STATE OF THE CLIMATE IN 2018

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Ice-rich permafrost exposed on the face of Itkillik Bluff on the North Slope of Alaska. The bluffs and surrounding ice-rich permafrost have lost large volumes of ice over recent years due to lateral erosion and surface disturbances such as wildfire and climate warming. Members of NASA's Arctic-Boreal Vulnerability Experiment visit this site annually to collect frozen soil and ground ice for carbon analysis. The team also uses regional airborne and space-borne remote sensing to identify potential volume of major ground ice loss in previously unidentified ice-rich parts of the landscape.

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EDITOR AND AUTHOR AFFILIATIONS (ALPHABETICAL BY NAME)

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

Adler, R., University of Maryland, College Park, Maryland

Aldeco, Laura S., Servicio Meteorológico Nacional, Buenos Aires, Argentina

Alejandra, G., Instituto Geofísico del Perú, Lima, Perú

Alfaro, Eric J., Center for Geophysical Research and School of Physics, University of Costa Rica, San José, Costa Rica

Aliaga-Nestares, Vannia, Servisâo Nacional de Meteorología e Hidrología del Perú, Lima, Perú

Allan, Richard P., University of Reading, Reading, United Kingdom

Allan, Rob, Met Office Hadley Centre, Exeter, United Kingdom

Alves, Lincoln M., Centro de Ciencias do Sistema Terrestre, Instituto Nacional de Pesquisas Espaciais, Cachoeira Paulista, Sao Paulo, Brazil

Amador, Jorge A., Center for Geophysical Research and School of Physics, University of Costa Rica, San José, Costa Rica

Andersen, J. K., Geological Survey of Denmark and Greenland, Copenhagen, Denmark

Anderson, John, Department of Atmospheric and Planetary Science, Hampton University, Hampton, Virginia

Arndt, Derek S., NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina

Arosio, C., University of Bremen, Bremen, Germany

Arrigo, Kevin, Department of Earth System Science, Stanford University, Stanford, California

Azorin-Molina, César, Regional Climate Group, Department of Earth Sciences, University of Gothenburg, Gothenburg, Sweden; Centro de Investigaciones sobre Desertificación – Spanish National Research Council, Moncada (Valencia), Spain

Bardin, M. Yu, Yu. A. Izrael Institute of Global Climate and Ecology, and Institute of Geography, Russian Academy of Sciences, Russia

Barichivich, Jonathan, Instituto de Geografía, Pontificia Universidad Católica de Valparaíso, Valparaíso, Chile

Barreira, Sandra, Argentine Naval Hydrographic Service, Buenos Aires, Argentina

Baxter, Stephen, NOAA/NWS Climate Prediction Center, College Park, Maryland

Beck, H. E., Department of Civil and Environmental Engineering, Princeton University, Princeton, New Jersey

Becker, Andreas, Global Precipitation Climatology Centre, Deutscher Wetterdienst, Offenbach am Main., Germany

Bell, Gerald D., NOAA/NWS Climate Prediction Center, College Park, Maryland

Bellouin, Nicolas, University of Reading, Reading, United Kingdom

Belmont, M., Seychelles National Meteorological Services, Pointe Larue, Mahé, Seychelles

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

Benedict, Imme, Meteorology and Air Quality Group, Wageningen University and Research, Wageningen, Netherlands

Bernhard, G. H., Biospherical Instruments Inc., San Diego, California

Berrisford, Paul, NCAS-Climate, European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom

Berry, David I., National Oceanography Centre, Southampton, United Kingdom

Bettio, Lynette, Bureau of Meteorology, Melbourne, Victoria, Australia

Bhatt, U. S., Geophysical Institute, University of Alaska Fairbanks, Fairbanks, Alaska

Biskaborn, B. K., Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Potsdam, Germany

Bissolli, Peter, Deutscher Westterdienst, WMO RA VI Regional Climate Centre Network, Offenbach, Germany

Bjella, Kevin L., Cold Regions Research and Engineering Laboratory (CRREL), Fairbanks, Alaska

Bjerke, J. K., Norwegian Institute for Nature Research, Tromsø, Norway

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

Bock, Olivier, Paris Institute of Globe Physics, Université Paris Diderot, Sorbonne Paris Cité, Paris, France

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

Boucher, Olivier, Sorbonne Université, Paris, France

Box, J. E., Geological Survey of Denmark and Greenland, Copenhagen, Denmark

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

Braathen, Geir, WMO Atmospheric Environment Research Division, Geneva, Switzerland

Bringas, Francis. G., NOAA/OAR Atlantic Oceanographic and Meteorological Laboratory (AOML), Miami, Florida

Bromwich, David. H., Byrd Polar and Climate Research Center, The Ohio State University, Columbus, Ohio

Brown, Alrick, Department of Physics, The University of the West Indies, Jamaica

Brown, R., Climate Research Division, Environment and Climate Change Canada, Montréal, Quebec, Canada

Brown, Timothy J., Western Regional Climate Center, Desert Research Institute, Reno, NV

Buehler, S. A., Universität Hamburg, Hamburg, Germany

Cáceres, Luis, Instituto Nacional de Meteorología e Hidrología de Ecuador, Ecuador

Calderón, Blanca, Center for Geophysical Research, University of Costa Rica, San José, Costa Rica

Camargo, Suzana J., Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York

Campbell, Jayaka D., Department of Physics, The University of the West Indies, Jamaica

Campos Diaz, Diego A., Dirección Meteorológica de Chile, Santiago de Chile, Chile
Cappelen, J., Danish Meteorological Institute, Copenhagen, Denmark
Carrea, Laura, Department of Meteorology, University of Reading, Reading, United Kingdom
Carrier, Seth B., National Institute of Water and Atmospheric Research, Ltd., Auckland, New Zealand
Carter, Brendan R., Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, and NOAA/OAR Pacific Marine Environmental Laboratory, Seattle, Washington
Castro, Anabel Y., Servicio Nacional de Meteorología e Hidrología del Perú, Lima, Perú
Cetinić, Ivona, NASA Goddard Space Flight Center, Greenbelt, Maryland, and Universities Space Research Association, Columbia, Maryland
Chambers, Don P., College of Marine Science, University of South Florida, St. Petersburg, Florida
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
Christiansen, Hanne H., Geology Department, University Centre in Svalbard, Longyearbyen, Norway
Christy, John R., The University of Alabama in Huntsville, Huntsville, Alabama
Chung, E.-S., IBS Center for Climate Physics, Busan, South Korea
Claus, Federico, Argentine Naval Hydrographic Service, Buenos Aires, Argentina,
Clem, Kyle R., Institute of Earth, Ocean, and Atmospheric Sciences, Rutgers, the State University of New Jersey, New Brunswick New Jersey
Coelho, Caio A. S., CPTEC/INPE Center for Weather Forecasts and Climate Studies, Cachoeira Paulista, Brazil
Coldewey-Egbers, Melanie, German Aerospace Center (DLR) Oberpfaffenhofen, Wessling, 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, and NOAA/OAR Earth System Research Laboratory, Boulder, Colorado
Cosca, Cathy, NOAA/OAR Pacific Marine Environmental Laboratory, Seattle, Washington
Covey, Curt, Lawrence Livermore National Laboratory, Livermore, California
Coy, Lawrence, Science Systems and Applications, Inc., NASA Goddard Space Flight Center, Greenbelt, Maryland
Dávila, Cristina P., Servicio Nacional de Meteorología e Hidrología del Perú, Lima, Perú
Davis, Sean M., Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, and NOAA/OAR Earth System Research Laboratory, Boulder, Colorado
de Eyto, Elvira, Marine Institute, Furnace, Newport, Ireland
de Jeu, Richard A. M., VanderSat B.V., Haarlem, Netherlands
De Laat, Jos, Royal Netherlands Meteorological Institute (KNMI), DeBilt, Netherlands
Decharme, B., Centre National de Recherches Météorologiques, France
DeGasperi, Curtis L., King County Water and Land Resources Division, Seattle, Washington
Degenstein, Doug, University of Saskatchewan, Saskatoon, Saskatchewan Canada
Demircan, Mesut, Turkish State Meteorological Service, Ankara, Turkey
Derksen, C., Climate Research Division, Environment and Climate Change Canada,Downsview, Ontario, Canada
Dhurmea, K. R., Mauritius Meteorological Service, Vacoas, Mauritius
Di Girolamo, Larry, University of Illinois at Urbana-Champaign, Champaign, Illinois
Diamond, Howard J., NOAA/OAR Air Resources Laboratory, College Park, Maryland
Diaz, Eliecer, Instituto de Hidrología de Meteorología y Estudios Ambientales de Colombia (IDEAM), Bogotá, Colombia
Diniz, Fransisco A., Instituto Nacional de Meteorologia, Brasilia, Brazil
Dlugokencky, Ed J., NOAA/OAR Earth System Research Laboratory, Boulder, Colorado
Dohan, Kathleen, Earth and Space Research, Seattle, Washington
Dokulil, Martin T., Research Department for Limnology Mondsee, University of Innsbruck, Austria
Dolman, A. Johannes, Department of Earth Sciences, VU University Amsterdam, Amsterdam, Netherlands
Domingues, Catia M., Institute for Marine and Antarctic Studies, University of Tasmania, Antarctic Climate and Ecosystems Cooperative Research Centre, and Australian Research Council's Centre of Excellence for Climate System Science, Hobart, Tasmania, Australia
Domingues, Ricardo, Cooperative Institute for Marine and Atmospheric Studies, University of Miami and NOAA OAR Atlantic Oceanographic and Meteorological Laboratory (ADML), Miami, Florida,
Donat, Markus G., Barcelona Supercomputing Centre, Barcelona, Spain
Dorigo, Wouter A., Department of Geodesy and Geoinformation, TU Wien - Vienna University of Technology, Vienna, Austria
Drozdov, D. S., Earth Cryosphere Institute, and Tyumen State University, Tyumen, Russia
Druckenmiller, Matthew L., National Snow and Ice Data Center, 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
Dutton, Geoff S., Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, and NOAA/OAR Earth System Research Laboratory, Boulder, Colorado
ElKharrim, M., Direction de la Météorologie Nationale Maroc, Rabat, Morocco
Elkins, James W., NOAA/OAR Earth System Research Laboratory, Boulder, Colorado
Epstein, H. E., Department of Environmental Sciences, University of Virginia, Charlottesville, Virginia
Espinoza, Jhan C., Instituto Geofisico del Perú, Lima, Perú, and Université Grenoble Alpes, Grenoble, France
Famiglietti, James S., Global Institute for Water Security, School of Environment and Sustainability, and Department of Geography and Planning, University of Saskatchewan, Saskatoon, Canada
Farrell, Sinead L., NOAA Earth System Science Interdisciplinary Center, University of Maryland, College Park, Maryland
Fausto, R. S., Geological Survey of Denmark and Greenland, Copenhagen, Denmark
Feely, Richard A., NOAA/OAR Pacific Marine Environmental Laboratory, Seattle, Washington
Feng, Z., Atmospheric Sciences and Global Change Division, Pacific Northwest National Laboratory, Richland, Washington
Fenimore, Chris, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina
Fettweis, X., University of Liège, Liège, Belgium
Fioletov, Vitali E., Environment and Climate Change Canada, Toronto, Canada
Flemming, Johannes, European Centre for Medum-Range Weather Forecasts, Reading, United Kingdom
Fogt, Ryan L., Department of Geography, Ohio University, Athens, Ohio
Forbes, B. 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
Francis, S. D., National Weather Forecasting and Climate Research Centre, Nigerian Meteorological Agency, Abuja, Nigeria
Franz, Bryan A., NASA Goddard Space Flight Center, Greenbelt, Maryland
Frey, Richard A., Cooperative Institute for Meteorological Satellite Studies, Space Science and Engineering Center, University of Wisconsin-Madison, Madison, Wisconsin
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
Ganter, Catherine, Bureau of Meteorology, Melbourne, Victoria, Australia
Garforth, J., Woodland Trust, Grantham, United Kingdom
Gerland, Sebastian, Norwegian Polar Institute, Fram Centre, Tromsø, Norway
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, Knowledge Management for Sustainable Development and Food Security Unit, European Commission, Joint Research Centre, Ispra, Italy
Goetz, S., School of Informatics, Computing, and Cyber Systems, Northern Arizona University, Flagstaff, Arizona
Goldenberg, Stanley B., NOAA/OAR/AOML Hurricane Research Division, Miami, Florida
Goni, Gustavo, NOAA/OAR Atlantic Oceanographic and Meteorological Laboratory (AOML), Miami, Florida
Gray, Alison, School of Oceanography, University of Washington, Seattle, Washington
Grooß, Jens-Uwe, Forschungszentrum Jülich, Jülich, Germany
Gruber, Alexander, Department of Geodesy and Geoinformation, TU Wien - Vienna University of Technology, Vienna, Austria; Department of Earth and Environmental Sciences, KU Leuven, Heverlee, Belgium
Gu, Guojun, University of Maryland, College Park, Maryland
Guard, Charles "Chip" P., NOAA/NWS Weather Forecast Office, Guam
Gupta, S. K., Science Systems and Applications, Inc., Hampton, Virginia
Gutiérrez, Dimitri, Instituto del Mar del Perú, Callao, Perú
Haas, Christian, Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany
Hagos, S., Atmospheric Sciences and Global Change Division, Pacific Northwest National Laboratory, Richland, Washington
Hahn, Sebastian, Department of Geodesy and Geoinformation, TU Wien - Vienna University of Technology, Vienna, Austria
Haimberger, Leo, Department of Meteorology and Geophysics, University of Vienna, Vienna, Austria
Hall, Brad D., NOAA/OAR Earth System Research Laboratory, Boulder, Colorado
Halpert, Michael S., NOAA/NWS Climate Prediction Center, College Park, Maryland
Hamlington, Benjamin D., NASA Jet Propulsion Laboratory, Pasadena, California
Hanna, E., School of Geography and Lincoln Centre for Water and Planetary Health, University of Lincoln, Lincoln, United Kingdom
Hanssen-Bauer, I., Norwegian Meteorological Institute, Blindern, Oslo, Norway
Harris, Ian, National Centre for Atmospheric Science (NCAS), University of East Anglia, Norwich, United Kingdom and Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich, United Kingdom

Hazeleger, Wilco, Meteorology and Air Quality Group, Wageningen University and Research, Wageningen, Netherlands; Netherlands eScience Center, Amsterdam, Netherlands; and Faculty of Geosciences, Utrecht University, Utrecht, Netherlands.
He, Q., Earth System Modeling Center, Nanjing University of Information Science and Technology, Nanjing, China
Heidinger, Andrew K., NOAA/NESDIS/STAR University of Wisconsin-Madison, Madison, Wisconsin
Heim, Jr., Richard R., NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina
Hemming, D. 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
Hernández, Rafael, Instituto Nacional de Meteorología e Hidrología de Venezuela (INAMEH), Caracas, Venezuela
Hersbach, H. E., European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom,
Hidalgo, Hugo G., Center for Geophysical Research and School of Physics, University of Costa Rica, San José, Costa Rica
Ho, Shu-peng (Ben), NOAA/NESDIS Center for Satellite Applications and Research, College Park, Maryland
Holmes, R. M., Woods Hole Research Center, Falmouth, Massachusetts
Hu, Chuanmin, College of Marine Science, University of South Florida, St. Petersburg, Florida
Huang, Boyin, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina
Hubbard, Katherine, Florida Fish and Wildlife Conservation Commission, St. Petersburg, Florida
Hubert, Daan, Royal Belgian Institute for Space Aeronomy (BIRA), Brussels, Belgium
Hurst, Dale F., Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, and NOAA/OAR Earth System Research Laboratory, Boulder, Colorado
Ialongo, Iolanda, Finnish Meteorological Institute, Helsinki, Finland
Ijampy, J. A., Nigerian Meteorological Agency, Abuja, Nigeria
Inness, Antje, European Centre for Medium Range Weather Forecasts, Reading, United Kingdom
Isaac, Victor, Environment and Climate Change Canada, Toronto, Ontario, Canada
Isaksen, K., Norwegian Meteorological Institute, Blindern, Oslo, Norway
Ishii, Masayoshi, Climate Research Department, Meteorological Research Institute, Japan Meteorological Agency, Tsukuba, Japan
Jeffries, Martin O., Cold Regions Research and Engineering Laboratory, ERDC-USACE, Hanover, New Hampshire
Jevrejeva, Svetlana, National Oceanography Centre, Liverpool, United Kingdom
Jia, G., Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China
Jiménez, C., Estellus, Paris, France
Jin, Xiangze, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts
John, Viju, EUMETSAT, Darmstadt, Germany
Johnsen, Bjørn, Norwegian Radiation and Nuclear Safety, Østerås, Norway
Johnson, Gregory C., NOAA/OAR Pacific Marine Environmental Laboratory, Seattle, Washington
Johnson, Kenneth S., Monterey Bay Aquarium Research Institute, Moss Landing, California
Johnson, Bryan, NOAA/OAR Earth System Research Laboratory, Global Monitoring Division, and University of Colorado, Boulder, Colorado
Jones, Philip D., Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich, United Kingdom
Jumaux, Guillaume, Météo France, Direction Interrégionale pour l'Océan Indien, Réunion
Kabidi, Khadija, Direction de la Météorologie Nationale Maroc, Rabat, Morocco
Kaiser, J. W., Max Planck Institute for Chemistry, Mainz, Germany; Deutscher Wetterdienst, Offenbach, Germany
Karaköylü, Erdem M., NASA Goddard Space Flight Center, Greenbelt, Maryland, and Science Application International Corporation, Beltsville, Maryland
Karlsen, S.-R., Norut Northern Research Institute, Tromsø, Norway
Karnauskas, Mandy, NOAA/NMFS Southeast Fisheries Science Center, Miami, Florida
Kato, Seiji, NASA Langley Research Center, Hampton, Virginia
Kazemi, A. Fazl, Islamic Republic of Iranian Meteorological Organization, Iran
Kelble, Christopher, NOAA/OAR Atlantic Oceanographic and Meteorological Laboratory (AOML), Miami, Florida
Keller, Linda M., Department of Atmospheric and Oceanic Sciences, University of Wisconsin-Madison, Madison, Wisconsin
Kennedy, John, Met Office Hadley Centre, Exeter, United Kingdom
Kholodov, A. L., Geophysical Institute, University of Alaska Fairbanks, Fairbanks, Alaska
Khoshkam, Mahbobeh, Islamic Republic of Iranian Meteorological Organization, Iran
Kidd, R., Earth Observation Data Centre for Water Resources Monitoring GmbH, Vienna, Austria
Killick, Rachel, Met Office Hadley Centre, Exeter, United Kingdom,
Kim, Hyungjun, Institute of Industrial Science, The University of Tokyo, Tokyo, Japan
Kim, S.-J., Korea Polar Research Institute, Incheon, Republic of Korea
King, A. D., University of Melbourne, Melbourne, Australia
King, Brian A., National Oceanography Centre, Southampton, United Kingdom

Kipling, Z., 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
Korhonen, Johanna, Freshwater Centre, Finnish Environment Institute (SYKE, Helsinki, Finland
Korshunova, Natalia N., All-Russian Research Institute of Hydrometeorological Information - World Data Center, Obninsk, Russia
Kramarova, Natalya A., NASA Goddard Space Flight Center, Greenbelt, Maryland
Kratz, D. P., NASA Langley Research Center, Hampton, Virginia
Kruger, Andries, South African Weather Service and Department of Geography, Geoinformatics, and Meteorology, University of Pretoria, Pretoria, South Africa,
Kruk, Michael C., KBR, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina
Krumpen, Thomas, Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany
Labbé, L., Météo France, Direction Interrégionale pour l'Océan Indien, Réunion
Ladd, C., NOAA/OAR Pacific Marine Environmental Laboratory, Seattle, Washington
Lakatos, Mónika, Climatology Division, Hungaran Meteorological Service, Budapest, Hungary
Lakkala, Kaisa, Finnish Meteorological Institute, Arctic Research Centre, Sodankylä, Finland
Lander, Mark A., University of Guam, Mangilao, Guam
Landschützer, Peter, Max Planck Institute for Meteorology, Hamburg, Germany
Landsea, Chris W., NOAA/NWS National Hurricane Center, Miami, Florida,
Lareau, Neil P., Department of Physics, University of Nevada, Reno, NV
Lavado-Casimiro, Waldo, Servicio Nacional de Meteorología e Hidrología del Perú, Lima, Perú
Lazzara, Matthew A., Department of Physical Sciences, School of Arts and Sciences, Madison Area Technical College, and Space Science and Engineering Center, University of Wisconsin-Madison, Madison, Wisconsin
Lee, T. C., Hong Kong Observatory, Hong Kong, China
Leuliette, Eric, NOAA/NWS NCWCP Laboratory for Satellite Altimetry, College Park, Maryland
L'Heureux, Michelle, NOAA/NWS Climate Prediction Center, College Park, Maryland
Li, Bailing, Hydrological Sciences Laboratory, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA; Earth System Science Interdisciplinary Center, University of Maryland, College Park, Maryland
Li, Tim, Department of Atmospheric Sciences, University of Hawaii, Honolulu, Hawaii
Lieser, Jan L., Antarctic Climate and Ecosystems Cooperative Research Centre and Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, Australia
Lim, J.-Y., Climate Prediction Division, Korea Meteorological Administration, South Korea
Lin, I.-I., National Taiwan University, Taipei, Taiwan
Liu, Hongxing, Department of Geography, University of Cincinnati, Cincinnati, Ohio
Locarnini, Ricardo, NOAA/NESDIS National Centers for Environmental Information, Silver Spring, Maryland
Loeb, Norman G., NASA Langley Research Center, Hampton, Virginia
Long, Craig S., NOAA/NWS National Centers for Environmental Prediction, College Park, Maryland
López, Luis A., Instituto de Hidrología, Meteorología y Estudios Ambientales de Colombia, Bogotá, Colombia
Lorrey, Andrew M., National Institute of Water and Atmospheric Research, Ltd., Auckland, New Zealand
Loyola, Diego, German Aerospace Center (DLR) Oberpfaffenhofen, Wessling, Germany
Lumpkin, Rick, NOAA/OAR Atlantic Oceanographic and Meteorological Laboratory (AOML), Miami, Florida
Luo, Jing-Jia, Institute for Climate and Application Research (ICAR)/KLME/ILCEC/CIC-FEMD, Nanjing University of Information Science and Technology, Nanjing, China
Luojus, K., Finnish Meteorological Institute, Helsinki, Finland
Lyman, John M., NOAA/OAR Pacific Marine Environmental Laboratory, Seattle, Washington, and Joint Institute for Marine and Atmospheric Research, University of Hawaii, Honolulu, Hawaii
Malkova, G. V., Earth Cryosphere Institute, Tyumen Science Center, Tyumen, Russia
Manney, Gloria L., NorthWest Research Associates, and New Mexico Institute of Mining and Technology, Socorro, New Mexico
Marchenko, S. S., Geophysical Institute, University of Alaska Fairbanks, Fairbanks, Alaska
Marengo, José A., Centro Nacional de Monitoramento e Alertas aos Desastres Naturais, Cachoeira Paulista, São Paulo, Brazil
Marin, Dora, Servicio Nacional de Meteorología e Hidrología de Perú, Lima, Perú
Marquardt Collow, Allison B., Universities Space Research Association, Columbia, Maryland; NASA GSFC Global Modeling and Assimilation Office, Greenbelt, Maryland
Marra, John J., NOAA/NESDIS National Centers for Environmental Information, Honolulu, Hawaii
Marszelewski, Wlodzimierz, Department of Hydrology and Water Management, Nicolaus Copernicus University, Toruń, Poland
Martens, B., Laboratory of Hydrology and Water Management, Ghent University, Ghent, Belgium
Martínez-Güingla, Rodney, Centro Internacional para la Investigación del Fenómeno de El Niño, Guayaquil, Ecuador

Massom, Robert A., Australian Antarctic-Division, and Antarctic Climate and Ecosystems Cooperative Research Centre, University of Tasmania, Hobart, Tasmania, Australia

May, Linda, Centre for Ecology and Hydrology, Edinburgh, United Kingdom

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

Mazloff, Matthew, Scripps Institution of Oceanography, University of California San Diego, La Jolla, California

McBride, Charlotte, South African Weather Service, Pretoria, South Africa

McCabe, M., Division of Biological and Environmental Sciences and Engineering, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia

McClelland, J. W., Marine Science Institute, University of Texas at Austin, Port Aransas, Texas

McEvoy, Daniel J., Western Regional Climate Center, Desert Research Institute, Reno, Nevada

McGree, Simon, Bureau of Meteorology, Melbourne, Victoria, Australia

McVicar, Tim R., CSIRO Land and Water, Canberra, Australian Capital Territory; and Australian Research Council Centre of Excellence for Climate Extremes, Sydney, New South Wales, Australia

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

Meier, Walt, National Snow and Ice Data Center, University of Colorado, Boulder, Boulder, Colorado

Meijers, Andrew, British Antarctic Survey, Cambridge, United Kingdom

Mekonnen, Ademe, Department of Physics, North Carolina A & T State University, Greensboro, North Carolina

Mengistu Tsidu, G., Department of Earth and Environmental Sciences, Botswana International University of Science and Technology, Palapye, Botswana, and Department of Physics, Addis Ababa University, Addis Ababa, Ethiopia

Menzel, W. Paul, Space Science and Engineering Center, University of Wisconsin-Madison, Madison, Wisconsin

Merchant, Christopher J., Department of Meteorology, University of Reading, Reading, United Kingdom; National Centre for Earth Observation, University of Reading, Reading, United Kingdom

Meredith, Michael P., British Antarctic Survey, Cambridge, United Kingdom

Merrifield, Mark A., Scripps Institution of Oceanography, University of California San Diego, La Jolla, California

Miller, Ben, Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, and NOAA/OAR Earth System Research Laboratory, Boulder, Colorado

Miralles, Diego G., Laboratory of Hydrology and Water Management, Ghent University, Ghent, Belgium

Misevicius, Noelia, Instituto Uruguayo de Meteorología, Montevideo, Uruguay

Mitchum, Gary T., College of Marine Science, University of South Florida, St. Petersburg, Florida

Mochizuki, Y., Tokyo Climate Center, Japan Meteorological Agency, Japan

Monselesan, Didier, CSIRO Oceans and Atmosphere, Hobart, Tasmania, Australia

Montzka, Stephen A., NOAA/OAR Earth System Research Laboratory, Boulder, Colorado

Mora, Natali, Center for Geophysical Research and School of Physics, University of Costa Rica, San José, Costa Rica

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

Mosquera-Vásquez, Kobi, Instituto Geofísico del Perú, Lima, Perú

Mostafa, Awatif E., Department of Seasonal Forecast and Climate Research, Cairo Numerical Weather Prediction, Egyptian Meteorological Authority, Cairo, Egypt

Mote, T., Department of Geography, University of Georgia, Athens, Georgia

Mudryk, L., Climate Research Division, Environment and Climate Change Canada, Downsview, Ontario, Canada

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

Mullan, A. Brett, National Institute of Water and Atmospheric Research, Ltd., Wellington, New Zealand

Müller, Rolf, Forschungszentrum Jülich, Jülich, Germany

Myneni, R., Department of Earth and Environment, Boston University, Boston, Massachusetts

Nash, Eric R., Science Systems and Applications, Inc., NASA Goddard Space Flight Center, Greenbelt, Maryland

Nauslar, Nicholas J., NOAA/NWS/NCEP Storm Prediction Center, Norman, Oklahoma

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, Reading, United Kingdom

Nieto, Juan José, Centro Internacional para la Investigación del Fenómeno de El Niño, Guayaquil, Ecuador

Noetzli, Jeannette, WSL Institute for Snow and Avalanche Research SLF, Davos-Dorf, Switzerland

Osborn, Tim J., Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich, United Kingdom

Osborne, Emily, NOAA/OAR Arctic Research Program, Silver Spring, Maryland

Overland, J., NOAA/OAR Pacific Marine Environmental Laboratory, Seattle, Washington

Oyunjargal, Lamjav, Hydrology and Environmental Monitoring, Institute of Meteorology and Hydrology, National Agency for Meteorology, Ulaanbaatar, Mongolia

Park, T., Department of Earth and Environment, Boston University, Boston, Massachusetts

Pasch, Richard J., NOAA/NWS National Hurricane Center, Miami, Florida
Pascual Ramírez, Reynaldo, National Meteorological Service of Mexico, Mexico
Pastor Saavedra, Maria Asuncion, Agencia Estatal de Meteorología, Madrid, Spain
Paterson, Andrew M., Dorset Environmental Science Centre, Ontario Ministry of the Environment and Climate Change, Dorset, Ontario, Canada
Pearce, Petra R., National Institute of Water and Atmospheric Research, Ltd., Auckland, New Zealand
Pelto, Mauri S., Nichols College, Dudley, Massachusetts
Perovich, Don, Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire
Petropavlovskikh, Irina, Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, and NOAA/OAR Earth System Research Laboratory, Boulder, Colorado
Pezza, Alexandre B., Greater Wellington Regional Council, Wellington, New Zealand
Phillips, C., Department of Atmospheric and Oceanic Sciences, University of Wisconsin-Madison, Madison, Wisconsin
Phillips, David, Environment and Climate Change Canada, Toronto, Ontario, Canada
Phoenix, G., Department of Animal and Plant Sciences, University of Sheffield, Sheffield, United Kingdom
Pinty, Bernard, European Commission, Joint Research Centre, Ispra, Italy
Pitts, Michael, NASA Langley Research Center, Hampton, Virginia
Po-Chedley, S., Lawrence Livermore National Laboratory, Livermore, California
Polashenski, Chris, USACE, ERDC, Cold Regions Research and Engineering Laboratory, and Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire
Preimesberger, W., Department of Geodesy and Geoinformation, TU Wien - Vienna University of Technology, Vienna, Austria
Purkey, Sarah G., Scripps Institution of Oceanography, University of California San Diego, La Jolla, California
Quispe, Nelson, Servicio Nacional de Meteorología e Hidrología del Perú, Lima, Perú
Rajeevan, Madhavan, Earth System Science Organization, Ministry of Earth Sciences, New Delhi, India
Rakotoarimalala, C. L., Madagascar Meteorological Service, Antananarivo, Madagascar
Ramos, Andrea M., Instituto Nacional de Meteorologia, Brasilia, Brazil
Ramos, Isabel, Servicio Nacional de Meteorología e Hidrología del Perú, Lima, Perú
Randel, W., National Center for Atmospheric Research, Boulder, Colorado
Raynolds, M. K., Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, Alaska
Reagan, James, Earth System Science Interdisciplinary Center/ Cooperative Institute for Climate and Satellites–Maryland, University of Maryland, College Park, Maryland and NOAA/ NESDIS National Centers for Environmental Information, Silver Spring, Maryland
Reid, Phillip, Australian Bureau of Meteorology, and Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart, Tasmania, Australia
Reimer, Christoph, Earth Observation Data Centre for Water Resources Monitoring GmbH, Vienna, Austria
Rémy, Samuel, Institut Pierre-Simon Laplace, CNRS / UPMC, Paris, France
Revadekar, Jayashree V., Indian Institute of Tropical Meteorology, Pune, India
Richardson, A. D., School of Informatics, Computing, and Cyber Systems and Center for Ecosystem Science and Society, Northern Arizona University, Flagstaff, Arizona
Richter-Menge, Jacqueline, University of Alaska Fairbanks, Fairbanks, Alaska
Ricker, Robert, Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany
Ripaldi, A., Climate Variability Division, Center for Climate Change Information, BMKG, Indonesia
Robinson, David A., Department of Geography, Rutgers University, Piscataway, New Jersey
Rodell, Matthew, Hydrological Sciences Laboratory, NASA Goddard Space Flight Center, Greenbelt, Maryland
Rodriguez Camino, Ernesto, Agencia Estatal de Meteorología, Madrid, Spain
Romanovsky, Vladimir E., Geophysical Institute, University of Alaska Fairbanks, Fairbanks, Alaska; Earth Cryosphere Institute, Tyumen Science Center, Tyumen, Russia
Ronchail, Josyane, Université Paris Diderot/Laboratoire LOCEAN-IPSL, Paris, France
Rosenlof, Karen H., NOAA/OAR Earth System Research Laboratory, Boulder, Colorado
Rösner, Benajamin, Laboratory for Climatology and Remote Sensing, Faculty of Geography, University of Marburg, Marburg, Germany
Roth, Chris, University of Saskatchewan, Saskatoon, Saskatchewan, Canada
Rozanov, A., University of Bremen, Bremen, Germany
Rusak, James A., Dorset Environmental Science Centre, Ontario Ministry of the Environment and Climate Change, Dorset, Ontario, Canada
Rustemeier, Elke, Global Precipitation Climatology Centre, Deutscher Wetterdienst, Offenbach am Main, Germany
Rutishäuser, T., Institute of Geography and Oeschger Center, University of Berne, Berne, Switzerland
Sallée, Jean-Baptiste, Sorbonne Universités, UPMC University of Paris, L'OCEAN-IPSL, Paris, France
Sánchez-Lugo, Ahira, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina
Santee, Michelle L., NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

Sawaengphokhai, P., Science Systems and Applications, Inc., Hampton, Virginia

Sayouri, Amal, Direction de la Météorologie Nationale Maroc, Rabat, Morocco

Scambos, Ted A., Earth Science and Observation Center, CIRES, University of Colorado, Boulder Colorado

Scanlon, T., Department of Geodesy and Geoinformation, TU Wien - Vienna University of Technology, Vienna, Austria

Scardilli, Alvaro S., Argentine Naval Hydrographic Service, Buenos Aires, Argentina

Schenzinger, Verena, Department of Meteorology and Geophysics, University of Vienna, Vienna, Austria

Schladow, S. Geoffey, Tahoe Environmental Research Center, University of California at Davis, Davis, California

Schmid, Claudia, NOAA/OAR Atlantic Oceanographic and Meteorological Laboratory (AOML), Miami, Florida

Schmid, Martin, Eawag, Swiss Federal Institute of Aquatic Science and Technology, Kastanienbaum, Switzerland,

Schoeneich, P., Institut de Géographie Alpine, Grenoble, France

Schreck III, Carl J., North Carolina State University, Cooperative Institute for Climate and Satellites – North Carolina (CICS-NC), Asheville, North Carolina

Selkirk, H. B., Universities Space Research Association, NASA Goddard Space Flight Center, Greenbelt, Maryland

Sensoy, Serhat, Turkish State Meteorological Service, Ankara, Turkey

Shi, Lei, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina

Shiklomanov, A. I., University of New Hampshire, Durham, New Hampshire; Arctic and Antarctic Research Institute, St. Petersburg, Russia

Shiklomanov, Nikolai I., Department of Geography, George Washington University, Washington, DC

Shimpo, A., Tokyo Climate Center, Japan Meteorological Agency, Tokyo, Japan

Shuman, Christopher A., UMBC JET at NASA Goddard Space Flight Center, Code 615, Greenbelt, Maryland

Siegel, David A., Earth Research Institute and Department of Geography, University of California - Santa Barbara, Santa Barbara, California

Sima, Fatou, Division of Meteorology, Department of Water Resources, Banjul, The Gambia

Simmons, Adrian J., European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom

Smeets, C. J. P. P., Institute for Marine and Atmospheric Research Utrecht, Utrecht University, Utrecht, Netherlands

Smith, Adam, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina

Smith, Sharon L., Geological Survey of Canada, Natural Resources Canada, Ottawa, Ontario, Canada

Soden, B., Rosenstiel School of Marine and Atmospheric Science, University of Miami, Key Biscayne, Florida

Sofieva, Viktoria, Finnish Meteorological Institute (FMI), Helsinki, Finland

Sparks, T. H., Poznań University of Life Sciences, Poznań, Poland

Spence, Jacqueline, Meteorological Service, Jamaica, Kingston, Jamaica

Spencer, R. G. M., Florida State University, Tallahassee, Florida

Spillane, Sandra, Met Éireann, Irish Meteorological Service, Dublin, Ireland

Srivastava, A.K., India Meteorological Department, Pune, India

Stabeno, P. J., NOAA Pacific Marine Environmental Laboratory, Seattle, Washington

Stackhouse Jr., Paul W., NASA Langley Research Center, Hampton, Virginia

Stammerjohn, Sharon, Institute of Arctic and Alpine Research, University of Colorado, Boulder, Colorado

Stanitski, Diane M., NOAA/OAR Earth System Research Laboratory, Boulder, Colorado

Steinbrecht, Wolfgang, Deutscher Wetterdienst (DWD), Hohenpeissenberg, Germany

Stella, José L., Servicio Meteorológico Nacional, Buenos Aires, Argentina

Stengel, M., Deutscher Wetterdienst, Offenbach, Germany

Stephenson, Tannecia S., Department of Physics, The University of the West Indies, Jamaica

Strahan, Susan E., Universities Space Research Association, NASA Goddard Space Flight Center, Greenbelt, Maryland

Streeter, Casey, Florida Commercial Watermen's Conservation, Matlacha, Florida

Streletskiy, Dimitri A., Department of Geography, George Washington University, Washington, DC

Sun-Mack, Sunny, Science Systems and Applications, Inc., Hampton, Virginia

Suslova, A., Woods Hole Research Center, Falmouth, Massachusetts

Sutton, Adrienne J., NOAA/OAR Pacific Marine Environmental Laboratory, Seattle, Washington

Swart, Sebastiann, Department of Marine Sciences, University of Gothenburg, Gothenburg, Sweden and Department of Oceanography, University of Cape Town, Rondebosch, South Africa

Sweet, William, NOAA/NOS Center for Operational Oceanographic Products and Services, Silver Spring, Maryland

Takahashi, Kenneth S., Servicio Nacional de Meteorología e Hidrología del Perú, Lima, Perú

Tank, S.E., University of Alberta, Edmonton, Alberta, Canada

Taylor, Michael A., Department of Physics, The University of the West Indies, Jamaica

Tedesco, M., Lamont Doherty Earth Observatory, Columbia University, Palisades, New York, and NASA Goddard Institute of Space Studies, New York, New York

Thackeray, S. J., Centre for Ecology and Hydrology, Lancaster, United Kingdom

Thompson, Philip R., Joint Institute for Marine and Atmospheric Research, University of Hawaii, Honolulu, Hawaii

Timbal, Bertrand, Centre for Climate Research, Singapore Meteorological Service, Singapore
Timmermans, M.-L., Yale University, New Haven, Connecticut
Tobin, Skie, Bureau of Meteorology, Melbourne, Victoria, Australia
Tømmervik, H., Norwegian Institute for Nature Research, Tromsø, Norway
Tourpali, Kleareti, Aristotle University, Thessaloniki, Greece
Trachte, Katja, Laboratory for Climatology and Remote Sensing, Faculty of Geography, University of Marburg, Marburg, Germany
Tretiakov, M., Arctic and Antarctic Research Institute, St. Petersburg, Russia
Trewin, Blair C., Australian Bureau of Meteorology, Melbourne, Victoria, Australia
Triñanes, Joaquin A., Laboratory of Systems, Technological Research Institute, Universidad de Santiago de Compostela, Campus Universitario Sur, Santiago de Compostela, Spain; NOAA/OAR Atlantic Oceanographic and Meteorological Laboratory (AOML), Miami, Florida, and Cooperative Institute for Marine and Atmospheric Studies, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida
Trotman, Adrian R., Caribbean Institute for Meteorology and Hydrology, Bridgetown, Barbados
Tschudi, Mark, Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado
Tye, Mari R., Capacity Center for Climate and Weather Extremes (C3WE), National Center for Atmospheric Research, Boulder, Colorado
van As, D., Geological Survey of Denmark and Greenland, Copenhagen, Denmark
van de Wal, R. S. W., Institute for Marine and Atmospheric Research Utrecht, Utrecht University, Utrecht, Netherlands; Geosciences, Physical Geography, Utrecht University, Utrecht, Netherlands
van der A, Ronald J., Royal Netherlands Meteorological Institute (KNMI), De Bilt, Netherlands
van der Schalie, Robin, VanderSat B.V., Haarlem, Netherlands
van der Schrier, Gerard, Royal Netherlands Meteorological Institute (KNMI), De Bilt, Netherlands
van der Werf, Guido R., Faculty of Earth and Life Sciences, VU University Amsterdam, Netherlands
van Heerwaarden, Chiel, Meteorology and Air Quality Group, Wageningen University and Research, Wageningen, Netherlands
Van Meerbeeck, Cedric J., Caribbean Institute for Meteorology and Hydrology, Bridgetown, Barbados
Verburg, Piet, National Institute of Water and Atmospheric Research, Hamilton, New Zealand
Vieira, G., CEG/IGOT, Universidade de Lisboa, Lisbon, Portugal
Vincent, Lucie A., Environment and Climate Change Canada, Toronto, Ontario, Canada
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, D. A., Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, Alaska
Walsh, J. E., International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, Alaska
Wang, Bin, Department of Atmospheric Science and IPRC, University of Hawaii, Honolulu, Hawaii
Wang, Hui., NOAA/NWS Climate Prediction Center, College Park, Maryland
Wang, Lei, Department of Geography and Anthropology, Louisiana State University, Baton Rouge, Louisiana
Wang, M., Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle, Washington
Wang , Mengqiu, College of Marine Science, University of South Florida, St. Petersburg, Florida
Wang, Ray, Georgia Institute of Technology, Atlanta, Georgia
Wang, Sheng-Hung, Byrd Polar and Climate Research Center, The Ohio State University, Columbus, Ohio
Wanninkhof, Rik, NOAA/OAR Atlantic Oceanographic and Meteorological Laboratory (AOML), Miami, Florida
Watanabe, Shohei, Tahoe Environmental Research Center, University of California at Davis, Davis, California
Weber, Mark, University of Bremen, Bremen, Germany
Webster, Melinda, NASA Goddard Space Flight Center, Greenbelt, Maryland
Weerts, Albrecht, Deltares, Delft, Netherlands, and Hydrology and Quantitative Water Management Group, Wageningen University and Research, Wageningen, Netherlands
Weller, Robert A., Woods Hole Oceanographic Institution, Woods Hole, Massachusetts
Westberry, Toby K., Department of Botany and Plant Pathology, Oregon State University, Corvallis, Oregon
Weyhenmeyer, Gesa A., Department of Ecology and Genetics/Limnology, Uppsala University, Uppsala, Sweden
Widlansky, Matthew J., Joint Institute for Marine and Atmospheric Research, University of Hawaii, Honolulu, Hawaii
Wijffels, Susan E., Woods Hole Oceanographic Institution, Woods Hole, Massachusetts
Wilber, Anne C., Science Systems and Applications, Inc., Hampton, Virginia
Wild, Jeanette D., NOAA Climate Prediction Center, College Park, MD, USA; ESSIC/University of Maryland, College Park, Maryland
Willett, Kate M., Met Office Hadley Centre, Exeter, United Kingdom
Wong, Takmeng, NASA Langley Research Center, Hampton, Virginia
Wood, E. F., Department of Civil and Environmental Engineering, Princeton University, Princeton, New Jersey

Woolway, R. Iestyn, Dundalk Institute of Technology, Dundalk, Ireland
Xue, Yan, NOAA/NWS National Centers for Environmental Prediction, Climate Prediction Center, College Park, Maryland
Yin, Xungang, ERT Inc., NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina
Yu, Lisan, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts
Zambrano, Eduardo, Centro Internacional para la Investigación del Fenómeno de El Niño, Guayaquil, Ecuador
Zeyaeyan, Sadegh, Islamic Republic of Iran Meteorological Organization, Tehran, Iran
Zhang, Huai-Min, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina
Zhang, Peiqun, Beijing Climate Center, Beijing, China
Zhao, Guanguo, University of Illinois at Urbana-Champaign, Champaign, Illinois
Zhao, Lin, Cold and Arid Regions Environmental and Engineering Research Institute, Lanzhou, China
Zhou, Xinjia, Center for Satellite Applications and Research, NOAA, College Park, Maryland
Zhu, Zhiwei, Nanjing University of Information Science and Technology, China
Ziemke, Jerry R., Goddard Earth Sciences Technology and Research, Morgan State University, Baltimore, Maryland, and NASA Goddard Space Flight Center, Greenbelt, Maryland
Ziese, Markus, Global Precipitation Climatology Center, Deutscher Wetterdienst, Offenbach am Main, Germany

EDITORIAL AND PRODUCTION TEAM

Andersen, Andrea, Technical Editor, TeleSolv Consulting LLC, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina
Griffin, Jessicca, Graphics Support, Cooperative Institute for Satellite Earth System Studies, North Carolina State University, 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
Misch, Deborah J., Graphics Support, TeleSolv Consulting 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., Visualization Team Lead, Communications and Outreach, NOAA/NESDIS National Centers for Environmental Information, Asheville, North Carolina

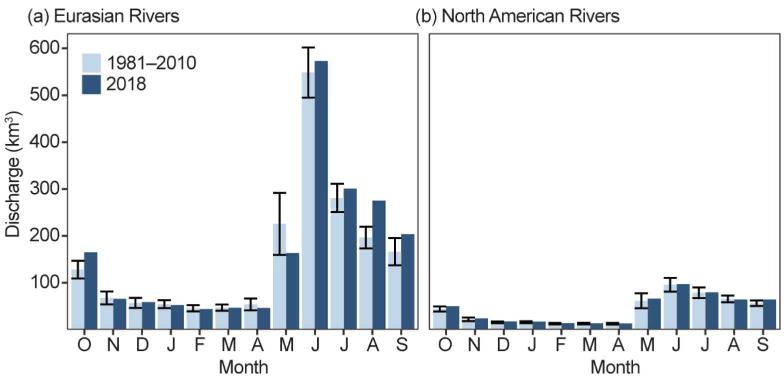

Fig. 5.23. 2018 seasonal discharge (km³), relative to the 1981–2010 average, for the (a) six Eurasian and (b) two North American rivers. Error bars represent ±1 std. dev.

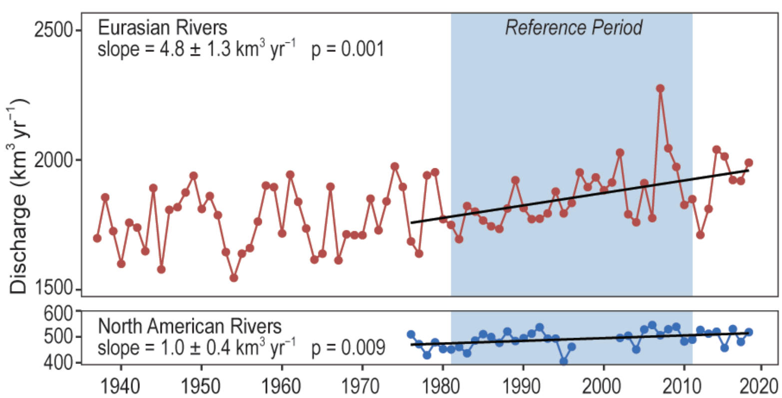

Fig. 5.24. Long-term trends in annual discharge (km³ yr⁻¹) for Eurasian and North American Arctic rivers. Gaps in the North American rivers time-series span from 1996 to 2001 due to missing Yukon data from 1996 to 2001 and missing Mackenzie measurements in 1997 and 1998. Note the different scales for the Eurasian and North American river discharge; discharge from the former is 3–4 times greater than from the latter.

of record (1976–2018) was 1.0 km³ per year. When the Eurasian data are also considered for the same period, the average annual increase in discharge was 4.8 km³ per year (Fig. 5.24). These observations indicate that Arctic river discharge continues to increase, providing powerful evidence for the intensification of the Arctic hydrologic cycle.

i. *Tundra greenness*—H. Epstein, U. Bhatt, M. Raynolds, D. Walker, B. Forbes, G. Phoenix, J. Bjerke, H. Tømmervik, S.-R. Karlsen, R. Myneni, T. Park, S. Goetz, and G. Jia

Arctic tundra vegetation has responded to dramatic environmental changes over the course of the last several decades by increasing the above-ground quantity of live vegetation, a process commonly referred to as greening. Vegetation changes vary spatially, in both sign and magnitude, throughout the circumpolar Arctic, and are not necessarily consistent over time (e.g., Bhatt et al. 2013; Reichle et al. 2018). This variability suggests complex interactions among the atmosphere, vegetation, soils, permafrost, and grazing animals of the Arctic system. Changes in tundra vegetation can have important effects on carbon cycling and soil–atmosphere energy exchange (e.g., Treharne et al. 2016; Frost et al. 2018; Lafleur and Humphreys 2018). The latter has implications for active layer depth and permafrost stability, thereby impacting Arctic landscapes. Changes in tundra vegetation also affect wildlife habitats. For instance, bird and terrestrial mammal species have shown favorable responses (e.g., greater range and larger populations) to Arctic greening, including shrub expansion (e.g., Wheeler et al. 2018). Continued evaluation of the current state and dynamics of circumpolar Arctic vegetation improves our understanding of these complex interactions and their influences on the Arctic system and beyond.

There is a number of controls on the inter-annual dynamics of tundra productivity. Summer air temperature is the most widely acknowledged factor responsible for increasing (greening) tundra vegetation (Ackerman et al. 2018; Keenan and Riley 2018; Myers-Smith and Hik 2018; Weijers et al. 2018; Bjorkman et al. 2018). However, several reports have shown that increased temperatures can have a detrimental (browning) or no effect on tundra vegetation (Lara et al. 2018; Maliniemi et al. 2018; Opala-Owczarek et al. 2018; Xu et al. 2018). Tundra browning has also been observed in response to extreme events, such as winter snowmelt followed by frost, drought, icing during rain-on-snow episodes, and insect outbreaks (Phoenix and Bjerke 2016; Treharne et al. 2016). Precipitation and moisture availability are also important controls on tundra vegetation dynamics (Lara et al. 2018; Maliniemi et al. 2018; Opala-Owczarek et al. 2018; Wang et al. 2018; Bjorkman et al. 2018) and are linked to the effects of air temperature changes; increased temperatures may lead to reduced growing-season soil moisture and increased water stress in tundra plants (Ackerman et al. 2018; Keenan and Riley 2018; Opala-Owczarek et al. 2018). Deeper snow packs have been shown to lead to increased shrub growth, increasing vegetation net uptake of CO_2 (Christiansen et al. 2018; Maliniemi et al. 2018; Opala-Owczarek et al. 2018; Parmentier et al. 2018; Wang et al. 2018). Changes in the land cover also affect tundra greenness; for example, reductions in cryogenic disturbances (e.g., frost circles; Becher et al. 2018) and increased lake drainage (Lara et al. 2018) can both lead to greening.

Arctic tundra vegetation has been monitored continuously since 1982 using the Normalized Difference Vegetation Index (NDVI) derived via satellites. NDVI is highly correlated with the quantity (greenness) of above-ground Arctic tundra vegetation (e.g., Raynolds et al. 2012; Karlsen et al. 2018). The data reported here are from the Global Inventory Modeling and Mapping Studies (GIMMS) 3g V1 dataset (GIMMS 2013) and are based largely on the AVHRR sensors aboard NOAA satellites (Pinzon and Tucker 2014). The GIMMS product (at 1/12° resolution for this report) is a bi-weekly, maximum-value composite dataset of the NDVI, calculated from Earth-surface reflectances in the red and near infrared wavelengths. Two metrics based on the NDVI are used: MaxNDVI and TI-NDVI. MaxNDVI is the peak NDVI value for the year, observed during the growing season, and is related to the yearly maximum above-ground vegetation biomass. TI (time-integrated) NDVI is the sum of the bi-weekly NDVI values for the growing season and is correlated with the total above-ground vegetation productivity. Collectively, these two indices describe the abundance and activity of tundra vegetation for a given growing season.

According to the overall trend in tundra greenness for the 37-year record (1982–2018), the MaxNDVI and the TI-NDVI have increased throughout a majority of the geographic circumpolar Arctic tundra (Figs. 5.25a,b). Regions with the greatest increases in tundra greenness are the North Slope of Alaska, the southern subzones of the Canadian tundra, and eastern Siberia. Tundra greenness has declined or shown browning throughout the Yukon-Kuskokwim Delta of western Alaska, the High Arctic of the Canadian Archipelago, and the northwestern and north-coastal Siberian tundra. Specific regions of observed greening and browning tend to be consistent between MaxNDVI and TI-NDVI; however, decreases in TI-NDVI tend to be more spatially extensive than decreases in MaxNDVI, suggesting that in certain locations the length of the growing season may be decreasing, whereas the actual growth of vegetation may not be affected.

Considering variability on a year-to-year basis, NDVI declined in 2018 from the prior year for both indices over North America and slightly increased for Eurasia (Fig. 5.26). For both regions, this follows a year of decreases in NDVI from 2016 to 2017, after particularly high NDVI values were observed in 2016. In North America, TI-NDVI declined by 11.2% from 2017 to 2018 (the largest single-year decline in the record) and declined 14.7% since 2016. MaxNDVI in North America declined by 5.9% from 2017 to 2018 (the second largest single-year decline in the record), and 9.9% since 2016. Note that the mean NDVI values for Eurasian tundra are substantially greater than those for the North American tundra, because most of the Eurasian tundra occurs at relatively lower latitudes.

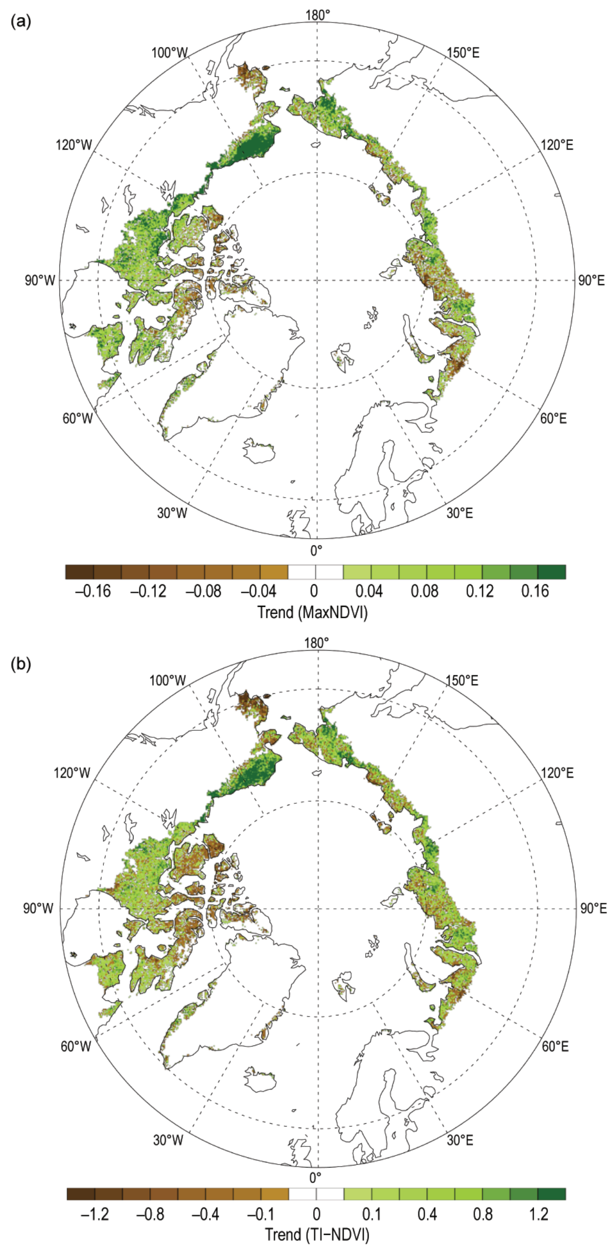

Fig. 5.25. Magnitude of the trend (calculated as the total change over a least squares, linear fit trend line) in (a) MaxNDVI and (b) TI-NDVI for 1982–2018.

With the 2017 to 2018 decline, the North American NDVI values dropped below the mean for the 37-year record. In 2018, MaxNDVI for North America ranked 25th and TI-NDVI ranked 36th (second lowest in the record, behind 1992). NDVI values for Eurasia remained above the mean; MaxNDVI ranked ninth and TI-NDVI ranked 11th. For the Arctic as a whole, MaxNDVI in 2018 was essentially at the mean value (ranked 19th) and TI-NDVI was less than the mean value (ranked 31st).

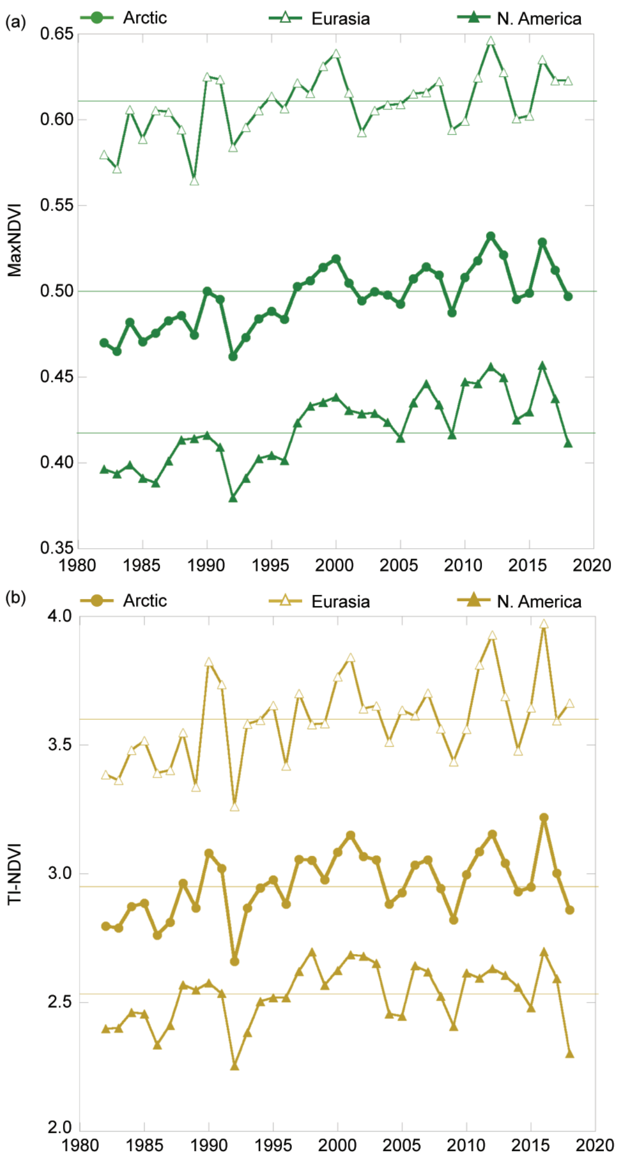

Fig. 5.26. (a) MaxNDVI and (b) TI-NDVI for Eurasia (top), Arctic as a whole (middle), and North America (bottom) for 1982–2018. Horizontal lines are the means for each time series.

j. Ozone and UV radiation—G. H. Bernhard, V. E. Fioletov, J.-U. Grooß, I. Ialongo, B. Johnsen, K. Lakkala, G. L. Manney, and R. Müller

The release of man-made substances that deplete Earth's ozone layer, such as chlorofluorocarbons (CFCs), has reinforced the chemical destruction of ozone in the polar stratosphere. The resulting ozone loss has led to increased UV radiation with adverse effects on human health (e.g., sunburn) and Earth's environment (EEAP 2019). Chemical processes that drive ozone depletion are initiated at temperatures below about 195 K (–78°C) in the lower stratosphere, at an approximate altitude of 15–25 km. These chemical processes lead to the formation of polar stratospheric clouds (PSCs), which act as a catalyst to transform inactive forms of chlorine-containing substances (e.g., HCl and $ClONO_2$) to active, ozone-destroying chlorine species such as chlorine monoxide (ClO). Chemically-induced loss of polar ozone occurs predominantly during winter and spring (WMO 2018a), hence November 2017–April 2018 is emphasized in this report.

Chemical destruction of ozone was unusually large over the winter/spring 2017/18. Temperatures in the lower Arctic stratosphere dropped below the threshold for PSC formation in mid-November 2017, approximately 15 days earlier than typical, and remained below the average temperature in the observational record (1979–2016) through mid-February 2018. On 12 February, a major sudden stratospheric warming event split the polar vortex (i.e., the low-temperature cyclone in which most of the springtime chemical ozone destruction occurs), and lower stratospheric temperatures abruptly rose above the threshold temperature for PSC formation (Karpechko et al. 2018; Rao et al. 2018). The larger of the two offspring vortices remained intact, and chemical destruction of ozone continued within its boundary until late March. Despite this event, vortex-averaged ozone mixing ratios (OMRs; a measure of ozone concentrations) observed by the Microwave Limb Sounder (MLS) during February 2018 were the lowest in the MLS observational record (2004–17; Fig. 5.27). Although chlorine was not fully deactivated until late March, according to MLS measurements, OMRs within the vortex started to increase in early March, partly due to influx of ozone from higher altitudes. Vortex-averaged OMRs between March and early April 2018 were among the lowest in the MLS record, with lower values only in 2011 and 2016, the years with the largest chemical ozone loss observed to date (Fig. 5.27).

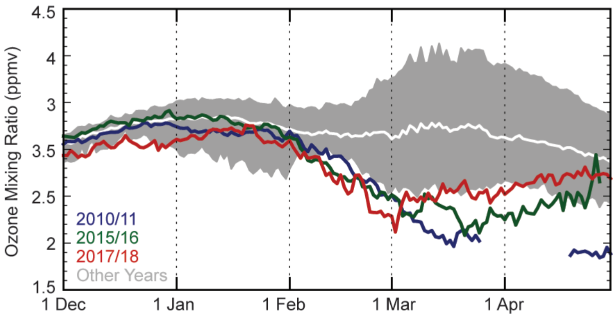

Fig. 5.27. Average ozone mixing ratios (ppmv) measured by *Aura* MLS at an altitude of ~18 km for the area bounded by the polar vortex. Data from 2017/18 (red), 2015/16 (green), and 2010/11 (blue) are compared with the average (solid white) and minimum/maximum range (gray shading) from 2004/05 to 2016/17, excluding 2010/11, 2015/16, and 2017/18. Gaps in the record for 2010/11 are due to missing data.

The evolution of the Arctic total ozone column (TOC; i.e., ozone amounts integrated from the surface to the top of the atmosphere) in March 2018 is compared to the 1979–2017 observational record in Fig. 5.28. March TOC is evaluated because chemically induced Arctic ozone loss typically has the largest variability in this month (Fig. 5.27; WMO 2018a). The minimum Arctic daily TOC measured by satellites in March 2018 was 380 Dobson units (DU), which was 1.2% (4 DU) above the average of the observational record (376 DU) and 3.7% (14 DU) above the average when MLS data are available (2005–17).

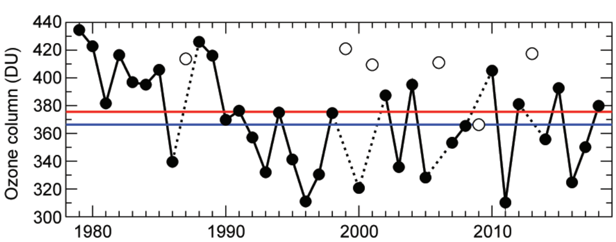

Fig. 5.28. Area-averaged monthly minimum total ozone column (DU) for Mar poleward of 63° equivalent latitude (Butchart and Remsberg 1986). Open circles represent years in which the polar vortex broke up before Mar, resulting in relatively high values due to mixing with lower latitude air masses and a lack of significant chemical ozone depletion. Red and blue lines indicate the average TOC for 1979–2017 and 2005–17, respectively. Data are adapted from Müller et al. (2008) and WMO (2018), updated using ERA-Interim reanalysis data (Dee et al. 2011). Ozone data from 1979–2016 are based on the combined total column ozone database version 3.4 produced by Bodeker Scientific (www.bodekerscientific.com/data/total-column-ozone). Data for 2017/18 are from OMI.

Spatial deviations of monthly average TOCs from historical (2005–17) averages (Figs. 5.29a,b) were estimated using ozone monitoring instrument (OMI; co-located with MLS on the *Aura* satellite) measurements. Despite the low ozone concentrations inside the lower stratospheric polar vortex during March (Fig. 5.27), TOCs over most regions of the Arctic were well above average (Fig. 5.29a) because Arctic TOCs are predominantly controlled by dynamical processes such as the transport of ozone-rich air from lower latitudes (Manney et al. 2011). Chemical loss in 2018 was only a secondary factor in controlling TOC within the vortex and a negligible factor outside the vortex. Average TOCs for March 2018 were about 15% higher than the long-term mean over Scandinavia, the Norwegian Sea, Greenland, and northeastern Canada; 10% lower over north-central Siberia; and 10% higher over northeastern Siberia (Fig. 5.29a). By July, monthly TOC anomalies showed a distinct geographical pattern that was significantly different from March (Fig 5.29b): TOCs were about 5% below the long-term average over Scandinavia and northwest Russia and 5% above the long-term average over Greenland, northeastern Canada, and the North Pole.

The ultraviolet index (UVI) is a measure of the ability of UV radiation to cause erythema (sunburn) in human skin (WHO 2002). In addition to its dependence on TOC, UVI depends on the sun's angle, cloud cover, and surface albedo (Weatherhead et al. 2005). In the Arctic, the UVI scale ranges from 0 to about 7, with the smallest annual peak radiation levels (UVI values <4) observed at sites closest to the North Pole. UVI values ≤5 indicate low-to-moderate risk of erythema (WHO 2002).

UVI anomalies are assessed using both satellite-based OMI and ground-based measurements, with the former providing better spatial coverage and the latter providing greater regional accuracy (Bernhard et al. 2015). Figures 5.29c,d quantify the spatial differences in monthly average noontime UVIs from historical (2005–17) averages based on OMI measurements. Figures 5.29c,d also indicate anomalies calculated from ground-based measurements at nine research stations located throughout the Arctic and Scandinavia.

Areas with high UVIs roughly match areas with low TOCs and vice versa, but UVI anomalies have larger spatial variability because of their added dependence on cloud cover (Fig. 5.29). In March 2018, average noontime UVIs calculated from OMI observations and ground-based measurements were 0%–15% below historical averages with a few exceptions, such as northwestern Siberia, where UVIs were

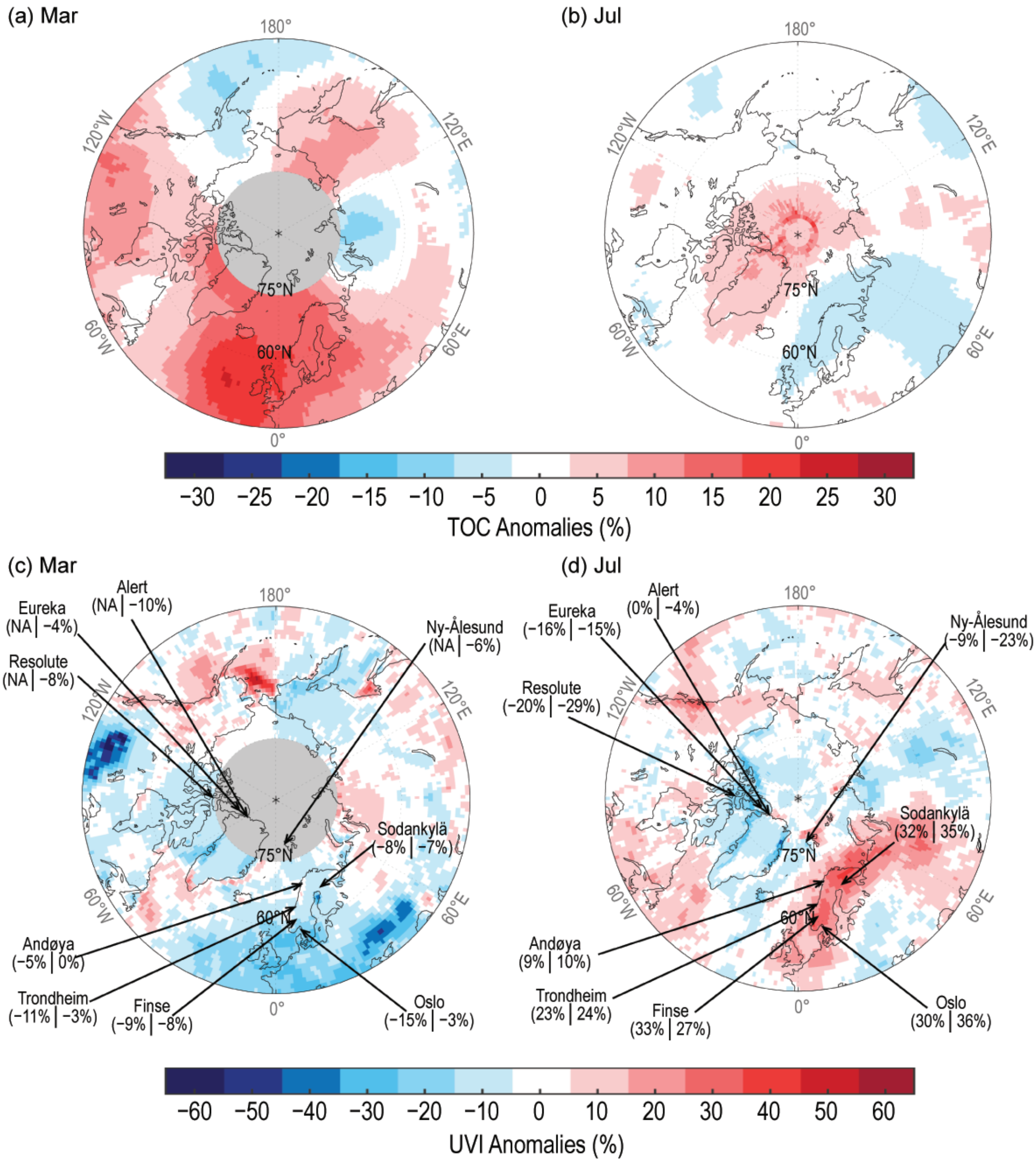

Fig. 5.29. Anomalies of TOC (%) for (a) Mar and (b) Jul 2018. Noontime UVI (%) for (c) Mar and (d) Jul 2018. Anomalies are relative to 2005–17 averages. Maps are based on the OMTO3 Level 3 total ozone product (Bhartia and Wellemeyer 2002). (c) and (d) also compare UVI anomalies from OMI (first value in parenthesis) with ground-based measurements at nine locations (second value presented). Gray shading indicates areas where no OMI data are available.

actually elevated by several percent (Fig. 5.29c). Large positive UVI anomalies were observed over Scandinavia in May and July, with a 20%–40% range in both months (absolute anomalies of up to 1.4 UVI units). In July, areas of high UVI (Fig. 5.29d) and low ozone (Fig 5.29b) were correlated. However, these large UVI anomalies cannot be explained by low TOCs alone and were partly caused by exceptionally long periods of clear skies and record dry and warm conditions. For example, at Sodankylä, the mean temperature in July 2018 was 5.6°C above the 1981–2010 average and the sunshine duration in 2018 was 405 hours, exceeding the 1981–2010 average of 245 hours by 65%. Anomalies at Trondheim, Oslo, and Sodankylä have exceeded historical means by 2.1, 2.3, and 2.5 standard deviations, respectively. In contrast to high UV radiation levels in Scandinavia, UV indices measured during July in northern Nunavut, Canada, were up to 29% below the long-term mean. UVI anomalies for the rest of the Arctic remained within ±20% with few exceptions such as the eastern coast of Greenland (Fig. 5.29d). Generally, OMI observations are consistent with ground-based measurements (Fig. 5.29d).