Supplement of Earth Syst. Dynam., 12, 17–35, 2021
https://doi.org/10.5194/esd-12-17-2021-supplement

Earth System Dynamics
Open Access

Supplement of

Impact of precipitation and increasing temperatures on drought trends in eastern Africa

Sarah F. Kew et al.

Correspondence to: Sarah F. Kew (sarah.kew@knmi.nl)

1 Data project and model descriptions

The reanalysis and model data are obtained from different projects. A brief description of these projects and models is given below, see the references herein for more details.

CLM

The Community Land Model version 4 (CLM, Lawrence et al. (2011); Oleson et al. (2010)) was forced with 6-hourly atmospheric forcing from two datasets. Once with raw ERA-Interim data (CLM-ERA-I) and once with bias-corrected ERA-Interim data from the Water and Global Change (WATCH) project (CLM-WFDEI); i.e., the WATCH-Forcing-Data-ERA-Interim (WFDEI Weedon et al., 2014) . CLM is the land component of the Community Earth System Model and has 10 hydrologically active soil layers of exponentially increasing thickness and a groundwater module.

RefET

The daily reference ET (RefET Hobbins et al., 2018)) used in this study was generated by the US National Oceanic and Atmospheric Administration from hourly drivers provided by the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) of the US National Aeronautics and Space Administration (NASA) Global Modeling and Assimilation Office (GMAO). Hourly MERRA-2 drivers for 2-m air temperature, 2-m specific humidity, surface pressure, 2-m wind speeds, and downwelling shortwave radiation at the surface were aggregated to daily input to the American Society of Civil Engineers Standardized Reference ET Equation [Allen et al. (2005); identical to the international standard FAO-56 report (Allen et al., 1998) at the daily timescale] for a 0.12-m short grass reference crop. The reference ET data are available daily from January 1, 1980 to within a few weeks of the present at a resolution of 0.125°, which was downscaled from the native MERRA2 resolution of 0.5°latitude × 0.625°longitude (https://www.esrl.noaa.gov/psd/eddi/globalrefet/).

ISIMIP

Within the second phase of the Inter-Sectoral Impact Model Intercomparison project (ISIMIP2 Gosling et al., 2019), global hydrological models are used for intercomparison of climate impacts. The model simulations use input from GCMs or observations, e.g., precipitation and PET. For more details on the ISIMIP project, please refer to Warszawski et al. (2014) and Rosenzweig et al. (2017). We used modelled soil moisture (0.5°× 0.5°spatial resolution) for the period 1850/1861–2018 from four global hydrological models: H08 (Hanasaki et al., 2008a, b), LPJmL (Bondeau et al., 2007; Rost et al., 2008; Schaphoff et al., 2013), PCR-GLOBWB (van Beek et al., 2011; Wada et al., 2011, 2014) and WaterGAP2 (Müller Schmied et al., 2016). The GCMs used are GFDL-ESM2M (GFDL, Dunne et al., 2012, 2013), HadGEM2-ES (HadGEM, Jones et al., 2011), MIROC5 (MIROC, Watanabe et al., 2010), IPSL-CM5A-LR (IPSL, Dufresne et al., 2013). All simulations were carried out under the modelling framework of phase 2b of the ISIMIP Project (ISIMIP2b: Frieler et al., 2017, https://www.isimip.org/protocol/#isimip2b). For the ISIMIP models we also have access to the adjusted (i.e., bias corrected for the ISIMIP project) GCM data that is used as input for the hydrological models (see also Section 3.2 of the paper). For precipitation and temperature, the original GCM data is analysed for trends.

Weather@home

For weather@home we use the large-ensemble regional modelling approach as in (Uhe et al., 2018) employing the distributed computing framework climateprediction.net (Massey et al., 2015; Guillod et al., 2017). For this study, two large ensembles of simulations of temperature, precipitation and soil-moisture are available for the present day climate (2005–2016) and a counterfactual climate representing how conditions might have been without anthropogenic greenhouse gas and aerosol emissions for the same time-frame. Trends are calculated by dividing the difference in the variables between the present day climate and the counterfactual climate by the difference in GMST in the model in these two ensembles.

EC-Earth - PCR-GLOBWB

EC-Earth - PCR-GLOBWB has been developed using large-ensemble simulations of EC-Earth (Hazeleger et al., 2012) in combination with the PCR-GLOBWB model (Sutanudjaja et al., 2018). The EC-Earth - PCR-GLOBWB (EC-PCRGLOB) ensemble was originally developed by van der Wiel et al. (2019) to study changes in hydrological extremes.

2 Synthesis diagrams

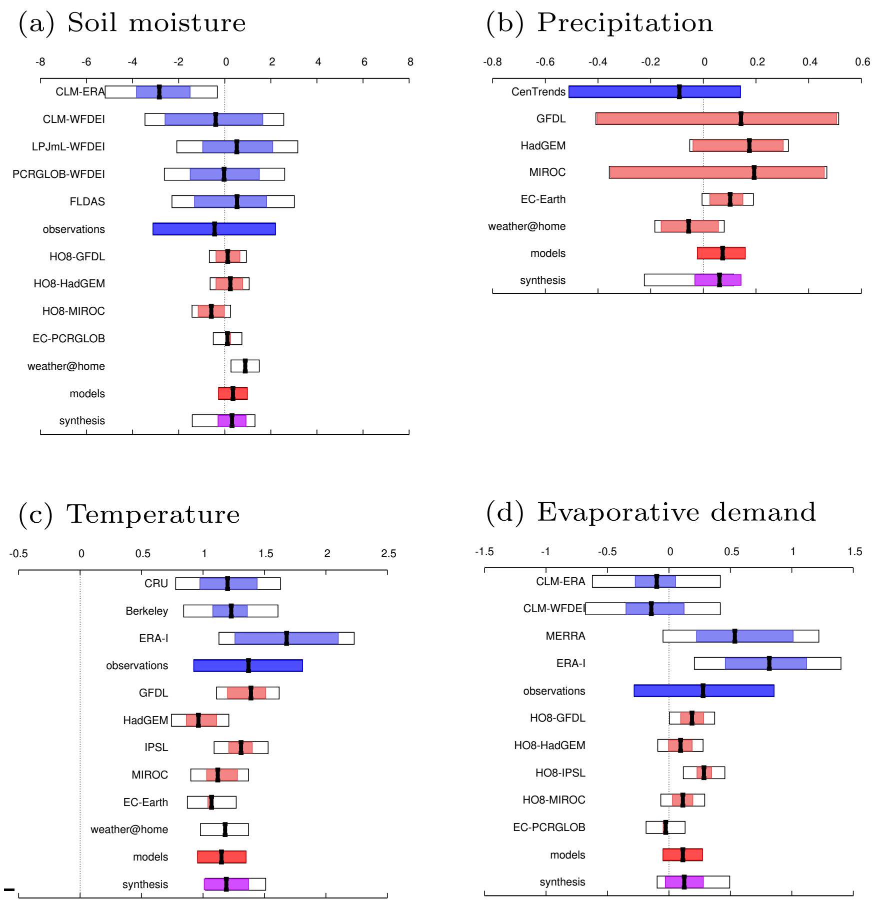

Figure S1. Synthesized values of trends per 1K GMST rise for Soil moisture [/K] (a), precipitation [mm/day/K] (b), temperature [K/K](c) and E_0 [mm/day/K] (d) for region WE. Black bars are the average trends, colored boxes denote the 95% CI. Blue represents observations and reanalyses, red represents models and magenta the weighted synthesis. Coloured bars denote natural variability, white boxes also take representativity / model errors into account if applicable (see Section on Methods). In the synthesis, the magenta bar denotes the weighted average of observations and models and the white box denotes the unweighted average. Soil moisture trends are based on standardized data, the other trends are absolute trends.

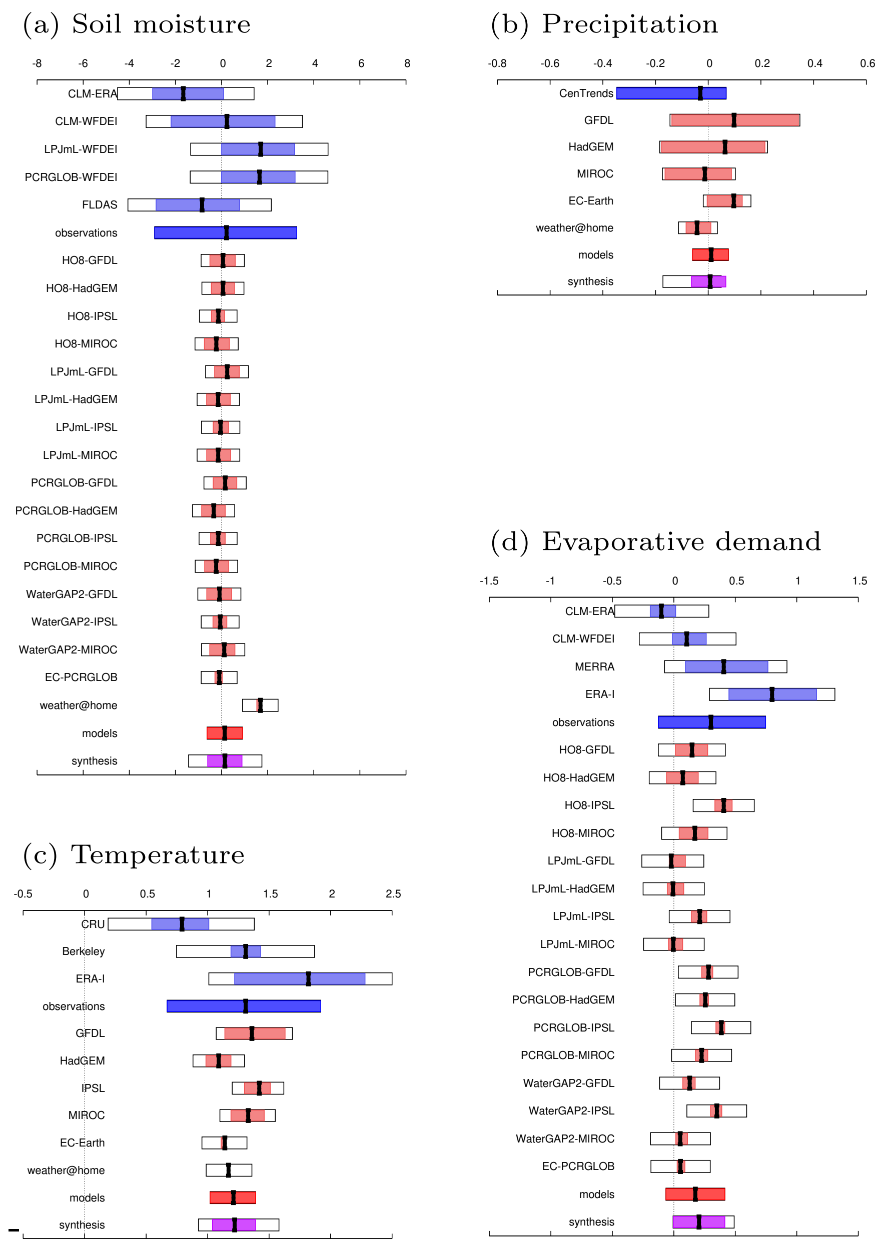

Figure S2. As for Fig. S1 but for region EE

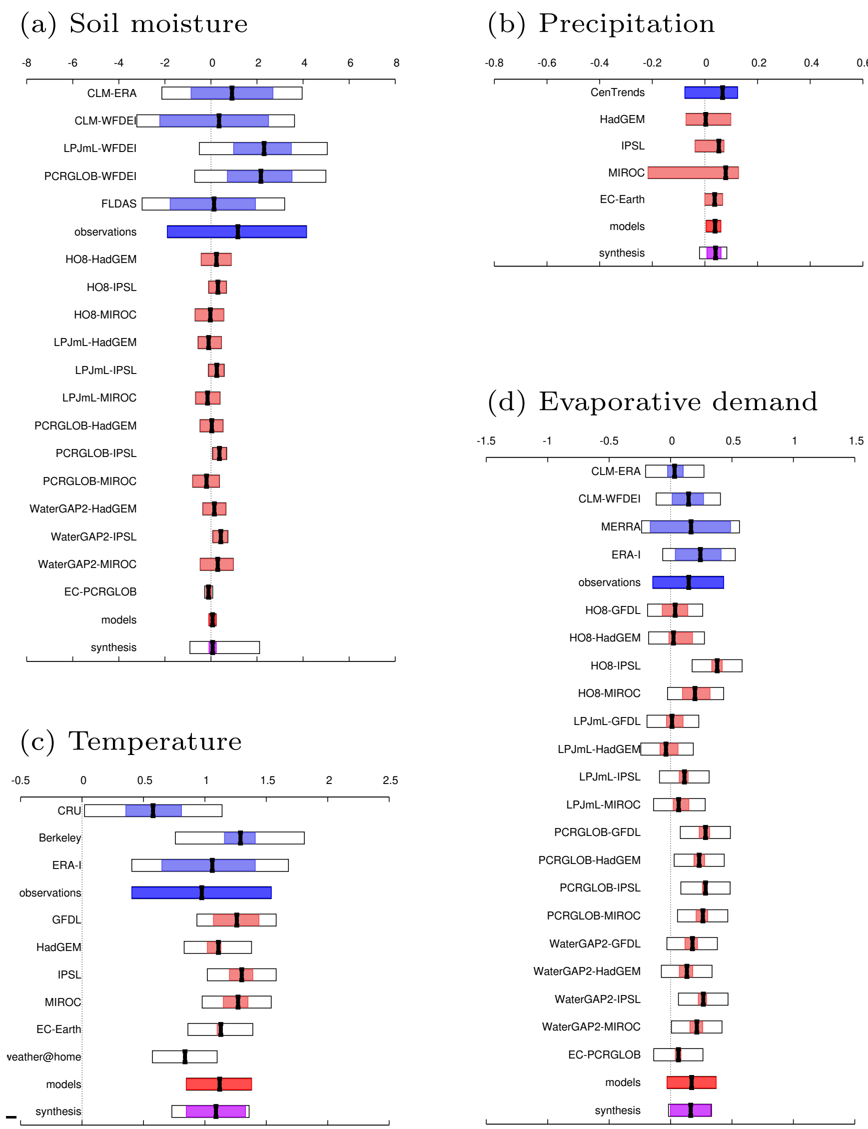

Figure S3. As for Fig. S1 but for region NS

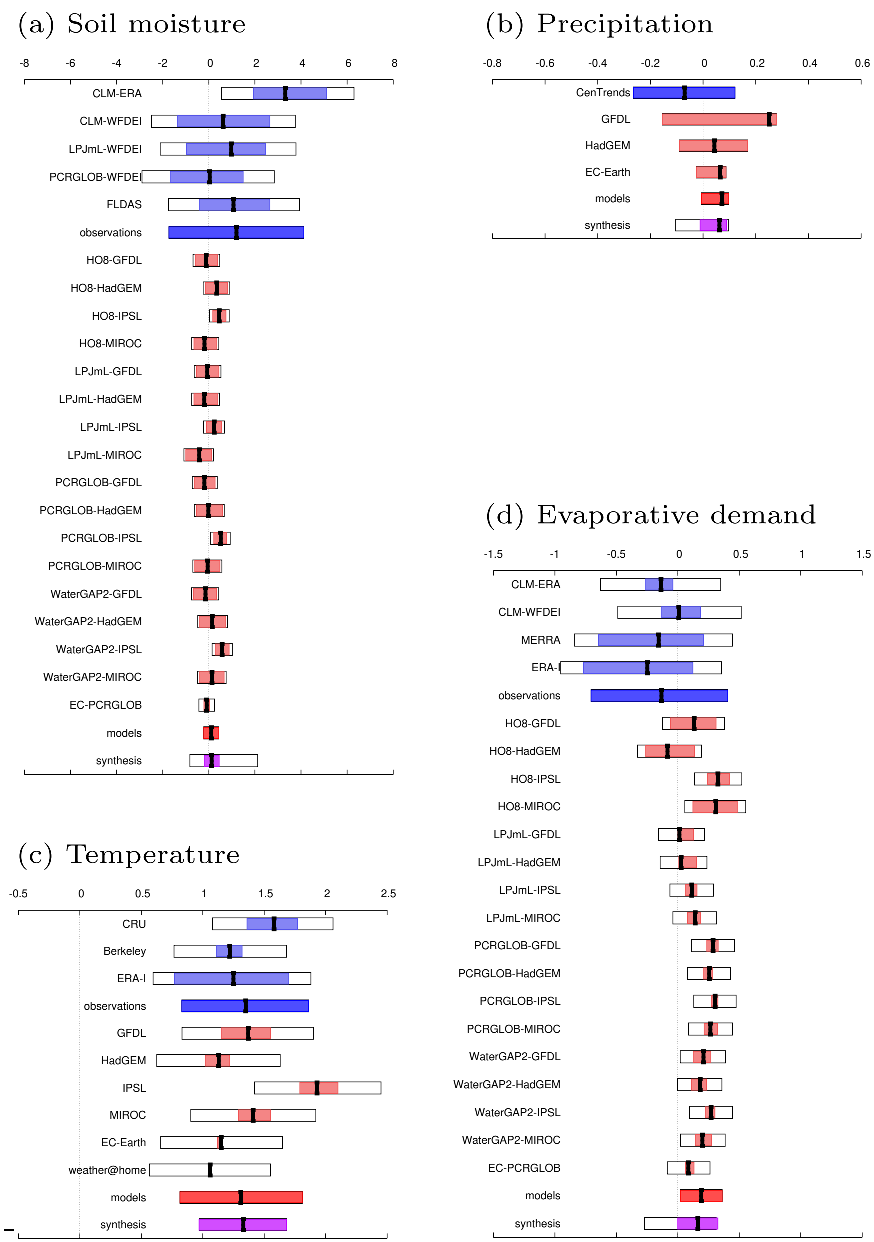

Figure S4. As for Fig. S1 but for region NK

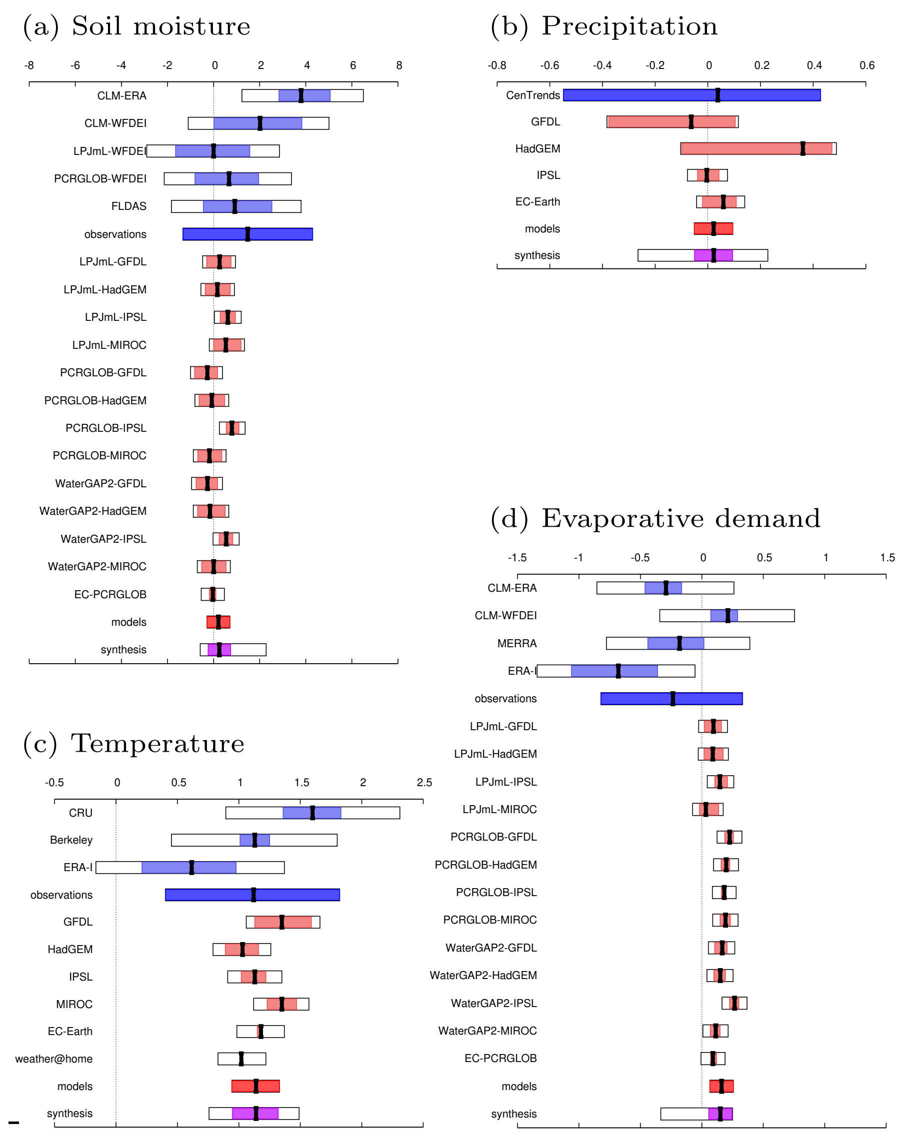

Figure S5. As for Fig. S1 but for region CK

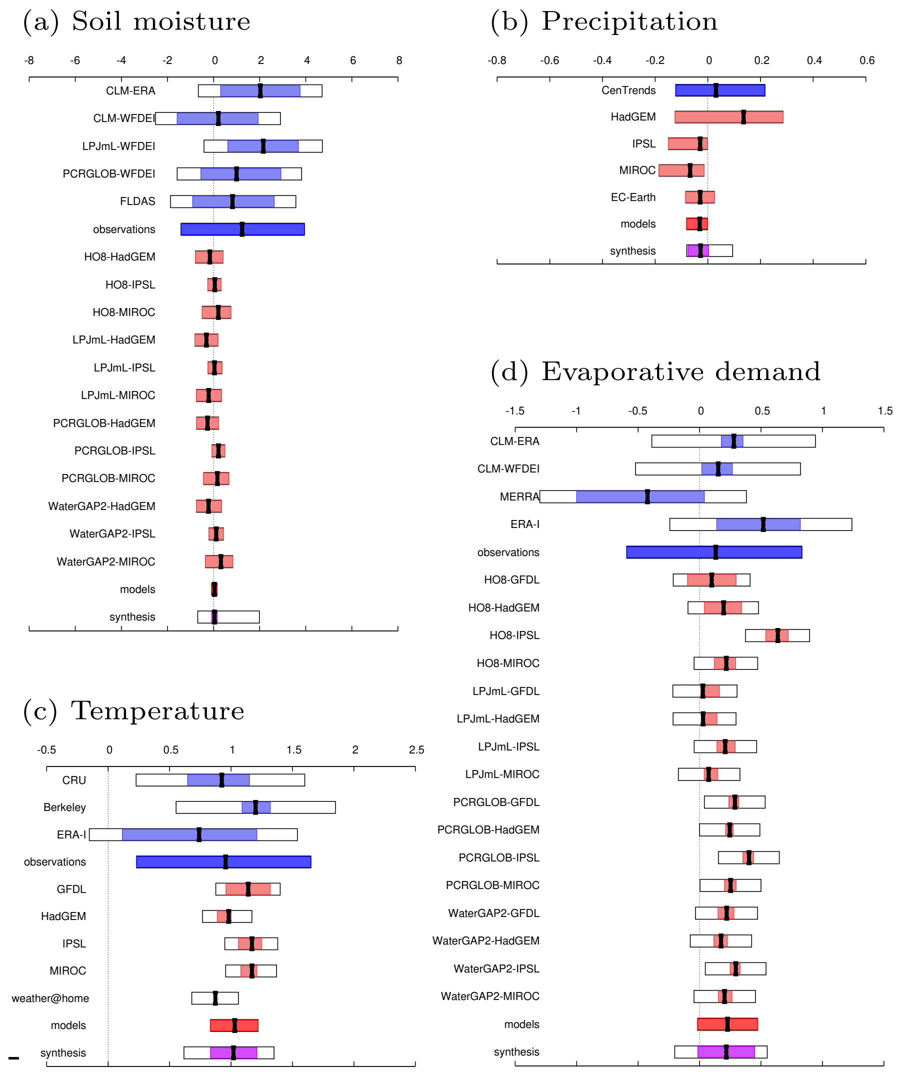

Figure S6. As for Fig. S1 but for region SS

References

Allen, R. G., Pereira, L., Raes, D., and Smith, M.: Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56, vol. 56, FAO Rome, Italy, 1998.

Allen, R. G., Walter, I. A., Elliott, R. L., Howell, T. A., Itenfisu, D., Jensen, M. E., and Snyder, R. L.: The ASCE Standardized Reference Evapotranspiration Equation, American Society of Civil Engineers, https://doi.org/10.1061/9780784408056, 2005.

Bondeau, A., Smith, P., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W.and Gerten, D., Lotze-Campen, H., Müller, C., Reichstein, M., and Smith, B.: Modelling the role of agriculture for the 20th century global terrestrial carbon balance, Global Change Biology, 13, 679–706, https://doi.org/10.1111/j.1365-2486.2006.01305.x, 2007.

Dufresne, J.-L., Foujols, M.-A., Denvil, S., Caubel, A., Marti, O., Aumont, O., Balkanski, Y., Bekki, S., Bellenger, H., Benshila, R., Bony, S., Bopp, L., Braconnot, P., Brockmann, P., Cadule, P., Cheruy, F., Codron, F., Cozic, A., Cugnet, D., de Noblet, N., Duvel, J.-P., Ethé, C., Fairhead, L., Fichefet, T., Flavoni, S., Friedlingstein, P., Grandpeix, J.-Y., Guez, L., Guilyardi, E., Hauglustaine, D., Hourdin, F., Idelkadi, A., Ghattas, J., Joussaume, S., Kageyama, M., Krinner, G., Labetoulle, S., Lahellec, A., Lefebvre, M.-P., Lefevre, F., Levy, C., Li, Z. X., Lloyd, J., Lott, F., Madec, G., Mancip, M., Marchand, M., Masson, S., Meurdesoif, Y., Mignot, J., Musat, I., Parouty, S., Polcher, J., Rio, C., Schulz, M., Swingedouw, D., Szopa, S., Talandier, C., Terray, P., Viovy, N., and Vuichard, N.: Climate change projections using the IPSL-CM5 Earth System Model: from CMIP3 to CMIP5, Climate Dynamics, 40, 2123–2165, https://doi.org/10.1007/s00382-012-1636-1, 2013.

Dunne, J. P., John, J. G., Adcroft, A. J., Griffies, S. M., Hallberg, R. W., Shevliakova, E., Stouffer, R. J., Cooke, W., Dunne, K. A., Harrison, M. J., Krasting, J. P., Malyshev, S. L., Milly, P. C. D., Phillipps, P. J., Sentman, L. T., Samuels, B. L., Spelman, M. J., Winton, M., Wittenberg, A. T., and Zadeh, N.: GFDL's ESM2 Global Coupled Climate—Carbon Earth System Models. Part I: Physical Formulation and Baseline Simulation Characteristics, Journal of Climate, 25, 6646–6665, https://doi.org/10.1175/JCLI-D-11-00560.1, 2012.

Dunne, J. P., John, J. G., Shevliakova, E., Stouffer, R. J., Krasting, J. P., Malyshev, S. L., Milly, P. C. D., Sentman, L. T., Adcroft, A. J., Cooke, W., Dunne, K. A., Griffies, S. M., Hallberg, R. W., Harrison, M. J., Levy, H., Wittenberg, A. T., Phillips, P. J., and Zadeh, N.: GFDL's ESM2 Global Coupled Climate—Carbon Earth System Models. Part II: Carbon System Formulation and Baseline Simulation Characteristics, Journal of Climate, 26, 2247–2267, https://doi.org/10.1175/JCLI-D-12-00150.1, 2013.

Frieler, K., Lange, S., Piontek, F., Reyer, C. P. O., Schewe, J., Warszawski, L., Zhao, F., Chini, L., Denvil, S., Emanuel, K., Geiger, T., Halladay, K., Hurtt, G., Mengel, M., Murakami, D., Ostberg, S., Popp, A., Riva, R., Stevanovic, M., Suzuki, T., Volkholz, J., Burke, E., Ciais, P., Ebi, K., Eddy, T. D., Elliott, J., Galbraith, E., Gosling, S. N., Hattermann, F., Hickler, T., Hinkel, J., Hof, C., Huber, V., Jägermeyr, J., Krysanova, V., Marcé, R., Müller Schmied, H., Mouratiadou, I., Pierson, D., Tittensor, D. P., Vautard, R., van Vliet, M., Biber, M. F., Betts, R. A., Bodirsky, B. L., Deryng, D., Frolking, S., Jones, C. D., Lotze, H. K., Lotze-Campen, H., Sahajpal, R., Thonicke, K., Tian, H., and Yamagata, Y.: Assessing the impacts of 1.5 °C global warming – simulation protocol of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b), Geoscientific Model Development, 10, 4321–4345, https://doi.org/10.5194/gmd-10-4321-2017, 2017.

Gosling, S., Müller Schmied, H. Betts, R., Chang, J., Ciais, P., Dankers, R., Döll, P., Eisner, S., Flörke, M., Gerten, D., Grillakis, M., Hanasaki, N., Hagemann, S., Huang, M., Huang, Z., Jerez, S., Kim, H., Koutroulis, A., Leng, G., Liu, X., Masaki, Y., Montavez, P., Morfopoulos, C., Oki, T., Papadimitriou, L., Pokhrel, Y., Portmann, F., Orth, R., Ostberg, S., Satoh, Y., Seneviratne, S., Sommer, P., Stacke, T., Tang, Q., Tsanis, I., Wada, Y., Zhou, T., Büchner, M., Schewe, J., and Zhao, F.: ISIMIP2a Simulation Data from Water (global) Sector (V. 1.1). GFZ Data Services, https://doi.org/http://doi.org/10.5880/PIK.2019.003, 2019.

Guillod, B. P., Jones, R. G., Bowery, A., Haustein, K., Massey, N. R., Mitchell, D. M., Otto, F. E. L., Sparrow, S. N., Uhe, P., Wallom, D. C. H., Wilson, S., and Allen, M. R.: weather@home 2: validation of an improved global–regional climate modelling system, Geoscientific Model Development, 10, 1849–1872, https://doi.org/10.5194/gmd-10-1849-2017, 2017.

Hanasaki, N., Kanae, S., Oki, T., Masuda, K., Motoya, K., Shirakawa, N., Shen, Y., and Tanaka, K.: An integrated model for the assessment of global water resources – Part 1: Model description and input meteorological forcing, Hydrology and Earth System Sciences, 12, 1007–1025, https://doi.org/10.5194/hess-12-1007-2008, 2008a.

Hanasaki, N., Kanae, S., Oki, T., Masuda, K., Motoya, K., Shirakawa, N., Shen, Y., and Tanaka, K.: An integrated model for the assessment of global water resources – Part 2: Applications and assessments, Hydrology and Earth System Sciences, 12, 1027–1037, https://doi.org/10.5194/hess-12-1027-2008, 2008b.

Hazeleger, W., Wang, X., Severijns, C., Ştefănescu, S., Bintanja, R., Sterl, A., Wyser, K., Semmler, T., Yang, S., Van den Hurk, B., et al.: EC-Earth V2. 2: description and validation of a new seamless earth system prediction model, Climate dynamics, 39, 2611–2629, 2012.

Hobbins, M. T., Dewes, C. F., McEvoy, D. J., Shukla, S., Harrison, L. S., Blakeley, S. L., McNally, A. L., and Verdin, J. P.: A new global reference evapotranspiration reanalysis forced by MERRA2: Opportunities for famine early warning, drought attribution, and improving drought monitoring, in: proceedings of the 98th annual meeting, American Meteorological Society Annual Meeting, Austin, TX, 2018.

Jones, C. D., Hughes, J., Bellouin, N., Hardimann, S., Jones, G., Knight, J., Liddicoat, S., O'Connor, F., Andres, R. J., Bell, C., Boo, K.-O., Bozzo, A., Butchart, N., Cadule, P., Corbin, K., Doutriaux-Boucher, M., Friedlingstein, P., Gornall, J., Gray, L., Halloran, P., Hurtt, G., Ingram, W., Lamarque, J.-F., Law, R., Meinshausen, M., Osprey, S., Palin, E. J., Parsons Chini, L., Raddatz, T., Sanderson, M. G., Sellar, A. A., Schurer, A., Valdes, P., Wood, N., Woodward, S., Yoshioka, M., and Zerroukat, M.: The HadGEM2-ES implementation of CMIP5 centennial simulations, Geosci. Model Dev., 4, 543–570, https://doi.org/10.5194/gmd-4-543-2011, 2011.

Lawrence, D. M., Oleson, K. W., Flanner, M. G., Thornton, P. E., Swenson, S. C., Lawrence, P. J., Zeng, X., Yang, Z.-L., Levis, S., Sakaguchi, K., Bonan, G. B., and Slater, A. G.: Parameterization improvements and functional and structural advances in Version 4 of the Community Land Model, Journal of Advances in Modeling Earth Systems, 3, https://doi.org/10.1029/2011MS00045, 2011.

Massey, N., Jones, R., Otto, F. E. L., Aina, T., Wilson, S., Murphy, J. M., Hassell, D., Yamazaki, Y. H., and Allen, M. R.: weather@home—development and validation of a very large ensemble modelling system for probabilistic event attribution, Quarterly Journal of the Royal Meteorological Society, 141, 1528–1545, https://doi.org/10.1002/qj.2455, 2015.

Müller Schmied, H., Adam, L., Eisner, S., Fink, G., Flörke, M., Kim, H., Oki, T., Portmann, F. T., Reinecke, R., Riedel, C., Song, Q., Zhang, J., and Döll, P.: Variations of global and continental water balance components as impacted by climate forcing uncertainty and human water use, Hydrology and Earth System Sciences, 20, 2877–2898, https://doi.org/10.5194/hess-20-2877-2016, 2016.

Oleson, K. W., Lawrence, D. M., Bonan, G. B., Flanner, M. G., Kluzek, E., Lawrence, P. J., Levis, S., Swenson, S. C., Thornton, P. E., Dai, A., Decker, M., DIckinson, R., Feddema, J., Heald, C. L., Hoffman, F., Lamarque, J. F., Mahowald, N., Niu, G., Qian, T., Randerson, J., Running, S., Sakaguchi, K., Slater, A., Stockli, R., Wang, A., Yang, Z., Zeng, X., and Zeng, X.: Technical description of version 4.0 of the Community Land Model, NCAR Technical Note 257, NCAR, https://doi.org/doi:10.5065/D6FB50WZ, 2010.

Rosenzweig, C., Arnell, N. W., Ebi, K. L., Lotze-Campen, H., Raes, F., Rapley, C., Smith, M. S., Cramer, W., Frieler, K., Reyer, C. P. O., Schewe, J., van Vuuren, D., and Warszawski, L.: Assessing inter-sectoral climate change risks: the role of ISIMIP, Environmental Research Letters, 12, 010 301, https://doi.org/10.1088/1748-9326/12/1/010301, 2017.

Rost, S., Gerten, D., Bondeau, A., Lucht, W., Rohwer, J., and Schaphoff, S.: Agricultural green and blue water consumption and its influence on the global water system, Water Resources Research, 44, https://doi.org/10.1029/2007WR006331, 2008.

Schaphoff, S., Heyder, U., Ostberg, S., Gerten, D., Heinke, J., and Lucht, W.: Contribution of permafrost soils to the global carbon budget, Environmental Research Letters, 8, 014 026, https://doi.org/10.1088/1748-9326/8/1/014026, 2013.

Sutanudjaja, E. H., van Beek, R., Wanders, N., Wada, Y., Bosmans, J. H. C., Drost, N., van der Ent, R. J., de Graaf, I. E. M., Hoch, J. M., de Jong, K., Karssenberg, D., López López, P., Peßenteiner, S., Schmitz, O., Straatsma, M. W., Vannametee, E., Wisser, D., and Bierkens, M. F. P.: PCR-GLOBWB 2: a 5 arcmin global hydrological and water resources model, Geoscientific Model Development, 11, 2429–2453, https://doi.org/10.5194/gmd-11-2429-2018, 2018.

Uhe, P., Philip, S., Kew, S., Shah, K., Kimutai, J., Mwangi, E., van Oldenborgh, G. J., Singh, R., Arrighi, J., Jjemba, E., Cullen, H., and Otto, F.: Attributing drivers of the 2016 Kenyan drought, International Journal of Climatology, 38, e554–e568, https://doi.org/10.1002/joc.5389, 2018.

van Beek, L. P. H., Wada, Y., and Bierkens, M. F. P.: Global monthly water stress: 1. Water balance and water availability, Water Resources Research, 47, https://doi.org/10.1029/2010WR009791, 2011.

van der Wiel, K., Wanders, N., Selten, F. M., and Bierkens, M. F. P.: Added Value of Large Ensemble Simulations for Assessing Extreme River Discharge in a 2° C Warmer World, Geophysical Research Letters, 46, 2093–2102, https://doi.org/10.1029/2019GL081967, 2019.

Wada, Y., van Beek, L. P. H., and Bierkens, M. F. P.: Modelling global water stress of the recent past: on the relative importance of trends in water demand and climate variability, Hydrology and Earth System Sciences, 15, 3785–3808, https://doi.org/10.5194/hess-15-3785-2011, 2011.

Wada, Y., Wisser, D., and Bierkens, M. F. P.: Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources, Earth System Dynamics, 5, 15–40, https://doi.org/10.5194/esd-5-15-2014, 2014.

Warszawski, L., Frieler, K., Huber, V., Piontek, F., Serdeczny, O., and Schewe, J.: The Inter-Sectoral Impact Model Intercomparison Project (ISI–MIP): Project framework, Proceedings of the National Academy of Sciences, 111, 3228–3232, https://doi.org/10.1073/pnas.1312330110, 2014.

Watanabe, M., Suzuki, T., O'ishi, R., Komuro, Y., Watanabe, S., Emori, S., Takemura, T., Chikira, M., Ogura, T., Sekiguchi, M., Takata, K., Yamazaki, D., Yokohata, T., Nozawa, T., Hasumi, H., Tatebe, H., and Kimoto, M.: Improved Climate Simulation by MIROC5: Mean States, Variability, and Climate Sensitivity, Journal of Climate, 23, 6312–6335, https://doi.org/10.1175/2010JCLI3679.1, 2010.

Weedon, G. P., Balsamo, G., Bellouin, N., Gomes, S., Best, M. J., and Viterbo, P.: The WFDEI meteorological forcing data set: WATCH Forcing Data methodology applied to ERA-Interim reanalysis data, Water Resources Research, 50, 7505–7514, https://doi.org/10.1002/2014WR015638, 2014.