of atmospheric coastal dynamics: current state and perspectives. *Atmosphere* **9**(9): 337.

Tebaldi C, Debeire K, Eyring V *et al*. 2021. Climate model projections from the Scenario Model Intercomparison Project (ScenarioMIP) of CMIP6. *Earth Syst. Dyn.* **12**(1): 253–293.

Thornthwaite CW. 1948. An approach toward a rational classification of climate. *Geogr. Rev.* **38**(1): 55.

Vera CS, Díaz L. 2015. Anthropogenic influence on summer precipitation trends over South America in CMIP5 models: preccipitation trends over South America in CMIP5 models. *Int. J. Climatol.* **35**(10): 3172–3177.

van der Wiel K, Matthews AJ, Stevens DP *et al*. 2015. A dynamical framework for the origin of the diagonal South Pacific and South Atlantic Convergence Zones. *Q. J. R. Meteorol. Soc.* **141**(691): 1997–2010.

Zaninelli PG, Menéndez CG, Falco M *et al*. 2019. Future hydroclimatological changes in South America based on an ensemble of regional climate models. *Clim. Dyn.* **52**(1–2): 819–830.

Correspondence to: L. van Garderen

linda.vangarderen@hereon.de

doi: 10.1002/wea.4185

The Bristol CMIP6 Data Hackathon

Dann M. Mitchell[1], Emma J. Stone[1], Oliver D. Andrews[1], Jonathan L. Bamber[1], Rory J. Bingham[1], Jo Browse[2], Matthew Henry[3], David M. MacLeod[1], Joanne M. Morten[2], Christoph A. Sauter[4], Christopher J. Smith[5,6], James Thomas[7], Stephen I. Thomson[3], Jamie D. Wilson[8] and the Bristol CMIP6 Data Hackathon Participants*

[1]*Cabot Institute for Environmental Change and Geographical Sciences, University of Bristol, Bristol, UK*

[2]*College of Life and Environmental Sciences, University of Exeter, Exeter, UK*

[3]*College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter, UK*

[4]*Civil and Environmental Engineering, University of Strathclyde, Glasgow, UK*

[5]*Priestley International Center for Climate, University of Leeds, Leeds, UK*

[6]*International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria*

[7]*Jean Golding Institute, University of Bristol, Bristol, UK*

[8]*School of Earth Sciences, University of Bristol, Bristol, UK*

*Complete CMIP6 Data Hackathon Participant list included in the online Supporting Information.

The Bristol CMIP6 Data Hackathon (BCD Hackathon; Figure 1) formed part of the Met Office Climate Data Challenge Hackathon series during 2021 (Climate Data Challenge Hackathon series, 2021), bringing together around 100 UK early career researchers (ECRs) from a wide range of environmental disciplines. The purpose was to interrogate the under-utilised climate model intercomparison project datasets to develop new research ideas and create new networks and outreach opportunities in the lead up to COP26. Experts in different science fields, supported by a core team of scientists and data specialists at Bristol, had the unique opportunity to explore together interdisciplinary environmental topics summarised in this article.

The BCD Hackathon was set up noting that data from the most advanced climate model intercomparison projection (CMIP6) was significantly under-utilised. Academics from Met Office Academic Partnership (MOAP) universities were asked to develop a research question that could employ CMIP6 data, even if they had never used that data before, with the advanced data science methods being facilitated by a core team of scientists at the University of Bristol. Centralising CMIP6 expertise meant academics from different fields could pose climate change questions that they normally would not have been able to. An overview of the BCD Hackathon projects is described below, and a companion paper (Thomas *et al*., 2022) gives a full description of how to run a data hackathon, including software and code examples.

Project 1 focused on sea level rise (SLR), one of the more certain consequences of global warming. However, predicting the amount of future SLR is complicated because

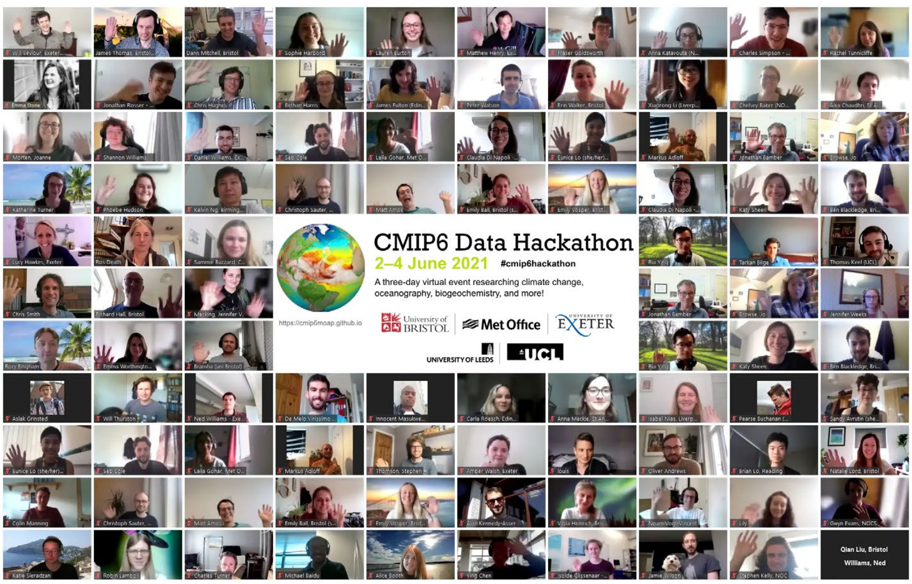

Figure 1. Group photo of the CMIP6 Data Hackathon Participants that took place virtually from 2 to 4 June 2021.

RMetS Royal Meteorological Society

multiple different parts of the climate system play a role, each of which has a different sensitivity to external forcing and a different time constant for a response. Typically, each component – glaciers, ice sheets, land hydrology and thermal expansion of sea water – has been calculated separately and summed to produce a global estimate. A different approach examines the response of sea level to a centennial change in temperature from both historical observations and climate model projections, termed the transient sea level sensitivity (TSLS). A recent study estimated the TSLS for the IPCC Fifth Assessment Report (AR5), the Special Report on the Ocean and Cryosphere in a Changing Climate and historical data (Grinsted and Christensen, 2021). Some CMIP6 projections, however, have a greater sensitivity to greenhouse gas forcings than previous climate models (e.g. Zelinka *et al*., 2020) potentially affecting the TSLS. This group investigated the TSLS of CMIP6 projections by combining their thermosteric expansion of the ocean with the latest off-line projections for the Antarctic and Greenland Ice Sheets, glaciers and ice caps (forced by CMIP6 projections). Building on the original study (Grinsted and Christensen, 2021), the group also investigated the transient response of each component of SLR, in addition to the total contribution from all components. Figure 2 shows that in the case of the Greenland Ice Sheet, the modelled response in TSLS is a quasi-linear function of temperature for the timescales investigated.

Project 2 investigated the representation of the tropical rain belt (TRB) over Africa in CMIP6 models. The TRB is a key determinant of regional climate in Africa and accurate simulation of it is essential to build confidence in future projections of regional African rainfall. However, previous generations of climate models have shown significant problems with fundamental aspects of TRB seasonality, particularly over East Africa (Tierney *et al*., 2015). This group applied the TRB detection algorithm of Nikulin and Hewitson (2019) to CMIP6 data and then used it to evaluate TRB intensity, position and width in both historical and future projections as well as decadal predictions from the Decadal Climate Prediction Project. Results showed a northward shift in the rain belt during boreal summer and the intensity of the TRB was projected to increase across nearly all models. However, more than half of models showed significant errors in reproducing historical intensity. As the TRB is highly convective, errors were likely related to unphysical parameterised convection schemes.

Project 3 was concerned with plankton living in the surface layers of the global oceans. These planktons continuously move carbon from the atmosphere to the deep ocean in the form of sinking particles of organic detritus: the 'Biological Carbon Pump' (BCP) (Passow and Carlson, 2012). The relatively fast timescale of sinking particles (days/months) versus the much longer ventilation time of ocean circulation (100–1000 years depending on depth) leads to ~1700Pg of dissolved inorganic carbon accumulating in the ocean, effectively lowering atmospheric CO_2 by ~150–250ppm beyond the concentration expected solely with physiochemical drivers (Ito and Follows, 2005). The group aimed to fully characterise the historical and future changes in the BCP predicted by CMIP6 models including the amount of organic carbon entering the ocean interior (export production), the proportion of export production sinking to the deepest ocean where it is stored for longest (transfer efficiency) and the total amount of carbon stored. All models showed that globally the BCP accumulates carbon up to 2100 likely due to warming-driven stratification such that the BCP will act as a sink for atmospheric CO_2, albeit smaller in size to other concurrent sources/sinks in the marine carbon cycle. However, there is a significant disagreement in both the magnitude and direction of changes in the projected transfer efficiency of the BCP. This reflects significant variation in which processes affecting particle sinking and degradation rates are resolved across the CMIP6 biogeochemical models. The group found evidence that this uncertainty may dictate the long-term impact of the BCP on atmospheric CO_2 beyond 2100.

Project 4 considered the Atlantic Meridional Overturning Circulation (AMOC) and the robustness of so-called AMOC proxies, which aim to determine changes in the AMOC from observations of more readily observed quantities such as sea-surface temperature (SST) and coastal sea level. Such proxies are made necessary by the relatively short record of direct and continuous AMOC observations produced by the RAPID array at 26.5°N, which do not allow for an assessment of long-term variability or elucidation of anthropogenic effects. The AMOC was calculated for over 400 CMIP6 model runs, covering the historical experiment and the Shared Socio-Economic Pathway (SSP) projection experiments: SSP1-2.6, SSP2-4.5 and SSP5-8.5. Correlation analysis examined the meridional coherence of the AMOC variability in the models as a function of timescale and tested the degree to which the variability at three key latitudes was representative of the variability at neighbouring latitudes. Sea-surface height was extracted from CMIP6 model grid points corresponding to the locations of tide-gauges along the US east coast. Analysis revealed a set of locations where the variability was well represented by a single mean time series computed from the individual time series at these locations. CMIP6 SST was averaged over several key locations in the North Atlantic to produce a set of representative temperature time series. Future work will look at the relationship between the AMOC variability and the sea-surface height and temperature time series.

Project 5 explored warming rates at high latitudes, known as polar amplification, whereby the lower atmosphere in the polar regions warms faster than the global average. The impacts that polar amplification

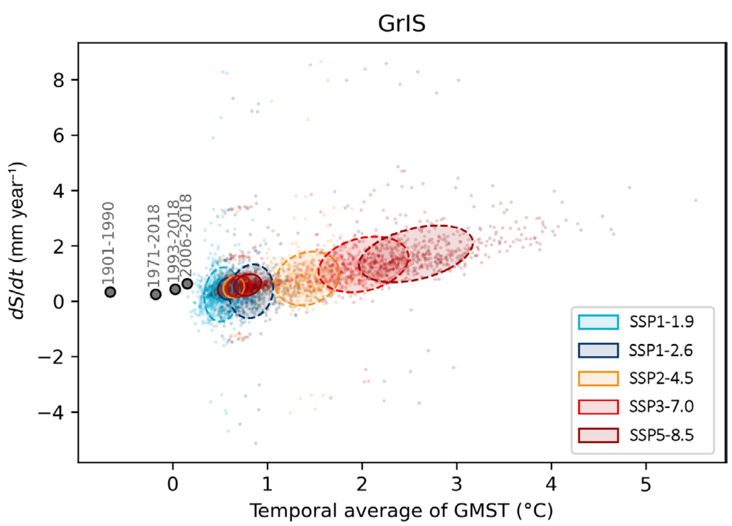

Figure 2. The transient sea level sensitivity (TSLS) of the Greenland Ice Sheet (GrIS). The coloured dots show the sea level contribution of the ice sheet in mm year^{-1} for a given mean centennial temperature change based on CMIP6 Global Circulation Model forcing and temperature change for different Shared Socio-Economic Pathways (SSPs). Also shown as grey circles are observations and historical estimates of the ice sheet response. The x-axis shows the temporal average of global mean surface temperature (GMST). The y-label (dS/dt) is the change in mean global sea-surface height per unit time, in this case a year. It is apparent that over these timescales, the modelled response is a quasi-linear function of temperature.

may have on the global climate system are not well understood. The group looked at results from the Polar Amplification Model Intercomparison Project (PAMIP) contribution to CMIP6. The PAMIP experiments prescribe sea-ice loss (a key cause of polar amplification) in a controlled way to isolate how the atmosphere responds to sea-ice loss alone, without confounding influences. The group focused on the response of the tropospheric jet streams and of the stratospheric polar vortex to both projected future Arctic and Antarctic sea-ice loss and compared these with projected changes in experiments with increased greenhouse gases. This comparison gave an indication of how relevant model uncertainty in the response to sea-ice loss is for future projections of the jet stream, and whether models that respond strongly to sea-ice loss also respond strongly to other drivers. Work is ongoing to understand how the variety in the jet stream and polar vortex responses across models are related to model errors and whether uncertainties in the responses to different drivers, such as Arctic and Antarctic sea-ice loss or greenhouse gas increases, have the same root cause.

Project 6 used the Geoengineering Model Intercomparison Project (GeoMIP) showing that simulations reduced the warming from the high-tier SSP emission scenario (SSP5-8.5) to the medium-tier SSP emission scenario (SSP2-4.5) by adding a stratospheric sulphate aerosol layer or by imposing a uniform reduction in the solar constant. While both sulphur and solar experiments have the same global mean target climate, their different ways of increasing Earth's albedo result in spatial differences in climate variables, including the extremes. The group focused on extremes in temperature and precipitation and found sulphate geoengineering to be very effective at moderating extreme day-time and night-time heat. The sulphur experiment was then compared with its target climate experiment, SSP2-4.5, to understand the trade-offs between a high emissions scenario with sulphate injection and a moderate emissions scenario. A reduction in precipitation in the tropics and winter warming of the Eurasian continent was found.

Project 8 aimed to update famous IPCC figures from AR5, using the CMIP6 data. Figures in IPCC reports, especially those in the Summaries for Policy Makers, are often densely packed and show only a narrow section of the data. This is confounded by the high dimensionality and size of climate data, which can make informative figures complex and hard to interpret. This project explored to what extent interactive features could be added to such figures to improve their accessibility to a diverse audience, making them more interesting and easier to understand for those lacking scientific computing abilities. The group explored a number of figures with different elements of interaction and two are described here:

1. A figure showing global historical and future net carbon emissions under different SSPs. This figure was enhanced by adding clickable buttons for each scenario, highlighting the corresponding carbon emission graph and displaying an info-box with further explanations for the scenario.
2. An interactive world map plot showing the temperature anomaly relative to the 1861–1890 average using SSP3-7.0 Regional Rivalry. The figure allows for the viewer to hover the mouse over individual regions providing further information for the corresponding region. It also features a slider, where the viewer can either select a specific time or choose to display all time steps as an animation.

Project 9 focused on the need to understand how species and ecosystems may respond to future climate change (e.g. Moritz and Agudo, 2013). Climate change is a major threat to global seabird populations and the most challenging to mitigate (Dias *et al*., 2019). Arctic terns, *Sterna paradisaea*, are a small seabird species that annually migrate from breeding colonies in the Arctic to overwintering areas in the Antarctic during the longest recorded migration of any animal (Egevang *et al*., 2010). Their reliance on both poles, which are experiencing the greatest impacts of global climate change (IPCC, 2007), Along with the extreme distances that arctic terns travel means that they are sensitive to more temporal and spatial variety in climate than any other species of biodiversity. By forging a collaborative link with climate scientists during the hackathon, the ecologists in the team were able to use both data and analytical approaches that would otherwise have been intractable (Figure 3). The group investigated climate-driven changes in multiple climatic variables that could affect Arctic terns during key life history stages: (1) wind support during both the south- and north-bound migration; (2) productivity at stopover areas where migrating Arctic terns refuel, and sites that overwintering Arctic terns use during the non-breeding season in the Southern Ocean and (3) sea-ice that is important for aggregating Arctic tern prey as well as providing roosting locations. Highlights include the following: under the high emission scenario (SSP5-8.5), there is a predicted poleward shift in the average easterly winds from the present day to 2080–2100, which Arctic terns use to support their westward movements whilst overwintering in Antarctica, and that primary productivity at a key stopover and refuelling site for Arctic terns in the North Atlantic is likely to decline by a third by 2081–2100 compared with the levels from 1850 to 1950.

Project 10 investigated how climate change affects human heat stress using a single metric called the Universal Thermal Climate Index (UTCI), which combines humidity, wind speed and solar radiation to describe the level of heat stress experienced by the human body (Błażejczyk *et al*., 2013). Di Napoli *et al*. (2021) used ERA5 reanalysis to produce a UTCI dataset for the present-day and recent past. This project aimed to extend this to future projections using data from CMIP6. It was found that heat

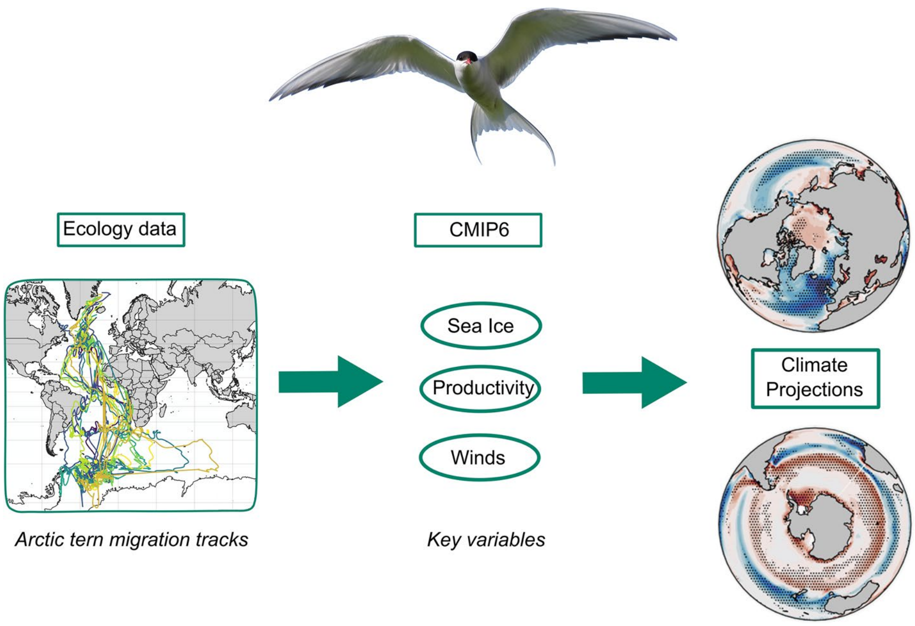

Figure 3. A schematic figure demonstrating the interdisciplinary approach to investigate the potential impacts of climate change on Arctic terns (Sterna paradisaea), a small seabird that annually undertakes the longest recorded migration. CMIP6 models were used to predict changes to key environmental variables that are likely to affect this species during their transequatorial migration and non-breeding periods in the Southern Ocean during the austral summer.

stress is generally projected to be higher in climate models that have a higher climate sensitivity (greater temperature response to the same emissions projection). One of the most striking results from the preliminary analysis was that 4% of the Earth's land surface becomes difficult to inhabit under the SSP2-4.5 scenario by 2100, whereas today, that level is close to zero. The results still need to be bias corrected using the ERA5 dataset to ensure that models agree with regional reanalysis projections of UTCI in the recent past.

The BCD Hackathon generated much interest across the UK and further afield despite being restricted to UK residents and ECRs. The interactions of interdisciplinary scientists have resulted in new networks with several projects continuing after the hackathon event. The success of the hackathon means that such an event could be considered in the future if felt to be worthwhile and of value to the community.

Acknowledgements

The 2021 Climate Data Challenge Hackathon series, including the events hosted by Met Office Academic Partnership (MOAP) universities, was supported by the Met Office. We thank the JASMIN data analysis facility and team for providing support, computing services and access to the CMIP6 and other datasets via the CEDA Archive. We are also grateful for data science and administrative support provided by the Jean Golding and Cabot Institutes, University of Bristol.

The authors have no conflicts of interest to declare.

References

Błażejczyk K, **Jendritzky G**, **Bröde P** ***et al***. 2013. An introduction to the Universal Thermal Climate Index (UTCI). *Geogr. Pol.* **86**(1): 5–10.

Climate Data Challenge Hackathon series. 2021. Met Office website. https://www.metoffice.gov.uk/weather/climate/cop/climate-data-challenge (accessed 1 December 2021).

Di Napoli C, **Barnard C**, **Prudhomme C** ***et al***. 2021. ERA5-HEAT: a global gridded historical dataset of human thermal comfort indices from climate reanalysis. *Geosci. Data J.* **8**(1): 2–10.

Dias MP, **Martin R**, **Pearmain EJ** ***et al***. 2019. Threats to seabirds: a global assessment. *Biol. Conserv.* **237**: 525–537.

Egevang C, **Stenhouse IJ**, **Phillips RA** ***et al***. 2010. Tracking of Arctic terns Sterna paradisaea reveals longest animal migration. *Proc. Natl. Acad. Sci. USA.* **107**: 2078–2081.

Grinsted A, **Christensen JH**. 2021. The transient sensitivity of sea level rise. *Ocean Sci.* **17**: 181–186.

IPCC. 2007. in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Solomon S, Qin D, Manning M *et al*. (eds). Cambridge University Press: Cambridge, UK and New York, NY.

Ito T, **Follows MJ**. 2005. Preformed phosphate, soft-tissue pump and atmospheric CO2. *J. Mar. Res.* **64**(4): 813–839.

Moritz C, **Agudo R**. 2013. The future of species under climate change: resilience or decline? *Science* **341**(6145): 504–508.

Nikulin G, **Hewitson B**. 2019. A simple set of indices describing the Tropical Rain Belt over central and southern Africa. *Atmos. Sci. Lett.* **20**(12): e946.

Passow U, **Carlson CA**. 2012. The biological pump in a high CO2 world. *Mar. Ecol. Prog. Ser.* **470**: 249–271.

Thomas J, **Stone EJ**, **Mitchell DM** ***et al***. 2022. Organising a collaborative online hackathon for cutting-edge climate research. *Weather*. **77**(6): 221–226.

Tierney JE, **Ummenhofer CC**, **Demenocal PB**. 2015. Past and future rainfall in the Horn of Africa. *Sci. Adv.* **1**(9). https://doi.org/10.1126/sciadv.1500682.

Zelinka MD, **Myers TA**, **McCoy DT** ***et al***. 2020. Causes of higher climate sensitivity in CMIP6 Models. *Geophys. Res. Lett.* **47**(1): e2019GL085782.

Supporting Information

Table S1. The CMIP6 Data Hackathon Participants

Correspondence to: D. M. Mitchell

d.m.mitchell@bristol.ac.uk

doi: 10.1002/wea.4161

Organising a collaborative online hackathon for cutting-edge climate research

James Thomas[1], Emma J. Stone[2,3], Dann M. Mitchell[2,3], William Seviour[4], Clair Barnes[5], Hannah Bloomfield[3,6], Julia Crook[7], Hayley Jones[8] and Calum MacLeod[9]

[1]*Jean Golding Institute, University of Bristol, Bristol, UK*
[2]*Cabot Institute for Environmental Change, Bristol, UK*
[3]*Geographical Sciences, University of Bristol, Bristol, UK*
[4]*Global Systems Institute and Mathematics, University of Exeter, Exeter, UK*
[5]*Statistical Science, University College London, London, UK*
[6]*Meteorology, University of Reading, Reading, UK*
[7]*Earth and Environment, University of Leeds, Leeds, UK*
[8]*Met Office, Exeter, UK*
[9]*CDT Environmental Intelligence, University of Exeter, Exeter, UK*

Introduction

Hackathons are an exciting way in which a group of people who do not usually work together can collaborate on one or more self-contained challenges over a short but concentrated period of time. They may be from separate institutions and communities, so participation also fosters the creation of new networks and possible future collaborations. Hackathons are not a new idea – they originate from the field of software engineering (Briscoe and Mulligan, 2014; OpenBSD, 2021). When used for cutting-edge research in the climate