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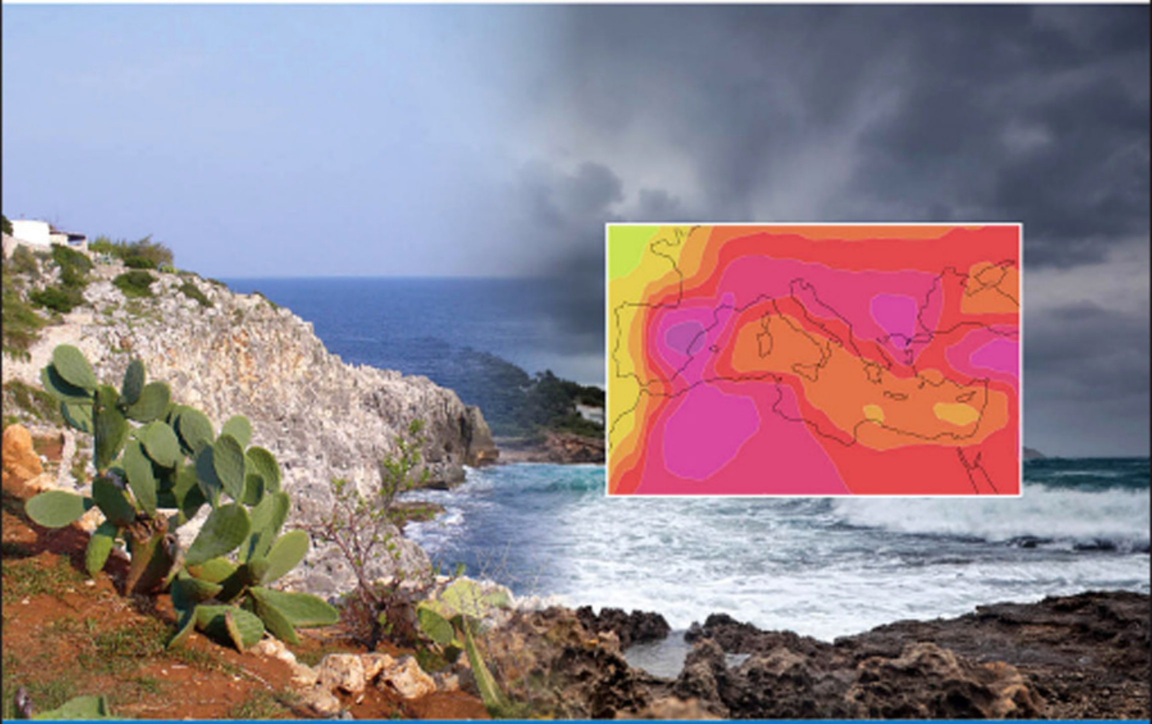

THE CLIMATE OF THE MEDITERRANEAN REGION

FROM THE PAST TO THE FUTURE

Edited by
PIERO LIONELLO

The Climate of the Mediterranean Region

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The Climate of the Mediterranean Region

From the Past to the Future

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2.1 Introduction

Currently, there are several multiproxy reconstructions of global or hemispheric temperature covering the last 1000 to 2000 years (see Jones et al., 2009 for a review; Mann et al., 2008, 2009; Ljungqvist et al., 2012). Although based on the same few data sets (mainly tree rings), many of these synthetic reconstruction studies differ from one other by applying different statistical methods; by resolving annual means, summer, or growing season conditions; or by referring either to the full hemisphere or parts of it or to land areas only. Present and future paleoclimate research will focus more on regional climatic and environmental responses to global or hemispherical changes and on changes specific to the past hydrological cycle (PAGES, 2009). The US National Research Council (2006) has already called for regional reconstructions for a range of relevant climatic variables, including temperature and precipitation. Regional climatic and environmental fluctuations affect societies and form the basis for efficient adaptation measures. Regional climate is the result of the interaction of large-scale dynamics with orography and physical properties at the regional and local scales. A perspective on the mechanisms operating at hemispherical and large scales, and their linkages to regional and local climates including extremes, remains highly relevant. But only information on past climate dynamics at regional scales allows us to characterize local amplitudes and rates of change. Despite significant progress over the last two decades, we still do not sufficiently understand the detailed interactions between regional climate forcings, internal variability, system feedbacks, and the responses of surface climate, land cover, and bio- and hydrosphere that determine local climate variation (PAGES, 2009).

New analytical techniques have increased the array of proxies and archives that can be used for paleoscientific studies (e.g., corals; tree rings; ice cores; speleothems; marine, lake, and other sediments; soils and landforms; and documentary data), forming a steadily growing base for data synopsis and data-model comparisons (Jones et al., 2009, and references therein). Combining evidence from the different archives with evidence of past human activity obtained from historical, archaeological, and paleoecological records can advance our understanding of climatic sensitivity, environmental response, ecological processes, and human impact on smaller spatial scales (for recent examples applied to the Roman world, see McCormick et al., 2012). An overarching theme is the synthesis and integration of diverse observations, combined with models and process understanding, to advance climate prediction. Advances in modeling techniques, such as atmosphere–ocean–biosphere coupling, high spatial resolution, transient runs, and representation of climate modes, have made it more productive to exploit those regional proxy data sets that are well dated, of high resolution, and carefully calibrated. Producing long time series of key climate variables, analyzing these time series for information on climate variability and trends, and characterizing the natural background state of the climate system are also very relevant for the purposes of detection and attribution of past and present climate change.

The Mediterranean region offers an unusually rich combination of long, high-quality instrumental time series, natural archives, and documentary information across time and space, making possible sufficiently sensitive reconstructions of climate in past centuries to shed light on both changes in climate extremes and socioeconomic impacts prior to the instrumental period. Luterbacher et al. (2006) used an in-depth review of early instrumental data and high-temporal-resolution proxies to support statistically based multiproxy field reconstructions of winter temperature and precipitation covering the last 500 years. This chapter begins the project of extending this work much further back in time, through an overview of existing paleo information from the Mediterranean covering the last 2000 years (2k hereinafter). This is a first contribution to the regional PAGES 2k initiative (Newman et al., 2009), whose goal is to produce new quantitative reconstructions of the climate of the last 2k years for different regions of the world, including the Euro-Mediterranean region, using sophisticated new statistical methods to combine different proxy archives (see Section 2.15). The use of a 2k-year framework has important implications for the focus of this chapter. Though documentary records from the Mediterranean area are widespread, they do not cover this longer interval with the same intensity or spatial coverage (for comparison, see a review covering the last approximately 500 years in the Mediterranean from the outcome of the EU Project MILLENNIUM (Camuffo et al., 2010b)). However, there are some exceptions (see Luterbacher et al., 2006). Vogt et al. (2011), for example, make innovative use of Arabic sources to reconstruct past climate in the Middle East, as far back as AD 800. Ellenblum (2012) recently reports on the calamitous nature of the climatic events that hit the eastern Mediterranean between 950 and 1072 AD. He reviews the current theories that deal with historical "collapses," and represents the potential contribution of this specific climatic disaster. Further, White (2011) reports in detail about The Climate of Rebellion in the Early Modern Ottoman Empire. Yavuz et al. (2007) have used historical data to reconstruct freezing events in the Black Sea and Bosporus area over the last 2k years. There is also enormous potential in the wealth of textual evidence available, as one moves back in time from the Byzantine to the Late Roman, Roman, and Greco-Roman periods, for several areas of the Mediterranean. Such testimonies range from direct observations of climatic or environmental phenomena to the indirect testimony of records of events such as famine and plague—especially suggestive when they are not entirely local (Neumann 1985; Garnsey, 1988; Sallares, 1991; Stathakopoulos, 2000, 2004; Teleles, 2004; Little, 2006; McCormick et al., 2012). Some of these data have been exploited to reconstruct climatic episodes of political and cultural significance (McCormick et al., 2007; McCormick et al., 2012), to the extent that grand, if as yet quite speculative, claims have been made as to causal links between climate "deterioration" and the fall of the Roman empire (Büntgen et al., 2011). A key new resource for the Roman and Medieval period is provided by the *Digital Atlas of Roman and Medieval Civililizations*, (eds.), M. McCormick, G. Huang, K. Gibson, et al. at http://darmc.harvard.edu.

As we move back in time, nevertheless, the range and quality of documentary sources deteriorates, making natural proxies all the more relevant. Yet, few, if any, natural proxies provide sufficiently high resolution (i.e., annual or seasonal resolution) while covering the whole period. Therefore, the analysis of the climate during the last 2k years must rely on a combination of data from disparate proxy archives, including both high- and low-resolution proxies. Finne et al. (2011) recently published a review on paleoclimate data and reconstructions from the eastern Mediterranean with a focus on the last 6000 years.

With this framework in mind, this chapter presents a systematic review of a range of natural proxies, already considered less exhaustively in Luterbacher et al. (2006). The chapter is divided into several sections. First, we reconsider long instrumental data series, as they are crucial for calibration with proxy information. Then, we provide a quantitative review of the availability of ships' logbooks in the Mediterranean and suggest how this source can be used to produce new circulation indices.

The next sections review the primary terrestrial and marine proxies: tree rings; speleothems; lake, river, and marine sediments; boreholes; and pollen records.

Given the nature of the proxies, regional-scale variations in the hydrological cycle receive considerable emphasis. Furthermore, in the Mediterranean, as in similar regions, water availability has frequently been a crucial constraint on both societies and ecosystems. Especially important in this context is the identification of historical extreme events—including the onset, intensity, duration, and frequency of droughts and floods—that severely stressed human or natural systems. We report on the variability of those extremes, the identification of the space and timescales that are resolved in the different Mediterranean paleo records, and the associated uncertainties. Based on this review of diverse proxies, we establish a common framework for a comparison of paleo and modern estimates of mean and extreme climate, with resolution sufficient to include even relatively rapid shifts. We place special emphasis on dating issues; distinguishing climatic and nonclimatic influences; seasonality effects in proxy records (where appropriate); and specific aspects of these proxies that contribute to reconstruction uncertainties.

Over more than 2k years, humans in the Mediterranean strongly influenced the environment, to such an extent that their impact may obscure the climatic signal, especially with regard to forest, vegetation, and the fire regime (Colombaroli et al., 2007; Carrion et al., 2010a,b). Land use is both a significant parameter affecting regional climate in the Mediterranean and a key indicator of changing environments and landscapes. A multiproxy approach may make it possible to assess critically the complex interrelationship of climate forcing and land-use response. Rich measures of land cover are crucial: only via multiproxy studies can we expect to disentangle complex relationships between climate, land use, fire, forest cover, and other vegetation dynamics. Thus, we also provide examples of the use of multiple proxies to reconstruct past climate behavior—for example, vegetation dynamics, including land use and fire and sea-level variations covering the last 2k years.

The last two sections highlight how paleo models can be used to evaluate paleoclimate reconstructions in the Mediterranean, by narrowing the range of plausible climate-sensitivity estimates, and show how models can be used to assimilate multiple proxies.

Each section ends with a short summary and an assessment of potential and future challenges associated with the relevant archives, so as to allow them to contribute optimally to our understanding of past Mediterranean climate variations. The chapter as a whole is complemented by that of Abrantes et al. (in this book), dealing with Mediterranean paleoclimatic evidence covering the past hundreds thousands of years.

2.2 Long Instrumental Data Series from the Mediterranean

The Mediterranean region provides a uniquely rich body of long instrumental climate data sets, going back as far as 350 years. The history of modern meteorology begins in Italy, where Galileo claimed to have invented the first thermometer, at Padua in 1592. In the next generation, his students were involved in the first concerted effort to develop meteorological instrumentation and gather detailed weather data, under the patronage of Ferdinand II, Grand Duke of Tuscany (1610–1670), and his brother, Cardinal Leopold de' Medici, Governor of Siena (1617–1675). With their sponsorship, key meteorological instruments (the thermometer, rain gauge, perhaps the barometer, and some hygrometers) were invented or improved and the first network of meteorological stations created. Ferdinand II founded the *Rete Medicea* ("Medici Network," active 1654–1670) and the first academy of sciences, the *Accademia del Cimento* (1657–1667), which incorporated the *Rete Medicea* (Camuffo et al., 2010a,b). The *Rete Medicea* set up measuring stations in Italy (Florence, Vallombrosa, Cutigliano, Bologna, Parma, and Milan) and elsewhere (Paris; Innsbruck, Austria; Osnabrück, Germany; and Warsaw, Poland) (Camuffo, 2002). Using standardized protocols and instruments sent out from a single workshop, daily temperature measurements were taken and sent to Florence, until the closure of the *Accademia del Cimento* put an end to the network. Another seventeenth-century Italian meteorological data set was the work of Bernardino Ramazzini (1633–1714), professor of medicine at Modena, a pioneer of epidemiology, and perhaps one of the inventors of the barometer. His *Ephemerides Barometricae 1694*, published in 1695, include "daily observations of air pressure, wind direction (in quarters), state of the sky and [the frequency of] precipitation … for the calendar year 1694," elsewhere recorded as exceptionally cold (Ramazzini, 1695, 1718; Camuffo et al., 2010a).

By the late seventeenth century, daily meteorological observations were also being recorded in London and Paris (Cornes et al., 2010), and the expansion of meteorological networks accelerated greatly during the eighteenth century. Official scientific organizations played a key role: in England, the Royal Society (founded 1660); in France, the Société Royale de Médécine (1776–1789), in Bavaria, the Bayerische Ephemeriden (Bavarian Academy of Science, 1781–1789) and, for Germany, Austria, and Switzerland, but also regions as distant as Russia, Greenland, and Massachusetts, the short-lived Mannheim Societas Meteorologica Palatina (1781–1795). Alongside these quasi-official networks, a diverse range of groups and individuals recorded instrumental data. These included astronomical observatories and expeditions, medical institutions (e.g., hospitals) and professionals (e.g., doctors and ships' surgeons), military bodies (e.g., engineering corps), consulates and consular officials, botanic gardens, pilot and signal stations, lighthouses, port authorities (e.g., harbormasters), shipping companies, missionaries, and learned societies, while data are also preserved by diarists, newspapers, government gazettes, pamphlets, and other archival and published records. Such early observational networks and bodies often provided the basis for the emergence of National Meteorological Services that would characterize the mid-nineteenth century. For further detail on the development of meteorological networks in this period, see Camuffo et al. (2010a,b, and references therein).

Recovering eighteenth-century meteorological data series from scattered archives and publications is an arduous task, and the data quality is varied and often poor. Nevertheless, the eighteenth century saw the beginnings of widespread, continuous meteorological observation, and a number of very long, high-quality series of pressure, temperature, and precipitation observations were made in the Mediterranean region (Figure 2.1). Camuffo et al. (2010a,b) have recovered, collated, and analyzed

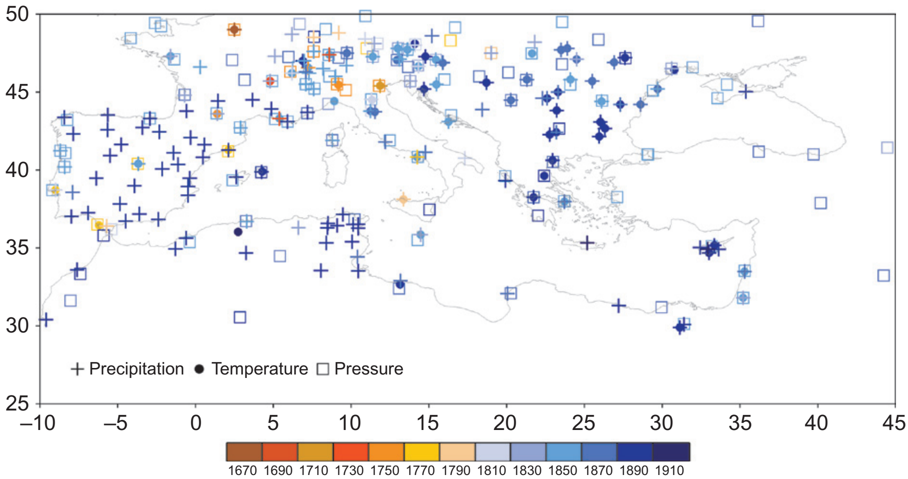

Figure 2.1 Monthly Mediterranean, temperature, precipitation, and surface pressure observations that cover >100 years. Symbols correspond to the climatic variables and colors denote the starting decade of the time series (the compilation is from different recent digitization efforts and outcome of EU projects and national programs). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this book.)

early continuous instrumental observations from Mediterranean regions including Italy, France, Spain, and Portugal; in some cases, these cover 350 years.

In Europe and the Mediterranean, the mid-nineteenth century saw the establishment of National Meteorological Services. Once the telegraphic network was established, in the 1860s and 1870s, National Meteorological Services often gathered weather observations from neighboring countries and territories, material that is often published in their Daily Weather Reports (DWRs). In the same decades, there emerged a tradition of exchanging meteorological publications and Yearbooks between the different National Meteorological Services. Simultaneously, each of the major European powers extended these systems into their colonies, so as to cover much of the world. Thus, nineteenth-century data series for given meteorological stations can often be enriched or improved by examining a wide range of publications, not only by the relevant National Meteorological Service but also from nearby countries or the archives of the colonial powers, which may confirm previously known observations or, crucially, supply additional or missing data.

Across the Mediterranean region, the DWRs, Yearbooks, and other publications of the early French, English, Spanish, Portuguese, Dutch, German, Russian, Italian, Algerian, Egyptian, Ottoman, and Austro-Hungarian National Meteorological Services preserve a wealth of overlapping weather observations. For example, for North Africa, weather observations for Morocco, Algeria, Tunisia, and Libya can be found in a mix of French, English, Algerian, and Italian sources, while for Egypt, the Middle East, and the Balkans, such material occurs in Egyptian, French, Italian, Greek, English, Ottoman, Russian, and Austro-Hungarian publications. These sources have been vital in current efforts under Atmospheric Circulation Reconstructions over the Earth (ACRE, http://www.met-acre.org; Allan et al., 2011) to recover, image, and digitize long historical terrestrial weather observation series, with emphasis on pressure series for important locations in the region, such as those from Malta, Cyprus, Constantinople/Istanbul, and Baghdad.

In recent years, national, European, and international initiatives, including EU programs and projects, have been launched to recover, collate, and translate into modern terms climate data sets from these archives and early publications, making them available to scientists today.[1] Overall, those projects and initiatives are yielding increasing quantities of monthly, daily, and subdaily instrumental data, which can then be combined, imaged, digitized, and homogenized across the entire Mediterranean sector (Figures 2.1 and 2.2).

Recent and ongoing national and international data rescue and digitization initiatives have laid the groundwork for future efforts to integrate historical instrumental data with non-instrumental approaches, so that soon it should be possible for all such weather data to be assimilated into historical surface-input-only reanalyses, like those being facilitated by the international Atmospheric Circulation Reconstructions over the Earth (ACRE) initiative (www.met-acre.org; Allan et al., 2011). This work will require recovering historical weather data, including instrumental data, from a wide range of repositories, some of which, such as the Ottoman and Venetian archives, are as yet little known to climate scientists.

Records of climate variability and change in the form of instrumental meteorological data are the cornerstones of our understanding and, ultimately, prediction of climate. But regional climate analyses from such data demand long, reliable, and continuous time series, with good spatial distribution and density. High-density data sets support accurate representation of climate variability across space and yield richer reconstructions of climate processes ongoing in the study area. By contrast,

[1] The World Meteorological Organization (WMO) Mediterranean Climate Data Rescue (MEDARE, www.omm.urv.cat/MEDARE/index.html) initiative focuses on the Greater Mediterranean Region (GMR). The European Climate Assessment & Dataset (ECA&D, http://ecad.knmi.nl); the European Climate Support Network (ECSN, www.eumetnet.eu.org/ECSN_home.htm); the Portuguese Signatures of Environmental Change in the Observations of the Geophysical Institutes (SIGN, www.idl.ul.pt/SIGN) project; the sixth EU-FP IP Climate Change and Impact Research: the Mediterranean Environment (CIRCE, www.circeproject.eu); the Historical Instrumental Climatological Surface Time Series of the Greater Alpine Region (HISTALP, www.zamg.ac.at/histalp); and the ALP-IMP projects (www.zamg.ac.at/ALPIMP) focused on the Greater Alpine region. The Atmospheric Circulation Reconstructions over the Earth (ACRE, www.met-acre.org; Allan et al., 2011) initiative; the International Environmental Data Rescue Organization (IEDRO, http://www.iedro.org); the Climate Database Modernization Program (CDMP) of the National Oceanographic and Atmospheric Administration (NOAA, http://www.ncdc.noaa.gov/oa/climate/cdmp/cdmp.html); the International Surface Temperature Initiative (www.surfacetemperatures.org); the Climate, Health and Environment: Data Rescue and Modeling (CHEDAR, www.lsce.ipsl.fr/en/Phocea/Vie_des_labos/Ast/ast_visu.php?id_ast=283); the Mediterranean Climate Variability and Predictability (MedCLIVAR, www.medclivar.eu) program, the Observations Phenologiques pour reconstruire le climat de l'Europe (OPHELIE, www.ipsl.jussieu.fr/~ypsce/ophelie.html) project, EU Sixth Framework Programme (FP6), IP MILLENNIUM, the EU FP4 and FP5 projects Mediterranean Desertification and Land Use (MEDALUS), ADVICE, and IMPROVE.

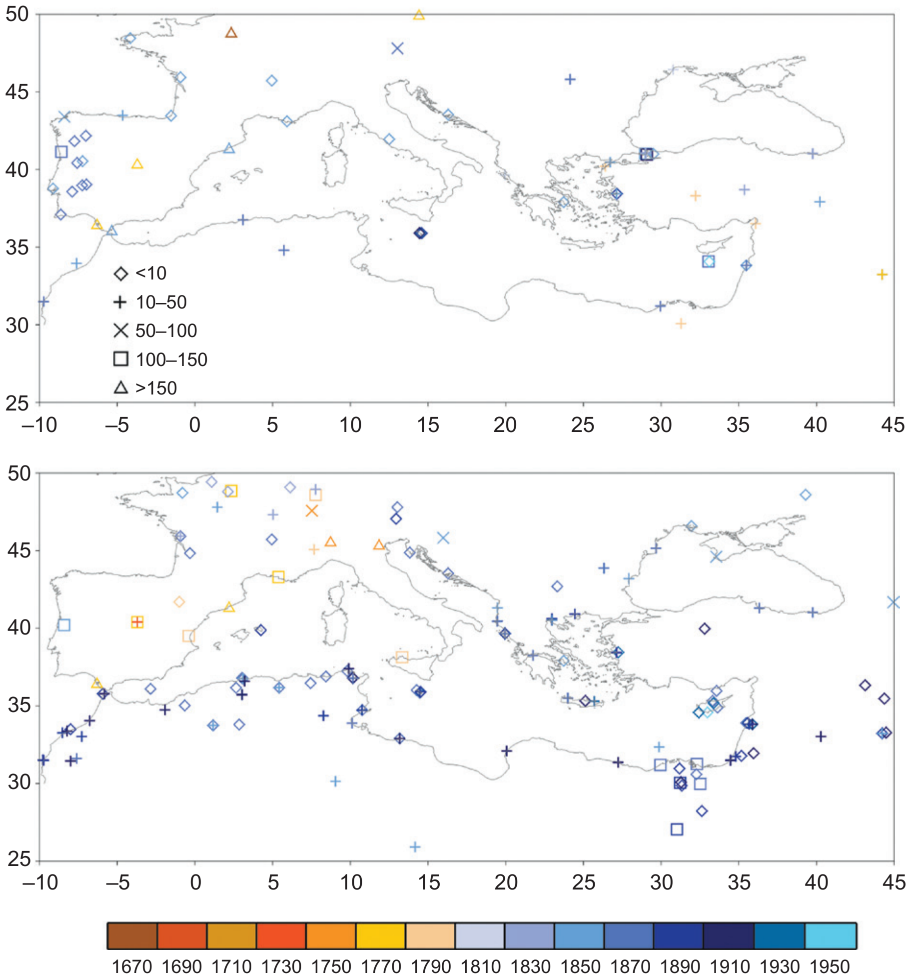

Figure 2.2 Daily surface pressure observations in the Mediterranean from the ACRE project (www.met-acre.org). Top: Digitized time series; Bottom: Identified time series available in archives, not yet digitized or currently digitized. Colors denote the starting decade and the symbols the length of the daily time series. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this book.)

geographically sparse data sets cannot adequately represent the area of interest, since spatial variation cannot be precisely resolved (notably, in relation to orography, but also to smaller-scale factors). The timescale on which a meteorological variable is measured also constrains climate analysis in various ways. For example, seasonal features can be derived from data with monthly resolution, but the assessment of extreme events requires daily, even subdaily, data collection, as well as high spatial resolution (Xoplaki, 2002; Kuglitsch, 2010; Toreti, 2010). Long, widespread, and reliable instrumental information is also crucial for statistical calibration/verification and reconstruction of past climates, together with careful analysis and knowledge of the statistical properties of the climatic variables under study.

Furthermore, even for instrumental data, a variety of uncertainties can impede analysis if these were not directly addressed during the developmental phase. Problems of this kind affect the majority of early instrumental data series, despite efforts at standardization going back to the seventeenth century's *Rete Medicea.* Such uncertainties include changes in station location and in the environment around the station; changes in instruments, instrument malfunctions, miscalibrations, and variation over time in instrumental biases; inadequate spatial resolution, temporal resolution, and data set length; changes in temporal and spatial sampling and aliased temporal sampling; and biases introduced in the context of data assimilation and model reanalysis (NOAA, Climate Program Office).

2.3 Ships' Logbooks from the Mediterranean as Quasi-Instrumental Climate Information

Among the most comprehensive sources for historical climatology are ships' logbooks. For the Mediterranean region, centered around its sea, the abundant marine data found in these sources provides a crucial complement to historical terrestrial and island data series (see Section 2.2). Logbook information sheds light most distinctively on storm histories, while also recording wider spatial patterns, as reflected by the tracks and intensities of storms and similar high-impact phenomena. This type of data also facilitates important comparisons, cross-checks, quality control, and homogenization of sources from different platforms: for example, land-based harbor and port station series can be checked against records from marine vessels at anchor in the same locations. Several European institutions hold these logbooks, including examples dating to the late seventeenth century or even earlier (Wheeler and Garcia-Herrera, 2008; Woodruff et al., 2011). They contain firsthand information about the weather ships encountered and records that can yield very long and highly resolved climate series, thus providing a unique source of early marine meteorological observations. Unfortunately, up to the second half of the nineteenth century, the vast majority of ships did not carry meteorological instruments; data from such logbooks are therefore—with some partial exceptions—noninstrumental.

Logbook data can be categorized under three basic headings: wind direction, wind force (usually estimated by reference to the state of the sea), and general notes on the weather. In long climatic time series reconstructed from ships' logbooks, wind force and direction are the key parameters (Jones and Salmon, 2005; Gallego et al., 2005, 2008; Küttel et al., 2010). Wind-force records, however, suffer profoundly from homogeneity problems. Before about 1850 (varying by country), ships' logbooks did not use quantitative or, often, even standardized qualitative wind-force scales. To represent an early wind-force record in terms of a current scale, the descriptor must be analyzed and converted to a numerical wind velocity. This method, known as "content analysis" (Prieto et al., 2005), introduces an uncertainty that is difficult to quantify.

In contrast to wind force, early measurements of wind direction can be regarded as quasi-instrumental observations. Wind direction was usually recorded with respect to magnetic north, and magnetic variation can easily be corrected for, so that wind direction involves negligible uncertainty. Wheeler et al. (2010) developed a “westerly index” over the English Channel, defined as the percentage of days in a month when winds came from the west (on a four-point scale), which covered the period 1685–1750. This index tracks wind direction only, so it is free of the uncertainty associated with wind-force records. In order to compare the index with current measurements of climate variables, it was extended forward from 1750 to 2008 using modern instrumental marine databases, including CLIWOC (Climatological Database for the World’s Oceans 1750–1850) (Garcia-Herrera et al., 2005) and ICOADS (International Comprehensive Ocean-Atmosphere Data Set), and data recovered from British archives on an ad hoc basis.

Although ICOADS currently has some data back to 1662, its information for the Mediterranean prior to 1849 is scarce. By contrast, the abundance of ICOADS data for the Mediterranean after 1850 means that Mediterranean indices up to the present time can be generated using this database alone. Expansion of Mediterranean marine indices back in time therefore begins with the recovery of observations made before 1850. Much relevant data can be abstracted from the National Archives at Kew, United Kingdom (TNA below). As part of the work of the Mediterranean Climate Variability and Predictability (MedCLIVAR) network, marine data from the Royal Navy in the Mediterranean between 1680 and 1850 has been examined (Alvarez-Castro, 2008); preliminary results appear in Luterbacher et al. (2006). As of the beginning of 2011, digitization of these data is still in progress, but the availability of wind-strength and direction records over the Mediterranean for the period 1673–2010 can already be assessed (Figure 2.3). This initial overview suggests that Royal Navy records at TNA cover the western Mediterranean better than the eastern Mediterranean (Alvarez-Castro, 2008).

As Figure 2.3 shows, coverage in Royal Navy records at TNA becomes quite good from 1710 on: for most years, between 1000 and 10,000 daily observations are preserved. From 1900 (with the exception of the World War I and II periods), 50,000 to more than 100,000 data entries per year are available. Prior to 1710, some years are still entirely absent, and there is an important gap between 1814 and 1820. The logbooks corresponding to these years are, very likely, archived at TNA, but for unknown reasons, the index documents used to locate the original logbooks cannot be found. Without these indices, the identification of ships that sailed the Mediterranean and the location of their logbooks is extremely time consuming, and has not yet been attempted. The survey presented in this section, therefore, considers only data currently available in public databases or already localized at TNA. It is certain that the gaps in British logbook records before 1710 can be filled, whether by locating nonindexed documents deposited at TNA, or by using records held at the National Maritime Museum in Greenwich or at the British Library. Archives in other European and Mediterranean countries, including France, Italy, Turkey, Greece, and Egypt, as well as the United States for the end of the period, certainly hold additional unexploited information for the seventeenth to nineteenth centuries. The abundant

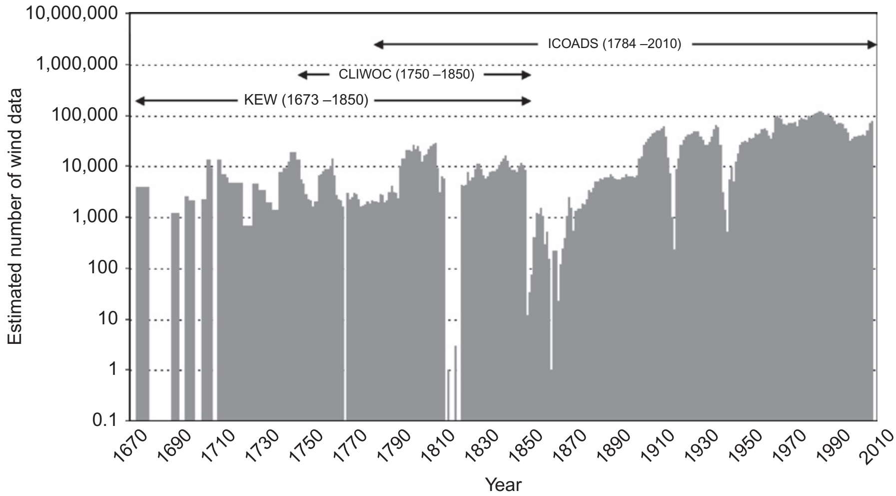

Figure 2.3 Estimation of the data availability for the wind strength and direction in the Mediterranean Sea between 1673 and 2010 from the evidences of The National Archives at Kew, CLIWOC, and ICOADS databases.

quasi-instrumental wind data preserved in ships' logbooks could, as the results for the English Channel suggest (Wheeler et al., 2010), be used to create new climatic indices that would provide powerful new tools to characterize high-frequency atmospheric circulation variability, including storm climatology, for the Mediterranean region. Logbook data can also be included in future multiproxy reconstructions and used to calibrate new climate proxies. Together with the results of projects such as CLIWOC, studies of ships' logbooks are laying the groundwork for future efforts to integrate instrumental with noninstrumental approaches, holding out the promise that all such weather data will eventually be assimilated into historical surface-input-only reanalyses (i.e., ACRE, http://www.met-acre.org; Allan et al., 2011).

2.4 Tree-Ring Information from the Mediterranean

A total of 847 tree-ring width (TRW) site chronologies were downloaded from the International Tree-Ring (ITRDB, http://www.ncdc.noaa.gov/palaeo/treering.html) or provided through personal contacts. The TRW data come from various species. Spruce (*Picea abies*; 228 sites), fir (*Abies alba*; 137), Scots pine (*Pinus sylvestris*; 111), and larch (*Larix decidua*; 79) are the dominant conifers. Data are located within 30°N to 50°N and 10°W to 40°E (Figure 2.4), with a clear focus on the Alpine arc. Site elevations range from 0 to 2500 m above sea level (asl). The highest site is located in the Spanish Pyrenees (Büntgen et al., 2008, 2010b). Many of the currently available chronologies do not cover a sufficient time span to address climate conditions during Medieval and earlier periods. One limitation is the age of the oldest trees available: the mean

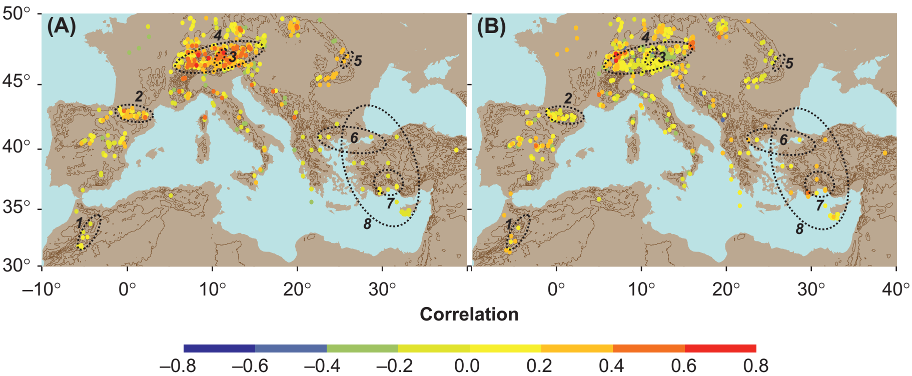

Figure 2.4 Location and climate sensitivity of 847 TRW chronologies within the GMR. Pearson's correlation coefficients are computed against gridded JJA: (A) temperature and (B) precipitation indices. Black circles refer to climate reconstructions >600 years (see Table 2.1 for details).

Table 2.1 Summary Information of the Tree Ring-Based Climate Reconstructions >600 years as Introduced in Figure 2.1 and Detailed in Figure 2.2

Site	Location	Period	Signal (Parameter)	Seasonality	Reference
1	Atlas Mountains, Morocco	AD 1049–2001	Drought (PDSI)	FMAMJ	Esper et al. (2007)
2	Pyrenees Mountains	AD 1260–2005	Temperature (°C)	MJJAS	Büntgen et al. (2008)
3	Austrian Alps	500 BC–AD 2003	Temperature (°C)	JJA	Nicolussi et al., in preparation
4	Alpine Arc	AD 951–2004	Temperature (°C)	JJ	Büntgen et al. (2009)
5	Rumanian Carpathians	AD 1163–2005	Temperature (°C)	JJ	Popa and Kern (2009)
6	Aegean Region	AD 1089–1989	Precipitation (mm)	MJ	Griggs et al. (2007)
7	Southwest Turkey	AD 1334–1998	Precipitation (mm)	MJ	Touchan et al. (2003)
8	Eastern Mediterranean	AD 1400–2000	Precipitation (mm)	MJ	Touchan et al. (2005)

number of rings per sample at the site level ranges from 50 to 1081 years, with an average time span of 188 years. The oldest trees (*Cedrus atlantica*) have been found in the Atlas Mountains in Morocco (Till and Guiot, 1990; Serre-Bachet et al., 1992; Glueck and Stockton, 2001; Esper et al., 2007; Touchan et al., 2008) and Algeria

(Touchan et al., 2010) and in southern France, where living larch (*Larix decidua* Mill.) trees date back into the first millennium (Serre, 1978). Similarly old trees have also been reported in the Balkan Peninsula. Recent pines (*Pinus heldreichii* Christ.) in Albania date back to AD 617 (Seim et al., 2010), and in Bulgaria, they roughly span the past millennium (Panayotov et al., 2010). In the east Mediterranean, absolute chronologies of *Quercus* sp. and *Juniperus* sp. from the Aegean–Anatolia region cover the past millennium (Touchan et al., 2003, 2005, 2007; Griggs et al., 2007). Anatolia and Cyprus have yielded large population sample series of *Pinus nigra* covering more than half of the past millennium (Köse et al., 2011; Kulick et al., n.d.). Similar data on *Juniperus phoenicia* and *Cedrus libani* exist for the Levant (Touchan et al., 1999, 2005, 2007) and for *Cedrus brevifolia* from Cyprus (Rich et al. 2012). Long-time-span tree information for the Iberian Peninsula is scarce, but some promising data are now available. Génova and Cancio (1999), Génova (2000), and Manrique and Cancio (2000) reported on the existence of 400-year-old forest sites in the center of the Iberian Peninsula; exciting new work in southern Spain reported at EuroDendro 2011 by M. Domínguez-Delmás of a 700-year old *Pinus nigra* chronology raises high hopes for the future. Since the preservation of long-term variability in most of the existing Iberian studies may be limited because of the detrending applied, and since their results are not always publicly available, ongoing joint tree-ring research on the Iberian Peninsula is a very high priority (Gonzalez-Rouco, personal communication).

Tree-ring data from the Alpine arc provides crucial evidence for climate variation, since the region's harsh growing conditions make tree growth particularly sensitive to fluctuations in temperature (Figure 2.4A), a factor central to previous paleoclimatic reconstructions (Frank and Esper, 2005; Battipaglia et al., 2010; Corona et al., 2010). TRW formation controlled by temperature can also be found in the Pyrenees (Schweingruber, 1985). Studies of sub-Alpine forest (Ruiz-Flaño, 1988; Rolland and Schueller, 1994; Camarero et al., 1998; Tardif et al., 2003; Andreu et al., 2007) and tree-line responses to climate change (Camarero and Gutiérrez, 2004; Camarero et al., 2005; Wiegand et al., 2006) have so far focused on local scales and living trees, but have never been used for reconstruction purposes. Larger compilations of maximum latewood density (MXD) measurements from relict wood and temporal calibration against different climatic variables are still lacking (Büntgen et al., 2010b). Additional, more scattered temperature-sensitive sites have been identified in the northern Apennines (Carrer et al., 2010), the Balkans (Panayotov et al., 2010; Seim et al., 2010), and the northwestern and southern Carpathians (Büntgen et al., 2007; Popa and Kern, 2009). Radial growth responses to changes in warm-season temperatures of higher-elevation conifers in southern Spain are still under debate (Dorado Linan, personal communication).

Heterogeneous growth-climate response patterns are obtained when TRW chronologies are correlated with June-August precipitation totals (Figure 2.4B). The highest correlations between TRW and summer precipitation are found in Iberia (Richter et al., 1991; Génova and Cancio, 1999; Génova, 2000; Manrique and Cancio, 2000), and southern France (Brewer et al., 2006; Nicault et al., 2008). Some lower-elevation sites in the Swiss Alps (Affolter et al., 2010), in the Vienna basin and Slovakia (see Büntgen et al., 2010a, for a European overview), and in southern Turkey (Akkemik and Aras, 2005; Touchan et al., 2003, 2005, 2007, 2008, 2010) also reflect fingerprints of hydroclimatic variability. Because of their pronounced growth-climate sensitivity and longevity, *Cedrus atlantica* in northern Africa and *Pinus nigra* and *P. sylvestris* north of the Mediterranean Sea are most suitable for dendroclimatic studies. Negative correlations between TRW chronologies and summer precipitation are obtained from higher elevations in the Alps and Balkan Mountains that have been demonstrated to reflect a distinct temperature signal, most likely reflecting the inverse relationship between summer temperature and precipitation (Figure 2.4). Tree-ring chronologies that cover several centuries to millennia have been developed for mountainous terrain where harsh growth conditions reduce growth rates, less anthropogenic pressure (e.g., felling, burning, and pasturing) persisted, and historical construction timber exists. However, lower-elevation sites that most likely reflect stronger signals of summer drought generally do not cover more than 250–300 years (Nicault et al., 2008) and have not been a focus of much past research; among others, the Malcolm and Carolyn Wiener Laboratory for Aegean and Near Eastern Dendrochronology at Cornell University has been attempting to address this weakness in existing data through extensive collection and building of lower-elevation chronologies of *P. brutia* in Cyprus and *P. halepensis* in the southern Levant (Griggs et al. in prep; PhD project of B.E. Lorentzen: Manning pers. comm.). Additional tree-ring parameters, such as stable isotopes, provide a promising source to capture other environmental factors (Treydte et al., 2007).

The temporal evolution of eight local- to regional-scale tree ring-based climate reconstructions reveals a rather complex picture of past climate variability. Only one record spans the entire past two millennia (Figure 2.5). Data include one reconstruction of spring/summer drought (Palmer Drought Severity Index (PDSI)) from Morocco (Esper et al., 2007), four records that reflect summer temperatures in the Pyrenees (Büntgen et al., 2006, 2010b; Morellón et al., 2012), the Alps (Büntgen et al., 2005, 2006, 2009; Nicolussi et al., in preparation), and the Carpathians (Popa and Kern, 2009), as well as three reconstructions of spring/summer precipitation in the eastern Mediterranean (Griggs et al., 2007; Touchan et al., 2005, 2007). See Figure 2.5 for the reconstructed climate histories and Table 2.1 for further information on the data used.

Overall, these data indicate that the hydroclimate of North Africa was generally drier before ~1350, characterized by a transition period until ~1450, then generally wetter until the 1970s. Superimposed on this long-term behavior are distinct decadal fluctuations, including current drought since the early 1980s (Esper et al., 2007). The temperatures of the Pyrenees were warmer than average in the fourteenth and fifteenth centuries, as well as in the twentieth century. A prolonged cooling occurred from ~1450 to 1850. Six of the ten warmest decades fall in the twentieth century, whereas the remaining four are reconstructed for 1360–1440 (Büntgen et al., 2008, 2010b). In the Alps, temperatures begin to increase ca. 600, reaching Roman levels again in the early 800s. Temperature variability was lower during ~700–1300. Colder summers, corresponding to the Little Ice Age (LIA), are characteristic of the period ca. 1300–1850. More recent anthropogenic warming registered in these data is unprecedented in the light of past natural variability (Büntgen et al., 2009; Nicolussi et al., in preparation). The Carpathian temperatures agree well with those of the Alps, showing the cold summers associated with the LIA from 1370 to 1630, followed by cold decades again in 1820 and 1840. Recent warming is most

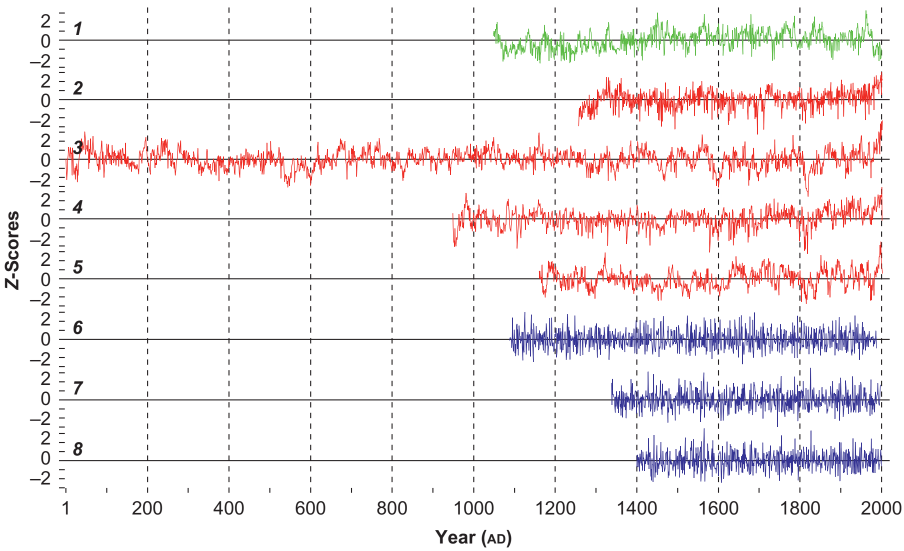

Figure 2.5 Climate reconstructions >600 years as introduced in Figure 2.4, after *Z*-transformation over their individual lengths. Green, red, and blue colors refer to drought, temperature, and precipitation sensitivity, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this book.)

pronounced from the 1980s onward (Popa and Kern, 2009). Precipitation measurements for the Mediterranean are restricted to high-frequency, interannual to decadal-scale variations and cover time spans ranging from 350 (Turkey, Jordan) to 1000 (Algeria, Morocco) years. Results are in line with other studies from the eastern Mediterranean and Middle East (Touchan et al., 1999, 2003, 2005, 2007, 2008, 2010; D'Arrigo and Cullen, 2001; Akkemik and Aras, 2005; Akkemik et al., 2005, 2008; Griggs et al., 2007). These records, however, do not allow conclusions to be drawn regarding long-term hydroclimatic changes, since the individual ring-width measurement series have been standardized in a manner that eliminates any possible lower-frequency variability.

For the eastern Mediterranean, the enormous existing data pool could fruitfully be reanalyzed, with the overall aim of preserving the full range of past natural and recent anthropogenic hydroclimatic variability. Current endeavors in developing multicentennial to millennium-long composite TRW and MXD chronologies from across the Balkan Peninsula—Slovenia, Croatia, Bosnia, Herzegovina, and Montenegro (Levanič, personal communication), as well as Albania (Levanič and Toromani, 2010; Seim et al., 2010) and Bulgaria (Panayotov et al., 2010)—should soon yield results that enhance our knowledge of past variation in both warm-season drought and temperature. Further, enormous efforts already underway to collect historical and archaeological wood remains in the eastern Mediterranean should make it possible to extend the TRW network toward the Near East, and prior to the Common Era (T. Wazny, personal communication; Kuniholm, 1996; Kuniholm et al., 2007; Manning et al., 2012). A dendrochronology covering >1500 years already exists from that region, placed within ±5 calendar years with 95% confidence limits, based on long-floating but near-absolutely dated *Juniperus* sp. and other conifer species (Manning et al., 2001, 2010). While work on historical construction timber and archaeological wood has indicated that in some cases provenance might be a critical issue (Tegel, personal communication), this may provide the impetus to develop isotopic records from such archaeological tree-ring records, since these isotopic records tend to record a regional rather than a local signal (Gagen et al., 2007; Andreu et al., 2008).

2.5 Speleothem Information from the Mediterranean

Speleothems (stalagmites, stalactites) are cave deposits that form when calcium carbonate precipitates from degassing solutions as they seep into limestone caves. During the past decade, speleothems have emerged as one of the highest quality archives now available for continental climate variability. Stalagmites in particular can now yield precisely dated and highly resolved records of either precipitation or temperature (Mangini et al., 2005; Zhang et al., 2008; Baker and Bradley, 2010). This climate archive has several strengths: it can potentially provide long records (10^3–10^4 years) at temporal resolution as high as subannual, with very precise chronologies (Cheng et al., 2009). Yet, by comparison to other terrestrial climate archives, such as lake sediments or tree rings, speleothems remain underexploited. This is particularly true for the Mediterranean: although karst areas and caves are abundant, very few stalagmite records covering the late Holocene (last 2k years) have been constructed so far (Figure 2.6).

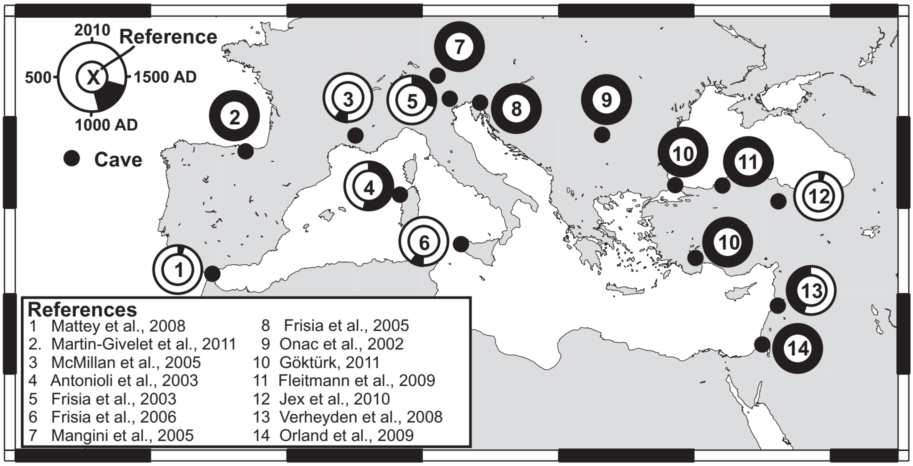

Figure 2.6 Geographical distribution of speleothem-based climate reconstructions. The filled section of the "wheel-diagram" shows the timer interval represented by each record. Assigned numbers denote references listed in the inserted text box.

The analysis of speleothems involves measuring various physical and chemical parameters, yielding information on precipitation, temperature, and other aspects of the environment (McDermott, 2004). The three most frequently measured parameters are the oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotope ratios found in stalagmite calcite and the thickness of annual growth layers (Frisia et al., 2003; Orland et al., 2009). In principle, stalagmite $\delta^{18}O$ values depend on the isotopic composition of cave drip water and therefore of precipitation. In turn, climatic effects influence $\delta^{18}O$ in precipitation; these include temperature, seasonality, and the origin and quantity of precipitation (Lachniet, 2009). Stalagmite $\delta^{13}C$ values depend on a number of processes including: (1) changes in surface vegetation (the proportion of C3 to C4 photosynthetic pathway plants), (2) soil microbial activity, and (3) changing rates of kinetic fractionation as calcite precipitates (in turn, due to changes in drip rates or cave air pCO_2). As most of these processes are ultimately governed by temperature and precipitation, calcite $\delta^{13}C$ values are a suitable proxy for moisture (Fleitmann et al., 2009). Finally, the supply and Ca content of drip water largely govern the rate at which speleothems grow, typically by the annual deposition of calcite bands ranging in thickness from 0.1 to 0.8 mm. Comparison of annual bands in stalagmites with instrumental time series of precipitation and temperature reveals that thicker bands correlate with either higher temperatures (Frisia et al., 2003) or higher effective moisture (Fleitmann et al., 2009). To date, very few stalagmite-based paleoclimate reconstructions exist for any part of the Mediterranean, and most studies have focused on centennial- to millennial-scale change. Figure 2.6 shows the location of speleothem records that cover any period from the past century up to the last 2k years. Many of these records are rather short (Antonioli et al., 2003; Mattey et al., 2008; Jex et al., 2010, 2011), fragmentary (Orland et al., 2009), or coarsely resolved (Bar-Matthews et al., 2003; Verheyden et al., 2008). But even though few speleothem time series covering the last 2k years have been published, these already show that high-quality time series of temperature and precipitation can be constructed from this recently developed paleoclimate archive.

As yet, few studies of speleothems from Mediterranean-region caves have tried to construct quantitative records of temperature and precipitation. To our knowledge, the only examples published to date are those from Spannagel Cave in Austria (point 6 in Figure 2.6; Mangini et al., 2005) and Akçale Cave in Turkey (point 11 in Figure 2.6; Jex et al., 2010). Only the work of Mangini et al. (2005) involves speleothem time series extending far back before the availability of instrumental data and thus begins to develop the promise of this new climate proxy for paleoclimate reconstruction. For Spannagel Cave, Mangini et al. (2005) found a strong correlation between stalagmite $\delta^{18}O$ and alpine yearly air temperatures. Based on a transfer function, Mangini et al. (2005) found that mean annual air temperature varied between 0°C and 2.7°C, with an uncertainty of ±0.3°C over the past 2k years. During the Medieval Climate Anomaly (MCA; AD 800–1300), temperatures were higher than the modern mean temperature of 1.8°C (Figure 2.7). The lowest temperatures, around 0°C, were observed during the Maunder Minimum (end of the seventeenth/early eighteenth century). Other studies published to date focus on correlating speleothem parameters with contemporary instrumental data, thus developing our

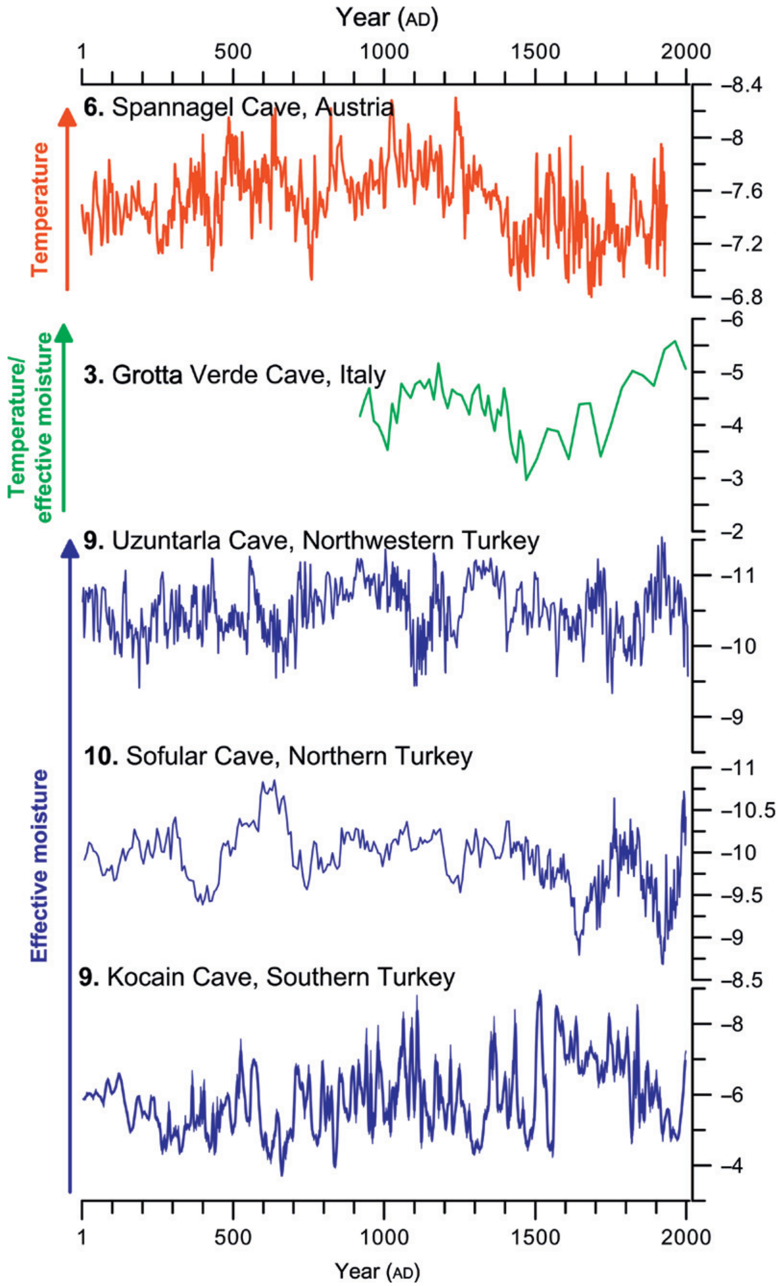

Figure 2.7 High-resolution stalagmite isotope profiles (oxygen and carbon) from Spannagel Cave in Austria (Mangini et al., 2005), Grotta Verda Cave in Italy (Antonioli and Frisia et al., 2003), Sofular Cave in northern Turkey (Fleitmann et al., 2009; Göktürk et al., 2011), Urzuntala Cave in northwestern Turkey (Göktürk, 2011), and Kocain Cave in southern Turkey (Göktürk, 2011).

understanding of the factors likely to control variation in these parameters for earlier periods and perhaps for other sites as well, but not as yet contributing directly to paleoclimate reconstruction. For a stalagmite from northeast Turkey, Jex et al. (2010) correlated δ^{18}O with instrumental data, finding the strongest correlation between δ^{18}O and the total quantity of late autumn–winter precipitation (October–January), smoothed by 6 years as storage and event water mixed in this particular karst system. Although the stalagmite studied began to form around AD 1750, published data covered only AD 1961–2005. Similarly, in New St. Michaels Cave in Gibraltar (point 1 in Figure 2.6), Mattey et al. (2008) developed an oxygen and carbon isotope record with bimonthly resolution for the period between 1951 and 2004, unique not only for its temporal resolution but also for its accurate dating. Stalagmite δ^{18}O correlates especially closely with δ^{18}O of winter precipitation. This result extends our understanding of factors governing δ^{18}O and δ^{13}C in speleothem calcite, which should help interpret samples from other caves. But the study did not extend climate data for Gibraltar before the period covered by instrumental records.

Martín-Chivelet et al. (2011) reconstructed the surface temperature changes for the last 4000 years in the northern part of Castilla-León, in northern Spain using a high resolution of carbon stable isotope records of stalagmites from three caves separated several tens of kilometers away in N Spain. The record shows a warm period 2500 -1650 yr BP (Roman Warm Period), with maximum temperatures between 2150 and 1750 yr BP, from 1650 -1350 yr BP a cold interval (Dark Ages Cold Period), with a thermal minimum at ~1500 yr BP. Also, Martín-Chivelet et al. (2011) show also generally warm conditions from 1350 -750 yr BP (Medieval Warm Period) punctuated by two cooler events at ~1250 and ~850 yr BP followed by lower temperatures during the subsequent period 750 -100 yr BP (Little Ice Age) with extremes occurring at 600 -500 yr BP, 350 -300 yr BP. The last 150 years, characterized by rapid but no linear warming (Modern Warming). Annually laminated stalagmites from Grotta di Ernesto (point 4 in Figure 2.6; Frisia et al., 2003), northern Italy, show a close correlation between growth rate and temperature, with thinner annual layers correlating with lower temperatures. Thin and dark layers are reported for the intervals between AD 1650 and 1713 and from AD 1798 to 1840, which coincide with low solar activity (Maunder Minimum and Dalton Minimum).

Currently, paleoprecipitation records are almost entirely lacking for the eastern Mediterranean. Speleothems promise to be one of the climate proxy archives best suited for reconstructing precipitation on a local to regional scale; speleothem studies, therefore, hold great promise for filling this gaping hole in our knowledge of Mediterranean paleoclimates. Stalagmites have been collected in three different regions of Turkey (points 9, 10, and 11 in Figure 2.6), and several records cover the last 2k years continuously at high resolutions (monthly to pentadal) (Fleitmann et al., 2009; Göktürk et al., 2011; Göktürk, 2011). A 250-year-long, seasonally resolved oxygen and carbon isotope record from a stalagmite from Sofular Cave (point 10 in Figure 2.6) shows a strong correlation with the amount of precipitation and thus effective moisture (Figure 2.7), once again demonstrating that stalagmites can record local- to regional-scale hydrological changes. A longer record from Sofular Cave (Fleitmann et al., 2009), covering the last 2k years continuously, shows a long-term decrease in precipitation and effective moisture, but no distinct MCA or LIA.

Remarkably, none of the three stalagmite records from Turkey strongly expresses the MCA or LIA (Göktürk et al., 2011; Göktürk, 2011). A stalagmite from Kocain Cave in southern Turkey yielded the clearest MCA and LIA pattern, indicating decreased precipitation during the MCA, then a wetter LIA, consistent with models simulating the MCA (Graham et al., 2011). All three stalagmite time series from Turkey reveal multidecadal drought episodes prior to the twentieth century, during which spring–summer precipitation was considerably lower than today. This indicates that the aridification trend postulated for present-day Turkey remains within the range of natural climate variability over the past two millennia, at least in western Turkey (Göktürk et al., 2011; Göktürk, 2011). Supporting the same inference, instrumental records from western Turkey do not reveal statistically significant changes in precipitation (Xoplaki, 2002). Thus, ongoing desertification in Turkey is best explained by destructive land use, including excessive grazing, urbanization, soil erosion, and unsustainable fire patterns. As yet, human-induced climate change is not implicated (Çetin et al., 2007).

Further south, a stalagmite from Soreq Cave in Israel was analyzed at very high resolution for ca. AD 1–1100 (point 13 in Figure 2.6; Orland et al., 2009). Underlying dating precision, however, is not of equally high resolution, and coverage is irregular (Orland et al., 2009; see especially Table 2.1 and Figure 2.6). Based on studies of the modern water-carbonate system in Soreq Cave (Bar-Matthews et al., 1996), $\delta^{18}O$ calcite values are interpreted to relate to changes in the amount of winter and spring precipitation and, on shorter timescales, to changes in seasonal distribution of precipitation. Based on the linear correlation between annual precipitation and annual average $\delta^{18}O$, Orland et al. (2009) found a decrease in average annual precipitation of 300–400 mm (with respect to current conditions) between AD 100 and 700, with abrupt shifts at AD 100 and 400. This reconstruction of a long-term trend toward lower annual precipitation correlates with some claims for a drop of 10–15 m in the level of the Dead Sea between 100 BC and AD 700 (Bookman et al., 2004) – but runs counter other reconstructions (Migowski et al. 2006; cf. also Rambeau and Black 2011, Figure 7.2, 99).

Since karst formations extend across broad areas throughout the Mediterranean region, and limestone caves are numerous, there is endless potential to expand and improve stalagmite-based climatic reconstructions for the region. Meaningful comparison with data from other climate proxies, such as tree rings (see Section 2.4), demands that future stalagmite records be of high quality, with high temporal resolution. However, at least three serious obstacles remain. First, even from stalagmites showing clearly visible annual layers, it can be very difficult to construct annually resolved time series. At the same time, since thorium concentrations in many stalagmites are very low, it is difficult to date nonlaminated late Holocene stalagmites by the uranium (U)-series method, leaving typical age uncertainties for stalagmites younger than 2k years in the 5–50-year range. Second, speleothem-based climate transfer functions, in order to be applied to long speleothem time series, require the prior availability of high-quality cave-monitoring data. But relevant extended cave-monitoring data are largely absent, strictly limiting our understanding of the most frequently used speleothem climate proxies ($\delta^{18}O$, $\delta^{13}C$, annual layer thickness, and trace elements). Third, multisample and multiproxy (stable isotopes, annual layer thickness, trace elements) approaches are needed even to begin defining the uncertainties associated with individual speleothem proxies. However, such approaches demand that samples be included from several caves within one region, a substantial additional requirement. The most important task for the next few years, then, will be to identify caves we know must exist—for example, in karstic terrain—across the Mediterranean, which can be studied with careful attention to known sources of uncertainty so as to yield high-quality samples covering all of the last 2k years.

2.6 Paleoflood and Storm Records from the Mediterranean

Mediterranean river hydrology strongly reflects the seasonal distribution of precipitation (Xoplaki, 2002; Thornes et al., 2009). The river flow regime in the region is characterized by maximum discharge during the cold season, minimum discharge in the summer, and extreme variability on both seasonal and annual timescales, with peak discharges frequently more than 50 times average flows. Past hydrological records reflect similar hydroclimatic variability, with wet and dry episodes alternating over decadal to centennial timescales, punctuated by abrupt transitions reflecting changes in atmospheric circulation (Macklin et al., 1995; Benito et al., 2003a,b; Macklin and Woodward, 2009). To date, five types of sedimentary flood record have been studied for the Mediterranean: (1) overbank floodplain deposits (Zielhofer and Faust, 2008), (2) flood-basin environments (Sancho et al., 2008), (3) river-channel gravels (Schulte, 2002), (4) mountain-torrent deposits (i.e., debris flows and boulder berms) (Maas and Macklin, 2002); and (5) slack water flood sediments (Benito et al., 2003a). Alluvial valley floor cut-and-fill sequences, where river channel (3), floodplain (1), and flood-basin (2) deposits are most often preserved, tend to record changing discharge-sediment load relationships over longer periods (decades to centuries). By contrast, bedrock systems, where slack water (5) and boulder berm (4) deposits are most commonly found, can resolve individual flood events, sometimes on annual to decadal scales (Maas and Macklin, 2002; Thorndycraft and Benito, 2006).

More recent fluvial research in the Mediterranean has focused on extending and increasing the resolution of flood series across both time and space. Flood patterns are of interest primarily as indicators of changing atmospheric circulation patterns, modulated in turn by climate variability (Maas and Macklin, 2002; Macklin et al., 2006; Thorndycraft and Benito, 2006; Macklin et al., 2010). Both site-based flood chronologies (Benito et al., 2003a; Benvenuti et al., 2006) and regionally aggregated flood histories (Arnaud-Fassetta et al., 2010) have been incorporated into large radiocarbon-dated fluvial databases; meta-analysis has yielded increasingly higher-resolution chronological frameworks. However, regional coverage remains uneven. Here, we focus on regions where flood chronologies are relatively well understood, including Spain, France, and Italy for the western Mediterranean; Tunisia; and Turkey, Greece, and Israel for the eastern Mediterranean. Following the approach pioneered by Macklin and Lewin (2003), systematic and probability-based analysis has been applied to radiocarbon-dated fluvial deposits from a growing number of Mediterranean regions, facilitated by the analysis of different subsets of radiocarbon dates and the classification of flood chronologies by depositional environment and drainage basin physiography (Macklin et al., 2006; Thorndycraft and Benito, 2006;

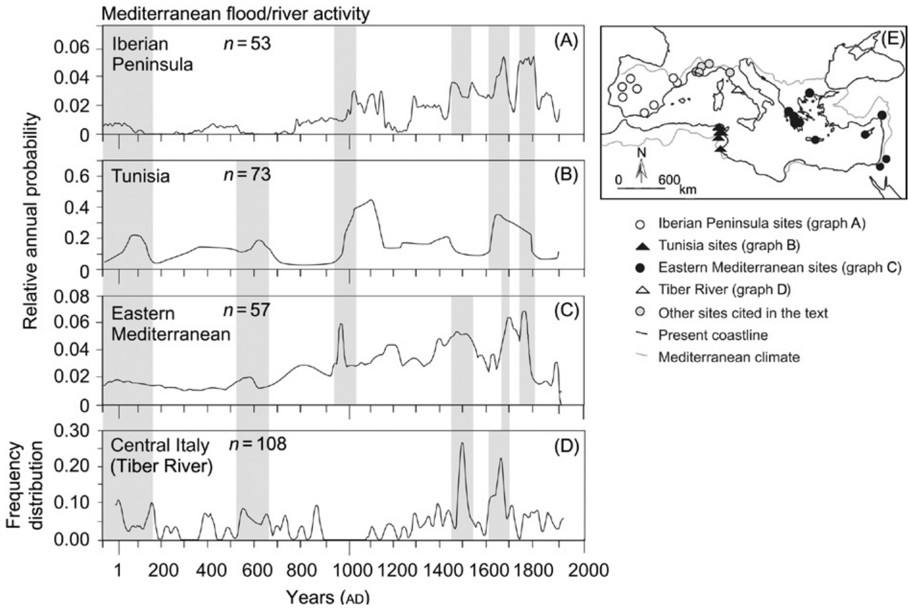

Figure 2.8 Periods of enhanced flood/fluvial activity (vertical gray bars) with distribution of region-wide flood periods identified in the second, sixth to seventh, tenth, late fifteenth, and late eighteenthh centuries. (A) Cumulative probability density (CPD) plot resulting from summed distributions of calibrated radiocarbon dates collected from slack water flood deposits in the Iberian Peninsula (Thorndycraft and Benito, 2006; Benito et al., 2008). CPD plot provides a best estimate for the temporal distribution of the radiocarbon dates entered into the calculation, with peaks being interpreted as an increase in flooding (Macklin et al., 2006); (B) CDP plot of radiocarbon samples from Tunisian floodplain sequences (Zielhofer and Faust, 2008); (C) CDP plot of radiocarbon samples ($n = 25$) and optically stimulated luminescence ($n = 32$) from eastern Mediterranean alluvial sequences based on bibliographic sources; (D) temporal distribution of the Tiber river annual flood series as recorded in documentary archives, filtered using a Hamming–Tukey filter (after Camuffo and Enzi, 1995); (E) location of rivers used in the CDP plots and/or described in the text.

Macklin and Woodward, 2009). We review the results of these analyses region by region, so as to evaluate changes in the spatial and temporal distribution of floods in the Mediterranean as a whole over the last 2k years.

For the Iberian Peninsula, written documents and sedimentary archives have yielded evidence for flood variability going back a millennium. The sedimentary record reveals increased flood frequency and magnitude at 1000–1150, 1430–1700, and 1730–1800 cal AD (Figure 2.8), though the chronological resolution possible from radiocarbon dating is relatively poor for the last 300 years (Benito et al., 2008). For Iberian Atlantic rivers, written documentary records also note a period of increased flooding, associated with unusually wet winters, between AD 1000 and 1200 (Benito et al., 2003b). The largest peak flood discharges since AD 1500 (Benito et al., 2003b, 2008) occurred when the North Atlantic Oscillation during the winter months was in its negative phase, as reconstructed by Luterbacher et al. (2002).

For Iberian Mediterranean rivers, documentary sources indicate that the most severe floods occurred during AD 1580–1620 and AD 1840–1870 (Barriendos and Martín Vide, 1998; Llasat et al., 2005). The period AD 1760–1800 was also noteworthy for its strong climatic variability, bringing both significant floods and major droughts (Barriendos and Llasat, 2003). The lack of slack water deposits between AD 1200 and 1400 suggests that this was a period when large floods were particularly infrequent, as the documentary record also indicates, in its only clear correlation with sediment archive evidence (Benito et al., 2003b). However, this period saw one of the main phases of historical floodplain aggradation of Iberian rivers (Vita-Finzi, 1969; Butzer et al., 1985); this has been interpreted as a result of changing land use, rather than climate (Butzer, 1980). This high medieval phase of accelerated alluviation is ubiquitous for Spanish rivers and was great enough that it commonly resulted in the burial of irrigation structures (Butzer et al., 1985).

Flooding in the Mediterranean rivers of southern France has been studied as far back as 100 BC. Three alternating flow regimes characterize these rivers: flood dominated (i.e., large floods and high mean discharge), drought dominated (i.e., large floods absent and low mean discharge), and irregular (i.e., major floods combined with low mean discharge) (Arnaud-Fassetta and Landuré, 2003). Flood-dominated regimes, recorded by channel avulsion and fluvial metamorphosis, characterized the periods 100 BC to AD 200, AD 450–700, and AD 1350–1850, corresponding to the LIA (Arnaud-Fassetta et al., 2010). The Durance River (Jorda and Provansal, 1996; Jorda et al., 2002), South Alpine rivers (Miramont et al., 1999), and middle Rhône and pre-Alpine rivers all experienced the same periods of increased fluvial activity (Berger, 2003). The period between 100 BC and AD 200 was also one of higher river-channel and floodplain sedimentation rates (Arnaud-Fassetta, 2002; Arnaud-Fassetta and Landuré, 2003). Several large floods occurred within a predominantly wet period (Provansal et al., 1999). Human activity and land-use change likely amplified this first- and second-century aggradation phase in the Rhone catchment (Salvador et al., 2002; Berger, 2003). In the Durance River, increased flood frequency, the result of greater spring and winter rainfall, was recorded at AD 1550–1610 and 1750–1810, with four to five floods per decade for each of these periods (Guilbert, 1994). Periods of frequent flooding in French Mediterranean rivers, at 850–1050 and 1400–1850 cal AD, partly coincide with those recorded in the Spanish catchments at these times.

Varied records reveal both individual major floods and broader patterns of change in flood frequency, for rivers in western Italy going back to the first centuries CE. A detailed investigation of the alluvial stratigraphy of the Arno and Serchio rivers in western Tuscany, Italy, reported the discovery of at least 16 well-preserved Roman ships, most probably destroyed by flows generated by levee crevassing of the Arno River (Benvenuti et al., 2006; Mariotti-Lippi et al., 2007). Radiocarbon dating of these shipwrecks and other archaeological wood remains demonstrated major flooding at AD 150, 375, 500–700, and 900. Similar periods of flooding on the Tiber are also recorded in documentary sources (Camuffo and Enzi, 1995; Figure 2.8), with the exception of the episode around AD 375 (Camuffo and Enzi, 1995). Over the last 1k years, floods in the Tiber River were particularly frequent at AD 1400–1500 and

Table 2.2 Major Periods of Flooding in the Mediterranean Region over the Last 2000 Years

Spain	France	Tunisia	Italy	Eastern Mediterranean
AD 1730–1800	AD 1400–1850	AD 1625–1800	AD 1400–1700	AD 1675–1775
AD 1430–1700				AD 1350–1550
				AD 1200
AD 1000–1150	AD 850–1050	AD 975–1150	AD 900	AD 950
	AD 450–700	AD 625	AD 500–700	AD 575
			AD 375	
	AD 1–200	AD 150	AD 150	

1600–1700 (Camuffo and Enzi, 1995). The periods AD 1000–1400, 1500–1600, and 1700 onward show low flood frequencies.

While evidence of flood activity is almost absent for North Africa, one study using radiocarbon dating of floodplain deposits in central Tunisia has identified periods of increased flood activity at AD 150, 625, 975–1150, and 1625–1800 (Zielhofer and Faust, 2008; Figure 2.8).

For the eastern Mediterranean, sediment data from Greece, Turkey, and Israel cover the last 1.5k years. A similar picture emerges from numerous studies of sites on the Greek mainland (Fuchs and Lang, 2001; Koukouvelas et al., 2001; Fuchs and Wagner, 2003, 2005; Jing and Rapp, 2003; Lespez, 2003; Pavlides et al., 2004; Pope and Wilkinson, 2006) and islands (Maas, 1998; Maas et al., 1998; Deckers, 2005; Zacharias et al., 2009; Macklin et al., 2010); in Turkey (Beach and Luzzadder-Beach, 2008; Casana, 2008); and in Israel (Goldberg, 1984; Greenbaum et al., 2000). For each of these regions, periods of significant flooding are recorded at AD 575, 950, 1200, 1350–1550, and 1675–1775 (Figure 2.8).

Table 2.2 lists major flooding periods in the Mediterranean over the last 2k years. Taking the Mediterranean as a whole, periods of region-wide flooding can be identified ca. AD 100–200, 500–700, 900–1000, 1450–1500, and 1750–1800, which all coincide with relatively wet and cold climatic conditions. Conversely, periods of very low flood frequency in the Mediterranean begin ca. AD 200, 675, 910, 1225, 1600, and 1825. The relationship between recent climate change and flooding in the Mediterranean is difficult to evaluate because of extensive human modification of floodplains and widespread river regulation structure, particularly over the last 100 years. Nevertheless, it does appear that more frequent and severe floods were recorded in the late fifteenth and late eighteenth century than in the twentieth century (Sheffer et al., 2008). Mediterranean steepland catchments, less affected by human activity, experienced a significant reduction in both the frequency and magnitude of major floods in the second half of the twentieth century: this reduction may be more readily attributable to reduced precipitation and broader climate change (Maas and Macklin, 2002; Macklin et al., 2010).

Coastal populations are exposed to frequent and intense storm events, the human and socioeconomic impacts of which—whether infrastructure damage and its associated economic effects or human mortality—cannot be underestimated. In recent years, interest in past histories of major storm events has increased, leading to the emergence of the field of paleotempestology. The brief time span covered by instrumental records has motivated researchers to extend storm records further into the past by developing methods to study sediment archives reflecting past storms and their frequency, intensity, and effects; to correlate these archives with documentary records; and to investigate both the physical mechanisms at work and their links to climate variability and, potentially, to global warming. Relevant sediment archives record storms preceding the period covered by instrumental data, and contribute to understanding their patterns of occurrence. But even more important, they shed light on the vulnerability of low-lying coastal regions, and provide a basis for risk assessment—both crucial issues in the context of future predictions, given the increasing human populations in the coastal Mediterranean.

In particular, coastal lagoons preserve storm-induced overwash deposits, which potentially represent high-quality proxies for paleostorm activity. During the past decade, investigation of backbarrier sediments has yielded reconstructions of the long history of storm events, allowing exploration of the links between climate variability and the frequency and intensity of these extreme events on longer timescales. Strong winds can cause the breaching of lagoon sand bars, so that marine flooding carries coarse-grained material containing shell and shell fragments into the lagoon. Identification of such events relies on geochemical and biological indicators in the overwashed deposits, and cross-validation with textual sources (Sabatier et al., 2008, 2012; Woodruff et al., 2008; Dezileau et al., 2011). Current methods involve a multiproxy approach, integrating sedimentary textures, microfossils, sedimentary organic elemental ratios, and stable isotopes to diagnose storm deposits. Among biostratigraphic indicators, marine organisms or microfossils (such as coccolithophorids, diatoms, and foraminiferas) transported onshore and deposited in the backbarrier are used to detect depositional storm layers. These can be further characterized by the C:N ratios and $\delta^{13}C$ of their organic matter content, both easily measured in these sediments, since sudden influxes of marine organic matter result in heavier $\delta^{13}C$ and lower C:N ratios. Based on geo- and bio-indicators in sediment cores, Dezileau et al. (2011) have shown increased paleostorm frequency in the Languedoc region of southern France during the late LIA. A 7000 year high-resolution record of paleostorm events along the French Mediterranean coast over established from a lagoonal sediment core in the Gulf of Lions indicates periods of increased storm activity at 400 -50 cal yr BP (within the Little Ice Age) and low storm activity within the Medieval Climate Anomaly (1150 -650 cal yr BP). Future investigations should target lagoons in other Mediterranean regions, especially those whose shoreline orientation differs so as to allow a variety of conditions with regard to storm exposure to be reflected, and thus to document different wind/climatic regimes.

2.7 Lake Sediments from the Mediterranean

Mediterranean lakes record past changes in climate and water balance via a range of proxy indicators preserved in their sediments. A fundamental distinction is between open and closed lakes—that is, those with and without surface outflow. In climatically wetter regions of the Mediterranean basin, most lakes have a positive water balance and they discharge solutes via outflow (see also Section 2.6), so that their waters remain fresh. However, in some high mountain regions, such as the Pyrenees, hydrologically open alpine lake systems have been sensitive to temperature variations both directly (e.g., ice cover) and indirectly (e.g., tree-line elevation) (Pla and Catalan, 2005). By contrast, lakes in drier Mediterranean regions lose water mainly through evaporation from the lake surface and their waters may become saline (Roberts and Reed, 2009). An important attribute of these closed (i.e., nonoutlet) lakes is that they respond dynamically to changes in water balance by adjusting their volume and surface area. At times of negative water balance, the area of a closed lake shrinks, water levels fall, and salinity increases, while the opposite occurs at times of positive water balance. Water levels thus change constantly in these endorheic lakes in response to fluctuations in climate, particularly in precipitation. Crater lakes and other "simple" closed water bodies, as well as some karstic systems, can therefore act as giant rain gauges, whose water level and/or salinity variations reflect past periods of drought and flood. Hence, closed lakes are of particular value in reconstructing regional hydroclimatic changes.

There are several ways in which past changes in the water balance of Mediterranean lakes have been recorded in their sedimentary and geomorphological records. Past water-level fluctuations can be reconstructed via dated lake marginal depositional facies, such as shoreline terraces and carbonate platforms (Magny, 2006), and by changes in the planktic:benthonic ratio of diatoms and other biological indicators (Barker et al., 1994). Shifts in lake-water salinity are preserved in proxies, both chemical (e.g., Sr:Ca ratio) and biological (e.g., ostracod assemblages). In the case of diatoms, past changes in lake salinity have been quantified via transfer functions that model statistically the relationship between modern water chemistry and species assemblages, as developed for Spanish lakes by Reed (1998). An especially useful technique for reconstructing lake-water balance over a hierarchy of timescales is oxygen isotope analysis. Freshwater lakes with a short residence time have an oxygen isotopic composition similar to that of incoming precipitation, while those with a longer residence time and large evaporative losses have increasingly positive $\delta^{18}O$ values. Lake $\delta^{18}O$ values can be sensitive to regional water-balance changes even in freshwater systems in the Mediterranean, so long as hydrological losses occur mainly through evaporation rather than surface outflow (Roberts et al., 2008). Stable isotopic signatures are preserved in lake sedimentary records as authigenic calcite–aragonite crystals or in the shells of mollusks and ostracods.

Both intrinsic features of lake records, and the types of paleolimnological research most common in the Mediterranean to date, mean that these records are of value primarily in reconstructing fluctuations in climate over multidecadal and longer timescales (Fritz, 2008), though some—which will be the focus of this discussion—do provide subdecadal resolution, and therefore can yield insight into higher-frequency climate variability. Further, paleolimnological studies of Mediterranean lakes have usually involved Holocene or longer timescales (see Abrantes et al., in this book); relatively few have focused specifically on the last 2k years. Most published lake-sediment records are thus often of limited value for reconstructing late-Holocene climatic fluctuations. First, given the long timescales targeted, sampling intervals for most lake cores are no better than centennial, so that they can detect only long-term, multicentury climate trends. Physical mixing of sediments in shallow lakes compounds the problem, leading to a smoothed climate signal. Second, dating control for the past two millennia is often very poor and frequently compounded by recent wetland desiccation or drainage, so that the uppermost (i.e., most recent) part of the sedimentary record is missing or perturbed. Third, human impact during the late Holocene has frequently been significant enough to overlay any climatic signal: for example, when inwashed detrital carbonate compromises the integrity of $\delta^{18}O$ measurements on nonbiogenic materials (Leng et al., 2010) or in cases in which drainage and water consumption for irrigation have led directly to decreased lake levels. Deforestation, too, has altered the hydrology of many catchments (see Section 2.6), increasing runoff rates and potentially raising lake-water levels. For these reasons, we focus here on the limited number of Mediterranean lakes with well-resolved late-Holocene climate records, supplementing them where appropriate with information based on more ubiquitous lower-resolution lake sequences. A compilation of lake records discussed in this section is presented in Figure 2.10.

2.7.1 Late-Holocene Climate Records from Eastern Mediterranean Lake Sediments

Stable isotopes, paleosalinity changes inferred from biological and geochemical indicators, and other proxy-climate data from lakes suggest more favorable water-balance conditions during the early to mid-Holocene in the East Mediterranean (Roberts et al., 2008). The "modern" range of climate appears to have been established during the past four millennia. In the eastern Mediterranean, Nar Crater Lake in Turkey has one of the best-resolved late-Holocene climate records. Its continuously varved sediments provide a well-dated proxy-climate sequence for the last 1720 years, with decadal or better time resolution (Jones et al., 2006; Woodbridge and Roberts, 2011). $\delta^{18}O$ measurements on authigenic carbonates provide a record of changes in regional water balance, and mass-balance modeling has been used to calibrate these isotope data climatically (Jones et al., 2005). $\delta^{18}O$ data show more positive values, inferred to indicate drier climatic conditions, from AD 300 to 500 and again from AD 1400 to 1960, with more negative isotopic values, and a wetter climate, between AD 560–750, 1000–1400, and 1960–2000 (Figure 2.10). Diatom evidence for high lake salinities ca. AD 400–500 (Woodbridge and Roberts, 2011) appears to confirm that this was a period of extended drought in central Anatolia. The Nar sequence provides a basis for comparison with lower-resolution lake isotope records from the eastern Mediterranean; the record from Lake Van, in eastern Turkey (Wick et al., 2003), may be especially useful, because it is also varved and unaffected by sediment mixing/smoothing. Van is the largest lake by volume in the entire circum-Mediterranean region, and the world's biggest soda lake. In order to facilitate comparison, standard normalized data are shown along with the 100-year mean values for Nar. Figure 2.9 also includes $\delta^{18}O$ results on ostracods from the Greek lake at

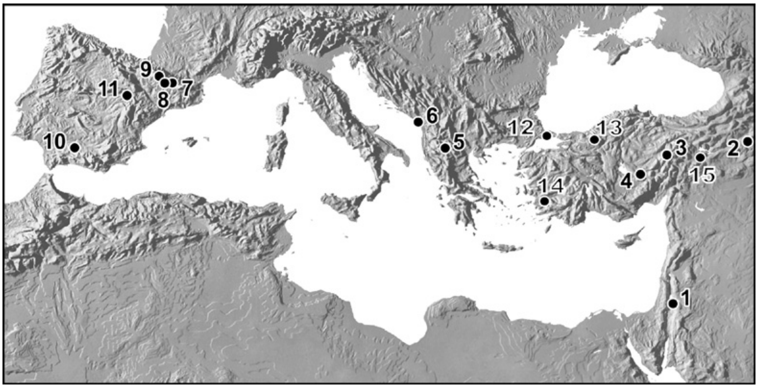

Figure 2.9 Lake records discussed in text and partly shown in Figure 2.10. 1. Dead Sea, 2. Van, 3. Tecer, 4. Nar, 5. Ioannina, 6. Skhodra, 7. Redó, 8. Montcortès, 9. Estanya, 10. Zoñar, 11. Taravilla, 12. Kucukcekmece Lagoon (Istanbul), 13. Yenicaga Lake (Bolu), 14. Bafa Lake (Aydin-Mugla), 15. Hazar Lake (Elazig).

Ioannina (Frogley et al., 2001) and freshwater phases at Tecer Lake in central Turkey inferred from sedimentological and mineralogical analyses (Kuzucuoğlu et al., 2011). These lake records show similar overall trends for the last 2k years, with generally drier hydroclimatic conditions between AD 1400 and the twentieth century, a wetter phase during the period AD 950–1350, and a marked dry-to-wet climatic transition between AD 400 and 600. The result of multiproxy data (XRF, MSCL, TOC/TIC, $d^{18}O$- $d^{13}C$) from Bafa Lake , Kucukcekmece Lagoon and Yenicaga Lake sediment cores, wet conditions are observed between ca AD 750-1350 and AD 1700-1880 and dry conditions are found ca AD 250-750, AD 1350-1700 and AD 1880-1950 (Akcer-On, 2011). The LIA Phase I (~1880-1700 AD) was wet. The LIA Phase II (1350–1700 AD) was rather dry in these regions. Between 750-1350 AD wet conditions occurred in the region.

Further southeast, the Dead Sea is a >300 m deep, hypersaline terminal lake lying below sea level in the Jordan Rift Valley of the Middle East. The best direct evidence of late-Holocene lake-level fluctuations derives from a sequence of well-dated paleoshorelines (Bookman et al., 2004) and marginal facies (Heim et al., 1997; Neumann et al., 2007). This provides a semicontinuous record of lake high-stands, with low lake-level stages largely based on inference—for example, based on the presence of unconformities in some sequences at AD 250, ~AD 600–1000, and AD 1400. The rapid fall in the Dead Sea water level during the twentieth and twenty-first centuries is linked to increasing abstraction of water from the river Jordan rather than to climate change, and it has led to desiccation of the shallow southern basin of the Dead Sea. The reconstructed late-Holocene lake-level curve (Figure 2.10) shows high water levels around 2k years BP, and again during the nineteenth century, with minimum water levels around AD 800–1000.

Comparisons between the Dead Sea records and those from Nar (Figure 2.10), Van, and Ioannina shows generally good agreement for the period between ~AD 800 and 1750,

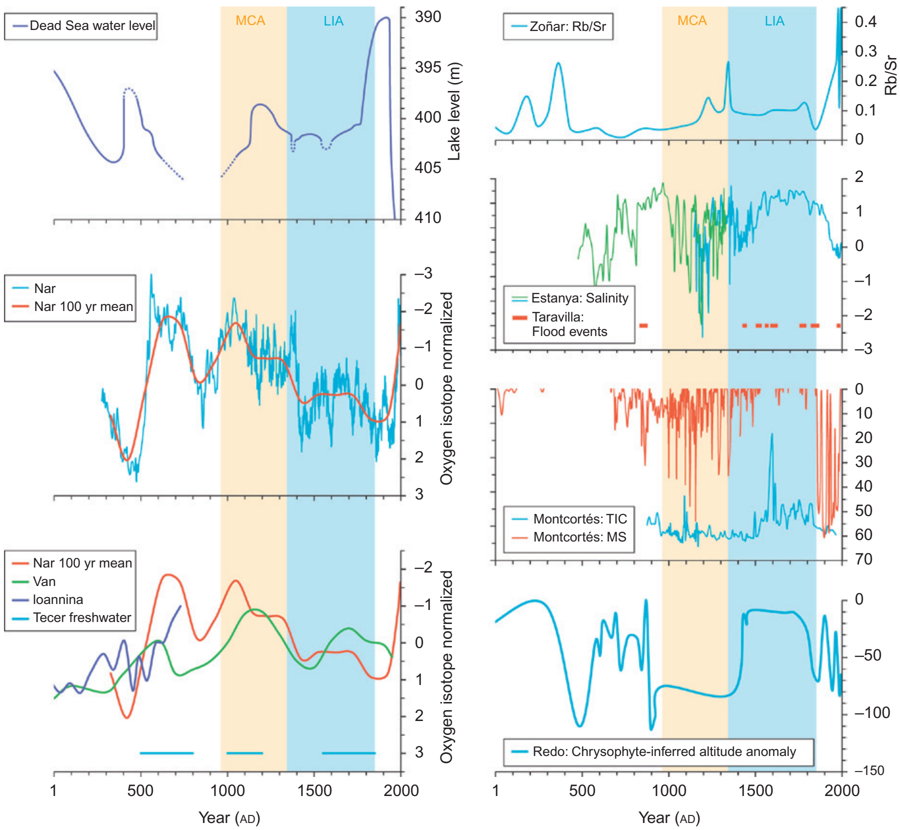

Figure 2.10 Comparative proxy-climate data from key lake records (left, eastern Mediterranean; right, Iberia). For sources see text. Redo shows inferred cold-warm shifts (colder upwards), all other graphs show high lake levels and lower lake salinities (=wet conditions) upwards, and low levels and higher salinities (=drought) downwards. Note that some of these lakes show human impact on lake hydrology and sedimentation during the twentieth century AD. For Montcortès, MS = magnetic susceptibility and TIC = total inorganic carbon.

indicating generally wetter climatic conditions around AD 1200 and somewhat drier conditions later on. This agrees with the overall picture for the eastern Mediterranean area that emerges from paleoflood studies, as synthesized in Section 2.6. On the other hand, the late-nineteenth-century high water-level stage in the Dead Sea has no equivalent in isotope records from the lakes in the northeastern Mediterranean, and the pattern of inferred lake-water balance changes during the first millennium AD appears to be somewhat different in the two data sets. These offsets may be explained by dating uncertainty, but alternatively, the climate histories of the southern Levant and Greece–Anatolia may have differed during parts of the last 2k years. Despite their geographical proximity, the northern and southern sectors of the eastern Mediterranean do not show a good correlation in interannual precipitation variability during the period of instrumental records. Some areas of Turkey, for example, show a weak positive correlation between precipitation and the North Atlantic Oscillation (NAO) Index, while the southern Levant shows a negative correlation with the NAO Index (Xoplaki, 2002; Oldfield and Thompson, 2004; cf. Black 2011). In addition, it should be borne in mind that as an amplifier lake in a semi-arid region, the Dead Sea is highly sensitive to land-cover changes in its large drainage basin, which could have altered runoff coefficients and catchment hydrology. Pollen and other records show that significant land-use changes have taken place during the last 2k years (Neumann et al., 2007), and these may have altered the volume of runoff entering the Dead Sea.

Most current lake-sediment records from Italy and the Balkans do not have sufficient stratigraphic resolution to provide detailed histories of climate during the last 2k years, although $\delta^{18}O$ data from Shkodra/Scutari (Albania/Montenegro) indicate the existence of a period of wetter climate in Roman times (Zanchetta et al., 2012).

2.7.2 The Western Mediterranean: Late-Holocene Climate Records from Iberian Lakes

In the Iberian Peninsula, several lake reconstructions based on geochemical and biological analyses have centennial or better resolution for the last 2k years. At high elevations in the Pyrenees, a chrysophyte transfer function applied to 70 m deep glacial Lake Redó (Pla and Catalan, 2005) has provided a temperature reconstruction that shows that the warmest Holocene winters occurred at 2.7–2.4k years BP, around AD 450 and at the start of the MCA ~AD 900. Winters were coldest during the LIA but also in the period AD 1050–1175. In southern Spain, the karstic, 15 m-deep Zoñar Lake (Córdoba province) (Martín Puertas et al., 2008, 2010) contains a varved interval deposited during the Iberian–Roman ages (2.5–1.6k years BP, 550 BC–AD 350). This is the most humid period during the last 4k years in southern Spain, although it includes an arid interval from 190 BC–AD 150. Pollen and sedimentological data indicate another arid period between AD 700 and 1400 and two humid periods, between AD 1200 and 1400 and around AD 1600, of lower intensity than during the Roman Empire. None of the available records in northern Spain shows such a large hydrological response during Roman times as at Zoñar, but they present similarly coherent patterns during the last 2k years. In Estanya Lake (Morellón et al., 2012), a brackish, karstic, 20 m-deep lake in the Pre-Pyrenean range, shallow lake levels and saline conditions predominated during high medieval times (AD 1150–1300), and generally higher water levels and more diluted waters from AD 1300 to 1850, although this period shows a complex pattern of wet and arid intervals. Maximum lake levels occurred during the nineteenth century, coinciding with higher population and agricultural expansion in the area. Declining lake levels during the twentieth century are associated with warmer climatic conditions and also a decrease in human impact. In the nearby meromictic, karstic, 30 m-deep Montcortès Lake (Corella et al., 2011), increased carbonate production and lower clastic input occurred during wetter periods of the Roman Period and from AD 1400 to 1770, while higher clastic input occurred during the more arid period AD 690–1460. However, a strong human impact partly obscures the climate signal during the last part of the LIA (Rull et al., 2011), and increased clastic input from AD 1770 to 1950 was likely triggered by increased human occupation. In the Iberian Range, the Taravilla lake sequence (Guadalajara province) reflects changes in the intensity of paleofloods (Moreno et al., 2008), coherent with fluvial activity reconstructions in the Tagus River (Benito et al., 2003b; see also Section 2.6). The lake sequence contains minimal extreme flood events during high medieval times and an increase since the fourteenth century not related to deforestation or increased human impact as shown by pollen analyses. In La Cruz Lake (Cuenca province) (Juliá et al., 1998), lower lake levels occurred during the ninth to eleventh centuries, indicative of drier conditions, and the development of meromictic conditions for later centuries is related to the synergetic effects of colder temperatures and higher lake levels, suggesting wetter conditions. Regional climate variability between northern and southern Iberia may explain some of the differences in lake responses during the last 2k years, but the different sensitivities of the lake systems must also be taken into account. Particularly, the stronger humid signal during Roman times in the south is less intense in the Iberian Range and the Pyrenees and may reflect a more southern location of the winter storm tracks during this period. However, warmer temperatures, lower lake levels, and higher salinities are reconstructed from all records from the ninth to thirteenth centuries (indicative of a drier climate) and generally colder and more humid conditions during the fourteenth to the nineteenth centuries.

The two western Mediterranean proxy-climate records from Montcortès and Estanya show a pattern of change that is almost the mirror image of that from Nar Lake in the eastern Mediterranean since ~AD 750 (Figure 2.10). These and other lake sequences indicate that northern Spain was dry during the MCA (Moreno et al., 2012) and wet during most of the LIA, whereas evidence from central Turkey (Nar Lake) showed a reverse pattern. Northern Iberia is located geographically close the strongest precipitation anomalies linked to the NAO dynamics, with wet years associated with anomalous high pressure dominance over northern Europe and negative NAO conditions. It therefore seems likely that during the LIA, the western Mediterranean experienced more frequent negative NAO Index states (Luterbacher et al., 1999, 2002; Cook et al., 2002; Rodrigo et al., 2001) and a persistent positive NAO state during the MCA (Trouet et al., 2009). However, other teleconnection patterns, including the eastern Atlantic/western Russia (EA/WRUS) and POL patterns (Xoplaki, 2002; Xoplaki et al., 2004), are relevant as well. By contrast, and possibly linked to the Mediterranean climate seesaw, parts of the eastern Mediterranean experienced an opposite precipitation regime, with reduced winter-season precipitation and enhanced summer drought (see Roberts et al., 2012, for further discussion). The pattern for the period before AD 1000 is less clear. Dermody et al. (2012) present a reconstruction of the change in climatic humidity around the Mediterranean between 3000 -1000 yr BP. They use a range of proxy archives as discussed here and model simulations and demonstrate that climate during this period was typified by a millennial-scale seesaw in climatic humidity between Spain and Israel on one side and the Central Mediterranean and Turkey on the other. This is in agreement with Roberts et al. (2012) for the past millennium and Xoplaki et al. (2004) for the last century.

Future challenges for lake-sediment–based reconstruction of climate change during the last 2k years include transforming the sedimentary proxy data into specific and quantitative hydroclimatic parameters (e.g., drought indices) and extrapolating from point-based, site-specific records to area-based reconstructions of regional climate. Calibration of sedimentological, geochemical, and biological proxies to instrumental data would require specific monitoring of the lake systems for longer periods. There is also need for improved geographical coverage of high-resolution late-Holocene lake records. Finally, we also need to improve the chronologies to achieve robust annual to decadal climate reconstructions.

2.8 Corals and Lower-Resolution Marine Proxies from the Mediterranean

2.8.1 Tropical Corals

Annually banded reef corals from the northern Red Sea provide a high-resolution archive of past climate variations at the southeastern rim of the Mediterranean basin (Felis and Rimbu, 2010, and references therein). In contrast to the Mediterranean Sea, warm-water coral reefs are well developed in the northern Red Sea, where winter sea-surface temperatures (SSTs) are well above 20°C. Subseasonally resolved records of isotopic and elemental tracers derived from the carbonate skeletons of massive *Porites* colonies robustly document seasonality and interannual to decadal climate variability (Felis et al., 2000, 2004; Rimbu et al., 2001). In contrast to seasonal timescales, during which coral $\delta^{18}O$ is dominated by the annual SST cycle, on interannual and longer timescales, the $\delta^{18}O$ signal in northern Red Sea corals reflects variations in both temperature and $\delta^{18}O_{seawater}$ (Felis et al., 2000). Corals only live for a few centuries (Felis and Pätzold, 2003). Well-preserved fossil corals, however, can be accurately dated using the radiocarbon or U-series method and provide subseasonally resolved proxy records of climate for time windows of several decades up to a century or more. These coral-based snapshots of past climate variability represent floating chronologies, but with accurate internal age models, and are therefore well suited to study past changes in seasonality and interannual to decadal climate variability in the eastern Mediterranean/Middle East region (Felis et al., 2004). The bimonthly resolved coral $\delta^{18}O$ records documenting SST and surface evaporation in the northern Red Sea reveal the prominent role of the Arctic Oscillation/North Atlantic Oscillation (AO/NAO) in controlling eastern Mediterranean/Middle East temperature, precipitation, and evaporation on seasonal and interannual to decadal timescales, most pronounced during winter. The winter coral $\delta^{18}O$ record explains 29% of the variance in the instrumental AO Index (January–March) during the period AD 1940–1994 (Felis et al., 2004; Felis and Rimbu, 2010). An important outcome of the paleoclimatic work on northern Red Sea coral $\delta^{18}O$ records is the observation of precipitation anomalies of opposite signs between the northeastern Mediterranean region and the southeastern rim of the Mediterranean Sea on interannual to decadal timescales (Felis et al., 2000; Rimbu et al., 2006; Felis and Rimbu, 2010), which was also noted by others (Cullen and deMenocal, 2000; Xoplaki et al., 2004). Such a spatial pattern complicates the reconstruction of past rainfall variability in the Levant, which is the transition zone between positive and negative rainfall anomalies (Felis and Rimbu, 2010).

2.8.2 *Temperate Corals:* Cladocora caespitosa

Although the typical tropical corals, such as *Porites*, are at present not inhabiting the Mediterranean Sea, other colonial species are thriving in this basin, with the temperate coral *Cladocora caespitosa* being the major carbonate producer. Previous geochemical results obtained from this coral have revealed that *C. caespitosa* can serve as a monthly resolved environmental archive of the photic zone, between depths of 5 and 40 m, extending the instrumental climate data back in time (Silenzi et al., 2005; Montagna et al., 2007; for an extensive review, refer to Montagna et al., 2008). However, further geochemical investigations demonstrated that the coral physiology plays a significant role in controlling the elemental uptake within the coral skeleton (Montagna et al., 2009). Based on these findings, Montagna et al. (2009) explored the possibility of using the coral Li:Mg ratio as a new paleotemperature proxy. This ratio shows a negative and highly significant correlation with the ambient water temperature, suggesting a pure temperature control, independent of the coral physiology and with an overall precision of ±0.8°C. Two long-lived *C. caespitosa* samples collected from Bonassola (northern Tyrrhenian Sea) and Ustica (southern Tyrrhenian Sea) at depths of ~30 and 40 m, respectively, are currently being investigated with the aim of quantifying the SST evolution for the past ~100 years at monthly/fortnightly resolution. In addition, the colony from Ustica will be analyzed for B isotopes at 5-year resolution to reconstruct the variation in seawater pH for the past century, an important source of information for properly evaluating the natural versus the anthropogenic forcing and the current status of ocean acidification. Unfortunately, living colonies of *C. caespitosa* older than 50–80 years and fossil samples of Holocene age are extremely rare, and so far they have been found only in Bonassola and Ustica (Figure 2.11), strongly limiting the use of this coral species as a paleoclimate archive for the last 2k years.

2.8.3 *Deep-Water Corals:* Desmophyllum dianthus, Lophelia pertusa, Madrepora oculata, Caryophyllia smithii

Deep-water corals are a spectacular and widespread component of the ocean biota. Their aragonitic exoskeleton incorporates trace elements and radiogenic and stable isotopes as a function of seawater temperature, nutrient content, and ambient seawater neodymium composition (Montagna et al., 2006; Rüggeberg et al., 2008; van de Flierdt et al., 2010). Being precisely datable through U/Th and radiocarbon, and having substantial fossil records in the Mediterranean Sea (McCulloch et al., 2010), the deep-water corals represent good candidates to provide multicentury, subannual resolution records of the most important physical and chemical marine parameters, including seawater temperature, nutrient content, pH, and variations in the water-mass circulation. Montagna et al. (2006) developed for the first time a direct

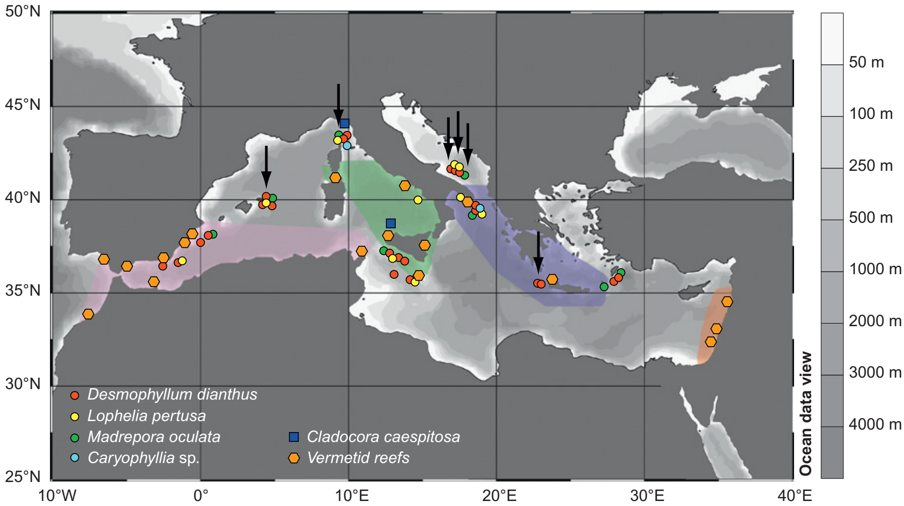

Figure 2.11 Sampling locations of the Mediterranean corals and Vermetid reefs discussed in the text. U-series dating indicates that deep-water corals have thrived in the Mediterranean for over 480,000 years, especially during cool interstadial periods. The Younger Dryas (12,900 to 11,700 years BP) was a period of prolific growth in the Mediterranean Sea, followed by the last 2000 years of almost continuous growth (McCulloch et al., 2010). Trace elements, stable and radiogenic isotopes will be analyzed in shallow- and deep-water corals to reconstruct changes in surface, intermediate and bathyal temperature, pH, and water mass circulation. Arrows show deep-water coral samples with an age younger than 2000 years. The colored areas represent the regional distributions of the four main clades of the vermetid *Dendropoma petraeum* as reported in Calvo et al. (2009) (see text for details).

method to reconstruct seawater paleophosphorus concentration by analyzing the P/Ca encoded in the skeletal aragonite of the deep-water coral species *Desmophyllum dianthus* and comparing those values with the corresponding seawater dissolved inorganic phosphorus (DIP) concentration (Montagna et al., 2006). Although limited by the presence of traces of hydroxylapatite in fossil corals (Mason et al., 2011), this proxy still represents the only direct method available so far to obtain information on the paleophosphate content of individual water masses and to reconstruct the past ocean productivity. At present, new geochemical proxies are being developed in the Mediterranean deep-water corals, specifically neodymium (Nd) and boron (B) isotopes (Montagna et al., 2010a). The Nd isotopes (expressed as $\varepsilon_{Nd} = [(^{143}Nd/^{144}Nd)_{sample}/(^{143}Nd/^{144}Nd)_{reference} - 1] \times 10^4$) preserved in coral skeleton serves as a proxy to trace variation in water-mass composition and water-mass mixing (van de Flierdt et al., 2010). This can open new perspectives to quantify the water dynamics of the Mediterranean Sea and the exchanges between the eastern and the western basin. Several living specimens of the deep-water coral *D. dianthus*, *Lophelia pertusa*, and *Madrepora oculata* were retrieved from the Strait of Sicily and the southern Adriatic Sea at different water depths and analyzed for Nd isotopes, together with the surrounding seawater. The ε_{Nd} of the deep-water corals match the ambient seawater, proving that the Mediterranean corals can reliably reconstruct the water-mass circulation (Montagna et al., 2010b). The B isotopes extracted from coral aragonite have the potential to reconstruct the seawater pH evolution with a precision better than ± 0.02 pH units (Wei et al., 2009). Montagna et al. (unpublished data) have analyzed the B isotopes on a suite of Mediterranean corals (*D. dianthus*, *L. pertusa*, and *M. oculata*). The results, together with the B isotope data obtained on *C. caespitosa* (Trotter et al., 2011), support the evidence that the B-isotopic composition of these coral species is pH-dependent and open new perspectives in reconstructing the paleo-pH evolution of the Mediterranean Sea (Montagna et al., unpublished data).

2.8.4 Low-Resolution Marine Proxies

Sediment Cores

A study combining SST reconstructions from marine sediment cores derived by the alkenone method revealed a trend toward warmer conditions since the early Holocene in the eastern Mediterranean Sea, whereas a trend toward cooler conditions was detected in the western Mediterranean (Rimbu et al., 2003). The age model of these alkenone records is usually based on radiocarbon dating and the average temporal resolution is typically multicentennial to centennial. However, an alkenone-based reconstruction of winter SSTs with a resolution of about 4 years was generated from sediments south of Italy, covering the period 1305–1979 (Versteegh et al., 2007). The reconstruction was dated by using radiometric and tephra analysis methods and suggests a centennial-scale solar forcing of central Mediterranean winter SSTs since 1420 (Versteegh et al., 2007). A 2200-year-long record based on foraminiferal $\delta^{18}O$ has been obtained by Taricco et al. (2009) along the Gulf of Taranto in the Central Mediterranean Sea, very close to the site studied by Versteegh et al. (2007). Based on the comparison with the alkenone reconstruction by Versteegh et al., they showed that the long-term trend and the 200-year oscillation in the $\delta^{18}O$ record are temperature-driven. The record reveals a minimum in $\delta^{18}O$ at the Medieval Optimum (ca. AD 1000) and a maximum at the LIA (AD 1600–1800), followed by a steep variation since the beginning of the Industrial Era. Multiproxy records derived from sediments of the southeastern Mediterranean Sea (Schilman et al., 2001) and the Adriatic Sea (Piva et al., 2008) reveal complex paleo-oceanographic changes during the late Holocene, with pronounced anomalies during the Medieval Warm Period (MWP) (ca. AD 1150) and the LIA (ca. AD 1730).

Vermetids

Vermetid reefs can serve as archives to reconstruct the SST variability and the sea-level changes. The thermophile and sessile marine gastropods belonging to the Vermetidae family form extensive reefs in the intertidal or shallow-subtidal zones (Figure 2.11) in several locations of the Mediterranean Sea (Pirazzoli et al., 1996; Antonioli et al., 1999). The application of geochemical tools to specific portions of a colony of the species *Dendropoma petraeum* collected in the northwest part of

Sicily revealed for the first time the possibility of using these gregarious organisms in reconstructing the sea-level (Antonioli et al., 1999) and the seawater temperature evolution (Silenzi et al., 2004) of the Mediterranean Sea during the last ~500 years. In a review, Montagna et al. (2008) summarized major geochemical results collected so far, providing a new interpretation of the stable isotopic composition of the vermetid reefs, which enabled a reconstruction of a more accurate seawater temperature range, varying between 17.6°C and 21.1°C during the cold period extending from the sixteenth to the nineteenth century. The temperature range is somewhere in the middle of the present-day annual temperature cycle characteristic of the sampling site (data not shown). Therefore, considering that each sample represents an average of about 30–50 years (Silenzi et al., 2004), each calculated temperature value corresponds to a multidecadal temperature average. Sisma-Ventura et al. (2009) analyzed seven cores of *D. petraeum* collected along the Israeli coast for their stable isotopic composition, with an average resolution of 6 years. The δ^{18}O signal extended back in time reveals two cold periods (ca. 1590 and 1700 year AD) in the Levantine basin SSTs, separated by an intermediate warm period (~1600–1680 calendar year). From the comparison with previous temperature data during the cold first half of the eighteenth century from the North Atlantic (Keigwin, 1996; Cronin et al., 2003; Silenzi et al., 2004), Sisma-Ventura et al. (2009) suggested that the eastern basin cooled by 1°C more than the western basin during such a period. In addition, they interpreted the δ^{13}C signal retained in the aragonitic shell as a proxy for primary productivity of the surface water, which was enriched in nutrient levels during this coldest LIA (ca. AD 1700) period, due to increased vertical mixing and upwelling. The oxygen isotope records of recently radiocarbon-dated samples suggest that during the LIA maximum the seawater temperature was about 2°C and 3°C colder than the present day in the western and the eastern Mediterranean basins, respectively.

Although marine sediment cores can provide continuous paleoclimate reconstructions, their utility is often limited by the lack of an accurate age model and adequate time resolution. In the near future, tephrostratigraphic studies on high-accumulation sediment cores from around Italy might lead to more well-dated proxy records covering the last 2k years. Deltaic and turbiditic deposits with sedimentation rates reaching 2 m per thousand years, as in the case of the Rhone Delta, provide expanded sequences for the production of detailed paleorecords of past environmental changes, using both continental and marine proxies. However, they are often discontinuous because sediment depot-centers and/or point sources have switched in response to natural/anthropic avulsion of distributary channels. High-resolution seismic profiles are subsequently needed to reconstruct continuous sequences if long time series are needed.

Further, most of the new geochemical proxies (Li/Mg, B, and Nd isotopes) that have been calibrated on Mediterranean living coral samples will be applied to key samples selected from the extensive collection of U-series dated corals available from the Mediterranean Sea (Figure 2.11). Reconstructions with subannual or decadal resolution of seawater temperatures, pH, and water-mass circulation at intermediate and bathyal depths will be obtained for specific time windows spanning 50–100 years (the average lifetime for most of the deep-water coral species) during the last 500k years.

2.9 Borehole Information from the Mediterranean

Borehole temperature profiles (BTPs) have significantly contributed to the understanding of the climate evolution of the past millennium (Jansen et al., 2007). Climate reconstructions based on BTPs assume that surface-air temperature (SAT) is coupled to ground-surface temperature (GST) and its changes propagate to the subsurface by thermal conduction merging with the geothermal temperature gradient at depth. The downward propagation of the climate disturbance is a function of the low thermal diffusivity of the rock, with typical values in the range of 10-6 m2/s. Such low values produce an slow propagation so that first few hundred meters store multicentennial temperature changes at the surface. Also, heat conduction attenuates the amplitude of surface changes with depth (Carslaw and Jaeger, 1959), acting as a low-pass filter that hampers the ability of borehole inversions to recover high-frequency changes. As biological proxy records, there are limitations that contribute to uncertainty in borehole reconstructions (e.g., vegetation and land-use changes, horizontal heat advection, subsurface hydrology, and noise) (Pollack and Huang, 2000), climate reconstructions from this source are viable, and many papers have provided estimations of temperature changes at global, hemispherical, and regional scales (Pollack and Huang, 2000, and references therein). Because of the limited depth of most available boreholes (~300 m on average) (González-Rouco et al., 2009), the part of the climate history that can be reconstructed typically reaches the past half millennium; therefore, inferences about the last 2k years are available at very few locations. The reconstruction of past surface-temperature changes from borehole temperature profiles has no “chronology” in the narrow sense. The GSTHs (ground-surface temperature histories) are the result of the solution of an inverse problem, usually based on a simple analytical representation of the forward model (see, among many others, Mareschal and Beltrami, 1992). The main uncertainties of the time-scale arise from the assumptions made for the forward model (e.g., parameters such as the thermal diffusivity or assumptions of subsurface homogeneity, which need to be carefully assessed). The distribution of most available borehole profiles is shown in Huang and Pollack (1998), a database created under the auspices of the International Heat Flow Commission that compiles on the order of 700 profiles globally, though with a somewhat irregular distribution that clusters more measurements over North America, eastern Europe, South Africa, and Australia. Although this network has been shown to constitute a meaningful sampling of global and hemispheric temperature changes (González-Rouco et al., 2006), inferences at the regional scale are hampered by the low density of information in some areas. The Mediterranean is one of the areas that show still a large potential for future sampling and analysis. Figure 2.12 shows the distribution of locations where BTPs have been analyzed and inverted, producing estimations of past GST changes. Circles represent sites where published analyses have reported about recent temperature changes, and squares correspond to locations with available information in the Huang and Pollack (1998) database that continues to be updated. Because of the relatively shallow depths of available BTPs, the map shows only information regarding temperature changes in the past two centuries. Most of the sites report temperature increases, with the largest

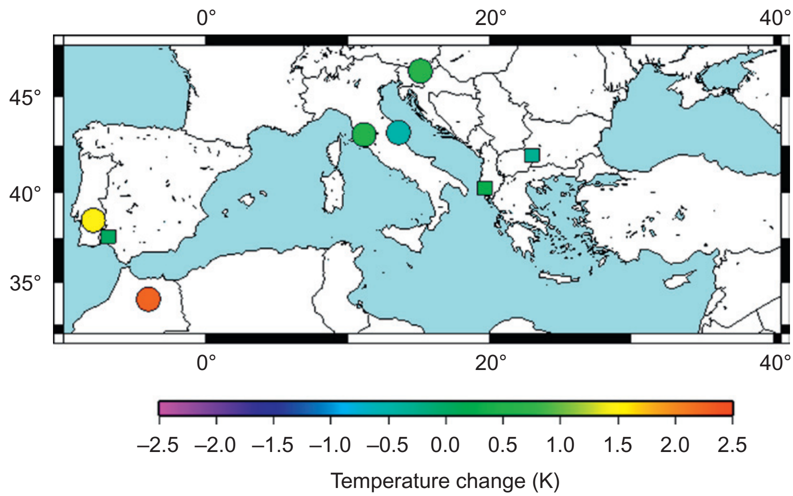

Figure 2.12 Estimated temperature change for the last two centuries from borehole temperature profiles in the Mediterranean. Circles depict published record estimations (see text for details) and squares values obtained from BTPs available in the borehole database described by Huang and Pollack (1998).

values being attained in the western Mediterranean from the analysis of Rimi (2000) of BTPs in Morocco and that of logs in southern Portugal by Correia and Safanda (2001), later updated in Safanda et al. (2007). Several logs nearby in southwestern Iberia from the borehole data set produce in a relatively small region contradictory trends averaging out to no significant warming in the past two centuries. Therefore, the present situation requires further sampling to gain a more robust regional perspective on the estimation of GSTs in the recent past.

The same message can be extended to other parts of the Mediterranean where valuable local information has been obtained, although it is still premature to extrapolate a basinwide pattern. For instance, in Italy, Pasquale et al. (2000, 2005) detect ~0.5 K temperature changes for the past two centuries, but of opposite sign on the two sides of the Apennines, which is found to be compatible with meteorological observations and independent proxy records. In Slovenia, Rajver et al. (1998) report warmings over half a degree for Slovenia, while for the eastern side of the Mediterranean, only a couple of measurements are available in the borehole data set for Albania, and Bulgaria reporting slight warming and cooling of 0.3 K, respectively. Information about temperature changes beyond the past centuries is scarce and for the Mediterranean still only available at a borehole in Slovenia (Rajver et al., 1998), where an almost 2000 m-deep profile allowed for a reconstruction spanning the Holocene and the last glacial period. A transition from present times to a colder LIA-like period is evidenced for the past two centuries of the millennium in the inversion of this BTP as well as a transition from the LIA to warmer temperatures around the fifteenth to seventeenth centuries is also shown. This maximum is preceded at the beginning of the millennium by temperatures about 3–4 K lower than present and before that warming in the first millennium toward the Holocene optimum located in this borehole 2k–3k years ago. The amplitude and timing of these values is nevertheless very qualitative because of the diffusive nature of heat conduction and the assumptions on the parameters used in inversion routines that blur temperature changes in the distant past.

The situation briefly described herein highlights the necessity for further sampling in order to attain a more sound picture of Mediterranean-wide temperature changes from borehole estimations. In addition to sampling, future efforts should consider establishing more consistent or coordinated methodological approaches, since it is likely that part of the noise in currently available estimates from BTPs is due to variability produced by different methods and inherent methodological assumptions. Obtaining such information from BTPs in the future would be a step forward in the comparison with other proxy records. BTPs can provide relevant information particularly on the amplitude of low-frequency changes, a part of the signal that in the case of other proxy records is often argued to show more uncertainty (Jones et al., 2009). In addition, the availability of a denser BTP network in the Mediterranean would be useful in the task of performing model-borehole comparisons and constraining model simulations, a path that has been initiated for other areas in which the density of observations is larger (Stevens et al., 2008; MacDougall et al., 2010).

2.10 Vegetation, Land Use, and Fire History in Mediterranean Ecosystems

2.10.1 Mediterranean Vegetation Belts and Climate

With 25,000 estimated species, the flora in the Mediterranean is among the most diverse of any region on earth (Allen, 2001). High floristic and vegetational diversity is linked to strong latitudinal, longitudinal, and altitudinal environmental gradients. Three major units are often used to characterize the Mediterranean vegetation. The thermo-Mediterranean vegetation in the lowlands south of 41–39°N (Carrion et al., 2010a,b) is dominated by evergreen broad-leaved species (e.g., evergreen *Quercus*, *Ceratonia siliqua*, *Olea europaea*, *Chamaerops humilis*, *Myrtus communis*, and *Pistacia lentiscus*) (Lang, 1994). In the transitional meso-Mediterranean belt, evergreen and deciduous trees co-occur, whereas deciduous species (e.g., deciduous *Quercus*, *Castanea sativa*, *Ostrya carpinifolia*, and *Fraxinus ornus*) dominate in the cooler sub-Mediterranean (or supra-Mediterranean) zone (Lang, 1994). In some areas (e.g., Spanish Sierra Nevada, Greece, and Turkey), coniferous taxa such as *Pinus* (e.g., *P. nigra* and *P. brutia*), *Abies*, *Cedrus*, *Cupressus*, and *Juniperus* are frequent in the sub-Mediterranean belt (Lang, 1994). The subdivision of Mediterranean vegetation in these three major units or belts is presented in Figure 2.13.

2.10.2 Vegetation Changes and Land Use

Few forest relicts are preserved around the Mediterranean, a region profoundly altered by human activities since prior to the expansion of the Roman Empire

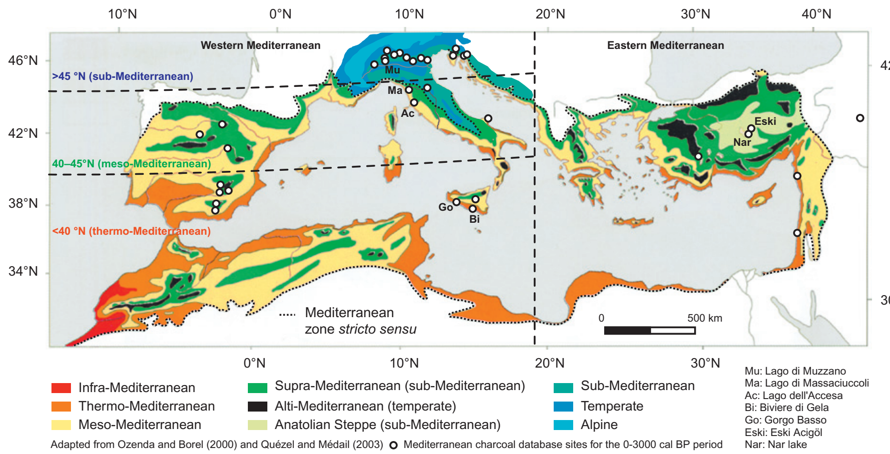

Figure 2.13 Vegetation belts and position of important paleoecological records. Vegetation classification follows Ozenda and Borel (2000) and Quézel and Médail (2003). The dots represent fire-history records used to generate the charcoal synthesis curves (see Figure 2.15). Latitudes were used to group the sites for the charcoal synthesis curves: sites north of 45°N were assigned to the sub-Mediterranean, sites north of 40°N to the meso-Mediterranean, and sites south of 40°N to the thermo-Mediterranean belt (Figure 2.14). Sites located east of 20°E (eastern Mediterranean) were not subdivided into these three vegetation categories.

~2k years ago. In a few regions (e.g., meso-Mediterranean Lago dell'Accesa in Tuscany, Italy) (Colombaroli et al., 2008; Figure 2.14), human impact is detectable palynologically as early as Neolithic times, but more commonly, human disturbance became substantial during the Bronze Age. The late detection of human impact is partly explained by the abundance of palynological indicators of past cultural activity (e.g., Cerealia-type pollen), which are present naturally (or have been naturalized) in the Mediterranean and provide an ambiguous indicator of prehistoric farming activity as compared with northern and central Europe. The date of first major deforestation varies regionally, with some parts of the eastern Mediterranean showing a decline in percent arboreal pollen (AP) associated with cultural land-use indicators from around 5k years BP—for example, at Eski Acıgöl in Central Anatolia (Roberts et al., 2001) and Ioannina in Greece (Lawson et al., 2004). In wetter, more densely forested regions of the Mediterranean, the first significant forest decline occurs later than this, typically during the second millennium BC—for example, at Lago di Mezzano in Latium (Sadori et al., 2004) and at Gölhisar in the mountains of southwest Turkey (Eastwood et al., 1999). At some sites in thermo-Mediterranean Sicily, such as Gorgo Basso, evergreen coastal forests persisted until Greek colonization ca. 700 BC (Tinner et al., 2009). In any case, the overwhelming majority of Mediterranean pollen records show substantial evidence of human impact on vegetation prior to 2k years cal BP. In several cases, this included phases of occupation followed by abandonment and the development of secondary forest, for example, at Birket Ram in the Golan Heights of the Levant (Schwab et al., 2004).

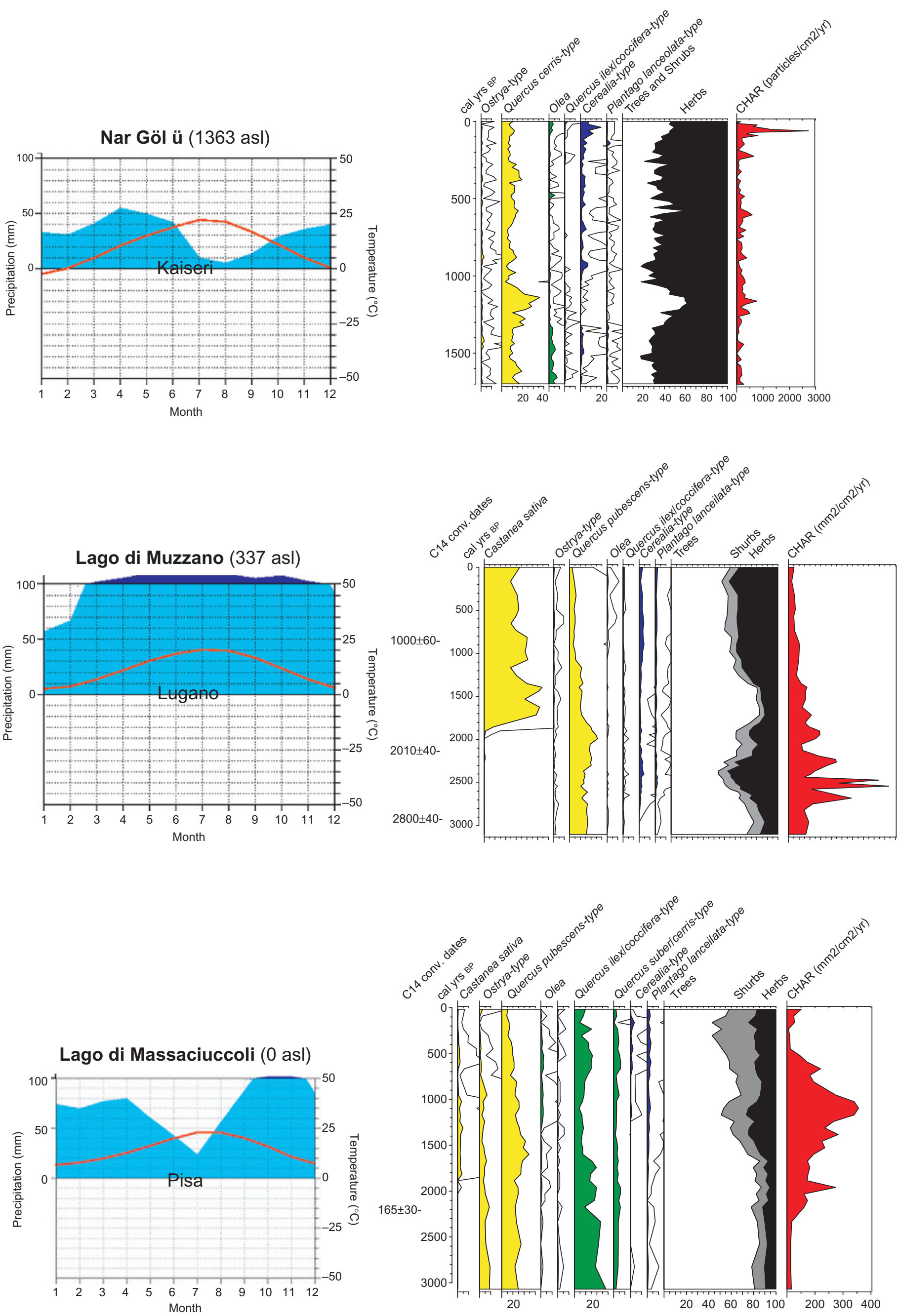

Figure 2.14 (Continued)

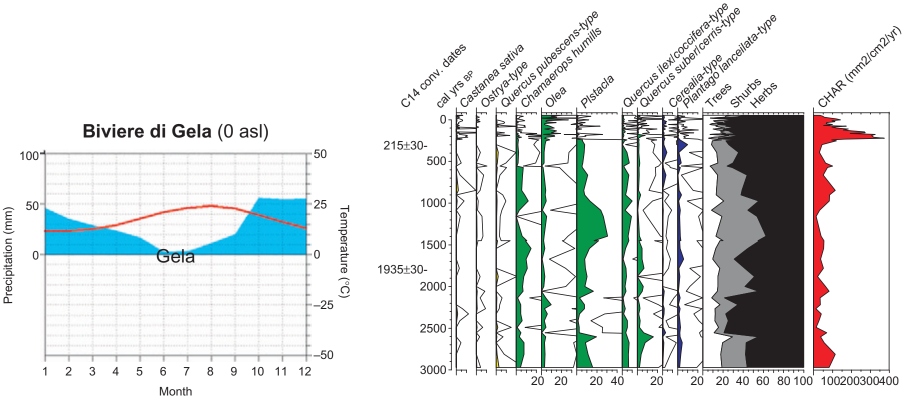

Figure 2.14 Simplified sedimentary pollen and microscopic charcoal diagrams from the lakes Nar Gölü (dry sub-Mediterranean vegetation type), Lago di Muzzano (humid sub-Mediterranean), Lago di Massaciuccoli (meso-Mediterranean), and Biviere di Gela (thermo-Mediterranean) compared with climate diagrams from nearby climatic stations (source of climate diagrams: www.klimadiagramme.com, modified). The chronology of Nar Gölü is based on ^{210}Pb and ^{137}Cs dating of the top 50 cm and varve counts providing a basal age of 1701 varve years (VY) BP or AD 300. The varve counts were replicated and correlated between two additional cores from different parts of the basin. Comparisons of these three counts show that varve ages from the sequence have maximum chronological uncertainty of 40 years at 1700 VY BP. The chronology of Lago di Muzzano, Lago di Massaciuccoli, and Biviere di Gela is based on age-depth models using calibrated radiocarbon ages. Only terrestrial plant macrofossils were used for dating. The original radiocarbon dates are provided on the left of the pollen and charcoal diagrams. July, January, and annual mean temperatures are around 0°C, 23°C, and 11°C at Nar Gölü; 3°C, 22°C, and 12°C at Lago di Muzzano; 7°C, 22°C, and 15°C at Lago di Massaciuccoli; and 12°C, 25°C, and 19°C at Biviere di Gela. Annual precipitation is around 350 mm at Nar Gölü, 1500 mm at Lago di Muzzano, 900 mm at Lago di Massaciuccoli, and 400 mm at Biviere di Gela. Vegetation composition reflects climate with deciduous trees and shrubs (yellow) decreasing and evergreen trees and shrubs (green) increasing from top (Nar Gölü) to bottom (Biviere di Gela). Note the prominent role of European fan palm (*Chamaerops humilis*) at the warmest site. Human impact is illustrated by pollen of selected crops (*Cerealia*-type) and weeds (*Plantago lanceolata* type). Some trees such as *Castanea sativa* and *Olea europaea* are also used as crops. The pollen sum of arboreal pollen (trees and shrubs) is a proxy for woodland or shrubland cover, whereas microscopic charcoal is a proxy for fire activity within ca. 20–100 km around the sites. Original pollen and charcoal data were published by England et al. (2008) (Nar Gölü), Gobet et al. (2000) (Lago di Muzzano), Colombaroli et al. (2007) (Lago di Massaciuccoli), and Noti et al. (2009) (Biviere di Gela). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this book.)

The "triad" of wheat, olive, and vine was probably established in Bronze-Age Greece and became widely adopted around the shores of the "Roman Sea" (*Mare Nostrum*), along with the cultivation of other trees such as *Juglans regia*, a valuable palynological indicator of agricultural land use. Arboriculture is a prominent feature around the Mediterranean Sea, with the earliest evidence involving the use of *Ficus carica*, *Juglans regia*, and *Castanea sativa* dating back to the Neolithic period (prior to cal 6000 BP) in the Levant and Italy (Kislev et al., 2006; Tinner et al., 2009; Kaltenrieder et al., 2011). Pollen data suggest Bronze-Age cultivation of *J. regia* and *C. sativa* in Greece (Bottema, 1980). During the so-called Beyşehir Occupation clearance phase, pollen evidence from southwest Turkey (Eastwood et al., 1998) suggests an intensification of arboriculture. Typically starting around 3000 cal BP, this exceptionally well-marked cultural landscape phase came to an end ca. 1400 cal BP (AD 600), and was followed by forest regeneration, typically dominated by pine. After 2000 cal BP, the Romans initiated and promoted the large-scale cultivation of *C. sativa* around the entire Mediterranean Sea, not primarily for fruit, but for timber production (Conedera et al., 2004). The first center of *C. sativa* cultivation during Roman times was in the Insubrian region of the Italian peninsula (see Lago di Muzzano in Figure 2.14), where precipitation was sufficient to maintain monospecific stands of this rather mesophilous tree. In addition, big rivers and lakes allowed the transport of sweet-chestnut timber to the Po Plain and the adjacent Adriatic Sea (Conedera et al., 2004). Also, in other parts of the Mediterranean, woodland was modified and used as a managed resource for grazing, fuel, and other products, rather than deforested or burned. The *dehesa* system for using southwest Iberia's cork oak woodlands, for example, has been dated to Bronze Age times through archaeology and pollen research (Stevenson and Harrison, 1992). Analyses from Spain and Italy show that over the millennia anthropogenic fire has decisively contributed to the establishment of the present fire-adapted vegetation types such as sclerophyllous macchia or garriga (Carrion et al., 2003, 2007; Colombaroli et al., 2007, 2008; Vannière et al., 2008; Noti et al., 2009; Tinner et al., 2009; Rull et al., 2011). Many Mediterranean regions experienced a new phase of intensified land management in medieval times (onset ca. AD 700–800) (see Lago di Muzzano and Massaciuccoli in Figure 2.14). This process also occurred on islands—for example, in Crete's White Mountains (Atherden and Hall, 1999) and reached a maximum during the nineteenth and twentieth centuries (McNeil, 1992; Grove and Rackham, 2001). The past millennium has seen Mediterranean scrub and heathlands expand, in large part because of the continual grazing by sheep and goats and repeated anthropogenic burning. As the plagioclimax (i.e., continually humanized) formations of macchia and garriga have increased, subhumid forests have decreased, including deciduous oak and fir. Exotic plants such as eucalypts, agaves, and Indian-fig opuntias have been planted ubiquitously across the Mediterranean during the last 200 years and are currently invading native garriga, macchia, and forest environments.

For most regions of the Mediterranean, human-induced land-cover change is the dominant causal agent during the last 2k years. For example, in a high-resolution, multiproxy varved-lake-sediment record from Nar Lake in central Anatolia, England et al. (2008) found changes in pollen matched closely with historically documented periods of rural land use, but the pollen failed to correlate with an independent climate proxy from stable isotopes within the same sediment core (see Section 2.7). Nonetheless, forest cover remained well developed in a few isolated upland areas of the Mediterranean until historic times. For example, pollen evidence from the cedar forests of the Middle Atlas Mountains of Morocco suggests continuous unbroken forest through the later Holocene (Lamb and van der Kaars, 1995). In other contexts, individual pollen records are most effective as a paleoclimate signal where major changes in human land-use intensity have been documented as absent.

2.10.3 Fire Activity

The Mediterranean area is one of the most fire-prone regions of the world. Wildfires inflict an annual toll on human life and property, with economic costs reaching billions of euros. Ecological impacts are both immediate and long-lasting, with fire-triggered vegetational dynamics ranging in length from decades to centuries. More than 95% of fires in the Mediterranean region are of human origin, including a significant proportion of intentional burning (Moreno, 1998). While fire ignition is predominantly related to human activities, the annual number of fires and area burned are closely related to climatic factors (Piñol et al., 1998; Pausas, 2004; Good et al., 2008; Vannière et al., 2008, 2010). At local to regional scales, past fire activity is well recorded in sedimentary charcoal deposits (Conedera et al., 2009). From these archives, fire appears to have been a natural component of Mediterranean ecosystems already during the Holocene, though increased sedimentary charcoal influx beginning at least 4k years ago is mostly associated with prehistoric and protohistoric forest clearances (Tinner et al., 1999, 2009; Turner et al., 2008, Vannière et al., 2008, 2010; Kaltenrieder et al., 2011). Inverse fire dynamics between the eastern and western Mediterranean that occurred during the last 1k years (Vannière et al., 2011) nevertheless indicate that climate dominates fire dynamics. In the relatively dry east (especially Anatolia), fire activity tended to be limited by sparse biomass, so that in this case, dryer conditions reduced fires (Turner et al., 2008). In the moister and more vegetated west, dry climatic conditions enhanced fire (Tinner et al., 1999, 2009; Vannière et al., 2008, 2011). Thus, similar climatic trends may have resulted in opposite fire-regime changes prior to AD 1000 (Figure 2.15, with a minimum of fire activity in the west at 200 BC and AD 900, corresponding to a maximum in the east; maximum in the west at 800 BC and AD 400, corresponding to a minimum in the east).

Following a period of high fire activity during the Iron Age (ca. 800–200 BC), burning had declined with the onset of the Roman period (200 BC) and remained low until the Migration period, beginning in the West ca. AD 400. However, low fire activity persisted longer in the East, where East Roman and Byzantine rule continued through the Middle Ages (Figure 2.15), while the Umayyad and Abbasid caliphates and their regional successors largely continued late Roman economic and administrative practices in Syria, Palestine, Egypt, and their hinterlands, down to the Mongol invasions in the 1200s. During the twentieth century in much of Mediterranean Europe, fire activity often reached a maximum during phases of land abandonment and secondary scrub-woodland development (Moreno, 1998). Similarly, fire activity increased after the end of Roman rule and the subsequent weakening or disappearance of centralized administration in the western Mediterranean ca. AD 400–800 (Figure 2.15). After AD 1000, charcoal records from the southern and central Mediterranean indicate harmonized changes in fire activity,

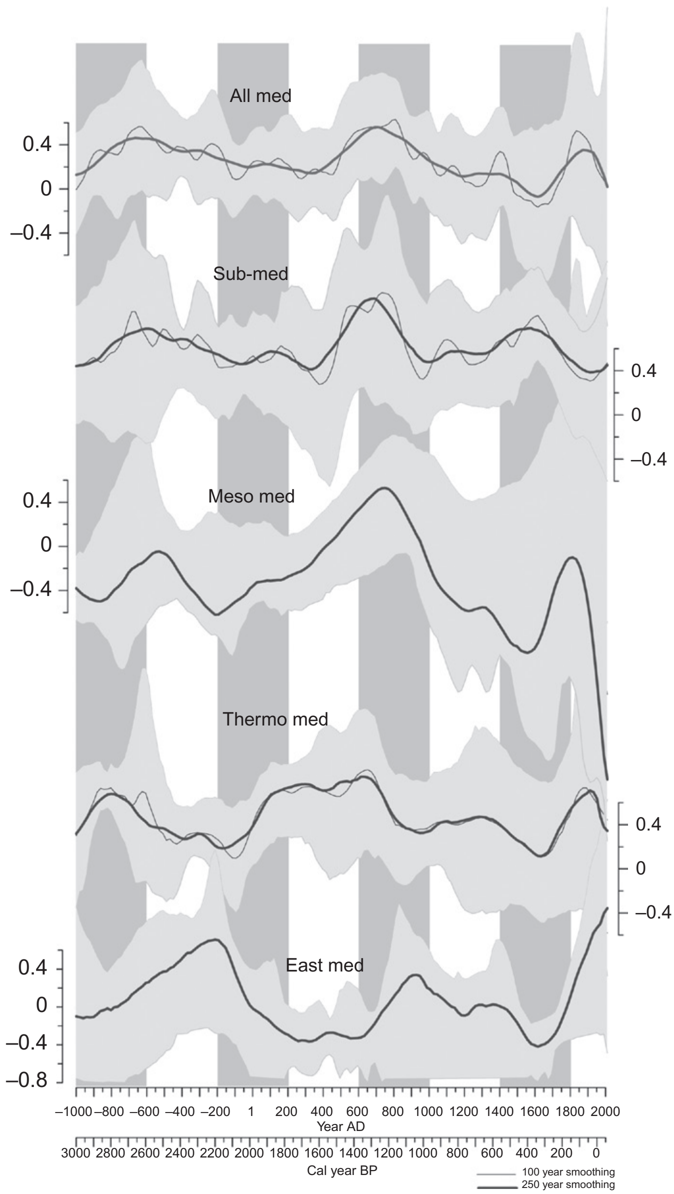

Figure 2.15 3000-Year composite, time-series of 250-year smoothed, *Z*-score charcoal anomalies, from five constituent regions. Synthesis charcoal curves were produced from 34 records for the entire Mediterranean and subregions (see Vannière et al., 2011 for regional partition). The approach follows a protocol that normalizes individual records in order to stabilize the variance and standardize the results (Power et al., 2010). Individual charcoal time series were smoothed as part of a two-stage process by fitting a lowess curve (Cleveland and Devlin, 1988). This procedure prevents higher-resolution records from affecting regional signals and avoids introducing, by interpolation, data into lower-resolution records (see Vannière et al., 2011 for details on methods).

which appear in antiphase with charcoal records from the northern sub-Mediterranean region (Figure 2.14). This pattern is most pronounced during the LIA (AD 1400–1800), again pointing to a substantial climatic influence.

Despite the preponderance of human-caused fire ignition during historic times, favorable fire-weather conditions are important for the propagation of fires (Pausas, 2004; Good et al., 2008). Climate in the Mediterranean region is closely linked to both the temperate Atlantic and the tropical African realms on millennial-to-centennial timescales (Magny et al., 2009; Kaltenrieder et al., 2011; Vannière et al., 2011). Previous studies from southern and central Europe (Tinner et al., 2003, 2005) suggest a rather close link between fire, land use, and European and Greenland climates during the late Holocene. Generally, warmer climatic conditions in Greenland (NGRIP Dating Group, 2006) appear positively correlated with phases of increased fire activity in the western Mediterranean. A direct climatic influence on fire regimes is conceivable, although an alternative working hypothesis suggests that fire excursions were triggered or amplified by changing land-use activities. The pattern of change is similar between the western and eastern Mediterranean during the past millennium, but diverges prior to AD 1000, possibly as a consequence of dissimilar cultural development, fuel availability (see discussion above), or climatic change. To better address this issue, more local paleo-environmental and paleoclimatic reconstructions are needed. Currently, no clear relationship emerges between our charcoal synthesis curves and proxy P-E records in either eastern or western Mediterranean lake records during the last 1500 years.

Taken together, paleoecological evidence shows that the Mediterranean region was profoundly altered by human activities before the expansion of the Roman Empire (ca. 2.2k years ago). Landscape humanization included disruption of natural evergreen and deciduous forests, the introduction of crops, sylviculture, more frequent burning and, primarily as a result of increased fire disturbance, the prevalence of today's maquis (or macchia) and garrigue (or garriga) vegetation. This pattern is in agreement with observations during the twentieth century, wherein much of Mediterranean Europe fire activity often reached a maximum during phases of land abandonment and secondary scrub-woodland development. Increased fire activity, climate variability, and drought in response to global change during the next several decades may severely endanger biodiversity in the Mediterranean region. For example, some remaining relict forest stands (e.g., *Picea abies*, *Abies alba*, and *Quercus ilex*) are close to their climatic and disturbance limits, so that crossing these thresholds may result in irrecoverable diversity losses (Colombaroli et al., 2009; Tinner et al., 2009; Vescovi et al., 2010). An ongoing challenge in interpreting late-Holocene environmental records (e.g., pollen as a proxy for vegetation or charcoal as a proxy for fire) from the Mediterranean is to separate the contributions of climate change and human impact. The use of multiproxy techniques within the same record, careful site selection, appropriate statistical techniques partitioning variance between different causal agencies, and dynamic modeling approaches, however, can do a great deal to disentangle the various forcing mechanisms of long-term environmental change.

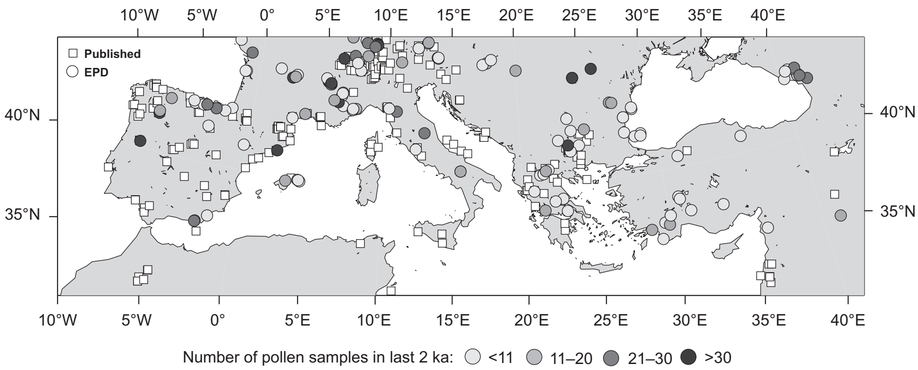

Figure 2.16 The distribution of pollen sites in the Mediterranean region covering the last 2k years. Public data held in the European Pollen Database (EPD), as well as all published sites, is shown shaded according to the number of samples available at each site.

2.11 Pollen Data: Their Distribution and Possibilities/ Challenges for Climate Reconstructions over the Mediterranean

Pollen data represent a widely available source of paleoclimate data for the Mediterranean region over the last 2k years, providing quantitative reconstructions on a comprehensive range of temperature and precipitation parameters. Climate is likely the most important control on vegetation at the regional scale, but nonclimatic factors, including anthropogenic disturbance, may well be significant at individual sites. Lakes, bogs, and other suitable sediment sinks allowing for pollen preservation occur widely, not only in the wetter and higher-altitude regions but also in the more arid lowland areas. Furthermore, the sediments of the Mediterranean Sea itself provide an additional source of information about nearby land regions. Pollen analysis has been undertaken at a large number of these sites for the 2k-year period, and the raw pollen data and chronological information of over 120 of these studies is available from public databases such as the European Pollen Database (EPD) (Figure 2.16). At most sites, wide sampling intervals and radiocarbon dating uncertainties mean that temporal resolution is centennial at best, although high-resolution studies on annually laminated sediments indicate that near-decadal resolution is possible (England et al., 2008; Kamenik et al., 2009). Transfer functions allow raw pollen data to be interpreted as quantitative climate values (Brewer et al., 2007), more commonly using modern pollen surface-sample data sets, but also using bioclimatic models (Wu et al., 2007) and modern plant distributions (Neumann et al., 2007). Applied in this way, pollen data have provided estimates of a large number of different climate parameters in the region, including summer, winter, and annual temperatures and precipitation, growing degree days, and actual and potential evapotranspiration and moisture stress (Table 2.3).

Table 2.3 A Summary of Holocene Pollen-Climate Studies for the Mediterranean Region

Author	Region	Sites	Time	Methods	Climate Parameters
Davis et al. (2003)	Europe	EPD, Pangeae, Other	0–12k	MAT (PFT)	MTCO, MTWA, TANN
Eastwood et al. (2007)	Turkey, Greece, Iran	Ioannina, Van, Golhisar, Zeribar	0–10.5k	MAT (PFT)	PANN
Cheddadi et al. (1998)	Morocco	Tigalmamine	0–10.5k	MAT	TJan, TJul, PANN
Allen et al. (1996)	Northwest Spain	Laguna de la Roya, Sanabria Marsh	0–20.5k	RS	MTCO, GDD5, AET/PET
Allen et al. (2002)	Southern Italy	Monticchio	0–15k	RS	MTCO, GDD5, AET/PET
Kelly and Huntley (1991)	Central Italy	Lago di Martignano	0–11k	RS	Tjan, Tjul, TANN, PANN
Bordon et al. (2009)	Albania	Lake Maliq	0.5–16k	MAT	MTCO, MTWA, TANN, GDD5, Psum, Pwin, PANN
Combourieu Nebout et al. (2009)	Alboran Sea	ODP976	0.2–25k	MAT	Twin, Tsum, TANN, Pwin, Psum
Neumann et al. (2007)	Israel	Birkat Ram	0–6.5k	PDF (MCR/Baysian)	Twin, Tsum, PANN
Peñalba et al. (1997)	Northern Spain	Quintanar de la Sierra	0–13.5k	MAT	Tjul, TANN, Pjul, PANN
Di Donato et al.	Central Italy	Sele Plain, Gulf of Solemo	0–35k	MAT	TJan, TJul, TANN, PANN

(*Continued*)

Table 2.3 (Continued)

Other Holocene pollen-climate studies from the Mediterranean region

Author	Region	Sites	Time	Methods	Climate Parameters
Cheddadi et al. (2009)	Morocco, Algeria	Ifrah, Chataigneraie	4.5–25k	MAT	Tjan, Pann
Davis and Stevenson (2007)	Northeast Spain	Laguna Guallar, Hoya del Castillo	5.5–9.5k	MAT (PFT)	MTCO, MTWA, PANN
Dormoy et al. (2009)	Alboran and Aegian Sea	ODP976, SL152	4–15k	MAT, NMDS/GAM, PLS	MTCO, MTWA, Pwin, Psum
Kotthof et al. (2008)	Aegian Sea	SL152	4.3–10.3k	MAT (Biome Constrained)	MTCO, MTWA, PANN, Pwin, Psum
Huntley et al. (1999)	S Italy	Monticchio	11.5–15.5k	RS	MTCO, GDD5, AET/PET
Brewer et al. (2007)	Europe	EPD, Pangeae, Other	6k	MAT (PFT)	MTCO, GDD5, AET/PET
Cheddadi et al. (2009)	Europe	EPD	6k	MAT	MTCO, GDD5, AET/PET, P–E
Wu et al. (2007)	Eurasia	EPD	6k	IM	MTCO, MTWA, TANN, GDD5, Pjan, Pjul, PANN, AET/PET
Conner and Kvavadze (2008)	Georgia	Misc	14–1k	WA	PANN
Finsinger et al. (2007)	Italy	Misc	0k	WA, WA-PLS	Twin, Tsum, Pwin, Psum
Barboni et al. (2004)	Mediterranean	Misc	0k	Plant Traits Study	

Methods: MAT, modern analogue technique; MAT (PFT), MAT (plant functional type); MCR, mutual climatic range; PDF, probability density function; RS, response surface; NMDS, non-metric multidimensional scaling; GAM, generalized additive model; IM, inverse modeling.
Climate parameters: MTCO, mean temperature of the coldest month; Twin, winter temperature; Tjan, January temperature; MTWA, mean temperature of the warmest month; Tsum, summer temperature; Tjul, July temperature; TANN, mean annual temperaure; Pwin, winter precipitation; Pjan, January precipitation; Psum, summer precipitation; Pjul, July precipitation; PANN, annual precipitation; AET/PET, actual/potential evapotranspiration; P–E, precipitation minus evaporation.

Pollen data reflect changes in vegetation (see also Section 2.10) that are influenced not only by climate but also by other natural factors such as migration lag, ecological competition, succession, disease, soil development, and fire. To these are added human impacts such as deforestation, plantation, erosion, grazing, cropping, and, again, fire. The Mediterranean region has experienced a long history of human impact, as many pollen records clearly reflect (Pons and Quézel, 1998; de Beaulieu et al., 2005). Nonclimatic influences on the pollen record, especially human impacts, are a potentially significant source of noise or error in climate reconstructions, becoming particularly important over the last 2k years as (despite abatement during some periods in some regions) population expanded and agriculture intensified overall (Kaplan et al., 2009). Nevertheless, analysis of modern pollen surface-sample data sets can still demonstrate significant relationships between pollen and climate, even in today's highly modified landscape (Barboni et al., 2004; Finsinger et al., 2007, and other references in Table 2.3). The effect of nonclimatic influences are captured in error ranges that reflect the performance of the transfer function, both in cross-validation of the modern training set and in the fossil reconstruction. These error ranges vary according to the data set and calibration method and are difficult to compare. Furthermore, typical error ranges on the order of ± 0.8–1.6°C are probably close to the maximum amplitude of change experienced over the last 2k years. For all these reasons, pollen data must be used with caution over this period, but this is no reason to abandon these data entirely.

One approach to reducing error is to select sites where evidence of human impact in the pollen record has been minimal, although most pollen diagrams indicate some form of disturbance, even in remote mountain areas (Allen et al., 1996; Peñalba et al., 1997; Cheddadi et al., 1998). Even where this is possible, modern surface-sample calibration data sets require samples from across a wide climatic range, and therefore from a wide range of locations that necessarily include more disturbed areas. Other authors using the modern analogue technique (MAT) have constrained the selection of modern analogues from those of the same biome (Prentice et al., 1996) as the fossil sample, in an attempt to reduce the influence of human impacts (Bordon et al., 2009). In Davis et al. (2003), modern and fossil pollen data were matched based on Plant Functional Type (PFT) scores (Prentice et al., 1996) rather than on taxa percentages, thereby excluding the influence of changes in taxa of the same PFT, which may have resulted from nonclimatic factors. The same study also used four-dimensional gridding (three-dimensional space plus time) to integrate the results of many hundreds of sites, allowing an underlying regional climate signal to emerge from individual site records potentially subject to local impacts. However, by assimilating multiple age-depth models, each with its own dating uncertainty, this technique may reduce temporal resolution. Furthermore, uncertainties in these reconstructions are likely to be large in relation to climatic changes experienced over the short periods covered. Areas of uncertainty include the response time of long-lived vegetation, such as trees, and errors generated by pollen-climate transfer functions when nonclimatic influences have had important impacts on present and past vegetation distributions. Records from large lakes and marine cores represent an alternative to this method, since in drawing their pollen rain from a wide region they integrate vegetation change over a large spatial area without also integrating dating uncertainties from multiple sites.

The detection of common changes in pollen records over a large spatial area has been crucial in resolving the debate about whether the observed expansion of Mediterranean schlerophyll vegetation during the last 6k to 8k years was the result of climate change or human impact. This is clearly important for the interpretation of pollen-based climate reconstructions for this period. Some authors maintain that the evidence remains ambiguous (De Beaulieu et al., 2005), but others suggest that the synchronous and extensive nature of the expansion points primarily to a climatic cause (Huntley and Birks, 1983; Jalut et al., 1997, 2008; Huntley, 1998, 1990a,b; Davis et al., 2003; Sadori, 2007). This change in vegetation would suggest a progressive warming and increase in aridity in the mid- to late Holocene that is also supported by other proxies, including lake-level reconstructions (Harrison and Digerfeldt, 1993), fossil wood physiology (Terral and Mengual, 1999), isotopic analysis of speleothems (McGarry et al., 2004) and lakes (Roberts et al., 2008), and foraminifera-based SST reconstructions (Melki et al., 2009). However, more recent lake-level, pollen, and charcoal evidence (Magny et al., 2007; Noti et al., 2009; Tinner et al., 2009) question the notion of a persisting mid- to late-Holocene warming and aridity trend over the entire Mediterranean region, while continuous cross-correlation analyses emphasize the role of human impact for the expansion of highly flammable sclerophyllous maquis and garrigue vegetation (Colombaroli et al., 2007). A contrary trend, involving late-Holocene cooling, seems to be reflected in some alkenone-based SST reconstructions from the Mediterranean (Marchal et al., 2002). But more recent studies suggest that the common understanding that this proxy reflects annual temperatures may not hold true in this region (Versteegh et al., 2007). This is so because the two main periods of alkenone production are spring and fall, as demonstrated by water-column and sediment-trap studies in the northwest Mediterranean (Ternois et al., 1996; Sicre et al., 1999).

A characteristic feature of the Mediterranean is the complexity of local climates resulting from the dissecting mountainous relief; the interaction of competing air masses from the Atlantic, North Africa, and continental Europe; and the effects of the Mediterranean Sea itself. This leads to strong horizontal and vertical climatic gradients in the region and the possibility that these can be dramatically modified at a local scale in response to subtle changes in regional climate. This can mean a strong vegetation response to climate change in certain sensitive locations, accompanied by contrary responses at nearby sites. Analogously, Davis et al. (2001) identified contrary trends in Holocene moisture availability on opposing sides of the Sierra Nevada rain shadow, while Cheddadi et al. (1998) note that a late-Holocene cooling found in Morocco contrasts with a warming trend identified by Allen et al. (1996) in northwest Spain. Davis and Brewer (2009) also identify a contrary warming and cooling between high- and low-altitude sites during the mid-Holocene in the Mediterranean. This suggests that the regional significance of climatic changes observed at individual sites in the Mediterranean must be interpreted with caution, particularly when using climate models that operate at low (horizontal and vertical) resolutions. This could be argued for all climatic records from the region, but pollen data has the advantage of occurring widely enough that records from individual sites can be assimilated to provide a more accurate assessment of regional climatic change (Davis et al., 2003). Marine pollen records also effectively assimilate vegetation change over large regional areas, while also providing data for lowland arid areas where there may be few suitable terrestrial sites. Interpretation of pollen-climate marine records, however, present a number of problems, not least that with such a potentially large and ill-defined pollen source area, it is difficult to determine the source-area climate. This can be only loosely related to the marine-site location, making it problematic to evaluate the ability of marine pollen surface samples to predict sample-site climate (Combourieu Nebout et al., 2009). Evidence suggests that marine records may also be biased to pollen produced from higher mountain areas (Combourieu Nebout et al., 2009) or pollen in river outflows (Beaudouin et al., 2007) and that source areas may change over time as prevailing atmospheric circulation changes (Magri and Parra, 2002). A further problem relates to the low pollen counts found in marine pollen records. These typically range from 100 to 300 pollen grains per sample, significantly lower than the counts of 500 grains per sample usually considered necessary to ensure statistically reliable pollen analysis (Birks and Birks, 1980). The reliability of smaller changes in the pollen record can therefore be difficult to evaluate, and with it, any pollen-climate reconstruction based on such changes. The low pollen count arises from a reduced pollen rain and, more subtly, from the overrepresentation of *Pinus* pollen in the marine pollen record, since it can travel for longer distances over the sea. However, *Pinus* also forms an important part of the woodland cover in the Mediterranean, so that its exclusion could lead to underestimation of precipitation, particularly where the transfer function cannot be guided by other equivalent taxa. Evaluation of transfer functions excluding *Pinus* have so far only been undertaken on large surface-sample data sets covering the entire Eurasian region (Dormoy et al., 2009); the reliability of such approaches in the specific context of typically Mediterranean vegetation remains to be evaluated.

Future work will likely concentrate on reducing the uncertainties just discussed, through careful site selection, integrated multisite and multiproxy analysis, increasing temporal (sampling) resolution, and improvements in pollen-climate modeling, including the development of larger modern pollen training sets specific to the Mediterranean region. These efforts are also likely to benefit from ongoing community-based initiatives to improve pollen data sharing (the European Pollen Database), the understanding of vegetation–pollen relationships (LANDCLIM), and the dynamic modeling of climate and nonclimatic influences on vegetation (TERRABITES).

2.12 Sea-Level Variations over the Last 2000 Years in the Mediterranean

Chapter 4 of this book (Gomis et al., 2012) deals with Mediterranean sea-level variability and trends within the instrumental period and in future projections. Sea-level variations are the sum of climatic and geological factors (Lambeck et al., 2010a,b), which can be divided into: (1) changes in water volume (ice sheet and alpine glaciers melting, thermal expansion of sea water masses), (2) vertical land movements (tectonic, geological, and anthropogenic subsidence), and (3) glacio-hydro–isostasy rebound of the sea floor and the continental lands, consequences of ice melting, and sea-level increases mediated by lithosphere rheology responses. While water volume changes (1) are global factors and thus climate- and time-dependent, while both land-movement factors (2 and 3) are regional and local, and therefore time- and site-dependent (Milne et al., 2009). In this sense, any oscillation recorded along a single coastal sector should be defined as a relative sea-level change, and its determination requires a multiparameter approach (Morner, 2010). Timing and dynamics of the ice-volume equivalent sea-level contribution in the Mediterranean area during the Holocene are discussed in many papers (Lambeck et al., 2004a). Available data clearly describe the sea-level rise during the Early and Middle Holocene (see Milne et al., 2009, and references therein): in this period the sea-level rose by more than 100 m in 10k years (Fairbanks, 1989; Bard et al., 1996). The sea level reached an elevation quite close to the present one at 4k to 6k years BP. Fewer data are available for the past 2k years, mainly because the sea level rose no more than a few decimeters and few markers can detect such small variations.

In the Mediterranean Sea, a very complex area from a geodynamic point of view, local tectonic and glacio-hydro isostasy varies significantly site by site. During the last 2k years, the values of such local displacements (uplift or downlift) may well have been greater than the global sea-level rise. This makes it impossible to define a sea-level curve valid for the whole basin. However, during the last 2k years, available data and models (Lambeck et al., 2004b) converge on a total eustatic contribution very close to 13 cm, whether such a rise occurred gradually or only in recent times. As a consequence of glacio-hydro isostatic adjustments, in tectonically stable areas the coastal lines of 2 ka vary between 0 m (Eastern Mediterranean) (Sivan et al., 2004) and ~2 m (Central Mediterranean) (Antonioli et al., 2007) below the present sea-level. It is widely accepted that long-term vertical displacements due to tectonics can be determined by comparing the present height of paleo-sea-level markers formed during the Last Interglacial maximum with the well-known paleoeustatic elevation at that time (6 ± 1 m above the present sea level 125 ka BP) (Nisi et al., 2003). This allows the long-term contribution of tectonics to relative-sea-level variation to be reliably measured. Determination of short-term displacements at a given site requires a reliable glacio-hydro-isostatic model: by comparing the expected height of sea level deduced by the model with the height of well-dated paleo-sea-level markers at a certain time, it is possible to obtain accurate measurements of recent vertical movements (Lambeck et al., 2010a).

With this in mind, isostatic models can be the key to understand the relative sea level of the recent past. Many models try to describe the Mediterranean isostasy (Peltier et al., 2002; Lambeck and Purcell, 2005; Stocchi and Spada, 2007) over this period. In particular, the Australian National University model (Lambeck et al., 2004a, 2006, 2010a,c) was tested in the Mediterranean by comparing stratigraphical and morphological evidence, supported by Th/U and ^{14}C datings, with model data

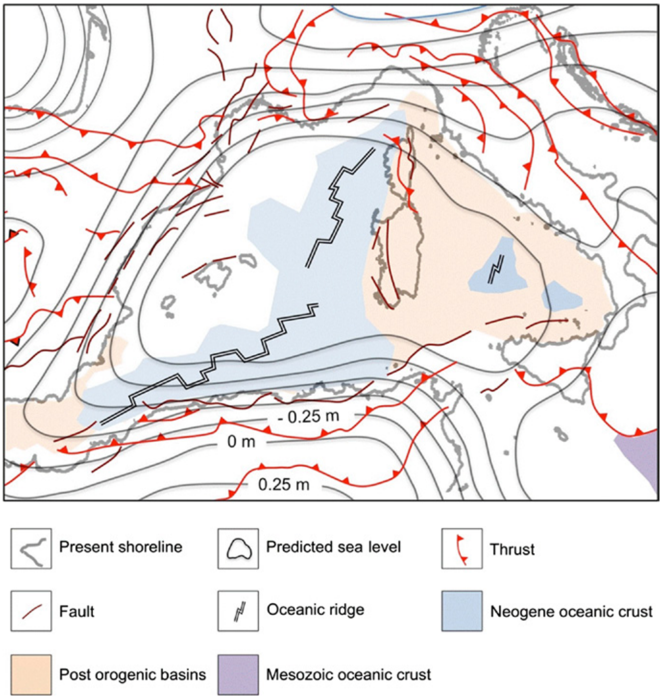

Figure 2.17 The predicted sea-level lines of 2 ka ago (redrawn by Lambeck and Purcell, 2005) are superimposed on a simplified tectonic sketch (redrawn by Barrier et al., 2004) of the western Mediterranean. Through this comparison it is possible to note that to an apparently homogeneous distribution of the expected sea-level of 2 ka bp, corresponds a complex geodynamic pattern of the region. Such evidence might (partially) explain why not all the published paleoeustatic data fit with isostatic predictions along the Mediterranean, especially where models are not calibrated with field evidence. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this book.)

from hundreds of sites (Lambeck and Bard, 2000; Lambeck et al., 2004a,b, 2010a). However, not all the data available for the Mediterranean seem to be in agreement with the sea level predicted by isostatic models (Pirazzoli, 2005). This is probably due to the complexity of the lithosphere (Figure 2.17), with the convergence of many plates, the presence of regional thrust faults, subduction areas, interplate volcanism, oceanic spearing ridges, extensional basins, alpine folds, and thrust belts (Faccenna et al., 2001, 2004, for the Central Mediterranean geological history).

Geological vertical movements are a fundamental component of relative sea-level oscillations along Mediterranean coastlines. For instance, sea-level uplift of up to 10 m in western Crete (Greece) after the AD 365 earthquake (Shaw et al., 2008) is verified by tidal notches and marine terraces formed at that time, as well as by the ancient harbor of Falasarna, all now far from the sea. In the North Adriatic Sea, data from coastal and deep-sea cores show that during the Holocene this sector was affected by strong subsidence (Lambeck et al., 2010a). These lines of evidence

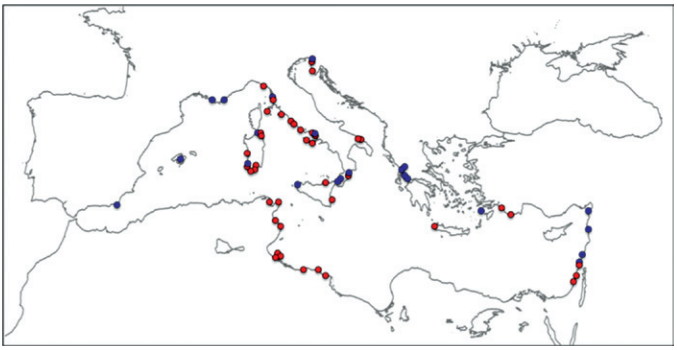

Figure 2.18 Sketch of the Mediterranean Sea including the main sites with sea-level markers of 2.0 ± 0.5 ka BP (blue circles: bio- and geological makers; red circles: archaeological remains) cited in the present review (Lambeck and Bard, 2000; Morhange et al., 2001; Lambeck et al., 2004a,b; Sivan et al., 2004; Pirazzoli, 2005; Antonioli et al., 2007; Vött, 2007; Silenzi et al., 2009; Anzidei et al., 2011a,b; Lambeck et al., 2010a; Tuccimei et al., 2010). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this book.)

clearly illustrate that in the Mediterranean basin, apparently proximate regions have had very different relative sea-level histories. Vertical movements in a coastal sector can be reconstructed over long periods by using marine isotope stage (MIS) 5.5 (Last Interglacial, 125k years) markers, such as erosional and depositional forms (tidal notches, marine terraces, erosional platforms, paleobeaches), where these are present. In the absence of vertical tectonic movements, these markers are elevated 6–8 m above present sea level (see Nisi et al., 2003; Ferranti et al., 2006, in press). Several markers can be successfully used as paleo-sea-level proxies. Since the Mediterranean lacks tropical corals, many other markers of past sea level have been tested across the Mediterranean basin (Figure 2.18). Some of those most used include archeological remains (fish tanks, wells, harbors, prehistoric food remains); beach rocks; paleobeaches, marsh environments, or lagoons; fossil serpulid overgrowth on submerged speleothems; speleothems; tidal notches; vermetid reefs; and the slope of river terraces (see also the review in Lambeck et al., 2004a, 2010b, for main references). Along the western Italian coast, Lambeck et al. (2004b) found a local relative-sea-level increase of 1.35 ± 0.07 m, on the basis of Roman archaeological remnants dated 2k years ago. They applied glacio-hydro-isostatic adjustments, thus accounting for the response of the Earth's crust to the redistribution of ice sheets, which reduced the increase to 0.13 ± 0.09 m. This corresponds to an increase equivalent to that which the Mediterranean has experienced over the past century (Lambeck et al., 2004b). Thus, they conclude that the sea-level rise observed over the last 2k years might all have happened over the last 100 years. It is worth mentioning that previous researchers using the same values as Lambeck et al. (2004b) estimated sea-level rise in that area to be on average about 0.6 m less than Lambeck et al. (2004b) suggest (see Pirazzoli, 1976; Auriemma and Solinas, 2009, for an assessment of the confidence in the various types of archaeological remnants). Antonioli et al. (2007), on the basis of tidal notch data and archaeological sites, have found Sardinia tectonically stable and sea-level change there consistent with the isostatic model of Lambeck et al. (2006). In particular, they find an increase of relative sea level by up to 2.0 ± 0.23 m over the last 2k years.

If Lambeck et al. (2004b) are correct, then there is no discrepancy between the trends from land movements and the tide gauge records. The overall sea-level change reflects a relatively quiet period of eustatic change, lasting for ~1800 years, which ended about 200 years ago. Along continental Spain and in Sicily (Italy), preliminary data based on seven radiocarbon analyses performed on *D. petraeum* (Silenzi et al., 2009) show that the sea level rose (with respect to the present level) from −27.5 ± 1.6 cm in the year 435 ± 40 BC to −10.5 ± 1.6 cm in the year AD 429 ± 45, with a rate of 0.20 ± 0.02 mm/yr for this period. These data are comparable to the present regional sea-level rise in the Mediterranean and to the eustatic level reconstructed by Lambeck et al. (2004b) based on the Roman piscinae. During the past three centuries, radiocarbon data on vermetids suggest that the sea level has risen at a rate of 0.32 ± 0.07 mm/yr and 0.35 ± 0.07 mm/yr in Spain and Sicily, respectively (Silenzi et al., 2009). Tuccimei et al. (2010) suggest that the Spanish island of Mallorca has not experienced any sea-level rise over the last 2800 years. Their conclusions clearly contradict Lambeck et al. (2004b), as well as the direct estimates of Marcos and Tsimplis (2008) for an average basin sea-level rise of about 1.2 mm/yr. Along the Mediterranean coast of France, Laborel et al. (1994) and Morhange (1994, 2001), based on in situ *Lithophyllum lichenoides* and *Balanus* sp. remains, suggest the relative sea level constantly rose during the last 5k years, with a total increase of 1.5 m, until the period beginning ca. 1500 CE, when levels became nearly stable and remained so through the past century.

Moving to the eastern Mediterranean basin, Vött (2007) has produced sea-level–change curves for seven coastal areas of northwestern Greece. The range of relative sea-level changes identified varies between 3.5 and 13 m over the last 8k years. Along the Turkish coasts (between Knidos and Kekova), Anzidei et al. (2011a) reported that the relative sea level rose between 2.4 and 4.5 ± 0.3 m during the last 2.3k years. Such values are due to the high rate of tectonic subsidence that affects southwest Turkey (1.48 ± 0.3 mm/yr). Along the Israeli coast, Sivan et al. (2004) determined the past sea level on the basis of 64 coastal water wells from the first century AD to the mid-thirteenth century AD. Results show that at the beginning of the Roman period (1950 years BP), relative sea level was very close to the present-day level; during the Crusade period (AD 1001–1265) the mean relative sea level was 40 cm below the present one. Toker et al. (2012) provide evidence supporting a sea-level drop of up to about 50 ± 20 cm at the eastern coasts of the Mediterranean basin (Israel) during the period AD 900 -1300. The estimate of Toker et al. (2012) is based on a variety of archaeological remains, mostly from the Crusader period, compared with other archaeological and biological proxies of sea level from the periods before and after. Anzidei et al. (2011a), studying the coastal sector from Akziv to Caesarea, reported a eustatic rise of 13.5 ± 2.6 cm during the past two millennia, in agreement with Lambeck et al. (2004b).

For the southern Mediterranean, including the coasts of Tunisia (15 sites between Tunisia and Jerba Island) and western Libya (4 sites between Sabratha and Leptis Magna), Anzidei et al. (2011b) analyzed Punic and Roman age archaeological remains. Markers for sea level during the last 2k years that they analyze include pools, harbors, quarries, fish tanks, slipways, a road, and a tidal notch. From these results, they conclude that, along the coast of Tunisia and Libya, local relative sea level has increased 0.2–0.5 m during the last 2k years. They attribute the observed changes primarily to eustatic and glacio-hydro-isostatic variations, with some minor vertical tectonic movements.

In order to maximize the reliability with which the isostatic model can predict past relative sea levels, future studies are expected to extend the calibration of models with field data to the entire Mediterranean coastline, following the approach of Lambeck et al. (2004a,b, 2010a,c) and Pirazzoli (2005). Moreover, the contribution offered by short-term alpine glacier variations and water-column height oscillations, including thermal expansion, to the isostatic signal of the Mediterranean area should be reconsidered. New high-resolution sea-level proxies (e.g., archaeological remains, vermetids, *Lithophyllum lichenoides* and *Balanus* sp., foraminifera, testate amoebas and diatoms, and speleothems) need to be tested and compared to each other.

2.13 Paleoclimate Modeling and Data Assimilation for Paleoclimatological Analysis in the Mediterranean

Analyzing proxy-reconstructed paleoclimate records and models in tandem allows for the evaluation of climate transitions through the analysis of forcing and feedback mechanisms in past and future climate changes. In return, model simulations can aid in the interpretation of the causes of observed variations in paleoclimate data. Models sometimes make it possible to separate the externally forced climate signal from internal variability (to the extent that signal and noise are distinguishable), a level of analysis that proxy data alone cannot support. But all such analyses require that data and model simulations can be meaningfully compared (Lohmann, 2008). Modeling efforts contribute to this overall project from three distinct perspectives: (1) through methodological evaluation using pseudoproxies, (2) through the development of model-based analogue reconstructions, and (3) through the use of assimilation approaches to generate model simulations that are closest to the available observations.

Present climate models lack the spatial resolution to provide a detailed view of the evolution of the climate in the Mediterranean. Neither smaller-scale factors, such as complex coastlines and orography and short timescale sea–land interactions, nor major processes, such as the connection between the Mediterranean Sea and the North Atlantic, can be represented realistically. Some global simulations are available, however, that allow for an evaluation of simulated variability in the past millennia. A few experiments, the results of which are shown in Figure 2.20, will be briefly discussed: a 7k-year-long run (OETZI) and two simulations of the past millennium

(ERIK1 and ERIK2; González-Rouco et al., 2003, 2006; Zorita et al., 2005) with the model ECHO-G; one simulation over the last 500 years with the model HadCM3 (Tett et al., 2007); and one simulation over the last 1150 years with the model CSM (Ammann et al., 2007). The ERIK1 and ERIK2 runs were driven by the same forcing, the only differences between them being the initial conditions in year 1000. Since the real initial conditions are not known, the spread between the two simulations can yield a rough estimate of the influence of this uncertainty on the simulations. The OETZI simulation is a much longer simulation, using the same model starting in year 7000 BP; in addition to the solar and greenhouse gas forcing implemented in ERIK1 and ERIK2, this simulation included slowly varying orbital forcing. For the past millennium, OETZI is more similar to ERIK2 in the period 1000–1300 than to ERIK1, indicating that the initial conditions in ERIK1 may be too warm (Goosse et al., 2005; Osborn et al., 2006).

The simulation with HadCM3 covers the past 500 years: in addition to solar variations, volcanism, and greenhouse gases, it also included orbital forcing and forcing by changes in land cover (Tett et al., 2007). The CSM simulation, starting in AD 850, used the same forcings (Ammann et al., 2007).

The most relevant factor determining the differences among the simulations on the global scale are the external forcings used and the climate sensitivity and thermal inertia of each model. The amplitude of reconstructed variations of solar output is based on the calibration of ^{10}Be or ^{14}C records. The latest estimations tend to yield smaller-amplitude variations. The total solar irradiance (TSI) change between the present and the Late Maunder Minimum (end of seventeenth, beginning of eighteenth century) was estimated in the 1990s to be 0.25% (Lean and Rind, 1999), but more recently, much smaller values, on the order of 0.1%, have been published (Steinhilber et al., 2009; Figure 2.19).

The simulations presented here lay in the possible upper and middle ranges of the amplitude of TSI. Furthermore, although the ^{10}Be and ^{14}C records agree in their time evolution (Bard et al., 2000), they may disagree in particular multidecadal periods (Figure 2.20). The magnitude of the volcanic forcing, estimated based on acidity analysis of polar ice cores, is still uncertain for the past millennium (but cf. case made for volcanic forcing and MCA in Goosse et al., 2012), and even more for periods further back in time. Also, the implementation is different among models, being more realistic in HadCM3 and CSM than in ECHO-G.

Finally, the orbital forcing may become discernible for the longer timescale: the position of the perihelion has been advancing within the calendar year from July, about 10k years ago, to early January at present (Berger and Loutre, 1991). This shift should cause a slow cooling of Northern Hemisphere summers. The effect, included in all the simulations except ERIK1 and ERIK2, is essentially insignificant over the past centuries. The upper panel of Figure 2.20 shows the evolution of temperature in the Mediterranean basin as simulated with different climate models. OETZI, the only simulation covering the last 2k years, displays quite stable temperature conditions in the first millennium, with wider variations in the second millennium mainly characterized by the strong cooling during the LIA (from about 1400 to 1800): about 2.0°C by comparison with the twentieth century mean, and slightly greater in winter than in summer.

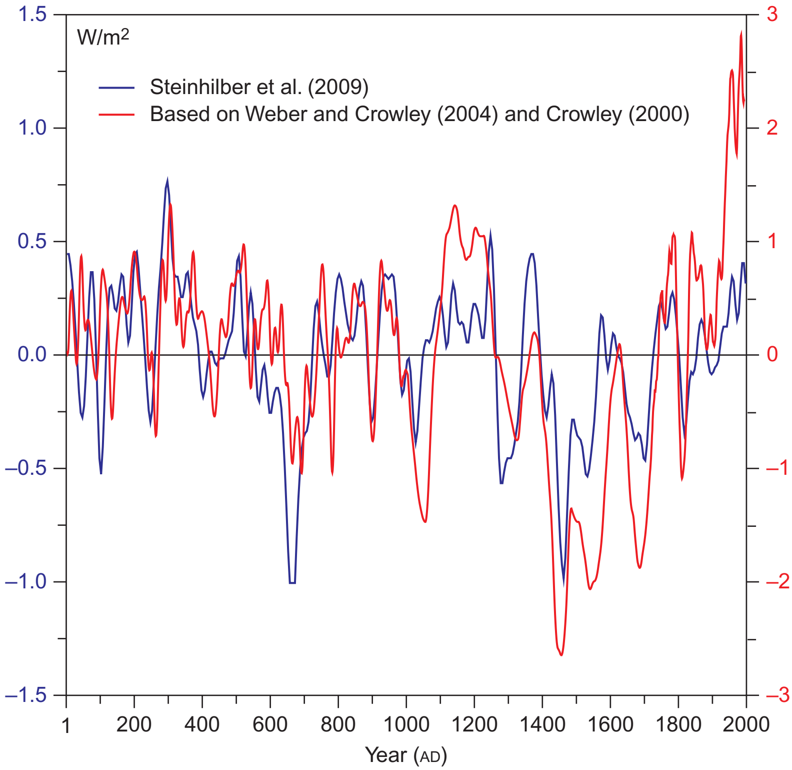

Figure 2.19 Reconstructions of total solar irradiance in the last 2k years. The record by Steinhilber et al. (2009) is based on the ^{10}Be record. The red line is based on the ^{14}C record in tree rings in 0–1000 and on ^{10}Be thereafter. Note the different scaling for both curves. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this book.)

The stable conditions during the first millennium are probably related to the fairly constant value of TSI in the Weber et al. (2004) reconstruction, which lacks the sharp minimum in the decades around AD 600 that are prominent in the Steinhilber et al. (2009) record (see Figure 2.19). The two shorter ECHO-G simulations over the second millennium display a very similar evolution, quite probably caused by the external forcing. The simulation with the models HadCM3 and CSM, on the other hand, reflect much narrower past variations over the last 500 and 1150 years, respectively. The different external forcings used in the simulations and the different climate sensitivities modulate the magnitude of the temperature variations. However, the temperature patterns show some discrepancies as well. Figure 2.21 displays the simulated annual temperature anomalies in the Late Maunder Minimum (1680–1710), a cold period within the millennium (Jansen et al., 2007; see also Luterbacher et al., 2004, 2006, and information in this chapter). The cooling trends are more pronounced for northern parts of the Mediterranean in the CSM and ECHO-G

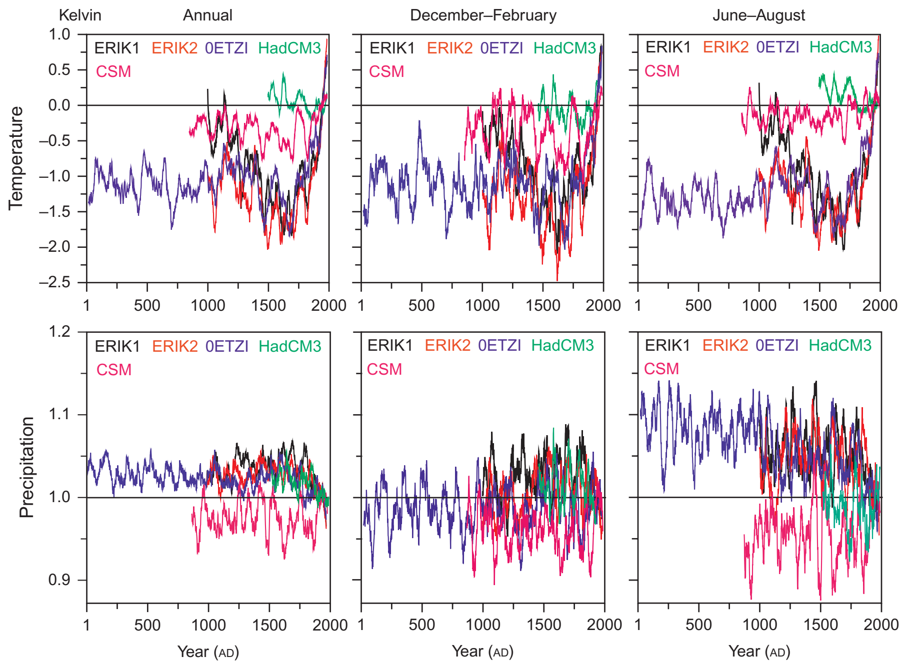

Figure 2.20 Evolution of the air temperature and precipitation in the Mediterranean region (30°N–45°N; 10°W–40°E) simulated by ECHO-G, HadCM3, and CCSM. The curves represent the respective temperature anomalies or the ratio to the mean precipitation in 1900–1990. All are smoothed with a 31-year running mean.

simulations. In ECHO-G they are stronger in midcontinent; in CSM, they are more marked near the Atlantic Ocean. On the other hand, the HadCM3 model produces warmer temperatures than in the twentieth century in the northern areas of the Mediterranean domain. This different pattern is mostly caused by the temperatures in the summer season (not shown), which, as indicated in Figure 2.21, displays a surprising negative trend through the past few centuries. Proxy-based reconstructions of summer temperature can, therefore, specifically assess the validity of the HadCM3 simulations in this area.

Climate reconstructions in the Mediterranean region, therefore, have the potential to discriminate among these different global models. Important aspects in this respect would be to ascertain with confidence the overall amplitude of the temperature variations in the past and whether or not the temperature variations in the second millennium were larger than in the first. In the first millennium, there are important target periods that offer also a possibility to distinguish between reconstructions of solar irradiance, such as the decades around AD 600, in which societies were probably less resilient to climate vagaries. Strong climate anomalies in this period indicated by historical or natural archives presented in this chapter would be helpful to reduce the uncertainty originating in an unconstrained suite of climate models.

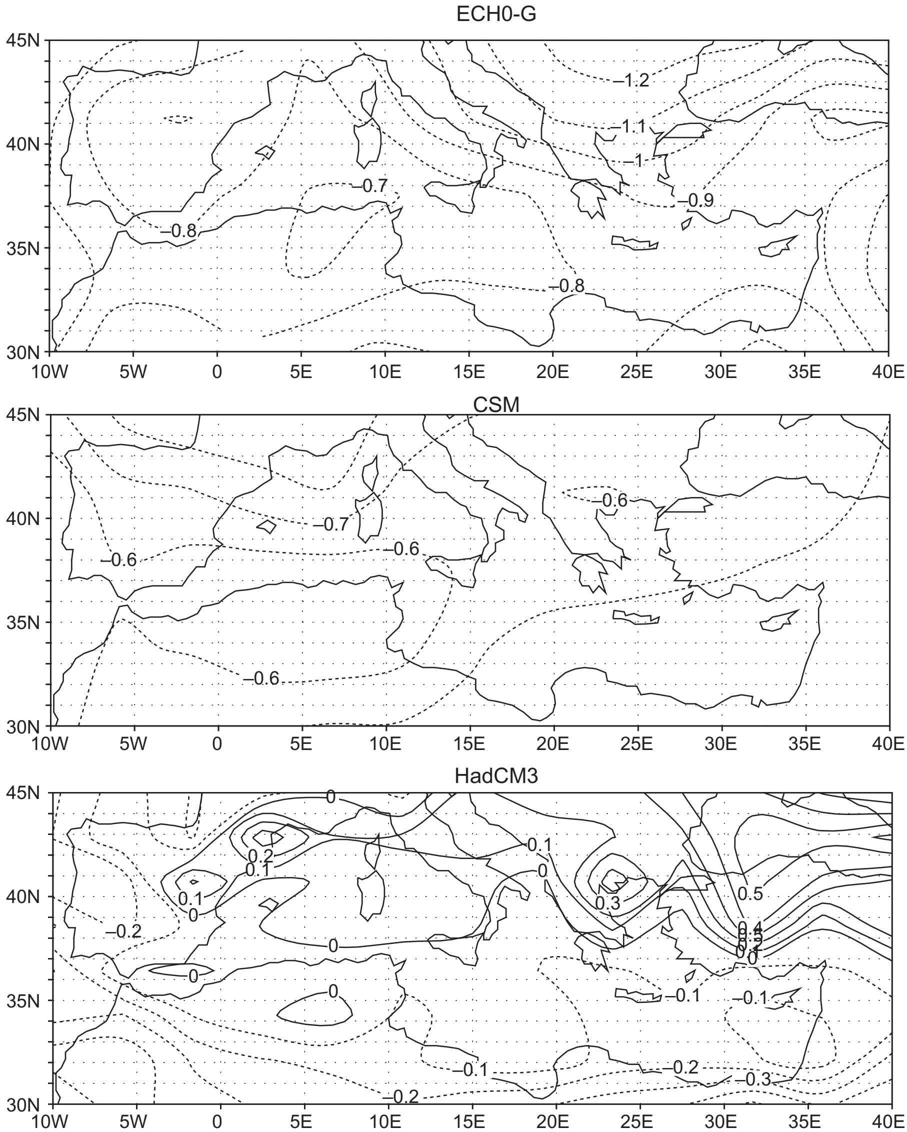

Figure 2.21 Spatial pattern of simulated mean annual temperature deviations (with respect to the 1900–1990 average) in the Late Maunder Minimum (1680–1710) simulated by three different global climate models in the Mediterranean region.

Precipitation is a very important variable in this region. The Mediterranean has been identified as a hot-spot region (Giorgi, 2006), with temperature projections higher than the global mean. However, projections of precipitation are still uncertain, and the comparison between climate simulations and reconstructions will be particularly important to evaluate the skill of climate-model projections at regional scales. In fact, the climate models considered here do not quite agree in the simulated precipitation anomalies in the past few centuries (see Figure 2.20, lower panel), both on an annual and a seasonal basis. Annually, ECHO-G and HadCM3 both indicate higher precipitation in the last 500 years than at present, and the longer ECHO-G simulation indicates that this could have happened also for the last 2k years. The recent period would thus have been an exceptionally dry period that would continue into the future if the projections by the ECHAM5 model turn out to be correct. On the other hand, the CSM model simulated lower annual precipitation in the last 1200 years than at present. The disagreement between ECHO-G and HadCM3 on the one hand and CSM on the other is also reflected in the simulated winter precipitation in the past few centuries, although at longer timescales the ECHO-G model simulates roughly stable or somewhat lower precipitation over the last 2k years. In the summer season, it is the ECHO-G model that simulates higher precipitation in the past and thus disagrees with CSM and HadCM3. Winter precipitation, which in this region represents the bulk of the annual total (Xoplaki, 2002), is partly controlled by the northern annual modes (Arctic Oscillation, AO/NAO; strongest link over the western Iberian Peninsula with an explained variance of ~30%). Future projections by the models included in the Intergovernmental Panel on Climate Change (IPCC) suite (Miller et al., 2007) mostly indicate a strengthening of the NAO/AO in the future and thus a reduction of winter precipitation in parts of the Mediterranean area. It is therefore of interest to test model simulations of past precipitation in this region or simulations of past variations of the NAO. However, this requires a robust proxy-based reconstruction of Mediterranean winter precipitation, including lower-elevation locations.

The patterns of winter-precipitation changes in the Late Maunder Minimum also present clear divergences (not shown). The ECHO-G simulations present increased precipitation in the Late Maunder Minimum relative to the twentieth century in the west part of the domain, but in ERIK2 the precipitation anomalies are more marked in the south-western Mediterranean areas. In contrast, the CSM model indicates higher precipitation than present in the North East of the basin, and as discussed in the previous paragraph, the anomalies over the whole basin average to lower precipitation than in the twentieth century. The HadCM3 model produces higher precipitation than in the twentieth century mean almost over the entire Mediterranean domain, with the exception of the northwest fringes. This variability in the simulated winter-precipitation change is probably related to the representation of the storm tracks in the models and its response to changing external forcing. Moreover, because of the high internal variability at these spatial scales, the identification of a robust pattern of regional precipitation response may require a larger ensemble of simulations. By the same token, the comparison between a particular simulation with proxy-based reconstruction should also take into consideration the large spread among model responses and the large internal variability. It should be noted that other measures of hydrological stress, such as the PDSI, which includes the effects of temperature on soil moisture, tend to agree more strongly across models (Brewer et al., 2006).

Future studies should include ensembles of simulations with sufficient large size to identify the robust climate change signals above the regional internal climate noise. Gradual but continuous changes in the mean climate may be less or more important than a sequence of extreme seasonal events. Climate modeling may help disentangle the relationship between mean climate changes and frequency of extreme events and, together with the analysis of past natural and historical archives (e.g. McCormick et al., 2012), may provide useful insights for the future consequences of regional climate change in the Mediterranean. Another important objective for the future is the joint evaluation of simulation and reconstructions for Europe, the Mediterranean, and the Middle East region. Regional models include a much better representation of topographic features, coast lines, and land cover, so that they can simulate the important atmospheric processes that occur at subregional scales in the Mediterranean basin also for the past. Several ongoing projects are currently contributing to produce regional simulations following this rationale. This is the case of the SPECT-more and Salva Sinobas projects (Spanish Ministries of Education and Environment) that target a comparison of the information from natural and documentary proxies with that provided from regional simulations with the MM5 model (Gómez-Navarro et al., 2010, 2011).

2.14 Data Assimilation with Paleo Data

With the advent of increasing quantities of proxy records for the Mediterranean, a new and potentially valuable approach to a comprehensive climate reconstruction for that area is possible. Central to this approach is the use of newly developed assimilation procedures that combine dynamic climate models and empirical information to find estimates for past climate that are consistent with both empirical findings and a dynamic understanding of the climate system. The benefit of using a model-based reconstruction of climate, constrained by assimilated empirical information, is that these simulations also provide dynamically consistent estimates of variables that cannot be directly derived from the proxy records. In a model-based reconstruction of climate, the use of empirical information is essential. Simulating the historic natural variability without data assimilation is impossible because of the chaotic nature of the climate system. In paleoclimatology, this is likely to be of high relevance for any area characterized by a high level of natural variability. Numerical weather forecasts and paleoclimatic simulations both use General Circulation Models (GCMs). However, assimilation methods developed for weather forecasting cannot be implemented in paleoclimatic models because the extent, temporal resolution, and type of empirical information available for the system state are fundamentally different. The quantity of data used in initializing weather-forecasting models is several orders of magnitude larger than that available for paleoclimates. In addition, the types of data available for paleoclimates are fundamentally different; among other crucial differences, paleoclimate data typically measure seasonal or annual climate signals rather than the instantaneous information used in weather-forecasting models. Moreover, the relation between the climatic state and paleoclimatic information is often indirect. But these problems can be overcome. New approaches to assimilate proxy data in GCMs have been developed (reviewed in Widmann et al., 2010). Here, we discuss two methods used to assimilate data on paleoclimatic timescales.

In ensemble techniques, the time changes in the system are estimated using a finite number of states obtained from an ensemble simulation performed with a model. The members of the ensemble have a different behavior because of different initial conditions, model parameters, and forcing, for example. Various ensemble techniques are available to perform data assimilation (Evensen, 1997; van Leeuwen, 2009). However, until recently, only a very simple one has been applied to study the climate of the past millennium (Collins, 2003; Goosse et al., 2006a,b, 2010a). First, small perturbations are applied to some estimate of the initial state of the system in order to generate an ensemble of about 100 initial conditions. From this set of initial conditions, short simulations are performed, generally of 1 year's duration. The results of all the simulations are then compared to the available observations. The best one (i.e., the one that displays the best agreement with data using a specified metric) is kept as the basis for the initial condition for the next group of simulations, and the procedure then continues until the end of the period of interest. By selecting this best ensemble member for each time interval, it is then possible to track the signal recorded in the proxies. This method is a degenerate particle filter in which only one ensemble member is kept rather than several. In the full particle filter, a weight is then attributed to each of those members according to its likelihood with regard to the available proxy records (van Leeuwen, 2009). From the ensemble of simulations and the weights, it is then easy to compute the (weighted) mean and the dispersion of the ensemble, providing an estimate of the state of the system and of the uncertainty on this estimate. Some experiments have been performed using a full particle filter, and the results suggest that this would lead to significant improvement as compared with the simpler technique applied in previous studies (Dubinkina et al., 2011; Goosse et al., 2012). Using the ensemble-member selection briefly described above, Goosse et al. (2010a) reconstructed large-scale temperature changes from 11 simulations performed over the past 600 years with the climate model of intermediate complexity LOVECLIM. The 11 simulations differ in some model parameters, the forcing applied as well as in some parameters of the data-assimilation technique. However, they are all constrained by the same set of 56 proxy series derived from a compilation by Mann et al. (2008) based on a screening procedure devoted to keep only the ones that are significantly correlated with instrumental time series over the years 1850–1995. The proxies are been decadally smoothed, so the model results have also been decadally smoothed before plotting them (Figure 2.22). As discussed in Goosse et al. (2010a), the quality of the reconstruction of past temperature changes using data assimilation depends on many elements, such as the uncertainties in the forcing, in the physics applied in the model, and in the data-assimilation technique itself. In addition, a crucial element is the amount and the quality of the proxy data that are used to constrain the model results in the region of interest. The set of 56 proxies selected in Goosse et al. (2010b) did not include any proxy from the Mediterranean region, so we should not expect to see particularly good results there. When the reconstruction of annual mean temperature is compared to independent thermometer observations over the period 1850–1995 (Brohan et al., 2006), a correlation of 0.62 is obtained. This is much less than for global mean or for Europe as a whole (0.82 and 0.86, respectively). In 2012, Goosse et al. used a full particle filter

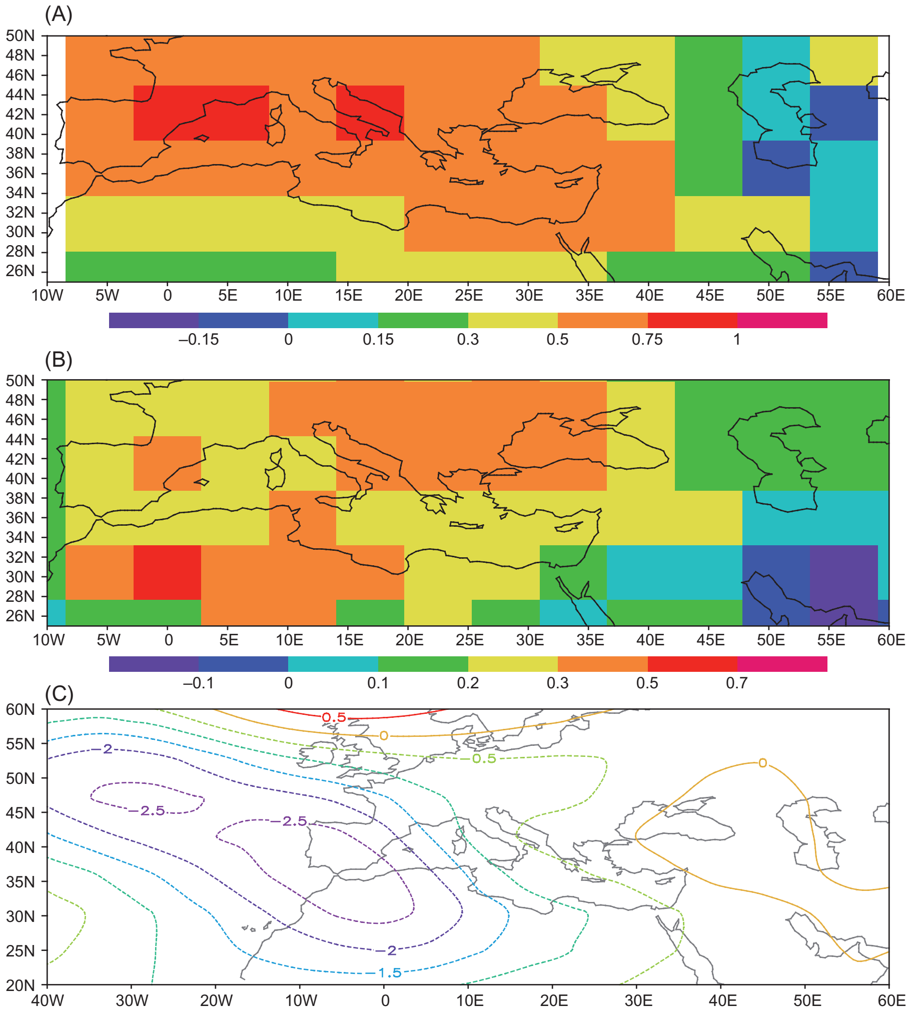

Figure 2.22 (A) Difference in growing season surface temperature (April to September, °C) between key periods of the Medieval Climate Anomaly (900–1050) and the Little Ice Age (1500–1650) in the reconstruction of Guiot et al. (2010), (B) in a simulation with the climate model assimilating the reconstruction of Guiot et al. (2010), and (C) the difference in summer mean geopotential height (m) between those two periods in the same simulation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this book.)

to assimilate the spatial temperature reconstructions of Mann et al. (2009) and Guiot et al. (2010), which cover nearly the whole globe and Europe, respectively. This allows a much better representation of Mediterranean climate, as both reconstructions have a reasonably good skill at the scale of the basin. In particular, during the MCA (defined here as the years 900–1050), the Mediterranean summer temperature is particularly high in the Guiot et al. (2010) reconstruction and in the simulation with data assimilation. In the model, in addition to the impact of the forcing, this is due to relatively high pressure over northern Europe and southeasterly winds coming from North Africa over the central Mediterranean Sea (Figure 2.22). A next step will be to investigate the precipitation anomalies associated with such changes in the circulation.

An alternative method to the ensemble approach is the assimilation of statistical reconstructions of large-scale atmospheric circulation. These are based on a statistical upscaling of available early instrumental and proxy data, which is in contrast to the ensemble method discussed in the previous section, in which empirical data are directly assimilated. Using statistical relationships between the local data and large-scale atmospheric circulation obtained from spatially complete fields, which are available for large parts of the twentieth century, a statistical reconstruction of the past atmospheric circulation can be made. In this section, we describe a method that uses artificial forcings to the climate model to keep the simulated states close to the target patterns. This approach was first suggested by von Storch et al. (2000), with the exception that the construction of the forcings of the method discussed here is different. These forcings result in large-perturbation growth when used as tendency perturbations. The forcings are referred to as forcing singular vectors (FSV) (Barkmeijer et al., 2003) and relate to sensitive structures in the model tendencies. An extensive and more technical discussion of this approach can be found in Barkmeijer et al. (2003) and van der Schrier and Barkmeijer (2005). This method has been used in several paleoclimatic studies (van der Schrier and Barkemijer, 2005, 2007; van der Schrier et al., 2007; Luterbacher et al., 2010). Here, we show results of van der Schrier and Barkmeijer (2005), focused exclusively on the Mediterranean area. In this study, the averaged atmospheric circulation over the North Atlantic sector for the period 1790–1820 is assimilated, one of the cold spells in the LIA. A statistical reconstruction of winter atmospheric circulation is assimilated in the model; the model evolves freely in the remaining seasons. Figure 2.23 shows that there is a compelling similarity between reconstructed temperatures for this period, based on available early instrumental and documentary data (Luterbacher et al., 2004) and simulated temperatures for both the winter and summer season. The model results indicate that summer warming in the central and eastern Mediterranean region coincides with greatly reduced summer precipitation.

It is interesting that the model assimilates only the winter atmospheric circulation, the summer temperature signal over the Mediterranean apparently depends largely on the preceding winter. Model data indicate that the conservative nature of boundary conditions, like soil moisture and SSTs, carry the winter signal into the summer season. In the central Mediterranean, winter precipitation is up to 70% lower because of the advection of cold and dry continental air. In the eastern part of the Mediterranean area, advection of air from southwesterly directions increases the winter temperatures. The result is that SSTs in the eastern Mediterranean increase and that bottom moisture in the central and eastern Mediterranean are below normal for the winter season. The increasing number of proxy records available for the Mediterranean region makes it possible now to perform a comprehensive reconstruction of climate for that region using a modeling approach. Central to this approach would be newly

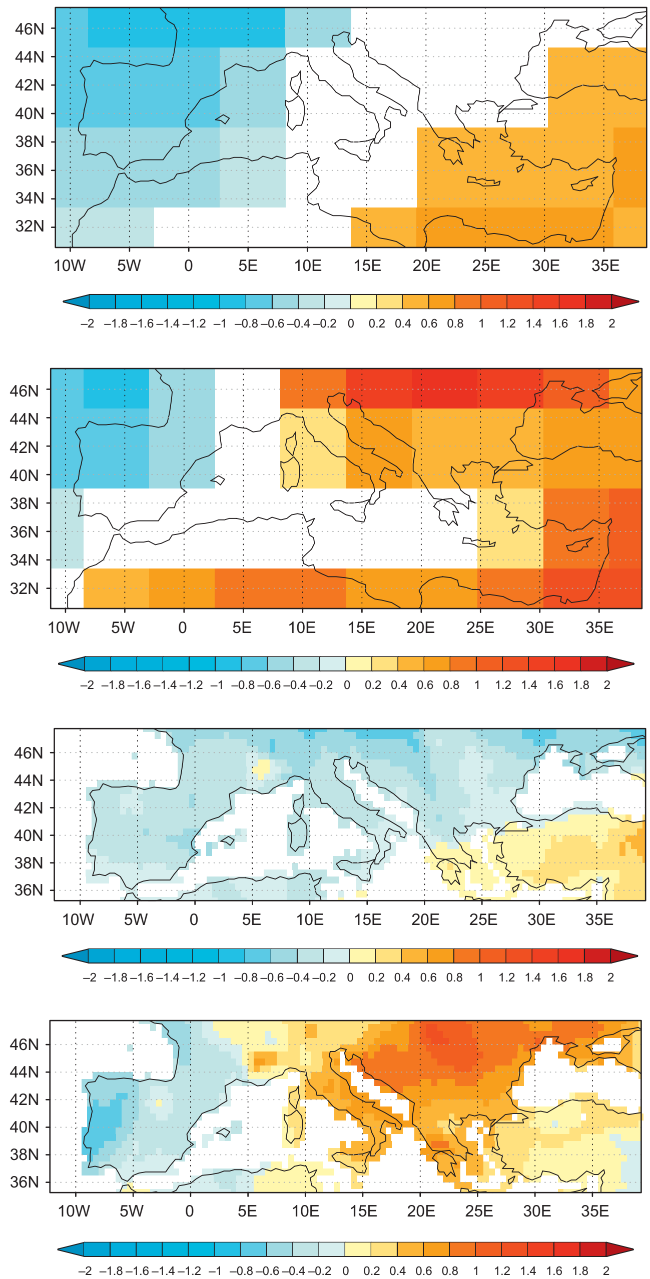

Figure 2.23 Difference in 2 m temperature (in °C) for the 1790–1820 period with respect to the 1961–1990 normal period. The left panels show model results, the right panels show results from a statistical reconstruction (Luterbacher et al., 2004) based on available early instrumental and documentary data. The upper panels show results from winter (DJF), the lower panels refer to summer (JJA). Temperature changes in the model results are significant at the 95% level. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this book.)

developed assimilation tools that ensure that the model results reproduce the empirical knowledge for that region and are dynamically consistent estimates of climate as well. In this contribution, two alternative methods are discussed. One is based on an ensemble approach and has the proxy records directly as input. The other method is based on a technique in which an artificial forcing to the model is calculated. Both approaches give satisfactory results on a large scale, including the Mediterranean area. However, much more detailed analysis could be obtained if a compilation of proxy records specifically devoted to study the Mediterranean surroundings were used in the data-assimilation procedure. The different sections of this chapter illustrate that many proxy time series are available for such a purpose and that the exercise would be very valuable. The wealth of proxy-climate data from the region as presented in this study and the use of data assimilation in climate models opens new opportunities in reconstructing climate and in assessing the quality of the reconstruction. When assimilating data in a climate model, with data specifically targeted to provide a Mediterranean climate reconstruction, an independent set of proxy records can be used to assess the quality of the model-based reconstruction. For instance, using atmospheric circulation or a selection of (proxy) temperature records as input for the data assimilation, the resulting model-based climate reconstruction could then be compared to early observations of SSTs or reconstructions of sea-level variations. Drought variations in the model could be compared to the frequency of reconstructed wildfires; the models produce growing degree days or moisture stresses that relate to a host of biological indicators. Finally, the statistics of paleofloods and storminess in the model-based reconstruction could be related to proxy-based reconstructions. These different comparisons make clear in what aspects of the climate system the data assimilation produces reliable results and in which aspects it performs poorly.

2.15 Conclusions and Outlook

This chapter reviewed the availability and potential of terrestrial and marine archives from the Mediterranean to provide important climate information for the last 2k years. An overview with the locations of marine and terrestrial proxies with seasonal to multidecadal resolution covering at least the last 600 years is presented in Figure 2.24. There is a lot of paleoclimate information available, though the length of the proxies varies, proxies reflect different climate information (e.g., temperature, precipitation, sea-level changes, pH, seawater temperature, and water-mass circulation), and proxies may record climate conditions at different times of the year.

Combining information from natural archives, documentary and instrumental data with evidence of past human activity obtained from historical, paleoecological, and archaeological records is of major relevance for our understanding of climate sensitivity, environmental response, ecological processes, and human impact. As has been shown above, temporally and spatially high-resolution climate information from marine archives is still limited. However, different archives (for instance, shallow- and deep-water corals) will provide future seawater temperature estimates, the nutrient content, the pH, and the variations in the water-mass circulation for the last 2k

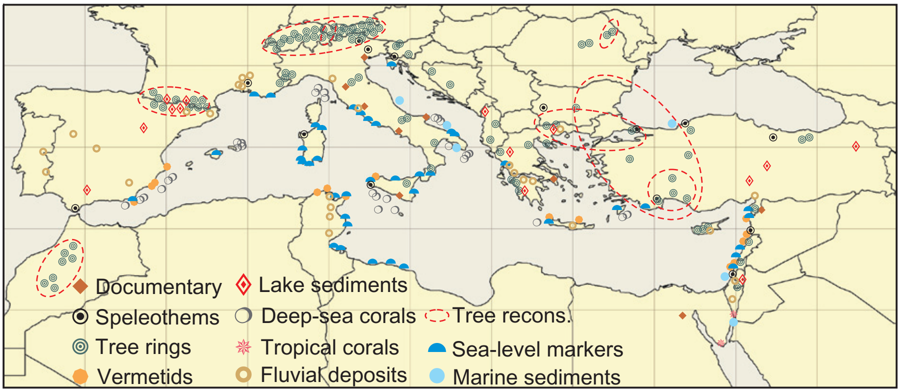

Figure 2.24 Marine and terrestrial proxies (time series and sampling locations; pollen data are provided in Figure 2.16) from the Mediterranean with seasonal to multidecadal resolution covering the last at least 600 years (except for the Red Sea corals). Note that the length of the proxies varies, proxies reflect different climate information (temperature, precipitation, sea-level changes, pH, sea water temperature, water mass circulation, etc.) and proxies may record climate conditions at different times of the year. See text for details. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this book.)

years for different regions, yet on discontinuous time intervals. New approaches and strategies in the field focusing on sedimentary setting, such as deltaic or lagoon sedimentary environments, need to be explored not only because they allow high temporal resolution studies but also to investigate land–ocean interactions. Marine records combining marine and terrestrial proxies should also be encouraged because they can help improve chronology by testing the synchronicity of proxy events in land and ocean archives. Future research work should put efforts into increasing historical and paleodata coverage to better document trends and variability of the southern and eastern Mediterranean climate, in particular in northern Africa and the Levant regions, where data are sorely missing (e.g. PAGES 2k network http://www.pages-igbp.org/workinggroups/2k-network; Kaniewski et al., 2010, 2011a,b, 2012; Finne et al. 2011 and references therein). Water isotopes of paleoprecipitation derived from multiple archives at the same location should improve our understanding of how environmental factors are affecting the incorporation of proxies in their carrier phase. The use of atmospheric circulation models implemented with water-stable isotopes is a complementary approach to better understand how the climatic signal (e.g., stable isotopic composition of precipitations) is recorded by multiple archives (e.g., ice, speleothems, lacustrine ostracods, and tree rings). Simulation of water isotopes by GCM can also be used to evaluate present-day spatial and seasonal variability of different timescales, as well as their capacity to simulate changes in the past (Risi et al., 2010). Regarding the strategy in the field, coastal sediments from deltas and lagoons should be explored more than they have been in the past, as they provide continuous and expanded records for resolving climatic and environmental changes at decadal timescales and can potentially yield a wealth of new data to link continental and marine environmental changes induced by physical forcings in the coastal zone.

We also discussed the limitations of proxies to sufficiently reconstruct the full range of natural climate variability, including interannual to multicentennial variations. We focused on dating uncertainties, distinguished climatic and nonclimatic influences, and addressed seasonality effects in proxy records and sources of uncertainties in reconstructions. We highlighted the need to study the different proxy archives in an integrative way, and we discussed the importance for multiproxy studies to disentangle the complex relationships between climate, land use, sea-level changes, human interactions, fire, vegetation, and forests. Paleoecological evidence showed that the Mediterranean region has been profoundly altered by human activities since prior to the expansion of the Roman Empire ~2k years ago up to the present. Comparison with previous interglacials shows that the late-Holocene expansion of sclerophyllous taxa is unusual (Tzedakis, 2007), and therefore, together with Holocene high-resolution multiproxy evidence (Colombaroli et al., 2007), clearly points to an anthropogenic forcing. Nonetheless, Mediterranean vegetation would certainly have been influenced by climatic variations as well as human impact during the past two millennia.

Mediterranean water availability, in particular, is arguably of great importance to societies and ecosystems. However, our understanding of variations in hydroclimatology (including short-duration and extensive drought and flood periods) across the Mediterranean is still limited because only a small number of well-dated high-temporal-resolution proxies are available unevenly distributed over the Mediterranean area. In this context, we highlighted the importance of identifying and characterizing historical extreme events that have severely stressed human or natural systems (e.g., the onset, duration, frequency, and intensity of droughts and floods). We reported on the variability of those extremes, the identification of the space and timescales that are resolved in the different Mediterranean paleorecords with associated uncertainties, and established a common framework for a comparison of paleo and modern estimates of mean and extreme climate, including relatively rapid shifts.

Based on current knowledge, it is too preliminary to draw detailed conclusions on spatiotemporal high-resolution climate behavior over the entire Mediterranean covering the last 2k years (for two reviews trying to address aspects of the Roman world, see McCormick et al., 2012; Manning n.d.). In southern Spain, varve-based evidence indicates that the most humid period during the last 4k years occurred during the Iberian–Roman ages (2.5–1.6 ka BP, 550 BC–AD 350) followed by an arid interval during the Roman Imperial Epoch (190 BC to AD 150). The first six centuries AD included some of the most intense and long-lasting droughts of the late Holocene in the Middle Eastern region. High-resolution paleolimnological data from northern Spain show good intersite coherence and indicate lower water levels and higher salinities synchronous with the MCA and generally more humid conditions during the LIA (Roberts et al., 2012). This pattern is in agreement with other lake, marine, and tree-ring records from Iberia and Morocco. In contrast, lake and partly speleothem evidence from Turkey shows an opposite pattern of a wet MCA and a dry LIA. This is supported by cross-correlations of decadal-average proxy-climate data for different lake records, as well as by lower-resolution marine and lake data from the eastern Mediterranean area. An east–west bipolar climate seesaw therefore appears to have operated in the Mediterranean for the last 1.1k years (Roberts et al., 2012, and references therein). Thus, there appears to be generally good agreement between the records from Anatolia, Greece, and the Middle East for the period between ~AD 800 and 1750, indicating generally wetter climatic conditions around AD 1200 and somewhat drier conditions afterward.

Currently, only scattered proxy information is available from natural archives that provide highly temporally resolved information of land- and sea-temperature variations covering the last 2k years. Several lake reconstructions based on geochemical and biological analyses indicate that in the Pyrenees the warmest winters occurred during the Roman Warm Period (2.7–2.4 ka BP), around AD 450 and at the start of the MCA ~AD 900. Tree-ring data suggest that summer temperatures in the Pyrenees were warm in the fourteenth and fifteenth centuries and within the twentieth century, separated by a prolonged cooling from ~1450 to 1850.

We showed the importance of proxy-reconstructed paleoclimate records and climate-model comparisons that allow for the evaluation of climate transitions through the analysis of forcing and feedback mechanisms in past climate changes. We highlighted the use of paleomodels to evaluate paleoclimate reconstructions in order to narrow the range of climate-sensitivity estimates and show how models can be used to assimilate proxies. However, based on the current evidence from the different proxy archives, we are still far away from quantifying variations in the hydrological cycle/temperature changes at different time and space scales and from understanding the underlying mechanisms responsible for the observed changes over the last 2k years.

The review of Mediterranean paleoclimatic evidence from the last 2k years is a first contribution to the efforts of the Euro-Med 2k regional group, which will not only cover the Mediterranean region but also encompass the greater European area (Luterbacher et al., 2011, in preparation). PAGES (Past Global Changes) has developed the "Regional 2k Network" (http://www.pages-igbp.org/workinggroups/2k-network) with the aim of obtaining detailed climate reconstructions of the last 2k years from all over the globe. This 2k Network consists of nine regional working groups, covering the ocean and each of the continents and their adjacent ocean regions. One review for the Southern Hemisphere is already available (Neukom and Gergis, 2011). The central focus of each regional group is spatiotemporal quantitative reconstruction and dynamic interpretation of the climate of the last 2k years based on information from natural archives, documentary sources, and instrumental measurements. Sophisticated methods including Bayesian hierarchical modeling will be applied; they assimilate both proxy and instrumental data to estimate the probability distribution of all parameters and the climate field through time on a regular spatial grid (Tingley and Huybers, 2010a,b). A better understanding of the strengths and weaknesses of reconstruction procedures and the behavior of different climate proxies will be essential and will reduce uncertainties and biases. The output will include an estimate of the full covariance structure of the temperature and hydrological reconstructions over Europe, the Mediterranean, and the Middle East, as well as diagnostic measures that indicate the utility of the different proxy time series for successful reconstruction. More detailed climate field reconstructions will provide the crucial understanding and benefit studies of future climate, particularly those focusing on the regional level (PAGES, 2009). Spatial field reconstructions provide insight into the mechanisms or forcings underlying observed climate variability and are particularly important in comparison with AOGCM integrations. The ultimate aim is to bring these regional groups together to publish a global-scale synthesis of the last 2k years. Their patterns will be combined with transient paleo runs from models of different complexity and resolution. One important objective for the future is also to evaluate whether global, continental, and regional climate simulations are consistent with proxy-derived reconstructions for Europe, the Mediterranean, and the Middle East. The last 2k years include several interesting climate periods in the Mediterranean basin, such as the Roman Optimum, the MCA, the LIA, and the present warm period. Climate simulations with global ocean–atmosphere models are now long enough to cover the past few millennia, permitting a reasonable comparison with proxy-based climate reconstructions in order to benchmark the models. Regional models include a much better representation of topographic features, coastlines, and land cover, so they can simulate the important atmospheric processes that occur at subregional scales in the Mediterranean basin also for the past. Further, mechanistic modeling of proxies is of importance to decode proxies (Hughes et al., 2010) if they are used in the inverse mode. This approach is also a good way to work with multiproxies (Guiot et al., 2009).

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