Chapter 1: Climate change in the coffee belt

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1 Recent climate change and uncertainties

The coffee belt is the band of coffee suitable regions between the tropics of Cancer and Capricorn, from around 23°S to 23°N. This area has experienced a sharp increase in temperatures since the 1960s, and this trend is expected to increase. Figure 1 displays the yearly average temperature in this belt over the instrumental record. The average increase in recent decades has been 0.16°C per decade. The equator is generally expected to warm more slowly than the poles. This correspondingly represents an intermediate rate of warming, greater than the rate of ocean warming at 0.11°C per decade and less than the global average for land at 0.28°C per decade (GISTEMP Team, 2015; Hansen et al., 2010).

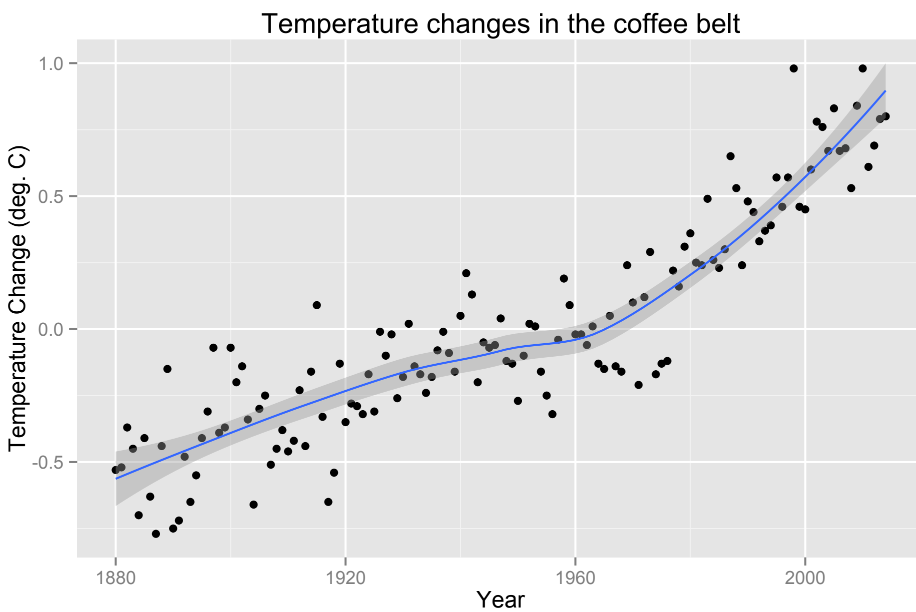

Figure 1: Yearly average temperatures in the coffee belt (dots), including temperatures over land and oceans, and a smooth running average with 95% confidence intervals.

As temperatures increase, coffee production will be forced toward the poles and to higher elevations. If warming continues at its current rate, with an average increase of 0.16°C degrees per decade, coffee production will need to shift an average of 46km per decade toward the poles or 29m higher per decade.[1]

1.1 Counterbalancing effects

Not all of the effects of climate change are necessarily detrimental to coffee production. One of the major threats to coffee farms is frost (Varangis et al., 2003), and where minimum temperatures shift away from 0°C without otherwise affecting conditions, coffee production will benefit. Elsewhere, the variability of

[1]Average change in temperature with latitude and elevation from `http://landterms.com/Articles_and_FAQ_s/Conservation_and_Ecology_Articles_and_FAQ_s/Latitude__Elevation_and_Temperature/`, reported as 3°F / 300 miles latitude and 3°F / 1000 ft elevation. This equates to 290 km / °C and 183 m / °C.

temperature will become greater, increasing the risk of cold snaps and frost damage even as average temperatures warm.

Carbon fertilization will also have uncertain effects. Many crops see yield benefits from carbon fertilization (McGrath and Lobell, 2013), as plant produce more carbohydrates (Körner et al., 2007). However, a wider carbon-to-nitrogen ratio generally produces a loss of quality for agricultural products. Quality coffee production may need to move to higher elevations to offset this increase in carbohydrate productivity. At higher elevations, bean development slows and flavors have more time to accumulate, but this also places coffee back into zones of high frost risk.

As temperatures rise, coffee will be forced generally up slopes and away from the equator. Under 2-2.5°C of warming, the minimum altitude suitable for coffee production in Central America and Kenya is expected to increase by around 400m (IPCC, 2014). However, this will open up new areas to coffee production, even as it eliminates traditional areas, for example in high-elevation regions of Guatemala.

1.2 Climate predictability

The primary drivers of yields, suitability, and other responses of coffee to climate are temperature and precipitation. Although we have extensive predictions of future temperature and precipitation patterns through the end of the century, these need to be treated with some circumspection. Our understanding of the future impacts of climate on coffee is limited by the fundamental predictability of the climate system.

Climate change and the long-term increase in global average temperatures are a virtual certainty. However, predictions for the equilibrium change in global temperature resulting from a doubling of CO_2 range from 1°C to 6°C (Stocker et al., 2014, Box 12.2). Many feedback loops in the climate are poorly understood, and predictions that agree on eventual changes in the climate can disagree on the timing. Furthermore, the patterns of how temperature, precipitation and other aspects of weather will change locally are more uncertain than the global average. Finally, the uncertainty around how society will respond to climate change is even greater than the uncertainty in climate.

One way to understand the amount of uncertainty in annual average temperatures and precipitation in coffee-growing regions that results from the natural climate system is to identify the sources of variability in historical temperature and precipitation. We can separate the series of average temperature and precipitation totals per year into components that are driven by (1) long-term trends, (2) decadal cycles, and (3) interannual variation.

Long-term trends can be predicted many years in advance. Decadal cycles are more difficult to predict, but forecasts are often available months or years ahead. The remaining unpredicted changes in temperature and precipitation are idiosyncratic to a particular year and typically unpredictable before that year.

The table below shows the portion of variability over the past hundred years that falls into each of these three components for land areas between 30°N and 30°S.

Temperature and precipitation show very different patterns of uncertainty. A large part of the region's temperature is described by the long-term trend (60-64%), reflecting the relative certainty of long-term temperature increases. Most of the remaining uncertainty for temperature is represented by inter-annual variation, and this portion of each year's temperature is very difficult to predict.

In contrast, there is very little long-term trend in precipitation. While climate change is expected to increase the rate of precipitation on average, observed changes are very small. However, in the case of precipitation, decadal cycles explain some amount of the variation (17-25%), with changes in ocean temperatures driving decade-long increases and decreases in precipitation. There remains still a large fraction of each year's precipitation which is unaccounted for.

Temperature	Component	Annual Average	Sep. - Nov.
	Long-term Trend	64%	60%
	Decadal Cycles	6%	11%
Precipitation	Inter-Annual Variation	29%	26%
	Long-term Trend	1%	1%
	Decadal Cycles	17%	25%
	Inter-Annual Variation	81%	69%

Table 1: From `http://iridl.ldeo.columbia.edu/maproom/Global/Time_Scales/temperature.html` and `http://iridl.ldeo.columbia.edu/maproom/Global/Time_Scales/precipitation.html`. Blossoming has been found to be the most sensitive time for coffee plants[2], and Sep. - Nov. is this period in Brazil, the largest coffee producer.

As the relative importance of each of these components varies widely by location, it is useful to look at regional maps of these patterns. The Time Scales Maproom from the International Research Institute for Climate and Society (IRI) provides a way of decomposing variability in temperature and precipitation over space. This decomposition represents how much of the "story" of year-to-year temperatures and precipitation amounts is explained by either a long-term trend, a 10-year long running average, or by neither of these. Decompositions for temperature and precipitation, against the long-term trend and decadal cycles drivers, are shown in figures 2 and 3.

The temperature maps show that little of the year-to-year variation is explained by a long-term trend in many coffee-growing regions. In particular, this historical analysis shows almost no explanatory capacity for Colombia and much of Indonesia. However, coffee growing regions of Brazil and India are strongly explained by the long-term trend, suggesting that future climate predictions for these areas will be most reliable. As above, almost none of the the year-to-year variation in precipitation is explained by the long-term trend, but moderate amounts driven by decadal cycles, particularly in Colombia and India.

[2] E.g., for Nicaragua: `http://www.academia.edu/2243528/Coffee_yield_variations_and_their_relations_to_rainfall_events_in_Nicaragua`.

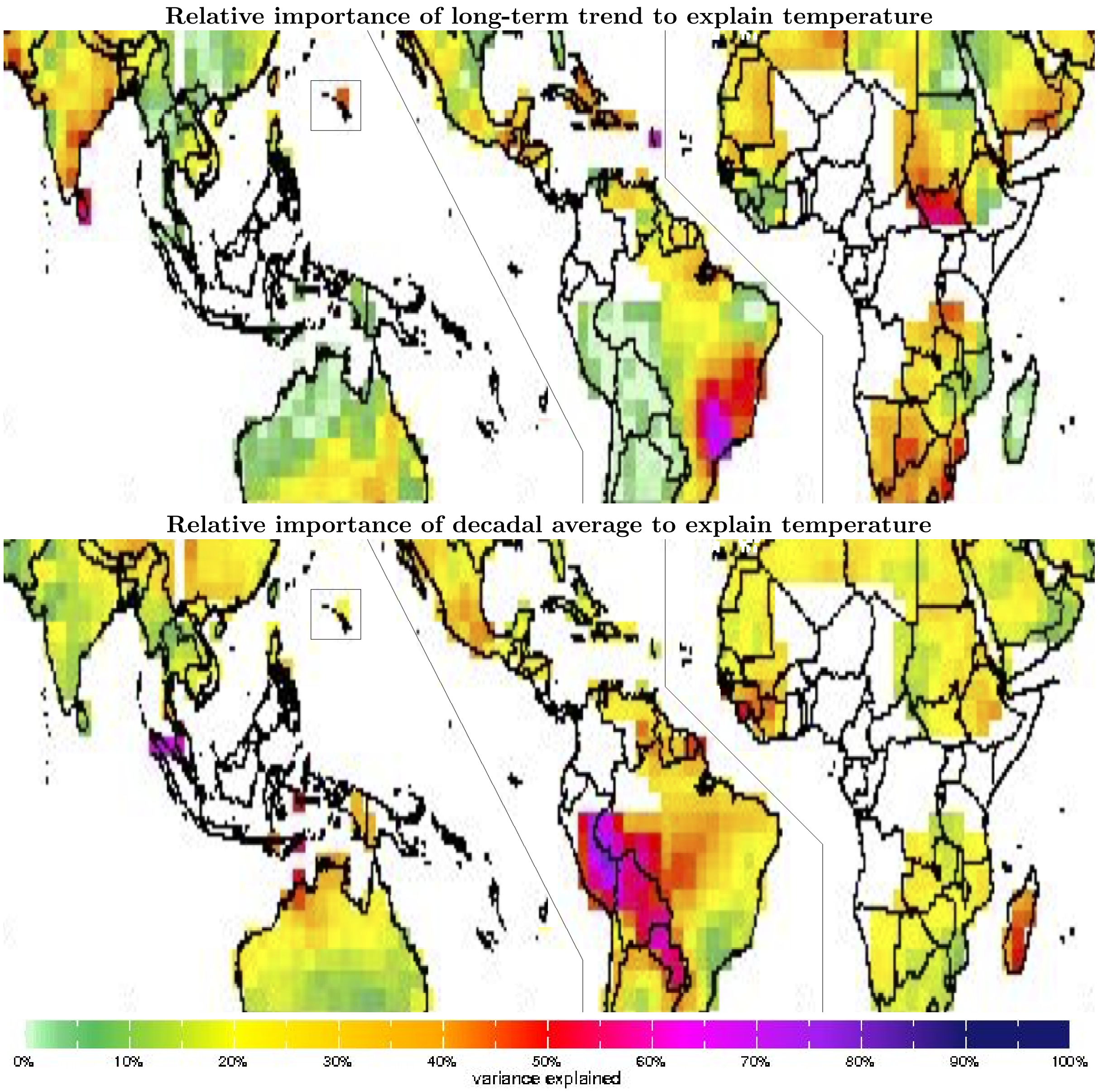

Figure 2: The role of long-term and decadal variation in temperature for explaining total temperature variation, from `http://iridl.ldeo.columbia.edu/maproom/Global/Time_Scales/temperature.html`. The colors show the percentage of variance in year-by-year annual temperatures explained by a trend (top) or decadal average (bottom).

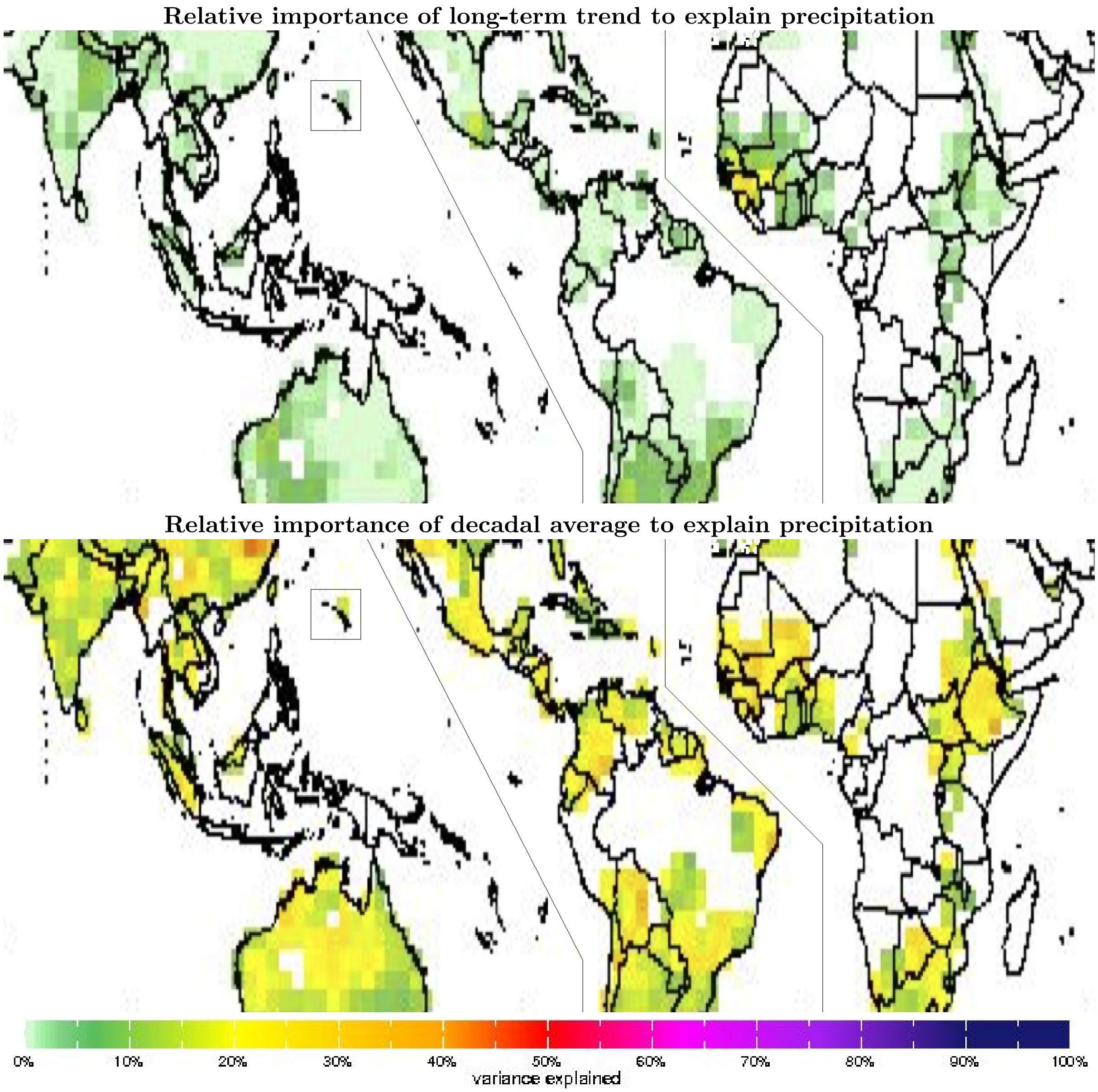

Figure 3: The role of long-term and decadal variation in precipitation for explaining total precipitation variation, from `http://iridl.ldeo.columbia.edu/maproom/Global/Time_Scales/precipitation.html`. The colors show the percentage of variance in year-by-year annual precipitation totals explained by a trend (top) or decadal average (bottom).

2 Future climate projections

Climate projections are produced by sophisticated physical models called Global Climate Models (GCMs). They apply scientific knowledge about the radiative heating of the atmosphere, its interaction with the ocean, and the movement of heat and water in response to human and natural drivers. The most recent report from the IPCC (Stocker et al., 2014) was produced in conjunction with a project to collect and harmonize results from all available GCMs. We use these 'CMIP5' models to study the changes in future climate and uncertainty surrounding them.

GCMs are calculated at a lower spatial resolution than we require to study coffee. A further process of downscaling expands the changes predicted by GCMs to produce high resolution projections. This process comes with additional uncertainty, since the feedbacks embodied in the GCM are not used when the resolution is improved. The downscaling dataset we use is WorldClim (Hijmans et al., 2005), available at a resolution of 5 arc-minutes (about 9km at the equator), the same resolution as the coffee database. WorldClim contains downscaled results for 17 GCMs under the "business-as-usual" emissions scenario, IPCC RCP 8.5. We study not only the impact of the expected change in climate, but also the range of impacts across the available models of future climate. Table 2 and figure 4 describe shifts in average climate metrics. The baseline climate is representative of 1950 - 2000. Changes in climate are shown as a distribution over estimates of the change in 2050, according to each GCM. The range of uncertainty in these models is a proxy, but almost certainly an underestimate, for the total uncertainty in future climate.

Quantity	Baseline (1950-2000)	Change (to 2050)	50% range
Annual mean temperature	23.6°C	2.1°C	[1.7 - 2.5]
Mean diurnal range	12.6°C	-0.5°C	[-0.6 - -0.5]
Temperature seasonality	3055.0	3.9 %	[1.9 - 4.4]
Max temperature of warmest month	34.2°C	2.5°C	[1.9 - 2.7]
Min temperature of coldest month	12.3°C	1.9°C	[1.7 - 2.4]
Annual precipitation	1068.0 mm	1.7%	[-0.1 - 3.2]
Precipitation of wettest month	191.0 mm	8.0%	[5.5 - 11.3]
Precipitation of driest month	22.0 mm	-6.8%	[-12.3 - -2.0]

Table 2: Mean changes over the coffee belt and the 25% to 75% quantiles.

As an example, figure 5 shows the range of changes in one coffee growing region of Colombia across these 17 GCMs. For some of the aspects of climate listed in table 2, all 17 GCMs agree on the direction of the change in this region. The annual mean temperature, and maximum and minimum temperatures are all expected to increase about 2°C over a baseline period from 1950 - 2000. This represents a future average increase of 0.28°C per decade, 75% greater than the current rate. The temperature seasonality, defined as the standard deviation of temperature, is also expected to increase. The other values are less certain, with some models predicting increases and others decreases.

2.1 Spatial patterns of change and uncertainty

The median changes in climate across 17 GCMs are displayed in figures 6 and 8 as they vary across the coffee belt in 2050, under a business-as-usual scenario. We report impacts consistent with RCP 8.5, the highest IPCC emissions pathway, throughout this report because current emissions appear to be following this path. Strong climate change action can mitigate these impacts, but the largest benefits of such mitigation will occur after 2050.

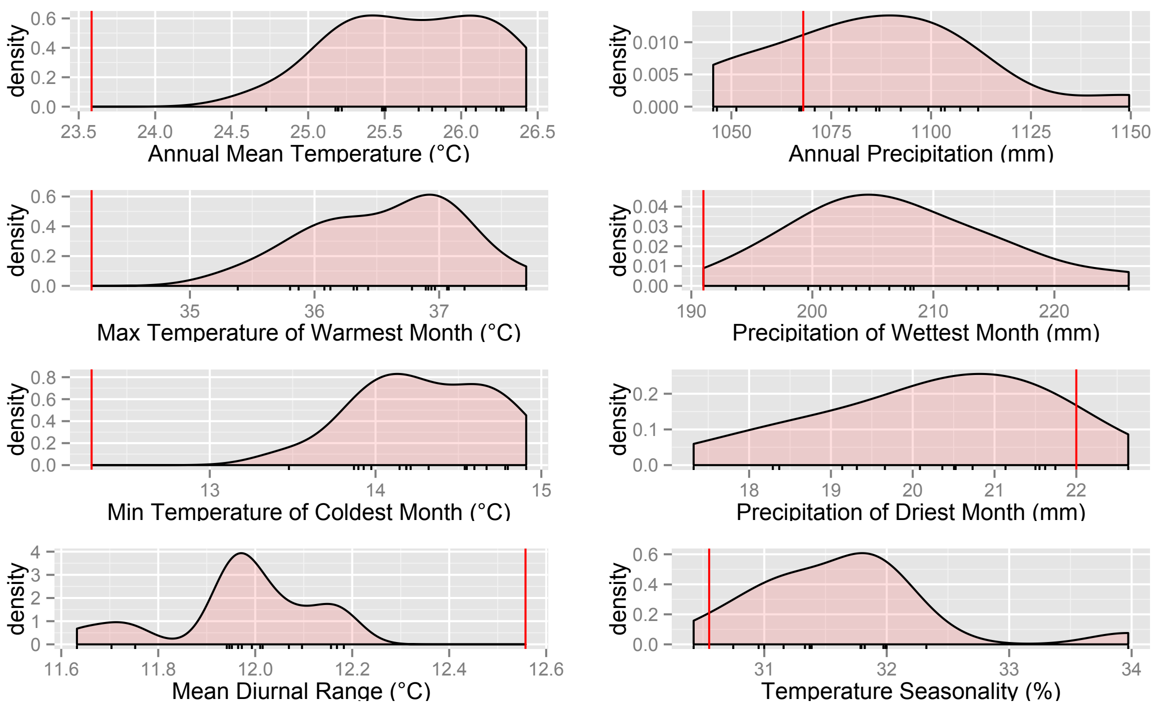

Figure 4: The average baseline climatology (red lines) and distribution of possible future climate values in 2050 under RCP 8.5, averaged over all tropic belt land. Small dashes at the bottom show the estimates of each individual GCM model, with the area above it representing this distribution as a curve.

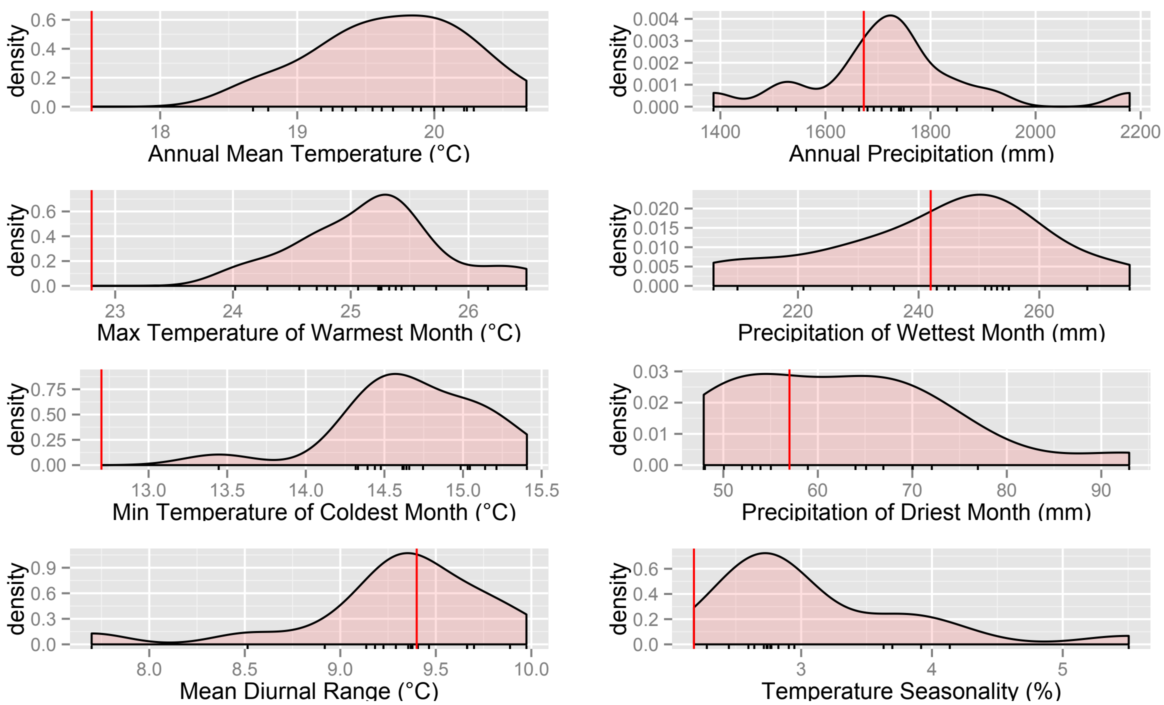

Figure 5: The baseline climatology (red lines) and distribution of possible future climate values in 2050 under RCP 8.5, for a location in Colombia at 4°N 76°W. Small dashes at the bottom show the estimates of each individual GCM model, with the area above it representing this distribution as a curve.

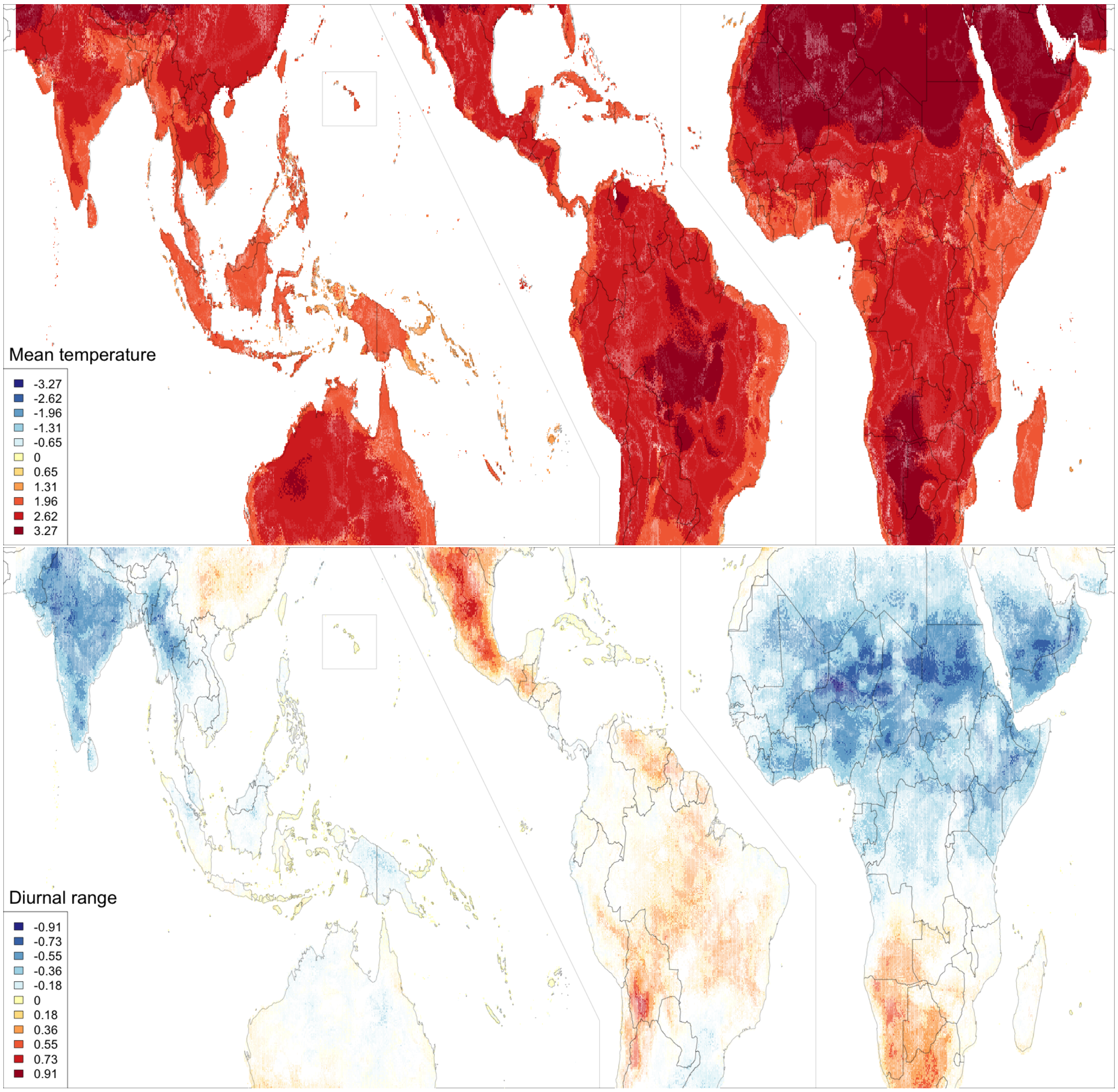

Figure 6: Global patterns of level changes in mean annual temperature and diurnal temperature range for 2050 from Hijmans et al. (2005). Areas are faded in proportion to the number of GCMs that do not agree with the sign of the median GCM.

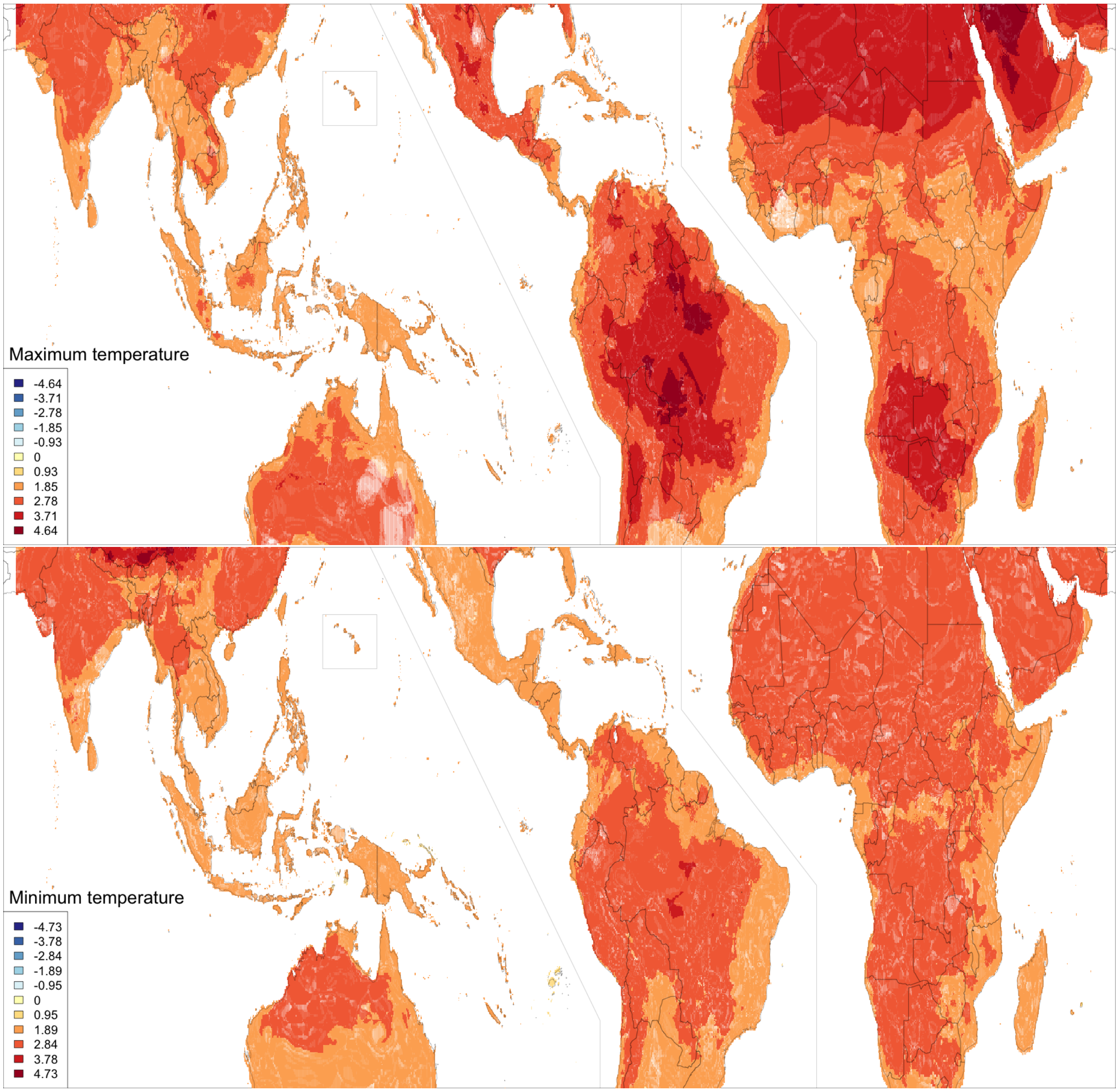

Figure 7: Global patterns of level changes in maximum yearly temperature and minimum yearly temperature for 2050 from Hijmans et al. (2005). Areas are faded in proportion to the number of GCMs that do not agree with the sign of the median GCM.

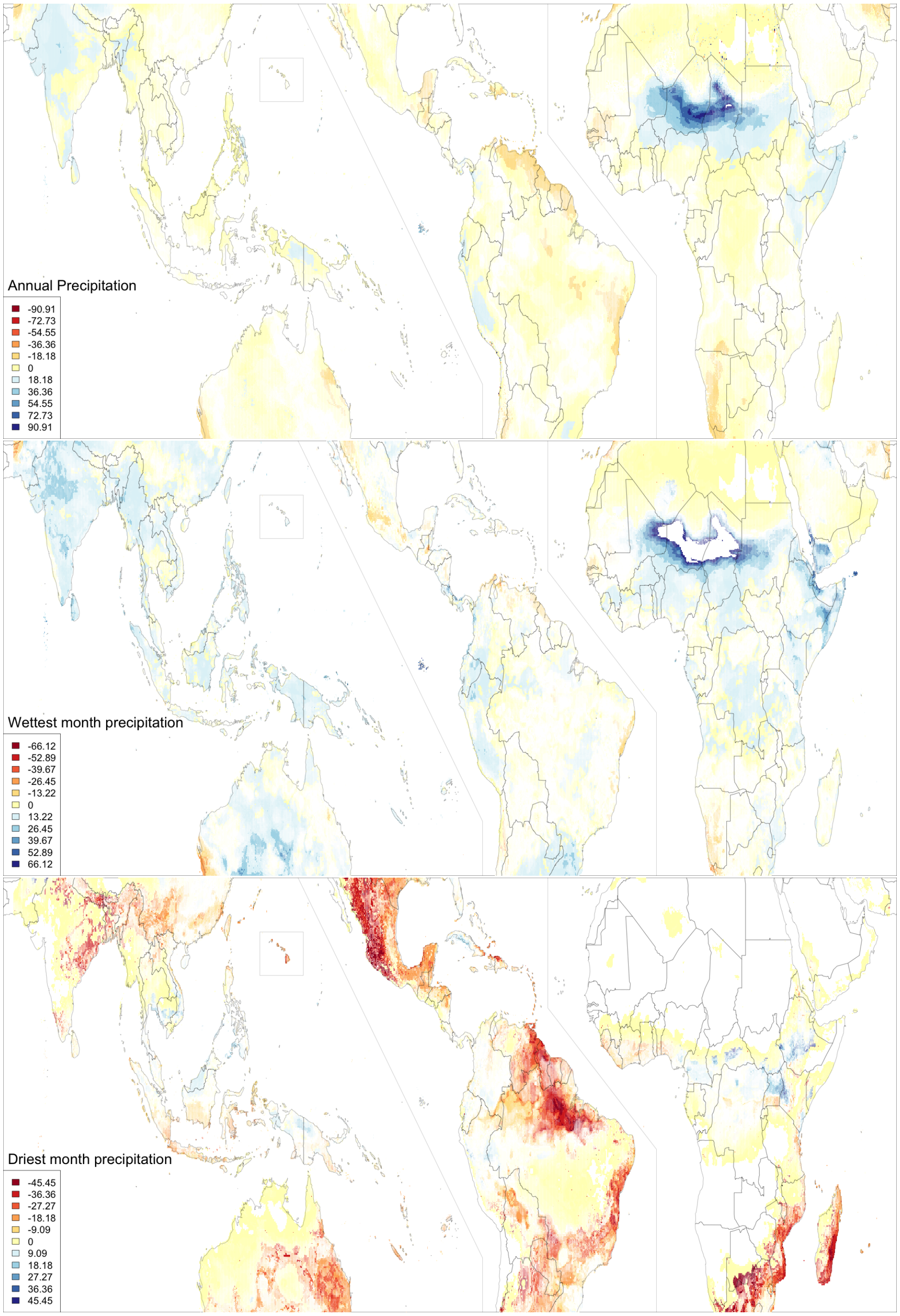

Figure 8: Global patterns of percent changes in annual total precipitation, precipitation in the wettest month, and precipitation in the driest month, for 2050 from Hijmans et al. (2005). Areas are faded in proportion to the number of GCMs that do not agree with the sign of the median GCM.

Temperatures increase across the entire region with high confidence, within the explanatory power of these GCMs. The size of these temperature changes generally increases away from the equator, with most coffee growing regions seeing an increase of 1 - 2°C by 2050. The pattern for the diurnal (day-night) temperature range is more complicated, with increases in the Americas and decreases across northern Africa and South Asia. Precipitation changes are less certain, with decreases on the coasts of Brazil, and increases in northern Africa and India.

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