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Introduction

Tim Boyer, Ellen Bartow-Gillies, A. Abida, Melanie Ades, Robert Adler, Susheel Adusumilli, W. Agyakwah, Brandon Ahmasuk, Laura Aldeco, Mihai Alexe, et al.

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STATE OF THE CLIMATE IN 2022



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Climate Change - Skiing and snowboarding during Winter Holidays in the Bavarian Alps around Oberstdorf.

Oberstdorf, Germany

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Corresponding author: Full Report: Jessica Blunden / jessica.blunden@noaa.gov

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STATE OF THE CLIMATE IN 2022

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Abstract

—J. BLUNDEN, T. BOYER, AND E. BARTOW-GILLIES

Earth's global climate system is vast, complex, and intricately interrelated. Many areas are influenced by global-scale phenomena, including the "triple dip" La Niña conditions that prevailed in the eastern Pacific Ocean nearly continuously from mid-2020 through all of 2022; by regional phenomena such as the positive winter and summer North Atlantic Oscillation that impacted weather in parts the Northern Hemisphere and the negative Indian Ocean dipole that impacted weather in parts of the Southern Hemisphere; and by more localized systems such as high-pressure heat domes that caused extreme heat in different areas of the world. Underlying all these natural short-term variabilities are long-term climate trends due to continuous increases since the beginning of the Industrial Revolution in the atmospheric concentrations of Earth's major greenhouse gases.

In 2022, the annual global average carbon dioxide concentration in the atmosphere rose to 417.1 ± 0.1 ppm, which is 50% greater than the pre-industrial level. Global mean tropospheric methane abundance was 165% higher than its pre-industrial level, and nitrous oxide was 24% higher. All three gases set new record-high atmospheric concentration levels in 2022.

Sea-surface temperature patterns in the tropical Pacific characteristic of La Niña and attendant atmospheric patterns tend to mitigate atmospheric heat gain at the global scale, but the annual global surface temperature across land and oceans was still among the six highest in records dating as far back as the mid-1800s. It was the warmest La Niña year on record. Many areas observed record or near-record heat. Europe as a whole observed its second-warmest year on record, with sixteen individual countries observing record warmth at the national scale. Records were shattered across the continent during the summer months as heatwaves plagued the region. On 18 July, 104 stations in France broke their all-time records. One day later, England recorded a temperature of 40°C for the first time ever. China experienced its second-warmest year and warmest summer on record. In the Southern Hemisphere, the average temperature across New Zealand reached a record high for the second year in a row. While Australia's annual temperature was slightly below the 1991–2020 average, Onslow Airport in Western Australia reached 50.7°C on 13 January, equaling Australia's highest temperature on record.

While fewer in number and locations than record-high temperatures, record cold was also observed during the year. Southern Africa had its coldest August on record, with minimum temperatures as much as 5°C below normal over Angola, western Zambia, and northern Namibia. Cold outbreaks in the first half of December led to many record-low daily minimum temperature records in eastern Australia.

The effects of rising temperatures and extreme heat were apparent across the Northern Hemisphere, where snow-cover extent by June 2022 was the third smallest in the 56-year record, and the seasonal duration of lake ice cover was the fourth shortest since 1980. More frequent and intense heatwaves contributed to the second-greatest average mass balance loss for Alpine glaciers around the world since the start of the record in 1970. Glaciers in the Swiss Alps lost a record 6% of their volume. In South America, the combination of drought and heat left many central Andean glaciers snow free by mid-summer in early 2022; glacial ice has a much lower albedo than snow, leading to accelerated heating of the glacier. Across the global cryosphere, permafrost temperatures continued to reach record highs at many high-latitude and mountain locations.

In the high northern latitudes, the annual surface-air temperature across the Arctic was the fifth highest in the 123-year record. The seasonal Arctic minimum sea-ice extent, typically reached in September, was the 11th-smallest in the 43-year record; however, the amount of multiyear ice—ice that survives at least one summer melt season—remaining in the Arctic continued to decline. Since 2012, the Arctic has been nearly devoid of ice more than four years old.

In Antarctica, an unusually large amount of snow and ice fell over the continent in 2022 due to several landfalling atmospheric rivers, which contributed to the highest annual surface mass balance, 15% to 16% above the 1991–2020 normal, since the start of two reanalyses records dating to 1980. It was the second-warmest year on record for all five of the long-term staffed weather stations on the Antarctic Peninsula. In East Antarctica, a heatwave event led to a new all-time record-high temperature of -9.4°C — 44°C above the March average—on 18 March at Dome C. This was followed by the collapse of the critically unstable Conger Ice Shelf. More than 100 daily low sea-ice extent and sea-ice area records were set in 2022, including two new all-time annual record lows in net sea-ice extent and area in February.

Across the world's oceans, global mean sea level was record high for the 11th consecutive year, reaching 101.2 mm above the 1993 average when satellite altimetry measurements began, an increase of 3.3 ± 0.7 over 2021. Globally-averaged ocean heat content was also record high in 2022, while the global sea-surface temperature was the sixth highest on record, equal with 2018. Approximately 58% of the ocean surface experienced at least one marine heatwave in 2022. In the Bay of Plenty, New Zealand's longest continuous marine heatwave was recorded.

A total of 85 named tropical storms were observed during the Northern and Southern Hemisphere storm seasons, close

to the 1991–2020 average of 87. There were three Category 5 tropical cyclones across the globe—two in the western North Pacific and one in the North Atlantic. This was the fewest Category 5 storms globally since 2017. Globally, the accumulated cyclone energy was the lowest since reliable records began in 1981. Regardless, some storms caused massive damage. In the North Atlantic, Hurricane Fiona became the most intense and most destructive tropical or post-tropical cyclone in Atlantic Canada’s history, while major Hurricane Ian killed more than 100 people and became the third costliest disaster in the United States, causing damage estimated at \$113 billion U.S. dollars. In the South Indian Ocean, Tropical Cyclone Batsirai dropped 2044 mm of rain at Commerson Crater in Réunion. The storm also impacted Madagascar, where 121 fatalities were reported.

As is typical, some areas around the world were notably dry in 2022 and some were notably wet. In August, record high areas of land across the globe (6.2%) were experiencing extreme drought. Overall, 29% of land experienced moderate or worse categories of drought during the year. The largest drought footprint in the contiguous United States since 2012 (63%) was observed in late October. The record-breaking megadrought of central Chile continued in its 13th consecutive year, and 80-year record-low river levels in northern Argentina and Paraguay disrupted fluvial transport. In China, the Yangtze River reached record-low values. Much of equatorial eastern

Africa had five consecutive below-normal rainy seasons by the end of 2022, with some areas receiving record-low precipitation totals for the year. This ongoing 2.5-year drought is the most extensive and persistent drought event in decades, and led to crop failure, millions of livestock deaths, water scarcity, and inflated prices for staple food items.

In South Asia, Pakistan received around three times its normal volume of monsoon precipitation in August, with some regions receiving up to eight times their expected monthly totals. Resulting floods affected over 30 million people, caused over 1700 fatalities, led to major crop and property losses, and was recorded as one of the world’s costliest natural disasters of all time. Near Rio de Janeiro, Brazil, Petrópolis received 530 mm in 24 hours on 15 February, about 2.5 times the monthly February average, leading to the worst disaster in the city since 1931 with over 230 fatalities.

On 14–15 January, the Hunga Tonga-Hunga Ha’apai submarine volcano in the South Pacific erupted multiple times. The injection of water into the atmosphere was unprecedented in both magnitude—far exceeding any previous values in the 17-year satellite record—and altitude as it penetrated into the mesosphere. The amount of water injected into the stratosphere is estimated to be 146 ± 5 Terragrams, or $\sim 10\%$ of the total amount in the stratosphere. It may take several years for the water plume to dissipate, and it is currently unknown whether this eruption will have any long-term climate effect.

Editor and Author Affiliations (alphabetical by name)

- Abida, A.**, Agence Nationale de l'Aviation Civile et de la Météorologie, Moroni, Union of the Comoros
- Ades, Melanie**, European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom
- Adler, Robert**, CMNS-Earth System Science Interdisciplinary Center, University of Maryland, College Park, Maryland
- Adusumilli, Susheel**, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California
- Agyakwah, W.**, NOAA/NWS National Centers for Environmental Prediction Climate Prediction Center, College Park, Maryland
- Ahmasuk, Brandon**, Kawerak Inc., Nome, Alaska
- Aldeco, Laura S.**, Servicio Meteorológico Nacional, Buenos Aires, Argentina
- Alexe, Mihai**, European Centre for Medium-Range Weather Forecasts, Bonn, Germany
- Alfaro, Eric J.**, Center for Geophysical Research and School of Physics, University of Costa Rica, San José, Costa Rica
- Allan, Richard P.**, Department of Meteorology and National Centre for Earth Observation, University of Reading, Reading, United Kingdom
- Allgood, Adam**, NOAA/NWS National Centers for Environmental Prediction Climate Prediction Center, College Park, Maryland
- Alves, Lincoln M.**, Centro Nacional de Monitoramento e Alertas de Desastres Naturais CEMADEN, São Paulo, Brazil
- Amador, Jorge A.**, Center for Geophysical Research and School of Physics, University of Costa Rica, San José, Costa Rica
- Anderson, John**, Hampton University, Hampton, Virginia
- Andrade, B.**, Seychelles Meteorological Authority, Mahe, Seychelles
- Anneville, Orlane**, National Research Institute for Agriculture, Food and Environment (INRAE), CARRTEL, Université Savoie Mont Blanc, Chambéry, France
- Aono, Yasuyuki**, Graduate School of Agriculture, Osaka Metropolitan University, Sakai, Japan
- Arguez, Anthony**, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina
- Arosio, Carlo**, University of Bremen, Bremen, Germany
- Atkinson, C.**, Met Office Hadley Center, Exeter, United Kingdom
- Augustine, John A.**, NOAA Global Monitoring Laboratory, Boulder, Colorado
- Avalos, Grinia**, Servicio Nacional de Meteorología e Hidrología del Perú, Lima, Perú
- Azorin-Molina, Cesar**, Centro de Investigaciones sobre Desertificación – Spanish National Research Council (CSIC-UV-GVA), Valencia, Spain
- Backensto, Stacia A.**, National Park Service, Fairbanks, Alaska
- Bader, Stephan**, Federal Office of Meteorology and Climatology MeteoSwiss, Switzerland
- Baez, Julian**, Universidad Católica Nuestra Señora de la Asunción, Asunción, Paraguay
- Baiman, Rebecca**, Department of Atmospheric and Oceanic Sciences, University of Colorado Boulder, Boulder, Colorado
- Ballinger, Thomas J.**, International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, Alaska
- Banwell, Alison F.**, Earth Science Observation Center, Cooperative Institute for Research in Environmental Sciences (ESOC/CIRES), University of Colorado Boulder, Boulder, Colorado
- Bardin, M. Yu**, Yu. A. Izrael Institute of Global Climate and Ecology, Institute of Geography, Russian Academy of Sciences, Moscow, Russia
- Barichivich, Jonathan**, Instituto de Geografía, Pontificia Universidad Católica de Valparaíso, Valparaíso, Chile; Laboratoire des Sciences du Climat et de l'Environnement (LSCE), LSCE/IPSL, CEA-CNRS-UVSQ, Gif-sur-Yvette, France
- Barnes, John E.**, retired, NOAA Global Monitoring Laboratory, Boulder, Colorado
- Barreira, Sandra**, Argentine Naval Hydrographic Service, Buenos Aires, Argentina
- Bartow-Gillies, Ellen**, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina
- Beadling, Rebecca L.**, Department of Earth and Environmental Science, Temple University, Philadelphia, Pennsylvania
- Beck, Hylke E.**, Physical Science and Engineering Division, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia
- Becker, Emily J.**, University of Miami Rosenstiel School of Marine and Atmospheric Science, Miami, Florida
- Bekele, E.**, NOAA/NWS National Centers for Environmental Prediction Climate Prediction Center, College Park, Maryland
- Bellido, Guillem Martín**, Govern d'Andorra, Andorra la Vella, Andorra
- Bellouin, Nicolas**, University of Reading, Reading, United Kingdom
- Benedetti, Angela**, European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom
- Benestad, Rasmus**, Norwegian Meteorological Institute, Oslo, Norway
- Berne, Christine**, Météo France, Toulouse, France
- Berner, Logan T.**, Northern Arizona University, Flagstaff, Arizona
- Bernhard, Germar H.**, Biospherical Instruments Inc., San Diego, California
- Bhatt, Uma S.**, Geophysical Institute, University of Alaska Fairbanks, Fairbanks, Alaska
- Bhuiyan, MD A. E.**, NOAA/NWS Climate Prediction Center, Silver Spring, Maryland
- Bigalke, Siiri**, Plant, Soils and Climate Department, Utah State University, Logan, Utah
- Biló, Tiago**, Cooperative Institute for Marine and Atmospheric Studies, University of Miami, Miami, Florida; NOAA/OAR Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida
- Bissolli, Peter**, Deutscher Wetterdienst, WMO RA VI Regional Climate Centre Network, Offenbach, Germany
- Bjerke Jarle, W.**, Department of Arctic Ecology, Norwegian Institute for Nature Research, Trondheim, Norway
- Blagrove, Kevin**, Department of Biology, York University, Toronto, Canada
- Blake, Eric S.**, NOAA/NWS National Hurricane Center, Miami, Florida
- Blenkinsop, Stephen**, School of Engineering, Newcastle University, Newcastle-upon-Tyne, United Kingdom
- Blunden, Jessica**, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina
- Bochníček, Oliver**, Slovak Hydrometeorological Institute, Bratislava, Slovakia
- Bock, Olivier**, Université Paris Cité, Institut de Physique du Globe de Paris, CNRS, IGN, F-75005 Paris, France; ENSG-Géomatique, IGN, F-77455 Marne-la-Vallée, France
- Bodin, Xavier**, Laboratoire EDYTEM, CNRS/Université Savoie Mont-Blanc, Chambéry, France
- Bosilovich, Michael**, Global Modeling and Assimilation Office, NASA Goddard Space Flight Center, Greenbelt, Maryland
- Boucher, Olivier**, Sorbonne Université, Paris, France
- Boyer, Tim**, NOAA/NESDIS National Centers for Environmental Information, Silver Spring, Maryland
- Bozkurt, Deniz**, Department of Meteorology, University of Valparaíso, Valparaíso, Chile; Center for Climate and Resilience Research (CR)2, Santiago, Chile
- Brettschneider, Brian**, NOAA/NWS Alaska Region, Anchorage, Alaska
- Bringas, Francis G.**, NOAA/OAR Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida
- Bringas, Francis**, NOAA/OAR Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida
- Buehler, Dennis**, University of Alabama in Huntsville, Huntsville, Alabama
- Buehler, Stefan A.**, Universität Hamburg, Hamburg, Germany
- Bukunt, Brandon**, NOAA/NWS Weather Forecast Office, Tiyan, Guam
- Calderón, Blanca**, Center for Geophysical Research, University of Costa Rica, San José, Costa Rica

Editor and Author Affiliations (continued)

- Camargo, Suzana J.**, Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York
- Campbell, Jayaka**, Department of Physics, The University of the West Indies, Kingston, Jamaica
- Campos, Diego**, Dirección Meteorológica de Chile (DMC), Santiago, Chile
- Carrea, Laura**, Department of Meteorology, University of Reading, Reading, United Kingdom
- Carter, Brendan R.**, Cooperative Institute for Climate, Ocean, and Ecosystem Studies, University of Washington, Seattle, Washington; NOAA/OAR Pacific Marine Environmental Laboratory, Seattle, Washington
- Cetinić, Ivona**, NASA Goddard Space Flight Center, Greenbelt, Maryland; Morgan State University, Baltimore, Maryland
- Chambers, Don P.**, College of Marine Science, University of South Florida, St. Petersburg, Florida
- Chan, Duo**, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts
- Chandler, Elise**, Bureau of Meteorology, Melbourne, Australia
- Chang, Kai-Lan**, Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, Boulder, Colorado; NOAA Chemical Sciences Laboratory, Boulder, Colorado
- Chen, Hua**, Nanjing University of Information Science and Technology, Nanjing, China
- Chen, Lin**, Institute for Climate and Application Research (ICAR)/KLME/ILCEC/CIC-FEMD, Nanjing University of Information Science and Technology, Nanjing, China
- Cheng, Lijing**, International Center for Climate and Environment Sciences, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China
- Cheng, Vincent Y. S.**, Environment and Climate Change Canada, Toronto, Ontario, Canada
- Chomiak, Leah**, Cooperative Institute for Marine and Atmospheric Studies, University of Miami; NOAA/OAR Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida; Rosenstiel School of Marine, Atmospheric, and Earth Science, University of Miami, Miami, Florida
- Christiansen, Hanne H.**, Geology Department, University Centre in Svalbard, Longyearbyen, 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
- Clarke, Leonardo**, Department of Physics, The University of the West Indies, Kingston, Jamaica
- Clem, Kyle R.**, School of Geography, Environment and Earth Sciences, Victoria University of Wellington, Wellington, New Zealand
- Clingan, Scott**, Cooperative Institute for Research in the Earth Sciences, NOAA Global Monitoring Laboratory, Boulder, Colorado
- Coelho, Caio A.S.**, Centro de Previsão do Tempo e Estudos Climáticos/National Institute for Space Research, Center for Weather Forecasts and Climate Studies, Cachoeira Paulista, Brazil
- Cohen, Judah L.**, Atmospheric and Environmental Research, Lexington, Massachusetts
- Coldewey-Egbers, Melanie**, DLR (German Aerospace Center) Oberpfaffenhofen, Germany
- Colwell, Steve**, British Antarctic Survey, Cambridge, United Kingdom
- Cooper, Owen R.**, Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, Boulder, Colorado; NOAA Chemical Sciences Laboratory, Boulder, Colorado
- Cornes, Richard C.**, National Oceanography Centre, Southampton, United Kingdom
- Correa, Kris**, Servicio Nacional de Meteorología e Hidrología del Perú, Lima, Perú
- Costa, Felipe**, Centro Internacional para la Investigación del Fenómeno de El Niño (CIIFEN), Guayaquil, Ecuador
- Covey, Curt**, Lawrence Livermore National Laboratory, Livermore, California
- Coy, Lawrence**, Science Systems and Applications, Inc., Lanham, Maryland; NASA Goddard Space Flight Center, Greenbelt, Maryland
- Créatux, Jean-François**, LEGOS (CNES/CNRS/IRD/UPS), University of Toulouse, Toulouse, France
- Crhova, Lenka**, Czech Hydrometeorological Institute, Prague, Czech Republic
- Crimmins, Theresa**, USA National Phenology Network, School of Natural Resources and the Environment, University of Arizona, Tucson, Arizona
- Cronin, Meghan F.**, NOAA/OAR Pacific Marine Environmental Laboratory, Seattle, Washington
- Cropper, Thomas**, National Oceanography Centre, Southampton, United Kingdom
- Crotwell, Molly**, Cooperative Institute for Research in the Earth Sciences, NOAA Global Monitoring Laboratory, Boulder, Colorado
- Culpepper, Joshua**, Department of Biology, York University, Toronto, Canada
- Cunha, Ana P.**, Centro Nacional de Monitoramento e Alertas de Desastres Naturais CEMADEN, São Paulo, Brazil
- Cusicanqui, Diego**, Université Grenoble Alpes, Institut de Géosciences de l'Environnement (IGE), Grenoble, France
- Datta, Rajashree T.**, Department of Atmospheric and Oceanic Sciences, University of Colorado Boulder, Boulder, Colorado
- Davis, Sean M.**, NOAA Chemical Sciences Laboratory, Boulder, Colorado
- De Boek, Veerle**, Royal Meteorological Institute of Belgium (KMI), Brussels, Belgium
- de Jeu, Richard A. M.**, Planet Labs, Haarlem, The Netherlands
- De Laat, Jos**, Royal Netherlands Meteorological Institute (KNMI), DeBilt, The Netherlands
- Decharme, Bertrand**, Centre National de Recherches Météorologiques, Météo-France/CNRS, Toulouse, France
- Degenstein, Doug**, University of Saskatchewan, Saskatoon, Canada
- Delaloye, Reynald**, Department of Geosciences, University of Fribourg, Fribourg, Switzerland
- Demircan, Mesut**, Turkish State Meteorological Service, Igdir, Türkiye
- Derksen, Chris**, Climate Research Division, Environment and Climate Change Canada, Toronto, Canada
- Deus, Ricardo**, Portuguese Sea and Atmosphere Institute, Lisbon, Portugal
- Dhurmea, K. R.**, Mauritius Meteorological Service, Vacoas, Mauritius
- Diamond, Howard J.**, NOAA/OAR Air Resources Laboratory, College Park, Maryland
- Dirkse, S.**, Namibia Meteorological Service, Windhoek, Namibia
- Divine, Dmitry**, Norwegian Polar Institute, Fram Centre, Tromsø, Norway
- Dokulil, Martin T.**, Research Institute for Limnology, University of Innsbruck, Mondsee, Austria
- Donat, Markus G.**, Barcelona Supercomputing Centre, Barcelona, Spain; Catalan Institution for Research and Advanced Studies (ICREA), Barcelona, Spain
- Dong, Shenfu**, NOAA/OAR Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida
- Dorigo, Wouter A.**, TU Wien, Department of Geodesy and Geoinformation, Vienna, Austria
- Drost Jensen, Caroline**, Danish Meteorological Institute, Copenhagen, Denmark
- Druckenmiller, Matthew L.**, National Snow and Ice Data Center, Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, Colorado
- Drumond, Paula**, Portuguese Sea and Atmosphere Institute, Lisbon, Portugal
- du Plessis, Marcel**, Department of Marine Sciences, University of Gothenburg, Gothenburg, Sweden
- Dugan, Hilary A.**, Center for Limnology, University of Wisconsin-Madison, Madison, Wisconsin
- Dulamsuren, Dashkhuu**, Institute of Meteorology, Hydrology and Environment, National Agency for Meteorology, Ulaanbaatar, Mongolia
- Dunmire, Devon**, Department of Atmospheric and Oceanic Sciences, University of Colorado Boulder, Boulder, Colorado
- Dunn, Robert J. H.**, Met Office Hadley Centre, Exeter, United Kingdom
- Durre, Imke**, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina

Editor and Author Affiliations (continued)

- 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
- Ekici, Mithat**, Turkish State Meteorological Service, Ankara, Türkiye
- Elias Chereque, Alesksandra**, Department of Physics, University of Toronto, Toronto, Canada
- ElKharrim, M.**, Direction de la Météorologie Nationale Maroc, Rabat, Morocco
- Epstein, Howard E.**, University of Virginia, Charlottesville, Virginia
- Espinoza, Jhan-Carlo**, Université Grenoble Alpes, Institut des Géosciences de l'Environnement, IRD, CNRS, Grenoble INP, Grenoble, France
- 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
- Fauchereau, Nicolas**, National Institute of Water and Atmospheric Research, Ltd., Auckland, New Zealand
- Fausto, Robert S.**, Geological Survey of Denmark and Greenland (GEUS), Copenhagen, Denmark
- Feely, Richard A.**, NOAA/OAR Pacific Marine Environmental Laboratory, Seattle, Washington
- Fenimore, Chris**, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina
- Fereday, David**, Met Office Hadley Centre, Exeter, United Kingdom
- Fettweis, Xavier**, University of Liège, Belgium
- Fioletov, Vitali E.**, Environment and Climate Change Canada, Toronto, Canada
- Flemming, Johannes**, European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom
- Fogarty, Chris**, Canadian Hurricane Centre, Environment and Climate Change Canada, Dartmouth, Nova Scotia, Canada
- Fogt, Ryan L.**, Department of Geography, Ohio University, Athens, Ohio
- Forbes, Bruce C.**, Arctic Centre, University of Lapland, Rovaniemi, Finland
- Foster, Michael J.**, Cooperative Institute for Meteorological Satellite Studies, Space Science and Engineering Center, University of Wisconsin-Madison, Madison, Wisconsin
- Franz, Bryan A.**, NASA Goddard Space Flight Center, Greenbelt, Maryland
- Freeman, Natalie M.**, Department of Atmospheric and Oceanic Sciences, University of Colorado Boulder, Boulder, Colorado
- Fricke, Helen A.**, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California
- 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
- Frost, Gerald V. (JJ)**, ABR Inc., Fairbanks, Alaska
- Fuhrman, Steven**, NOAA/NWS NOAA/NWS National Centers for Environmental Prediction Climate Prediction Center, College Park, Maryland
- Füllekrug, Martin**, University of Bath, Bath, United Kingdom
- Ganter, Catherine**, Bureau of Meteorology, Melbourne, Australia
- Gao, Meng**, NASA Goddard Space Flight Center, Greenbelt, Maryland;
- Gardner, Alex S.**, NASA Jet Propulsion Laboratory, Pasadena, California
- Garforth, Judith**, Woodland Trust, Grantham, United Kingdom
- Garg, Jay**, Science Systems and Applications Inc., Hampton, Virginia
- Gerland, Sebastian**, Norwegian Polar Institute, Fram Centre, Tromsø, Norway
- Gibbes, Badin**, School of Civil Engineering, The University of Queensland, Brisbane, Australia
- Gille, Sarah T.**, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California
- Gilson, John**, Scripps Institution of Oceanography, University of California San Diego, La Jolla, California
- Gleason, Karin**, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina
- Gobron, Nadine**, European Commission Joint Research Centre, Ispra, Italy
- Goetz, Scott J.**, Northern Arizona University, Flagstaff, Arizona
- Goldenberg, Stanley B.**, NOAA/OAR Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida
- Goni, Gustavo**, NOAA/OAR Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida
- Goodman, Steven**, Thunderbolt Global Analytics, Huntsville, Alabama
- Goto, Atsushi**, World Meteorological Organization, Geneva, Switzerland
- Grooß, Jens-Uwe**, Forschungszentrum Jülich, Jülich, Germany
- Gruber, Alexander**, TU Wien, Department of Geodesy and Geoinformation, Vienna, Austria
- Gu, Guojun**, CMNS-Earth System Science Interdisciplinary Center, University of Maryland, College Park, Maryland
- Guard, Charles "Chip" P.**, Tropical Weather Sciences, Sinajana, Guam
- Hagos, S.**, Pacific Northwest National Lab, Department of Energy, Richland, Washington
- Hahn, Sebastian**, TU Wien, Department of Geodesy and Geoinformation, Vienna, Austria
- Haimberger, Leopold**, University of Vienna, Vienna, Austria
- Hall, Bradley D.**, NOAA Global Monitoring Laboratory, Boulder, Colorado
- Hamlington, Benjamin D.**, Center for Coastal Physical Oceanography, Old Dominion University, Norfolk, Virginia
- Hanna, Edward**, Department of Geography and Lincoln Climate Research Group, Lincoln, United Kingdom
- Hanssen-Bauer, Inger**, Norwegian Meteorological Institute, Oslo, Norway
- Harnos, Daniel S.**, NOAA/NWS National Centers for Environmental Prediction Climate Prediction Center, College Park, Maryland
- Harris, Ian**, 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
- He, Qiong**, Earth System Modeling Center, Nanjing University of Information Science and Technology, Nanjing, China
- Heim, Richard R. Jr.**, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina
- Hellström, Sverker**, Swedish Meteorological and Hydrological Institute, Norrköping, Sweden
- Hemming, Deborah L.**, Met Office Hadley Centre, Exeter, United Kingdom; Birmingham Institute of Forest Research, Birmingham University, Birmingham, United Kingdom
- Hendricks, Stefan**, Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany
- Hicks, J.**, NOAA/NWS National Centers for Environmental Prediction Climate Prediction Center, College Park, Maryland
- Hidalgo, Hugo G.**, Center for Geophysical Research and School of Physics, University of Costa Rica, San José, Costa Rica
- Hirschi, Martin**, ETH Zurich, Department of Environmental Systems Science, Zürich, Switzerland
- Ho, Shu-peng (Ben)**, Center for Satellite Applications and Research, NOAA, College Park, Maryland; Remote Sensing Systems, Santa Rosa, California
- Hobbs, W.**, Australian Antarctic Program Partnership, Institute for Marine and Antarctic Studies; Australian Research Council Centre of Excellence for Climate Extremes, University of Tasmania, Hobart, Tasmania
- Holmes, Robert M.**, Woodwell Climate Research Center, Falmouth, Massachusetts
- Holzworth, Robert**, University of Washington, Seattle, Washington
- 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
- Hu, Zeng-Zhen**, NOAA/NWS Climate Prediction Center, College Park, Maryland

Editor and Author Affiliations (continued)

- Huang, Boyin**, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina
- Huang, Hongjie**, Nanjing University of Information Science and Technology, Nanjing, China
- Hurst, Dale F.**, Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, Boulder, Colorado; NOAA Global Monitoring Laboratory, Boulder, Colorado
- Ialongo, Iolanda**, Finnish Meteorological Institute, Helsinki, Finland
- Inness, Antje**, European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom
- Isaksen, Ketil**, Norwegian Meteorological Institute, Oslo, Norway
- Ishii, Masayoshi**, Department of Atmosphere, Ocean and Earth System Modeling Research, Meteorological Research Institute, Japan Meteorological Agency, Tsukuba, Japan
- Jadra, Gerardo**, Instituto Uruguayo de Meteorología, Montevideo, Uruguay
- Jevrejeva, Svetlana**, National Oceanography Centre, Liverpool, United Kingdom
- John, Viju O.**, EUMETSAT, Darmstadt, Germany
- Johns, W.**, Rosenstiel School of Marine, Atmospheric, and Earth Science, University of Miami, Miami, Florida
- Johnsen, Bjørn**, Norwegian Radiation and Nuclear Safety, Østerås, Norway
- Johnson, Bryan**, NOAA/OAR Earth System Research Laboratory, Global Monitoring Division, Boulder, Colorado; University of Colorado Boulder, Boulder, Colorado
- Johnson, Gregory C.**, NOAA/OAR Pacific Marine Environmental Laboratory, Seattle, Washington
- Jones, Philip D.**, Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich, United Kingdom
- Jones, Timothy**, Coastal Observation and Seabird Survey Team, University of Washington, Seattle, Washington
- Josey, Simon A.**, National Oceanography Centre, Southampton, United Kingdom.
- Jumaux, G.**, Météo France, Direction Interregionale Pour L'Océan Indien, Reunion
- Junod, Robert**, Earth System Science Center (ESSC), University of Alabama in Huntsville, Huntsville, Alabama
- Kääb, Andreas**, Department of Geosciences, University of Oslo, Norway
- Kabidi, K.**, Direction de la Météorologie Nationale Maroc, Rabat, Morocco
- Kaiser, Johannes W.**, SatFire Kaiser, Hofheim am Taunus, Germany
- Kaler, Robb S.A.**, U.S. Fish and Wildlife Service, Alaska Region, Anchorage, Alaska
- Kaleschke, Lars**, Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany
- Kaufmann, Viktor**, Institute of Geodesy, Working Group Remote Sensing and Photogrammetry, Graz University of Technology, Graz, Austria
- Kazemi, Amin Fazl**, Iran National Climate and Drought Crisis Management, National Meteorology Organization, Tehran, Iran
- Keller, Linda M.**, Antarctic Meteorological Research and Data Center, Space Science and Engineering Center, University of Wisconsin-Madison, Madison, Wisconsin
- Kellerer-Pirklbauer, Andreas**, Institute of Geography and Regional Science, Cascade – The Mountain Processes and Mountain Hazards Group, University of Graz, Graz, Austria
- Kendon, Mike**, Met Office National Climate Information Centre, Exeter, United Kingdom
- Kennedy, John**, Met Office Hadley Centre, Exeter, United Kingdom
- Kent, Elizabeth C.**, National Oceanography Centre, Southampton, United Kingdom
- Kerr, Kenneth**, Trinidad and Tobago Meteorological Service, Piarcó, Trinidad
- Khan, Valentina**, Hydrometcenter of Russia, WMO North EurAsia Climate Center, Moscow, Russia
- Khiem, Mai Van**, Vietnam National Center for Hydro-Meteorological Forecasting, Vietnam Meteorological and Hydrological Administration, Hanoi, Vietnam
- Kidd, Richard**, EODC GmbH, Vienna, Austria
- Kim, Mi Ju**, Climate Change Monitoring Division, Korea Meteorological Administration, Seoul, South Korea
- Kim, Seong-Joong**, Korea Polar Research Institute, Incheon, South Korea
- Kipling, Zak**, European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom
- Klotzbach, Philip J.**, Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado
- Knaff, John A.**, NOAA/NESDIS Center for Satellite Applications and Research, Fort Collins, Colorado
- Koppa, Akash**, Hydro-Climate Extremes Lab (H-CEL), Ghent University, Ghent, Belgium
- Korshunova, Natalia N.**, All-Russian Research Institute of Hydrometeorological Information, World Data Center, Obninsk, Russia
- Kraemer, Benjamin M.**, University of Konstanz, Konstanz, Germany
- Kramarova, Natalya A.**, NASA Goddard Space Flight Center, Greenbelt, Maryland
- Kruger, A. C.**, Climate Service, South African Weather Service, Pretoria, South Africa
- Kruger, Andries**, Climate Service, South African Weather Service, Pretoria, South Africa
- Kumar, Arun**, NOAA/NWS National Centers for Environmental Prediction Climate Prediction Center, College Park, Maryland
- L'Heureux, Michelle**, NOAA/NWS National Centers for Environmental Prediction Climate Prediction Center, College Park, Maryland
- La Fuente, Sofia**, Dundalk Institute of Technology, Dundalk, Ireland
- Laas, Alo**, Estonian University of Life Sciences, Tartumaa, Estonia
- Labe, Zachary M.**, Princeton University, Princeton, New Jersey
- Lader, Rick**, International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, Alaska
- Lakatos, Mónika**, Climatology Unit, Hungarian Meteorological Service, Budapest, Hungary
- Lakkala, Kaisa**, Finnish Meteorological Institute, Sodankylä, Finland
- Lam, Hoang Phuc**, Vietnam National Center for Hydro-Meteorological Forecasting, Vietnam Meteorological and Hydrological Administration, Hanoi, Vietnam
- Lan, Xin**, CIRES, University of Colorado Boulder & NOAA Global Monitoring Laboratory, Boulder, Colorado
- Landschützer, Peter**, Flanders Marine Institute, InnovOcean Campus, Ostend, Belgium
- Landsea, Chris W.**, NOAA/NWS National Hurricane Center, Miami, Florida
- Lang, Timothy**, NASA Marshall Space Flight Center, Huntsville, Alabama
- Lankhorst, Matthias**, Scripps Institution of Oceanography, University of California San Diego, La Jolla, California
- Lantz, Kathleen O.**, NOAA Global Monitoring Laboratory, Boulder, Colorado
- Lara, Mark J.**, University of Illinois at Urbana-Champaign, Urbana, Illinois
- Lavado-Casimiro, Waldo**, Servicio Nacional de Meteorología e Hidrología del Perú, Lima, Perú
- Lavers, David A.**, European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom
- Lazzara, Matthew A.**, Department of Physical Sciences, School of Arts and Sciences, Madison Area Technical College, Madison, Wisconsin; Antarctic Meteorological Research and Data Center, Space Science and Engineering Center, University of Wisconsin-Madison, Madison, Wisconsin
- Leblanc, Thierry**, Jet Propulsion Laboratory, California Institute of Technology, Wrightwood, California
- Lee, Tsz-Cheung**, Hong Kong Observatory, Hong Kong, China
- Leibensperger, Eric M.**, 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
- Leuliette, Eric**, NOAA/NWS NCWCP Laboratory for Satellite Altimetry, College Park, Maryland
- Leung, Kinson H. Y.**, Environment and Climate Change Canada, Toronto, Ontario, Canada
- Lieser, Jan L.**, Australian Bureau of Meteorology and Institute for Marine and Antarctic Studies (IMAS), University of Tasmania, Hobart, Australia

Editor and Author Affiliations (continued)

- Likso, Tanja**, Croatian Meteorological and Hydrological Service, Zagreb, Croatia
- Lin, I-I.**, National Taiwan University, Taipei, Taiwan
- Lindsey, Jackie**, Coastal Observation and Seabird Survey Team, University of Washington, Seattle, Washington
- Liu, Yakun**, Massachusetts Institute of Technology, Cambridge, Massachusetts
- Locarnini, Ricardo**, NOAA/NESDIS National Centers for Environmental Information, Silver Spring, Maryland
- Loeb, Norman G.**, NASA Langley Research Center, Hampton, Virginia
- Loomis, Bryant D.**, NASA Goddard Space Flight Center, Greenbelt, Maryland
- Lorrey, Andrew M.**, National Institute of Water and Atmospheric Research, Ltd., Auckland, New Zealand
- Loyola, Diego**, DLR (German Aerospace Center) Oberpfaffenhofen, Germany
- Lu, Rui**, Nanjing University of Information Science and Technology, Nanjing, China
- Lumpkin, Rick**, NOAA/OAR Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida
- Luo, Jing-Jia**, Institute for Climate and Application Research, Nanjing University of Information Science and Technology, Nanjing, China
- Luojus, Kari**, Arctic Research Centre, Finnish Meteorological Institute, Helsinki, Finland
- Lyman, John M.**, Cooperative Institute for Marine and Atmospheric Research, University of Hawaii, Honolulu, Hawaii; NOAA/OAR Pacific Marine Environmental Laboratory, Seattle, Washington
- Maberly, Stephen C.**, UK Centre for Ecology & Hydrology, Lancaster, United Kingdom
- Macander, Matthew J.**, ABR Inc., Fairbanks, Alaska
- MacFerrin, Michael**, Earth Science and Observation Center, CIRES, University of Colorado, Boulder, Colorado
- MacGilchrist, Graeme A.**, University of St. Andrews, St Andrews, United Kingdom; Princeton University, Princeton, New Jersey
- MacLennan, Michelle L.**, Department of Atmospheric and Oceanic Sciences, University of Colorado Boulder, Boulder, Colorado
- Madelon, Remi**, CESBIO, Université de Toulouse, CNES/CNRS/INRAe/IRD/UPS, Toulouse, France
- Magee, Andrew D.**, Centre for Water, Climate and Land, School of Environmental and Life Sciences, University of Newcastle, Callaghan, Australia
- Magnin, Florence**, Laboratoire EDYTEM, CNRS/Université Savoie Mont-Blanc, Chambéry, France
- Mamen, Jostein**, Norwegian Meteorological Institute, Oslo, Norway
- Mankoff, Ken D.**, Business Integra, New York, New York; NASA Goddard Institute for Space Studies, New York, New York
- Manney, Gloria L.**, NorthWest Research Associates, Socorro, New Mexico
- Marcinonienė, Izolda**, Lithuanian Hydrometeorological Service, Vilnius, Lithuania
- Marengo, Jose A.**, Centro Nacional de Monitoramento e Alertas de Desastres Naturais CEMADEN, São Paulo, Brazil
- Marjan, Mohammadi**, Iran National Climate and Drought Crisis Management, National Meteorology Organization, Tehran, Iran
- Martínez, Ana E.**, National Meteorological Service of Mexico, Mexico City, Mexico
- Massom, Robert A.**, Australian Antarctic Division, Australian Antarctic Program Partnership (AAPP) and Australian Centre for Excellence in Antarctic Science (ACEAS), Tasmania, Australia
- Matsuzaki, Shin-Ichiro**, National Institute for Environmental Studies, Tsukuba, Japan
- May, Linda**, UK Centre for Ecology & Hydrology, Edinburgh, United Kingdom
- Mayer, Michael**, University of Vienna, Vienna, Austria; European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom
- Mazloff, Matthew R.**, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California
- McAfee, Stephanie A.**, Department of Geography, University of Nevada Reno, Reno, Nevada
- McBride, C.**, Climate Service, South African Weather Service, Pretoria, South Africa
- McCabe, Matthew F.**, Climate and Livability Initiative, Division of Biological and Environmental Sciences and Engineering, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia
- McClelland, James W.**, Marine Biological Laboratory, Woods Hole, Massachusetts
- McPhaden, Michael J.**, NOAA/OAR Pacific Marine Environmental Laboratory, Seattle, Washington
- McVicar, Tim R.**, CSIRO Environment, Canberra, Australia; Australian Research Council Centre of Excellence for Climate Extremes, Sydney, Australia
- Mears, Carl A.**, Remote Sensing Systems, Santa Rosa, California
- Meier, Walter N.**, National Snow and Ice Data Center, Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, Colorado
- Mekonnen, A.**, North Carolina A&T University, Greensboro, North Carolina
- 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.**, Department of Meteorology, University of Reading, Reading, United Kingdom
- Merrifield, Mark A.**, Cooperative Institute for Marine and Atmospheric Research, University of Hawaii, Honolulu, Hawaii
- Meyer, Michael F.**, United States Geological Survey, Madison, Wisconsin
- Meyers, Tristan**, National Institute of Water and Atmospheric Research, Ltd. (NIWA), Auckland, New Zealand
- Mikolajczyk, David E.**, Antarctic Meteorological Research and Data Center, Space Science and Engineering Center, University of Wisconsin-Madison, Madison, Wisconsin
- Miller, John B.**, NOAA Global Monitoring Laboratory, Boulder, Colorado
- Miralles, Diego G.**, Hydro-Climate Extremes Lab (H-CEL), Ghent University, Ghent, Belgium
- Misevicius, Noelia**, Instituto Uruguayo de Meteorología, Montevideo, Uruguay
- Mishonov, Alexey**, Earth System Science Interdisciplinary Center/Cooperative Institute for Satellite Earth System Studies Maryland, University of Maryland, College Park, Maryland; NOAA/NESDIS National Centers for Environmental Information, Silver Spring, Maryland
- Mitchum, Gary T.**, College of Marine Science, University of South Florida, St. Petersburg, Florida
- Moat, Ben I.**, National Oceanography Centre, Southampton, United Kingdom
- Moesinger, Leander**, TU Wien, Vienna, Austria
- Moise, Aurel**, Centre for Climate Research Singapore, Meteorological Service Singapore, Singapore
- Molina-Carpio, Jorge**, Universidad Mayor de San Andrés, La Paz, Bolivia
- Monet, Ghislaine**, Université Savoie Mont Blanc, INRAE, CARRTEL, Chambéry, France
- Montzka, Stephan A.**, NOAA Global Monitoring Laboratory, Boulder, Colorado
- Moon, Twila A.**, National Snow and Ice Data Center, Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, Colorado
- Moore, G. W. K.**, University of Toronto Mississauga, Mississauga, Canada
- Mora, Natali**, Center for Geophysical Research, University of Costa Rica, San José, Costa Rica
- Morán, Johnny**, Centro Internacional para la Investigación del Fenómeno de El Niño (CIIFEN), Guayaquil, Ecuador
- Morehen, Claire**, Environment and Climate Change Canada, Vancouver, British Columbia, Canada
- Morice, Colin**, Met Office Hadley Centre, Exeter, United Kingdom
- Mostafa, A. E.**, Department of Seasonal Forecast and Climate Research, Cairo Numerical Weather Prediction, Egyptian Meteorological Authority, Cairo, Egypt
- Mote, Thomas L.**, University of Georgia, Athens, Georgia
- Mrekaj, Ivan**, Technical University in Zvolen, Zvolen, Slovakia
- Mudryk, Lawrence**, Climate Research Division, Environment and Climate Change Canada, Toronto, Canada

Editor and Author Affiliations (continued)

- Mühle, Jens**, AGAGE, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California
- Müller, Rolf**, Forschungszentrum Jülich, Jülich, Germany
- Nance, David**, Cooperative Institute for Research in the Earth Sciences, NOAA Global Monitoring Laboratory, Boulder, Colorado
- Nash, Eric R.**, Science Systems and Applications, Inc., Lanham, Maryland; NASA Goddard Space Flight Center, Greenbelt, Maryland
- Nerem, R. Steven**, Colorado Center for Astrodynamics Research, Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, Boulder, Colorado
- Newman, Paul A.**, NASA Goddard Space Flight Center, Greenbelt, Maryland
- Nicolas, Julien P.**, European Centre for Medium-Range Weather Forecasts, Bonn, Germany
- Nieto, Juan J.**, Centro Internacional para la Investigación del Fenómeno de El Niño (CIIFEN), Guayaquil, Ecuador
- Noetzi, Jeannette**, WSL Institute for Snow and Avalanche Research SLF, Davos-Dorf, Switzerland; Climate Change, Extremes and Natural Hazards in Alpine Regions Research Center CERC, Davos Dorf, Switzerland
- Noll, Ben**, National Institute of Water and Atmospheric Research, Auckland, New Zealand
- Norton, Taylor**, Antarctic Meteorological Research and Data Center, Space Science and Engineering Center, University of Wisconsin-Madison, Madison, Wisconsin
- Nyland, Kelsey E.**, Department of Geography, George Washington University, Washington, DC
- O'Keefe, John**, The Harvard Forest, Harvard University, Petersham, Massachusetts
- Ochwat, Naomi**, Earth Science Observation Center, Cooperative Institute for Research in Environmental Sciences (ESOC/CIRES), University of Colorado Boulder, Boulder Colorado
- Oikawa, Yoshinori**, Tokyo Climate Center, Japan Meteorological Agency, Tokyo, Japan
- Okunaka, Yuka**, Tokyo Climate Center, Japan Meteorological Agency, Tokyo, Japan
- Osborn, Timothy J.**, Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich, United Kingdom
- Overland, James E.**, NOAA Pacific Marine Environmental Laboratory, Seattle, Washington
- Park, Taejin**, NASA Ames Research Center, Mountain View, California; Bay Area Environmental Research Institute, Mountain View, California
- Parrington, Mark**, European Centre for Medium-Range Weather Forecasts, Bonn, Germany
- Parrish, Julia K.**, Coastal Observation and Seabird Survey Team, University of Washington, Seattle, Washington
- Pasch, Richard J.**, NOAA/NWS National Hurricane Center, Miami, Florida
- Pascual Ramírez, Reynaldo**, National Meteorological Service of Mexico, Mexico City, Mexico
- Pellet, Cécile**, Department of Geosciences, University of Fribourg, Fribourg, Switzerland
- Pelto, Mauri S.**, Nichols College, Dudley, Massachusetts
- Perčec Tadić, Melita**, Croatian Meteorological and Hydrological Service, Zagreb, Croatia
- Perovich, Donald K.**, University of Dartmouth, Hanover, New Hampshire
- Petersen, Guðrún Nína**, Icelandic Meteorological Office, Reykjavik, Iceland
- Petersen, Kyle**, Cooperative Institute for Research in the Earth Sciences, NOAA Global Monitoring Laboratory, Boulder, Colorado
- Petropavlovskikh, Irina**, NOAA/OAR Earth System Research Laboratory, Global Monitoring Division, Boulder, Colorado; University of Colorado Boulder, Boulder, Colorado
- Petty, Alek**, NASA Goddard Space Flight Center, Greenbelt, Maryland
- Pezza, Alexandre B.**, Greater Wellington Regional Council, Wellington, New Zealand
- Pezzi, Luciano P.**, Laboratory of Ocean and Atmosphere Studies (LOA), Earth Observation and Geoinformatics Division (DIOTG), National Institute for Space Research (INPE), São José dos Campos, Brazil
- Phillips, Coda**, Cooperative Institute for Meteorological Satellite Studies, Space Science and Engineering Center, University of Wisconsin-Madison, Madison, Wisconsin
- Phoenix, Gareth, K.**, University of Sheffield, Sheffield, United Kingdom
- Pierson, Don**, Department of Ecology and Genetics, Uppsala University, Uppsala, Sweden
- Pinto, Izidine**, Royal Netherlands Meteorological Institute (KNMI), De Bilt, The Netherlands
- Pires, Vanda**, Portuguese Sea and Atmosphere Institute, Lisbon, Portugal
- Pitts, Michael**, NASA Langley Research Center, Hampton, Virginia
- Po-Chedley, Stephen**, Lawrence Livermore National Laboratory, Livermore, California
- Pogliotti, Paolo**, Environmental Protection Agency of Valle d'Aosta, Saint-Christophe, Italy
- Poinar, Kristin**, University at Buffalo, Buffalo, New York
- Polvani, Lorenzo**, Columbia University, New York, New York
- Preimesberger, Wolfgang**, TU Wien, Department of Geodesy and Geoinformation, Vienna, Austria
- Price, Colin**, Tel Aviv University, Tel Aviv, Israel
- Pulkkanen, Merja**, Finnish Environment Institute (SYKE), Jyväskylä, Finland
- Purkey, Sarah G.**, Scripps Institution of Oceanography, University of California San Diego, La Jolla, California
- Qiu, Bo**, Department of Oceanography, University of Hawaii at Manoa, Honolulu, Hawaii
- Quisbert, Kenny**, Servicio Nacional de Meteorología e Hidrología de Bolivia, La Paz, Bolivia
- Quispe, Willy R.**, Servicio Nacional de Meteorología e Hidrología de Bolivia, La Paz, Bolivia
- Rajeevan, M.**, Ministry of Earth Sciences, New Delhi, India
- Ramos, Andrea M.**, Instituto Nacional de Meteorología, Brasília, Brazil
- Randel, William J.**, National Center for Atmospheric Research, Boulder, Colorado
- Rantanen, Mika**, Finnish Meteorological Institute, Helsinki, Finland
- Raphael, Marilyn N.**, Department of Geography, University of California, Los Angeles, Los Angeles, California
- Reagan, James**, NOAA/NESDIS National Centers for Environmental Information, Silver Spring, Maryland
- Recalde, Cristina**, NOAA/NWS National Centers for Environmental Prediction, Climate Prediction Center, College Park, Maryland
- Reid, Phillip**, Australian Bureau of Meteorology and Australian Antarctic Program Partnership (AAPP), Hobart, Australia
- Rémy, Samuel**, HYGEOS, Lille, France
- Reyes Kohler, Alejandra J.**, Dirección de Meteorológica de Chile, Santiago de Chile, Chile
- Ricciardulli, Lucrezia**, Remote Sensing Systems, Santa Rosa, California
- Richardson, Andrew D.**, School of Informatics, Computing, and Cyber Systems, Flagstaff, Arizona; Center for Ecosystem Science and Society, Northern Arizona University, Flagstaff, Arizona
- Ricker, Robert**, NORCE Norwegian Research Centre, Tromsø, Norway
- Robinson, David A.**, Rutgers University, Piscataway, New Jersey
- Robjhon, M.**, NOAA/NWS National Centers for Environmental Prediction Climate Prediction Center, College Park, Maryland
- Rocha, Willy**, Servicio Nacional de Meteorología e Hidrología, Bolivia
- Rodell, Matthew**, Earth Sciences Division, NASA Goddard Space Flight Center, Greenbelt, Maryland
- Rodriguez Guisado, Esteban**, Agencia Estatal de Meteorología, Madrid, Spain
- Rodriguez-Fernandez, Nemesio**, CESBIO, Université de Toulouse, CNES/CNRS/INRAe/IRD/UPS, Toulouse, France

Editor and Author Affiliations (continued)

- Romanovsky, Vladimir E.**, Geophysical Institute, University of Alaska Fairbanks, Fairbanks, Alaska; Earth Cryosphere Institute, Tyumen Science Center, Tyumen, Russia
- Ronchail, Josyane**, Laboratoire LOCEAN-IPSL, Paris, France
- Rosencrans, Matthew**, NOAA/NWS National Centers for Environmental Prediction Climate Prediction Center, College Park, Maryland
- Rosenlof, Karen H.**, NOAA Chemical Sciences Laboratory, Boulder, Colorado
- Rösner, Benjamin**, Laboratory for Climatology and Remote Sensing, Faculty of Geography, University of Marburg, Marburg, Germany
- Rösner, Henrieke**, Humboldt University, Berlin, Germany
- Rozanov, Alexei**, University of Bremen, Bremen, Germany
- Rozkošný, Jozef**, Slovak Hydrometeorological Institute, Bratislava, Slovakia
- Rubek, Frans**, Danish Meteorological Institute, Copenhagen, Denmark
- 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
- Salinas, Roberto**, Dirección de Meteorología e Hidrología / Dirección Nacional de Aeronáutica Civil, Asunción, Paraguay
- Sánchez-Lugo, Ahira**, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina
- Santee, Michelle L.**, NASA Jet Propulsion Laboratory, Pasadena, California
- Santini, Marcelo**, Laboratory of Ocean and Atmosphere Studies (LOA), Earth Observation and Geoinformatics Division (DIOTG), National Institute for Space Research (INPE), São José dos Campos, Brazil
- Sato, Katsunari**, Japan Meteorological Agency, Tokyo, Japan
- Sawaengphokhai, Parnchai**, Science Systems and Applications, Inc. (SSAI), Hampton, Virginia
- Sayouri, A.**, Direction de la Météorologie Nationale Maroc, Rabat, Morocco
- Scambos, Theodore**, Earth Science Observation Center, Cooperative Institute for Research in Environmental Sciences (ESOC/CIRES), University of Colorado Boulder, Boulder, Colorado
- Schenzinger, Verena**, Medical University of Innsbruck, Innsbruck, Austria
- Schimanke, Semjon**, Swedish Meteorological and Hydrological Institute, Norrköping, Sweden
- Schlegel, Robert W.**, Laboratoire d'Océanographie de Villefranche, Sorbonne Université, CNRS, Villefranche-sur-mer, France
- Schmid, Claudia**, NOAA/OAR Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida
- Schmid, Martin**, Eawag, Swiss Federal Institute of Aquatic Science and Technology, Surface Waters - Research and Management, Kastanienbaum, Switzerland
- Schneider, Udo**, Global Precipitation Climatology Centre, Deutscher Wetterdienst, Offenbach, Germany
- Schreck, Carl J.**, North Carolina State University, North Carolina Institute for Climate Studies, Cooperative Institute Satellite Earth System Studies, Asheville, North Carolina
- Schultz, Cristina**, Northeastern University, Boston, Massachusetts
- Science Systems and Applications Inc., Lanham**, Maryland
- Segele, Z. T.**, NOAA/NWS National Centers for Environmental Prediction Climate Prediction Center, College Park, Maryland
- Sensoy, Serhat**, Turkish State Meteorological Service, Ankara, Türkiye
- Serbin, Shawn P.**, Brookhaven National Laboratory, Upton, New York
- Serreze, Mark C.**, National Snow and Ice Data Center, University of Colorado, Boulder, Colorado
- Setiawan, Amsari Mudzakir**, Division for Climate Variability Analysis, BMKG, Jakarta, Indonesia
- Sezaki, Fumi**, Japan Meteorological Agency, Tokyo, Japan
- Sharma, Sapna**, Department of Biology, York University, Toronto, Canada
- Sharp, Jonathan D.**, Cooperative Institute for Climate, Ocean, and Ecosystem Studies, University of Washington, Seattle, Washington; NOAA/OAR Pacific Marine Environmental Laboratory, Seattle, Washington
- Sheffield, Gay**, Alaska Sea Grant, Marine Advisory Program, University of Alaska Fairbanks, Nome, Alaska
- Shi, Jia-Rui**, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts
- Shi, Lei**, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina
- Shiklomanov, Alexander I.**, University of New Hampshire, Durham, New Hampshire; Arctic and Antarctic Research Institute, St. Petersburg, Russia
- Shiklomanov, Nikolay I.**, Department of Geography, George Washington University, Washington, DC
- Shimaraeva, Svetlana V.**, Irkutsk State University, Institute of Biology, Irkutsk, Russia
- Shukla, R.**, NOAA/NWS National Centers for Environmental Prediction Climate Prediction Center, College Park, Maryland
- Siegel, David A.**, University of California, Santa Barbara, Santa Barbara, California
- Silow, Eugene A.**, Irkutsk State University, Institute of Biology, Irkutsk, Russia
- Sima, F.**, Division of Meteorology, Department of Water Resources, Banjul, The Gambia
- Simmons, Adrian J.**, European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom
- Smeed, David A.**, National Oceanography Centre, Southampton, United Kingdom
- Smith, Adam**, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina
- Smith, Sharon L.**, Geological Survey of Canada, Natural Resources Canada, Ottawa, Canada
- Soden, Brian J.**, University of Miami, Miami, Florida
- Sofieva, Viktoria**, FMI (Finnish Meteorological Institute), Helsinki, Finland
- Souza, Everaldo**, Federal University of Pará (UFPA), Belém, Brazil
- Sparks, Tim H.**, Poznań University of Life Sciences, Poznań, Poland
- Spence-Hemmings, Jacqueline**, Meteorological Service, Jamaica, Kingston, Jamaica
- Spencer, Robert G. M.**, Florida State University, Tallahassee, Florida
- Spillane, Sandra**, Climate Services Division, Met Éireann, The Irish Meteorological Service, Dublin, Ireland
- Spillane, Sandra**, Met Éireann, Dublin, Ireland
- Sreejith, O. P.**, India Meteorological Department, Ministry of Earth Sciences, Pune, India
- Srivastava, A. K.**, India Meteorological Department, Pune, India
- Stackhouse Jr., Paul W.**, NASA Langley Research Center, Hampton, Virginia
- Stammerjohn, Sharon**, Institute of Arctic and Alpine Research, University of Colorado Boulder, Boulder, Colorado
- Stauffer, Ryan**, NASA Goddard Space Flight Center, Greenbelt, Maryland
- Steinbrecht, Wolfgang**, DWD (German Weather Service), Hohenpeissenberg, Germany
- Steiner, Andrea K.**, Wegener Center for Climate and Global Change, University of Graz, Graz, Austria
- Stella, Jose L.**, Servicio Meteorológico Nacional, Buenos Aires, Argentina
- Stephenson, Tannecia S.**, Department of Physics, The University of the West Indies, Kingston, Jamaica
- Stradiotti, Pietro**, TU Wien, Department of Geodesy and Geoinformation, Vienna, Austria
- Strahan, Susan E.**, University of Maryland, Baltimore County, Baltimore, Maryland; NASA Goddard Space Flight Center, Greenbelt, Maryland
- Streletskiy, Dmitry A.**, George Washington University, Washington DC
- Surendran, Divya E.**, India Meteorological Department, Ministry of Earth Sciences, Pune, India

Editor and Author Affiliations (continued)

- Suslova, Anya**, Woodwell Climate Research Center, Falmouth, Massachusetts
- Svendby, Tove**, Norwegian Institute for Air Research, Kjeller, Norway
- Sweet, William**, NOAA/NOS Center for Operational Oceanographic Products and Services, Silver Spring, Maryland
- Takahashi, Kiyotoshi**, Tokyo Climate Center, Japan Meteorological Agency, Tokyo, Japan
- Takemura, Kazuto**, Tokyo Climate Center, Japan Meteorological Agency, Tokyo, Japan
- Tank, Suzanne E.**, University of Alberta, Edmonton, Canada
- Taylor, Michael A.**, Department of Physics, The University of the West Indies, Kingston, Jamaica
- Tedesco, Marco**, Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York; NASA Goddard Institute of Space Studies, New York, New York
- Thackeray, Stephen J.**, UK Centre for Ecology and Hydrology, Lancaster, United Kingdom
- Thiaw, W. M.**, NOAA/NWS National Centers for Environmental Prediction Climate Prediction Center, College Park, Maryland
- Thibert, Emmanuel**, Université Grenoble Alpes, INRAE, CNRS, IRD, Grenoble INP, IGE, Grenoble, France.
- Thoman, Richard L.**, International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, Alaska
- Thompson, Andrew F.**, California Institute of Technology, Pasadena, California
- Thompson, Philip R.**, Cooperative Institute for Marine and Atmospheric Research, University of Hawaii, Honolulu, Hawaii
- Tian-Kunze, Xiangshan**, Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany
- Timmermans, Mary-Louise**, Yale University, New Haven, Connecticut
- Timofeyev, Maxim A.**, Irkutsk State University, Institute of Biology, Irkutsk, Russia
- Tobin, Skie**, Bureau of Meteorology, Melbourne, Australia
- Tømmervik, Hans**, Arctic Department, Norwegian Institute for Nature Research, Tromsø, Norway
- Tourpali, Kleareti**, Aristotle University, Thessaloniki, Greece
- Trescilo, Lidia**, State Hydrometeorological Service, Chisinau, Republic of Moldova
- Tretiakov, Mikhail**, Arctic and Antarctic Research Institute, St. Petersburg, Russia
- Trewin, Blair C.**, Australian Bureau of Meteorology, Melbourne, Australia
- Triñanes, Joaquin A.**, Laboratory of Systems, Technological Research Institute, Universidad de Santiago de Compostela, Campus Universitario Sur, Santiago de Compostela, Spain; Cooperative Institute for Marine and Atmospheric Studies, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida; NOAA/OAR Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida
- Trotman, Adrian**, Caribbean Institute for Meteorology and Hydrology, Bridgetown, Barbados
- Truchelut, Ryan E.**, WeatherTiger, Tallahassee, Florida
- Trusel, Luke D.**, Pennsylvania State University, University Park, Pennsylvania
- 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 Meerbeek, Cedric J.**, Caribbean Institute for Meteorology and Hydrology, Bridgetown, Barbados
- van Vliet, Arnold J.H.**, Environmental Systems Analysis Group, Wageningen University and Research, The Netherlands
- Vazife, Ahad**, Iran National Climate and Drought Crisis Management, National Meteorology Organization, Tehran, Iran
- Verburg, Piet**, National Institute of Water and Atmospheric Research, 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 Alabama in Huntsville, Huntsville, Alabama
- Vivero, Sebastián**, Department of Geosciences, University of Fribourg, Fribourg, Switzerland
- Volkov, Denis L.**, Cooperative Institute for Marine and Atmospheric Studies, University of Miami; NOAA/OAR Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida
- Vömel, Holger**, Earth Observing Laboratory, National Center for Atmospheric Research, Boulder, Colorado
- Vose, Russell S.**, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina
- Walker, Donald (Skip) A.**, Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, Alaska
- Walsh, John E.**, International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, Alaska
- Wang, Bin**, School of Ocean and Earth Science and Technology, Department of Meteorology, University of Hawaii; International Pacific Research Center, Honolulu, Hawaii
- Wang, Hui**, NOAA/NWS National Centers for Environmental Prediction Climate Prediction Center, College Park, Maryland
- Wang, Muyin**, NOAA Pacific Marine Environmental Laboratory, Seattle, Washington; Cooperative Institute for Climate, Ocean, and Ecosystem Studies, University of Washington, Seattle, Washington
- Wang, Ray H. J.**, Georgia Institute of Technology, Atlanta, Georgia
- Wang, Xinyue**, National Center for Atmospheric Research, Boulder, Colorado
- Wanninkhof, Rik**, NOAA/OAR Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida
- Warnock, Taran**, University of Saskatchewan, Saskatoon, Canada
- Weber, Mark**, University of Bremen, Bremen, Germany
- Webster, Melinda**, University of Washington, Seattle, Washington
- Wehrlé, Adrian**, University of Zürich, Zürich, Switzerland
- Wen, Caihong**, NOAA/NWS National Centers for Environmental Prediction Climate Prediction Center, College Park, Maryland
- Westberry, Toby K.**, Oregon State University, Corvallis, Oregon
- Widlansky, Matthew J.**, Cooperative Institute for Marine and Atmospheric Research, University of Hawaii, Honolulu, Hawaii
- Wiese, David N.**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California
- Wild, Jeannette D.**, ESSIC/University of Maryland, College Park, Maryland; NOAA NESDIS/STAR, College Park, Maryland
- Wille, Jonathan D.**, Institute for Atmospheric and Climate Science, ETH Zürich, Zürich, Switzerland; Institut des Géosciences de l'Environnement, CNRS/UGA/IRD/G-INP, Saint Martin d'Hères, France
- Willems, An**, Royal Meteorological Institute of Belgium (KMI), Brussels, Belgium
- Willett, Kate M.**, Met Office Hadley Centre, Exeter, United Kingdom
- Williams, Earle**, Massachusetts Institute of Technology, Cambridge, Massachusetts
- Willis, J.**, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California
- Wong, Takmeng**, NASA Langley Research Center, Hampton, Virginia
- Wood, Kimberly M.**, Department of Geosciences, Mississippi State University, Mississippi State, Mississippi
- Woolway, Richard Iestyn**, School of Ocean Sciences, Bangor University, Menai Bridge, Anglesey, Wales
- Xie, Ping-Ping**, NOAA/NWS National Centers for Environmental Prediction Climate Prediction Center, College Park, Maryland
- Yang, Dedi**, Environmental and Climate Sciences Department, Brookhaven National Laboratory, Upton, New York; Department of Ecology and Evolution, Stony Brook University, Stony Brook, New York

Editor and Author Affiliations (continued)

Yin, Xungang, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina

Yin, Ziqi, Department of Atmospheric and Oceanic Sciences, University of Colorado Boulder, Boulder, Colorado

Zeng, Zhenzhong, School of Environmental Science and Engineering, Southern University of Science and Technology, Shenzhen, China

Zhang, Huai-min, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina

Zhang, Li, NOAA/NWS National Centers for Environmental Prediction Climate Prediction Center, College Park, Maryland; ERT, Laurel, Maryland

Zhang, Peiqun, Beijing Climate Center, Beijing, China

Zhao, Lin, School of Geographical Sciences, Nanjing University of Information Science and Technology, Nanjing, China

Zhou, Xinjia, Center for Satellite Applications and Research, NOAA, College Park, Maryland

Zhu, Zhiwei, Nanjing University of Information Science and Technology, Nanjing, China

Ziemke, Jerry R., Goddard Earth Sciences Technology and Research, Morgan State University, Baltimore, Maryland; NASA Goddard Space Flight Center, Greenbelt, Maryland

Ziese, Markus, Global Precipitation Climatology Centre, Deutscher Wetterdienst, Offenbach, Germany

Zolkos, Scott, Woodwell Climate Research Center, Falmouth, Massachusetts

Zotta, Ruxandra M., TU Wien, Vienna, Austria

Zou, Cheng-Zhi, NOAA/NESDIS Center for Satellite Applications and Research, College Park, Maryland

Editorial and Production Team

Allen, Jessica, Graphics Support, Cooperative Institute for Satellite Earth System Studies, North Carolina State University, Asheville, North Carolina

Camper, Amy V., Graphics Support, Innovative Consulting and Management Services, LLC, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina

Haley, Bridgette O., Graphics Support, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina

Hammer, Gregory, Content Team Lead, Communications and Outreach, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina

Love-Brotak, S. Elizabeth, Lead Graphics Production, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina

Ohlmann, Laura, Technical Editor, Innovative Consulting and Management Services, LLC, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina

Noguchi, Lukas, Technical Editor, Innovative Consulting and Management Services, LLC, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina

Riddle, Deborah B., Graphics Support, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina

Veasey, Sara W., Visual Communications Team Lead, Communications and Outreach, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina

STATE OF THE CLIMATE IN 2022

INTRODUCTION

T. Boyer, E. Bartow-Gillies, J. Blunden, and R. J. H. Dunn



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Corresponding author: Jessica Blunden / jessica.blunden@noaa.gov

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Self portrait: Traveling of a lone tourist in the snowy Carpathians among wild forests and fields, during a strong storm with a winter thunderstorm against the backdrop of mountains.

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Editor and Author Affiliations (alphabetical by name)

Bartow-Gillies, Ellen, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina

Blunden, Jessica, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina

Boyer, Tim, NOAA/NESDIS National Centers for Environmental Information, Silver Spring, Maryland

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

Editorial and Production Team

Allen, Jessica, Graphics Support, Cooperative Institute for Satellite Earth System Studies, North Carolina State University, Asheville, North Carolina

Camper, Amy V., Graphics Support, Innovative Consulting and Management Services, LLC, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina

Haley, Bridgette O., Graphics Support, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina

Hammer, Gregory, Content Team Lead, Communications and Outreach, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina

Love-Brotak, S. Elizabeth, Lead Graphics Production, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina

Ohlmann, Laura, Technical Editor, Innovative Consulting and Management Services, LLC, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina

Noguchi, Lukas, Technical Editor, Innovative Consulting and Management Services, LLC, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina

Riddle, Deborah B., Graphics Support, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina

Veasey, Sara W., Visual Communications Team Lead, Communications and Outreach, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina

1. INTRODUCTION

T. Boyer, E. Bartow-Gillies, J. Blunden, and R. J. H. Dunn

The year 2022 was marked by unusual (though not unprecedented) disruptions in the climate system. The first was the third successive year of below-average temperatures in the tropical Pacific. A “triple-dip” La Niña nearly continuous from August 2020 through the end of 2022 marked the first such occurrence in the twenty-first century. Note that the triple-dip La Niña should not be confused with the double-dip La Niña described in the *State of the Climate 2021*, as the double-dip referred to the short interruption between two La Niña events in 2021 which was the only break in the triple-dip period. Descriptions of the large-scale characteristics of the triple-dip La Niña are found in Chapters 2 (Global Climate) and 3 (Global Ocean). The El Niño–Southern Oscillation phenomena, of which the triple-dip La Niña is an anomalous manifestation, has major short-term influence on the climate system. The specific details of the effects of the triple-dip La Niña on other aspects of the climate system are found throughout the report. A perspective of the triple-dip La Niña and its implications for long-term climate are discussed in a sidebar of Chapter 3.

The second unusual event was the extraordinary amount of precipitation over Antarctica in 2022, which led to a record-high annual surface mass balance (since 1980) and the first net positive annual ice-sheet mass balance on the continent since satellite measurements began in 1993. The heavy precipitation was closely tied to an unusually high number of atmospheric rivers over the continent, which carry moisture over Antarctica that mainly falls as snow. March precipitation totals in the Wilkes and Adelie regions were particularly high, estimated to exceed 300% of the 1991–2020 climatological mean. While an increase in ice-sheet mass in Antarctica has positive implications for global continental water storage and hence lessening sea-level increase, atmospheric rivers also have a large impact on surface melt and ice-sheet stability. Surface melt in turn has an impact on ‘firn’, the underlying layer of recrystallized snow from previous years. Firn density is an important factor in determining how surface melt water flows on and within ice shelves, which can reduce glacial stability and lead to their breakup and collapse. There was also record-low sea ice surrounding Antarctica in 2022, and on the eastern Antarctic Peninsula which allowed large swells to reach the coast and caused a breakout of fast ice that contributed to an acceleration of upstream glaciers. The complex interactions of climate factors on the Antarctic continent are discussed in Chapter 6, with particulars in the two sidebars: 1) The Antarctic heatwave of March 2022 and 2) Larsen-B fast ice breakout and glacier response.

A third event in 2022 was the eruption of the Hunga Tonga–Hunga Ha’apai underwater volcano (HTHH) in January. This eruption propelled immense amounts of water vapor (50 Tg to 150 Tg, upwards of 10% of the total stratospheric water vapor burden) and other gases into the stratosphere, with a plume higher than any previous eruption in the satellite era. Implications of the eruption, detailed in a sidebar and elsewhere in Chapter 2, include increased stratospheric aerosols and observations of cool stratospheric temperatures outside normal ranges with correspondingly anomalous winds. Long-term effects on tropospheric temperatures and the Antarctic ozone hole remain to be seen. The HTHH eruption also had an effect on our ability to make observations. For example, as detailed in Chapter 3, the calculation of ocean carbon biomass from satellite measurements has been greatly affected by the amount of sulfate aerosols injected by the HTHH eruption.

Another instance of volcanic activity, though not of the scale of HTHH, but with significant effects on the climate observing system, was the eruption of Mauna Loa in late November 2022. This eruption and subsequent lava flow shut down access and power to the NOAA Mauna Loa Observatory (featured on the cover of Chapter 8, Datasets), interrupting one of the longest time series for a variety of atmospheric variables, including atmospheric carbon dioxide (CO₂) levels. After a 10-day interruption, NOAA's CO₂ measurements were transferred to the University of Hawaii's Maunakea Observatories. The Mauna Loa CO₂ time series is an invaluable monitor of the changes in our climate system (as detailed in Chapter 2). This serves as a reminder of the importance of long-term continuous time series in our understanding of Earth's climate system and the importance of continuing such time series.

All the above singular events, along with the status of essential climate variables (ECVs) and their implications for Earth's climate system are detailed in the *State of the Climate 2022* due to the persistent dedication of the chapter editors and section authors—this year 576 authors from 66 different countries, including Andorra and Namibia for the first time. A distillation of the state of the climate for 2022 in the context of long-term trends and variability of selected essential climate variables is found in the 36 panels of Plate 1.1. The *State of the Climate* report continues to advance toward a more comprehensive survey of essential climate variables (ECVs). A new section on lightning (Chapter 2, Global Climate) documents global distributions in this ECV. A new section on Arctic Precipitation (Chapter 5, the Arctic) adds regional insight into the precipitation ECV.

The layout of this Supplement is similar to previous years. Following this introduction (Chapter 1), Chapter 2 catalogs global climate, Chapter 3 the oceans, Chapter 4 the tropics, Chapters 5 and 6 the high latitudes (Arctic and Antarctic, respectively), and Chapter 7 other specific regions of the globe (North America, Central America/Caribbean, South America, Africa, Europe, Asia, and Oceania). Finally, Chapter 8 is a listing of many (though not all) datasets used in the various sections of the *State of the Climate in 2022* and a link to dataset access and further information. Datasets are listed by chapter. Most of the datasets are readily downloadable by the reader who would like to reproduce the results found in the *State of the Climate* report or investigate further.

GLOBAL AVERAGE TEMPERATURE
The Jan-Dec 2022 average global surface temperature was among the sixth highest since global records began in the mid- to late-1800s.

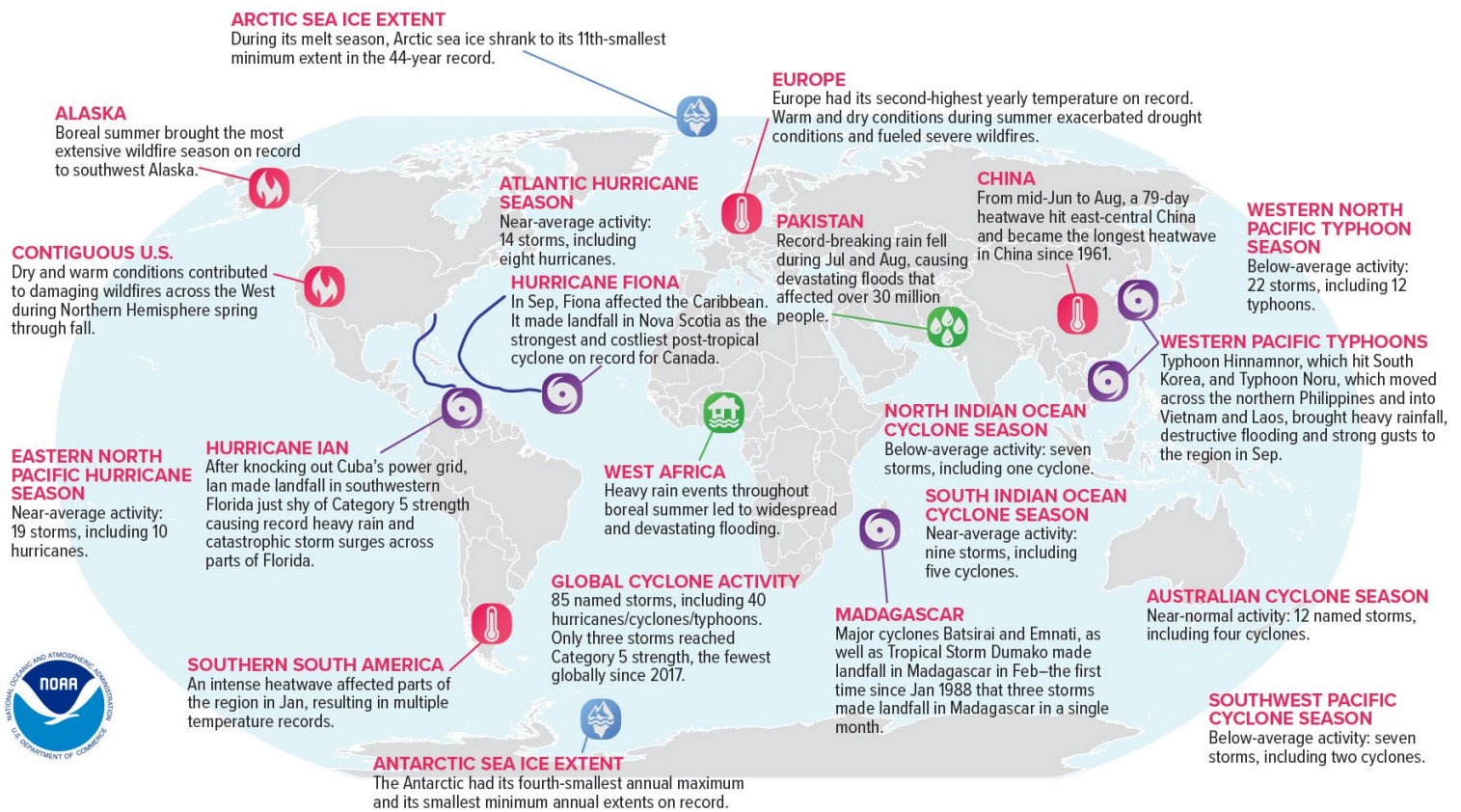
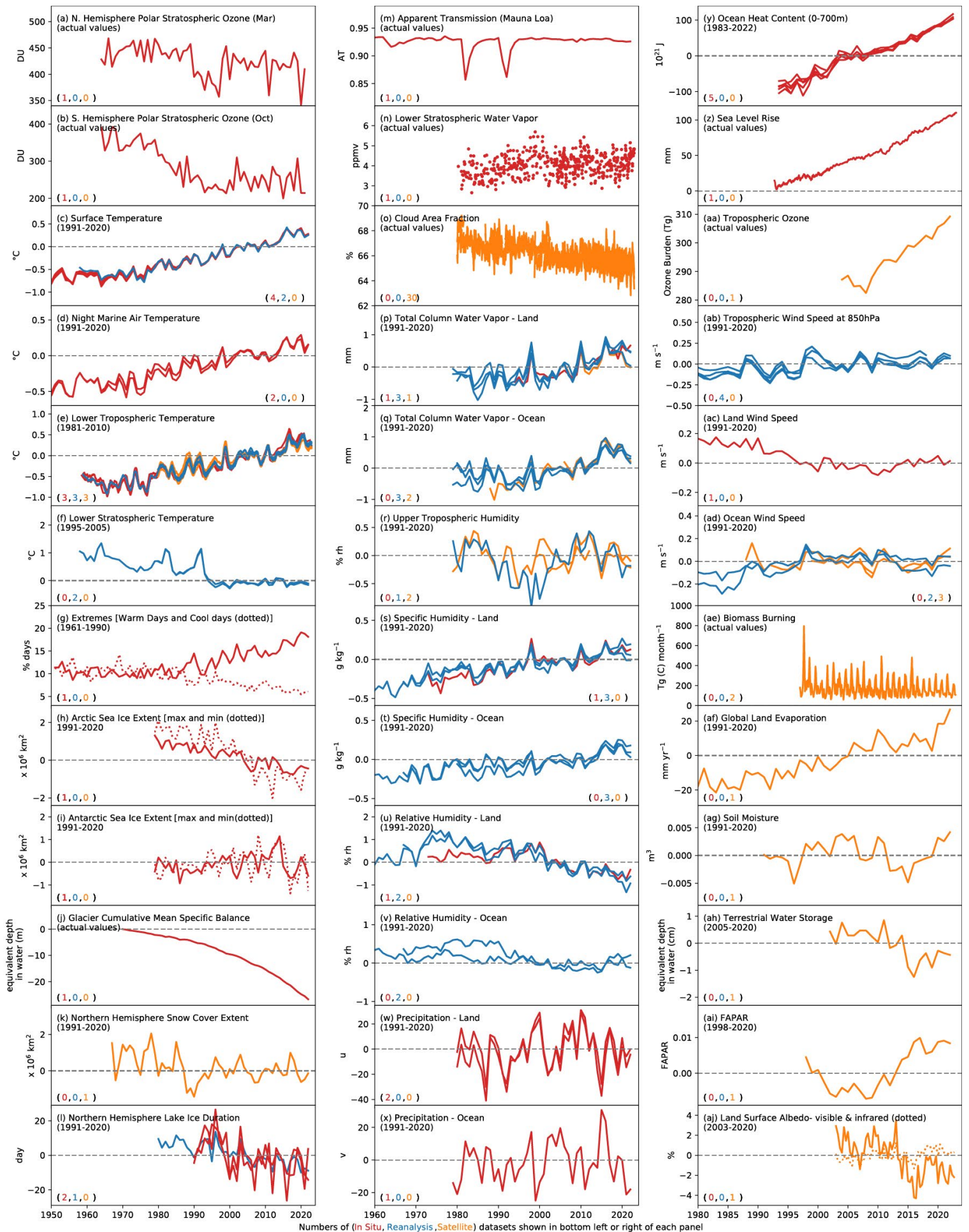


Fig. 1.1. Geographical distribution of selected notable climate anomalies and events in 2022.

Plate 1.1. (Next page) Global (or representative) average time series for essential climate variables through 2019. Anomalies are shown relative to the base period in parentheses although base periods used in other sections of the report may differ. The numbers in the parentheses in the lower left or right side of each panel indicate how many in situ (red), reanalysis (blue), and satellite (orange) datasets are used to create each time series in that order. (a) NH polar stratospheric ozone (Mar); (b) SH polar stratospheric ozone (Oct); (c) surface temperature; (d) night marine air temperature; (e) lower-tropospheric temperature; (f) lower-stratospheric temperature; (g) extremes (warm days [solid] and cool days [dotted]); (h) Arctic sea-ice extent (max [solid]) and min [dotted]); (i) Antarctic sea-ice extent (max [solid] and min [dotted]); (j) glacier cumulative mean specific balance; (k) NH snow-cover extent; (l) NH lake ice duration; (m) Mauna Loa apparent transmission; (n) lower-stratospheric water vapor; (o) cloud area fraction; (p) total column water vapor – land; (q) total column water vapor – ocean; (r) upper-tropospheric humidity; (s) specific humidity – land; (t) specific humidity – ocean; (u) relative humidity – land; (v) relative humidity – ocean; (v) precipitation – land; (x) precipitation – ocean; (y) ocean heat content (0 m–700 m); (z) sea-level rise; (aa) tropospheric ozone; (ab) tropospheric wind speed at 850 hPa; (ac) land wind speed; (ad) ocean wind speed; (ae) biomass burning; (ae) global land evaporation; (af) soil moisture; (ag) terrestrial groundwater storage; (ah) fraction of absorbed photosynthetically active radiation (FAPAR); (ai) land surface albedo – visible (solid) and infrared (dotted).



Numbers of (In Situ, Reanalysis, Satellite) datasets shown in bottom left or right of each panel

Essential Climate Variables

—T. BOYER, E. BARTOW-GILLIES, J. BLUNDEN, AND R.H. DUNN

The following variables are considered fully monitored in this report, in that there are sufficient spatial and temporal data, with peer-reviewed documentation to characterize them on a global scale:

- Surface atmosphere: air pressure, precipitation, temperature, water vapor, wind speed and direction
- Upper atmosphere: Earth radiation budget, temperature, water vapor, wind speed and direction, lightning
- Atmospheric composition: carbon dioxide, methane and other greenhouse gases, ozone
- Ocean physics: ocean surface heat flux, sea ice, sea level, surface salinity, sea-surface temperature, subsurface salinity, subsurface temperature, surface currents, surface stress
- Ocean biogeochemistry: ocean color
- Ocean biogeosystems: plankton
- Land: albedo, river discharge, snow

The following variables are considered partially monitored, in that there is systematic, rigorous measurement found in this report, but some coverage of the variable in time and space is

lacking due to observing limitations or availability of data or authors:

- Atmospheric composition: aerosols properties, cloud properties, precursors of aerosol and ozone
- Ocean physics: subsurface currents
- Ocean biogeochemistry: inorganic carbon
- Land: above-ground biomass, anthropogenic greenhouse gas fluxes, fire, fraction of absorbed photosynthetically active radiation, glaciers, groundwater, ice sheets and ice shelves, lakes, permafrost, soil moisture
- Surface atmosphere: surface radiation budget

The following variables are not yet covered in this report, or are outside the scope of it.

- Ocean physics: sea state
- Ocean biogeochemistry: nitrous oxide, nutrients, oxygen, transient tracers
- Ocean biogeosystems: marine habitat properties
- Land: anthropogenic water use, land cover, land surface temperature, latent and sensible heat fluxes, leaf area index, soil carbon

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