IMPACT OF EL NIÑO–SOUTHERN OSCILLATION ON EUROPEAN CLIMATE

S. Brönnimann[1]

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[1] El Niño–Southern Oscillation (ENSO) is arguably the most important global climate pattern. While the effects in the Pacific–North American sector and the tropical regions are relatively well understood, the impacts on the circulation in the North Atlantic–European sector are discussed more controversially. Studies from the past 10 years demonstrate that ENSO does affect European climate. However, some of the effects undergo a seasonal modulation or are nonlinear. The signal can be modified by other factors and might be nonstationary on multidecadal scales, contributing to a large interevent variability. Here I review observational and model-based evidence for ENSO's effect on European climate and discuss possible mechanisms, also including troposphere-stratosphere coupling. The paper ends with a schematic depiction of the effects and a discussion of their relevance with respect to our scientific understanding of the climate system and of their relevance for seasonal climate forecasts.

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1. INTRODUCTION

[2] El Niño–Southern Oscillation (ENSO) is the globally dominating mode of interannual climate variability. It affects vast regions of the tropics, the Pacific, and the Indian Ocean as well as the surrounding landmasses. ENSO warm or cold events (commonly termed El Niño and La Niña), which occur every few years and last for about a year, can lead to severe droughts in one part of the world and devastating floods in other parts [e.g., *Philander*, 1989; *Allan et al.*, 1996; *Glantz*, 1996; *Harrison and Larkin*, 1998; *Diaz and Markgraf*, 2000; *Diaz et al.*, 2001]. The environmental, economical, and social impacts are tremendous. Consequently, large efforts have been undertaken in the past few years to understand and eventually forecast ENSO and its effects on global climate [e.g., *Barnett et al.*, 1988; *Chen et al.*, 2004]. While the effect in the Pacific area and the tropics has been thoroughly analyzed [*Harrison and Larkin*, 1998; *Alexander et al.*, 2002; *Diaz and Markgraf*, 2000; *Wang*, 2004; *Wang et al.*, 2004; *McPhaden et al.*, 2006], the impacts on Europe are less well established. The interannual variability of atmospheric circulation over the Atlantic-European sector is large, which makes signal detection difficult. However, if ENSO does affect Europe, this might have important implications with respect to improving seasonal climate forecasts, as well as for our understanding of past climate variability and for assessing future climate scenarios.

[3] Studies of ENSO teleconnections published during the 1980s, mostly with a global focus, often found a comparably small effect in Europe [e.g., *Ropelewski and Halpert*, 1987]. It was therefore often assumed that ENSO is irrelevant for Europe or is just a marginal factor. Later studies [e.g., *Fraedrich and Müller*, 1992; *Moron and Plaut*, 2003], however, found that there exists a consistent ENSO signal in European climate, but the signal itself may be variable [e.g., *Mathieu et al.*, 2004]. It has a seasonal course [*Moron and Gouirand*, 2003; *Mariotti et al.*, 2002], is nonlinear with respect to ENSO [*Wu and Hsieh*, 2004a; *Pozo-Vázquez et al.*, 2005a], is modified by other factors, and is possibly nonstationary in time [*Greatbatch et al.*, 2004; *Gouirand and Moron*, 2003].

[4] In this review I attempt to put together the results from the past 10–20 years into a consistent picture of ENSO effects on Europe. The reader is also referred to the studies by *Fraedrich* [1994], *Fraedrich and Müller* [1992], *Cassou and Terray* [2001b], *Xoplaki* [2002], *Gouirand and Moron* [2003], *Moron and Gouirand* [2003], *Pozo-Vázquez et al.* [2005a], *Raible et al.* [2004], *Mathieu et al.* [2004], and *Alpert et al.* [2006], all of which give comprehensive discussions of some aspects reviewed here.

[5] The structure of the paper is as follows. In section 2 a short introduction to the tropical ENSO cycle is given, followed by an overview of global ENSO teleconnections. This section is short as the topics are well covered by other review papers. The specialist reader may want to move

[1]Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland.

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directly to section 3, which summarizes observational studies on ENSO effects on European climate. This section comprises case studies and statistical analyses of instrumental climate data and of climate reconstructions covering the past few centuries. Special emphasis is devoted to observational evidence for a nonstationary behavior or modulating factors. Section 3.3 addresses effects on the stratosphere, which may be important for understanding the signal at the Earth's surface in winter. Section 4 deals with model studies that address ENSO impacts on European climate and the stratosphere. In section 5 the underlying mechanisms are discussed. Section 6 presents conclusions in the form of a schematic depiction of ENSO effects on Europe. It ends with assessing the relevance of the detected relations with respect to our scientific understanding of the atmosphere as well as their value for seasonal climate forecasting.

2. ENSO PHENOMENON

2.1. Tropical Pacific

[6] This section gives a brief overview of the ENSO phenomenon. It starts with a description of the tropical Pacific ENSO and discusses ways to measure ENSO. Then timescales of variability are addressed and finally changes in the phenomenon over time.

[7] ENSO is a coupled mode of the ocean-atmosphere system in the tropical Pacific or Indo-Pacific region [e.g., *Philander*, 1989; *Glantz*, 1996; *Allan et al.*, 1996; *Harrison and Larkin*, 1998; *Diaz and Markgraf*, 2000; *McPhaden et al.*, 2006]. The atmospheric part, the Southern Oscillation, was first identified by *Walker* [1923, 1924] and *Walker and Bliss* [1932] as a seesaw of surface pressure between the central tropical Pacific and the Indonesian Archipelago (following earlier studies by *Hildebrandsson* [1897], who noted an inverse relation between surface pressure at Sydney and Buenos Aires). The three-dimensional circulation causing this seesaw was described by *Bjerknes* [1969] and named "Walker circulation." Around the same time it was realized that the quasiperiodic warming of the waters off the coasts of Peru and Ecuador, called El Niño by local fishermen because it generally occurred around Christmastime, is part of an oceanic oscillation that extends westward along the equator. The relation between these two phenomena, i.e., El Niño and the Southern Oscillation, was first identified by *Bjerknes* [1966, 1969].

[8] During normal years, waters off the coasts of Peru and Ecuador as well as along the equator are relatively cold because of coastal and equatorial upwelling. Temperatures rise toward the western tropical Pacific where a pool of warm water forms and atmospheric convection is most intensive. The rising air and the east-west temperature gradient at the surface maintain strong trade winds, which push the warming surface water to the western Pacific and promote oceanic upwelling (and hence cooling) in the eastern Pacific. A particularly strong cooling in this area is addressed as a La Niña event. Hence positive feedbacks maintain this surface branch of the Walker circulation, which is complemented by a reversed circulation at upper levels: the moist air that rises over the western tropical Pacific, flows eastward along the equator, and sinks over the eastern tropical Pacific.

[9] During El Niño conditions, trade winds weaken, oceanic upwelling is suppressed in the eastern tropical Pacific, and sea surface temperatures (SSTs) rise as much as 5°C above normal. As a result the temperature gradient decreases and further weakens the trade winds. Convective activity shifts to the central and eastern tropical Pacific, and the Walker circulation reverses. As an example for an El Niño, Figure 1 (top) shows SSTs for the boreal winter during the particularly strong event 1997/1998. Figure 1 (top) also shows that El Niño is not restricted to the Pacific basin but also has a branch in the Indian Ocean. When addressing both, many scientists use the term Indo-Pacific ENSO. Together with the (zonal) Walker circulation, the (meridional) Hadley circulation is also altered. During warm ENSO phases it is strengthened over the central and eastern Pacific but weakened over the western Pacific and the Atlantic [*Wang et al.*, 2004].

[10] While the atmospheric circulation during ENSO warm and cold phases is relatively well understood, the triggers for onset and termination of events as well as the required negative feedbacks are a matter of current discussion and are not reviewed here. It is important to note, however, that there is a typical life cycle of El Niño events that tends to be phase locked with the seasonal cycle [*Wang*, 1995; *Wang and Picaut*, 2004]. Typically, the first atmospheric anomalies (cyclones over Australia or the Philippines) appear in boreal winter. The warm anomalies in the SSTs then gradually strengthen during the year and are often strongest in the boreal fall and winter (1 year after the onset).

[11] There are different ways of measuring the strength of ENSO [see *Trenberth*, 1997]. For the oceanic component the most common way is to average SSTs over certain regions termed NINO1 + 2, NINO3, NINO4, and NINO3.4 (see Figure 1). El Niño events are then defined based on thresholds and exceedance conditions [see *Larkin and Harrison*, 2005]. Figure 1 (bottom) shows a time series of monthly anomalies of the NINO3.4 index since 1875. Another index that is sometimes used in climate research is the cold tongue index, measuring SST anomalies in an even larger region (see Figure 1). These SST-based indices are statistically positive for El Niño and negative for La Niña. A way of measuring the atmospheric part of the phenomenon is the Southern Oscillation index (SOI), which in essence is the standardized sea level pressure (SLP) difference between Tahiti and Darwin ("*Troup* [1965] SOI"), but again there are slightly different definitions in use. It is important to note that positive values of the SOI are related to La Niña, and negative values are related to El Niño. In addition to atmospheric and oceanic indices, coupled indices (classification schemes that involve both NINO3.4 and SOI) have been proposed [see *Gergis and Fowler*, 2005] as well as multivariate indices. For instance, the multivariate ENSO index by *Wolter and Timlin* [1998] involves surface wind and temperature fields as well as cloudiness in addition to

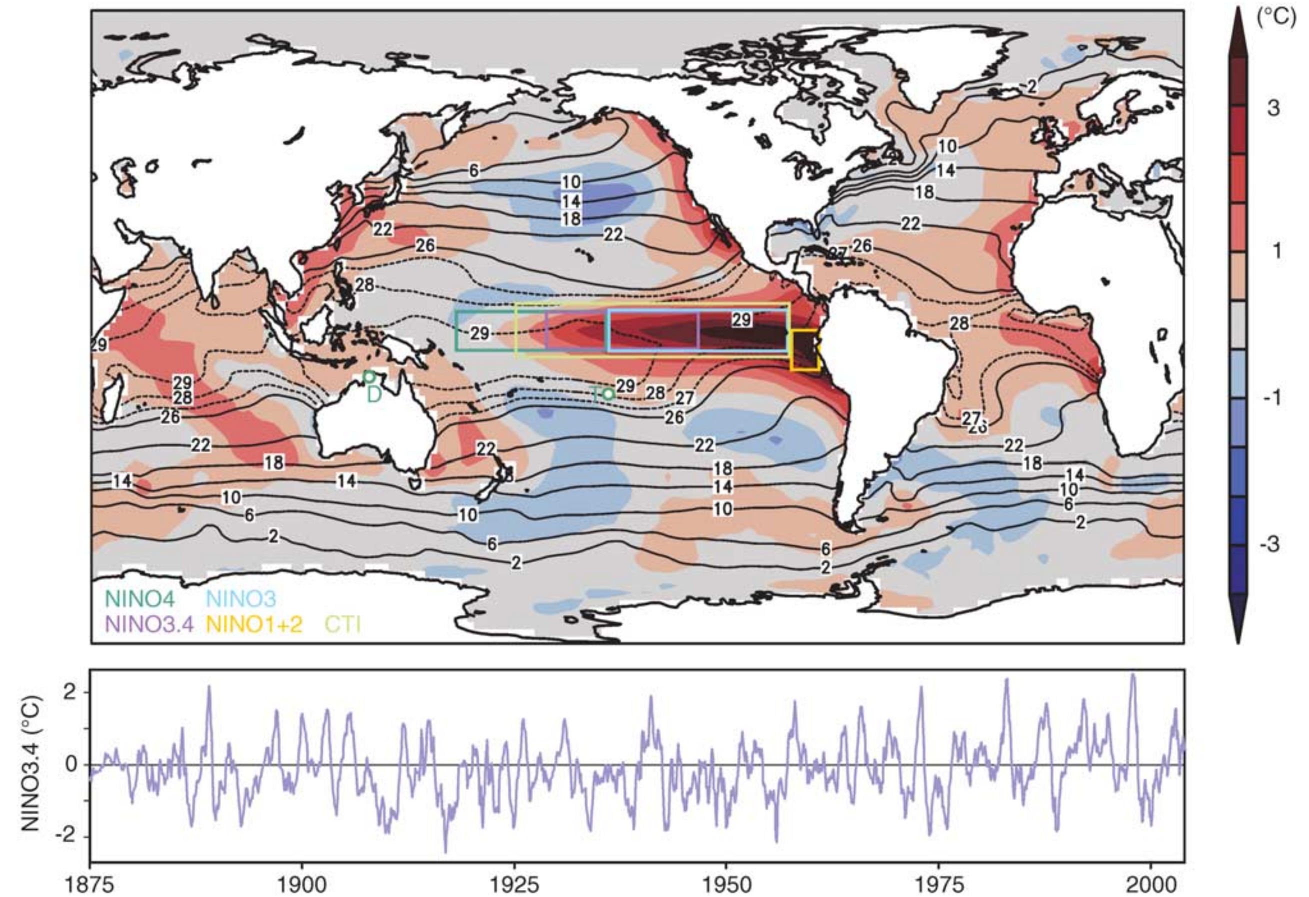

Figure 1. (top) Absolute values (contours) and anomalies (with respect to 1961–1990) (color shadings) of sea surface temperatures from December 1997 to February 1998 (ERSST version 2 data from *Smith and Reynolds* [2004]). The rectangles denote the averaging regions used for the most common ENSO indices (see text). Circles denote Darwin and Tahiti. (bottom) Monthly anomalies of the NINO3.4 index.

SST and SLP and is then extracted using a principal component (PC) analysis. Data for many ENSO indices can be found at http://www.cdc.noaa.gov/ClimateIndices/.

[12] El Niño events occur every few years on average, and their duration is around a year, but prolonged events occur occasionally [*Allan and D'Arrigo*, 1999]. El Niño events are not always followed by La Niña (and vice versa); sometimes neutral conditions follow El Niña and La Niña events. ENSO varies on different timescales, which is important when addressing effects. Apart from the interannual-to-multiannual ENSO variability described in this section, there is also a widely discussed interdecadal variability, which is sometimes called "ENSO-like" variability or Interdecadal Pacific Oscillation (IPO). There is an ongoing debate as to what extent this is the same as the Pacific Decadal Oscillation (PDO) [*Mantua et al.*, 1997] in the North Pacific. The IPO could be a modulation in frequency and amplitude of interannual-to-multiannual ENSO variability [see *Gershunov and Barnett*, 1998; *Power et al.*, 1999], or it could reflect different mechanisms [see *Folland et al.*, 2001, 2002; *Cobb et al.*, 2003].

[13] Related to the question of low-frequency ENSO variability is the problem of stationarity. Because of changes in the background state or because of interaction with other modes the ENSO phenomenon in the tropical Pacific changes its characteristics. This concerns the strength, duration, and frequency but also the onset phase of the events and the global teleconnections. Most noteworthy is a shift in Pacific SSTs in the 1970s that is a likely cause for the global climate shift observed in the 1970s [*Trenberth*, 1990]. *Wang* [1995] reports a different onset phase of El Niño after that time, and El Niño events became more frequent and longer lasting [*Fedorov and Philander*, 2000; *Folland et al.*, 2001; *Philander and Fedorov*, 2003]. More details on changes in ENSO behavior due to interaction of different timescales of variability are given by *Allan et al.* [2003] and *Verdon and Franks* [2006].

2.2. Global ENSO Teleconnections

[14] Effects of ENSO on Europe are indirect in the sense that the underlying circulation changes must have strong impacts elsewhere between the ENSO area and Europe. Therefore they can only be understood in the context of global ENSO effects. In this section I briefly discuss the well-known ENSO teleconnections, with a focus on the tropics and the North Pacific. For more detailed information the reader is referred to other review studies [*Harrison and Larkin*, 1998; *Trenberth and Caron*, 2000; *Diaz et al.*, 2001;

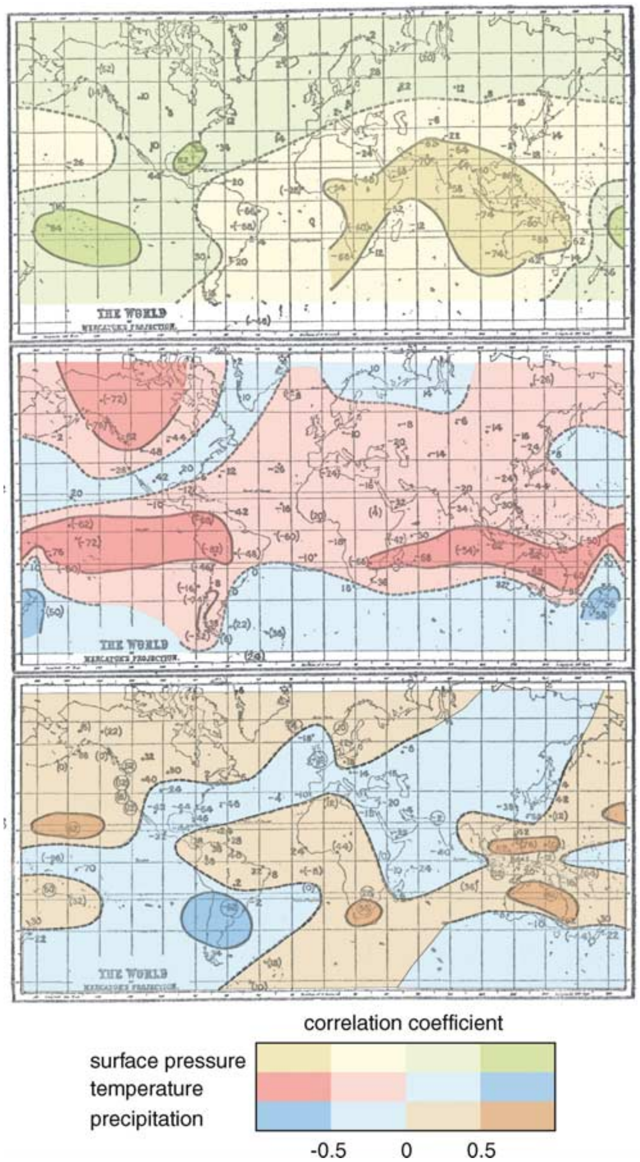

Figure 2. Maps of the simultaneous correlation between the Southern Oscillation index and (top) surface pressure, (middle) temperature, and (bottom) rainfall from December to February based on station data from 1875 to 1930 (colored for comparison with Figure 3). Reprinted with permission from *Walker and Bliss* [1932].

Liu and Alexander, 2007] and the large number of ENSO-teleconnection studies that have been published since the 1980s [e.g., *van Loon and Madden*, 1981; *Ropelewski and Halpert*, 1987; *Kiladis and Diaz*, 1989; *Halpert and Ropelewski*, 1992; *van Oldenborgh et al.*, 2000].

[15] *Walker* [1923, 1924] and *Walker and Bliss* [1932] were the first to study the correlations between the Southern Oscillation and global climate. A modified (colored) reproduction of Charts 11–14 from *Walker and Bliss* [1932] is shown as Figure 2. Many of the well-known ENSO teleconnections such as the temperature imprint in North America or the precipitation anomalies in Australia and southeast Africa appear in this graph. Figure 3 shows a modern version of this plot. Seasonally averaged, global fields of surface air temperature (merged with SST), SLP, and precipitation are regressed upon a cold season NINO3.4 index. In the summer before the mature phase of the event (year 0) the typical SST anomaly pattern is already well developed in the tropical Pacific, but no signal is found in other tropical regions. Teleconnections are visible in the Pacific–North American sector, with (for El Niño conditions) a deepened Aleutian low, cold anomalies in the central North Pacific, and warm anomalies along the Pacific coast of Alaska. A clear signal is also found in South Pacific SLP. Precipitation shows an increase in South America south of the equator and a decrease globally between 0° and 30°N. In late fall the tropical Pacific SST signal as well as the extratropical teleconnections in temperature and SLP increases in strength (note that the ENSO index is defined as a September–February average). The precipitation signal also becomes stronger, with positive anomalies in the southeastern United States.

[16] Very strong temperature signals are also found in the January-to-March period (year 1). All tropical oceans are now in phase with the Pacific; that is, the tropics generally warm during El Niños (but not after strong volcanic eruptions, which were excluded in Figure 3 [see *Angell*, 2000]). The warming of the tropical Atlantic and Indian oceans during El Niño is well known and, at least partially, understood [*Enfield and Meyer*, 1997; *Alexander et al.*, 2002; *Wang et al.*, 2004]. The anomalies reportedly lag the tropical Pacific anomalies by around 3–6 months [*Wang*, 2004] (clearly visible in Figure 3), which might be important with respect to the timing of the signal in Europe (see section 3). The precipitation signal is similar to that in the fall (note that the strongest precipitation anomalies are expected over the oceans and the maritime continent [*Diaz et al.*, 2001], where we have no data).

[17] The teleconnections in the northern extratropics, especially in the SLP field, are strongest in late winter. Of special importance with respect to the effect in Europe is the North Pacific region. During El Niño situations we find particularly low SSTs in the central North Pacific and high surface air temperatures in western Canada and Alaska that sometimes stretch across the entire continent. These anomalies are related to an intensified Aleutian low. Corresponding changes were also found in the Pacific storm track [e.g., *Hoerling and Ting*, 1994; *Sardeshmukh et al.*, 2000]. The resulting circulation anomaly at 500 hPa resembles the Pacific North American pattern (PNA) [*Horel and Wallace*, 1981; *van Loon and Madden*, 1981]. The correlation between ENSO and PNA is strong in winter. However, *Straus and Shukla* [2003] posit that ENSO does not only modify the PNA but forces distinct circulation patterns in the extratropics. The analogue with the PNA, which is defined as a linear circulation anomaly pattern, is also limited by the nonlinear nature of ENSO teleconnections in the North Pacific [e.g., *Montroy et al.*, 1998]. *Hoerling et al.* [1997] found that, in the North Pacific sector, 500 hPa geopotential

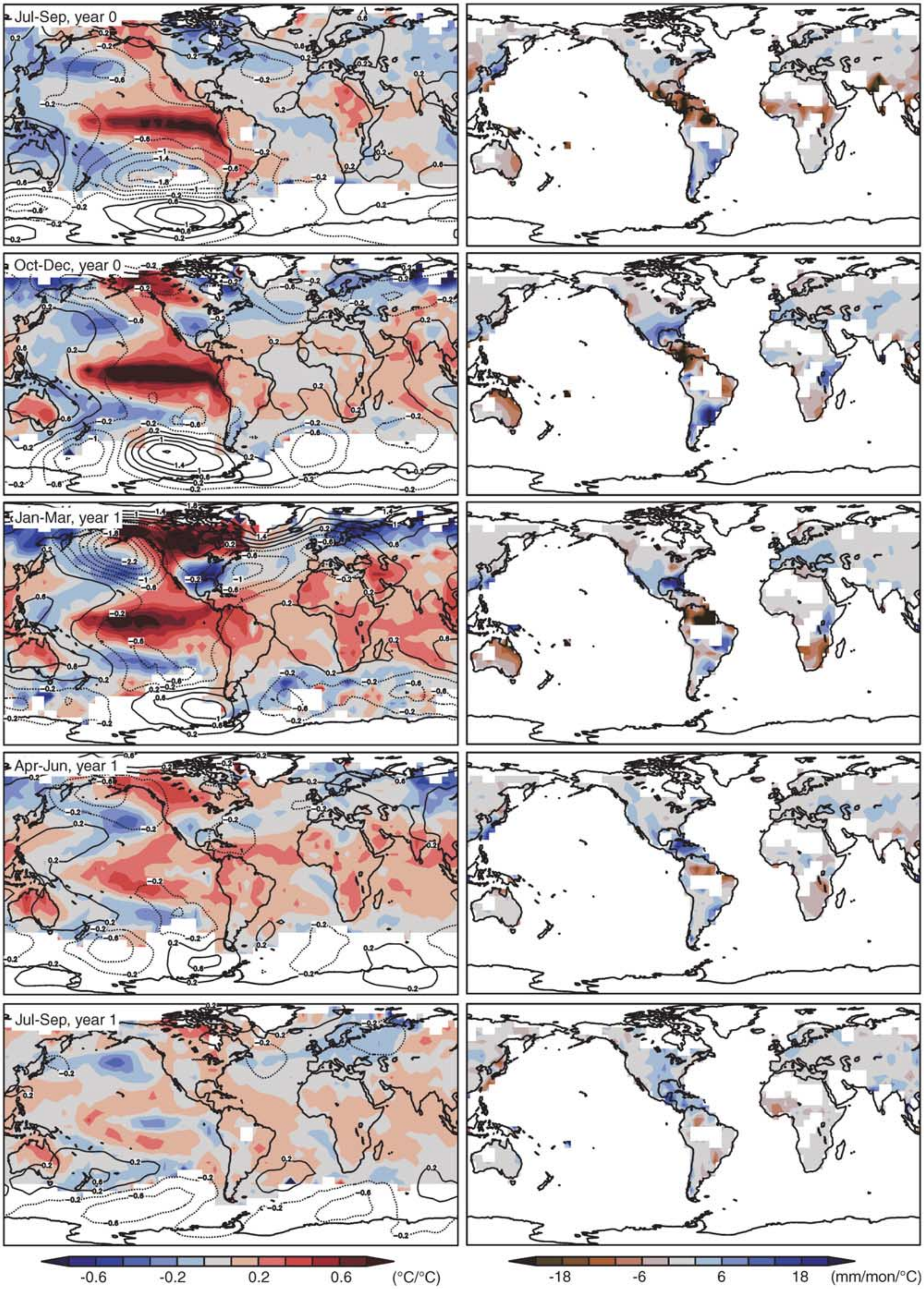
Jul-Sep, year 0
Oct-Dec, year 0
Jan-Mar, year 1
Apr-Jun, year 1
Jul-Sep, year 1
-0.6
-0.2
0.2
0.6
(°C/°C)
-18
-6
6
18
(mm/mon/°C)

Figure 3

height (GPH) anomalies for warm and cold ENSO events show a 35° longitudinal phase shift rather than a sign change. Both the strength and the spatial phase of the response in the upper troposphere over the North Pacific sector were found to be nonlinear in climate model simulations [*Hoerling et al.*, 2001a]. In addition, *Compo et al.* [2001] found a dependence of the spatial pattern of ENSO-induced variability on the timescale analyzed.

[18] The effect of ENSO on the zonal mean northern extratropical circulation in late winter was first addressed by *van Loon and Rogers* [1981] at the 700 hPa level. By compositing El Niño against La Niña (using the SOI) they found positive anomalies in zonal wind at 30°N and negative anomalies north of 50°N. The meridional eddy heat flux was positive at 50°N, and GPH increased near the North Pole and decreased at 55°N. This is consistent with the SLP pattern discussed above. The subtropical jet, in a zonal mean sense, is strengthened during El Niño.

[19] In Figure 3 a wave structure is also clearly visible that connects to the Atlantic and leads to a pronounced anomaly pattern in SLP, surface air temperature, and precipitation over the Atlantic-European sector. Most notably, temperatures are very low in northeastern Europe, and a clear SLP-dipole pattern appears over the North Atlantic. The effects of ENSO on European surface climate will be discussed in detail in section 3.

[20] In spring (year 1) the signal in the Pacific and Indian oceans, though still in phase, is clearly weaker, and the same holds for the northern extratropics and for the SLP and precipitation signals (Figure 3). The signal in the tropical Atlantic is strongest in spring. Finally, in the summer of year 1 the northern extratropical teleconnections are further weakened, while the tropical Pacific already shows a negative sign, i.e., a changeover to the other ENSO phase.

[21] Figure 3 does not account for the fact that the ENSO effect might be nonlinear or highly variable. In fact, the interevent variability is relatively large in some respects. *Gershunov and Barnett* [1998] found that the effect in North America is modulated by the North Pacific climate anomalies related to the North Pacific Oscillation (which is equivalent to the PDO). Stratifying the data accordingly, they found a more pronounced El Niño signal over North America for the positive phase of the PDO and a slightly more pronounced La Niña signal for the negative phase of the PDO. However, the PDO is probably controlled by ENSO on interannual timescales [*Newman et al.*, 2003]. Hence stratifying ENSO events by the PDO phase emphasizes those ENSO events that have a strong effect on the North Pacific. Not surprisingly, these events also have a strong effect on North America.

[22] The nonstationary behavior of the tropical ENSO signal also leads to a nonstationary behavior in its teleconnections. For instance, the global climate shift in the 1970s (see section 2.1) also changed the relation between ENSO and the Indian monsoon or the strength of the Hadley cell [*Kumar et al.*, 1999; *Quan et al.*, 2004, and references therein], which is important for many other ENSO teleconnections. Section 3.4 will be more specific with respect to a nonstationary signal in the Atlantic-European sector.

3. OBSERVATIONAL EVIDENCE FOR AN EFFECT ON EUROPE

[23] In this section the observational evidence for ENSO effects on European climate (temperature, SLP, and precipitation) and on the planetary wave structure over the North Atlantic–European sector is reviewed. This evidence is based on case studies (section 3.1) and on statistical analyses of instrumental data or climate reconstructions covering the past few centuries (section 3.2). Emphasis is devoted to the seasonally varying effects and the possible nonlinearity of the signal. In section 3.3 I summarize ENSO's effect on the stratosphere and stratosphere-troposphere coupling, which may help to better understand the effects in Europe. Section 3.4 specifically addresses the question of nonstationarity and of modulating effects.

3.1. Case Studies

[24] Case studies are important for understanding ENSO effects. Every El Niño event evolves somewhat differently in the tropics and is accompanied by different anomalies in the other ocean basins. Individual ENSO events also differ from each other with respect to the climatic anomalies in the extratropics. This is especially the case for the Atlantic-European sector. *Mathieu et al.* [2004] advocate analyzing ENSO events individually in order to estimate potential predictability. They argue that there is some predictability for the North Atlantic European sector for different studied events, even though the effects were not the same (but see also *van Oldenborgh* [2005]). In this section I summarize the reported case studies that cover Europe (even if Europe was not the focus of these studies).

[25] Anomaly maps of temperature, SLP, or other fields for historical (preinstrumental) El Niño or La Niña winters can be found in the studies of *Mann et al.* [2000] and *Brönnimann et al.* [2007b]. *Mann et al.* [2000] show global fields of reconstructed annual mean temperature for the El Niño years 1652, 1720, 1747, 1791, 1804, 1828, 1877, and 1884 as well as for the two La Niña years 1732 and 1777. With respect to Europe all El Niño years except 1791

Figure 3. Coefficients of regressions between an ENSO index and (left) surface air temperature (color shadings, HadCRUT2v data [*Jones and Moberg*, 2003]) and sea level pressure (contours, in hPa, HadSLP2 [*Allan and Ansell*, 2006]) and (right) precipitation (GHCN version 2 [*Vose et al.*, 1992]) for different seasons, 1870–2003 (1880–2003 for precipitation). The ENSO index used for all seasons was NINO3.4 (averaged from September of year 0 to February of year 1). Prior to regression a linear trend was subtracted from all data. The two winters following each tropical volcanic eruption (1883, 1902, 1963, 1982, and 1991) were excluded from the NINO3.4 index.

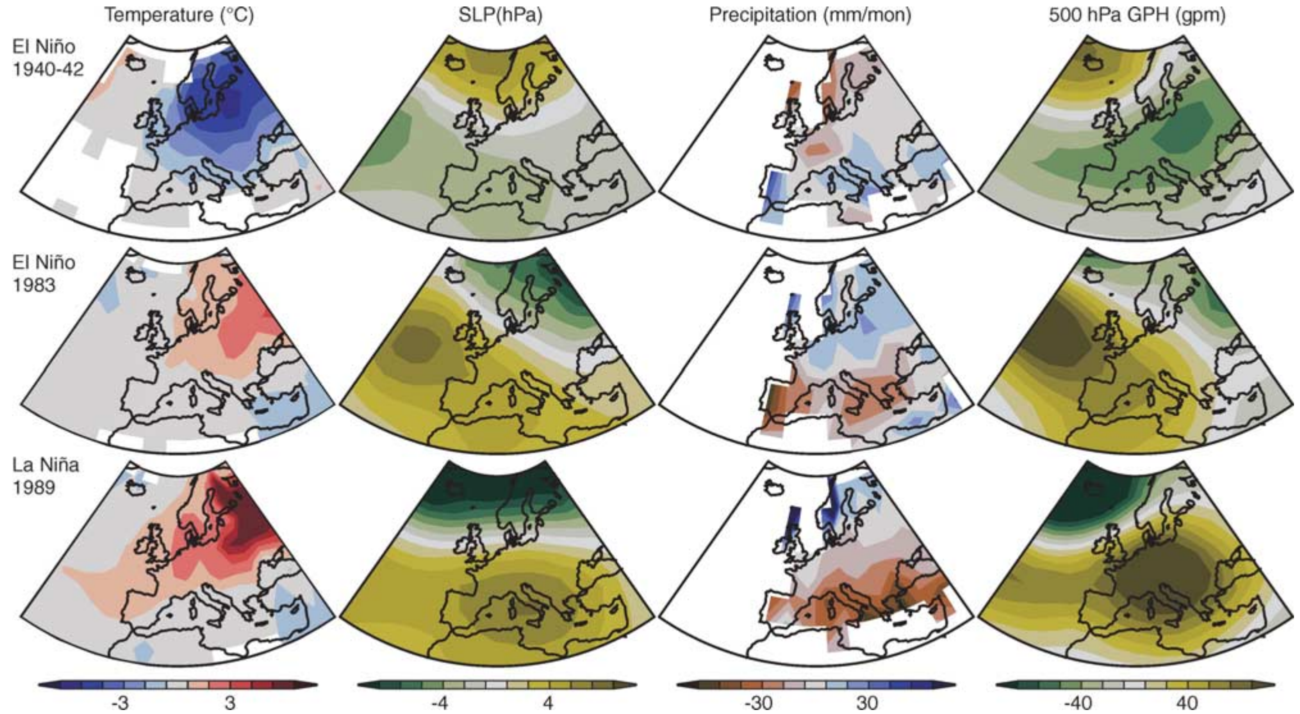

Figure 4. Anomalies (with respect to the 1961–1990 mean annual cycle) of January-to-March averages of surface air temperature, SLP, precipitation, and 500 hPa GPH over the North Atlantic–European sector for three events: El Niño 1940–1942 (average of three winters), El Niño 1983, and La Niña 1989. Surface temperature and SLP are from HadCRUT2v [*Jones and Moberg*, 2003] and HadSLP2 [*Allan and Ansell*, 2006], respectively; precipitation is from GHCN Version 2 [*Vose et al.*, 1992]; and 500 hPa GPH is from National Centers for Environmental Prediction/National Center of Atmospheric Research (NCEP/NCAR) reanalysis [*Kistler et al.*, 2001] and from *Brönnimann and Luterbacher* [2004] for the 1940–1942 period.

show negative or neutral temperature departures over northeastern Europe. The two La Niña years, however, show negative temperature anomalies in the same region. On the basis of reconstructed monthly fields of SLP, surface air temperature, precipitation, and 500 hPa GPH over Europe, *Brönnimann et al.* [2007b] present late winter anomalies for a number of very strong ENSO events after subtracting the multidecadal variability. For El Niño (1833, 1877, 1878, and 1889) the interevent variability was large. Some cases (such as 1877), but not all, were accompanied by cold winters in northeastern Europe and enhanced precipitation in central western Europe. For La Niña (1725, 1790, 1820, 1842, and 1872) a tendency toward warm winters in northeastern Europe appeared but again with relatively large variability.

[26] For 20th century events the information on both El Niño strength and European climate is much more reliable. Still, the variability between the events is large. *Hamilton* [1988] showed Northern Hemispheric SLP anomaly fields for the El Niño winters 1925/1926, 1957/1958, and 1972/1973 and found large differences between these events over the North Atlantic. A detailed case study was performed for the strong and long-lasting El Niño 1939–1942 [*Brönnimann et al.*, 2004]. The most pronounced, or at least most famous, of the climatic anomalies were the cold winters in northeastern Europe in 1940, 1941, and 1942, which include the two coldest of the 20th century (at a European scale they were among the coldest of the past half millennium [*Luterbacher et al.*, 2004]). The winter 1941/1942 even affected the course of World War II. Figure 4 (top) shows anomaly fields of SLP, surface air temperature, precipitation, and 500 hPa GPH over the eastern North Atlantic and Europe averaged for the three winters. The index of the NAO, the dominant mode of interannual circulation variability over the North Atlantic area [*Wanner et al.*, 2001], was strongly negative. The pressure over Scandinavia was frequently high, or the western Russian anticyclone expanded toward Europe. The Atlantic storm track was shifted to more southern latitudes, and precipitation increased in parts of the Mediterranean area and decreased in northwestern Europe. The frequency of upper trough situations over central Europe was very high. All anomalies were most pronounced in middle and late winter, but below-normal temperatures were also found in the other seasons.

[27] Another well-studied El Niño occurred in 1957/1958 during the International Geophysical Year. In fact, this event was the first El Niño to be studied in the context of ocean-atmosphere interaction [*Bjerknes*, 1966]. *Bjerknes* [1966] also addressed the anomalies in Europe and found a weakened Icelandic low, which he ascribed to the El Niño. Temperatures were below normal in northeastern Europe,

and the NAO was negative. At 300 hPa, negative GPH anomalies were prevalent over central Europe.

[28] The El Niño of 1982/1983 was accompanied by pronounced anomalies in global climate. To some extent this event "shaped" our view of ENSO teleconnections as, for the first time, El Niño hit the headlines of major newspapers and magazines. Figure 4 (middle) shows anomaly fields of SLP, surface air temperature, precipitation, and 500 hPa GPH over the eastern North Atlantic and Europe for the El Niño winter (January–March) 1983 [see also *Rogers*, 1984]. The anomalies were strong but very different than in the 1940–1942 period. In fact, they show an almost opposite pattern, and comparing the two, one might ask whether there is a consistent ENSO effect on Europe at all. It should be noted, however, that the 1982/1983 El Niño coincided with a strong volcanic eruption (El Chichón, Mexico). In fact, the fields are very similar to the expected volcanic effect [*Robock*, 2000].

[29] The subsequent ENSO cycle 1986–1989 was studied by several authors [e.g., *Fraedrich*, 1994]. *Brönnimann et al.* [2006] found very similar patterns for late winter 1987 as in the early 1940s, i.e., very low temperatures in northeastern Europe, a negative NAO, and increased/decreased precipitation in the northern Mediterranean region and Norway, respectively. These anomalies were contrasted with those for the La Niña winter 1989, which are shown in Figure 4. In many respects the anomalies were opposite to those in the El Niño winters 1987 and 1940–1942 (Figure 4, top). *Mathieu et al.* [2004] investigated the winter (December–February) signal in 500 hPa GPH over the North Atlantic and Europe for three strong El Niños and three strong La Niña events. For the El Niños 1986/1987 and 1997/1998 they found a dipole between Greenland (positive) and off the coast of France (negative). However, for the 1991/1992 El Niño they note a strong positive anomaly over the United Kingdom (note that this El Niño coincided with the Pinatubo eruption). The anomaly patterns for the three La Niña events were characterized by a dipole with positive anomalies west of France (although the longitude of the anomaly center varied) and negative anomalies between Iceland and Norway.

[30] To summarize this section on case studies, we find that each El Niño event is accompanied by somewhat different circulation anomalies over the North Atlantic–European area. The interevent variability is quite large. A common feature for many El Niño winters is the low temperature in northeastern Europe and the negative height anomalies at 500 hPa west of France (though with spatial variability). Precipitation often shows a decrease over northern Europe and an increase in France or parts of the Mediterranean, but the location of this latter anomaly varies. The most pronounced "outliers" among recent El Niño events are the 1983 and 1992 cases, which followed major volcanic eruptions (El Chichón in 1982 and Pinatubo in 1991, see section 3.4 for further discussion), but strong interevent variability also appears for nonvolcanic events. The La Niña events discussed in this section show a more or less opposite pattern to El Niño, but there are much less published case studies.

3.2. Statistical Analyses

[31] Differences between individual ENSO events with respect to climate in Europe can partly be explained by the large "internal" variability of the circulation over the Atlantic-European sector. To take into account this variability, the long period of available data is analyzed with statistical methods. However, the number of strong events in the analyzed period (even if 100 years of data are available) is small in statistical terms, which makes the extraction of an ENSO signal difficult. In recent years the notion has become increasingly popular that part of the interevent variability of ENSO effects in Europe is systematic. The signal leaving the tropical Pacific is not constant. For instance, the tropical SST signal varies from event to event, and along its way to Europe the signal might be modulated or modified in a systematic way. Volcanic eruptions and anthropogenic influences may interfere or interact with the ENSO effect. Possible nonlinearity and seasonality have to be addressed. Moreover, the relation between ENSO and European climate may be nonstationary in time. This means that predictability of European climate through ENSO might be greater than implied by the large interevent variability.

[32] As a consequence of all these possible complications a wide range of statistical techniques is used, and different analyses often find different results. Independent verification (e.g., repeating the analysis in an independent time period) is normally not possible. Yet in recent years a clearer picture has started to emerge from a number of statistical and modeling studies. In section 3.2.1 I discuss statistical analyses on the ENSO signal in European climate, focusing on SLP, temperature, and precipitation. I start with a brief historical overview and present the "canonical" late winter signal. Then I discuss deviating views and the problem of nonlinearity as well as the signal in other seasons. The last paragraph deals with climate reconstructions.

3.2.1. "Canonical" Winter Signal

[33] In their work on global teleconnections, *Walker* [1923, 1924] and *Walker and Bliss* [1932] also addressed relations between the SOI and the NAO or European climate. For El Niño (negative SOI) the signal in their correlation fields for winter (Figure 2) corresponds to negative temperature and positive SLP anomalies over northeastern Europe as well as negative rainfall anomalies in Scandinavia and positive rainfall anomalies between approximately 35°N and 50°N. This is consistent with the above described case studies, but the correlations are rather weak.

[34] The statistical ENSO signal in Europe was only revisited much later. A series of papers in the early 1980s addressed the global signal of the Southern Oscillation, including (though mostly not specifically addressing) Europe. The work of *van Loon and Madden* [1981] indicated a significant influence of ENSO on winter SLP and temperature records in the North Atlantic European sector.

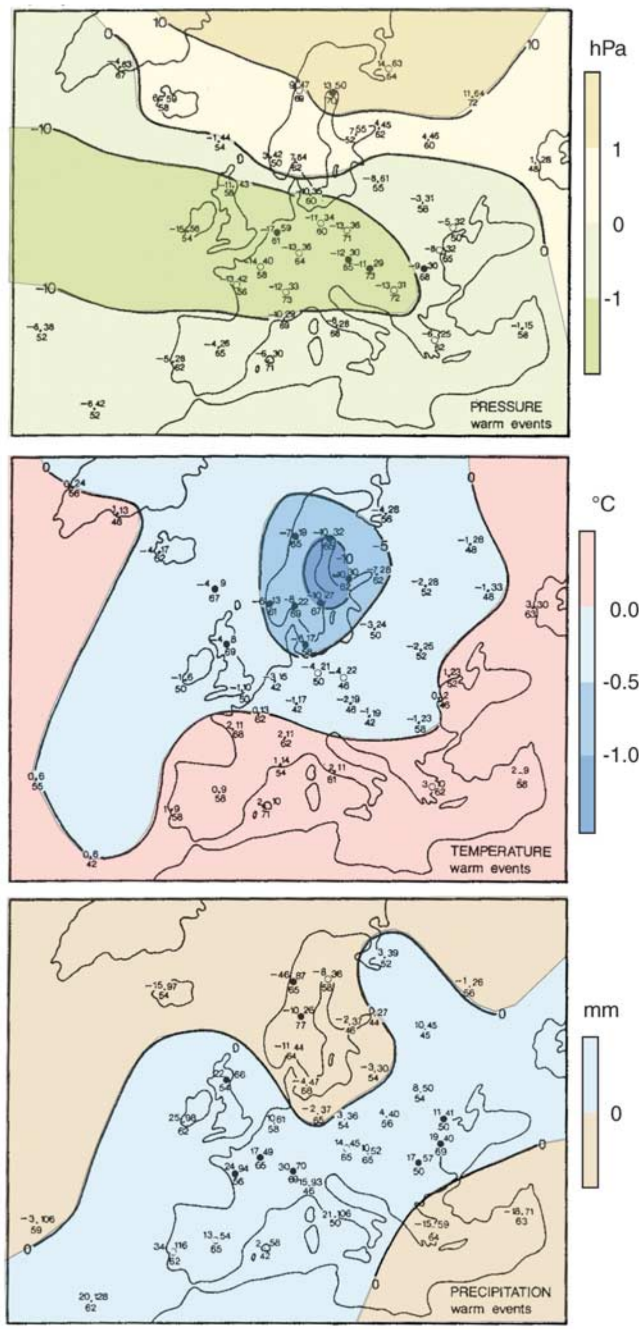

Figure 5. Composite anomaly maps of (top) surface pressure, (middle) temperature, and (bottom) rainfall based on station data for 26 ENSO warm events from 1880 to 1988 (colored for comparison with Figures 2 and 3). From *Fraedrich and Müller* [1992]. Copyright 1992 Royal Meteorological Society. Reproduced with permission. Permission is granted by John Wiley and Sons Ltd on behalf of RMETS.

Similar results were found by others (as discussed in more detail below), most notably by *Fraedrich* [1990, 1994], *Fraedrich and Müller* [1992], and *Fraedrich et al.* [1992]. A "canonical" El Niño late winter signal has emerged from these studies and was further supported by later work (though not without questions and alterations, even contradictions). A classical illustration of this signal is given in Figure 5 (color version of left part of Figure 1 from *Fraedrich and Müller* [1992]). Figure 5 shows composite anomaly fields of wintertime SLP, temperature, and precipitation for selected strong ENSO warm events (El Niño) based on a long series of station data. The canonical winter signal, as it is conveyed in Figure 5, consists of low temperatures in northern Europe, high SLP from Iceland to Scandinavia, and low SLP over central and western Europe, as well as increased precipitation over parts of the Mediterranean and decreased precipitation in Norway. It also appears clearly in Figure 3, where the linear part of the ENSO response in temperature, SLP, and precipitation is shown, and it corresponds well with the 1940s case. Other studies found similar results [e.g., *van Loon and Madden*, 1981; *Gouirand and Moron*, 2003; *Moron and Gouirand*, 2003]. With respect to the synoptic timescale a significant change in "European Grosswetterlagen" [*Hess and Brezowsky*, 1969] could be found, with more cyclonic and less anticyclonic weather types over central Europe during El Niño and a southward shift of the Atlantic cyclone track and vice versa for La Niña [e.g., *Fraedrich*, 1990, 1994; *Wilby*, 1993; *May and Bengtsson*, 1998; *Moron and Plaut*, 2003]. *Graf and Funke* [1986] found more frequent blocking situations in the European-Atlantic sector during El Niño events. In general, El Niño tends to be accompanied by a negative mode of the NAO, but it would be wrong to describe the El Niño effect simply as a negative NAO. Rather, during El Niño events the SLP anomaly centers are often shifted northeastward compared to the classical NAO pattern [e.g., *Brönnimann et al.*, 2007b] (see Figures 3 and 5).

[35] Studies that explicitly address La Niña winters often find a signal that is close to symmetric to the El Niño signal [e.g., *Fraedrich and Müller*, 1992; *Gouirand and Moron*, 2003; *Moron and Gouirand*, 2003; *Moron and Plaut*, 2003; *Brönnimann et al.*, 2007b], but this does not hold for all of the features, as is discussed in more detail in section 3.2.2. For La Niña the positive NAO-like signal is pronounced [*Pozo-Vázquez et al.*, 2001, 2005b], and *Cassou and Terray* [2001a] found a clear weakening of the Atlantic jet.

[36] ENSO also affects the Mediterranean winter climate. During El Niño events the Mediterranean cyclone track is shifted northward, which affects precipitation. *Fraedrich and Müller* [1992] found less precipitation in southwestern Europe as well as the Black Sea area during cold events but more precipitation in the same regions during warm events. Temperature in Turkey in late winter was found by *Brönnimann et al.* [2007b] to be high during El Niño and low during La Niña. *Kadioğlu et al.* [1999] found an increase (decrease) of precipitation in northwestern (southern) Turkey during El Niño events. For Israel, *Price et al.* [1998] found a positive correlation between October-to-March rainfall and ENSO indices, but the correlation was only significant during the past 25 years. *Arpe et al.* [2000] found a clear correlation between indices of the Caspian Sea level (or precipitation minus evaporation in the Volga River

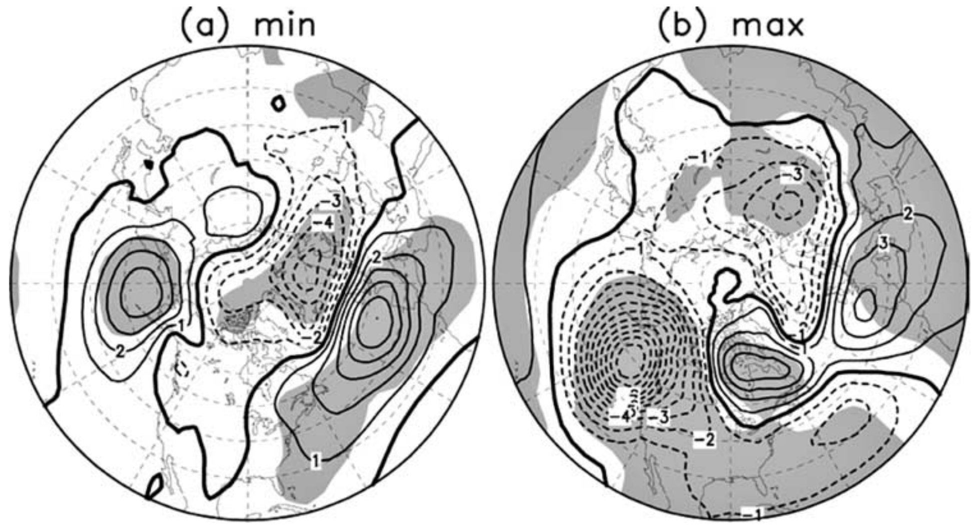

Figure 6. Minima and maxima of the response to ENSO in the northern extratropical SLP field based on a neural network projection of the 11 leading principal components of the SLP field (December to March, 1950–2003) (excerpt of Figure 4 from *Wu and Hsieh* [2004a]). Copyright Springer 2004, reprinted with kind permission of Springer Science and Business Media.

basin) and ENSO, with wetter conditions coinciding with El Niño events (most pronounced in fall).

3.2.2. Noncanonical Views and Nonlinearity

[37] The "canonical ENSO winter signal" sketched above is not unequivocally accepted. Many authors find no winter signal. Examples include *Rocha* [1999] (using correlation analysis) for Iberian precipitation, *Pozo-Vázquez et al.* [2001, 2005b] (compositing) for winter temperatures and SLP during "winter" and "autumn El Niños," *Quadrelli et al.* [2001] (PC decomposition and regression) for Alpine precipitation, and *Rogers* [1984] and *Wang* [2002] (correlations) for the NAO [see also *Trenberth and Caron*, 2000]. This list could easily be extended. One reason for the apparent disagreement is the limited comparability of the studies because of the use of different statistical methods, ENSO indices, definitions of seasons, data used, and treatment of the data (such as detrending, filtering, removing volcanic eruptions, or application of PC analysis). Another reason is the possible nonlinearity. Similar to the nonlinearity found for the Pacific–North American ENSO signal, a possible nonlinearity has been discussed for the relation between ENSO and SLP or precipitation in Europe. The El Niño effect might not be symmetric to the La Niña effect, and strong El Niño events might have a different effect from weak El Niño events [*Toniazzo and Scaife*, 2006]. Correlations can only detect the linear part of a relation; other methods (such as compositing, clustering, nonlinear regression, or neural networks) must be used to detect nonlinear relations.

[38] *Wu and Hsieh* [2004a, 2004b] (see also *Hsieh et al.* [2006]) used a neural network to project the 11 leading PCs of northern extratropical SLP in winter (December–March) onto an ENSO index. They found a nonlinear response, the maxima and minima of which are shown in Figure 6 [*Wu and Hsieh*, 2004a]. For both extremes the response shows a positive NAO mode (but mostly insignificant in the extreme El Niño case, i.e., the maximum of the response). There is some indirect confirmation from the work by *Pozo-Vázquez et al.* [2001, 2005b], who found a winter SLP signal resembling the positive mode of the NAO for La Niña, but the opposite was not found for El Niño and from a modeling study [*Melo-Gonçalves et al.*, 2005] (see section 4). A nonlinearity also appears for precipitation in the eastern Mediterranean area, which shows negative anomalies for both El Niño and La Niña [*Pozo-Vázquez et al.*, 2005a].

[39] A nonlinearity or asymmetry of the signal can appear in the higher moments of the distributions. It is generally assumed that the variability is larger for El Niño winters than for La Niña winters [e.g., *Gouirand and Moron*, 2003; *Alpert et al.*, 2006], and therefore a signal in the mean is more difficult to detect. However, most of the studies refer to the past 50–100 years, which comprise too few strong events to address changes in the frequency distributions. Figure 7 (left and middle) shows histograms of temperature at Uppsala (Sweden) and of an NAO index [*Luterbacher et al.*, 2002], both January-to-March mean values, for strong El Niño and strong La Niña cases since 1706 [see *Brönnimann et al.*, 2007b]. The data were filtered to focus on the interannual-to-multiannual variability, and events coinciding with volcanic eruptions were excluded. The signal in the mean and median appears clearly in both variables, consistent with the canonical signal. Contrary to the studies cited above, the variability is smaller for strong El Niños than for strong La Niñas. In the case of temperature the distribution appears slightly skewed for La Niña events but less so for El Niño. Very cold winters during strong La Niñas are rare but are more frequent than very warm winters during strong El Niños. Figure 7 (right) shows a similar histogram for precipitation in Oxford (United Kingdom), which also agrees well with the "canonical" signal. In this case the variability is higher

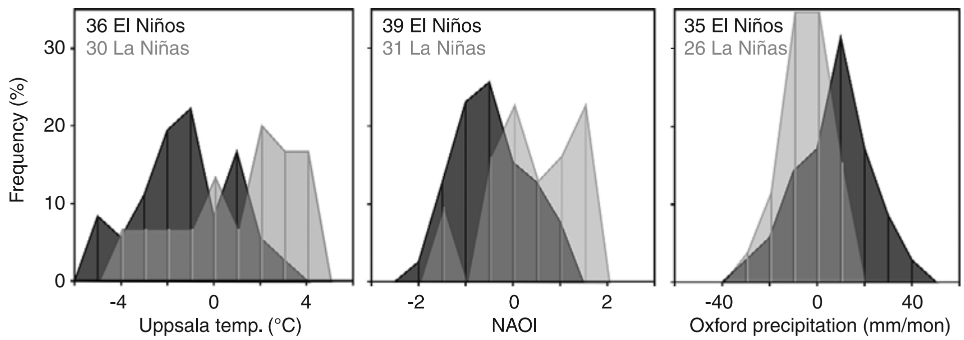

Figure 7. Histograms of January-to-March averages of temperature at (left) Uppsala, (middle) the NAO index, and (right) precipitation in Oxford for strong El Niño events and strong La Niña events based on data from between 1706 and 2000. The data were filtered with a Gaussian high-pass filter (σ = 3 years) to focus on the interannual-to-multiannual variability, and winters perturbed by volcanic eruptions were excluded [see *Brönnimann et al.*, 2007b]. Copyright Springer 2007, reprinted with kind permission of Springer Science and Business Media.

for strong El Niño than for strong La Niña events. Very dry winters occur with equal probability during El Niño or La Niña events, but very wet winters are much more frequent during strong El Niños.

[40] Related to the issue of nonlinearity is the question of whether or not there are several distinct, robust ENSO signals. *Gouirand and Moron* [2003] performed a cluster analysis on North Atlantic–European SLP fields (January–March) for the strongest 30 El Niño winters and the strongest 30 La Niña winters (selected from 130 years of observational data). In each sample they used three clusters. Figure 8 shows the cluster-averaged SLP anomaly fields (including the Pacific–North American sector that was not included for the clustering). The clusters labeled 1 in Figure 8 represent a close to symmetric response that resembles, though not exactly, the NAO (negative for El Niño and positive for La Niña), and that is in close agreement with the "canonical" response sketched in section 3.2.1. Note that the two patterns are also close to symmetric in the North Pacific. The other two clusters show a clearly different signal, with limited symmetry both over Europe and over the North Pacific. *Brönnimann et al.* [2007b] performed a multifield clustering based on SLP, temperature, and precipitation over the North Atlantic–European sector for strong El Niños and La Niñas during the past 300 years. Their (close to symmetric) pair of first clusters agrees well with *Gouirand and Moron* [2003] and represents the "canonical" signal in all variables.

3.2.3. Signal in Other Seasons

[41] In the spring season, ENSO-induced anomalies in European climate are slightly different than in late winter. The SLP anomaly pattern shows a much weaker signal (see Figure 3), and the temperature anomaly pattern, though similar in central and northern Europe as in later winter, shows differences in the Mediterranean region. The wet anomaly in central Europe might even be stronger than in winter [*Kiladis and Diaz*, 1989; *Moron and Ward*, 1998; *van Oldenborgh et al.*, 2000] when the Pacific SST signal is strongest, and therefore several authors invoke a lag in ENSO-Europe relationships [e.g., *van Oldenborgh et al.*, 2000]. In contrast to central Europe the eastern Iberian peninsula and Morocco are dry [*Rodó et al.*, 1997; *Moron and Ward*, 1998; *Muñoz-Díaz and Rodrigo*, 2005] and cold [*Halpert and Ropelewski*, 1992]. Again, there is the question of symmetry. *Mason and Goddard* [2001] found a signal in springtime precipitation during La Niña but not El Niño events. On the other hand, *Lloyd-Hughes and Saunders* [2002] found a symmetric precipitation signal.

[42] In summer, no clear ENSO signal appears in temperature and SLP fields (see Figure 3). However, significant relations have been found for precipitation in the Mediterranean area. La Niña events tend to lead to droughts in southwestern Spain [*Muñoz-Díaz and Rodrigo*, 2005] but increased precipitation farther east [*Mariotti et al.*, 2002].

[43] The signal in late fall and early winter (during the mature phase of an ENSO event) is also different from the late winter signal sketched above [*Mariotti et al.*, 2005; *Knippertz et al.*, 2003; *Moron and Plaut*, 2003]. In fact, in November and December the signal can be almost opposite to the "canonical" signal in some respects. For instance, El Niño events (relative to La Niña) are related to more zonal weather and less "west blocking" types, whereas the opposite is found for late winter [*Moron and Plaut*, 2003].

[44] Compositing the seasonal development of an NAO index during strong El Niño events (after removing 30% of the events because NINO3 and NAO were "incoherent" based on a multiresolution cross-spectral analysis), *Huang et al.* [1998] found a positive NAO index in November and December and a negative one in late winter and spring. Figure 3 also shows a change in the SLP pattern over the North Atlantic between October–December (with a neutral NAO) and January–March (negative NAO). For precipitation in the Mediterranean area a seasonal change of the signal was found by *Mariotti et al.* [2002] (see also *Mariotti et al.* [2005] and *Muñoz-Díaz and Rodrigo* [2005] as well as reviews by *Xoplaki* [2002] and *Alpert et al.* [2006]). Figure 9 shows coefficients of the correlation between western Mediterranean rainfall and the NINO3.4 index for 3 month moving averages [*Mariotti et al.*, 2002]. During the course of fall and winter the correlations change from

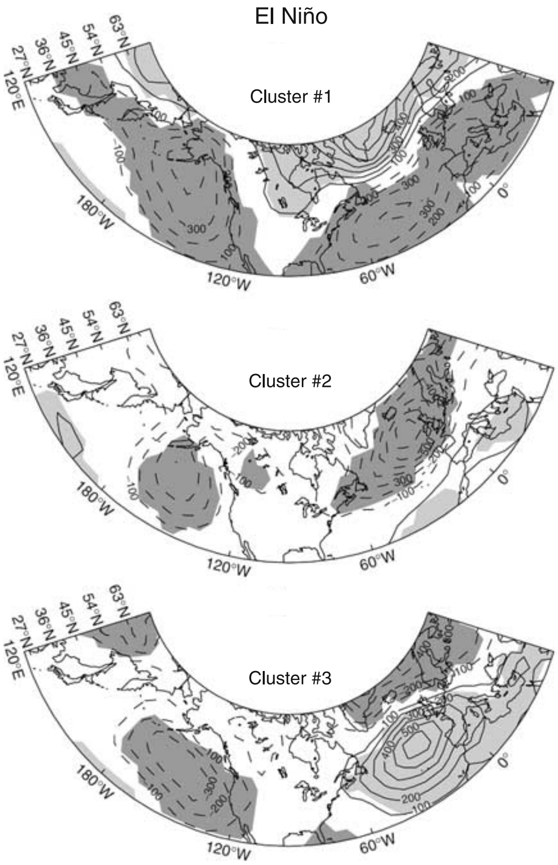

Figure 8. Averaged SLP anomalies for clusters constructed using Ward's hierarchical method for (left) 30 warm ENSO events and (right) 30 cold ENSO events between 1874 and 1996 [from *Gouirand and Moron*, 2003]. Cluster analysis is performed on the sector (25°–70°N, 100°W–50°E). Units are pascals, and the contour interval is 100 Pa. The positive (negative) significant anomalies at the two-tailed 0.1 level and relative to the mean of the "neutral" years are shaded in light (dark) grey. Copyright 2003 Royal Meteorological Society. Reproduced with permission. Permission is granted by John Wiley & Sons Ltd on behalf of RMETS.

significantly positive in fall to significantly negative in late winter and spring, with a good consistency between the data sets. This changeover of the ENSO signal in early winter is a complicating factor when comparing different studies. If winter is defined as December to February, a mixed signal is expected, which possibly contributes to the discrepancy between different studies. The available literature results suggest that January to March is more appropriate for studying the ENSO signal.

3.2.4. ENSO Signal in Climate Reconstructions

[45] Most of the above studies were performed based on instrumental data that reach back to around 1900. Some recent studies have also addressed the effect of ENSO on European and Mediterranean climate during previous centuries. The reconstruction-based studies by *Mann et al.* [2000] and *Brönnimann et al.* [2007b] provide statistical analyses of the ENSO signal over the past 500 years. *Mann et al.* [2000] compared global fields of annual mean temperature with a NINO3 index and found lower than normal temperatures in northeastern Europe for El Niño conditions. *Brönnimann et al.* [2007b] used statistically reconstructed fields of temperature, SLP, precipitation, and

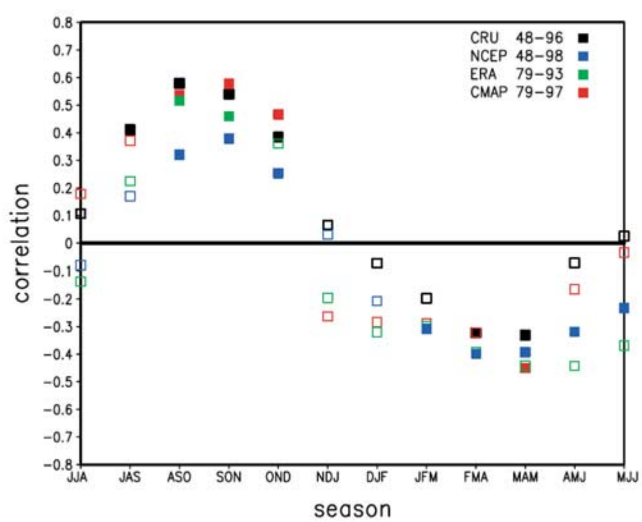

Figure 9. Correlations between western Mediterranean rainfall (10°W–20°E, 30°–45°N) and the NINO3.4 index for 3 month means for different data sets (note that time periods differ because of availability, CRU data are land only). Solid symbols denote significant values (95% confidence level). From *Mariotti et al.* [2002].

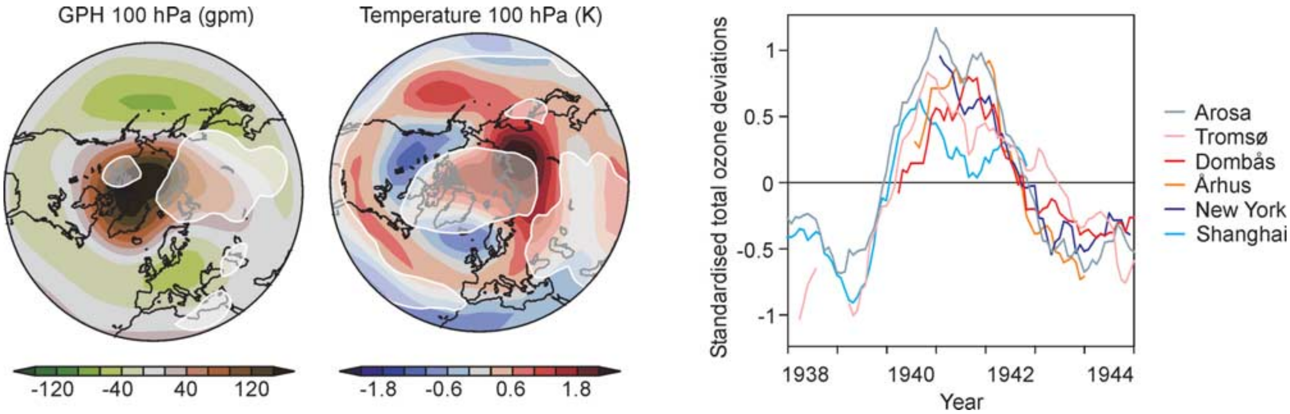

Figure 10. Averaged anomaly fields (with respect to 1961–1990) of (left) GPH and (middle) temperature at 100 hPa for January–April, 1940–1942, statistically reconstructed based on surface and upper air data (shading denotes a low reconstruction skill). (right) Standardized and filtered (12 month moving average) total ozone anomalies (with respect to 1938–1944) for six sites, 1938–1944. From *Brönnimann et al.* [2004].

500 hPa GPH over the North Atlantic–European sector after high-pass filtering and removing volcanic eruptions. For the 18th and 19th centuries they found similar results as mentioned in section 3.2.1 for the 20th century including the "canonical" signal in late winter as well as some of the seasonal differences. *Felis et al.* [2000] and *Rimbu et al.* [2003] found a winter ENSO signal over the past 245 years based on oxygen isotope records from northern Red Sea corals.

3.3. Signal in the Stratosphere

[46] It has been demonstrated that the circulation over the North Atlantic is affected by the stratosphere, particularly by the state of the polar vortex [e.g., *Baldwin and Dunkerton*, 2001]. Hence, in order to better understand ENSO effects on European climate, one also should consider ENSO's effect on the stratosphere [*Randel*, 2004]. In this section I briefly review observational studies on the effect of ENSO on the northern stratosphere, which is a relatively recent research topic.

[47] ENSO is a climatic oscillation that includes the upper level circulation over the tropical Pacific. Not surprisingly, ENSO affects the tropopause over the tropical Pacific region. The tropopause altitude is lower over the western Pacific and higher over the equatorial eastern Pacific during El Niño compared with La Niña. In other words, the cold tropopause region shifts eastward related to the shift in the convective activity [*Hatsushika and Yamazaki*, 2001]. Associated changes in upper level divergent flow and vertical motion can be found [*Hastenrath*, 2003]. El Niño is accompanied by a generally cold tropical lower stratosphere (except over Southeast Asia and the western tropical Pacific), most pronounced over the eastern Pacific [e.g., *Claud et al.*, 1999].

[48] El Niño also affects the extratropical stratosphere. Figure 10 shows averaged anomaly fields for late winter and spring (January–April) for the particularly strong and pronounced 1940–1942 El Niño [*Brönnimann et al.*, 2004]. The dominant feature was a weak and meridionally expanded polar vortex, which is apparent in 100 hPa GPH (Figure 10 left). The 100 hPa temperature (Figure 10 middle) exhibits a cooling over the eastern North Atlantic and a warming over the North Pacific and northern Eurasia, which was most likely related to major midwinter warmings (MMW) in the middle stratosphere [see *Labitzke and van Loon*, 1999; *Limpasuvan et al.*, 2004] in each of the winters. Stratospheric ozone was also affected. The only six total ozone series that cover this time period (Figure 10 right) all show pronounced positive anomalies during the El Niño

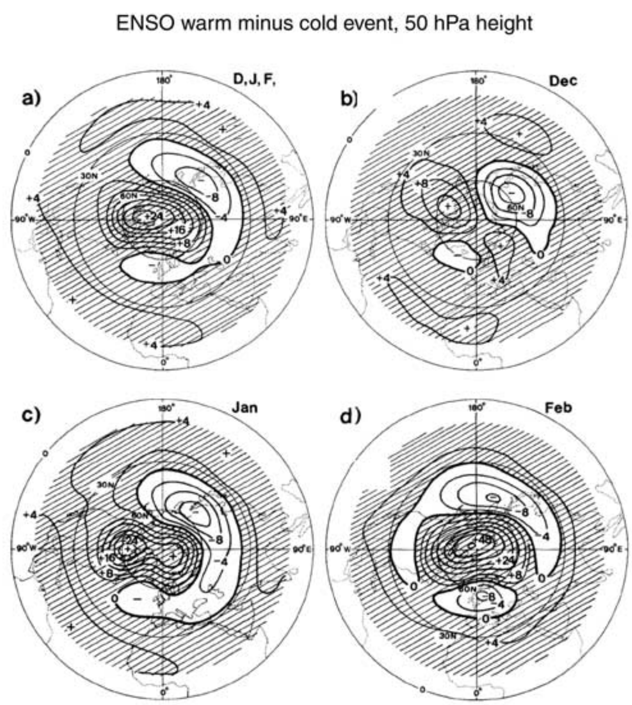

Figure 11. Composites of 50 hPa GPH (in dam) for ENSO warm minus ENSO cold events (selected based on the SOI) for (a) December–February, (b) December, (c) January, and (d) February. Reprinted from *van Loon and Labitzke* [1987].

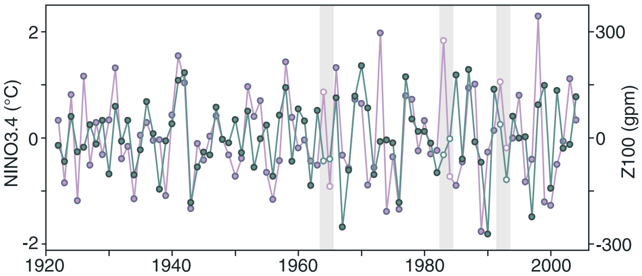

Figure 12. September-to-February averages of NINO3.4 (purple, ERSST version 2) and January-to-March averages of Z100, representing the weakness of the polar vortex (green, 100 hPa GPH difference between 75°–90°N and 40°–55°N from NCEP/NCAR reanalysis after 1948 and statistically reconstructed from surface and historical upper air data back to 1922 using the same data and methods as described by *Brönnimann et al.* [2007a]). The series were filtered with a Gaussian high-pass filter (σ = 3 years) to focus on the interannual-to-multiannual variability. Shaded bars denote the first two winters after major volcanic eruptions.

compared to the years before and after. *Brönnimann et al.* [2004] interpreted this finding as an increased meridional ozone transport (in addition to local effects related to the changing planetary wave structure).

[49] Two of the first to study the relation between ENSO and the arctic stratosphere statistically were *van Loon and Labitzke* [1987]. They found that strong El Niños are associated in the stratosphere with a strong Aleutian high and a weak polar vortex. Their results are shown in Figure 11 for 50 hPa GPH. The difference between El Niño and La Niña in the polar stratosphere first appears over northern Canada in December and then shifts over the pole in January. The mature stage, showing a strong positive GPH anomaly centered over the pole, is reached only in February. A band of negative anomalies appears at midlatitudes, with centers over western Europe and the Sea of Okhotsk. The robustness of these results was questioned, but they were supported by later studies [e.g., *Hamilton*, 1993a; *Perlwitz and Graf*, 1995; *Sassi et al.*, 2004; *Manzini et al.*, 2006; *García-Herrera et al.*, 2006; see also *Chen et al.*, 2003], even though some authors [e.g., *Calvo Fernández et al.*, 2004] find only a small ENSO signal in the extratropical stratosphere.

[50] The weakening of the polar vortex due to El Niño is accompanied by a strong warming (10–15 K difference between El Niño and La Niña) [*Sassi et al.*, 2004] that is related to more frequent MMWs [*Labitzke and van Loon*, 1999]. The warming propagates downward from the upper stratosphere in early winter to the tropopause in late winter [*Sassi et al.*, 2004; *Manzini et al.*, 2006; *García-Herrera et al.*, 2006]. This downward propagation is important as it might affect the ENSO signal at the surface in Europe.

[51] The statistical analysis of the stratospheric response to El Niño is complicated by several factors such as seasonality and nonlinearity [*van Loon and Labitzke*, 1987; *Sassi et al.*, 2004; *Manzini et al.*, 2006], volcanic eruptions [see *Labitzke and van Loon*, 1989; *Perlwitz and Graf*, 1995], and, most importantly, the quasi-biennial oscillation (QBO) [*Hamilton*, 1993a; *Baldwin and O'Sullivan*, 1995; *Baldwin et al.*, 2001]. Consequences of this will be addressed in section 3.4. Nevertheless, the main signal, i.e., the weak polar vortex in late winter, appears relatively clearly. Figure 12 shows times series (after removing the low-frequency component) of a cold season NINO3.4 index and an index of the weakness of the polar vortex at 100 hPa in late winter since 1922. The correlation (without volcanically perturbed winters) is 0.42. This is not only highly significant ($p < 0.05$) but also higher than the correlations normally found between ENSO and European climate variables.

3.4. Modulating Factors and Nonstationary Behavior

[52] Why are some El Niño winters accompanied by different climate anomalies over Europe than others? Is this due to chaotic behavior of a complex dynamical system (i.e., internal variability in the extatropical circulation), or can deviations be attributed to differences in the signal itself or a modulation of the signal by other influences? This has important implications for seasonal forecasting. In this section I discuss possible modulating factors as well as the problem of nonstationary behavior of teleconnections (see further discussion of mechanisms in section 5).

[53] The first factor to be considered is the tropical Pacific signal itself. *Greatbatch et al.* [2004] tentatively suggest that differences in the signal leaving the tropics (which may vary on low-frequency scales) might lead to different ENSO effects in Europe [see also *Knippertz et al.*, 2003; *Sutton and Hodson*, 2003]. This may concern strength, position, and timing of the tropical Pacific SST signal. *Larkin and Harrison* [2005] investigated global El Niño effects for the "new" (NINO3.4 based) NOAA definition of El Niño and compared results with a "conventional" list of El Niño seasons. The new definition adds a few seasons that are characterized by a high NINO3.4 index but no strong anomalies in the eastern tropical Pacific, and they are therefore called "dateline" El Niños. Interestingly, the latter show a different signal over Europe. Whereas the conventional cases show a slight (insignificant) warming, the "dateline" cases show a significant cooling in northeastern Europe. This is demonstrated in Figure 13 (top), where late winter temperature at Uppsala (January–March) is plotted against NINO3.4 (September–February) from 1870 to 1995 (from both series, low-frequency variability was removed and volcanically perturbed winters were excluded). The data were stratified as to whether the standardized ENSO signal was stronger in NINO1 + 2 (i.e., the eastern tropical Pacific) or in NINO4 (the western to central tropical Pacific). Clearly, an ENSO signal in Uppsala temperature is mainly found in the latter case. The difference between the two correlation coefficients is statistically significant ($p < 0.05$). This information is important with respect to seasonal prediction.

[54] Apart from differences in the tropical Pacific signal, there may also be modulating factors along the way between

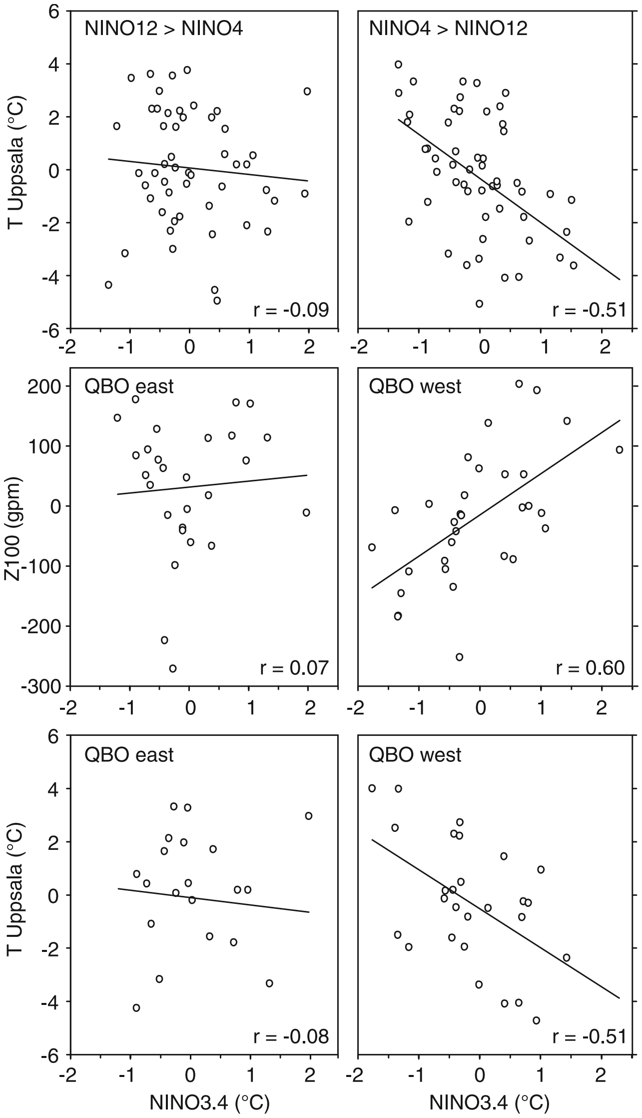

Figure 13. (top and bottom) Temperature at Uppsala and (middle) weakness of the polar vortex (see Figure 12) in January–March as a function of September-to-February averages of NINO3.4, stratified according to whether the standardized ENSO signal was stronger in NINO1+2 or NINO4 (top plots, data were available from 1870 to 1995) or according to the phase of the QBO in November–February [*Labitzke et al.*, 2006] (middle and bottom plots, data were available from 1942 to 1995 and 2006, respectively). All data were filtered with a Gaussian high-pass filter (σ = 3 years) to focus on the interannual-to-multiannual variability. Two winters following each volcanic eruption were excluded.

the tropical Pacific and Europe because of nonlinear interaction with SSTs in other ocean basins. For instance, it has been suggested that the tropical Atlantic modulates the ENSO signal in Europe [*Mathieu et al.*, 2004; see also *Gouirand and Moron*, 2003; *Spencer and Slingo*, 2003; *Sutton and Hodson*, 2003]. From these studies it is expected that the effect would be strongest if SSTs in the tropical Pacific and tropical Atlantic are in phase. *Gershunov and Barnett* [1998] found a dependence of the North American ENSO signal on the PDO. A similar modulation could also affect the European signal [see also *Huang et al.*, 1998]. In fact, *Brönnimann et al.* [2007b] found an influence of North Pacific climate on the ENSO signal in Europe. If ENSO and PDO were in phase in the year prior to the analyzed winter, the correlation between ENSO and the NAO index was significantly stronger than otherwise. The signal might also be modulated farther downstream, i.e., over the North Atlantic. Focusing on low-frequency variations, *Gouirand and Moron* [2003] attributed the possible nonstationary behavior of the El Niño signal in part to interdecadal variations in the strength of the basin-wide westerlies, arguing that weak westerlies lead to a more pronounced negative NAO response to El Niño but to a less pronounced positive NAO response to La Niña.

[55] Yet another modification might be related to the region of Southeast Asia and to the western tropical Pacific. Especially for precipitation in the Mediterranean region the influence of the circulation over the Indian Ocean and Asia is relatively strong [*Xoplaki*, 2002; *Mariotti et al.*, 2005; *Alpert et al.*, 2006]. This might also hold for the NAO [*Hoerling et al.*, 2001b]. A modulating effect including the Indian Ocean and Southeast Asia is therefore possible. *van Oldenborgh et al.* [2000] find a 3 to 6 month lag in the European precipitation signal, which could possibly be explained by Southeast Asian temperatures that might act as an intermediate variable between ENSO and European climate (see section 3.2).

[56] The probably most important factor interfering with the ENSO signal, at least in the stratosphere, is tropical volcanic eruptions. Apart from the global cooling effects, such eruptions are expected to lead to a differential heating of the lower stratosphere, which may cause a strengthened polar vortex and, through mechanisms of downward propagation, a strong NAO and warm winters in northern Europe [*Robock*, 2000]. The latter has been found in a statistical analysis of climate reconstructions by *Fischer et al.* [2007]. Hence it is expected that this effect counteracts the canonical El Niño signal in the stratosphere and in Europe. Since there is a systematic tendency for El Niño events to occur after volcanic eruptions [*Adams et al.*, 2003], this might systematically affect the El Niño signal found in statistical analyses. *Brönnimann et al.* [2007a] found a strong influence of volcanic eruptions on the ENSO signal in Europe, especially in the second half of the 20th century, when all three major eruptions were followed by El Niño conditions. As this is also a period on which many ENSO studies are based, volcanoes could be an important reason for the difficulties in extracting an ENSO signal from the data (and for differences between different studies). Volcanic eruptions are an important factor that is inadequately dealt with in most analyses of ENSO effects on Europe.

[57] Another possible modulating factor, again acting from the stratosphere, is the QBO. It affects the polar vortex through changing the planetary wave propagation character-

istics [*Holton and Tan*, 1980; *Baldwin et al.*, 2001]. It appears that an easterly QBO at 50 hPa weakens the polar vortex (similar to the El Niño signal) and a westerly QBO strengthens the vortex (similar to La Niña), which leaves an imprint in the tropospheric circulation over the North Atlantic [*Baldwin et al.*, 2001]. However, the QBO also has other, yet unexplained, modulating effects [e.g., *Labitzke et al.*, 2006]. Figure 13 (middle) shows the weakness of the polar vortex at 100 hPa in late winter (as in Figure 12) as a function of NINO3.4, stratified according to the QBO phase at 50 hPa during the winter. ENSO affects the polar vortex significantly more during the westerly phase of the QBO than during the easterly phase. This could be a "saturation effect"; that is, during the easterly QBO phase the vortex is already disturbed and an additional ENSO-related disturbance is less effective. Alternatively, the same modulating effects as for the solar signal could be operating. In any case the apparent QBO modulation could be important for the ENSO signal in European climate, which is stronger (though not significantly) during the westerly phase of the QBO (Figure 13 bottom).

[58] Many of the modulating factors mentioned above precede the ENSO signal in Europe (such as the characteristics of the tropical signal, the state of the North Pacific, or volcanic eruptions) or are predictable to some extent (SSTs and QBO). Hence accounting for them in a proper way may increase the predictability of European climate during ENSO events.

[59] Related to the problem of modulating factors is the problem of stationarity. Several studies find variations in the ENSO signal in Europe depending on the time period, and the question of stationarity of the El Niño phenomenon and its teleconnection is widely discussed [e.g., *van Oldenborgh et al.*, 2000; *Rimbu et al.*, 2003; *Sutton and Hodson*, 2003; *Knippertz et al.*, 2003; *Moron and Plaut*, 2003; *Gouirand and Moron*, 2003; *Moron and Gouirand*, 2003; *van Oldenborgh and Burgers*, 2005] (see also the discussion of coherency and related issues by *Rogers* [1984], *Huang et al.* [1998], and *Mokhov and Smirnov* [2006]). It seems that the ENSO phenomenon and its global teleconnections have undergone a change in the 1970s (section 2), which itself was related to a Pacific warming. It is interesting that many authors find a change in the teleconnections around the 1970s also for the North Atlantic–European sector. This concerns, for instance, the response in SLP fields over Europe [*Gouirand and Moron*, 2003; *Moron and Plaut*, 2003; *Greatbatch et al.*, 2004], precipitation in Israel [*Price et al.*, 1998], and oxygen isotopes in Red Sea corals [*Rimbu et al.*, 2003]. Hence empirical evidence suggests that there might have been a change in ENSO teleconnection with Europe around the 1970s. (It should be noted, however, that the latter period contains two El Niño events coincident with strong tropical volcanic eruptions.)

[60] Other nonstationarities have also been suggested. *Kadioğlu et al.* [1999] found a nonstationary behavior for the relation between SOI and precipitation in Turkey in December when comparing 1931–1960 with 1961–1990. *Knippertz et al.* [2003], analyzing precipitation in Europe and North Africa, distinguish three periods with a different signal: 1900–1925, 1931–1956, and 1962–1987. This fits relatively well with suggested climate regimes: *Raible et al.* [2004] analyze the stationarity of NAO variability in a climate model and find two regimes, a regional and a hemispheric, in the latter of which there is a strong association between NAO and ENSO. The authors use the period 1933–1962 as an example for the hemispheric regime.

[61] Still other studies suggest stationarity. *van Oldenborgh and Burgers* [2005] found little evidence for a nonstationary behavior of ENSO teleconnections with global precipitation during the instrumental period, with the possible exception of Europe. Climate reconstructions, though based on the assumption of a stationary local predictor-predictand relationship, can give some indications with respect to the stationarity of very remote teleconnections such as between ENSO and European climate. *Mann et al.* [2000] analyzed global ENSO teleconnections during the past 350 years for subsequent 50 year periods and found a similar temperature signal over northeastern Europe in all subperiods but relatively large variations in southwestern Europe and over the Atlantic. *Brönnimann et al.* [2007b], based on early instrumental series and climate field reconstructions, found no evidence for a nonstationary behavior of the main features in western, central, and northern Europe on multidecadal scales during the past 300 years.

[62] There is no definitive answer to the question of stationarity of ENSO effects on European climate. Some authors find nonstationarities that are in line with the global climate shift in the 1970s or with suggested regime changes during the 20th century. On the other hand, climate reconstructions show no clear evidence for a nonstationary behavior in the main ENSO signal in central and northern Europe over multidecadal to centennial scale. It is clear, however, that ENSO effects can be modulated by various factors on an interannual scale, which, if systematic on longer timescale, would appear as a nonstationary behavior.

3.5. Summary

[63] Despite the large interevent variability, robust ENSO effects in Europe appear in case studies, statistical analyses, and analyses of climate reconstructions. The numerous studies provide evidence for a signal in temperature, SLP, and precipitation in late winter as well as somewhat different signals in early winter and spring. Not all regions are affected, though, and the correlations are sometimes low.

[64] While recent research has led to the establishment of a "canonical" late winter ENSO pattern, there are still differing views. Also, issues of linearity, seasonality, and stationarity are not fully solved yet. The evidence from empirical studies adds together to form a complex puzzle, which will be further discussed from a model perspective (section 4) and in the context of mechanisms (section 5). Another gap in our knowledge concerns links between ENSO and European climate on decadal and multidecadal scales, which may be different from interannual effects

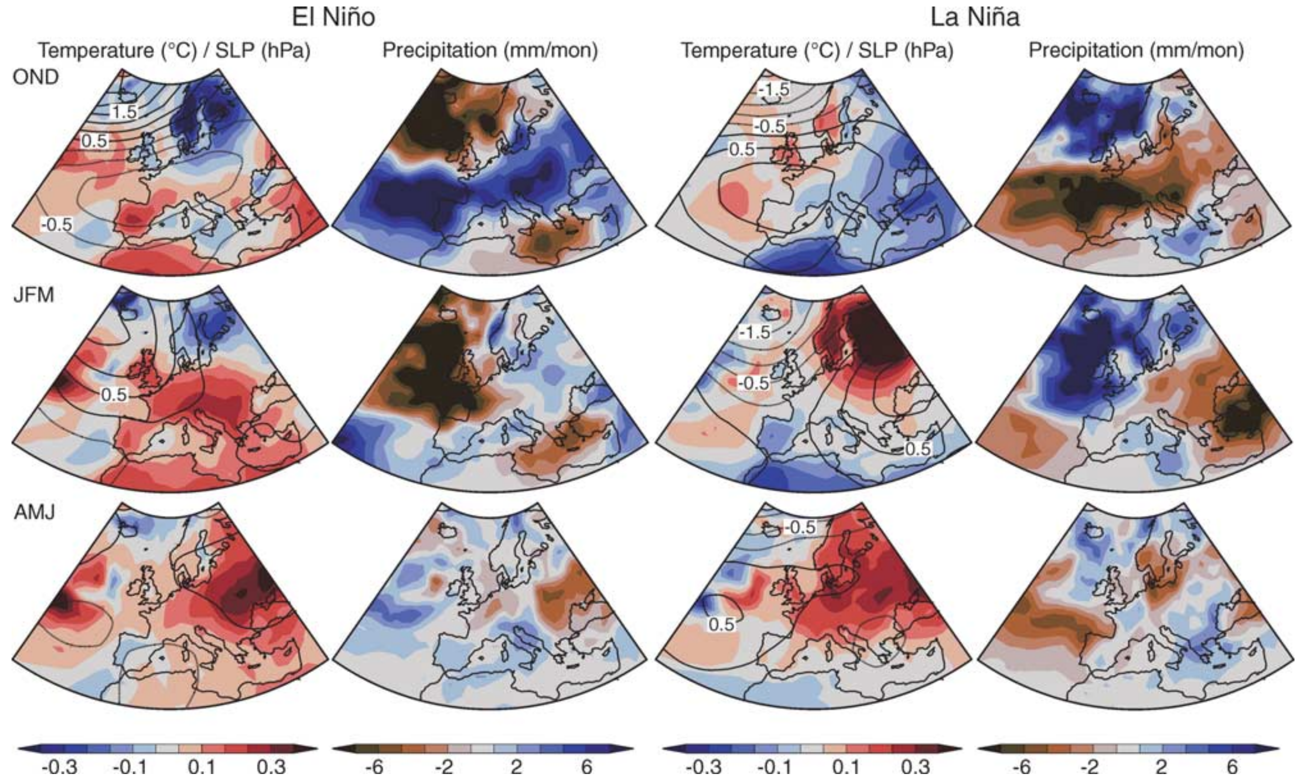

Figure 14. Anomaly fields of temperature, SLP (contours), and precipitation for strong El Niño and strong La Niña events in 540 years of the control run b30.009 of version 3 of the Community Climate System Model (CCSM3) for different seasons. ENSO events were defined as cases when the September-to-February average of NINO3.4 was outside 1 standard deviation.

[e.g., *Mann et al.*, 2000; *Brönnimann et al.*, 2007b; see also *Allan et al.*, 2003; *Meinke et al.*, 2005].

4. MODEL STUDIES ON THE EFFECT ON EUROPE

[65] In this section, results from model simulations on the effect of ENSO on climate in the Atlantic-European sector are discussed and compared with observations. These model experiments comprise control runs of coupled ocean-atmosphere general circulation models (OAGCMs), transient runs of atmospheric general circulation models (AGCMs) forced with observed SSTs or with idealized SSTs, and runs with more complex middle atmosphere models or chemistry-climate models (CCMs) in order to focus on the stratosphere. Model results on the effect of ENSO on climate in the Atlantic-European sector are relatively recent; most of the studies have been published during the past 10 years. In recent years the topic has received even more attention in context with the advent of seasonal prediction studies (note, however, that seasonal prediction was the primary target already of Walker's work).

4.1. Ocean-Atmosphere General Circulation Models

[66] If remote ENSO effects are studied in OAGCMs, it is important that the model reproduces the main features of the Pacific ENSO signal. While this is not the case for all details of the ENSO signal (see below) and its temporal variability, the broad features are often sufficiently well captured to make an analysis of teleconnections meaningful. In a 100 year simulation with an OAGCM, *Roeckner et al.* [1996] found a good representation of ENSO. With respect to the circulation over the North Atlantic they found a weakening of the westerlies related to a weakening and southwestward shift of the Icelandic low and a tendency to cold winters in Europe.

[67] In version 3 of the Community Climate System Model (CCSM3) from the National Center for Atmospheric Research (NCAR), ENSO characteristics as well as global teleconnection are well reproduced in the high-resolution (T85) control run except for the temporal variability, which is biased toward the shorter (biennial) timescales [*Deser et al.*, 2006]. Figure 14 shows an analysis of the ENSO signal in Europe in a control simulation (540 years). On the basis of the September-to-February averaged NINO3.4 index, strong El Niño and La Niña events were selected (outside 1 standard deviation, which corresponds to about 85 cases each). Composites for surface temperature, SLP, and precipitation anomalies for different seasons are shown. During El Niño in late winter (January–March) the "canonical" signal also appears in the model but with some differences. The cold winters in northeastern Europe do not appear as pronounced as in the observations, whereas there is a considerable warming in southern central Europe, and the SLP anomalies are shifted southward when compared with observations. The precipitation signal in central Europe is different from what is expected, whereas in the Mediterra-

nean area the model fits well with observations. Note, for instance, that it reproduces the asymmetry in precipitation anomalies in the eastern Mediterranean in winter that was reported by *Pozo-Vázquez et al.* [2005a]. Apart from that the La Niña signal is close to symmetric to the El Niño signal and includes a pronounced warming in northeastern Europe. Interestingly, a strong "canonical" El Niño signal appears in October–December (again close to symmetric), when the observations suggest a different effect. The changeover of the correlation between ENSO and western Mediterranean rainfall from positive in fall to negative in winter is not well reproduced, but at least the model shows a positive correlation in late fall which decreases to near zero.

[68] OAGCM simulations allow addressing longer timescales and can give indications on possible interactions with low-frequency variability. *Raible et al.* [2004] analyzed a 600 year experiment and detected two different regimes of the North Atlantic atmospheric circulation related to the strength of decadal variability in the NAO. In the hemispheric regime the NAO variability is strongly coupled to ENSO via a PNA-like pattern. Over the Atlantic the storm track is shifted, with corresponding anomalous precipitation patterns. In the regional regime, however, NAO and ENSO seem to be decoupled [see also *Raible et al.*, 2001]. As pointed out in section 3.4, both regimes have counterparts in the observational record of the 20th century.

[69] Simulations with OAGCMs are often performed with respect to future climate. Using a state-of-the-art model configuration (5th version of the European Centre/Hamburg model coupled to the ocean model of the Max Planck Institute (the European Centre model/Hamburg model ECHAM5 coupled to the Max Planck Institute ocean model MPI-OM) driven with emissions scenarios from the Intergovernmental Panel on Climate Change termed SRES, *Müller and Roeckner* [2006] found that the correlation between NINO3.4 and the NAO index is relatively weak in the 20th century but will strengthen (i.e., become increasingly negative) in the 21st and 22nd centuries and reach values of around −0.4.

4.2. Atmosphere Models

[70] In simulations with AGCMs, SSTs are prescribed and hence are realistic in the tropical Pacific, but this also determines the direction of ocean-atmosphere interaction. This might be unrealistic in the extratropics, where (for seasonal-to-interannual scales) it is generally assumed that the atmosphere forces the ocean rather than vice versa [e.g., *Bjerknes*, 1964]. Because SST fields are to some extent predictable, AGCM experiments are often performed with regard to seasonal predictability. However, for assessing predictability or attributing a signal to a forcing (such as ENSO), different experiments need to be performed. Apart from the "global ocean/global atmosphere" (GOGA) experiments, where models are forced by global SSTs and the global atmospheric response is analyzed, only the tropical oceans (Tropical Ocean–Global Atmosphere (TOGA) experiment) can be forced or only the tropical Pacific or Indian and Pacific oceans (I-POGA) can be forced, while in the remaining areas SSTs are set to climatological values.

[71] Many of these studies find that the anomalous atmospheric circulation over Europe during ENSO events can be reproduced to some extent. *Dong et al.* [2000] were able to simulate the marked differences in 500 hPa GPH over the Atlantic-European sector between the winters 1997/1998 (El Niño) and 1998/1999 (La Niña) by forcing SSTs outside the Atlantic [see also *Grötzner et al.*, 2000]. The late winter climate anomalies in Europe in 1987 (El Niño) and 1989 (La Niña) with respect to the NAO, surface temperature, precipitation, and 500 hPa GPH were successfully reproduced by several models in ensemble GOGA experiments [*Palmer and Anderson*, 1993; *Mathieu et al.*, 2004; *Sardeshmukh et al.*, 2000; *Brönnimann et al.*, 2006]. *Sardeshmukh et al.* [2000] also reproduced the nonlinear behavior in the ENSO response of extreme precipitation in the eastern Mediterranean. When Atlantic SSTs were set to climatological values, *Mathieu et al.* [2004] were not able to reproduce the anomaly in 500 hPa GPH. In the same study the observed signal of the 1997/1998 El Niño was also successfully modeled in an I-POGA experiment, while the signal of the 1991/1992 El Niño (note that this event was perturbed by the Pinatubo eruption), on the other hand, was not well reproduced. The main features in 500 hPa GPH for three La Niña events (a dipole with positive anomalies west of France and negative anomalies between Iceland and Norway, though with some variations from event to event) were successfully modeled by *Mathieu et al.* [2004].

[72] In statistical analyses of transient GOGA simulations many authors found the expected "canonical" late winter signal [e.g., *Bengtsson et al.*, 1996; *Martineu et al.*, 1999; *Feddersen*, 2000]. *Merkel and Latif* [2002] were able to reproduce this signal very well but only when running their model on a high resolution (T106). *Feddersen* [2000] found the expected ENSO-induced pattern of temperature anomalies at 850 hPa in a set of ensemble simulations. *Pohlmann and Latif* [2005] successfully simulated an NAO-like response to ENSO in ensemble I-POGA experiments. Using a principal-component-based analysis technique, *Pavan et al.* [2000] found a significant effect of an ENSO-like mode on the zonal wind structure over Eurasia similar to the observations, but the Pacific-Atlantic coupling was not well reproduced, which is important during strong ENSO events. In ensemble GOGA experiments, *Friedrichs and Frankignoul* [2003] found significant covariability between 500 hPa GPH over the Atlantic and Europe and remote ENSO forcing. However, the seasonality of the response in the northern extratropics was not correctly reproduced. *Martineu et al.* [1999], in ensemble GOGA experiments, were able to reproduce the NAO response to ENSO and were also able to simulate some of the interevent variability in a statistical sense when increasing the number of ensemble members. In a transient ensemble simulation (1871–1999, Hadley Centre Atmospheric Model HadAM3), *Sutton and Hodson* [2003] found a similar imprint of ENSO on SLP over the North Atlantic

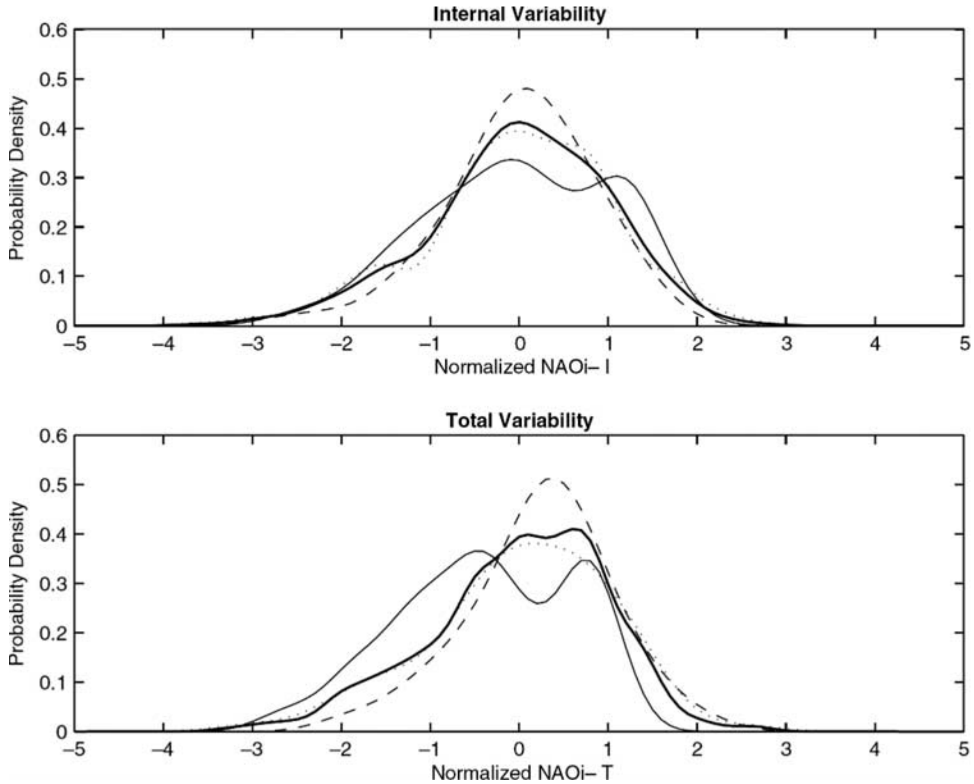

Figure 15. Estimated probability density functions for (top) internal and (bottom) total NAO variability for all years (thick solid curve), ENSO warm events (thin solid curve), ENSO cold events (dotted curve), and neutral years (dashed curve). Probability density functions were estimated by the kernel method using a normalized Gaussian kernel function; smoothing parameters are 0.28, 0.30, 0.38, and 0.24 (top plot) and 0.20, 0.28, 0.34 and 0.35 (bottom plot). From *Melo-Gonçalves et al.* [2005]. Copyright Springer 2005, reprinted with kind permission of Springer Science and Business Media.

as in the observations but noted a nonstationarity of that relationship.

[73] Several authors analyzed the position and strength of the jet streams in AGCM simulations. For El Niño most studies find a strong Atlantic jet that is shifted equatorward (to around 40°N) with respect to its normal position, whereas for La Niña a latitudinal broadening and weakening of the jet is found [*Bengtsson et al.*, 1996; *Roeckner et al.*, 1996; *Martineu et al.*, 1999]. *Cassou and Terray* [2001a] found the latter effect (weakening jet during La Niña) to be more pronounced than the former in their simulations, similar to the observations.

[74] By performing ensemble simulations with AGCMs the variability of the ENSO signal in Europe can be addressed. *Melo-Gonçalves et al.* [2005] performed a 30-member ensemble simulation over 27 years and analyzed NAO variability in relation to ENSO. The results are shown in the form of probability density functions in Figure 15, where total variability (bottom) refers to the variability over all El Niños and all ensemble members (thus including the effect on the ensemble mean), while the internal variability (top) refers to the variability with respect to the ensemble mean but calculated over all years (thus centered around 0). Total variability can be used to analyze the signal of the NAO response to ENSO forcing. This ensemble mean signal is negative for El Niño conditions; however, the ensemble mean might not be meaningful as the distribution for El Niño (thin solid curve) shows a clear bimodality. The bimodality is not due to interevent differences, which is demonstrated by subtracting the ensemble mean from each event (internal variability, Figure 15 top). The finding of a bimodality is interesting with respect to the possible nonlinearities suggested by *Wu and Hsieh* [2004a, 2004b] and also *Pozo-Vázquez et al.* [2001, 2005b] based on observational data (see section 3.2).

[75] In addition to interevent differences, AGCM experiments are also interesting with respect to differences in the synoptic-to-intraseasonal variability. *Compo et al.* [2001] performed large ensembles of GOGA simulations with an AGCM. While on the synoptic and monthly scales, variability patterns for 500 hPa GPH are generally opposite for El Niño and La Niña, they have the same sign in the Atlantic sector on the intraseasonal scale. For extremes the ENSO signal in the seasonal variance is as important as the signal in the mean value [*Sardeshmukh et al.*, 2000].

4.3. Modeling ENSO's Effect on the Stratosphere

[76] In order to study the relation between ENSO and the northern stratosphere, GCMs with high vertical resolution

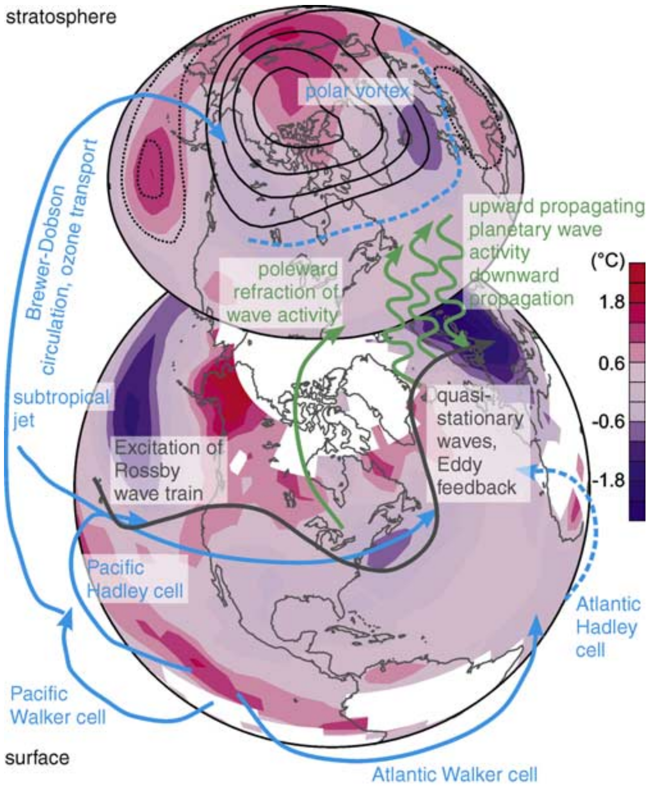

Figure 16. Schematic depiction of the mechanisms relating El Niño to European climate and the stratosphere. Solid arrows denote a strengthening of the circulation; dotted arrows denote a weakening of the circulation. The maps show anomalies of temperature (bottom) at the surface and (top) at 100 hPa averaged from January 1940 to February 1942. Contours show 100 hPa GPH anomalies (interval 20 geopotential meters, zero contour not shown). See *Brönnimann et al.* [2004] for data references.

and model top or CCMs are used. This is a relatively recent research topic. Different modeling studies were performed in the past few years, which were often (but not always) successful (see *Manzini et al.* [2006] for a brief overview). *Hamilton* [1993b] correctly simulated an El Niño–induced mixed zonal wave one and two perturbation in the stratospheric wavefield, giving rise to an intensified Aleutian high. The warming of the Arctic middle stratosphere during El Niño events was reproduced by *Sassi et al.* [2004] in an ensemble of transient simulations (Whole-Atmosphere Community Climate Model (WACCM1) model) but was more zonally asymmetric than in the observations. The positive temperature anomaly appeared already in December at around 30 km altitude and then moved downward until March. Downward propagation was also found by *Manzini et al.* [2006] in an ensemble of transient simulations with the middle atmosphere GCM Middle Atmosphere ECHAM (MAECHAM5). For ENSO warm events they found a zonal wave number one response in 50 hPa temperature in January, which then gives rise to a polar warming in February. The zonal wind at 60°N shows a stronger than normal polar vortex in November and December and then a weakening from January through March.

[77] *Taguchi and Hartmann* [2006] analyzed the occurrence of MMWs in a model experiment (WACCM) with perpetual January conditions (El Niño or La Niña). They found a higher frequency of MMWs during El Niño. This is interesting because MMWs can propagate downward, and some may eventually affect weather at the ground [*Baldwin and Dunkerton*, 2001]. *García-Herrera et al.* [2006] found a stronger Brewer-Dobson circulation (wintertime poleward transport) during El Niño in two models (WACCM and MAECHAM5) and observations. All of these results are consistent with each other.

[78] In order to analyze the ENSO signal in stratospheric ozone, chemistry-climate models are employed. *Brönnimann et al.* [2006] used the Solar Climate Ozone Links (SOCOL) model for ensemble simulations of the ENSO cycle 1986–1989. The model reproduced well the weaker lower stratospheric polar vortex in late winter 1987 compared to 1989 and increased poleward ozone transport due to a strengthened Brewer-Dobson circulation, but other features were less well reproduced.

4.4. Summary

[79] In all, climate models are an important tool for analyzing and understanding ENSO effects on European climate. In general, both OAGCMs and AGCMs (in GOGA mode) often successfully reproduce the broad features of the ENSO signal in Europe, but some models have problems in simulating the seasonality of the signal as well as the more local features. Also, several models tend to produce a too strong coupling between North Pacific and North Atlantic, which might affect the simulated ENSO signal in Europe [e.g., *Cassou and Terray*, 2001b]. AGCM simulations in many cases capture some of the interevent variability, and middle atmosphere models successfully reproduce many features of the stratospheric ENSO response, including the downward propagation of the anomalies in the zonal circulation and temperature from the upper and middle stratosphere in January to the lower stratosphere in March.

[80] From the reported results it seems that a better understanding of ENSO could eventually contribute to better seasonal forecasts of Euro-Atlantic climate, but that stage has not yet been reached. Also, some events (such as the 1991/1992 El Niño) seem to be more difficult to reproduce than others (such as the 1986–1989 ENSO cycle). It is also clear that model resolution has an impact and that the use of ensembles is particularly important for studying the ENSO effect on Europe in climate models.

5. MECHANISMS

[81] A large amount of work has been devoted in the past few decades to understanding the mechanisms behind global climatic effects of ENSO. In this section, possible mechanisms are discussed, starting with the effects on the

tropical oceans and the North Pacific region. The main mechanisms are summarized schematically in Figure 16.

5.1. Effect on the Tropical Oceans and the North Pacific

[82] Relations between El Niño events and SST anomalies in other tropical oceans and in the North Pacific are relatively well understood today and are often termed "atmospheric bridge" [e.g., *Enfield and Meyer*, 1997; *Trenberth et al.*, 1998; *Alexander et al.*, 2002; *Wang et al.*, 2004; *Liu and Alexander*, 2007]. As for the tropical Atlantic, weakened trade winds (a change in the Atlantic Walker circulation) and reduced latent heat flux have been suggested as possible causes for the bridge [*Alexander et al.*, 2002; *Wang*, 2004], but the effect may also operate indirectly via an altered extratropical circulation [*Wang*, 2004]. The "atmospheric bridge" to the North Pacific operates via changes in the extratropical branch of the Hadley circulation including anomalous upper level convergence and divergence. This process can act as a source of Rossby waves, which then propagate poleward and eastward [see *Hoskins and Karoly*, 1981; *Sardeshmukh and Hoskins*, 1988] and interact with the extratropical circulation, in particular the quasi-stationary wave over the Pacific–North American sector. The Aleutian low is intensified, leading to a cooling of the central North Pacific and a warming along the Alaskan coast. Interaction between the stationary component of the flow and traveling weather systems as well as extratropical air-sea interaction further modify the response. However, the net effect of these processes is less well established. Some model simulations suggest that the SST changes driven by the intensified Aleutian low tend to reinforce the same atmospheric anomaly [*Lau*, 1997; see also *Trenberth and Hurrell*, 1994], whereas other studies suggest a damped effect [see *Liu and Alexander*, 2007].

[83] The role of oceanic processes in the extratropics is subject to ongoing discussion, even though it is generally assumed that, on the interannual scale, extratropical SSTs react to the atmosphere rather than vice versa. In the case of the ENSO response of the North Pacific, Ekman transport might contribute to SST anomalies in the central North Pacific. Also, because of the seasonal cycle of the mixed layer depth and the process of "reemergence" of temperature anomalies buried under a shallow thermocline during summer, there is an extratropical oceanic memory from one winter to the next [*Trenberth and Hurrell*, 1994; *Alexander et al.*, 2002; *Liu and Alexander*, 2007].

5.2. Effect on Europe

[84] El Niño can possibly affect the North Atlantic–European sector through different chains of mechanisms, the key players being the North Pacific area, the tropical Atlantic, and the stratosphere. The traditional view of ENSO teleconnections with the Atlantic European area is that of a downstream effect. This mechanism was probably first suggested by *Bjerknes* [1966] and implies that the disturbance of the circulation over the North Pacific sector, originating from ENSO's impact on the Pacific Hadley circulation, propagates downstream and leads to a change in the quasi-stationary wave structure (gray arrow in Figure 16). Over the Pacific–North American sector the response to El Niño resembles (but not exactly) the positive PNA phase. Enhanced stationary eddy activity and a stronger jet are found over the east coast of North America in a climate model [*Raible et al.*, 2004]. The change of the quasi-stationary wave over the North Atlantic has been addressed as an eastward extension of a PNA-like pattern to the western North Atlantic (and was found to be overestimated in their model) by *Cassou and Terray* [2001b]. However, the emerging wave pattern over the Atlantic is less clear than over the Pacific as the signal interacts with a highly variable extratropical circulation [*Trenberth et al.*, 1998; see also *Quadrelli and Wallace*, 2002].

[85] The Pacific-Atlantic coupling may be amplified or modified by interaction with the land surface or the stratosphere. *Moron and Gouirand* [2003] argue that the continent-ocean thermal contrast that develops over the northwestern North Atlantic during El Niño winters (Figure 3) reduces cyclogenesis in this area [see also *Hoerling et al.*, 1997], contributing to a weakening of the Icelandic low. *Ulbrich and Christoph* [2001] tentatively suggest a Pacific-Atlantic coupling through changes in the growth conditions of transient eddies over the Atlantic via latent heat transport and changes in baroclinicity. *Honda et al.* [2001] find a seesaw between the Aleutian and Icelandic low that develops in late winter. It is initiated by an amplification of the Aleutian low and proceeds in the form of two stationary wave trains that propagate to the North Atlantic. *Castanheira and Graf* [2003] argue that the stratosphere might be involved in the Pacific-Atlantic coupling but only when the polar vortex is strong.

[86] Over the North Atlantic, additional interactions may take place and modify the signal. It has been shown that ENSO not only forces or modifies low-frequency modes such as the PNA and NAO but also affects the synoptic eddy statistics [*Compo et al.*, 2001]. A number of authors suggest that eddies may be important in maintaining or amplifying the stationary wave disturbance over the North Atlantic. An initially small perturbation may affect the sensitive tail end of the North Atlantic storm track, which through transient eddy–mean flow interaction may produce a persistent ENSO signal over Europe [e.g., *Fraedrich*, 1994; *Cassou and Terray*, 2001b; *Raible et al.*, 2004]. Hence the signal found in Europe may arise from both the stationary component and an eddy feedback and therefore comprises interactions between different scales of flow [*Martineu et al.*, 1999; *Alpert et al.*, 2006].

[87] If the European ENSO signal arises from a downstream propagation from the North Pacific signal as described above, a nonlinearity of the former could be related to a nonlinearity of the latter [see also *Pozo-Vázquez et al.*, 2001]. *Lin and Derome* [2004], using a primitive equations dry atmospheric model, found a stronger response of the circulation over the North Atlantic for El Niño compared to La Niña as a result of a strong sensitivity of the response to

changes in the mean state. *Cassou and Terray* [2001a, 2001b] suggest that the eddy feedback on the mean flow (as described above) might possibly promote an asymmetric response. The seasonality of the European ENSO signal, in this view, can possibly be explained by seasonal changes in the climatological background flow [see also *Kumar and Hoerling*, 1998], a strong signal requiring a minimum speed of the low-level westerlies over the Atlantic [*Moron and Gouirand*, 2003]. The same mechanism could also explain interevent variability. The mechanisms suggested by *Honda et al.* [2001] and *Moron and Gouirand* [2003] would favor a strong Pacific-Atlantic coupling, and hence corresponding ENSO signal in Europe, in late winter. (*Honda et al.* [2001] found a weak in-phase relationship between the Aleutian and Icelandic low in early winter.) If Pacific-Atlantic coupling is stronger during periods with a strong polar vortex [*Castanheira and Graf*, 2003], this might favor a relatively stronger La Niña than El Niño signal.

[88] Another important aspect is the role of the longitude of the tropical SST forcing for the effect in the North Atlantic. *Lin and Derome* [2004], in a primitive equations model, found almost no effect for a 30° westward shift of the tropical forcing. *Li et al.* [2006], in a GCM coupled with a slab mixed layer ocean, found that SST forcing in the western tropical Pacific induces an annular response in the northern extratropical 500 hPa GPH field (reinforced through extratropical air-sea interaction), while eastern tropical Pacific heating generates a more localized response.

[89] Other authors see a likely influence of ENSO on the North Atlantic and Europe via the tropical Atlantic. It is well established that El Niño affects the tropical Atlantic and weakens the Atlantic Hadley circulation [e.g., *Ruiz-Barradas et al.*, 2003; *Wang et al.*, 2004]. Through this path, ENSO may affect the Azores high [*Cassou and Terray*, 2001b] and hence the NAO and the strength of the westerlies. In fact, tropical Atlantic SSTs (regardless of the ENSO phase) may affect North Atlantic climate via the NAO [see also *Czaja et al.*, 2003; *Wang*, 2004]. However, *Wang* [2002], studying the circulation over the tropical Atlantic found no relation between ENSO and the NAO and only a weak relation between the tropical Atlantic and the NAO. At the least, tropical Atlantic climate has to be considered as a possible modulating factor. For instance, *Mathieu et al.* [2004] note that the relation between ENSO and European climate is different when SST anomalies in the tropical Atlantic are out of phase with El Niño [see also *Pozo-Vázquez et al.*, 2001; *Gouirand and Moron*, 2003; *Sutton and Hodson*, 2003].

[90] The path via the tropical Atlantic might help to explain the seasonality of the ENSO signal. As the tropical Atlantic SSTs lag the tropical Pacific ENSO signal by 3–6 months, the maximum signal in Europe might be expected in spring (when several authors find a particularly strong precipitation signal in Europe) rather than in winter. Hence it is possible that the ENSO signal in Europe is influenced by the North Pacific–North Atlantic link in winter but by a tropical Atlantic–North Atlantic link in spring. The dominance of one mechanism over the other might also help to explain some of the interevent variability or the apparent nonlinear behavior. Concerning the ENSO signal in Europe in fall and early winter, *Moron and Gouirand* [2003] speculate that it might be a consequence of a change in the general tropical-extratropical thermal gradient and its effect on the extratropical westerlies.

[91] A third way in which ENSO might affect European climate in late winter is via downward propagation of stratospheric anomalies [see *Randel*, 2004]. The downward propagation of the ENSO signal from the upper stratosphere in January to the lower stratosphere in February and March is clearly observed and reproduced by models [e.g., *Manzini et al.*, 2006]. Also, it is known from the work of *Baldwin and Dunkerton* [2001] and others that downward propagating stratospheric anomalies may affect the weather at the ground for several weeks. As a downward propagation from the stratosphere has been suggested as a mechanism for the volcanic and solar influences on extratropical circulation [e.g., *Robock*, 2000], a similar mechanism is plausible also for ENSO. One would expect the signal to project onto the NAO [*Limpasuvan et al.*, 2004], which is the case for the ENSO signal. This mechanism could only explain a signal in late winter (which is when the "canonical" signal is strongest). It could explain the QBO modulation of ENSO's effect on temperature at Uppsala (Figure 13). Although in good agreement with observations, more evidence for this mechanism is necessary.

5.3. Effect on the Stratosphere

[92] Stratosphere-troposphere coupling is a two way interaction, and the possible downward propagation is normally preceded by an upward coupling. The strength and temperature of the late winter stratospheric polar vortex is to a large extent controlled by tropospheric planetary waves, entering the stratosphere and interacting with the mean flow [*Holton et al.*, 1995; *Newman et al.*, 2001]. During El Niño winters, enhanced planetary wave activity propagates from the troposphere to the stratosphere where it decelerates the zonal mean flow and accelerates the meridional (poleward) flow [e.g., *Brönnimann et al.*, 2004; *García-Herrera et al.*, 2006; *Manzini et al.*, 2006; *Taguchi and Hartmann*, 2006; *Brönnimann et al.*, 2006]. This mechanism is in agreement with most of the stratospheric features of the ENSO signal described in section 3 such as a weak polar vortex, warm temperatures of the Arctic middle stratosphere in spring, frequent MMWs during El Niño, increased poleward ozone transport (strengthened Brewer-Dobson circulation [see *Randel et al.*, 2002]) and hence increased extratropical total ozone during El Niño, especially in the late winter polar region [see also *Labitzke and van Loon*, 1999], and decreased ozone on the tropical stratosphere [*Pyle et al.*, 2005; *Brönnimann et al.*, 2006].

[93] Which tropospheric wave patterns cause the increased planetary wave activity? It seems that especially a PNA-like wave number one pattern is responsible [*Manzini et al.*, 2006; *Taguchi and Hartmann*, 2006]. *Chen et al.* [2003] showed that this pattern affects poleward refraction of wave activity and is clearly related to ENSO. In addition,

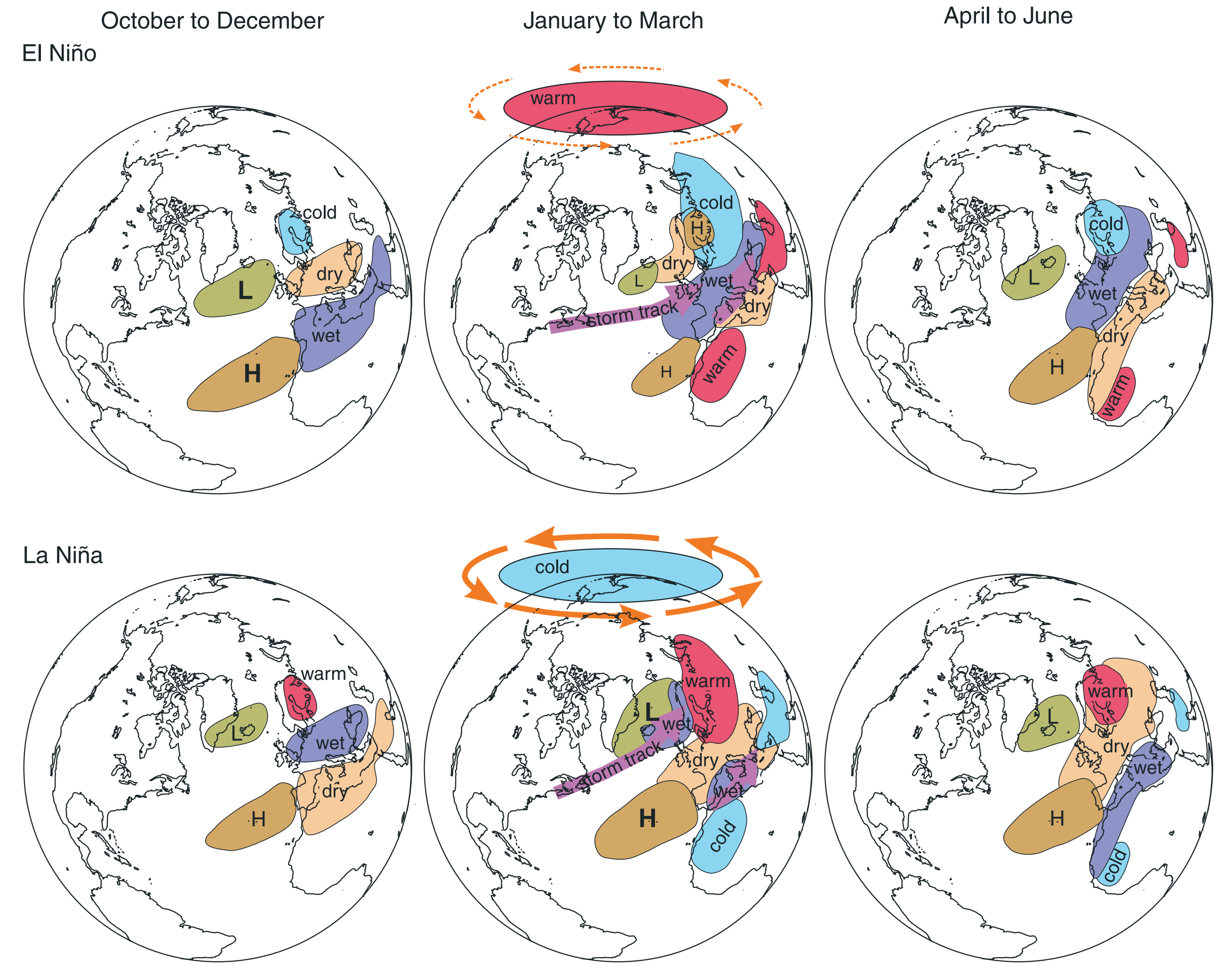

Figure 17. Schematic depiction of El Niño and La Niña effects on climate in Europe and the polar stratosphere for different seasons. Note that for the pressure centers as well as for the position of the storm tracks and the strength of the polar vortex, absolute values are shown (the relative deviations can be judged from the size and style of the font and arrows), while precipitation and temperature refer to relative values.

the NAO-like pattern over the North Atlantic also contributes during some El Niño events through increasing the upward component of the wave activity flux [*Brönnimann et al.*, 2006].

[94] Though plausible, the concept of stratospheric ENSO effects via upward propagating planetary wave activity may be too simple [see also *Baldwin and O'Sullivan*, 1995]. *Labitzke and van Loon* [1999] suggest a stratospheric mechanism in which the radiative cooling of the tropical lower stratosphere due to clouds (related to the convective activity) affects the Aleutian high, which then disturbs and eventually weakens the vortex. More research is still needed in this area.

6. CONCLUSIONS

[95] While many questions remain open concerning the relative importance of various mechanisms as well as the role of different modulating factors, this review of recent studies reveals that the effect of El Niño on European climate is statistically significant, climatologically relevant, and at least partly understood. Figure 17 summarizes the effects schematically.

[96] The signal in European climate is most consistent in late winter and resembles (though not exactly!) the negative mode of the North Atlantic Oscillation (NAO) for El Niño and the positive mode for La Niña. In early winter the signal is almost opposite in many respects, and a somewhat different signal is also found in spring. Different mechanisms might be involved and together produce a signal that varies with season (with strongest anomalies in late winter), from event to event, and on a low-frequency scale. In general, the signal is close to symmetric for El Niño and La Niña, with some confirmed asymmetries in Mediterranean precipitation and possibly in the North Atlantic SLP anomalies. The imprint in the stratosphere consists of a

weak and warm polar vortex in the Arctic stratosphere during El Niño, propagating from the middle to the lower stratosphere during the course of a winter. The stratospheric signal might affect the tropospheric circulation in late winter.

[97] Figure 17 shows the "canonical signal," which is the dominating signal, e.g., in a clustering analysis. However, not all El Niños show this signal. While this is to a large extent caused by internal variability of the extratropical circulation, there are also some more systematic effects. Depending on the boundary conditions, the ENSO signal in Europe is not always the same. A particularly important factor is tropical volcanic eruptions.

[98] The ENSO signal in Europe is not strong on average but may still be important under certain conditions. Some El Niño events may have a particularly strong effect. The prolonged 1940–1942 El Niño was accompanied in northeastern Europe by three of the coldest winters of the 20th century. This was not only an extreme event but is also important from a climatological point of view. In fact, removing these three winters from the 20th century record of northeastern Europe temperature [*Brönnimann et al.*, 2004], the interannual variance decreases by as much as 17%. Hence one strong ENSO event can be important for the European climate variability of a whole century.

[99] Another important aspect of the studies on ENSO effects on European climate is potential predictability on a seasonal scale. Any improvement of the forecasts would by highly beneficial as currently the seasonal prediction skill for European winters is near zero [*van Oldenborgh*, 2005]. The studies reviewed in this paper imply that there is some potential predictability of European climate on a seasonal scale induced by ENSO, even though not all model studies are successful and the interpretation of the model results is debated. It will be crucial to disentangle the (possibly predictable) causes of the strong interevent variability such as differences in the tropical signal, modulating factors, and nonlinear responses.

[100] Finally, understanding ENSO effects on European climate might also be beneficial for our understanding and assessment of future climate change. The frequency and strength of ENSO events has changed in the past and might change in the future. Moreover, its teleconnection might change. This is of particular interest in the light of the results by *Müller and Roeckner* [2006], who predict a strengthened ENSO-NAO relationship in the future.

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REFERENCES

Adams, J. B., M. E. Mann, and C. M. Ammann (2003), Proxy evidence for an El Niño–like response to volcanic forcing, *Nature*, *426*, 274–278.

Alexander, M. A., et al. (2002), The atmospheric bridge: Influence of ENSO teleconnnections on air-sea interaction over the global oceans, *J. Clim.*, *15*, 2205–2231.

Allan, R., and T. Ansell (2006), A new globally-complete monthly historical gridded mean sea level pressure data set (HadSLP2): 1850–2003, *J. Clim.*, *19*, 5816–5842.

Allan, R., and R. D. D'Arrigo (1999), "Persistent" ENSO sequences: How unusual was the 1990–1995 El Niño?, *Holocene*, *9*, 101–118.

Allan, R., J. Lindesay, and D. Parker (1996), *El Niño Southern Oscillation and Climatic Variability*, Commonw. Sci. and Ind. Res. Organ., Collingwood, Victoria, Australia.

Allan, R. J., C. J. C. Reason, J. A. Lindesay, and T. J. Ansell (2003), Protracted ENSO episodes and their impacts in the Indian Ocean region, *Deep Sea Res., Part II*, *2*, 2331–2347.

Alpert, P., et al. (2006), Relations between climate variability in the Mediterranean region and the Tropics: ENSO, South Asian and African monsoons, hurricanes and Saharan dust, in *The Mediterranean Climate: An Overview of the Main Characteristics and Issues*, edited by P. Lionello, P. Malanotte-Rizzoli, and R. Boscolo, pp. 149–177, Elsevier, New York.

Angell, J. K. (2000), Tropospheric temperature variations adjusted for El Niño, 1958–1998, *J. Geophys. Res.*, *105*, 11,841–11,849.

Arpe, K., L. Bengtsson, G. S. Golitsyn, I. I. Mokhov, V. A. Semenov, and P. V. Sporyshev (2000), Connection between Caspian Sea level variability and ENSO, *Geophys. Res. Lett.*, *27*, 2693–2696.

Baldwin, M. P., and T. J. Dunkerton (2001), Stratospheric harbingers of anomalous weather regimes, *Science*, *294*, 581–584.

Baldwin, M. P., and D. O'Sullivan (1995), Stratospheric effects of ENSO-related tropospheric circulation anomalies, *J. Clim.*, *8*, 649–667.

Baldwin, M. P., et al. (2001), The quasi-biennial oscillation, *Rev. Geophys.*, *39*, 179–229.

Barnett, T., N. Graham, M. Cane, S. Zebiak, S. Dolan, J. O'Brien, and D. Legler (1988), On the prediction of the El Niño of 1986–1987, *Science*, *241*, 192–196.

Bengtsson, L., K. Arpe, E. Roeckner, and U. Schulzweida (1996), Climate predictability experiments with a general circulation model, *Clim. Dyn.*, *12*, 261–278.

Bjerknes, J. (1964), Atlantic air-sea interaction, *Adv. Geophys.*, *10*, 1–82.

Bjerknes, J. (1966), A possible response of the atmospheric Hadley circulation to anomalies of ocean temperature, *Tellus*, *18*, 820–829.

Bjerknes, J. (1969), Atmospheric teleconnections from the equatorial Pacific, *Mon. Weather Rev.*, *97*, 163–172.

Brönnimann, S., and J. Luterbacher (2004), Reconstructing Northern Hemisphere upper-level fields during World War II, *Clim. Dyn.*, *22*, 499–510.

Brönnimann, S., J. Luterbacher, J. Staehelin, T. M. Svendby, G. Hansen, and T. Svenøe (2004), Extreme climate of the global troposphere and stratosphere 1940–1942 related to El Niño, *Nature*, *431*, 971–974.

Brönnimann, S., M. Schraner, B. Müller, A. Fischer, C. Schnadt, D. Brunner, E. Rozanov, and T. Egorova (2006), The 1986–1989 ENSO cycle in a chemical climate model, *Atmos. Chem. Phys.*, *6*, 4669–4685.

Brönnimann, S., T. Ewen, T. Griesser, and R. Jenne (2007a), Multidecadal signal of solar variability in the upper troposphere during the 20th century, *Space Sci. Rev.*, *125*, 305–315.

Brönnimann, S., E. Xoplaki, C. Casty, A. Pauling, and J. Luterbacher (2007b), ENSO influence on Europe during the last centuries, *Clim. Dyn.*, *28*, 181–197.

Calvo Fernández, N., R. García Herrera, D. Gallego Puyol, E. Hernández Martín, R. R. García, L. Gimeno Presa, and P. Ribera Rodríguez (2004), Analysis of the ENSO signal in tropospheric and stratospheric temperatures observed by MSU, 1979–2000, *J. Clim.*, *17*, 3934–3946.

Cassou, C., and L. Terray (2001a), Dual influence of Atlantic and Pacific SST anomalies on the North Atlantic/Europe winter climate, *Geophys. Res. Lett.*, *28*, 3195–3198.

Cassou, C., and L. Terray (2001b), Oceanic forcing of the wintertime low-frequency atmospheric variability in the North Atlantic European sector: A study with the ARPEGE model, *J. Clim.*, *14*, 4266–4291.

Castanheira, J. M., and H.-F. Graf (2003), North Pacific–North Atlantic relationships under stratospheric control?, *J. Geophys. Res.*, *108*(D1), 4036, doi:10.1029/2002JD002754.

Chen, D., M. A. Cane, A. Kaplan, S. E. Zebiak, and D. J. Huang (2004), Predictability of El Niño over the past 148 years, *Nature*, *428*, 733–736.

Chen, W., M. Takahashi, and H.-F. Graf (2003), Interannual variations of planetary wave activity in the northern winter troposphere and stratosphere and their relations to NAM and SST, *J. Geophys. Res.*, *108*(D24), 4797, doi:10.1029/2003JD003834.

Claud, C., N. A. Scott, and A. Chedin (1999), Seasonal, interannual and zonal temperature variability of the tropical stratosphere based on TOVS satellite data: 1987–1991, *J. Clim.*, *12*, 540–550.

Cobb, K. M., C. D. Charles, R. L. Edwards, H. Cheng, and M. Kastner (2003), El Niño/Southern Oscillation and tropical Pacific climate during the last millennium, *Nature*, *424*, 271–276.

Compo, G. P., P. D. Sardeshmukh, and C. Penland (2001), Changes of subseasonal variability associated with El Niño, *J. Clim.*, *14*, 3356–3374.

Czaja, A., A. W. Robertson, and T. Huck (2003), The role of Atlantic ocean–atmosphere coupling in affecting North Atlantic Oscillation variability, in *The North Atlantic Oscillation: Climatic Significance and Environmental Impacts*, *Geophys. Monogr. Ser.*, vol. 134, edited by J. W. Hurrell et al., pp. 147–172, AGU, Washington, D. C.

Deser, C., A. Capotondi, R. Saravanan, and A. Phillips (2006), Tropical Pacific and Atlantic climate variability in CCSM3, *J. Clim.*, *19*, 2451–2481.

Diaz, H., and V. Markgraf (Eds.) (2000), *El Niño and the Southern Oscillation: Multiscale Variability and Global and Regional Impacts*, Cambridge Univ. Press, New York.

Diaz, H. F., M. P. Hoerling, and J. K. Eischeid (2001), ENSO variability, teleconnections, and climate change, *Int. J. Climatol.*, *21*, 1845–1862.

Dong, B. W., R. T. Sutto, S. P. Jewson, A. O'Neill, and J. M. Slingo (2000), Predictable winter climate in the North Atlantic sector during the 1997–1999 ENSO cycle, *Geophys. Res. Lett.*, *27*, 985–988.

Enfield, D. B., and D. A. Meyer (1997), Tropical Atlantic sea surface temperature variability and its relation to El Niño–Southern Oscillation, *J. Geophys. Res.*, *102*, 929–945.

Feddersen, H. (2000), Impact of global sea surface temperature on summer and winter temperatures in Europe in a set of seasonal ensemble simulations, *Q. J. R. Meteorol. Soc.*, *126*, 2089–2109.

Fedorov, A., and S. Philander (2000), Is El Niño changing?, *Science*, *288*, 1997–2002.

Felis, T., J. Pätzold, Y. Loya, M. Fine, A. H. Nawar, and G. Wefer (2000), A coral oxygen isotope record from the northern Red Sea documenting NAO, ENSO, and North Pacific teleconnections on Middle East climate variability since the year 1750, *Paleoceanography*, *15*, 679–694.

Fischer, E. M., J. Luterbacher, E. Zorita, S. F. B. Tett, C. Casty, and H. Wanner (2007), European climate response to tropical volcanic eruptions over the last half millennium, *Geophys. Res. Lett.*, *34*, L05707, doi:10.1029/2006GL027992.

Folland, C., et al. (2001), Observed climate variability and change, in *Climate Change 2001: The Scientific Basis: Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, edited by J. Houghton et al., pp. 99–181, Cambridge Univ. Press, New York.

Folland, C. K., J. A. Renwick, M. J. Salinger, and A. B. Mullan (2002), Relative influences of the Interdecadal Pacific Oscillation and ENSO on the South Pacific Convergence Zone, *Geophys. Res. Lett.*, *29*(13), 1643, doi:10.1029/2001GL014201.

Fraedrich, K. (1990), European Grosswetter during the warm and cold extremes of the El Niño/Southern Oscillation, *Int. J. Climatol.*, *10*, 21–31.

Fraedrich, K. (1994), ENSO impact on Europe?—A review, *Tellus, Ser. A*, *46*, 541–552.

Fraedrich, K., and K. Müller (1992), Climate anomalies in Europe associated with ENSO extremes, *Int. J. Climatol.*, *12*, 25–31.

Fraedrich, K., K. Müller, and R. Kuglin (1992), Northern Hemisphere circulation regimes during the extremes of ENSO, *Tellus, Ser. A*, *44*, 33–40.

Friedrichs, P., and C. Frankignoul (2003), Potential seasonal predictability of the observed Euro-Atlantic atmospheric variability using SST forced ECHAM4-T42 simulations, *Q. J. R. Meteorol. Soc.*, *129*, 2879–2896.

García-Herrera, R., N. Calvo, R. R. Garcia, and M. A. Giorgetta (2006), Propagation of ENSO temperature signals into the middle atmosphere: A comparison of two general circulation models and ERA-40 reanalysis data, *J. Geophys. Res.*, *111*, D06101, doi:10.1029/2005JD006061.

Gergis, J. L., and A. M. Fowler (2005), Classification of synchronous oceanic and atmospheric El Niño–Southern Oscillation (ENSO) events for palaeoclimate reconstruction, *Int. J. Climatol.*, *25*, 1541–1565.

Gershunov, A., and T. P. Barnett (1998), Interdecadal modulation of ENSO teleconnections, *Bull. Am. Meteorol. Soc.*, *79*, 2715–2725.

Glantz, M. H. (1996), *Currents of Change: El Niño's Impact on Climate and Society*, Cambridge Univ. Press, New York.

Gouirand, I., and V. Moron (2003), Variability of the impact of El Niño–Southern Oscillation on sea-level pressure anomalies over the North Atlantic in January to March (1874–1996), *Int. J. Climatol.*, *23*, 1549–1566.

Graf, H.-F., and H. Funke (1986), Blockierungssituationen im europäisch-atlantischen Raum, Teil 1: Phänomenologische Untersuchungen, *Z. Meteorol.*, *36*, 104–112.

Greatbatch, R. J., J. Lu, and K. A. Peterson (2004), Nonstationary impact of ENSO on Euro-Atlantic winter climate, *Geophys. Res. Lett.*, *31*, L02208, doi:10.1029/2003GL018542.

Grötzner, A., M. Latif, and D. Dommenget (2000), Atmospheric response to sea surface temperature anomalies during El Niño 1997/98 as simulated by ECHAM4, *Q. J. R. Meteorol. Soc.*, *126*, 2175–2198.

Halpert, M. S., and C. F. Ropelewski (1992), Surface temperature patterns associated with the Southern Oscillation, *J. Clim.*, *5*, 577–593.

Hamilton, K. (1988), A detailed examination of the extratropical response to tropical El Niño/Southern Oscillation events, *J. Climatol.*, *8*, 67–86.

Hamilton, K. (1993a), An examination of observed Southern Oscillation effects in the Northern Hemisphere stratosphere, *J. Atmos. Sci.*, *50*, 3468–3473.

Hamilton, K. (1993b), A general circulation model simulation of El Niño effects in the extratropical Northern Hemisphere stratosphere, *Geophys. Res. Lett.*, *20*, 1803–1806.

Harrison, D. E., and N. K. Larkin (1998), El Niño–Southern Oscillation sea surface temperature and wind anomalies, *Rev. Geophys.*, *36*, 353–399.

Hastenrath, S. (2003), Upper-air circulation of the Southern Oscillation from the NCEP-NCAR reanalysis, *Meteorol. Atmos. Phys.*, *83*, 51–65.

Hatsushika, H., and K. Yamazaki (2001), Interannual variations of temperature and vertical motion at the tropical tropopause associated with ENSO, *Geophys. Res. Lett.*, *28*, 2891–2894.

Hess, P., and H. Brezowsky (1969), Katalog der Grosswetterlagen Europas. 2. Neu bearbeitete und ergänzte Auflage, *Ber. Dtsch. Wetterdienstes*, *15*(113), 56 pp.

Hildebrandsson, H. H. (1897), Quelques recherches sur les centres d'action de l'atmosphere, *Kongl. Sven. Vetenskaps Akad. Hand.*, *29*(3), 36 pp.

Hoerling, M. P., and M. Ting (1994), On the organization of extratropical transients during El Niño, *J. Clim.*, *7*, 745–766.

Hoerling, M. P., A. Kumar, and M. Zhong (1997), El Niño, La Niña, and the nonlinearity of their teleconnections, *J. Clim.*, *10*, 1769–1786.

Hoerling, M. P., A. Kumar, and T.-Y. Xu (2001a), Robustness of the nonlinear atmospheric response to opposite phases of ENSO, *J. Clim.*, *14*, 1277–1293.

Hoerling, M. P., J. W. Hurrell, and T.-Y. Xu (2001b), Tropical origins for recent North Atlantic climate change, *Science*, *292*, 90–92.

Holton, J. R., and H.-C. Tan (1980), The influence of the equatorial quasi-biennial oscillation on the global circulation at 50 mb, *J. Atmos. Sci.*, *37*, 2200–2208.

Holton, J. R., P. H. Haynes, M. E. McIntyre, A. R. Douglass, R. B. Rood, and L. Pfister (1995), Stratosphere-troposphere exchange, *Rev. Geophys*, *33*, 403–439.

Honda, M., H. Nakamura, J. Ukita, I. Kousaka, and K. Takeuchi (2001), Interannual seesaw between the Aleutian and Icelandic lows, part I: Seasonal dependence and life cycle, *J. Clim.*, *14*, 1029–1041.

Horel, J. D., and J. M. Wallace (1981), Planetary-scale atmospheric phenomena associated with the Southern Oscillation, *Mon. Weather Rev.*, *103*, 813–829.

Hoskins, B. J., and D. J. Karoly (1981), The steady linear response of a spherical atmosphere to thermal and orographic forcing, *J. Atmos. Sci.*, *38*, 1179–1196.

Hsieh, W. W., A. Wu, and A. Shabbar (2006), Nonlinear atmospheric teleconnections, *Geophys. Res. Lett.*, *33*, L07714, doi:10.1029/2005GL025471.

Huang, J., K. Higuchi, and A. Shabbar (1998), The relationship between the North Atlantic Oscillation and El Niño–Southern Oscillation, *Geophys. Res. Lett.*, *25*, 2707–2710.

Jones, P. D., and A. Moberg (2003), Hemispheric and large-scale surface air temperature variations: An extensive revision and update to 2001, *J. Clim.*, *16*, 206–223.

Kadioğlu, M., Y. Tulunay, and Y. Borhan (1999), Variability of Turkish precipitation compared to El Niño events, *Geophys. Res. Lett.*, *26*, 1597–1600.

Kiladis, G. N., and H. F. Diaz (1989), Global climatic anomalies associated with extremes in the Southern Oscillation, *J. Clim.*, *2*, 1069–1090.

Kistler, R., et al. (2001), The NCEP-NCAR 50-year reanalysis: Monthly means CD-ROM and documentation, *Br. Am. Meteorol. Soc.*, *82*, 247–267.

Knippertz, P., U. Ulbrich, F. Marques, and J. Corte-Real (2003), Decadal changes in the link between El Niño and springtime North Atlantic Oscillation and European–North African rainfall, *Int. J. Climatol.*, *23*, 1293–1311.

Kumar, A., and M. P. Hoerling (1998), Annual cycle of Pacific/North American seasonal predictability associated with different phases of ENSO, *J. Clim.*, *11*, 3295–3308.

Kumar, K. K., B. Rajagopalan, and M. A. Cane (1999), On the weakening relationship between the Indian monsoon and ENSO, *Science*, *284*, 2156–2159.

Labitzke, K., and H. van Loon (1989), The Southern Oscillation. part IX: The influence of volcanic eruptions on the Southern Oscillation in the stratosphere, *J. Clim.*, *2*, 1223–1226.

Labitzke, K. G., and H. van Loon (1999), *The Stratosphere: Phenomena, History, and Relevance*, Springer, New York.

Labitzke, K., M. Kunze, and S. Brönnimann (2006), Sunspots, the QBO and the stratosphere in the North Polar region—20 years later, *Meteorol. Z.*, *15*, 355–363.

Larkin, N. K., and D. E. Harrison (2005), Global seasonal temperature and precipitation anomalies during El Niño autumn and winter, *Geophys. Res. Lett.*, *32*, L16705, doi:10.1029/2005GL022860.

Lau, N. C. (1997), Interactions between global SST anomalies and the midlatitude atmospheric circulation, *Bull. Am. Meteorol. Soc.*, *78*, 21–33.

Li, S., M. P. Hoerling, S. Peng, and K. M. Weickmann (2006), The annular response to tropical Pacific SST forcing, *J. Clim.*, *19*, 1802–1818.

Limpasuvan, V., D. W. J. Thompson, and D. L. Hartmann (2004), On the life cycle of Northern Hemisphere stratospheric sudden warming, *J. Clim.*, *17*, 2584–2596.

Lin, H., and J. Derome (2004), Nonlinearity of the extratropical response to tropical forcing, *J. Clim.*, *17*, 2597–2608.

Liu, Z., and M. Alexander (2007), Atmospheric bridge, oceanic tunnel, and global climatic teleconnections, *Rev. Geophys.*, *45*, RG2005, doi:10.1029/2005RG000172.

Lloyd-Hughes, B., and M. A. Saunders (2002), Seasonal prediction of European spring precipitation from El Niño–Southern Oscillation and local sea-surface temperatures, *Int. J. Climatol.*, *22*, 1–14.

Luterbacher, J., et al. (2002), Extending North Atlantic Oscillation reconstructions back to 1500, *Atmos. Sci. Lett.*, *2*, 114–124.

Luterbacher, J., D. Dietrich, E. Xoplaki, M. Grosjean, and H. Wanner (2004), European seasonal and annual temperature variability, trends, and extremes since 1500, *Science*, *303*, 1499–1503.

Mann, M. E., R. S. Bradley, and M. K. Hughes (2000), Long-term variability in the El Niño Southern Oscillation and associated teleconnections, in *El Niño and the Southern Oscillation: Multiscale Variability and Its Impacts on Natural Ecosystems and Society*, edited by H. F. Diaz and V. Markgraf, pp. 321–372, Cambridge Univ. Press, New York.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis (1997), A Pacific interdecadal oscillation with impacts on salmon production, *Bull. Am. Meteorol. Soc.*, *78*, 1069–1079.

Manzini, E., M. A. Giorgetta, M. Esch, L. Kornblueh, and E. Roeckner (2006), The influence of sea surface temperatures on the northern winter stratosphere: Ensemble simulations with the MAECHAM5 model, *J. Clim.*, *19*, 3863–3881.

Mariotti, A., N. Zeng, and K.-M. Lau (2002), Euro-Mediterranean rainfall and ENSO—A seasonally varying relationship, *Geophys. Res. Lett.*, *29*(12), 1621, doi:10.1029/2001GL014248.

Mariotti, A., J. Ballabrera-Poy, and N. Zeng (2005), Tropical influence on Euro-Asian autumn rainfall variability, *Clim. Dyn.*, *24*, 511–521.

Martineu, C., J. Y. Caneill, and R. Sadourny (1999), Potential predictability of European winters from the analysis of seasonal simulations with an AGCM, *J. Clim.*, *12*, 3033–3061.

Mason, S. J., and L. Goddard (2001), Probabilistic precipitation anomalies associated with ENSO, *Bull. Am. Meteorol. Soc.*, *82*, 619–638.

Mathieu, P. P., R. T. Sutton, B. W. Dong, and M. Collins (2004), Predictability of winter climate over the North Atlantic European region during ENSO events, *J. Clim.*, *17*, 1953–1974.

May, W., and L. Bengtsson (1998), The signature of ENSO in the Northern Hemisphere midlatitude seasonal mean flow and high-frequency intraseasonal variability, *Meteorol. Atmos. Phys.*, *69*, 81–100.

McPhaden, M. J., S. E. Zebiak, and M. H. Glantz (2006), ENSO as an integrating concept in Earth science, *Science*, *314*, 1740–1745.

Meinke, H., P. deVoil, G. L. Hammer, R. C. Stone, A. Potgieter, S. Power, R. Allan, and C. Folland (2005), Rainfall variability at decadal and longer time scales: Signal or noise?, *J. Clim.*, *18*, 89–96.

Melo-Gonçalves, P., A. C. Rocha, J. M. Castanheira, and J. A. Ferreira (2005), North Atlantic Oscillation sensitivity to the El Niño/Southern Oscillation polarity in a large-ensemble simulation, *Clim. Dyn.*, *24*, 599–606.

Merkel, U., and M. Latif (2002), A high resolution AGCM study of the El Niño impact on the North Atlantic/European sector, *Geophys. Res. Lett.*, *29*(9), 1291, doi:10.1029/2001GL013726.

Mokhov, I. I., and D. A. Smirnov (2006), El Niño–Southern Oscillation drives North Atlantic Oscillation as revealed with nonlinear techniques from climatic indices, *Geophys. Res. Lett.*, *33*, L03708, doi:10.1029/2005GL024557.

Montroy, D. L., M. B. Richman, and P. J. Lamb (1998), Observed nonlinearities on monthly teleconnections between tropical Pacific sea surface temperature anomalies and central and eastern North American precipitation, *J. Clim.*, *11*, 1812–1835.

Moron, M., and I. Gouirand (2003), Seasonal modulation of the ENSO relationship with sea level pressure anomalies over the North Atlantic in October–March 1873–1996, *Int. J. Climatol.*, *23*, 143–155.

Moron, M., and G. Plaut (2003), The impact of El Niño Southern Oscillation upon weather regimes over Europe and the North Atlantic boreal winter, *Int. J. Climatol.*, *23*, 363–379.

Moron, V., and M. N. Ward (1998), ENSO teleconnections with climate variability in the European and African sectors, *Weather*, *53*, 287–294.

Müller, W. A., and E. Roeckner (2006), ENSO impact on midlatitude circulation patterns in future climate projections, *Geophys. Res. Lett.*, *33*, L05711, doi:10.1029/2005GL025032.

Muñoz-Díaz, D., and F. S. Rodrigo (2005), Influence of the El Niño–Southern Oscillation on the probability of dry and wet seasons in Spain, *Clim. Res.*, *30*, 1–12.

Newman, M., G. Compo, and M. A. Alexander (2003), ENSO-forced variability of the Pacific decadal oscillation, *J. Clim.*, *16*, 3853–3857.

Newman, P. A., E. R. Nash, and J. Rosenfield (2001), What controls the temperature of the Arctic stratosphere during the spring?, *J. Geophys. Res.*, *106*, 19,999–20,010.

Palmer, T. N., and D. L. T. Anderson (1993), Scientific assessment of the prospect of seasonal forecasting: A European perspective, *Tech. Rep. 70*, 34 pp., Eur. Cent. for Medium-Range Weather Forecasts, Bracknell, U. K.

Pavan, V., F. Molteni, and C. Brankovic (2000), Wintertime variability in the Euro-Atlantic region in observations and in ECMWF seasonal ensemble experiments, *Q. J. R. Meteorol. Soc.*, *126*, 2142–2173.

Perlwitz, J., and H.-F. Graf (1995), The statistical connection between tropospheric and stratospheric circulation of the Northern Hemisphere in winter, *J. Clim.*, *8*, 2281–2295.

Philander, S. G. (1989), *El Niño, La Nina, and the Southern Oscillation*, Elsevier, New York.

Philander, S., and A. Fedorov (2003), Is El Niño sporadic or cyclic?, *Annu. Rev. Earth Planet. Sci.*, *31*, 579–594.

Pohlmann, H., and M. Latif (2005), Atlantic versus Indo-Pacific influence on Atlantic-European climate, *Geophys. Res. Lett.*, *32*, L05707, doi:10.1029/2004GL021316.

Power, S., T. Casey, C. K. Folland, A. Colman, and V. Mehta (1999), Inter-decadal modulation of the impact of ENSO on Australia, *Clim. Dyn.*, *15*, 319–323.

Pozo-Vázquez, D., M. J. Esteban-Parra, F. S. Rodrigo, and Y. Castro-Diez (2001), The association between ENSO and winter atmospheric circulation and temperature in the North Atlantic region, *J. Clim.*, *14*, 3408–3420.

Pozo-Vázquez, D., S. R. Gámiz-Fortis, J. Tovar-Pescador, M. J. Esteban-Parra, and Y. Castro-Díez (2005a), ENSO events and associated European winter precipitation anomalies, *Int. J. Climatol.*, *25*, 17–31.

Pozo-Vázquez, D., S. R. Gámiz-Fortis, J. Tovar-Pescador, M. J. Esteban-Parra, and Y. Castro-Díez (2005b), North Atlantic winter SLP anomalies based on the autumn ENSO state, *J. Clim.*, *18*, 97–103.

Price, C., L. Stone, A. Huppert, B. Rajagopalan, and P. Alpert (1998), A possible link between El Niño and precipitation in Israel, *Geophys. Res. Lett.*, *25*, 3963–3966.

Pyle, J. A., P. Braesicke, and G. Zeng (2005), Dynamical variability in the modelling of chemistry-climate interactions, *Faraday Discuss.*, *130*, 27–39.

Quadrelli, R., and J. M. Wallace (2002), Dependence of the structure of the Northern Hemisphere annular mode on the polarity of ENSO, *Geophys. Res. Lett.*, *29*(23), 2132, doi:10.1029/2002GL015807.

Quadrelli, R., V. Pavan, and F. Molteni (2001), Wintertime variability of Mediterranean precipitation and its links with large-scale circulation anomalies, *Clim. Dyn.*, *17*, 457–466.

Quan, X. W., H. F. Diaz, and M. P. Hoerling (2004), Change of the Hadley circulation since 1950, in *The Hadley Circulation: Past, Present, and Future*, edited by H. F. Diaz and R. S. Bradley, pp. 85–120, Springer, New York.

Raible, C. C., U. Luksch, K. Fraedrich, and R. Voss (2001), North Atlantic decadal regimes in a coupled GCM simulation, *Clim. Dyn.*, *18*, 321–330.

Raible, C. C., U. Luksch, and K. Fraedrich (2004), Precipitation and Northern Hemisphere regimes, *Atmos. Sci. Lett.*, *5*, 43–55.

Randel, W. J. (2004), Climate: Wider connections for El Niño, *Nature*, *431*, 920–921.

Randel, W. J., F. Wu, and R. Stolarski (2002), Changes in column ozone correlated with the stratospheric EP flux, *J. Meteorol. Soc. Jpn.*, *80*, 849–862.

Rimbu, N., G. Lohmann, T. Felis, and J. Patzold (2003), Shift in ENSO teleconnections recorded by a northern Red Sea coral, *J. Clim.*, *16*, 1414–1422.

Robock, A. (2000), Volcanic eruptions and climate, *Rev. Geophys.*, *38*, 191–219.

Rocha, A. (1999), Low-frequency variability of seasonal rainfall over the Iberian Peninsula and ENSO, *Int. J. Climatol.*, *19*, 889–901.

Rodó, X., E. Baert, and F. A. Comin (1997), Variations in seasonal rainfall in southern Europe during the present century: Relationship with the North Atlantic Oscillation and the El Niño–Southern Oscillation, *Clim. Dyn.*, *13*, 275–284.

Roeckner, E., J. M. Oberhuber, A. Bacher, M. Christoph, and I. Kirchner (1996), ENSO variability and atmospheric response in a global coupled atmosphere-ocean GCM, *Clim. Dyn.*, *12*, 737–754.

Rogers, J. C. (1984), The association between the North Atlantic Oscillation and the Southern Oscillation in the Northern Hemisphere, *Mon. Weather Rev.*, *122*, 1999–2015.

Ropelewski, C. F., and M. S. Halpert (1987), Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation (ENSO), *Mon. Weather Rev.*, *115*, 1606–1626.

Ruiz-Barradas, A., J. A. Carton, and S. Nigam (2003), Role of the atmosphere in climate variability of the tropical Atlantic, *J. Clim.*, *16*, 2052–2065.

Sardeshmukh, P. D., and B. J. Hoskins (1988), The generation of global rotational flow by steady idealized tropical divergence, *J. Atmos. Sci.*, *45*, 1228–1251.

Sardeshmukh, P. D., G. P. Compo, and C. Penland (2000), Changes of probability associated with El Niño, *J. Clim.*, *13*, 4268–4286.

Sassi, F., D. Kinnison, B. A. Boville, R. R. Garcia, and R. Roble (2004), Effect of El Niño–Southern Oscillation on the dynamical, thermal, and chemical structure of the middle atmosphere, *J. Geophys. Res.*, *109*, D17108, doi:10.1029/2003JD004434.

Smith, T. M., and R. W. Reynolds (2004), Improved extended reconstruction of SST (1854–1997), *J. Clim.*, *17*, 2466–2477.

Spencer, H., and J. M. Slingo (2003), The simulation of peak and delayed ENSO teleconnections, *J. Clim.*, *16*, 1757–1774.

Straus, D. M., and J. Shukla (2003), Does ENSO force the PNA?, *J. Clim.*, *15*, 2340–2358.

Sutton, R. T., and D. L. R. Hodson (2003), Influence of the ocean on North Atlantic Climate variability 1871–1999, *J. Clim.*, *16*, 3296–3313.

Taguchi, M., and D. L. Hartmann (2006), Increased occurrence of stratospheric sudden warmings during El Niño as simulated by WACCM, *J. Clim.*, *19*, 324–332.

Toniazzo, T., and A. A. Scaife (2006), The influence of ENSO on winter North Atlantic climate, *Geophys. Res. Lett.*, *33*, L24704, doi:10.1029/2006GL027881.

Trenberth, K. E. (1990), Recent observed interdecadal climate changes in the Northern Hemisphere, *Bull. Am. Meteorol. Soc.*, *71*, 988–993.

Trenberth, K. E. (1997), The definition of El Niño, *Br. Am. Meteorol. Soc.*, *78*, 2771–2777.

Trenberth, K. E., and J. M. Caron (2000), The Southern Oscillation revisited: Sea level pressures, surface temperatures and precipitation, *J. Clim.*, *13*, 4358–4365.

Trenberth, K. E., and J. W. Hurrell (1994), Decadal atmosphere-ocean variations in the Pacific, *Clim. Dyn.*, *9*, 303–319.

Trenberth, K. E., et al. (1998), Progress during TOGA in understanding and modeling global teleconnections associated with tropical sea surface temperatures, *J. Geophys. Res.*, *103*, 14,291–14,324.

Troup, A. J. (1965), The Southern Oscillation, *Q. J. R. Meteorol. Soc.*, *91*, 490–506.

Ulbrich, U., and M. Christoph (2001), Variable coupling of the NAO to PNA, *Eos Trans. AGU*, *82*(47), Fall Meet. Suppl., Abstract A21C-07.

van Loon, H., and K. Labitzke (1987), The Southern Oscillation. part V. The anomalies in the lower stratosphere of the Northern Hemisphere in winter and a comparison with the Quasi-Biennial Oscillation, *Mon. Weather Rev.*, *115*, 357–369.

van Loon, H., and R. A. Madden (1981), The Southern Oscillation. part I. Global associations with pressure and temperature in northern winter, *Mon. Weather Rev.*, *109*, 1150–1162.

van Loon, H., and J. C. Rogers (1981), The Southern Oscillation. part II. Associations with changes in the middle troposphere in the northern winter, *Mon. Weather Rev.*, *109*, 1163–1168.

van Oldenborgh, G. J. (2005), Comments on ''Predictability of winter climate over the North Atlantic European region during ENSO events'', *J. Clim.*, *18*, 2770–2772.

van Oldenborgh, G. J., and G. Burgers (2005), Searching for decadal variations in ENSO precipitation teleconnections, *Geophys. Res. Lett.*, *32*, L15701, doi:10.1029/2005GL023110.

van Oldenborgh, G. J., G. Burgers, and A. Klein Tank (2000), On the El Niño teleconnection to spring precipitation in Europe, *Int. J. Climatol.*, *20*, 565–574.

Verdon, D. C., and S. W. Franks (2006), Long-term behaviour of ENSO: Interactions with the PDO over the past 400 years inferred from paleoclimate records, *Geophys. Res. Lett.*, *33*, L06712, doi:10.1029/2005GL025052.

Vose, R. S., R. L. Schmoyer, P. M. Steurer, T. C. Peterson, R. Heim, T. R. Karl, and J. K. Eischeid (1992), The Global Historical Climatology Network: Long-term monthly temperature, precipitation, sea-level pressure, and station pressure data, *Rep. 3912*, Environ. Sci. Div., Oak Ridge Natl. Lab., Oak Ridge, Tenn.

Walker, G. T. (1923), Correlation in seasonal variation of weather VIII: A preliminary study of world weather, *Mem. Indian Meteorol. Dep.*, *24*, 75–131.

Walker, G. T. (1924), Correlation in seasonal variation of weather IX: A further study of world weather, *Mem. Indian Meteorol. Dep.*, *24*, 225–232.

Walker, G. T., and E. W. Bliss (1932), World weather V, *Mem. R. Meteorol. Soc.*, *4*, 53–84.

Wang, B. (1995), Interdecadal changes in El Niño onset in the last four decades, *J. Clim.*, *8*, 267–285.

Wang, C. (2002), Atlantic climate variability and its associated atmospheric circulation cells, *J. Clim.*, *15*, 1516–1536.

Wang, C. (2004), ENSO, climate variability and the Walker and Hadley circulations, in *The Hadley Circulation: Present, Past and Future*, *Adv. Global Change Res.*, vol. 21, edited by H. F. Diaz and R. S. Bradley, pp. 173–202, Springer, New York.

Wang, C., and J. Picaut (2004), Understanding ENSO physics—A review, in *Earth's Climate: The Ocean-Atmosphere Interaction*, *Geophys. Monogr. Ser.*, vol. 147, edited by C. Wang et al., pp. 21–48, AGU, Washington, D. C.

Wang, C., S.-P. Xie, and J. A. Carton (2004), A global survey of ocean atmosphere interaction and climate variability, in *Earth's Climate: The Ocean-Atmosphere Interaction*, *Geophys. Monogr. Ser.*, vol. 147, edited by C. Wang et al., pp. 1–19, AGU, Washington, D. C.

Wanner, H., S. Brönnimann, C. Casty, D. Gyalistras, J. Luterbacher, C. Schmutz, D. Stephenson, and E. Xoplaki (2001), North Atlantic Oscillation—Concept and studies, *Surv. Geophys.*, *22*, 321–381.

Wilby, R. (1993), Evidence of ENSO in the synoptic climate of the British Isles since 1880, *Weather*, *48*, 234–239.

Wolter, K., and M. S. Timlin (1998), Measuring the strength of ENSO—How does 1997/98 rank?, *Weather*, *53*, 315–324.

Wu, A., and W. W. Hsieh (2004a), The nonlinear association between ENSO and the Euro-Atlantic winter sea level pressure, *Clim. Dyn.*, *23*, 859–868.

Wu, A., and W. W. Hsieh (2004b), The nonlinear Northern Hemisphere winter atmospheric response to ENSO, *Geophys. Res. Lett.*, *31*, L02203, doi:10.1029/2003GL018885.

Xoplaki, E. (2002), Climate variability over the Mediterranean, Ph.D. thesis, Univ. of Bern, Bern, Switzerland.

S. Brönnimann, Institute for Atmospheric and Climate Science, ETH Zurich, Universitätsstrasse 16, CH-8092 Zürich, Switzerland. (stefan.broennimann@env.ethz.ch)