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Mediterranean water cycle changes: transition to drier 21st century conditions in observations and CMIP3 simulations

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Abstract

We use CMIP3 multi-model simulations to show how individual hydroclimatic changes will concur to determine even greater alterations of 21st century Mediterranean water cycle characteristics, with contrasting behavior over land and sea. By 2070–2099, the average of the models predicts a 20% decrease in land surface water availability and a 24% increase in the loss of fresh water over the Mediterranean Sea due to precipitation reduction and warming-enhanced evaporation, with a remarkably high consensus among analyzed models. The projected decrease in river runoff from the surrounding land will further exacerbate the increase in Mediterranean Sea fresh water deficit.

20th century simulations indicate that the 'transition' toward drier conditions has already started to occur and has accelerated around the turn of the century towards the larger rates projected for the 21st century. These tendencies are supported by observational evidence of century-long negative trends in regionally averaged precipitation, PDSI and discharge from numerous rivers; and are consistent with reported increases in Mediterranean sea water salinity.

S Supplementary data are available from stacks.iop.org/ERL/3/044001

Keywords: Mediterranean water cycle, climate change, drought, salinity

1. Introduction

The Southern Europe-Mediterranean region is well known for its pleasant climate that has favored the rise of past great civilizations. People have learned to deal with an almost total lack of rainfall during the summer months, but water is still one of the most vulnerable aspects of life in the region, now supporting an increased local population. Under a suite of global climate change scenarios, the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-AR4 hereafter; (IPCC 2007)) projects major changes in the Mediterranean region, in particular as a 'Hot Spot' in hydrological change with significant impacts on both mean precipitation and variability (Gibelin and Deque 2003, Giorgi 2006, Ulbrich *et al* 2006, Giorgi and Lionello 2008, Sheffield and Wood 2008). However, the combined effects of future precipitation decrease and increasing surface temperature on Mediterranean water cycle, and in particular the impact on

Mediterranean Sea water budget, are less well known. In this study we use the World Climate Research Program Coupled Model Intercomparison Project Phase 3 (CMIP3 hereafter) multi-model projections to show how individual hydroclimatic changes will concur to determine even greater alterations of future Mediterranean water cycle characteristics, with contrasting behavior over land and sea. We focus on the 'transition phase' from recent past conditions to the much drier conditions expected at the end of the 21st century. Diverse data are analyzed to assess whether the water cycle changes depicted by the 20th century model simulations are consistent with observed variations.

2. Data and methodology

The 20th century CMIP3 model simulations analyzed in this study are coupled runs with various observed forcings (Climate of the 20th Century Experiment; details at http://www-pcmdi.llnl.gov/ipcc/standard_output.html#Experiments). Model–data intercomparison for the Mediterranean region indicates that these simulations capture reasonably well both regional precipitation and temperature climatology (see table 1S (available at stacks.iop.org/ERL/3/044001); also Giorgi and Lionello 2008). Mediterranean-averaged annual precipitation bias over the period 1950–2000 is about −3%, land surface air temperature (T_s) bias is about −1 K and SST bias is about −2 K. CMIP3 simulations also capture the long-term temperature increase observed in the Mediterranean region during the 20th century, although trends are smaller than observed (see figure 1S (available at stacks.iop.org/ERL/3/044001)). We analyze 21st century projections for the SRESA1B emission scenario, intermediate in the IPCC-AR4 scenario range with results also expected to be intermediate. Ensemble means include data from 14 different models and multiple runs from each model. Standard deviation is used to characterize the distribution of individual models around the ensemble mean. Anomalies are relative to 1950–2000 means. Annual, dry season (Apr–Sep) and wet season (Oct–Mar) means are analyzed. Area-averages for the Mediterranean region are computed over the domain 10°W–40°E and 28°N–47°N, separately for land and sea. Spatial patterns are derived using data interpolated to a common 2.5° × 2.5° grid. In budget calculations, the Mediterranean Sea is assumed to have an area of 2.5×10^{12} m^2 and a drainage basin of 1.85×10^{12} m^2.

Observational precipitation datasets are the monthly precipitation dataset from the National Center for Atmospheric Research (Dai *et al* 1997) (DAI hereafter), 1900–1995; the National Climatic Data Center Global Historical Climatology Network V2 data (Vose *et al* 1992) (GHCN hereafter), 1900–2007; and a 'merged' time-series derived using Climate Research Unit (CRU) TS2.1 data (Mitchell and Jones 2005) (1901–2002) and the Climate Prediction Center PRECL data (Chen *et al* 2002) (1948–2007), to cover the 1901–2007 period (CRU/PRECL hereafter). T_s is from the CRU TS2.1 dataset and sea surface temperatures (SSTs) are from the Met Office HadISST 1.1 dataset Rayner *et al* (2003). The Palmer drought severity index (PDSI) is as in Dai *et al* (2004). River discharge is from the database described in Struglia *et al* (2004).

Table 1. Mediterranean-averaged precipitation (P), evaporation (E) and precipitation minus evaporation ($P - E$) anomalies in 2070–2099 relative to 1950–2000. (a) Land-only. (b) Sea-only. In each column: annual, 'wet' and 'dry' mean anomalies based on an average of CMIP3 model runs; relative (%; left) and absolute (mm/day; right) values are reported (annual $P - E$ anomaly over land is absolute value only).

	P	E	$P - E$
		(a) Land	
Annual	−15.5%/−0.17	−8.1%/−0.08	−0.09
Wet	−9.7%/−0.12	−1.5%/−0.01	−19.6%/−0.11
Dry	−23.6%/−0.21	−11.8%/−0.14	−23.4%/−0.07
		(b) Sea	
Annual	−15.0%/−0.19	7.2%/0.21	−24.2%/−0.41
Wet	−11.6%/−0.22	7.5%/0.26	−29.6%/−0.48
Dry	−23.8%/−0.17	6.7%/0.17	−19.2%/−0.34

3. Simulated long-term mean water cycle changes

CMIP3 model simulations show a progressive decrease in rainfall in the Mediterranean region that has been on-going during the 20th century (−0.007 mm/d per decade; see table 2S (available at stacks.iop.org/ERL/3/044001) for a summary of all trends) and accelerates around the turn of the 21st century, followed by rapid drying from 2020 and onwards (figure 1; −0.02 mm/d per decade). The projected changes will cause Mediterranean land regions to become gradually more arid, with roughly 15% less precipitation in 2070–2099 compared to 1950–2000, and an 8% decrease already by 2020–2049 (see table 1). The amplitude of the mean change foreseen by 2020–2049 (about 0.1 mm/d) is comparable to that of the driest spells experienced by the region during the 20th century (see figures 1 and 4). Since the multi-model ensemble average has internal variability with reduced amplitude, the actual variability, with multi-year droughts and pluvials, will cause greater changes than those depicted by the ensemble mean. As precipitation is the main driver of land surface hydrological cycle, other major hydrological indicators will also change correspondingly. Soil moisture progressively decreases (see figure 2S (available at stacks.iop.org/ERL/3/044001); similar results were found by Gibelin and Deque (2003)); so will runoff and river discharge, reducing the water available for irrigation and other uses. Because of the drier land surface, evapotranspiration (evaporation hereafter) will also decrease but, as increased surface temperature favors higher evaporation, the rate of decrease will be half that of precipitation. By 2070–2099, effective precipitation ($P - E$) decrease over land is about −0.09 mm/d (−0.01 mm/d per decade).

While the drying on land is large, the projection over the Mediterranean sea is even more dramatic. Unlike the surrounding land region where evaporation decreases, the precipitation reduction over the sea is accompanied by a roughly equal increase in evaporation due to increased sea

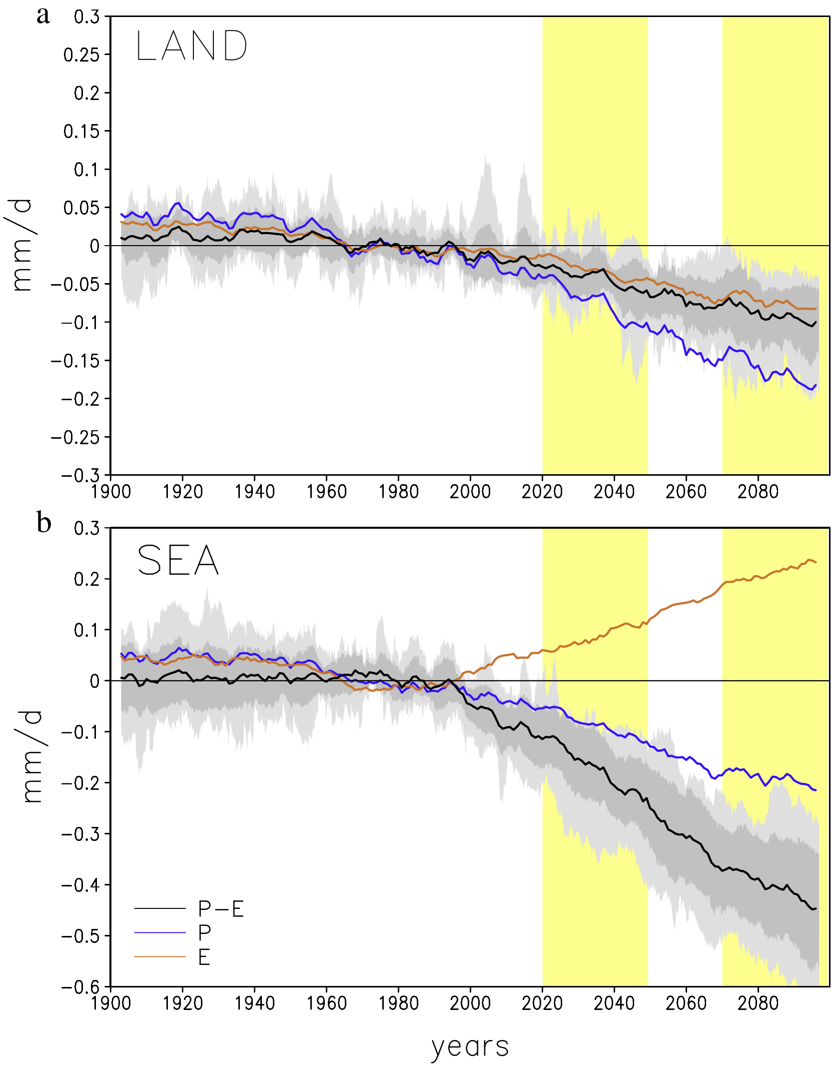

Figure 1. Mediterranean water cycle anomalies over the period 1900–2100 relative to 1950–2000. Area-averaged evaporation (brown), precipitation (blue) and precipitation minus evaporation (black; $P - E$) are based on an average of CMIP3 model runs. For $P - E$, the envelope of individual model anomalies and the 1 standard deviation interval around the ensemble mean are also shown (light gray and dark gray shading respectively). Data are six years running means of annual mean area-averages over the box of figure 3 broadly defining the Mediterranean region. Panel a: land-only. Panel b: sea-only. Focus periods are highlighted (yellow).

surface temperature (ultimately due to more energy input from greenhouse warming). As a result, a 24% (0.4 mm/d) increase in the loss of freshwater ($E - P$) at the sea surface is projected towards the end of the 21st century. This change is large, roughly equal to what is typically received in total by the Mediterranean Sea on an annual basis as discharge from neighboring land and as inflow from the Black Sea (Mariotti *et al* 2002). Currently a main freshwater source to the southeastern Mediterranean, the Black Sea inflow may also change as it will receive less fresh water at the surface.

As a result, the freshwater deficit which already characterizes the Mediterranean Sea will significantly increase, with a cumulative freshwater deficit by 2100 of 1.54×10^8 m^3 (trend is −0.045 mm/d per decade). This will be further exacerbated by the decrease in river discharge from surrounding regions (cumulative decrease is 2.54×10^7 m^3). As in the past, this can have important implications for the Mediterranean Sea (Rohling and Hilgen 1991). Overall, the increase in the sea's freshwater deficit will contribute to increased salinity. The degree of the salinity increase will depend on the strength of the fresh water input from the Atlantic Ocean at the Gibraltar Strait.

Regional climate change projections typically suffer from major uncertainties, with models often not even agreeing on the direction of change (IPCC 2007), but model consistency regarding 21st century Mediterranean water cycle change is among the highest globally. Most models show a decrease in $P - E$ already by 2020–2049, all by 2070–2099 (figure 1 and figure 3S (available at stacks.iop.org/ERL/3/044001)). By 2070–2099, all models show a decrease in precipitation and an increase in evaporation over the sea; most show a more moderate decrease in evaporation on land. Fresh water deficit increase over the sea is estimated between −0.25 and −0.55 mm/d.

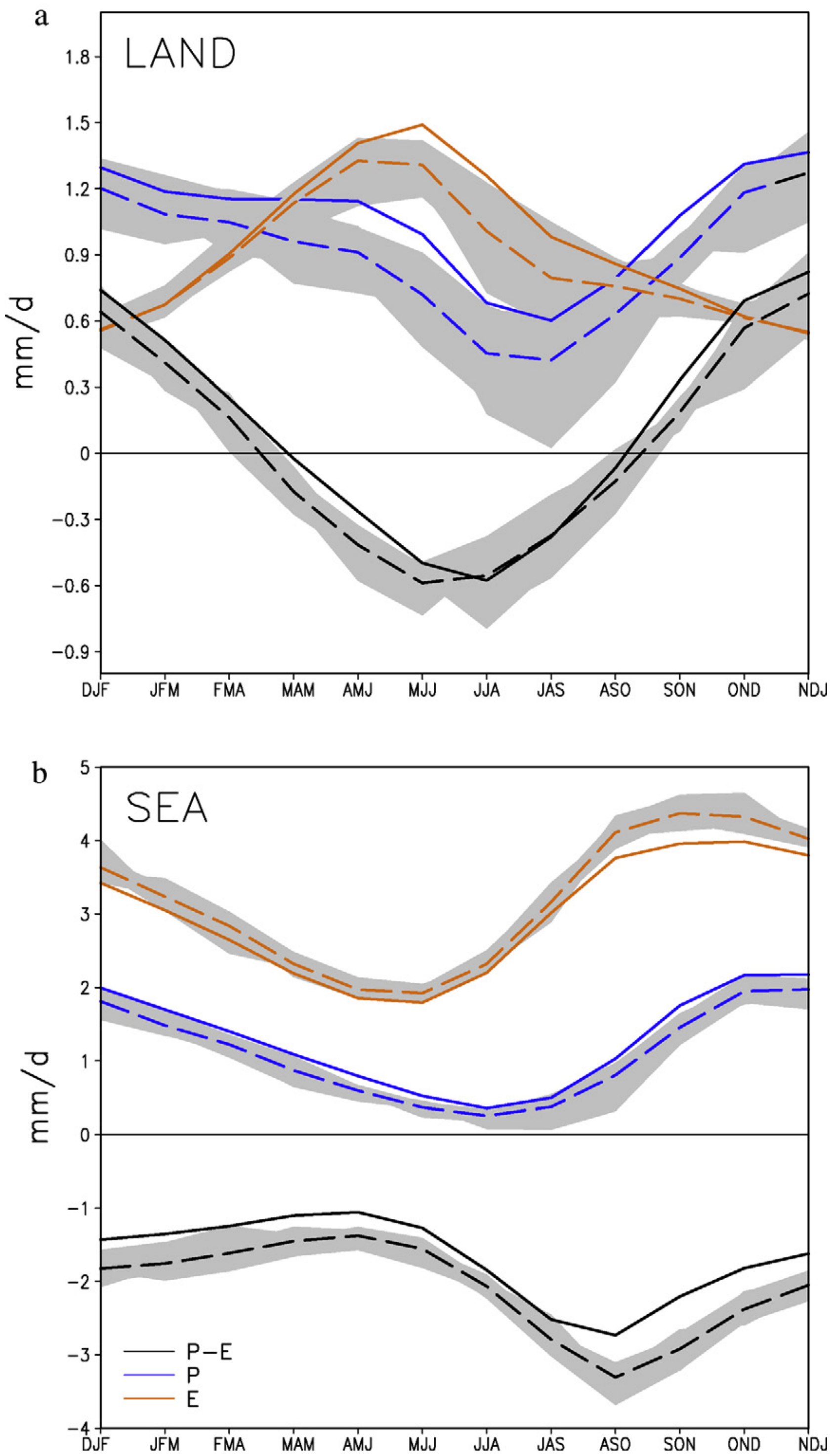

Figure 2. Mediterranean water cycle in 2070–2099 (dashed) compared to the 1950–2000 period (solid) based on an average of CMIP3 model simulations. Shown are the seasonal cycles of evaporation (brown), precipitation (blue) and precipitation minus evaporation (black). For each, gray shading depicts the envelope of individual model anomalies. (a) Land-only. (b) Sea-only.

4. Seasonal and spatial characteristics of projected mean changes

Precipitation is projected to decrease throughout the year and particularly during the dry season (figure 2; about −10% and −23% for the wet and dry seasons, respectively; see table 1). In contrast, most of the land evaporation decrease occurs during the summer dry season (−12%) when land surface aridity will be greatest. The combination of these changes results in a decrease in effective land precipitation that is similar during the wet and dry seasons (about 20%). Over the sea, freshwater deficit will increase throughout the year and particularly during

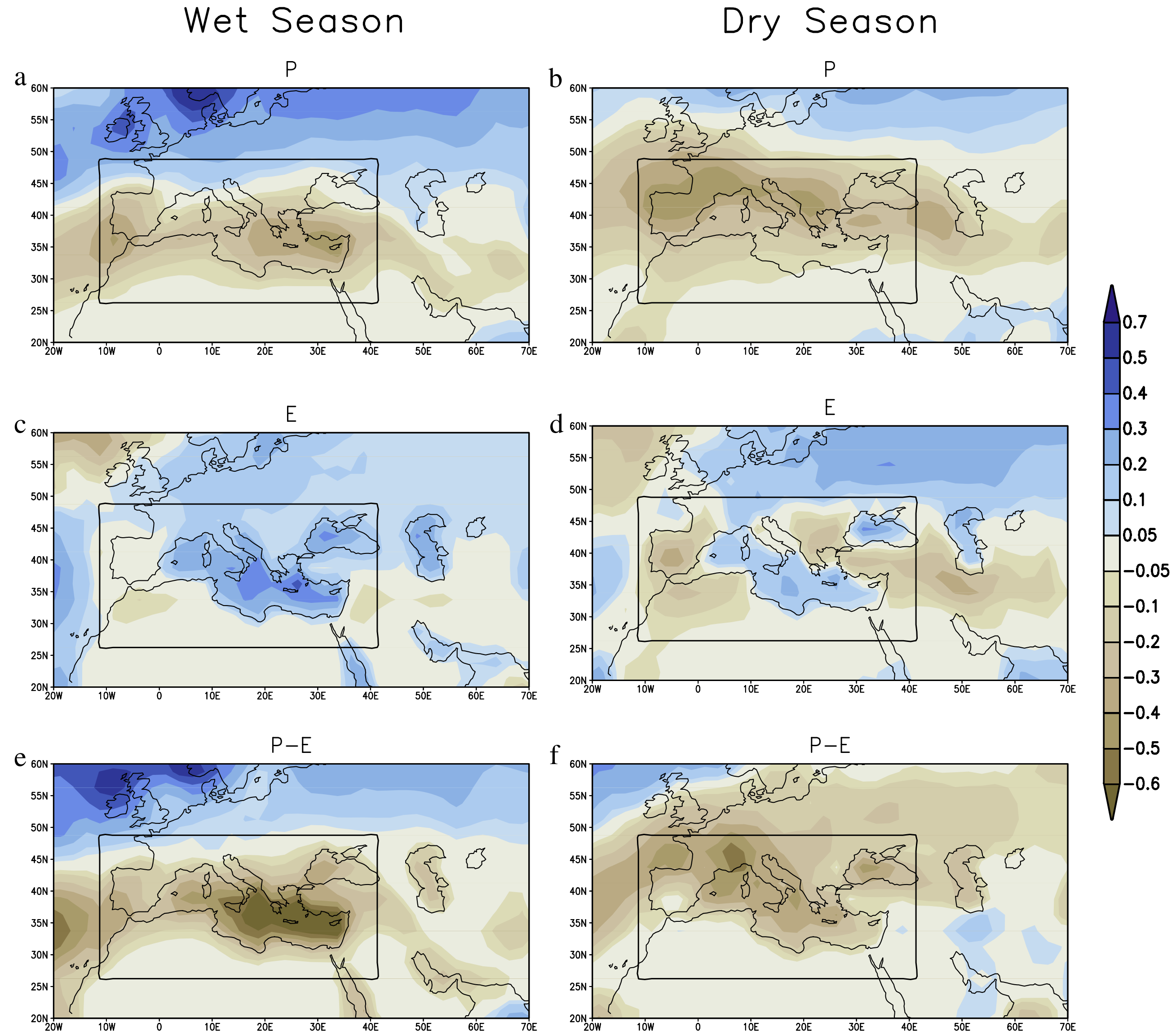

Figure 3. Mediterranean water cycle changes by 2070–2099 compared to 1950–2000 for the 'wet' and 'dry' seasons. Precipitation (a) and (b), evaporation (c) and (d), and precipitation minus evaporation (e) and (f). Anomalies are based on an average of CMIP3 model runs. For all, units are mm/d. The box broadly depicts the Mediterranean region.

the wet season (29%) when evaporation increase will be at a maximum (about 7%).

The pattern of maximum precipitation changes (in absolute sense) has a general South to North migration going from winter into summer, following the climatological seasonal cycle of precipitation (figure 3). During the wet season, precipitation decreases South of 42°N, with a maximum decrease around 35°N particularly in southeastern parts of the Mediterranean Sea and westernmost land regions. During the dry season, most of the precipitation decrease will occur in northern parts between 40°N and 45°N as the southern part has near zero climatological rainfall. The southeastern Mediterranean Sea during the wet season will see the greatest overall $P - E$ decrease, as this is where most of the precipitation decrease and evaporation increase occurs. The wet season $P - E$ decrease over land is mostly driven by precipitation decrease. During the dry season, decrease in land evaporation over southern parts leads to smaller $P - E$ decrease over these regions. Central and northwestern parts of the Mediterranean region will experience maximum surface fresh water loss during this season. Overall, it is over the Mediterranean Sea that $P - E$ anomalies are particularly outstanding if compared with the inter-model variance (figure 4S (available at stacks.iop.org/ERL/3/044001)). The general features of the patterns of change described above will already be in place by 2020–2049 with anomalies progressively intensifying by 2070–2099 (figure 5S (available at stacks.iop.org/ERL/3/044001)).

5. Observed 20th century changes

CMIP3 simulations for the 20th century suggest that the impact of greenhouse gas increase (IPCC 2007) may have already been manifesting itself in the Mediterranean region as

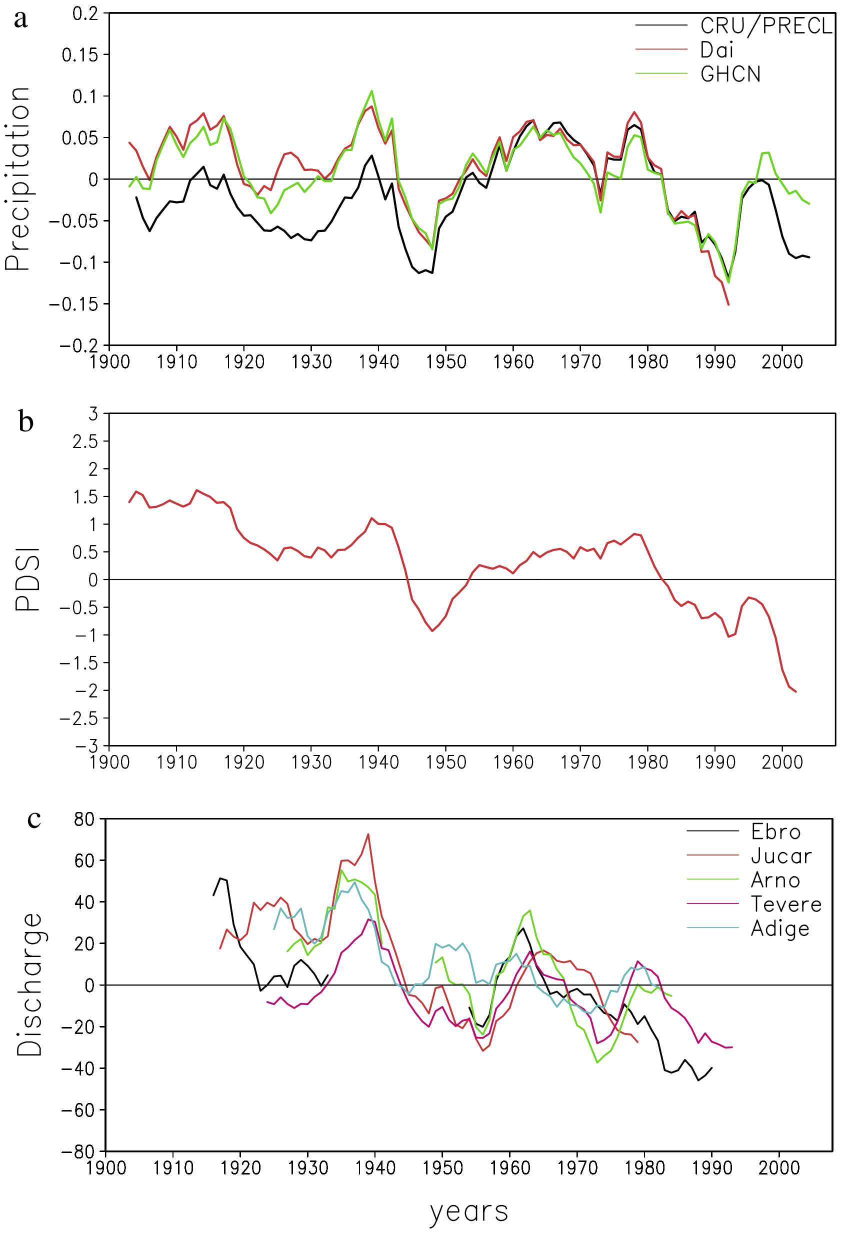

Figure 4. Mediterranean water cycle changes observed during the 20th century relative to the period 1950–2000. Area-averaged annual mean precipitation anomalies (six years running means) from various datasets (panel a; mm/d) and PDSI (panel b; au); discharge anomalies (units are % of climatology) for various Mediterranean rivers (panel c). Due to data availability, discharge anomalies are relative to the 1960–1980 period.

a tendency toward drier and warmer conditions (figure 1 and figure 1S (available at stacks.iop.org/ERL/3/044001)). Diverse observational evidence appears to support this case (figure 4 and figure 1S (available at stacks.iop.org/ERL/3/044001)). A weak albeit significant long-term negative precipitation trend is found in both GHCN and DAI data (for GHCN this is −0.005 ± 0.003 mm/d per decade); instead, CRU/PRECL data shows no trend, likely an artifact from combining two datasets. CMIP3 simulated precipitation trend is somewhat higher than that from GHCN or DAI data, possibly suggesting a tendency for the models to exaggerate future precipitation decrease. In all datasets, winter season precipitation shows a major downward deviation over the period 1960–2004 (−0.09 ± 0.02 mm/d per decade), with interdecadal variations (a decrease during the period mid-1960s to early-1990s and an increase after that) largely related to the behavior of the North Atlantic Oscillation (Hurrell 1995) (figure 6S (available at stacks.iop.org/ERL/3/044001)). Dry season negative trends over the period 1950–2000 have also been observed in relation to a blocking-like pattern deflecting storms away from much of western and southern Europe (Pal *et al* 2004). The PDSI, which reflects the combined effects of precipitation and surface temperature changes, shows a progressive and substantial drying of the land surface over this region since 1900 (−0.2 PDSI units/decade) consistent with a decrease in precipitation and an increase in T_s (figure 1S (available at stacks.iop.org/ERL/3/044001)). The interdecadal fluctuations are similar to those of precipitation, with the wetter 1960s compared to the drier 1940s. Most Mediterranean rivers for which long-time series are available also show long-term decreases in discharge during the 20th century. While such a decrease could be in part due to intensified water use, we suspect an important contribution from the general drying trend. Mediterranean SST have increased during the course of the 20th century (figure 1S (available at stacks.iop.org/ERL/3/044001)) suggesting an increase in evaporation over the sea. Mediterranean Sea water salinity has been observed to be steadily increasing in recent decades (Bethoux *et al* 1998, Millot *et al* 2006, Roether *et al* 1996), which is consistent an increased sea fresh water deficit.

6. Discussion and concluding remarks

CMIP3 simulations show how precipitation and evaporation changes will concur to determine even greater alterations of 21st century Mediterranean water cycle characteristics, with contrasting behavior over land and sea. By 2070–2099, the average of the models predicts a 20% decrease in land surface water availability, with a decrease in soil moisture and river runoff, and a 24% increase in the loss of fresh water over the Mediterranean Sea due to precipitation reduction and warming-enhanced evaporation. This will result in an increased export of atmospheric moisture out of the Mediterranean to surrounding regions.

The linkage between observed and simulated 20th century hydroclimatic changes lends confidence to 21st century projections of a progressive drying of the Mediterranean region. These are also supported by a good level of understanding of the mechanisms, including a general increase in moisture divergence across the sub-tropical dry zones, a result of mean climatological moisture divergence and rising humidity; the northward expansion of the Atlantic Hadley Cell (Held and Soden 2006, Lu *et al* 2007, Seager *et al* 2007) (see figure 7S (available at stacks.iop.org/ERL/3/044001)) and, to a large extent, a positive trend of the Northern Hemisphere Annular Mode (Previdi and Liepert 2007). During the dry season, local processes involving increased land–sea temperature contrasts and decreased soil moisture and vegetation have been identified as important in future regional precipitation reduction (Rowell and Jones 2006).

Despite the remarkably high degree of model consistency, one major caveat exists specifically regarding Mediterranean climate change projections (see Deque *et al* (2007) for a general assessment of uncertainties in model projections over Europe). Current IPCC-AR4 class models, in view of their limited resolution, fail to adequately represent the exchange of Mediterranean and Atlantic waters at the Gibraltar Strait. Hence, it is arguable whether they are able to realistically represent mean Mediterranean Sea circulation and its potential changes. The effect of this limitation on the projections presented here still needs to be evaluated. As the next generation of climate projections is being developed, it is important to improve our capability to monitor Mediterranean water cycle characteristics and understand their variability so as to be able to detect future long-term changes early-on.

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