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Impact of Large-scale Circulation on Precipitation Events in the Mediterranean Region

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1. Introduction

The Mediterranean region is located in-between the dry, subtropical Saharan and the relatively wet European climates, making it highly sensitive to changes in the mean climate state. Long-term atmospheric circulation changes, either radiatively forced or caused by intrinsic climate features, will likely impact the future Mediterranean hydroclimate. Nevertheless, observations are neither sufficiently long nor homogenous to diagnose robust, low-frequency patterns allowing decadal-scale future predictions. Long control simulations can serve as a good alternative. However, they often struggle to correctly reproduce the main mechanisms controlling Mediterranean hydroclimate and have resolutions that are too coarse to realistically simulate extreme hydroclimatic phenomena.

In this study, long free control simulations of the GFDL CM2.1 and CM2.5 global couple models are analyzed to derive a representation of the large-scale circulation variability in the subtropical-midlatitude section and determine its relationship to the Mediterranean mean and extreme hydroclimate. These results serve as a basis for further analysis and investigation of possible changes in atmospheric circulation under the influence of anthropogenic forcing and associated effects on the Mediterranean hydroclimate.

2. Data and methodology

Low-frequency variability of large-scale circulation over the North Atlantic region is analyzed, using GFDL CM2.1 and CM2.5 control simulations with fixed radiative forcing at levels from the year 1860. GFDL CM2.1 provides 4000yrs data with 2ºx2º horizontal resolution. GFDL CM2.5 provides 1000yrs data on 0.5º x 0.5º horizontal resolution. Analysis was performed on data for the December – February season (DJF). The climatological mean is computed for SLP and precipitation values in DJF season. Multi-Channel Singular Spectrum Analysis (MSSA, Plaut and Vautard 1994, Allen and Smith 1996, Moron *et al.* 1998, Ghil *et al.* 2002) was used to isolate fingerprints of multi-decadal scale ocean-atmosphere components. Prior to the analysis, winter data of sea level pressure (SLP), sea surface temperature (SST) and precipitation were interpolated to 5ºx5º horizontal grid, standardized to zero mean and unit variance. Statistical significance of derived components has been tested against the red noise hypothesis, using Chi-Square test.

3. The mean state and variability of winter circulation over the North Atlantic simulated with low-resolution CM2.1 and high-resolution CM2.5

Atmospheric circulation in midlatitudes is shaped by the intensity of the meridional SLP gradient, which determines zonal mean flow and direction of storm tracks transporting moisture towards Europe and North Africa. It is usually northwardly deviated, due to the land-sea contrast. Therefore, simulated mean zonal flow, as well as the climatology of North Atlantic storms and their impact on Mediterranean hydroclimate, is usually better represented in simulations with finer horizontal resolution (Nakamura and Wallace 1993, Woolings *et al.* 2010, Jung *et al.* 2012).

Atmospheric flow in both CM2.1 and CM2.5 shows realistic features including a strong SLP gradient between Iceland and the subtropical band. As expected, the SLP gradient is better captured by CM2.5, in comparison with the overly zonal gradient in CM2.1. Isobars in CM2.5 are tilted northeastward. This is also

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consistent with an improved precipitation pattern over N Atlantic (NA), which in CM2.5 is extended and oriented north-eastwardly, towards region between Great Britain and Iceland.

Simulated large–scale circulation over the North Atlantic shows pronounced low-frequency variability, which modulates mean atmospheric flow in the NA and European sector. Spatio-temporal features of those components, similarly for both models, closely resemble the observation-based North Atlantic Oscillation (NAO) and East Atlantic (EA) patterns. Here we present fingerprints of coupled atmosphere-ocean components dominating multi-decadal variability, which have been isolated using MSSA.

The first component is an oscillatory mode with a time scale of ~45-48 yrs (herafter referred to as RC45). Figure 1a,b shows that its spatial pattern strongly resembles a NAO pattern, with an out-of phase SLP relationship between the Icelandic Low and Azores High and a characteristic tripole SST pattern. Reconstructed time series for those regions (rc SLP 30-40°N, rc SLP 60-70°N), as shown in Figure 1c, confirm strong anticorrelation and explain up to 18% (for rc SLP 35-45°N) of SLP decadal variance (smoothed with a 10-yr filter). Reconstructed SST changes, centered in the subpolar gyre, northern equatorial region and subtropical gyre, contributes mostly to the SST along the Gulf Stream (30-40°N, 70-50°W), accounting for more than 27% of SST (decadal) variance.

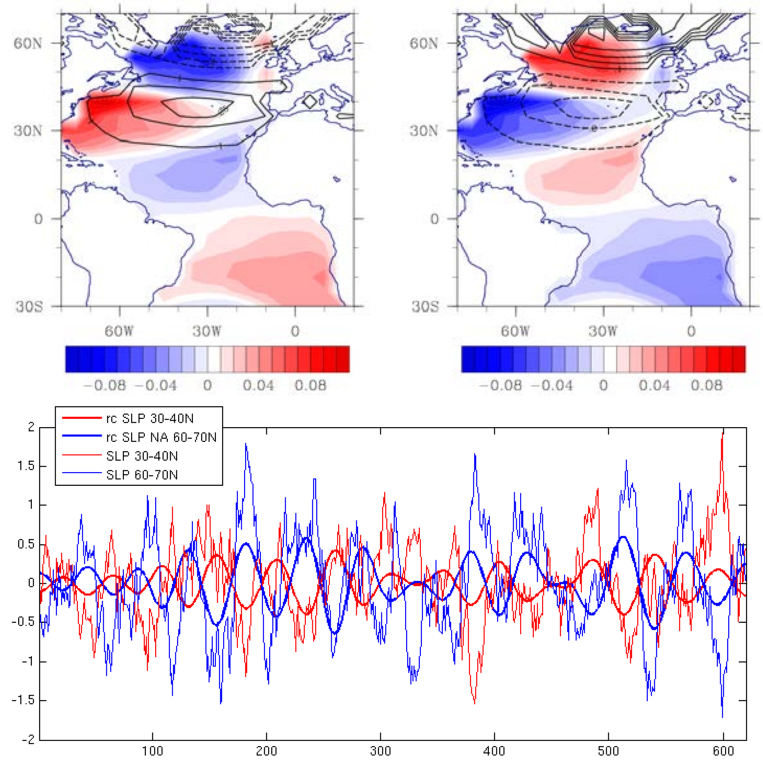

Fig. 1 Signature of RC45 component [SLP, contours; SST, shaded], represented in the GFDL CM2.5 model, during positive/negative (left/right) phase. Shown are trend coefficients of SST [C/decade] and SLP [hPa/decade]. Action is centered over mid- and high-latitudes. Pattern of SLP anomalies resembles signature of positive/negative NAO phase: dipole with opposite sign anomalies centered over Azores Islands and Iceland.

The second component has a longer period, which varies between ~55-62 yrs (hereafter referred to as RC60). Figure 2a,b shows that the spatial pattern of RC60 strongly resembles features of the East Atlantic pattern (EA) pattern (Barnston and Livezey, 1987; Woolings *et al.* 2010; Moore and Renfrew 2012; Murphy and Washington, 2001). It is centered along the 53°N latitude band, where it accounts for more than 22% of decadal SLP.

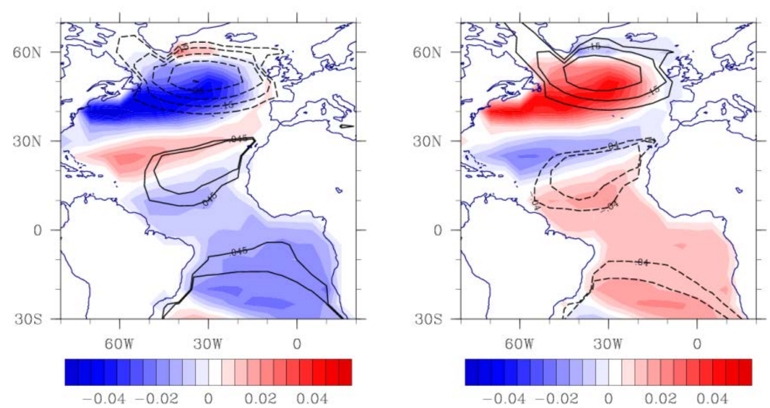

Fig. 2 Signature of RC60 component [SLP, contours; SST, shaded], represented in the GFDL CM2.5 model, during two opposite phases. Shown are linear regression trend coefficients. Action regions are shifted southward, with lower-latitude center located in the subtropical area.

Interannual variability of NAO, has been shown to have an impact on Mediterranean winter hydroclimate in numerous studies (Corte-Real *et al.* 1998, Trigo *et al.* 2002, Gomes 2001, Gomes 2006). Mariotti and Dell' Aquilla (2012) suggested that NAO could explain up to 30% of winter decadal variance in Mediterranean precipitation. The EA pattern has been studied less extensively, but some studies highlighted its importance for various aspects of European climate, *e.g.* precipitation in the Iberian Peninsula and location of storm track over North Atlantic (*e.g.* Seierstadt 2007, Vicente-Serrano and Lopez-Moreno 2008, Moore *et al*. 2011).

In the next part, we will investigate a relationship between reconstructed North Atlantic large-scale circulation components (RC45 and RC60) and Mediterranean hydroclimate.

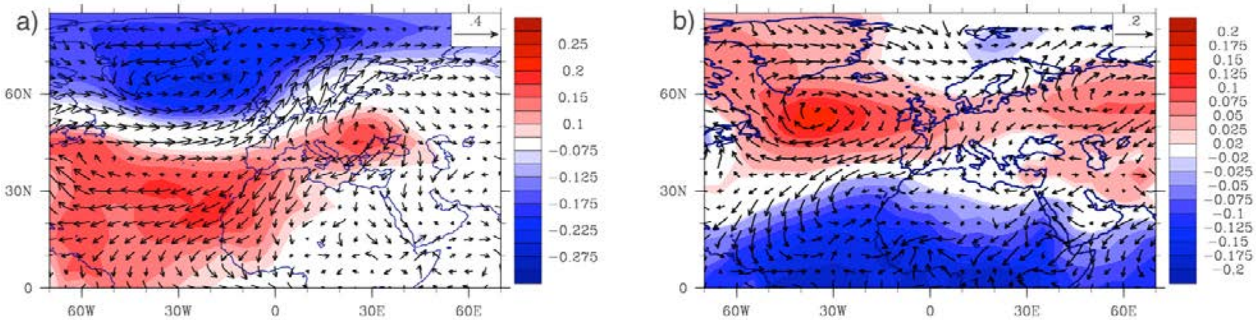

Fig. 3 Composites of SLP and wind components anomalies tendencies ([%/decade], anomalies normalized to unit variance) for a) RC45 and b) RC60 components of the GFDL CM2.5 model.

4. Relationship between derived large-scale circulation components (RC45 and RC60) and Mediterranean hydroclimate

Reconstructed with RC45 and RC60 large-scale atmospheric changes over North Atlantic are reflected in sea level pressure, wind components, vorticity and precipitation fields over Europe and N Africa. Composites of SLP and wind vectors (Figure 3a), constructed for the positive and negative RC45 phase show a north-eastward extension of anomalous atmospheric flow towards Europe and Mediterranean. Linear regression on DJF SLP in RC45 depicts almost zonal bands of opposite sign in the 30-40N latitude band and in the vicinity of Icelandic Low for both vorticity and precipitation fields. Precipitation anomalies in the subtropical band extend further east through the south Iberian Peninsula, the coasts of north-east Africa and north-eastward to the Balkan region in the north-east part of Mediterranean. The out-of-phase relationship between SLP and vorticity suggests that derived changes in precipitation and associated anomalous circulation in RC45 SLP are due to the low-level convergence (divergence) facilitating condensation of precipitable water.

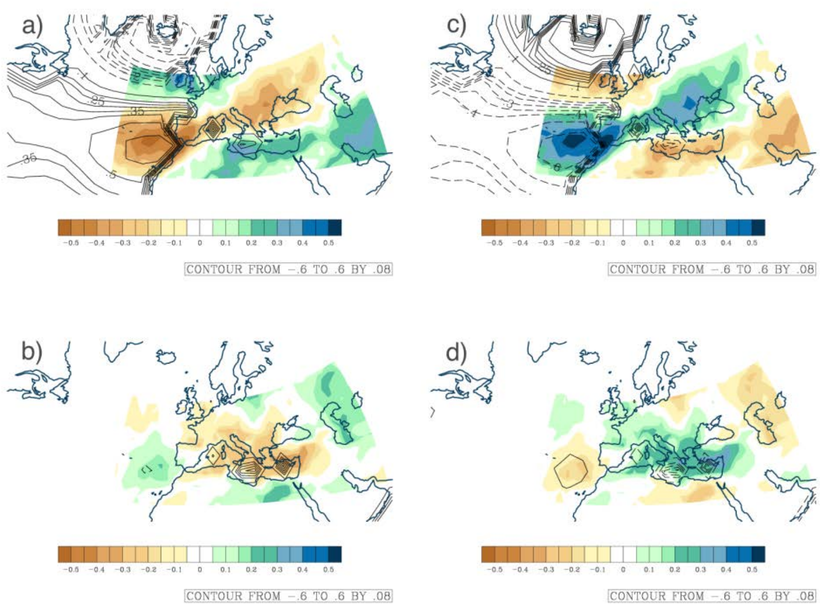

Fig. 4 Signature of RC45 component, represented with SLP (contours) and precipitation (shaded) anomalies in GFDL CM2.5 model, during four phases: positive (a) /negative(c), and two transition phases (b,d). Shown are linear regression trend coefficients, which represent decadal change ([%/decade].

Additionally, composites of SLP and wind vectors, derived for the positive (Figure 3b) RC60 phase, imply a remarkable influence on atmospheric flow over Europe and Mediterranean. Anticyclonic anomalies in the midlatitudes extend eastward across Central Europe, while cyclonic anomalies, associated with strengthened easterly trade winds over subtropical North Atlantic, spread eastward across North and Central Africa and West Indian Ocean. A strengthened SLP gradient and northward vorticity shift suggest a northward shift of transient eddies transporting moisture, which is consistent with negative precipitation anomalies over Mediterranean Sea, Mediterranean region and South Italy, Adriatic Sea countries.

4.1 Association of atmospheric circulation and Mediterranean hydroclimate

Application of MSSA analysis allows also for detailed description of the spatio-temporal evolution of derived coupled ocean–atmosphere mechanism. Figure 4 presents four phases of the RC45 cycle reconstructed with SLP and precipitation anomalies. It depicts a link between the meridional contrast in SLP anomalies and the contrast between the north-vs-south part of Mediterranean precipitation. Phase A and C, similarly to Figure 1, resemble a standard NAO pattern, with out-of–phase SLP variability between regions surrounding Iceland and the Azores Islands. Intensified precipitation (phase C)/drying (phase A) anomalies, associated with cyclonic/anticyclonic circulation over subtropical North Atlantic and Mediterranean, are most pronounce in the south Iberian Peninsula and Strait of Gibraltar. Those anomalies extend through the north Mediterranean up to the eastern Europe and Black Sea. As Figure 4a indicates, precipitation anomalies in Black Sea region area are collocated with strong divergent (convergent) during phase A (phase C) wind field and are associated with northwesterly export of moisture. Southward moisture transport leads to the opposite sign precipitation anomalies in the south Mediterranean and the Gulf of Persia. Phase B and D are transient phases, with SLP anomalies changing sign and precipitation anomalies rotated clockwise. Drying tendencies, observed in the Black Sea region during phase A, are during phase B shifted southward. At the same time, wetting (drying) tendencies emerge in the vicinity of Iberian Peninsula, and intensify and propagate through the north Mediterranean until phase C is reached.

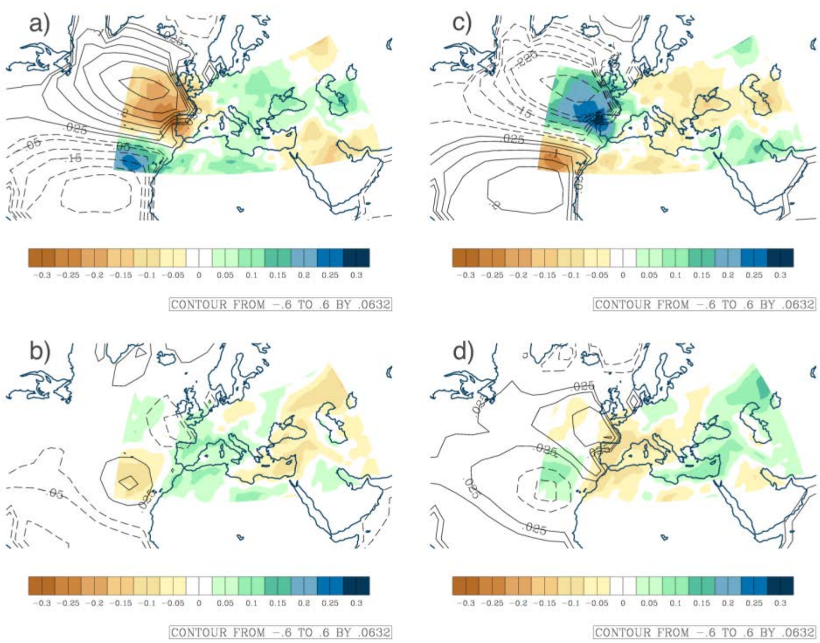

Fig. 5 Like in Figure 4, except for RC60 component.

Figure 5 depicts four phases of the RC60 cycle. Out-of–phase atmospheric variability (phase A and C), between midlatitudes and tropical-subtropical regions, leads to the latitudinal contrast in precipitation tendencies between Iberian Peninsula and south Mediterranean region. Anomalous in phase A (C) cyclonic (anticyclonic) circulation in the subtropical region extends eastward (Figure 3b) and coincides with positive precipitation anomalies mostly in the west and central part of the south Mediterranean region. At the same time, positive SLP anomalies in the midlatitude NA (Figure 3b) coincide with drying tendencies over whole Iberian Peninsula.

The model-based relationship between North Atlantic low-frequency atmospheric circulation changes and Mediterranean hydroclimate described here is consistent with observation-based studies. The high contribution of low-frequency NAO-type simulated variability in the Iberian Peninsula confirms Mariotti and Dell' Aquilla 2012, who showed NAO accounting up to 30% of winter decadal changes. Gomes 2011, applying MSSA analysis to the winter SLP and precipitation fields, identified a quasi-decadal scale oscillatory component with a spatio-temporal evolution that closely resembles our model-based component.

5. Summary

The GFDL CM2.1 and CM2.5 models have been shown to provide a reliable representation of large-scale circulation over North Atlantic, Europe and N Africa. This representation is better captured by high resolution CM2.5, which further leads to the improved simulated precipitation fields.

Analysis of long control runs allowed us to investigate the main components of multidecadal climate variability in the North Atlantic sector and their impact on low-frequency changes in the Mediterranean hydroclimate. Multi-channel singular spectrum analysis (MSSA) was applied to isolate spatio-temporal patterns of two components, RC60 and RC45, which together dominate the coupled ocean-atmosphere multidecadal variability over the Northern Atlantic and a large part of Europe. These components resemble the observed North Atlantic Oscillation and Eastern Atlantic Pattern (Hurrell 1995, Hurrel *et al.* 2003). Both modulate the winter mean state atmospheric flow over the North Atlantic and European regions in their own unique way, which impacts precipitation over North Africa, the Mediterranean Sea and southern Europe on decadal time scales.

The results shown here also provide useful information for detection and attribution studies. Multidecadal-scale climate changes, caused here only by intrinsic climate variability, significantly impact atmospheric circulation and hydroclimate changes. This suggests that separating internal climate variability signal from anthropogenic forcing will require observational data sets much longer than those currently available.

These results provide a necessary foundation for further research investigating the influence of anthropogenic forcing on large-scale atmospheric circulation and its associated effects on the Mediterranean hydroclimate.

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