STATE OF THE CLIMATE IN 2023

GLOBAL CLIMATE

R. J. H. Dunn, J. Blannin, N. Gobron, J. B. Miller, and K. M. Willett, Eds.

Special Online Supplement to the *Bulletin of the American Meteorological Society*, Vol. 105, No. 8, August 2024

https://doi.org/10.1175/BAMS-D-24-0116.1
Corresponding author: Robert Dunn / robert.dunn@metoffice.gov.uk

Cover Credit:
Aerial photo of smoke from wildfires in Alberta, Canada, on 5 May 2023. (Photo credit: Alberta Forestry and Parks)

How to cite this document:
Global Climate is one chapter from the *State of the Climate in 2023* annual report and is available from https://doi.org/10.1175/BAMS-D-24-0116.1. Compiled by NOAA's National Centers for Environmental Information, *State of the Climate in 2023* is based on contributions from scientists from around the world. It provides a detailed update on global climate indicators, notable weather events, and other data collected by environmental monitoring stations and instruments located on land, water, ice, and in space. The full report is available from https://doi.org/10.1175/2024BAMSStateoftheClimate.1.

Citing the complete report:
Blunden, J. and T. Boyer, Eds., 2024: "State of the Climate in 2023". *Bull. Amer. Meteor. Soc.*, **105** (8), Si–S483 https://doi.org/10.1175/2024BAMSStateoftheClimate.1.

Citing this chapter:
Dunn, R. J. H., J. Blannin, N. Gobron, J. B Miller, and K. M. Willett, Eds., 2024: Global Climate [in "State of the Climate in 2023"]. *Bull. Amer. Meteor. Soc.*, **105** (8), S12–S155, https://doi.org/10.1175/BAMS-D-24-0116.1.

Citing a section (example):
Azorin-Molina, C., R. J. H. Dunn, L. Ricciardulli, C. A. Mears, J. P. Nicolas, T. R. McVicar, Z. Zeng, and M. G. Bosilovich, 2024: Land and ocean surface winds [in "State of the Climate in 2023"]. *Bull. Amer. Meteor. Soc.*, **105** (8), S76–S79, https://doi.org/10.1175/BAMS-D-24-0116.1.

Editor and Author Affiliations (alphabetical by name)

Ades, Melanie, European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom

Adler, Robert, University of Maryland, College Park, Maryland

Alexe, Mihai, European Centre for Medium-Range Weather Forecasts, Bonn, Germany

Allan, Richard P., Department of Meteorology and National Centre for Earth Observation, University of Reading, Reading, United Kingdom

Anderson, John, Hampton University, Hampton, Virginia

Anneville, Orlane, National Research Institute for Agriculture, Food and Environment (INRAE), CARRTEL, Université Savoie Mont Blanc, Thonon les Bains, France

Aono, Yasuyuki, Graduate School of Agriculture, Osaka Metropolitan University, Sakai, Japan

Arguez, Anthony, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina

Armenteras Pascual, Dolores, Science Faculty, Universidad Nacional de Colombia, Bogotá, Colombia

Arosio, Carlo, University of Bremen, Bremen, Germany

Asher, Elizabeth, NOAA Global Monitoring Laboratory, Boulder, Colorado

Augustine, John A., NOAA Global Monitoring Laboratory, Boulder, Colorado

Azorin-Molina, Cesar, Centro de Investigaciones sobre Desertificación – Spanish National Research Council (CSIC-UV-GVA), Valencia, Spain

Baez-Villanueva, Oscar M., Hydro-Climate Extremes Lab (H-CEL), Ghent University, Ghent, Belgium

Barichivich, J., Laboratoire des Sciences du Climat et de l'Environnement (LSCE), LSCE/IPSL, CEA-CNRS-UVSQ, Gif-sur-Yvette, France; Instituto de Geografía, Pontificia Universidad Católica de Valparaíso, Valparaíso, Chile

Beck, Hylke E., Physical Science and Engineering Division, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia

Bellouin, Nicolas, University of Reading, Reading, United Kingdom; Institute Pierre Simon Laplace (IPSL), Guyancourt, France

Benedetti, Angela, European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom

Blannin, Josh, Met Office Hadley Centre, Exeter, United Kingdom

Blenkinsop, Stephen, School of Engineering, Newcastle University, Newcastle-upon-Tyne, United Kingdom

Bock, Olivier, Université Paris Cité, Institut de physique du globe de Paris, CNRS, IGN, F-75005 Paris, France; Univ Gustave Eiffel, ENSG, IGN, F-77455 Marne-la-Vallée, France

Bodin, Xavier, Laboratoire EDYTEM, CNRS/Université Savoie Mont-Blanc, Le Bourget-du-Lac, France

Bonte, Olivier, Hydro-Climate Extremes Lab (H-CEL), Ghent University, Ghent, Belgium

Bosilovich, Michael G., Global Modeling and Assimilation Office, NASA Goddard Space Flight Center, Greenbelt, Maryland

Boucher, Olivier, Institute Pierre Simon Laplace (IPSL), Guyancourt, France

Buehler, Stefan A., Universität Hamburg, Hamburg, Germany

Byrne, Michael P., Climate Dynamics Lab, University of St Andrews, St Andrews, United Kingdom

Campos, Diego, Earth Sciences Department, Barcelona Supercomputing Center, Barcelona, Spain

Cappucci, Fabrizio, European Commission Joint Research Centre, Ispra, Italy

Carrea, Laura, University of Reading, Reading, United Kingdom

Chang, Kai-Lan, Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, Boulder, Colorado; NOAA Chemical Sciences Laboratory, Boulder, Colorado

Christiansen, Hanne H., Arctic Geophysics Department, University Centre in Svalbard, Longyearbyen, Norway; Geology Department, University Centre in Svalbard, Longyearben, Norway

Christy, John R., University of Alabama in Huntsville, Huntsville, Alabama

Chung, Eui-Seok, Korea Polar Research Institute, Incheon, South Korea

Ciasto, Laura M., NOAA/NWS National Centers for Environmental Prediction Climate Prediction Center, College Park, Maryland

Clingan, Scott, Cooperative Institute for Research in Earth Science, University of Colorado, Boulder, Colorado; NOAA Global Monitoring Laboratory, Boulder, Colorado

Coldewey-Egbers, Melanie, German Aerospace Center (DLR), Oberpfaffenhofen, Germany

Cooper, Owen R., NOAA Chemical Sciences Laboratory, Boulder, Colorado

Cornes, Richard C., National Oceanography Centre, Southampton, United Kingdom

Covey, Curt, Lawrence Livermore National Laboratory, Livermore, California

Crétaux, Jean-Francois, LEGOS (CNES/CNRS/IRD/UPS), Université de Toulouse, Toulouse, France

Crimmins, Theresa, USA National Phenology Network, School of Natural Resources and the Environment, University of Arizona, Tucson, Arizona.

Crotwell, Molly, Cooperative Institute for Research in Earth Science, University of Colorado, Boulder, Colorado; NOAA Global Monitoring Laboratory, Boulder, Colorado

Culpepper, Joshua, Department of Biology, York University, Toronto, Canada

Cusicanqui, Diego, Institut de Géosciences de l'Environnement (IGE), Université Grenoble Alpes, INRAE, CNRS, IRD, Grenoble INP, ISTerre, Grenoble, France

Davis, Sean, NOAA Chemical Sciences Laboratory, Boulder, Colorado

de Jeu, Richard A. M., Planet Labs, Haarlem, The Netherlands

Degenstein, Doug, University of Saskatchewan, Saskatoon, Canada

Delaloye, Reynald, Department of Geosciences, University of Fribourg, Fribourg, Switzerland

DiGangi, Elizabeth, AEM R&D, Germantown, Maryland

Dokulil, Martin T., Research Institute for Limnology, University of Innsbruck, Mondsee, Austria

Donat, Markus G., Barcelona Supercomputing Center, Barcelona, Spain; Catalan Institution for Research and Advanced Studies (ICREA), Barcelona, Spain

Dorigo, Wouter A., Department of Geodesy and Geoinformation, TU Wien, Vienna, Austria

Duchemin, Diane, CESBIO, Université de Toulouse, CNES/CNRS/INRAe/IRD/UPS, Toulouse, France

Dugan, Hilary, Department of Integrative Biology, University of Wisconsin-Madison, Madison, Wisconsin

Dunn, Robert J. H., Met Office Hadley Centre, Exeter, United Kingdom

Durre, Imke, NOAA/NESDIS National Center for Environmental Information, Asheville, North Carolina

Dutton, Geoff, Cooperative Institute for Research in the Earth Sciences, NOAA Global Monitoring Laboratory, Boulder, Colorado

Duveiller, Gregory, Max Planck Institute for Biogeochemistry, Jena, Germany

Estilow, Thomas W., Rutgers University, Piscataway, New Jersey

Estrella, Nicole, Ecoclimatology, Department of Life Science Systems, TUM School of Life Sciences, Technical University of Munich, Freising, Germany.

Fereday, David, Met Office Hadley Centre, Exeter, United Kingdom

Fioletov, Vitali E., Environment and Climate Change Canada, Toronto, Canada

Flemming, Johannes, European Centre for Medium-Range Weather Forecasts, Bonn, Germany

Foster, Michael J., Cooperative Institute for Meteorological Satellite Studies, Space Science and Engineering Center, University of Wisconsin-Madison, Madison, Wisconsin

Frederikse, Thomas, Planet Labs, Haarlem, The Netherlands

Frith, Stacey M., Science Systems and Applications, Inc., Lanham, Maryland; NASA Goddard Space Flight Center, Greenbelt, Maryland

Froidevaux, Lucien, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

Füllekrug, Martin, University of Bath, Bath, United Kingdom

Garforth, Judith, Woodland Trust, Grantham, United Kingdom.

Editor and Author Affiliations (continued)

Garg, Jay, ADNET Systems, Inc., Hampton, Virginia

Gobron, Nadine, European Commission Joint Research Centre, Ispra, Italy

Godin-Beekmann, Sophie, Laboratoire Atmosphères, Observations Spatiales (LATMOS), UVSQ, Sorbonne Université, CNRS, IPSL, Guyancourt, France

Goodman, Steven, Thunderbolt Global Analytics, Huntsville, Alabama

Goto, Atsushi, World Meteorological Organization, Geneva, Switzerland

Grimm, Alice, Federal University of Parana, Curitiba, Brazil

Gruber, Alexander, Department of Geodesy and Geoinformation, TU Wien, Vienna, Austria

Gu, Guojun, University of Maryland, College Park, Maryland

Guglielmin, Mauro, Department of Theoretical and Applied Sciences, Insubria University, Varese, Italy

Hahn, Sebastian, Department of Geodesy and Geoinformation, TU Wien, Vienna, Austria

Haimberger, Leopold, University of Vienna, Vienna, Austria

Hall, Brad D., NOAA Global Monitoring Laboratory, Boulder, Colorado

Harlan, Merritt E., U.S. Geological Survey, Denver, Colorado

Harris, I., National Centre for Atmospheric Science (NCAS), University of East Anglia, Norwich, United Kingdom; Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich, United Kingdom

Hemming, Deborah L., Met Office Hadley Centre, Exeter, United Kingdom.; Birmingham Institute of Forest Research, Birmingham University, Birmingham, United Kingdom.

Hirschi, Martin, Institute for Atmospheric and Climate Science, ETH Zurich, Zürich, Switzerland

Ho, Shu-peng (Ben), NOAA/NESDIS Center for Satellite Applications and Research, College Park, Maryland

Holzworth, Robert, University of Washington, Seattle, Washington

Horton, Radley M., Columbia Climate School, Columbia University, New York, New York

Hrbáček, Filip, Department of Geography, Masaryk University, Brno, Czech Republic

Hu, Guojie, Cryosphere Research Station on Qinghai-Tibet Plateau, Northwestern Institute of Eco-Environment and Resources, CAS, Beijing, China

Hurst, Dale, NOAA Global Monitoring Laboratory, Boulder, Colorado

Inness, Antje, European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom

Isaksen, Ketil, Norwegian Meteorological Institute, Oslo, Norway

John, Viju O., EUMETSAT, Darmstadt, Germany

Jones, P. D., Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich, United Kingdom

Junod, Robert, Earth System Science Center, University of Alabama in Huntsville, Huntsville, Alabama

Kääb, Andreas, Department of Geosciences, University of Oslo, Norway

Kaiser, Johannes W., Norwegian Institute for Air Research (NILU), Kjeller, Norway

Kaufmann, Viktor, Institute of Geodesy, Working Group Remote Sensing and Photogrammetry, Graz University of Technology, Graz, Austria

Kellerer-Pirklbauer, Andreas, Institute of Geography and Regional Science, Cascade – The Mountain Processes and Mountain Hazards Group, University of Graz, Graz, Austria

Khaykin, Sergey, Laboratoire Atmosphères, Observations Spatiales (LATMOS), UVSQ, Sorbonne Université, CNRS, IPSL, Guyancourt, France

Kidd, Richard, EODC GmbH, Vienna, Austria

King, Tyler V., U.S. Geological Survey, Boise, Idaho

Kipling, Zak, European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom

Koppa, Akash, Hydro-Climate Extremes Lab (H-CEL), Ghent University, Ghent, Belgium

Kraemer, Benjamin M., University of Freiburg, Freiburg, Germany

La Fuente, R. Sofia, Vrije Universiteit Brussel, Brussels, Belgium

Laas, Alo, Institute of Agricultural and Environmental Sciences, Estonian University of Life Sciences, Tartumaa, Estonia

Lan, Xin, Cooperative Institute for Research in the Earth Sciences, NOAA Global Monitoring Laboratory, Boulder, Colorado; NOAA Global Monitoring Laboratory, Boulder, Colorado

Lantz, Kathleen O., NOAA Global Monitoring Laboratory, Boulder, Colorado

Lapierre, Jeff, AEM R&D, Germantown, Maryland

Lavers, David A., European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom

Leblanc, Thierry, Jet Propulsion Laboratory, California Institute of Technology, Wrightwood, California

Leibensperger, Eric, Department of Physics and Astronomy, Ithaca College, Ithaca, New York

Lennard, Chris, Department of Environmental and Geographical Science, University of Cape Town, Cape Town, South Africa

Liley, Ben, National Institute of Water & Atmospheric Research (NIWA), Lauder, New Zealand

Liu, Yakun, Massachusetts Institute of Technology, Cambridge, Massachusetts

Lo, Y. T. Eunice, Cabot Institute for the Environment, University of Bristol, Bristol, United Kingdom

Loeb, Norman G., NASA Langley Research Center, Hampton Virginia

Loyola, Diego, German Aerospace Center (DLR), Oberpfaffenhofen, Germany

Magnin, Florence, Laboratoire EDYTEM, CNRS/Université Savoie Mont-Blanc, Le Bourget-du-Lac, France

Matsuzaki, Shin-Ichiro, National Institute for Environmental Studies, Tsukuba, Japan

Matthews, Tom, Department of Geography, King's College London, London, United Kingdom

Mayer, Michael, University of Vienna, Vienna, Austria; European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom

McCarthy, Michael, University of Washington, Seattle, Washington

McVicar, Tim R., CSIRO Environment, Canberra, Australian Capital Territory; Australian Research Council Centre of Excellence for Climate Extremes, Sydney, Australia

Mears, Carl A., Remote Sensing Systems, Santa Rosa, California

Menzel, Annette, Ecoclimatology, Department of Life Science Systems, TUM School of Life Sciences, Technical University of Munich, Freising, Germany; Institute for Advanced Study, Technical University of Munich, Garching, Germany

Merchant, Christopher J., University of Reading, Reading, United Kingdom

Merio, Leo-Juhani, Finnish Environment Institute (SYKE), Oulu, Finland

Meyer, Michael F., U.S. Geological Survey, Madison, Wisconsin

Miller, John B., NOAA Global Monitoring Laboratory, Boulder, Colorado

Miralles, Diego G., Hydro-Climate Extremes Lab (H-CEL), Ghent University, Ghent, Belgium

Montzka, Stephan A., NOAA Global Monitoring Laboratory, Boulder, Colorado

Morice, Colin, Met Office Hadley Centre, Exeter, United Kingdom

Morino, Isamu, National Institute for Environmental Studies, Tsukuba, Japan

Mrekaj, Ivan, Technical University in Zvolen, Zvolen, Slovakia

Mühle, Jens, Scripps Institution of Oceanography, University of California San Diego, La Jolla, California

Nance, D., Cooperative Institute for Research in Earth Science, University of Colorado, Boulder, Colorado; NOAA Global Monitoring Laboratory, Boulder, Colorado

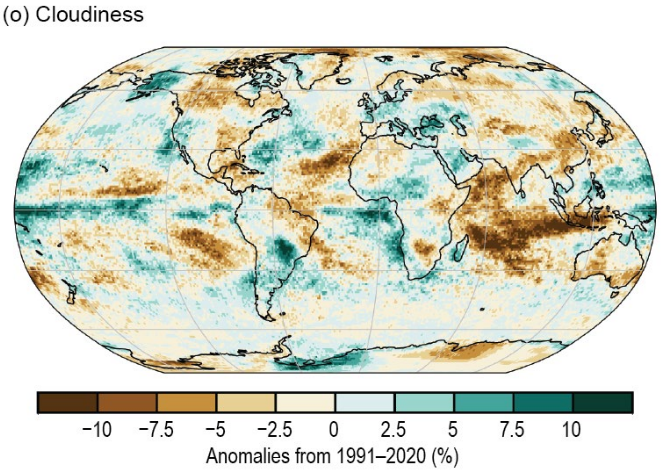
Nicolas, Julien P., European Centre for Medium-Range Weather Forecasts, Bonn, Germany

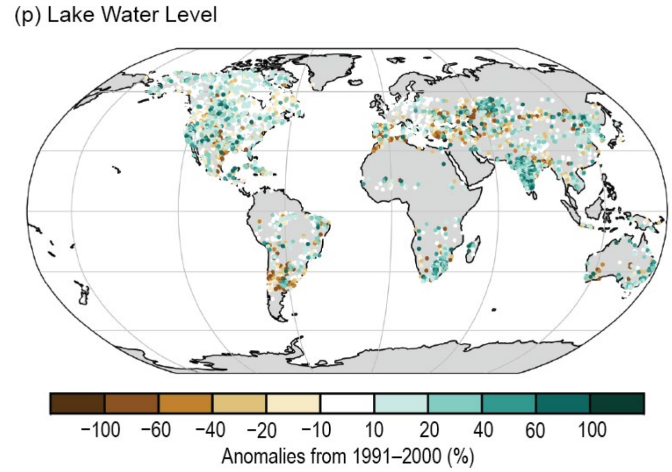
Noetzli, Jeannette, WSL Institute for Snow and Avalanche Research SLF Climate Change, Davos Dorf, Switzerland; Extremes and Natural Hazards in Alpine Regions Research Center CERC, Davos Dorf, Switzerland

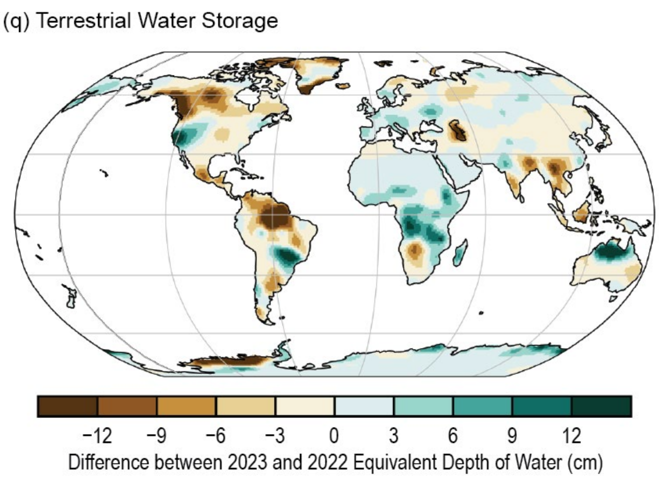
Noll, Ben, National Institute of Water and Atmospheric Research (NIWA), Auckland, New Zealand

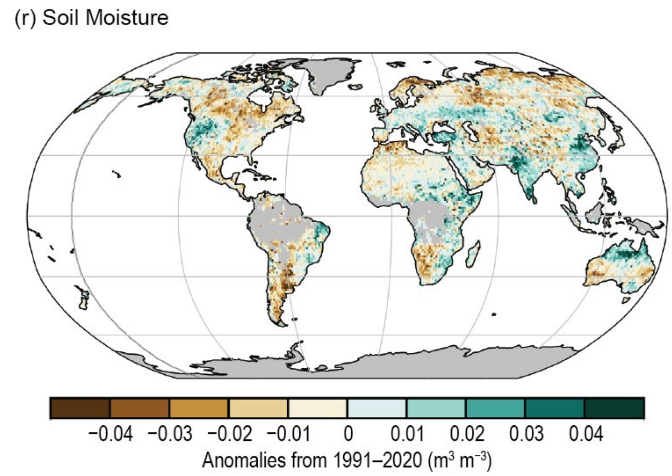
Editor and Author Affiliations (continued)

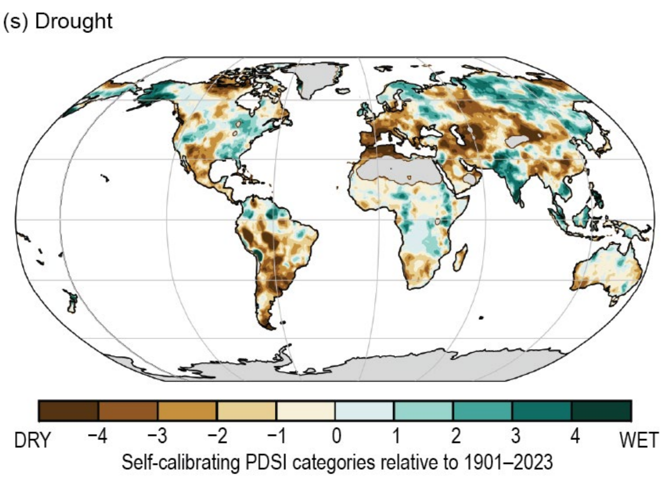
O'Keefe, John, The Harvard Forest, Harvard University, Petersham, Massachusetts
Osborn, Tim J., Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich, United Kingdom
Parrington, Mark, European Centre for Medium-Range Weather Forecasts, Bonn, Germany
Pellet, Cécile, Department of Geosciences, University of Fribourg, Fribourg, Switzerland
Pelto, Mauri S., Nichols College, Dudley, Massachusetts
Petersen, Kyle, Cooperative Institute for Research in Earth Science, University of Colorado, Boulder, Colorado; NOAA Global Monitoring Laboratory, Boulder, Colorado
Phillips, Coda, Cooperative Institute for Meteorological Satellite Studies, Space Science and Engineering Center, University of Wisconsin-Madison, Madison, Wisconsin
Pierson, Don, Department of Ecology and Genetics, Uppsala University, Uppsala, Sweden
Pinto, Izidine, Royal Netherlands Meteorological Institute (KNMI), De Bilt, The Netherlands
Po-Chedley, Stephen, Lawrence Livermore National Laboratory, Livermore, California
Pogliotti, Paolo, Environmental Protection Agency of Valle d'Aosta, Saint Christophe, Italy
Polvani, Lorenzo, Columbia University, New York, New York
Preimesberger, Wolfgang, Department of Geodesy and Geoinformation, TU Wien, Vienna, Austria
Price, Colin, Tel Aviv University, Tel Aviv, Israel
Randel, William J., National Center for Atmospheric Research, Boulder, Colorado
Raymond, Colin, University of California, Los Angeles, Los Angeles, California
Rémy, Samuel, HYGEOS, Lille, France
Ricciardulli, Lucrezia, Remote Sensing Systems, Santa Rosa, California
Richardson, Andrew D., School of Informatics, Computing, and Cyber Systems, Northern Arizona University, Flagstaff, Arizona; Center for Ecosystem Science and Society, Northern Arizona University, Flagstaff, Arizona
Robinson, David A., Rutgers University, Piscataway, New Jersey
Rodell, Matthew, Earth Sciences Division, NASA Goddard Space Flight Center, Greenbelt, Maryland
Rodriguez-Fernandez, Nemesio, CESBIO, Université de Toulouse, CNES/CNRS/INRAe/IRD/UPS, Toulouse, France
Rogers, Cassandra D. W., Bureau of Meteorology, Melbourne, Australia
Rohini, P., India Meteorological Department, Ministry of Earth Sciences, Pune, India
Rosenlof, Karen, NOAA Chemical Sciences Laboratory, Boulder, Colorado
Rozanov, Alexei, University of Bremen, Bremen, Germany
Rozkošný, Jozef, Slovak Hydrometeorological Institute, Bratislava, Slovakia
Rusanovskaya, Olga O., Irkutsk State University, Institute of Biology, Irkutsk, Russia
Rutishauser, This, Swiss Academy of Sciences (SCNAT), Bern, Switzerland
Sabeerali, C. T., India Meteorological Department, Ministry of Earth Sciences, Pune, India
Said, Ryan, Vaisala R&D, Louisville, Colorado
Sakai, Tetsu, Meteorological Research Institute, Japan Meteorological Agency, Tsukuba, Japan
Sánchez-Lugo, Ahira, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina
Sawaengphokhai, Parnchai, ADNET Systems, Inc., Hampton Virginia
Schenzinger, Verena, Medical University of Innsbruck, Innsbruck, Austria
Schlegel, Robert W., Laboratoire d'Océanographie de Villefranche, Sorbonne Université, Villefranche-sur-mer, France
Schmid, Martin, Eawag, Department Surface Waters - Research and Management, Kastanienbaum, Switzerland
Seneviratne, Sonia I., ETH Zurich, Department of Environmental Systems Science, Zürich, Switzerland
Sezaki, Fumi, Japan Meteorological Agency, Tokyo, Japan
Shao, Xi, NOAA/NESDIS Center for Satellite Applications and Research, College Park, Maryland
Sharma, Sapna, Department of Biology, York University, Toronto, Canada
Shi, Lei, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina
Shimaraeva, Svetlana V., Irkutsk State University, Institute of Biology, Irkutsk, Russia
Shinohara, Ryuichiro, Regional Environment Conservation Division, National Institute for Environmental Studies, Tsukuba, Japan
Silow, Eugene A., Irkutsk State University, Institute of Biology, Irkutsk, Russia
Simmons, Adrian J., European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom
Smith, Sharon L., Geological Survey of Canada, Natural Resources Canada, Ottawa, Canada
Soden, Brian J., University of Miami, Miami, Florida
Sofieva, Viktoria, Finnish Meteorological Institute, Helsinki, Finland
Soldo, Logan, Cooperative Institute for Research in the Environmental Sciences, University of Colorado, Boulder, Boulder, Colorado
Sreejith, O. P., India Meteorological Department, Ministry of Earth Sciences, Pune, India
Stackhouse, Jr., Paul W., NASA Langley Research Center, Hampton, Virginia
Stauffer, Ryan, Atmospheric Chemistry and Dynamics Laboratory, NASA Goddard Space Flight Center, Greenbelt, Maryland
Steinbrecht, Wolfgang, Deutscher Wetterdienst, Hohenpeissenberg, Germany
Steiner, Andrea K., Wegener Center for Climate and Global Change, University of Graz, Graz, Austria
Stoy, Paul, C., Biological Systems Engineering, College of Agricultural and Life Sciences, University of Wisconsin-Madison, Madison, Wisconsin
Stradiotti, Pietro, Department of Geodesy and Geoinformation, TU Wien, Vienna, Austria
Streletskiy, Dmitry A., Department of Geography, George Washington University, Washington, DC
Taha, Ghassan, Morgan State University, Baltimore, Maryland; NASA Goddard Flight Center, Greenbelt, Maryland
Thackeray, Stephen J., United Kingdom Centre for Ecology & Hydrology, Lancaster, United Kingdom.
Thibert, Emmanuel, Institut de Géosciences de l'Environnement (IGE), Université Grenoble Alpes, INRAE, CNRS, IRD, Grenoble INP, ISTerre, Grenoble, France
Timofeyev, Maxim A., Institute of Biology, Irkutsk State University, Irkutsk, Russia
Tourpali, Kleareti, Aristotle University, Thessaloniki, Greece
Tronquo, Emma, Hydro-Climate Extremes Lab (H-CEL), Ghent University, Ghent, Belgium
Tye, Mari R., National Center for Atmospheric Research, Boulder, Colorado
van der A, Ronald, Royal Netherlands Meteorological Institute (KNMI), De Bilt, The Netherlands
van der Schalie, Robin, Planet Labs, Haarlem, The Netherlands
van der Schrier, Gerard, Royal Netherlands Meteorological Institute (KNMI), De Bilt, The Netherlands
van Vliet, Arnold J. H., Environmental Systems Analysis Group, Wageningen University & Research, The Netherlands
Verburg, Piet, National Institute of Water and Atmospheric Research (NIWA), Wellington, New Zealand
Vernier, Jean-Paul, NASA Langley Research Center, Hampton, Virginia
Vimont, Isaac J., NOAA Global Monitoring Laboratory, Boulder, Colorado
Virts, Katrina, University of Huntsville in Alabama, Huntsville, Alabama
Vivero, Sebastián, Department of Geosciences, University of Fribourg, Fribourg, Switzerland
Vömel, Holger, National Center for Atmospheric Research, Boulder, Colorado

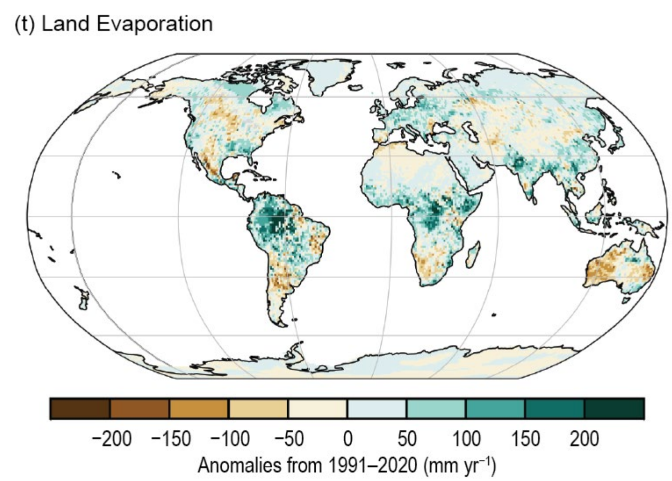












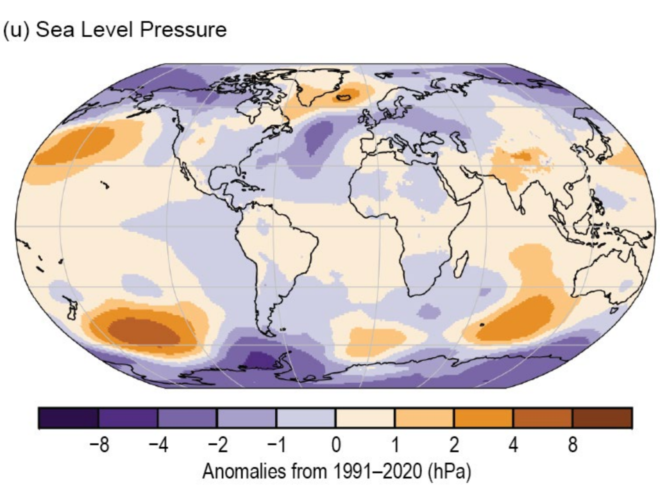


Plate 2.1 (cont.) (o) PATMOS-x 6.0 cloud fraction annual anomalies (%); (p) GloLakes lake water storage anomalies (%); (q) GRACE-FO difference in annual-mean terrestrial water storage between 2022 and 2023 (cm); (r) Copernicus Climate Change Service (C3S) average surface soil moisture anomalies (m3 m^{-3}). Data are masked where no retrieval is possible or where the quality is not assured and flagged, for example due to dense vegetation, frozen soil, or radio frequency interference; (s) Mean self-calibrating Palmer Drought Severity Index (scPDSI) for 2021. Droughts are indicated by negative values (brown), wet episodes by positive values (green). No calculation is made where a drought index is meaningless (gray areas: ice sheets or deserts with approximately zero mean precipitation); (t) GLEAM land evaporation anomalies (mm yr^{-1}); (u) ERA5 mean sea level pressure anomalies (hPa);

started the year with strong wet anomalies that persisted for most of the year, while in the central and southeast part of the country, severe below-normal conditions started to emerge at the end of 2023 (e.g., Clarke et al. 2024; see section 7d2).

In contrast to these regionally confined wet soil moisture anomalies of 2023, dry conditions were observed in numerous regions (Plate 2.1r). The most pronounced dry anomaly was observed in southern South America, especially in the River Plate basin and Patagonia (below 50% of normal soil moisture in some areas). This region has been suffering from a multi-year drought since 2019 (Naumann 2021). Pronounced dry conditions also persisted in the Canadian Prairies for the third consecutive year (see section 7b1; van der Schalie et al. 2022; Stradiotti et al. 2023). Although soil moisture remained below normal, drought conditions in the Great Plains of central North America weakened in 2023 compared to 2022. Mexico experienced drier-than-normal conditions during June–September (Appendix Fig. A2.6). Similarly, below-normal soil moisture was observed in southwestern Africa (including South Africa and Namibia), with the most pronounced dry anomalies recorded from February to May. Many of the regions around the Mediterranean Sea (including Spain, northern Morocco, Algeria, and Tunisia) also experienced moderately dry conditions in 2023. In addition, widespread mild-to-moderate negative soil moisture anomalies were observed over much of inland China, southern Central Asia, northern Asia, and in the higher latitudes in general. In southeast Australia, the strong positive soil moisture anomalies of 2022 (Stradiotti et al. 2023) turned into widespread dry anomalies covering most of the southern part of the continent (except for parts of Victoria), but with intermittent periods of wetter-than-normal conditions in January, April, June, and July.

Soil moisture was observed by microwave satellite remote sensing of the surface soil layer down to approximately 5-cm depth, as provided by the COMBINED product of the Copernicus Climate Change Service (C3S) version 202212 (Dorigo et al. 2023). C3S combines multi-sensor data in the 1978–2023 period through statistical merging (Dorigo et al. 2017; Gruber et al. 2017, 2019). Wet and dry anomalies here refer to the deviation from the 1991–2020 climatological average. Note that changes in spatiotemporal coverage (also between product versions, e.g., resulting from the inclusion of additional sensors) can introduce uncertainties in the domain-averaged soil moisture time series (e.g., Bessenbacher et al. 2023).

11. MONITORING GLOBAL DROUGHT USING THE SELF-CALIBRATING PALMER DROUGHT SEVERITY INDEX

—J. Barichivich, T. J. Osborn, I. Harris, G. van der Schrier, and P. D. Jones

The self-calibrating Palmer Drought Severity Index (scPDSI; Wells et al. 2004; van der Schrier et al. 2013) over the period 1950–2023 shows that the increasing trend in severity and extent of global drought, which has been ongoing since mid-2019 (Barichivich et al. 2020, 2021, 2022), reached a new historical peak during the second half of 2023 (Fig. 2.43). During June–September, extreme drought conditions (scPDSI ≤–4) surpassed 7% of the global land area for the first time in the record, peaking at a new historical maximum of 7.9% in July. Similarly, the extent of severe plus extreme drought conditions (scPDSI ≤–3) in 2023 exceeded 16% of the global land area for the first time during the same period, reaching a historical maximum of 16.8% in July. Moderate or worse drought conditions (scPDSI ≤–2) peaked in September at a historical maximum of 29.7% of the global land area.

The global pattern of regional droughts seen in 2022 largely persisted through 2023, with the most extensive severe-to-extreme

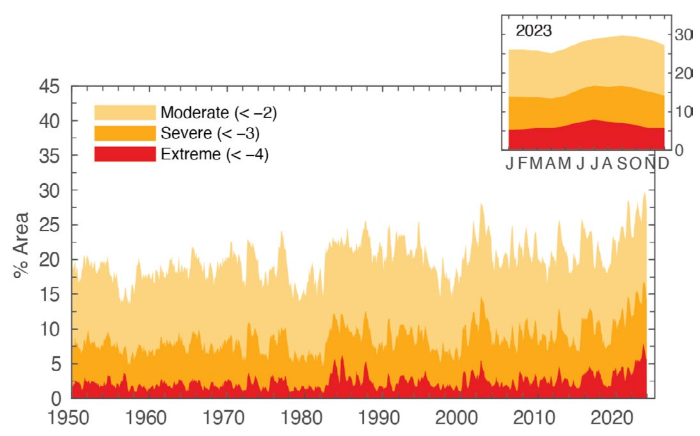


Fig. 2.43. Percentage of global land area (excluding ice sheets and deserts) with self-calibrating Palmer Drought Severity Index (scPDSI) indicating moderate (≤–2), severe (≤–3), and extreme (≤–4) drought for each month during the period 1950–2023. Inset: each month of 2023.

drought conditions occurring over South America, parts of North America, the Mediterranean, and the midlatitudes of Asia (Plate 2.1s). Drought severity eased through western North America and parts of northern and eastern Europe but worsened in tropical South America and the midlatitudes of Asia (Fig. 2.44). In western North America, California experienced a shift from dry to wet conditions, but the overall west–east moisture contrast observed across the United States since 2017 continued as Arizona and New Mexico were under moderate drought (Plate 2.1s). Moderate drought conditions also affected Mexico and Central America. In South America, El Niño conditions during the latter half of 2023 led to extremely wet conditions in coastal areas of Peru and extreme drought through the Amazon basin to the La Plata basin and central Chile. By the end of October, the Rio Negro at Manaus, a major tributary of the Amazon River (Barichivich et al. 2018), fell to its lowest water level since records began in 1902. The megadrought of central Chile reached its 14th consecutive year in 2023, but an increase in winter rainfall broke the drought in the south-central part of the country (section 2d5).

Although precipitation was above normal in parts of northern, central, and eastern Europe in 2023 (section 2b5), most of the southern part of the continent, particularly countries around the Mediterranean, continued under severe-to-extreme drought (Plate 2.1s). In northern Africa, previous extreme drought conditions along the Mediterranean coast from Morocco to Tunisia continued through 2023 (Plate 2.1s). Most of the Middle East from eastern Türkiye to Pakistan also saw a continuation of severe-to-extreme drought conditions.

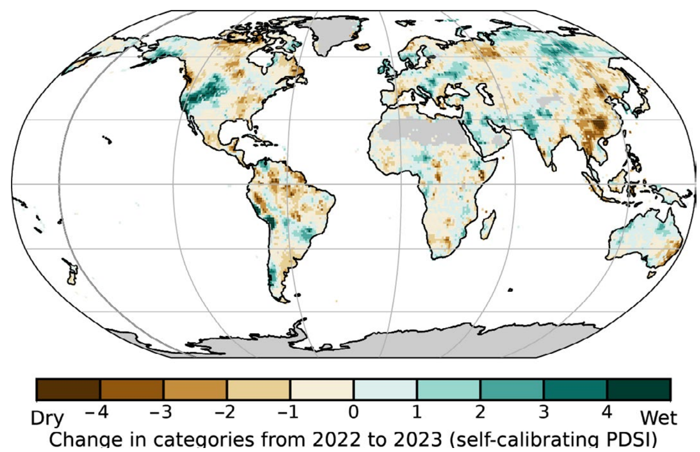


Fig. 2.44. Change in drought categories from 2022 to 2023 (mean self-calibrating Palmer Drought Severity Index [scPDSI] for 2023 minus mean scPDSI for 2022). Increases in drought severity are indicated by negative values (brown) and decreases by positive values (green). No calculation is made where a drought index is meaningless (gray areas: ice sheets or deserts with approximately zero mean precipitation).

Although uncertain due to sparse in situ data, moisture patterns in Africa did not change much in 2023 (Plate 2.1s). Tropical Africa saw a continuation of moderate wet conditions that were observed since 2019. Southern Africa saw a continuation of drought conditions that began in 2018, and its severity remained mostly as moderate. In Australia, drought eased in many northern regions, was sustained in the southwest, and worsened in the easternmost parts during 2023; some parts of the country continued under moderate drought (Plate 2.1s). Wet conditions seen through most of India and southeast Asia in 2022 continued during 2023. In contrast, severe-to-extreme drought conditions extended farther through China, Mongolia, and Kazakhstan. Previous severe-to-extreme drought continued through part of northeastern Siberia (Plate 2.1s).

Hydrological drought results from a period of abnormally low precipitation, sometimes exacerbated by a concurrent increase in evapotranspiration (ET). Its occurrence can be apparent in reduced river discharge, soil moisture, and/or groundwater storage, depending on the season and duration of the event. Here, the scPDSI is calculated, using gridded global precipitation and Penman-Monteith Potential ET from an early update of the CRU TS 4.08 dataset (Harris et al. 2020). A simple water balance at the core of the scPDSI estimates actual evapotranspiration, soil moisture content, and runoff based on the input precipitation and potential loss of moisture to the atmosphere. Estimated soil moisture categories are calibrated over the complete 1901–2023 period to ensure that “extreme” droughts and pluvials (wet periods) relate to events that do not occur more frequently than in approximately 2% of the months. This calibration affects direct comparison with other hydrological cycle variables in Plate 2.1s that use a different baseline period.

Cassandra Rogers is supported with funding from the Australian Government under the National Environmental Science Program.

Thank you to Tim Cowan from the University of Southern Queensland and Blair Trewin from the Bureau of Meteorology for providing initial reviews of the humid heat extremes over land section.

d7 Cloudiness

Clouds and Earth's Radiant Energy Systems Energy Balanced and Filled (CERES EBAF) data were obtained from the NASA Langley Research Center CERES ordering tool at https://ceres.larc.nasa.gov/data/.

d8 Lake water storage

B. M. Kraemer acknowledges support from the University of Freiburg Chair of Environmental Hydrosystems. M. F. Meyer and M. E. Harlan were supported by the United States Geological Survey (USGS) Mendenhall Fellowships from the Water Mission Area. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. R. S. La Fuente was funded by the Irish HEA Landscape programme and Dundalk Institute of Technology (DkIT) Research Office. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

d9 Groundwater and terrestrial water storage

Work on the Groundwater and Terrestrial Water Storage section was funded by NASA's Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) Science Team.

d10 Soil moisture

This study uses satellite soil moisture observations from the Copernicus Climate Change Service (C3S) Climate Data Store (CDS) (2018): Soil moisture gridded data from 1978 to present. C3S CDS. (Accessed on 16 01 2024), 10.24381/cds.d7782f18.

d11 Monitoring drought using the Self Calibrating Palmer Drought Severity Index

Jonathan Barichivich was supported by the European Research Council (ERC) under the Horizon Europe research and innovation programme (ERC-starting grant CATES, grant agreement No. 101043214). Tim Osborn received funding from the U.K. Natural Environment Research Council (NERC) (NE/S015582/1). Ian Harris received funding from U.K. National Centre for Atmospheric Science (NCAS). The research presented in the drought section was carried out on the High-Performance Computing Cluster supported by the Research and Specialist Computing Support service at the University of East Anglia.

d12 Land evaporation

D. G. Miralles acknowledges support from the European Research Council (ERC) under grant agreement no. 101088405 (HEAT). H. E. Beck is supported by the King Abdullah University of Science and Technology.

e2 Surface winds

C. Azorin-Molina was supported by CSIC-UV-GVA and funded by AICO/2021/023, LINCGLOBAL-CSIC ref. INCGLO0023, and PTI-CLIMA.

Robert Dunn was supported by the Met Office Hadley Centre Climate Programme funded by the Department for Business, Energy and Industrial Strategy (BEIS).

L. Ricciardulli was supported by NASA Ocean Vector Wind Science Team grant 80NSSC23K0984. Z. Zeng was supported by the National Natural Science Foundation of China grant 42071022.

e4 Lightning

The work of M. Füllekrug was sponsored by the Royal Society (U.K.) grant NMG/R1/180252 and the Natural Environment Research Council (U.K.) under grants NE/L012669/1 and NE/H024921/1.

E. Williams is supported for studies on global circuit response to climate change from the Physical and Dynamic Meteorology Program at the National Science Foundation (NSF) on grant no. 6942679.

Sub-section	General Variable or Phenomenon	Specific dataset or variable	Source
2d11	Drought	Climatic Research Unit gridded Time Series (CRU TS) 4.07	https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.07/
2d12	Land Evaporation	Climatic Research Unit gridded Time Series (CRU TS) 4.07	https://www.gleam.eu/
2d1	Modes of Variability	Southern Oscillation Index	https://crudata.uea.ac.uk/cru/data/soi/

Section 2e Atmospheric circulation

Sub-section	General Variable or Phenomenon	Specific dataset or variable	Source
2e1	Modes of Variability	Antarctic Oscillation (AAO)/Southern Annular Mode (SAM)	https://ftp.cpc.ncep.noaa.gov/cwlinks/norm.daily.aao.index.b790101.current.ascii
2e1	Pressure, Sea Level or Near-Surface	ERA5	https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5
2e2	Modes of Variability	Antarctic Oscillation (AAO)/Southern Annular Mode (SAM)	https://ftp.cpc.ncep.noaa.gov/cwlinks/norm.daily.aao.index.b790101.current.ascii
2e2	Wind, [Near] Surface	ERA5	https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5
2e2	Wind, [Near] Surface	HadISD v3.3.0.2022f	https://hadleyserver.metoffice.gov.uk/hadisd/v330_2022f/index.html
2e2	Wind, [Near] Surface	Modern-Era Retrospective Analysis for Research and Applications version 2 (MERRA-2)	http://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/
2e2	Wind [Near Surface]	Remote Sensing System (RSS) Merged 1-deg monthly radiometer winds	https://www.remss.com/measurements/wind/
2e2	Wind [Near Surface]	Remote Sensing System (RSS) Advanced Scatterometer (ASCAT)	https://www.remss.com/missions/ascat/
2e2	Wind [Near Surface]	Remote Sensing System (RSS) QuickScat4	https://www.remss.com/missions/qscat/
2e3	Wind [Upper Atmosphere]	Quasi biennial Oscillation (QBO)	https://www.atmohub.kit.edu/data/singapore2023.dat
2e3	Modes of Variability	Antarctic Oscillation (AAO), Southern Annular Mode (SAM)	https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/aao/aao.shtml, http://www.nerc-bas.ac.uk/icd/gjma/sam.html

References

Adler, R., G. Gu, M. Sapiano, J. Wang, and G. Huffman, 2017: Global precipitation: Means, variations and trends during the satellite era (1979–2014). *Surv. Geophys.*, **38**, 679–699, https://doi.org/10.1007/s10712-017-9416-4.

——, and Coauthors, 2018: The Global Precipitation Climatology Project (GPCP) monthly analysis (new version 2.3) and a review of 2017 global precipitation. *Atmosphere*, **9**, 138, https://doi.org/10.3390/atmos9040138.

Alden, C. B., J. B. Miller, and J. W. C. White, 2010: Can bottom-up ocean CO_2 fluxes be reconciled with atmospheric ^{13}C observations? *Tellus*, **62B**, 369–388, https://doi.org/10.1111/j.1600-0889.2010.00481.x.

Ali, H., H. J. Fowler, and V. Mishra, 2018: Global observational evidence of strong linkage between dew point temperature and precipitation extremes. *Geophys. Res. Lett.*, **45**, 12 320–12 330, https://doi.org/10.1029/2018GL080557.

Allan, R. J., J. A. Lindesay, and D. E. Parker, 1996: El Niño Southern Oscillation and Climatic Variability. CSIRO Publishing, 405 pp.

Allan, R. P., C. Liu, M. Zahn, D. A. Lavers, E. Koukouvagias, and A. Bodas-Salcedo, 2014: Physically consistent responses of the global atmospheric hydrological cycle in models and observations. *Surv. Geophys.*, **35**, 533–552, https://doi.org/10.1007/s10712-012-9213-z.

Ammann, C. M., G. A. Meehl, W. M. Washington, and C. S. Zender, 2003: A monthly and latitudinally varying volcanic forcing dataset in simulations of 20th century climate. *Geophys. Res. Lett.*, **30**, 1657, https://doi.org/10.1029/2003GL016875.

Aono, Y., and K. Kazui, 2008: Phenological data series of cherry tree flowering in Kyoto, Japan, and its application to reconstruction of springtime temperatures since the 9th century. *Int. J. Climatol.*, **28**, 905–914, https://doi.org/10.1002/joc.1594.

Arguez, A., S. Hurley, A. Inamdar, L. Mahoney, A. Sanchez-Lugo, and L. Yang, 2020: Should we expect each year in the next decade (2019–28) to be ranked among the top 10 warmest years globally? *Bull. Amer. Meteor. Soc.*, **101**, E655–E663, https://doi.org/10.1175/BAMS-D-19-0215.1.

Arosio, C., A. Rozanov, E. Malinina, M. Weber, and J. P. Burrows, 2019: Merging of ozone profiles from SCIAMACHY, OMPS and SAGE II observations to study stratospheric ozone changes. *Atmos. Meas. Tech.*, **12**, 2423–2444, https://doi.org/10.5194/amt-12-2423-2019.

Augustine, J. A., K. O. Lantz, J.-P. Vernier, and J. E. Barnes, 2023: Mauna Loa apparent transmission record update for 2022 [in "State of the Climate in 2022"]. *Bull. Amer. Meteor. Soc.*, **104** (9), S81–S84, https://doi.org/10.1175/BAMS-D-23-0090.1.

Ayarzagüena, B., S. Ineson, N. J. Dunstone, M. P. Baldwin, and A. A. Scaife, 2018: Intraseasonal effects of El Niño–Southern Oscillation on North Atlantic climate. *J. Climate*, **31**, 8861–8873, https://doi.org/10.1175/JCLI-D-18-0097.1.

Azisov, E., M. Hoelzle, S. Vorogushyn, T. Saks, R. Usubaliev, M. Esenaman uulu, and M. Barandun, 2022: Reconstructed centennial mass balance change for Golubin glacier, Northern Tien Shan. *Atmosphere*, **13**, 954, https://doi.org/10.3390/atmos13060954.

Azorin-Molina, C., R. J. H. Dunn, L. Ricciardulli, C. A. Mears, T. R. McVicar, J. P. Nicolas, Z. Zeng, and M. G. Bosilovich, 2023a: Land and ocean surface winds [in "State of the Climate in 2022"]. *Bull. Amer. Meteor. Soc.*, **104** (9), S72–S74, https://doi.org/10.1175/BAMS-D-23-0090.1.

——, and Coauthors, 2023b: Biases in wind speed measurements due to anemometer changes. *Atmos. Res.*, **289**, 106771, https://doi.org/10.1016/j.atmosres.2023.106771.

Baldwin, J. W., T. Benmarhnia, K. L. Ebi, O. Jay, N. J. Lutsko, and J. K. Vanos, 2023: Humidity's role in heat-related health outcomes: A heated debate. *Environ. Health Perspect.*, **131**, 055001, https://doi.org/10.1289/EHP11807.

Baldwin, M. P., and Coauthors, 2001: The quasi-biennial oscillation. *Rev. Geophys.*, **39**, 179–229, https://doi.org/10.1029/1999RG000073.

Barichivich, J., E. Gloor, P. Peylin, R. J. Brienen, J. Schöngart, J. C. Espinoza, and K. C. Pattnayak, 2018: Recent intensification of Amazon flooding extremes driven by strengthened Walker circulation. *Sci. Adv.*, **4**, eaat8785, https://doi.org/10.1126/sciadv.aat8785.

——, T. J. Osborn, I. Harris, G. van der Schrier, and P. D. Jones, 2020: Monitoring global drought using the self-calibrating Palmer Drought Severity Index [in "State of the Climate in 2019"]. *Bull. Amer. Meteor. Soc.*, **101** (8), S59–S60, https://doi.org/10.1175/BAMS-D-20-0104.1.

——, ——, ——, ——, and ——, 2021: Monitoring global drought using the self-calibrating Palmer Drought Severity Index [in "State of the Climate in 2020"]. *Bull. Amer. Meteor. Soc.*, **102** (8), S68–S70, https://doi.org/10.1175/BAMS-D-21-0098.1.

——, ——, ——, ——, and ——, 2022: Monitoring global drought using the self-calibrating Palmer Drought Severity Index [in "State of the Climate in 2021"]. *Bull. Amer. Meteor. Soc.*, **103** (8), S66–S67, https://doi.org/10.1175/BAMS-D-22-0092.1.

Bartow-Gillies, E., J. Blunden, and T. Boyer, 2023: A look at 2022: Takeaway points from the state of the climate. *Bull. Amer. Meteor. Soc.*, **104**, 810–820, https://doi.org/10.1175/BAMS-D-23-0192.1.

Basu, S., and Coauthors, 2022: Estimating emissions of methane consistent with atmospheric measurements of methane and $\delta^{13}C$ of methane. *Atmos. Chem. Phys.*, **22**, 15 351–15 377, https://doi.org/10.5194/acp-22-15351-2022.

Becker, A., P. Finger, A. Meyer-Christoffer, B. Rudolf, K. Schamm, U. Schneider, and M. Ziese, 2013: A description of the global land-surface precipitation data products of the Global Precipitation Climatology Centre with sample applications including centennial (trend) analysis from 1901–present. *Earth Syst. Sci. Data*, **5**, 71–99, https://doi.org/10.5194/essd-5-71-2013.

Behera, S. K., J. J. Luo, S. Masson, S. A. Rao, H. Sakuma, and T. Yamagata, 2006: A CGCM study on the interaction between IOD and ENSO. *J. Climate*, **19**, 1688–1705, https://doi.org/10.1175/JCLI3797.1.

Bell, B., and Coauthors, 2021: The ERA5 global reanalysis: Preliminary extension to 1950. *Quart. J. Roy. Meteor. Soc.*, **147**, 4186–4227, https://doi.org/10.1002/qj.4174.

Bell, G. D., and M. S. Halpert, 1998: Climate assessment for 1997. *Bull. Amer. Meteor. Soc.*, **79** (Suppl.), S1–S50, https://doi.org/10.1175/1520-0477-79.5s.S1.

Bellouin, N., and Coauthors, 2020: Radiative forcing of climate change from the Copernicus reanalysis of atmospheric composition. *Earth Syst. Sci. Data*, **12**, 1649–1677, https://doi.org/10.5194/essd-12-1649-2020.

GLIMS, 2023: Glacier viewer. Accessed 2 January 2024, https://www.glims.org/maps/glims.

Gobron, N., and M. Robustelli, 2013: Monitoring the state of the global terrestrial surfaces. Proc. 2013 ESA Living Planet Symp., Edinburgh, United Kingdom, European Space Agency, JRC84937, https://publications.jrc.ec.europa.eu/repository/handle/JRC84937.

——, A. S. Belward, B. Pinty, and W. Knorr, 2010: Monitoring biosphere vegetation 1998–2009. *Geophys. Res. Lett.*, **37**, L15402, https://doi.org/10.1029/2010GL043870.

——, and Coauthors, 2022: Evaluation of Sentinel-3A and Sentinel-3B ocean land colour instrument green instantaneous fraction of absorbed photosynthetically active radiation. *Remote Sens. Environ.*, **270**, 112850, https://doi.org/10.1016/j.rse.2021.112850.

Godin-Beekmann, S., and Coauthors, 2022: Updated trends of the stratospheric ozone vertical distribution in the 60°S–60°N latitude range based on the LOTUS regression model. *Atmos. Chem. Phys.*, **22**, 11 657–11 673, https://doi.org/10.5194/acp-22-11657-2022.

Goodman, S. J., D. E. Buechler, K. Knupp, K. Driscoll, and E. W. McCaul Jr., 2000: The 1997-98 El Niño event and related wintertime lightning variations in the southeastern United States. *Geophys. Res. Lett.*, **27**, 541–544, https://doi.org/10.1029/1999GL010808.

Granier, C., and Coauthors, 2011: Evolution of anthropogenic and biomass burning emissions of air pollutants at global and regional scales during the 1980–2010 period. *Climatic Change*, **109**, 163–190, https://doi.org/10.1007/s10584-011-0154-1.

Grant, L., and Coauthors, 2021: Attribution of global lake systems change to anthropogenic forcing. *Nat. Geosci.*, **14**, 849–854, https://doi.org/10.1038/s41561-021-00833-x.

Grifoni, F., N. Cannone, P. Convey, and M. Guglielmin, 2024: A decade (2013–2022) of permafrost and active layer thickness monitoring in Antarctic Peninsula Area. Extended Abstracts, 12th Int. Conf. on Permafrost, Whitehorse, YT, Canada, 83–84, https://www.permafrost.org/proceedings-of-the-12th-international-conference-on-permafrost-icop/.

Grimm, A. M., 2003: The El Niño impact on the summer monsoon in Brazil: Regional processes versus remote influences. *J. Climate*, **16**, 263–280, https://doi.org/10.1175/1520-0442(2003)016<0263:TENIOT>2.0.CO;2.

——, and A. Natori, 2006: Climate change and interannual variability of precipitation in South America. *Geophys. Res. Lett.*, **33**, L19706, https://doi.org/10.1029/2006GL026821.

Gruber, A., W. A. Dorigo, W. Crow, and W. Wagner, 2017: Triple collocation-based merging of satellite soil moisture retrievals. *IEEE Trans. Geosci. Remote Sens.*, **55**, 6780–6792, https://doi.org/10.1109/TGRS.2017.2734070.

——, T. Scanlon, R. van der Schalie, W. Wagner, and W. Dorigo, 2019: Evolution of the ESA CCI Soil Moisture climate data records and their underlying merging methodology. *Earth Syst. Sci. Data*, **11**, 717–739, https://doi.org/10.5194/essd-11-717-2019.

Gulev, S. K., and Coauthors, 2021: Changing state of the climate system. Climate Change 2021: The Physical Science Basis, V. Masson-Delmotte et al., Eds., Cambridge University Press, 287–422, https://doi.org/10.1017/9781009157896.004.

Haimberger, L., C. Tavolato, and S. Sperka, 2012: Homogenization of the Global Radiosonde Temperature dataset through combined comparison with reanalysis background series and neighboring stations. *J. Climate*, **25**, 8108–8131, https://doi.org/10.1175/JCLI-D-11-00668.1.

Hansen, J., and S. Lebedeff, 1987: Global trends of measured surface air temperature. *J. Geophys. Res.*, **92**, 13 345–13 372, https://doi.org/10.1029/JD092iD11p13345.

——, S. Makiko, R. Ruedy, K. Lo, D. W. Lea, and M. Medina-Elizade, 2006: Global temperature change. *Proc. Natl. Acad. Sci. USA*, **103**, 14 288–14 293, https://doi.org/10.1073/pnas.0606291103.

——, R. Ruedy, M. Sato, and K. Lo, 2010: Global surface temperature change. *Rev. Geophys.*, **48**, RG4004, https://doi.org/10.1029/2010RG000345.

Harris, I., T. J. Osborn, P. D. Jones, and D. H. Lister, 2020: Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. *Sci. Data*, **7**, 109, https://doi.org/10.1038/s41597-020-0453-3.

Hassan, T., R. Gulzar, M. Hamid, R. Ahmad, S. A. Waza, and A. A. Khuroo, 2024: Plant phenology shifts under climate warming: A systematic review of recent scientific literature. *Environ. Monit. Assess.*, **196**, 36, https://doi.org/10.1007/s10661-023-12190-w.

Held, I. M., and B. J. Soden, 2006: Robust responses of the hydrological cycle to global warming. *J. Climate*, **19**, 5686–5699, https://doi.org/10.1175/JCLI3990.1.

Hersbach, H., and Coauthors, 2020: The ERA5 global reanalysis. *Quart. J. Roy. Meteor. Soc.*, **146**, 1999–2049, https://doi.org/10.1002/qj.3803.

Ho, S.-P., and Coauthors, 2020: The COSMIC/FORMOSAT-3 radio occultation mission after 12 years: Accomplishments, remaining challenges, and potential impacts of COSMIC-2. *Bull. Amer. Meteor. Sci.*, **101**, E1107–E1136, https://doi.org/10.1175/BAMS-D-18-0290.1.

Hobday, A. J., and Coauthors, 2016: A hierarchical approach to defining marine heatwaves. *Prog. Oceanogr.*, **141**, 227–238, https://doi.org/10.1016/j.pocean.2015.12.014.

——, and Coauthors, 2018: Categorizing and naming marine heatwaves. *Oceanography*, **31** (2), 162–173, https://doi.org/10.5670/oceanog.2018.205.

Hodnebrog, O., and Coauthors, 2020a: Updated global warming potentials and radiative efficiencies of halocarbons and other weak atmospheric absorbers. *Rev. Geophys.*, **58**, e2019RG000691, https://doi.org/10.1029/2019RG000691.

——, and Coauthors, 2020b: The effect of rapid adjustments to halocarbons and N_2O on radiative forcing. *npj Climate Atmos. Sci.*, **3**, 43, https://doi.org/10.1038/s41612-020-00150-x.

Hofmann, D. J., and S. A. Montzka, 2009: Recovery of the ozone layer: The ozone depleting gas index. *Eos, Trans. Amer. Geophys. Union*, **90** (1), 1–2, https://doi.org/10.1029/2009EO010001.

——, J. H. Butler, E. J. Dlugokencky, J. W. Elkins, K. Masarie, S. A. Montzka, and P. Tans, 2006: The role of carbon dioxide in climate forcing from 1979 to 2004: Introduction of the annual greenhouse gas index. *Tellus*, **58B**, 614–619, https://doi.org/10.1111/j.1600-0889.2006.00201.x.

Holzworth, R. H., J. B. Brundell, M. P. McCarthy, A. R. Jacobson, C. J. Rodger, and T. S. Anderson, 2021: Lightning in the Arctic. *Geophys. Res. Lett.*, **48**, e2020GL091366, https://doi.org/10.1029/2020GL091366.

Hong Kong Observatory, 2024: Ranking of air temperature and rainfall in annual in Hong Kong. Accessed 15 February 2024, https://www.hko.gov.hk/en/cis/statistic/erank.htm.

Hou, J., A. I. J. M. Van Dijk, and L. J. Renzullo, 2022: Merging Landsat and airborne LiDAR observations for continuous monitoring of floodplain water extent, depth and volume. *J. Hydrol.*, **609**, 127684, https://doi.org/10.1016/j.jhydrol.2022.127684.

——, and Coauthors, 2021: COVID-19 crisis reduces free tropospheric ozone across the Northern Hemisphere. *Geophys. Res. Lett.*, **48**, e2020GL091987, https://doi.org/10.1029/2020GL091987.

Steiner, A. K., and Coauthors, 2020: Observed temperature changes in the troposphere and stratosphere from 1979 to 2018. *J. Climate*, **33**, 8165–8194, https://doi.org/10.1175/JCLI-D-19-0998.1.

Stocker, M., A. K. Steiner, F. Ladstädter, U. Foelsche, and W. J. Randel, 2024: Observed impacts of the Hunga Tonga eruption on stratospheric temperature. *EGU General Assembly 2024*, Vienna, Austria, EGU, EGU24-11683, https://doi.org/10.5194/egusphere-egu24-11683.

Stoy, P. C., J. Roh, and G. T. Bromley, 2022: It's the heat and the humidity: The complementary roles of temperature and specific humidity to recent changes in the energy content of the near-surface atmosphere. *Geophys. Res. Lett.*, **49**, e2021GL096628, https://doi.org/10.1029/2021GL096628.

Stradiotti, P., and Coauthors, 2023: Soil moisture [in "State of the Climate in 2022"]. *Bull. Amer. Meteor. Soc.*, **104** (9), S65–S66, https://doi.org/10.1175/BAMS-D-23-0090.1.

Streletskiy, D., J. Noetzli, S. L. Smith, G. Vieira, P. Schoeneich, F. Hrbacek, and A. M. Irrgang, 2021: Strategy and implementation plan for the Global Terrestrial Network for Permafrost (GTN-P) 2021-2024. Zenodo, https://doi.org/10.5281/ZENODO.6075468.

Susskind, J., G. Molnar, L. Iredell, and N. G. Loeb, 2012: Interannual variability of outgoing longwave radiation as observed by AIRS and CERES. *J. Geophys. Res.*, **117**, D23107, https://doi.org/10.1029/2012JD017997.

Szopa, S., and Coauthors, 2021: Short-lived climate forcers. *Climate Change 2021: The Physical Science Basis*, V. Masson-Delmotte et al., Eds., Cambridge University Press, 817–922, https://doi.org/10.1017/9781009157896.008.

Taha, G., R. Loughman, P. R. Colarco, T. Zhu, L. W. Thomason, and G. Jaross, 2022: Tracking the 2022 Hunga Tonga-Hunga Ha'apai aerosol cloud in the upper and middle stratosphere using space-based observations. *Geophys. Res. Lett.*, **49**, e2022GL100091, https://doi.org/10.1029/2022GL100091.

Tapley, B. D., S. Bettadpur, J. C. Ries, P. F. Thompson, and M. M. Watkins, 2004: GRACE measurements of mass variability in the Earth system. *Science*, **305**, 503–505, https://doi.org/10.1126/science.1099192.

Tarasick, D. W., and Coauthors, 2019: Tropospheric Ozone Assessment Report: Tropospheric ozone from 1877 to 2016, observed levels, trends and uncertainties. *Elementa*, **7**, 39, https://doi.org/10.1525/elementa.376.

The Watchers, 2023: Extreme rainfall in Telangana results in at least 23 fatalities, India. The Watchers, 30 July, accessed 16 February 2024, https://watchers.news/2023/07/30/extreme-rainfall-in-telangana-results-in-at-least-23-fatalities-india/.

Thibert, E., and X. Bodin, 2022: Changes in surface velocities over four decades on the Laurichard rock glacier (French Alps). *Permafrost Periglacial Processes*, **33**, 323–335, https://doi.org/10.1002/ppp.2159.

Tian, H., and Coauthors, 2024: Global nitrous oxide budget (1980–2020). *Earth Syst. Sci. Data*, **16**, 2543–2604, https://doi.org/10.5194/essd-16-2543-2024.

Timmermann, A., and Coauthors, 2018: El Niño–Southern Oscillation complexity. *Nature*, **559**, 535–545, https://doi.org/10.1038/s41586-018-0252-6.

Toreti, A., and Coauthors, 2023: Drought in Central America and Mexico August 2023. JRC Tech. Rep. 135033, 17 pp., https://doi.org/10.2760/00589.

Torralba, V., F. J. Doblas-Reyes, and N. Gonzalez-Reviriegol, 2017: Uncertainty in recent near-surface wind speed trends: A global reanalysis intercomparison. *Environ. Res. Lett.*, **12**, 114019, https://doi.org/10.1088/1748-9326/aa8a58.

Ultee, L., S. Coats, and J. Mackay, 2022: Glacial runoff buffers droughts through the 21st century. *Earth Syst. Dyn.*, **13**, 935–959, https://doi.org/10.5194/esd-13-935-2022.

van der A, R. J., M. A. F. Allaart, and H. J. Eskes, 2015: Extended and refined multi sensor reanalysis of total ozone for the period 1970–2012. *Atmos. Meas. Tech.*, **8**, 3021–3035, https://doi.org/10.5194/amt-8-3021-2015.

van der Schalie, R., and Coauthors, 2017: The merging of radiative transfer based surface soil moisture data from SMOS and AMSR-E. *Remote Sens. Environ.*, **189**, 180–193, https://doi.org/10.1016/j.rse.2016.11.026.

——, and Coauthors, 2022: Soil moisture [in "State of the Climate in 2021"]. *Bull. Amer. Meteor. Soc.*, **103** (8), S64–S66, https://doi.org/10.1175/BAMS-D-22-0092.1.

van der Schrier, G., J. Barichivich, K. R. Briffa, and P. D. Jones, 2013: A scPDSI-based global dataset of dry and wet spells for 1901–2009. *J. Geophys. Res. Atmos.*, **118**, 4025–4048, https://doi.org/10.1002/jgrd.50355.

van der Werf, G. R., and Coauthors, 2017: Global fire emissions estimates during 1997–2016. *Earth Syst. Sci. Data*, **9**, 697–720, https://doi.org/10.5194/essd-9-697-2017.

Vivero, S., X. Bodin, D. Farías-Barahona, S. MacDonell, N. Schaffer, B. A. Robson, and C. Lambiel, 2021: Combination of aerial, satellite, and UAV photogrammetry for quantifying rock glacier kinematics in the Dry Andes of Chile (30°S) since the 1950s. *Front. Remote Sens.*, **2**, 784015, https://doi.org/10.3389/frsen.2021.784015.

Vömel, H., S. Evan, and M. Tully, 2022: Water vapor injection into the stratosphere by Hunga Tonga-Hunga Ha'apai. *Science*, **377**, 1444–1447, https://doi.org/10.1126/science.abq2299.

von Schuckmann, K., and Coauthors, 2023: Heat stored in the Earth system 1960–2020: Where does the energy go? *Earth Syst. Sci. Data*, **15**, 1675–1709, https://doi.org/10.5194/essd-15-1675-2023.

Vose, R. S., and Coauthors, 2021: Implementing full spatial coverage in NOAA's global temperature analysis. *Geophys. Res. Lett.*, **48**, e2020GL090873, https://doi.org/10.1029/2020GL090873.

Vreugdenhil, M., and Coauthors, 2022: Microwave remote sensing for agricultural drought monitoring: Recent developments and challenges. *Front. Water*, **4**, 1045451, https://doi.org/10.3389/frwa.2022.1045451.

Wang, M., Q. Fu, A. Hall, and A. Sweeney, 2023: Stratosphere-troposphere exchanges of air mass and ozone concentrations from ERA5 and MERRA2: Annual-mean climatology, seasonal cycle, and interannual variability. *J. Geophys. Res. Atmos.*, **128**, e2023JD039270, https://doi.org/10.1029/2023JD039270.

Wang, X., and Coauthors, 2023: Stratospheric climate anomalies and ozone loss caused by the Hunga Tonga-Hunga Ha'apai volcanic eruption. *J. Geophys. Res. Atmos.*, **128**, e2023JD039480, https://doi.org/10.1029/2023JD039480.

Wang, Z., and Coauthors, 2024: Severe global environmental issues caused by Canada's record-breaking wildfires in 2023. *Adv. Atmos. Sci.*, **41**, 565–571, https://doi.org/10.1007/s00376-023-3241-0.

Weatherhead, E. C., and Coauthors, 1998: Factors affecting the detection of trends: Statistical considerations and applications to environmental data. *J. Geophys. Res.*, **103**, 17 149–17 161, https://doi.org/10.1029/98JD00995.

Webb, E. E., A. K. Liljedahl, J. A. Cordeiro, M. M. Loranty, C. Witharana, and J. W. Lichstein, 2022: Permafrost thaw drives surface water decline across lake-rich regions of the Arctic. *Nat. Climate Change*, **12**, 841–846, https://doi.org/10.1038/s41558-022-01455-w.

Weber, M., and Coauthors, 2022: Global total ozone recovery trends attributed to ozone-depleting substance (ODS) changes derived from five merged ozone datasets. *Atmos. Chem. Phys.*, **22**, 6843–6859, https://doi.org/10.5194/acp-22-6843-2022.

Wells, N., S. Goddard, and M. J. Hayes, 2004: A self-calibrating Palmer drought severity index. *J. Climate*, **17**, 2335–2351, https://doi.org/10.1175/1520-0442(2004)017<2335:ASPDSI>2.0.CO;2.

Wentz, F. J., 1997: A well calibrated ocean algorithm for special sensor microwave/imager. *J. Geophys. Res.*, **102**, 8703–8718, https://doi.org/10.1029/96JC01751.

——, 2015: A 17-year climate record of environmental parameters derived from the Tropical Rainfall Measuring Mission (TRMM) microwave imager. *J. Climate*, **28**, 6882–6902, https://doi.org/10.1175/JCLI-D-15-0155.1.

——, L. Ricciardulli, K. Hilburn, and C. Mears, 2007: How much more rain will global warming bring? *Science*, **317**, 233–235, https://doi.org/10.1126/science.1140746.

Western, L. M., and Coauthors, 2023: Author correction: Global increase of ozone-depleting chlorofluorocarbons from 2010 to 2020. *Nat. Geosci.*, **16**, 546, https://doi.org/10.1038/s41561-023-01205-3.

WGMS, 2023: Global Glacier Change Bulletin No. 5 (2020–2021). ISC(WDS)/IUGG(IACS)/UNEP/UNESCO/WMO, World Glacier Monitoring Service, 134 pp., https://doi.org/10.5904/wgms-fog-2023-09.

Wielicki, B. A., B. R. Barkstrom, E. F. Harrison, R. B. Lee III, G. L. Smith, and J. E. Cooper, 1996: Clouds and the Earth's Radiant Energy System (CERES): An Earth observing system experiment. *Bull. Amer. Meteor. Soc.*, **77**, 853–868, https://doi.org/10.1175/1520-0477(1996)077<0853:CATERE>2.0.CO;2.

——, and Coauthors, 1998: Clouds and the Earth's Radiant Energy System (CERES): Algorithm overview. *IEEE Trans. Geosci. Remote Sens.*, **36**, 1127–1141, https://doi.org/10.1109/36.701020.

Wiese, D. N., F. W. Landerer, and M. M. Watkins, 2016: Quantifying and reducing leakage errors in the JPL RL05M GRACE mascon solution. *Water Resour. Res.*, **52**, 7490–7502, https://doi.org/10.1002/2016WR019344.

Willett, K., 2023a: HadISDH.extremes Part I: A gridded wet bulb temperature extremes index product for climate monitoring. *Adv. Atmos. Sci.*, **40**, 1952–1967, https://doi.org/10.1007/s00376-023-2347-8.

——, 2023b: HadISDH.extremes Part II: Exploring humid heat extremes using wet bulb temperature indices. *Adv. Atmos. Sci.*, **40**, 1968–1985, https://doi.org/10.1007/s00376-023-2348-7.

——, C. N. Williams Jr., R. J. H. Dunn, P. W. Thorne, S. Bell, M. de Podesta, P. D. Jones, and D. E. Parker, 2013: HadISDH: An updated land surface specific humidity product for climate monitoring. *Climate Past*, **9**, 657–677, https://doi.org/10.5194/cp-9-657-2013.

——, R. J. H. Dunn, P. W. Thorne, S. Bell, M. de Podesta, D. E. Parker, P. D. Jones, and C. N. Williams Jr., 2014: HadISDH land surface multi-variable humidity and temperature record for climate monitoring. *Climate Past*, **10**, 1983–2006, https://doi.org/10.5194/cp-10-1983-2014.

——, ——, J. Kennedy, and D. Berry, 2020: Development of the HadISDH marine humidity climate monitoring dataset. *Earth Syst. Sci. Data*, **12**, 2853–2880, https://doi.org/10.5194/essd-12-2853-2020.

——, A. J. Simmons, M. Bosilovich and D. A. Lavers, 2023: [Global climate] Surface humidity [in "State of the Climate in 2022"]. *Bull. Amer. Meteor. Soc.*, **104**, S49–S51, https://doi.org/10.1175/BAMS-D-23-0090.1.

Williams, E., and Coauthors, 2021: Evolution of global lightning in the transition from cold to warm phase preceding two super El Niño events. *J. Geophys. Res. Atmos.*, **126**, e2020JD033526, https://doi.org/10.1029/2020JD033526.

WMO, 2018: Scientific assessment of ozone depletion: 2018. Global Ozone Research and Monitoring Project Rep. 58, 588 pp., https://csl.noaa.gov/assessments/ozone/2018.

——, 2022: Scientific assessment of ozone depletion: 2022. Global Ozone Research and Monitoring Project Rep. 278, 520 pp., https://ozone.unep.org/sites/default/files/2023-02/Scientific-Assessment-of-Ozone-Depletion-2022.pdf.

——, 2023: Significant weather and climate events in 2023. Supplement to Provisional State of the Climate 2023 Rep., World Meteorological Organization, 7 pp., https://wmo.int/sites/default/files/2023-12/Supplement.pdf.

——, 2024: State of the Global Climate 2023. WMO-1347, 53 pp., https://library.wmo.int/idurl/4/68835.

Wohland, J., N.-E. Omrani, D. Witthaut, and N.-S. Keenlyside, 2019: Inconsistent wind speed trends in current twentieth century reanalyses. *J. Geophys. Res. Atmos.*, **124**, 1931–1940, https://doi.org/10.1029/2018JD030083.

Wolf, S. T., D. J. Vecellio, and W. L. Kenney, 2022: Adverse heat-health outcomes and critical environmental limits (Pennsylvania State University Human Environmental Age Thresholds project). *Amer. J. Hum. Biol.*, **35**, e23801, https://doi.org/10.1002/ajhb.23801.

Woolway, R. I., and C. J. Merchant, 2018: Intralake heterogeneity of thermal responses to climate change: A study of large Northern Hemisphere lakes. *J. Geophys. Res. Atmos.*, **123**, 3087–3098, https://doi.org/10.1002/2017JD027661.

——, and Coauthors, 2017: Lake surface temperature [in "State of the Climate in 2016"]. *Bull. Amer. Meteor. Soc.*, **98** (8), S13–S14, https://doi.org/10.1175/2017BAMSStateoftheClimate.1

——, and Coauthors, 2018: Lake surface temperature [in "State of the Climate in 2017"]. *Bull. Amer. Meteor. Soc.*, **99** (8), S13–S15, https://doi.org/10.1175/2018BAMSStateoftheClimate.1.

Xing, J., and M. Wang, 2023: Trend and drivers of satellite-detected burned area changes across Arctic region since the 21st century. *J. Geophys. Res. Atmos.*, **128**, e2023JD038946, https://doi.org/10.1029/2023JD038946.

Yan, D., 2023: This extreme rainfall in Beijing is the largest rainfall in 140 years. Beijing China News, 2 August, accessed 16 February 2024, https://web.archive.org/web/20230805112504/http://www.bj.chinanews.com.cn/news/2023/0802/91478.html.

Yang, Y., and Coauthors, 2023: Evapotranspiration on a greening Earth. *Nat. Rev. Earth Environ.*, **4**, 626–641, https://doi.org/10.1038/s43017-023-00464-3.