North Atlantic Influence on Tigris-Euphrates Streamflow

Heidi M. Cullen and Peter B. deMenocal
Lamont-Doherty Earth Observatory of Columbia University

e-mail: cullen@ldeo.columbia.edu

phone: (914) 365-8571

fax: (914) 365-8157

Abstract.

Changes in streamflow of the Tigris and Euphrates Rivers are shown to be associated with the North Atlantic Oscillation (NAO), a large-scale mode of natural climate variability which governs the path of Atlantic mid-latitude storm tracks and precipitation in the eastern Mediterranean. We develop composite indices of Turkish winter (December through March) temperature and precipitation which capture the interannual-decadal climate variability for the Tigris-Euphrates headwater region, a significant source of freshwater for Turkey, Syria, and Iraq. These indices of Turkish winter temperature and precipitation are significantly correlated with the NAO, with 27% of the variance in precipitation accounted for by this natural mechanism. As evidenced by the recent widespread drought events of 1984, 1989, and 1990, Tigris-Euphrates streamflow also exhibits significant, $\sim\pm 40\%$ variability, associated with extrema.

KEY WORDS: *Turkey, interannual-decadal variability, temperature, precipitation, streamflow.*

Introduction

With regional population increasing by 3.5% each year and irrigation practices consuming at least 80% of available water supply, water is a key variable affecting the public health and political stability of the Middle East (Fig. 1). As a result, the Middle East is extremely vulnerable to any, natural or anthropogenic, reductions in available surface and ground water. Much of the current focus in Middle Eastern water policy has been the environmental and socio-economic impacts associated with increased damming along the Tigris-Euphrates River system. These anthropogenic changes have escalated transboundary water disputes threatening the security of the region and arousing international concern [McCaffrey, 1993; Shapland, 1997; Kinzer, 1999]. Here we demonstrate that much of the observed interannual-decadal variability in Middle Eastern climate and Tigris-Euphrates streamflow is physically linked to a well-known, natural mode of climate variability; the North Atlantic Oscillation (NAO) [Hurrell, 1995]. The NAO, like the El-Niño Southern Oscillation (ENSO), is one of the large-scale modes of climate variability in the Northern Hemisphere (NH). The NAO defines a large-scale meridional oscillation of atmospheric mass between the center of subtropical high surface pressure located near the Azores and the sub-polar low surface pressure near Iceland. Synchronous strengthening (positive NAO state) and weakening (negative NAO state) have been shown to result in distinct, dipole-like climate change patterns between western Greenland/Mediterranean, and northern Europe/northeast US/Scandinavia [Walker, 1932; Walker and Bliss, 1932; van Loon and Rogers, 1978; Rogers and van Loon, 1979].

The primary focus of this study is to investigate the regional extent of the NAO in the Eastern Mediterranean sector, quantify the effects of these linkages in terms of measured environmental parameters (i.e., temperature and precipitation), and finally focus on the far-field impacts of the NAO in terms of Turkish temperature, precipitation, and Tigris-Euphrates streamflow. This paper intends to explore the spatial extent of the

NAO beyond the standard maritime north Atlantic and into the Middle East, a region commonly neglected from North Atlantic study due its proximity to the monsoonal region and relatively sparse data coverage.

Turkey: home to the Tigris-Euphrates headwaters

Most of the Middle East has impoverished surface and groundwater resources due to the subtropical predominance of evaporation over precipitation. One notable exception is Turkey, which has abundant excess precipitation due primarily to orographic capture of winter rainfall from eastward propagating mid-latitude cyclones generated in the North Atlantic Ocean and eastern Mediterranean Sea [Turkes, 1996a]. Consequently, the Taurus Mountains and the Anatolian Highlands of eastern Turkey are the headwater regions for the Tigris and Euphrates Rivers (Fig 1.), whose waters are shared primarily between Turkey, and downstream riparians, Syria and Iraq. **Figure 1.**

Spatio-temporal variations of temperature & precipitation in Turkey

Turkey is typically classified as having a Mediterranean macro-climate, which is defined by hot, dry summers and cool, wet winters resulting from the seasonal alternation of maritime subpolar and subtropical air masses [Henderson-Sellers and Mitchell, 1992]. The main geographical controls on precipitation variability in Turkey are 1) continental seas (Mediterranean, Black, and Caspian Sea) which provide natural passages for frontal cyclones and 2) a west-east oriented mountain range where the forced orographic ascent of air masses promotes heavy rainfall along windward slopes and the loss of moisture content due to adiabatic 'drying' upon descent along the leeward side [Turkes, 1996b].

Home to the headwater region of both the Tigris and Euphrates Rivers, runoff from the Taurus mountains of Turkey (Fig. 1) supplies water to 2/3 of the Arabic-speaking population of the Middle East. Conservative estimates state that 88% of the water in the Euphrates River is derived from precipitation falling in Turkey, with the remaining 12% coming from underground springs in Syria. Kolars and Mitchell [1991] however, believe much of the water in these springs is Turkish in origin, and thereby calculate that 98% of Euphrates streamflow originates in the Turkish headwater region. The Tigris receives almost 60% of its water below Baghdad, making it less sensitive to variations in Turkish precipitation, but still linked to it.

The spatial distribution of precipitation over Turkey shows a range from more than 2,000 mm/year along the eastern coast of the Black Sea to 350 mm/year in the semi-arid central Anatolia region, with an average of 650 mm/year (Fig. 1). In general, mean annual rainfall totals decrease from coastal belts to the interior, with a steep gradient over the Northern Anatolian and Taurus Mountain ranges. Rainfall decreases as it passes over the Taurus mountains due to rainshadow and subsidence, marking the point of entrance into Turkey's arid and semi-arid regions located in 1) the central Anatolia region and 2) the south-eastern Anatolia region. Local effects account for the large spatial variability seen in Turkish precipitation and introduce inter-station variability.

Summer rainfall accounts for 10% of the annual mean, while autumn accounts for another 23% [Turkes, 1996b]. The remaining 67% of countrywide annual rainfall occurs during winter (DJF) and spring (MAM) when the eastern Mediterranean basin, Balkans, and Turkey are influenced by eastward propagating mid-latitude and Mediterranean depressions [Turkes, 1996b].

Origin and genesis of cyclones

The Atlantic Ocean and the Mediterranean Sea are the primary source regions for the formation of winter (December through March; DJFM) precipitation-laden mid-latitude cyclones [Turkes, 1996b]. These migratory low-pressure systems have 4 primary cyclonic centers near Crete, Cyprus, southern Italy, and the Gulf of Genoa. Secondary centers are also found over the Black Sea and Caspian Sea due to their relatively warm SST [Alpert *et al.*, 1990]. Satellite studies have shown that cyclones tend to follow the northern part of the Mediterranean Sea and then move onto land along three routes: 1) between the Balkan and Turkish mountains, 2) between the Swiss and Dinarc Alps, and 3) between the Turkish and Syria/Lebanon mountains [Alpert *et al.*, 1990]. Orographic ascent of the Atlantic maritime polar and Mediterranean air masses leads to heavy rainfall along the windward slopes of the Northern Anatolian Mountains and Taurus Mountains. These two centers are the principal precipitation control for the region and determine the abundance and intensity of rainfall draining into the Tigris-Euphrates river system [Turkes, 1996b]. In the following section the relationship between these secondary cyclones and NAO will be further described.

The North Atlantic Oscillation

Originally described in the diaries of the missionary Hans Egede Saabye as a see-saw in temperature between Greenland and Denmark [Saabye, 1942], the NAO was later defined by Sir Gilbert Walker as a meridional alternation of atmospheric mass [Walker, 1932; Walker and Bliss, 1932]. Accounting for more than 1/3 of the total variance of the sea level pressure (SLP) field over the North Atlantic, the NAO is most pronounced during the winter months (DJFM) due to an increased sea-air temperature contrast [Barnston and Livezey, 1987].

Because the signature of the NAO is strongly regional, a simple NAO index was defined as the difference between the normalized mean winter SLP anomalies at locations representative of the relative strengths of the Azores High (AH) and Icelandic Low (IL). The first NAO_{SLP} index was defined by Walker and Bliss [1932] and simplified by Rogers [1984], who constructed an NAO_{SLP} index starting in 1894, using SLP anomalies from Ponta Delgados, Azores and Akuyreyri, Iceland. Hurrell [1995] selected Lisbon, Portugal and Stykkisholmur, Iceland in order to extend the record another 30 years (Fig. 2a). A positive NAO_{SLP} index implies more meridional storm tracks while a negative

NAO_{SLP} index implies more zonal storm tracks which ultimately penetrate into the Mediterranean Sea [Alpert *et al.*, 1990], thereby remotely linking the Middle East to the North Atlantic. Investigation of the power spectrum of the NAO_{SLP} index for the past 130 winters (1864-1995) reveals a somewhat red spectrum with an indication for enhanced energy in the interannual (2-3 year) and decadal (6-10 year) frequency bands [Hurrell and Van Loon, 1997]. **Figure 2.**

Hurrell [1995] investigated the relationship between variations in the NAO_{SLP} index and decadal trends in NH temperature and precipitation, successfully demonstrating the existence of a climate dipole. Coherent, large-scale changes in the NAO since 1981 were linked to recent dry conditions over western Greenland and the Mediterranean, and wetter and warmer than normal conditions in northern Europe, the northeast US, and parts of Scandinavia [Hurrell, 1995, 1996; Hurrell and Van Loon, 1997]. Using multi-variate linear regression to quantify temperature variability associated with the NAO, it was shown that the NAO accounts for 31% of NH interannual variance [Hurrell, 1996]. Moreover, the NAO accounts linearly for 0.15°C of the 0.29°C NH extra-tropical temperature increase for the period 1981-1994, with respect to the 1935-1994 mean. Lamb and Peppler [1987] provided the first focused regional investigation of NAO teleconnections. They successfully linked decreased Moroccan rainfall to a positive state of the NAO, after receiving an invitation from the government of Morocco, then concerned over the severe and persistent drought of 1979-1984.

Most relevant to the present study is the effect of NAO-related changes in mean atmospheric circulation on the strength and direction of precipitation-laden mid-latitude cyclones. A positive (negative) NAO refers to an intensified (weakened) poleward pressure gradient resulting from a synchronous strengthening (weakening) of the AH and deepening (shallowing) of the IL on the order of 15 mb [Hurrell, 1995]. Resultant changes in mean circulation show meridionally (zonally) oriented westerlies moving onto Europe, increased (decreased) moisture transport, and a winter of higher (lower) than average precipitation in northern Europe, the northeast US, and Scandinavia, and lower (higher) than average precipitation in western Greenland and the Mediterranean. The NAO is the dominant mode of interannual-decadal climate variability for the Atlantic sector, accounting for 20 to 60% of the variance over the last 150 years [Hurrell, 1995]. It is these mid-latitude cyclones, associated with a negative state of the NAO, which migrate into the Mediterranean and generate secondary centers of precipitation-laden low pressure systems, thereby extending the spatial extent of the NAO-dipole.

The Tigris-Euphrates River System

The Euphrates River, the longest river in southwest Asia (2,700 km) is formed by two tributaries: the Kara Su (elevation 2,744 m) north of Erzurum, and the Murat (elevation 3,135) north of Lake Van (Fig. 1). These two tributaries, along with the Balikh and Khabur tributaries which join further downstream, drain the heavy winter/spring precipitation in the form of runoff from the southeastern Taurus Mountains [Gleick, 1993]. Of the 509 billion cubic meters (BCM) of rainfall per year received by Turkey, 38% is in the form of surface runoff to the Tigris-Euphrates [Hillel, 1994].

The Tigris River, the second longest river in southwest Asia (1,840 km), originates in eastern Turkey near Lake Hazar (elevation 1,150 m) and flows southeast to the Turkish city of Cizre where it forms the border with Syria before flowing into Iraq. Several tributaries contribute to the Tigris including the Greater Zab, the Lesser Zab, the Adhaim, and the Diyala. The Tigris and Euphrates converge near the Iraqi city of Qurna, and continue as the Shatt-al-Arab before draining into the Persian Gulf [Kolars and Mitchell, 1991].

The rivers have two primary flooding periods. November through March constitutes the first rise and is due mostly to surface runoff from November through March rainfall. The second rise, during April and May, results from snowmelt and generates 50% of annual runoff [Kolars and Mitchell, 1991].

Annual streamflow volumes of the Tigris-Euphrates system exhibit nearly sixfold variability during the period 1929-1972, before large-scale damming occurred, when records for this now tightly guarded variable are still available. Mean annual Euphrates streamflow is $\sim$ 32.5 billion cubic meters (BCM), of which $\sim$ 30 BCM form within Turkey. The historical minimum of Euphrates streamflow is 10.7 BCM [1929-1930] whereas the maximum is 63.4 BCM [1968-1969]) [Kolars and Mitchell, 1991]. Mean annual Tigris streamflow at Cizre is $\sim$ 19.7 BCM, with 29.5 BCM added by tributaries in Iraq Shapland [1997].

Secondary cyclogenesis in the Eastern Mediterranean provides a physical link between the Middle East and NAO, and assigns the North Atlantic the role of primary provider of precipitation to the Middle East. Further quantifying this far-field link will be accomplished by 1) expressing the climate signature of the NAO in the Eastern Mediterranean by means of spatial correlation analysis, 2) constructing a spatially averaged Turkish temperature and precipitation index, and 3) quantifying the impact of variations in the NAO on Turkish temperature, precipitation, and Euphrates River streamflow.

Data & Methodology

Data

The data used in this study consist of National Climatic Data Center (NCDC) Global Climate Perspectives System (GCPS) global monthly temperature and precipitation station data containing 6,039 temperature and 7,475 precipitation stations worldwide and extending from 1700-1995 [Baker *et al.*, 1995]. The domain used in this study was [20°N to 50°N, 10°W to 50°E] and consists of 770 temperature and 591 precipitation stations extending from the Iberian Peninsula to the Middle East. The

NAO_{SLP} index (Fig. 2a) is the normalized winter SLP difference between Lisbon, Portugal and Stykkisholmur, Iceland, extending from 1864-1995, as constructed by Hurrell [1995].

The streamflow records used in this study, measured by tide-gauge (m^3/s), were obtained through UNESCO. Euphrates streamflow was measured at Keban, Turkey, and spans the time period 1938-1972 [Vorosmarty *et al.*, 1996]. The end of the record in 1972 coincides with the initiation of the Southeast Anatolia Project, a massive network of dams, hydroelectric power plants, and irrigation projects, which marked the end of publication of Turkish hydrological data [Kolars and Mitchell, 1991]. A short record (1965-1972) of Tigris streamflow was measured at Baghdad, Iraq.

Methodology: Spatial Correlation

Correlations were calculated using temperature and precipitation records as a means of identifying those regions with the highest sensitivity to the NAO_{SLP} index (Fig. 2a). Only stations having a record greater than or equal to 30 years, and a complete winter (DJFM) record were selected. Table 1 lists the total number of temperature and precipitation stations after screening all records with less than 30 years of data and an incomplete winter (DJFM) season. Also shown is the number of stations containing at least 30, 40, 50, 60, and 70 years of temperature and precipitation data with the corresponding correlation coefficient indicating the 90%, 95%, and 99% significance level. From this reduced dataset, containing 211 temperature and 403 precipitation stations, average winter temperature and precipitation were calculated, standardized, and correlated against the Hurrell [1995] NAO_{SLP} index as a means of exploring linkages between changes in North Atlantic surface ocean conditions and Middle Eastern climate. Figures 2b and 2c demonstrate spatial correlations between the NAO_{SLP} index and mean winter (DJFM) temperature and precipitation for the circum-Atlantic and Mediterranean sectors. **Table 1.**

Methodology: Turkish temperature & precipitation indices

Spatially integrated Turkish winter (DJFM) temperature and precipitation indices were constructed by first normalizing each temperature and precipitation station, then averaging all temperature and precipitation records for the time period 1930-1995. The station-averaged time series was then correlated against the Hurrell [1995] NAO_{SLP} index.

For the temperature anomaly index, 23 Turkish stations (Fig. 1) were normalized (1930-1995 mean removed) and then averaged to produce a single composite index of Turkish winter temperature variability (in units of °C). For the Turkish winter precipitation anomaly index, a total of 27 stations (Fig. 1) were normalized (1930-1995 mean removed) and then averaged to produce a single index of Turkish winter precipitation variability (in units of mm/DJFM) spanning the same interval. Table 2 provides a listing of all Turkish stations (sorted by descending elevation) with respective record length (n), latitude (lat), longitude (lon), and elevation (elev). The correlation between Turkish temperature/precipitation indices and the NAO_{SLP} index (T_{r-val}, P_{r-val}), as well as the winter (DJFM) average temperature (T_{DJFM}) and precipitation (P_{DJFM}) are also presented. **Table 2.**

Results

The primary focus of this study is to establish and quantify the regional extent of the NAO and its impact on the Middle East. The following results demonstrate that interannual-decadal changes in Middle Eastern temperature, precipitation, and Euphrates River streamflow are tied to coeval changes in North Atlantic climate.

Regional extent of NAO climate signatures

Global correlation analysis between the NAO_{SLP} index and global station temperature (Fig. 2b) and precipitation (Fig. 2c) shows the far-field influence of the NAO on Middle Eastern climate and illustrates the distinct dipole relationship related to the subtropic-subpolar NAO pressure gradient. Figure 2b demonstrates that Eastern Mediterranean temperature is negatively correlated with the NAO, whereas northern Europe is positively correlated. Much of the Mediterranean sector (stretching from the Iberian Peninsula to Italy) returns non-significant correlation values with respect to temperature. In Figure 2c, the entire Mediterranean sector, extending from Portugal and Morocco through to Turkey is negatively correlated with the NAO. The southeastern rim of the Mediterranean exhibits a positive correlation. All stations are shaded with respect the 90, 95, and 99% significance levels for 40 years of data as listed in Table 1. Those stations which are not significantly correlated are not shaded.

During positive NAO years Turkey becomes significantly cooler (Fig. 2b) and drier (Fig. 2c). The more zonal trajectories of Atlantic heat and moisture during negative NAO years bring anomalously warmer and wetter conditions to Turkey. This connection between the Middle East and the North Atlantic sector is evidently the easternmost limit of the NAO influence on Mediterranean climate, extending from Portugal and Morocco [Lamb and Peppler, 1987] to eastern Turkey. Correlations were also calculated for station in Syria and Iraq (Table 3). Northern Syria retains a significant NAO signal, albeit weaker than in Turkey, whereas there is no significant correlation in Iraq. Lower winter rainfall correlations outside of Turkey reflect, in part, the characteristically low and highly variable rainfall pattern of the Middle East (Fig. 2c). **Table 3.**

The Impact of the NAO in Turkey

In a study of the spatial and temporal variations of rainfall in Turkey, Turkes [1996a] notes that rainfall in the region is characterized by two major wet periods 1940-1948 and 1962-1970, and two major dry periods 1971-1974 and 1989-1993, with severe and wide-spread droughts occurring in 1973, 1984, 1989, and 1990. These periods, when compared with the the NAO_{SLP} index shown in Figure 2a, establish a connection between wet periods and a negative NAO, and drought periods and a positive NAO.

The resulting composite Turkish temperature and precipitation anomaly indices for the period 1930-1995 are significantly correlated with the NAO_{SLP} index. The Turkish temperature correlation r-value (r=-0.42, Fig. 3a) indicates that 18% of the temperature variance is linearly related to the NAO_{SLP} index. The Turkish precipitation correlation r-value (r=-0.52, Fig. 3b) indicates that 27% of the Turkish winter precipitation variance is linearly related to the NAO_{SLP} index. **Figure 3.**

Tigris and Euphrates River streamflow acts to integrate regional precipitation, thereby providing a spatially averaged time series of precipitation variability for stations located in the headwater region. Discharge data obtained from UNESCO [Vorosmarty *et al.*, 1996], measured at the headwater station Keban, in eastern Turkey (Fig. 1; 38.48°N, 38.45°E), confirm that the 1938-1972 DJFMA Euphrates streamflow time series is also highly correlated to the NAO_{SLP} index (r=-0.42, Fig. 3c), with 18% of the variance linearly related to the NAO_{SLP}. A short, 8-year time series of Tigris streamflow measured at Baghdad, Iraq (Fig. 1; 33.20°N, 44.30°E) follows the Euphrates streamflow variability from 1965-1972 (Fig. 3c). All correlations exceed the 98% confidence level, and temperature and precipitation correlations exceed the 99.9% confidence level. The DJFMA interval was selected because it represents $\sim$ 50% of the total annual streamflow and is representative of both precipitation and snowmelt, thereby combining temperature and precipitation variations.

The annual, measured from September through August, streamflow time series exhibits many of the same interdecadal trends evident in the NAO_{SLP} index, with low flow values during the 1950's and high flow values during the early 1940's and late 1960's. The NAO influence on Euphrates streamflow is even more profound when NAO-extrema years are considered. The calculated average river runoff at Keban for the three highest (1945, 1949 and 1961; mean = 447 m^3/s) and three lowest (1940, 1963 and 1969; mean = 983 m^3/s) NAO years demonstrates that Euphrates streamflow exhibits $\sim \pm 40\%$ variability about the 35-year mean value (663 m^3/s) associated with NAO extrema (Fig.4). **Figure 4.**

Correlation with other Indices

Previous studies have investigated links between Eastern Mediterranean climate and other large-scale climate phenomena [De Putter *et al.*, 1998; Price *et al.*, 1998; Kadioglu *et al.*, 1999]. Price *et al.,* [1998] examined the relationship between ENSO and precipitation in Israel and concluded that statistically significant correlations only appear in the last 25 years. As a follow-up to this study, variations in Turkish precipitation were investigated by Kadioglu *et al.* [1999]. Results showed that changes associated with ENSO are primarily relegated to Southern Turkey, with variations on the order of ±6% of the monthly total precipitation value [Kadioglu *et al.*, 1999].

We also examined the possible influence of other large-scale climate phenomena on Middle Eastern climate. Correlations between our Turkish climate anomaly indices and indices of ENSO (NINO3 index) and the Asian monsoon intensity (All-India Rainfall index) were calculated. The Turkish temperature and precipitation indices are not significantly correlated with either NINO3 (r=0.20 and 0.04, respectively) or Asian monsoon intensity (r=0.02 and -0.12, respectively).

Conclusions

This study uses standard statistical techniques and a global archive of temperature and precipitation data to succinctly demonstrate the regional extent and expected variability of measured physical parameters with respect to the NAO pressure dipole. A positive (negative) NAO dipole is the result of a strong (weak) meridional pressure gradient leading to a colder, dryer (warmer, wetter) Greenland/Mediterranean sector and a warmer, wetter (colder, dryer) northern Europe/northeast US/Scandinavia sector, as first noted by Walker [1924]. Results described here provide evidence that the NAO is not limited to this classic dipole, but rather extends beyond the maritime north Atlantic and into the Middle East, a region commonly neglected from North Atlantic study due its proximity to the monsoonal region and relatively sparse data coverage. The physical mechanism for this link is the secondary genesis of cyclonic storms, originating in the Atlantic; near Crete, Cyprus, and the Black Sea.

Investigations of NAO impacts have been extended to agricultural and fishery yields [Friedland *et al.*, 1997], as well as African dust transport [Moulin *et al.*, 1997], and hurricane activity [Schaeffer, 1996], demonstrating the increasingly important economic and political significance of this phenomenon. The impacts of the NAO are especially meaningful in light of recent episodes of drought in the Middle East, a region extremely sensitive to even the smallest changes in streamflow. Ongoing research efforts are aimed at understanding whether the NAO, like ENSO, is a coupled ocean-atmosphere phenomenon as opposed to a purely white noise time series. Coupled or ocean-only modes of variability are of interest because they have the potential to elevate predictability over a white noise (atmosphere) - red noise (ocean) system. Should the NAO prove to be predictable, future work should include long-range, early warning systems for drought/flood monitoring in the Middle East and the prediction of Turkish precipitation and streamflow.

Turkish temperature and precipitation time series show decreasing trends during the 1980's consistent with the persistently positive NAO_{SLP} index during that time. We suggest that the Tigris-Euphrates streamflow time series would show this same decreasing trend, related solely to natural climate variability, were discharge information for this period available. Calculation of the linear trend of Turkish temperature and precipitation anomaly indices shown in Fig. 3a and 3b for the period 1982-1995, returns values of 1^{o}C/decade and 82 cm/decade, significant at the 95% confidence limit. This precipitation trend is 26% of the of the 1930-1995 mean of 310/mm winter. Effective policy initiatives would be best served by incorporating both anthropogenic and natural variations in Tigris-Euphrates streamflow.

Increasing hydroelectric and agricultural demands on Tigris and Euphrates runoff related to the $32 billion Greater Anatolia Project (GAP), have exacerbated tense relations between the riparian neighbors and have led to claims of decreased water supply by Syria and Iraq. Turkey, because it has the good fortune of being situated at the headwaters of the Tigris-Euphrates River system, can literally turn off the supply of water to its downstream neighbors and has threatened to do so on occasion [McCaffrey, 1993]. For example, when the Ataturk Dam was completed in 1990, Turkey stopped the flow of the Euphrates entirely for one month, leaving Iraq and Syria in considerable distress. Similarly, in 1975 when the Syrians began filling Lake Assad after completion of work on the Tabqa Dam, Iraq threatened to bomb the dam alleging that it seriously reduced the river's flow. Both countries amassed troops along the border. These military actions were in response to anthropogenic changes in water use imposed by one state against the others. Natural climate variability, however, which has no political alliances, affects water supply to this region as well and could easily be misinterpreted as anthropogenic.

Acknowledgements: We wish to thank Alexey Kaplan, Yochanan Kushnir, Balaji Rajagopolan, and Rosanne D'Arrigo for comments.

Correspondence and requests for materials to Heidi M. Cullen (cullen@ldeo.columbia.edu)

References

Alpert P, Neeman B, Shay-ell Y, 1990. Climatological analysis of Mediterranean cyclones using ECMWF data. *Tellus* **18**: 65–67.

Baker C, Eischeid J, Karl T, Diaz H, 1995. The quality control of long-term climatological data using objective data analysis. In *Preprints of AMS Ninth Conference on Applied Climatology, Dallas, TX., January 15-20*, Data accessed via the LDEO climate server (http://ingrid.ldgo.columbia.edu/SOURCES/.NOAA/.NCDC/.GCPS/).

Barnston A, Livezey R, 1987. Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. *Mon. Weath. Rev.* **115**: 1083–1126.

De Putter T, Loutre M, Wansard G, 1998. Decadal periodicities of Nile River historical discharge (ad 622-1470) and climatic implications. *Geophysical Research Letters* **25(16)**: 3193–3196.

Friedland K, Reddin D, Kocok J, 1997. Marine survival of North American and European Atlantic salmon - effects of growth and environment. *ICES Journal of Marine Science* **50**: 481–492.

Gleick P, 1993. Water and conflict: fresh water resources and international security. *International Security* **18**: 79–112.

Henderson-Sellers A, Mitchell P, 1992. *Contemporary Climatology*. Longman Scientific and Technical, 1st edn.

Hillel D, 1994. *Rivers of Eden: The Struggle for Water and the Quest for Peace in the Middle East*. Oxford University Press, 1st edn.

Hurrell J, 1995. Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation. *Science* **269**: 676–679.

Hurrell J, 1996. Influence of variations in extratropical wintertime teleconnections on Northern Hemisphere temperature. *Geophysical Research Letters* **23**: 665–668.

Hurrell J, Van Loon H, 1997. Decadal variations in climate associated with the North Atlantic Oscillation. *Climatic Change* **36(3-4)**: 301–326.

Kadioglu M, Tulunay Y, Borhan Y, 1999. Variability of Turkish precipitation compared to El Niño events. *Geophysical Research Letters* **26(11)**: 1597–1600.

Kinzer S, 1999. Where the Kurds seek a land, Turks want the water. *The New York Times* **Feb. 28**: 3.

Kolars J, Mitchell W, 1991. *The Euphrates River and the Southeast Anatolia Development Project*. Southern Illinois University Press, 1st edn.

Lamb P, Peppler R, 1987. North Atlantic Oscillation: Concept and application. *Bulletin of the American Meteorological Society* **68**: 1218–1225.

McCaffrey S, 1993. Water, politics, and international law. In Gleick P, ed., *Water in Crisis*, 92–99, Oxford University Press.

Moulin C, Lambert C, Dulac F, Dayan U, 1997. Control of atmospheric export of dust from North Africa by the North Atlantic Oscillation. *Nature* **387**: 691–694.

Price C, Stone L, Huppert A, B. R, P. A, 1998. A possible link between El Niño and precipitation in Israel. *Geophysical Research Letters* **25(21)**: 3963–3966.

Rogers JC, van Loon H, 1979. The seesaw in winter temperatures between Greenland and northern Europe. Part ii: Some oceanic and atmospheric effects in middle and high latitudes. *Mon. Wea. Rev.* **107**: 509–519.

Saabye H, 1942. Brudstykker sd en dagbog holden i groenland i aarene 1770-1778. In *Medd. Gronland, H. Oesterman*.

Schaeffer J, 1996. Tropical cyclone activity as a diagnostic climate indicator. In

Proceedings of the 20th Annual Climate Diagnostics Workshop, University of Washington, October 1995.

Shapland G, 1997. *Rivers of Discord: International water disputes of the Middle East*. St. Martin's Press, 1st edn.

Turkes M, 1996a. Meteorological drought in Turkey: *A Historical Perspective 1930-1993. Drought Network News* **8**: 17–21.

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

van Loon H, Rogers JC, 1978. The seesaw in winter temperatures between Greenland and northern Europe. Part I: Winter. *Mon. Wea. Rev.* **104**: 365–380.

Vorosmarty B, Fekete B, Tucker B, 1996. Global river discharge data (rivdis v1.0). Tech. rep., UNESCO.

Walker G, 1932. Correlations in seasonal variations of weather. *IX. Mem. Ind. Meteor. Dept.* **24**: 275–332.

Walker G, Bliss E, 1932. World Weather V. *Mem. Roy. Meteor. Soc.* **4**: 53–84.

Route 9W, Palisades, NY 10964, USA

August 4, 1999

This manuscript was prepared with AGU's LaTeX macros v4, with the extension package 'AGU^{++}' by P. W. Daly, version 1.5c from 1997/03/14.

Figure Captions

Figure 1. Middle East precipitation with selected Turkish temperature (23 small dark circles) and precipitation stations (27 large white circles); stations with less than 30 years of data or any incomplete DJFM series were omitted [Baker *et al.*, 1995]. Tigris and Euphrates River streamflow measurement stations in Keban, Turkey and Baghdad, Iraq are depicted with star symbols [Vorosmarty *et al.*, 1996].

Figure 2. (a) The North Atlantic Oscillation sea level pressure index (NAO_{SLP}, 1864-1995) defined by Hurrell [1995], (b) spatial correlation between the NAO_{SLP} index and mean winter (DJFM) station temperature, and (c) spatial correlation between the NAO_{SLP} index and mean winter station precipitation.

Figure 3. Correlation between the NAO_{SLP} index and (a) Turkish winter temperature index, (b) Turkish winter precipitation index and (c) DJFMA average streamflow of the Euphrates (filled circles) and Tigris River (open circles). (Note: the NAO_{SLP} index has been multiplied by -1 for easier comparison.)

Figure 4. Monthly Euphrates River streamflow (solid line) measured at Keban, Turkey (35 year mean). Monthly averages for the three lowest NAO years (1940, 1963, 1969; dashed line with filled circles, 2σ standard deviation shown), and monthly averages of the three highest years (1945, 1949, 1961; dashed line with triangles, 2σ standard deviation shown).

Tables

Table 1. Temperature and precipitation station data after screening procedure. Also listed is number of stations containing at least 30, 40, 50, 60, and 70 years of temperature and precipitation data with the corresponding correlation coefficient indicating the 90%, 95%, and 99% significance level.

	TEMP	PRCP	$t_{90\%}$	$t_{95\%}$	$t_{99\%}$
n_{total}	770	591	⋆	⋆	⋆
$n_{>70}$	79	192	0.195	0.232	0.302
$n_{>60}$	95	245	0.211	0.250	0.325
$n_{>50}$	113	277	0.231	0.273	0.354
$n_{>40}$	142	323	0.257	0.304	0.393
$n_{>30}$	211	403	0.295	0.349	0.449

Table 2. Turkish stations used in temperature and precipitation indices; *** denotes 99.9%, ** the 99%, and * the 95% significance level (see text for more details).

Station	n	lon °E	lat °N	elev	T_{r-val}	T_{DJFM} (°C)	P_{r-val}	P_{DJFM} (mm)
Kars	57	43.08	40.60	1775	⋆	⋆	0.32**	92.8
Erzurum	61	41.27	39.92	1756	0.45***	-5.84	0.51***	111.8
Van	40	43.32	38.45	1667	0.52***	-1.89	0.19	141.3
Sivas	61	37.02	39.75	1285	0.44***	-1.28	0.38**	164.6
Erzincan	40	39.50	39.73	1156	0.54***	-0.32	0.38*	124.6
Kayseri	40	35.48	38.78	1053	0.63***	1.02	0.41**	140.4
Afyon	40	30.53	38.75	1034	0.57***	2.32	0.50***	159.6
Konya	40	32.55	37.97	1032	0.61***	2.43	0.42***	137.6
Bursa	40	29.07	40.18	1001	0.38**	6.72	0.57***	322.6
Isparta	40	30.55	37.75	997	0.67***	3.49	0.68***	285.5
Ankara	60	32.90	40.00	894	0.37**	2.28	0.44***	156.7
Malatya	40	38.08	38.43	862	0.48**	2.40	0.27	178.8
Igdir	47	44.03	39.93	858	⋆	⋆	0.11	65.7
Kastamonu	40	33.77	41.37	799	0.50***	1.29	0.45**	120.2
Diyarbakir	60	40.18	37.88	686	0.47***	4.27	0.18	271.3
Mugla	40	28.35	37.20	646	0.52***	6.60	0.59***	771.8
Cankiri	38	33.60	40.60	630	⋆	⋆	0.47***	163.3
Urfa	40	38.77	37.13	547	0.42**	7.58	⋆	⋆
Adana	61	35.42	37.00	73	0.34**	10.97	0.29*	387.4
Antalya	61	30.73	36.70	50	0.55***	11.07	0.34**	750.2
Edirne	61	26.57	41.67	48	⋆	⋆	0.64***	222.6
Istanbul	60	29.10	41.00	40	⋆	⋆	0.32***	319.7
Giresun	56	38.40	40.92	38	⋆	⋆	0.23	443.6
Kumkoy	40	29.00	41.30	30	⋆	⋆	0.27	346.9
Izmir	60	27.30	38.40	25	0.35**	9.52	0.44***	419.1
Samsun	68	36.33	41.28	4	0.44***	7.67	0.36**	251.9
Rize	60	40.50	41.00	4	0.49***	7.47	0.28*	820.4
Canakkale	40	26.40	40.13	3	0.38**	7.39	0.68***	329.6

Table 3. Precipitation stations in Syria and Iraq with corresponding r-values (see text for more details).

Station	n	lon	lat	elev	P_{r-val}
Damascus, SYRIA	35	36.52	33.32	610	-0.15
Kamishli, SYRIA	37	41.22	37.05	452	-0.26
Aleppo, SYRIA	39	37.22	36.18	390	-0.36**
Baghdad, IRAQ	70	44.23	33.23	45	0.10