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Paraná River Basin

The past is neither the present nor the future.

Rainfall patterns that facilitated economic expansion in the 1980s and 90s are unlikely to return in the next 10-20 years.

Agriculture, shipping, and hydropower dams drive much of the Paraná Basin's economy. Governments and private enterprise established these sectors in the 1980s and 90s when rainfall was high and water was abundant. Average annual rainfall has declined since 2000 and reached critically low levels since 2020. Though some models project a return to rainfall patterns similar to those from the 2000s, others project that the low rain of the past five years will persist. While rainfall may return to patterns seen between 2000-2020, no models project a return to the wet decades pre-2000.

Soy Production & 9-Month Forecast

A drier-than-normal forecast through September suggests agriculture, shipping, and hydropower sectors will need to sustain drought management measures.

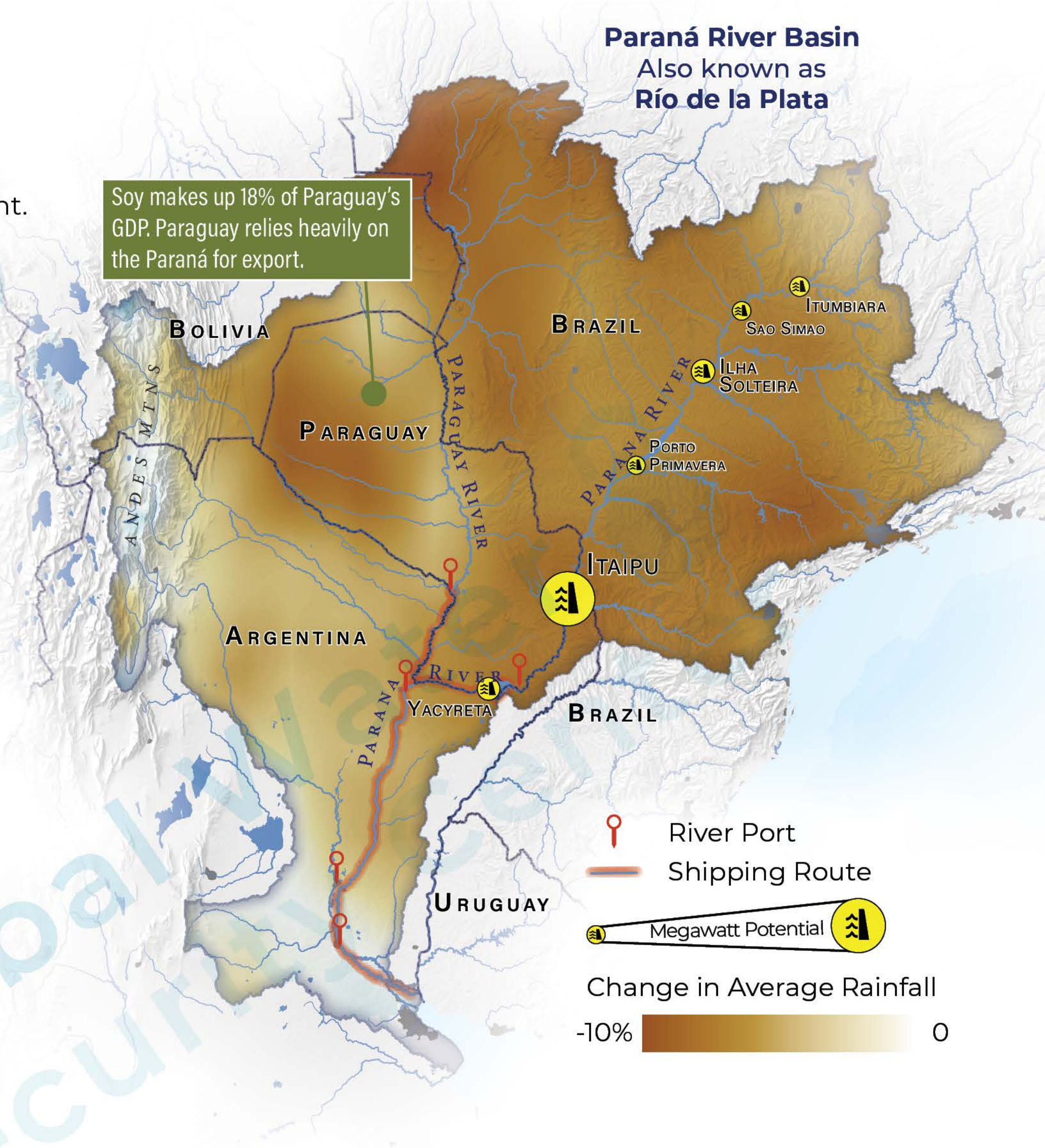
Hydropower Production 2035

Hydropower may not be sufficient to meet electricity demand if rainfall does not rebound in alignment with the high rainfall projection.

River Shipping 2035

Dredging required to bring larger ships upriver will increase in low- and mid-rainfall projections, while more rain may increase risk of infrastructure damage in the high-rain projection.

Map 1: Though projections vary, rainfall of the past five years resembles the DRY projection for 2035 (SSP 585).
For more information on projections, see Supplemental Page 2.



Global Water Security Center

PARANÁ: 9-Month Rainfall Forecast Suggests No Substantive Drought Recovery for Soy, Shipping, or Hydropower This Year

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BLUF

A drier-than-normal forecast through September suggests agriculture, shipping, and hydropower sectors will need to sustain drought management measures.

SOY PRODUCTION: Most soy is rainfed, but grown on large farms with sufficient technology to withstand all but the most severe drought. Despite low rainfall forecasted through the growing season, **USDA projects a 2-10% increase in soy production** over 2023-2024, which saw normal production[1].

SHIPPING: Current dry season forecasts indicate that **a return to 2024's soy shipping difficulties** is possible.

HYDROPOWER: As **forecasts are not favorable for a rebound in reservoir levels this wet season**, high-cost, careful management measures carried out at the Itaipu dam may once again be necessary in the dry season.

Table 1: Paraguay is the most vulnerable to drought impacts on soy as the crop makes up nearly 20% of their GDP.

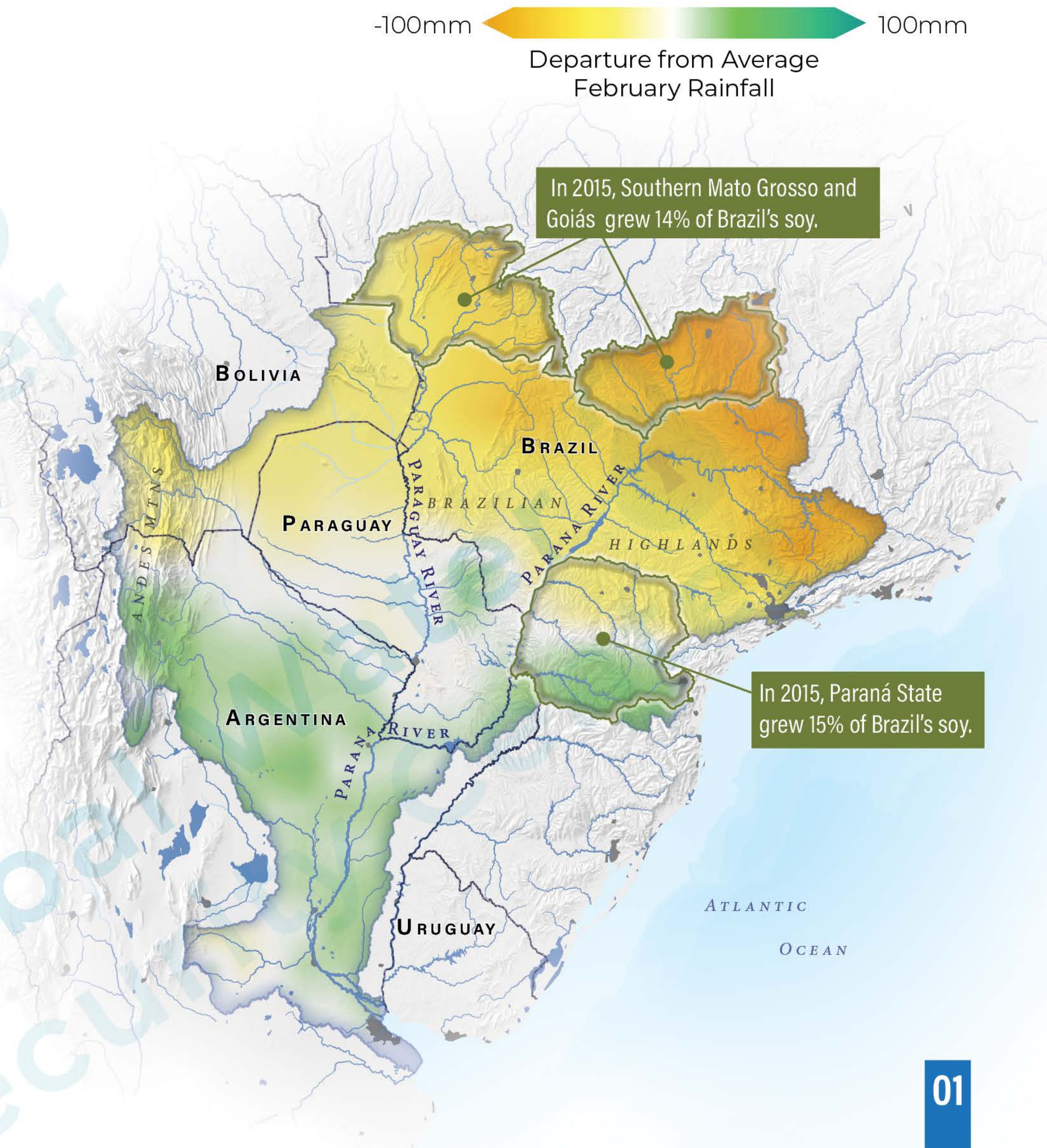
	% soy grown in Paraná	Soy as % of total cropland[2]	Total soy as % of GDP
Argentina	42	48	3.5
Brazil	42	49	1.3
Paraguay	100	72	18

DROUGHT, AGRICULTURE, AND MIGRATION

Most soy production in Argentina, Paraguay, and Brazil is carried out by large multinational companies on large farms that have successfully used technology to weather drought since 2020[4]. Though smallholder farmers may face difficult conditions through 2025, most drought-driven migration is rural to urban in-country as families supplement household income to retain land. Drought is unlikely to drive mass migration in the basin.

Map 1: February is projected to be the driest month relative to normal rainfall over Brazil's densest soy crops, which could impact growth.

Though the USDA projects increased soy production in Argentina, Brazil, and Paraguay 2024-25, USDA may revise projections for Brazil if a dry February affects crops in peak growing season.



Global Water Security Center

PARANÁ 2035: Declining Rainfall and Increasing Sedimentation Squeeze Storage Capacity and Hydropower Production at Dams

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BLUF **Hydropower may not be sufficient to meet electricity demand if rainfall does not rebound in alignment with the high rainfall projection.**

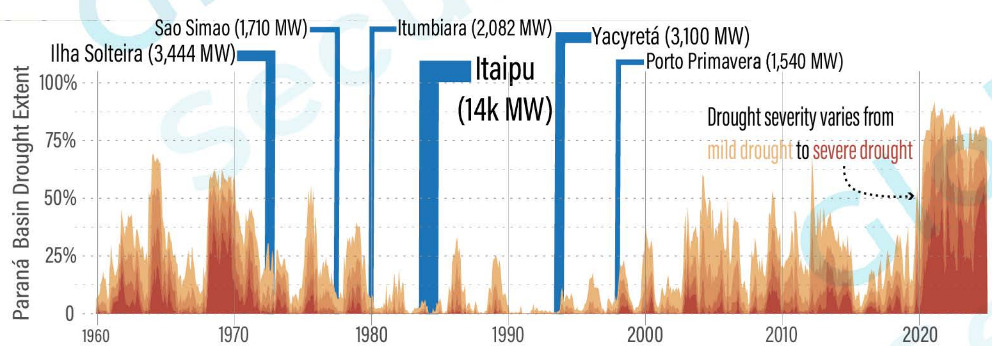
Background

Most of the basin's big hydropower plants were commissioned in the wet years of 1980-2000. Electricity production in the Itaipu, the world's 2nd-largest hydropower plant, has been declining due to low rainfall since 2017[1]. Sedimentation has filled up to 8% of reservoir capacity across all of the basin's big dams[2].

Map 2: Mean annual Rainfall is highest just upstream of the Itaipu Dam.
Though the Itaipu can produce more power than the 5 next-largest dams combined, all dams are important as they offset the need for expensive fossil fuels.

1000mm — 2800mm

Figure 1: Big hydropower dams were built when drought was minimal.
Dams are built for a certain rainfall variability so they can store rain for dry periods and safely release excess water during floods. The Paraná's dams, built when rain was abundant and drought covered smaller extents of the basin, are no longer filled as fully and must release more of what they store in these drier conditions.



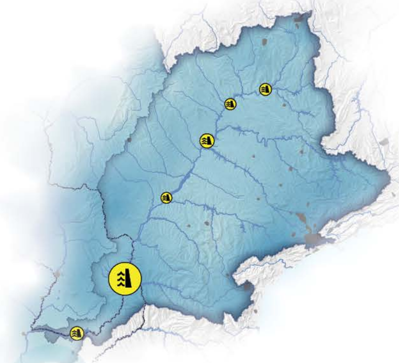
Map Series 1: Around 2035, changes in mean annual rainfall (SSP 585) could improve or limit hydropower production
Three possible futures summarize a range of model projections. The DRY projection resembles rainfall over the last 5 years.

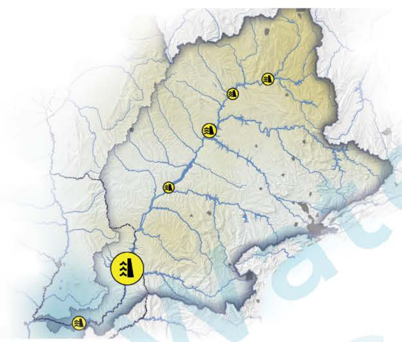
-10% — 0 — 15%
Less Rain — More Rain

WET — Years-Long Recovery

Average annual rain exceeds that of 2010 by 3%, but wet periods over drought-baked soils flush more sediment into reservoirs. Power returns to mid 2010s production levels after a few years of refilling.

Analog year: 2016, Itaipu produced record power at over 100 million MWh, as the reservoir was filled by a major wet season flood that year.





MID — Limited Recovery

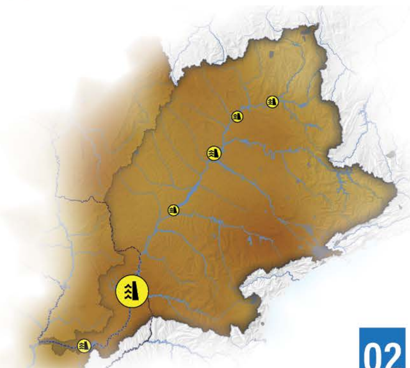
A mix of wet and dry years around the 2010 average slowly refills reservoirs. However, supply is still strained as industrial expansion increases demand and sediment fills 4% more storage[2].

Analog year: 2018, very average rain and the last year the Itaipu dam produced more than 90 million MWh.

DRY — Persistent Low Rain

Average annual rainfall declines by 7% from that of 2010. Reservoirs continue shrinking while downstream demand for shipping water increases. Meeting energy demand requires more fossil fuels.

Analog year: 2023, Itaipu limited production to 83 million MWh while releasing water to parched Paraná delta.



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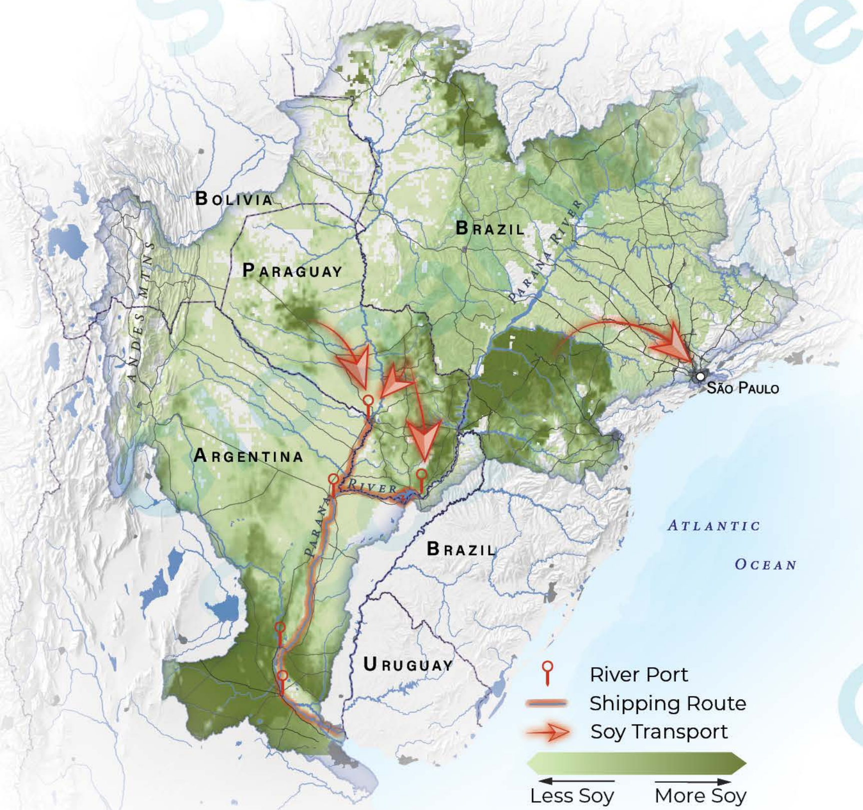
PARANÁ 2035: Extended Dry Spells Strain Shipping Even In Wetter Rainfall Projections

BLUF **Dredging required to bring larger ships upriver will increase in low- and mid-rainfall projections while more rain may increase risk of infrastructure damage in the high-rain projections.**

Background

Dredging to bring larger ships further upstream began in earnest in the 1990s when river levels were high. Dredging and other river works have become more complicated and expensive as river levels have dropped. Low river levels in the DRY projection would increase dredging costs.

Map 3: Argentina and Paraguay depend on the Parana river to ship soy and other goods, while Brazil transports goods via coastal São Paolo.
Longer stretches between rainfall could increase river level fluctuations. A doubling of heatwaves (see Supplemental Page 6) means rains flush more sediment from hot, dry soils into rivers[1], exacerbating dredging and shipping issues.

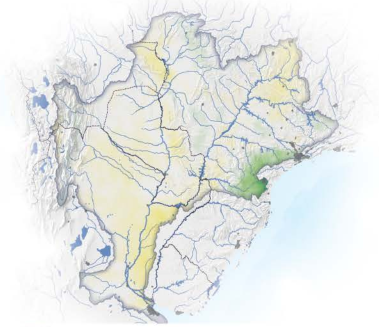


Map Series 2: Around 2035, dry spells are most impactful to shipping in the DRY projection (SSP 585).

Three possible futures summarize a range of model projections. The DRY projection resembles rainfall over the last 5 years.

WET — Fewer Dry Spells
Rain similar to 2010 replenishes rivers. However, wet periods can flood rivers, hampering shipping.

Analog year: 2015, high river flows and fast currents from a rainy July slowed transport for weeks during the high shipping season.



MID — Normal with Dry Spells
Rain consistent with 2010 average. A 4% increase in dry spells increases river fluctuations and flushes dry soils into rivers, which risks groundings.

Analog year: 2018, total rain was normal but winter dry spells forced ships to substantially reduce cargo due to low water levels.

DRY — Multiple Dry Spells
Average rains are higher than last 5 years, but a 14% increase in dry spells keep dredging needs high. Overlapping dry spells and heat waves impact soy, meaning less to ship.

Analog year: 2023, hot, dry conditions halved Argentina's soy production in the 2022-23 growing season.

Sources:

9-month

1. Foreign Agricultural Service. (2025). World Agricultural Production (Circular Series, Issue WAP 01-25).

2. Global Yield Gap Atlas. https://www.yieldgap.org/

3.Bianchi, E., & Szpak, C. (2017). Soybean prices, economic growth and poverty in Argentina and Brazil (Background paper to the UNCTAD-FAO).

4. Gaeda, O. (2018). Paraguay: Sustainable Soy and Beef (UNDP Food And Agricultural Commodity Systems).

5. Wesz Junior, V. J. (2021). Soybean production in Paraguay: Agribusiness, economic change and agrarian transformations. Journal of Agrarian Change, 22(2), 317-340. https://doi.org/10.1111/joac.12436

Hydropower

1. Yearly MWh production listed in annual financial reports by Itaipu Binacional. See https://itaipu.energy/

2. Perera, D., Williams, S., & Smakhtin, V. (2022). Present and Future Losses of Storage in Large Reservoirs Due to Sedimentation: A Country-Wise Global Assessment. Sustainability, 15(1). https://doi.org/10.3390/su15010219

Shipping

1. Cunha, E. R. D., et al. (2022). Assessment of current and future land use/cover changes in soil erosion in the Rio da Prata basin (Brazil). Sci Total Environ, 818, 151811. https://doi.org/10.1016/j.scitotenv.2021.151811

Map Sources:

Basemap:

Airbus, USGS, NGA, NASA, CGIAR, NLS, OS, NMA, Geodatastyrelsen, GSA, GSI and the GIS User Community. "Terrain: Multi-Directional Hillshade". October 28, 2024. https://elevation.arcgis.com/arcgis/rest/services/WorldElevation/Terrain/ImageServer

Esri, TomTom, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community. "World Topographic Map (WGS84)". September 16, 2024. https://basemaps.arcgis.com/arcgis/rest/services/World_Basemap_GCS_v2/VectorTileServervt

Made with Natural Earth. Free vector and raster map data @ naturalearthdata.com.

Map 1 - Parana 9-month Outlook

Kebede, E.A., Oluoch, K.O., Siebert, S. et al. A global open-source dataset of monthly irrigated and rainfed cropped areas (MIRCA-OS) for the 21st century. Sci Data 12, 208 (2025). https://doi.org/10.1038/s41597-024-04313-w

Map 2 - Parana Hydropower

Lehner, B., Beames, P., Mulligan, M., Zarfl, C., De Felice, L., van Soesbergen, A., Thieme, M., Garcia de Leaniz, C., Anand, M., Belletti, B., et al. (2024). The Global Dam Watch database of river barrier and reservoir information for large-scale applications. Scientific Data, 11(1), 1069. doi: 10.1038/s41597-024-03752-9

Map 3 - Parana Soy:

Kebede, E.A., Oluoch, K.O., Siebert, S. et al. A global open-source dataset of monthly irrigated and rainfed cropped areas (MIRCA-OS) for the 21st century. Sci Data 12, 208 (2025). https://doi.org/10.1038/s41597-024-04313-w

Data Analysis Methods:

DATA SETS: ERA5 Historical Weather Data 1950-2024. NASA Earth Exchange Global Daily Downscaled Projection CMIP6. Climate change scenarios: SSP245 & SSP585 | years: 2025 – 2045. Historical 2000-2020. 17 models were used: ACCESS-ESM1-5, BCC-CSM2-MR, CanESM5, CMCC-ESM2, FGOALS-g3, GISS-E2-1-G, MIROC-ES2L, MPI-ESM1-2-HR, MRI-ESM2-0, NESM3, NorESM2-MM, CNRM-ESM2-1, EC-Earth3-Veg-LR, GFDL-ESM4, INM-CM5-0, IPSL-CM6A-LR, KIOST-ESM. North American Multi-Model Ensemble (NMME) seasonal forecast for February 2024 through September 2024 obtained from the Earth System Prediction Lab at the University of Oklahoma

METRIC CALCULATION: Baseline (sometimes called "normal") and representative future values for each year of interest are calculated using 21-year time intervals around the date of interest. Our historic normal is based on the year 2010 (2000-2020) using ERA5 data. We also include data from 1985 (1975-1995) to depict trends through time. To bias correct future values, we calculate the difference or ratio between NEX-GDDP-CMIP6 modeled future [2035 (2025-2045)] and modeled historic [2010 (2000-2020)] values and add this difference to the historic baseline value or multiply the ratio by the historic baseline value for each metric of interest. All calculations are spatially distributed (quarter-degree grid cells) an d aggregated as the final step.

Precipitation

Mean Annual Precipitation: The sum of the total daily precipitation for each year, averaged over the time period of interest.
Consecutive Dry Days: The number of 7 days in a row that received less than 1 mm of rain each year, averaged over the time period of interest.
Precipitation anomaly: The summed monthly difference from the 1991 – 2020 reference period (for NMME data only).

Temperature

Mean Annual Temperature: The mean of the daily average temperature for each year, averaged over the time period of interest.
Heatwaves: The number of 5 or more days in a row where the maximum temperature reached or exceeded 35C, averaged over the time period of interest.

Model projection sets

To provide insight into three potential futures, we split the 17 CMIP models into three sets for mean annual precipitation projections and consecutive dry day projections. To create the three sets, we calculated the regional average mean annual precipitation projections for 2035 under ssp 585. We then grouped took the four models that comprised the lowest 20% of projections, the four that comprised highest 20% of projections, and the nine that comprised the projections between these two cut-offs. We then calculated the mean and standard deviation of the projections for each model set group to represent the central tendency and interannual variability of each group, respectively.
The 'dry' models (lowest 20%) includedwere: CanESM5, GFDL-ESM4, NESM3, and NorESM2-mm.
The 'mid' models includedwere: ACESS-ESM1-5, BCC-CSM2-MR, CNRM-ESM2-1, FGOALS-g3, INM-CM5-0, IPSL-CM6A-LR, KIOST-ESM, MIROC-ES2L, and MPI-ESM1-2-HR.
The 'wet' models (upper 20%) includedwere: CMCC-ESM2, EC-Earth3-Veg-LR, GISS-E2-1-G, and MRI-ESM2-0.

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R Core Team (2023). _R: A Language and Environment for Statistical Computing_. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

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Tye, M. R., Ge, M., Richter, J. H., Gutmann, E. D., Rugg, A., Bruyère, C. L., Haupt, S. E., Lehner, F., McCrary, R., Newman, A. J., and Wood, A. (2023)Evaluating an Earth system model from a water user perspective, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2023-2326

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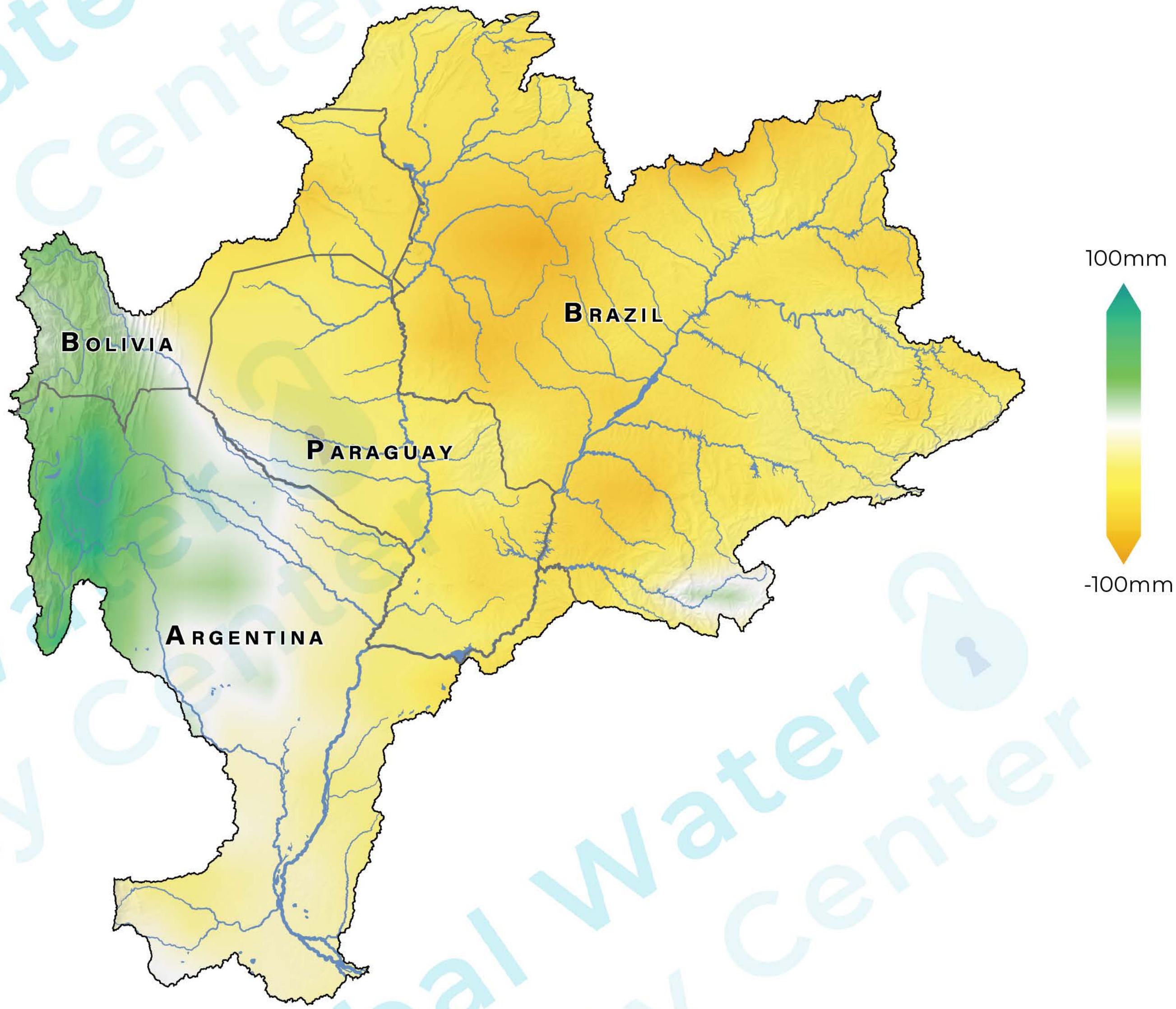
Supplemental Materials:

Forecast in the Parana River Basin February Through September Departure from Average Rainfall

The rainfall forecast, derived from the North American Multimodel Ensemble, (see References) shows drier-than-normal conditions for much of 2025.

According to current forecasts, some regions can expect to receive up to 100 mm less rain than normal from February through September.

NOTE: Forecasts are not intended to capture extreme events and lose accuracy at longer time scales.



Supplemental Materials:

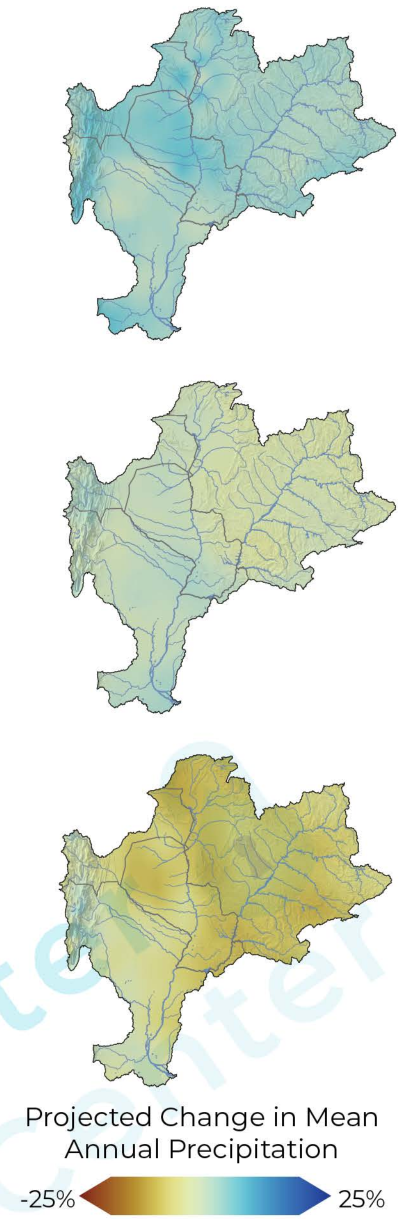
Ensemble Projections

To provide insight into three potential futures, we **split the 17 CMIP models** into three sets for mean annual precipitation projections and consecutive dry day projections. To create the three sets, we calculated the **regional mean annual precipitation projections for 2035 under SSP 585**. We then grouped the four models that comprised the **lowest 20%** of projections, the four that comprised **highest 20%** of projections, and the nine that comprised the projections between these two cut-offs. We then calculated the mean and standard deviation of the projections for each model set group to represent the central tendency and interannual variability of each group.

The ‘**wet**’ models (upper 20%) were: CMCC-ESM2, EC-Earth3-Veg-LR, GISS-E2-1-G, and MRI-ESM2-0.

The ‘**mid**’ models were: ACESS-ESM1-5, BCC-CSM2-MR, CNRM-ESM2-1, FGOALS-g3, INM-CM5-0, IPSL-CM6A-LR, KIOST-ESM, MIROC-ES2L, and MPI-ESM1-2-HR.

The ‘**dry**’ models (lowest 20%) were: CanESM5, GFDL-ESM4, NESM3, and NorESM2-mm.



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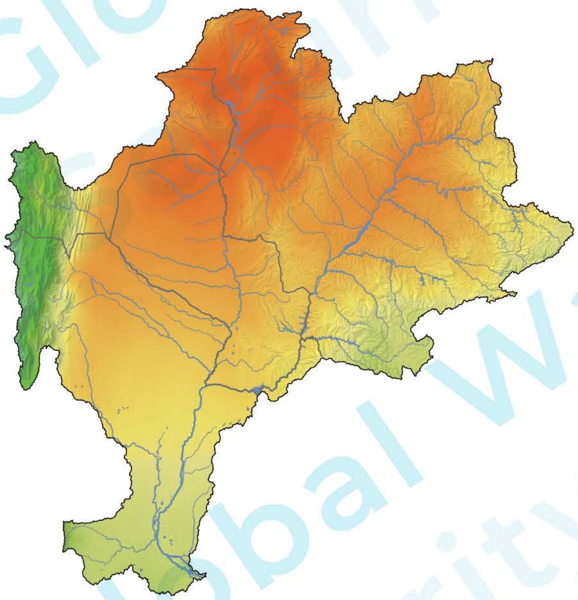
Supplemental Materials:

Mean Annual Temperature in the Parana River Basin

Mean annual temperature

(reference period 2000-2020)

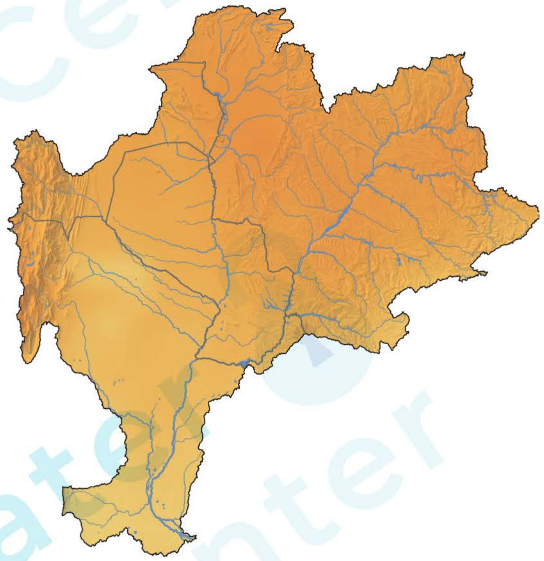
0°C 30°C



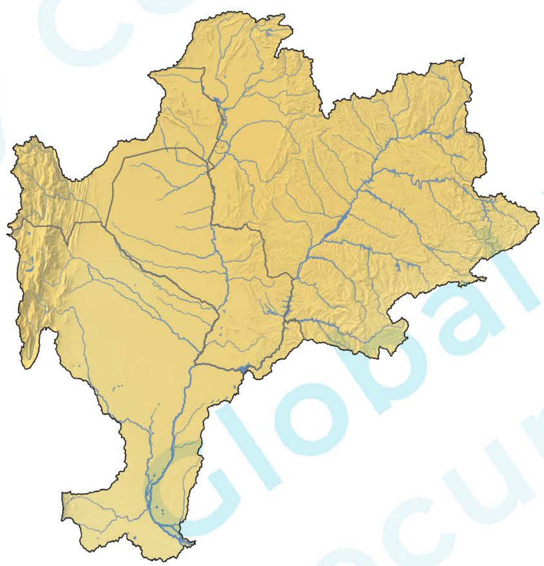
Percent difference in mean annual temperature

0 2%

(SSP245 projection period 2025-2045)

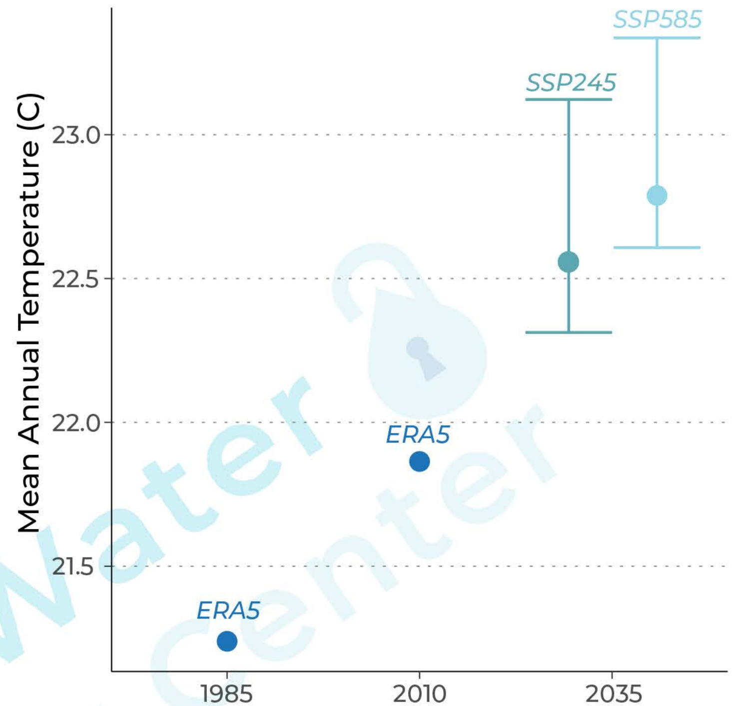


(SSP585 projection period 2025-2045)



Multidecadal temperature means compared to 1985

Projections show a significant temperature increase between 2010 and 2035.



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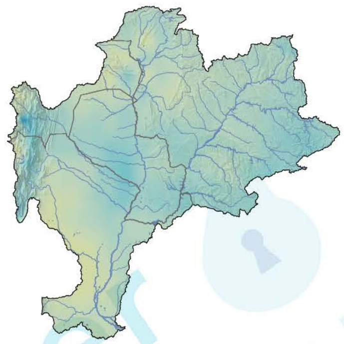
Supplemental Materials:

Mean Annual Precipitation in the Parana River Basin
CMIP6 SSP 245

CMIP6 SSP 245 and 585 show slight variations around 2035. Both are presented in this supplement for reference. For SSP 585, see the following page.

Percent change in precipitation 2035 (averaged across three sets of CMIP6 models) as projected by SSP 245.

Mean annual precipitation 2010 (mm)
(reference period 2000-2020)

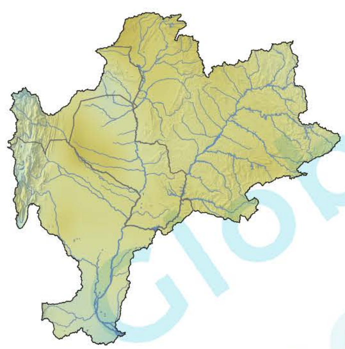


WET

High mean annual rainfall ensemble

MID

Medium mean annual rainfall ensemble

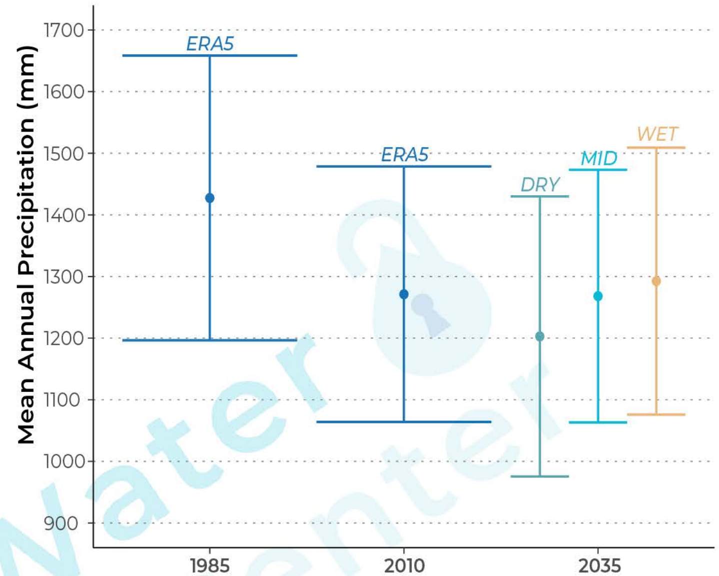


DRY

Low mean annual rainfall ensemble

Multidecadal precipitation means compared to 1985

No projection shows an increase in rainfall in line with the wet decades around 1985.



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Supplemental Materials:

Mean Annual Precipitation in the Parana River Basin
CMIP6 SSP 585

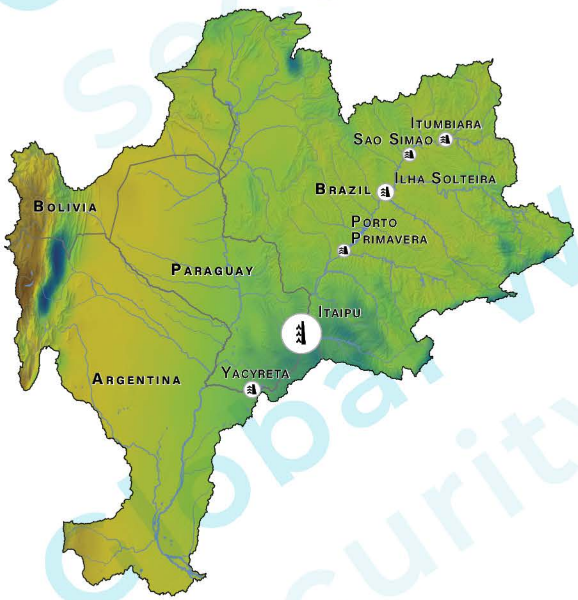
CMIP6 SSP 245 and 585 show slight variations around 2035. Both are presented in this supplement for reference. For SSP 585, see the previous page.

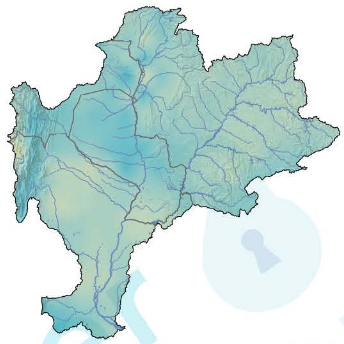
Percent change in precipitation 2035 (averaged across three sets of CMIP6 models) as projected by SSP 585.

-25% 25%

Mean annual precipitation 2010 (mm)
(reference period 2000-2020)

250mm 2800mm



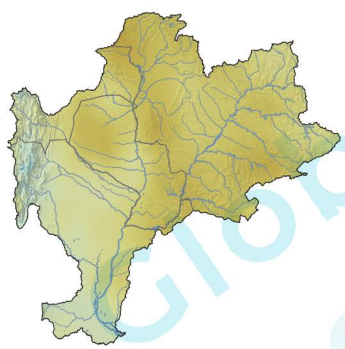


WET

High mean annual rainfall ensemble

MID

Medium mean annual rainfall ensemble

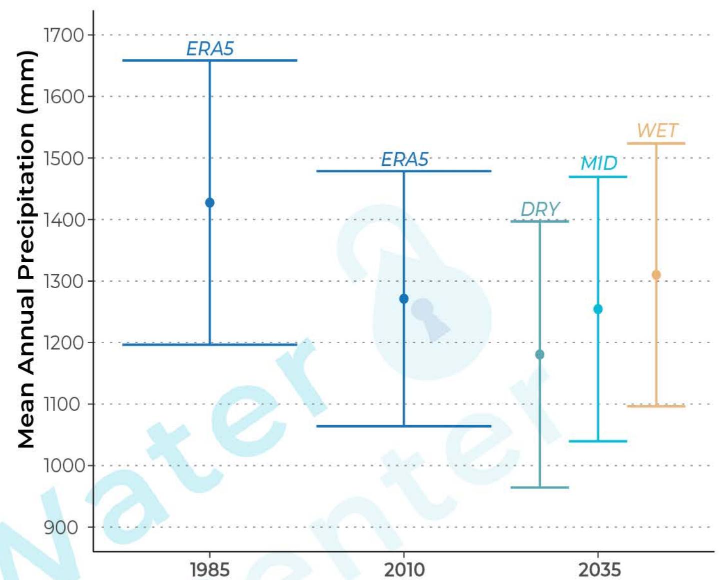


DRY

Low mean annual rainfall ensemble

Multidecadal precipitation means compared to 1985

No projection shows an increase in rainfall in line with the wet decades around 1985.



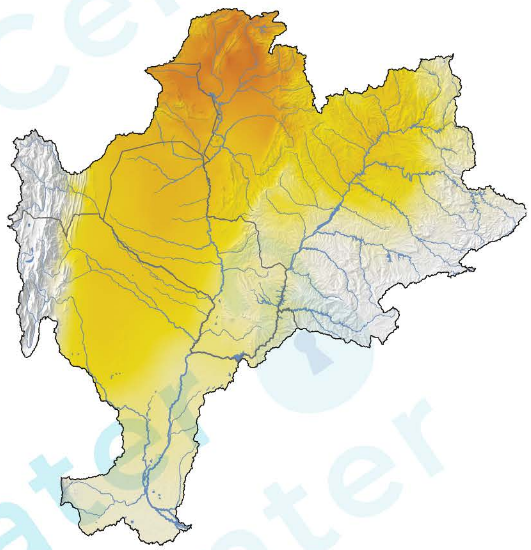
Supplemental Materials:

Annual 5-Day Heatwaves >35°C in the Parana River Basin

Percent Change in Annual Frequency of 5-day heatwaves

0 20%

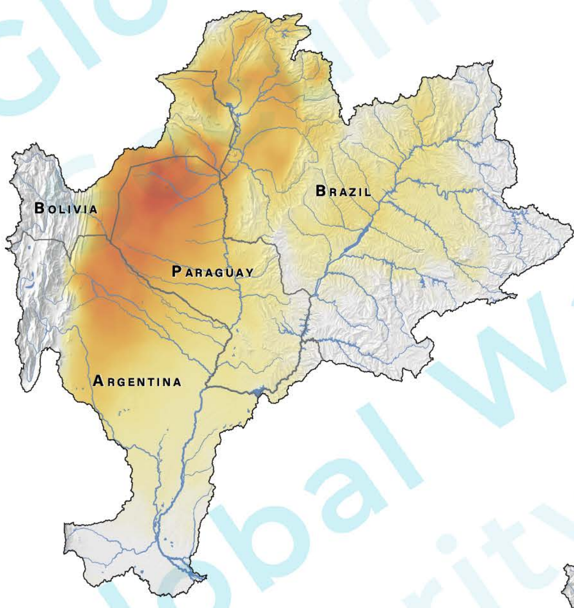
(SSP245 projection period 2025-2045)



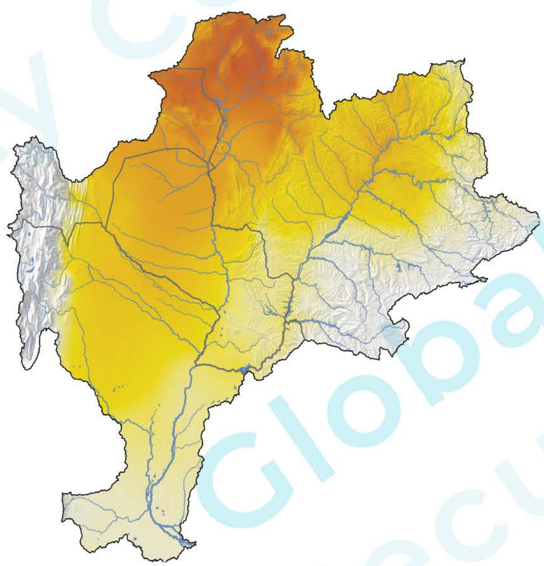
Annual frequency of 5-day heatwaves >35°C in 2010 and 2035

0 20

(reference period 2000-2020)

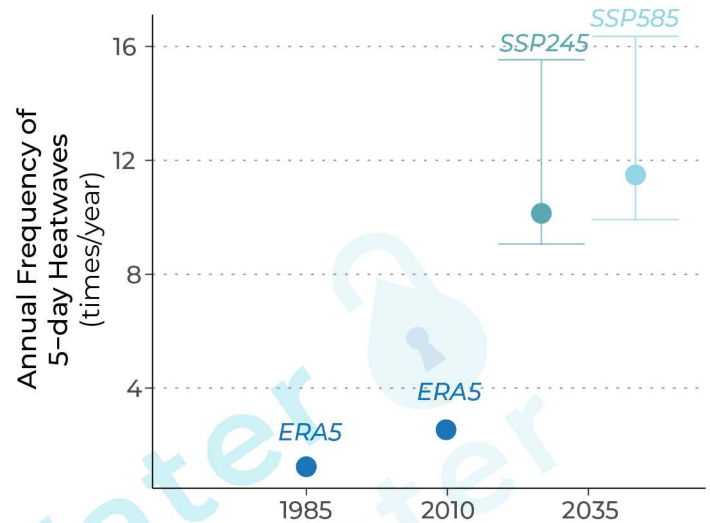


(SSP585 projection period 2025-2045)



Multidecadal heatwave means compared to 1985

Projections show a significant increase in the number of heatwaves between 2010 and 2035.



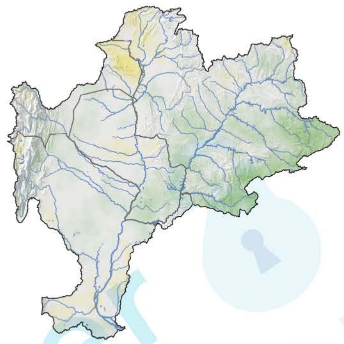
Supplemental Materials:

Annual 7-Day Dry Spells in the Parana River Basin CMIP6 SSP 245

CMIP6 SSP 245 and 585 show slight variations around 2035. Both are presented in this supplement for reference. For SSP 585, see the following page.

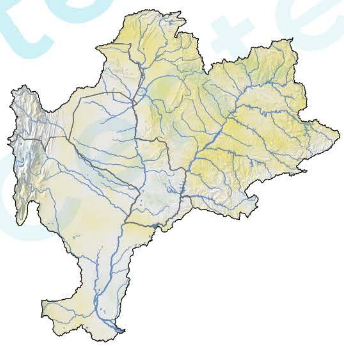
Number of 7-day dry spells 2010
(reference period 2000-2020)

Change in number of 7-day dry spells 2035 (averaged across three sets of CMIP6 models) as projected by SSP245.



WET

High mean annual rainfall ensemble



MID

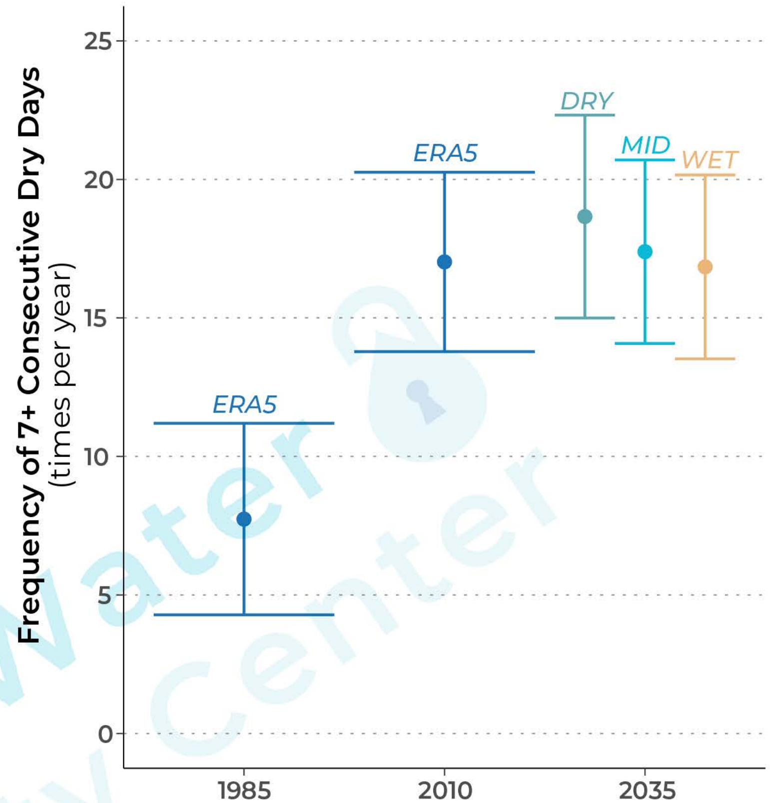
Medium mean annual rainfall ensemble

DRY

Low mean annual rainfall ensemble

Multidecadal dry spell means compared to 1985

Projections show a significant increase in the number of dry spells between 2010 and 2035.



Supplemental Materials:

Annual 7-Day Dry Spells in the Parana River Basin CMIP6 SSP 585

CMIP6 SSP 245 and 585 show slight variations around 2035. Both are presented in this supplement for reference. For SSP 245, see the previous page.

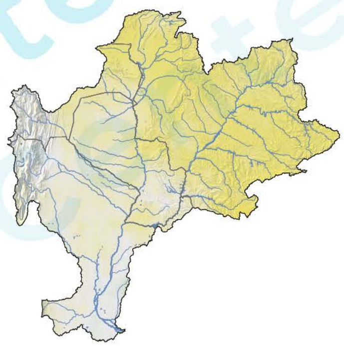
Number of 7-day dry spells 2010
(reference period 2000-2020)

Change in number of 7-day dry spells 2035 (averaged across three sets of CMIP6 models) as projected by SSP585.

-40% 40%

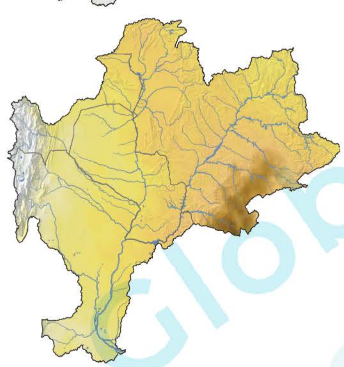
WET

High mean annual rainfall ensemble



MID

Medium mean annual rainfall ensemble



DRY

Low mean annual rainfall ensemble

Multidecadal dry spell means compared to 1985

Projections show a significant increase in the number of dry spells between 2010 and 2035.