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# Climatic trends in Puerto Rico: observed and projected since 1980

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ABSTRACT: This study considers observed and CMIP5 (Coupled Model Intercomparison Project 5) projected climate trends in Puerto Rico, with a focus on change maps and time series since 1980. The Hadley circulation has accelerated and sinking motions have warmed the lower atmosphere faster (+0.03°C $yr^{-1}$) than the underlying ocean (+0.01°C $yr^{-1}$). Increased evaporation and northerly winds are generating upward trends in rainfall on the Atlantic side of Puerto Rico, while the Caribbean side is drying. Global warming appears to enhance shallow clouds and vegetation, and inhibit deep convection around the island. The impact on natural resources appears limited, but rising sea levels will necessitate pro-active coastal management.

KEY WORDS: Puerto Rico · Climate trends · Rainfall change



## 1. INTRODUCTION

Global warming affects the carrying capacity of ecosystems and natural resources by accelerating the water cycle. Densely populated and less-developed island states in the Caribbean rely on subsistence food production and economic ties with neighboring countries (Watts 1995, Trotman et al. 2009). Located in the sub-tropics, the region experienced warmer conditions in the 20th century (Peterson et al. 2002, Mimura et al. 2007, Gamble et al. 2010), and model projections are for these trends to continue in the 21st century (Nurse & Sem 2001, Taylor et al. 2013). Yet each island has a different means of adapting to climate change, and detailed analysis is needed to consider local strategies.

Climate projections make use of global and regional coupled general circulation ensemble models to simulate physical processes within the earth system. Earlier CMIP (Coupled Model Intercomparison Project) version 3 simulations (Meehl et al. 2007) exhibited a cool, dry, windy bias in the Caribbean (Angeles et al. 2007, Christensen et al. 2007, Campbell et al. 2010), and underrepresented the Atlantic Multidecadal Oscillation (AMO; Enfield et al. 2001). Local circulations were not well captured (Jury 2009) due to a resolution of ~2 degrees. CMIP5 models have similar issues, but are better coupled with ocean and land sub-models to simulate interactions with the atmosphere and its moist convection (K. E. Taylor et al. 2011). Observed data for assessing climate change and validating models is growing (Jury 2012). Higher resolution (<0.3 degree) coupled reanalysis products (e.g. the Coupled Forecast System) assimilate station and satellite data to provide ample coverage over the Antilles Islands and surrounding marine areas. Station networks have benefited from automation, particularly in the jurisdiction of overlapping services by the National Weather Service in Puerto Rico and MeteoFrance in the Antilles.

The circulation of the sub-tropics around Puerto Rico is characterized by persistent trade winds and a shallow marine layer. Just above this moist, unstable layer is subsidence from the Hadley circulation. Wind observations (Fu et al. 2006) and model simulations (IPCC 2007) suggest a meridional widening and poleward shift of the Hadley cell (Frierson et al. 2007) leading to intensification of mid-latitude storms (Bengts-

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son et al. 2006) and concurrent expansion of subtropical deserts (Seager et al. 2007). Radiative forcing by short-lived greenhouse gases and aerosols has been shown to alter the tropical circulation far from emission sources such as Africa (Wong et al. 2007).

Here, climate change around Puerto Rico is described in terms of trends in temperature, rainfall and related climatic elements in the satellite era, similar to Karmalkar et al. (2013). We seek to understand how trends are driven by physical/chemical, local/remote, and thermodynamic/kinematic processes. The impacts of climate change are discussed for Puerto Rico.

## 2. DATA

Air temperature, air pressure, winds and specific humidity were analyzed from interpolated quality-controlled land, ocean and atmosphere station and satellite data, assimilated by the National Center for Environmental Prediction (NCEP; Kanamitsu et al. 2002), the Coupled Forecast System (CFS; Saha et al. 2010) and the European Community Medium-range Weather Forecast (ECMWF; Dee et al. 2011) reanalyses. In particular, the CFS (30 km) resolution and its assimilation of $CO_2$ has enabled the detection of climate change in Puerto Rico since 1980. Sea surface temperature (SST) trends were studied using the Hadley reanalysis (Kennedy et al. 2011); sensible and latent heat fluxes were estimated from CFS and ECMWF reanalyses. The investigation focused on the period 1980–2014 to avoid the known discontinuity at the start of the satellite era (Hurrell et al. 2000) and to capture the accelerating global warming signal. The premise is that climate change has already started to occur.

To alleviate concern about the AMO influence, temporal trends since 1900 were analyzed around Puerto Rico (17.7–18.7° N, 67.5–65.2° W) for surface air temperature and rainfall. The intercept, linear slope and $r^2$ fit were determined. For satellite era trends with ~33 df, 95% confidence was achieved at $r^2 > 0.32$. Trends in ECMWF marine wind stress, multi-satellite observed ozone ($O_3$; van der A et al. 2010) and vegetation fraction (NDVI; Tucker et al. 2005) were analyzed for the period 1980–2014. Observed trends were compared with CMIP5 projections up to 2050 (K. E. Taylor et al. 2011) using the ensemble mean of all 25 models and models that better followed the mean annual cycle of air temperature (CCSM4) and rainfall (CSIRO3, MIROC5). Projections employed the CMIP5 Representative Concentration Pathway (RCP) 6.0 W $m^{-2}$ scenario.

The Puerto Rico area-average used here has similar amounts of land and sea (see Fig. 1), so observations were derived from a variety of sources. Puerto Rico's trade winds originate in the central Atlantic, and flow past several small flat islands with little perturbation. Puerto Rico casts a wind shadow westward toward Hispaniola, and warming trends there are greater (Perez & Jury 2013).

To study the trend pattern across the island, the CHIRPS (Climate Hazards Group InfraRed Precipitation with Station) 5 km resolution rainfall dataset was utilized. Monthly totals from ~50 National Weather Service and cooperative agency gauges were blended with multi-satellite observations as described in Funk et al. (2014). The interpolation procedure gives primary influence to *in situ* observations and gauge climatology, and secondary influence to satellite and model data (Janowiak et al. 2001, Huffman et al. 2009, Saha et al. 2010, Knapp et al. 2011). The climatology of daytime land surface temperature and SST from 5 km MODIS satellite data was also calculated.

## 3. RESULTS AND DISCUSSION

### 3.1. Mean climate and rainfall

The geography of Puerto Rico, in isolation from the neighboring Antilles Islands, is illustrated in Fig. 1a–c. The MODIS satellite vegetation climatology identifies areas of urbanization and sandy beaches around the perimeter of the island. Dense forest canopies still occupy much of the interior (Fig. 1a), generating diurnal transpiration. Puerto Rico's population is declining by ~1% annually from a peak of 3.9 million people in 2000, so there is little pressure for new development. Agriculture contributes <1% of total economic value; most food is imported. The island relies on coastal tourism and transfers from the USA for ca. one-quarter of its gross domestic product (http://data.worldbank.org/country/puerto-rico).

Puerto Rico's thermal footprint is illustrated in Fig. 1b,c. The higher elevations (>600 m) have mean daytime land surface temperatures below 24°C (Waide et al. 2013), while the urban area of San Juan and the leeward south coast exceed 29°C (González et al. 2007). The east coast with onshore winds has temperatures near 26°C, while in contrast the west coast wind shadow has values of 28°C. Marine winds are from 080° or east–north–easterly. SSTs have a narrow range: the Atlantic coast is 1°C cooler than the Caribbean (27.8°C) due to the northerly component of trade winds and southerly solar angle during

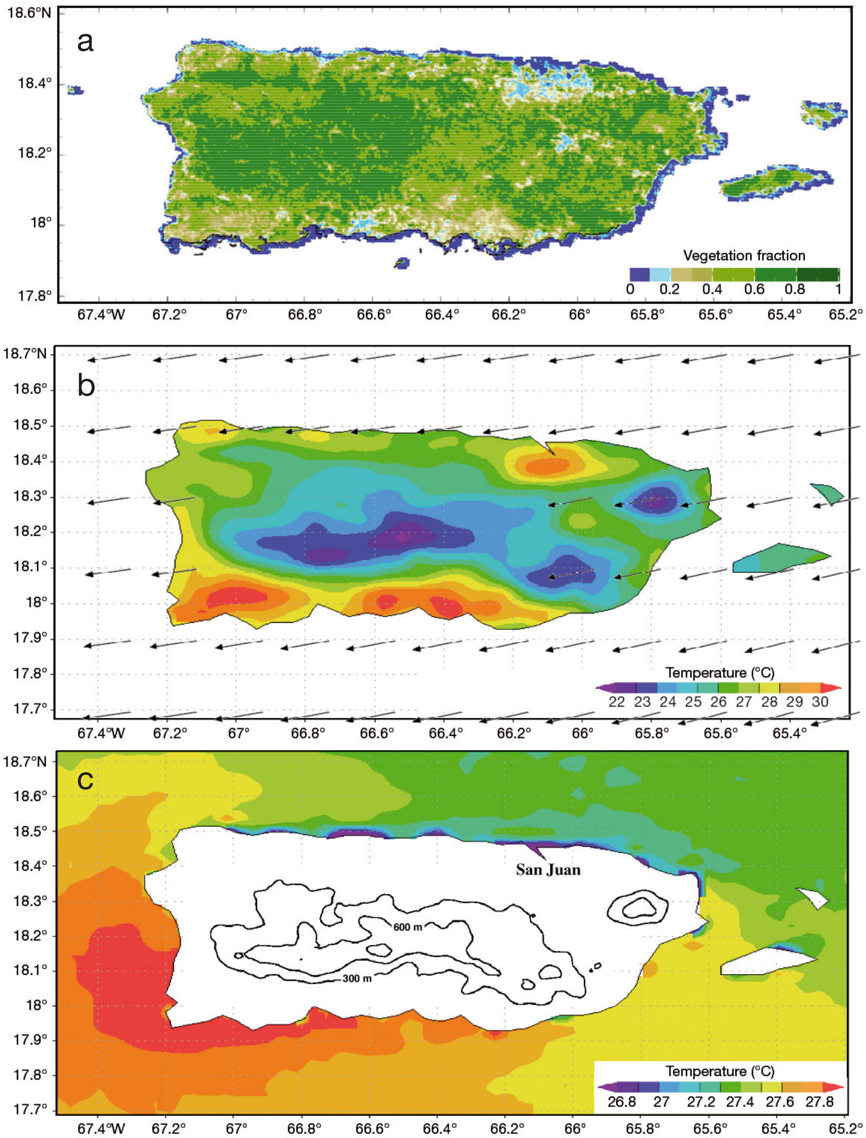


Fig. 1. Climatology of Puerto Rico showing (a) satellite vegetation fraction with coast/urban in blue, (b) satellite daytime land surface temperature and marine wind stress (largest vector 0.08 N $m^{-2}$) and (c) sea surface temperature and elevation contours

winter. These temperatures are close to the known threshold for hurricanes, but upper westerly winds and anticyclonic vorticity inhibits tropical convection from November to July.

CFS reanalysis trends from 1980–2014 are highlighted in Fig. 2a–d and reveal the island's climatic imprint. Surface air temperature (+0.03°C $yr^{-1}$) and sensible heat flux trends (+0.01 W $m^{-2}$ $yr^{-1}$) are greatest over the interior (Fig. 2a,c). On the other hand, declining rainfall (–0.005 mm $d^{-1}$ $yr^{-1}$) and increasing solar radiation trends (+0.02 W $m^{-2}$ $yr^{-1}$) affect the eastern half of the island and upstream ocean (Fig. 2b,d), consistent with Karmalkar et al. (2013). The vegetation fraction exhibits a rising trend (+0.0023 $yr^{-1}$) consistent with CMIP5 latent heat flux ($r^2$ = 56–82%). GRACE (Gravity Recovery and Climate Experiment) soil moisture (Tapley et al. 2004) also trends upward at 0.28 cm $yr^{-1}$ over 2003–2014. The projection to 2050 is for accelerated evaporation (+0.003 mm $d^{-1}$ $yr^{-1}$). The ability of CMIP5 to simulate the observed inter-annual variability is uncanny. This uncovers a climatic conundrum: the surface moisture flux is rising, while rainfall is diminishing.

### 3.2. Hadley circulation and ozone trends

Analysis of linear trends in the NCEP meridional Hadley circulation and air temperature between 1980–2014 in height section over the Caribbean (Fig. 3a) reveals accelerated overturning. Strong southerly trends above 400 hPa and opposing northerly trends below 800 hPa are joined by a sinking motion over Puerto Rico. The resulting compression heats and dries the air, strengthening the trade wind inversion +0.03°C $yr^{-1}$ in the 800 hPa layer (cf. Jury & Winter 2010). A stronger inversion reduces the Froude number below unity, so the wind shadow and thermal footprint west of the Antilles Islands grows. Intercomparison of the Hadley circulation trend here and in Perez & Jury (2013) gives evidence of northward expansion.

The horizontal trend map for marine wind stress (Fig. 3b) confirms the tendency for an increased northerly component from 1980–2014 (–0.001 m $s^{-1}$ $yr^{-1}$). The surface part of the accelerating Hadley circulation extends from Venezuela to Florida, 5–25° N latitude. In the south, there is an increase of short-lived ozone (Fig. 3c, +0.1 Dobson Units [DU] $yr^{-1}$) that is related to the smoke plume from biomass burning in Africa and (secondarily) the Amazon

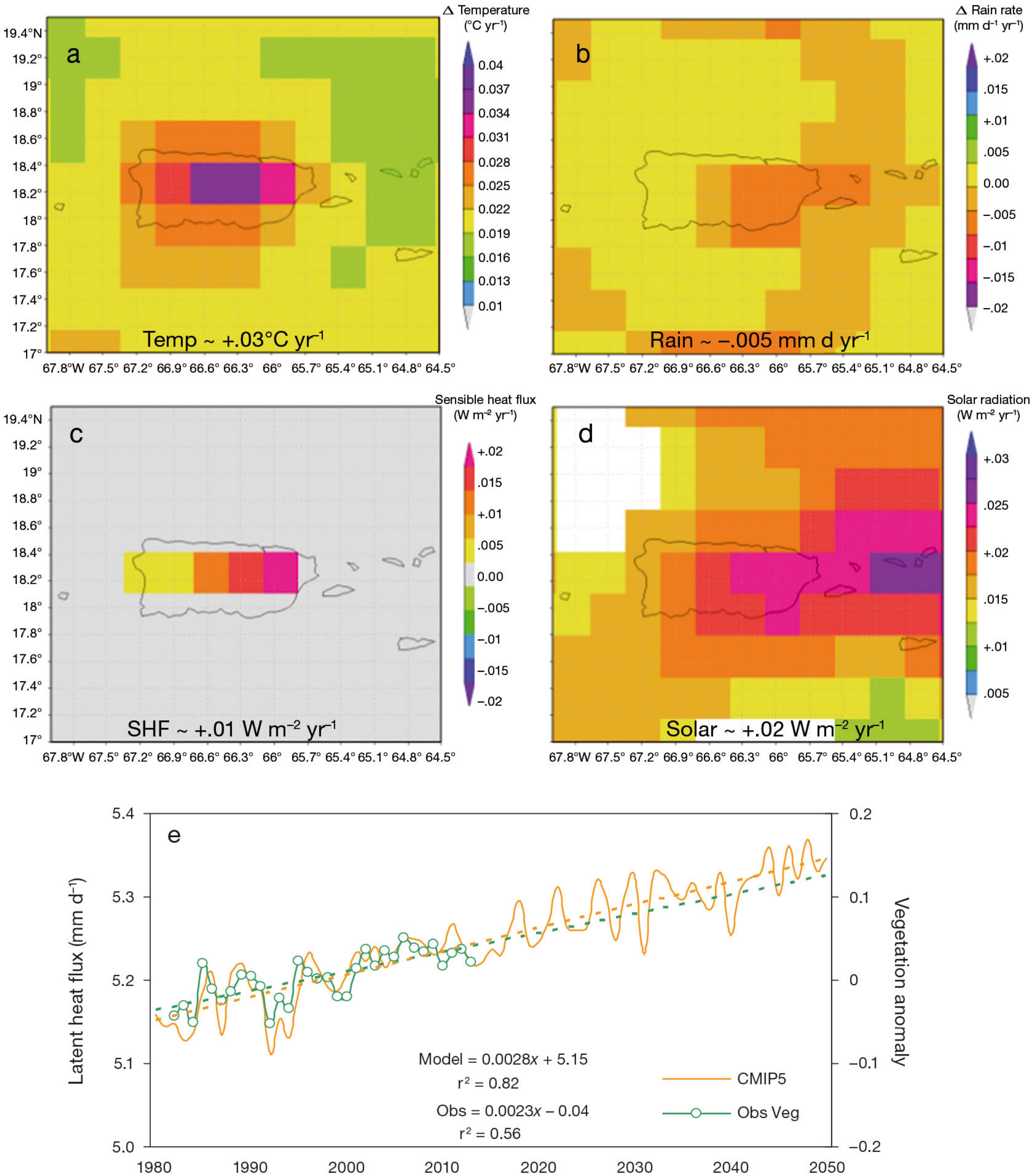


Fig. 2. Coupled Forecast System (CFS) reanalysis of observed linear trends in (a) surface air temperature, (b) rain rate, (c) sensible heat flux and (d) solar radiation; 1980–2014, with scale inverted for rain. Values at bottom of (a–d): area mean trend. (e) Island area-average time series of projected CMIP5 ensemble mean latent heat flux and observed satellite vegetation anomaly with trends

(Hobbs 2000, Pilewskie et al. 2003, Bergstrom et al. 2003, Sinha et al. 2003, Hawkins et al. 2007). The peak ozone trend is closer to Africa (+0.25 DU $yr^{-1}$, data not shown) and arises from photochemical aging during westward dispersion over the Atlantic. Part of the warming over South America is from ozone, while over Puerto Rico it is from subsidence.

### 3.3. CMIP5 model evaluation

An analysis of CMIP5 projections should first consider the ability to simulate mean climate. CMIP5 upper ocean currents (data not shown) are similar to SODA/GODAS (Simple Ocean Data Assimilation/Global Ocean Data Assimilation System) reanalysis, so the residence time for cumulative heating is realistic. Difference maps of the CMIP5 ensemble mean minus observed (Fig. 4a,b) exhibit a −1.5°C cold bias in the Caribbean corresponding with a +1 hPa high pressure bias over the Atlantic (Taylor et al. 2011, 2012). There is a −1.5 hPa low pressure bias over the western Amazon, creating an artificial pressure gradient over the Caribbean which leads to unrealistically strong trade winds. While most CMIP5 models have a dry bias, some (e.g. CSIRO, MIROC) replicate the bi-modal distribution of observed rainfall (Fig. 4c) with minor discrepancies.

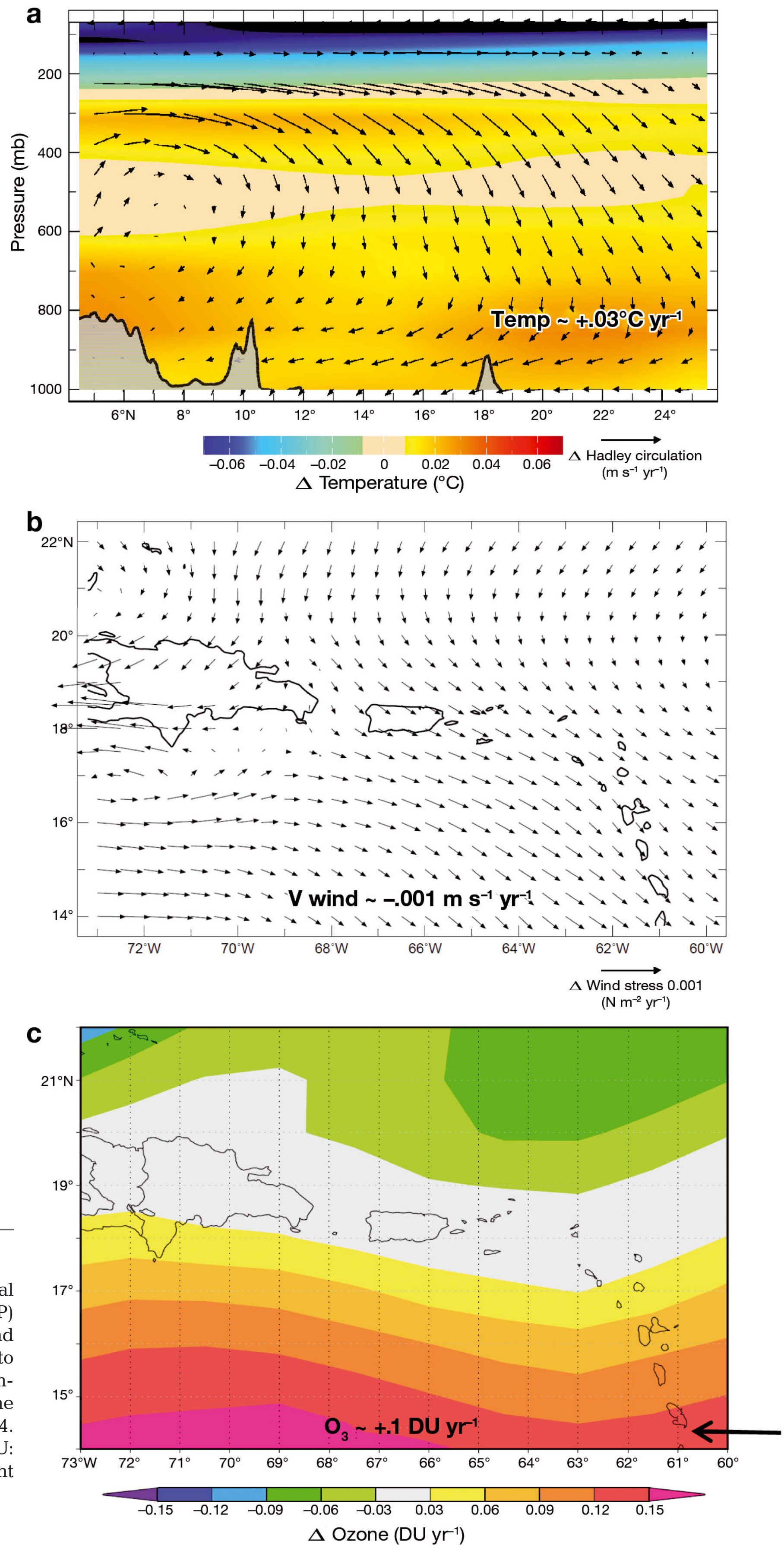


Fig. 3. Observed linear trends in (a) the National Center for Environmental Prediction (NCEP) reanalysis meridional Hadley circulation and air temperature in height section over Puerto Rico, (b) the European Community Medium-range Weather Forecasts (ECMWF) marine wind stress and (c) satellite ozone; 1980–2014. Arrow: incoming African smoke plume. DU: Dobson Units. Values in the panels highlight trend at that location

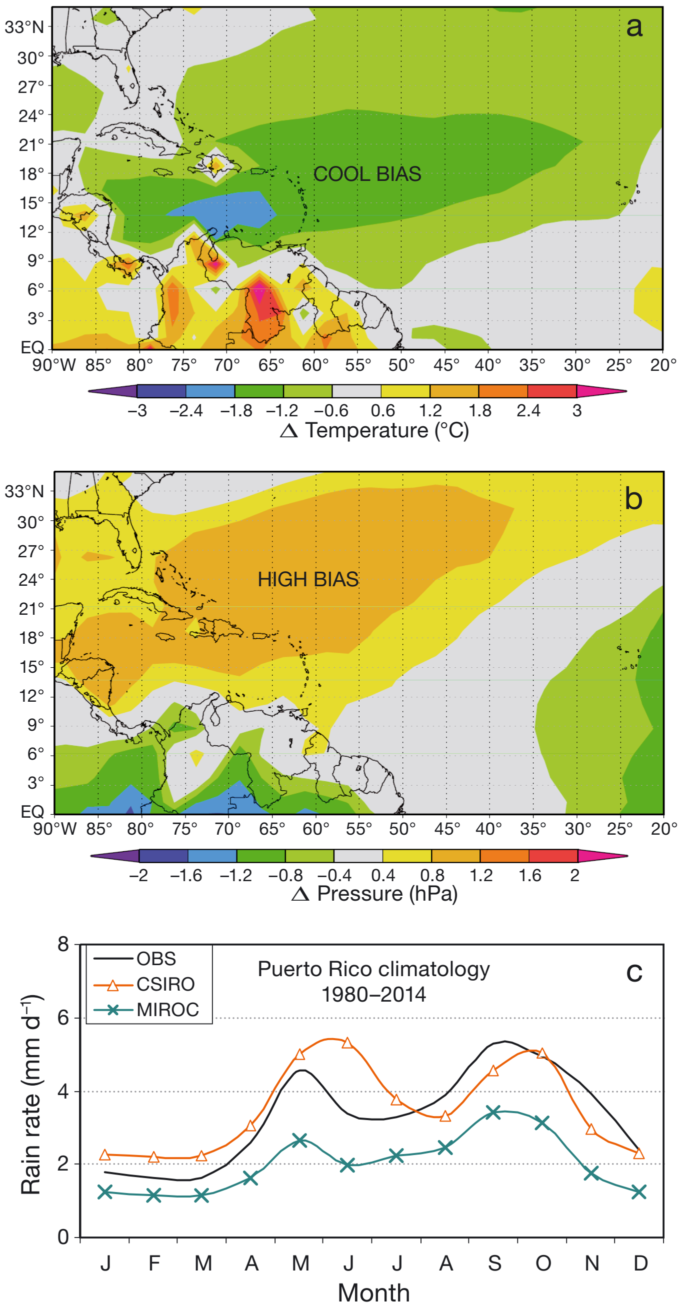


Fig. 4. CMIP5 ensemble-mean simulated difference with respect to observed (a) European Community Medium-range Weather Forecast (ECMWF) surface air temperature (°C) and (b) Hadley surface air pressure; 1980–2014. (c) Mean annual cycle of rainfall for observed and CMIP5 model simulations (CSIRO and MIROC) over the Puerto Rico area

### 3.4. Temperature and rainfall trends

All-island average surface air temperature observations from the Climate Research Unit (CRU) version 3, San Juan station and CCSM4 model projection with the CMIP5 RCP6 are shown in Fig. 5a for the period since 1900. Linear trends are +0.013°C yr$^{-1}$ for the model and compare favorably with observations of +0.014°C yr$^{-1}$, while the San Juan trend is higher (+0.022°C yr$^{-1}$) due to urbanization. These values are well below the CFS reanalysis air temperature trend (+0.03°C yr$^{-1}$) reported above, which relates to the acceleration of global warming since 1980 and interference from the AMO. The observed long-term air temperature trend has a very significant linear fit ($r^2 = 0.67$).

All-island average rainfall from the Global Precipitation Climatology Center (GPCC) observations and the CMIP5 CSIRO model with RCP6 show weak linear trends of −0.0018 to −0.0032 mm d$^{-1}$ yr$^{-1}$ since 1900 (Fig. 5b) consistent with declining Puerto Rico river flow (http://pr-ccc.org/publications/prccc-documents/). The observed long-term rainfall trend is insignificant ($r^2$ = 0.006) due to large multi-year variability. The CHIRPS rainfall trend map (Fig. 5c) indicates that rainfall is actually increasing over the northeast (windward) coastal plains. Conversely, rainfall is declining over the southwest coastal plains. This is in keeping with the increase of northerly wind (cf. Fig. 3b) upslope on the Atlantic side of the island. Wet zones are getting wetter, dry zones are getting drier: moisture gradients have sharpened since 1980.

### 3.5. Caribbean trends and annual cycle

Using the CMIP5 25-model ensemble mean, maps were analyzed for air temperature, rainfall and air pressure trends across the Caribbean near Puerto Rico (Fig. 6a–c). The maps show an interrelated pattern of faster warming in the west with declining pressure near Panama, and a drying trend in the east under high pressure influence. Hence the pre-existent zonal gradient is expected to strengthen in the 21st century.

To understand the seasonality of climate change, mean annual cycle projections were analyzed (Fig. 7a,b). Air temperatures indicate that the CMIP5 mean closely follows the CRU3 model observation, rising a bit too slowly in May–June, but otherwise keeping pace. While the observations show faster warming from April to September, the CMIP5 RCP6 projection suggests that warming will be equally shared across the seasons. The CMIP5 ensemble projection is for drying from April to October, while the MIROC model anticipates an increase of May rainfall but little change in the hurricane season. Overall, the rainfall trends are weaker than temperature. Perhaps there are negative feedbacks to consider?

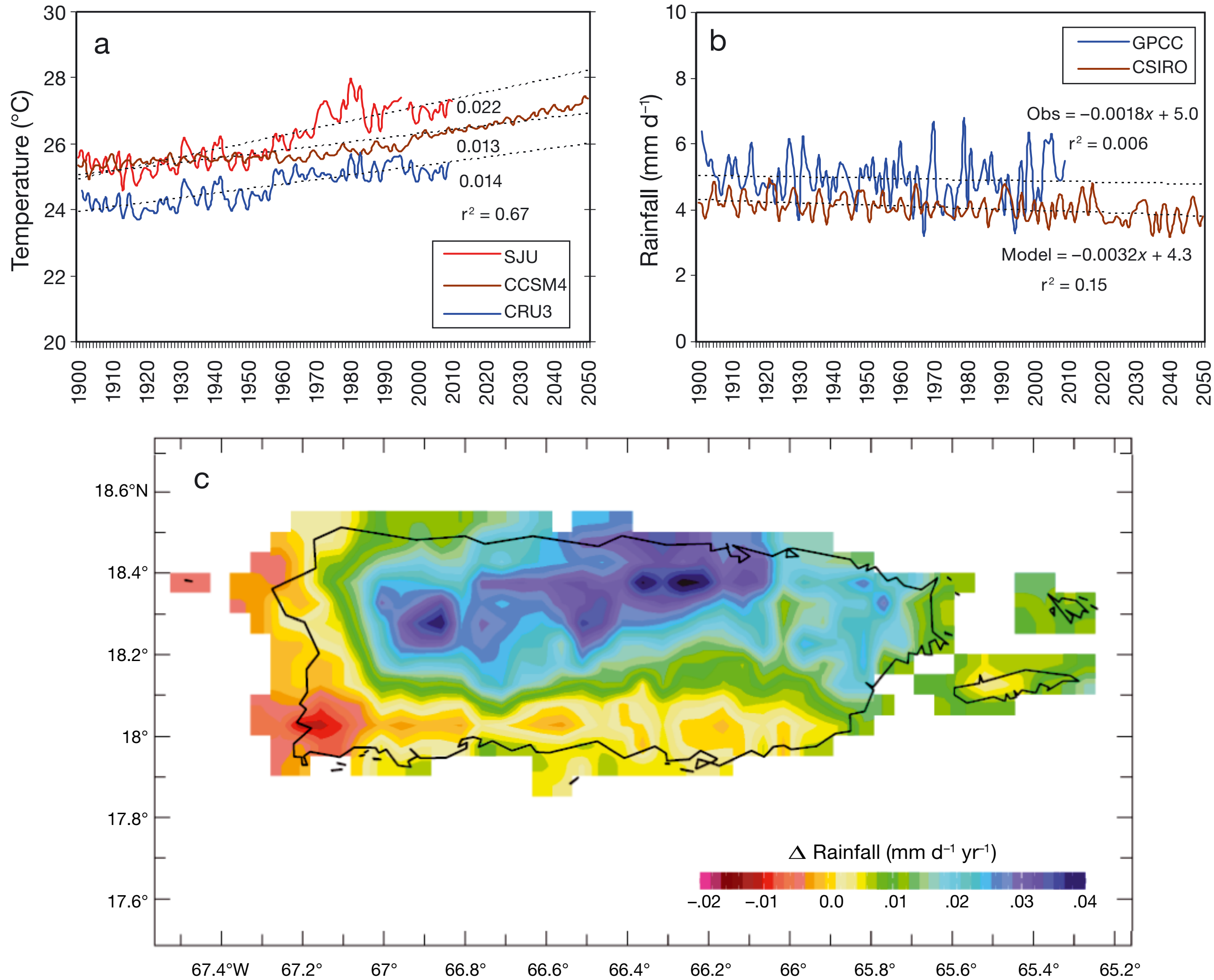


Fig. 5. Puerto Rico island average time series of observed and CMIP5 CCSM4/CSIRO model projected (a) surface air temperature and (b) rainfall since 1900. (c) Observed Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) rainfall trend for 1981–2014

### 3.6. Marine environment

The oceans are warming more slowly than the atmosphere, as evident in Fig. 8a. SST around Puerto Rico has increased +0.008°C $yr^{-1}$ since 1980. The CMIP5 projection is for +0.019°C $yr^{-1}$, well below the +0.03°C $yr^{-1}$ in air temperature. In keeping with warmer seas and thermal expansion, the sea level around Puerto Rico is rising by +0.11 to +0.14 cm $yr^{-1}$ (Fig. 8b). Many beaches are receding at ~1 m $yr^{-1}$ (Thieler et al. 2007). However, there is no geological subsidence, unlike the southeastern USA.

One effect of the differential rate of warming is a down-trend in sensible heat flux around Puerto Rico (Fig. 8c). While there is still an upward supply of heat, the rate of transfer from sea to air is projected to diminish with time. Hence the sub-cloud layer will become relatively more stable. Although evaporation shows an increase (cf. Fig. 2e), turbulence is inhibited over the ocean.

### 3.7. Underlying factors

Warming of the trade wind inversion by Hadley subsidence and greenhouse gases (Held & Soden 2006, Jury & Winter 2010) contribute to a drying trend that is partially offset by accelerating evaporation. An analysis of these opposing factors is given in Fig. 9a as a vertical profile. The trend in moisture weighted vertical motion (qW) shows a surplus in the 1000–925 hPa layer. This would benefit the frequent

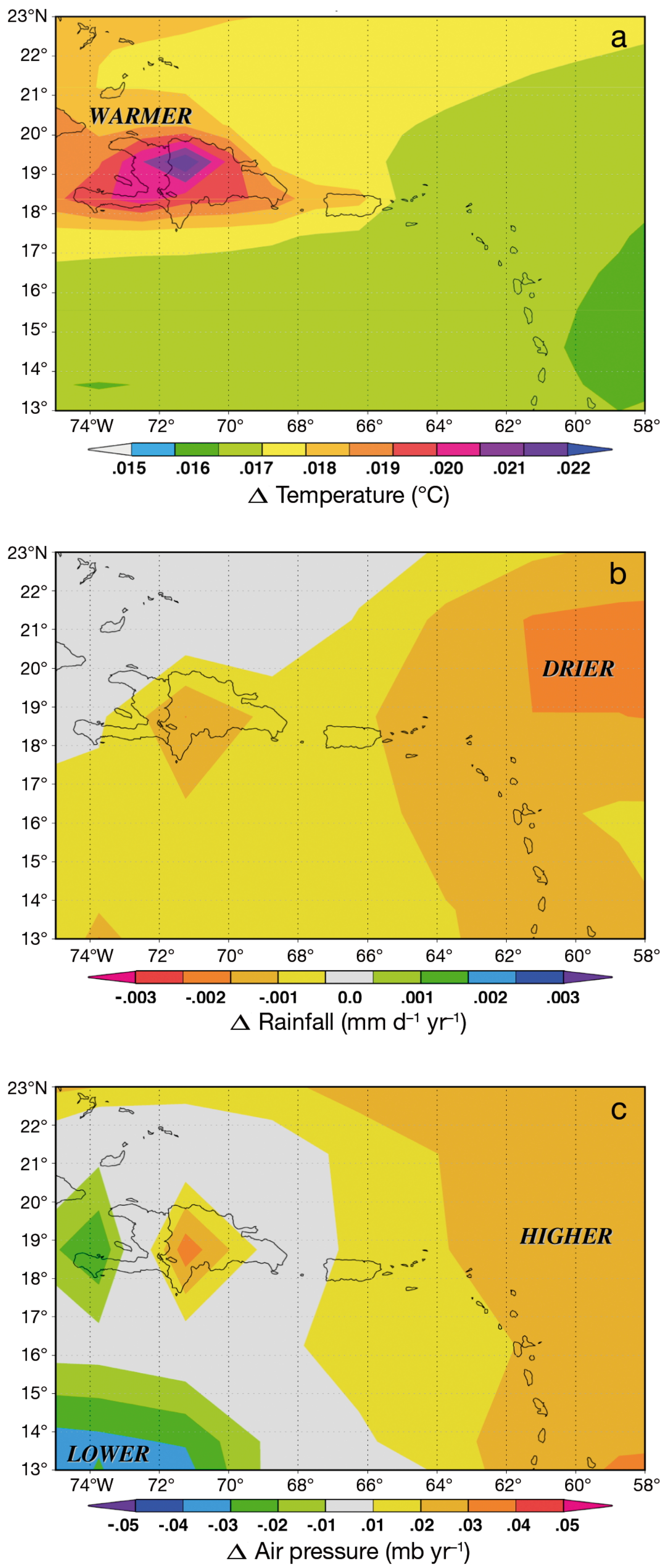


Fig. 6. CMIP5 ensemble mean projected linear trends in the period 1980–2050 for (a) air temperature, (b) rainfall and (c) air pressure

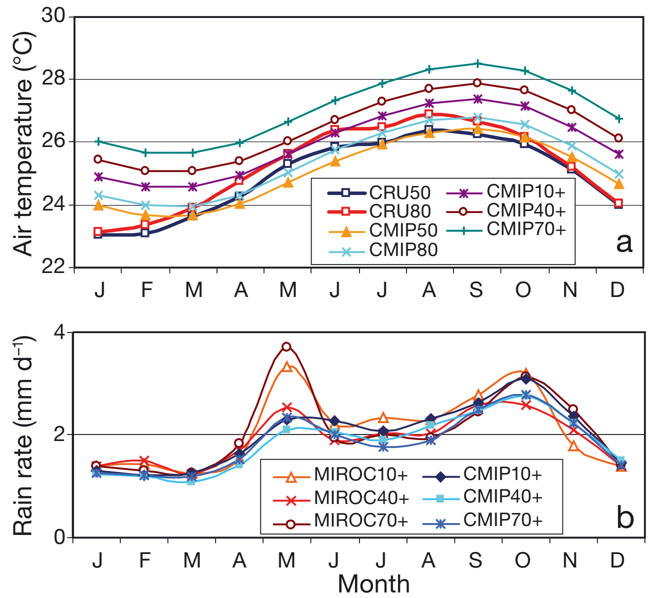


Fig. 7. Mean annual cycle in 30 yr intervals of (a) CMIP5 ensemble mean projected and observed air temperature, (b) CMIP5 ensemble mean and MIROC model projected rainfall. Forcing: RCP6. Legend numbers refer to the starting year of the 30 yr period (e.g. 50 = 1950–1979, 70+ = 2070–2099)

stratiform and shallow cumulus convection embedded in northeast winds, producing a wet trend over the Atlantic side of Puerto Rico (cf. Fig. 5c). However, the deficit in the 800–300 hPa layer (Fig. 9a) suppresses the infrequent, deep convection associated with troughs and hurricanes, leaving a dry trend over the Caribbean side of Puerto Rico.

Another question in this research is whether nonlinear SST effects could significantly deepen the surface moist layer. Analysis of the relationship between Convective Available Potential Energy (CAPE) and SST is given in Fig. 9b. In the period from 1980–2014, CAPE exhibited 2nd order seasonal and synoptic fluctuations. If the mean SST rises to 28.6°C by 2050 (cf. Fig. 8a) and CAPE reaches 1100 J $kg^{-1}$, it is plausible that Hadley subsidence could play a diminished role.

## 4. CONCLUSIONS

The Hadley circulation has accelerated over the Caribbean. Sinking motions have intensified, warming the trade wind inversion faster than the underlying ocean. Increased surface moisture and northerly winds in the period from 1980–2014 correspond with upward (downward) trends of rainfall on the Atlantic (Caribbean) side of Puerto Rico. Global warming appears to enhance shallow clouds and inhibit deep

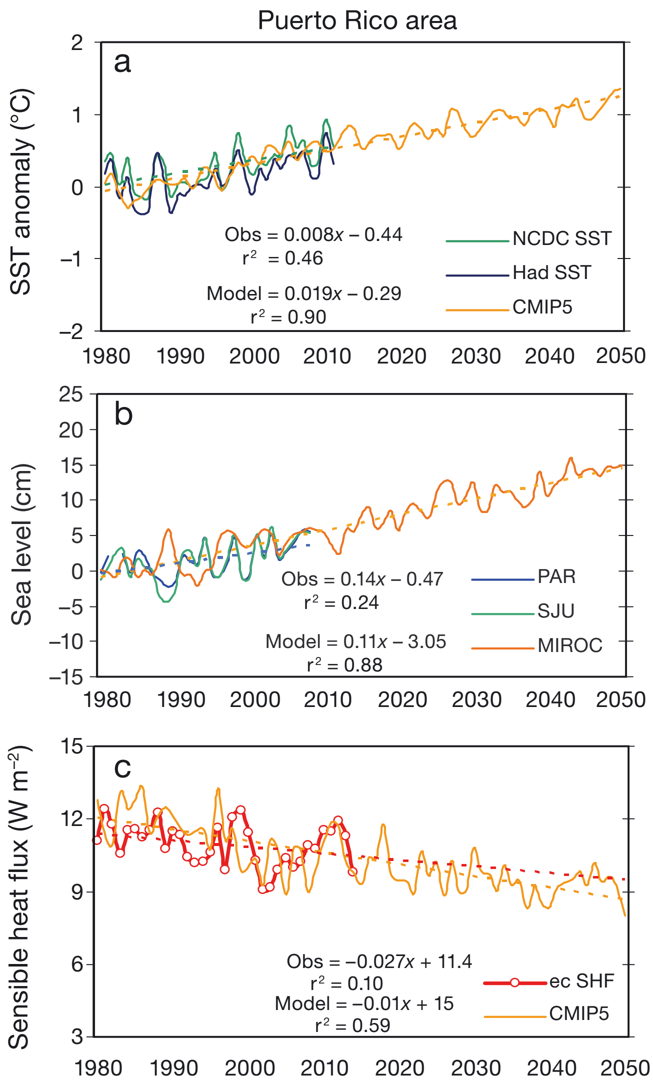


Fig. 8. Observed and projected island area-averaged time series and linear trends yr$^{-1}$: (a) sea surface temperature anomaly observed in NCDC and Hadley datasets, and CMIP5 ensemble mean, (b) sea surface height observed at PAR and SJU stations, and the MIROC model, and (c) European Community Medium-range Weather Forecasts (ECMWF) (ec) sensible heat flux and CMIP5 ensemble mean

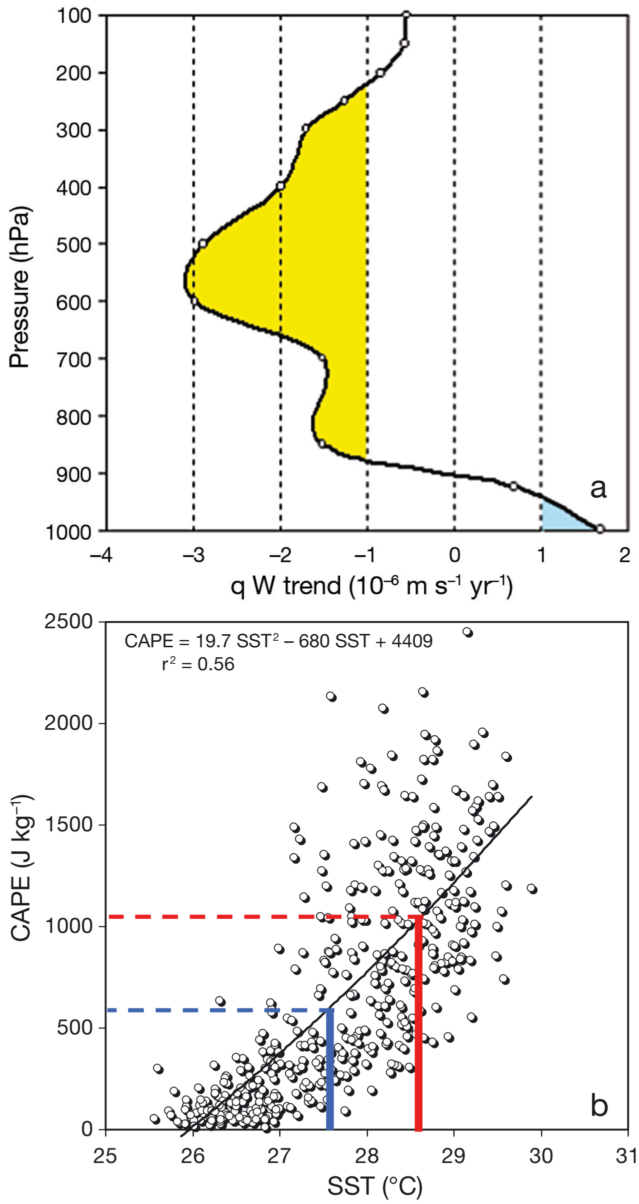


Fig. 9. National Center for Environmental Prediction (NCEP) observed (a) trend of specific humidity × vertical motion (qW) in profile with shading for dry subsident and moist layers (yellow and blue, respectively); (b) scatterplot of sea surface temperature (SST) and convective available potential energy (CAPE); 1980–2014. Bars reflect 1980 observed and 2050 projected (blue, red, respectively) mean SST and CAPE

convection around the island, contributing to rising vegetation and evaporation. CFS reanalysis and CMIP5 model projections are for continued warming at a rate of 0.02–0.03°C yr$^{-1}$ and small decreases in rainfall except in the spring.

Apart from the indirect effects of climate change on Puerto Rico's resources, most of its beaches and coastal resorts will be impacted by rising sea levels, similar to neighboring islands (Moore 2010, Simpson et al. 2010). Thus, mitigation plans should be readied to control beach erosion and set back development.

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