storms reaching north-western Europe, and propagating into central Europe during a NAO+. For example Trigo et al. (2004) shows that PPT in western Europe is coverable with the NAO's periodicities, at a minimal lag. The NAO's control on ET is typically lagged by 6 months, meaning a strong winter NAO can modulate European ET rates in the subsequent summer (Wedgbrow *et al.* 2002).

In southern Europe, this relationship is inversed. The region experiences anomalous anticyclonic activity during a NAO+ due to the meridionally tilted storm track, the influence of which decays inland (Tabari et al. 2014; Türkeş & Erlat 2003).

Although this model of NAO control on westerly storm tracks is well corroborated (Alexander et al. 2005; Sickmoller et al. 2000; Taylor & Stephens 1998), the NAO index only accounts for a portion of total atmospheric variability. For example, Walter & Graf (2005) suggest that teleconnection control on storm track strength can be better explained by accounting for higher geopotential heights in the mid to upper troposphere. This accounts for atmospheric blocking at higher altitudes, a process which has been shown to block storm development towards northern Europe in a 'traditional' NAO+, skewing correlation analyses (Shabbar et al. 2001; Peings & Magnusdottir 2014). Despite this, the original NAO definition is more widely used in research due to its fewer data requirements.

Extra-Atlantic TC systems, such as ENSO, have a negligible control on storm propagation across Europe (Alexander et al. 2002). As such these have not been reviewed in any further detail.

4.2. Oceanic currents and thermal exchange

The dominant mechanism of oceanic influence on thermal exchange in Europe is the Gulf Stream (Frankignoul et al. 2001). It accounts for increased winter temperatures and an enhanced storm path in western Europe (Ezer 2015; Davis et al. 2013). The Gulf Stream exhibits control over both PPT frequency and potential evapotranspiration (PET) in the region (Seager et al. 2002). Zonal heat transfer, seen in oceanic systems such as the Gulf Stream, can be viewed as the oceanic counterpart to westerly and storm track moister transfers.

The NAO (in particular the Subpolar Low) modulates the Gulf Stream strength through extraction of heat from the Subpolar Gyre and Labrador Sea (Delworth & Zeng, 2016). A positive NAO (NAO+) increases deep water formation (DWF) thereby steepening thermal gradients across the Atlantic and enhancing the Gulf Stream (Chaudhuri et al. 2011; Delworth & Zeng 2016; Walter & Graf 2005; Drinkwater et al. 2014). This increase in DWF in the Polar Regions has also been shown to increase the meridional tilt of the Gulf Stream, extending the enhanced thermal exchange further into northern Europe (Bakke et al. 2008).

The long-term average NAO phase is more influential on the Gulf Stream than its finer-scale fluctuations, due to the oceanic system's ability to filter high-frequency variability from external drivers (Hurrel & Desser, 2010). As a result of this memory capacity, the NAO's influence on the Gulf Stream strength and tilt can be lagged by an average of 1 – 2 years (Taylor 1995; Joyce et al. 2000; Frankignoul et al. 2001), and up to 7 years (Wyatt et al. 2012; Hurrell & Deser 2010).

Other patterns, such as the EA and AO, have been shown to have similar influences on the Gulf Stream, predominantly through spatiotemporal covariance with the NAO signal (Wedgbrow et al. 2002). The similarity of control between the NAO, EA and AO further validates the assertion of Walter & Graf (2005) and Wedgbrow et al (2002) who suggest that these systems are regional expressions of a more complex, vertically heterogeneous, air-sea system over the North Atlantic. Additionally, Principle Component Analysis (PCA) of Gulf Stream data has revealed no periodicities greater than 10 years, making a systematic control of thermal exchange over Europe from non-NAO-like systems unlikely (Chaudhuri et al. 2011). Since drivers of groundwater recharge (PPT and ET) are primarily influenced by the NAO and NAO-like oscillations (such as the EA pattern and the AO), the remainder of this paper will focus on NAO-like signal propagation through groundwater systems.

4.3. Spatial distribution of periodic precipitation anomalies

Figure 2 shows a synthesis of spatial correlation data from published studies between winter NAO index values and PPT or Palmer Drought Severity Index (PDSI). Studies that give point, gridded or regional correlation values between 0 and 1 (such as R) were used. The spatially aggregated data can be considered a generalised correlation between NAO and moisture availability (either directly as PPT or as measured by PDSI). Direct ET correlation data has not been included due to paucity of research. Voronoi polygons were used to distribute the correlation data across a map of Europe shown in Figure 2.

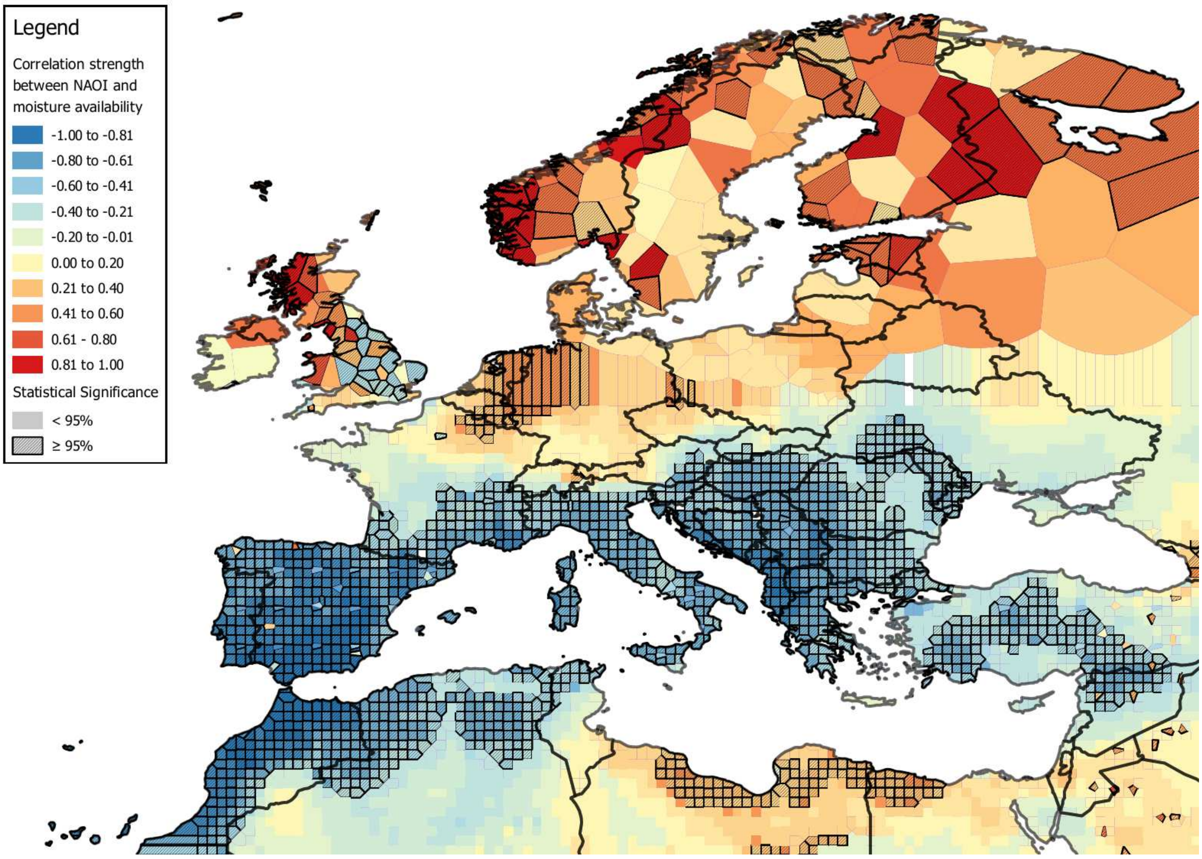

Figure 2 - Correlation between Winter NAO and Precipitation and PDSI. (based on correlation coefficients from Brandimarte et al. 2010; Cullen & DeMenocal 2000; Fowler & Kilsby 2002; Hurrell 1995; Lopez-Bustins et al. 2008; Luković, Bajat, Blagojević 2014; Lavers et al. 2010; López-Moreno et al. 2011; Murphy & Washington 2001; Queralt et al. 2009; Rogers et al. 2001; Soediono 1989; Tabari et al. 2014; Türkeş & Erlat 2003; Uvo 2003; Wang et al. 2015; Wilby et al. 1997)

Four primary spatial patterns can be described from Figure 2:

1. There is a positive correlation between a winter NAO index and PPT / PDSI in northern regions of Europe, including the UK and the Scandinavian countries. Highest correlations can be seen in areas dominated by orographic rainfall (for instance Wales, northwest England and Scotland), and western coastlines (such as the Scandinavian Mountains in Norway). This reflects the NAO's control on the Gulf Stream and Atlantic Storm Track strength and tilt.

2. The only area which appears to exhibit an opposite trend to wider northern Europe is central and south east England. At this location, wetter conditions have a weak negative correlation with the winter NAO. This may be the result of orographic rainfall to the west imposing a barrier to storm progression (Wilby et al. 1997), or a sensitivity of this region to the NAO's sub-tropical component (Wedgbrow et al 2002).

3. Southern and Mediterranean Europe show a strong negative correlation between the winter NAO and PPT / PDSI. As such these areas are dryer during a positive winter NAO. This is most likely the result of the increased meridional tilt of the westerly storm track in a positive NAO, which limits moisture transport to south Europe.

4. In general, the strength of the correlation is low in the intermediate zone between positive and negative correlation and diminishes eastward or with distance from the coastline.

It should be noted that the data aggregated in Figure 2 are from multiple studies which have used separate methodologies, and have differing levels of confidence. As such this figure should be considered a general representation of winter NAO influence on catchment wetness.

The ability of TC systems to control PPT and ET independently over time and space is critical for determining control on the total water available for recharge. In central Europe, the NAO and NAO-like systems are more capable of driving ET than they are of PPT (Trigo et al. 2002; Mares et al. 2002). This is possibly due to the decay of NAO-driven storm tracks with distance from the Atlantic, while anticyclonic systems are able to drive ET further inland. The result is a dominant NAO control on ET towards central Europe (Merino et al. 2015; López-Moreno et al. 2011; Türkeş & Erlat 2003; Bozyurt & Özdemir 2014). For example, Ghasemi & Khalili (2008) and Tabari et al. (2014) found a greater NAO control on Reference ET in Iran, compared to PPT. The independent control of PPT and ET is still unclear in current research due the effect of local topography, differing study methodologies or the influence of external forcing beyond the TC systems under consideration (Wedgbrow et al. 2002).

5. Controls on periodic recharge signals

The nature of teleconnections and their control on weather is spatially variable, as shown in section 4. However, a wide range of intrinsic catchment characteristics, for example land cover, soil or geological properties, modify the propagation of potential recharge signals by varying degrees (Nimmo 2005; Rust et al. 2014). Here we discuss the current understanding of how the influence of catchment characteristics, and the distribution of such parameters, affect the propagation of low-frequency periodic signals from PPT and ET through to aquifer recharge.

5.1. Land surface Processes and Recharge

The land surface and root zones provide the interface between meteorological processes and infiltration. These include the effect of vegetation, actual ET, surface storage, soil type, and soil storage. While climatic and weather systems are shown to control anomaly signals in both PPT and ET at multiple time scales, the surface and root zones mediate the actual volumes of water that infiltrate into the unsaturated zone. Indeed long-term changes in these near-surface processes may confound low frequency signal propagation toward groundwater recharge (Ferguson & Maxwell 2010; Healy

2010).

While shallow soil horizons and surface stores have been shown to filter finer-scale variability (hourly-daily) from incoming signals (Baram et al. 2012), surface processes have minimal impact on the propagation of long-period signals (Bakker & Nieber 2009; Dickinson et al. 2014). For example, Rust et al. (2014) showed that vegetation type can affect annual and seasonal climate signal propagation into groundwater recharge with little effect on extra-annual scales. It is therefore considered that surface processes bear little impact within the presented conceptual model of long period climate signal propagation.

5.2. Unsaturated Zone influence on Recharge Signals

Signal propagation below the root zone is one of the most poorly quantified components of the hydrological cycle. This is, in part, because of the complex nonlinear relationship between flow, water content, and hydraulic diffusivity (Cuthbert et al. 2010). While this is an area of much ongoing research, the development of periodic signals through the unsaturated zone is still an area of much research paucity. There is an established literature, however, on drought development through the water cycle (Loon 2013; Van Loon et al. 2014; Van Loon et al. 2012; Peters et al. 2003; Peters et al. 2006; Di Domenico et al. 2010; Tallaksen et al. 2009; Peters 2003; Tallaksen et al. 2006; Bloomfield & Marchant 2013; Mishra & Singh 2010). These focus on the propagation of episodic negative anomalies in PPT through to groundwater level, and are a useful parallel to periodic signal propagation.

Van Loon (2015) provides a comprehensive text on drought propagation between meteorology and groundwater, in which four signal modulations are characterised. These are; i) Pooling of meteorological droughts into prolonged groundwater drought; ii) Attenuation of PPT deficits in surface stores; iii) Lags in the onset of drought between meteorological, soil moisture, and groundwater systems; and finally iv) Lengthening of droughts when moving between soil moisture and groundwater drought, as a result of attenuation. Features i, iii and iv can be considered descriptions of the unsaturated zone's ability to dampen incoming signals in PPT and ET.

The ability of a groundwater system to propagate, or dampen, drought signals from PPT and ET is often related to properties of the unsaturated zone, such as storage or thickness (Bloomfield & Marchant 2013; Van Loon 2015; Van Loon et al. 2014). For example, Bloomfield & Marchant (2013) identified lags and lengthening of drought signals between PPT and groundwater level, similar to those described by Van Loon (2015). They propose that long autocorrelations seen in the a Standardised Groundwater Index for multiple boreholes across the UK may be explained by the unsaturated zone's ability to filter out higher autocorrelation frequencies in PPT, while allowing longer-period signals to pass. This is corroborated well by Kumar et al. (2016), who showed that groundwater head anomalies at locations of thicker unsaturated zones achieved higher correlations with SPI at longer accumulation periods, when compared with thinner unsaturated zones.

As an indicator of available storage in an unsaturated zone, soil type is an important characteristic in modulating the degree of signal damping. Dickinson et al (2014) describes a greater damping rate (with depth) for periodic signal propagation through clayey soils, compared to sandy soils. They concluded that soils with lower hydraulic diffusivity (such as clay soils) filter out sinusoidal frequencies more effectively than soils with greater diffusivity (such as sandy soils). They also propose that extra-annual periodic signals are unlikely to reach steady state through an unsaturated zone, meaning these signals will persist through to recharge. These findings are supported by Valesco et al. (2015).

In addition to damping incoming infiltration signals, the unsaturated zone is conceptualised to lag signal perturbations between infiltration and groundwater recharge (Gurdak et al. 2007; Crosbie et al. 2005; Cao et al. 2016; Dickinson 2004; Cuthbert & Tindimugaya 2010). Despite this, very few studies have quantified this lag for unsaturated zones in Europe. Holman et al (2011) found significant transient lagged correlations between the NAO index and groundwater level data in the UK. Highest correlations were found at 4 year and 16 year period scales. Although lag times were not directly quantified in the study, phase-shifts were presented as tending towards 180° for the NAO signal, indicating a 2 - 8 year lag provided by unsaturated zones in the UK.

While there has been little quantification of periodic signal damping and lagging through unsaturated zones in Europe, many groundwater resources globally provide a clearer view of the dampening capability of the unsaturated zone. For example, Kuss & Gurdak et al (2014) found an (up to) 93% dependence between groundwater variability on PDO-like signals, at a lag of between 11 to 46 years, in the USA High Plains aquifer. By undertaking a lag correlation between a coupled PDO-like periodic component of rainfall and groundwater level, they attributed the damping detected to the varying thickness of the unsaturated zone. Similar results have been found by Cao et al (2015) in assessing recharge in the North China Plain aquifer, finding that an increase in unsaturated thickness greater than 30 m, results in a reduction in maximum recharge rate of up to 70%. It is worth noting that the North China Plain and the High Plains aquifers cover considerably larger spatial domains compared to those found in Europe. It is not clear, at present, to what extent the strength of these recorded signals is a result of larger aquifer domains or the influence of different TC patterns in these locations, for instance the PDO or ENSO.

While the geometry and storage of an unsaturated zone can affect the amount of signal damping, this effect is not absolute. For example, Velasco et al. (2015) described the degree of damping through an unsaturated zone is also dependent on the periodicity of the boundary oscillation itself. They report that at an example depth of 10 m, between 100% (for sandy soils) and ~70% (for silty clay loam) of an NAO-like boundary flux is preserved. They conclude that rate of signal damping with depth decreases with increasing period length of a boundary condition, and that this is modulated by soil type and infiltration rate. This is corroborated with other research in this area (Bakker et al. 2009, Cao et al. 2016; Dickinson et al. 2014; Ataie-Ashtiani et al. 1999; Nimmo 2005; Currell et al. 2014; Bloomfield & Marchant 2013; Van Loon 2015; Van Loon et al. 2014).

There are still significant knowledge gaps in describing low-frequency periodic signals progress through the unsaturated zone in Europe. Principally, the quantification of NAO-like signal lags and attenuation through spatially varying soil and geological materials. Despite this, four conceptual effects of surface and unsaturated zone parameters on periodic signal propagation can be described at present:

1. The unsaturated zone dampens signals between PPT and recharge. The damping capacity of an unsaturated zone becomes greater with increased depth to the water table and/or lower hydraulic diffusivity. Increased damping results in a decreased amplitude in signals at the water table. Damping appears proportional to unsaturated zone thickness, meaning periodic recharge signals tend towards steady-state with increased damping capacity. This is comparable to the attenuation described by Van Loon (2015); resulting in a smoothing of the incoming PPT signal.

2. Shorter periodic recharge signals are more sensitive to damping. This is true of compound periodic signals, such as those found in the NAO index. In the case of the NAO, it would be expected that the secondary periodicity of 3-4 years would be dampened to a greater extent than the primary periodicity of 8-9 years. This is again comparable to Van Loon (2015); however, period-dependent damping rates appear to be a character specific to periodic signal progression.

3. The unsaturated zone acts to lag periodic signals between PPT and recharge. The lag provided by the unsaturated zone is a function of its damping capacity and is driven by the same characteristics. Measured lags range from 5 – 75 years for different periodic signals, highlighting the sensitivity and variability of lag to unsaturated zone characteristics (Kuss & Gurdak et al 2014; Holman et al. 2011). Lag is independent of signal periodicity and amplitude. Here there is a strong parallel with 'Lagging' as described by Van Loon (2015), with periodic signals showing a lagging of a perturbation within the signal.

4. The unsaturated zone does not stretch periodic signals, meaning periodicity of recharge signals is preserved (Dickinson et al. 2014). As such, 'Lengthening', as described in Van Loon (2015), is not considered to occur for periodic signals.

5.3. Spatial sensitivity of recharge signal damping

As concluded in section 5.2, unsaturated zone signal damping is dependent, in part, on unsaturated zone thickness. Here we have produced an indicative map (Figure 3) to show the expected effects of periodic NAO control on recharge to aquifers in Europe, based unsaturated zone thickness. Thicker unsaturated zones are considered to provide greater damping and lagging (and produce signals closer to steady state). Figure 3 combines the spatial distribution of NAO control on PPT and PDSI given in Figure 2, with modelled unsaturated zone thickness at 0.5 degree resolution published in Fan et al (2013). This figure does not account for textural effects of the soil and geology, which are known to modulate signal propagation (Dickinson et al. 2014; Velasco et al. 2015), as there is as yet incomplete understanding of the spatial distribution of these controls. As such this figure should be considered a generalised view of groundwater recharge sensitivity to the NAO.

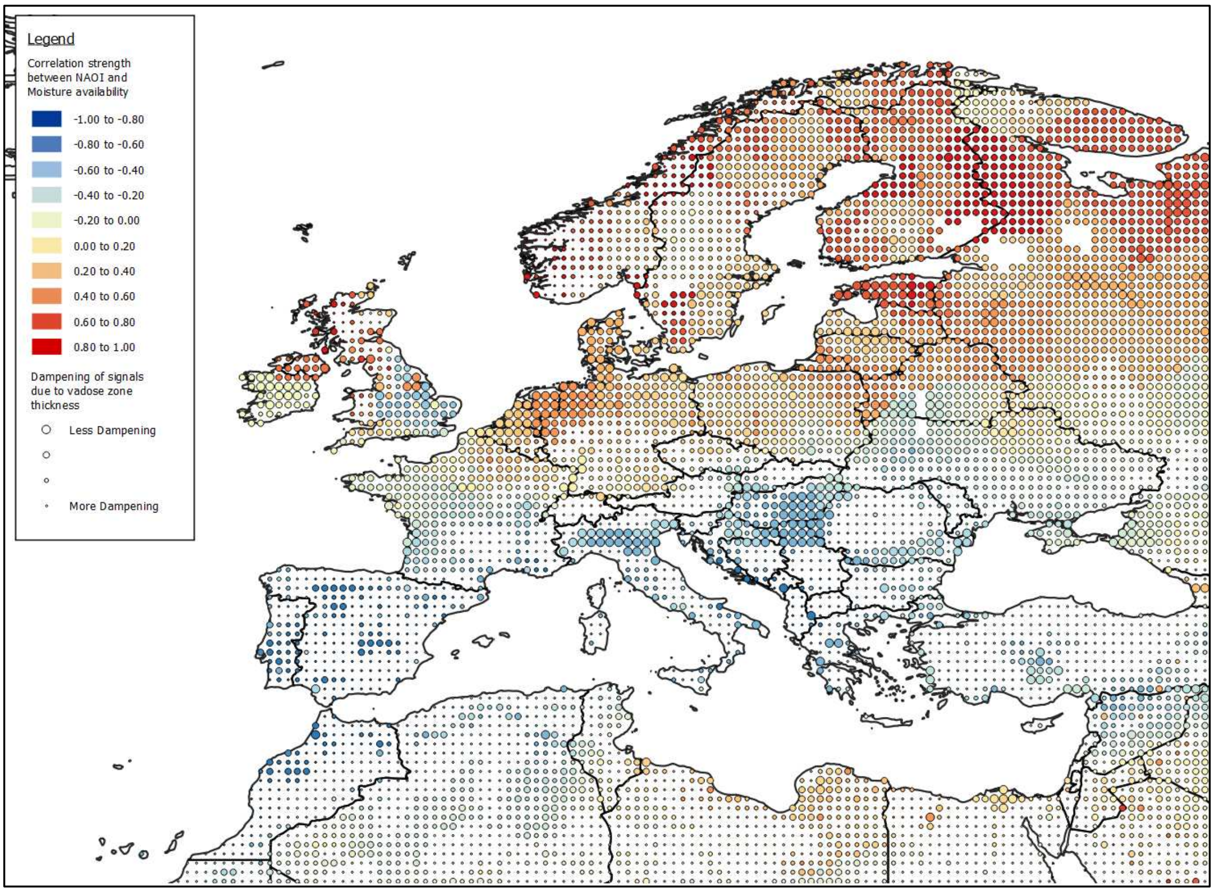

Figure 3 – Composite plan combining NAO correlation with PPT and PDSI (Figure 1) into a 0.5 degree point grid, and expected damping capacity of the unsaturated zone inferred from modelled depth-to-groundwater data produced by Fan et al (2013), where size of circles is proportional to expected damping capacity.

Mid- to high-latitude Europe generally shows reduced thickness of the unsaturated zone, resulting in greater amplitude of NAO signals arriving at the saturated zone. Local areas of minimal signal damping can be seen in the UK, Netherlands, northern Italy, Hungary, Estonia and eastern Scandinavia. Some areas with the strongest correlations, such as the western Norwegian coast and much of Spain, are expected to receive a greater damping and lagging of the NAO signal due to the relatively thick unsaturated zone. A similar divide is seen in the UK, with larger depths to water table producing damped NAO signals in Scotland. The primary chalk aquifer in England, despite showing a generally weaker correlation with the NAO, is expected to receive a greater exposure to NAO signals in recharge due to relatively shallow aquifers in the region. It can also be seen that the Chalk is potentially subject to varying teleconnection control across its domain, as a result of anomalous moisture control seen in south east England. Stronger NAO correlations are expected in the Triassic Sandstone in central England, with minimal signal damping. These findings may explain results from Holman et al. (2011) which show varying strength of covariance between borehole data from across the UK and the NAO index.

6. Saturated Zone influence on Discharge Signals

In section 5, we discussed that the distribution of unsaturated zone properties is likely to generate a spatially varied damping effect on TC signals propagation to the water table. Unlike the unsaturated zone, the saturated zone exhibits dominant flow vectors orthogonal to the surface of groundwater saturation. Therefore, it can display complex cumulative interactions with spatially distributed recharge, hydrogeological properties, and discharge boundary conditions (Simpson et al. 2013). We therefore expect that the saturated zone will display considerable local- and wide-scale spatial sensitivity when compared to the unsaturated zone. Here we discuss the current understanding of how periodic signals progress through the saturated zone. A synthesis of the principal modulations of TC-like signal propagation through the saturated zone will be given.

The saturated zone produces a damping effect on signals between recharge and discharge. The extent of damping is dependent on the characteristic aquifer length and properties such as transmissivity and storage (Bloomfield & Marchant 2013; Cuthbert et al. 2010; Cuthbert et al. 2009; Cook et al. 2003; Simpson et al. 2013; Van Loon 2015; Cuthbert et al. 2016). Specifically, aquifer response to periodic recharge is proportional to the ratio between the aquifer response time (*t*), calculated from $t = L^2S/T$ (where *L* is the length of the aquifer [L], *S* is the Storativity [-], *T* is the Transmissivity [L^2/T]), and the period of the sinusoidal boundary flux, P [T] (Townley 1995; Dickinson 2004). *t* can range, for an aquifer length of 1km, from 0.3 days for highly permeable geological materials such as sandstone to >100 days for poorly permeable chalk (Bricker 2016; Townley 1995). Where t:P >> 1, an aquifer response is too slow to reach equilibrium with the periodic forcing meaning any periodic recharge signals are significantly damped and attenuated at the point of groundwater discharge. Where t:P <<1, an aquifer responds quickly to a boundary flux and is therefore close to equilibrium at any instance in time (Townley 1995). Where t:P ≈ 1, the response of an aquifer is comparable to the periodicity of the boundary flux and therefore may produce more complex phase-shifted, or out-of-phase, responses (Currell et al. 2014).

The damping response of an aquifer, as represented by the ratio t:P, is not necessarily constant across its catchment. For example Townley (1995) showed that for aquifers with *t:P ≈>1* or *t:P >1* the amplitude of a periodic signal is increased close to the downstream boundary. This is considered to be due to the inability of the aquifer to carry larger lateral flows near the boundary. Farther away from the downstream boundary, this effect is diminished (Townley 1995).

The propagation of perturbations in recharge signals throughout an aquifer may also be controlled by aquifer properties such as transmissivity and storage (Van Loon 2013). Such progressions can provide useful information regarding the hydrogeological controls on signal damping. For example, Cook et al. (2003) shows that aquifer discharge responses can dampen to 95% and 10% of the perturbation at 1km and 30km aquifer length, respectively, within 200 years of the original recharge perturbation. They also show that the magnitude of this effect is most sensitive to aquifer transmissivity and the distance between the perturbation point and discharge area. This is in agreement with other research that indicates that response times can extend into geological timescales (Schwartz et al, 2010; Rousseau-Gueutin et al, 2013). Again, parallels can be drawn here between the damping expected in periodic signal propagation through saturated rock, and the processes of 'Attenuation' and 'Lagging' of episodic drought signals described by Van Loon (2015). The extent of 'Lengthening' and 'Pooling' of incoming signals to groundwater resources, as discussed by Van Loon (2015), are currently unknown for periodic signals.

Given the dependence of signal dampening on aquifer transmissivity and storage, it can be said that the spatial distribution of aquifer properties is critical in determining the spatial structure of teleconnection signal propagation (Yu & Lin 2015; Simpson et al. 2013). While this is understood conceptually, it is rarely known how such characteristics are distributed across an aquifer. Therefore it can be difficult to characterise how signals may spatially propagate through an aquifer (Peters et al. 2006).

Groundwater flow rates typically show a linear relationship with groundwater levels close to downstream boundaries of the aquifer. At these locations, discharge can be fixed irrespective of aquifer properties or groundwater head (Peters 2003). For groundwater catchments with slower response rates, these boundary conditions allow for an additional degree of spatial variability in responsiveness, as the groundwater system can contains both slow-responding and quick-responding components. Peters et al. (2006) discuss that such catchments are more responsive to short-term variations in recharge close to discharge boundaries. Although periodic signals are not directly discussed in this research, a comparison can be made for short-frequency and long-frequency periodic signals. It is therefore expected that areas close to points of discharge may be more sensitive to shorter-period components of climatic signals (for instance, the secondary 3-4 year component of the NAO), compared to the wider aquifer (Peters et al. 2006; Peters 2003).

Symmetry between positive and negative anomalies is informative in that it provides information on the geological modulation of teleconnection signals. Analysis of the asymmetry of the relationship is equally informative as it sheds light on the connectivity between the signal and surface stores. For instance, Eltahir and Yeh (1999) describe that during a positive ground water anomaly, water table connectivity with surface drainage (such as rivers) is increased, allowing groundwater to be drained away more efficiently. Therefore, negative anomalies tend to persist for longer than positive anomalies.

Groundwater discharge provides springflow and river baseflow. While many studies have related total river flow to signals of climatic circulations, showing detectable correlations between climatic circulations, hydrogeological properties and baseflow (Singh et al. 2015; Bloomfield et al. 2009), relevantly little research has been undertaken which directly assesses mechanistic propagations of climate signals through to spatial and temporal variability in baseflow and spring flow.

Recent research has introduced the concept of climate-induced groundwater abstraction, resulting in a human-influenced exacerbation of periodic climate signal presence within groundwater resources (Gurdak 2017). For example, Russo and Lall (2017) have shown that groundwater resources in the USA display a greater coherence with indices of climatic oscillations (such as NAO and ENSO) in areas of agricultural land use (and therefore heavier groundwater abstraction). Conceptually, these influences are expected to exacerbate the negative anomaly component between recharge and discharge. Similar results have been found by Asoka et al. (2017) between monsoon precipitation and groundwater storage in India. There is currently a paucity of information as to the impacts of climate-induced abstraction in Europe, however existing research for other areas indicates the importance of a human component within the conceptual model of climate-groundwater teleconnections.

7. Current understanding of climatic teleconnection signal control on groundwater variability

Presently there exists no comprehensive, unified understanding of how teleconnection signals propagate through to spatiotemporal variability in groundwater levels and flows. Through a review of hydroclimatological and hydrogeological literature, we present a conceptual model of teleconnection signal propagation through to groundwater variability based. This conceptual model is given as an overview, with the NAO as an example, in Figure 4.

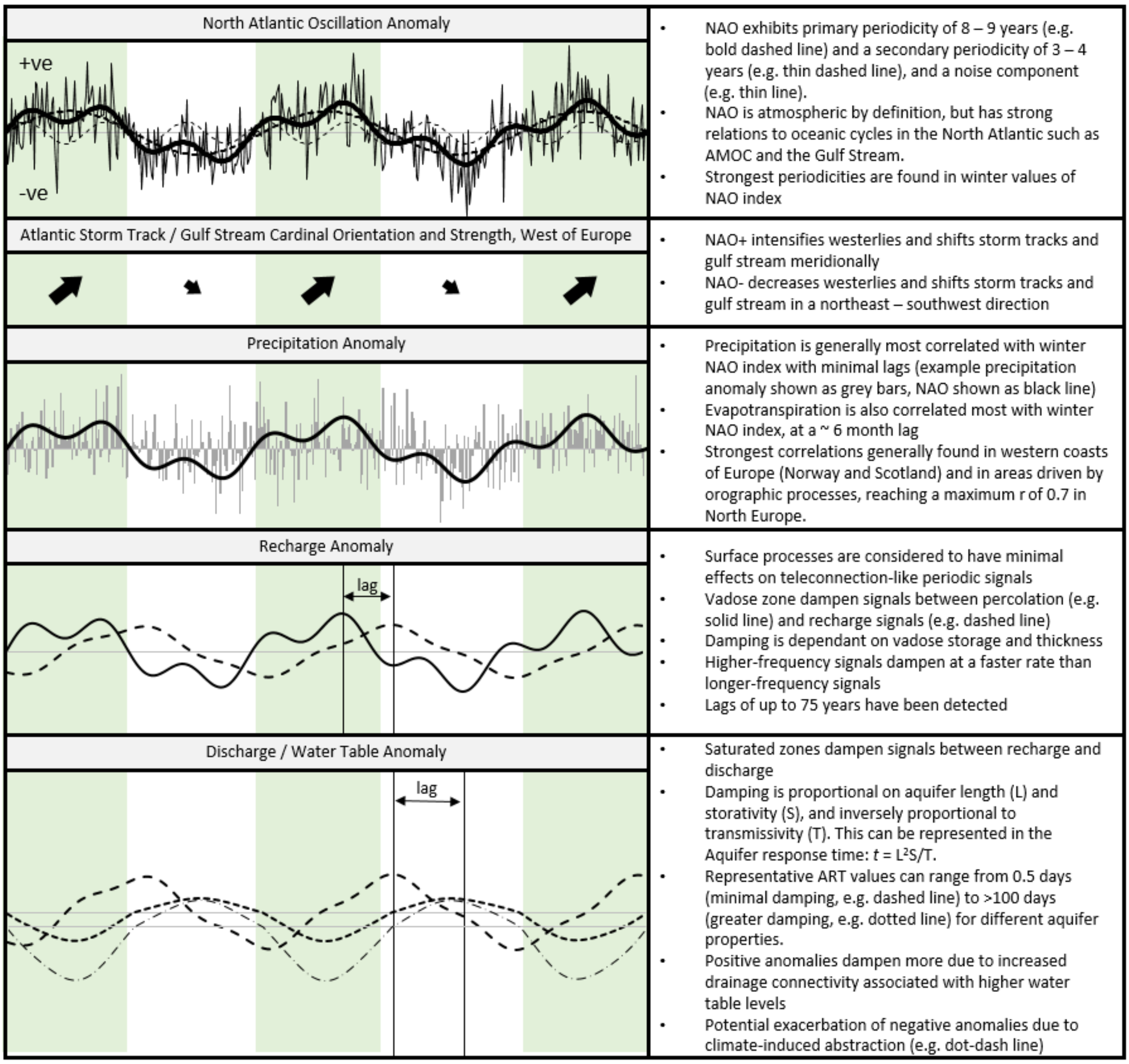

Figure 4 – Conceptual model of signal propagation from Teleconnection through to groundwater discharge, using the NAO in the UK as an example

The mechanics of signal propagation of teleconnection signals through to atmospheric and oceanic variability is relatively well understood. However, the terrestrial water cycle is shown to exhibit complex non-linear spatial relationships as a result of distributed hydraulic properties of the unsaturated and saturated zone. While a few principal characteristics of periodic flow progression have been reviewed in this paper, there are still many knowledge gaps. Specifically regarding how teleconnection processes, such as the NAO, manifest in spatiotemporal groundwater variability. As a result of the developed conceptual model, we have identified the following research gaps:

1. *Hydrogeology and periodic signals.* There is currently limited research that quantifies the propagation of teleconnection signals through an entire aquifer system. For instance, from PPT and ET to groundwater discharge. In order for information on teleconnection dependency to be of practical use for water resource managers, further quantification of damping and lagging effects for a range of aquifers is required.

2. *Distributed signal sensitivity.* Existing studies that have looked at groundwater sensitivity to a teleconnection control are generally based on limited point measurements. Therefore, at present, limited comment can be made on the spatial distribution of this sensitivity and how this influences flow across an aquifer catchment.

3. *Importance of multiple or confounding signals.* Much hydroclimatology research in the North Atlantic focuses on the NAO, which does not account for the influence of other teleconnection signals. In addition, the method of teleconnection indexing is critical to how well the true variability of a system is represented. This is shown in the NAO, in which the typical index does not account for atmospheric blocking which can lead to significant alteration of moisture variability across Europe. This may represent an important modulation of teleconnection control on groundwater variability. In addition, the anthropomorphic influence of climate-induced abstraction may also lead to important signals modulations. Despite this, the quantification of these mechanisms in Europe is limited in the existing literature.

Teleconnection control on periodic groundwater variability offers an indicator for near-future resource availability. This is therefore a useful tool for water companies and water managers to address the lack of longer-term forecasting of droughts (Water UK 2016). This paper has shown, there is a developing conceptual understanding of the atmospheric, hydrological and hydrogeological controls on such periodic variability. However, there is insufficient knowledge at present to enable the use of teleconnection systems as predictors of spatiotemporal groundwater variability.

So that our understanding of such controls linkages can produce useful tools for improved water resource management, current research needs to move beyond detection of teleconnection signal presence, towards the development of indicative or predictive capabilities across a range of groundwater catchments.

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