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Climate model predictions for Honduras, with emphasis on water availability

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Climate model predictions for Honduras, with emphasis on water availability

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Abstract. We use two climate models selected for their skill at predicting Honduran precipitation and temperature to estimate year 2100 climate. We selected greenhouse gas emission scenarios that are consistent with observed trends (RCP8.5 and SSP585). Climate model CESM1 CAM5 predicts that year 2100 rainfall in Honduras will decrease by 20% from today, and water availability (the rainfall that makes it into rivers, lakes and aquifers) by 41%. The reduced water availability by itself is not considered large enough to cause water stress in Honduras, as availability will still surpass generally accepted levels indicating water stress. However, given recent water shortages in Tegucigalpa and other cities, Honduras will be strongly challenged in supplying sufficient water for its people. Future year-to-year variability in rainfall may involve periods of time one year or longer without sufficient rainfall, despite the long-term rainfall average being adequate. Using output from climate model CESM2, temperatures across Honduras are predicted to increase by an average of 5.3 ˚C in year 2100. CESM2 predicts an increase in year 2100 wind speeds by 10% over today. These increases would theoretically cause an increase of 30% in wind energy power output. CESM2 also predicts cloud cover will decrease by 5%, relative humidity by 9% and specific humidity will increase by 22%. The increase in atmospheric moisture is likely to exacerbate the severe storm floods to which Honduras is frequently subject.

Key Words: climate change, precipitation, CESM2, CESM1, evapotranspiration

Predicciones de modelos climáticos para Honduras con énfasis en la disponibilidad de agua.

Resumen. Utilizamos dos modelos climáticos, seleccionados por su habilidad para predecir la precipitación y la temperatura de Honduras, para estimar el clima del país en el año 2100. Seleccionamos escenarios de emisión de gases de efecto invernadero que son consistentes con las tendencias observadas (RCP8.5 y SSP585). El modelo climático CESM1 CAM5 predice que en el año 2100 las precipitaciones en Honduras disminuirán en un 20% a partir de hoy y la disponibilidad de agua (la lluvia que llega a ríos, lagos y acuíferos) en un 41%. Esta reducción en la disponibilidad de agua no se considera, por sí sola, lo suficientemente grande como para causar estrés hídrico en Honduras, ya que la disponibilidad aún superará los niveles generalmente aceptados que indican estrés hídrico. Sin embargo, dada la reciente escasez de agua en Tegucigalpa y otras ciudades, Honduras tendrá un gran desafío en el suministro de agua suficiente para su gente. La variabilidad futura de un año a otro en la lluvia puede involucrar períodos de tiempo de un año o más sin suficiente lluvia, a pesar de que el promedio de lluvia a largo plazo sea adecuado. Utilizando el modelo climático CESM2, se pronostica que las temperaturas en Honduras aumentarán en un promedio de 5.3 °C en el año 2100. CESM2 predice un aumento en las velocidades del viento del año 2100 en un 10% respecto a la actual. Estos aumentos teóricamente causarían un aumento del 30% en la producción de energía eólica. CESM2 también predice que la cobertura de nubes disminuirá en un 5%, la humedad relativa en un 9% y la humedad específica aumentará en un 22%. Es probable que el aumento de la humedad atmosférica exacerbe las tormentas con inundaciones a las que Honduras está sometida con frecuencia.

Palabras clave: cambio climático, precipitación, CESM2, CESM1, evapotranspiración

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Introduction

Earth System Models (ESM) are state-of-the art products, used to predict future climates under a variety of plausible greenhouse gas emission scenarios. ESMs are extremely complex, and consider the interactions between the atmosphere, oceans, and land surfaces, including biological-chemical interactions such as carbon and sulphur cycles (Flato et al. 2013).

There are many existing climate models with varying methodologies, developed by researchers throughout the world. In order to focus on simulations that are most important to end-users, and to permit easy comparison between model outputs, the CMIP (Coupled Model Intercomparison Project) was created. Each CMIP runs for several years, and participating institutions agree beforehand on areas of focus for that period. Results for CMIP periods are summarized by the Intergovernmental Panel on Climate Change (IPCC), with the latest IPCC Assessment Reports covering CMIP5 released in 2013-2014. Currently CMIP6 is underway, and reports will be prepared by the IPCC in 2021–2022 (IPCC 2020).

Representative Climate Pathways (RCP) developed in CMIP5 established standardized greenhouse gas emission scenarios RCP2.6, RCP4.5, RCP6, and RCP8.5. These denote emissions levels in increasing order, with RCP8.5 frequently referred to as the "business-as-usual" scenario, because it appears to agree well with current observations (Sanford et al. 2014) The remaining scenarios reflect varying levels of worldwide greenhouse gas mitigation efforts. In CMIP6, the equivalent emissions scenario to RCP8.5 is SSP585.

Climate models are evaluated by simulating past climate and comparing the results to observed meteorological data, using inputs of known solar radiation, aerosol and greenhouse gas concentrations, among others. These historical runs show that climate models are accurate for temperature but less accurate for precipitation. Flato et al. (2013), specify "high Confidence" that large-scale temperature patterns are well-simulated by CMIP5 models, as well as modest agreement in broad-scale features of precipitation, with systematic errors in the tropics. The report shows that in Central America, the CMIP5 errors on average monthly precipitation range from -60 to -90 mm/month, depending on which of the 41 CMIP5 models is used.

In CEPAL (2010), the authors analyzed results from climate models to determine future effects of climate change on Central America, measured against a baseline period from 1980–2000. The authors used climate model results from CMIP3 emissions scenarios A2 (comparable to RCP8.5 in CMIP5 and SSP585 in CMIP6), and B2 (which assumes moderate reduction in greenhouse gas emissions). The authors found that Central American countries may experience acute water shortages, elevated temperatures and significantly reduced crop yields by year 2100 under the A2 scenario. Five climate models were used, selected to determine a range of uncertainty of the results. The authors of CEPAL (2010) also predicted an average increase in temperature for Honduras of 3.47 ˚C between 2020 and 2100 and a decrease in rainfall of 29.8%, using the A2 emissions scenario. Also calculated was the difference between precipitation and evapotranspiration (evapotranspiration is water evaporation summed with plant transpiration), referred to here as water availability. The available water represents the portion of rainfall that enters rivers and aquifers, as defined by Falkenmark et al. (1989). The authors used the Turc method (Turc 1954) to calculate evapotranspiration and found a 71% drop in availability from 2020 to 2100, from 79.15 mm^3/yr to 22.6 mm^3/yr.

In CEPAL (2012), the authors projected future monthly trends of rainfall and temperature across Central America using the A2 emission scenario. The climate models predicted the two peaks currently seen in the Honduran rainy season lasting from roughly May to November. However, by year 2100, a single peak around October is predicted. The authors reported similar results to CEPAL (2010) for year 2100 temperature and rainfall.

The CEPAL (2015) report projected a 96% drop in per capita water availability by year 2100, also using the A2 emission scenario and the Turc method for evapotranspiration. The authors concluded that Honduras will be in a state of water stress in 2100, falling below limits proposed by Falkenmark et al. (1989).

Falkenmark et al. (1989) developed one of the most widely used measures of water stress and scarcity (Taylor 2009, Brown and Matlock 2011). The authors cite water availabilities between 1000–1700 m^3/person-year as conditions of "water stress", 500–1000 m^3/person-year as "water scarcity", and less than 500 m^3/person-year as "absolute scarcity".

Downscaling of climate models is performed when greater resolution of climate model data is desired. A global climate model with comparatively coarse resolution is used to provide boundary conditions for a regional model with a higher resolution. This is necessary because running global models at a high resolution requires prohibitively long computational times. There are two forms of downscaling. In statistical downscaling, observed relationships between large scale atmospheric parameters are statistically linked with local parameters. This form of downscaling is relatively easy to run and can be done with readily available computers. Dynamic downscaling involves physics-based algorithms that are very similar to climate models. These regional models require more sophisticated hardware to run, as computational times can be quite long. Dynamic downscaling is considered superior, since there is no guarantee that statistical relationships will be the same with changing climate.

The IPCC (Flato et al. 2013) reports with high confidence that downscaling adds value in regions of highly variable topography. However, the regional models can inherit biases that may be present in the global model.

Imbach et al. (2018) applied the HadGEM2-ES climate model to Central America, with RCP4.5 emission scenario. Dynamic downscaling was applied with 8 km resolution using the Eta Regional Climate Model. The authors found reasonable agreement with homogenized historical data (CHIRPS 2014 and CRU 2020) and benefits to downscaling, for example improved modeling of seasonal precipitation cycles. The authors modeled the time period 2021–2050, and found generally reduced precipitation and water availability, as well as increased air temperatures. The authors also found the model under-represented rainfall in historical simulations.

Navarro et al. (2018) predicted climate change in Honduras using 18 climate models. The authors first established a climate baseline for Honduras for years 1981–2010 by analyzing results from meteorological stations in and around Honduras. The analysis included removing questionable data and filling in missing values using a variety of homogenized sources such as CHIRPS (2014) and CRU (2020). The authors combined climate model results and performed downscaling to determine future climate to a 1 km^2 resolution, far beyond the resolution of the source climate models (for example, CESM1 CAM5 has a resolution of about 100 kilometers). Navarro's data demonstrate that CESM1 CAM5 had the lowest RMSE (root-mean-square error) for annual average precipitation compared to station data and an interpolated baseline.

Typically, climate change studies involve running simulations of a large number of climate models, in order to demonstrate the range of possible outcomes. As part of the latest IPCC report, Flato et al. (2013) show results from 41 CMIP5 climate models. Parker (2013) cautions that this technique does not necessarily yield the uncertainty in climate simulations, since many of the climate models share methodologies; true uncertainty may be greater. Rather, multi-model studies should be thought of as "a collection of best guesses".

In the recent past, studies have been conducted which show that some models are better (or as is commonly expressed, more skillful) than others at specific environmental parameters. For example, in a study of Central American skill, Imbach et al. (2018) found that CNRM CM5 model and CESM1 CAM5 were best at predicting precipitation. As mentioned before, Navarro et al. showed CESM1 CAM5 was best at annual precipitation. CESM1 CAM5 was the top-rated climate model by Knutti et al. (2013) and by Hidalgo et al. (2014) for Latin America. Gettelman et al. (2019) showed that CESM2 is better than CESM1 at reproducing past temperature observations. Hidalgo et al. (2014) rated the CNRM CM5 model as first in predicting precipitation, and second overall for Central America. Our own results will show CESM1 CAM5 and CESM2 are more skillful at predicting precipitation than CNRM CM5, and that CESM2 appears best for surface temperature among the three.

Furthermore, historical simulations by Gettelman et al. (2019) beginning in 1900 and running through year 2000 using an ensemble of CESM2 simulations (with different but equally likely initial parameters) reproduce global temperatures to within about ± 0.2 ˚C of actual values (Gettelman et al. 2019).

It then seems logical to analyze climate predictions using the most skillful climate models to complement multi-model studies. We consider climate model CESM1 CAM5 for precipitation and evapotranspiration, and climate model CESM2 for temperature and other parameters. In the results section we demonstrate the validity of this approach.

CESM1 belongs to the CMIP5 generation, while CESM2 is its descendant for CMIP6. Both are Earth System Models (ESM) with a resolution of 142 km and 107 km in latitude and longitude in the area of Honduras. Recently there has been controversy involving the CESM2 Equilibrium Climate Sensitivity (ECS). ECS represents the average warming at the Earth's surface due to a doubling of carbon dioxide from pre-industrial levels (NOAA 2019). CESM2 predicts an ECS of 5.3 ˚C, which is well outside the accepted range of 1.5–4.5 ˚C. (Gettelman et al. 2019). However, we feel justified in using this model, in that recent trends in Honduran temperature are very well-reproduced by CESM2, as will be shown in this report.

This work will focus on yearly national averages of environmental parameters, in an effort to understand the macro-scale effects of climate change. The primary focus and analysis will be on precipitation and evapotranspiration, although other parameters will be reported. We will use climate model output from CESM1 CAM5 for precipitation and evapotranspiration in Honduras, and CESM2 for temperature, wind speed, humidity, and cloud cover.

Materials and methods

We first compare the performance of three climate models, CESM1 CAM5 (CESM1 2017a and CESM1 2017b), CESM2 (CESM2 2019a and CESM2 2019b), and CNRM CM5 (CNRM 2017a and CNRM 2017b), at predicting rainfall and temperature over Honduras. These three models were selected from the literature for their skill at predicting Honduran or Central American climate (Gettelman et al. 2019, Navarro et al. 2018, Imbach et al. 2018, Hidalgo et al. 2014, Knutti et al. 2013). The top-performing models from the three were then used to predict year 2100 climate parameters using the RCP8.5/SSP585 emission scenarios, as these have been shown to most closely follow current trends (Sanford et al. 2014).

Data

CESM1 CAM5 and CESM2 use identical grids measuring 1.25 degrees longitude by 1.875 degrees latitude (Figure 1). The horizontal and vertical distances between points are 142 km and 107 km, respectively. Three of the CESM points fall just outside of Honduras along its southeast border, within 20 km of the border. Our results show that using these points simulate current Honduran precipitation and temperatures well. The CNRM CM5 mesh is somewhat coarser, measuring 158 km vertically and horizontally.

FAO CROPWAT/CLIMWAT (2020) lists meteorological stations close to the CESM points and is used to compare with climate model results. Figure 2 shows the location of these stations and their geographical coordinates, as well as the CESM grid points. Our results will show that the selected grid points represent well the available meteorological data.

Data files and manipulation

The climate output files were downloaded from ESGF (2020) and CEDA (2020) websites. These were accessed using the NetCDFExtractor software (Agrimetsoft 2019) and analyzed using Microsoft Excel (Microsoft 2016).

The data files used were precipitation 'PR', specific humidity 'HUSS', surface wind 'sfcWind', total cloud coverage 'CLT', near surface temperature, 'TAS', evapotranspiration, 'evspsbl'. These were all monthly data, using the r1i1p1f1 initialization parameters.

Figure 1. Location of points simulated by CESM2 and CESM1, with near-by cities. The points are at latitude and longitude: (15.55, -87.55), (15.55, -86.25), (15.55,-85), (14.61, -88.75), (14.61, -87.5), (14.61, -86.25), (14.61, -85), (14.61, -83.75), (13.67, -87.5), (13.67, -86.25). Google Maps, 2020.

Figure 2. CESM points are balloon markers, meteorological stations are stars. Stations are: Nacaome (13.53, -87.5), Catacamas (14.9, -85.93), Puerto Lempira (15.21, -83.8), Tela (15.71, -87.48), La Ceiba (15.73,-86.86), Villa Ahumada (14.03, -86.56), Playitas (14.43, -87.7), and Santa Rosa de Copán (14.78, -88.78). Two of the station and CESM points overlap. Google Maps, 2020.

There was no significant change to rainfall or temperature when r2i1p1f1 or r3i1p1f1 initialization parameters were used (these are equally likely but unknown meteorological conditions at the onset of the simulation): CESM1 historical precipitation runs spanning 95 years were within 5% of each other, and temperatures were within 0.02 ˚C of each other after 150 years of simulated climate.

For historical precipitation and temperature data we used CRU CY V4.03 and CRU TS V4.03 (CRU 2019) from the Climate Research Unit, University of East Anglia. These products are created from meteorological station observations, but are filtered for inconsistencies, and interpolated to fill in gaps in coverage. When compared to station data (FAO CROPWAT/CLIMWAT 2020), the CRU 2019 precipitation values are quite accurate (within 2%, as is shown in the results). For this reason, we felt confident in using CRU 2019 precipitation data to make up for sparse station data.

Since CESM1 precipitation results from historical runs showed a bias, as compared to the station data and CRU data (the climate models we tested ranged in error for average Honduran precipitation by -20% to -50%), and CESM1 captured the correct trend in historical rainfall (measured against the CRU data), we felt justified in scaling up the future precipitation plots by the error calculated from the historical runs. More details and discussion on this topic are given in the results.

Results and Discussion

Picking the best model: comparison between historical observations and climate model output

We compared the performance of the CRU (2019) filtered observational data against FAO meteorological station data for years spanning 1971–2000 (FAO CROPWAT/CLIMWAT 2020). The FAO data are compiled using careful scrutiny of the station data and averaged over that time period.

Precipitation: The station precipitation average for 1971–2000, (FAO CROPWAT/CLIMWAT 2020) was 166.2 mm/month using the eight stations listed in the methods section. The CRU 2019 data for all of Honduras for the same time period was 164 mm/month. This gives us confidence that the CRU 2019 data represent the station precipitation data well.

Figure 3 shows the performance of CESM1 CAM5 (referred to as CESM1 from this point), CESM2 and CNRM CM5 (now referred to as CNRM) models, as compared to the CRU (2019) precipitation data. The dashed lines show second degree polynomial trendlines to the data. The monthly values used to generate the plots are also displayed to demonstrate the range of the data. Each plot was made by joining two separate climate model output files: one a historical run from 1850–2005, and a future run from 2006–2100. Only the time period from 1950–2100 is used for the trendlines.

As a test of the rainfall trendline, the average rainfall for years 2071–2100 was calculated using the trendline and compared to the average using the CESM1 output, with results of 110 and 106 mm/month, respectively, a difference of less than 4%. We consider this to be acceptable performance, despite the trendline's coefficient of determination (R^2) value of 0.026.

On Figure 3, the red dashed line represents the CRU filtered observational data. The black-dashed line is CESM1, blue dashed is CESM2, and the green line is CNRM output. Clearly, CESM1 is closest in value to the CRU trendline.

In addition, CESM1 best reproduces the trendline slope of the CRU data from 1950–2018, as shown in Figure 4. The plot shows that the slopes (calculated by taking the derivative with respect to time of the 2nd degree polynomial fit to the monthly rainfall) are so close to each other that, if trends are extrapolated to year 2100, CRU data would exhibit a drop in precipitation of 282 mm/month from year 2020 values, and CESM1 292 mm/month. The CESM1 simulation predicted average precipitation of 133 mm/month for the time period 1961–1990, which is 33 mm/month less than the station data. We then scale up the CESM1 rainfall plot by 33 mm/month and refer to it as the Adjusted Rainfall.

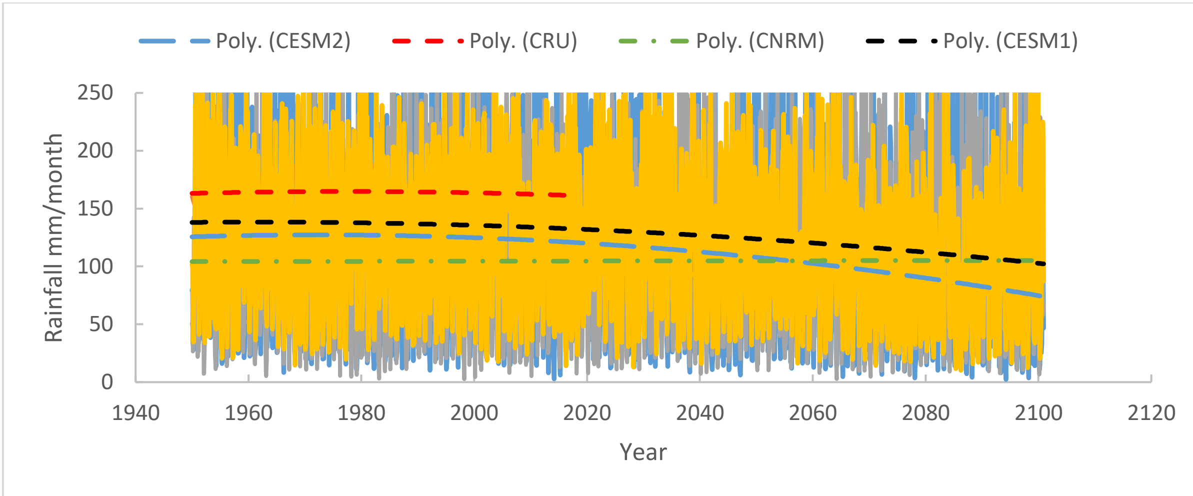

Figure 3. Past and future monthly rainfall for CRU, CESM1, CESM2, and CNRM climate models. CESM1 is closest to the CRU data.

We do this with the understanding that the 33 mm/month under-reporting of CESM1 is not necessarily a systematic error, but we are encouraged by the similarity between CESM1 and observed rainfall rates of change over the past 70 years. Climate change impact modelers frequently make this type of adjustment, known as a "bias correction" (Maraum and Widman 2018). This practice is especially important when downscaling of climate model data, since regional models inherit any bias from the global model used to provide boundary conditions (Flato et al. 2013).

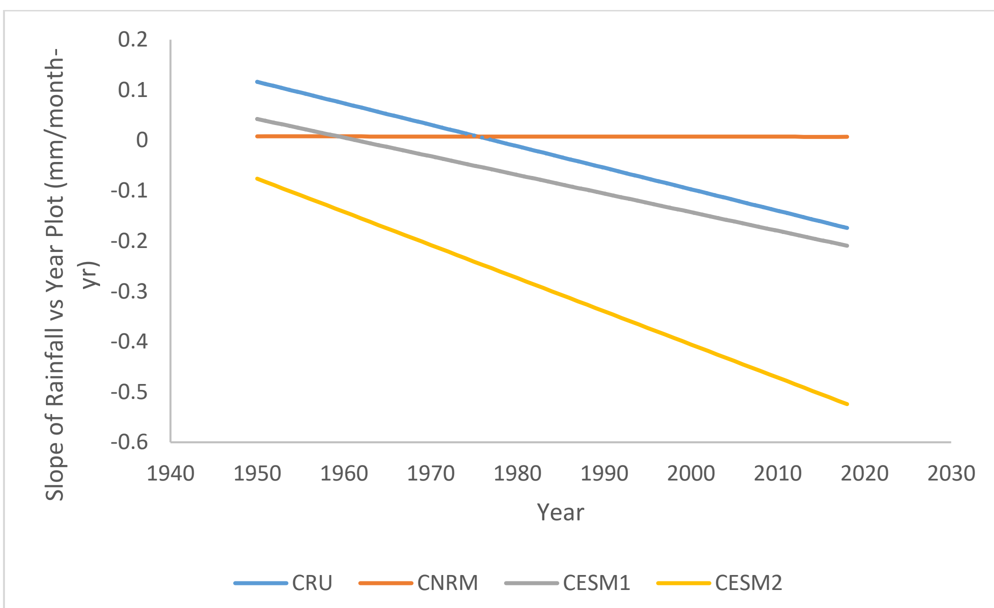

Figure 4 Rate of change of monthly average rainfall vs. year. CESM1 is clearly the best choice if slope is considered, being closest in absolute value as well as trend.

We can test the EVT calculations of CESM1 using observed values of average water availability. FAO calculates a Honduras availability of 67.9 mm/month, with a yearly rainfall of 162 mm/month, for the time period 1961–1990 (FAO 2019). This results in an EVT value of 94.1 mm/month yearly average across Honduras. The value for 1976 (the median of 1961–1990) for CESM1 EVT is 96 mm/month, an accuracy of 2% relative to FAO. Balairón et. al (2002) give results, averaged from 1970 to 2001, of 157 mm/month with EVT of 92.3 mm/month and available water of 64.3. The CESM1 EVT value for 1985 is 96 mm/month.

Temperature: Temperatures for FAO (FAO CROPWAT/CLIMWAT 2020) reference years 1971–2000 across Honduras are shown in Table 1, in conjunction with CRU, CESM1 and CESM2. CESM2 has the closest value to the FAO station data, with an error of 0.2 ˚C.

The FAO value in Table 1 was calculated using the station data from the 8 locations specified in the Methods section. These stations were selected for their proximity to the CESM grid points (see Figures 1 and 2). CESM1 and CESM2 temperatures were calculated by averaging the values from 1971–2000 from the climate model historical runs starting in year 1850 and running to 2015. The table above shows that CESM2 has considerably better accuracy than CESM1, with an error of 0.2 ˚C.

Table 1. Temperatures for reference years 1971–2000 across Honduras.

Source	Temp (˚C) 1971–2000
FAO	24.2
CRU	23.7
CESM1	22.8
CESM2	24.4

Figure 5 shows that CESM2 tracks the CRU line very well: the difference between CESM2 and CRU is 0.701 ˚C in year 1950, and 0.722 in 2018, over a time period of 69 years. This gives us confidence in using CESM2, as in addition it gave the most accurate temperature for the period 1971–2000.

Future precipitation

Figure 6 shows adjusted rainfall plotted with evapotranspiration (EVT) and water availability (Rainfall - EVT). The trendline of the CESM1 data indicates decreasing rainfall across Honduras from 2020 to year 2100, dropping from 171 mm/month to 136 mm/month, a drop of 20.5%.

The evapotranspiration (EVT, or the sum of plant transpiration and surface evaporation) is seen to drop slightly in Figure 7 beginning around year 2020, after a very slight increasing trend from 1950. Decreasing EVT is a plausible result despite global trends pointing to increased EVT, since EVT is dependent on rainfall (Zhang et al. 2016, Hanson et al. 1991). Jung (2010) noted a rise in global EVT rates from years 1982–1997, and a marked drop in years 1998–2008.

The authors found a relationship between southern hemisphere soil moisture during 1998–2008 and global EVT. Furthermore, future elevated CO^2 levels may cause stomatal closure, decreasing transpiration (van de Geijn 1996). However, Jung (2010) considered that for the period between 1982–1997, the effects of stomatal closure were not nearly as important as reduced rainfall.

Figure 6 also shows the CESM1 water availability (Rainfall – EVT), which is seen to drop from 77 to 45 mm/month between 2020 and 2100, a drop of 41%. CEPAL (2015) cites 1700 m^3/person-year of available water as a threshold for water stress, as proposed by Falkenmark et al. (1989). Based on a current population of 9.1 million people (CEPAL 2010 and 2015), a yearly average of at least 11.46 mm/month of rain would be required today to meet Falkenmark's criterion. The year 2020 availability of 77 mm/month easily exceeds this figure. In 2100, with a projected population of 12.4 million people (CEPAL 2010), availability greater than 15.6 mm/month is required to surpass Falkenmark's level for water stress. This is well below the CESM1 predicted availability of 45 mm/month.

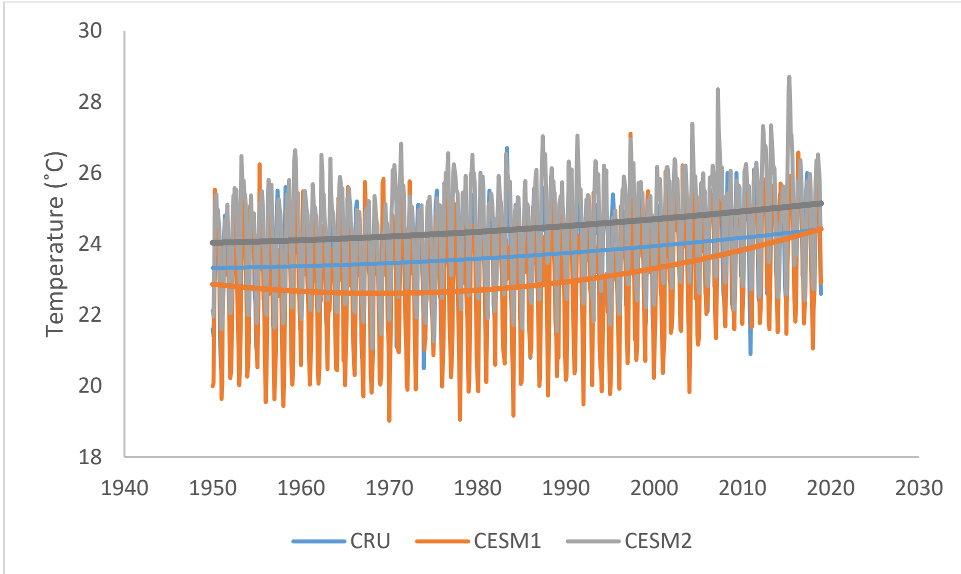

Figure 5. Temperature trends for CRU, CESM1 and CESM2 from 1950 to 2018. CESM2 displays the same trend as the CRU data.

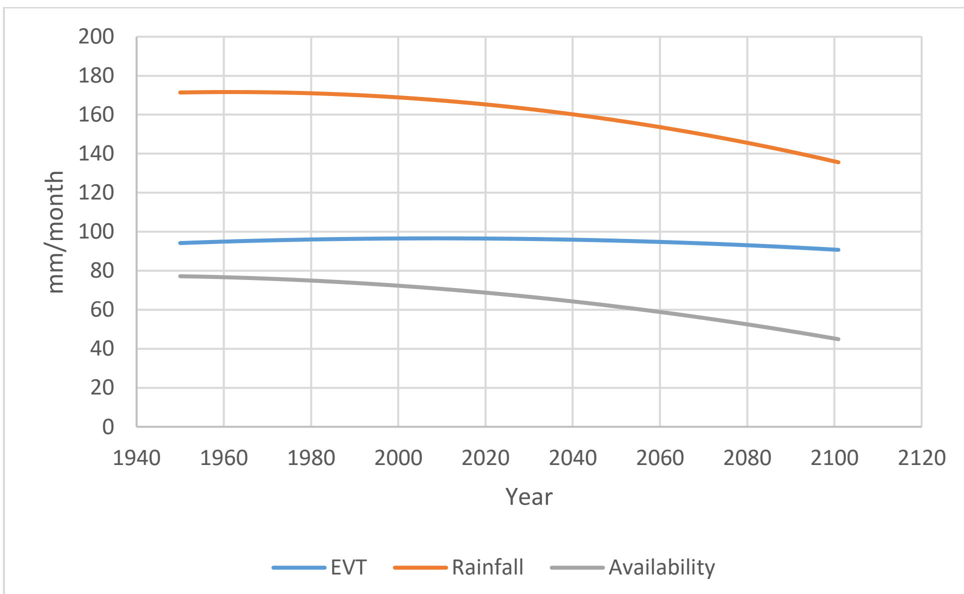

Figure 6. CESM1 monthly rainfall, evapotranspiration (EVT) and availability.

According to these measures, despite a 41% drop in water availability, Honduras will have sufficient rainfall in year 2100. On the other hand, CEPAL (2010) and CEPAL (2015) predict that in year 2100, Honduras will be below Falkenmark's limit, with drops in available water of 71% and 96% from year 2020.

But Falkenmark's paper shows that the figure of 1700 m^3/person-year is not absolute. Figure 7 is adapted from Falkenmark et al. (1989), showing the degree of difficulty involved in meeting varying water needs, as a function of the fraction of the per capita available water extracted. The diagonal lines are lines of constant usage rate, as a percentage of per capita available water. Moving upwards through the diagonal lines presents greater and greater challenges in meeting water demand.

We placed Honduras and other Central American countries on Falkenmark's plot but used the per capita water extraction (FAO 2019) for the *y*-axis, rather than the water needed. This allows us to make some useful estimates.

For example, we are certain that Honduras needs to deliver more water to its people: the recent persistent water shortages and rationing in Tegucigalpa and other cities make this clear. From the plot we can answer that, even if Honduras were to double the amount of water it uses (in order to meet its water needs) and simultaneously have its water availability cut in half (a much more demanding scenario than the year 2100 CSEM1 predictions), Honduras would still be in a portion of the plot corresponding to "limited water management problems", a portion of the plot Honduras would share with some European countries.

The message from Figure 7 is that there is enough rainfall falling on Honduras, but it needs to be properly managed. Falkenmark et al. (1989) do not specify exactly what "limited management problems" are; the term is meant to express a relatively low level of difficulty in extracting and supplying required water. For Honduras, solving these problems may involve public education, rationing, repair of leaking pipelines, drilling more wells, or constructing more reservoirs.

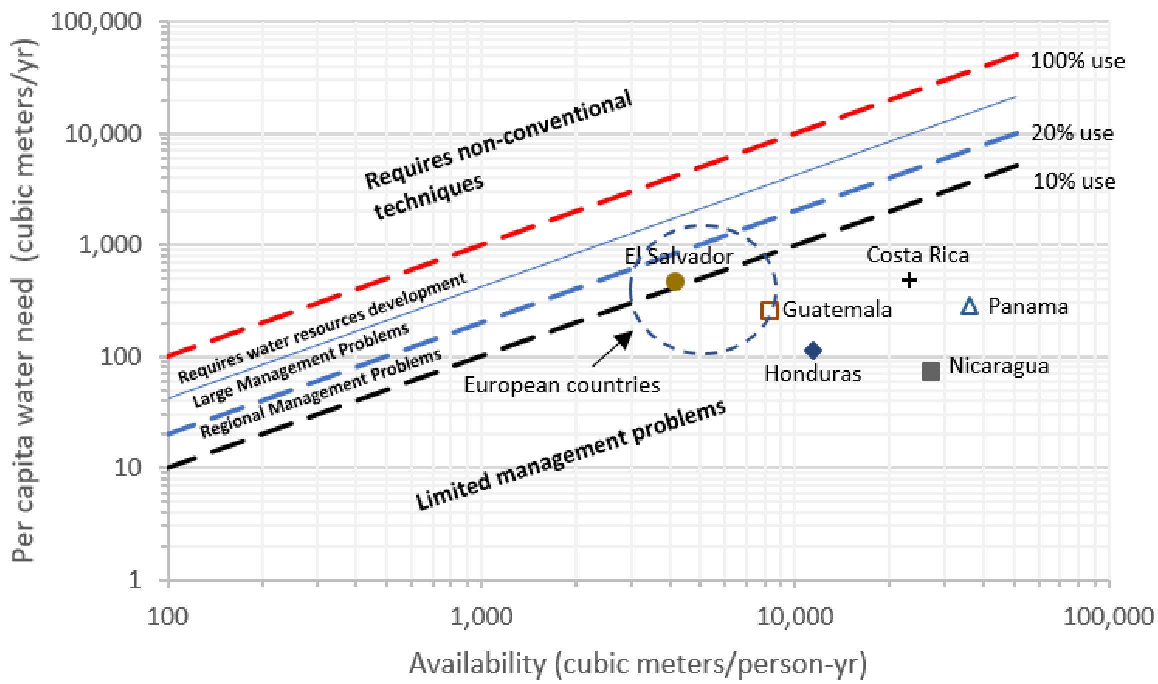

Figure 7. Difficulty of extracting and using available water, as a function of water availability and water need.

Figure 8 shows the per capita water extraction of Honduras and its neighbors, as well as the per-capita water available (precipitation minus evapotranspiration). The plot shows that, compared to most of its neighbors, Honduras is extracting less water per capita, except for Nicaragua, despite being blessed with an abundance of water.

Honduras's water management problems are caused in part by a temporal distribution of rainfall, involving a rainy season from roughly May to November, followed by a very dry winter season for the remainder of the year (FAO 2015). Obviously, this requires storage of large amounts of water. In addition, rainy season precipitation can be quite severe, with dangerous floods that can sweep away bridges and other structures.

Close examination of future monthly rainfall plots reveals that the storage of water may also be complicated by year-to-year variability in rainfall, requiring storage for years at a time. For example, Figure 9 shows monthly predicted adjusted rainfall from 2080 through 2100, with peaks in monthly rainfall varying by more than a factor of two, and particularly low precipitation for almost two years between 2081 and 2083.

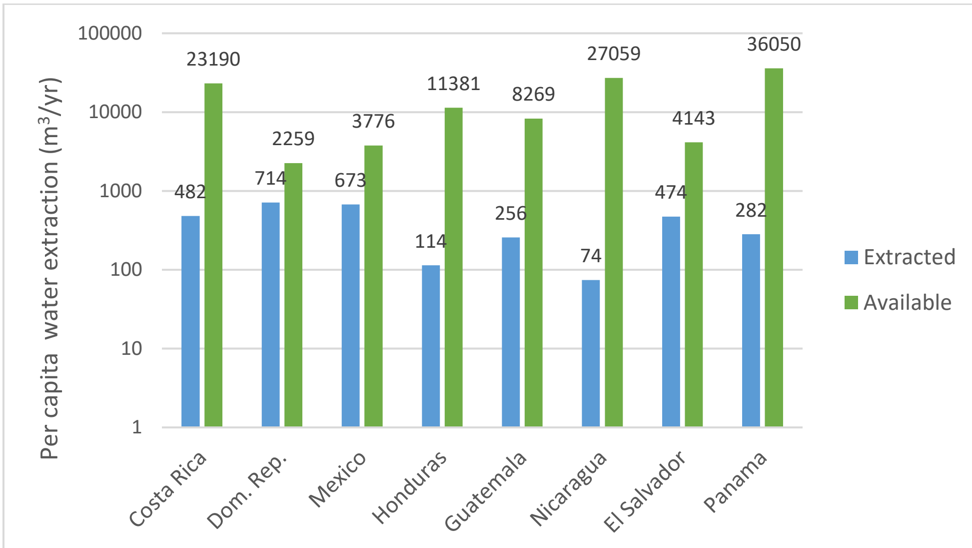

Figure 8. Water extraction rates and availabilities for Honduras and its neighbors. Source: FAO Aquastat.

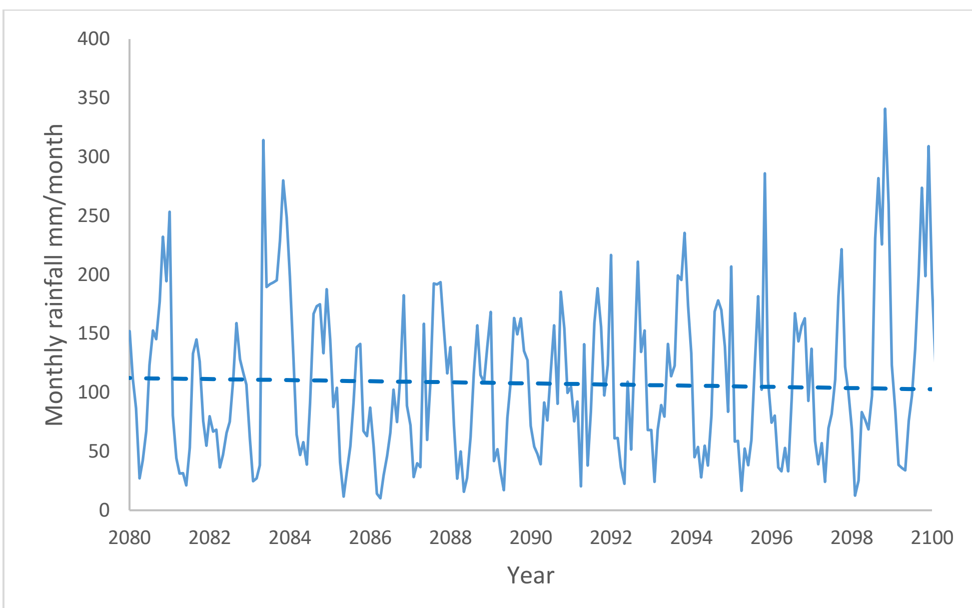

Figure 9. Predicted adjusted rainfall from 2080 to 2100. The dashed line is a linear trendline. There is much year-to-year variability

Another complicating factor is that Honduras is a mountainous country, with more than 75% of its surface area having a grade of 25% or more (FAO 2015), making the distribution of water more difficult. Power required for pumping is affected by friction of the water against pipe walls and by the net elevation change between source and destination (White 2003). Friction can be controlled by using large diameter pipes with slow moving flow, but there is no remedy for elevation changes, and additional costs are incurred. In addition, there are complications involved with the construction of piping systems over mountainous terrain which substantially increase project costs (Kennedy 1993).

Furthermore, some of the Honduran surface water is currently contaminated by waste from coffee production, mining, industry, agrochemical use/manufacture, and untreated sewage from urban areas, complicating the use of surface water (FAO 2015).

There are solutions to water shortages involving technology, such as desalination and water recycling. For example, in some communities in the United Sates where water shortages are present, sewage water is treated and injected back into aquifers. But given the projected Honduran abundance of water in the future, it is hard to imagine that such energy-intensive and complicated techniques are required, except perhaps in areas where it may be difficult to access stored water.

Honduras has plans for addressing some of the water shortages. For example, the construction of a new reservoir in Tegucigalpa and the diverting of additional river water to an already existing reservoir. According to the Honduran national water authority (SANAA), these measures are necessary short-term to address a critical need and will only serve to reduce the rationing that has recently been occurring (La Tribuna 2019). Officials are considering larger long-term civil engineering projects as well to better address water shortages.

One possibility for storage of water is ASR (Aquifer Storage and Recovery), involving the pumping of river water directly into aquifers. The need to construct reservoirs and damming of rivers is avoided, and evaporation losses are prevented. However, the aquifer used for ASR should meet numerous requirements (Gibson 2018), such as low hydraulic gradient, high water transmissivity, a minimum storage thickness, and proximity of river water, among others. Furthermore, pumping contaminated river water into aquifers may cause unwanted changes in aquifer water quality.

Whatever storage technique is used, water distribution and treatment will have to be enhanced, which will require greater energy use. But decreasing available water would negatively affect the hydroelectric power facilities of Honduras. In CEPAL (2017), the authors predicted a decrease of 32% for the El Cajon hydroelectric power plant in Honduras due to a 68% decrease in water availability. A viable possibility for addressing greater energy needs may be an increased use of wind technology for power generation. As mentioned earlier, power generation capability of existing wind systems will increase by about 30% in year 2100 if CESM2 wind speed predictions are correct.

Temperature

Figure 10 was made by joining a CESM2 historical run from 1860 to 2014 with a future run from 2015 to 2100. The plot trendline, made from 1950 to year 2100, shows a rise from an average temperature of 25.2 ˚C in year 2020, to 30.5 ˚C in year 2100, an increase of 5.3 ˚C.

Comparison with previous work

Figure 11 shows the percent change in precipitation between year 2020 and 2100 for our results, CEPAL (2010), and Navarro (2018). Navarro's results give the range from 18 climate models, marked by vertical lines; the triangular marker indicates the average of all of Navarro's models. CESM1 lies within the range found by Navarro, but the CEPAL (2010) results are below the range by 3%. Figure 12 compares our temperature results with Navarro (2018) and CEPAL (2010). CESM2 is substantially far outside of Navarro's range of results, and CEPAL's average is about the same as Navarro's.

Other CESM2 results

The Figure 13 trendline shows a drop of 5% in cloud cover between 2015 and 2100, while Figure 14 displays a predicted increase in wind speed of 10%.

The increased wind speed would theoretically result in 30% greater output from wind turbines by year 2100 (White 2003). In addition, the increased wind speed would tend to increase mass transfer coefficients (Cengel 2003), increasing instantaneous evaporation rates (however, we note that the average yearly amount of evaporation will decrease because rainfall will decrease, as mentioned earlier). An increase in solar energy extraction of 5% may be expected from the decrease in cloud cover.

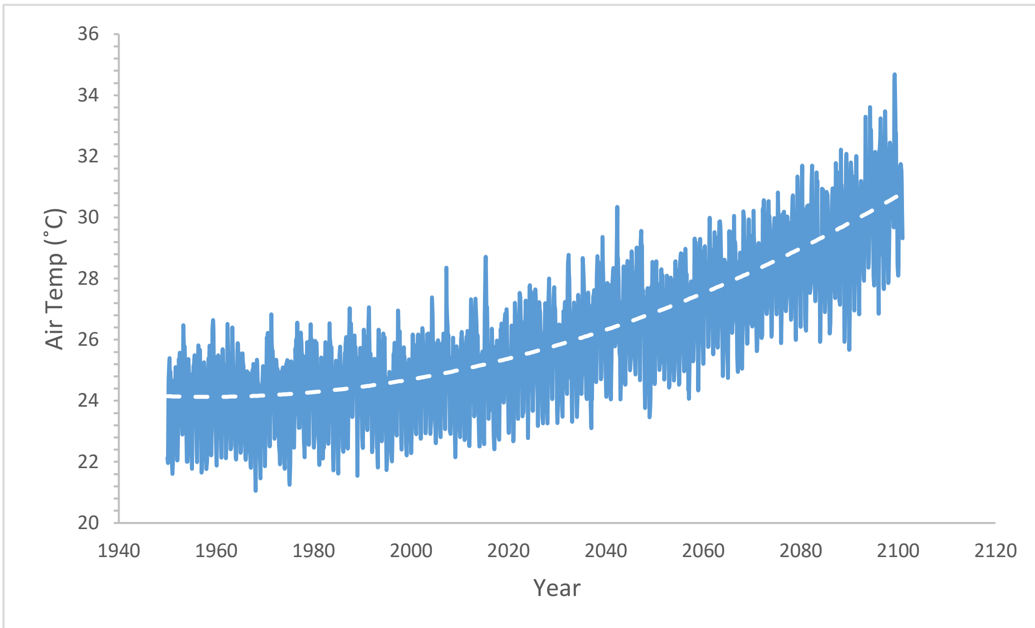

Figure 10. CESM2 temperature prediction, based on a historical run coupled with a future run.

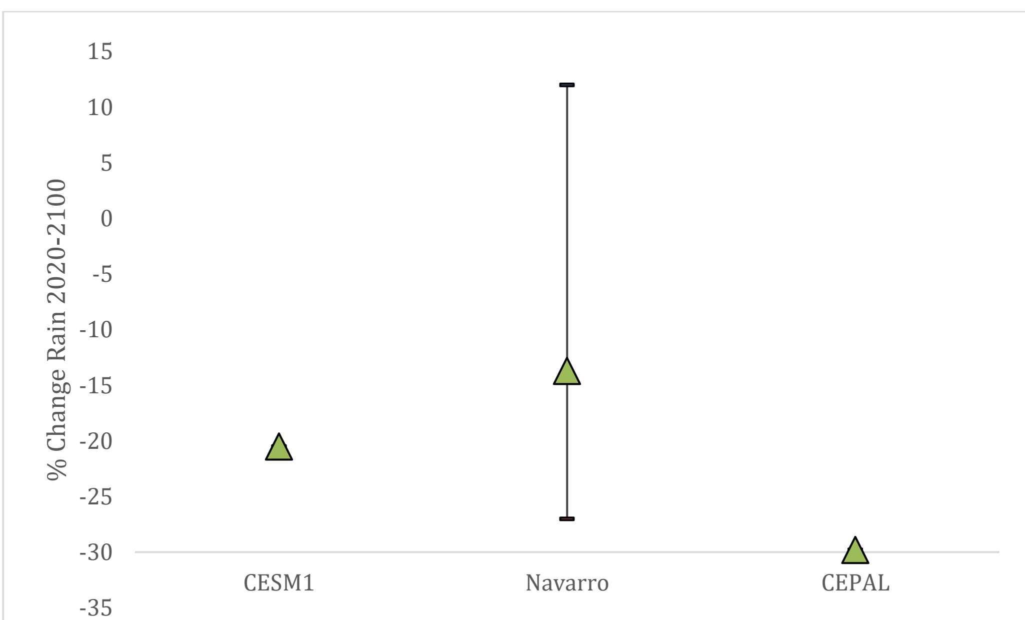

Figure 11. Predicted precipitation changes by CESM1, Navarro (2018) and CEPAL (2010)

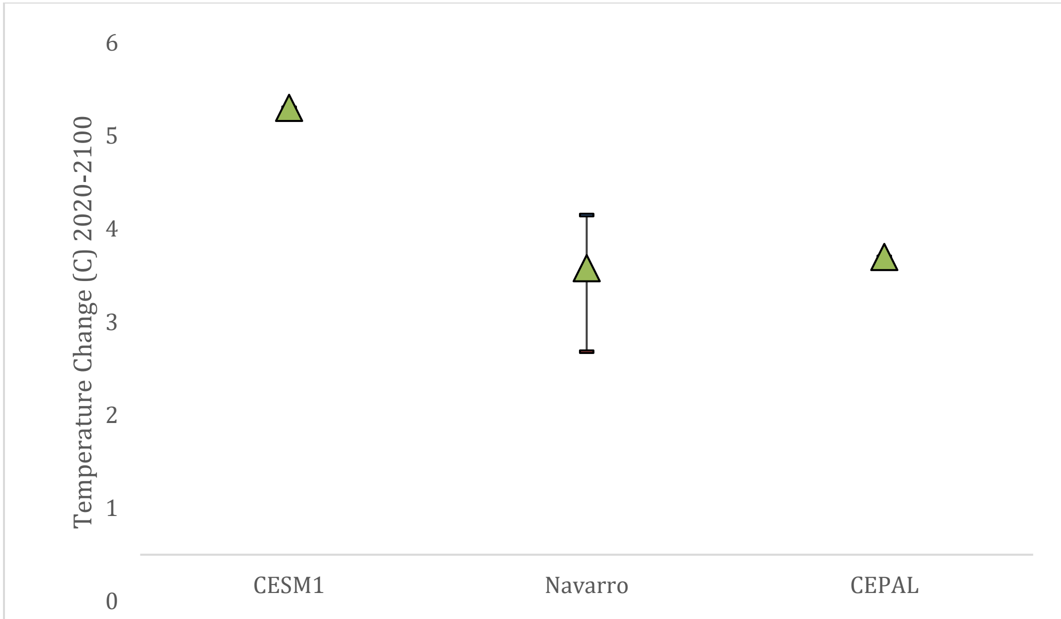

Figure 12. Predicted temperature changes 2020-2100 by CESM1, Navarro (2018) and CEPAL (2010).

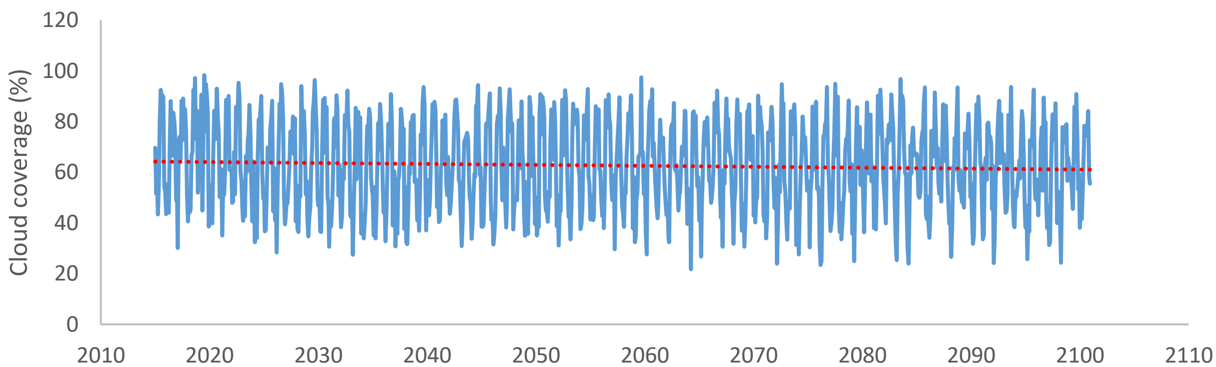

Figure 13. Cloud cover over Honduras, as a percentage.

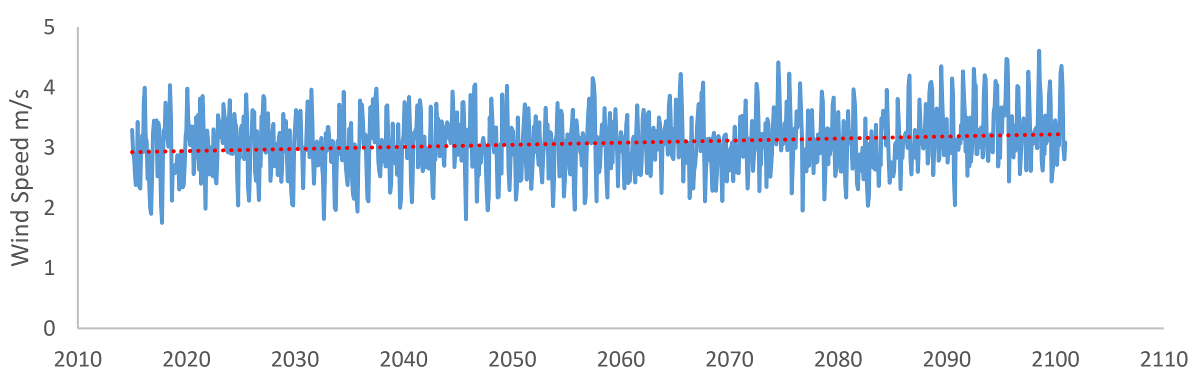

Figure 14. Wind speed over Honduras in meters/ second.

Increasing trends in specific humidity (22 %) and decreasing trends in relative humidity (9.3 %) for year 2100 are shown in Figures 15 and 16. The increasing specific humidity could increase the severity of future storms over Honduras (Ornes 2018). The high humidity values might provide opportunities for harvesting dew.

However, this practice requires clear nighttime conditions to permit radiative cooling of the earth's surface (Tomaszkiewicz 2015); our results show that Honduras will continue being a relatively cloudy country well into the future.

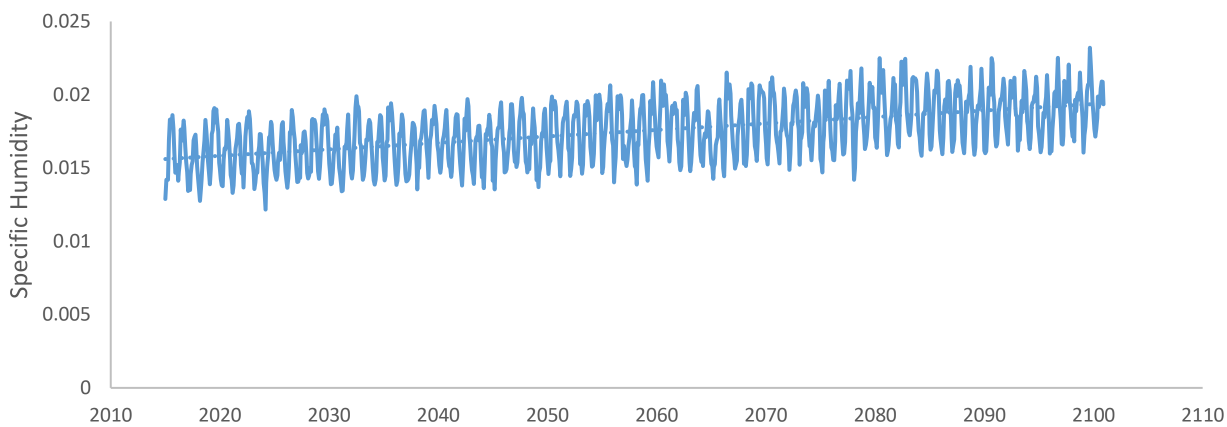

Figure 15. Specific humidity over Honduras.

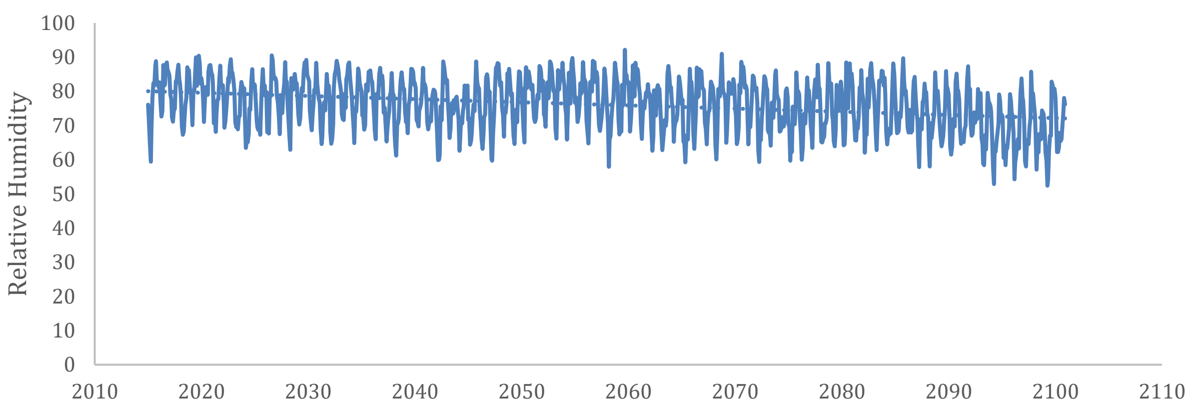

Figure 16. Relative humidity over Honduras, as a percentage.

Results by coordinate

Figure 17 displays temperature and precipitation changes at geographical points from the CESM1 and CESM2 grid. The pacific and central regions of Honduras show larger temperature increases than the atlantic regions, and the smallest increases in temperature are found around Honduras's eastern tip.

Year 2100 precipitation decreases of 22–26% from today are predicted throughout the country, except for the western and southern regions, with decreases of 12–17%. These are areas in the "dry corridor" that already have lower rainfall (FAO 2016).

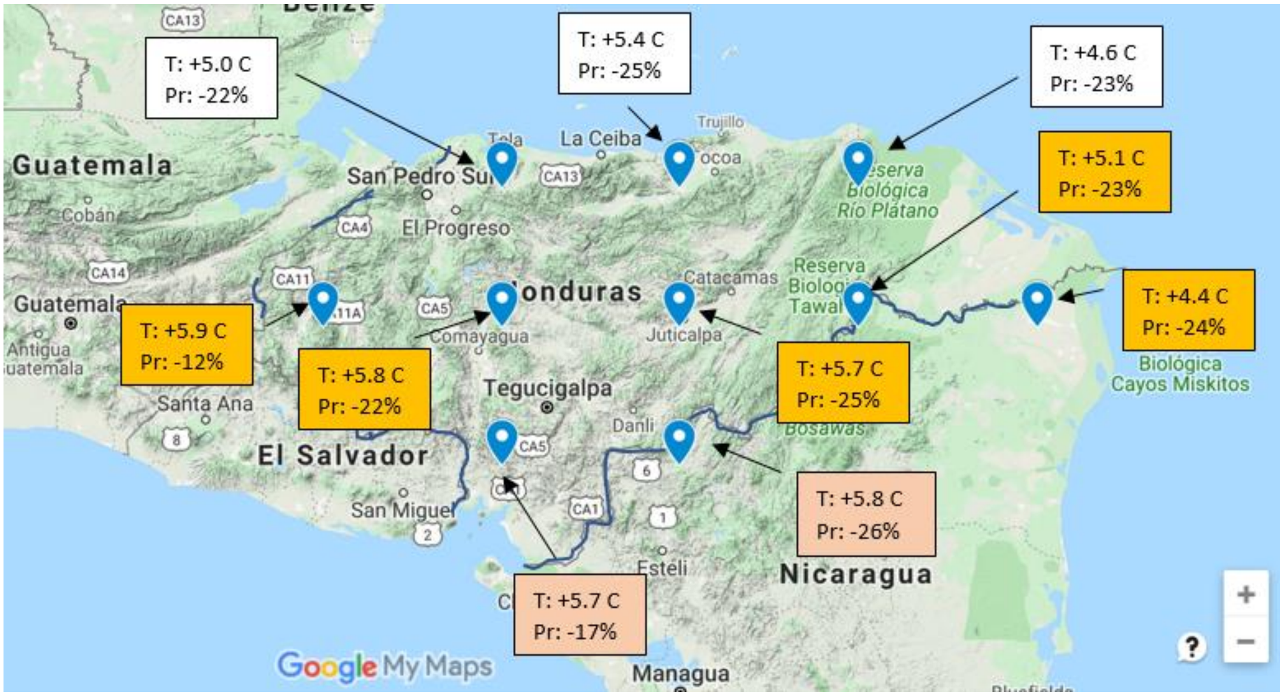

Figure 17. Temperature (T) (CESM2) and rainfall (Pr) (CESM1 CAM5) changes in Honduras, with RCP8.5 emission scenario. All changes are relative to year 2020 values.

Conclusions

We find that CESM1 CAM5 climate model is best at predicting annual precipitation over Honduras, out of a group of climate models selected for their skill at predicting rainfall. CESM2, a descendant of CESM1 and one of the newest generations of climate models (from CMIP6) was found to be best at predicting annual temperatures.

Our findings, using output from climate model CESM1 CAM5 with greenhouse gas emission rates consistent with observed trends in Honduras, show that year 2100 precipitation will be reduced by 20% from today, and water availability (the rainfall that makes it to rivers, lakes and aquifers) will be reduced by 41%. Both the current and year 2100 water availabilities are considered in the literature as adequate to address a nation's needs (Falkenmark et al. 1989).

Nevertheless, Honduras is currently experiencing water shortages requiring severe rationing in the capital and other cities. In September of 2019, the Honduran government declared a national emergency due to a lack of water (CNN 2019). Clearly, if Honduras is experiencing problems meeting water needs today, the future is likely to present even greater challenges.

Honduras's current water shortages appear to be caused by a dry season lasting roughly 5 months coupled with insufficient water extraction and storage.

Decreasing available water would almost certainly negatively affect the hydroelectric power facilities of Honduras. A viable possibility for addressing future energy needs may be an increased use of wind technology. As mentioned in the Results section, predicted year 2100 wind speed increases of 10% result in a theoretical increase in power generation of 30%.

Using output from climate model CESM2, temperatures across Honduras are predicted to dramatically increase by an average of 5.3 ˚C. In studies done by CEPAL (2010), with smaller year 2100 changes in temperature and larger drops in water availability, profound decreases in agricultural output were predicted.

CESM2 also predicts cloud cover will decrease by 5%, relative humidity by 9% and specific humidity will increase by 22%. The increases in atmospheric moisture could fuel more severe storms in the future (Ornes 2018), a problem that Honduras is already facing.

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