Projected precipitation and air temperature over Europe using a performance-based selection method of CMIP5 GCMs

Dmitry Basharin, Alexander Polonsky and Gintautas Stankūnavičius

ABSTRACT

An assessment of the plausible climate change in precipitation and surface air temperature (SAT) over the European region by the end of the 21st century is provided. The assessment is based on the results of output of the ocean–atmosphere models participating in the Coupled Model Intercomparison Project, phase 5 (CMIP5). Six climate models that best reproduce the historical behaviour of SAT over greater Europe were selected from the CMIP5 project using a performance-based selection method of CMIP5 general circulation models for further assessments. The analysis of historical simulations within the scope of the CMIP5 project reveals that six models (namely, CNRM-CM5, HadGEM2ES, GFDL-CM3, CanESM2, MIROC5 and MPI-ESM-LR) sufficiently reproduce historical tendencies and natural variability over the region of interest. The climate change in SAT and precipitation by the end of the 21st century (2070–2099) was examined within the scope of RCP4.5 and RCP8.5 scenarios for these selected models. Typical regional warming due to RCP4.5 (RCP8.5) scenario is assessed as 3–4.5 °C (as 4–8 °C) in summer and winter, while a significant reduction of precipitation (typically 20–40%) is obtained only in summer.

Key words | climate change, CMIP5, Europe, precipitation and temperature

Dmitry Basharin (corresponding author)
Alexander Polonsky
Department of Marine Climatic Research,
Marine Hydrophysical Institute and Institute of Natural-Technical Systems,
2 Kapitanskay St.,
299011 Sevastopol,
Russia
E-mail: *dbasharin@rambler.ru*

Gintautas Stankūnavičius
Department of Hydrology and Climatology,
Vilnius University,
Ciurlionio 21/27, LT – 03101,
Vilnius,
Lithuania

INTRODUCTION

General circulation models (GCMs) are able to simulate a large set of features of the atmosphere–ocean system, namely geopotential height, surface pressure, surface air temperature (SAT), wind and moisture parameters, sea surface temperature, sea level change and so forth. SAT and precipitation are widely discussed climate variables. The climatology and variability of precipitation and temperature may be analysed independently or concurrently by employing diverse statistical methods (Zhang *et al.* 2011; Stankūnavičius *et al.* 2012; Hao *et al.* 2013). An increase in the frequency of climate extremes has been found in the last few decades, resulting in a significant loss of life and serious economic impacts on European countries. Owing to the high population density, Europe is a region potentially vulnerable to climatic changes. Therefore, trends in climatic extremes and climate variability, particularly SAT and precipitation, are of great concern to the European community (IPCC 2007; Giorgi & Lionello 2008).

The most advanced tools for the projection of future climate change are up-to-date GCMs (Shukla *et al.* 2009). Estimates based on their simulation will help in creating adaptive strategies to mitigate climatic change and eventually finding the most appropriate measures for adaptation. The use of coupled ocean–atmosphere model simulations is a significant step forward in studying climate change in vulnerable regions, including Europe, which have been identified as conspicuous 'hot-spots' in future climate change projections (Giorgi 2006). Climate change and its manifestation have been frequently examined in regional impact studies (like the PRUDENCE/CORDEX projects) by using regional high-resolution models. Such regional models provide useful information for impact assessments

doi: 10.2166/wcc.2015.081

in different regions and require high-performance computing resources. Therefore, many studies consider a smaller set of GCMs as a sensible way to obtain high-resolution projections for future climate change (Pierce *et al.* 2009; Overland *et al.* 2011; Bennett *et al.* 2012; Corney *et al.* 2013).

The GCMs of the recently initiated fifth phase of the International Coupled Model Intercomparison Project (CMIP5) have finer spatial and temporal resolution, parameterization enhancement and use improved climate change scenarios with an expanded set of climate experiments (Taylor *et al.* 2012). They can better represent important global processes such as the effect of aerosols, the interaction at the land–ice boundary, stratosphere–troposphere interactions, the carbon cycle, runoff, and biochemical interactions between ecosystems and other processes. These diverse processes could lead to different assessments of changes in the SAT and precipitation fields and their statistical significance.

There are certain approaches to choosing a subset of better performing GCMs which lead to less uncertain climate projections. Some of them use the multistaged process of increased resolution with bias adjustment methods (Johnson *et al.* 2011; Corney *et al.* 2013). Others are more focussed on analysing information on model errors and the processes that may lead to these errors (Guilyardi *et al.* 2012). Many of them try to assess the performance of GCMs over a range of metrics, variables, statistics, spatial scales and temporal scales for a region of interest aimed at improving projections (e.g., van Oldenborgh 2005; Smith & Chandler 2010). However, only a few of these studies assess historical trends to reach a 'better' performance compared to the above-mentioned results.

The preliminary results of the CMIP5 project have already been discussed (Stoner *et al.* 2009; Guilyardi *et al.* 2012; Zappa *et al.* 2013; Jacob *et al.* 2013). These results show that most of the El Niño–Southern Oscillation (ENSO) features become more consistent with observational data (Guilyardi *et al.* 2012). It is important because many authors have shown that ENSO influences climate variability in the European area (Polonsky *et al.* 1997, 2008; Basharin 2004; Bulić & Kucharski 2012; López-Parages *et al.* 2014). Also, research papers have argued that the recent warming over Europe is characterized by high spatial and temporal heterogeneity because of intense mid-latitude cyclones generating devastating storms and heavy precipitation (Bengtsson *et al.* 2006; Polonsky 2008). The impact of atmospheric circulation on future warming has already been considered in the North Atlantic and European regions using the CMIP5 results (Zappa *et al.* 2013). This analysis showed that the total number of cyclones in the future climate will decrease in winter and summer, but their intensity will increase. Therefore, diversity in the projected mid-latitude circulation may have a direct impact on the quality of the assessment of changes in temperature and precipitation.

In general, not all climate models involved in CMIP (particularly newly designed GCMs) have enough capacity for accurate description of the regional changes and their spatial–temporal variability in retrospective simulations (Polonsky *et al.* 2011; Handorf & Dethloff 2012). From the entire set of available models it is worth choosing a few that describe the current climate more precisely. Errors in simulating natural climate variability, climatic tendencies and extreme climatic values can cause multi-model spread to become too large, resulting in projections that are too uncertain to be useful for decision-makers. Therefore, the main task of this study is to assess future climate changes in the SAT and precipitation fields by the end of the 21st century based on a selected ensemble of models from the CMIP5 project that are capable of reproducing the current European climate more realistically.

The 'Data and methods' section includes a description of the data and methods used in this study. Then the research results are presented, while the discussion and conclusions are provided in the final section. The 'Results and analysis' section has two subsections. The first one deals with the historical climate CMIP5 simulations in order to select better models. Based on the obtained results, the description of temperature and precipitation change assessment according to two CMIP5 climate scenarios are presented in the second subsection.

DATA AND METHODS

The results of simulations from 12 well-established GCMs included in the CMIP5 were used in this study. Spatial resolution of the models typically varies from 0.9 to 2.8 degrees on a regular latitude–longitude grid. The output from these models is stored at the Program for Climate Model Diagnosis and Intercomparison and is publicly accessible (http://www-pcmdi.llnl.gov). The list of the models used in this study is given in Table 1. Earlier versions of many of these models were reasonably well validated in the previous phase of the CMIP3 project. Data for verification were taken from the Climatic Research Unit of the University of East Anglia (further CRU3.1), constructed on the basis of *in situ* observations of climatic variables, and interpolated into regular 0.5×0.5 degree latitude–longitude grid space (Mitchell & Jones 2005; Harris *et al.* 2014).

At the very beginning, the CMIP5 historical climate simulations of SAT were analysed to select the models that best reproduce the observed tendencies and variability over Europe, affected by interactions between mid-latitude and tropical processes (Polonsky *et al.* 2008; Stankūnavičius *et al.* 2012). Supposedly, such a model selection procedure can reduce the area of inconsistency in the model responses and prevent diverging projections (Tebaldi *et al.* 2005; Deser *et al.* 2012; Knutti & Sedlacek 2013). At the subsequent stage, the projections of the SAT and precipitation fields in the selected climate models were examined according to the RCP4.5 and RCP8.5 scenarios for the 21st century. The historical simulations of precipitation fields were not analysed in this study because even the main re-analysis projects (NCEP, ERA40, JRA25) show a wide range of uncertainties in regional precipitation fields (Bosilovich *et al.* 2008; Basharin 2009).

The decision about the significance of all further statistical values (mean, linear trends and the others) was made at the 95% confidence level, according to Student's *t*-test, therefore only significant changes estimated with $p > 0.95$ were highlighted. All statistical characteristics and indices were performed using standard algorithms.

RESULTS AND ANALYSIS

Historical climate CMIP5 simulations: selection of the GCMs

The selection of the GCMs was done in three steps.

At the first stage, the linear trends of SAT for each model were estimated for the period 1950–2005 and the results

Table 1 | List of CMIP5 models considered in this paper; the model resolution (horizontal and vertical) of atmospheric variables, the number of available historical simulations and climate projections are presented

	Basic information		Model resolution		Number of runs	
No.	**Name of model**	**Organization**	**Horizontal**	**Vertical**	**HIST**	**RCP**
1	BCC-CSM1.1	BCC, China	128×64	26	3	1
2	CanESM2	CCCma, Canada	128×61	35	6	5
3	CNRM-CM5	CNRM, France	256×128	31	10	1
4	CSIRO-Mk3.6.0	CSIRO, Australia	192×96	18	3	3
5	CSIRO-ACCESS-1	CSIRO, Australia	192×144	26	1	1
6	GFDL-CM3	GFDL/USA	144×90	24	5	1
7	HadGEM2ES	MOHC, UK	192×144	38	5	4
8	HadGEM2AO	MOHC, UK	192×144	38	1	1
9	INMCM4	INM, Russia	180×120	21	6	6
10	IPSL-CM5A-LR	IPSL, France	96×96	39	6	4
11	MPI-ESM-LR	MPI-M, Germany	192×96	47	3	3
12	MPI-ESM-MR	MPI-M, Germany	192×96	95	3	1
13	NCAR-CCSM4	NCAR, USA	288×192	26	6	6
14	MIROC5	MIROC, Japan	256×128	80	5	3
15	MRI-CGCM3	Met. Res. Inst., Japan	320×160	48	5	1
16	NorESMl-M	NCC, Norway	144×96	26	3	1

were compared with the CRU data for the same period. The second half of the 20th century was chosen for the comparison because the observations became more numerous over a larger part of Europe. Preference was given to those climate models that have had more scenario runs.

For the winter season, when the atmospheric processes in the northern hemisphere mid-latitudes are particularly intense over Europe, the simulations of climate models show some differences. The Russian (INMCM4), Australian (CSIRO-MK36) and Norwegian (NorESM1) models (Figure 1(a)–1(c)) demonstrate the presence of false negative SAT trends over the European region instead of positive CRU linear trends (Figure 1(d)). Consequently, the final criterion for the selection of models was the observed non-negative linear trends of SAT over the European region.

In particular, the simulations of the Australian (CSIRO-MK36) and Russian (INMCM4) models (Figure 1(a) and 1(b)) demonstrate significant negative linear SAT trends with the highest magnitude in the northeastern part of Europe up to $-3\,^{\circ}$K/100 years and $-10\,^{\circ}$K/100 years, respectively. Meanwhile, the Norwegian model has an area with insignificant negative trends (Figure 1(c)), primarily in the eastern part of Europe – from 0 to $-1.5\,^{\circ}$K/100 years. As the negative trends are insignificant, the Norwegian (NorESM1) model was also included in the analysis for consideration of its simulated variability at the further stage of the research (see the results in Table 2). Thus, the comparison of the results of the simulation of climate models showed that the SAT linear trends for the period 1950–2005 are satisfactorily reproduced in sign and magnitude in the following models: CNRM-CM5, HadGEM2ES, GFDL-CM3, CanESM2, IPSL-CM5A, MIROC5, MPI-ESM, MRI-CGCM3, CSIRO-ACCESS1, BCC-CSM1.1 and NCAR-CCSM4. The 11 selected models also show satisfactory results for the linear trends in temperature over Europe for the summer season. Therefore, these models were examined in more detail in the later stages of the research.

Second, realistic simulation of the European multidecadal variability by GCMs is important because of its profound influence on the projected climate values. The decadal variability is closely related to the multidecadal variability due to nonlinearities in the ocean–atmosphere system (Alvarez-Garcia *et al.* 2011; Li *et al.* 2013). For example, a non-stationary relationship between the North Atlantic oscillation (NAO) and the Atlantic multidecadal oscillation has already been recognized in reports of the Intergovernmental Panel on Climate Change (IPCC 2007). That is why the realistically reconstructed decadal climate variability has to be a prerequisite for better reproduction of lower time scales, which is important for assessing climate changes.

Therefore, at the second stage, the reproduced interannual to decadal variability was analysed using the ensemble mean of every model. So for this reason, the leading spatial–temporal mode of SAT variability was determined over the European region, where high natural variability takes place. In winter it represents the well-known NAO pattern revealed in all seasons of the year (Barnston & Livezey 1987; Basharin 2004; Stankūnavičius *et al.* 2012 and others). Its spatial–temporal pattern determines the climate anomalies on interannual as well as on decadal time scales over the European region. For identification of patterns, empirical orthogonal function (EOF) decomposition can be an effective method for separating natural variability from the noise (Barnston & Livezey 1987; Kim & Wu 1999). Certainly there are other, more advanced techniques able to identify and compare low-frequency variability in GCM simulations and observations, for example presented in Ghil *et al.* (2002) and Jamison & Kravtsov (2010). However, the EOF analysis remains a quite simple and effective technique often applied in recognizing natural climate variability.

It is widely believed within the CMIP3 project that the leading spatial mode of climate variability of each model ensemble mean is very similar to the one received by using observation-based data (Handorf & Dethloff 2012). It represents an NAO-like meridional dipole pattern. This result was confirmed by our analysis. At the same time, the temporal variation of the leading modes within the CMIP3 project was simulated poorly (Polonsky *et al.* 2011). Therefore, the contingency between the temporal behaviour of the leading SAT mode for each model and the corresponding mode based on CRU data was calculated for the CMIP5 models selected previously (Table 2). The correlation analysis shows that seven models are partly capable of reproducing the interannual to decadal time scale of the SAT leading mode at a statistically significant level, suggesting that the simulation of this temporal variability

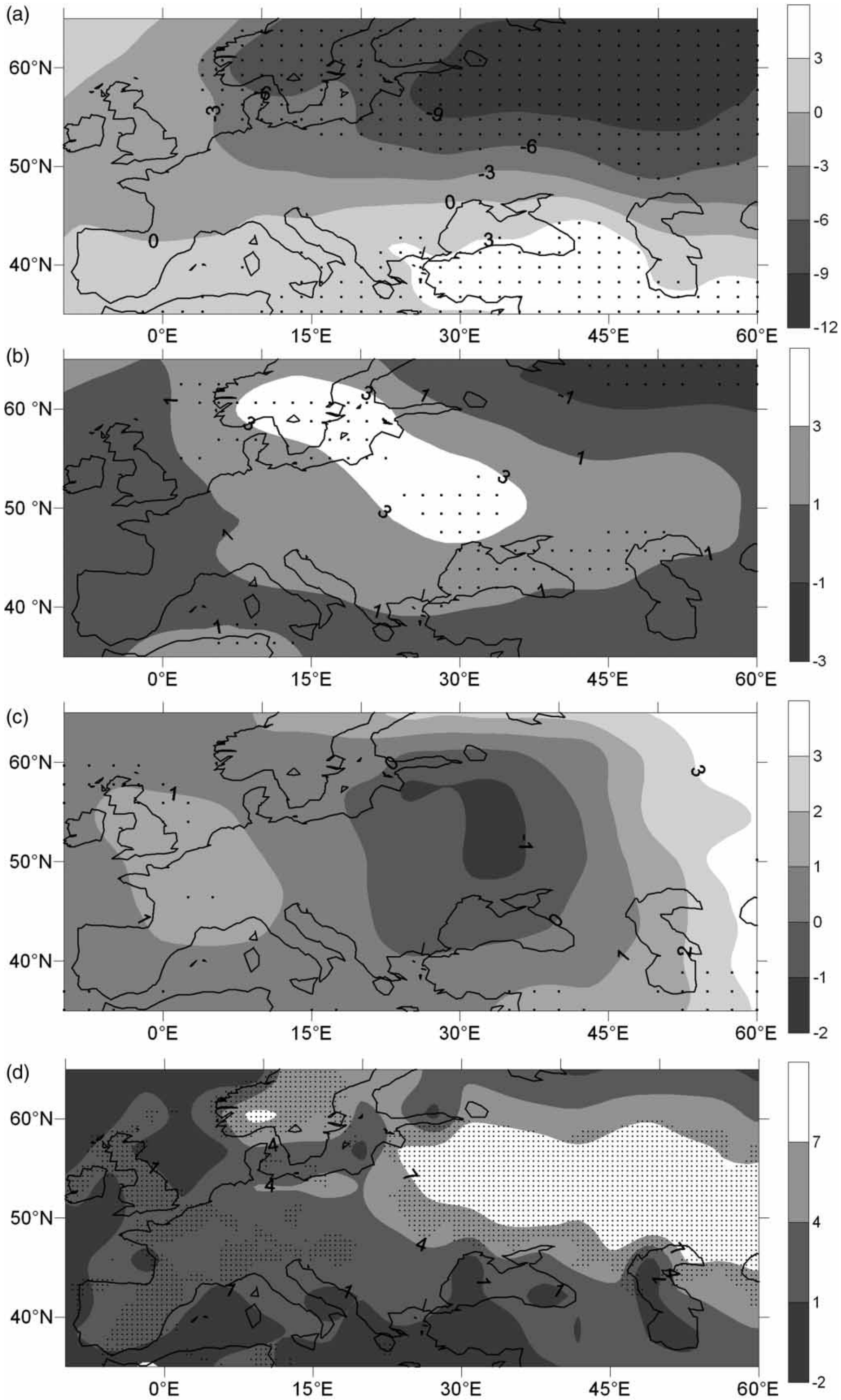

Figure 1 | Spatial distribution of the linear SAT trends for January (in degrees K/100 yr). Output of the INMCM4, CSIRO-MK36, NorESM1 models and CRU data ((a), (b), (c) and (d), respectively) for January of 1950–2005 were used. The thick solid lines indicate negative SAT trends. Dotted areas indicate statistically significant trends at the 95% confidence level. Note that the scale is not fixed for all figures.

Table 2 | Correlation between the temporal high-pass filtered (up to 15 years) EOF coefficient of the leading SAT mode for each model and CRU for the period 1950–2005

No.	Name of model	Correlations
1	CanESM2	**0.3**
2	CNRM-CM5	**0.27**
3	CSIRO-ACCESS-1	0.17
4	GFDL-CM3	**0.25**
5	HadGEM2ES	**0.24**
6	IPSL-CM5A-LR	**0.29**
7	MPI-ESM-LR	**0.21**
8	NCAR-CCSM4	0.07
9	MIROC5	**0.24**
10	BCC-CSM1.1	0.18
11	NorESMl-M	0.07
12	MRI-CGCM3	0.09

Significant correlation coefficients (at the 95% confidence level) are in bold.

within the CMIP5 project has taken a step forward compared to the results obtained within CMIP3 (Polonsky *et al.* 2011; Handorf & Dethloff 2012). It points to the constructive enhancement (like the finer spatial resolution/parameterization and others) of GCMs within CMIP5. Correlations show that most of the analysed models are able to reproduce the large-scale temporal SAT variability over the European region at a significant level. Therefore, the analysis of historical simulation of the models within the CMIP5 project reveals that CNRM-CM5, HadGEM2ES, GFDL-CM3, CanESM2, IPSL-CM5A, MIROC5 and MPI-ESM models sufficiently reproduce historical tendencies and natural variability at least over the Eurasian continent, and could give a more accurate simulation of future climate change compared to other models.

Third, the subsequent SAT variance of the historical climate simulations throughout the multi-model ensemble was analysed at the final stage of the current research. For this purpose, the maximum SAT variance of the multi-model ensemble (1950–2005) over Europe was calculated step-by-step for the seven models (CNRM-CM5, HadGEM2ES, GFDL-CM3, CanESM2, IPSL-CM5A, MIROC5, MPI-ESM-LR) based on a stepwise addition technique (Troccoli *et al.* 2008). As a result, this procedure shows that included IPSL ensemble members cause a statistically significant increase (at the 95% confidence level) of the maximum SAT variance of the multi-model ensemble from 20.25 $^{\circ}K^2$ to 44.89 $^{\circ}K^2$ over the European region (35–65N, 10E–60W). This indicates that simulation of the IPSL model could lead to a significantly larger spread of the multi-model ensemble and more uncertain climate assessment. Therefore, the IPSL model has been excluded from the final multi-model ensemble.

Thus, the analysis of historical SAT simulations within the CMIP5 project reveals that the use of the subset of climate models, namely CNRM-CM5, HadGEM2ES, GFDL-CM3, CanESM2, MIROC5 and MPI-ESM-LR, appears to be optimal for a more accurate assessment of future climate change over Europe.

Projections of climate change over Europe based on the selected CMIP5 models

Four new climate scenarios of greenhouse gas emissions (representative concentration pathway (RCP)) emerged in the CMIP5 project (Moss *et al.* 2010; Meinshausen *et al.* 2011). Only two of the most discussed future scenarios are generally considered: RCP4.5 and RCP8.5 (Knutti & Sedlacek 2013; Jacob *et al.* 2013; Dirmeyer *et al.* 2013). Moreover, these climate scenarios include a much broader set of numbers of GCMs runs for all climate models in comparison with the other two scenarios: RCP2.6 and RCP6.0. (http://www-pcmdi.llnl.gov). Their amount ranges from 1 to 5 members for each climate model. The RCP4.5 and RCP8.5 scenarios suppose a gradual increase in external radiative forcing of 4.5 Wm^{-2} and 8.5 Wm^{-2} by the end of the 21st century. The RCP4.5 scenario provides for an increase in carbon emissions up to 10 Gt/year (as well as other greenhouse gases) in the atmosphere by the middle of the 21st century, and a reduction to almost the current level by the end of the century. The worst case scenario – RCP8.5 provides for a quasi-exponential increase in greenhouse gas emissions by the end of the 21st century, which exceeds the present level of CO_2 by about 2.5 times. The further analysis is conducted within these selected scenarios.

Future climate change by the end of the 21st century expressed in the SAT and precipitation fields was assessed using a selected multi-model (CNRM-CM5, HadGEM2ES, GFDL-CM3, CanESM2, MIROC5 and MPI-ESM-LR) ensemble data according to the two existing scenarios (Figures 2 and 3). The climate change is determined as the

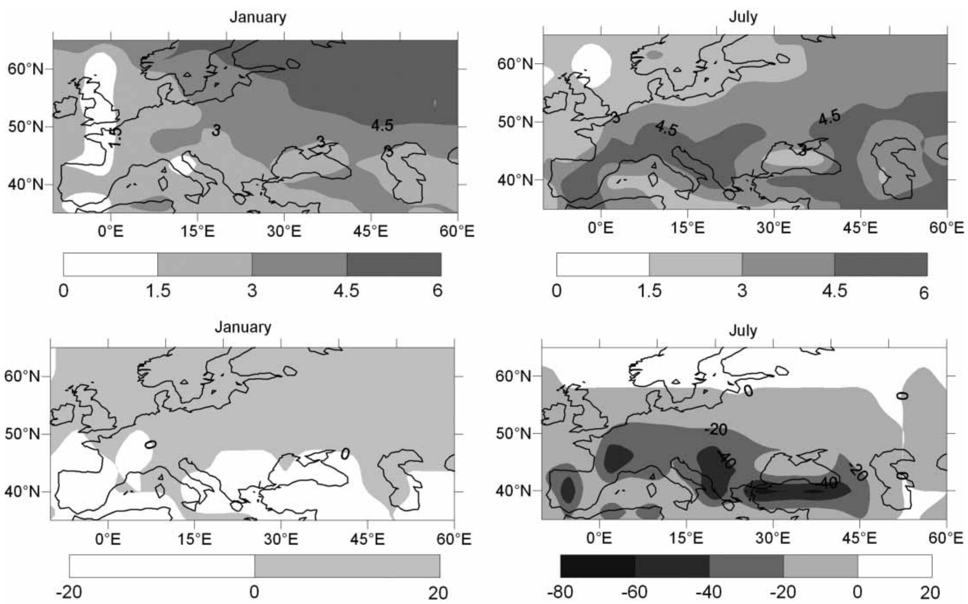

Figure 2 | Estimated changes of SAT (above) and precipitation (below) in January (left) and in July (right) based on multi-model ensemble (CNRM-CM5, HadGEM2ES, GFDL-CM3, CanESM2, MIROC5 and MPI-ESM-LR) simulations according to the RCP4.5 scenario. The change in temperature (in degrees K) was calculated as the multi-model mean difference between the two time intervals, 2070–2099 minus 1976–2005. The change in precipitation (in per cent) was calculated as the multi-model ensemble mean difference between the two time intervals, 2070–2099 minus 1976–2005, normalized by the CRU data for 1976–2005. Changes in SAT (more than 1.5 °C) and in precipitation (more than 20% and less than minus 20%) are significant at the 95% confidence level. Note that the scale is not fixed for all figures.

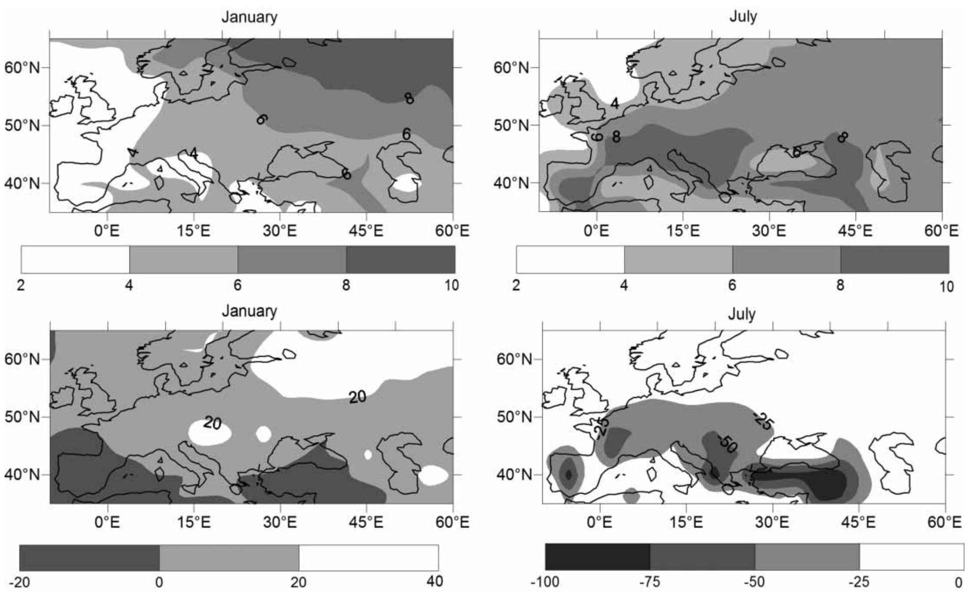

Figure 3 | The same as in Figure 2, but for RCP8.5.

difference between the multi-model means for the 2070–2099 period minus the period of 1976–2005. However, the precipitation data were additionally normalized according to the observed data in CRU. In their study, Knutti & Sedlacek (2013) normalized the simulated precipitation fields of 2070–2099 to the climate model. However, the most accurate way of doing the precipitation standardization procedure is to normalize the model difference to the observations, since the regional precipitation in the CMIP5 simulations (Dirmeyer *et al.* 2013; Chadwick *et al.* 2013) and even in the reanalysis projects may have a great regional variation in space and time (Bosilovich *et al.* 2008; Basharin 2009).

Thus, based on the previously selected CMIP5 models, the plausible changes in SAT and precipitation over Europe by the end of the 21st century were obtained (Figures 2 and 3). According to the RCP4.5 scenario, in the winter season (Figure 2), the maximum warming magnitude – 5–5.5 °C is expected in the northeastern part of Europe by the end of the 21st century. Typical changes in SAT over Europe vary between 2 and 4 °C. In the summer season, the expected temperature increase varies from 5 °C in southern Europe to 2.5–3 °C in the north. Precipitation changes are not significant in the winter all over Europe, while in summer a precipitation decrease is expected over much of Europe (on average 20–40%), with maximum values in Spain, Greece and Turkey (60–70%). The exception is the northern part of Europe, where changes are not significant in the summer season.

The RCP8.5 scenario (Figure 3), of course, demonstrates a greater magnitude of warming because of stronger radiative forcing. In winter, the maximum temperature rise (up to 9 °C) is expected in the furthermost northeastern part of Europe, while the typical values of the SAT increment around Europe vary around 3–7 °C. In the summer season, the maximum SAT change (also up to 9 °C) will occur in southern Europe and the Balkans, while the least change is expected in northwestern Europe, of about 3–5 °C. However, estimated changes in precipitation in winter are not statistically significant over most of Europe, except for the northern and central parts of the European territory of Russia, where expected changes slightly exceed 20%. In summer, a precipitation decrease is expected over larger Europe, while the maximum decrease (up to 80%) appears over some parts of Spain, Greece and Turkey.

DISCUSSION AND CONCLUSIONS

The estimated change of SAT and precipitation over Europe using the presented GCMs selection method is mostly similar to the Fourth Assessment Report of the IPCC (IPCC 2007) and the preliminary CMIP5 results (Cattiaux *et al.* 2013; Knutti & Sedlacek 2013). However, the structure of the temperature change coincides less closely with the shape of continents, as in Knutti & Sedlacek's (2013) paper, quite possibly due to poor resolution of one of the models, CanESM2, included in the selected multi-model ensemble. There are also differences in the magnitude of changes: the winter temperature change over northern Eurasia is smaller by 1–2 °C than those given by Knutti & Sedlacek (2013). This value of winter maximal SAT warming over northern Europe might be crucial in determining the rate of the Arctic Sea ice melting and shrinking (Jun *et al.* 2013).

The current analysis of the changes in the precipitation field suggests that lack of precipitation in the summer season is very likely in most parts of central, southern Europe and the Anatolia peninsula (20–40%), as in previous studies (Giorgi & Lionello 2008; Knutti & Sedlacek 2013). Essentially, such a decrease in precipitation agrees with simulations of the climate models showing a future reduction in the number of Mediterranean cyclones (Bengtsson *et al.* 2006; Raible *et al.* 2010), which could increase the susceptibility of the region to droughts. At the same time, our results show that in winter there is no significant precipitation change and drying tendency over southern Europe (Figures 2 and 3) that contradicts the IPCC report (IPCC 2007). It may be caused by the well-known fact that this region is characterized by an intense spatial–temporal variability of storm tracks, while such variability is still insufficiently reproduced (see the correlations in Table 2) by climate models (Polonsky *et al.* 2011; Handorf & Dethloff 2012). Also, the lack of reliable and consistent precipitation estimations found for GCM simulations might result from model deficiencies in the representation of organized convective systems (Toreti *et al.* 2013). Therefore, this result has to be interpreted as a rough regional climate assessment.

It is worth mentioning that spatial patterns of changes in both precipitation and SAT for two profoundly different emission scenarios are very similar and differ mostly in magnitude, particularly in summer (compare Figures 2 and 3 for July). This is quite striking indication linear response to external forcing to a certain extent.

The physical processes underlying these projected changes have been widely discussed (Rowell & Jones 2006;

Giorgi & Lionello 2008; Guilyardi *et al.* 2012). These studies show that the high summer drying over southern Europe is the result of seasonal migration of the atmospheric centres of action in the North Atlantic measured by the NAO index, probably having a bimodal structure in a warming climate (Coppola *et al.* 2005). It is associated with an increasingly anticyclonic circulation over the southern part of Europe and a northward shift of the mid-latitude storm track, which reaches its maximum in summer and minimum in winter. Rowell & Jones (2006) highlighted two main mechanisms of summer drying which are: (1) the spring decrease in soil moisture leading to low summer convection and (2) the large sea–land contrast leading to reduced relative humidity and precipitation over the continent. A reduction in the summer convection in a warming climate is recognized in Kendon *et al.* (2010) and Efimov & Anisimov (2012). It reveals the significant reduction of the convective part in total precipitation. The comparative analysis presented in this study, as well as in the studies listed above, confirm that the European region (particularly its southern part) is among the most vulnerable regions to future global climate change.

In this study, relatively simple comparisons of selected CMIP5 climate models have been done without any in-depth analysis of variation related to model resolution and representation of physical process in the CMIP5 models. The current and related studies (Guilyardi *et al.* 2012; Zappa *et al.* 2013; Jacob *et al.* 2013) have shown that the majority of the climate models within the CMIP5 project reproduce historical climate and its statistical characteristics better than the models in the previous phase (CMIP3). Together with these studies, our results also show that the simulation of temporal large-scale SAT variability within the CMIP5 project has been improved compared to the results obtained within CMIP3 (Polonsky *et al.* 2011; Handorf & Dethloff 2012). The reason for such improvement is a better description of processes in the selected CMIP5 models leading to a better representation of SST annual cycle amplitude, reduction of the heat flux RMS error and others (Guilyardi *et al.* 2012). The poor correlations between the leading SAT mode and CRU data of the non-selected climate models (non-bold values and correspondent name of the models in the Table 2) do not necessarily mean they are unable to simulate low-frequency climate variability. These models most likely need more ensemble members (Deser *et al.* 2012).

Despite constant enhancement, climate models are still uncertain and imperfect to some extent, because they can never fully describe the ocean–atmosphere–biosphere system that they attempt to specify (McWilliams 2007; Knutti *et al.* 2008; Kundzewicz & Stakhiv 2010; Guilyardi *et al.* 2012; Dirmeyer *et al.* 2013). The underestimation or overestimation of changes in temperature, precipitation, soil moisture and other parameters, would result in an inadequate description of the climate extreme conditions and their variability (on different time scales). However, the worst features of the up-to-date climate model simulations are the inadequacy of historical climate trends. In this regard, the continuous development of the coupled ocean–atmosphere system models, their resolution, the implementation of more high-performance computing technology for data transfer and processing hopefully will improve the accuracy of future climate projections (Shukla *et al.* 2009).

ACKNOWLEDGEMENTS

We would like to thank the modelling groups for making their simulations available for analysis, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for collecting and archiving the CMIP5 model output, and the WCRP's Working Group on Coupled Modelling (WGCM) for making the WCRP CMIP5 multi-model data set available for users. Special thanks to E. Swenson for the initial revision of the manuscript and remarks. We are very grateful to the reviewers for the constructive and helpful criticism of this paper.

REFERENCES

Alvarez-Garcia, F., Ortizbevia, M. & Cabosnarvaez, W. 2011 On the structure and teleconnections of North Atlantic decadal variability. *J. Climate* **24**, 2209–2223.

Barnston, A. G. & Livezey, R. F. 1987 Classification, seasonality and persistence of low frequency atmospheric circulation patterns. *Monthly Weather Rev.* **115**, 1083–1126.

Basharin, D. 2004 On the problem of influence of the North Atlantic and Southern Oscillations on the variability of surface air temperature in the European-Mediterranean region in summer and autumn. *Phys. Oceanogr.* **14** (5), 313–319.

Basharin, D. 2009 Inter-comparison of monthly total precipitation field between JRA, NCEP re-analyses and in situ observations over the Black Sea region. In: *Proceedings of the conference 'Lomonosovsky chteniya 2009'* (V. A. Trifonova, V. I. Kuzishina, O. A. Ivanova & N. N. Milenko, eds). Black Sea branch office of Moscow State University, Ukraine, pp. 5–7 (in Russian).

Bengtsson, L., Hodges, K. & Roeckner, E. 2006 Storm tracks and climate change. *J. Climate* **19** (15), 3518–3543.

Bennett, J. C., Ling, F. L., Post, D. A., Grose, M. R., Corney, S. P., Graham, B., Holz, G. K., Katzfey, J. J. & Bindoff, N. L. 2012 High-resolution projections of surface water availability for Tasmania, Australia. *Hydrol. Earth Syst. Sci.* **16** (5), 1287–1303.

Bosilovich, M. G., Chen, J., Robertson, F. & Adler, R. 2008 Evaluation of global precipitation in reanalyses. *J. Appl. Meteorol. Climatol.* **47**, 2279–2299.

Bulić, I. H. & Kucharski, F. 2012 Delayed ENSO impact on spring precipitation over North/Atlantic European region. *Climate Dynamics* **38** (11–12), 2593–2612.

Cattiaux, J., Douville, H. & Peings, Y. 2013 European temperatures in CMIP5: origins of present-day biases and future uncertainties. *Climate Dynamics* **41** (11–12), 2889–2907.

Chadwick, R., Boutle, I. & Martin, G. 2013 Spatial patterns of precipitation change in CMIP5: Why the rich do not get richer in the tropics. *Journal of Climate* **26** (11), 3803–3822.

Coppola, E., Kucharski, F., Giorgi, F. & Molteni, F. 2005 Bimodality of the North Atlantic Oscillation in simulations with greenhouse gas forcing. *Geophys. Res. Lett.* **32** (23), L23709.

Corney, S., Grose, M., Bennett, J., White, C., Katzfey, J., McGregor, J., Holz, G. & Bindoff, N. L. 2013 Performance of downscaled regional climate simulations using a variable-resolution regional climate model. *J. Geophys. Res. Atmos.* **118** (21), 11936–11950.

Deser, C., Phillips, A., Bourdette, V. & Teng, H. 2012 Uncertainty in climate change projections: the role of internal variability. *Climate Dynamics* **38** (3–4), 527–546.

Dirmeyer, P., Jin, Y., Singh, B. & Yan, X. 2013 Trends in land–atmosphere interactions from CMIP5 simulations. *J. Hydrometeorol.* **14**, 829–849.

Efimov, V. V. & Anisimov, A. E. 2012 Numerical assessment of the precipitation change in Black Sea region in XXI century. *Marine Hydrophys. J.* **6**, 45–58.

Ghil, M., Allen, R. M., Dettinger, M. D., Ide, K., Kondrashov, D., Mann, M. E., Robertson, A. W., Saunders, A., Tian, Y., Varadi, F. & Yiou, P. 2002 Advanced spectral methods for climatic time series. *Rev. Geophys.* **40** (1), 3.1–3.41.

Giorgi, F. 2006 Climate change hot-spots. *Geophys. Res. Lett.* **33** (8), L08707.

Giorgi, F. & Lionello, P. 2008 Climate change projections for the Mediterranean region. *Global Planet. Change* **63** (2–3), 90–104.

Guilyardi, E., Bellenger, H., Collins, M., Ferrett, S., Cai, W. & Wittenberg, A. 2012 A first look at ENSO in CMIP5. *CLIVAR Exchanges* **17**, 29–32.

Handorf, D. & Dethloff, K. 2012 How well do state-of-the-art Atmosphere-Ocean general circulation models reproduce atmospheric teleconnection patterns? *Tellus* **64A**, 19777.

Hao, Z., AghaKouchak, A. & Phillips, T. J. 2013 Changes in concurrent monthly precipitation and temperature extremes. *Environ. Res. Lett.* **8**, 034014.

Harris, I., Jones, P. D., Osborn, T. J. & Lister, D. H. 2014 Updated high-resolution grids of monthly climatic observations. *Int. J. Climatol.* **34** (3), 623–642.

IPCC 2007 Climate Change 2007: The Physical Science Basis. In: *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor & H. L. Miller, eds). Cambridge University Press, Cambridge, NY, USA, 996 pp.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O. B., Bouwer, L. M., Braun, A., Colette, A., Deque, M., Georgievski, G., Georgopoulou, E., Gobiet, A., Menut, L., Nikulin, G., Haensler, A., Hempelmann, N., Jones, C., Keuler, K., Kovats, S., Kroner, N., Kotlarski, S., Kriegsmann, A., Martin, E., van Meijgaard, E., Moseley, C., Pfeifer, S., Prueschmann, S., Radermacher, C., Radtke, K., Rechid, D., Rounsevell, M., Samuelsson, P., Somot, S., Soussana, J.-F., Teichmann, C., Valentini, R., Vautard, R., Weber, B. & Yiou, P. 2013 EURO-CORDEX: new high-resolution climate change projections for European impact research. *Region. Environ. Change* **14** (2), 563–578.

Jamison, N. & Kravtsov, S. 2010 Decadal variations of North Atlantic Sea surface temperature in observations and CMIP3 simulations. *J. Climate* **23** (17), 4619–4636.

Johnson, F., Westra, S., Sharma, A. & Pitman, A. J. 2011 An assessment of GCM skill in simulating persistence across multiple time scales. *Journal of Climate* **24**, 3609–3623.

Jun, S. Y., Ho, C. H., Kim, B. M. & Jeong, J. H. 2013 Sensitivity of Arctic warming to sea surface temperature distribution over melted sea-ice region in atmospheric general circulation model experiments. *Climate Dynamics* **42** (3–4), 941–955.

Kendon, E. J., Rowell, D. P. & Jones, R. G. 2010 Mechanisms and reliability of future projected changes in daily precipitation. *Climate Dynamics* **35**, 489–509.

Kim, K. Y. & Wu, Q. 1999 A comparison study of EOF techniques: analysis of nonstationary data with periodic statistics. *J. Climate* **12** (1), 185–199.

Knutti, R. & Sedlacek, J. 2013 Robustness and uncertainties in the new CMIP5 climate model projections. *Nature Climate Change* **3**, 369–373.

Knutti, R., Allen, M., Friedlingstein, P., Gregory, J. M., Hegerl, G. C., Meehl, G. A., Meinshausen, M., Murphy, J. M., Plattner, G.-K., Raper, S. C. B., Stocker, T. F., Stott, P. A., Teng, H. & Wigley, M. L. 2008 A review of uncertainties in global temperature projections over the twenty-first century. *J. Climate* **21**, 2651–2663.

Kundzewicz, Z. W. & Stakhiv, E. Z. 2010 Are climate models 'ready for prime time' in water resources management applications, or is more research needed? *Hydrolog. Sci. J.* **55** (7), 1085–1089.

Li, J., Sun, C. & Jin, F. 2013 NAO Implicated as a predictor of Northern Hemisphere mean temperature multidecadal variability. *Geophys. Res. Lett.* **40** (20), 5497–5502.

López-Parages, J., Rodríguez-Fonseca, B. & Terray, L. 2014 A mechanism for the multidecadal modulation of ENSO teleconnection with Europe. *Climate Dynamics* **45** (3–4), 867–880.

McWilliams, J. C. 2007 Irreducible imprecision in atmospheric and oceanic simulations. *Proc. Natl Acad. Sci. USA* **104** (21), 8709–8713.

Meinshausen, M., Smith, S., Calvin, K. & Daniel, J. 2011 The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change* **109** (1–2), 213–241.

Mitchell, T. D. & Jones, P. D. 2005 An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *Int. J. Climatol.* **25** (6), 693–712.

Moss, R. H., Edmonds, J. A., Hibbard, K. A. & Manning, M. R. 2010 The next generation of scenarios for climate change research and assessment. *Nature* **463**, 747–756.

Overland, J. E., Wang, M., Bond, N. A., Walsh, J. E., Kattsov, V. M. & Chapman, W. L. 2011 Considerations in the selection of global climate models for regional climate projections: the Arctic as a case study. *J. Climate* **24** (6), 1583–1597.

Pierce, D. W., Barnett, T. P., Santer, B. D. & Gleckler, P. J. 2009 Selecting global climate models for regional climate change studies. *Proc. Natl Acad. Sci.* **106** (21), 8441–8446.

Polonsky, A. 2008 The role of the ocean in climate change. *Naukova Dumka*, Kiev, Russia, 183 pp. (in Russian).

Polonsky, A. B., Voskresenskaya, E. N. & Belokopytov, V. N. 1997 Variability of northwestern Black sea hydrography and river discharges as part of global ocean-atmosphere fluctuations. In: *Sensitivity to Change: Black Sea, Baltic Sea, North Sea* (E. Ozsoy & A. Mikaelyan, eds). Springer, Dordrecht, The Netherlands, pp. 11–24.

Polonsky, A., Torbinsky, A. & Basharin, D. 2008 The influence of North Atlantic oscillation, El-Nino/Southern oscillation and Indian dipole on spatial-temporal variability of the surface air temperature and pressure over Mediterranean-Black Sea region. *Herald Odessa State Ecological University* **6**, 181–197 (in Russian).

Polonsky, A., Basharin, D. & Stankunavicius, G. 2011 Comparison of the climate variability of the surface air temperature between observation and results of climate's model estimation: regional and global scales. In: *Ecological safety of the coastal and shelf areas and complex use of shelf resources, Sevastopol* **24**, 142–150 (in Russian).

Raible, C., Ziv, B., Saaroni, H. & Wild, M. 2010 Winter synoptic-scale variability over the Mediterranean Basin under future climate conditions as simulated by the ECHAM5. *Climate Dynamics* **35** (2–3), 473–488.

Rowell, D. P. & Jones, R. G. 2006 Causes and uncertainty of future summer drying over Europe. *Climate Dynamics* **27** (2–3), 281–299.

Shukla, J., Hagedorn, R. & Miller, M. 2009 Revolution in climate prediction is both necessary and possible: a Declaration at the World Modelling Summit for Climate Prediction. *Bull Am. Meteorol Soc.* **90** (2), 175–178.

Smith, I. & Chandler, E. 2010 Refining rainfall projections for the Murray Darling Basin of south-east Australia – the effect of sampling model results based on performance. *Climatic Change* **102**, 377–393.

Stankūnavičius, G., Basharin, D. & Pupienis, D. 2012 Relationship between Eurasian large-scale patterns and regional climate variability over the Black and Baltic Seas. *Boreal Environ. Res.* **17**, 327–346.

Stoner, A., Hayhoe, K. & Wuebbles, D. 2009 Assessing general circulation model simulations of atmospheric teleconnection patterns. *J. Climate* **22** (16), 4348–4372.

Taylor, K. E., Stouffer, R. J. & Meehl, G. A. 2012 An overview of CMIP5 and the experiment design. *Bull. Amer. Meteorol. Soc.* **93** (4), 485–498.

Tebaldi, C., Smith, R., Nychka, D. & Mearns, L. 2005 Quantifying uncertainty in projections of regional climate change: a Bayesian approach to the analysis of multimodel ensembles. *J. Climate* **18** (10), 1524–1540.

Toreti, A., Naveau, P., Zampieri, M., Schindler, A., Scoccimarro, E., Xoplaki, E., Dijkstra, H. A., Gualdi, S. & Luterbacher, J. 2013 Projections of global changes in precipitation extremes from Coupled Model Intercomparison Project Phase 5 models. *Geophys. Res. Lett.* **40** (18), 4887–4892.

Troccoli, A., Harrison, M., Anderson, D. & Mason, S. 2008 *Seasonal Climate: Forecasting and Managing Risk*. NATO Science Series, Springer Academic Publishers, Dordrecht, The Netherlands, p. 467.

van Oldenborgh, G. J., Philip, Y. S. & Collins, M. 2005 El-Nino in a changing climate: a multi-model study. *Ocean Science* **1**, 81–95.

Zappa, G., Shaffrey, L., Hodges, K., Sansom, P. & Stephenson, D. 2013 A multi-model assessment of future projections of North Atlantic and European extratropical cyclones in the CMIP5 climate models. *J. Climate* **26** (16), 5846–5862.

Zhang, X., Alexander, L., Hegerl, G. C., Jones, P., Tank, A. K., Peterson, T. C., Trewin, B. & Zwiers, F. 2011 Indices for monitoring changes in extremes based on daily temperature and precipitation data. *Wiley Interdisciplinary Reviews: Climate Change* **2**, 851–870.

First received 16 April 2014; accepted in revised form 7 May 2015. Available online 7 July 2015