

# Linkages between common wheat yields and climate in Morocco (1982–2008)

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**Abstract** In Morocco, wheat production shows a high inter-annual variability due to uncertain rainfall. In view of the importance of this resource to the country's economy, it is important to gain a better understanding of the natural large-scale climate oscillation governing this variability. In this study, we analyzed de-trended (1) time series of common wheat yields (1983–2008) from 11 agricultural provinces that account for 80 % of national wheat production; (2) monthly rainfall and 10-day temperature from ten meteorological stations; (3) 10-day normalized difference vegetation index (NDVI) from the AVHRR sensor; (4) monthly atmospheric climate indices [North Atlantic Oscillation (NAO) and Scandinavian Pattern (SCA)] and monthly 500 hPa geopotentials fields; and (5) monthly sea surface temperature (SST) fields and indices (NIÑO3, Tropical North Atlantic and Tropical South Atlantic). The relationship between rainfall and temperature during tillering in early winter and grain filling in early spring and wheat yields already observed at

the plot scale was also found to be significant at the provincial scale. The linkages between wheat yields and large scale climate have been analyzed for the first time over Morocco. In agreement with previous studies, results show a complex and competing influence of different climate phenomena. The NAO is found to be significantly related to yields during the early stage of wheat growth in December, whereas the SCA correlates with yields later in the season, in January and February. Interesting lagged correlations with higher lead time are also highlighted, with the leading modes of SST variability in the equatorial Atlantic during October (the “Atlantic Niño” mode) and in the North Atlantic (the “Atlantic tripole” mode) in February. Our conclusion is that regional climate indices and variables represent valuable information with which to increase lead time and skill regarding wheat yield predictions in Morocco.

**Keywords** Wheat yield · Large scale-climate · NDVI · North Atlantic Oscillation

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## Introduction

Population growth and the associated increase in demand for food have led to an urgent need for efficient agricultural production monitoring systems (Funk and Brown 2009). Rainfed farming dominates global production, with 80 % of arable areas and 60 % of production (Harris 1991). In southern Mediterranean countries, climate is characterized by long periods of drought and a strong interannual variability in rainfall amount and distribution (Bolle 2002) leading to high discrepancies in year-to-year production. Cereals are of great importance to national food security. In Morocco, cereals represents the main crop, with wheat accounting for up to 54 % of total cereal production. Due to the importance of the cereal market for the country's economy, it is important to gain a better understanding of the factors governing the interannual

variability in agricultural production, among which climate is by far the most important.

The phenological development of wheat is well-known to be related to local environmental conditions, among which water availability and temperature are the most important. The relationship between rainfall and temperature on the one hand and wheat yields on the other, has been studied extensively in the past. It is now widely accepted that crop water deficit and heat waves coinciding with a particular growth stage can result in low yields (Angus et al. 1981; Porter and Gawith 1999). Over the Southern Mediterranean region, water stress is especially sensitive during two periods of the year: the first in late autumn during the tillering phase, and the second in early spring during anthesis and the grain filling phase. Significant temperature anomalies should also be avoided during early winter, with low temperatures at this time ( $< 10\text{ }^{\circ}\text{C}$ ) affecting tillering by reducing the ears, leading consequently to lower cereal yield (Farooq et al. 2005), and during the high temperature period affecting grain-filling in early spring. However, most of these studies have been conducted at the plot scale while decision makers are interested in larger scales (from agricultural province to country) in order to pre-empt grain importation in the event of insufficient production for internal consumption or for the storage of seed. To our knowledge, no detailed study exists of the relationship between meteorological variables and wheat yields at the provincial scale over Morocco.

Regarding the low density of the meteorological network most often characterizing semi-arid areas and the difficulty of Global Circulation Models to reproduce rainfall fields, recent studies have pointed out interesting linkages between yields and large-scale climate oscillation as proxy for local rainfall and temperature conditions. In particular, cereal yields at the sub-continental level in several regions of the globe have been found to be significantly related to the El Niño Southern Oscillation (ENSO) indices (Hansen et al. 1999; Podesta et al. 2002; Martinez et al. 2009; Royce et al. 2011). These indirect linkages, through rainfall and temperature, between wheat growth or grain production and atmospheric/oceanic parameters including ENSO are usually not concomitant because of the remote nature of climate phenomena impacting local weather through teleconnections. This could be a significant added value in terms of lead time with regard to the sole use of rainfall and temperature measurement in order to develop an early forecasting system for wheat yields. Nevertheless, few studies have analyzed the linkage between such indices and climatic variables and agricultural yields, except for ENSO sensitive areas. In Southern Mediterranean countries, the main reason for this is probably that the effects of this global ocean–atmosphere phenomenon are embedded within the complex variability of the northern hemisphere climate and local specific elements such as orography over Morocco.

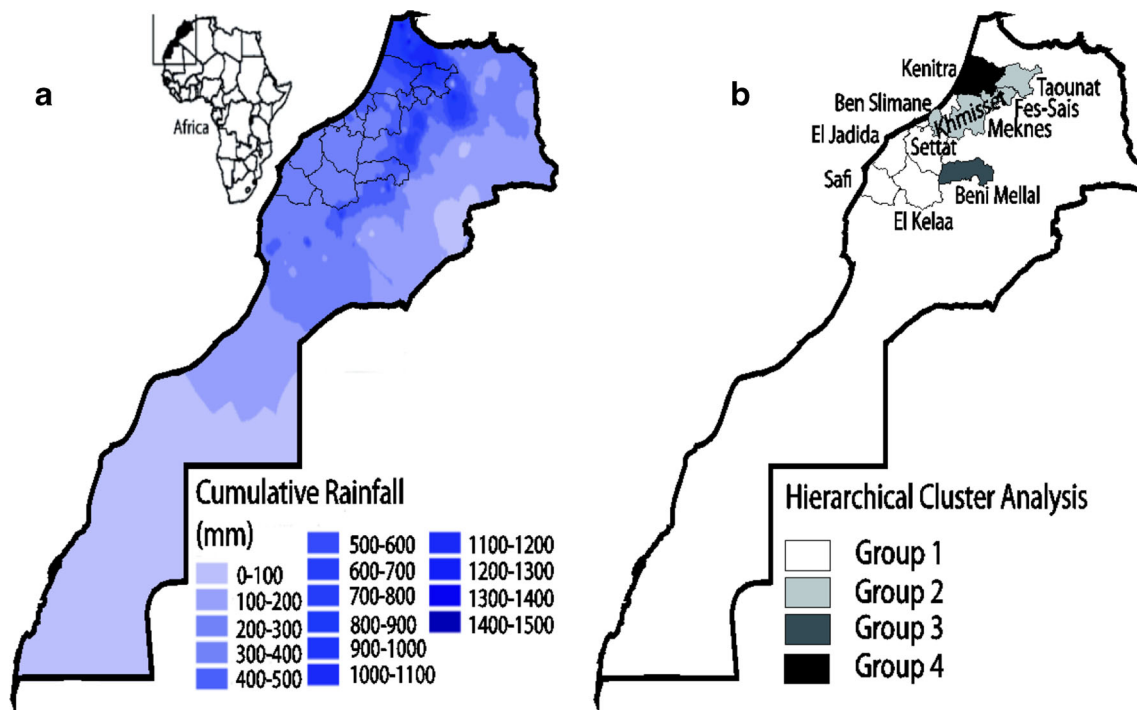
The impact of the North Atlantic Oscillation (NAO) on the Moroccan climate and, in particular, on winter precipitation, is well-known (Lamb and Pepper 1987; Knippertz et al. 2003). The NAO is considered the most prominent and recurrent pattern of atmospheric variability at mid- and high-latitudes of the Atlantic basin and is related to the Northern Hemisphere Annular Mode (NAM) and the Arctic Oscillation (AO, see Marschall et al. 2001). The positive phase of NAO (i.e., the deepening of the Icelandic low and the reinforcement of the Azores anticyclone) is associated with precipitation deficit above southern Europe and the Mediterranean basin (Lamb and Pepper 1987; Hurrell et al. 2003) through a southwest–northeast orientation of the North Atlantic Storm track that carries synoptic systems and rainfall away from North West Africa (Rogers 1997). During the negative phase, the effects are reversed, with enhanced rainfall over North West Africa and Southern Europe through weakened westerlies and a more zonal storm track. The NAO during fall has been found to also impact vegetation status (seen through the vegetation indices measured from space by the AVHRR sensor) over Morocco until the vegetation peak in spring through precipitation amount during the early stage of vegetation development (Jarlan et al. 2013). Some studies also point out the role that the tropical Atlantic Ocean may play in early autumn in enhancing particular phases of the NAO during the following winter (Cassou and Terray 2001; Knippertz et al. 2002). The oceanic thermal inertia makes SST a persistent and slowly varying boundary variable that is usually considered a good candidate for lagged analyses.

The objective of this study was to characterize the linkages between those climate signals and agricultural yields over Morocco. The following section describes the data and methods used. The linkages between wheat yields and climate signals are then assessed and potential mechanisms discussed. Finally, conclusions and perspectives are drawn.

## Data and methods

### Study region and agro-climatic conditions

Morocco is characterized by a Mediterranean climate whose main feature is the coincidence of dry and hot seasons in summer. The rainy season extends from October to April (Xoplaki 2002). Figure 1a displays the annual rainfall amount averaged from November to May (1979–2007). Meteorological data are taken from the synoptic stations of the Morocco's National Weather Center (Direction de la Météorologie Nationale, Casablanca). Data is checked for compliance by the World Meteorological Organization (WMO). The annual amount varies from less than 200 mm in the South to more than 1,000 mm in the North near Tangiers (Lamb and Pepper 1987). Morocco is under the influence of the Atlantic Ocean to the



**Fig. 1** **a** Rainfall in Morocco from November to May averaged from 1979 to 2007. **b** Location of study provinces and results of hierarchical cluster analysis (see text)

West, the Mediterranean to the North, and the Sahara desert to the South, and climate is modulated locally by a marked orography (i.e., the Atlas mountains). Annual precipitation can vary a lot from 1 year to another with a coefficient of variation ranging from 25 % along the Atlantic coast to 100 % in semi-arid areas of the center and South of the country (Knippertz et al. 2003). Winters are milder along the Atlantic coastline and colder inland and as elevation increases.

In Morocco, 85 % of arable lands are occupied by rainfed crops (Jlibene and Balaghi 2009). The growing cycle of rainfed wheat matches the rainy season from November to May, except in the foothills where it can last until July. Seeding may occur after the first significant rainfalls between November and mid-January. Wheat growth extends until the green leaf area index (LAI) peak between mid-March and mid-April, after which grain filling and leaf senescence occur. Harvest usually takes place between mid-May and mid-June. Official yields statistics are supplied by the Direction of Strategy and Statistics (DSS) of the Ministry for Agriculture and Fishing. Data used in this study comprise total yields of common wheat at the farming province level from the growing seasons 1982–1983 to 2007–2008. Please note that the growing season extending from autumn of year  $y-1$  to spring of year  $y$  will be named the growing season of year  $y$ . Cereal areas are sampled by the DSS based on area frame sampling (AFS) methodology. This methodology has been used by the DSS since 1980 and is considered satisfactory for major crops. The Moroccan AFS accounts for 3,000 segments (SSU) and covers 19 million ha. Data is collected

starting from sample surveys at the province level, then given as provincial averages. Yields are expressed in quintals (100 kg) per hectare ( $qt\ ha^{-1}$ ). Only provinces producing more than 2 % of national yields on average over the period of study are taken into account here. The 11 selected provinces (Table 1, Fig. 1b) account for 79.3 % of total Moroccan production of common wheat grain yields. The selected provinces are located mostly along the Atlantic region, as defined in Knippertz et al. (2003), and characterized by favorable rainfall conditions for agriculture, with annual precipitation ranging from 275 to 398 mm per year, apart from the El Kelaa province (185 mm/year). There is one synoptic station for each agricultural province (Fig. 1b), except for Khmisset where the Kenitra station is used. Monthly precipitation and 10-day air temperature were computed from the raw daily time step data.

Normalized difference vegetation index data and pre-processing

The use of the normalized difference vegetation index (NDVI; Tucker 1979) to characterize the dynamics of vegetated surfaces relies on the contrasting spectral response of vegetative tissues between the strong absorption of chlorophyll in the red band and the strong reflection of leaves in the infra-red. NDVI values increase with the density and greenness of the vegetation. Typical NDVI values lie between 0.1 for bare soil and 0.9 for all-covering green vegetation. NDVI is commonly used to monitor vegetation development.

**Table 1** Soft wheat yields and rainfall statistics by province

Province	Contribution to national production of common wheat (%)	Average yields (qt ha <sup>-1</sup> )	Coefficient of variation in average yields [SD/mean (%)]	Trends of average yields (kg ha <sup>-1</sup> year <sup>-1</sup> )	Rain sum during growing period (mm year <sup>-1</sup> )	Coefficient of variation of rain sum (%)	Trend of rain sum (mm year <sup>-1</sup> )	Rain use efficiency (kg ha <sup>-1</sup> mm <sup>-1</sup> )
Kenitra	21.4	19.50	39.3	3	352	36.3	1.23	5.5
Beni Mellal	11.8	17.30	34.5	20	295	31.6	0.37	5.9
Khmisset <sup>a</sup>	8.2	13.10	45.6	3	352	36.3	1.23	3.7
Meknes	6.7	18.40	42.0	-9	398	28.5	-2.68	4.6
Settat	6.3	10.90	67.5	1	282	42.0	2.27	3.9
Taounat	5.1	13.40	52.9	-7	373	31.8	2.13	3.6
El Kelaa	4.7	8.00	55.4	3	185	38.6	-0.71	4.3
El Jadida	4.5	15.10	33.2	8	370	40.7	-0.79	4.1
Fes	4.5	14.30	65.9	12	373	44.0	2.36	3.8
Ben Slimane	3.4	15.60	54.7	2	275	39.2	0.09	5.7
Safi	2.75	6.19	65.9	12	358	44.03	2.36	1.7

<sup>a</sup> The synoptic station of Kenitra was used

The NDVI sum during the growing season, in particular, exhibits good correlation with above-ground biomass for annual herbaceous grasses of the Sahel (Prince 1991; Lo seen et al. 1995) and with agricultural yields in several areas of the world (Mkhabela et al. 2005; Becker-Reshef et al. 2010) including Morocco (Balaghi et al. 2008). Data used in this study is gathered by the series of AVHRR sensors on board NOAA satellites (NOAA-7, -9,-11,-14,-16 and -17). Data processed by the GIMMS (Global Inventory Modelling and Mapping Studies) are known as NDVI-g version 4 and are dispatched by the ADDS (Africa Data Dissemination System; <http://earlywarning.usgs.gov/adds/>). This data covers the period from January 1982 to December 2008 with a spatial resolution of 8 km. Images are corrected for stratospheric aerosols, in particular the El Chichon (1984) and Pinatubo (1991) eruptions, and are intercalibrated with observations of the VEGETATION sensor. No atmospheric correction (ozone and water vapor) is applied. The NDVI daily values are synthesized for each 10-day period according to a maximum value composite (MVC) approach. Processing details are described in Tucker et al. (2005). Several recent studies have shown the quality of these corrections by minimizing intra-sensors drifts and inter-sensor jumps (Kaufmann et al. 2000; Slayback et al. 2003).

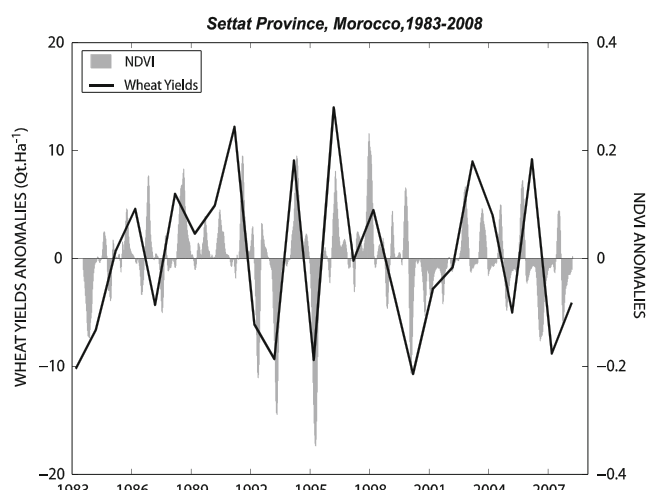
In order to focus on interannual variability, raw NDVI data are de-seasonalized (i.e., transformed in 10-days anomalies with regards to the average of the annual cycle over the study period). A linear trend is then removed in order to avoid bias in the correlation analysis. Finally, a NDVI time series is extracted for each province through a spatial average. As an example, Fig. 2 displays the time series of averaged NDVI anomalies and yields anomalies for Settat Province. There is a close match between both variables, with below normal yield production associated

with below average NDVI in 1983, 1992, 1993, 1995, 2000 and 2007. Likewise, above average NDVI of years 1988–1991, 1994 and 1996 are correlated to above normal yields.

#### Atmospheric and oceanic variables

Climate indices likely to impact Moroccan climate were first identified:

- The “Northern Hemisphere Teleconnection Patterns” (NHTP; Barnston and Livezey 1987) provide several indices summarizing the Northern Hemisphere extratropics



**Fig. 2** Spatially averaged 10-day normalized difference vegetation index (NDVI) time series over Settat Province after removing linear trends and the annual cycle. Wheat yields anomalies are superimposed for comparison purposes

circulation patterns. Their impact on local climate (temperature and rainfall) has also been investigated (Hurrell and Van Loon 1997). NHTP indices are provided by the Climate Prediction Center (CPC; URL://<http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml>). Only NHTP affecting the Southern Europe/Northern Africa climate were kept. NAO is characterized by a dipole of pressure with a trough above Iceland and an anticyclone above the Azores. Its impacts are much greater in winter than in summer (cf. Marschall et al. 2001). The Scandinavia pattern (SCA) consists of a primary circulation center over Scandinavia, with weaker centers of opposite sign over Western Europe and Eastern Russia/Western Mongolia. The impact of SCA on precipitation and temperature has been studied by Wibig (1999). The enhanced southern flow related to the positive phase of the SCA pattern was found to increase precipitation over southern Europe, and possibly Northern Africa.

- The observed persistence of a NAO positive phase during recent decades (except for the last two winters) could have been stimulated by a rise of the tropical Atlantic temperature (Cassou and Terray 2001). Indices representing signatures of SST variability in the tropical Atlantic are kept: “Tropical North Atlantic” (TNA; 15°W–57.5°W and 5.5°N–23.5°N) and “Tropical South Atlantic” (TSA; 10°E–30°W and 0°–20°S) derived from Rajagopalan et al. (1998). In order to complete the analysis, the “NIÑO3” index (150°W–90°W and 3°S–3°N, from OGP/NOAA) was considered as a proxy for the ENSO phenomenon, which is known to impact climate in many parts of the world (Trenberth et al. 1998). All SST indices were from the Earth System Research Laboratory <http://www.esrl.noaa.gov/psd/data/climateindices/>.

Finally, as climate index aims to summarize a complex pseudo-oscillatory climatic phenomenon into a simple time series (Stenseth et al. 2002), the following spatio-temporal climatic fields were used to further analyze wheat yield variability:

- It is well known that, owing to the high thermal inertia of water, the anomalous SST is a good candidate for lagged analysis (Barnston 1994). Global SST data come from Reynolds et al. (2002), provided by NOAA weekly on a 1° grid-point.
- Global 500 hPa geopotentials are used as proxy for regional atmospheric circulation. This data set is from the National Center for Environmental Prediction (NCEP) re-analyses, available on a 2.5° horizontal scale resolution from 1948 to the present (Kalnay et al. 1996). Xoplaki et al. (2004) showed that the most valuable atmospheric information for winter precipitation variability over the Mediterranean area was contained in a window spanning from 90°W to 90°E and 10°N to 80°N. The same window was used here.

The raw monthly values of SST and geopotentials were also detrended and de-seasonalized.

#### Data processing methods

Yields and climate data sets were submitted to classical data analysis tools. Significance of yields and precipitation trends were tested using the non-seasonal Mann-Kendall test based on the Kendall’s rank correlation (Hirsch et al. 1982). The Mann-Kendall test is a non parametric test to identify monotonic trends in time series. More details can be found in Hipel and McLeod (1994). Yields time series were grouped using cluster analysis. A hierarchical clustering with weighted pair-wise average based on correlative distance (i.e.,  $\sqrt{\frac{1-r}{2}}$  with  $r$ , the correlation coefficient between two time series) was used (Kaufmann and Rousseeuw 2005). The correlative distance is preferred to more classical absolute distance criteria here as we aim to identify time series exhibiting similar interannual variability patterns. Finally, the key modes of variability of the SST fields were identified with an empirical orthogonal function analysis (EOF; Preisendorfer and Mobley 1988).

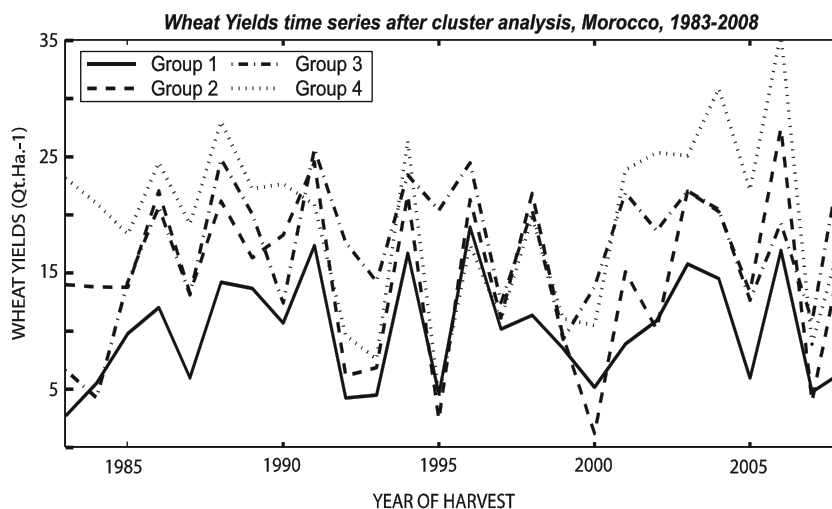
#### Results

First, yields time series were analyzed together with rainfall amount in terms of variability, trends and rain use efficiency (RUE; i.e., weight of grain  $\text{ha}^{-1} \text{mm rain}^{-1}$ ). Afterwards, the lagged correlation between yields and local (temperature, precipitation and NDVI) and large-scale climate information was investigated.

#### Classification of yields time series

The 11 yields time series were grouped initially using cluster analysis. From the dendrogram obtained, four groups were kept. The first group (El Jadida, El Kelaa, Safi and Settati) gathers the southern provinces whereas the second group (Ben Slimane, Fes-Saïs, Khmisset, Meknes, Taounat) is located in the northern part of the study region. Finally, groups 3 and 4 represent the last two provinces, Beni Mellal and Kenitra, respectively. Kenitra is dominated by irrigated agriculture and Beni Mellal is characterized by a marked orography, which may explain the different interannual patterns from the two first groups. Grouping is mapped in Fig. 1b and yields time series, averaged for each group, are displayed in Fig. 3. The time series show a strong interannual variability, and the strong droughts of 1992, 1993, 1995, 2000 and 2007 already reported by Jlibene and Balaghi (2009) appear clearly in Fig. 3. In addition, the southern provinces are characterized by lower annual rainfall (Fig. 1a) and associated lower yields

**Fig. 3** Wheat yields time series after hierarchical cluster analysis (see text) from 1983 to 2008. The raw yields time series are averaged over each group. Group 1: El Jadida, El Kelaa, Safi and Settat; group 2: Ben Slimane, Fes-Saïs, Khmisset, Meknes and Taounat; groups 3 and 4 are composed of Beni Mellal and Kenitra provinces, respectively



than Northern provinces of group 2. The lagged correlation analysis between yields and climate information carried out below was performed on these averaged yield time series.

#### Spatio-temporal variability of wheat yields time series

Table 1 displays average yields per hectare and average rainfall amount from October to April, together with coefficients of variability (standard deviation divided by the mean in percent) and linear rainfall and yields trends. All values were computed over the period of study (1982–2008). October–April rainfall amount represents about 85 % of the annual amount on average for the 11 selected provinces. Table 1 shows that:

- Wheat yield values are low compared to potential yields, which could reach 75 to 80 qt ha<sup>-1</sup> (Bouaziz 1999; Jlibene 2011). Apart from water stress and poor soils, the explanation lies in the traditional agricultural practices leading to inappropriate crop rotation, insufficient nitrogen fertilization, poor weed control, late sowing (Ryan et al. 2009; Bouaziz 1999). In addition, the use of modern techniques such as water harvesting, fallow management and the use of improved varieties are very limited in the region (Oweis and Hachum 2003).
- The relation between yield and rainfall amount during the growing period is poor ( $r^2=0.15$ ) though it is widely acknowledged that water is the major constraint affecting crop production under a Mediterranean climate (Zhang and Oweis 1999). Nevertheless, point-scale rainfall observations may suffer from insufficient spatial representation. In particular, Beni Mellal province is a mountainous area where spatial variability of rainfall is large. In addition, as no synoptic station is available for Khmisset province, the one in Kenitra, used within this

study, may also not be representative of local rainfall conditions. Finally, Safi province is characterized by shallow and pebbly soil (consisting of clay, flint and sand) with a poor nutrient content leading to low yields, whereas rainfall amount reaches 358 mm on average from October to April. Discarding these three provinces leads to a higher correlation coefficient of  $r^2=0.55$  (significant at the 97 % level). In addition, rainfall timing during sensitive wheat development stages, rather than the total amount, should be taken into account.

- Wheat yields trends have been slightly positive over the last 25 years except for the Taounat and Meknes provinces and only the decreasing trend of the Meknes yield is supported by a drop in rainfall. Nevertheless, neither rainfall nor yields trends for all provinces pass the Mann-Kendall test at 90 %. The positive trends of wheat yields all over the world during the second half of the twentieth century has been widely documented (Anderson et al. 2005; Lobell et al. 2005), and has been attributed to the adoption of improved genotypes, better crop management and a higher level of inputs. In Mediterranean countries, the slight (but not significant) increase observed is corroborated by the findings of Latiri et al. (2010) for Tunisia and Balaghi et al. (2008) for Morocco, also highlighting a slowing down of the trend from the mid-1980s onwards; this period being dominated by high interannual variability. Indeed, the mean variation coefficients (1983–2008) for the 11 selected provinces are 51 % and 37 % for yields and rainfall, respectively.
- RUE values range from 1.7 kg ha<sup>-1</sup> mm<sup>-1</sup> for the Safi province because of poor soils to 5.9 kg ha<sup>-1</sup> mm<sup>-1</sup> for Beni Mellal province. Values are similar to what has been reported in the literature (Latiri et al. 2010 for Tunisia). These low values illustrate that cumulative rainfall is not

the major explanatory factor: drought periods that occur frequently can cause damage at crucial phenological stages (tillering, pollination and grain filling). In addition, runoff water in case of violent storms limits water use by the plant and could lead to high nitrogen leaching. Finally, traditional practices used in the Mediterranean region—as outlined above—also result in low RUE values.

#### Correlation with local environmental conditions

Figure 4a–d shows the lagged correlation from November to April between the local climate information (10-day air temperature and NDVI and monthly precipitation) and yield time series for provinces group 1, 2, 3 and 4, respectively. Figure 4a and b reveals that major water stress during two periods of the year resulted in lower yields than normal for groups 1 and 2, which account for 9 out of 11 provinces. The first period corresponds to the early stages of wheat growth in November during which germination, emergence and/or tillering may occur, depending on the sowing date. Drought in the early stages of wheat growth induces tiller losses. Based on an experimental study carried out on spring wheat in Morocco, El Hafid et al. (1998) demonstrated that even if more favorable conditions follow an early drought, stressed wheat does not yield as much as early-developing tillers. The linkages between autumn precipitation and grain yields could also be related to the date of sowing. In this region, the latter depends on the timing of the first rainfall (between November and mid-January). Early sowing has been found to have a positive impact on final production for Mediterranean areas (Photiades and Hadjichristodoulou 1984) by extending the tillering period and avoiding the coincidence of the pollination and grain filling stages with a water deficit as shown by Heng et al. (2007) from a modelling study carried out for Morocco and Jordan.

The second period is when the crop is in the grain filling phase for early sowing or in the pollinating phase for late sowing (Karrou 2003; Hadria 2006). The highlighted connection between winter precipitation and grain yield (for 10 of 11 provinces; Fig. 4a–c) has also been well documented for Mediterranean climate areas (Oweis et al. 1992; Latiri et al. 2010) and has been attributed to the decline of carbon assimilation and the grain hampering caused by water stress during the grain filling phase (Johnson and Moss 1976). Notably, Austin et al. (1998) have shown correlations of above 0.3 between yields and rainfall in the Ebro valley (Spain) for the same period.

Temperature anomalies impact grain yield also during two periods of the wheat growth cycle (Fig. 4a,b; 9 out of 11 provinces). A positive correlation was found during the early stage of wheat growth in December and a negative correlation

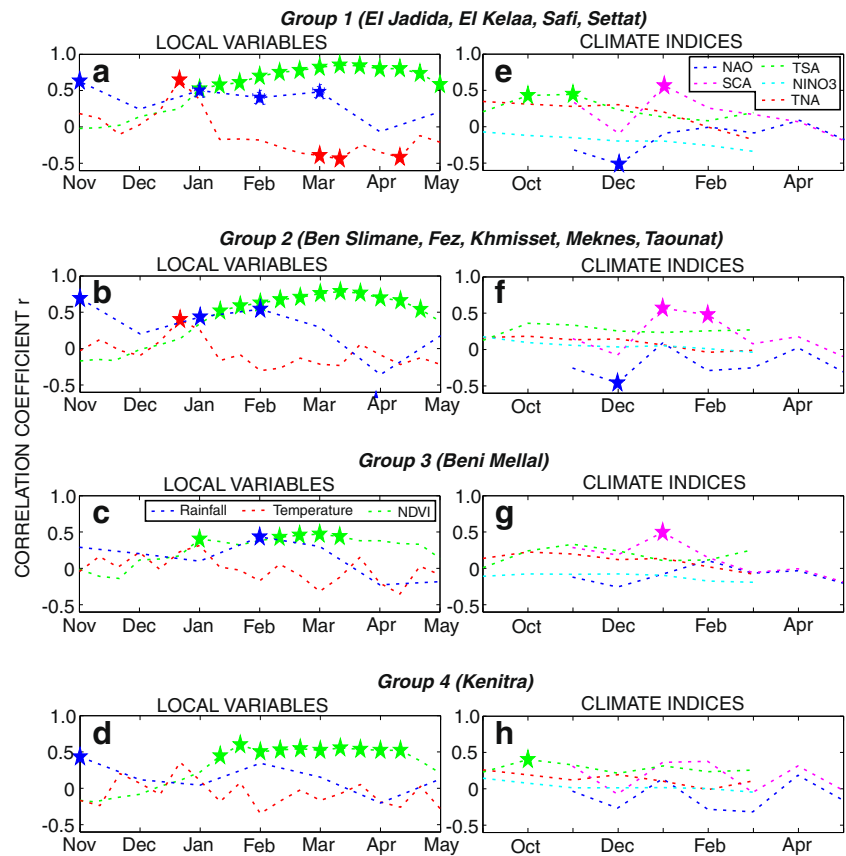
at the end of the cycle in March for provinces of group 1 (Fig. 4a). The latter corresponds to the high temperatures (longer day) generally encountered during the grain-filling stage in early spring; water stress may even worsen the effect of high temperatures, and grain yields suffer from a final water deficit (Heng et al. 2007) when the high evaporative demands cannot be met. Wheat grown to the South of the region, where provinces of group 1 are located, may suffer more from higher temperatures than wheat in more northern parts. Germination and emergence or tillering generally occur during the month of December. Negative temperature anomalies cause poor emergence (Timmermans et al. 2007). Temperature is also known to play an important role in tillering, with low temperatures at this time ( $<10$  °C) affecting tillering by reducing the number of ears and leading to lower yield (Farooq et al. 2005). Likewise, milder temperatures in late autumn and early winter (December, January) have also been found to stimulate plant development, which results generally in a quicker switch from the vegetative to the reproductive stages, and so to a potentially shortened plant organ cycle (Benaouda and Balaghi 2009).

Finally, NDVI anomalies were correlated significantly to yields during all the development phases until senescence from January to April (Fig. 4a, b, d) except in Beni Mellal Province. The perturbed lagged correlation curve for this latter region may be attributed to noisy satellite acquisitions due to orography and associated angle effects. Duchemin et al. (2006) found a strong correlation between LAI and NDVI during a field experiment carried out on irrigated wheat in the central region of Morocco (the Haouz plain near Marrakech). The positive correlation between NDVI and grain yields encountered here is related to the fact that a high leaf area and the associated tiller numbers, together with a fast leaf area development (from tillering to flowering) results in greater biomass production and high vegetation cover. By limiting water loss because of soil evaporation, high vegetation cover is well known to be a key factor for good grain yields in low rainfall environments (Cooper et al. 1987; Van Oosterom and Acevedo 1992; El Hafid et al. 1998).

#### Correlation with large-scale climate

Figure 4 (right) shows the lagged correlation coefficient between the NAO, SCA, TNA, TSA and NIÑO3 indices and wheat yields for each group of provinces. The NAO and SCA reflect atmospheric circulation, which may have a concomitant impact on local temperature and precipitation (Barnston and Livezey 1987; Wibig 1999), whereas NIÑO3, TNA and TSA apply to SST that may be related to local climate with a certain delay through teleconnections. Lagged correlation analysis is thus carried out from November to May for atmospheric indices and from September to March for SST indices.

**Fig. 4** Lagged correlation between average yields and local variables and climate indices by group of provinces obtained from a hierarchical cluster analysis (see text) from 1982 to 2008: *left column* lagged correlation with local variables (10-day NDVI, 10-day temperature and monthly precipitation) for groups 1 (a), 2 (b), 3 (c) and 4 (d); *right column* same figures with climate indices (NAO, SCA, TNA, TSA and NiNO3)



#### Northern hemispheric teleconnection patterns and 500 hPa geopotentials

Only the December NAO value was correlated negatively to wheat yields for the two first groups (Fig. 4e, f), probably through the influence of water and temperature stress at the early stage of the wheat cycle (tillering) as discussed above. In Morocco, Knippertz et al. (2003) studied the long-term variability of precipitation and stressed the strong influence of the NAO over the West coast of the country where the most productive agricultural provinces studied here are located. Lamb et al. (1997) demonstrated that NAO control on Moroccan precipitation decreases strongly from January onwards, which could also explain the absence of significant correlation with yields, except for the beginning of the growing season. In addition to precipitation control, Wang et al. (2005) found a strong impact of NAO on winter temperature; the positive phase of NAO being associated with cold conditions over Northwestern Africa, including Morocco. This below-normal temperature, associated to the positive phase of NAO, could enhance the already observed negative effects of the positive NAO by slowing down wheat crop development during the early stage of plant growth, and thus finally impacting yields.

The connection between yields and the SCA index is also related to the time patterns of the precipitation–yield correlation. The positive phase of SCA is associated with above-average precipitation over Southern Europe and North Africa. Figure 4e–g illustrates the high impact of water stress on grain yields during the first stages of wheat development for 10 out of 11 provinces. The temperature impact cannot be referred to for SCA as its positive phase is associated mainly with below normal temperatures over Northern Africa, and should lead to negative effects.

Figures 5e, f shows lagged correlation (significant at the 95 % level) maps between yields and the monthly average of 500 hPa geopotential for the four groups of provinces from November to February. Although the exact location of minimum and maximum iso-correlation may vary among groups, the spatial patterns obviously remain quite similar since the agricultural provinces analyzed here are located within the same climatic region of Morocco as defined by Knippertz et al. (2003). In November and December, mostly two homogeneous persistent patterns of correlation can be distinguished for group 1, 2 and, to a lesser extent, 4: a distinct maximum of positive correlation extending from Greenland to Scandinavia centred above Iceland, and a Southern negative correlation stretching from Southern Europe towards the West, above the Atlantic Ocean. The



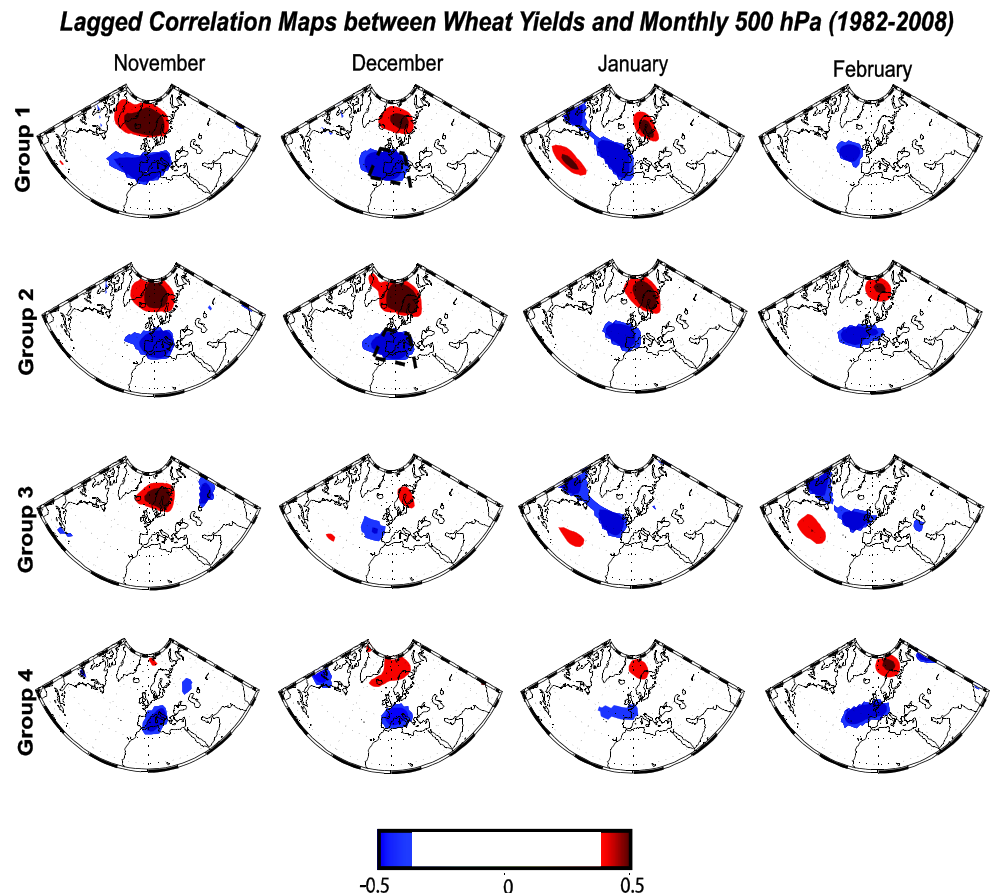
northern pattern of positive correlation illustrates that a deepening of the Iceland trough (i.e., a global decrease in 500 hPa geopotentials), distinctive of the positive phase of the NAO, is associated with lower wheat yields in Northern Africa through the induced decrease in rainfall already shown by Lamb and Pepper (1987). Conversely, the Southern pattern exhibits negative correlations as a reinforcement of the Azores anticyclone (i.e., a global increase in 500 hPa geopotentials), also typical of the NAO positive phase, is likely to cause low wheat yields in these regions. This confirms the significant correlation between wheat yields and the NAO index, underpinning the dependence of wheat production on the entire North Atlantic storm tracks during autumn, for most of these provinces located along the Atlantic coast. The main discrepancies between the groups are related to the position and extension of the southern poles. For groups 1 and 2, in particular, the latter is located inland above southern Europe and Northern Africa. 500 hPa geopotential anomalies in December averaged over the windows displayed by dotted lines on Fig. 5 correlates at  $r=-0.66$  and  $-0.61$ , with yields time series of groups 1 and 2, respectively. In January, the dipole etiolates and toggles to the east for group 1 and, to a lesser extent, for group 2, confirming the decreasing impact of NAO on Moroccan climate after January (Lamb and Pepper 1987). Interestingly, the dipole even moves to a tripole for

group 1 at this time of the year. By relaxing the significance level of correlation to 90 %, the tripole is also present on group 3 (not shown). This tripole pattern is very close to the SCA in line with the correlation found between yields and the SCA index at this period of the year (Fig. 4). Patterns are more scattered for Beni Mellal and Kenitra provinces (groups 3 and 4) because of marked orography that may disrupt the large scale flow originating from the Atlantic as already underlined for Beni Mellal and water supplies by irrigation for Kenitra, which mitigates the impact of climate on yields. As a conclusion, these maps not only confirm the linkages with the dominant mode of atmospheric variability (i.e., NAO and SCA) already highlighted but also show the linkages of yields with regional atmospheric variability through the different locations of the Southern poles.

#### Sea surface temperature

No linkages were found with the TNA or with the Niño3 indices (Fig. 4e–h). By contrast, the positive correlation found with the TSA index in October and November for group 1 highlights that a warming in the tropical South Atlantic may be favorable for wheat yields in Morocco (Fig. 4e, h). The same approach as for Fig. 5 was applied to show the lagged correlation maps between wheat yields and monthly SST for the four groups

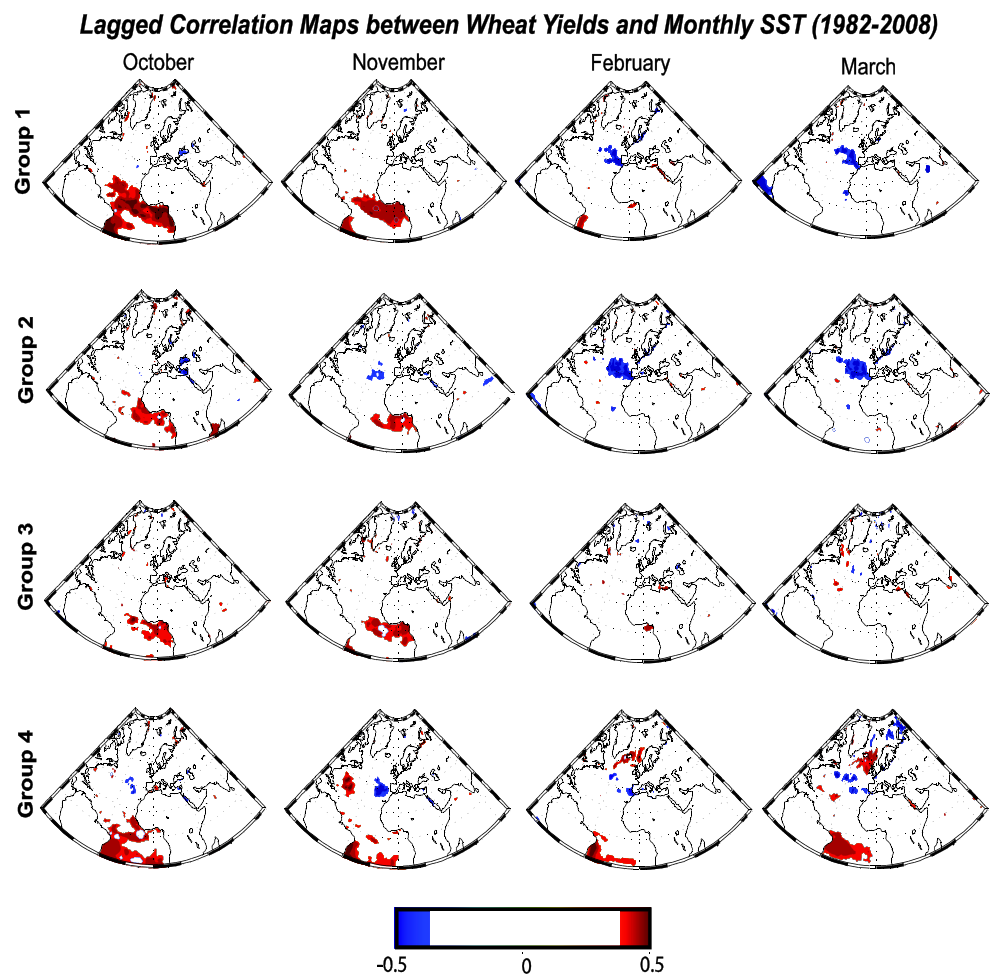
**Fig. 5** Lagged correlation maps from November to March between monthly geopotential at 500 hPa and yields average for the four groups during the period 1982–2008. Only significant correlation values at the 95 % level are displayed



(Fig. 6). Patterns of correlation appear more scattered than the one obtained with 500 hPa geopotentials. Nevertheless, two spatial patterns of correlation can be distinguished:

- An area of positive correlation located in the equatorial and the tropical Southern Atlantic along the Western African Coastline in October and November. This pattern appears clearly for groups 1 and 2 but is also present for group 3 and, to a lesser extent, for group 4. Interestingly, the pattern for the Southern provinces (group 1) is particularly prominent regarding the three other groups, corroborating the correlation with the TSA index. This area corresponds roughly to the foothills of the Atlas. In these areas, Knippertz et al. (2003) demonstrated that the influence of the tropical-extratropical interactions on the generation of early autumn rainfall, during which moisture source originates from the tropics, is strong and decreases when moving northward along the much wetter Atlantic coast. This may also explain the presence of a well-marked pattern for the Beni Mellal province—also situated on the foothills of the Atlas—and a quasi-absence of positive correlation in the equatorial Atlantic for Kenitra.
- An area of negative correlation later in the season in January and February for group 2 and, to a lesser extent, groups 1 and 4. This pattern covers the neighboring ocean and extends to the North along the Iberian coastline. This pattern may be related to the leading mode of interannual variability of the North Atlantic SST, which is also well documented (Cayan 1992), showing a tripole with warm anomalies off the east coast of the United States and cold anomalies north of 40°N and south of 25°N. For group 2, by relaxing the correlation significance to 90 %, the warm anomalies of the east coast of the United States are still hardly found, whereas the negative anomalies south of 20°N appear through a pattern of negative correlation (not shown) along the tropical Western Africa coastline. Li (2003) investigated the role of this tripole on the Northwestern Africa rainfall and found that a positive tripole (enhanced negative SST anomalies north of 40°N and south of 25°N) is associated with reduced rainfall over this region, which is in agreement with the sign of the correlation found here. The more scattered patterns obtained for the other groups are

**Fig. 6** Lagged correlation maps from November to March between monthly sea surface temperature (SST) and yields average for the four groups during the period 1982–2008. Only significant correlation values at the 95 % level are displayed



certainly to be related to the influence of the Atlas Mountains.

In order to confirm these assumptions, the yield time series have been correlated to the leading EOF mode of SST anomalies variability in the North and equatorial Atlantic (Fig. 7): the “North Atlantic tripole” (Cayan 1992) mode and the Tropical South Atlantic mode also called “Atlantic Niño” (Houghton and Tourre 1992). Both modes have been described extensively in the past. The North Atlantic tripole results from anomalous surface winds and air temperature associated to NAO phases during winter creating a horseshoe-like pattern of SST through latent and sensible heat fluxes anomalies (Czaja and Frankignoul 2002). The “Atlantic Niño” consists in Atlantic warm events (Houghton and Tourre 1992), which resembles the Pacific El Niño phenomenon. Note that the associated time coefficient is highly correlated to the TSA index during the period of study ( $r=0.90$ ). In agreement with the correlation map (Fig. 6), groups 2 and 4 are significantly correlated at the 97 % level with the time coefficients of the Atlantic Tripole modes in February at  $r=-0.44$  and  $-0.43$ , respectively. Similarly, the yield time series of groups 1, 2 and 4 are correlated with the Atlantic Niño time coefficients in October at  $r=0.62$  (99 % level),  $0.52$  (99 % level) and  $0.49$  (98 % level), respectively.

## Discussion and conclusions

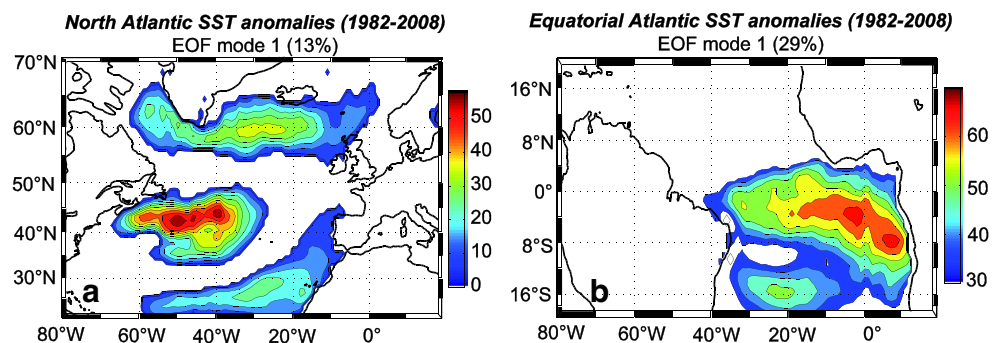
In Morocco, common wheat production exhibits high inter-annual variability. The aim of this study was to analyze the local and regional climate factors governing this variability. To this objective, we analyzed de-trended (1) time series of wheat yields (1983–2008) from 11 agricultural provinces accounting for 80 % of national wheat production; (2) monthly rainfall and 10-day temperature from nine meteorological stations; (3) 10-day NDVI from the AVHRR Sensor; (4) monthly atmospheric climate indices (NAO and TSA) and monthly 500 hPa geopotentials fields; and (5) monthly SST fields and indices (NIÑO3, TNA and TSA).

Correlation between grain yields and temperature/precipitation anomalies were highlighted for most of the provinces during the early stage of wheat development. Vegetation index was also related to yields from January onwards, with a maximum correlation between mid-March and the end of March. These relationships, already observed at plot level by other authors, were also found significant at province level in this study. The NAO in the early phase of the growing season in December has also been found to be significantly related to yields. This finding is in line with the well-known anomalous patterns of precipitation (Lamb and Pepper 1987; Lamb et al. 1997) and possibly temperature (Wang et al. 2005) associated to the NAO phases. The Scandinavian Pattern (SCA)—another leading mode of atmospheric variability in the Northern hemisphere—is also related to yields, later in the season during the development phase, in January and February. The correlation with the 500 hPa geopotentials fields not only confirm the linkages with NAO and SCA, but also shows that part of yield interannual variability may be explained by regional atmospheric variability.

The SST impact on mid-latitudes climate is more controversial and still subject to an ongoing debate over whether the SST anomalies force or are induced by the atmosphere (Cayan 1992; Hurrell et al. 2003). No correlation between the NIÑO3 index and Moroccan wheat yields was found here. Previous works attempting to highlight a connection between Euro-Mediterranean precipitation and ENSO have also been rather inconclusive (Hurrell et al. 2003). A recent work by Zanchettin et al. (2008) demonstrates the influence of ENSO on Mediterranean precipitation but also shows that it depends on the phasing of the phenomenon and on the concurrent phase of the NAO, which may explain the absence of correlation encountered here.

By contrast, a significant correlation between yields and the leading mode of SST variability in the Northern Hemisphere (so-called “Atlantic tripole”) in February is found for the Northern provinces of the study area. This winter tripole has been found to respond to atmospheric forcing through latent and sensible heat fluxes (Kushnir 1994) but some studies demonstrated that the tripole induces a NAO-

**Fig. 7a,b** Leading empirical orthogonal function (EOF) modes of monthly SST anomalies for the period 1982–2008. **a** North Atlantic (20–70°N/–80/20°E), **b** Equatorial Atlantic (–20–20°N/–80/20°E)



like atmospheric response (Rodwell et al. 1999), possibly through re-emergence processes (Cassou et al. 2007). In addition, interesting correlation patterns with higher lead time are highlighted with SST fields in the equatorial and tropical Atlantic in October. It was also shown that this pattern could be related to the leading mode of SST variability in this region: the so-called “Atlantic Niño” mode. The winter climate in the Mediterranean basin is dominated by the alternation of extra-tropical weather regimes and subsidence of tropical dry air through the descending branch of the Hadley cell (Bolle 2002). Knippertz et al. (2002) demonstrate that tropical West Africa and the adjacent tropical Atlantic are potential sources of moisture for Morocco. This remote impact of tropical Atlantic could be explained by perturbation of the Hadley cell and the associated perturbation of the intensity and location of the jet stream at mid-latitude (Cassou and Terray 2001). Czaja and Frankignoul (2002) and Cassou et al. (2004) have further demonstrated that a warming (cooling) tropical Atlantic during late summer/early autumn (JJAS) leads preferably to NAO negative (positive) phase situations. Rodriguez-Fonseca et al. (2006) even developed with some success empirical models for precipitation prediction over North West Africa with up to 5 months lead time. The strong pattern of positive correlation between yields of the Southern provinces and the SST in the equatorial Atlantic early in the season (October–November) shows that higher yields may be associated to a warming equatorial Atlantic, probably thanks to enhanced rainfall in Morocco during the early phase of wheat development, caused by the predominance of NAO negative phases at this time associated to this warming.

In conclusion, the enhanced sensitivity of yields to temperature and water stress at particular growth stages early in the season has been demonstrated at the province level. The well-known complex and competing influence on the Moroccan climate of the leading modes of oceanic and atmospheric variability is also highlighted for the first time, through the assessment of linkages between local and large-scale climate variables, on the one hand, and wheat yields, on the other. Regarding the overall scarcity of the meteorological network in semi-arid areas, large-scale climate signals, in particular, could be a valuable alternative to more classical predictors such as temperature and rainfall to improve the lead time of existing wheat yields forecasting systems at the seasonal scale. Within this context, our current work deals with the development of empirical models for seasonal yields forecasting at the scale of the agricultural province in Morocco.

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