Evaluate and Assess Changes of Precipitation Characteristics for Implications on Neotropical Bird Conservations

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Evaluate and Assess Changes of Precipitation Characteristics for Implications on Neotropical Bird Conservations

A thesis submitted in partial satisfaction

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in Atmospheric and Oceanic Sciences

by

Mingxin Qu

2022

ABSTRACT OF THE THESIS

Evaluate and Assess Changes of Precipitation Characteristics

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Master of Science in Atmospheric and Oceanic Sciences

University of California, Los Angeles, 2022

Professor Rong Fu, Chair

Precipitation characteristics have a great influence on tropical ecosystems under a changing climate. It has been widely suggested that precipitation changes are expected to impact the populations and communities of tropical birds. Here I investigated the changes of the precipitation regime, length of the dry season (defined as months with precipitation lower than the annual mean), and the vapor pressure deficit in the tropical South America projected for 2080 – 2100 under emission scenario SSP5-8.5. It has been found that most of the studied area will experience decreasing annual precipitation (up to 37%) and increasing vapor pressure deficit (up to 190%) compared to 1970 – 2000, with seasonal variations. Furthermore, dry seasons are expected to extend over most regions and the monthly averaged precipitation within dry seasons

is projected to decrease especially in Central Amazon. The protection areas identified to experience lower impacts concentrate along the east side of the Andes and northeastern Amazon.

The thesis of Mingxin Qu is approved.

Gang Chen

Karen A. McKinnon

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University of California, Los Angeles

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I would like to acknowledge the use of a published material (Figure 1) in Section 1, from [Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W., & Courchamp, F. (2012). Impacts of climate change on the future of biodiversity. Ecology letters, 15(4), 365-377.], with permission.

I would also like to acknowledge the contribution of Professor Jeffrey D. Brawn, Professor David A. Luther and W. Justin Cooper, for their great work and permission for me to use the results of Figure 13 in Section 5, from our unpublished collaboration [Brawn, J. D., Luther, D., Qu, M., Cooper, W. J., & Fu, R. (2022). Prospects for neotropical birds under future precipitation regimes. Work in progress.].

Lastly, I would like to thank my family and friends for their support during my study.

1 Introduction

Climate change significantly impacts biodiversity worldwide, mainly through its impact on the ecological structures and geographical distribution ranges of species (Chen et al., 2011). For example, in areas where climate no longer supports local species, these species will have to shift their geographical ranges, or even go extinct locally, depending on their capacity to adapt and migrate (Guisan and Zimmermann 2000; Bellard et al., 2012). Furthermore, Species' phenology (the timing of seasonal activities of animals and plants, defined by Walther et al., 2002) and physiology are also influenced by climate change (Bellard et al., 2012). Previous studies have found the progressing influence of climate change on phenological trends since the 1960s (Walther et al., 2001), especially through spring activities such as changes in the timing of earlier breeding, first singing of birds, earlier arrival of migrant birds, and earlier appearance of flowers and insects (Crick & Sparks, 1999; Brown et al., 1999; Visser et al., 2006; Charmantier & Gienapp 2014). In addition, it is also expected that the interactions within the community (such as productivity) will be affected. SÆther et al. (2004) placed importance on population density and reproductive success, because some species may not cope with climate change if their response differs from that of organisms at lower levels of the food chain. This could lead to a mismatch between the timing of reproduction and the main food supply, where we would expect a population decline in species that are the most mistimed (McLaughlin et al., 2002; Visser et al., 2004; Both et al., 2006). A general diagram summarized by Bellard et al. (2012) shows the biodiversity components that are affected by predicted climate factors. All these impacts highlight the challenge to manage and conserve biodiversity.

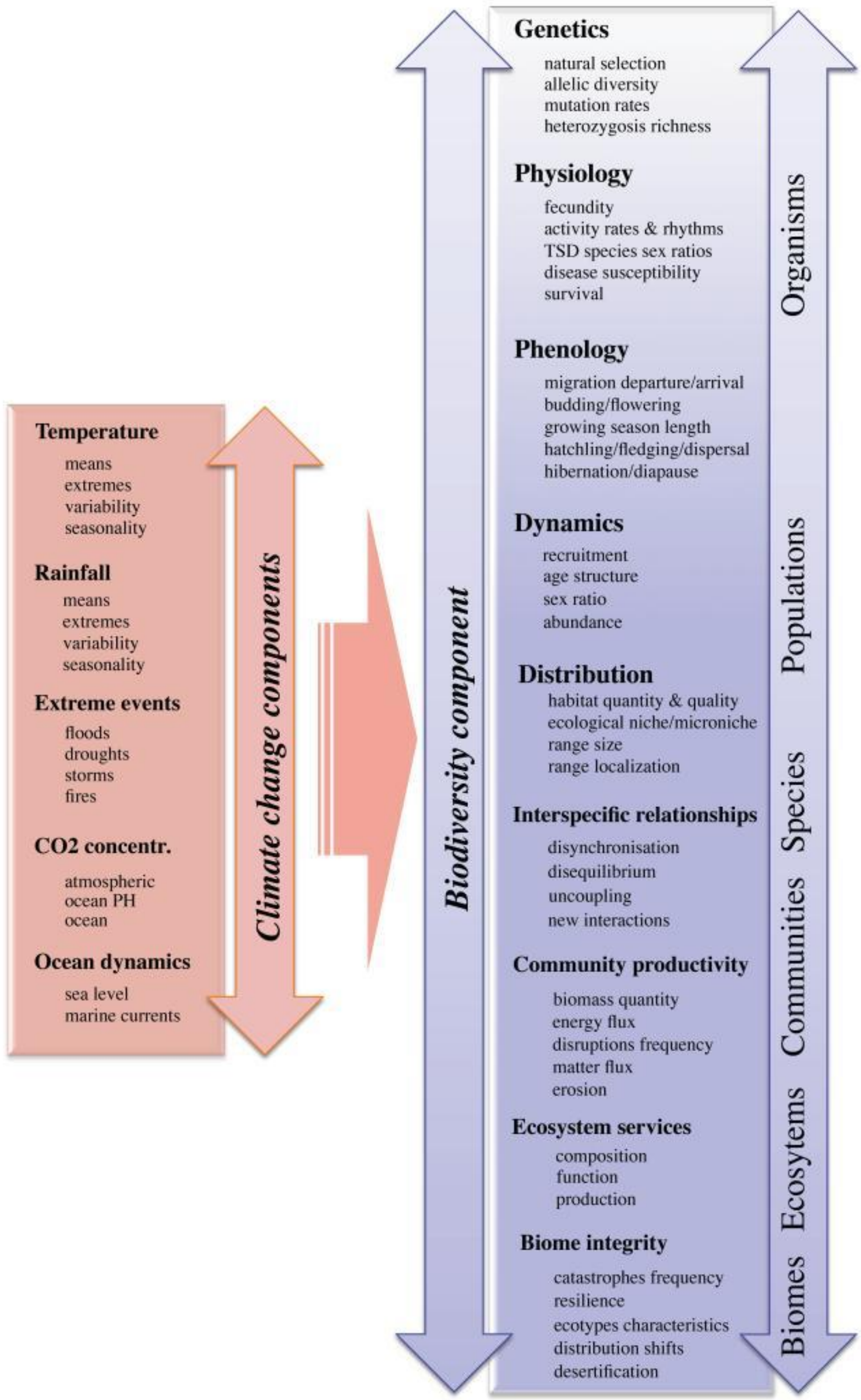


Figure 1. Summary of some of the predicted aspects of climate change and some examples of their likely effects on different levels of biodiversity. Source: From Bellard et al. (2012).

This concern is especially relevant in the tropics because biodiversity is more concentrated there (Frishkoff et al., 2016), and tropical species are adapted to narrow climate bounds (Janzen, 1967). In addition, the tropics are expected to experience the earliest emergence of historically unprecedented climates globally, because the narrow range of natural climate variability can be easily exceeded by future climate changes, having substantial biological influences on the ecosystem which has been adapted to relatively small natural variabilities (Gaston, 2000; Deutsch et al., 2008; Mora et al., 2013). More than half of the tropical regions are projected to face large changes in climatology, and extreme drying and warming events compared to historical interannual variability (Garcia et al., 2014). The most significant climate effects on tropical terrestrial ecosystem result from precipitation and temperature. It is suggested that human-induced warming reached approximately 1°C above pre-industrial levels in 2017, with more increase over land (IPCC, 2018). The effects of warming on neotropical birds have been debated and are spatially heterogeneous (Tewksbury et al., 2008; Brodie et al., 2012; Huey et al., 2012; Brawn et al., 2017). Decreases in rainfall and more severe seasonal droughts in many tropical regions have also been suggested in previous analyses, despite of the disagreement of spatial distribution of precipitation trends among climate model simulations, especially at regional scales (Stott and Kettleborough 2002; Neelin et al., 2006; Li et al. 2007; Meehl et al., 2007; Chou et al., 2009; Allen et al., 2010; Yin et al. 2012; Fu et al. 2013; Zhang et al., 2020). Precipitation over the tropical Americans shows a strong spatial-temporal variability (Alves et al., 2017). Many studies have indicated that the timing and dryness of dry seasons greatly affect tropical ecosystems. Decreasing regional precipitation, increasing frequency and intensity of dry periods, associated reduction of deep convection and magnification of evaporative demands (driven by global warming) could greatly worsen droughts in many regions (Prudhomme et al., 2014; Wanders et al., 2015; Zhao & Dai, 2016; Naumann et al., 2018; Espinoza et al., 2018). For instance, decreases in rainfall are predicted to amplify the effects of the mid-summer drought in Central America (Rauscher et al., 2008). On the other hand, it has been shown that in addition to areas with reduced precipitation, areas that expect little drying or even wetting from precipitation trends can also experience intensified drought, due to an increased atmospheric evaporative demand due to warming (Cook et al., 2014; Vicente-Serrano et al., 2015).

Climate change also pose threats to tropical forests, contributing to degradation and fragmentation of habitats, which is another main driver of biodiversity loss. In southern Amazon, deforestation has been associated with delays of the wet season onset, advanced dry season onset and shortenings of rainy season length (Butt et al., 2011; Fu et al., 2013; Debortoli et al., 2015; Leite-Filho et al., 2019). Protected forests help provide refuge (climatically stable regions) for local species, facilitate migrations and maintain biodiversity (Karyn et al., 2018). It has been suggested that long-term decreases in precipitation will have negative effects on tree growth and mortality, change the species composition, and weaken the carbon sink and water regulation abilities of tropical forests (D'Almeida et al., 2006; Phillips et al. 2010; Corlett, 2016; Zhou et al., 2022). The experiment of Newbold et al. (2015) revealed that under the worst-case scenario, local species can be reduced by up to 76.5% due to land use changes, with species at the highest risks mostly endemic to the tropics (Jetz et al., 2007). It is also expected that land-use change would increase the extinction rate even more with the presence of climate change (Brook et al., 2008; Mantyka-Pringle et al., 2012; de Moraes et al., 2020).

Birds have been proven to be greatly affected by climate changes in the neotropics, where birds reach the peak of their global diversity (Morrison, 1986; Harvey et al., 2020), climate change and its interactions with deforestation intensify their negative impacts on tropical bird demography

(Brawn et al., 2017; Tabor et al., 2018; Miranda et al., 2019; Borges & Loyola, 2020). Previous studies suggest that increasing precipitation in wet seasons is in favor of nesting success, food availability and species structure evenness of tropical birds (Boyle, 2011; Santillán et al., 2018; Zuckerburg et al., 2018); and that prolonged dry season length with decreasing dry season precipitation negatively impacts the reproductive activities of tropical birds (Nesbitt Styrsky & Brawn, 2011; Brawn et al., 2017). To mitigate the impacts of climate change on these species and provide information for determining conservation investments, assessment of the current system of protected areas and identification of the most vulnerable ones in terms of climate change is necessary (Hurlbert et al., 2007; Dawson et al., 2011; Tabor et al., 2018). It will improve the future conservation planning to be effective in conserving these species or their migration corridors under the predicted climate change. Development of effective conservation strategy provides high value to habitat connectivity and regional biodiversity.

In this paper we analyze the projected changes in precipitation regimes in the neotropics of the South America to provide implications on the local avifauna of the lowland forests. The remainder of this paper will be organized as follows: Section 2 briefly summarizes the sources of the low-resolution data for model evaluation and the downscaled data for precipitation analysis and introduces the definitions and methods of dry season length (DSL) and vapor pressure deficit (VPD). Section 3 evaluates the models from the Coupled Model Intercomparison Project Phase 6 (CMIP6). Section 4 presents the results of the analysis on rainfall regimes, with respect to the projected change of precipitation, dry season length and vapor pressure deficit. Section 5 provides the discussion and conclusions associated with the avian protected areas.

2 Data and Method

2.1 Observation and Simulation Data for Evaluation

Beginning from 1979, satellite-based measurements along with ground-based observations greatly improved spatial and temporal resolution and the reliability of the reanalysis products, supporting our choice of the 1980–2010 period for model evaluation. The Global Precipitation Climatology Project (GPCP) provides combined precipitation products (Adler et al., 2003) over this period. It relies on a relatively homogeneous record of satellite precipitation and rain gauge analysis as inputs, taking advantage of the strengths of each data set, and is one of the most recognized and used merged data sets (Sun et al., 2018).

We used precipitation data from the GPCP version 2.3 (Alder et al., 2018) to evaluate the model performance on precipitation. GPCP version 2.3 estimates monthly precipitation on a global 2.5° grid based on data from satellites, sounding observations, and rain gauge stations over land.

The models we selected for evaluation include the BCC-CSM2-MR (Beijing Climate Center Climate System Model), CanESM5 (Canadian Earth System Model version 5), CESM2 (Community Earth System Model version 2), E3SM-1-0 (Energy Exascale Earth System Model), FIO-ESM-2-0 (First Institute of Oceanography Earth System Model version 2), GFDL-ESM4 (Geophysical Fluid Dynamics Laboratory's Earth System Model Version 4), HadGEM3-GC31-LL (Hadley Centre Global Environment Model in the Global Coupled configuration 3.1), and MIROC-ES2L (Model for Interdisciplinary Research on Climate, Earth System version 2 for Long-term simulations). The spatial resolutions for the model simulations are around 1°- 2°, and we used monthly data during 1980-2010 from the historical experiment of each model to compare with the observations.

2.2 Downscaled Data

2.2.1 Historical Climate Data

Highly localized bird species in neotropics require high resolution climate projections, therefore, we use WorldClim downscaled climate projection for this study. In this downscaled climate model outputs, historical data is downscaled to a resolution of 2.5 arc minutes and obtained in the WorldClim database version 2.1 (approximately 5 km, available at https://worldclim.org/, Fick & Hijmans, 2017). The historical data, used for the downscaled model outputs, include databases with long-term averaged values (WMO, 1996; FAO, 2001), time-series of monthly averages by year (Lawrimore et al., 2011; Rohde et al., 2013; Harris et al., 2014), and daily weather data (NCEI, 2015).

The input weather station data used by WorldClim is collected from several sources, including The Global Historical Climate Network Dataset (GHCN), the WMO climatological normals (CLINO), the FAOCLIM 2.0 global climate database (FAO, 2001), a database assembled by Peter G. Jones and collaborators at the International Center for Tropical Agriculture (CIAT) in Colombia, and some additional regional databases. The monthly precipitation is measured at more than forty-seven thousand weather stations globally, mostly for the 1950–2000 period. Only stations with observations for at least 25 years within this period, and stations with at least 10 years of data between 1960 and 2010, after removing duplicates, were considered for surface fitting. These observational data sets were compiled and interpolated using the thin-plate smoothing spline algorithm implemented in ANUSPLIN (Fick & Hijmans, 2017), creating global climate land surfaces for monthly precipitation. The compiled database consisted of precipitation records from 47554 locations after removing stations with errors (Hijmans et al., 2005).

The construction of the downscaled grids was done by SPLINA in the package ANUSPLIN (Hutchinson, 2004), after dividing the global domain into 13 overlapping zones. The downscaled grid can be constructed for any specific location and elevation within the specified domain. SPLINA fits a continuous surface to the points, but the surface does not necessarily go through every observed point. The elevation data were from the Shuttle Radar Topography Mission (SRTM), and the latitude/longitude geographical coordinate system was used for all climate variables.

In ANUSPLIN, spline models of the n observed data values z_i are fit by setting:

$$z_i = f(x_i) + \sum_{j=1}^{p} \beta_j \varphi_j(x_i) + \varepsilon_i \quad (i = 1, \cdots, n; j = 1, \cdots, p). \qquad \text{Equation-1}$$

where f is an unknown smooth function to be estimated, the φ_j are a set of p known functions and the β_j are a set of unknown parameters which have also to be estimated (Hutchinson, 1995). The x_i commonly represent coordinates in three-dimensional Euclidean space (latitude, longitude, and elevation in this case). The ε_i are zero mean random errors.

They were all aggregated to monthly climate averages after downscaled to finer resolutions. The target temporal range for station data was between 1970 and 2000.

2.2.2 Future Projections

The source data for future projections under the emission scenario SSP5-8.5 (which represents the high end of greenhouse gases emissions pathway, where SSP5 assumes an energy intensive, fossil-based economy, and 8.5 indicates the 8.5 W/m^2 radiative forcing reached by the year 2100) are from the Coupled Model Intercomparison Project Phase 6 (CMIP6; Eyring et al., 2016). Ensemble simulations from many climate modeling groups around the world have been collected and organized, with support from several international programs, for the

Intergovernmental Panel for Climate Change Sixth Assessment Report (IPCC-AR6) and other regional climate assessments. The latest data sets of climate model simulations are released from CMIP6 and provided for IPCC-AR6. The model projections are calibrated based on the observed baseline climate. The result is averaged over the eight available models in WorldClim, including BCC-CSM2-MR, CNRM-CM6-1, CNRM-ESM2-1, CanESM5, IPSL-CM6A-LR, MIROC-ES2L, MIROC6, and MRI-ESM2-0 (more detailed model description shown in Table 1).

Table 1. Model description used in the precipitation analysis.

Model	Description	Research Center	Country
BCC-CSM2-MR	Beijing Climate Center climate system model version 2	National Climate Center	China
CNRM-CM6-1	Sixth generation atmosphere-ocean general circulation model	Centre National de Recherches Météorologiques and Cerfacs	France
CNRM-ESM2-1	Second generation of the Earth System Model	Centre National de Recherches Météorologiques and Cerfacs	France
CanESM5	The Canadian Earth System Model version 5	Canadian Centre for Climate Modelling and Analysis	Canada
IPSL-CM6A-LR	model developed by Institut Pierre-Simon Laplace, as part of the sixth phase of the CMIP6	Institut Pierre-Simon Laplace	France
MIROC-ES2L	Model for Interdisciplinary Research on Climate, Earth System version-2 for Long-term simulations	Japan Agency for Marine-Earth Science and Technology, the Atmosphere and Ocean Research Institute, the National Institute for Environmental Studies, and the RIKEN Center for Computational Science	Japan
MIROC6	The sixth version of the Model for Interdisciplinary Research on Climate	Japan Agency for Marine-Earth Science and Technology, the Atmosphere and Ocean Research Institute, the National Institute for Environmental Studies, and the RIKEN Center for Computational Science	Japan
MRI-ESM2-0	The Meteorological Research Institute Earth System Model version 2.0	Meteorological Research Institute	Japan

For future projections, the data were calibrated using the following steps:

1. The projected change in precipitation is computed as the relative difference between the output of the Global Climate Models simulations at their originally low resolutions for the baseline years (1960-1990) and for the target future years (2020-2100), respectively.
2. These changes are interpolated onto the high-resolution surface grid created, with the assumption that the change in climate does not change the spatial gradient of the climate variable that is been downscaled using Equation 1.

These high-resolution changes are added to the high-resolution, interpolated historical climate data for the baseline years, to produce the predicted climate.

2.3 Calculation of dry season length

We defined the length of dry season as the consecutive months with precipitation lower than the annual mean of monthly precipitation. To better assess the effect of rainfall regime on bird demographics, we calculated the dry season length (DSL) in months per year for the studied area, based on the annual mean precipitation of the reference period (Marengo et al., 2001; Li & Fu, 2004). Where the start of the dry season is determined when the monthly rain rate changes from above to below the climatological annual mean rain rate, and vice versa for the end (Fu et al., 2013). This definition captures the temporal patterns of the rainfall variation to find DSL, and it is not influenced by the bias in precipitation amount in a particular dataset or model. Using the monthly precipitation provided by WorldClim, we assume that the change of rainfall amount between adjacent months are continuous and linear. We thus determine the start (and end) of dry seasons as the intercept between the precipitation timeseries and the reference annual mean.

When there are more than one periods in a year below annual mean, DSL is defined as the sum of their lengths.

2.4 VPD Data and Calculation

In addition to precipitation and DSL, we also investigated projected changes of vapor pressure deficit (VPD), the difference between the saturation vapor pressure and the actual vapor pressure (Barkhordarian et al., 2019). Due to the lack of documentation for projected humidity-related variables in the WorldClim database, we selected two models, the Community Earth System Model Version 2 (CESM2) and the third Hadley Centre Global Environment Model in the Global Coupled configuration 3.1 (HadGEM- GC31-LL), from the CMIP6 products, to obtain the relative change of VPD from the past to the future. After interpolating and applying the change to the high-resolution historical VPD calculated from the WorldClim database, we generated a projected future VPD in high resolution, assuming that the change in VPD is relatively stable over space. Therefore, we used temperature and vapor pressure from the downscaled product of WorldClim version 2.1 to calculate VPD for the historical period (1970-2000), and temperature and relative humidity from CMIP6 for both the historical and future simulations (2080-2100) to calculate the relative change.

To calculate VPD from temperature (T) and vapor pressure (e_a), we use the following equation (Eq. 2) (Seager et al., 2015; Barkhordarian et al., 2019):

$$VPD = c_1 \times \exp\left(\frac{c_2 \times T}{c_3 + T}\right) - e_a \qquad \text{Equation-2}$$

Where, c_1 = 0.611 KPa, c_2 = 17.5, c_3 = 240.978 °C. Temperature is in °C and VPD is in KPa. The first and the second term in Eq. 2 are the saturation vapor content of air T (e_s) and the actual vapor pressure (e_a), respectively.

Temperature (T) and relative humidity (RH) are used to calculate dew point (Td, °C) and then the actual vapor pressure (e_a) in climate models based on the following equations (Eq. 3 and 4):

$$Td = \frac{a_1 \times \{\ln\left(\frac{RH}{100}\right) + \frac{a_2 \times T}{a_1 + T}\}}{a_2 - \{\ln\left(\frac{RH}{100}\right) + \frac{a_2 \times T}{a_1 + T}\}} \qquad \text{Equation-3}$$

$$e_a = c_1 \times \exp\left(\frac{c_2 \times Td}{c_3 + Td}\right) \qquad \text{Equation-4}$$

Where, a_1 = 243.04, a_2 = 17.625. Then VPD can be inferred using Eq. 2.

3 CMIP6 Model Evaluation

The CMIP, coordinates the comparison of comprehensive climate models, and provide model outputs to advance climate science. The common precipitation biases in global climate models undermine our ability to understand future changes in the neotropics and their ecological consequences. Previous modeling experiments (such as CMIP3 and CMIP5) have been widely assessed and referenced in many studies (Yin et al., 2012; Sakaguchi et al., 2018; Cai et al., 2018; Yazdandoost & Moradian, 2019), where CMIP3 models were shown to have highly variable biases in precipitation and the seasonality of precipitation in the tropical South America (Li et al., 2006). Evaluations of CMIP5 historical simulations shows that few climate models that participated in the CMIP5 realistically simulate the spatial distribution of rainfall, because some models underestimate rainfall over Amazonia, due to the underestimation of convective and large-scale precipitation during dry season (Li et al. 2006; Yin et al., 2012). Diverse processes and model components can contribute to precipitation bias, such as radiative transfer, terrestrial processes, and atmospheric circulation (Betts & Jakob, 2002; Richter et al., 2012; Sakaguchi et al., 2018). The results of recent regional evaluation studies have shown that CMIP6 models have improved relative to the previous products, despite some inter-model variability over different climate zones and bias in the spatial and temporal distribution due to high altitude (Rivera & Arnould, 2019; Yazdandoost et al., 2021; Almazroui et al., 2021).

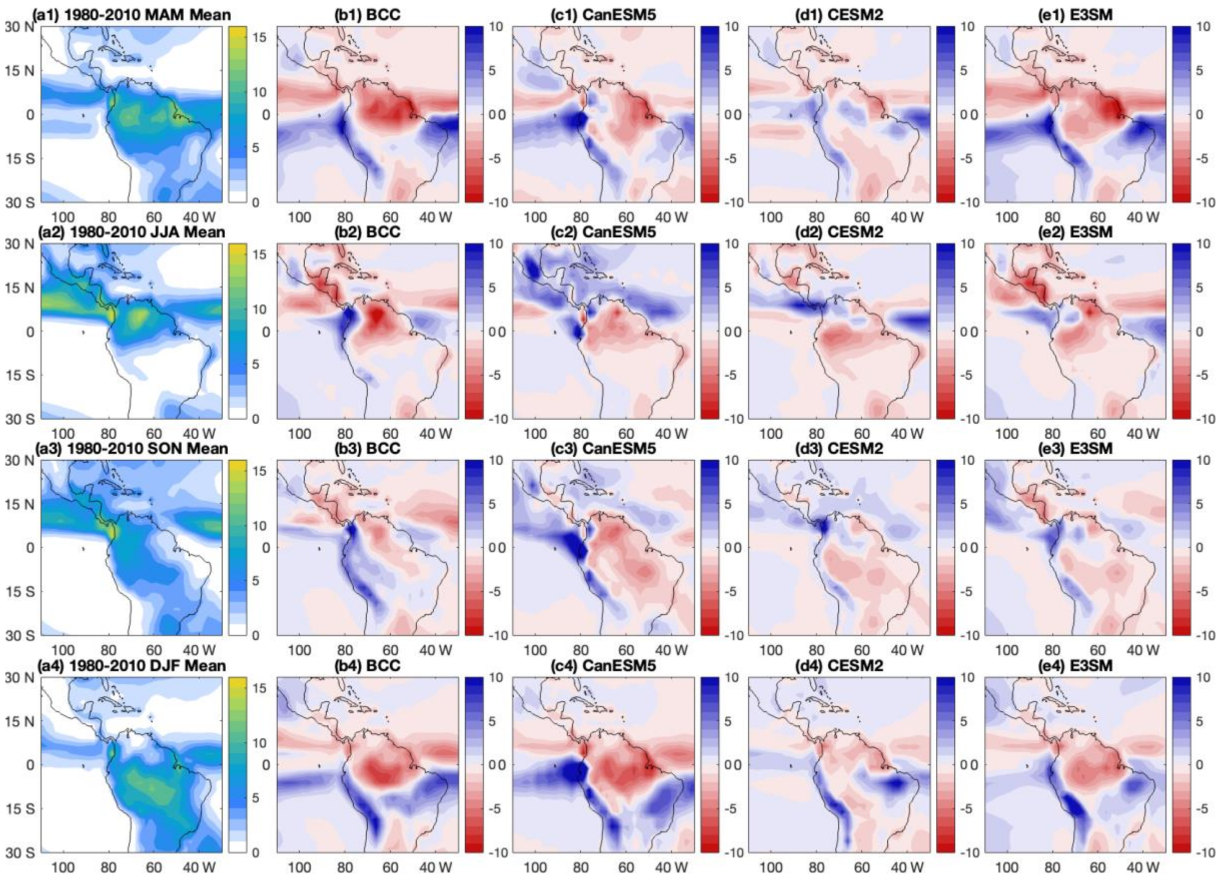
We examined the precipitation simulated in the historical runs of the eight CMIP6 models. All the models that provided multiple ensemble runs in order to increase the signal-to-noise ratio were averaged over all the ensemble runs before comparing to observations. After comparing averaged seasonal model bias from the observation (Fig. 2), we found that in most models generally show reasonable patterns of seasonal precipitation, with the bias of less than 10 mm/day over the Amazonia, except for BCC and FIO during JJA. However, the overall level of correspondence between the models and observation mean is low at regional scale, with the globally largest bias lying in the Intertropical Convergence Zone (ITCZ). For our region of interest (northern and central South America), all models exhibit greatest bias during the wet seasons in the Amazonia (DJF and MAM) and show a regionally varied pattern in all seasons, especially BCC-CSM2-MR, CanESM5 and E3SM-1-0. They have a dry bias of more than 5mm/day over most of the northern and central Amazonia, a wet bias around the Andes and northeastern Brazil. On the other hand, the FIO-ESM model shows an overall underestimation east of the Andes all year round except for JJA, where there is an overestimation of more than 5mm/day in the northwestern Amazon Basin.

Among most of the models, there are some differences such as the bias associated with the ITCZ, but the bias of rainfall over South America is generally similar. In most models, there is an underestimation over southwest Amazon during all seasons and a notable overestimation over the high-altitude regions along the Central and South Andes and in the northeastern Brazilian highlands during all seasons except for JJA, which agrees with previous evaluations (Sakaguchi et al., 2018; Almazroui et al., 2021). The similarity between model bias variabilities and their dissimilarity from the observed means suggests that internal climate variability between models drive these biases (Scaife et al., 2009; Andrews et al., 2020). During JJA, there's a regional overestimation over southern Central America and northwestern Amazon, while during other seasons an underestimation in northeastern South America and in the Atlantic, indicating that the ITCZ is not well represented by the CMIP6. A similar spatial pattern is observed for the CMIP5 ensemble, with a significant improvement in CMIP6 models despite the remaining bias (Ortega et al., 2021). The BCC-CSM2-MR model showed the largest bias in seasonal variability, especially in SON and DJF, with a remarkable negative bias over the northern Amazon Basin and a positive bias over the most of central South America. This is consistent with other evaluations of BCC-CSM2 models and is likely influenced by the influence of monsoon precipitation processing leeward of the Andes (Rivera et al., 2020).

During all seasons, the HadGEM3-GC31, GFDL-ESM4 and CESM2 model can adequately simulate the rainfall patterns over the Panamas and the Amazon basin. CESM2 showed a relatively small bias (less than 1 mm/day) for most of the lowland regions in South America, except for DJF over northeastern Brazil. While most of the models having a negative bias over the Amazonia in JJA, HadGEM3-GC31 resembles the observation better, with a slight positive bias over northwestern Amazon. Especially during JJA and SON, HadGEM3-GC31 simulations have a bias lower than 1 mm/day over most of the regions in South America, compared to the larger underestimation in central and eastern Amazon during JJA and the overall underestimation over most of South America during SON in GFDL-ESM4.

Therefore, we take a closer regional look at the precipitation bias relative to the historical standard deviation for the two relatively more accurate models, CESM2 and HadGEM3-GC31. Figure 3 (a) shows that the two models have a precipitation bias over southern Amazon and central South America of around one standard deviation (less than 1mm/month, (b)), with CESM2 tending to present a dry bias over most of South America and HadGEM3-GC31 a slight wet bias over the eastern and southern South America. Both models position the ITCZ similarly to observations, despite noticeable precipitation biases over the oceans and continental Central America (Fig. 3 SON & DJF). From SON to DJF, the precipitation migrates south, and the maximum precipitation appears over the Andes (Fig. 2 (a1) - (a4)), where both models overestimate the precipitation west to and over the Andes. Comparing the two model simulations for SON and DJF precipitation over southern Amazon, CESM2 exhibits a greater dry bias over the southern Amazon, consistent with Sakaguchi et al., (2018); likely this originates from the land model and deep convection parameterization (e.g., Sahany et al., 2012, Itterly et al., 2016), where tropospheric moisture divergence suppresses entrainment mixing and thus convective precipitation. Studies suggest that including a convective trigger based on both the moisture and temperature changes will help reduce the bias (Suhas & Zhang, 2014).

In conclusion, despite that the performance of precipitation simulations of CESM2 and HadGEM3-GC31-LL are relatively reliable compared to the other six models, there are dry bias in northeastern Amazon and wet bias over the high altitudes overall.


(a1) 1980-2010 MAM Mean
(b1) BCC
(c1) CanESM5
(d1) CESM2
(e1) E3SM
(a2) 1980-2010 JJA Mean
(b2) BCC
(c2) CanESM5
(d2) CESM2
(e2) E3SM
(a3) 1980-2010 SON Mean
(b3) BCC
(c3) CanESM5
(d3) CESM2
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(a4) 1980-2010 DJF Mean
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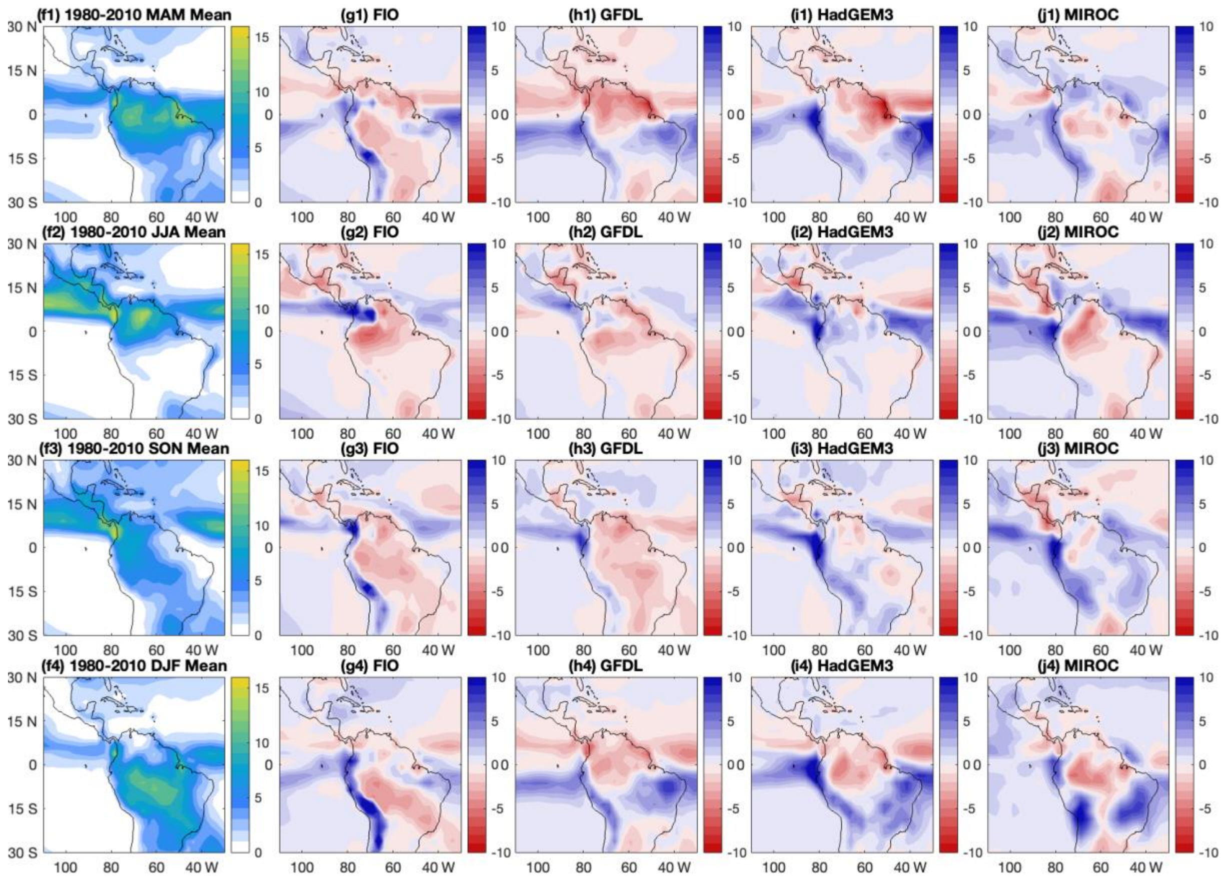


Figure 2. Observed climatological seasonal distribution of the precipitation (mm/day) in the first column of both panels, column (a) in upper and column (f) in lower; Deviation of the modeled precipitation from that observed for (mm/day) of the eight models in the last four column in the two panels, with columns (b)-(e) representing BCC-CSM2-MR, CanESM5, CESM2, and E3SM-1-0; and columns (g)-(j) representing FIO-ESM-2-0, GFDL-ESM4, HadGEM3-GC31-LL, and MIROC-ES2L, respectively. The rows (1)-(4) represent four seasons (MAM, JJA, SON, DJF).

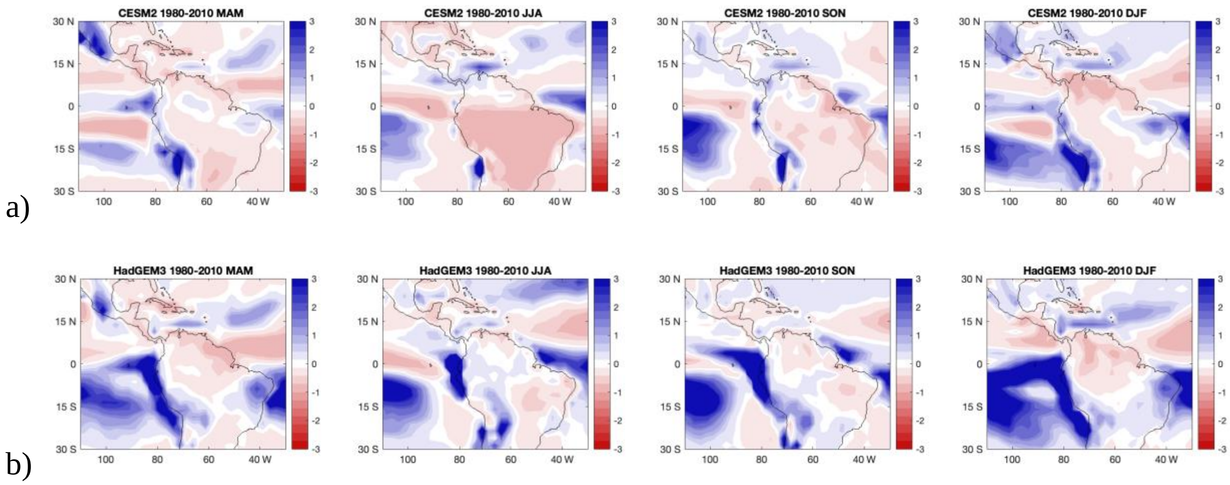


Figure 3. Precipitation bias of the models (a) CESM2 and (b) HadGEM3-GC31, relative to the standard deviation of observational monthly precipitation from 1981 to 2010, with the unit in number of standard deviations.

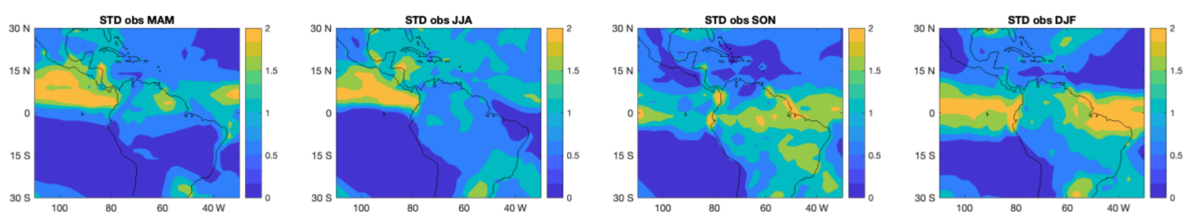


Figure 4. Precipitation standard deviation of the observational monthly precipitation.

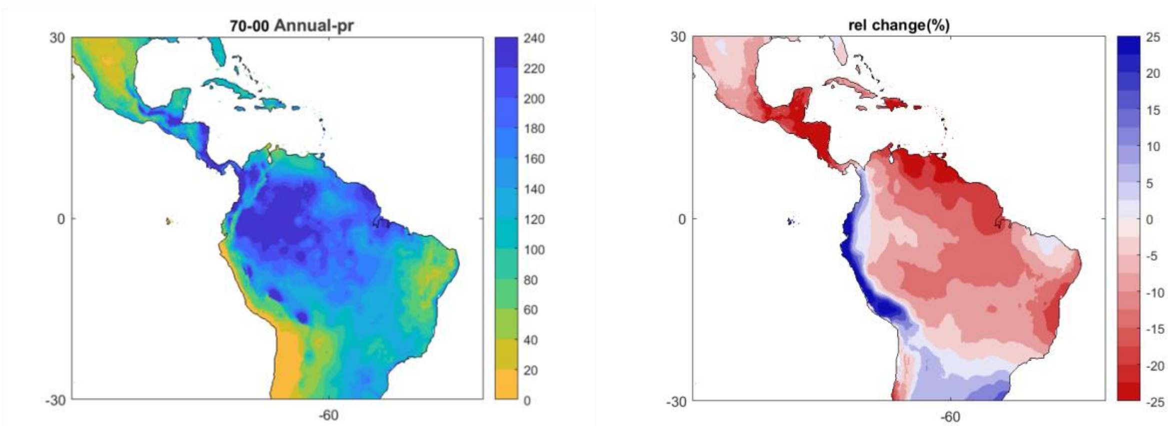
4 Results

4.1 Precipitation Patterns in the Tropical Americas

In this section we focus on the changing precipitation patterns. The average annual precipitation in mm/month over the historical period and its relative change to the future period 2081-2100 is shown in Figure 5. Except for the coastal region in Peru, the desert plateau west of the Andes, and northeast Brazil, most regions in South America receive annual precipitation more than 60 mm/month (Fig. 5(a)). Precipitation patterns generally show a decreasing orientation from northwestern Amazonia to southeastern Brazil over the continent due to (1) the features of the

South American Monsoon System (SAMS) variability over tropical South America especially in the wet season (Llopart et al., 2020), and (2) topographical influences: the Andes play an important role in maintaining the South America low-level jet on the east, which transports warm and moist air from the tropics to the subtropics (Vera et al., 2006; Kumar et al., 2020). The map for the relative change in precipitation (Fig. 5(b)) exhibits a decreasing pattern over most of the tropical Americas (around 75.2% of the area studied), especially around the coast of the Caribbean Sea, where changes are up to 28.9% over Panama and 23.8% over northern South America. Decreases in precipitation east of the northern Andes in tropical South America, and an increase in precipitation over southern South America and west of the northern Andes are pronounced (Llopart et al., 2020; Ortega et al., 2021; Thaler et al., 2021; Almazroui et al., 2021). These patterns intensify from the early-century (2021–2040) to the late-century (2081–2100) projection period and have greater magnitude in the higher emission pathway (SSP5-8.5) compared to the lower emission pathway, consistent with other studies (Riahi et al., 2011). While a small increase in precipitation can be observed in northeastern Brazil during DJF (Figure 6(l1) - (b1)), that precipitation reduction dominates annually in the region, suggesting an extended DSL in the northeast (Chou et al., 2014). According to Sena and Magnusdottir (2020), this increase of precipitation could be caused by increased moisture convergence over northeastern Brazil during the wet season, receiving more moisture both from the northern and southern tropical Atlantic.

Figure 6(a) – (l) show that the dry season over northern Amazon occurs between November to March, while the dry season in central and eastern South America occurs from April to October. During April to September, while high precipitation occurs over the northwest Amazon, many other parts of South America (over Brazil and west to southern Andes) experience a relatively dry period (less than 25 mm/month), because it is when South American Monsoon System (SAMS) starts to retreat (late April), with a northward movement of the ITCZ (Vera et al., 2006) and the wet season onset in the northwest (Espinoza et al., 2020). From October to March, a broad band of high precipitation (generally more than 100 mm/month) extending from western Amazonia to southeastern Brazil is developed, resulting from the development of SAMS over the continent during this time.



a) b)

Figure 5. (a) Annual mean precipitation (mm/month) of 1970-1999, and (b) its relative change (%) compared to 2081-2100 under the scenario SSP5-8.5. The model projections are calibrated using observations. This shows that most regions east to the Andes are getting drier.

The largest difference in decreasing precipitation between the historical period and the late-century projection occurs over northern South America, while the change in northwest South America (east to the Andes) is much less significant. Over northern and central South America, significant negative anomalies (with up to 37% less precipitation compared to the historical period) occur after wet season onset (September to November), consistent with other studies (Wainwright et al., 2021). These negative anomalies could occur due to the easterly anomalies in the zonal component of the low-level wind strengthens during the transition period to wet season (between July and September), delaying the beginning of wet season (Sena & Magnusdottir 2020), which reduces the precipitation in these months. Over northwestern South America, negative anomalies occur between July and November, and positive anomalies during the other months (Fig. 6(a1) - (l1)), but the increasing trend is not statistically significant. In contrast with the other areas, southern South America shows positive trends in annual precipitation due to increases in the warm season (DJF) rainfall. This could be due to the equatorward shift of the shrinking Hadley cell in winter, which causes an enhancement of the sinking motion and precipitation (Dogar et al., 2017; Saurral et al. 2017). In summer, the strength of the subsidence decreases, with an increase of the low-level moisture advection, which could also favor rainfall. Observational evidence suggests that the change of the Hadley cell position could be related to topography (Saurral et al., 2017). It is worth mentioning that despite the smallest regionally averaged precipitation changes over the northwest (Fig. 4), there is an increase in both wet and dry monthly extremes (Fig. 5(b)), which compensate each other and lead to apparently small annually averaged precipitation change.

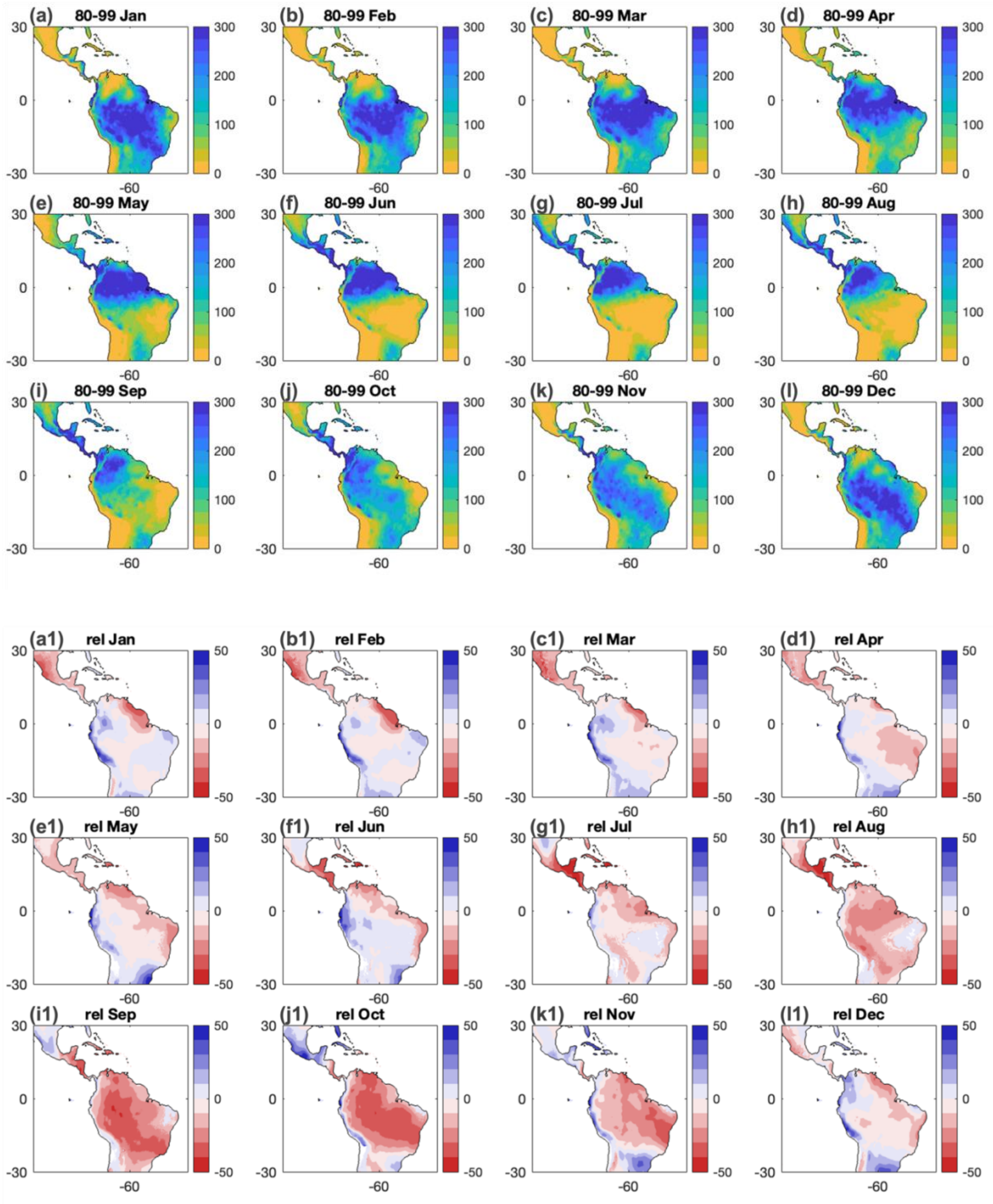
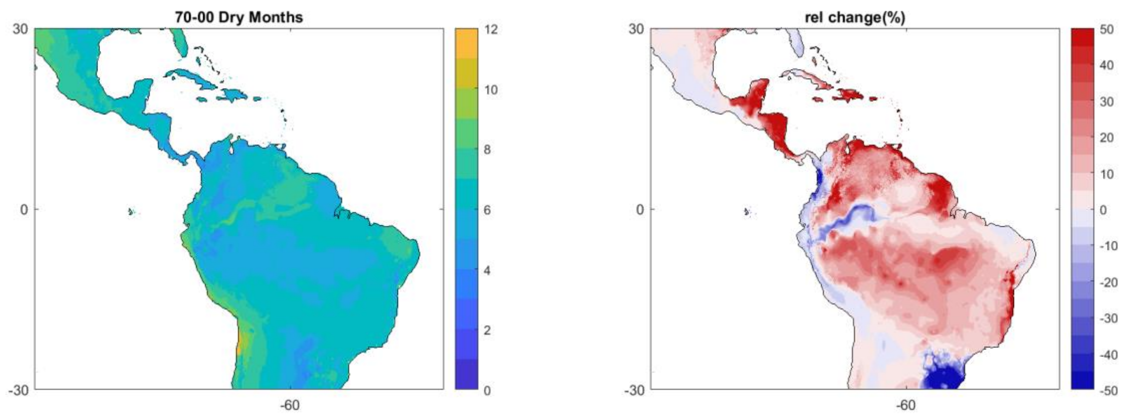


Figure 6. Monthly precipitation (mm/month) of the historical period (1970-1999) in the upper panel, with (a) - (l) representing months Jan-Dec; and relative precipitation change (%) in 2081-2100 in the lower panel, with (a1) - (l1) representing months Jan-Dec.



a) b)

Figure 7. (a) Calculated DSL (months/year) of the historical period (1970-1999), and (b) relative DSL change (%) in 2081-2100, using the high-resolution product.

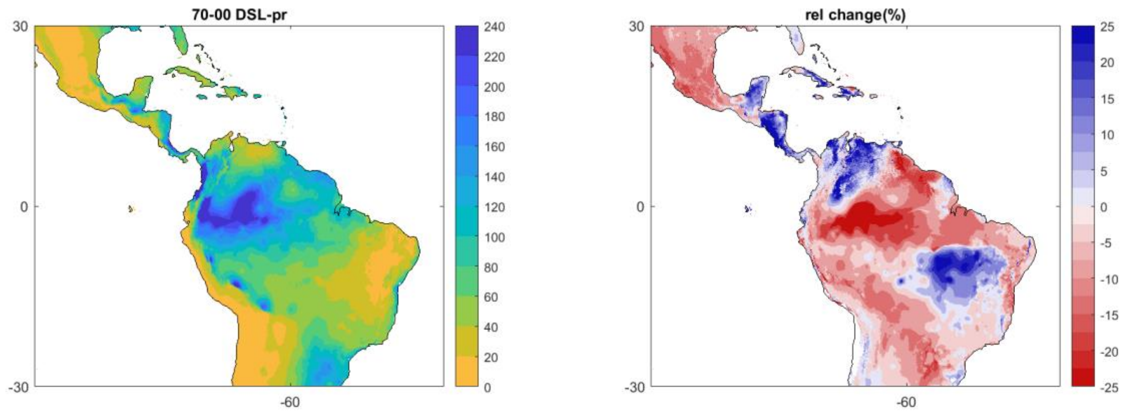
4.2 DSL Analysis

Apart from changing precipitation, the changes in dry-season length are important in determining the fate of the rainforests and bird demography in the tropics (Brawn et al, 2017). Since 1979, observations suggest that the dry season length increased over the Amazonia (Fu et al., 2013). We show that over most of Central and South America, the DSL varies between four to eight months, with decreases in the DSL in the west of Amazon and increases in the central Amazonia east of the Andes (nine to ten months).

From Figure 7(b), we can find an increase in mean DSL across South America and parts of Central America, with the highest increase over Panama and Yucatan Peninsula. Panama shows a 110.4% increase, around +2.9 months, while Guyana shows an increase around 61.7%, +2.7 months. This could be because wet season onset is projected to start later across South America (Correa et al., 2020; Wainwright et al., 2021). This could be due to stronger convective inhibition energy and poleward displacement of the subtropical jet before the onset that favors the late ending of a dry season (Li & Fu 2004; Li & Fu 2006) by impeding the uplift of air to the level of free convection and blocking cold-front incursions which favors large amount of rainfall. Figure

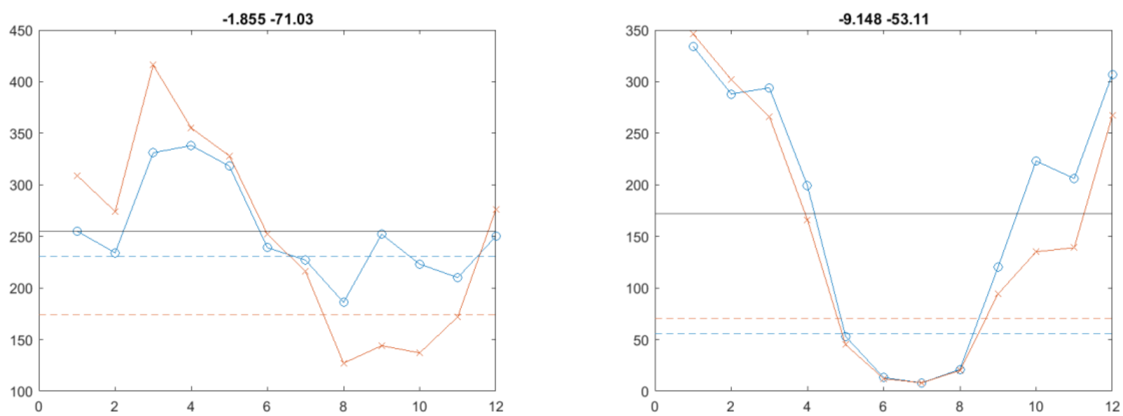
9(a) shows the annual cycle of precipitation around the equator in Central Amazon, where there is a decrease in DSL. The decrease is caused by an earlier ending of the dry season where the projected rainfall over the region increases relative to the reference period in the local wet season (DJF and MAM). Therefore, although there is an earlier wet season onset (from late February to November) to compensate for the dryness, the dry season over this region become drier than the historical period.

From Figure 8(a), the pattern of the average precipitation during historical DSL is close to that of average annual precipitation, due to our definition for DSL. Figure 8(b) shows a decrease in precipitation during the dry season over most regions, excluding southern Central America, northwestern Amazon, and southeastern Brazil. This decrease in precipitation could be due to their increasing length, which can reduce atmospheric moisture over the southern Amazon especially during late dry season (Agudelo et al., 2019). Other studies hypothesize that intensified low-level jet carries less moisture to central South America (Collini et al., 2008). Interestingly, there’s an increase (patch of dark blue) to the west and over the Brazilian Highlands. In the precipitation time series of this region (Figure 9(b)), we can see that this is caused by the decrease of October and November precipitation, which makes them fall into the ‘dry season’, increasing the DSL and the average precipitation during dry season. Therefore, the region is getting drier in general due to the prolonged DSL, but the change in dry season precipitation might make the dry season appears to be wetter. Similar situations also apply to the increase in dry season rainfall in Central America and northwestern Amazon, where large increase in DSL can be found.



a) b)

Figure 8. (a) Calculated DSL precipitation (mm/month) of the historical period (1970-1999), and (b) the relative change (%) of DSL precipitation in 2081-2100, using the high-resolution product.



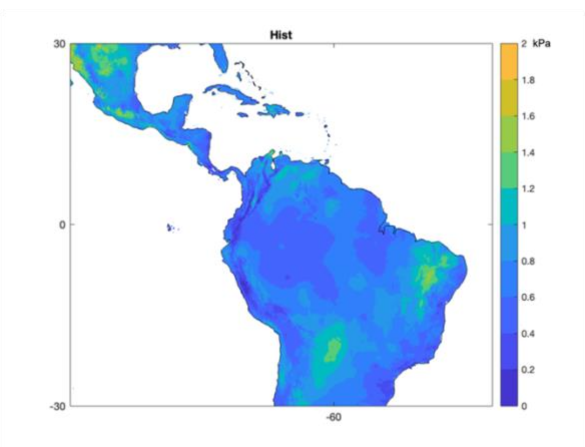
a) b)

Figure 9. Precipitation seasonal variation of (a) in central Amazon where DSL shortens, and (b) in central and eastern Brazil where DSL precipitation increases. The solid line represents the historical annual mean precipitation, the blue (orange) solid line represents the monthly precipitation averaged over the historical (future) period, and the blue (orange) dotted line represents the average DSL precipitation of the historical (future) period.

4.3 Changes in VPD Patterns

Vapor pressure deficit (VPD) is also an important climate factor for avian species, impacting their heat dissipation (Smit et al. 2013; Pattinson et al., 2020). Therefore, to further investigate the climate suitability for tropical birds in South America, we looked at the VPD pattern and its change. The special pattern for the historical VPD shows that the highest values (of up to around 1.5 kPa) lie in northeastern Brazil and Paraguay, while lower values are found in central and western Amazon at around 0.5 kPa. Low VPD values suggest that the air is close to saturation. During the dry season (August to October), VPD is high over the eastern South America, while during the local wet January to March, it is high in the northern Amazon and southern South America (not shown), consistent with Albright et al. (2021). During August to October, VPD shows a positive anomaly over the southern and eastern Amazon with up to 190% increase from 1970-1999 to 2081-2100 (Figure 10), which results from around 10°C warming (increased saturation vapor pressure) and up to 40% decrease in relative humidity (decreased actual vapor pressure). From September to March, VPD increases concentrate in the central Amazon and extends to Central America, while from May to July, the increase over central and western Amazon drops to less than 100% (Fig. 11(e) – (g)). These modeled VPD increases are consistent with current observations: Barkhordarian et al. (2021) shows that VPD has increased in the southeastern Amazon between 1987-2016, likely due to greenhouse gas forcing in the wet season and additionally anthropogenic aerosols and land use in the dry season. On the other hand, over the northwest Amazon rainforest, VPD increase can be mostly explained by the greenhouse gas induced warming and lack of moisture transport (Barkhordarian et al., 2019). From this it can be inferred that precipitable water vapor is necessary for wet season onset, therefore, increasing VPD in tropical rainforests due to warming can cause drought conditions regardless of soil moisture decrease (Harper et al., 2014), and more severe or more frequent droughts can negatively affect population size and species structure by limiting food availability and delaying reproductive activities (Cruz-McDonnell & Wolf, 2016; Brawn et al., 2017; Martin & Mouton, 2020).

From our calculations, the estimated annually averaged VPD for 2081-2100 has similar patterns as the historical one (Fig. 10 & Fig. 12), with lower values of 1.0-1.4 kPa in central and western Amazon. The regions with VPD > 1.8 kPa cover most of Central America, northern Amazon and Central South America, indicating less precipitable water and hence higher drought risk, especially from August to October. Starting from November, VPD increases from Central South America. Sena & Magnusdottir (2020) suggested that in the future, more moisture convergence from the tropical Atlantic to the Amazon is generated prior to the transition to the wet season (starting from July), which could result in the increase in the VPD annual cycle (Fig 10(b)). And after the wet season onset (after October), more moisture is carried from the Amazon to the subtropics through the low-level jet.

a) 

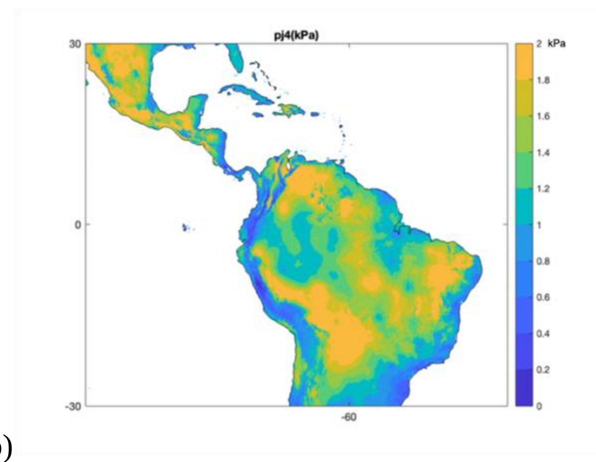
b) 

Figure 10. The annual average VPD values (kPa) for (a) historical period and (b) the estimated future.

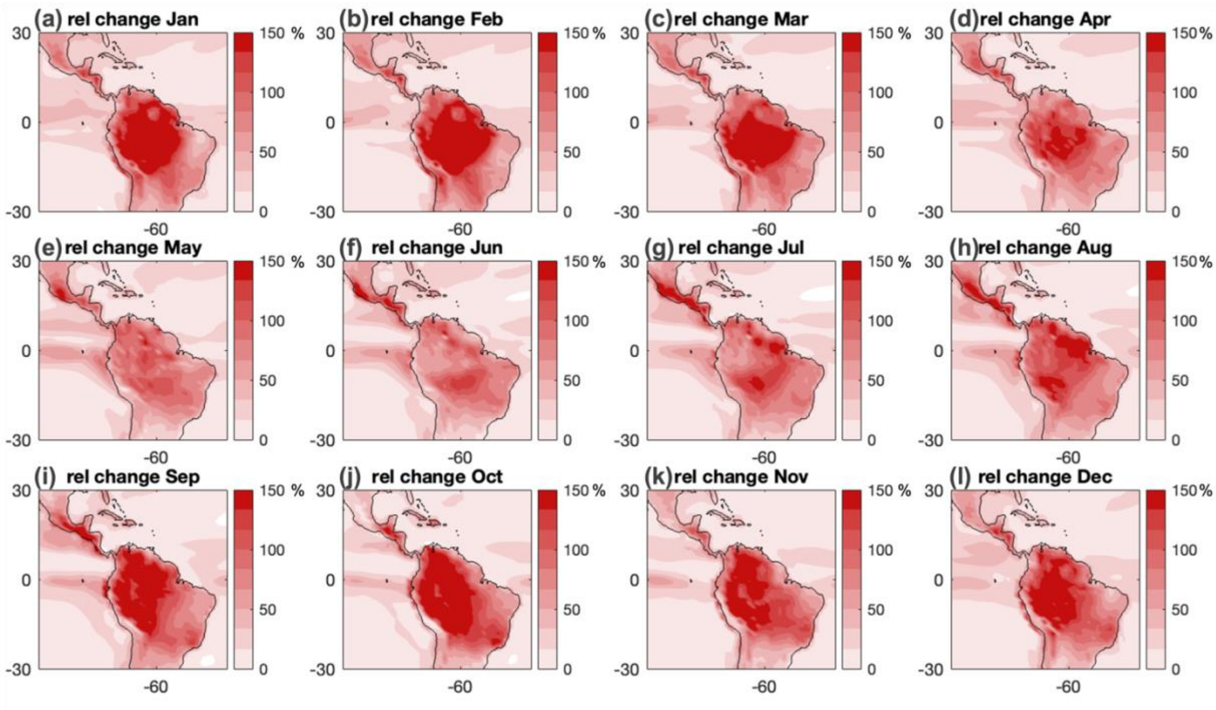


Figure 11. (a) – (l) January to December monthly relative change (%) of VPD from historical to future period (2081-2100).

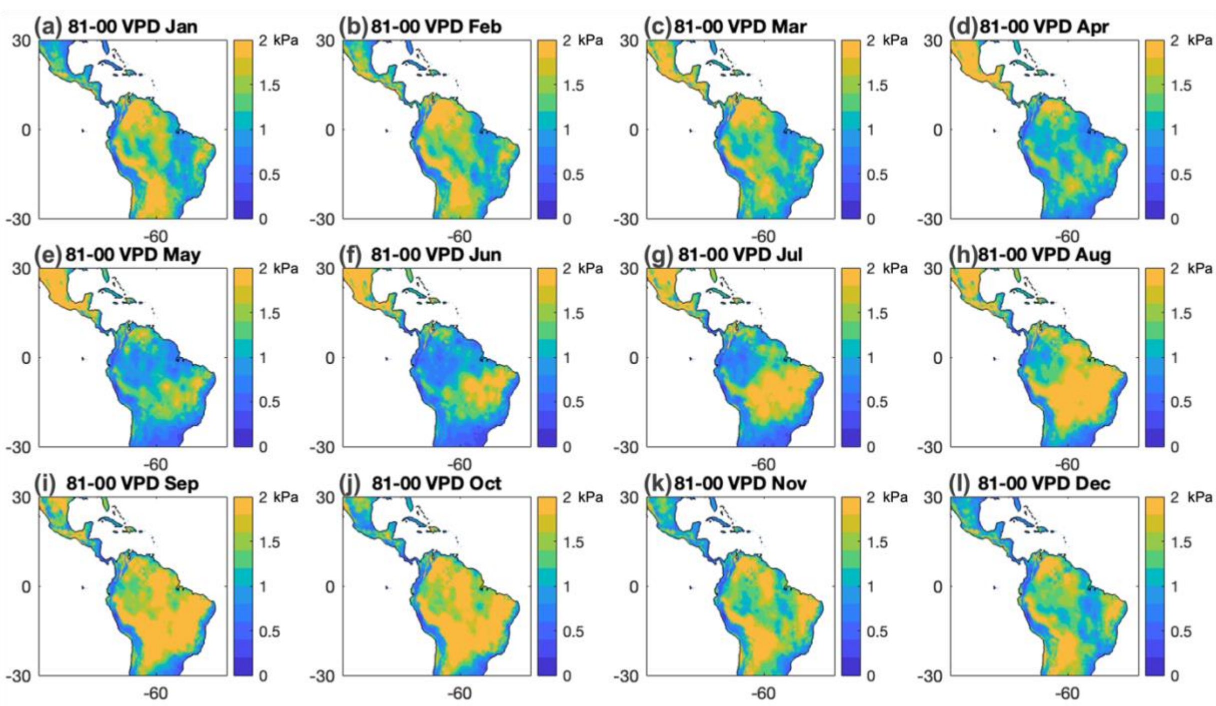


Figure 12. (a) – (l) January to December estimated VPD (kPa) of future period.

5 Discussion

5.1 Key Findings

Climate change has been identified to be a crucial factor in altering habitat suitability and species populations. If the climate changes exceed what the local species can tolerate, they will have to migrate or locally go extinct. Boyle et al. (2020) proposed a hygric niche concept to review the divergent responses of tropical bird populations to rainfall variations, which describes the environmental conditions that meet the species' minimum survival requirements (Chase & Leibold, 2009). These conditions differ among bird species but, in general, wetter conditions favor populations near the drier end of the niche and vice versa. It has been reported by Brawn et al. (2017) that a longer dry season in the Panamas decreased the population growth rates of nearly one-third of the sampled avian species, with or without direct influence on habitat alteration. Recher & Davis (2014) also found longer dry periods to be highly threatening for Australian woodland species, even with the presence of higher seasonal rainfall. Therefore, combined with the species-specific niche (suitable climate-change range) and protected area maps, our projected precipitation regime changes can then provide fundamental implications on the evaluation of the current conservation and the future planning. The management policies should refer to the threat levels faced by different areas, and the creation of new protected areas should avoid regions projected to be severely affected by climate change in the long term (Watson et al., 2013), including notable precipitation changes.

Based on the parameters we used to indicate the climatic effects on bird species, the projections performed in this study suggest notable changes in our target area. Our results indicate that under high radiative forcing pathways (SSP5-8.5), more than 75% of the studied area in tropical South

America are projected to experience a drying tendency of up to 30% in annual average precipitation by 2100. The greatest decrease occurs during August to October over central and southern Amazon and during December to March over northeastern Amazon. Moreover, the length of dry season in most of the area (around 72%) is expected to increase, concentrating over northern and eastern Amazon and central Brazil. Since the local species are highly dependent on the rainfall regimes, their population are likely to be greatly affected because of the high rates of rainfall reduction (Brawn et al., 2017). We also estimated VPD variations and showed that highest relative increases in VPD occur between September to March, especially in central Amazon. This is consistent with observed VPD increases over the past 30 years (Yuan et al., 2019; Barkhordarian et al., 2019). These increases are likely to result in tree mortality and reduction of local habitat, and eventually affect bird communities (Anderegg at al., 2015; Jucker et al., 2018).

By combining the analysis of the length and severity of dry periods in 2081-2100 under the emissions scenario SSP5-8.5 and current bird species, our results indicate the effect of precipitation regime on neotropics bird conservation. In the finalized analysis, about 82% of the studied avian species are expected to experience longer dry seasons relative to 1970-1999, and 34% of them will experience a substantial increase (larger than 99%) than the current DSL. In addition, the dry season intensity increases will be greater for more than half of the species. Jetz et al. (2007) estimates that hundreds of bird species will experience a reduction in occurrence range of more than 50%, with tropical species the most at risk. Moreover, Northrup et al. (2019) suggests that the population size will also decline in response to the reduction of mature forest resulting from drying. The reduction of suitable habitat areas due to climate change has been reported not only for birds but also for various other biospecies, such as mammals, amphibians and plants (Carvajal et al., 2018; Beyer et al., 2020). Therefore, we believe that the local bird biodiversity will be greatly affected under changing rainfall and VPD regimes. Conservation plans must take these changes into consideration to mitigate future species extinctions.

From our estimation for the Amazonia, combined with the current protected area information, we can see that the region expected to experience low precipitation changes (lower than 5%) are concentrated to the central and western Amazon, such as the protected areas of Alto Nanay-Pintuyacu-Chambira and Pacaya Samiria in northern Peru, and northeastern Brazil, where protected areas are scarce. Northeastern and eastern Amazon seem to be under the influence of greater drying in both wet and dry seasons, leaving the protected areas in northern Venezuela, Guyana and the large patch around Parque do Tumucumaque in northern Brazil with greater climatic threats.

As for regions with less change in dry season length (Fig. 13), most of the large group of the protected areas in northern Brazil will experience a relatively low increase (under 5%) in DSL, apart from the state of Amapa (on the east side). Scattered regions in central Amazon along the equator also show less changes (under 5%) in DSL, from Pacaya-Samiria (eastbound) to Floresta Nacional De Tapajós (westbound), extending to Canaima National Park (northbound). However, Central Amazon is expected to get much drier (more than 15% decrease in rainfall) during the dry seasons, including the protected areas from Alto Rio Negro to Central Amazon Conservation Complex. In conclusion, the areas that are projected to experience the least drying, in terms of annual precipitation and dry season length, are in western Amazon, northwestern Amazon, along the east side of the Andes and northern Brazil, where unfortunately, protected areas are very scattered.

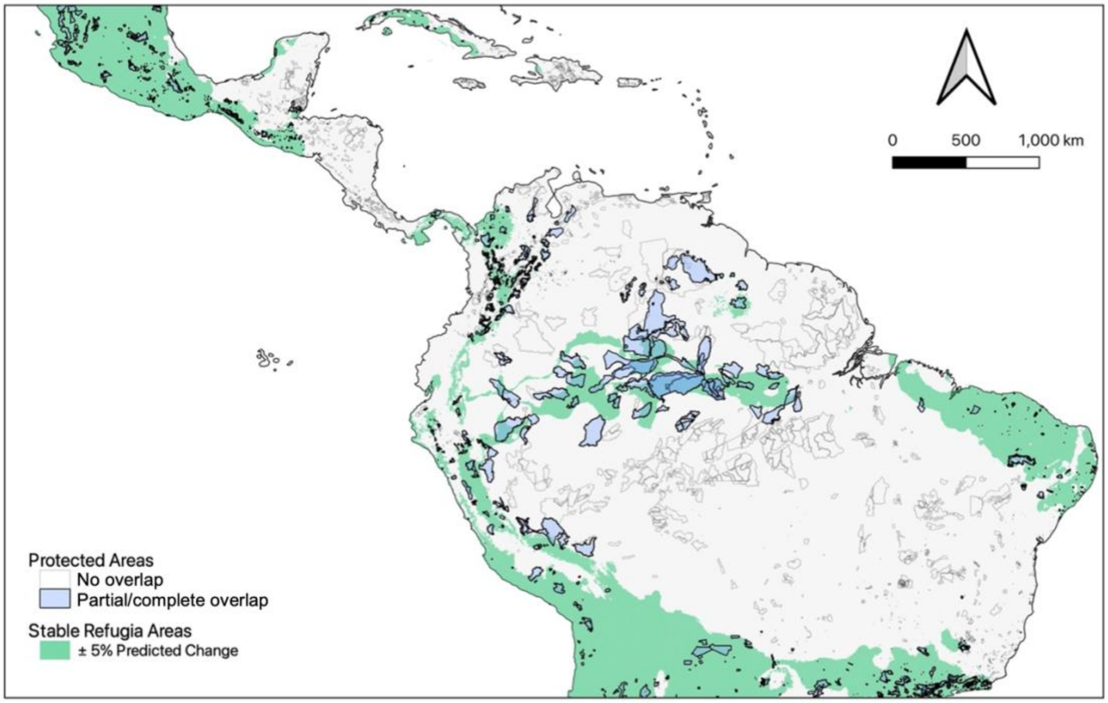


Figure 13. A map indicating which protected areas overlap areas considered to experience lower predicted change in DSL. Green areas indicate changes within ±5%. Transparent protected areas indicate protected areas that do not overlap low-change areas. Blue protected areas indicate partial to complete overlap with low-change areas (Source: Courtesy of Jeffrey D. Brawn, David A. Luther and W. Justin Cooper).

5.2 Limitations

The WorldClim downscaled product provides the necessary regional-scale projections for ecological investigation, but the analysis of this project is limited by the temporal resolution of the downscaled data set, which provides monthly precipitation simulations averaged over 20-year periods. Daily records of precipitation would be very helpful for a more accurate calculation for the dry season length, which is more often used in dry season analysis for the tropical Americas (Yin et al., 2014; Brawn et al., 2017). Our current determination of the start and end of the dry season is affected by the low temporal resolution, where we made the assumption that the precipitation variation between two adjacent months is linear, which is clearly not realistic.

Measuring DSL using monthly precipitation can cause other problems, such as showing a shorter projected DSL while the dry season is getting much drier (Fig. 7(b) and Fig. 9(a)). As explained in Section 4.2, the shortened DSL shown in Central Amazon is resulted from the increased wet season precipitation. In Figure 9(a), it is shown that the historical precipitation of January, September and December are very close to the climatological mean and are included in the ‘dry months’ by our definition. With daily precipitation records and more accurate definition of DSL (Li & Fu 2004), it is very likely that there would be multiple short dry periods over the year, which are more reasonable and much shorter than the very long dry season (from June to February) defined with the current method. This defect can be slightly compensated by showing the average precipitation during the dry season, where the dotted lines in Figure 9(b) suggest the greatly increased dryness in the projected period despite a wetter wet season. Another limitation lies in the downscaling method used in WorldClim. The calibration of the WorldClim dataset is done by applying the interpolated anomalies to the observations (baseline climate), which makes two assumptions: 1) Changes in climates only occur over large distances, and 2) the relationships between variable in the baseline climate are maintained towards the future. Therefore, in terms of future changes, we are relying on the models without any corrections, resulting in the limitation of biases in the climate models, which is explained in more detail in Section 3.2. In general, CMIP models tend to exhibit a wet season dry bias over the southwestern and central Amazon, and a wet bias over the high elevations, with large improvements from CMIP3 to CMIP6 (Almazroui et al., 2021). The model bias can be mitigated by using the averaged result of multiple models, but the common biases among the models still remain. A model weighting scheme can be developed and applied to take model performance into account and further improve model projections (Shin et al., 2020). This will take information from all models and still reduce the susceptibility of the mean to apparent outlier-introduced bias (Haughton et al., 2015).

5.3 Future Research Suggestions

Araújo et al. (2006) brought up the question that climate factors alone might not be sufficient to predict the change in species distribution and richness. When assessing the species distribution over large regions, previous studies have assumed that using climate predictors alone should provide enough support to estimate the main patterns (Pearson & Dawson, 2003). Determination of the answer requires quantifying how much climate can explain species distributions compared to other factors, such as human influences and land-use change (Luoto et al., 2006; Borges et al., 2020). As discussed in Section 1, land-use change (through conversion, degradation, and fragmentation of habitats) is considered one of the most important drivers of biodiversity loss in the tropics (Sodhi & Smith, 2007; Jetz et al., 2007; Watson et al., 2013; Newbold et al., 2015; Chapman et al., 2018). Borges et al. (2020) revealed that 74% of the bird species in the Brazilian Cerrado will hold less of their current geographic distribution, due to higher risk of native vegetation loss rather than climate anomalies.

Fire is another associated climate factor that greatly affects biodiversity. It is suggested that differences in fire regimes can greatly alter bird distributions (Valentine et al., 2007; Reside et al., 2012; Silveira et al., 2020; Mardiastuti et al., 2020). Amazonian Fires are greatly affected by the spatial and temporal characteristics of the dry season, in terms of fire occurrence density and seasonality (Asner & Alencar, 2010; Carvalho et al., 2021). Fu et al. (2013) suggested that a delayed dry season ending in southern Amazon favors increasing fire season and fire counts. Although species showed a mixed response to increased fire frequency, species distributions generally have a negative correlation with dry season fire. It has been estimated that under the pessimistic climate-land-use projections, there will be substantial increase in fire probability and the length of fire season (Fonseca et al., 2019; Dos Reis et al., 2021). Therefore, the length and timing for dry seasons in the Amazon also work as helpful indicators of wildfire and its influence on conservation planning.

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