State of the Climate 2024

Supplementary material

Report authorship and production team

Coordinating lead authors and editorial team

Neil Sims and Blair Trewin

Project coordinator

Colette Leary

Project advisors

John Clarke and Lynette Bettio

Section lead authors

Naomi Benger, Pep Canadell, Chris Chapman, Michael Grose, Benoit Legresy, Zoe Loh, Jannatun Nahar, Acacia Pepler, Hamish Ramsay, Phil Reid, Bronte Tilbrook, Blair Trewin and Xuebin Zhang.

Section contributing authors

Nada Derek, Catia Domingues, Andrew Dowdy, David Etheridge, Ming Feng, Ben Hague, Paul Krummel, Sugata Narsey and Bea Peña-Molino.

Communications

Chris Gerbing and Sharon Cooper

Graphic design

Siobhan Duffy

Citation

This document should be cited as:

State of the Climate 2024, CSIRO and Bureau of Meteorology, © Government of Australia.

References, further reading and notes

Many sections in this report draw on the Working Group I part of the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (**https://www.ipcc.ch/report/ar6/wg1/**), released in 2021 (hereafter referred to as IPCC AR6). Specific IPCC assessment findings or material used are cited in the individual sections below. The full citation for the IPCC report is:

IPCC (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. **https://doi.org/10.1017/9781009157896**.

General climate information

State of the Climate 2012: **http://www.bom.gov.au/state-of-the-climate/2012/Climate-Snapshot-2012-Brochure.pdf**

State of the Climate 2014: **http://www.bom.gov.au/state-of-the-climate/2014/**

State of the Climate 2016: **www.bom.gov.au/state-of-the-climate/2016**/

State of the Climate 2018: **http://www.bom.gov.au/state-of-the-climate/2018/**

State of the Climate 2020: **http://www.bom.gov.au/state-of-the-climate/2020/**

State of the Climate 2022: **http://www.bom.gov.au/state-of-the-climate/ 2022/**

Blunden, J. and T. Boyer, Eds., 2024: "State of the Climate in 2023". Bull. Amer. Meteor. Soc., 105(8), Si–S484, **https://www.ametsoc.org/index.cfm/ams/publications/bulletin-of-the-american-meteorological-society-bams/state-of-the-climate/**

CSIRO and Australian Bureau of Meteorology 2015, 'Climate Change in Australia', Climate Change in Australia, **http://www.climatechangeinaustralia.gov.au/en**

Bulletin of the American Meteorological Society. Explaining Extreme Events from a Climate Perspective', **https://www.ametsoc.org/ams/index.cfm/publications/bulletin-of-the-american-meteorological-society-bams/explaining-extreme-events-from-a-climate-perspective/**

The Global Carbon Project: **http://www.globalcarbonproject.org**

World Meteorological Organization WMO 'Statement on the Status of the Global Climate **https://public.wmo.int/en/our-mandate/climate/wmo-statement-state-of-global-climate**

State of the Environment 2021: **https://soe.dcceew.gov.au/**

Fifth US National Climate Assessment, 2023: **https://nca2023.globalchange.gov/**

Australian Bureau of Meteorology Climate Information: **http://www.bom.gov.au/climate/change/**

Australian Bureau of Meteorology Water Information: **http://www.bom.gov.au/water/**

Kennaook/Cape Grim greenhouse gas data: **https://www.csiro.au/greenhouse-gases/**

CSIRO Oceans and Atmosphere: Sea-level data, Sea-Level Rise: **https://research.csiro.au/slrwavescoast/sea-level/**

National Snow and Ice Data Centre (USA): **https://nsidc.org**

NOAA Global greenhouse gas reference network: **https://gml.noaa.gov/ccgg/about.html**

Global Climate Observing System: **https://gcos.wmo.int/en/home**

Copernicus Climate Change Service: **https://climate.copernicus.eu/**

WMO Global Atmosphere Watch: **https://community.wmo.int/en/activity-areas/gaw**

Report at a Glance

Huang, B., and coauthors. (2017). Extended Reconstructed Sea Surface Temperature, Version 5 (ERSSTv5): Upgrades, Validations, and Intercomparisons. *Journal of Climate, 30*, 8179-8205, **https://doi.org/10.1175/JCLI-D-16-0836.1**

Trewin, B., and coauthors. (2020). An updated long-term homogenized daily temperature data set for Australia. *Geoscience Data Journal, 7*, 149-169, **https://doi.org/10.1002/gdj3.95**

Australian temperature data used in figures in this section are drawn from version 2.5 of the Australian Climate Observations Reference Network – Surface Air Temperature (ACORN-SAT) dataset (Trewin et al., 2020) (**http://www.bom.gov.au/climate/data/acorn-sat/**). Sea surface temperature data are drawn from version 5 of the Extended Reconstructed Sea Surface Temperature (ERSSTv5) dataset (Huang et al., 2017) (**www.esrl.noaa.gov/psd/**).

The figure showing global temperatures is adapted and updated from Figure 4 in the World Meteorological Organization (WMO) Statement on the Status of Global Climate in 2012 (**WMO_1108**). Global temperature data used are a mean of four different global data sets as described in IPCC AR6 Section 2.3.1.1.3 and Table 2.3.

Citations for key points are in the associated sections below.

Australia's changing climate

Temperature

Dittus, A.J., Karoly, D.J., Lewis, S.C. and Alexander, L.V. (2014). An investigation of some unexpected frost day increases in southern Australia. *Aust. Met. Oceanogr. J.*, 64, 261-271. DOI:**10.22499/2.6404.002**

Grainger, S., and coauthors. (2022). Estimating the uncertainty of Australian area-average temperature anomalies. *Int. J. Climatol.*, 42, 2815-2834. **https://doi.org/10.1002/joc.7392**

Nairn, J.R. and Fawcett, R.J.B. (2015). The excess heat factor: a metric for heatwave intensity and its use in classifying heatwave severity. *Int. J. Environ. Res. Public Heath*, 12, 227-253. **https://doi.org/10.3390/ijerph120100227**

Pepler, A., Ashcroft, L. and Trewin, B. (2018). The relationship between the subtropical ridge and Australian temperatures. *J. South. Hem. Earth Sys. Sci.*, 68, 201-214. **https://doi.org/10.1071/ES18011**

Trewin, B. (2018). The Australian Climate Observations Reference Network – Surface Air Temperature (ACORN-SAT) version 2. *Bureau Research Report 32*, Bureau of Meteorology. **http://www.bom.gov.au/research/publications/researchreports/BRR-032.pdf**

Trewin, B., and coauthors. (2020). An updated long-term homogenized daily temperature data set for Australia. *Geosci. Data J.*, 7, 149-169. **https://doi.org/10.1002/gdj3.95**

Australian temperature data used in this section are drawn from version 2.5 of the Australian Climate Observations Reference Network – Surface Air Temperature (ACORN-SAT) dataset (Trewin et al., 2020) (**http://www.bom.gov.au/climate/data/acorn-sat/**).

Box 1 – Changes in weather systems and climate influences

Abram, N.J., Hargreaves, J.A., Wright, N.M., Thirumalai, K., Ummenhofer, C.C. and England, M.H. (2020). Palaeoclimate perspectives on the Indian Ocean Dipole. *Quart. Sci. Rev.*, 237, 106302. **https://doi.org/10.1016/j.quascirev.2020.106302**

Grose, M., Timbal, B., Wilson, L., Bathols, J. and Kent, D. (2015). The subtropical ridge in CMIP5 models, and implications for projections of rainfall in southeast Australia. *Aust. Met. Oceanogr. J.*, 65, 90-106. **https://doi.org/10.1071/ES15007**

Pepler, A., Hope, P. and Dowdy, A. (2019). Long-term changes in southern Australian anticyclones and their impacts. *Clim. Dyn*, 53, 4701-4714. **https://doi.org/10.1007/s00382-019-04819-9**

Pepler, A. (2020). Record lack of cyclones in Australia during 2019. *Geophys. Res. Lett.*, 47, e2020GL088488. **https://doi.org/10.1029/2020GL088488**

Pepler, A.S., Dowdy, A.J. and Hope, P. (2021). The differing role of weather systems in southern Australian rainfall between 1979-1996 and 1997-2015. *Clim. Dyn.*, 56, 2289-2302. **https://doi.org/10.1007/s00382-020-05588-6**

Pepler, A.S. and Dowdy, A.J. (2022). Australia's future extratropical cyclones. *J. Climate*, 35, 7795-7810. **https://doi.org/10.1175/JCLI-D-22-0312.1**

Timbal, B. and Drosdowsky, W. (2013). The relationship between the decline of southeastern Australian rainfall and the strengthening of the subtropical ridge. *Int. J. Climatol.*, 33, 1021-1034. **https://doi.org/10.1002/joc.3492**

The assessment of changes in climate influences draws on the assessment findings of IPCC AR6: sections 2.4.1.2 (SAM), 2.4.2 (ENSO) and 2.4.3 (IOD).

Fire weather

Canadell, J.G., and coauthors. (2018, December). Higher than expected CO2 fertilisation inferred from leaf to global observations. In *AGU Fall Meeting Abstracts*.

Canadell, J.G., Meyer, C.P., Cook, G.D., Dowdy, A., Briggs, P.R., Knauer, J., Pepler, A. and Haverd, V. (2021). Multi-decadal increase of forest burned area in Australia is linked to climate change. *Nature communications*, 12(1), pp.1-11. **https://doi.org/10.1038/s41467-021-27225-4**

Clarke, H., Pitman, A.J., Kala, J., Carouge, C., Haverd, V. & Evans, J. (2016). An investigation of future fuel load and fire weather in Australia. *Climatic Change,* 139 (3), 591-605. **https://doi.org/10.1007/s10584-016-1808-9**

Di Virgilio, G., Evans, J.P., Blake, S.A., Armstrong, M., Dowdy, A.J., Sharples, J. and McRae, R. (2019). Climate change increases the potential for extreme wildfires. *Geophysical Research Letters*, 46(14), pp.8517-8526. **https://doi.org/10.1029/2019GL083699**

Dowdy, A.J., Fromm, M.D. and McCarthy, N. (2017). Pyrocumulonimbus lightning and fire ignition on Black Saturday in southeast Australia. *Journal of Geophysical Research: Atmospheres*, 122(14), pp.7342-7354. **https://doi.org/10.1002/2017JD026577**

Dowdy, A.J. (2018). Climatological Variability of Fire Weather in Australia. *Journal of Applied Meteorology and Climatology*, 57, 221-234. **https://doi.org/10.1175/JAMC-D-17-0167.1**

Dowdy, A.J. and Pepler, A. (2018). Pyroconvection Risk in Australia: Climatological Changes in Atmospheric Stability and Surface Fire Weather Conditions. *Geophysical Research Letters*, 45, 2005-2013. **https://doi.org/10.1002/2017gl076654**

Dowdy, A.J., Ye, H., Pepler, A., Thatcher, M., Osbrough, S.L., Evans, J.P., Di Virgilio, G. and McCarthy, N. (2019). Future changes in extreme weather and pyroconvection risk factors for Australian wildfires. *Scientific Reports*, 9(1), 1-11. **https://doi.org/10.1038/s41598-019-46362-x**

Dowdy, A.J. (2020). Seamless climate change projections and seasonal predictions for bushfires in Australia. *Journal of Southern Hemisphere Earth Systems Science*, 70(1), pp.120-138. **https://doi.org/10.1071/ES20001**

Harris, S. and Lucas, C. (2019). Understanding the variability of Australian fire weather between 1973 and 2017. *PLoS ONE*, 14. **https://doi.org/10.1371/journal.pone.0222328**

Hughes, L. (2003), Climate change and Australia: Trends, projections and impacts. *Austral Ecology*, 28: 423-443. **https://doi.org/10.1046/j.1442-9993.2003.01300.x**

McArthur, A.G. (1967). Fire behaviour in eucalypt forests. *Australia. Forestry and Timber Bureau : Leaflet ; no. 107*, Forestry and Timber Bureau, 36. **https://nla.gov.au/nla.cat-vn2275488**

Van Oldenborgh, G.J., and coauthors. *Natural Hazards and Earth System Sciences*, 21(3), pp.941-960. **https://doi.org/10.5194/nhess-21-941-2021**

The figure is updated and adapted from Dowdy (2020). **https://doi.org/10.1071/ES20001**

Rainfall

Rauniyar, S.P., Hope, P., Power, S.B., Grose, M and Jones, D. (2023). The role of internal variability and external forcing on southwestern Australian rainfall: prospects for very wet or dry years. *Sci Rep* 13, 21578. **https://doi.org/10.1038/s41598-023-48877-w**

Devanand, A. and coauthors. (2024). Australia's Tinderbox Drought: an extreme natural event likely worsened by human-caused climate change. *Science Advances*, 10, eadj3460. **https://doi.org/10.1126/sciadv.adj3460**

Evans, A., Jones, D., Smalley, R. and Lellyett, S. (2020). An enhanced gridded rainfall analysis scheme for Australia. *Bureau Research Report 41*, Bureau of Meteorology. **http://www.bom.gov.au/research/publications/researchreports/BRR-041.pdf**

Pepler, A.S., Dowdy, A.J. and Hope, P. (2021). The differing role of weather systems in southern Australian rainfall between 1979-1996 and 1997-2015. *Clim. Dyn.*, 56, 2289-2302. **https://doi.org/10.1007/s00382-020-05588-6**

Rauniyar, S.P. and Power, S.B. (2020). The impact of anthropogenic forcing and natural processes on past, present and future rainfall over Victoria, Australia. *J. Climate*, 33, 8087-8106. **https://doi.org/10.1175/JCLI-D-19-0759.1**

Timbal, B. and Drosdowsky, W. (2013). The relationship between the decline of southeastern Australian rainfall and the strengthening of the subtropical ridge. *Int. J. Climatol.*, 33, 1021-1034. **https://doi.org/10.1002/joc.3492**

Rainfall data used in this section are drawn from the Australian Gridded Climate Data (AGCD) dataset (Evans et al., 2020) (**http://www.bom.gov.au/climate/austmaps/about-agcd-maps.shtml**).

Box 2 – Australian temperatures and global warming

Grose, M.R., Boschat, G., Trewin, B., Round, V., Ashcroft, L., King, A.D., Narsey, S., and Hawkins, E. (2023) Australian climate warming: observed change from 1850 and global temperature targets. *Journal of Southern Hemisphere Earth Systems Science* 73, 30-43. **https://doi.org/10.1071/ES22018**

Heavy rainfall

Dowdy, A.J. (2020). Climatology of thunderstorms, convective rainfall and dry lightning environments in Australia. *Clim. Dyn.*, 54, 3041-3052. **https://doi.org/10.1007/s00382-020-05167-9**

Guerreiro, S.B., Fowler, H.J., Barbero, R., Westra, S., Lenderink, G., Blenkinsop, S., Lewis, E. and Li, X.-F. (2018). Detection of continental-scale intensification of hourly rainfall extremes. *Nat. Clim. Chang.*, **8**, 803–808. **https://doi.org/10.1038/s41558-018-0245-3**

Pearce, K.B., Holper, P.N., Hopkins, M., Bouma, W.J., Whetton, P.H., Hennessy, K.J. and Power, S.B. (2007). Climate Change in Australia: technical report 2007. **https://webarchive.nla.gov.au/awa/20080719070759/http://www.climatechangeinaustralia.gov.au/resources.php**

Pepler, A.S., Dowdy, A.J. and Hope, P. (2021). The differing role of weather systems in southern Australian rainfall between 1979–1996 and 1997–2015. *Climate Dynamics*, *56*(7), pp.2289-2302. **https://doi.org/10.1007/s00382-020-05588-6**

Box 3 – Extreme rainfall, climate change and flood risk

Ayat, H., Evans, J. P., Sherwood, S. C., and Soderholm, J. (2022). Intensification of subhourly heavy rainfall. *Science*, 378, 655–659. **https://doi.org/10.1126/science.abn8657**

Bao, J., Sherwood, S.C., Alexander, L.V. and Evans, J.P. (2017). Future increases in extreme precipitation exceed observed scaling rates. *Nat. Clim. Chang.*, 7, 128–132. **https://doi.org/10.1038/nclimate3201**

Chand, S.S., Dowdy, A.J., Ramsay, H.A., Walsh, K.J.E., Tory, K. J., Power, S. B., Bell, S. S., Lavendar, S. L., Ye, H. and Kuleshov, Y (2019). Review of tropical cyclones in the Australian region: Climatology, variability, predictability, and trends. *Wiley Interdisciplinary Reviews: Climate Change*. **https://doi.org/10.1002/wcc.602**

Dowdy, A.J. (2020). Climatology of thunderstorms, convective rainfall and dry lightning environments in Australia. *Clim. Dyn.*, 54, 3041-3052. **https://doi.org/10.1007/s00382-020-05167-9**

Dowdy, A.J., Pepler, A., Di Luca, A., Cavicchia, L., Evans, J. P., Louis, S., McInnes, K. L. and Walsh, K. (2019). Review of Australian east coast low pressure systems and associated extremes. *Climate Dynamics*. **https://doi.org/10.1007/s00382-019-04836-8**

Guerreiro, S.B., Fowler, H.J., Barbero, R., Westra, S., Lenderink, G., Blenkinsop, S., Lewis, E. and Li, X.-F. (2018). Detection of continental-scale intensification of hourly rainfall extremes. *Nat. Clim. Chang.*, **8**, 803–808. **https://doi.org/10.1038/s41558-018-0245-3**

Holgate, C. M., Pepler, A. S., Rudeva, I., and Abram, N. J. (2023). Anthropogenic warming reduces the likelihood of drought-breaking extreme rainfall events in southeast Australia. *Weather and Climate Extremes*, 42, 100607. **https://doi.org/10.1016/j.wace.2023.100607**

Johnson, F., and coauthors. (2016). Natural hazards in Australia: floods. *Climatic Change*, *139*(1), 21-35. **https://doi.org/10.1007/s10584-016-1689-y**

Knutson, T., and coauthors. (2019). Tropical Cyclones and Climate Change Assessment: Part I: Detection and Attribution. *Bulletin of the American Meteorological Society*, *100*(10), 1987-2007. **https://doi.org/10.1175/BAMS-D-18-0189.1**

Knutson, T., and coauthors. (2020). Tropical cyclones and climate change assessment: Part II. Projected response to anthropogenic warming. *Bulletin of the American Meteorological Society*, 101 (3): E303–E322. **https://doi.org/10.1175/BAMS-D-18-0194.1**

NESP (2020). Scenario analysis of climate-related physical risk for buildings and infrastructure: climate science guidelines. NESP Earth Systems and Climate Change (ESCC) Hub report for the Climate Measurement Standards Initiative, 116 pp. **https://uploads-ssl.webflow.com/5f1bdaf710347301b0c01fd4/5f5c2f4cb000cab9c03025d8_CMSI%20-%20Climate%20Science%20Technical%20Summary.pdf**

Osburn, L., Hope, P. and Dowdy, A. (2021). Changes in hourly extreme precipitation in Victoria, Australia, from the observational record. *Weather and Climate Extremes*, 31, 100294. **https://doi.org/10.1016/j.wace.2020.100294**

Pepler, A.S. and Dowdy, A.J. (2022). Australia's future extratropical cyclones. *J. Climate*, 35, 7795-7810. **https://doi.org/10.1175/JCLI-D-22-0312.1**

Reid, K. J., O'Brien, T. A., King, A. D., and Lane, T. P. (2021). Extreme Water Vapor Transport during the March 2021 Sydney Floods in the Context of Climate Projections. *Geophysical Research Letters*, e2021GL095335. **https://doi.org/10.1029/2021gl095335**

Tolhurst, G., Hope, P., Osburn, L., and Rauniyar, S. (2023). Approaches to Understanding Decadal and Long-Term Shifts in Observed Precipitation Distributions in Victoria, Australia. *Journal of Applied Meteorology and Climatology*, 62, 3–19. **https://doi.org/10.1175/JAMC-D-22-0031.1**

Wasko, C. and coauthors. (2024). A systematic review of climate change science relevant to Australian design flood estimation. *Hydrology and Earth System Sciences*, 28, 1251-1285. **https://doi.org/10.5194/hess-28-1251-2024**

The material in this box draws extensively on a systematic review (Wasko et al., 2024) of evidence on trends and projections in extreme rainfall. This review is also reflected in the updated climate change guidance for engineers as published in version 4.2 of *Australian Rainfall and Runoff* (**https://www.arr-software.org/arrdocs**).

Streamflow

Hamed, K.H. and Rao, A.R. (1998). A modified Mann-Kendall trend test for autocorrelated data. *Journal of hydrology*, 204(1-4), 182-196, **https://doi.org/10.1016/S0022-1694(97)00125-X**

Hu, Z., Liu, S., Zhong, G., Lin, H. and Zhou, Z. (2020). Modified Mann-Kendall trend test for hydrological time series under the scaling hypothesis and its application. *Hydrological Sciences Journal*, 65(14), 2419-2438, **https://doi.org/10.1080/02626667.2020.1810253**

Turner, M. (2012). Hydrologic Reference Station selection guidelines. Bureau of Meteorology, available at **http://www.bom.gov.au/water/hrs/media/static/papers/Selection_Guidelines.pdf**

The analysis draws on data from all available Australian Hydrologic Reference Stations with sufficient data in the 1970–2023 period (**http://www.bom.gov.au/water/hrs/**).

Details of Australia's Topographic Drainage Divisions are available at **http://www.bom.gov.au/water/about/riverBasinAuxNav.shtml**

Tropical cyclones

Bell, S.S. and coauthors. (2019). Projections of southern hemisphere tropical cyclone track density using CMIP5 models. *Climate Dynamics,* 52, 6065–6079. **https://doi.org/10.1007/s00382-018-4497-4**

Chand, S.S., and coauthors. (2019). Review of tropical cyclones in the Australian region: Climatology, variability, predictability, and trends. *WIREs Clim Change*, 10:e602. **https://doi.org/10.1002/wcc.602**

Callaghan, J. and Power, S.B. (2011). Variability and decline in the number of severe tropical cyclones making land-fall over eastern Australia since the late nineteenth century. *Clim. Dyn.*, 37, 647-662. **https://doi.org/10.1007/s00382-010-0883-2**

Chand, S.S., and coauthors. (2022). Declining tropical cyclone frequency under global warming. *Nat. Clim. Chang.* 12, 655–661, **https://doi.org/10.1038/s41558-022-01388-4**

Dowdy, A.J. (2014). Long-term changes in Australian tropical cyclone numbers. *Atmos. Sci. Lett.,* 15: 292-298, **https://doi.org/10.1002/asl2.502**

Knutson, T., and coauthors. (2020). Tropical cyclones and climate change assessment: Part II. Projected response to anthropogenic warming. *Bulletin of the American Meteorological Society*, 101, E303–E322. **https://doi.org/10.1175/BAMS-D-18-0194.1**

Kossin, J.P., Knapp, K.R., Olander, T.L. and Velden, C.S. (2020). Global increase in major tropical cyclone exceedance probability over the past four decades. *Proceedings of National Academy of Sciences of the United States of America*, **117**(22), 11975– 11980, **https://doi.org/10.1073/pnas.1920849117**

Nicholls, N. (1984). The southern oscillation, sea-surface temperature, and interannual fluctuations in Australian tropical cyclone activity. *J. Climatol.*, 4, 661–670, **https://doi.org/10.1002/joc.3370040609**

Ramsay, H.A., Leslie, L.M., Lamb, P.J., Richman, M.B. and Leplastrier, M. (2008). Interannual Variability of Tropical Cyclones in the Australian Region: Role of Large-Scale Environment, *Journal of Climate*, *21*(5), 1083-1103, **https://doi.org/10.1175/2007JCLI1970.1**

Snowfall

Pepler, A.S., Trewin, B. and Ganter, C. (2015). The influence of climate drivers on the Australian snow season. *Aust. Met. Oceanogr. J.*, 65, 195-205. DOI:**10.22499/2.6502.002**

Snow depth data for Spencers Creek are sourced from Snowy Hydro (**https://www.snowyhydro.com.au/generation/live-data/snow-depths/**).

Oceans

Sea surface temperature

Benthuysen, J.A., Oliver, E.C.J., Chen, K. and Wernberg, T. (2020). Editorial: advances in understanding marine heatwaves and their impacts. *Front. Mar. Sci*. 7:147. **https://doi.org/10.3389/fmars.2020.00147**

Huang, B., and coauthors. (2017). NOAA Extended Reconstructed Sea Surface Temperature (ERSST), Version 5. NOAA National Centers for Environmental Information. **doi:10.7289/V5T72FNM**

Huang, B., Liu, C., Banzon, V., Freeman, E., Graham, G., Hankins, B., Smith, T. and Zhang, H-M. (2020). Improvements of the Daily Optimum Interpolation Sea Surface Temperature (DOISST) Version 2.1, *J. Climate*, 34, 2923-2939. **https://doi.org/10.1175/JCLI-D-20-0166.1**

Feng, M., Caputi, N., Chandrapavan, A., Chen, M., Hart, A. and Kangas, M. (2021). Multi-year marine cold-spells off the west coast of Australia and effects on fisheries. *Journal of Marine Systems*, 214, 103473, **https://doi.org/10.1016/j.jmarsys.2020.103473**

Hobday, A.J., and coauthors. (2016a). A hierarchical approach to defining marine heatwaves. *Progress in Oceanography* 141, 227-238, **https://doi.org/10.1016/j.pocean.2015.12.014**

Hu, S. and Fedorov, A.V. (2017). The extreme El Niño of 2015–2016 and the end of global warming hiatus, *Geophys. Res. Lett.,* 44, 3816–3824, **https://doi.org/10.1002/2017GL072908**

Kajtar, J.B., Holbrook, N.J. and Hernaman, V. (2021). A catalogue of marine heatwave metrics and trends for the Australian region. *Journal of Southern Hemisphere Earth Systems Science*, 71, 284–302, **https://doi.org/10.1071/ES21014**

Vanderklift, M.A., and coauthors. (2020). The oceanography and marine ecology of Ningaloo, a world heritage area. In Oceanography and Marine Biology. Taylor & Francis. **https://www.taylorfrancis.com/chapters/oa-edit/10.1201/9780429351495-4/oceanography-marine-ecology-ningaloo-world-heritage-area-mathew-vanderklift-russell-babcock-peter-barnes-anna-cresswell-ming-feng-michael-haywood-thomas-holmes-paul-lavery-richard-pillans-claire-smallwood-damian-thomson-anton-tucker-kelly-waples-shaun-wilson**

Wu, L., and coauthors. (2012). Enhanced warming over the global subtropical western boundary currents. *Nature Clim Change* 2, 161–166, **https://doi.org/10.1038/nclimate1353**

This section draws upon data from version 5 of the Extended Reconstructed Sea Surface Temperature (ERSSTv5) dataset (Huang et al., 2017) (**www.esrl.noaa.gov/psd/**). The figure also draws upon version 2 of the Optimum Interpolation Sea Surface Temperature (OISST) dataset (Huang et al., 2020) (**https://www.ncei.noaa.gov/products/optimum-interpolation-sst**).

Box 4 – Marine heatwaves and coral reefs

Hobday, A.J., and coauthors. (2016). A hierarchical approach to defining marine heatwaves. *Progress in Oceanography* 141, 227-238, **doi:10.1016/j.pocean.2015.12.014**

Holbrook, N.J., Gupta, A.S., Oliver, E.C.J., Hobday, A.J., Benthuysen, J.A., Scannell, H.A., Smale, D.A. and Wernberg T. (2020). Keeping Pace with Marine Heatwaves as Oceans Warm. *Nature Reviews Earth & Environment*, **https://doi.org/10.1038/s43017-020-0068-4**

Spillman, C.M. and Smith, G.A. (2021). A new operational seasonal thermal stress prediction tool for coral reefs around Australia. *Frontiers of Marine Science*. **https://doi.org/10.3389/fmars.2021.687833**

Spillman, C.M., Smith, G.A., Hobday, A.J. and Hartog, J.R. (2021). Onset and decline rates of marine heatwaves: global trends, seasonal forecasts and marine management. *Frontiers of Climate*, **https://doi.org/10.3389/fclim.2021.801217**

Ocean heat content

Roemmich, D. and Gilson, J. (2009) The 2004-2008 mean and annual cycle of temperature, salinity, and steric height in the global ocean from the Argo Program. Progress in Oceanography, 82, 81-100. updated here: **https://sio-argo.ucsd.edu/RG_Climatology.html**

Liang, X., Liu, C., Ponte, R.M. and Chambers, D.P. (2021). A comparison of the variability and changes in global ocean heat content from multiple objective analysis products during the Argo period. *Journal of Climate*, 34(19), 7875-7895, **https://doi.org/10.1175/JCLI-D-20-0794.1**

Cheng, L., and coauthors. (2022). Another Record: Ocean Warming Continues through 2021 despite La Niña Conditions. *Advances in Atmospheric Sciences, 39*, 373-385, **https://doi.org/10.1007/s00376-022-1461-3**

Wang, L., Lyu, K., Zhuang, W., Zhang, W., Makarim, S. and Yan, X.H. (2021). Recent shift in the warming of the Southern Oceans Modulated by decadal climate variability. *Geophysical Research Letters*, 48(3), e2020GL090889, **https://doi.org/10.1029/2020GL090889**

Rathore, S., Bindoff, N.L., Phillips, H.E. and Feng, M. (2020). Recent hemispheric asymmetry in global ocean warming induced by climate change and internal variability. *Nature communications*, 11(1), 1-8, **https://doi.org/10.1038/s41467-020-15754-3**

Bagnell, A. and DeVries, T. (2021). 20th century cooling of the deep ocean contributed to delayed acceleration of Earth's energy imbalance. *Nature Communications*, 12(1), 1-10, **https://doi.org/10.1038/s41467-021-24472-3**

Johnson, G.C. and Lyman, J.M. (2020). Warming trends increasingly dominate global ocean. *Nature Climate Change*, 10(8), 757-761, **https://doi.org/10.1038/s41558-020-0822-0**

Johnson, G.C., Cadot, C., Lyman, J.M., McTaggart, K.E. and Steffen, E.L. (2020). Antarctic bottom water warming in the Brazil Basin: 1990s through 2020, from WOCE to Deep Argo. *Geophysical Research Letters*, 47(18), e2020GL089191, **https://doi.org/10.1029/2020GL089191**

Meyssignac, B., and coauthors. (2019). Measuring Global Ocean Heat Content to Estimate the Earth Energy Imbalance. *Frontiers in Marine Science, 6*, **https://doi.org/10.3389/fmars.2019.00432**

Purkey, S.G., Johnson, G.C., Talley, L.D., Sloyan, B.M., Wijffels, S.E., Smethie, W., Mecking, S., & Katsumata, K. (2019). Unabated Bottom Water Warming and Freshening in the South Pacific Ocean. *Journal of Geophysical Research: Oceans, 124*, 1778-1794, **https://doi.org/10.1029/2018JC014775**

von Schuckmann, K. and coauthors. (2020). Heat stored in the Earth system: where does the energy go? *Earth Syst. Sci. Data, 12*, 2013-2041, **https://doi.org/10.5194/essd-12-2013-2020**

Woods Hole Oceanographic Institute is cited in contributing to the time-series in the first figure, as Susan Wijffels has contributed to the methodology.

Scripps Institute of Oceanography (SIO) is cited as they are the custodians of the Roemmich and Gilson gridded Argo climatology.

Sea level

Abdalla, S., and coauthors. (2021). Altimetry for the future: Building on 25 years of progress. *Advances in Space Research,* 68, 319-363, **https://doi.org/10.1016/j.asr.2021.01.022**

Agarwal, N., Jungclaus, J.H., Köhl, A., Mechoso, C.R. and Stammer, D. (2015). Additional contributions to CMIP5 regional sea level projections resulting from Greenland and Antarctic ice mass loss. *Environmental Research Letters*, vol. 10, no. 7, pp. 1–8, **https://doi.org/10.1088/1748-9326/10/7/074008**

Boening, C., Willis, J.K., Landerer, F.W., Nerem, R.S. and Fasullo, J. (2012). The 2011 La Niña: So strong, the oceans fell. *Geophysical Research Letters*,39(19), p. L19602. **https://doi.org/10.1029/2012GL053055**

Burgette, R.J., Watson, C.S., Church, J.A., White, N.J., Tregoning, P. and Coleman, R. (2013). Characterizing and minimizing the effects of noise in tide gauge time series: relative and geocentric sea level rise around Australia. *Geophysical Journal International*, 194(2), 719–736. **https://doi.org/10.1093/gji/ggt131**

Chen, X., Zhang, X., Church, J.A., Watson, C.S., King, M.A., Monselesan, D., Legresy B. and Harig, C. (2017). The increasing rate of global mean sea-level rise during 1993-2014. *Nature Climate Change* 7, 492-495, **https://doi.org/10.1038/nclimate3325**

Church, J.A., Hunter, J.R., McInnes, K.L. and White, N.J. (2006). Sea-level rise around the Australian coastline and the changing frequency of extreme sea-level events. *Aust. Met. Mag*. 55 (2006) 253-260. **https://www.johnroberthunter.org/science/home_prof/papers/AMM_Church_et_al_2006.pdf**

Church, J.A. and White, N.J. (2011). Sea-Level Rise from the Late 19th to the Early 21st Century. *Surveys in Geophysics*,32(4-5), 585–602. **https://doi.org/10.1007/s10712-011-9119-1**

Fasullo, J.T., Boening, C., Landerer, F.W. and Nerem, R.S. (2013) Australia's unique influence on global sea level in 2010-2011. *Geophysical Research Letters*,40(16), 4368–4373. **https://doi.org/10.1002/grl.50834**

Featherstone, W.E., Penna, N.T., Filmer, M.S. and Williams, S.D.P. (2015). Nonlinear subsidence at Fremantle, a long-recording tide gauge in the Southern Hemisphere. *Journal of Geophysical Research: Oceans*, 120(10), 7004–7014. **https://doi.org/10.1002/2015JC011295**

Hinkel, J., and coauthors. (2019). Meeting User Needs for Sea Level Rise Information: A Decision Analysis Perspective. Earth's Future, 7(3), 320 – 327. **https://doi.org/10.1029/2018EF001071**

Hague, B.S., Murphy, B.F., Jones, D.A. and Taylor, A.J. (2019). Developing impact-based thresholds for coastal inundation from tide gauge observations. *Journal of Southern Hemisphere Earth Systems Science*, 69, 252-272. DOI:**10.1071/ES19024**

Hague, B.S, McGregor, S., Murphy, B.F., Reef, R. and Jones, D.A. (2020). Sea-Level Rise Driving Increasingly Predictable Coastal Inundation in Sydney, Australia. *Earth's Future*. **https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2020EF001607**

Hague, B.S., Jones, D.A., Jakob, D., McGregor, S. and Reef, R. (2022). Australian coastal flooding trends and forcing factors. *Earth's Future*, 10, e2021EF002483 **https://doi.org/10.1029/2021EF002483**

Hönisch, B., and coauthors. (2012). The Geological Record of Ocean Acidification. *Science, 335*, 1058-1063, **https://doi.org/doi:10.1126/science.1208277**

Jevrejeva, S., Moore, J.C., Grinsted, A. and Woodworth, P.L. (2008). Recent global sea level acceleration started over 200 years ago?. *Geophysical Research Letters*,35(8), L08715. **https://doi.org/10.1029/2008GL033611**

Masters, D., Nerem, R.S., Choe, C., Leuliette, E., Beckley, B., White, N. and Ablain, M. (2012). Comparison of Global Mean Sea Level Time Series from TOPEX/Poseidon, Jason-1, and Jason-2. *Marine Geodesy*, 35(sup 1), 20–41. **https://doi.org/10.1080/01490419.2012.717862**

McInnes, K.L., Church, J.A., Monselesan, D., Hunter, J.R., O'Grady, J.G., Haigh, I.D. and Zhang, X. (2015). Information for Australian Impact and Adaptation Planning in response to Sea-level Rise, *Australian Meteorological and Oceanographic Journal*, 65:1, 127–149. DOI:**10.22499/2.6501.009**

Palmer, M. D., Domingues, C.M., Slangen, A.B.A. and Dias, F.B. (2021). An ensemble approach to quantify global mean sea-level rise over the 20th century from tide gauge reconstructions. *Environ. Res. Lett.*, 16, 044043. **https://doi.org/10.1088/1748-9326/abdaec**

Ray, R.D. and Douglas, B.C. (2011). Experiments in reconstructing twentieth-century sea levels. *Progress in Oceanography*, 91(4), 496–515. **https://doi.org/10.1016/j.pocean.2011.07.021**

Rignot, E., Velicogna, I., Van Den Broeke, M.R., Monaghan, A. and Lenaerts, J. (2011). Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise. *Geophysical Research Letters*, 38(5), p. L05503. **https://doi.org/10.1029/2011GL046583**

Royston, S., Watson, C.S., Legrésy, B., King, M.A., Church, J.A. and Bos, M.S. (2018). Sea-Level Trend Uncertainty With Pacific Climatic Variability and Temporally-Correlated Noise. *Journal of Geophysical Research: Oceans*, 123(3), 1978–1993. **https://doi.org/10.1002/2017JC013655**

Slangen, A.B.A., Church, J.A., Agosta, C., Fettweis, X., Marzeion, B., and Richter, K. (2016). Anthropogenic forcing dominates global mean sea-level rise since 1970. *Nature Climate Change, 6*, 701-705, **https://doi.org/10.1038/nclimate2991**

Wang, J., Church, J.A., Zhang, X., & Chen, X. (2021). Reconciling global mean and regional sea level change in projections and observations. *Nature Communications, 12*, 990, **https://doi.org/10.1038/s41467-021-21265-6**

Wang, J., Church, J.A., Zhang, X., Gregory, J.M., Zanna, L. and Chen, X. (2021). Evaluation of the local sea-level budget at tide gauges since 1958. *Geophysical Research Letters*, 48, e2021GL094502. **https://doi.org/10.1029/2021GL094502**

Wang, J., Church, J. A., Zhang, X., & Chen, X. (2024). Improved sea-level reconstruction from 1900 to 2019. *Journal of Climate*. **https://doi.org/10.1175/JCLI-D-23-0410.1**

Watson, C.S., White, N.J., Church, J.A., King, M.A., Burgette, R.J. and Legresy, B. (2015). Unabated global mean sea-level rise over the satellite altimeter era. *Nature Climate Change*, 5(6), 565–568. **https://doi.org/10.1038/nclimate2635**

WCRP Global Sea Level Budget Group (2018). Global sea-level budget 1993–present. *Earth Syst. Sci. Data, 10*, 1551-1590, **https://doi.org/10.5194/essd-10-1551-2018**

White, N.J., and coauthors. (2014). Australian sea levels-trends, regional variability and influencing factors. *Earth-Science Reviews*, *136*, 155-174. **https://doi.org/10.1016/j.earscirev.2014.05.011**

Wijffels, S., and coauthors. (2018). A fine spatial-scale sea surface temperature atlas of the Australian regional seas (SSTAARS): seasonal variability and trends around Australasia and New Zealand revisited. *Journal of Marine Systems*, *87*, 156-196. **https://doi.org/10.1016/j.jmarsys.2018.07.005**

Woolworth, P.L., White, N.J., Jevrejeva, S., Holgate, S.J., Church, J.A. and Gehrels, W.R. (2008). Evidence for the accelerations of sea level on multi-decade and century timescales. *International Journal of Climatology*, 29(6), 777-789. **https://doi.org/10.1002/joc.1771**

Zhang, X. and Church, J.A. (2012). Sea level trends, interannual and decadal variability in the Pacific Ocean. *Geophys. Res. Lett., 39,* L21701. **https://doi.org/10.1029/2012GL053240**

Zhang, X., Church, J.A., Monselesan, D. and McInnes, K.L. (2017). Sea level projections for the Australian region in the 21st century. *Geophysical Research Letters*, *44*(16), 8481–8491. **https://doi.org/10.1002/2017GL074176**

The first figure includes reconstructions from CSIRO (Wang et al., 2024) and Palmer et al. (2021), and satellite altimetry data from NASA/JPL (**https://podaac.jpl.nasa.gov/dataset/MERGED_TP_J1_OSTM_OST_GMSL_ASCII_V42**).

Satellite altimetry data for the second figure are drawn from the NOAA/NESDIS/STAR satellite altimetry dataset (**https://www.star.nesdis.noaa.gov/socd/lsa/**).

Information about satellite altimetry calibration and validation can be accessed at **https://imos.org.au/facility/satellite-remote-sensing/satellite-altimetry-calibration-and-validation**

Ocean acidification

Comeau, S., Cornwall, C.E., DeCarlo, T.M., Doo, S.S., Carpenter, R.C., & McCulloch, M.T. (2019). Resistance to ocean acidification in coral reef taxa is not gained by acclimatization. *Nature Climate Change, 9*, 477-483, **https://doi.org/10.1038/s41558-019-0486-9**

Doney, S. C., Busch, D. S., Cooley, S. R., Kroeker, K. J. (2020). The Impacts of Ocean Acidification on Marine Ecosystems and Reliant Human Communities., *Annual Review of Environment and Resources* 2020 45:1, 83-112. **https://doi.org/10.1146/annurev-environ-012320-083019**

Fabricius, K.E., Neill, C., Van Ooijen, E., Smith, J. N., & Tilbrook, B. (2020). Progressive seawater acidification on the Great Barrier Reef continental shelf. *Scientific Reports*, *10*(1). **https://doi.org/10.1038/s41598-020-75293-1**

Gregor, L. and Gruber, N. (2021). OceanSODA-ETHZ: a global gridded data set of the surface ocean carbonate system for seasonal to decadal studies of ocean acidification, *Earth Syst. Sci. Data*, *13,* 777–808, **https://doi.org/10.5194/essd-13-777-2021**, Accessed 22 April 2024.

Hönisch, B., Ridgwell, A., Schmidt, D. N., Thomas, E., Gibbs, S. J., Sluijs, A., Williams, B. (2012) The geological record of ocean acidification. *Science*, *335*(6072), 1058–1063. **https://doi.org/10.1126/science.1208277**

Hurd, C. L., Lenton, A., Tilbrook, B., & Boyd, P. W. (2018) Current understanding and challenges for oceans in a higher-CO2 world. *Nature Climate Change*. **https://doi.org/10.1038/s41558-018-0211-0**

IPCC (2019). IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Portner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 755 pp. **https://doi.org/10.1017/9781009157964**

James, N.P. and Bone Y. (2011) Neritic Carbonate Sediments in a Temperate Realm: Southern Australia, Sringer Science, pp. 454, Springer Dordrecht Netherlands, ISBN: 978-90-48-9288-5, **https://doi.org/10.1007/978-90-481-9289-2**

Jiang, L.-Q., Carter, B. R., Feely, R. A., Lauvset, S. K., & Olsen, A. (2019) Surface ocean pH and buffer capacity: past, present and future. *Scientific Reports*, *9*(1), 18624. **https://doi.org/10.1038/s41598-019-55039-4**

Lenton A., Tilbrook B., Matear R.J., Sasse T, Nojiri Y (2016) Historical reconstruction of ocean acidification in the Australian region. *Biogeosciences*, *13*, 1753-1765 **https://doi.org/10.5194/bg-13-1753-2016**

Mongin, M., and coauthors. (2016). The exposure of the Great Barrier Reef to ocean acidification. *Nature Communications, 7*, 10732, **https://doi.org/10.1038/ncomms10732**

Smith, J. N., Mongin, M., Thompson, A., Jonker, M. J., De'ath, G., & Fabricius, K. E. (2020) Shifts in coralline algae, macroalgae, and coral juveniles in the Great Barrier Reef associated with present-day ocean acidification. *Global Change Biology*, *26*(4), 2149–2160. **https://doi.org/10.1111/gcb.14985**

Sunday, J.M., and coauthors. (2017). Ocean acidification can mediate biodiversity shifts by changing biogenic habitat. *Nature Climate Change, 7*, 81-85, **https://doi.org/10.1038/nclimate3161**

Sutton, A.J., and coauthors. (2016). Using present-day observations to detect when anthropogenic change forces surface ocean carbonate chemistry outside preindustrial bounds. *Biogeosciences, 13*, 5065-5083, **https://doi.org/10.5194/bg-13-5065-2016**

Tilbrook, B., and coauthors. (2020) Ocean acidification. In Richardson A.J, Eriksen R, Moltmann T, Hodgson-Johnston I, Wallis J.R. (Eds). *State and Trends of Australia's Ocean Report*. **https://doi.org/10.26198/5e16a38849e78**

The figure is based on the OceanSODA-ETHZ dataset (Gregor and Gruber, 2021).

Cryosphere

Abram, N.J., and coauthors. (2021). Connections of climate change and variability to large and extreme forest fires in southeast Australia. *Communications Earth & Environment, 2*, 8, **https://doi.org/10.1038/s43247-020-00065-8**

Cavalieri, D.J., Parkinson, C.L., Gloersen, P. and Zwally, H. J. (1996). Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data, Version 1. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. **https://doi.org/10.5067/8GQ8LZQVL0VL**

Hobbs, W.R., Massom, R., Stammerjohn, S., Reid, P., Williams, G. and Meier, W. (2016). A review of recent changes in Southern Ocean sea ice, their drivers and forcings. *Global and Planetary Change*, *143*. **https://doi.org/10.1016/j.gloplacha.2016.06.008**

Kusahara, K., Reid, P., Williams, G.D., Massom, R. and Hasumi, H. (2018). An ocean-sea ice model study of the unprecedented Antarctic sea ice minimum in 2016. *Environmental Research Letters*, *13*(8). **https://doi.org/10.1088/1748-9326/aad624**

Liang, D., Guo, H., Zhang, L., Cheng, Y., Zhu, Q. and Liu, X. (2021). Time-series snowmelt detection over the Antarctic using Sentinel-1 SAR images on Google Earth Engine. *Remote Sensing of Environment*, *256*, 112318. **https://doi.org/10.1016/j.rse.2021.112318**

Lim, E.-P., and coauthors. (2021). The 2019 Southern Hemisphere Stratospheric Polar Vortex Weakening and Its Impacts. *Bulletin of the American Meteorological Society, 102*, E1150-E1171, **https://doi.org/10.1175/BAMS-D-20-0112.1**

Maslanik, J. and Stroeve, J. (1999). updated daily: Near-Real-Time DMSP SSM/I-SSMIS Daily Polar Gridded Sea Ice Concentrations. National Snow and Ice Data Center, Boulder, CO, digital media. Retrieved from **https://doi.org/10.5067/YTTHO2FJQ97K**.

Massom, R.A., Scambos, T.A., Bennetts, L.G., Reid, P., Squire, V.A. and Stammerjohn, S.E. (2018). Antarctic ice shelf disintegration triggered by sea ice loss and ocean swell. *Nature*, 558(7710), 383–389. **https://doi.org/10.1038/s41586-018-0212-1**

Mazloff, M., and coauthors. (2017). Southern Ocean [in 'State of the Climate in 2016']. *Bulletin of the American Meteorological Society*, *98*(8), S166–S167. **https://www.researchgate.net/publication/319069239_Southern_Ocean_in_State_of_the_Climate_in_2016**

Meehl, G.A., Arblaster, J.M., Chung, C.T.Y., Holland, M.M., DuVivier, A., Thompson, L., Yang, D., and Bitz, C.M. (2019). Sustained ocean changes contributed to sudden Antarctic sea ice retreat in late 2016. *Nature Communications, 10*, 14, **https://doi.org/10.1038/s41467-018-07865-9**

Meredith, M., and coauthors. (2019). Polar Regions. In H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, ... W. N.M. (Eds.), IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. **ipcc.ch/site/assets/uploads/sites/3/2019/11/07_SROCC_Ch03_FINAL.pdf**

Noble, T.L., and coauthors. (2020). The Sensitivity of the Antarctic Ice Sheet to a Changing Climate: Past, Present, and Future. *Reviews of Geophysics, 58*, e2019RG000663, **https://doi.org/10.1029/2019RG000663**

Owens, I. and Zawar-Reza, P. (2015). Weather and Climate. In D. Liggett, B. Storey, Y. Cook, & V. Meduna (Eds.), Exploring the Last Continent: An Introduction to Antarctica (pp. 91–114). Springer International Publishing. **https://doi.org/10.1007/978-3-319-18947-5_6**

Purich, A. and England, M.H. (2019). Tropical Teleconnections to Antarctic Sea Ice During Austral Spring 2016 in Coupled Pacemaker Experiments. *Geophysical Research Letters*, 46(12), 6848–6858. **https://doi.org/10.1029/2019GL082671**

Reid, P.A. and Massom, R.A. (2022). Change and variability in Antarctic coastal exposure, 1979–2020. *Nature Communications*, 13(1). **https://doi.org/10.1038/s41467-022-28676-z**

Reid, P., S. Stammerjohn, R. A. Massom, S. Barreira, T. Scambos, and J. L. Lieser, 2022: Sea ice extent, concentration, and seasonality [in "State of the Climate in 2021"]. *Bull. Amer. Meteor. Soc. 103* (8), S325–S329, **https://doi.org/10.1175/2022BAMSStateoftheClimate.1**

Stammerjohn, S. and Maksym, T. (2017). Gaining (and losing) Antarctic sea ice: variability, trends and mechanisms. In *Sea Ice* (pp. 261–289). **https://doi.org/10.1002/9781118778371.ch10**

Teder, N., Bennetts, L., Reid, P. and Massom, R. (2022). Sea ice-free corridors for large swell to reach Antarctic ice shelves. *Environmental Research Letters*. Retrieved from **http://iopscience.iop.org/article/10.1088/1748-9326/ac5edd**

van Ommen, T.D. and Morgan, V. (2010). Snowfall increase in coastal East Antarctica linked with southwest Western Australian drought. *Nature Geoscience*, 3(4), 267–272. **https://doi.org/10.1038/ngeo761**

Vance, T.R., Roberts, J.L., Plummer, C.T., Kiem, A.S. and van Ommen, T.D. (2015). Interdecadal Pacific variability and eastern Australian megadroughts over the last millennium. *Geophysical Research Letters*, *42*(1), 129–137. **https://doi.org/10.1002/2014GL062447**

Wille, J.D., Favier, V., Dufour, A., Gorodetskaya, I.V, Turner, J., Agosta, C. and Codron, F. (2019). West Antarctic surface melt triggered by atmospheric rivers. *Nature Geoscience*, *12*(11), 911–916. **https://doi.org/10.1038/s41561-019-0460-1**

Yuan, X., Kaplan, M.R. and Cane, M.A. (2018). The interconnected global climate system-a review of tropical-polar teleconnections. *Journal of Climate*, *31*(15), 5765–5792. **https://doi.org/10.1175/JCLI-D-16-0637.1**

The assessment of the contribution of ice sheet melting to global sea level rise draws from IPCC AR6 Table 9.5.

Data sources for the figures are as follows:

- Figure 1. Sea-ice extent values are calculated from satellite passive-microwave ice concentration data obtained from the National Snow and Ice Data Center (Cavalieri et al. 1996, updated annually for 1979–2021, and Maslanik and Stroeve 1999 for 2022).
- Figure 2. Duration values are calculated from satellite passive-microwave ice concentration data obtained from the National Snow and Ice Data Center (Cavalieri et al. 1996, updated annually for 1979–2021, and Maslanik and Stroeve 1999 for 2022).

Greenhouse gases and carbon budgets

Derek, N., Krummel, P.B. and Cleland, S.J. (Eds) (2014). Baseline atmospheric program Australia 2009-2010, Australian Bureau of Meteorology and CSIRO Marine and Atmospheric Research. **http://www.bom.gov.au/inside/cgbaps/baseline.shtml**

Etminan, M., Myhre, G., Highwood, E.J. and Shine, K.P. (2016). Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. *Geophysical Research Letters*, *43*(24), 12,614-12,623. **https://doi.org/10.1002/2016GL071930**

Forster, P.M., and coauthors (2024). Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence. *Earth Syst. Sci. Data*, **https://doi.org/10.5194/essd-2024-149**

Friedlingstein, P., and coauthors. (2023). Global Carbon Budget 2023, *Earth Syst. Sci. Data*, 15, 5301–5369, **https://doi.org/10.5194/essd-15-5301-2023**

Gohar, L. K., and Shine, K. P. (2007). Equivalent CO_2 and its use in understanding the climate effects of increased greenhouse gas concentrations. *Weather*, *62*(11), 307–311. **https://doi.org/10.1002/wea.103**

IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. **https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf**

IPCC (2023). Summary for Policymakers. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 1-34, DOI:**10.59327/IPCC/AR6-9789291691647.001**

Graven, H., and coauthors. (2017). Compiled records of carbon isotopes in atmospheric CO2 for historical simulations in CMIP6. *Geosci. Model Dev., 10*, 4405-4417 **https://doi.org/10.5194/gmd-10-4405-2017**

Jackson, R.B. and coauthors. (2024). Human activities now fuel two-thirds of global methane emissions. *Env. Res. Lett.*, *19*, 101002, **https://doi.org/10.1088/1748-9326/ad6463**

Krummel, P.B., and coauthors. (2014). The AGAGE *in situ* program for non-CO_2 greenhouse gases at Cape Grim, 2009-2010, in *Baseline Atmospheric Program (Australia) 2009-2010*, Australian Bureau of Meteorology and CSIRO Marine and Atmospheric Research, Melbourne, Australia, 56-70. **http://hdl.handle.net/102.100.100/485886?index=1**

Langenfelds, R.L., Steele, L.P., Gregory, R.L., Krummel, P.B., Spencer, D.A. and Howden, R.T. (2014). Atmospheric methane, carbon dioxide, hydrogen, carbon monoxide, and nitrous oxide from Cape Grim flask air samples analysed by gas chromatography, in *Baseline Atmospheric Program (Australia) 2009-2010*, Australian Bureau of Meteorology and CSIRO Marine and Atmospheric Research, Melbourne, Australia, 45-49. **https://nla.gov.au/nla.obj-1908473834/view**

Levin, I., and coauthors. (2010). Observations and modelling of the global distribution and long-term trend of atmospheric $^{14}CO_2$. *Tellus, Series B: Chemical and Physical Meteorology*, vol. 62, no. 1, 26–46. **https://doi.org/10.1111/j.1600-0889.2009.00446.x**

Levin, I., Hammer, S., Kromer, B., Preunkert, S., Weller, R., and Worthy, D.E. (2022). Radiocarbon in global tropospheric carbon dioxide. *Radiocarbon, 64*, 781-791, **https://doi.org/10.1017/RDC.2021.102**

MacFarling Meure, C., Etheridge, D., Trudinger, C., Steele, P., Langenfelds, R., van Ommen, T., Smith, A., & Elkins, J. (2006). Law Dome CO2, CH4 and N2O ice core records extended to 2000 years BP. *Geophysical Research Letters, 33*, **https://doi.org/10.1029/2006GL026152**

Machida, T., Nakazawa, T., Fujii, Y., Aoki, S., & Watanabe, O. (1995). Increase in the atmospheric nitrous oxide concentration during the last 250 years. *Geophysical Research Letters, 22*, 2921-2924, **https://doi.org/10.1029/95GL02822**

Meinshausen, M., and coauthors. (2017). Historical greenhouse gas concentrations for climate modelling (CMIP6). *Geosci. Model Dev., 10*, 2057-2116, **https://doi.org/10.5194/gmd-10-2057-2017**

Park, S., and coauthors. (2012). Trends and seasonal cycles in the isotopic composition of nitrous oxide since 1940. *Nature Geoscience, 5*, 261-265, **https://doi.org/10.1038/ngeo1421**

Prinn, R.G., and coauthors. (2018). History of Chemically and Radiatively Important Atmospheric Gases from the Advanced Global Atmospheric Gases Experiment (AGAGE), *Earth Syst. Sci. Data*, 10, 985-1018. **https://doi.org/10.5194/essd-10-985-2018**

Rubino, M., and coauthors. (2013). A revised 1000 year atmospheric C-CO2 record from Law Dome and South Pole, Antarctica. *Journal of Geophysical Research: Atmospheres, 118*, 8482-8499, **https://doi.org/10.1002/jgrd.50668**

Rubino, M., and coauthors. (2019). Revised records of atmospheric trace gases CO2, CH4, N2O, and δ13C-CO2 over the last 2000 years from Law Dome, Antarctica. *Earth Syst. Sci. Data, 11*, 473-492, **https://doi.org/10.5194/essd-11-473-2019**

Saunois, M., and coauthors. (2020). The Global Methane Budget 2000–2017. *Earth Syst. Sci. Data, 12*, 1561-1623, **https://doi.org/10.5194/essd-12-1561-2020**

Smith, C., Z.R.J. Nicholls, K. Armour, W. Collins, P. Forster, M. Meinshausen, M.D. Palmer, and Watanabe, M. (2021). The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity Supplementary Material. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Available from **https://www.ipcc.ch/**

Steele, P., and coauthors. (2014). Baseline carbon dioxide monitoring. In, *Baseline Atmospheric Program (Australia) 2009-2010*, Australian Bureau of Meteorology and CSIRO Marine and Atmospheric Research, Melbourne, Australia, pp. 39-41. **http://www.bom.gov.au/inside/cgbaps/baseline/Baseline_2009-2010.pdf**

Sturrock, G.A., Etheridge, D.M., Trudinger, C.M., Fraser, P.J., and Smith, A.M. (2002). Atmospheric histories of halocarbons from analysis of Antarctic firn air: Major Montreal Protocol species. *Journal of Geophysical Research: Atmospheres, 107*, ACH 12-11-ACH 12-14, **https://doi.org/10.1029/2002JD002548**

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

Trudinger, C.M., Etheridge, D.M., Rayner, P.J., Enting, I.G., Sturrock, G.A., and Langenfelds, R.L. (2002). Reconstructing atmospheric histories from measurements of air composition in firn. *Journal of Geophysical Research: Atmospheres, 107*, ACH 15-11-ACH 15-13, **https://doi.org/10.1029/2002JD002545**

Villalobos Y. and coauthors (2023). A comprehensive assessment of anthropogenic and natural sources and sinks of Australasia's carbon budget. *Global Biogeochemical Cycles*, 37, e2023GB007845. **https://doi.org/10.1029/2023GB007845**

Data in figures in the Greenhouse Gases section are from in situ observations by CSIRO and the Bureau of Meteorology (commencing Kennaook/Cape Grim, Tasmania, 1976) and the Advanced Global Atmospheric Gases Experiment (Krummel, 2014; Prinn, 2018) (global, including Kennaook/Cape Grim, commencing 1978) and from measurements of flask air samples (global, including Kennaook/Cape Grim, commencing 1992), the Kennaook/Cape Grim Air Archive (1978-2023) at the CSIRO GASLAB (Aspendale, Melbourne), and air from Antarctic firn (compacted snow) and ice cores measured at CSIRO GASLAB and ICELAB (Aspendale, Melbourne).

The Global Carbon Budget figure is adapted from Friedlingstein, P., and coauthors. (2023). **https://doi.org/10.5194/essd-15-5301-2023**

The Australian Carbon Budget figure is from the NESP Climate Systems Hub and Global Carbon Project, with data as described in Villalobos Y. and coauthors (2023). **https://doi.org/10.1029/2023GB007845**

Future climate

Knutson, T., and coauthors. (2020). Tropical Cyclones and Climate Change Assessment: Part II: Projected Response to Anthropogenic Warming. *Bulletin of the American Meteorological Society*101, 3, E303-E322. **https://doi.org/10.1175/BAMS-D-18-0194.1**

Information is drawn from the following IPCC reports, notably AR6:

- Future temperature and heat extremes: Chapter 11.3, Atlas 6.4 and Interactive Atlas
- Rainfall and drought: Chapters 8.3, 8.4, 11.6, 12.4.3, Atlas 6.4 and Interactive Atlas
- Extreme rainfall: Chapters 8.3, 8.4, 11.4 and 12.4.3
- Tropical cyclones and storms: Chapters 11.7 and 12.3
- Coastal and marine: Box 9.2, Chapters 9.6, 12.3.5 and 12.4.3
- Compound events: 11.8, 12.4 and Special Report on the Ocean and Cryosphere in a Changing Climate, Chapter 6