Quaternary Research 75 (2011) 399–405

Contents lists available at ScienceDirect

Quaternary Research

journal homepage: www.elsevier.com/locate/yqres

Short Paper

A 500 yr speleothem-derived reconstruction of late autumn–winter precipitation, northeast Turkey

Catherine N. Jex [a,*], Andy Baker [a], Jonathan M. Eden [b], Warren J. Eastwood [b], Ian J. Fairchild [b], Melanie J. Leng [c], Louise Thomas [d], Hilary J. Sloane [c]

[a] *Connected Waters Initiative, affiliated to National Centre for Ground Water Research and Training, School of Civil and Environmental Engineering, University of New South Wales, 110 King St, Manly Vale, NSW 2093, Australia*
[b] *School of Geography, Earth and Environmental Sciences, The University of Birmingham, Birmingham B15 2TT, UK*
[c] *NERC Isotope Geosciences Laboratory, British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK*
[d] *Faculty of Science, Open University, Walton Hall, Milton Keynes, MK7 6AA, UK*

ARTICLE INFO

Article history:
Received 9 March 2010
Available online 11 March 2011

Keywords:
Speleothem
Oxygen isotopes
Turkey
Precipitation reconstruction
Caspian Sea
Black Sea

ABSTRACT

A verified instrumental calibration of annually resolved δ^{18}O for a stalagmite from Gümüşhane in northeast Turkey is presented and cross-validated using a 'leave-one-out' technique. The amount of late autumn to winter precipitation is negatively correlated with stalagmite δ^{18}O between AD 1938 and 2004. The observed relationship is extrapolated back to ~AD 1500 leading to the first long winter precipitation reconstruction for this region. Modern day October to January precipitation is linked to pressure fields in Western Russia. Anomalously lower reconstructed rainfall is recorded in AD 1540–1560 at which time higher pressure over the Caspian Sea region is inferred.

Introduction

During the late 20th century, large areas of the sub-tropics have experienced reductions in rainfall and increased temperatures to the extent that they are becoming increasingly vulnerable to water shortages (Christensen et al., 2007). The near-east region and Turkey in particular has been affected in this way (Sönmez et al., 2005; Camci Çetin et al., 2007). Temporal changes in precipitation during the last millennium in the Eastern Mediterranean region are of huge importance for water resource management where shortages in spring and summer precipitation may have direct impacts on crop yields, and shortages in autumn, winter and spring precipitation can lead to reductions in recharge to groundwater and in the availability of surface waters for all purposes (agricultural and domestic).

Globally, this time period is also considered as key in testing hypotheses that have in recent years become the focus of research of international importance. For instance, it is crucial to know whether observed trends towards increased aridity observed in large areas of the sub-tropics in the late 20th century are unusual for the last millennium. Also, to what extent can key events such as the "Little Ice Age" be classed as being truly global? Are they (and how are they) reported in proxy archives? Further, what can proxy archives tell us about the mechanisms and forcing behind decadal-scale climate variability in the pre-instrumental period?

To this end, this paper presents a 500 yr long reconstruction of late autumn–winter precipitation from a stalagmite in north east Turkey, following on from Jex et al. (2009) in which the climate controls on speleothem δ^{18}O in this region were investigated. The paper is organised as follows: first, we present a short review of the modern climatology, paleoclimate records of the Near and Middle East region and a summary of the previous investigations upon which this paper builds including the stalagmite under investigation; and second, we present the stalagmite δ^{18}O record of this study, followed by new climate analyses to investigate links to larger-scale atmospheric circulation.

Climatology of the Eastern Mediterranean region

Circulation over Europe is dominated by westerlies, which link the Mediterranean and Near and Middle East climates to the North Atlantic (Türkeş, 1996). These are modulated by the seasonal presence of the polar front jet stream (PFJ) and Siberian High in winter, promoting cyclogenesis in the Mediterranean and rainout as depressions propagate inland and over the Taurus and then Black Sea Mountains (Türkeş, 1996; Karaca et al., 2000). In summer the northward migration of the PFJ and the weakening of the Siberian High reduce Mediterranean cyclogenesis and allow weak circulation

---

* Corresponding author. Fax: +61 2 9949 4188.
E-mail addresses: cathnjex@gmail.com (C.N. Jex), a.baker@unsw.edu.au (A. Baker), jme184@adf.bham.ac.uk (J.M. Eden), w.j.eastwood@bham.ac.uk (W.J. Eastwood), fairchij@adf.bham.ac.uk (I.J. Fairchild), mjl@bgs.ac.uk (M.J. Leng), L.E.Thomas@open.ac.uk (L. Thomas), hjs@bgs.ac.uk (H.J. Sloane).

0033-5894/$ – see front matter © 2011 University of Washington. Published by Elsevier Inc. All rights reserved.
doi:10.1016/j.yqres.2011.01.005

from the south (promoted by the northward migration of the East Asian low). Sea-breezes from the north off the Black Sea coast also produce rainfall in the northeast region, modulated by the presence of the Black Sea Mountains that hug the coastal region (Türkeş, 1996; Karaca et al., 2000). Akçakale cave is located on the landward side of the Black Sea Mountains in northeast Turkey. Here spatial precipitation patterns in winter are predominantly influenced by high pressures in Eastern Europe and Siberia resulting in northeasterly circulation and northerly mid-latitude cyclones (Türkeş et al., 2009).

Decadal to inter-decadal variation in precipitation and temperature regimes in Turkey have been associated with large-scale atmospheric circulation indices (Jones et al., 2006). The dominant mode of variation for European climate is the North Atlantic Oscillation (NAO), defined as the pressure difference between the Icelandic low and Azores high. Negative (positive) NAO results in predominantly meridional (zonal) flow of storm tracks causing wetter (drier) winters in western and central Turkey (Türkeş and Erlat, 2005). The North Sea–Caspian pattern (NCP), and the East Atlantic–West Russia pattern (EA–WR) have pressure centres in essentially the same geographic areas, and are defined by the pressure difference between these locations at 500 mb (NCP) and at 850 mb and 700 mb (EAWR). Both have been reported to have significant impacts on Turkish winter rainfall (Kutiel and Benaroch, 2002). Negative (positive) NCP and EA–WR pattern indices are associated with increased south-westerly (north-easterly) circulation towards the Balkans and the Near and Middle East, resulting in warmer and drier (cooler and wetter) than normal winters in these regions (Kutiel and Benaroch, 2002; Kutiel et al., 2002). Despite these general associations, there remains much debate as to the actual extent to which these patterns affect precipitation regimes in Turkey, predominantly due to the variable nature of precipitation regimes throughout the country and the short length of instrumental time series available (typically from 1920s AD to present).

Paleoclimate records from the Eastern Mediterranean region

Proxy records capable of retaining a (modified) climate signal (e.g. historical records, tree rings, ice cores, speleothems, lake, peat and marine cores) can be used to reconstruct climatic conditions beyond the length of instrumental records (Jones and Mann, 2004; Jansen et al., 2007). There is, in general though, a lack of such proxy data in regions predicted to be worst affected by future moisture reductions, and these include the Near and Middle East (IPCC, 2007). Figure 1A shows the location of proxy record archives specifically in Turkey.

As a result, this region has poor representation in northern hemisphere reconstructions of paleoprecipitation. Regional reconstructions of precipitation have limited coverage in Turkey (Pauling et al., 2006), while in the 500-yr regional reconstruction of winter precipitation and temperature in the Mediterranean area of Turkey is represented by a single tree-ring record which actually responds to changes in temperature and/or precipitation during spring and summer growth season (Luterbacher and Xoplaki, 2003). A small number of high-resolution (sub-decadal) proxy records in Turkey have been published (Fig. 1A). A lake core δ^{18}O record (sampled at 1 to 5 yr resolution) appears to respond predominantly to spring/summer precipitation and evaporation variability, and demonstrated the persistent relationship between Turkish summer aridity and intensification of the East Asian monsoon (Jones et al., 2006). The large isotopic shifts associated with dry vs. wetter intervals during the last 1700 yr further suggest a spring teleconnection to the NCP (North Sea–Caspian Pattern) (Jones et al., 2006). Tree-ring archives are interpreted as preserving a record of spring/summer temperature and/or precipitation (Touchan et al., 2003; 2005; Akkemik and Aras, 2005). Most recently, a regional tree-ring chronology from NE Greece stretching to NW Turkey has reconstructed May–June precipitation back to 1090 AD (Griggs et al., 2007). However there are no published reconstructions using autumn–winter climate-responsive proxies. This is important for two reasons. First, this represents a large portion of the year in which the majority of recharge to groundwater supplies in semi-arid northern hemisphere regions occurs. Second, seasonal precipitation trends and their association to large-scale circulation modes over the last millennium are not yet satisfactorily described for the Near and Middle East region as a whole. In this context, the stable isotope (δ^{18}O) response of a stalagmite (2p) from Akçakale Cave in northeast Turkey (Fig. 1A) has previously been investigated (Jex et al., 2009). An annually resolved stalagmite record of oxygen isotopes ($\delta^{18}O_{spel}$) obtained from stalagmite 2p was correlated with climate parameters from the local meteorological station between 1961 and 2004 AD. The strongest correlations (obtained by linear regression) were observed between the amounts of late autumn–winter (ONDJ) precipitation (smoothed by a 6 yr running mean, to allow for mixing of waters in the karst aquifer) and $\delta^{18}O_{spel}$ and returned an r correlation coefficient of −0.72 (95% significance level). This confirmed the hypothesis that an increase in isotopically lighter precipitation during these months was represented by lighter $\delta^{18}O_{spel}$. Precipitation was calibrated over the instrumental period and observed values fell within ±35 mm (2 SE on the regression) of these predicted values. In the absence of a longer instrumental series pre-1961 AD, a qualitative verification of these relationships was made by comparison with the reconstructed gridded winter precipitation for this region (Pauling et al., 2006). A period of monitoring of the modern cave environment confirmed drip waters, surface waters and ground waters to have isotopic compositions within the range of those observed for snow and a combination of rain and snow ($\delta^{18}O = -12.7$ to -15.3‰ VSMOW) during these months (IAEA/WMO, 2006) and thus, further confirmed the likelihood of karst aquifer recharge during these months.

Here we build on this previous research and present the following new data and analyses:

(1) New analyses of modern climate data to better understand links to larger scale atmospheric circulations.
(2) An extended isotope ($\delta^{18}O_{spel}$) time-series for stalagmite 2p and an extended instrumental precipitation series (AD 1932 to 2004).
(3) A new and validated calibration of late autumn–winter precipitation for northeast Turkey using these data, and subsequently a long reconstruction of rainfall variability since ~AD 1500.

To date, this is the first autumn–winter precipitation reconstruction for Turkey.

Data and methods

Speleothem 2p: chronology and isotope sampling

Speleothem 2p was dripping (measured between 3 and 70 s per drip in July 2005) and actively depositing calcite when removed from Akçakale Cave (Elevation: 1530 m; Lat and long: N: 40°26′59.1″ E: 039°32′11.5″) in the Gümüşhane province of NE Turkey in July AD 2005. The regional setting of Akçakale cave, the modern cave microclimate and hydrochemistry is described in Jex et al. (2009). Images of a transect following the central growth axis of the polished stalagmite were taken using a low power Zeiss stemi SV 11 microscope (at 0.6–6.6× magnification), a Schott 1500 LCD light source (15 V/150 W) and a "Q-imaging" MicroPublisher 5.0 RTV camera. The laminae were counted from these images and their thickness from the base of one DCC (dark compact calcite) lamina to the top of a WPC (white porous calcite) lamina was measured as one lamina (following (Genty et al., 1997)) using Image Pro Plus, version 6 software. Where possible, multiple growth rates were measured across a lamina and averaged to give a mean thickness.

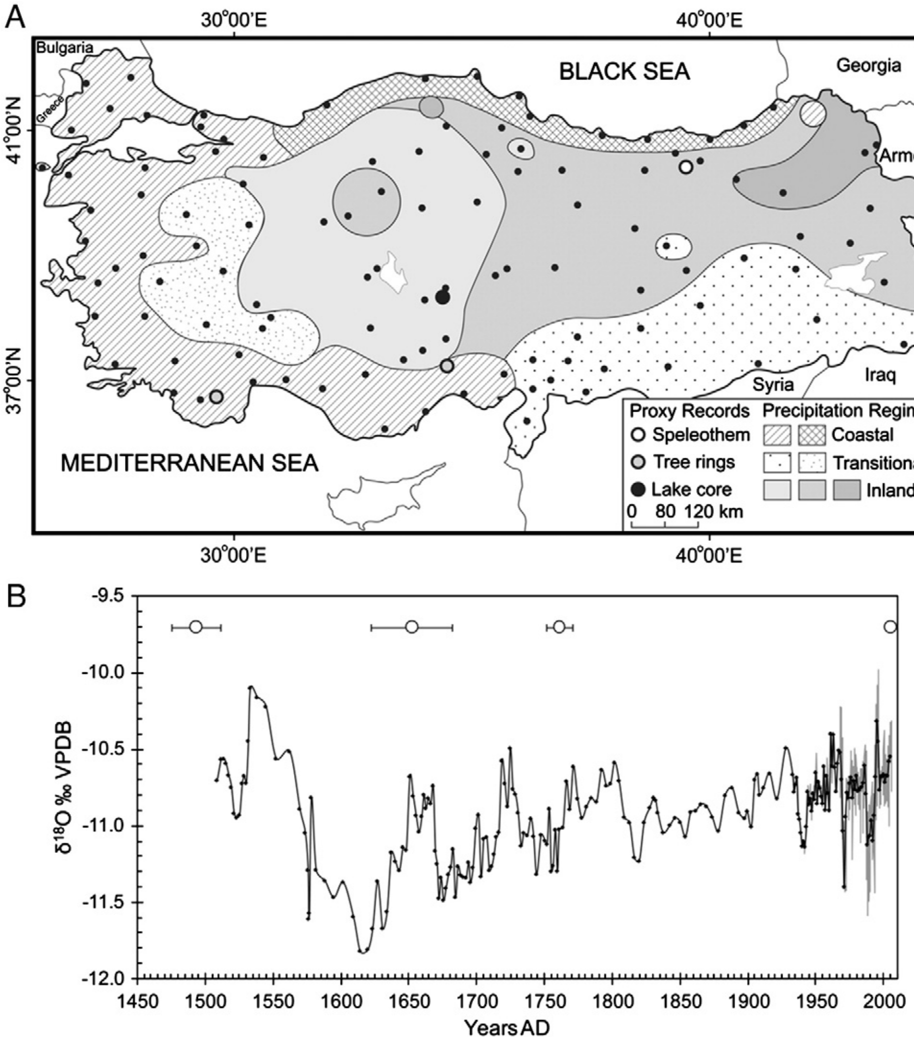


Figure 1. A: Precipitation regimes of Turkey (from Sariş et al. (2010)) overlain by the location of this study site Akçakale cave (labelled as speleothem); and of published tree-ring records and a lake-core record. Locations of meteorological stations are shown by small black dots. Akçakale cave and Lake Nar are located within an area characterised as variants of an "inland" precipitation regime, which is characterised by a peak in precipitation in spring (Saris et al., 2010), whilst hydrologically effective precipitation responsible for recharge of ground-water supplies takes place between late autumn to spring, when evaporation ratios are negligible and precipitation is accumulated in a snow pack (Jex et al., 2009). Each proxy record is therefore capable of capturing a different part of the seasonal cycle in their records. Tree ring sites are located within coastal regimes, and therefore may be expected to offer further commentary paleoclimate information specific to that precipitation regime area. B: The $\delta^{18}O_{spel}$ (‰ VPDB) record for stalagmite 2p along with dating tie points. The three U-series dates are presented in Table 1. The uppermost tie point is provided by confirmation of active calcite deposition at the time of collection based on drip-water chemistry (Jex et al., 2009) and collection of calcite on a tile left in place of the removed speleothem. The grey line shows the sub-annual isotope sampling over the instrumental period, an annual average of which was used in the calibration.

Lamina counts were confirmed as annual by U-series dating. Calcite powder (c. 0.5 g) was drilled from a fresh clean surface (treated with 2% HCl, then rinsed with de-ionised water) using a hand-held dentist's mini drill (COMO Drills, microturbo 1) with 0.5 mm diameter diamond tipped drill bits. Samples underwent wet column chemistry to separate Th and U fractions prior to loading onto graphite coated Re filaments, and measured using a Finnigan MAT262-II Thermal Ionization Mass Spectrometer. The chronology for stalagmite 2p is provided in the supplementary material (Fig. S1). Stalagmite 2p is comprised of light brown/milky porous calcite throughout, with regions of compact dark brown calcite and discontinuous laminae (WPC/DCC laminae as described by (Genty et al., 1997)) with no observable hiatuses. Notably there are 107 visible laminae from the top of 2p (mean thickness 0.52 ± 0.35 mm) and a further 150 visible laminae from the base of 2p (mean thickness 0.22 ± 0.17 mm). The latter visible laminae overlap the basal U—Th date at ~190 mm depth and are fixed to this U—Th date. Where lamina are not countable, linear interpolation between all tie points predicts growth rates of between ~0.4 mm yr^{-1} and ~0.5 mm yr^{-1} and are within the range of predicted growth rates (0.69 ± 0.35 mm) (as reported previously by Jex et al., 2009) while the measured growth rates reported above, all confirm the annual nature of these laminae. The expected error on the lamina counts (due to laterally discontinuous lamina) is not strictly quantified, but have been suggested to be around +/−2–3% (Tan et al., 2006). Such an uncertainty would have minimal effect on any observed correlations due to the smoothing of the rainfall data which exceeds this level of uncertainty in the lamina counts. Concentrations of 0.54 to 0.58 ppm ^{238}U are observed in 2p (Table 1). Low ^{232}Th contents (<7.4 ppb) suggest non-negligible detrital Th content and as such a detrital correction ratio ($^{232}Th/^{238}U$) of 3.12 (i.e. bulk earth) was applied. This results in the corrected dates given in Table 1 (and shown in Fig. S1).

The $\delta^{18}O_{spel}$ record for stalagmite 2p is illustrated in Figure 1B along with dating tie points. The U—Th error bars indicate the extent to which the time series may shift according to the detrital Th correction described above. Sampling for stable isotopes was carried

Table 1
U-Th dates for stalagmite 2p (1 sigma uncertainties associated with each measurement/ratio and the 2 sigma error associated with each age is shown in brackets). The corrected ages shown here are those associated with a detrital correction ratio (^{232}Th/^{238}U) of 3.12.

Laboratory code	Depth (mm)	^{238}U ppm	[^{234}U/^{238}U]	^{234}U ppm	^{230}Th ppb	^{232}Th ppb	[^{230}Th/^{234}U]$_{uncorr}$	[^{234}U/^{238}U]$_{uncorr}$	[^{230}Th/^{232}Th]	AGE$_{uncorr}$ Yrs BP	[^{230}Th/^{234}U]$_{corr}$	[^{234}U/^{238}U]$_{corr}$	AGE$_{corr}$ (yrs before AD 2005)
CJEX 2p	204.21	0.5394	2.6567	7.73E-05	0.000135	4.697	0.0058	2.657	7.091	631	0.00469	2.66148	512
(uncertainty)	(2.47)	(0.0010)	(0.0092)	(2.47E-07)	(0.000002)	(0.849)	(0.000071)	(0.0092)	(0.31873)	(16)	(0.00008)	(0.01304)	18
CJEX 2pB Mid	152.82	0.52	2.63	7.41E-05	(0.000113)	7.404	0.0050	2.63	3.239	550	0.00326	2.64208	353
(uncertainty)	(2.60)	(0.0007)	(0.0073)	(1.97E-07)	(0.000003)	(1.339)	(0.000147)	(0.0076)	(0.20059)	(32)	(0.00014)	(0.01032)	(30)
2pm	106.33	0.5758	2.6224	8.15E-05	0.000061	0.906	0.0024	2.622	23.492	268	0.00225	2.62321	244
(uncertainty)	(2.43)	(0.0009)	(0.0080)	(2.31E-07)	(0.000001)	(0.164)	(0.000034)	(0.0080)	(1.097)	(8)	(0.00004)	(0.01129)	10

out using both a micro-mill (drilling resolution set to 0.1 mm and 0.4 mm over the instrumental time period (AD 1932 to 2004)) for high resolution climate calibration and a hand-held mini drill (as described above) for the remainder of stalagmite 2p to obtain typically a 2–6 yr temporal resolution. Both methods followed the trench sampling method along individual lamina according to the protocols of Fairchild et al. (2006). Milled calcite powder samples were weighed (c. 50–100 µg) and analysed for carbon and oxygen isotopes (δ^{13}C and δ^{18}O) using an automated common acid bath VG Optima + ISOCARB mass spectrometer. Results are reported to VPDB and precision is better than ±0.1‰.

For comparison to the measured $\delta^{18}O_{spel}$ record we also obtained monthly records of mean temperature and precipitation totals at Gümüşhane meteorological station (WMO station code: 17088) were obtained from the Turkish State Meteorological Service. The records are largely continuous back to AD 1932, and previously tested for quality control and homogeneity (Göktürk et al., 2008).

Instrumental calibration

Previously the $\delta^{18}O_{spel}$ value of this stalagmite was shown to best represent a modified signal from precipitation at the surface between the months of October to January for the period AD 1964 to 2004 (Jex et al., 2009). It was demonstrated that this $\delta^{18}O_{spel}$ value captured precipitation information for the previous six years due to the natural storage times and mixing of event (<1 yr old water) and stored water (>1 yr old water) in the karst aquifer. In the previous study a simple six-year running mean provided the correlation coefficients from which a calibration of speleothem proxy vs. precipitation was presented. An alternative mixing model which weighted event water comparatively more than the contribution of each previous individual year did not significantly improve the *r* values, suggesting a simple reservoir with an overflow as a likely method of water delivery to stalagmite 2p.

Here, a 6-yr running mean was also applied to the precipitation data (AD 1938 to 2004) and used to fit a linear regression model to predict precipitation (mm) from (detrended) $\delta^{18}O_{spel}$ ($R^2 = 0.2719$ at the 90% significance level) during this period (Figs. 2A and B). Previously, the calibrated record was only qualitatively validated as described earlier. Despite the new data that extends both the proxy and instrumental rainfall series, the use of separate time slices for calibration and validation periods was avoided due to the low degrees of freedom associated with 1) an inherently auto-correlated proxy series (ACF = 0.5952, with a lag of 1 time step). This reflects the natural mixing of waters in the karst aquifer as described earlier, and results in an adjusted number of degrees of freedom (*d.f.* = 17) associated with $\delta^{18}O_{spel}$ record; 2) a smoothed precipitation series (*d.f.* = 11).

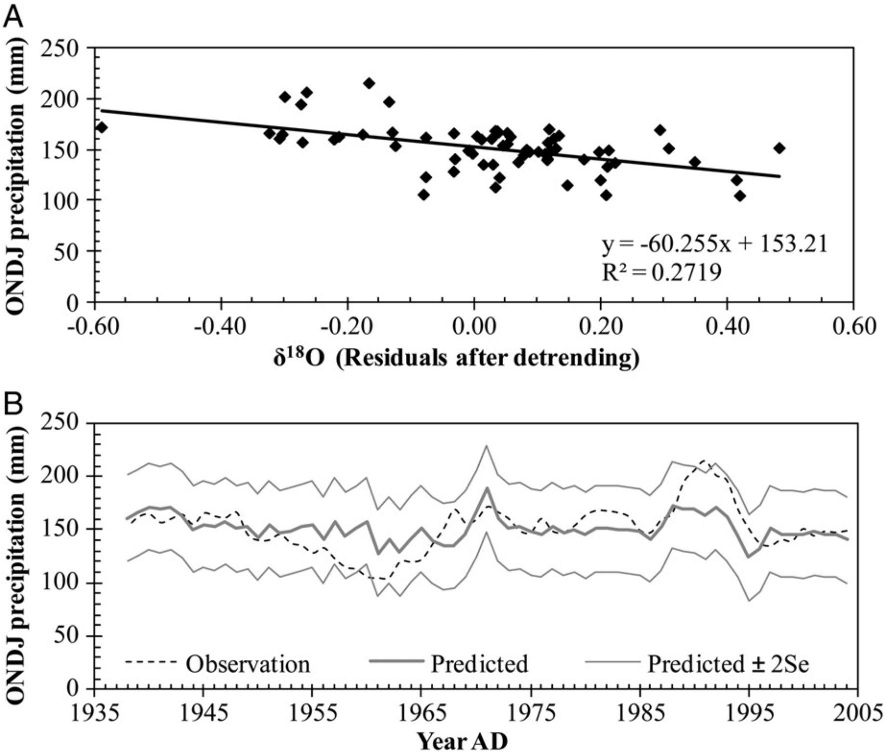


Figure 2. (A) Regression of $\delta^{18}O_{spel}$ ($R^2 = 0.27$) and six-year smoothed late autumn–winter precipitation. (B) Observed and regression-based estimate for six-year smoothed autumn–winter precipitation (AD 1938–2004). Dotted lines illustrate an uncertainty of ±40 mm (2 SE of the regression).

The regression model presented here was cross-validated using a leave-one-out technique. This was considered a more robust measure of a model's explanatory power than using separate time slices as fitting and validation periods. For a leave-one-out approach, a separate regression model is derived for each of *n* years in which the precipitation observation and corresponding $\delta^{18}O_{spel}$ value for a given year *t* are omitted (Wilks 2006). In this case, the six years preceding year *t* are also omitted so as to remove all precipitation information that is used to derive the smoothed precipitation value for year *t*. The result is *n* independently derived predictions of precipitation that form a validation series which can be compared with the observed precipitation series. A moderately strong correlation was found between the predicted and observed series ($r = 0.3814$ at the 99% significance level) and the root mean-squared error was of an acceptable magnitude ($RMSE = 20.92$ mm). The ratio of standard deviation (predicted/observed) was 0.51, indicating that the amplitude of variance is under-estimated in the predicted series by a factor of less than 2. It was concluded that the performance of a regression technique is sufficiently strong to merit further application. The regression model was applied to the remaining $\delta^{18}O_{spel}$ data to produce a reconstruction of the amount of late autumn to winter precipitation (mm yr^{-1}) from ~AD 1500 to 2004.

Results and discussion

Calibrated $\delta^{18}O_{spel}$ time series and reconstructed precipitation

The calibrated $\delta^{18}O_{spel}$ time series is presented in Figure 2B and the reconstructed rainfall record is presented in Figure 3. The driest winters of the last 500 yr are in the earliest part of the record until ~AD 1570, after which until AD 2004, winters are generally wetter than at any time since. No other records of winter time proxies are available in the Eastern Mediterranean region, but it may be noted that spring to summer responsive Anatolian tree rings record this period, up until ~AD 1570, as the most humid summers in Turkey during the last millennium (Touchan et al., 2007). Conversely, the central Turkey $\delta^{18}O$ lake record (reflecting effective precipitation throughout warm season) for the last 1700 yr describes the entire period between AD 1400 and 1960 as predominantly dry (Jones et al., 2006). This autumn–winter speleothem reconstruction from northeast Turkey shows that winters were only exceptionally dry during the mid C16th. During this portion of the reconstruction U—Th and lamina counting dating uncertainties constrain the timing of this event to within +/−30 yr.

Present day links to large-scale atmospheric circulation

As an indication of the influence of large-scale northern hemisphere circulation patterns on late autumn–winter precipitation at Gümüşhane, maps illustrating the spatial correlation coefficients (*r* values) between the instrumental ONDJ Gümüşhane precipitation series (AD 1932 to present) vs. (monthly) precipitation and pressure fields over Europe and East Asia (observation, reanalysis and historical reconstruction data, available from Climate Explorer at http://www.knmi.nl, as in Van Oldenborgh et al. (2005)) have been obtained and are presented in Figures 4 and S2 in the supplementary information. These demonstrate significant ($p < 1\%$) correlations between these data for European precipitation and pressure fields vs. Gümüşhane precipitation during the months ONDJ (Fig. 4) and are summarised below:

1) Between the months of ONDJ a dipole relationship is observed between precipitation at Gümüşhane and precipitation over NW and Central Europe (Figs. 4A and S2). Mostly positive correlations are observed in spring to autumn (not shown) and limited to the local area (Turkey, southwest Georgia and northwest Iran).
2) During ONDJ, correlations between Gümüşhane precipitation and pressure fields at all heights are observed, specifically these include 850 mb and 700 mb, heights at which the EAWR pattern is active; and 500 mb, the height at which the NCP is active (Figs. 4B, C and D). Negative correlations are observed with pressure fields located in the western Russia/Caspian Sea region and the Azores at all heights in October, November and January. December precipitation also shows persistent negative correlations only to the West Russia/Caspian Sea region at all heights. Positive correlations are observed with pressure fields located in NW and Central Europe at all heights in October, November and January (Fig. S2).

Increased ONDJ precipitation at Gümüşhane is thus suggested to be linked to reduced pressure over West Russia/Caspian Sea and increased pressure over NW Europe during late autumn to winter. This describes a +NCP and +EAWR suggesting that northerly circulation leads to an increase in the isotopically light precipitation observed in NE Turkey. During the remainder of the year, and particularly in the summer, it is likely that local convective processes (soil moisture–precipitation feedbacks and/or changes in land–sea thermal gradients (Boé et al., 2009) and the strength of the East Asian Monsoon (Jones et al., 2006) dominate precipitation patterns. No modern-day spatial NAO patterns are clearly identified here (Fig. 4) and additional temporal correlations between this reconstruction and the NAO reconstructions (not shown) found no clear relationships (Luterbacher et al., 1999; Trouet et al., 2009).

Comparison of speleothem data with existing records

Jones et al. (2006) also found no measurable NAO influence on Anatolian precipitation–evaporation dynamics during this time, instead suggesting a +NCP the (EAWR pattern was not considered) during spring was responsible for bringing northerly circulation and cold (and dry) air to western–central Turkey. At this point these two records diverge somewhat in their interpretations. Both of these

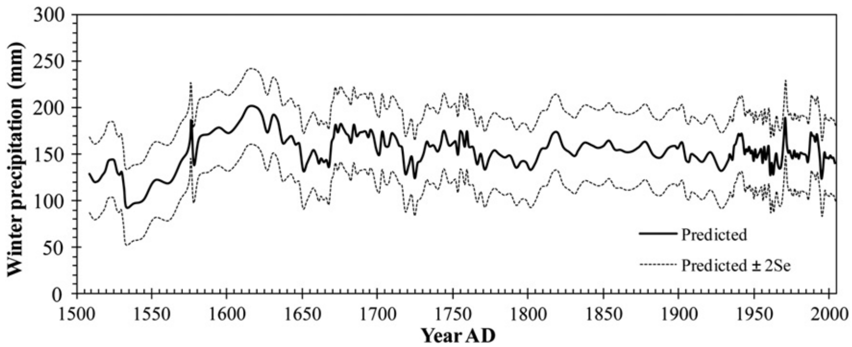
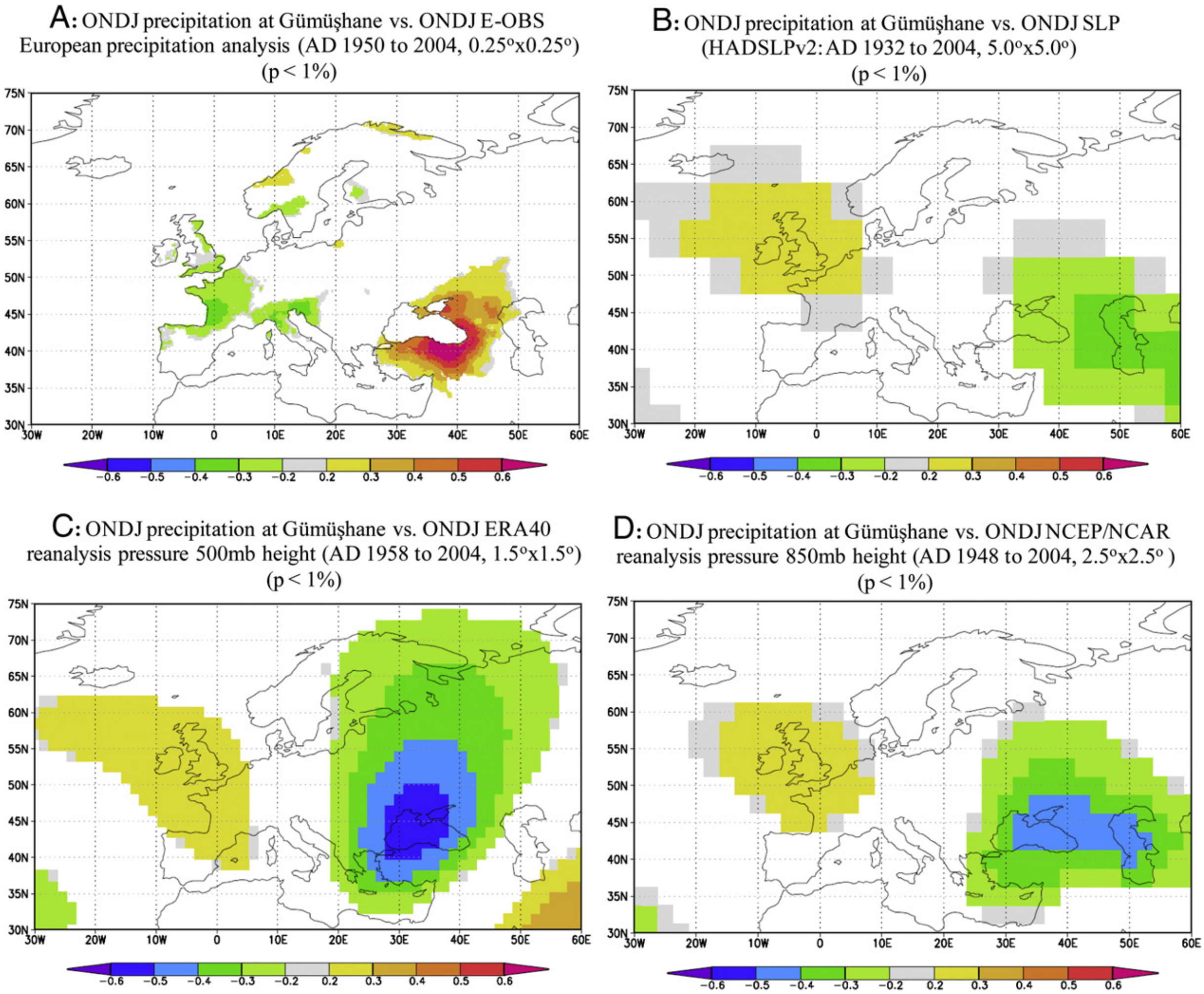


Figure 3. Regression-based reconstruction of late autumn–winter precipitation (AD 1509–1937) and model calibration period (AD 1938–2004). Dotted lines illustrate an uncertainty of ±40 mm (2 SE of the regression).


A: ONDJ precipitation at Gümüşhane vs. ONDJ E-OBS European precipitation analysis (AD 1950 to 2004, 0.25°x0.25°) (p < 1%)

B: ONDJ precipitation at Gümüşhane vs. ONDJ SLP (HADSLPv2: AD 1932 to 2004, 5.0°x5.0°) (p < 1%)

C: ONDJ precipitation at Gümüşhane vs. ONDJ ERA40 reanalysis pressure 500mb height (AD 1958 to 2004, 1.5°x1.5°) (p < 1%)

D: ONDJ precipitation at Gümüşhane vs. ONDJ NCEP/NCAR reanalysis pressure 850mb height (AD 1948 to 2004, 2.5°x2.5°) (p < 1%)

Figure 4. Correlation maps (p < 1%) of late autumn–winter precipitation at Gümüşhane vs. late autumn–winter observed and re-analysis precipitation and pressure fields throughout the European and East Asian sectors. Data were obtained from, and the maps drawn in KNMI Climate Explorer (http://climexp.knmi.nl Accessed January 2010 (van Oldenborgh et al., 2005)). (A) Late autumn–winter precipitation at Gümüşhane vs. European precipitation field (land only) (E-OBS European precipitation analysis 0.25° × 0.25°, AD 1950 to 2004) (Haylock et al., 2008). (B) Late autumn–winter precipitation at Gümüşhane vs. sea-level pressure field (HADSLPv2AD 5.0° × 5.0°, AD 1932 to 2004) (Allan and Ansell, 2006). (C) Late autumn–winter precipitation at Gümüşhane vs. pressure at 500 mb height (ERA40 reanalysis 1.5° × 1.5°, AD 1958 to 2004) (Uppala et al., 2005). The NCP is active at this height. (D) Late autumn–winter precipitation at Gümüşhane vs. pressure at 850 mb height (NCEP/NCAR reanalysis 2.5° × 2.5°, AD 1948 to 2004). The EA-WR pattern is active at this height.

proxy records are located within an "inland" precipitation regime according to Saris et al. (2010) as shown in Figure 1A. Consequently, it is likely that the divergence of interpretations from these records over recent centuries is due to the seasonal response of their respective proxies and the observed large inter-annual variability in the NCPI with seasonal changes in sign. This highlights the necessity of modern calibration studies to quantitatively understand proxy response to regional climate prior to extrapolating paleoclimate interpretations. The Akçakale $\delta^{18}O_{spel}$ record responds specifically to late autumn–winter precipitation and hence its ability to provide a long reconstruction of ONDJ rainfall amount with anomalous dry and wet periods inferred to be linked to pressure fields at all heights and specifically to negative and positive phases of the NCP and EAWR respectively (Fig. 4).

Conclusions

The meteorological data and speleothem oxygen isotope record presented here confirms the influence of pressure fields over the Caspian Sea/Western Russia to winter precipitation variability in northeast Turkey. Together with the spring–summer responsive lake $\delta^{18}O$ record of Jones et al. (2006) these highly resolved independent paleo-archives ultimately contribute to a more complete picture of seasonal precipitation trends in Turkey throughout the last 500 yr.

Specifically, the main conclusions drawn from this Akçakale speleothem record are:

(1) The first long winter precipitation reconstruction, back to AD 1500, for this region has been obtained by extrapolating observed relationships between $\delta^{18}O_{spel}$ and ONDJ precipitation at Gümüşhane between AD 1933 to 2004.
(2) Modern day ONDJ precipitation is demonstrated to be linked to larger-scale regional circulation patterns: the North Sea Caspian Pattern (NCP) and East Atlantic–West Russia pattern (EAWR) providing a basis for interpretation of this speleothem record.
(3) Lower reconstructed rainfall for the period AD 1540–1560 is anomalous over the whole of the last 500 yr, up to the present day (AD 2004). During this time higher pressure over the Caspian Sea region is inferred, the cause of which is unknown and requires further investigation.
(4) It is further demonstrated that independent proxy records from a similar geographic region can offer different climatic interpretations according to the seasonality of that particular proxy response. Ultimately a combination of proxies responsive to different seasons and from different rainfall regimes is necessary

to develop a complete picture of past climatic conditions for a region. Further, this study highlights the necessity of all paleoclimate studies to be accompanied by modern calibration studies to understand quantitatively, proxy response to regional climate prior to extrapolating paleoclimate interpretations.

Supplementary materials related to this article can be found online at doi:10.1016/j.yqres.2011.01.005.

Acknowledgments

Isotope analyses were undertaken at the NERC Isotope Geosciences Laboratory, British Geological Survey Keyworth, UK; U-Series at the Open University U-Series Facility, Milton Keynes, UK; and micromilling was undertaken in the Department of Earth Sciences, Oxford University, UK. We acknowledge the E-OBS dataset from the EU-FP6 project ENSEMBLES (http://www.ensembles-eu.org) and the data providers in the ECA&D project; the ERA-40 re-analysis data set; the Met Office Hadley Centre's mean sea level pressure (MSLP) data set, HadSLP2; and the NCEP/NCAR reanalysis data set all obtained and plotted via the climate explorer (http://eca.knmi.nl) website. We also thank staff at the British Institute of Archaeology at Ankara; Erdem Berkarağlu (University of Ankara) and Serhat Sensoy (Turkish State Meteorological Office) and Faize Sariş (The University of Birmingham) for logistical support and help with obtaining meteorological data. Finally Dr. Martin Widmann at The University of Birmingham for technical advice, Kevin Birkhill at The University of Birmingham for assistance with artwork, and two anonymous reviewers whose comments have greatly improved the manuscript.

References

Akkemik, U., Aras, A., 2005. Reconstruction (1689–1994 AD) of April–August precipitation in the southern part of central Turkey. International Journal of Climatology 25, 537–548.

Allan, R., Ansell, T., 2006. A new globally complete monthly historical gridded mean sea level pressure dataset (HadSLP2): 1850–2004. Journal of Climate 19, 5816–5842.

Boé, J., Terray, L., Cassou, C., Najac, J., 2009. Uncertainties in European summer precipitation changes: role of large scale circulation. Climate Dynamics 33, 265–276.

Camci Çetin, S., Karaca, A., Haktanır, K., Yildiz, H., 2007. Global attention to Turkey due to desertification. Environmental Monitoring and Assessment 128, 489–493.

Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., et al., 2007. Regional climate projections. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Fairchild, I.J., Smith, C.L., Baker, A., Fuller, L., Spötl, C., Mattey, D., McDermott, F., E.I.M.F., 2006. Modification and preservation of environmental signals in speleothems. Earth-Science Reviews 75, 105–153.

Genty, D., Baker, A., Barnes, W., 1997. Comparaison entre les lamines luminescentes et les lamines visibles annuelles de stalagmites. Comptes Rendus de l'Académie des Sciences — Series IIA. Earth and Planetary Science 325, 193–200.

Göktürk, O.M., Bozkurt, D., Şen, Ö.L., Karaca, M., 2008. Quality control and homogeneity of Turkish precipitation data. Hydrological Processes 22, 3210–3218.

Griggs, C., DeGaetano, A., Kuniholm, P., Newton, M., 2007. A regional high-frequency reconstruction of May–June precipitation in the north Aegean from oak tree rings. International Journal of Climatology 27, 1075–1089.

Haylock, M.R., Hofstra, N., Klein Tank, A.M.G., Klok, E.J., Jones, P.D., New, M., 2008. A European daily high-resolution gridded data set of surface temperature and precipitation for 1950–2006. Journal of Geophysical Research 113.

IAEA/WMO, 2006. Global network of isotopes in precipitation, The GNIP database. http://isohis.iaea.org 2006.

IPCC, 2007. Climate change 2007: synthesis report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC.

Jansen, E., Overpeck, J., Briffa, K.R., Duplessy, J.-C., Joos, F., Masson-Delmotte, V., Olago, D., et al., 2007. Palaeoclimate. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to The Fourth Assessment Report of the Intergovernmental Panel on Climate Change. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Jex, C.N., Baker, A., Leng, M.J., Sloane, H.J., Eastwood, W.J., Fairchild, I.J., Thomas, L., Bekaroglu, E., 2009. Calibration of speleothem δ^{18}O with instrumental climate records from Turkey. Journal of Global and Planetary Change 71, 207–217.

Jones, P.D., Mann, M.E., 2004. Climate over past millennia. Reviews of Geophysics 42.

Jones, M.D., Roberts, N.C., Leng, M.J., Türkeş, M., 2006. A high-resolution late Holocene lake isotope record from Turkey and links to North Atlantic and monsoon climate. Geology 34, 361–364.

Karaca, M., Deniz, A., Tayanç, M., 2000. Cyclone track variability over Turkey in association with regional climate. International Journal of Climatology 20, 1225–1236.

Kutiel, H., Benaroch, Y., 2002. North Sea–Caspian Pattern (NCP) — an upper level atmospheric teleconnection affecting the Eastern Mediterranean. Identification and definition: Theoretical and Applied Climatology 71, 17–28.

Kutiel, H., Maheras, P., Türkeş, M., Paz, S., 2002. North Sea–Caspian Pattern (NCP) – an upper level atmospheric teleconnection affecting the eastern Mediterranean – implications on the regional climate. Theoretical and Applied Climatology 72, 173–192.

Luterbacher, J., Xoplaki, E., 2003. 500-year winter temperature and precipitation variability over the Mediterranean area and its connection to the large-scale atmospheric circulation. In: Bolle, H.J. (Ed.), Mediterranean Climate — Variability and Trends: Berlin. Springer Verlag, Heidelberg, pp. 133–153.

Luterbacher, J., Schmutz, C., Gyalistras, D., Xoplaki, E., Wanner, H., 1999. Reconstruction of monthly NAO and EU indices back to AD 1675. Geophysical Research Letters 26 (17), 2745–2748.

Pauling, A., Luterbacher, J., Casty, C., Wanner, H., 2006. Five hundred years of gridded high-resolution precipitation reconstructions over Europe and the connection to large-scale circulation. Climate Dynamics 26, 387–405.

Saris, F., Hannah, D.M., Eastwood, W.J., 2010. Spatial variability of precipitation regimes over Turkey. Hydrological Sciences Journal 55, 234–249.

Sönmez, F., Kömüscü, A., Erkan, A., Turgu, E., 2005. An analysis of spatial and temporal dimension of drought vulnerability in Turkey using the standardized precipitation index. Natural Hazards 35, 243–264.

Tan, M., Baker, A., Genty, D., Smith, C., Esper, J., Cai, B., 2006. Applications of stalagmite laminae to paleoclimate reconstructions: comparison with dendrochronology/climatology. Quaternary Science Reviews 25, 2103–2117.

Touchan, R., Garfin, G.M., Meko, D.M., Funkhouser, G., Erkan, N., Hughes, M.K., Wallin, B.S., 2003. Preliminary reconstructions of spring precipitation in southwestern Turkey from tree-ring width. International Journal of Climatology 23, 157–171.

Touchan, R., Xoplaki, E., Funkhouser, G., Luterbacher, J., Hughes, M., Erkan, N., Akkemik, Ü., Stephan, J., 2005. Reconstructions of spring/summer precipitation for the Eastern Mediterranean from tree-ring widths and its connection to large-scale atmospheric circulation. Climate Dynamics 25, 75–98.

Touchan, R., Akkemik, Ü., Hughes, M.K., Erkan, N., 2007. May–June precipitation reconstruction of southwestern Anatolia, Turkey during the last 900 years from tree rings. Quaternary Research 68, 196–202.

Trouet, V., Esper, J., Graham, N.E., Baker, A., Scourse, J.D., Frank, D.C., 2009. Persistent positive North Atlantic Oscillation mode dominated the medieval climate anomaly. Science 324, 78–80.

Türkeş, M., 1996. Spatial and temporal analysis of annual rainfall variations in Turkey. International Journal of Climatology 16, 1057–1076.

Türkeş, M., Erlat, E., 2005. Climatological responses of winter precipitation in Turkey to variability of the North Atlantic Oscillation during the period 1930–2001. Theoretical and Applied Climatology 81, 45–69.

Türkeş, M., Koç, T., Sariş, F., 2009. Spatiotemporal variability of precipitation total series over Turkey. International Journal of Climatology 29, 1056–1074.

Uppala, S.M., Kallberg, P.W., Simmons, A.J., Andrae, U., Da Costa Bechtold, V., Fiorino, M., Gibson, J.K., et al., 2005. The ERA-40 re-analysis. Quarterly Journal of the Royal Meteorological Society 131, 2961–3012.

van Oldenborgh, G.J., Balmaseda, M.A., Ferranti, L., Stockdale, T.N., Anderson, D.L.T., 2005. Evaluation of atmospheric fields from the ECMWF seasonal forecasts over a 15 year period. Journal of Climate 18, 3250–3269.

Wilks, D.S., 2006. Statistical Methods in the Atmospheric Sciences London. Elsevier.