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Using feedback from summer subtropical highs to evaluate climate models

Carmen Sánchez de Cos,[1] Jose M. Sánchez-Laulhé,[1] Carlos Jiménez-Alonso[1] and Ernesto Rodríguez-Camino[2]*

[1]*Centro Meteorológico de Málaga, AEMET, Málaga, Spain*
[2]*Servicios Centrales, AEMET, Madrid, Spain*

Correspondence to:
E. Rodríguez-Camino, AEMET, Servicios Centrales, Leonardo Prieto Castro 8, 28040 Madrid, Spain.
E-mail: erodriguezc@aemet.es

Abstract

This letter aims to broaden the spectrum of methods for model evaluation by providing new physically based metrics that focus on accurate couplings between subsystems of the climate system. A simplified version of the feedback scheme that describes the dynamics of subtropical high-pressure systems is applied to evaluate how well CMIP5 climate models can simulate atmosphere–ocean–land interactions and resulting feedbacks in the Azores high-pressure system during summer, which affects climate throughout the Atlantic near southern Europe and North Africa.

Keywords: climate model evaluation; Azores high; feedback

1. Introduction

Climate models are numerical representations of the climate system that are based on the physical, chemical and biological properties of its components; they include the interactions and feedback processes between these components and account for some of the known properties of the climate system. The complex internal feedbacks of the climate system that determine its highly nonlinear behavior can either amplify (via 'positive feedbacks') or dampen (via 'negative feedbacks') the effects of a perturbation of one climate variable. Climate models, to the extent that they are faithful representations of the climate system, should be able to simulate the major feedbacks in the system (Flato *et al.*, 2013).

In this study, we base the evaluation of climate models on the importance of subtropical anticyclones for general circulation because these features influence climate over extensive regions. Subtropical anticyclones are characterized by strong atmospheric descent on their eastern flanks. Below and associated with this descent (Klein and Hartmann, 1993; Klein *et al.*, 1995) are marine stratus clouds; owing to their persistence, low altitude and high reflectivity, these clouds are important for the global radiation budget, providing unique and critical pathways for radiative cooling of the tropics (they have also been called 'radiator fins'; Pierrehumbert, 1995). During winter, the descending branch of the Hadley cell gives rise to a belt of high pressure in the subtropics of both hemispheres. However, different processes are required to explain the existence and intensification of these subtropical highs in summer, when the Hadley circulation is weakened (Liu *et al.*, 2001), although they are always linked to the land–sea thermal contrast. A pronounced land–sea pressure gradient develops during summer as the continents warm, leading to the formation of equatorward winds along the western continental coasts. These winds enhance evaporation off the coast and trigger the upwelling of cool waters from below. The cool surface waters help to stabilize the lower atmosphere and favor the development of reflective stratiform clouds, which in turn cool the lower atmosphere, effectively forcing the development of near-surface highs. This positive feedback loop, triggered by land-mass warming in late spring or early summer, mainly derives from the much smaller heat capacity of the land than of the oceanic mixed layer (Miyasaka and Nakamura, 2005).

High-pressure systems over the subtropical oceans largely shape the low- and mid-latitude climate. In particular, the Azores high-pressure system influences summertime climate in south-western Europe and north-western Africa. In this study, we seek to validate the performance of CMIP5 climate models in simulating atmosphere–ocean–land interactions, evaluating whether they can create the amplifying feedback loop that explains summertime Azores high-pressure system dynamics. The relationships between pairs of physical parameters involved in the feedback loop are described by 2D scatter-plots (Betts, 2004) and quantified with a metric based on the Hellinger coefficient (Sanchez de Cos *et al.*, 2013). This metric allows us to quantitatively estimate the resemblance between the same empirical relationship obtained from a climate model simulation and from reanalyses. Contrary to most metrics for evaluating climate models, which frequently focus on outcome variables (usually precipitation and temperature), this approach goes directly to the representation of physical processes, in particular the coupling between subsystems and climate system feedbacks.

2. Data

We use the ERA-Interim (EI) atmospheric reanalysis (Dee *et al.*, 2011) as a reference to establish the observed relationships between pairs of variables that describe the feedback mechanism underlying summertime Azores high dynamics. The climate models to be evaluated were selected from CMIP5 historical runs (Taylor *et al.*, 2012). Table S1, Supporting Information provides information on the 28 models (selected based on the availability of the variables listed below) considered in this study (the data were obtained from the Earth System Grid Federation web server: http://pcmdi9.llnl.gov/esgf-web-fe/). We note that this study emphasizes methodology and is not intended to comprehensively cover all CMIP5 models.

Although some objections could be raised concerning the use of reanalysis energy budget fluxes as an accurate representation of the observations, as well as other magnitudes that we did not directly analyse, we suggest that our approach is practical, circumventing the lack of spatial coverage of *in situ* data and the inaccuracy of satellite data for certain surface variables. Further information is provided by Sanchez de Cos *et al.* (2013), who discussed and validated EI land surface data against *in situ* and satellite observations over a domain close to our region of interest.

The following variables – from both EI and CMIP5 – were used in this study: monthly means of the daily averaged (at 0000, 0600, 1200, 1800 UTC) 10 m meridional wind component (V10m), 2 m air temperature (T2m) and mean sea level pressure (MSLP); monthly means of daily 12 h forecast accumulations (at 0000 and 1200 UTC) of cloudy-sky downward surface solar radiation (SW_{down}) as well as clear-sky ($SW_{down(clear)}$), top of atmosphere (TOA) net solar radiation (SW_{net}), TOA net thermal radiation (LW_{net}), clear-sky TOA net solar radiation ($SW_{net(clear)}$) and clear-sky TOA net thermal radiation ($LW_{net(clear)}$). As the EI data (covering 1979–2011) and the CMIP5 data (covering 1961–2000) do not completely overlap, we compare their common period (1979–2000). The EI data and the 28 CMIP5 models were interpolated to a common grid ($1.0°$ latitude $\times 1.0°$ longitude) over the domain ($34.0°$N, $2.0°$W, $20.0°$N, $26.0°$W) (see Figure 1).

3. Methodology

The complexity of the feedback loops explaining summertime subtropical high-pressure system dynamics has been confirmed by many studies (Hoskins, 1996; Rodwell and Hoskins, 2001; Seager *et al.*, 2003; Liu *et al.*, 2004) and was synthesized by Miyasaka and Nakamura (2005) using the simplified diagram in Figure 2. Our study focuses on the loop marked with red lines, which defines an amplifying feedback, and on the corresponding relationships between pairs of variables. This loop encompasses: (1) increasing
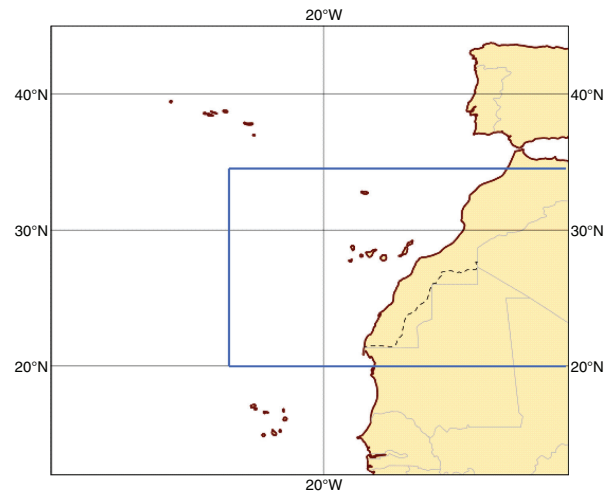

Figure 1. Map showing the area selected for this study (blue rectangle).

of land–sea thermal contrast; (2) intensification of along-shore wind; (3) development of reflective stratiform clouds favored by a stable lower atmosphere due to evaporation and upwelling of cool waters from below; and (4) increasing of radiative cooling (see Figure 2). The choice of this single loop was mainly determined by the availability of data (both from EI and CMIP5 datasets) that describe the different processes summarized in Figure 2. Because our main interest in this paper is to study the summertime intensification of the Azores high-pressure system (Li *et al.*, 2012), we restrict our analysis to the months of May, June and July and to the domain defined by Figure 1. We use only ocean grid points, except for the thermal contrast, which is calculated as the difference between land and ocean grid points. Figure 3 shows EI data for the period of 1979–2011, emphasizing the reinforcing of all magnitudes that intervene in the positive feedback loop from May to July.

Monthly means of the thermal contrast (the difference between sea and land grid point averages of 2 m air temperatures) are computed for the specified EI and CMIP5 periods. Monthly along-shore winds are computed as the meridional component of the 10 m wind averaged for the sea points. Marine stratus extension is estimated using effective cloud albedo (α_{cloud}) (Betts and Viterbo, 2005, Betts, 2007, Fasullo and Trenberth, 2012) by

$$\alpha_{cloud} = \left[SW_{down(clear)} - SW_{down} \right] / SW_{down(clear)} \quad (1)$$

where SW_{down} and $SW_{down(clear)}$ stand for, respectively, cloudy-sky and clear-sky downward surface solar radiation.

Radiative cooling is considered to be well represented by cloud radiative forcing (CRF) at the top of the atmosphere (TOA) (Charlock and Ramanathan, 1985, Ramanathan *et al.*, 1989, Wang and Su, 2013). It is computed by

$$CRF = \left(SW_{net} - SW_{net(clear)} \right) + \left(LW_{net} - LW_{net(clear)} \right) \quad (2)$$
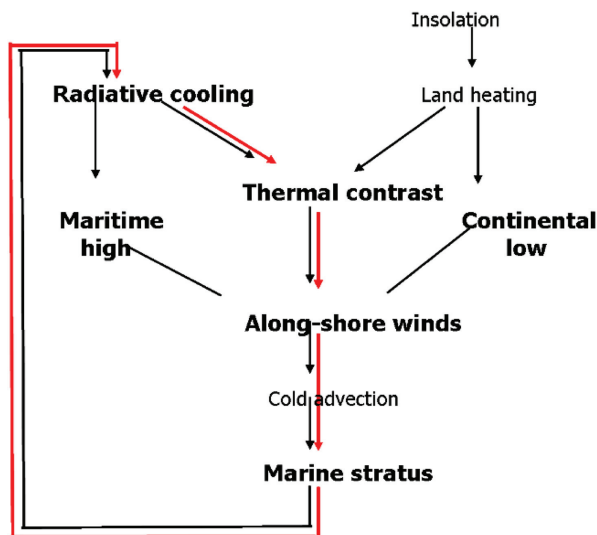
Figure 2. Schematic diagram of the feedbacks associated with the Azores high-pressure system (based on Miyasaka and Nakamura, 2005).

where the first term corresponds to the shortwave forcing and the second to the longwave forcing. If CRF > 0 (<0), clouds are a warming (cooling) mechanism. Although stratus clouds should ideally cause radiative cooling throughout the entire boundary layer, we use 2 m air temperature instead of the mean layer temperature. Allan (2011) compared CRF obtained from EI data with CRF retrieved from satellite data and showed remarkable agreement.

We note that when we refer to coupling between two variables or magnitudes, we mean that one variable controls the other (following Seneviratne *et al.* (2010)) in a way determined by the underlying processes. To quantify the similarities or differences in the empirical relationships defining the coupling between two variables (both for EI data and for each of the CMIP5 models), we use the Hellinger coefficient (Hellinger, 1909), following Sanchez de Cos *et al.* (2013). The Hellinger coefficient, originally designed to estimate the proximity of probability density functions (pdfs), can be thought of as a measure of the 'overlap' between two distributions. It gives information about the differences or similarities in the relative position, shape and orientation of the pdfs, returning values between 0 (fully disjoint distributions) and 1 (identical distributions). The Hellinger coefficient is defined as follows:

$$\text{dHell}^{(s)}(\text{P.Q}) = \int_R q(x)^s \, p(x)^{(1-s)} \, dx \qquad (3)$$

where $q(x)$ and $p(x)$ are the pdfs to be compared, and s is a parameter $(0 < s < 1)$. We calculate the Hellinger coefficient with $s = 1/2$, which yields a symmetric measure with values between zero and one. R stands for the phase space where the pdfs are defined.

4. Results

Scatterplots of EI data for the months of May and July (Figure 4) of the four relationships defining the

feedback loop show that some pairs of variables are highly correlated, indicating a strong coupling [e.g. the amount of marine stratus clouds and radiative cooling in July (Figure 4(c))]. However, others are only weakly correlated (e.g. the land–sea thermal contrast and radiative cooling in July (Figure 4(d))). We note that in the latter case, a land–sea contrast value that falls below a certain threshold, as usually occurs in May, may not be able to represent the feedback loop. In fact, the positive correlation between the land–sea thermal contrast and radiative cooling in May evolves to a slightly negatively correlation in July, which properly simulates the amplifying feedback loop.

After examining the corresponding four relationships in the 28 CMIP5 models, we find that only 11 of them can properly simulate the amplifying feedback loop. Therefore, the original 28 models can be initially classified into two main categories depending on their ability to simulate the intensification of the Azores high-pressure system at the beginning of boreal summer. Figures S1–S4 show scatterplots of the four relationships between pairs of magnitudes for EI data and for the 11 models able to simulate the amplifying feedback loop during the month of July. The 'wind–thermal contrast' relationship (see Figure S1) is properly simulated by all 28 CMIP5 models here considered (not shown). The 'wind–marine stratus' relationship only shows a positive correlation in 14 out of 28 models. In the remaining 14 models, the amount of marine stratus clouds decreases when the wind strengthens, breaking the amplifying feedback loop. This behavior contrasts with the results of previous studies (e.g. Klein and Hartmann, 1993, Seager *et al.*, 2003, Miyasaka and Nakamura, 2005, Nakamura, 2012) and with EI reanalysis data. The coupling between wind and cloud albedo is not very strong in most models, and the range of the variables also differs between the various models (see Figure S1). The scatterplot for radiative cooling and the amount of marine stratus clouds [represented by the equivalent relationship between CRF TOA and cloud albedo (see Figure S3)] shows that the two variables are strongly coupled in both the EI data and the CMIP5 models; the maximum value of CRF TOA in the EI data is lower than that in any of the CMIP5 models. The relationship between thermal contrast and radiative cooling (which is represented by CRF TOA) does not show a strong coupling in either the CMIP5 models or the EI data (see Figure S4). We note that there are large differences in the upper limit of the CRF TOA values, especially between the EI data and the CMIP5 models. Although most of the CMIP5 models use a solar constant of approximately 1365 Wm^{-2} (higher than the EI value of 1377 Wm^{-2}) we estimate that the difference of approximately 1% can hardly have effect in the results. These differences largely derive from the discrepancies in shortwave forcing between the EI data and the CMIP5 models. Nevertheless, some models, including BNU-ESM, MIROC-ESM-CHEM and NorESM1-M,
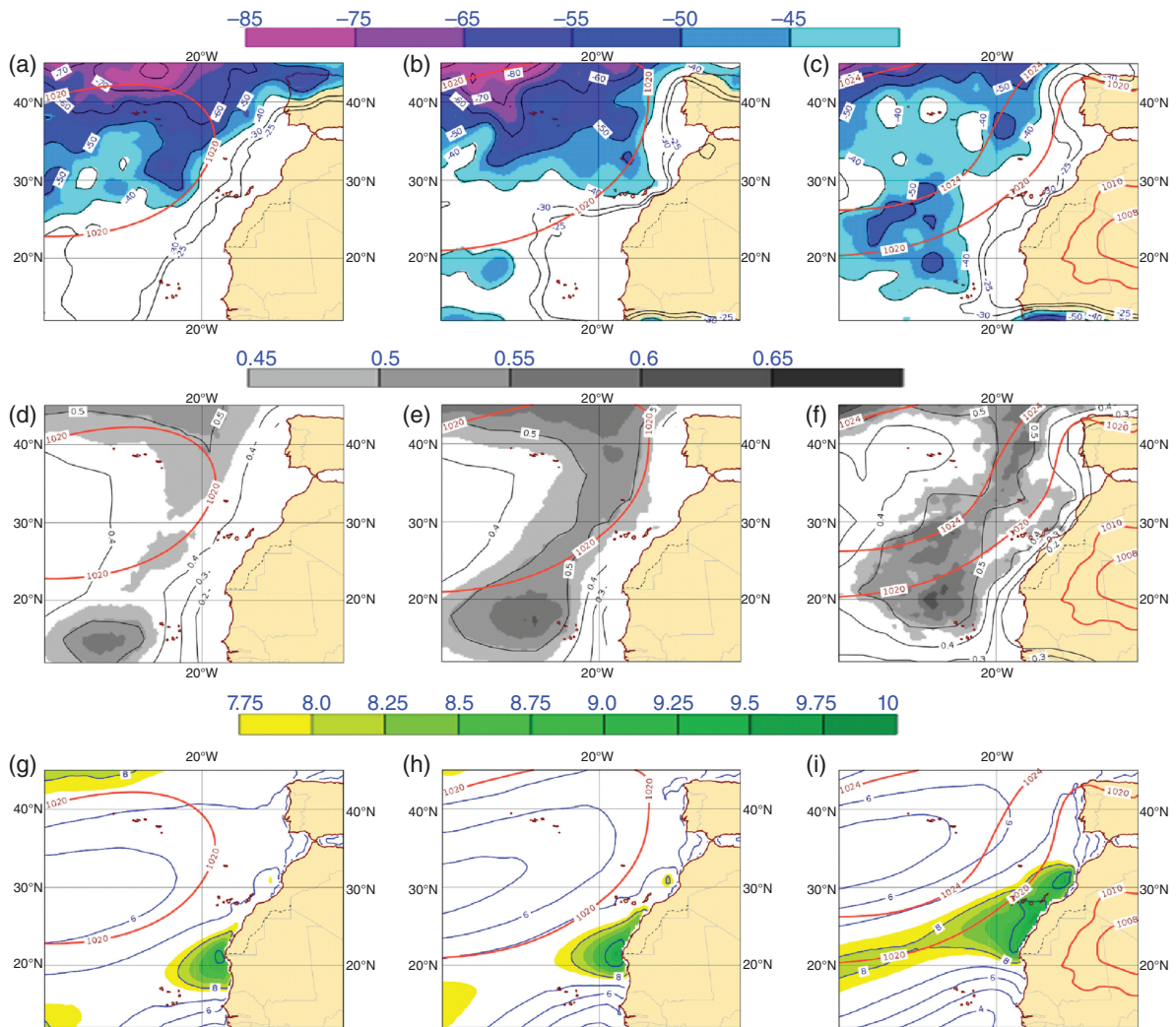
Figure 3. Radiative forcing by clouds (black lines and magenta-clear blue areas in Wm^{-2}) for May (a), June (b) and July (c). Cloudiness (black lines and grey areas in albedo units ranging from 0 to 1) for May (d), June (e) and July (f). Wind speed (blue lines and green−yellow areas in ms^{-2}) for May (g), June (h) and July (i). Note that sea level pressure (red lines in hPa) is included in all maps for the sake of completeness.

show a relatively strong coupling between both variables.

For each of the four relationships and each of the 11 CMIP5 models simulating the positive feedback loop, we compute Hellinger distances with respect to the EI data (see Table 1). We can use this metric to rank the 11 CMIP5 models that can simulate the positive feedback loop without considering any additional combination of the four coefficients, and we note that the metric was computed separately for the four relationships. Some models rank well based on a majority of the four distances, such as IPSL-CM5A-MR, ACCESS1-3 and BNU-ESM, whereas others have difficulty reproducing the processes described by the reanalysis data, such as MRI-CGCM3 and MIROC-ESM.

Although it is not easy to explain why so many models (17 out of 28) fail to simulate the positive feedback loop that describes the dynamics of subtropical high-pressure systems during summer, a preliminary analysis of deficiencies in these models suggests that they are unable to simulate the marine stratus layer, the

correct thermal contrast between land and sea or both. A more detailed analysis of each of the simulations is beyond the scope of this letter.

5. Conclusions

The evaluation of climate models conducted in this letter is based on the relevance of subtropical anticyclones to both global and regional climate. In particular, the intensification of the Azores high plays an important role in the climate of south-western Europe and north-western Africa during summer. We found that only 11 out of the 28 models examined were able to represent the positive feedback loop similarly to the reanalysis data. The relatively small number of models (11 out of 28) able to simulate the amplifying feedback loop indicates that climate models have difficulty representing some of the relevant physical processes that occur in the land−ocean−atmosphere subsystem, in particular those related to marine stratus clouds, which are underestimated by most of the CMIP5 models.
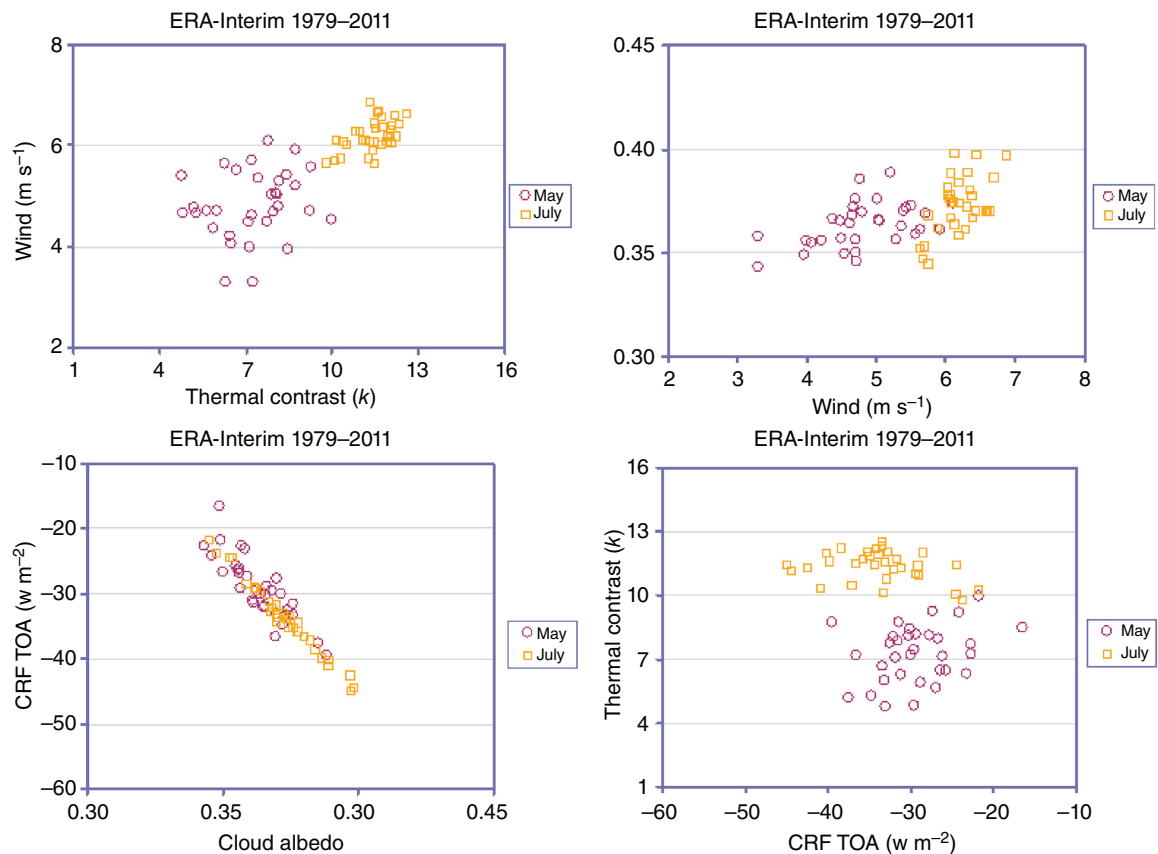
Figure 4. Relationships among pairs of variables over the area shown in Figure 1 (based on ERA-Interim data from 1979 to 2011) for the months of May and July.

Table 1. Values of the Hellinger coefficient for the following relationships: thermal contrast-wind, wind-cloud albedo, cloud albedo-CRF TOA and CRF TOA-thermal contrast for the month of July (from 1979 to 2000). Variables are expressed as differences from their mean value. The model acquiring the highest (bold) and the lowest value (underlined) of the Hellinger coefficient for each relationship is indicated, and ranking positions are noted within brackets.

Models	Thermal contrast-V10m	V10m-cloud albedo	Cloud albedo-CRF_TOA	CRF_TOA-thermal contrast
ACCESS1-0	0.96 [2]	0.94 [2]	0.90 [8]	0.92 [9]
ACCESS1-3	0.91 [5]	0.92 [3]	**0.99 [1]**	0.97 [2]
BNU-ESM	0.88 [7]	0.89 [6]	0.98 [3]	**0.98 [1]**
HadGEM2-ES	0.94 [3]	0.87 [7]	0.88 [9]	0.94 [5]
IPSL-CM5A-LR	0.88 [8]	0.91 [5]	0.96 [4]	0.92 [7]
IPSL-CM5A-MR	**0.97 [1]**	**0.99 [1]**	0.98 [2]	0.96 [3]
MIROC-ESM	0.86 [10]	0.77 [10]	0.80 [10]	0.89 [10]
MIROC-ESM-CHEM	<u>0.84 [11]</u>	0.82 [9]	0.91 [5]	0.94 [6]
MRI-CGCM3	0.87 [9]	<u>0.67 [11]</u>	<u>0.60 [11]</u>	<u>0.75 [11]</u>
NorESM1-M	0.90 [6]	0.85 [8]	0.90 [7]	0.96 [4]
NorESM1-ME	0.93 [4]	0.92 [4]	0.91 [6]	0.92 [8]

Our proposed method of evaluation aims to explore and quantify how well various models simulate the coupling between atmosphere, ocean and land surface. Climate models are based on sound and well-established physical laws, and their success in simulating the climate system depends on an accurate representation of relevant processes such as the dynamics of subtropical highs. We emphasize the importance of evaluation studies that focus on physical processes, particularly the features at the interface between subsystems. Analysis of the simulated coupling between subsystems, as in this study of the dynamics of the Azores anticyclone, could help to diagnose modeling deficiencies in representing climate variables that underlie poor performance.

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Supporting information

The following supporting information is available:

Table S1. The 28 CMIP5 models considered in this study.

Figure S1. Scatterplots of the relationship between V10m and thermal contrast for ERA-Interim data and for the 11 CMIP5 models able to simulate the positive feedback loop in July.

Figure S2. The same as Figure S1, but for cloud albedo and V10m.

Figure S3. The same as Figure S1, but for CRF TOA and cloud albedo.

Figure S4. The same as Figure S1, but for thermal contrast and CRF TOA.

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