

Supplementary Information for: Attributing observed and projected precipitation changes in Cape Town to atmospheric circulation

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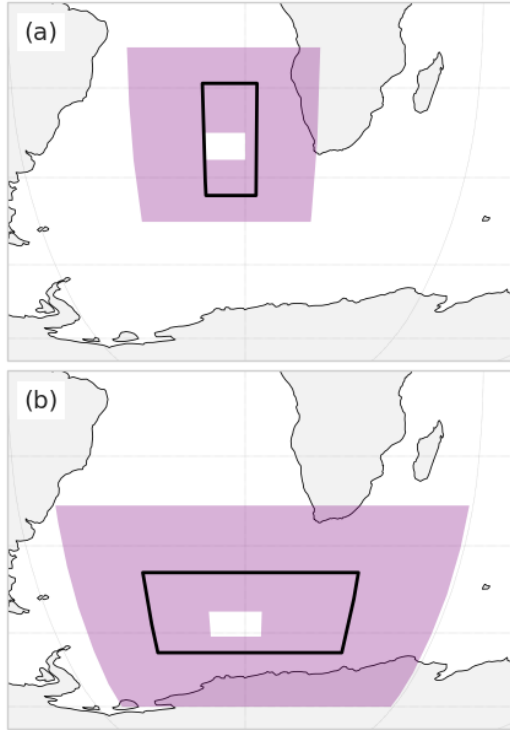
S1. Testing sensitivity of the regression model to the chosen regions

For the multi-linear regression model (MLR), we identify drivers as averages over boxes encompassing regions where zonal and meridional wind exhibit their strongest correlations with precipitation in the Southwestern Cape (SWC). To test the sensitivity of the results to the location and extent of the chosen boxes, we perform a bootstrapping sensitivity test. For this purpose, we select random latitudes and longitudes within the purple areas shown in Fig. S1 and fit a MLR model based on zonal and meridional wind averages over these random boxes. The resulting correlations between observed station precipitation and MLR reconstructed precipitation is shown in Fig. S2. Correlations in general lie within 0.4 and 0.65 for historical precipitation and in around 70% of the cases the correlation is greater than 0.55. Therefore, we conclude that sensitivity of the MLR model on the exact extent and location of the chosen boxes is small. The final boxes are chosen to optimize the regression coefficient of the MLR modelled and observed precipitation.

S2. Relationship of SWC precipitation and remote drivers

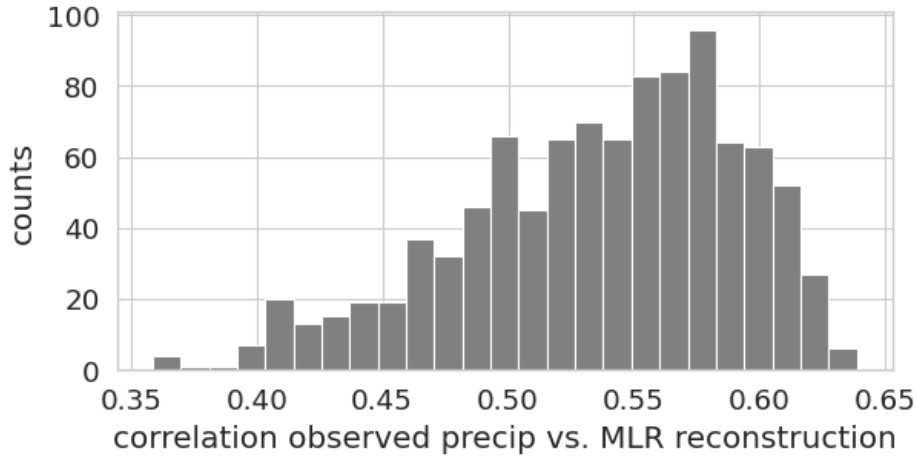
In the following, the correlations between several remote drivers and precipitation in the SWC observed by rainfall stations (pr_station) are shown, as well as the correlations between these drivers and the precipitation not explained by the MLR (pr_residual). The following definitions for remote drivers are used:

- **GMT**: Global mean temperature.
- **SAM**: Southern Annular Mode: Difference between zonal mean sea level pressure at 45°S and 60°S.
- **SST**: Mean sea surface temperatures in 70°E and 40°E and 30°S and 50°S.
- **CT_SST**: SSTs close to the coast of the SWC (in 5°W and 20°W and 20°S and 30°S).
- **pv**: Stratospheric polar vortex strength (zonal mean wind strength at 60°N, 50 hPa).
- **slp**: local sea level pressure (slp) anomalies (mean slp in 0°W to 20°W and 30°S to 45°S).



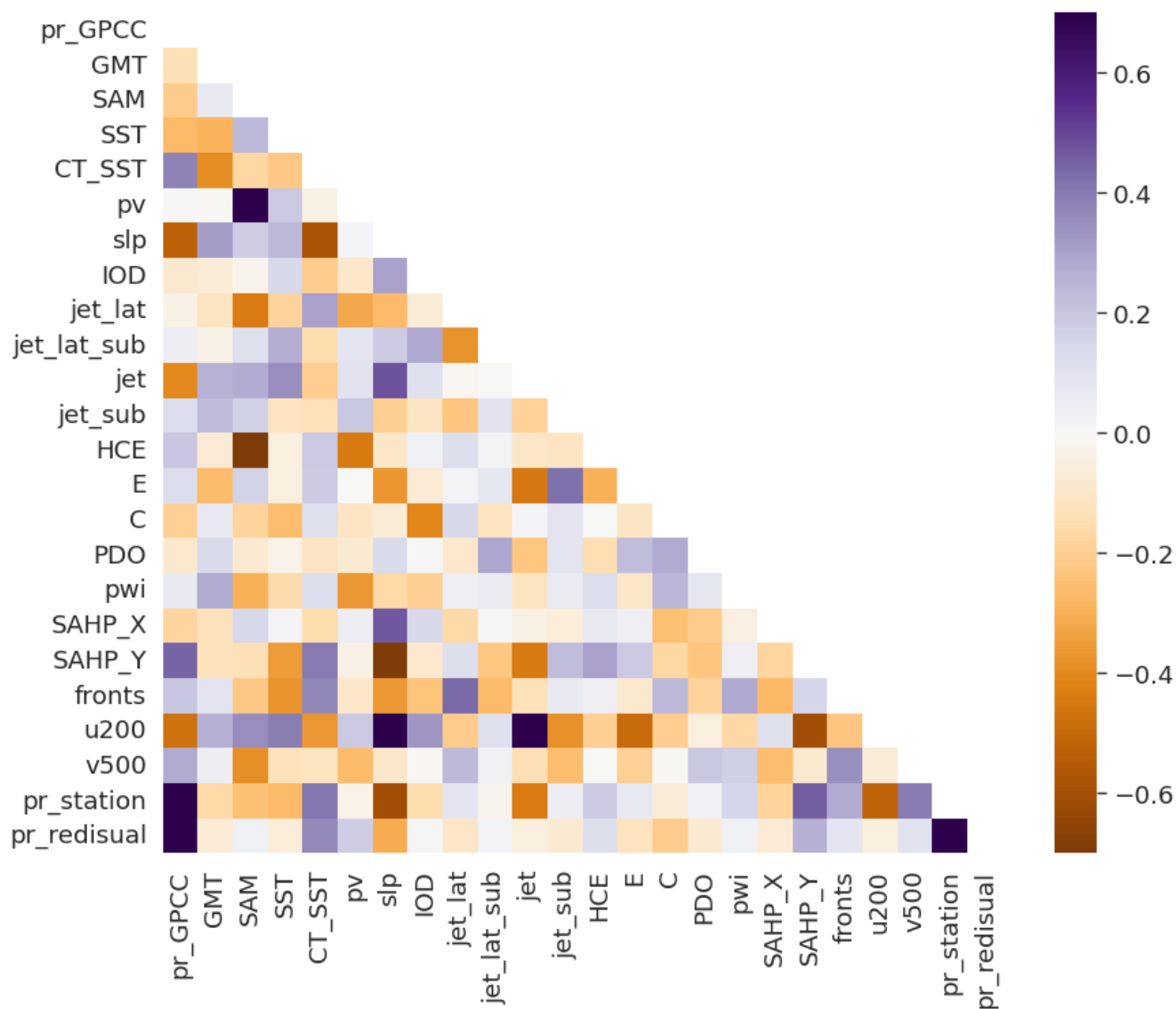
SI Figure S1. Extent of regions used to tune and test the sensitivity of the MLR model. Purple areas show the possible maximum and minimum extent of the boxes for zonal (a) and meridional (b) wind used for tuning and sensitivity testing of the MLR model. Black boxes are the final boxes used in the MLR model.

- **IOD**: Indian Ocean Dipole: difference between SSTs in the west and east Indian ocean, defined by 50°E to 70°E and 10°S to 10°N, and 90°E to 110°E and 10°S to 0°S.
- **jet_lat**: latitude of the eddy-driven jet within 50°E to 50°W, defined by the location of the maximum wind speed between 35 to 70°S at 850 hPa.
- 25 – **jet_lat_sub**: latitude of the subtropical jet within 0 to 20°W, defined by the location of the maximum wind speed between 20 to 40°S at 200 hPa.
- **jet**: strength of the eddy-driven jet, defined by wind speed at the respective jet latitude.
- **jet_sub**: strength of the subtropical jet, defined by wind speed at the respective jet latitude.
- **HCE**: Hadley cell edge: latitude where zonal mean zonal winds at 1000 hPa change sign from easterly to westerly (?).



SI Figure S2. Sensitivity test for the MLR model. Distribution of the possible correlations between observed (station) and MLR reconstructed precipitation following a bootstrapping sensitivity test with random regions within the purple areas of Fig. S1.

- 30 – **E and C**: East and Central Pacific El Niño Southern Oscillation (ENSO) index derived by combining the first two modes of the empirical orthogonal functions (EOFs) of monthly mean SSTs in the tropical Pacific ((15°S – 15°N, 140°E – 80°W) as in Geng et al. (2022).
- **PDO**: Pacific Decadal Oscillation defined as the leading EOF of SSTs in the North Pacific (110°W to 260°W and 20°N to 70°N) (Mantua et al., 1997).
- 35 – **pwi**: Southern Hemisphere planetary wave index derived from the wave envelope on meridional wind at 500hPa, as described in Irving and Simmonds (2015).
- **SAHP_X** and **SAHP_Y**: zonal and meridional location of the South Atlantic High pressure system. Data is taken from Quagraine et al. (2024), who defined the South Atlantic High pressure system as "the contiguous area around the maximum pressure, and the SAHP index is computed as the weighted centroid of the selected contiguous area around the
- 40 maximum pressure" (Quagraine et al., 2024).
- **fronts**: number of fronts reaching the coast of the SWC (defined as 17°W and 33.25°S to 35.25°S). The fronts have been detected with the wind algorithm as described and used by Burls et al. (2019).
- **v500**: meridional wind driver used in our MLR model (average over box shown in Fig. 2 c in the main text).
- **u200**: zonal wind driver used in our MLR model (average over box shown in Fig. 2 a in the main text).

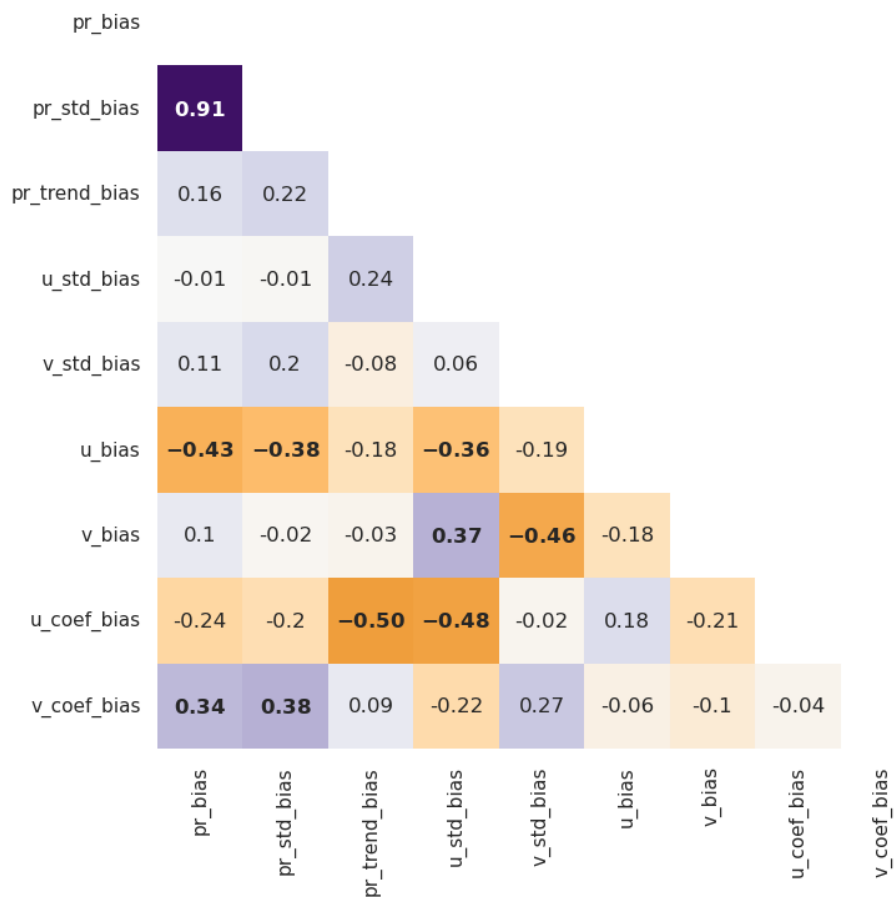


SI Figure S3. Correlations of SWC precipitation and remote drivers. Correlations are calculated based on extended winter (AMJJAS) averages from 1979 – 2017 in ERA5 and precipitation station data.

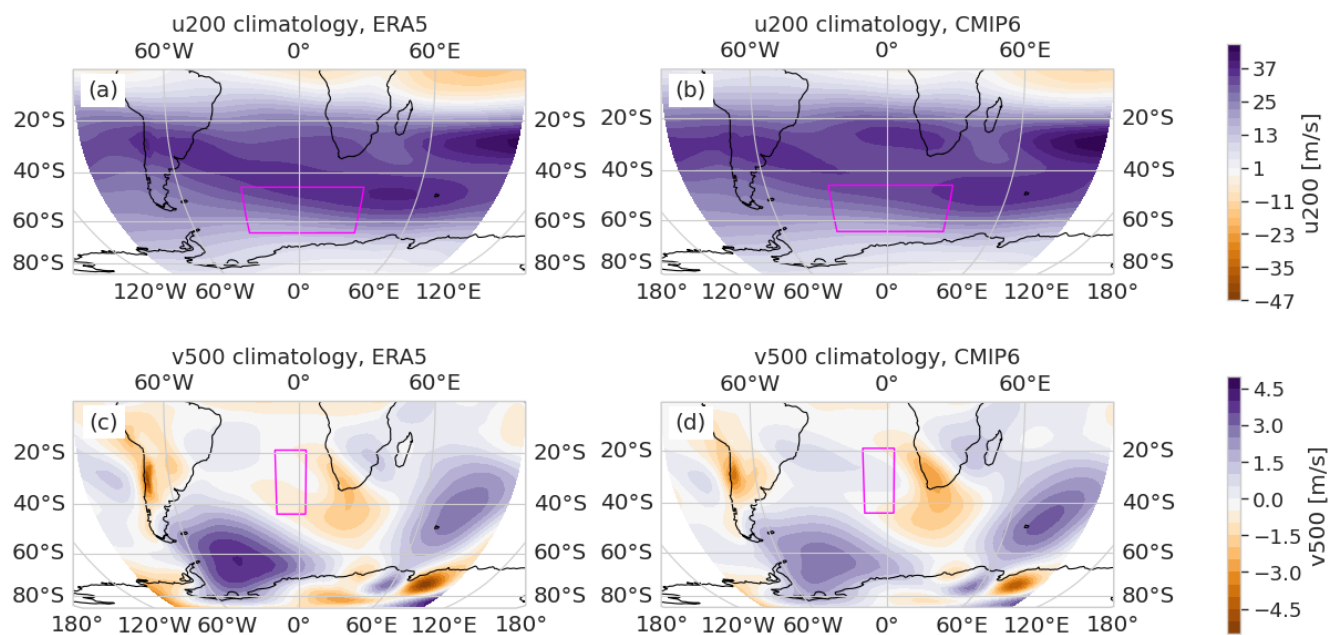
SI Table S1. CMIP6 models used in the analysis, including ensemble size and nominal horizontal resolution. For all models, historical simulations and scenario simulations for the SSP5-8.5 scenario are analysed.

Model	Ensemble members	Nominal resolution [km]
ACCESS-CM2	10	250
ACCESS-ESM1-5	10	250
BCC-CSM2-MR	1	100
CAMS-CSM1-0	2	100
CanESM5	50	500
CanESM5-1	2	500
CanESM5-CanOE	3	500
CAS-ESM2-0	2	100
CESM2	3	100
CESM2-WACCM	2	100
CIESM	1	100
CMCC-CM2-SR5	1	100
CMCC-ESM2	1	250
CNRM-CM6-1	6	250
CNRM-ESM2-1	5	250
E3SM-1-0	4	100
EC-Earth3	1	100
FGOALS-f3-L	1	100
FGOALS-g3	4	250
GISS-E2-1-G	14	250
GISS-E2-1-H	10	250
GISS-E2-2-G	5	250
HadGEM3-GC31-LL	4	250
HadGEM3-GC31-MM	4	100
IITM-ESM	1	250
INM-CM4-8	1	100
INM-CM5-0	1	100
KACE-1-0-G	3	250
MCM-UA-1-0	1	250
MIROC-ES2L	10	500
MIROC6	50	250
MPI-ESM1-2-LR	50	250
MRI-ESM2-0	5	100
NESM3	2	250
NorESM2-LM	1	250
NorESM2-MM	1	100
UKESM1-0-LL	5	250

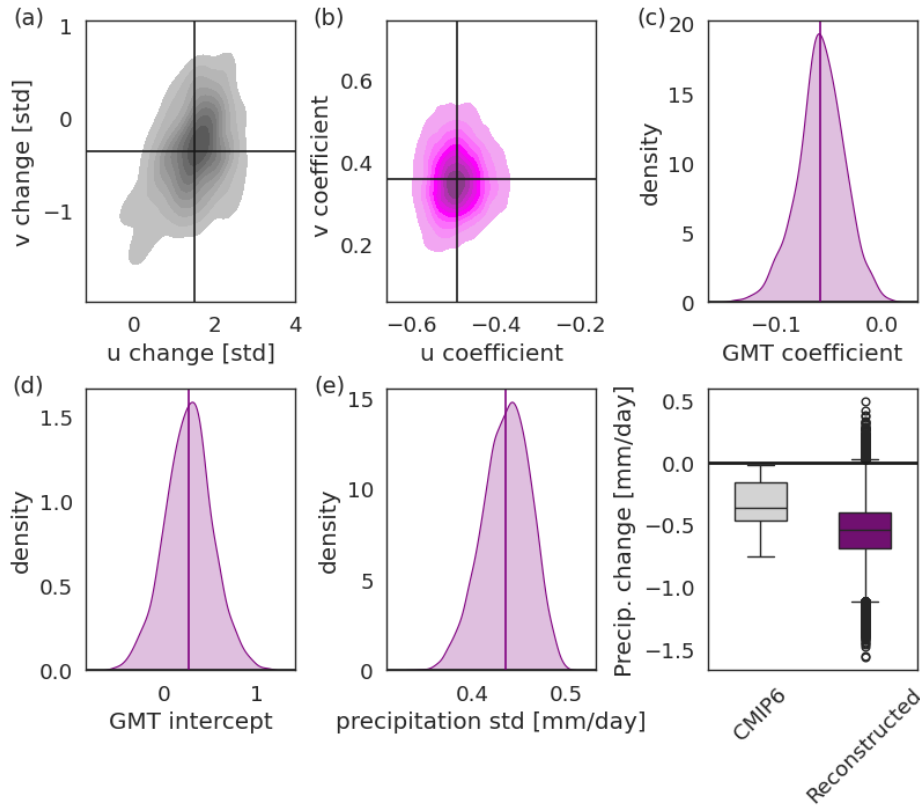
S4. Additional Figures



SI Figure S4. Relating biases in large-scale dynamics to precipitation. Correlations between biases in precipitation climatology (pr_bias), precipitation standard deviation (pr_std_bias), and trend (pr_trend), and climatologies (u_bias, v_bias), standard deviations (u_std_bias, v_std_bias), and MLR coefficients (u_coef_bias, v_coef_bias) of the two large-scale drivers evaluated for the reference period (1979 – 2023). Correlations that are significant on a 95% level are marked in bold. Colors indicate the strength of the correlation.



SI Figure S5. Climatologies of zonal and meridional wind in CMIP6 and ERA5. Zonal wind at 200 hPa (a, b) and meridional wind at 500 hPa (c, d) in ERA5 (left column) and CMIP6 multi-model mean (right column) for the reference period (1979 – 2023).



SI Figure S6. Illustration of dynamical MLR reconstruction including bootstrapping. End-of-century changes in the two drivers u200 and v500 for all models and all ensemble members (a), possible regression coefficients for u200 and v500 based on ERA5 and station rainfall observations derived via bootstrapping (b), uncertainties in the derived GMT coefficient (c) and intercept (d), and uncertainties in observed precipitation variability (e). The grey distribution in (f) shows the precipitation change as modeled by CMIP6 models. The purple distribution is the MLR reconstruction of precipitation changes following a bootstrapping approach (1000 samples) constructed by randomly sampling drivers from (a), coefficients and intercept from (b), (c), and (d), and observed precipitation standard deviation from (e).

S5. Influence of the location of the chosen boxes on model biases in the coefficients

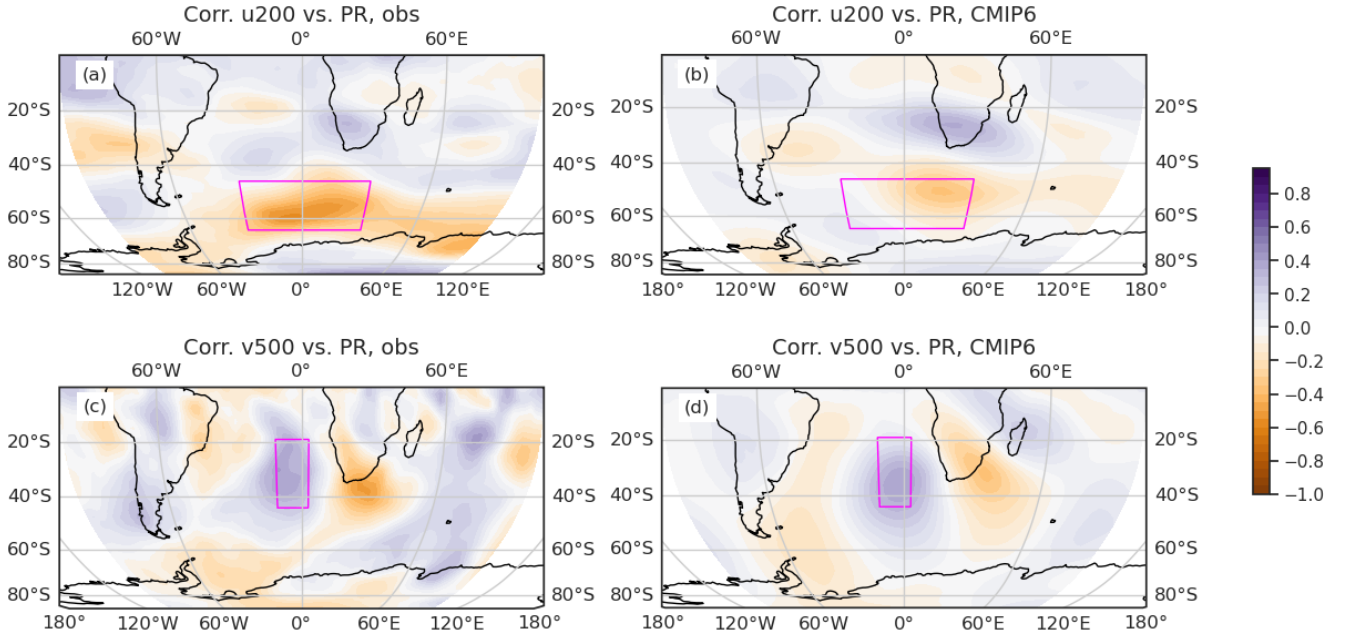
Since the boxes used for the calculation of regression indices are fixed in space, biases in the resulting coefficients might indicate that the chosen boxes might not adequately represent the location of large-scale drivers in the models. Therefore, in the following, we compare the full correlation patterns between precipitation and u200 and v500 in observations and models. This analysis yet again reveals a clear equatorward displacement of the jet stream in the models relative to observations (SI Fig. 7b). Moreover, correlation coefficients are generally weaker in the models than in observations, even after accounting for the positional bias of the westerlies, indicating systematically weaker relationships between zonal wind variability and precipitation in the models – independent of the location of the box. For the meridional wind component, in contrast, the models capture both the relevant regions and their associated links with precipitation comparatively well. Hence, the location of the chosen box

also represents the region with the strongest link between meridional wind and precipitation in the models. To further quantify model performance, we compute pattern correlations between observed and modeled zonal and meridional wind–precipitation patterns and calculate the mean pattern correlation across both wind components. Pattern correlations are calculated across the observed (X) and modeled (Y) correlation patterns for each wind component individually, applying weights according to the cosine of latitude (ω_i):

$$\text{corr}(X, Y) = \frac{\sum_{i=1}^N \omega_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^N \omega_i (x_i - \bar{x})^2 \sum_{i=1}^N \omega_i (y_i - \bar{y})^2}} \quad (1)$$

with x_i and y_i being the observed and modeled correlations at the grid cell i , $\bar{x}$ and $\bar{y}$ the mean observed and modeled correlation throughout the region and N the number of grid cells in the region. The pattern correlation is calculated in the region -90 to 0°N and -100 to 100°W.

The pattern correlations for u200 and v500 exhibit only a weak and non-significant relationship with biases in simulated precipitation climatology and variability (all correlation coefficients are smaller than 0.29), suggesting that it is less effective at explaining model biases in precipitation than the MLR coefficients and climatological biases.



SI Figure S7. Correlations of meridional as well as zonal wind and precipitation in CMIP6 models. (a) and (c) as in Fig. 2 (a) and (c). (b) and (d) show the multi-model mean correlation patterns between zonal (b) and meridional (d) wind and precipitation in the SWC in CMIP6 models.

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