JP2.6 CLIMATE ANALYSIS AND PREDICTION OVER THE ARNO RIVER BASIN, ITALY

Francesco Meneguzzo[1]*, Giovanni Menduni[2], Giampiero Maracchi[1], Marina Baldi[1], Giada Brandani[3], Alfonso Crisci[1], Francesca Marrese[3], Massimiliano Pasqui[1], and Francesco Piani[1]

[1]Institute of Biometeorology - National Research Council (IBIMET-CNR), Firenze, Italy
[2]Arno River Basin Authority, Firenze, Italy
[3]Applied Meteorology Foundation, Firenze, Italy

1. INTRODUCTION

The long term management and planning of a catchment require the accurate knowledge of heavy rainfall and drought regimes for flood protection and water resource conservation, which are driven by the climatic variability and trends; the same applies to the planning of agricultural practices (irrigation, crop types and yields), civil and industrial water supply and so on.

The climate system is forced by natural factors (solar energy output, volcanic ash and aerosols, internal dynamics and feedbacks) and anthropogenic forcings (emission of greenhouse gases and aerosols, land use changes), as stated for instance in the Third Assessment Report (TAR) of the IPCC (Houghton et al., 2001). While there is general agreement at least on the sign (positive) of the thermal response of the climate system, the surface and the atmosphere, to the current anthropogenic forcings, yet with large uncertainties concerning the warming rate (e.g. Houghton et al., 2001), the chance of abrupt warming resulting from temporary heat storage in large natural reservoirs, especially the deep oceans (Pielke, 2003), the effects of the land use, vegetation and carbon cycle feedbacks (Jones et al., 2003; Rial et al., 2003) and of the water vapor feedbacks (Del Genio, 2002), much uncertainty is left even on sign of the changes in the intensity of the hydrological cycles in the warming climate. Yang et al. (2003), in a recent very interesting work, demonstrated that the average global annual precipitation change is almost linearly dependent upon surface warming, and that in case of small surface warming, connected to small sea surface temperature (SST) variations, i.e. small sensitivity to CO_2 increases, the changes in precipitation are small or even negative (Fig. 2 in Yang et al., 2003). The key factor affecting this behavior is the leading mechanism maintaining equilibrium atmospheric temperature, i.e. the balance between radiative cooling and condensational heating. Yang et al. (2003) state: "for the case of a temperature perturbation initiated by a reduction in radiative cooling (e.g., due to an increase in CO2), a possible pathway for the atmosphere to adjust toward a new steady state of higher temperature is by a decrease in condensational heating and a corresponding reduction in precipitation. On the other hand, for the case of a temperature perturbation initiated by an enhancement in condensational heating, for instance, due to increased sea surface temperatures (SSTs), the atmosphere can adjust itself to a new steady state through an increase in radiative cooling. For both cases, although the new steady-state atmospheric temperature is higher, the changes in the hydrological cycle are in opposite directions".

Rial et al. (2003) show a comprehensive picture of the interrelations, nonlinearities and feedbacks in the climate system, which can lead to abrupt and sudden transitions between very different near-equilibrium states even in the absence of significant external forcings, and can anyway be triggered by such perturbations, today estimated at their maximum since several hundred thousands years.

Global surface temperature, heat content in large natural reservoirs and global hydrological cycle are not the only quantities and features affected by climate change and variability; recent evidences show significant impacts also to other natural physical and ecological systems, few of which, affecting directly the regional hydrological regimes, are shortly described in the following.

According to Chen et al. (2002), the Hadley meridional and Walker zonal overturning tropical circulations have strengthened in the 1990s, associated to stronger equatorial and monsoonal upwelling (convection patterns) and stronger downwelling (drying) in the subtropics (along with higher upward longwave fluxes). This agrees with predictions of enhanced monsoon

* *Corresponding author address:* Francesco Meneguzzo, Institute of Biometeorology, National Research Council, Via Caproni 8, I-50145 Firenze, Italy; e-mail: f.meneguzzo@ibimet.cnr.it

precipitations over some areas (e.g. over the West Africa, see Maynard et al., 2002).

Chang & Fu (2002), on the basis of the global NCEP-NCAR atmospheric and surface reanalyses (Kalnay et al., 1996; Kistler et al., 2001), showed that the northern hemisphere winter storm track intensity has increased since early 1970s, both the Pacific and the Atlantic branches, and the related work by Harnik & Chang (2003), after the comparison of the NCEP-NCAR reanalyses with unassimilated radiosonde data, confirmed this result, but limited the significant increase to North Atlantic, and showed that decadal timescale variations were most effective to decrease the correlation between the Atlantic and Pacific storm track.

Gulev et al. (2002) analyzed, among the other, the linear trends of the intensity of synoptic-scale processes in the North Atlantic at various time scales of variation (6 hours to 30 days), finding that the winter synoptic variability patterns increased from 1958 to 1998 over the northern North Atlantic and diminished over lower latitudes and the western Mediterranean, following trends in the low level atmospheric baroclinicity and the Northern Hemisphere Annular (NAM) mode or the North Atlantic Oscillation (NAO, e.g. Hurrell, 1995).

Hoerling et al. (2001) showed with great evidence, for the first time, the links between the gradual warming of the tropical oceans, mainly the Indo-Pacific area, and the North Atlantic winter climate change since 1950; their statistical and numerical analyses demonstrated that the forcing produced by the increasing SST in the global tropical oceans forced the long term increase of the phase of the winter NAO, that the extra-tropical SST don't show a relevant feedback to the NAO-like circulations, and the tropical Atlantic SST exert only a marginal impact; since the warming of the sea surface in the tropics is likely to be mainly a result of the changes in atmospheric composition, the changes of the North Atlantic climate can be considered a clear anthropogenic signal.

On the other hand, Hurrell and Folland (2002) found a significant increase in summertime sea level pressure over the north-eastern North Atlantic and a corresponding northward shift of the mean storm track (Fig. 2 of Hurrell and Folland, 2002); such variations, affecting mostly the latitude belt 45N-70N and impacting mostly central and northern Europe and the arctic latitudes of the Atlantic, could be linked to the patterns of organized atmospheric convection over the tropical Atlantic and the west Africa, mainly through an atmospheric bridge mechanism similar to that over the Pacific sector during El Niño – Southern Oscillation (ENSO): lower than normal precipitation over the Sahel is connected with higher than normal sea level pressure over the northeastern North Atlantic and central Europe.

A recent study (Gillett et al., 2003) shows evidence for anthropogenic impact on the sea level pressure trends over large portions of both hemispheres (mostly in the northern hemisphere), with large increases at low to mid-latitudes and decreases at higher latitudes, which especially agrees with the wintertime growing trend of the NAO.

Santer et al. (2003) compared the contributions of anthropogenic and natural forcings to the recent tropopause height increase, and found that the anthropogenic contribution to the ongoing warming of the troposphere and cooling of the stratosphere prevailed over natural forcing; a rising tropopause is likely to impact the chemical, dynamical and convective processes in the underlying troposphere.

2. GLOBAL AND REGIONAL VARIABILITY OF THE HYDROLOGICAL CYCLE AND MECHANISMS

2.1 Precipitation variability and trends

As a result of a variety of forcings (the anthropogenic ones likely to prevail since few decades), internal feedbacks and inherent nonlinearities, all affecting the climate system, the hydrological cycle itself undergoes significant changes in time, over a variety of time and spatial scales; Yang et al. (2003) pose the issue of the global hydrological cycle response over solid foundations.

Groisman et al. (1999) analyzed the trends of the summer daily rainfall regimes in eight countries worldwide, altogether covering about 40% of the global land mass: Canada, USA, Mexico, former Soviet Union, China, Australia, Norway and Poland. The observations show that the average monthly precipitation increased everywhere about 5% during the 20th century except in China; the frequency of rainy days didn't increase significantly, thus the average precipitation increase was due mostly to increased precipitation intensity: the heaviest rainfall events (daily rainfall exceeding area-specific thresholds) increased by about 20%, much more than the average precipitation. This increase of the intense summer precipitation is associated to a relevant increase of average tropospheric water vapor and low to mid-tropospheric temperature, thus suggesting an intensification of the hydrologic cycle, and in particular that the increase of the extreme precipitation will likely be much higher than the average seasonal precipitation.

Working over the Italian area, Brunetti et al. (2001) considered 67 sites during 46 years (1951-1996) where daily precipitation data were available, analyzing the frequency of rainy days and precipitation intensity, both at single stations and over large areas. Among the relevant results, it's worth mentioning:

- the annual number of rainy days decreases significantly, with most of contribution from winter;
- the daily average rainfall intensity increases significantly in all seasons but winter;
- in northern Italy, the increase of the precipitation intensity is mainly contributed by the extreme rainstorms, while in the south it is due to global increase of the average daily rainfall;
- the precipitation events over high thresholds show a definite increase since 1970s', the opposite of events below low thresholds, getting the highest and the lowest frequencies, respectively, since about 120 years.

The reduction of the frequency of rainy days agrees with the shifts of the atmospheric winter circulation regimes in the last 50 years, while the increase of the precipitation intensity agrees with other observational and modeling studies (e.g. Groisman et al., 1999).

In a more recent study, Brunetti et al. (2002) extended the Italian daily precipitation series to year 2000, showing that while the extreme annual or seasonal events don't show significant trends, probably due to their rarity, while the increasing trend is clear when more data are included, in particular the precipitation events over high thresholds.

Several recent studies have concerned the evaluation of the likely changes of the meteorological and climatic extremes associated with the climate change.

Palmer & Ralsanen (2002), on the basis of the integration of multiple Atmosphere-Ocean coupled General Circulation Models (AOGCMs), forced by increasing levels of CO_2 and sulphate aerosols, found that while the winter average precipitation moderately increases over central-northern Europe and decreases over southern Europe, the probability of extremely wet winters grows over most of Europe at the time of CO_2 doubling.

In another work, Christensen & Christensen (2003) showed that along with a likely decreasing trend of summer precipitation over central Europe and part of southern Europe (with significant exceptions over northern Italy and eastern Spain) during the current century, the probability of extreme events (precipitation in five consecutive days above the 99th percentile) could undergo significant increases, well over the local increase of the average seasonal precipitation.

Hegerl et al. (2003) compared the global distributions of the changes of precipitation at the time of CO_2 doubling as percentages with regard to present climate, as produced by the models CGCM1 of the Canadian Centre for Climate Modelling and Analysis (CCCma) and HadCM3 of the Hadley Centre for Climate Prediction and Research; the annual average and the wettest day of the year were taken into account. The changes resulted much higher for the wettest day of the year, and in greater agreement at the middle and higher latitudes than at the lower latitudes. The two models agreed, for example, to predict lower annual average precipitation and lower peak precipitation over the Iberian peninsula, a moderate increase of extreme events over central and northern Europe and no significant agreement over Italy.

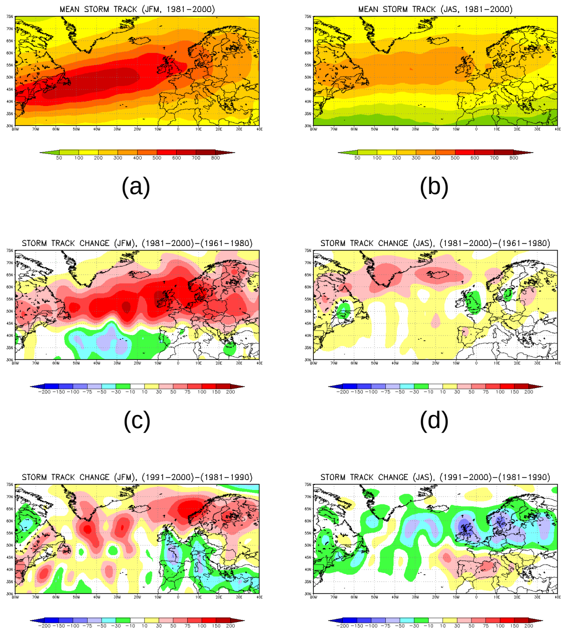
2.2 North Atlantic Storm track variability and trends

The baroclinic storms bring most of the precipitation, especially to the lower mid-latitude areas in at least fall, winter and spring (Chang & Fu, 2002), and are also significantly correlated with summer precipitation, especially at the higher mid-latitudes and high latitudes (Hurrell and Folland, 2002). They are also responsible for a significant amount of the meridional transport of heat and moisture, thus contributing to sustain the global circulation. Substantial evidence exists of a decadal intensification of the winter storm track over the North Atlantic and Europe (Harnik and Chang, 2003), confirmed also over a longer (secular) period (Chang and Fu, 2003) and preliminary evidence exists of a northward shift of the summer storm track over the North Atlantic (Hurrell and Folland, 2002).

Diagnosing the storm track strength by means of the 300-hPa meridional wind variance, computed using a 24-h difference filter (Wallace et al., 1988; Chang & Fu, 2002; Harnik & Chang, 2003), and using the NCEP-NCAR reanalysis data (Kalnay et al., 1996; Kistler et al., 2001), we have computed the average and differences of this field over North Atlantic, Europe and Mediterranean in recent periods. Fig. 1 shows the averages in the period 1981-2000 and the changes of the winter and summer storm tracks in recent decades (1981-2000 vs. 1961-1980 and 1991-2000 vs. 1981-1990).

The intensification and northward shift of the winter storm track is apparent and relevant in the longer period mostly over the North Atlantic, and in the last 20 years mostly over Europe, consistently with the observed north-eastward shift of the centers of action of the North Atlantic Oscillation along with the prevalence of its positive mode (Hurrell et al., 2003).

The summer storm track is far weaker than its winter counterpart, consistently with the reduced meridional baroclinic instability; it shows an intensification at very high latitudes (60-70N) in the last 40 years, and a significant reduction at the high mid-latitudes (50-65N) in the last 10 years, when a moderate increase appeared farther south, around 35-45N and east of 20W, whose origin is still unknown. The evolution of the storm track strength at high latitudes should be linked to a northward shift of the baroclinic instability.



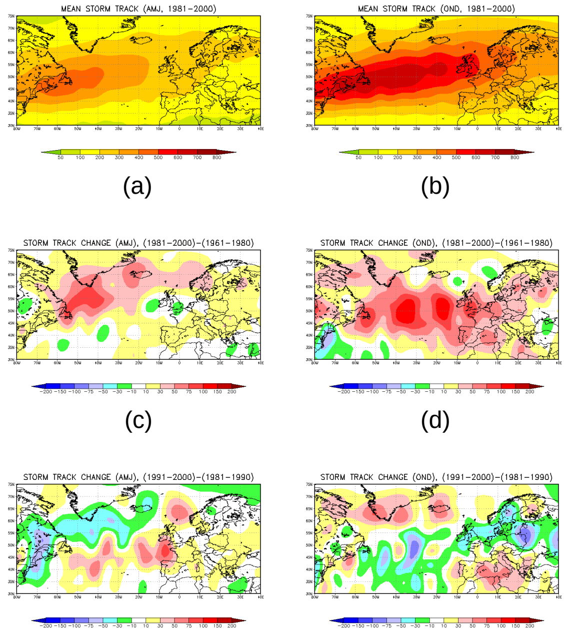
(a) (b) (c) (d) (e) (f)

Fig. 1. Storm tracks over the North Atlantic and Europe (units m^2/s^2): average in 1981-2000, in winter (a) and summer (b); difference in 1981-2000 vs. 1961-1980 in winter (c) and summer (d); difference in 1991-2000 vs. 1981-1990 in winter (e) and summer (f)

Fig. 2 shows the averages in the period 1981-2000 and the changes of the storm tracks in the transition seasons, spring and fall, in recent decades (1981-2000 vs. 1961-1980 and 1991-2000 vs. 1981-1990).

In spring, the long term intensification at very high latitudes was partially offset by the weakening in the most recent decade, when storms moderately intensified at lower latitudes; in fall, the relevant long term intensification at mid-latitudes (roughly 35-60N) has partially reduced in the last decade, while it continued over the western Mediterranean.

The links between the variability of the storm tracks and the simultaneous variability of the precipitation over the Arno River Basin, Italy, will be shown below.



(a) (b) (c) (d) (e) (f)

Fig. 2. Storm tracks over the North Atlantic and Europe (units m^2/s^2): average in 1981-2000, in spring (a) and fall (b); difference in 1981-2000 vs. 1961-1980 in spring (c) and fall (d); difference in 1991-2000 vs. 1981-1990 in spring (e) and fall (f)

2.3 Recent features and trends of the Mediterranean average precipitation climate

The Global Precipitation Climatology Centre (GPCC) 1° Lat-Lon monthly gridded land precipitation data (Schneider, 1993; Xie and Arkin, 1996) were used to produce large scale maps of the average seasonal precipitation during 1986-2002, which are shown in Fig. 3. The wettest season over northern Mediterranean and Italy is fall, followed by spring, summer (mostly limited to the Alps), and winter.

Fig. 4 shows the seasonal linear tendencies of the precipitation since 1986, limited to the Mediterranean area: the reduction in winter precipitation over most of northern Mediterranean land areas agrees with the weakening of the storms in the same season; the spring drying is more confined to the north-eastern areas and cannot be easily linked to shifts of the storm track; the weak but significant summer wetting is instead easily traced back to the recent intensification of the atmospheric transients over the Mediterranean; the precipitation increase in fall over the western Iberian peninsula, southern France, central and northern Italy and western Balkans is apparently linked to the intensification of the storm tracks over the same areas.

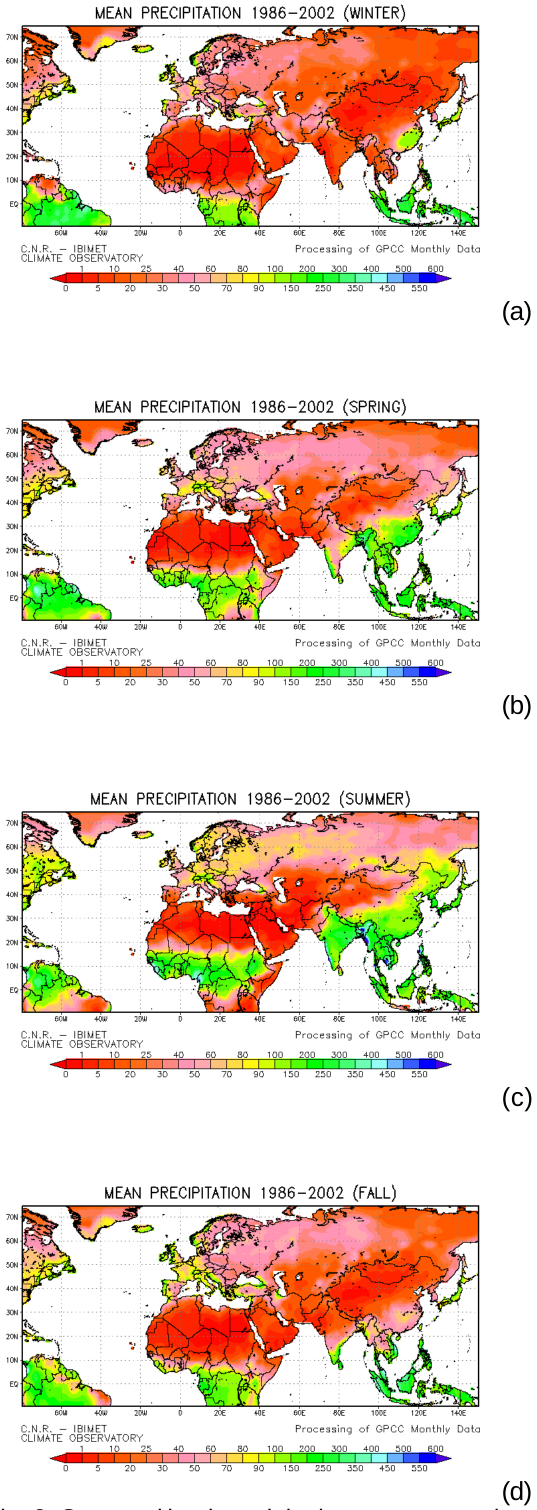


Fig. 3. Seasonal land precipitation maps over a large area comprising the Eurasian continent, central and northern Africa, during 1986-2002 (units mm), in winter (a), spring (b), summer (c), and fall (d)

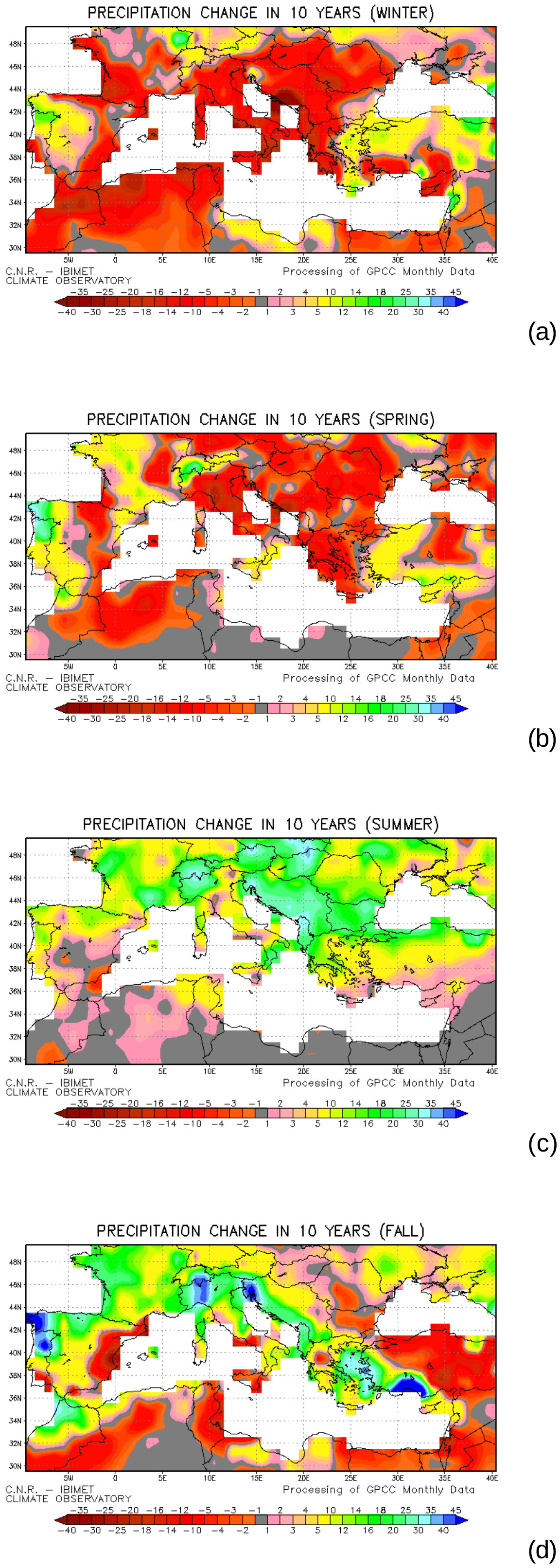


Fig. 4. Seasonal land precipitation maps over a large area comprising the Eurasian continent, central and northern Africa, during 1986-2002 (units mm/10 years), in winter (a), spring (b), summer (c), and fall (d)

2.4 Mechanisms underlying the Mediterranean summer average precipitation climate variability

In the normally semi-arid summer climate of the central and western Mediterranean, the occasional baroclinic storms which penetrate from the North Atlantic bring relevant widespread precipitation and relief from local and regional droughts, while the local scattered and short-life thunderstorms triggered in daytime over heated land areas bring locally relevant rainfall, especially to elevated hills and mountains.

The identification and the climatic-scale prediction of mechanisms driving the average circulation, the North Atlantic storm track and in particular the precipitation input is therefore critical, at least to the drought, low river discharge and forest fire risks assessment, and could also be useful to seasonal forecasting systems and climate scenario evaluation. The impact of the summer diabatic processes over the tropical Atlantic and the monsoon circulation over west Africa on the eastern North Atlantic, central Europe and, with special focus, on the Mediterranean high summer climate, are documented and investigated by Baldi et al. (2003); they found that the sea surface temperature anomalies (SSTAs) over the Gulf of Guinea, which are among the most effective drivers of the west Africa monsoon and in turn of the African easterly waves, also impact significantly the sea level pressure, mid-troposphere geopotential heights, Atlantic storm tracks at their exit regions in central Europe and western Mediterranean, and the precipitation patterns. Most notably, cold SSTAs over the Gulf of Guinea produce relevant geopotential height anomalies over the western and central Mediterranean and weaker baroclinic storms in late summer.

While some works suggest the dominant role of the Asian monsoon on the sub-tropical and mid-latitude summer climate of the North Atlantic and Mediterranean (e.g. Rodwell and Hoskins, 2001), others attach a role also to the West African monsoon (e.g. Hurrell and Folland, 2002). All authors demonstrate that the connection to the sub-tropical and mid-latitude climate works by means of “atmospheric bridges” made up mainly by propagating Rossby waves.

We have computed the composite differences of several atmospheric and surface fields over North Atlantic, Europe and Mediterranean, between years with strong Asian and West Africa monsoons and years with weak monsoons, in turn identified by means of the outgoing longwave radiation (OLR) anomalies.

The results concerning the geopotential height at 500 hPa, the storm track strength (both computed on the basis of the NCEP-NCAR reanalyses) and the precipitation (based on the data from the Climatic Research Unit at the University of East Anglia (CRU-UEA), gridded at 2.5° latitude by 3.75° longitude resolution (Hulme, 1992), during the high summer months (July-August), are shown in Fig. 5. Both the Asian monsoon and the West Africa monsoon show relevant effects to the European and Mediterranean climate. The Asian monsoon seems to produce a Rossby wave train that propagates from the far north-east top the sub-tropical south-west of the domain, revealed in the geopotential height pattern: the low south-west of British Isles is particularly deep (Fig. 5a).

The West African monsoon seems to produce a Rossby wave train that propagates from the Mediterranean, where a zonally elongated high is revealed, to the high mid-latitudes with a relatively deep low perturbation belt, to the far north-west of the domain (Fig. 5b).

Corresponding to the geopotential anomaly patterns, the stronger than average Asian monsoon produced enhances the baroclinic transients over the North Atlantic just west of France, and reduces them over central Europe, while little effect is produced over the Mediterranean (Fig. 5c); the stronger West African monsoon enhances the baroclinic storm track from west of the British Isles to the far east of the domain, with a weak or moderate increase over central and northern Italy too, and reduces them over the high latitudes (from the entrance region over eastern Canada) and also (moderately) west of the Iberian peninsula (Fig. 5d). It could be argued that a very strong West African monsoon could further shift the storms northward, far from the Mediterranean, along with the positive geopotential height perturbation.

The effects of the anomalies of the monsoons strength on the precipitation over remote areas should not be limited to those associated with the dynamics of the changes produced to the regional atmospheric circulation patterns (a role could be played for instance by the changing aerosol loading of the air masses advected to those regions, in turn impacting the cloud and precipitation microphysics), yet a signature of the dynamical variability can be found in the precipitation variability.

The most relevant feature of the European average precipitation climate associated with the stronger Asian monsoon, in July-August, is the drying of part of Scandinavia and north-eastern Europe, which is only partially associated with the changes of the storm track but is well connected with the geopotential height increase, with little effect on the Mediterranean areas (Fig. 5e). The weak wetting of central Europe, which apparently opposes the coincident storms weakening, could be due to the warm and moist southern inflow (mostly from the Mediterranean), associated with the concurrent actions of the low geopotential anomaly south-west of British Isles and the high anomaly over northern Europe (which persist at lower levels, e.g. 700 hPa; not shown), favoring convection. The wetting of northern Portugal and Spain, of western France, Wales and Ireland should be due to the direct effect of the same low anomaly and the corresponding storm activity.

The stronger West African monsoon is connected with heavier precipitation over north-eastern Europe and moderately reduced precipitation over most of western and central Mediterranean and central-eastern Europe (Fig. 5f). While the drying of western Mediterranean should be linked partly to the reduced storminess in the near Atlantic and partly to the mid-level subsidence which inhibits the moist convection, the wetting of north-eastern Europe and the drying of central-eastern Europe are not directly linked to changes in storminess, but appear as consequences of the northward shift and intensification of the warm and moist inflow from the Atlantic mid-latitudes, due to the concurrent effects of the positive height anomaly belt in the south and negative anomaly farther north, favoring convection.

Such results are suggestive of potentially dramatic consequences for the summer precipitation regime and drought intensity and recurrence over the Mediterranean land areas and a part of western and central Europe, if the West Africa monsoon, in particular, should intensify, as some climate scenarios predict (e.g. Maynard et al., 2002).

Clearly, deeper insights into the mechanisms linking average circulation and transients anomalies to regional precipitation variability, and into the impacts of “extreme” monsoons on the average European summer climate, is needed.

2.5 Other regional forcings of the water cycle variability in the western Mediterranean

The recent history of few basic surface and atmospheric forcings for the regional water cycle over western Mediterranean will be described in the following.

The sea surface temperature (SST) is a basic forcing, since it is known to force a significant part of the average and above all extreme precipitation regime over the Mediterranean land areas in both statistics (Xoplaki et al., 2003) and modeling studies (Pastor et al., 2001); warmer SSTs, in particular, concur to increase the intense rainstorms in the warm season over the northern Mediterranean land areas.

Moreover, the Mediterranean SSTs closely follows the larger scale atmospheric forcing in a wide spectrum of time scales, shorter in the warm season (several days to few weeks) and longer in the cool season (months to several years or decades), thus being an important indicator of regional warming.

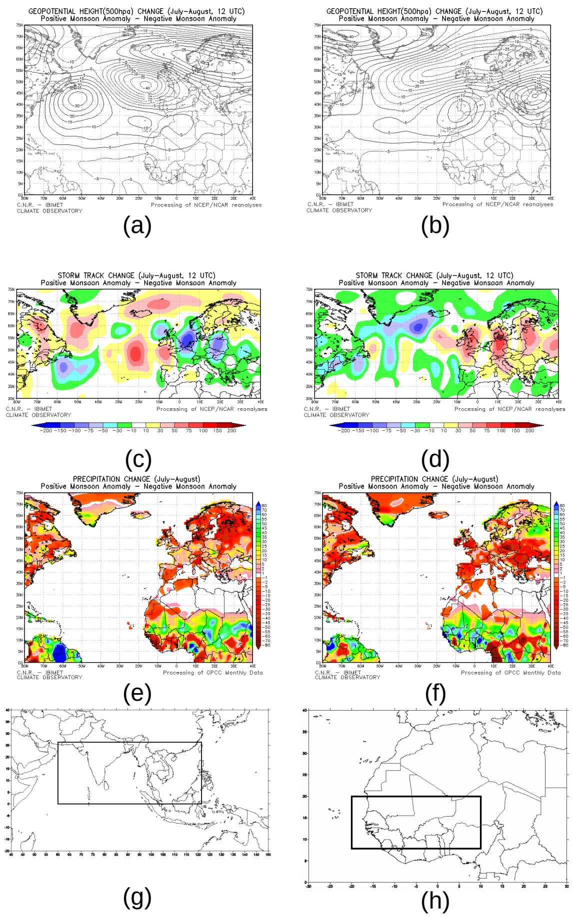
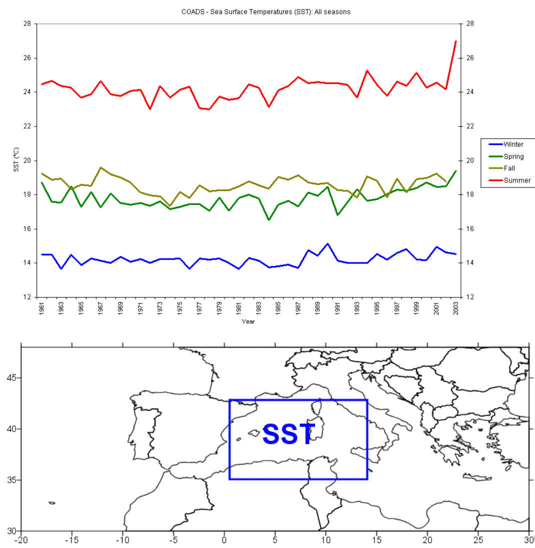


Fig. 5. Composite difference of the geopotential height at 500 hPa (a, b), the storm track strength (c, d), the GPCC gridded precipitation (e, f) in the period July-August, obtained subtracting the respective average in the years with stronger than average Asian monsoon (a, c, e) and West African monsoon (b, d, f). The Asian monsoon and West Africa monsoon areas are represented in (g) and (h), respectively

Fig. 6a shows the time series of seasonal average SST based on the COADS gridded data (Woodruff et al., 1998) over the western Mediterranean area represented in Fig. 6b. The summer warming is apparent and very fast, at least in the last two decades, the spring warming is moderate and continuous in the last 10-15 years, in winter the warming has been more abrupt during very few years in the late 1980s', after which a new "equilibrium state" seems to have been reached; in fall, no apparent trend is detectable. The regional warming is thus apparent and relevant, both in the average temperatures at the decadal time scale and in the extreme high summer temperatures.



(a)

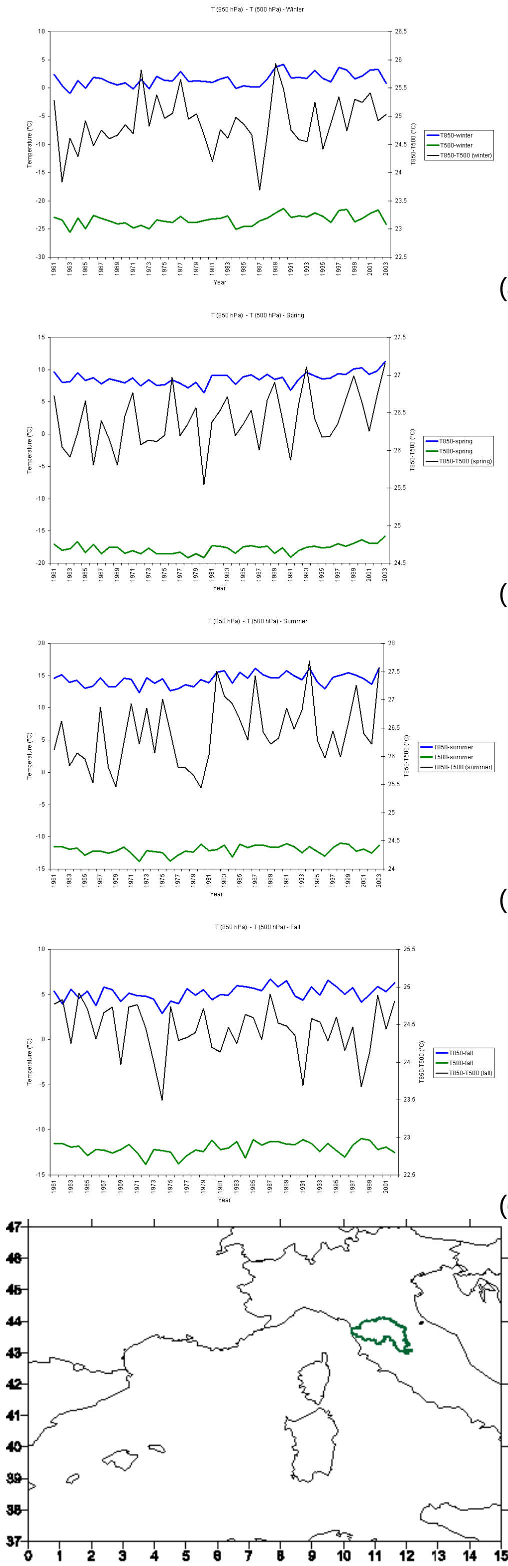
(b)

Fig. 6. Seasonal sea surface temperature (SST) time series in the four seasons from January-March (a), over the western Mediterranean (b)

The evolution of the air temperature at the pressure levels of 850 hPa and 500 hPa is relevant as forcing of the water cycle for the water vapor holding capacity of the atmosphere and its convective instability linked to the vertical lapse rate, especially in the warm season. Figs. 7a-d show the time series of seasonal average air temperature at the two pressure levels (based on NCEP-NCAR reanalyses gridded data) over the area represented in Fig. 7e.

The warming is apparent at both pressure levels in all seasons: it is faster in the last two decades, generally faster at 850 hPa than at 500 hPa (similar only in fall); at 500 hPa it is faster in winter and spring than in summer and fall while at 850 hPa it is weaker in fall than in all other seasons; consequently, the vertical temperature lapse rate increases in spring (gradually and continuously) and summer (with an abrupt step in early 1980s'). In the warm season, the regional atmosphere shows an increasing water vapor holding capacity and, in principle, an increased convective instability.

The evolution of the total columnar precipitable water (PW) and average relative humidity (RH) from the surface up to 500 hPa are relevant as forcings of the water cycle for the highest precipitation potential and precipitation efficiency, respectively, especially in the warm season.



(a)

(b)

(c)

(d)

(b)

Fig.7. Seasonal air temperature time series at 850 hPa and 500 hPa in the four seasons from January-March (a-d), over the area shown in (e), where the Arno River Basin boundaries are bold green

Figs. 8a-d show the time series of seasonal average PW and RH (based on NCEP-NCAR reanalyses gridded data) over the same area represented in Fig. 7e.

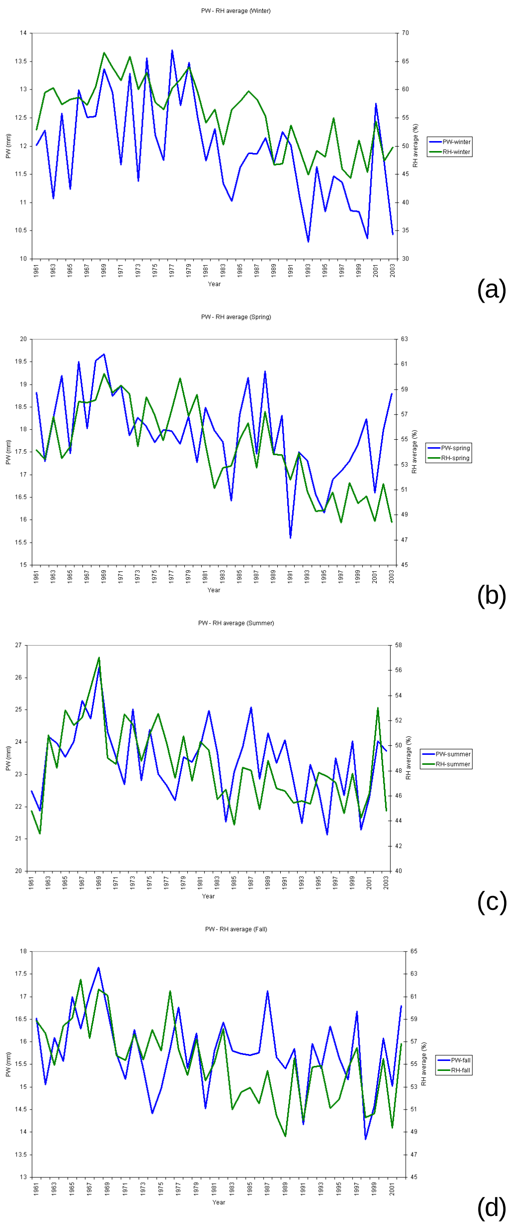


Fig.8. Seasonal precipitable water (PW) and average relative humidity (RH) time series in the four seasons from January-March (a-d)

In winter, both PW and RH undergo a fast decrease since early 1980s', coincidentally with the northward retreat of the storm track and the Atlantic south-westerlies; such trend has stopped since few years. In spring, while both PW and RH decreases continuously since the 1970s' to mid 1990s', in the last few years the PW shows an increasing trend and the RH is approximately stationary, a likely response to the accelerated warming and ideal background for the increase of intense rainstorms. In summer, the descending trend of both quantities is apparent since early 1970s', along with the recent short and moderate growth in late 1990s'; while intense rainstorms could be favored by this recent trend, it's interesting to note how, in the recent extremely hot summer of year 2003, the relative humidity dropped to very low values, consistently with the strong persistent subsidence, while the precipitable water didn't drop significantly, likely response to strong sea surface warming and evaporation. In fall, notwithstanding the apparent increase of atmospheric storminess also over the western Mediterranean, a long term decrease of both PW and RH is shown, the PW trend realized mostly since mid-1980s' to early 1990s' and the RH trend during the 1970s' and early 1980s', whose origin should be studied in more detail; a recent stationary or weakly growing trend is also shown in the data.

What is common to all the above time series is the long term drying trend, apparently stopped or even reversed in the last few years, suggestive of a new tendency towards wetter climate or at least faster water cycle, especially in spring and fall.

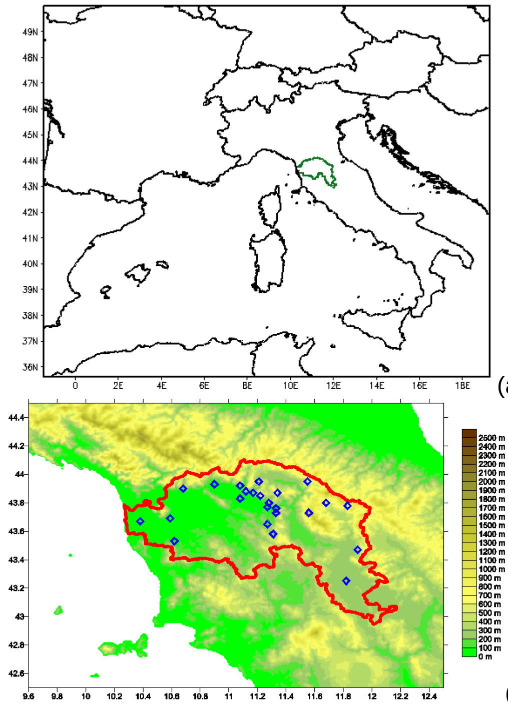
3. CASE STUDY: ARNO RIVER BASIN, ITALY

The project "Climate reanalysis and prediction over the Arno river basin", funded by the Arno River Basin Authority (Italy), aims at providing quantitative information concerning the past, current and future variability and trends of heavy rainfall and drought occurring over the Arno River Basin, Italy (about 9200 km^2; Fig. 9a,b). The broad scope is the support to the periodic update of the distributed constraints system around the basin, to the design and management of flood protection works, to the targeting of the local weather forecasting system, and to the water quality and conservation policies.

The ongoing project is based on the historical series of in-situ rainfall data, the GPCC (Schneider, 1993; Xie and Arkin, 1996), GPCP (Xie et al., 2003) and CRU-UEA (Hulme, 1992) gridded precipitation products, the NCEP/NCAR global atmospheric and surface reanalyses (Kalnay et al., 1996; Kistler et al., 2001), and the climate scenarios produced by the CCCma (Flato et al., 2000; Flato and Boer, 2001).

The in-situ data have been analyzed during at least 50 years in the past, till year 2000, to feature the seasonal inter-annual variability and trends of the frequency of rainy days, precipitation totals and average daily intensity, the frequency of local and basin-scale rainfall events above few thresholds; local and basin-scale depth-duration-frequency curves have been derived. The significance of any trend has been evaluated by means of the Mann-Whitney test (Kendall & Ord, 1990).

The same analyses concerning the historical in-situ data were performed on the climate scenarios provided by the CCCma, on the (coarse) grid cell covering the Arno River basin.



(a)

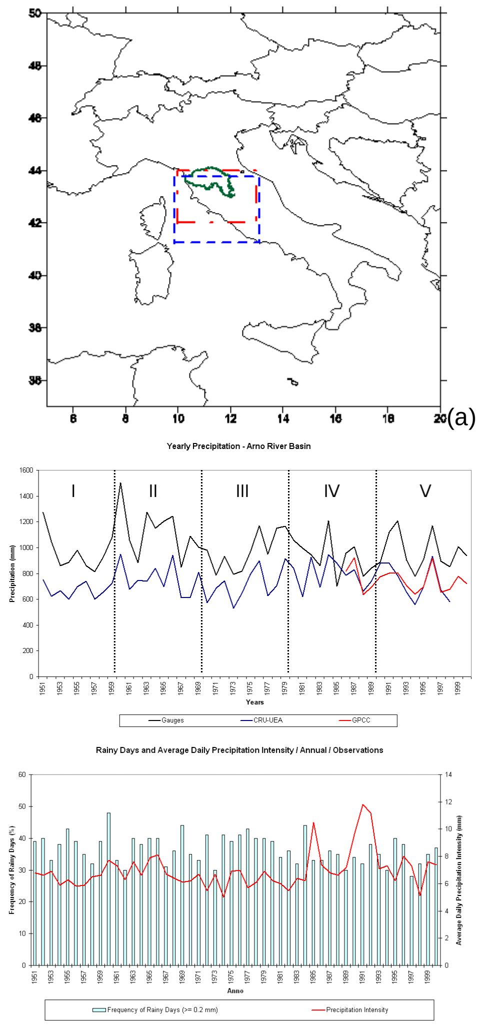
(b)

Fig. 9. Location of the Arno basin (dark green boundaries) in Europe (a); orography and rain gauges around the basin (b)

An advanced atmosphere-land surface coupled model, the Regional Atmospheric Modeling System (RAMS; Pielke et al, 1992; Pielke, 2002) is used in a double perspective. First, since most of the distributed constraints and the design of the flood protection works around the Arno river basin are based on the floodplain analysis of the catastrophic events occurred in November 1966 and October 1992 (estimated as the 100-year and 30-year events, respectively), these same events are reproduced both in the “observed” environment and in idealized regional climate change scenarios, where RAMS is initialized by means of the NCEP/NCAR reanalyses and the sea surface temperatures (SSTs) over the Mediterranean Sea are perturbed according to the CCCma warming scenarios at several lead times in the future.

Second, the RAMS is performing the dynamical downscaling of the CCCma climate change scenarios with the aim to fill the gap which separates the very coarse resolution of the global scenarios and the sub-grid scale regional and local phenomenology. The RAMS has proved its ability to accurately represent the rainstorms of 1966 and 1992 when executed at very high spatial horizontal resolution, initialized by means of the NCEP-NCAR reanalyses (Soderman et al., 2003; Meneguzzo et al., 2003).

Among the relevant results of the analysis carried on so far, the following are worth to be mentioned.



(a)

(b)

(c)

Fig. 10. Annual precipitation time series over the Arno River Basin: (a) Arno river basin (green), CRU grid cell (blue) and GPCC grid cells (red); (b) total annual precipitation; (c) annual frequency of rainy days and average daily precipitation intensity over the lower portion of the Arno River basin

The total annual precipitation, evaluated on the basis of the CRU and GPCC gridded data (respective grid cells shown in Fig. 10a) and rain gauge data, has not changed significantly since 1951 (Fig. 10b), but the frequency of rainy days has decreased until early 1980s’ and the year-round average daily rainfall intensity has increased significantly in the last 30 years (Fig. 10c). The average annual precipitation climate has not become drier, but the water cycle has shown a significant acceleration.

In winter, the total precipitation decreased significantly until mid-1990s' (Fig. 11a), consistently with the changes in the seasonal storm tracks and the moisture availability. In spring, the total precipitation increased in the 1980s' and didn't change in recent years (Fig. 11b), likely following the increased vertical lapse rate in the low to mid-troposphere; most of the increase is ascribed to the increasing average daily rainfall intensity. The summer precipitation time series show a strong inter-annual variability from the 1960s' to the 1980s', and a smoother behavior in the 1990s', with no apparent wetting in the last 10 years (Fig. 11c), as the moderately increased storminess could suggest (Fig. 1f), probably inhibited in this by the limited atmospheric moisture content (Fig. 8c); the spatial variability is also greater in summer: the total precipitation has decreased over the upper mountainous portion of the basin and the average daily rainfall intensity has significantly increased elsewhere (not shown). In fall, the 1990's were significantly wetter than the 1980s', approximately as the 1960s' (Fig. 11d) and likely associated with the relevant increase of storminess.

The daily precipitation events exceeding given thresholds, relevant for local flash-floods and floods, are growing in frequency both locally and averaged over the sub-basins, so that they are today more frequent than ever, at least in the last 150 years: such frequency, evaluated during subsequent decades each sharing 9years with the previous, has increased from about 20% in the upper portion of the basin to about 150% in the lower portion (Fig. 12a-c); the tendency to heavier rainstorms seems to follow the atmospheric and sea surface warming (Fig. 6a), and the increase in the vertical lapse rates.

The extreme annual precipitations have increased, but only at very short durations (1 hour and 3 hours, not shown).

The future climate around the Arno river basin has been preliminary analyzed by means of the gridded data provided by the Canadian Centre for Climate Modelling and Analysis (CCCma) on the basis of the simulations performed by means of the global coupled climate model CGCM2 under the emission scenarios A2 and B2 (Flato and Boer, 2001), over the grid cell of size 3.75° Lon 3.71° Lat around the Arno River basin.

Fig. 13 shows the warming trend of the sea surface temperature over the same area represented in Fig. 6b, simulated by the CGCM2-A2 climate scenario.

The simulated SST series are in close agreement with the observations shown in Fig. 6a, in the period 1961-2000, at least with regard to the long term trends, which allows more confidence with the future trends. The sea surface warming is also likely to lead to increased intense rainstorms in view of theoretical arguments, of the past decadal joint trends (Fig. 6a and Fig. 12a-c) and an analysis of the joint inter-annual variability of SST and average rainfall intensity over the Arno river basin (not shown).

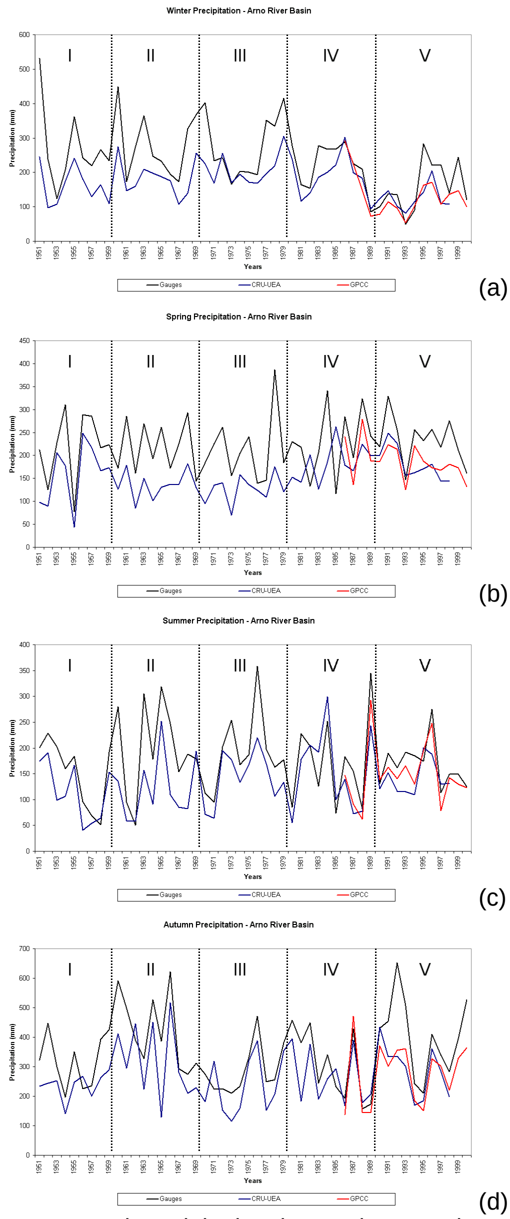
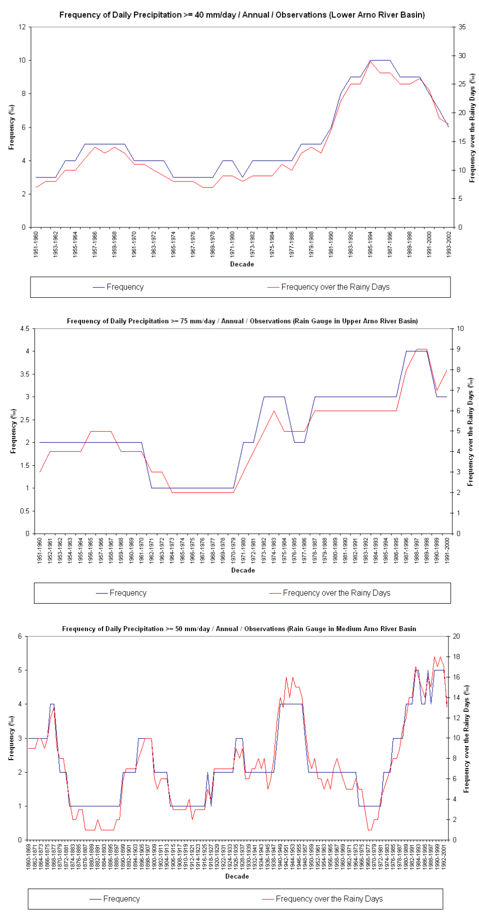


Fig. 11. Annual precipitation time series over the Arno River Basin: (a) winter; (b) spring; (c) summer; (d) fall

Fig. 14 shows the annual and seasonal precipitation time series simulated by the CGCM2-A2 and CGCM2-B2 climate scenarios in the period 1961-2100 (the same scenario till 1990), along with the time series from the CRU (1961-1985) and GPCC (1986-2002) datasets, over the respective grid cells represented in Fig. 15.



(a)

(b)

(c)

Fig. 12. Frequency of rainy days over high thresholds: (a) Lower Arno River basin; (b) Rain gauge in the upper Arno River basin; (c) Rain gauge in the medium Arno River basin

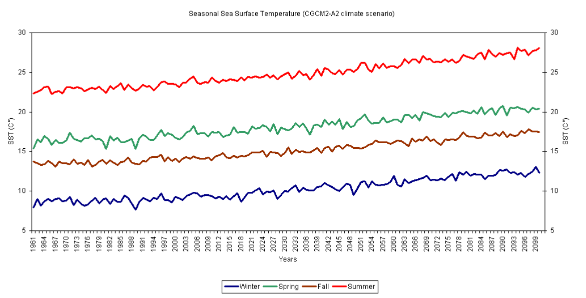


Fig. 13. Seasonal sea surface temperature (SST) time series in the four seasons from January-March, from the CGCM2-A2 climate scenario, over the area represented in Fig. 6b

A relevant underestimation of the precipitation volumes is apparent, nevertheless the annual simulated precipitation trends closely agree with the observed ones (Fig. 14a), and the next 30 years or so are predicted moderately wetter then the past ones, after which the probability of extremely dry years abruptly increases and the average annual precipitation slowly decreases to very low values around the end of the 21st century; the two climate scenarios appear quite close one another.

The winter precipitation, which is simulated in very close agreement with the observations even with regard to the absolute values, is predicted by both climate simulations to increase slowly for many decades to come. The spring precipitation, simulated reasonably well in the past, is predicted to increase slowly and moderately for several decades to come, along with a greater inter-annual variability and an higher chance for extremely wet seasons, until a gradual drying could occur near the end of this century. The summer precipitation is simulated quite well in the past with regard to the long term trends, but the high inter-annual variability is quite underestimated, which could suggest the failure of the model to explain some basic leading mechanisms (see Sect. 2.4); a moderate increase of summer precipitation is predicted by the A2 scenario for several decades to come, while no significant trend is predicted by the B2 scenario; the chance for very wet summers is predicted to increase, till the slow drying toward the end of the 21st century. The simulated fall precipitation shows a relevant underestimation with regard to both the absolute values and the inter-annual variability, but not with regard to the past trends; it is predicted to increase moderately by the A2 scenario for several decades to come, with higher chance for very wet fall seasons, while no significant trend is predicted by the B2 scenario; a slow drying is predicted toward the end of the 21st century.

The simulated precipitation time series produced by the A2 scenario show a further increase of the frequency of excessive daily rainfalls until at least 2015, henceforth it should remain constant, about 30% higher than in the current climate; such frequency was evaluated during subsequent decades each sharing 9 years with the previous (Fig. 16). The increasing chance for extremely wet spring, summer and fall seasons appears to be linked more to the intensification of the rainstorms than to more frequent rainy days.

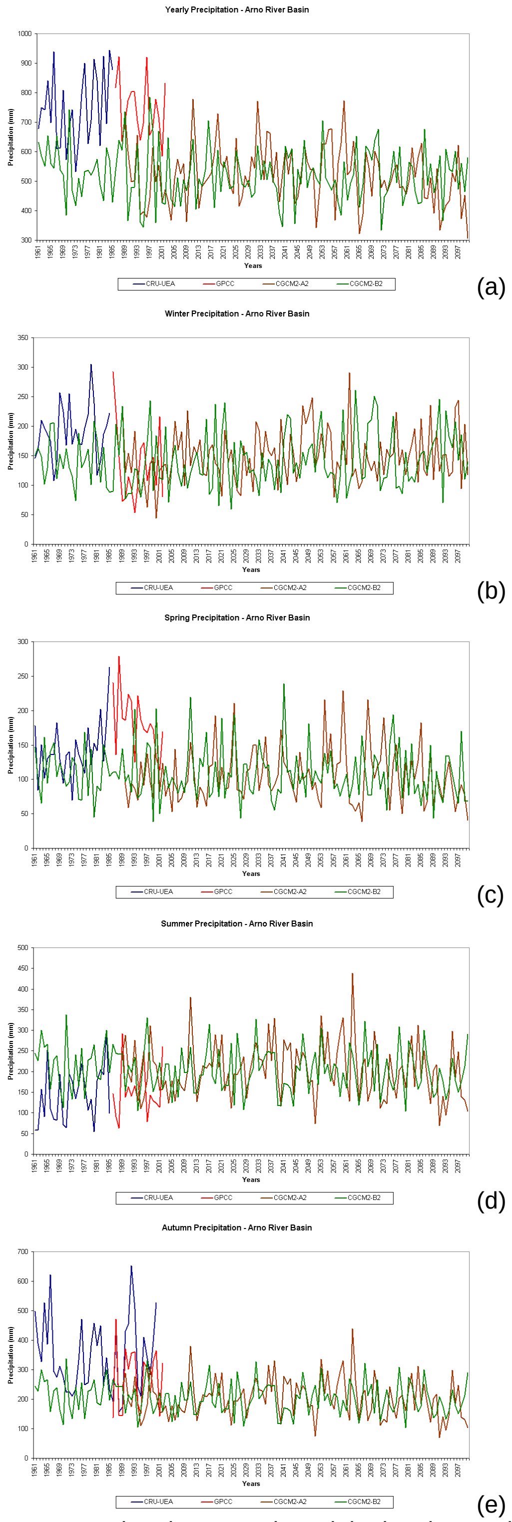


Fig. 14. Annual and seasonal precipitation time series over the Arno River Basin, from CRU, GPCC, GCGM2-A2 and CGCM2-B2: (a) annual; (b) winter; (c) spring; (d) summer; (e) fall

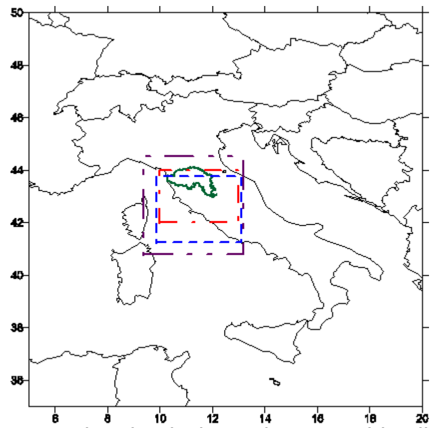


Fig. 15. Arno river basin (green), CRU grid cell (blue), GPCC grid cells (red) and CGCM2 grid cell (purple)

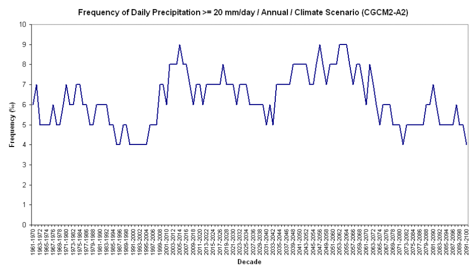


Fig. 16. Annual time series of the frequency of rainy days over the threshold of 20 mm around the Arno River basin (1961-2100), simulated by means of the CGCM2-A2 scenario (CCCma)

4. CONCLUSIONS

The results shown in this work, yet partial and related to an ongoing research, offer a comprehensive view of the ongoing climatic decadal variability and tendencies over the large North Atlantic, European and Mediterranean scale, along with the regional decadal and inter-annual tendencies of the climatic features related to the water cycle over the Mediterranean and the Arno River basin, Italy; few remote leading processes are shown too, especially for the summer season.

The variability of the storm tracks, of the air masses and the Mediterranean sea surface temperatures, in turn mutually linked, are shown to produce large effects on the basin-scale precipitation average and extreme regime.

The intense rainfall hazards are shown to be increasing over the Arno River basin, and are predicted to do so even in the next few decades.

The water cycle over land areas, along with the soil and vegetation conditions, are also very sensitive to the temperature variability and trends, and the predicted strong warming, faster in summer than in any other season (as observed in the recent past), could by itself increase the drought hazards, especially in case of very dry summer seasons. The chance of extreme summer droughts is predicted quite stationary in the next few decades; anyway, if the available climate models should be missing some important mechanisms driving the summer Mediterranean climate, and such regimes should shift to new states, unfavorable to summer precipitations over the western and central Mediterranean, the recurrent extreme drought events could lead to potentially dramatic emergencies with regard to water quality and availability in next decades.

The regional climate of late spring and summer 2003 in the central and western Mediterranean has been a very large outlier with regard to precipitation (in the lowest 5th percentile of the last 150 years) and temperature (May-August anomaly more than 3°C above the 1961-1990 climatological average), much higher than any past record and largely exceeding the inter-annual variability simulated by the CCCma climate scenarios: further research is needed to understand its connection to remote processes such as the West Africa monsoon, which has been far stronger than the average.

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REFERENCES

Baldi, M., V. Capecchi, A. Crisci, G.A. Dalu, G. Maracchi, F. Meneguzzo, and M. Pasqui, 2003a: Mediterranean summer climate and its relationship to regional and global processes. *Proceedings of the Sixth European Conference on Applications of Meteorology*, Rome, 15-19 September 2003.

Brunetti, M., M. Colacino, M. Maugeri, and T. Nanni, 2001: Trends in the daily intensity of precipitation in Italy from 1951 to 1996. *Int. J. Climatol.*, **21**, 299-316.

Brunetti, M., M. Maugeri, T. Nanni, and A. Navarra, 2002: Droughts and estreme events in regional daily italian precipitation series . *Int. J. Climatol.*, **22**, 5432-316.

Chang, E.K., and Y. Fu, 2002: Interdecadal variations in northern hemisphere winter storm track intensity. *J. Climate*, **15**, 642-658.

Chen, J., B.E. Carlson, and A.D. Del Genio, 2002: Evidence for strengthening of the tropical general circulation in the 1990s. *Science*, **295**, 838-841.

Christensen, J.H., and O.B. Christensen, 2003: Severe summertime flooding in Europe. *Nature*, **421**, 805-806.

Del Genio, A.D., 2002: The dust settles on water vapor feedbacks. *Science*, **296**, 665-666.

Flato, G.M., G.J. Boer, W.G. Lee, N.A. McFarlane, D. Ramsden, M.C. Reader, and A.J. Weaver, 2000: The Canadian Centre for Climate Modelling and Analysis Global Coupled Model and its Climate. *Clim. Dyn.*, **16**, 451-467.

Flato, G.M., and G.J. Boer, 2001: Warming Asymmetry in Climate Change Simulations. *Geophys. Res. Lett.*, **28**, 195-198.

Gillet, N.P., F.W. Zwiers, A.J. Weaver, and P.A. Stott, 2003: Detection of human influence on sea-level pressure. *Nature*, **422**, 292-294.

Groisman, P., T.R. Karl, D.R. Easterling, R.W. Knight, P.F. Jamason, K.J. Hennessy, R. Suppiah, C.M. Page, J. Wibig, K. Fortuniak, V.N. Razuvaev, A. Douglas, E.J. Førland, and P. Zhai, 1999: Changes in the probability of heavy precipitation: important indicators of climatic change. *Climate Change*, **42**, 243–283.

Gulev, S.K., T. Jung, and E. Ruprecht, 2002: Climatology and interannual variability in the intensity of synoptic-scale processes in the North Atlantic from the NCEP-NCAR reanalysis data. *J. Climate*, **15**, 809-828.

Harnik, N., and E.K. Chang, 2003: Storm track variations as seen in radiosonde observations and reanalysis data. *J. Climate*, **16**, 480-495.

Hegerl, G.C., F.W. Zwiers, P.A. Stott, and V.V. Kharin, 2003: Detectability of anthropogenic changes in temperature and precipitation extremes. *J. Climate* (submitted).

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

Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson, Eds., 2001: Summary for policymakers. A Report of Working Group I of the Intergovernmental Panel on Climate

Change, 20 pp. [*Available online at http://www.ipcc.ch*].

Hulme, M., 1992: A 1951-80 global land precipitation climatology for the evaluation of General Circulation Models. *Clim. Dyn.*, **7**, 57-72.

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

Hurrell, J.W., and C.K. Folland, 2002: A change in summer atmospheric circulation over the North Atlantic. CLIVAR Exchanges, **25**, 52-54 [Available online at http://www.clivar.ucar.edu/publications/exchanges/ex25/ex25.pdf].

Hurrell, J.W., Y. Kushnir, G. Ottersen, and M. Visbeck, 2003: An overview of The North Atlantic Oscillation. *The North Atlantic Oscillation: Climatic Significance and Environmental Impact. Geophysical Monograph 134. American Geophysical Union*, 1-35.

Jones, C.D., P.M. Cox, R.L.H. Essery, D.L. Roberts, and M.J. Woodage, 2003: Strong carbon cycle feedbacks in a climate model with interactive CO2 and sulphate aerosols. *Geophys. Res. Lett.*, **30**, 1479-1482.

Kalnay E., and coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Am. Met. Soc.*, **77**, 437-471.

Kendall, M., and J.K. Ord, 1990: Time Series, 3rd ed., *I Edward Arnold*, London.

Kistler R., E., and coauthors, 2001: The NCEP–NCAR 50-Year Reanalysis: Monthly Means CD-ROM and Documentation. *Bull. Am. Met. Soc.*, **82**, 247-268.

Maynard, K., J.-F. Royer, and F. Chauvin, 2002: Impact of greenhouse warming on the West Africa summer monsoon. *Clim. Dyn.*, **19**, 499-514.

Meneguzzo, F., M. Pasqui, G. Menduni, G. Messeri, B. Gozzini, D. Grifoni, M. Rossi, and G. Maracchi, 2003: Sensitivity of meteorological high-resolution numerical simulations of the biggest floods occurred over the Arno river basin, Italy, in the 20th century. Accepted for publication in: *Journal of Hydrology.*

Palmer, T.N., and J. Ralsanen, 2002: Quantifying the risk of exteme seasonal precipitation events in a changing climate. *Nature*, **415**, 512-514.

Pastor, F., M.J. Estrela, D. Peñarrocha, and M.M. Millán, 2001: Torrential rains on the Spanish coast: modeling the effects of the sea surface temperature. *J. Appl. Meteor.*, **40**, 1180-1195.

Pielke, R. A., W.R. Cotton, R.L. Walko, C.J. Tremback, W.A. Lyons, L.D. Grasso, M.E. Nicholls, M.D. Moran, D.A. Wesley, T.J. Lee, and J.H. Copeland, 1992: A comprehensive meteorological modeling system - RAMS. *Meteorol. Atmos. Phys.*, **49**, 69-91.

Pielke, R.A., 2002: Mesoscale Meteorological Modeling. 2nd Edition, Academic Press, New York, N.Y., 612 pp.

Pielke, R.A., 2003: Heat storage within the climate system. *Bull. Amer. Meteor. Soc.*, **84**, 331-335.

Rial, J.A., R.A. Pielke Sr., M. Beniston, M. Claussen, J. Canadell, P. Cox, H. Held, N. De Nobelt-Ducoudré, R. Prinn, J. Reynolds, and J.D. Salas, 2003: Nonlinearities, Feedbacks, and critical thresholds within the Earth's climate system. *Climatic Change*, in press.

Rodwell, M.J., and B.J. Hoskins, 2001: Subtropical anticyclones and summer monsoons. *J. Climate*, **14**, 3192-3211.

Rowell, D.P., 2003: The impact of Mediterranean SSTs on the Sahelian rainfall season. *J. Climate*, **16**, 849-862.

Santer, B.D., M.F. Wehner, T.M.L. Wigley, R. Sausen, G.A. Meehl, K.E. Taylor, C. Ammann, J. Arblaster, W.M. Washington, J.S. Boyle, and W. Brüggemann, 2003: Contributions of anthropogenic and natural forcing to recent tropopause height changes. *Science*, **301**, 479-483

Schneider, U., 1993: The GPCC quality-control system for gauge measured precipitation data. GEWEX Workshop on Analysis Methods of Precipitation on Global Scale. Rep. WCRP-81, WMP/TD-588, Koblenz, Germany, WMO, A5–A9.

Soderman, D., F. Meneguzzo, B. Gozzini, D. Grifoni, G. Messeri, M. Rossi, S. Montagnani, M. Pasqui, A. Orlandi, A. Ortolani, E. Todini, G. Menduni, and V. Levizzani, 2003: Very high resolution precipitation forecasting on low cost high performance computer systems in support of hydrological modeling. *Proceedings of the 17th Conference on Hydrology, AMS 83rd Annual Meeting, 9-13 February, Long Beach, CA* (available at http://ams.confex.com/ams/pdfview.cgi?username=55206)

Wallace, J. M., G.H. Lim, and M.L. Blackmon, 1988: Relationship between cyclone tracks, anticyclone tracks, and baroclinic wave guides. *J. Atmos. Sci.*, **45**, 439–462.

Ward, M.N., 1998: Diagnosis and short-lead time prediction of summer rainfall in tropical North Africa at interannual and multidecadal timescales. *J. of Climate*, **14**, 795-821.

Woodruff, S.D., H.F. Diaz, J.D. Elms, and S.J. Worley, 1998: COADS Release 2 data and metadata enhancements for improvements of marine surface flux fields. *Phys. Chem. Earth*, **23**, 517-527.

Xie, P., and P. A. Arkin, 1996: Analyses of global monthly precipitation using gauge observations, satellite estimates, and numerical model predictions. *J. Climate*, **9**, 840–858.

Xie, P., J.E. Janowiak, P.A. Arkin, R. Adler, A. Gruber, R. Ferraro, R., G.J. Huffman, and S. Curtis, 2003: GPCP pentad precipitation analyses: an experimental dataset based on gauge observations and satellite estimates. *J. Climate*, **16**, 2197-2214.

Xoplaki, E., J.F. González-Rouco, J. Luterbacher, and H. Wanner, 2003: Mediterranean summer air temperature variability and its connection to the large-scale atmospheric circulation and SSTs. *Clim. Dyn.*, **20**, 723-739.

Yang, F., A. Kumar, M.E. Schlesinger, and W. Wang, 2003: Intensity of hydrological cycles in warmer climates. *J. Climate*, **16**, 2419-2423