

*The dependence of wintertime
Mediterranean precipitation on the
atmospheric circulation response to
climate change*

Article

Published Version

Creative Commons: Attribution 3.0 (CC-BY)

Zappa, G., Hoskins, B. J. and Shepherd, T. G. ORCID:
<https://orcid.org/0000-0002-6631-9968> (2015) The
dependence of wintertime Mediterranean precipitation on the
atmospheric circulation response to climate change.
Environmental Research Letters, 10 (10). 104012. ISSN 1748-
9326 doi: <https://doi.org/10.1088/1748-9326/10/10/104012>
Available at <https://centaur.reading.ac.uk/43571/>

It is advisable to refer to the publisher's version if you intend to cite from the work. See [Guidance on citing](#).

To link to this article DOI: <http://dx.doi.org/10.1088/1748-9326/10/10/104012>

Publisher: Institute of Physics

All outputs in CentAUR are protected by Intellectual Property Rights law, including copyright law. Copyright and IPR is retained by the creators or other copyright holders. Terms and conditions for use of this material are defined in the [End User Agreement](#).

www.reading.ac.uk/centaur

CentAUR

Central Archive at the University of Reading

Reading's research outputs online

The dependence of wintertime Mediterranean precipitation on the atmospheric circulation response to climate change

This content has been downloaded from IOPscience. Please scroll down to see the full text.

2015 Environ. Res. Lett. 10 104012

(<http://iopscience.iop.org/1748-9326/10/10/104012>)

View [the table of contents for this issue](#), or go to the [journal homepage](#) for more

Download details:

This content was downloaded by: gzappa

IP Address: 134.225.31.10

This content was downloaded on 14/10/2015 at 16:30

Please note that [terms and conditions apply](#).

Environmental Research Letters



LETTER

The dependence of wintertime Mediterranean precipitation on the atmospheric circulation response to climate change

OPEN ACCESS

RECEIVED
22 July 2015REVISED
5 September 2015ACCEPTED FOR PUBLICATION
15 September 2015PUBLISHED
14 October 2015Giuseppe Zappa¹, Brian J Hoskins and Theodore G Shepherd

Department of Meteorology, University of Reading, Reading, UK

¹ Author to whom any correspondence should be addressed.E-mail: g.zappa@reading.ac.uk

Keywords: mediterranean precipitation, climate change, atmospheric circulation, CMIP5

Content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](https://creativecommons.org/licenses/by/3.0/).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.



Abstract

Climate models indicate a future wintertime precipitation reduction in the Mediterranean region but there is large uncertainty in the amplitude of the projected change. We analyse CMIP5 climate model output to quantify the role of atmospheric circulation in the Mediterranean precipitation change. It is found that a simple circulation index, i.e. the 850 hPa zonal wind (U850) in North Africa, well describes the year to year fluctuations in the area-averaged Mediterranean precipitation, with positive (i.e. westerly) U850 anomalies in North Africa being associated with positive precipitation anomalies. Under climate change, U850 in North Africa and the Mediterranean precipitation are both projected to decrease consistently with the relationship found in the inter-annual variability. This enables us to estimate that about 85% of the CMIP5 mean precipitation response and 80% of the variance in the inter-model spread are related to changes in the atmospheric circulation. In contrast, there is no significant correlation between the mean precipitation response and the global-mean surface warming across the models. It follows that the uncertainty in cold-season Mediterranean precipitation projection will not be narrowed unless the uncertainty in the atmospheric circulation response is reduced.

1. Introduction

Mediterranean countries critically depend on the rainfall falling during the cold season for their agricultural and societal needs. This makes the region prone to water stress conditions, and highly susceptible to rainfall deficits in the year to year variability. This precarious hydrological balance is projected to further deteriorate because of anthropogenic climate change, as climate models indicate a future reduction in Mediterranean precipitation and increased soil aridity in response to increasing greenhouse gas concentrations (Giorgi and Lionello 2008, Alessandri *et al* 2014). Furthermore, gauge-based reconstructions indicate that a negative wintertime precipitation trend has already occurred in the 20th century (Hoerling *et al* 2012). However, the extent that anthropogenic climate change has contributed to the observed trend is still unknown due to uncertainties in the observational record in the early part of the century and limited knowledge of the amplitude of internal climate

variability on multi-decadal to centennial timescales (Hoerling *et al* 2012, Kelley *et al* 2012a, 2012b, Mariotti *et al* 2015).

Adaptation planning to this scenario of increasing water stress conditions would be made much easier and less costly if there was increased confidence in the amplitude of the Mediterranean precipitation reduction. However, different global climate models project substantially different precipitation responses to a given scenario of future greenhouse gas concentrations and this constitutes the largest source of uncertainty in the Mediterranean precipitation projections by the end of the 21st century (Giorgi and Lionello 2008). Reducing this uncertainty ultimately requires a better understanding of the mechanisms controlling Mediterranean precipitation under climate change.

The thermodynamic increase in lower tropospheric specific humidity due to surface global warming is expected to directly impact moisture fluxes and precipitation regardless of any changes in atmospheric

circulation. In particular, this *thermodynamic* mechanism generally leads to wet regions getting wetter and dry regions drier (Held and Soden 2006). However, changes in atmospheric and oceanic circulation can also globally impact precipitation, for example by affecting the location of extratropical storm tracks, the meridional extent of the Hadley cell circulation or by altering sea surface temperature patterns (e.g. Seager *et al* 2010, Chadwick *et al* 2013). Climate model projections indicate a future increase in the Mediterranean mean surface pressure, an increase in the frequency of anticyclonic circulation, and a weakening of the local Mediterranean storm track (Lionello and Giorgi 2007, Rojas *et al* 2013, Seager *et al* 2014, Zappa *et al* 2015a). These changes suggest that the atmospheric circulation response to climate change might lead to a future reduction in Mediterranean precipitation, which was supported by analyses of the Mediterranean moisture budget (Seager *et al* 2014) and of the precipitation change associated with Mediterranean cyclones (Zappa *et al* 2015a). Consistently, Polade *et al* (2014) notes that it is a change in the number of dry days, rather than in the mean precipitation per rainy day, which most contributes to the precipitation reduction in the subtropics, including most of the Mediterranean area.

This work explores the potential to use the atmospheric circulation response to climate change to estimate the Mediterranean precipitation response in individual climate models. This enables us to evaluate the role of atmospheric circulation as a source of uncertainty in the Mediterranean precipitation projections. In particular, for each model participating in the fifth phase of the Coupled Model Intercomparison Project (CMIP5), we investigate the relationship between Mediterranean precipitation and atmospheric circulation in the inter-annual variability, and use this relationship to estimate the precipitation change related to the atmospheric circulation response. A similar approach has already been applied to evaluate the role of atmospheric circulation for the wintertime precipitation response in California (Chang *et al* 2015) and for the summertime European precipitation response (Bladé *et al* 2012, van Haren *et al* 2015), but it has not previously been applied to analyse the Mediterranean area in the cold season.

2. Data and methods

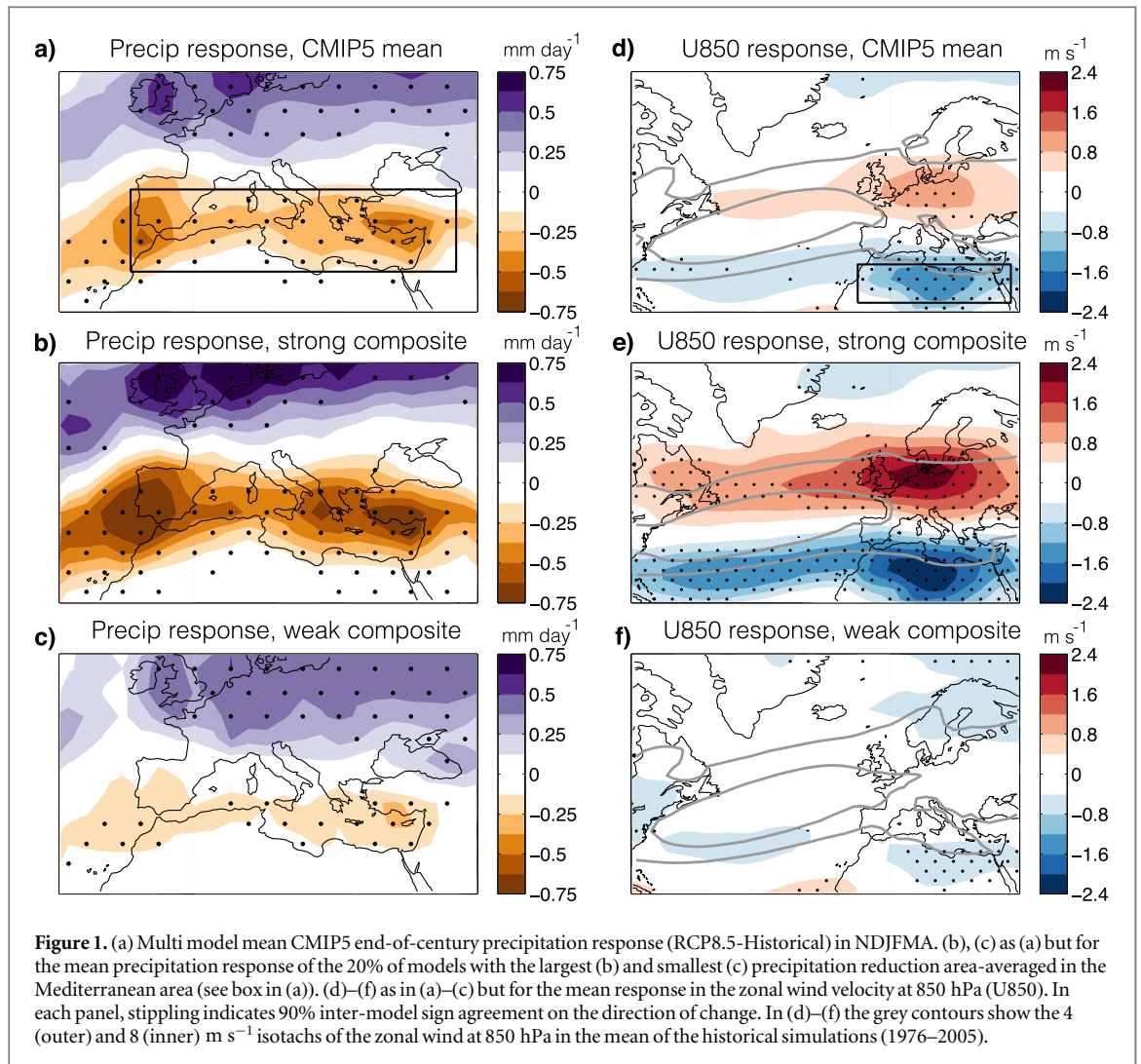
35 CMIP5 coupled climate models (Taylor *et al* 2012) are analysed in this study (see table 1). For each model, the climate change response is evaluated as the difference between a 30-year time mean in the RCP8.5 scenario (2070–2099) minus a 30-year mean in the historical simulation (1976–2005), and all the available ensemble members are considered in order to better sample the model climate statistics. The European Centre for Medium Range Weather Forecasts Interim

Table 1. List of CMIP5 models considered in the study. For each model the number of analysed runs in the HISTORICAL (HIST) and RCP8.5 simulations are indicated.

	Basic information		# runs	
	Model name	Institution	HIST	RCP8.5
1	ACCESS10	CSIRO-BOM, Australia	1	1
2	ACCESS13		3	1
3	BCC-CSM1-1		3	1
4	BCC-CSM1-1m	BCC, China	3	1
5	BNU-ESM	BNU, China	1	1
6	CCSM4	NCAR, USA	6	6
7	CESM1-CAM5		3	3
8	CESM1-WACCM	NSF-DOE-NCAR, USA	4	3
9	CMCC-CESM		1	1
10	CMCC-CM	CMCC, Italy	1	1
11	CMCC-CMS		1	1
12	CNRMCM5	CNRM, France	5	3
13	CSIRO-mk360	CSIRO, Australia	10	10
14	CanESM2	CCCma, Canada	5	5
15	EC-EARTH	European Consortium, Europe	5	5
16	FGOALS-G2	LASG, China	4	1
17	FIO-ESM	FIO, China	3	3
18	GFDL-CM3		5	1
19	GFDL-ESM2G	GFDL, USA	1	1
20	GFDL-ESM2M		1	1
21	GISS-E2H		5	1
22	GISS-E2R	NASA GISS, USA	5	1
23	HadGEM2-ES		4	4
24	HadGEM2-CC	MOHC, UK	3	3
25	INMCM4	INM, Russia	1	1
26	IPSL-CM5A-LR		5	4
27	IPSL-CM5A-MR	IPSL, France	3	1
28	IPSL-CM5B-LR		1	1
29	MIROC-ESM		3	1
30	MIROC-ESM-CHEM	MIROC, Japan	1	1
31	MIROC5		5	3
32	MPI-ESM-LR		3	3
33	MPI-ESM-MR	MPI-M, Germany	3	1
34	MRI-CGCM3	MRI, Japan	3	1
35	NORESM1-m	NCC, Norway	3	1

Reanalysis (ERA-Interim) and the Global Precipitation Climatology Project (GPCP) dataset are used to characterize the monthly mean atmospheric circulation and precipitation in the real world, both for 1979–2013.

The time mean zonal wind velocity at 850 hPa (U850) is used to quantify the climate change response in the atmospheric circulation. U850 is linked to the eddy driven jet and storm track activity (Woollings *et al* 2008) and, as shown in this paper, it well characterizes the atmospheric circulation associated with wintertime Mediterranean precipitation. Both the climate change response and the relationship between U850 and precipitation in the internal climate variability are evaluated for the 6-month November–April



time mean. Zappa *et al* (2015b) show that this temporal average is optimal to maximize the ratio of the U850 climate change response (the signal) to the noise due to internal climate variability in the Euro-Atlantic sector in the cold season, as well as that of precipitation over the Central European and Mediterranean regions. Zappa *et al* (2015b) also show that the climate change response (in 30-year means) in these fields relative to 1960–1990 will emerge within the next decade (by 2025) according to the models with a strong response. All the data has been first interpolated to a common low resolution T42 grid, using bilinear interpolation for U850 and using a conservative remapping method (Jones 1999) for precipitation.

3. Results

Figure 1(a) shows the extended winter (November–April) mean precipitation response to climate change in the CMIP5 multi-model mean. As in previous analyses (e.g. Collins *et al* 2013), precipitation is projected to increase in Europe north of the Alps, and to decrease in most of the Mediterranean area,

particularly close to Gibraltar and in the East Mediterranean region, e.g. Southern Turkey and the Middle-East. Both the increased precipitation to the north and the reduced precipitation to the south are robust in terms of inter-model agreement, with at least 90% of models showing a response of the same sign (stippling). However, models show substantial differences in the amplitude of the precipitation reduction. To visualize these differences, figures 1(b) and (c) show the multi-model mean precipitation response of the 20% of models with the largest and smallest precipitation change area-averaged within the box indicated in figure 1(a). A factor of about 3.5 is found on average between the Mediterranean precipitation response in the two sets of models. As will be shown in figure 4(b), the differences in the model responses mainly represent differences in the forced response rather than the effect of internal climate variability.

Figure 1(d) shows that the multi-model mean U850 response in the extended winter is characterized by a dipole between Central Europe, where the westerly zonal wind tends to increase, and North Africa, where it tends to decrease. Note that this zonal wind response implies an increased anticyclonic and/or

decreased cyclonic mean circulation in the Mediterranean area (Rojas *et al* 2013, Seager *et al* 2014). High inter-model agreement (stippling) on the direction of change is found in North Africa and, to a lesser extent, in Central Europe. By stratifying the models according to their Mediterranean precipitation response, figure 1(e) shows that the mean of the models with a strong Mediterranean precipitation reduction (as defined in figure 1(b)) is characterized by a U850 response with a pattern similar to that of the multi-model mean but twice the amplitude, and by more extended inter-model agreement. In contrast, figure 1(f) shows that the models with a weak Mediterranean precipitation response (as defined in figure 1(c)) have on average a very weak U850 response to climate change, with high inter-model agreement limited to the westward wind change in North Africa. This association in the inter-model spread between the Mediterranean precipitation and U850 responses is consistent with an influence of atmospheric circulation on future cold season Mediterranean precipitation (Hoerling *et al* 2012, Seager *et al* 2014, Zappa *et al* 2015a).

The westward wind change in North Africa is the only U850 multi-model mean signal which persists in the mean of the CMIP5 models with a weak Mediterranean precipitation reduction (figure 1). This suggests that U850 in North Africa might be dynamically linked to Mediterranean precipitation and a useful diagnostic to explain the precipitation change. To test this, we evaluate the impact that U850 circulation anomalies in North Africa have on Mediterranean precipitation in the inter-annual variability. In particular, we define P_{im}^{20c} as the area-averaged Mediterranean precipitation (see box in figure 1(a)) in year i and model m , and we define U_{im}^{20c} as U850 area-averaged in North Africa (see box in figure 1(d)), both in the historical simulations. Therefore, the inter-annual anomalies in the present day climate are given by

$$\delta P_{im}^{20c} = P_{im}^{20c} - \bar{P}_m^{20c} \quad (1)$$

$$\delta U_{im}^{20c} = U_{im}^{20c} - \bar{U}_m^{20c}, \quad (2)$$

where the overbar is the time mean in the historical period (1976–2005). δP_{im}^{20c} is plotted against δU_{im}^{20c} for all the CMIP5 models and years pooled together in the scatterplot of figure 2(a) (black dots). The two quantities are found to be strongly related ($r = 0.86$), with higher Mediterranean precipitation falling in the years characterized by more westerly zonal winds in North Africa. Furthermore, a similar relationship between Mediterranean precipitation and U850 in North Africa is also found in the real world data (figure 2(b)).

Interpreting this relationship requires caution as Mediterranean precipitation is not physically generated by zonal winds in North Africa, but primarily by the development of synoptic scale cyclones in the Mediterranean region (Zappa *et al* 2015a). However, it is well known that the development of Mediterranean

storminess and precipitation are strongly associated with the Euro-Atlantic low-frequency atmospheric circulation (Eshel and Farrell 2000, Quadrelli *et al* 2001, Dunkeloh and Jacobeit 2003, Xoplaki *et al* 2004, Krichak and Alpert 2005). The 850 hPa zonal wind velocity in North Africa is an excellent diagnostic of these atmospheric conditions and, consistently, we find it is strongly associated with the area-averaged Mediterranean precipitation for timescales longer than about 20 days in both the models and the observations (not shown). The choice of this simple circulation index is also motivated by the finding that the cold season Euro-Atlantic U850 response does not strongly project on any single teleconnection pattern. For example, we find that the spatial correlations of the U850 multi-model mean response (figure 1(d)) with the first two modes of Euro-Atlantic atmospheric variability¹ in U850, which broadly correspond to the North Atlantic Oscillation and the East Atlantic patterns, are 0.1 and 0.4 respectively. This differs from the warm season atmospheric circulation response which is instead well described in terms of a shift in the summer North Atlantic Oscillation (Bladé *et al* 2012).

A similar relationship between Mediterranean precipitation and U850 in North Africa is also found in the future climate simulations. In particular, the yearly precipitation and circulation anomalies in the future time period (2070–2100) relative to the present day (1976–2005) climatology are given by

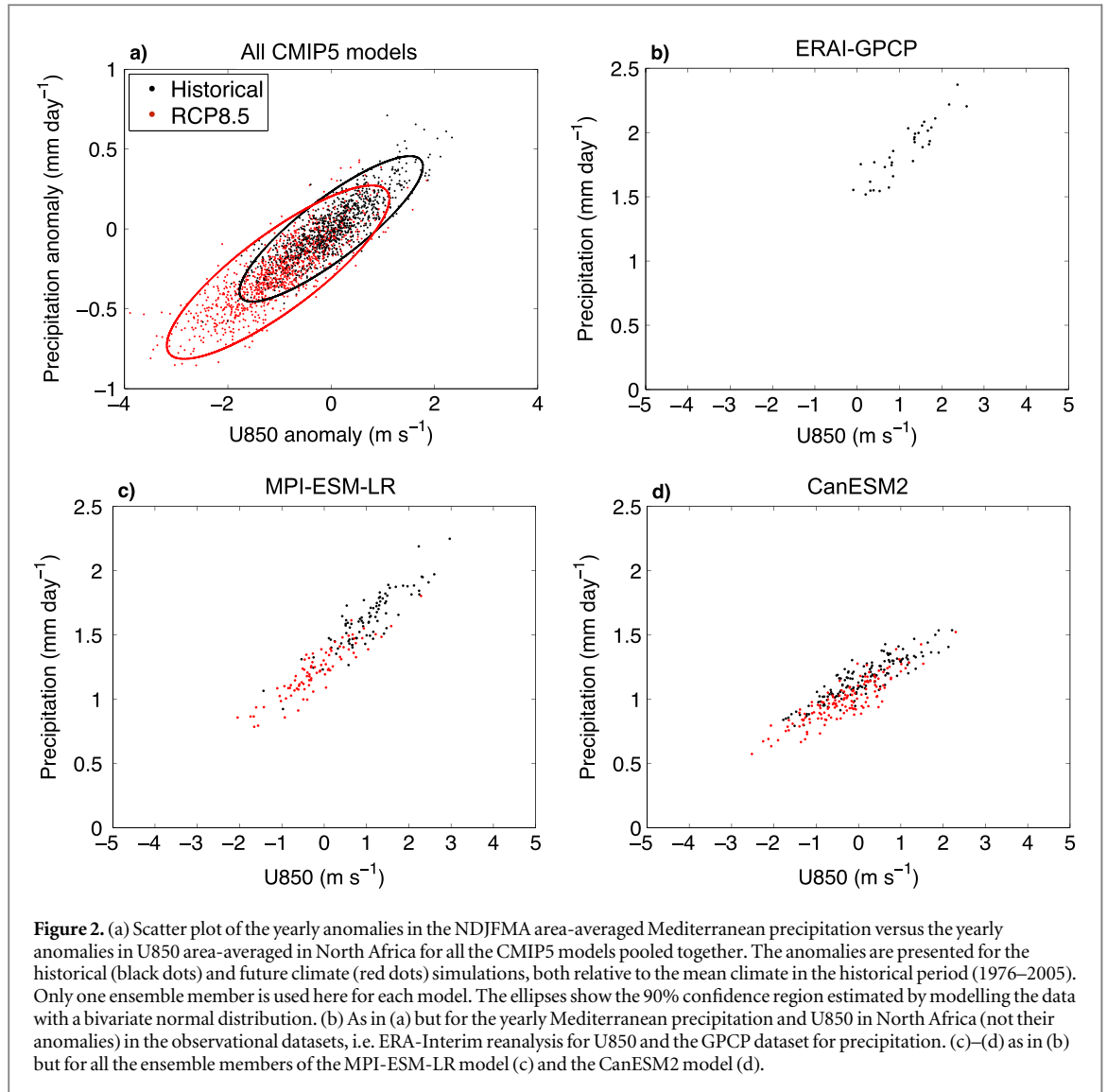
$$\delta P_{im}^{RCP} = P_{im}^{RCP} - \bar{P}_m^{20c} \quad (3)$$

$$\delta U_{im}^{RCP} = U_{im}^{RCP} - \bar{U}_m^{20c}, \quad (4)$$

and their association for all the CMIP5 models pooled together is presented as red dots in figure 2(a). Note that subtracting the historical climatologies implies that the year to year future climate precipitation (δP_{im}^{RCP}) and circulation (δU_{im}^{RCP}) anomalies also include the contribution from the forced climate change response.

By comparing the red and black dot distributions in figure 2(a), we find that the shift toward less Mediterranean precipitation and weaker westerlies in North Africa in the future climate is qualitatively consistent with the association between the two quantities in the year to year present day climate variability. This behaviour can also be identified in most of the individual climate models (see for example figure 2(c)), and it suggests that the Mediterranean precipitation response to climate change depends on atmospheric circulation in a manner similar to that found in the year to year variability. However, thermodynamic effects or residual dynamical influences not captured by U850 in North Africa can also affect the Mediterranean precipitation response. For example, the

¹ The teleconnection patterns have been simply evaluated from ERA-Interim as the first two EOFs of the inter-annual variability of U850 in the Euro-Atlantic sector (280W–40E, 20N–75N) in NDJFMA.



CanESM2 climate model (see figure 2(d)) shows a future reduction in Mediterranean precipitation in spite of little changes in U850 in North Africa. Nonetheless, all the models with a large U850 circulation response show a behaviour similar to figure 2(c) (not shown).

These results suggest that the mean precipitation change associated with the atmospheric circulation response to climate change ($\Delta \bar{P}_m^{\text{est}}$) can be estimated, for each model, by exploiting the relationship between Mediterranean precipitation and zonal wind in North Africa found in the internal climate variability. In particular

$$\Delta \bar{P}_m^{\text{est}} = \Delta \bar{U}_m \cdot \left(\frac{dP}{dU} \right)_m^{20c}, \quad (5)$$

where $\Delta \bar{U}_m = \bar{U}_m^{\text{RCP}} - \bar{U}_m^{20c}$ is the U850 response in North Africa and $\left(\frac{dP}{dU} \right)_m^{20c}$ is the slope of the regression between the area-averaged Mediterranean precipitation and U850 in North Africa in the present day climate inter-annual variability, for model m .

The values of the slopes $\left(\frac{dP}{dU} \right)_m^{20c}$ found in the individual climate models and in the real world data are reported in figure 3. With one exception, the slopes of the CMIP5 models range between 0.15 and 0.3 ($\text{mm d}^{-1}/(\text{m s}^{-1})$). The best estimate of the slope in the real world data is about 0.3 ($\text{mm d}^{-1}/(\text{m s}^{-1})$), which implies that many CMIP5 climate models tend to underestimate the sensitivity of Mediterranean precipitation to zonal wind changes in North Africa. A physical interpretation is that when the large-scale atmospheric conditions favourable to Mediterranean storminess develop, too little precipitation is generated by the Mediterranean storms. Consistently, we find that the bias in the slope and in the mean precipitation are associated: the models with reduced slope tend to have reduced mean area-averaged Mediterranean precipitation ($r = 0.79$). This suggests that predictions of precipitation change based on equation (5) might tend to be biased low compared to what would happen in the real world for the same circulation change. It also implies that simulating the 20th century Mediterranean

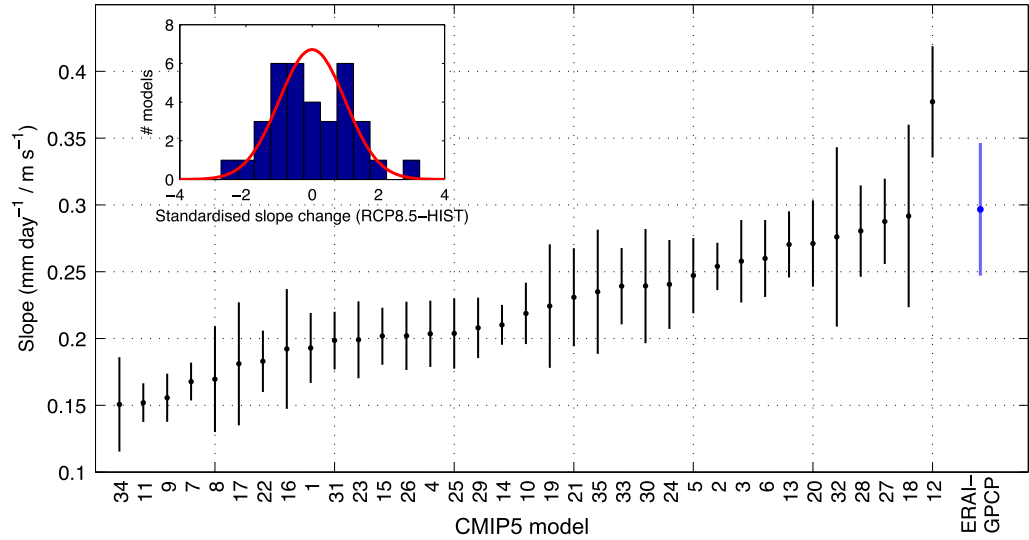


Figure 3. Slope of the regressions $\left(\frac{dP}{dU}\right)_m^{20c}$ between NDJFMA Mediterranean precipitation and U850 in North Africa identified in the inter-annual variability in the individual CMIP5 models. For each CMIP5 model (see table 1 for the label), the black dot indicates the slope of the regression in the present day climate, and the error bar the 95% confidence interval on the slope of the regression. The size of the confidence intervals mainly reflect the number of ensemble members available for each model. The models have been ordered according to the slope in the present day climate simulations. The blue dot and error bar to the right refer to the slope of the same regression but using the observational datasets. The inset shows a histogram of the standardized change (RCP8.5-HIST) in the slope in the CMIP5 models, and the distribution of changes expected due to sampling uncertainty alone, as estimated from the normal distribution (red line).

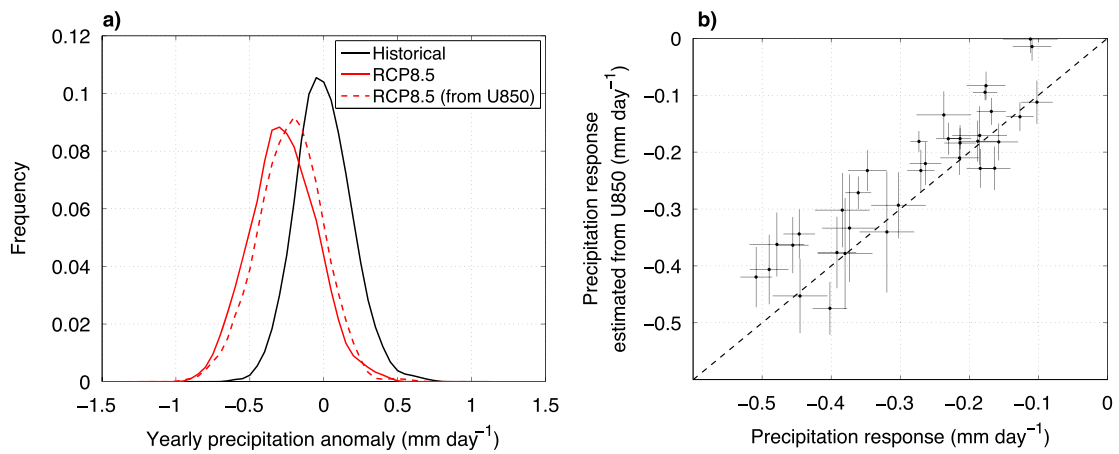


Figure 4. (a) Frequency distributions of the yearly NDJFMA precipitation anomalies in the present day climate δP_{im}^{20c} (black line), in the future climate δP_{im}^{RCP} (red line), and the estimate of the future precipitation anomalies based on the U850 circulation response $\delta P_{im}^{20c} + \Delta \bar{P}_m^{est}$ (red dashed line). All the CMIP5 models are pooled together as in figure 2(a). (b) Scatterplot of the precipitation response in the individual CMIP5 models ($\Delta \bar{P}_m$) against the estimated precipitation change from the U850 response ($\Delta \bar{P}_m^{est}$). Note that the spread in the model responses is much larger than the 95% confidence intervals (vertical and horizontal error bars) associated with internal climate variability.

climate well is pre-requisite for being able to make credible predictions and projections of precipitation in this region.

We find no evidence to suggest that the slope of the regression $\left(\frac{dP}{dU}\right)_m$ is affected by climate change. In particular, the slope is nearly unchanged between the present and the future climate simulations in the multi model mean (change of 0.3%), and the variations between present and future climate in the individual climate models are consistent with the fluctuations expected from sampling uncertainty alone (see inset in

figure 3). This justifies the use of present day climate simulations to infer the slope used in equation (5).

Figure 4(a) presents the frequency distribution of the present day (δP_{im}^{20c} , black line) and future climate (δP_{im}^{RCP} , red line) yearly precipitation anomalies for all the models and years pooled together. As expected, it shows a shift toward reduced future precipitation. We find that this shift can be well captured by adding the estimated precipitation change associated with the atmospheric circulation response to the present day climate inter-annual precipitation anomalies ($\Delta \bar{P}_m^{est} + \delta P_{im}^{20c}$, red dashed line). In particular, 85% of

the change in the mean of the distribution between δP_{im}^{20c} and δP_{im}^{RCP} is captured by $\Delta \bar{P}_m^{est} + \delta P_{im}^{20c}$. This indicates that the atmospheric circulation change, as diagnosed by U850 in North Africa, contributes to most of the area-averaged Mediterranean precipitation change in the mean of the CMIP5 models.

To further test the ability of equation (5) to estimate the Mediterranean precipitation change, figure 4(b) compares the precipitation response in each model ($\Delta \bar{P}_m$) against the precipitation response estimated from the circulation change ($\Delta \bar{P}_m^{est}$). The results show that $\Delta \bar{P}_m^{est}$ has, on average, good ability to predict the precipitation change in the individual models, although, as expected from figure 4(a), there is a tendency to underestimate the response. When the circulation response is large (models in the bottom-left part of figure 4(b)) the difference between the estimated and effective response is relatively small ($\lesssim 20\%$), although when the circulation response is weak (top-right part of figure 4(b)) the error incurred by using equation (5) can be substantial. Nonetheless, there is high correlation ($r = 0.9$) in the inter-model spread between the estimated precipitation response and the effective precipitation response. This implies that the uncertainty in cold-season Mediterranean precipitation projection will not be narrowed unless the uncertainty in the atmospheric circulation response is reduced.

4. Conclusions and discussion

By analysing CMIP5 climate model output, this study has quantified the role of atmospheric circulation in the Mediterranean precipitation response to climate change in the cold season (November–April). The main findings of this study are the following:

- A simple index of atmospheric circulation, the 850 hPa zonal wind (U850) in North Africa, well describes the impact of atmospheric circulation on the area-averaged Mediterranean precipitation in both inter-annual variability and enhanced greenhouse gas climate change. Under climate change, the westerly zonal wind in North Africa and Mediterranean precipitation are both projected to decrease, and their reduction is consistent with the relationship between precipitation and U850 in North Africa found in the year to year variability. This is consistent with previous findings that cold-season Mediterranean precipitation change cannot be solely explained by thermodynamic, wet get wetter, dry get drier arguments.
- Using the relationship found in the year to year variability, we quantify that 85% of the area-averaged Mediterranean precipitation reduction projected by the mean of the CMIP5 models depends on the atmospheric circulation response, as described by U850 in North Africa. Furthermore,

we quantify that 80% of the variance of the CMIP5 inter-model spread in the area-averaged Mediterranean precipitation future responses is related to uncertainties in the atmospheric circulation response to climate change. In contrast, there is no significant correlation ($r = -0.2$, p -value = 0.24) between the mean precipitation response and the global-mean surface warming across the models.

- Models generally tend to underestimate the ratio of the precipitation to circulation change in the year-to-year variability, although some models are realistic in this respect. This suggests that the CMIP5 model mean may underestimate the precipitation reduction for a given change in circulation, and it highlights the importance of using models able to simulate the Mediterranean climate well in order to have realistic projections.

Although this study has focused on the overall Mediterranean precipitation response, figures 1(a)–(c) suggest that local precipitation changes tend to scale with the area-averaged Mediterranean precipitation response. This implies that constraining the area averaged response would also have the benefit of reducing part of the uncertainty in the local precipitation responses. On the other hand, other processes, not captured by the scaling approach presented here, are also likely to be important in shaping the pattern in the precipitation response. For example, Zappa *et al* (2015a) finds that the weak mean precipitation response in the North Mediterranean area (just to the north of the box analysed in this study) is the result of a compensation between a reduction in the number of Mediterranean cyclones but an increase in the precipitation generated by each cyclone. This suggests that changes in the moisture environment in which cyclones grow also need to be taken into account to explain the spatial distribution of the precipitation response across the Mediterranean region.

A number of physical processes might determine changes in the Mediterranean atmospheric circulation and precipitation under climate change. An increase in the tropical sea surface temperature has been shown to force an increasing anticyclonic circulation in the Mediterranean area (Hoerling *et al* 2012), but the atmospheric mechanisms involved and its relevance for the end-of-century climate change response have not yet been clarified. An expansion of the Hadley circulation (e.g. Lu *et al* 2007), changes in the structure of stationary waves (e.g. Brandefelt and Körnich 2008) or changes in the North Atlantic sea surface temperature and stormtrack (e.g. Woollings *et al* 2012) might all be important. The identification of the role of these or other processes, and their quantitative contribution to the climate-change response, will be crucial to increase confidence in future projections of wintertime Mediterranean climate. Furthermore, understanding the interaction between the Mediterranean mean state

(Seager *et al* 2014) and storm track (Zappa *et al* 2015a) in driving changes in the Mediterranean hydro-climate will need to be addressed in future research.

Acknowledgments

We acknowledge the two reviewers for their useful comments. We also thank the European Centre for Medium Range Weather Forecasts for the ERA-interim reanalysis and the NASA Goddard Space Flight Center's Laboratory for Atmospheres for the GPCP combined precipitation data. CMIP5 data has been downloaded from the British Atmospheric Data Centre archive, and we acknowledge the World Climate Research Programme Working Group on Coupled Modelling, which is responsible for CMIP, and the modelling groups listed in table 1 for producing the simulations and making available their output. This study is supported by the 'Understanding the atmospheric circulation response to climate change' (ACRCC, ERC Advanced Grant) project.

References

- Alessandri A *et al* 2014 Robust assessment of the expansion and retreat of Mediterranean climate in the 21st century *Sci. Rep.* **4** 7211
- Bladé I, Fortuny D, van Oldenborgh G J and Liebmann B 2012 The summer North Atlantic oscillation in CMIP3 models and related uncertainties in projected summer drying in Europe *J. Geophys. Res.* **117** D16104
- Brandefelt J and Körnich H 2008 Northern Hemisphere stationary waves in future climate projections *J. Clim.* **21** 6341–53
- Chadwick R, Boutle I and Martin G 2013 Spatial patterns of precipitation change in CMIP5: Why the rich do not get richer in the tropics *J. Clim.* **26** 3803–22
- Chang E K M, Zheng C, Lanigan P, Yau A M W and Neelin J D 2015 Significant modulation of variability and projected change in California winter precipitation by extratropical cyclone activity *Geophys. Res. Lett.* **42** 5983–91
- Collins M *et al* 2013 Long-term climate change: projections, commitments and irreversibility *Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed T Stocker *et al* (Cambridge: Cambridge University Press)
- Dunkeloh A and Jacobeit J 2003 Circulation dynamics of Mediterranean precipitation variability 1948–98 *Int. J. Climatol.* **23** 1843–66
- Eshel G and Farrell B F 2000 Mechanisms of Eastern Mediterranean rainfall variability *J. Atmos. Sci.* **57** 3219–32
- Giorgi F and Lionello P 2008 Climate change projections for the Mediterranean region *Glob. Planet. Change* **63** 90–104
- Held I and Soden B 2006 Robust responses of the hydrological cycle to global warming *J. Clim.* **19** 5686–99
- Hoerling M, Eischeid J, Perlwitz J, Quan X, Zhang T and Pegion P 2012 On the increased frequency of Mediterranean drought *J. Clim.* **25** 2146–61
- Jones P W 1999 First- and second-order conservative remapping schemes for grids in spherical coordinates *Mon. Weather Rev.* **127** 2204–10
- Kelley C, Ting M, Seager R and Kushnir Y 2012a Mediterranean precipitation climatology, seasonal cycle, and trend as simulated by CMIP5 *Geophys. Res. Lett.* **39** L21703
- Kelley C, Ting M, Seager R and Kushnir Y 2012b The relative contributions of radiative forcing and internal climate variability to the late 20th century winter drying of the Mediterranean region *Clim. Dyn.* **38** 2001–15
- Krichak S O and Alpert P 2005 Signatures of the NAO in the atmospheric circulation during wet winter months over the Mediterranean region *Theor. Appl. Climatol.* **82** 27–39
- Lionello P and Giorgi F 2007 Winter precipitation and cyclones in the Mediterranean region: future climate scenarios in a regional simulation. *Adv. Geosci.* **12** 153–8
- Lu J, Vecchi G A and Reichler T 2007 Expansion of the Hadley cell under global warming *Geophys. Res. Lett.* **34** L06805
- Mariotti A, Pan Y, Zeng N and Alessandri A 2015 Long-term climate change in the Mediterranean region in the midst of decadal variability *Clim. Dyn.* **44** 1437–56
- Polade S D, Pierce D W, Cayan D R, Gershunov A and Dettinger M D 2014 The key role of dry days in changing regional climate and precipitation regimes *Sci. Rep.* **4** 4364
- Quadrelli R, Pavan V and Molteni F 2001 Wintertime variability of Mediterranean precipitation and its links with large-scale circulation anomalies *Clim. Dyn.* **17** 457–66
- Rojas M, Li L Z, Kanakidou M, Hatzianastassiou N, Seze G and Le Treut H 2013 Winter weather regimes over the Mediterranean region: their role for the regional climate and projected changes in the twenty-first century *Clim. Dyn.* **41** 551–71
- Seager R, Liu H, Henderson N, Simpson I, Kelley C, Shaw T, Kushnir Y and Ting M 2014 Causes of increasing aridification of the Mediterranean region in response to rising greenhouse gases *J. Clim.* **27** 4655–76
- Seager R, Naik N and Vecchi G A 2010 Thermodynamic and dynamic mechanisms for large-scale changes in the hydrological cycle in response to global warming *J. Clim.* **23** 4651–68
- Taylor K, Stouffer R and Meehl G 2012 An overview of CMIP5 and the experiment design *Bull. Am. Meteorol. Soc.* **93** 485–98
- van Haren R, Haarsma R J, de Vries H, van Oldenborgh G J and Hazeleger W 2015 Resolution dependence of circulation forced future central European summer drying *Environ. Res. Lett.* **10** 1–8
- Woollings T, Gregory J M, Pinto J G, Reyers M and Brayshaw D J 2012 Response of the North Atlantic storm track to climate change shaped by ocean–atmosphere coupling *Nat. Geosci.* **5** 313–7
- Woollings T, Hoskins B, Blackburn M and Berrisford P 2008 A new Rossby wave-breaking interpretation of the North Atlantic oscillation *J. Atmos. Sci.* **65** 609–26
- Xoplaki E, González Rouco J F, Luterbacher J and Wanner H 2004 Wet season Mediterranean precipitation variability: influence of large-scale dynamics and trends *Clim. Dyn.* **23** 63–78
- Zappa G, Hawcroft M K, Shaffrey L, Black E and Brayshaw D J 2015a Extratropical cyclones and the projected decline of winter Mediterranean precipitation in the CMIP5 models *Clim. Dyn.* in press (doi:10.1007/s00382-014-2426-8)
- Zappa G, Hoskins B J and Shepherd T G 2015b Improving climate change detection through optimal seasonal averaging: the case of the North Atlantic jet and European precipitation *J. Clim.* **28** 6381–97