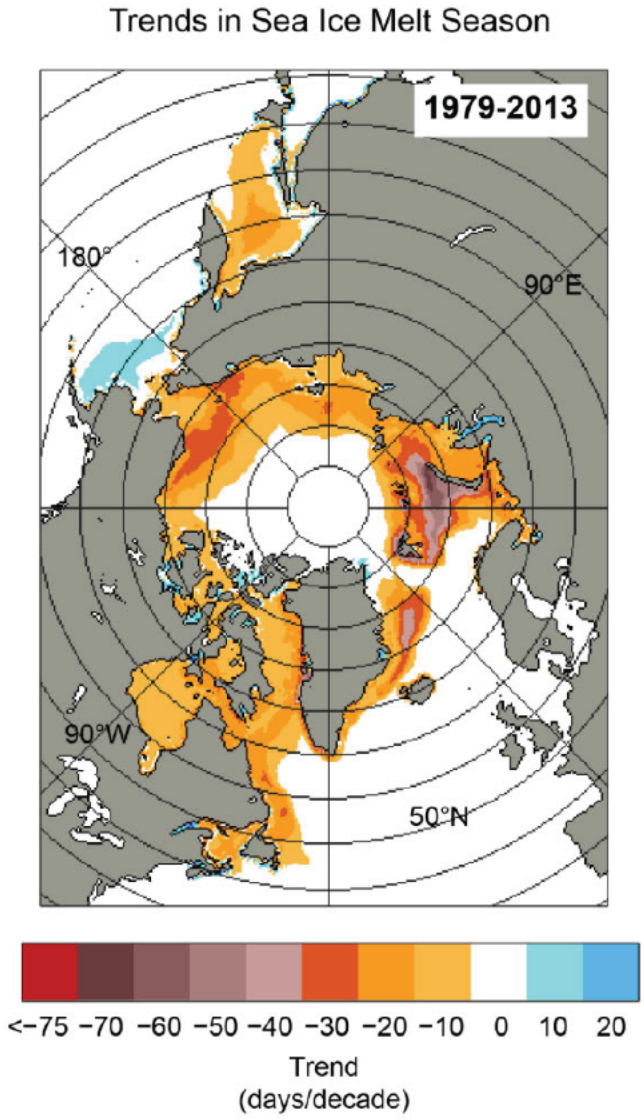

Figure 11.2: 35-year trend in Arctic sea ice melt season length, in days per decade, from passive microwave satellite observations, illustrating that the sea ice season has shortened by more than 60 days in coastal Alaska over the last 30 years. (Figure source: adapted from Parkinson 2014).

FINAL DRAFT

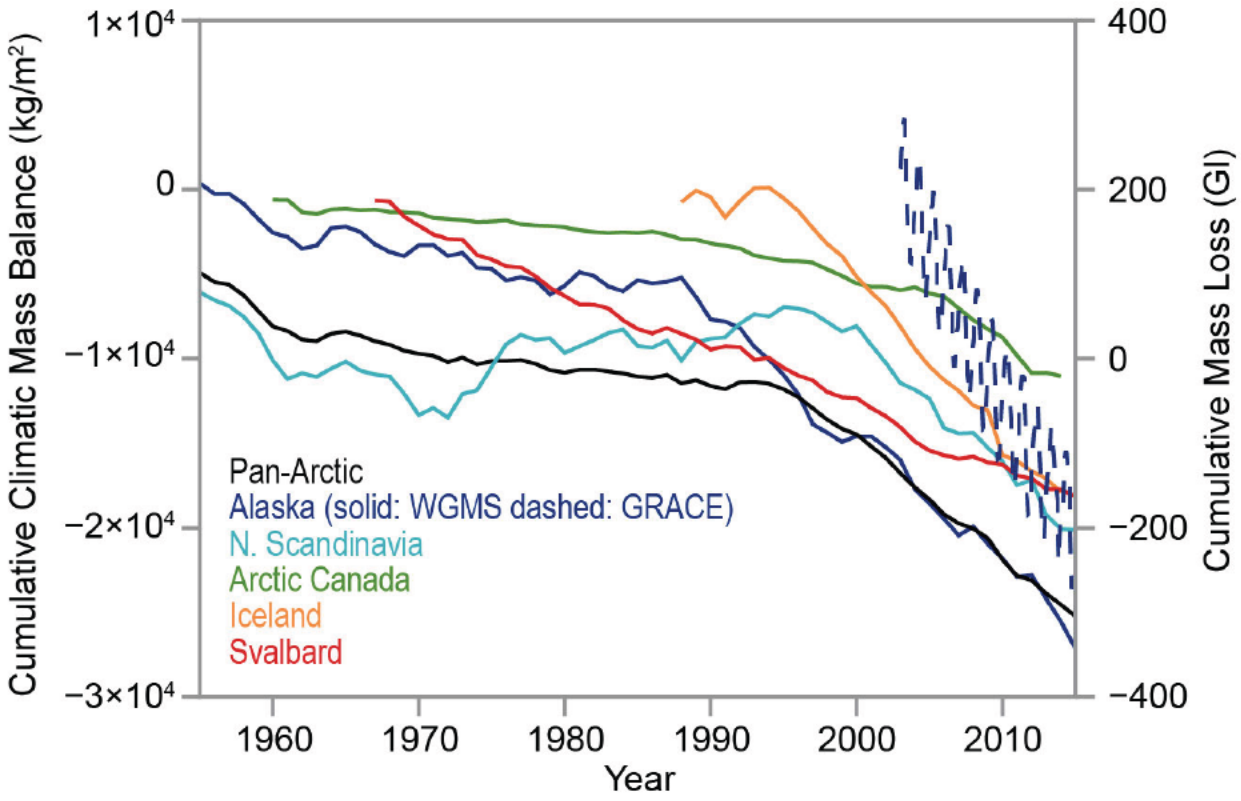

Figure 11.3: Time series of the cumulative climatic mass balance (units: kg/m^2) in five Arctic regions and for the Pan-Arctic from the World Glacier Monitoring Service (WGMS 2016; Wolken et al. 2016; solid lines, left y-axis), plus Alaskan glacial mass loss observed from NASA GRACE (Harig and Simons 2016; dashed blue line, right y-axis). (Figure source: Harig and Simons 2016 and Wolken et al. 2016; © American Meteorological Society, used with permission).

FINAL

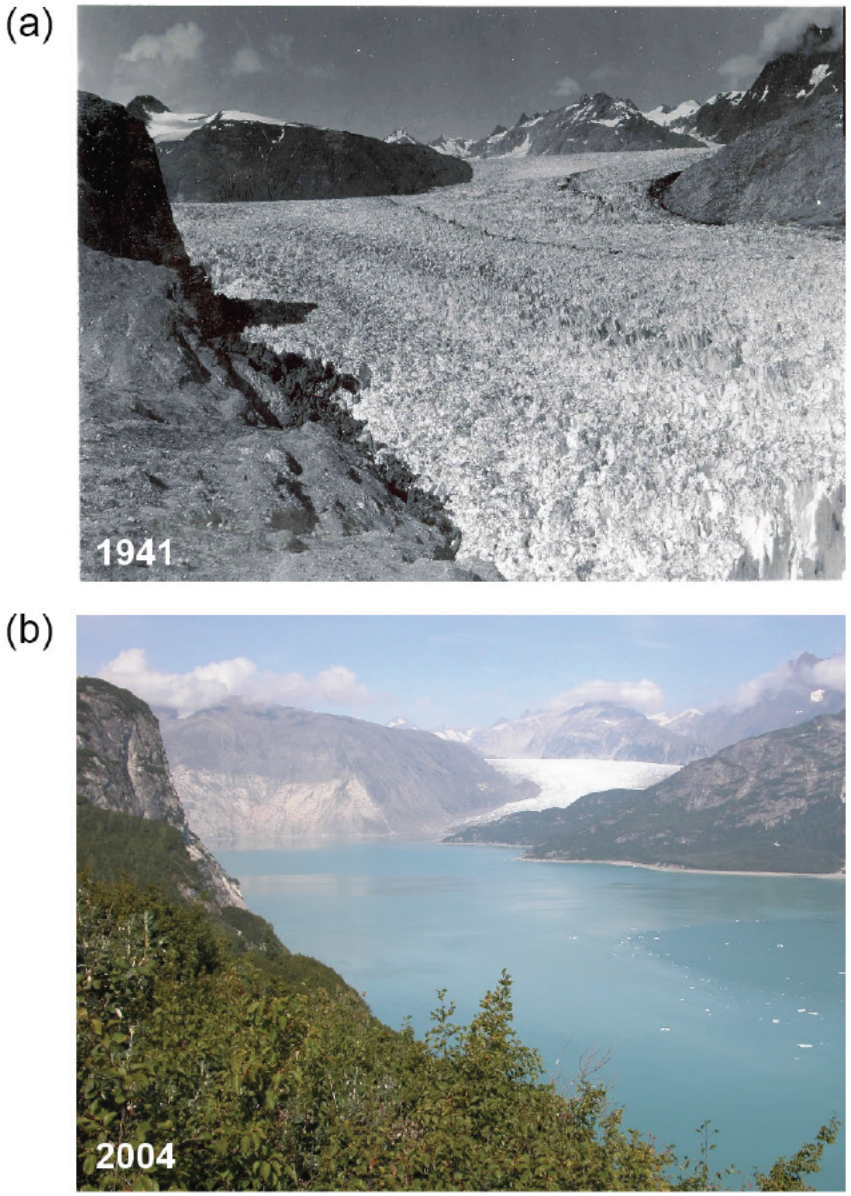

Figure 11.4: Two northeast-looking photographs of the Muir Glacier located in southeastern Alaska are shown taken from a Glacier Bay Photo station in (a) 1941 and (b) 2004. U.S. Geological Survey repeat photography allows the tracking of glacier changes, illustrating that between 1941 and 2004 the Muir Glacier has retreated more than 4 miles to the northwest and out of view. Riggs Glacier (in view) is a tributary to Muir Glacier and has retreated by as much as 0.37 miles and thinned by more than 0.16 miles. The photographs also illustrate a significant change in the surface type between 1941 and 2004 as bare rock in the foreground has been replaced by dense vegetation (Figure source: USGS 2004).

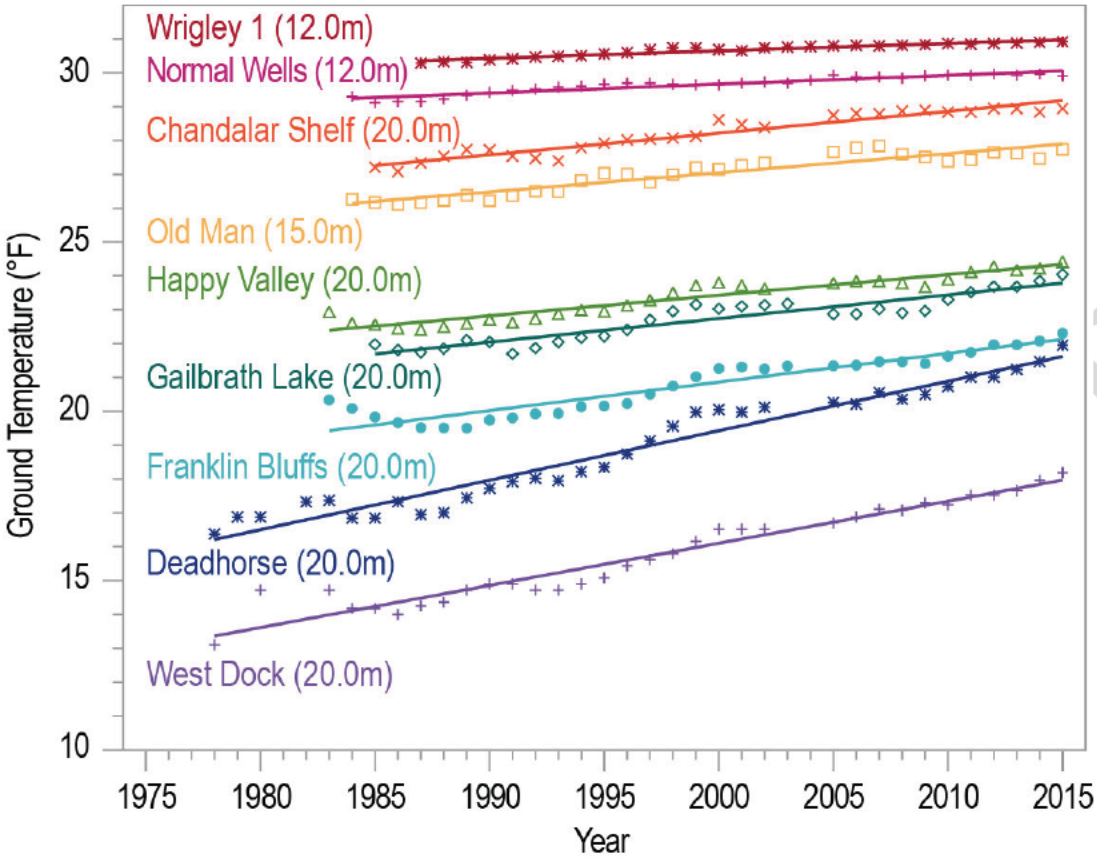

Figure 11.5: Time series of annual mean permafrost temperatures (units: °F) at various depths from 39 to 65 feet (12 to 20 meters) from 1977 through 2015 at several sites across Alaska, including the North Slope continuous permafrost region (purple/blue/green shades), and the discontinuous permafrost (orange/pink/red shades) in Alaska and northwestern Canada. Solid lines represent the linear trends drawn to highlight that permafrost temperatures are warming faster in the colder, coastal permafrost regions than the warmer interior regions. (Figure Source: adapted from Romanovsky et al. 2016; © American Meteorological Society, used with permission).

FINAL

REFERENCES

ACIA, 2005: Arctic Climate Impact Assessment. ACIA Secretariat and Cooperative Institute for Arctic Research, 1042 pp. http://www.acia.uaf.edu/pages/scientific.html

AMAP, 2011: Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere. Oslo, Norway. 538 pp. http://www.amap.no/documents/download/1448

Andresen, C.S., F. Straneo, M.H. Ribergaard, A.A. Bjork, T.J. Andersen, A. Kuijpers, N. Norgaard-Pedersen, K.H. Kjaer, F. Schjoth, K. Weckstrom, and A.P. Ahlstrom, 2012: Rapid response of Helheim Glacier in Greenland to climate variability over the past century. *Nature Geoscience,* **5,** 37-41. http://dx.doi.org/10.1038/ngeo1349

Archer, D., 2007: Methane hydrate stability and anthropogenic climate change. *Biogeosciences,* **4,** 521-544. http://dx.doi.org/10.5194/bg-4-521-2007

Arrigo, K.R., G. van Dijken, and S. Pabi, 2008: Impact of a shrinking Arctic ice cover on marine primary production. *Geophysical Research Letters,* **35,** L19603. http://dx.doi.org/10.1029/2008GL035028

Ayarzagüena, B. and J.A. Screen, 2016: Future Arctic sea ice loss reduces severity of cold air outbreaks in midlatitudes. *Geophysical Research Letters,* **43,** 2801-2809. http://dx.doi.org/10.1002/2016GL068092

Barnes, E.A. and L.M. Polvani, 2015: CMIP5 projections of arctic amplification, of the North American/North Atlantic circulation, and of their relationship. *Journal of Climate,* **28,** 5254-5271. http://dx.doi.org/10.1175/JCLI-D-14-00589.1

Barnes, E.A. and J.A. Screen, 2015: The impact of Arctic warming on the midlatitude jet-stream: Can it? Has it? Will it? *Wiley Interdisciplinary Reviews: Climate Change,* **6,** 277-286. http://dx.doi.org/10.1002/wcc.337

Bartholomew, I.D., P. Nienow, A. Sole, D. Mair, T. Cowton, M.A. King, and S. Palmer, 2011: Seasonal variations in Greenland Ice Sheet motion: Inland extent and behaviour at higher elevations. *Earth and Planetary Science Letters,* **307,** 271-278. http://dx.doi.org/10.1016/j.epsl.2011.04.014

Bates, N.R., R. Garley, K.E. Frey, K.L. Shake, and J.T. Mathis, 2014: Sea-ice melt CO_2–carbonate chemistry in the western Arctic Ocean: Meltwater contributions to air–sea CO_2 gas exchange, mixed-layer properties and rates of net community production under sea ice. *Biogeosciences,* **11,** 6769-6789. http://dx.doi.org/10.5194/bg-11-6769-2014

FINAL DRAFT

Bekryaev, R.V., I.V. Polyakov, and V.A. Alexeev, 2010: Role of polar amplification in long-term surface air temperature variations and modern Arctic warming. *Journal of Climate,* **23,** 3888-3906. http://dx.doi.org/10.1175/2010jcli3297.1

Bindoff, N.L., P.A. Stott, K.M. AchutaRao, M.R. Allen, N. Gillett, D. Gutzler, K. Hansingo, G. Hegerl, Y. Hu, S. Jain, I.I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari, and X. Zhang, 2013: Detection and attribution of climate change: From global to regional. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 867–952. http://www.climatechange2013.org/report/full-report/

Boisvert, L.N., T. Markus, and T. Vihma, 2013: Moisture flux changes and trends for the entire Arctic in 2003–2011 derived from EOS Aqua data. *Journal of Geophysical Research: Oceans,* **118,** 5829-5843. http://dx.doi.org/10.1002/jgrc.20414

Boisvert, L.N., D.L. Wu, and C.L. Shie, 2015: Increasing evaporation amounts seen in the Arctic between 2003 and 2013 from AIRS data. *Journal of Geophysical Research: Atmospheres,* **120,** 6865-6881. http://dx.doi.org/10.1002/2015JD023258

Boisvert, L.N., D.L. Wu, T. Vihma, and J. Susskind, 2015: Verification of air/surface humidity differences from AIRS and ERA-Interim in support of turbulent flux estimation in the Arctic. *Journal of Geophysical Research: Atmospheres,* **120,** 945-963. http://dx.doi.org/10.1002/2014JD021666

Bollmann, M., T. Bosch, F. Colijn, R. Ebinghaus, R. Froese, K. Güssow, S. Khalilian, S. Krastel, A. Körtzinger, M. Langenbuch, M. Latif, B. Matthiessen, F. Melzner, A. Oschlies, S. Petersen, A. Proelß, M. Quaas, J. Reichenbach, T. Requate, T. Reusch, P. Rosenstiel, J.O. Schmidt, K. Schrottke, H. Sichelschmidt, U. Siebert, R. Soltwedel, U. Sommer, K. Stattegger, H. Sterr, R. Sturm, T. Treude, A. Vafeidis, C.v. Bernem, J.v. Beusekom, R. Voss, M. Visbeck, M. Wahl, K. Wallmann, and F. Weinberger, 2010: *World Ocean Review: Living With the Oceans*. maribus gGmbH, 232 pp. http://worldoceanreview.com/wp-content/downloads/wor1/WOR1_english.pdf

Bourassa, M.A., S.T. Gille, C. Bitz, D. Carlson, I. Cerovecki, C.A. Clayson, M.F. Cronin, W.M. Drennan, C.W. Fairall, R.N. Hoffman, G. Magnusdottir, R.T. Pinker, I.A. Renfrew, M. Serreze, K. Speer, L.D. Talley, and G.A. Wick, 2013: High-latitude ocean and sea ice surface fluxes: Challenges for climate research. *Bulletin of the American Meteorological Society,* **94,** 403-423. http://dx.doi.org/10.1175/BAMS-D-11-00244.1

FINAL DRAFT

Brown, R.D. and D.A. Robinson, 2011: Northern Hemisphere spring snow cover variability and change over 1922–2010 including an assessment of uncertainty. *The Cryosphere,* **5,** 219-229. http://dx.doi.org/10.5194/tc-5-219-2011

Brown, D. R. N., M. T. Jorgenson, T. A. Douglas, V. E. Romanovsky, K. Kielland, C. Hiemstra, E. S. Euskirchen, and R. W. Ruess, 2015: Interactive effects of wildfire and climate on permafrost degradation in Alaskan lowland forests. *J. Geophys. Res. Biogeosci.*, **120**, 1619–1637. http://dx.doi.org/10.1002/2015JG003033

Cai, W.-J., L. Chen, B. Chen, Z. Gao, S.H. Lee, J. Chen, D. Pierrot, K. Sullivan, Y. Wang, X. Hu, W.-J. Huang, Y. Zhang, S. Xu, A. Murata, J.M. Grebmeier, E.P. Jones, and H. Zhang, 2010: Decrease in the CO_2 uptake capacity in an ice-free Arctic Ocean basin. *Science,* **329,** 556-559. http://dx.doi.org/10.1126/science.1189338

Carmack, E., I. Polyakov, L. Padman, I. Fer, E. Hunke, J. Hutchings, J. Jackson, D. Kelley, R. Kwok, C. Layton, H. Melling, D. Perovich, O. Persson, B. Ruddick, M.-L. Timmermans, J. Toole, T. Ross, S. Vavrus, and P. Winsor, 2015: Toward quantifying the increasing role of oceanic heat in sea ice loss in the new Arctic. *Bulletin of the American Meteorological Society,* **96 (12),** 2079-2105. http://dx.doi.org/10.1175/BAMS-D-13-00177.1

Chadburn, S.E., E.J. Burke, P.M. Cox, P. Friedlingstein, G. Hugelius, and S. Westermann, 2017: An observation-based constraint on permafrost loss as a function of global warming. *Nature Climate Change,* **7**, 340-344. http://dx.doi.org/10.1038/nclimate3262

Chang, R.Y.-W., C.E. Miller, S.J. Dinardo, A. Karion, C. Sweeney, B.C. Daube, J.M. Henderson, M.E. Mountain, J. Eluszkiewicz, J.B. Miller, L.M.P. Bruhwiler, and S.C. Wofsy, 2014: Methane emissions from Alaska in 2012 from CARVE airborne observations. *Proceedings of the National Academy of Sciences,* **111,** 16694-16699. http://dx.doi.org/10.1073/pnas.1412953111

Chapin III, F.S., S.F. Trainor, P. Cochran, H. Huntington, C. Markon, M. McCammon, A.D. McGuire, and M. Serreze, 2014: Ch. 22: Alaska. *Climate Change Impacts in the United States: The Third National Climate Assessment*. Melillo, J.M., Terese (T.C.) Richmond, and G.W. Yohe, Eds. U.S. Global Change Research Program, Washington, DC, 514-536. http://dx.doi.org/10.7930/J00Z7150

Christensen, J.H., K. Krishna Kumar, E. Aldrian, S.-I. An, I.F.A. Cavalcanti, M. de Castro, W. Dong, P. Goswami, A. Hall, J.K. Kanyanga, A. Kitoh, J. Kossin, N.-C. Lau, J. Renwick, D.B. Stephenson, S.-P. Xie, and T. Zhou, 2013: Climate phenomena and their relevance for future regional climate change. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A.

FINAL DRAFT

Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1217–1308. http://www.climatechange2013.org/report/full-report/

Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer, and A.S. Unnikrishnan, 2013: Sea level change. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1137–1216. http://www.climatechange2013.org/report/full-report/

Cohen, J., J. Jones, J.C. Furtado, and E. Tzipermam, 2013: Warm Arctic, cold continents: A common pattern related to Arctic sea ice melt, snow advance, and extreme winter weather. *Oceanography,* **26,** 150-160. http://dx.doi.org/10.5670/oceanog.2013.70

Cohen, J., J.A. Screen, J.C. Furtado, M. Barlow, D. Whittleston, D. Coumou, J. Francis, K. Dethloff, D. Entekhabi, J. Overland, and J. Jones, 2014: Recent Arctic amplification and extreme mid-latitude weather. *Nature Geoscience,* **7,** 627-637. http://dx.doi.org/10.1038/ngeo2234

Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver, and M. Wehner, 2013: Long-term climate change: Projections, commitments and irreversibility. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1029–1136. http://www.climatechange2013.org/report/full-report/

Comiso, J.C. and D.K. Hall, 2014: Climate trends in the Arctic as observed from space. *Wiley Interdisciplinary Reviews: Climate Change,* **5,** 389-409. http://dx.doi.org/10.1002/wcc.277

Day, J.J., J.C. Hargreaves, J.D. Annan, and A. Abe-Ouchi, 2012: Sources of multi-decadal variability in Arctic sea ice extent. *Environmental Research Letters,* **7,** 034011. http://dx.doi.org/10.1088/1748-9326/7/3/034011

Derksen, C. and R. Brown, 2012: Snow [in Arctic Report Card 2012]. ftp://ftp.oar.noaa.gov/arctic/documents/ArcticReportCard_full_report2012.pdf

FINAL DRAFT

Derksen, C., R. Brown, L. Mudryk, and K. Luojus, 2015: Terrestrial snow cover [in Arctic Report Card 2015]. ftp://ftp.oar.noaa.gov/arctic/documents/ArcticReportCard_full_report2015.pdf

Ding, Q., A. Schweiger, M. Lheureux, D.S. Battisti, S. Po-Chedley, N.C. Johnson, E. Blanchard-Wrigglesworth, K. Harnos, Q. Zhang, R. Eastman, and E.J. Steig, 2017: Influence of high-latitude atmospheric circulation changes on summertime Arctic sea ice. *Nature Climate Change,* **7,** 289-295. http://dx.doi.org/10.1038/nclimate3241

Ding, Q., J.M. Wallace, D.S. Battisti, E.J. Steig, A.J.E. Gallant, H.-J. Kim, and L. Geng, 2014: Tropical forcing of the recent rapid Arctic warming in northeastern Canada and Greenland. *Nature,* **509,** 209-212. http://dx.doi.org/10.1038/nature13260

Döscher, R., T. Vihma, and E. Maksimovich, 2014: Recent advances in understanding the Arctic climate system state and change from a sea ice perspective: A review. *Atmospheric Chemistry and Physics,* **14,** 13571-13600. http://dx.doi.org/10.5194/acp-14-13571-2014

Dupont, T.K. and R.B. Alley, 2005: Assessment of the importance of ice-shelf buttressing to ice-sheet flow. *Geophysical Research Letters,* **32,** n/a-n/a. http://dx.doi.org/10.1029/2004GL022024

Euskirchen, E.S., A.P. Bennett, A.L. Breen, H. Genet, M.A. Lindgren, T.A. Kurkowski, A.D. McGuire, and T.S. Rupp, 2016: Consequences of changes in vegetation and snow cover for climate feedbacks in Alaska and northwest Canada. *Environmental Research Letters,* **11,** 105003. http://dx.doi.org/10.1088/1748-9326/11/10/105003

Fetterer, F., K. Knowles, W. Meier, and M. Savoie, 2016, updated daily: Sea Ice Index, Version 2. National Snow and Ice Data Center, Boulder, CO.

Fisher, J.B., M. Sikka, W.C. Oechel, D.N. Huntzinger, J.R. Melton, C.D. Koven, A. Ahlström, M.A. Arain, I. Baker, J.M. Chen, P. Ciais, C. Davidson, M. Dietze, B. El-Masri, D. Hayes, C. Huntingford, A.K. Jain, P.E. Levy, M.R. Lomas, B. Poulter, D. Price, A.K. Sahoo, K. Schaefer, H. Tian, E. Tomelleri, H. Verbeeck, N. Viovy, R. Wania, N. Zeng, and C.E. Miller, 2014: Carbon cycle uncertainty in the Alaskan Arctic. *Biogeosciences,* **11,** 4271-4288. http://dx.doi.org/10.5194/bg-11-4271-2014

Flannigan, M., B. Stocks, M. Turetsky, and M. Wotton, 2009: Impacts of climate change on fire activity and fire management in the circumboreal forest. *Global Change Biology,* **15,** 549-560. http://dx.doi.org/10.1111/j.1365-2486.2008.01660.x

Francis, J. and N. Skific, 2015: Evidence linking rapid Arctic warming to mid-latitude weather patterns. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* **373**. http://dx.doi.org/10.1098/rsta.2014.0170

FINAL DRAFT

Francis, J.A. and S.J. Vavrus, 2012: Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophysical Research Letters,* **39,** L06801. http://dx.doi.org/10.1029/2012GL051000

Francis, J.A. and S.J. Vavrus, 2015: Evidence for a wavier jet stream in response to rapid Arctic warming. *Environmental Research Letters,* **10,** 014005. http://dx.doi.org/10.1088/1748-9326/10/1/014005

Francis, J.A, S.J. Vavrus, and J. Cohen, 2017: Amplified Arctic warming and mid-latitude weather: New perspectives on emerging connections. WIREs Climate Change, e474. http://dx.doi.org/10.1002/wcc.474

French, N.H.F., L.K. Jenkins, T.V. Loboda, M. Flannigan, R. Jandt, L.L. Bourgeau-Chavez, and M. Whitley, 2015: Fire in arctic tundra of Alaska: Past fire activity, future fire potential, and significance for land management and ecology. *International Journal of Wildland Fire,* **24,** 1045-1061. http://dx.doi.org/10.1071/WF14167

Friedlingstein, P., P. Cox, R. Betts, L. Bopp, W.v. Bloh, V. Brovkin, P. Cadule, S. Doney, M. Eby, I. Fung, G. Bala, J. John, C. Jones, F. Joos, T. Kato, M. Kawamiya, W. Knorr, K. Lindsay, H.D. Matthews, T. Raddatz, P. Rayner, C. Reick, E. Roeckner, K.-G. Schnitzler, R. Schnur, K. Strassmann, A.J. Weaver, C. Yoshikawa, and N. Zeng, 2006: Climate–carbon cycle feedback analysis: Results from the C^4MIP model intercomparison. *Journal of Climate,* **19,** 3337-3353. http://dx.doi.org/10.1175/JCLI3800.1

Gagné, M.È., N.P. Gillett, and J.C. Fyfe, 2015: Impact of aerosol emission controls on future Arctic sea ice cover. *Geophysical Research Letters,* **42,** 8481-8488. http://dx.doi.org/10.1002/2015GL065504

Gibbs, A.E. and B.M. Richmond, 2015: National Assessment of Shoreline Change: Historical Shoreline Change Along the North Coast of Alaska, U.S.–Canadian Border to Icy Cape. U.S. Geological Survey Open-File Report 2015–1048. U.S. Geological Survey, 96 pp. http://dx.doi.org/10.3133/ofr20151048

Giles, K.A., S.W. Laxon, A.L. Ridout, D.J. Wingham, and S. Bacon, 2012: Western Arctic Ocean freshwater storage increased by wind-driven spin-up of the Beaufort Gyre. *Nature Geoscience,* **5,** 194-197. http://dx.doi.org/10.1038/ngeo1379

Gillett, N.P., D.A. Stone, P.A. Stott, T. Nozawa, A.Y. Karpechko, G.C. Hegerl, M.F. Wehner, and P.D. Jones, 2008: Attribution of polar warming to human influence. *Nature Geoscience,* **1,** 750-754. http://dx.doi.org/10.1038/ngeo338

Graversen, R.G., 2006: Do changes in the midlatitude circulation have any impact on the Arctic surface air temperature trend? *Journal of Climate,* **19,** 5422-5438. http://dx.doi.org/10.1175/JCLI3906.1

FINAL DRAFT

Graves, C.A., L. Steinle, G. Rehder, H. Niemann, D.P. Connelly, D. Lowry, R.E. Fisher, A.W. Stott, H. Sahling, and R.H. James, 2015: Fluxes and fate of dissolved methane released at the seafloor at the landward limit of the gas hydrate stability zone offshore western Svalbard. *Journal of Geophysical Research: Oceans,* **120,** 6185-6201. http://dx.doi.org/10.1002/2015JC011084

Grosse, G., S. Goetz, A.D. McGuire, V.E. Romanovsky, and E.A.G. Schuur, 2016: Changing permafrost in a warming world and feedbacks to the Earth system. *Environmental Research Letters,* **11,** 040201. http://dx.doi.org/10.1088/1748-9326/11/4/040201

Harig, C. and F.J. Simons, 2016: Ice mass loss in Greenland, the Gulf of Alaska, and the Canadian Archipelago: Seasonal cycles and decadal trends. *Geophysical Research Letters,* **43,** 3150-3159. http://dx.doi.org/10.1002/2016GL067759

Hartmann, B. and G. Wendler, 2005: The significance of the 1976 Pacific climate shift in the climatology of Alaska. *Journal of Climate,* **18,** 4824-4839. http://dx.doi.org/10.1175/JCLI3532.1

Hartmann, D.L., A.M.G. Klein Tank, M. Rusticucci, L.V. Alexander, S. Brönnimann, Y. Charabi, F.J. Dentener, E.J. Dlugokencky, D.R. Easterling, A. Kaplan, B.J. Soden, P.W. Thorne, M. Wild, and P.M. Zhai, 2013: Observations: Atmosphere and surface. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 159–254. http://www.climatechange2013.org/report/full-report/

Holland, D.M., R.H. Thomas, B. de Young, M.H. Ribergaard, and B. Lyberth, 2008: Acceleration of Jakobshavn Isbrae triggered by warm subsurface ocean waters. *Nature Geoscience,* **1,** 659-664. http://dx.doi.org/10.1038/ngeo316

Hollesen, J., H. Matthiesen, A.B. Møller, and B. Elberling, 2015: Permafrost thawing in organic Arctic soils accelerated by ground heat production. *Nature Climate Change,* **5,** 574-578. http://dx.doi.org/10.1038/nclimate2590

Hoskins, B. and T. Woollings, 2015: Persistent extratropical regimes and climate extremes. *Current Climate Change Reports,* **1,** 115-124. http://dx.doi.org/10.1007/s40641-015-0020-8

Howat, I.M., I. Joughin, M. Fahnestock, B.E. Smith, and T.A. Scambos, 2008: Synchronous retreat and acceleration of southeast Greenland outlet glaciers 2000–06: Ice dynamics and coupling to climate. *Journal of Glaciology,* **54,** 646-660. http://dx.doi.org/10.3189/002214308786570908

FINAL DRAFT

Hu, F.S., P.E. Higuera, P. Duffy, M.L. Chipman, A.V. Rocha, A.M. Young, R. Kelly, and M.C. Dietze, 2015: Arctic tundra fires: Natural variability and responses to climate change. *Frontiers in Ecology and the Environment,* **13,** 369-377. http://dx.doi.org/10.1890/150063

Hunt, G.L., Jr., K.O. Coyle, L.B. Eisner, E.V. Farley, R.A. Heintz, F. Mueter, J.M. Napp, J.E. Overland, P.H. Ressler, S. Salo, and P.J. Stabeno, 2011: Climate impacts on eastern Bering Sea foodwebs: A synthesis of new data and an assessment of the Oscillating Control Hypothesis. *ICES Journal of Marine Science,* **68,** 1230-1243. http://dx.doi.org/10.1093/icesjms/fsr036

Hunter, S.J., D.S. Goldobin, A.M. Haywood, A. Ridgwell, and J.G. Rees, 2013: Sensitivity of the global submarine hydrate inventory to scenarios of future climate change. *Earth and Planetary Science Letters,* **367,** 105-115. http://dx.doi.org/10.1016/j.epsl.2013.02.017

Jahn, A., J.E. Kay, M.M. Holland, and D.M. Hall, 2016: How predictable is the timing of a summer ice-free Arctic? *Geophysical Research Letters,* **43,** 9113-9120. http://dx.doi.org/10.1002/2016GL070067

Johannessen, O.M., A. Korablev, V. Miles, M.W. Miles, and K.E. Solberg, 2011: Interaction between the warm subsurface Atlantic water in the Sermilik Fjord and Helheim Glacier in southeast Greenland. *Surveys in Geophysics,* **32,** 387-396. http://dx.doi.org/10.1007/s10712-011-9130-6

Johannessen, O.M., S.I. Kuzmina, L.P. Bobylev, and M.W. Miles, 2016: Surface air temperature variability and trends in the Arctic: New amplification assessment and regionalisation. *Tellus A,* **68**. http://dx.doi.org/10.3402/tellusa.v68.28234

Joly, K., P.A. Duffy, and T.S. Rupp, 2012: Simulating the effects of climate change on fire regimes in Arctic biomes: Implications for caribou and moose habitat. *Ecosphere,* **3,** 1-18. http://dx.doi.org/10.1890/ES12-00012.1

Joughin, I., S.B. Das, M.A. King, B.E. Smith, I.M. Howat, and T. Moon, 2008: Seasonal speedup along the western flank of the Greenland Ice Sheet. *Science,* **320,** 781-783. http://dx.doi.org/10.1126/science.1153288

Jungclaus, J.H., K. Lohmann, and D. Zanchettin, 2014: Enhanced 20th-century heat transfer to the Arctic simulated in the context of climate variations over the last millennium. *Climate of the Past,* **10,** 2201-2213. http://dx.doi.org/10.5194/cp-10-2201-2014

Kasischke, E.S. and M.R. Turetsky, 2006: Recent changes in the fire regime across the North American boreal region—Spatial and temporal patterns of burning across Canada and Alaska. *Geophysical Research Letters,* **33,** n/a-n/a. http://dx.doi.org/10.1029/2006GL025677

FINAL DRAFT

Kay, J.E. and A. Gettelman, 2009: Cloud influence on and response to seasonal Arctic sea ice loss. *Journal of Geophysical Research,* **114,** D18204. http://dx.doi.org/10.1029/2009JD011773

Kay, J.E., K. Raeder, A. Gettelman, and J. Anderson, 2011a: The boundary layer response to recent Arctic sea ice loss and implications for high-latitude climate feedbacks. *Journal of Climate,* **24,** 428-447. http://dx.doi.org/10.1175/2010JCLI3651.1

Kay, J.E., M.M. Holland, and A. Jahn, 2011b: Inter-annual to multi-decadal Arctic sea ice extent trends in a warming world. *Geophysical Research Letters,* **38,** L15708. http://dx.doi.org/10.1029/2011GL048008

Kelly, R., M.L. Chipman, P.E. Higuera, I. Stefanova, L.B. Brubaker, and F.S. Hu, 2013: Recent burning of boreal forests exceeds fire regime limits of the past 10,000 years. *Proceedings of the National Academy of Sciences,* **110,** 13055-13060. http://dx.doi.org/10.1073/pnas.1305069110

Kelly, R., H. Genet, A.D. McGuire, and F.S. Hu, 2016: Palaeodata-informed modelling of large carbon losses from recent burning of boreal forests. *Nature Climate Change,* **6,** 79-82. http://dx.doi.org/10.1038/nclimate2832

Khan, S.A., K.H. Kjaer, M. Bevis, J.L. Bamber, J. Wahr, K.K. Kjeldsen, A.A. Bjork, N.J. Korsgaard, L.A. Stearns, M.R. van den Broeke, L. Liu, N.K. Larsen, and I.S. Muresan, 2014: Sustained mass loss of the northeast Greenland ice sheet triggered by regional warming. *Nature Climate Change,* **4,** 292-299. http://dx.doi.org/10.1038/nclimate2161

Kirchmeier-Young, M.C., F.W. Zwiers, and N.P. Gillett, 2017: Attribution of extreme events in Arctic sea ice extent. *Journal of Climate,* **30,** 553-571. http://dx.doi.org/10.1175/jcli-d-16-0412.1

Knies, J., P. Cabedo-Sanz, S.T. Belt, S. Baranwal, S. Fietz, and A. Rosell-Melé, 2014: The emergence of modern sea ice cover in the Arctic Ocean. *Nature Communications,* **5,** 5608. http://dx.doi.org/10.1038/ncomms6608

Köhl, A. and N. Serra, 2014: Causes of decadal changes of the freshwater content in the Arctic Ocean. *Journal of Climate,* **27,** 3461-3475. http://dx.doi.org/10.1175/JCLI-D-13-00389.1

Kokelj, S.V., T.C. Lantz, J. Tunnicliffe, R. Segal, and D. Lacelle, 2017: Climate-driven thaw of permafrost preserved glacial landscapes, northwestern Canada. *Geology,* **45,** 371-374. http://dx.doi.org/10.1130/g38626.1

Koven, C.D., D.M. Lawrence, and W.J. Riley, 2015: Permafrost carbon–climate feedback is sensitive to deep soil carbon decomposability but not deep soil nitrogen dynamics.

FINAL DRAFT

Proceedings of the National Academy of Sciences, **112,** 3752-3757. http://dx.doi.org/10.1073/pnas.1415123112

Koven, C.D., E.A.G. Schuur, C. Schädel, T.J. Bohn, E.J. Burke, G. Chen, X. Chen, P. Ciais, G. Grosse, J.W. Harden, D.J. Hayes, G. Hugelius, E.E. Jafarov, G. Krinner, P. Kuhry, D.M. Lawrence, A.H. MacDougall, S.S. Marchenko, A.D. McGuire, S.M. Natali, D.J. Nicolsky, D. Olefeldt, S. Peng, V.E. Romanovsky, K.M. Schaefer, J. Strauss, C.C. Treat, and M. Turetsky, 2015: A simplified, data-constrained approach to estimate the permafrost carbon–climate feedback. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* **373**. http://dx.doi.org/10.1098/rsta.2014.0423

Kretschmer, K., A. Biastoch, L. Rüpke, and E. Burwicz, 2015: Modeling the fate of methane hydrates under global warming. *Global Biogeochemical Cycles,* **29,** 610-625. http://dx.doi.org/10.1002/2014GB005011

Kunkel, K.E., D.A. Robinson, S. Champion, X. Yin, T. Estilow, and R.M. Frankson, 2016: Trends and extremes in Northern Hemisphere snow characteristics. *Current Climate Change Reports,* **2,** 65-73. http://dx.doi.org/10.1007/s40641-016-0036-8

Kwok, R. and N. Untersteiner, 2011: The thinning of Arctic sea ice. *Physics Today,* **64,** 36-41. http://dx.doi.org/10.1063/1.3580491

Larsen, C.F., E. Burgess, A.A. Arendt, S. O'Neel, A.J. Johnson, and C. Kienholz, 2015: Surface melt dominates Alaska glacier mass balance. *Geophysical Research Letters,* **42,** 5902-5908. http://dx.doi.org/10.1002/2015GL064349

Lee, S., 2014: A theory for polar amplification from a general circulation perspective. *Asia-Pacific Journal of Atmospheric Sciences,* **50,** 31-43. http://dx.doi.org/10.1007/s13143-014-0024-7

Lee, S., T. Gong, N. Johnson, S.B. Feldstein, and D. Pollard, 2011: On the possible link between tropical convection and the Northern Hemisphere Arctic surface air temperature change between 1958 and 2001. *Journal of Climate,* **24,** 4350-4367. http://dx.doi.org/10.1175/2011JCLI4003.1

Liljedahl, A.K., J. Boike, R.P. Daanen, A.N. Fedorov, G.V. Frost, G. Grosse, L.D. Hinzman, Y. Iijma, J.C. Jorgenson, N. Matveyeva, M. Necsoiu, M.K. Raynolds, V.E. Romanovsky, J. Schulla, K.D. Tape, D.A. Walker, C.J. Wilson, H. Yabuki, and D. Zona, 2016: Pan-Arctic ice-wedge degradation in warming permafrost and its influence on tundra hydrology. *Nature Geoscience,* **9,** 312-318. http://dx.doi.org/10.1038/ngeo2674

Lim, Y.-K., D.S. Siegfried, M.J.N. Sophie, N.L. Jae, M.M. Andrea, I.C. Richard, Z. Bin, and V. Isabella, 2016: Atmospheric summer teleconnections and Greenland Ice Sheet surface mass

FINAL DRAFT

variations: Insights from MERRA-2. *Environmental Research Letters,* **11,** 024002. http://dx.doi.org/10.1088/1748-9326/11/2/024002

Liu, W., S.-P. Xie, Z. Liu, and J. Zhu, 2017: Overlooked possibility of a collapsed Atlantic Meridional Overturning Circulation in warming climate. *Science Advances,* **3,** e1601666. http://dx.doi.org/10.1126/sciadv.1601666

Liu, Y. and J.R. Key, 2014: Less winter cloud aids summer 2013 Arctic sea ice return from 2012 minimum. *Environmental Research Letters,* **9,** 044002. http://dx.doi.org/10.1088/1748-9326/9/4/044002

Manabe, S. and R.T. Wetherald, 1975: The effects of doubling the CO_2 concentration on the climate of a General Circulation Model. *Journal of the Atmospheric Sciences,* **32,** 3-15. http://dx.doi.org/10.1175/1520-0469(1975)032<0003:teodtc>2.0.co;2

Mao, J., A. Ribes, B. Yan, X. Shi, P.E. Thornton, R. Seferian, P. Ciais, R.B. Myneni, H. Douville, S. Piao, Z. Zhu, R.E. Dickinson, Y. Dai, D.M. Ricciuto, M. Jin, F.M. Hoffman, B. Wang, M. Huang, and X. Lian, 2016: Human-induced greening of the northern extratropical land surface. *Nature Climate Change,* **6,** 959-963. http://dx.doi.org/10.1038/nclimate3056

Maslowski, W., J. Clement Kinney, M. Higgins, and A. Roberts, 2012: The future of Arctic sea ice. *Annual Review of Earth and Planetary Sciences,* **40,** 625-654. http://dx.doi.org/10.1146/annurev-earth-042711-105345

Maslowski, W., J. Clement Kinney, S.R. Okkonen, R. Osinski, A.F. Roberts, and W.J. Williams, 2014: The large scale ocean circulation and physical processes controlling Pacific-Arctic interactions. *The Pacific Arctic Region: Ecosystem Status and Trends in a Rapidly Changing Environment*. Grebmeier, M.J. and W. Maslowski, Eds. Springer Netherlands, Dordrecht, 101-132. http://dx.doi.org/10.1007/978-94-017-8863-2_5

Mathis, J.T., J.N. Cross, W. Evans, and S.C. Doney, 2015: Ocean acidification in the surface waters of the Pacific–Arctic boundary regions. *Oceanography,* **28,** 122-135. http://dx.doi.org/10.5670/oceanog.2015.36

Mathis, J.T., R.S. Pickart, R.H. Byrne, C.L. McNeil, G.W.K. Moore, L.W. Juranek, X. Liu, J. Ma, R.A. Easley, M.M. Elliot, J.N. Cross, S.C. Reisdorph, F. Bahr, J. Morison, T. Lichendorf, and R.A. Feely, 2012: Storm-induced upwelling of high pCO2 waters onto the continental shelf of the western Arctic Ocean and implications for carbonate mineral saturation states. *Geophysical Research Letters,* **39,** L16703. http://dx.doi.org/10.1029/2012GL051574

McAfee, S.A., 2014: Consistency and the lack thereof in Pacific decadal oscillation impacts on North American winter climate. *Journal of Climate,* **27,** 7410-7431. http://dx.doi.org/10.1175/JCLI-D-14-00143.1

FINAL DRAFT

McGuire, A.D., L.G. Anderson, T.R. Christensen, S. Dallimore, L. Guo, D.J. Hayes, M. Heimann, T.D. Lorenson, R.W. MacDonald, and N. Roulet, 2009: Sensitivity of the carbon cycle in the Arctic to climate change. *Ecological Monographs,* **79,** 523-555. http://dx.doi.org/10.1890/08-2025.1

Melillo, J.M., T.C. Richmond, and G.W. Yohe, eds., 2014: *Climate Change Impacts in the United States: The Third National Climate Assessment*. U.S. Global Change Research Program: Washington, D.C., 842 pp. http://dx.doi.org/10.7930/J0Z31WJ2

Melillo, J.M., T.C. Richmond, and G.W. Yohe, eds., 2014: *Highlights of Climate Change Impacts in the United States: The Third National Climate Assessment*. U.S. Global Change Research Program: Washington, DC, 148 pp. http://dx.doi.org/10.7930/J0H41PB6

Mengel, M., A. Levermann, K. Frieler, A. Robinson, B. Marzeion, and R. Winkelmann, 2016: Future sea level rise constrained by observations and long-term commitment. *Proceedings of the National Academy of Sciences,* **113,** 2597-2602. http://dx.doi.org/10.1073/pnas.1500515113

Mernild, S.H., J.K. Malmros, J.C. Yde, and N.T. Knudsen, 2012: Multi-decadal marine- and land-terminating glacier recession in the Ammassalik region, southeast Greenland. *The Cryosphere,* **6,** 625-639. http://dx.doi.org/10.5194/tc-6-625-2012

Min, S.-K., X. Zhang, F.W. Zwiers, and T. Agnew, 2008: Human influence on Arctic sea ice detectable from early 1990s onwards. *Geophysical Research Letters,* **35,** L21701. http://dx.doi.org/10.1029/2008GL035725

Mishra, U., J.D. Jastrow, R. Matamala, G. Hugelius, C.D. Koven, J.W. Harden, C.L. Ping, G.J. Michaelson, Z. Fan, R.M. Miller, A.D. McGuire, C. Tarnocai, P. Kuhry, W.J. Riley, K. Schaefer, E.A.G. Schuur, M.T. Jorgenson, and L.D. Hinzman, 2013: Empirical estimates to reduce modeling uncertainties of soil organic carbon in permafrost regions: A review of recent progress and remaining challenges. *Environmental Research Letters,* **8,** 035020. http://dx.doi.org/10.1088/1748-9326/8/3/035020

Mishra, U. and W.J. Riley, 2012: Alaskan soil carbon stocks: Spatial variability and dependence on environmental factors. *Biogeosciences,* **9,** 3637-3645. http://dx.doi.org/10.5194/bg-9-3637-2012

Morison, J., R. Kwok, C. Peralta-Ferriz, M. Alkire, I. Rigor, R. Andersen, and M. Steele, 2012: Changing Arctic Ocean freshwater pathways. *Nature,* **481,** 66-70. http://dx.doi.org/10.1038/nature10705

Myers-Smith, I. H, J. W. Harden, M. Wilmking, C. C. Fuller, A. D. McGuire, and F. S. Chapin III, 2008. Wetland succession in a permafrost collapse: Interactions between fire and thermokarst. *Biogeosciences* **5**, 1273–1286. http://dx.doi.org/10.5194/bg-5-1273-2008

FINAL DRAFT

Myers-Smith, I.H., B.C. Forbes, M. Wilmking, M. Hallinger, T. Lantz, D. Blok, K.D. Tape, M. Macias-Fauria, U. Sass-Klaassen, E. Lévesque, S. Boudreau, P. Ropars, L. Hermanutz, A. Trant, L.S. Collier, S. Weijers, J. Rozema, S.A. Rayback, N.M. Schmidt, G. Schaepman-Strub, S. Wipf, C. Rixen, C.B. Ménard, S. Venn, S. Goetz, L. Andreu-Hayles, S. Elmendorf, V. Ravolainen, J. Welker, P. Grogan, H.E. Epstein, and D.S. Hik, 2011: Shrub expansion in tundra ecosystems: Dynamics, impacts and research priorities. *Environmental Research Letters,* **6,** 045509. http://dx.doi.org/10.1088/1748-9326/6/4/045509

Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura, and H. Zhang, 2013: Anthropogenic and natural radiative forcing. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 659–740. http://www.climatechange2013.org/report/full-report/

Najafi, M.R., F.W. Zwiers, and N.P. Gillett, 2015: Attribution of Arctic temperature change to greenhouse-gas and aerosol influences. *Nature Climate Change,* **5,** 246-249. http://dx.doi.org/10.1038/nclimate2524

Notz, D. and J. Marotzke, 2012: Observations reveal external driver for Arctic sea-ice retreat. *Geophysical Research Letters,* **39,** L08502. http://dx.doi.org/10.1029/2012GL051094

Notz, D. and J. Stroeve, 2016: Observed Arctic sea-ice loss directly follows anthropogenic CO_2 emission. *Science*, 354, 747-750. http://dx.doi.org 10.1126/science.aag2345

Nummelin, A., M. Ilicak, C. Li, and L.H. Smedsrud, 2016: Consequences of future increased Arctic runoff on Arctic Ocean stratification, circulation, and sea ice cover. *Journal of Geophysical Research: Oceans,* **121,** 617-637. http://dx.doi.org/10.1002/2015JC011156

Ogi, M. and I.G. Rigor, 2013: Trends in Arctic sea ice and the role of atmospheric circulation. *Atmospheric Science Letters,* **14,** 97-101. http://dx.doi.org/10.1002/asl2.423

Ogi, M. and J.M. Wallace, 2007: Summer minimum Arctic sea ice extent and the associated summer atmospheric circulation. *Geophysical Research Letters,* **34,** L12705. http://dx.doi.org/10.1029/2007GL029897

Oh, Y., B. Stackhouse, M.C.Y. Lau, X. Xu, A.T. Trugman, J. Moch, T.C. Onstott, C.J. Jørgensen, L. D'Imperio, B. Elberling, C.A. Emmerton, V.L. St. Louis, and D. Medvigy, 2016: A scalable model for methane consumption in Arctic mineral soils. *Geophysical Research Letters,* **43,** 5143-5150. http://dx.doi.org/10.1002/2016GL069049

FINAL DRAFT

Overland, J., J.A. Francis, R. Hall, E. Hanna, S.-J. Kim, and T. Vihma, 2015: The melting Arctic and midlatitude weather patterns: Are they connected? *Journal of Climate,* **28,** 7917-7932. http://dx.doi.org/10.1175/JCLI-D-14-00822.1

Overland, J., E. Hanna, I. Hanssen-Bauer, S.-J. Kim, J. Walsh, M. Wang, and U. Bhatt, 2014: Air temperature [in Arctic Report Card 2014]. ftp://ftp.oar.noaa.gov/arctic/documents/ArcticReportCard_full_report2014.pdf

Overland, J., E. Hanna, I. Hanssen-Bauer, S.-J. Kim, J. Walsh, M. Wang, U. Bhatt, and R.L. Thoman, 2016: Surface air temperature [in Arctic Report Card 2016]. http://arctic.noaa.gov/Report-Card/Report-Card-2016/ArtMID/5022/ArticleID/271/Surface-Air-Temperature

Overland, J., E. Hanna, I. Hanssen-Bauer, S.-J. Kim, J. Wlash, M. Wang, and U.S. Bhatt, 2015: [The Arctic] Arctic air temperature [in "State of the Climate in 2014"]. *Bulletin of the American Meteorological Society,* **96 (12),** S128-S129. http://dx.doi.org/10.1175/2015BAMSStateoftheClimate.1

Overland, J.E. and M. Wang, 2016: Recent extreme Arctic temperatures are due to a split polar vortex. *Journal of Climate,* **29,** 5609-5616. http://dx.doi.org/10.1175/JCLI-D-16-0320.1

Park, H.-S., S. Lee, S.-W. Son, S.B. Feldstein, and Y. Kosaka, 2015: The impact of poleward moisture and sensible heat flux on Arctic winter sea ice variability. *Journal of Climate,* **28,** 5030-5040. http://dx.doi.org/10.1175/JCLI-D-15-0074.1

Parkinson, C.L., 2014: Spatially mapped reductions in the length of the Arctic sea ice season. *Geophysical Research Letters,* **41,** 4316-4322. http://dx.doi.org/10.1002/2014GL060434

Partain, J.L., Jr., S. Alden, U.S. Bhatt, P.A. Bieniek, B.R. Brettschneider, R. Lader, P.Q. Olsson, T.S. Rupp, H. Strader, R.L.T. Jr., J.E. Walsh, A.D. York, and R.H. Zieh, 2016: An assessment of the role of anthropogenic climate change in the Alaska fire season of 2015 [in "Explaining Extreme Events of 2015 from a Climate Perspective"]. *Bulletin of the American Meteorological Society,* **97 (12),** S14-S18. http://dx.doi.org/10.1175/BAMS-D-16-0149.1

Pavelsky, T.M., J. Boé, A. Hall, and E.J. Fetzer, 2011: Atmospheric inversion strength over polar oceans in winter regulated by sea ice. *Climate Dynamics,* **36,** 945-955. http://dx.doi.org/10.1007/s00382-010-0756-8

Pelto, M.S., 2015: [Global Climate] Alpine glaciers [in "State of the Climate in 2014"]. *Bulletin of the American Meteorological Society,* **96 (12),** S19-S20. http://dx.doi.org/10.1175/2015BAMSStateoftheClimate.1

FINAL DRAFT

Perlwitz, J., M. Hoerling, and R. Dole, 2015: Arctic tropospheric warming: Causes and linkages to lower latitudes. *Journal of Climate,* **28,** 2154-2167. http://dx.doi.org/10.1175/JCLI-D-14-00095.1

Perovich, D., W. Meier, M. Tschudi, S. Farrell, S. Gerland, S. Hendricks, T. Krumpen, and C. Hass, 2016: Sea ice [in Arctic Report Cart 2016]. http://www.arctic.noaa.gov/Report-Card/Report-Card-2016/ArtMID/5022/ArticleID/286/Sea-Ice

Piñero, E., M. Marquardt, C. Hensen, M. Haeckel, and K. Wallmann, 2013: Estimation of the global inventory of methane hydrates in marine sediments using transfer functions. *Biogeosciences,* **10,** 959-975. http://dx.doi.org/10.5194/bg-10-959-2013

Polyakov, I.V., A.V. Pnyushkov, and L.A. Timokhov, 2012: Warming of the intermediate Atlantic water of the Arctic Ocean in the 2000s. *Journal of Climate,* **25,** 8362-8370. http://dx.doi.org/10.1175/JCLI-D-12-00266.1

Rahmstorf, S., J.E. Box, G. Feulner, M.E. Mann, A. Robinson, S. Rutherford, and E.J. Schaffernicht, 2015: Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. *Nature Climate Change,* **5,** 475-480. http://dx.doi.org/10.1038/nclimate2554

Rawlins, M.A., M. Steele, M.M. Holland, J.C. Adam, J.E. Cherry, J.A. Francis, P.Y. Groisman, L.D. Hinzman, T.G. Huntington, D.L. Kane, J.S. Kimball, R. Kwok, R.B. Lammers, C.M. Lee, D.P. Lettenmaier, K.C. McDonald, E. Podest, J.W. Pundsack, B. Rudels, M.C. Serreze, A. Shiklomanov, Ø. Skagseth, T.J. Troy, C.J. Vörösmarty, M. Wensnahan, E.F. Wood, R. Woodgate, D. Yang, K. Zhang, and T. Zhang, 2010: Analysis of the Arctic system for freshwater cycle intensification: Observations and expectations. *Journal of Climate,* **23,** 5715-5737. http://dx.doi.org/10.1175/2010JCLI3421.1

Rhein, M., S.R. Rintoul, S. Aoki, E. Campos, D. Chambers, R.A. Feely, S. Gulev, G.C. Johnson, S.A. Josey, A. Kostianoy, C. Mauritzen, D. Roemmich, L.D. Talley, and F. Wang, 2013: Observations: Ocean. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 255–316. http://www.climatechange2013.org/report/full-report/

Rignot, E., M. Koppes, and I. Velicogna, 2010: Rapid submarine melting of the calving faces of West Greenland glaciers. *Nature Geoscience,* **3,** 187-191. http://dx.doi.org/10.1038/ngeo765

Rigor, I.G., J.M. Wallace, and R.L. Colony, 2002: Response of sea ice to the Arctic oscillation. *Journal of Climate,* **15,** 2648-2663. http://dx.doi.org/10.1175/1520-0442(2002)015<2648:ROSITT>2.0.CO;2

FINAL DRAFT

Romanovsky, V.E., S.L. Smith, H.H. Christiansen, N.I. Shiklomanov, D.A. Streletskiy, D.S. Drozdov, G.V. Malkova, N.G. Oberman, A.L. Kholodov, and S.S. Marchenko, 2015: [The Arctic] Terrestrial permafrost [in "State of the Climate in 2014"]. *Bulletin of the American Meteorological Society,* **96 (12),** S139-S141. http://dx.doi.org/10.1175/2015BAMSStateoftheClimate.1

Romanovsky, V.E., S.L. Smith, K. Isaksen, N.I. Shiklomanov, D.A. Streletskiy, A.L. Kholodov, H.H. Christiansen, D.S. Drozdov, G.V. Malkova, and S.S. Marchenko, 2016: [The Arctic] Terrestrial permafrost [in "State of the Climate in 2015"]. *Bulletin of the American Meteorological Society,* **97,** S149-S152. http://dx.doi.org/10.1175/2016BAMSStateoftheClimate.1

Rupp, D.E., P.W. Mote, N.L. Bindoff, P.A. Stott, and D.A. Robinson, 2013: Detection and attribution of observed changes in Northern Hemisphere spring snow cover. *Journal of Climate,* **26,** 6904-6914. http://dx.doi.org/10.1175/JCLI-D-12-00563.1

Ruppel, C.D. *Methane hydrates and contemporary climate change*. Nature Education Knowledge, 2011. **3**.

Ruppel, C.D. and J.D. Kessler, 2017: The interaction of climate change and methane hydrates. *Reviews of Geophysics,* **55,** 126-168. http://dx.doi.org/10.1002/2016RG000534

Sanford, T., R. Wang, and A. Kenwa, 2015: *The Age of Alaskan Wildfires*. Climate Central, Princeton, NJ, 32 pp. http://assets.climatecentral.org/pdfs/AgeofAlaskanWildfires.pdf

Schädel, C., M.K.F. Bader, E.A.G. Schuur, C. Biasi, R. Bracho, P. Capek, S. De Baets, K. Diakova, J. Ernakovich, C. Estop-Aragones, D.E. Graham, I.P. Hartley, C.M. Iversen, E. Kane, C. Knoblauch, M. Lupascu, P.J. Martikainen, S.M. Natali, R.J. Norby, J.A. O'Donnell, T.R. Chowdhury, H. Santruckova, G. Shaver, V.L. Sloan, C.C. Treat, M.R. Turetsky, M.P. Waldrop, and K.P. Wickland, 2016: Potential carbon emissions dominated by carbon dioxide from thawed permafrost soils. *Nature Climate Change,* **6,** 950-953. http://dx.doi.org/10.1038/nclimate3054

Schaefer, K., H. Lantuit, E.R. Vladimir, E.A.G. Schuur, and R. Witt, 2014: The impact of the permafrost carbon feedback on global climate. *Environmental Research Letters,* **9,** 085003. http://dx.doi.org/10.1088/1748-9326/9/8/085003

Schuur, E.A.G., A.D. McGuire, C. Schadel, G. Grosse, J.W. Harden, D.J. Hayes, G. Hugelius, C.D. Koven, P. Kuhry, D.M. Lawrence, S.M. Natali, D. Olefeldt, V.E. Romanovsky, K. Schaefer, M.R. Turetsky, C.C. Treat, and J.E. Vonk, 2015: Climate change and the permafrost carbon feedback. *Nature,* **520,** 171-179. http://dx.doi.org/10.1038/nature14338

FINAL DRAFT

Schuur, E.A.G., J.G. Vogel, K.G. Crummer, H. Lee, J.O. Sickman, and T.E. Osterkamp, 2009: The effect of permafrost thaw on old carbon release and net carbon exchange from tundra. *Nature,* **459,** 556-559. http://dx.doi.org/10.1038/nature08031

Schweiger, A., R. Lindsay, J. Zhang, M. Steele, H. Stern, 2011: Uncertainty in modeled arctic sea ice volume. J. Geophys. Res. 116, C00D06, http://dx.doi.org/10.1029/2011JC007084

Screen, J.A., C. Deser, and I. Simmonds, 2012: Local and remote controls on observed Arctic warming. *Geophysical Research Letters,* **39,** L10709. http://dx.doi.org/10.1029/2012GL051598

Screen, J.A., C. Deser, and L. Sun, 2015: Reduced risk of North American cold extremes due to continued Arctic sea ice loss. *Bulletin of the American Meteorological Society,* **96 (12),** 1489-1503. http://dx.doi.org/10.1175/BAMS-D-14-00185.1

Screen, J.A., C. Deser, and L. Sun, 2015: Projected changes in regional climate extremes arising from Arctic sea ice loss. *Environmental Research Letters,* **10,** 084006. http://dx.doi.org/10.1088/1748-9326/10/8/084006

Screen, J.A. and J.A. Francis, 2016: Contribution of sea-ice loss to Arctic amplification is regulated by Pacific Ocean decadal variability. *Nature Climate Change,* **6,** 856-860. http://dx.doi.org/10.1038/nclimate3011

Screen, J.A. and I. Simmonds, 2010: The central role of diminishing sea ice in recent Arctic temperature amplification. *Nature,* **464,** 1334-1337. http://dx.doi.org/10.1038/nature09051

Seager, R., M. Hoerling, S. Schubert, H. Wang, B. Lyon, A. Kumar, J. Nakamura, and N. Henderson, 2015: Causes of the 2011–14 California drought. *Journal of Climate,* **28,** 6997-7024. http://dx.doi.org/10.1175/JCLI-D-14-00860.1

Serreze, M.C., A.P. Barrett, J.C. Stroeve, D.N. Kindig, and M.M. Holland, 2009: The emergence of surface-based Arctic amplification. *The Cryosphere,* **3,** 11-19. http://dx.doi.org/10.5194/tc-3-11-2009

Sharp, M., G. Wolken, D. Burgess, J.G. Cogley, L. Copland, L. Thomson, A. Arendt, B. Wouters, J. Kohler, L.M. Andreassen, S. O'Neel, and M. Pelto, 2015: [Global Climate] Glaciers and ice caps outside Greenland [in "State of the Climate in 2014"]. *Bulletin of the American Meteorological Society,* **96 (12),** S135-S137. http://dx.doi.org/10.1175/2015BAMSStateoftheClimate.1

Shiklomanov, N.E., D.A. Streletskiy, and F.E. Nelson, 2012: Northern Hemisphere component of the global Circumpolar Active Layer Monitory (CALM) program. In *Proceedings of the 10th International Conference on Permafrost,* Salekhard, Russia. Kane, D.L. and K.M. Hinkel, Eds., 377-382. http://research.iarc.uaf.edu/NICOP/proceedings/10th/TICOP_vol1.pdf

FINAL DRAFT

Sigmond, M. and J.C. Fyfe, 2016: Tropical Pacific impacts on cooling North American winters. *Nature Climate Change,* **6,** 970-974. http://dx.doi.org/10.1038/nclimate3069

Smedsrud, L.H., M.H. Halvorsen, J.C. Stroeve, R. Zhang, and K. Kloster, 2017: Fram Strait sea ice export variability and September Arctic sea ice extent over the last 80 years. *The Cryosphere,* **11,** 65-79. http://dx.doi.org/10.5194/tc-11-65-2017

Smeed, D.A., G.D. McCarthy, S.A. Cunningham, E. Frajka-Williams, D. Rayner, W.E. Johns, C.S. Meinen, M.O. Baringer, B.I. Moat, A. Duchez, and H.L. Bryden, 2014: Observed decline of the Atlantic meridional overturning circulation 2004–2012. *Ocean Science,* **10,** 29-38. http://dx.doi.org/10.5194/os-10-29-2014

Snape, T.J. and P.M. Forster, 2014: Decline of Arctic sea ice: Evaluation and weighting of CMIP5 projections. *Journal of Geophysical Research: Atmospheres,* **119,** 546-554. http://dx.doi.org/10.1002/2013JD020593

Solomon, A., M.D. Shupe, O. Persson, H. Morrison, T. Yamaguchi, P.M. Caldwell, and G.d. Boer, 2014: The sensitivity of springtime Arctic mixed-phase stratocumulus clouds to surface-layer and cloud-top inversion-layer moisture sources. *Journal of the Atmospheric Sciences,* **71,** 574-595. http://dx.doi.org/10.1175/JAS-D-13-0179.1

Spielhagen, R.F., K. Werner, S.A. Sørensen, K. Zamelczyk, E. Kandiano, G. Budeus, K. Husum, T.M. Marchitto, and M. Hald, 2011: Enhanced modern heat transfer to the Arctic by warm Atlantic water. *Science,* **331,** 450-453. http://dx.doi.org/10.1126/science.1197397

Stabeno, P.J., E.V. Farley, Jr., N.B. Kachel, S. Moore, C.W. Mordy, J.M. Napp, J.E. Overland, A.I. Pinchuk, and M.F. Sigler, 2012: A comparison of the physics of the northern and southern shelves of the eastern Bering Sea and some implications for the ecosystem. *Deep Sea Research Part II: Topical Studies in Oceanography,* **65-70,** 14-30. http://dx.doi.org/10.1016/j.dsr2.2012.02.019

Straneo, F., R.G. Curry, D.A. Sutherland, G.S. Hamilton, C. Cenedese, K. Vage, and L.A. Stearns, 2011: Impact of fjord dynamics and glacial runoff on the circulation near Helheim Glacier. *Nature Geoscience,* **4,** 322-327. http://dx.doi.org/10.1038/ngeo1109

Straneo, F., G.S. Hamilton, D.A. Sutherland, L.A. Stearns, F. Davidson, M.O. Hammill, G.B. Stenson, and A. Rosing-Asvid, 2010: Rapid circulation of warm subtropical waters in a major glacial fjord in East Greenland. *Nature Geoscience,* **3,** 182-186. http://dx.doi.org/10.1038/ngeo764

Stroeve, J., A. Barrett, M. Serreze, and A. Schweiger, 2014: Using records from submarine, aircraft and satellites to evaluate climate model simulations of Arctic sea ice thickness. *The Cryosphere,* **8,** 1839-1854. http://dx.doi.org/10.5194/tc-8-1839-2014

FINAL DRAFT

Stroeve, J., M.M. Holland, W. Meier, T. Scambos, and M. Serreze, 2007: Arctic sea ice decline: Faster than forecast. *Geophysical Research Letters,* **34,** L09501. http://dx.doi.org/10.1029/2007GL029703

Stroeve, J. and D. Notz, 2015: Insights on past and future sea-ice evolution from combining observations and models. *Global and Planetary Change,* **135,** 119-132. http://dx.doi.org/10.1016/j.gloplacha.2015.10.011

Stroeve, J.C., V. Kattsov, A. Barrett, M. Serreze, T. Pavlova, M. Holland, and W.N. Meier, 2012: Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations. *Geophysical Research Letters,* **39,** L16502. http://dx.doi.org/10.1029/2012GL052676

Stroeve, J.C., T. Markus, L. Boisvert, J. Miller, and A. Barrett, 2014: Changes in Arctic melt season and implications for sea ice loss. *Geophysical Research Letters,* **41,** 1216-1225. http://dx.doi.org/10.1002/2013GL058951

Stroeve, J.C., M.C. Serreze, M.M. Holland, J.E. Kay, J. Malanik, and A.P. Barrett, 2012: The Arctic's rapidly shrinking sea ice cover: A research synthesis. *Climatic Change,* **110,** 1005-1027. http://dx.doi.org/10.1007/s10584-011-0101-1

Sun, L., J. Perlwitz, and M. Hoerling, 2016: What caused the recent "Warm Arctic, Cold Continents" trend pattern in winter temperatures? *Geophysical Research Letters,* **43,** 5345-5352. http://dx.doi.org/10.1002/2016GL069024

Swain, D., M. Tsiang, M. Haughen, D. Singh, A. Charland, B. Rajarthan, and N.S. Diffenbaugh, 2014: The extraordinary California drought of 2013/14: Character, context and the role of climate change [in "Explaining Extreme Events of 2013 from a Climate Perspective"]. *Bulletin of the American Meteorological Society,* **95 (9),** S3-S6. http://dx.doi.org/10.1175/1520-0477-95.9.S1.1

Swanson, D. K, 1996: Susceptibility of permafrost soils to deep thaw after forest fires in Interior Alaska, USA, and some ecological implications. *Arct Antarct Alp Res*., **28**, 217–227. http://dx.doc.org/10.2307/1551763.

Swart, N.C., J.C. Fyfe, E. Hawkins, J.E. Kay, and A. Jahn, 2015: Influence of internal variability on Arctic sea-ice trends. *Nature Climate Change,* **5,** 86-89. http://dx.doi.org/10.1038/nclimate2483

Tarnocai, C., J.G. Canadell, E.A.G. Schuur, P. Kuhry, G. Mazhitova, and S. Zimov, 2009: Soil organic carbon pools in the northern circumpolar permafrost region. *Global Biogeochemical Cycles,* **23,** GB2023. http://dx.doi.org/10.1029/2008GB003327

FINAL DRAFT

Taylor, P.C., M. Cai, A. Hu, J. Meehl, W. Washington, and G.J. Zhang, 2013: A decomposition of feedback contributions to polar warming amplification. *Journal of Climate,* **26,** 7023-7043. http://dx.doi.org/10.1175/JCLI-D-12-00696.1

Taylor, P.C., R.G. Ellingson, and M. Cai, 2011: Geographical distribution of climate feedbacks in the NCAR CCSM3.0. *Journal of Climate,* **24,** 2737-2753. http://dx.doi.org/10.1175/2010JCLI3788.1

Taylor, P.C., R.G. Ellingson, and M. Cai, 2011: Seasonal variations of climate feedbacks in the NCAR CCSM3. *Journal of Climate,* **24,** 3433-3444. http://dx.doi.org/10.1175/2011jcli3862.1

Taylor, P.C., S. Kato, K.-M. Xu, and M. Cai, 2015: Covariance between Arctic sea ice and clouds within atmospheric state regimes at the satellite footprint level. *Journal of Geophysical Research: Atmospheres,* **120,** 12656-12678. http://dx.doi.org/10.1002/2015JD023520

Tedesco, M., T. Mote, X. Fettweis, E. Hanna, J. Jeyaratnam, J.F. Booth, R. Datta, and K. Briggs, 2016: Arctic cut-off high drives the poleward shift of a new Greenland melting record. *Nature Communications,* **7,** 11723. http://dx.doi.org/10.1038/ncomms11723

Teng, H. and G. Branstator, 2017: Causes of extreme ridges that induce California droughts. *Journal of Climate,* **30,** 1477-1492. http://dx.doi.org/10.1175/jcli-d-16-0524.1

Timmermans, M.-L. and A. Proshutinsky, 2015: [The Arctic] Sea surface temperature [in "State of the Climate in 2014"]. *Bulletin of the American Meteorological Society,* **96 (12),** S147-S148. http://dx.doi.org/10.1175/2015BAMSStateoftheClimate.1

Treat, C.C., S.M. Natali, J. Ernakovich, C.M. Iversen, M. Lupascu, A.D. McGuire, R.J. Norby, T. Roy Chowdhury, A. Richter, H. Šantrůčková, C. Schädel, E.A.G. Schuur, V.L. Sloan, M.R. Turetsky, and M.P. Waldrop, 2015: A pan-Arctic synthesis of CH_4 and CO_2 production from anoxic soil incubations. *Global Change Biology,* **21,** 2787-2803. http://dx.doi.org/10.1111/gcb.12875

Tschudi, M., C. Fowler, J. Maslanik, J.S. Stewart, and W. Meier, 2016: EASE-Grid Sea Ice Age, Version 3. In: NASA (ed.). National Snow and Ice Data Center Distributed Active Archive Center, Boulder, CO.

USGS 2004, Department of the Interior, U.S. Geological Survey, photo by Bruce F. Molnia. https://www2.usgs.gov/climate_landuse/glaciers/repeat_photography.asp)

van den Broeke, M., J. Bamber, J. Ettema, E. Rignot, E. Schrama, W.J. van de Berg, E. van Meijgaard, I. Velicogna, and B. Wouters, 2009: Partitioning recent Greenland mass loss. *Science,* **326,** 984-986. http://dx.doi.org/10.1126/science.1178176

FINAL DRAFT

Vaughan, D.G., J.C. Comiso, I. Allison, J. Carrasco, G. Kaser, R. Kwok, P. Mote, T. Murray, F. Paul, J. Ren, E. Rignot, O. Solomina, K. Steffen, and T. Zhang, 2013: Observations: Cryosphere. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 317–382. http://www.climatechange2013.org/report/full-report/

Velicogna, I., 2009: Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE. *Geophysical Research Letters,* **36,** L19503. http://dx.doi.org/10.1029/2009GL040222

Vihma, T., 2014: Effects of Arctic sea ice decline on weather and climate: A review. *Surveys in Geophysics,* **35,** 1175-1214. http://dx.doi.org/10.1007/s10712-014-9284-0

Vinnikov, K.Y., A. Robock, R.J. Stouffer, J.E. Walsh, C.L. Parkinson, D.J. Cavalieri, J.F.B. Mitchell, D. Garrett, and V.F. Zakharov, 1999: Global warming and Northern Hemisphere sea ice extent. *Science,* **286,** 1934-1937. http://dx.doi.org/10.1126/science.286.5446.1934

Wang, M. and J.E. Overland, 2012: A sea ice free summer Arctic within 30 years: An update from CMIP5 models. *Geophysical Research Letters,* **39,** L18501. http://dx.doi.org/10.1029/2012GL052868

Wendler, G., B. Moore, and K. Galloway, 2014: Strong temperature increase and shrinking sea ice in Arctic Alaska. *The Open Atmospheric Science Journal,* **8,** 7-15. http://dx.doi.org/10.2174/1874282301408010007

Wettstein, J.J. and C. Deser, 2014: Internal variability in projections of twenty-first-century Arctic sea ice loss: Role of the large-scale atmospheric circulation. *Journal of Climate,* **27,** 527-550. http://dx.doi.org/10.1175/JCLI-D-12-00839.1

WGMS, 2016: Fluctuations of Glaciers Database. World Glacier Monitoring Service, Zurich, Switzerland.

Wolken, G., M. Sharp, L.M. Andreassen, A. Arendt, D. Burgess, J.G. Cogley, L. Copland, J. Kohler, S. O'Neel, M. Pelto, L. Thomson, and B. Wouters, 2016: [The Arctic] Glaciers and ice caps outside Greenland [in "State of the Climate in 2015"]. *Bulletin of the American Meteorological Society,* **97,** S142-S145. http://dx.doi.org/10.1175/2016BAMSStateoftheClimate.1

Woods, C. and R. Caballero, 2016: The role of moist intrusions in winter Arctic warming and sea ice decline. *Journal of Climate,* **29,** 4473-4485. http://dx.doi.org/10.1175/jcli-d-15-0773.1

FINAL DRAFT

Wyser, K., C.G. Jones, P. Du, E. Girard, U. Willén, J. Cassano, J.H. Christensen, J.A. Curry, K. Dethloff, J.-E. Haugen, D. Jacob, M. Køltzow, R. Laprise, A. Lynch, S. Pfeifer, A. Rinke, M. Serreze, M.J. Shaw, M. Tjernström, and M. Zagar, 2008: An evaluation of Arctic cloud and radiation processes during the SHEBA year: Simulation results from eight Arctic regional climate models. *Climate Dynamics,* **30,** 203-223. http://dx.doi.org/10.1007/s00382-007-0286-1

Yang, Q., T.H. Dixon, P.G. Myers, J. Bonin, D. Chambers, and M.R. van den Broeke, 2016: Recent increases in Arctic freshwater flux affects Labrador Sea convection and Atlantic overturning circulation. *Nature Communications,* **7,** 10525. http://dx.doi.org/10.1038/ncomms10525

Yoshikawa, K., W. R. Bolton, V. E. Romanovsky, M. Fukuda, and L. D. Hinzman, 2003: Impacts of wildfire on the permafrost in the boreal forests of Interior Alaska. *J. Geophys. Res.*, **107**, 8148. http://dx.doi.org/10.1029/2001JD000438 2002.

Young, A.M., P.E. Higuera, P.A. Duffy, and F.S. Hu, 2016: Climatic thresholds shape northern high-latitude fire regimes and imply vulnerability to future climate change. *Ecography,* **Early view**. http://dx.doi.org/10.1111/ecog.02205

Zemp, M., H. Frey, I. Gärtner-Roer, S.U. Nussbaumer, M. Hoelzle, F. Paul, W. Haeberli, F. Denzinger, A.P. Ahlstrøm, B. Anderson, S. Bajracharya, C. Baroni, L.N. Braun, B.E. Cáceres, G. Casassa, G. Cobos, L.R. Dávila, H. Delgado Granados, M.N. Demuth, L. Espizua, A. Fischer, K. Fujita, B. Gadek, A. Ghazanfar, J.O. Hagen, P. Holmlund, N. Karimi, Z. Li, M. Pelto, P. Pitte, V.V. Popovnin, C.A. Portocarrero, R. Prinz, C.V. Sangewar, I. Severskiy, O. Sigurðsson, A. Soruco, R. Usubaliev, and C. Vincent, 2015: Historically unprecedented global glacier decline in the early 21st century. *Journal of Glaciology,* **61,** 745-762. http://dx.doi.org/10.3189/2015JoG15J017

Zhang, R. and T.R. Knutson, 2013: The role of global climate change in the extreme low summer Arctic sea ice extent in 2012 [in "Explaining Extreme Events of 2012 from a Climate Perspective"]. *Bulletin of the American Meteorological Society,* **94 (9),** S23-S26. http://dx.doi.org/10.1175/BAMS-D-13-00085.1

Zona, D., B. Gioli, R. Commane, J. Lindaas, S.C. Wofsy, C.E. Miller, S.J. Dinardo, S. Dengel, C. Sweeney, A. Karion, R.Y.-W. Chang, J.M. Henderson, P.C. Murphy, J.P. Goodrich, V. Moreaux, A. Liljedahl, J.D. Watts, J.S. Kimball, D.A. Lipson, and W.C. Oechel, 2016: Cold season emissions dominate the Arctic tundra methane budget. *Proceedings of the National Academy of Sciences,* **113,** 40-45. http://dx.doi.org/10.1073/pnas.1516017113

FINAL DRAFT

12. Sea Level Rise

KEY FINDINGS

1. Global mean sea level (GMSL) has risen by about 7–8 inches (about 16–21 cm) since 1900, with about 3 of those inches (about 7 cm) occurring since 1993 (*very high confidence*). Human-caused climate change has made a substantial contribution to GMSL rise since 1900 (*high confidence*), contributing to a rate of rise that is greater than during any preceding century in at least 2,800 years (*medium confidence*).

2. Relative to the year 2000, GMSL is *very likely* to rise by 0.3–0.6 feet (9–18 cm) by 2030, 0.5–1.2 feet (15–38 cm) by 2050, and 1 to 4 feet (30–130 cm) by 2100 (*very high confidence in lower bounds; medium confidence in upper bounds for 2030 and 2050; low confidence in upper bounds for 2100*). Future emissions pathways have little effect on projected GMSL rise in the first half of the century, but significantly affect projections for the second half of the century (*high confidence*). Emerging science regarding Antarctic ice sheet stability suggests that, for high emission scenarios, a GMSL rise exceeding 8 feet (2.4 m) by 2100 is physically possible, although the probability of such an extreme outcome cannot currently be assessed. Regardless of emissions pathway, it is *extremely likely* that GMSL rise will continue beyond 2100 (*high confidence*).

3. Relative sea level (RSL) rise in this century will vary along U.S. coastlines due, in part, to changes in Earth's gravitational field and rotation from melting of land ice, changes in ocean circulation, and vertical land motion (*very high confidence*). For almost all future GMSL rise scenarios, RSL rise is *likely* to be greater than the global average in the U.S. Northeast and the western Gulf of Mexico. In intermediate and low GMSL rise scenarios, RSL rise is *likely* to be less than the global average in much of the Pacific Northwest and Alaska. For high GMSL rise scenarios, RSL rise is *likely* to be higher than the global average along all U.S. coastlines outside Alaska. Almost all U.S. coastlines experience more than global mean sea level rise in response to Antarctic ice loss, and thus would be particularly affected under extreme GMSL rise scenarios involving substantial Antarctic mass loss (*high confidence*).

4. As sea levels have risen, the number of tidal floods each year that cause minor impacts (also called "nuisance floods") have increased 5- to 10-fold since the 1960s in several U.S. coastal cities (*very high confidence*). Rates of increase are accelerating in over 25 Atlantic and Gulf Coast cities (*very high confidence*). Tidal flooding will continue increasing in depth, frequency, and extent this century (*very high confidence*).

5. Assuming storm characteristics do not change, sea level rise will increase the frequency and extent of extreme flooding associated with coastal storms, such as hurricanes and nor'easters (*very high confidence*). A projected increase in the intensity of hurricanes in the North Atlantic could increase the probability of extreme flooding along most of the U.S. Atlantic

FINAL DRAFT

and Gulf Coast states beyond what would be projected based solely on RSL rise. However, there is *low confidence* in the magnitude of the increase in intensity and the associated flood risk amplification, and these effects could be offset or amplified by other factors, such as changes in storm frequency or tracks.

12.1 Introduction

Sea level rise is closely linked to increasing global temperatures. Thus, even as uncertainties remain about just how much sea level may rise this century, it is virtually certain that sea level rise this century and beyond will pose a growing challenge to coastal communities, infrastructure, and ecosystems from increased (permanent) inundation, more frequent and extreme coastal flooding, erosion of coastal landforms, and saltwater intrusion within coastal rivers and aquifers. Assessment of vulnerability to rising sea levels requires consideration of physical causes, historical evidence, and projections. A risk-based perspective on sea level rise points to the need for emphasis on how changing sea levels alter the coastal zone and interact with coastal flood risk at local scales.

This chapter reviews the physical factors driving global and regional sea level changes. It presents geological and instrumental observations of historical sea level changes and an assessment of the human contribution to sea level change. It then describes a range of scenarios for future levels and rates of sea level change, and the relationship of these scenarios to the Representative Concentration Pathways (RCPs). Finally, it assesses the impact of changes in sea level on extreme water levels.

While outside the scope of this chapter, it is important to note the myriad of other potential impacts associated with relative sea level (RSL) rise, wave action, and increases in coastal flooding. These impacts include loss of life, damage to infrastructure and the built environment, salinization of coastal aquifers, mobilization of pollutants, changing sediment budgets, coastal erosion, and ecosystem changes such as marsh loss and threats to endangered flora and fauna (Wong et al. 2014). While all of these impacts are inherently important, some also have the potential to influence local rates of RSL rise and the extent of wave-driven and coastal flooding impacts. For example, there is evidence that wave action and flooding of beaches and marshes can induce changes in coastal geomorphology, such as sediment build up, that may iteratively modify the future flood risk profile of communities and ecosystems (Lentz et al. 2016).

12.2 Physical Factors Contributing to Sea Level Rise

Sea level change is driven by a variety of mechanisms operating at different spatial and temporal scales (see Kopp et al. 2015a for a review). Global mean sea level (GMSL) rise is primarily driven by two factors: 1) increased volume of seawater due to thermal expansion of the ocean as it warms, and 2) increased mass of water in the ocean due to melting ice from mountain glaciers and the Antarctic and Greenland ice sheets (Church et al. 2013). The overall amount (mass) of ocean water, and thus sea level, is also affected to a lesser extent by changes in global land-water

FINAL DRAFT

storage, which reflects changes in the impoundment of water in dams and reservoirs and river runoff from groundwater extraction, inland sea and wetland drainage, and global precipitation patterns, such as occurs during phases of the El Niño–Southern Oscillation (ENSO) (Church et al. 2013; Reager et al. 2016; Rietbroek et al. 2016; Wada et al. 2016, 2017).

Sea level and its changes are not uniform globally for several reasons. First, atmosphere–ocean dynamics—driven by ocean circulation, winds, and other factors—are associated with differences in the height of the sea surface, as are differences in density arising from the distribution of heat and salinity in the ocean. Changes in any of these factors will affect sea surface height. For example, a weakening of the Gulf Stream transport in the mid-to-late 2000s may have contributed to enhanced sea level rise in the ocean environment extending to the northeastern U.S. coast (Boon 2012; Sallenger et al. 2012; Ezer 2013), a trend that many models project will continue into the future (Yin and Goddard 2013).

Second, the locations of land ice melting and land water reservoir changes impart distinct regional "static-equilibrium fingerprints" on sea level, based on gravitational, rotational, and crustal deformation effects (Mitrovica et al. 2011) (Figure 12.1a–d). For example, sea level falls near a melting ice sheet because of the reduced gravitational attraction of the ocean toward the ice sheet; reciprocally, it rises by greater than the global average far from the melting ice sheet.

Third, the Earth's mantle is still moving in response to the loss of the great North American (Laurentide) and European ice sheets of the Last Glacial Maximum; the associated changes in the height of the land, the shape of the ocean basin, and the Earth's gravitational field give rise to glacial-isostatic adjustment (Figure 12.1e). For example, in areas once covered by the thickest parts of the great ice sheets of the Last Glacial Maximum, such as in Hudson Bay and in Scandinavia, post-glacial rebound of the land is causing relative sea level (RSL) to fall. Along the flanks of the ice sheets, such as along most of the east coast of the United States, subsidence of the bulge that flanked the ice sheet is causing RSL to rise.

Finally, a variety of other factors can cause local vertical land movement. These include natural sediment compaction, compaction caused by local extraction of groundwater and fossil fuels, and processes related to plate tectonics, such as earthquakes and more gradual seismic creep (Zervas et al. 2013; Wöppelmann and Marcos 2016) (Figure 12.1f).

Compared to many climate variables, the trend signal for sea level change tends to be large relative to natural variability. However, at interannual timescales, changes in ocean dynamics, density, and wind can cause substantial sea level variability in some regions. For example, there has been a multidecadal suppression of sea level rise off the Pacific coast (Bromirski et al. 2011) and large year-to-year variations in sea level along the Northeast U.S. coast (Goddard et al. 2015). Local rates of land height change have also varied dramatically on decadal timescales in some locations, such as along the western Gulf Coast, where rates of subsurface extraction of fossil fuels and groundwater have varied over time (Galloway et al. 1999).

FINAL DRAFT

[INSERT FIGURE 12.1 HERE]

12.3 Paleo Sea Level

Geological records of temperature and sea level indicate that during past warm periods over the last several millions of years, GMSL was higher than it is today (Miller et al. 2005; Dutton et al. 2015). During the Last Interglacial stage, about 125,000 years ago, global average sea surface temperature was about 0.5° ± 0.3°C (0.9° ± 0.5°F) above the preindustrial level [that is, comparable to the average over 1995–2014, when global mean temperature was about 0.8°C (1.4°F) above the preindustrial levels] (Hoffman et al. 2017). Polar temperatures were comparable to those projected for 1°C–2°C (1.8°F–3.6°F) of global mean warming above the preindustrial level. At this time, GMSL was about 6–9 meters (about 20–30 feet) higher than today (Dutton and Lambeck 2012; Kopp et al. 2009) (Figure 12.2a). This geological benchmark may indicate the probable long-term response of GMSL to the minimum magnitude of temperature change projected for the current century.

Similarly, during the mid-Pliocene warm period, about 3 million years ago, global mean temperature was about 1.8°–3.6°C (3.2°–6.5°F) above the preindustrial level (Haywood et al. 2013). Estimates of GMSL are less well constrained than during the Last Interglacial, due to the smaller number of local geological sea level reconstruction and the possibility of significant vertical land motion over millions of years (Dutton et al. 2015). Some reconstructions place mid-Pliocene GMSL at about 10–30 meters (about 30–100 feet) higher than today (Miller et al. 2012). Sea levels this high would require a significantly reduced Antarctic ice sheet, highlighting the risk of significant Antarctic ice sheet loss under such levels of warming (Figure 12.2a).

For the period since the Last Glacial Maximum, about 26,000 to 19,000 years ago (Clark et al. 2009), geologists can produce detailed reconstructions of sea levels as well as rates of sea level change. To do this, they use proxies such as the heights of fossil coral reefs and the populations of different salinity-sensitive microfossils within salt marsh sediments (Shennan et al. 2015). During the main portion of the deglaciation, from about 17,000 to 8,000 years ago, GMSL rose at an average rate of about 12 mm/year (0.5 inches/year) (Lambeck et al. 2014). However, there were periods of faster rise. For example, during Meltwater Pulse 1a, lasting from about 14,600 to 14,300 years ago, GMSL may have risen at an average rate about 50 mm/year (2 inches/year) (Deschamps et al. 2012).

Since the disappearance of the last remnants of the North American (Laurentide) Ice Sheet about 7,000 years ago (Carlson et al. 2008) to about the start of the 20th century, however, GMSL has been relatively stable. During this period, total GMSL rise is estimated to have been about 4 meters (about 13 feet), most of which occurred between 7,000 and 4,000 years ago (Lambeck et al. 2014). The Third National Climate Assessment (NCA3) noted, based on a geological data set from North Carolina (Kemp et al. 2011), that the 20th century GMSL rise was much faster than at any time over the past 2,000 years. Since NCA3, high-resolution sea level reconstructions

FINAL DRAFT

have been developed for multiple locations, and a new global analysis of such reconstructions strengthens this finding (Kopp et al. 2016). Over the last 2,000 years, prior to the industrial era, GMSL exhibited small fluctuations of about ±8 cm (3 inches), with a significant decline of about 8 cm (3 inches) between the years 1000 and 1400 CE coinciding with about 0.2°C (0.4°F) of global mean cooling (Kopp et al. 2016). The rate of rise in the last century, about 14 cm/century (5.5 inches/century), was greater than during any preceding century in at least 2,800 years (Kopp et al. 2016; Figure 12.2b).

[INSERT FIGURE 12.2 HERE]

12.4 Recent Past Trends (20th and 21st Centuries)

12.4.1 Global Tide Gauge Network and Satellite Observations

A global tide gauge network provides the century-long observations of local RSL, whereas satellite altimetry provides broader coverage of sea surface heights outside the polar regions starting in 1993. GMSL can be estimated through statistical analyses of either data set. GMSL trends over the 1901–1990 period vary slightly (Hay et al. 2015: 1.2 ± 0.2 mm/year [0.05 inches/year]; Church and White 2011: 1.5 ± 0.2 mm/year [0.06 inches/year]) with differences amounting to about 1 inch over 90 years. Thus, these results indicate about 11–14 cm (4–5 inches) of GMSL rise from 1901 to 1990.

Tide gauge analyses indicate that GMSL rose at a considerably faster rate of about 3 mm/year (0.12 inches/year) since 1993 (Hay et al. 2015; Church and White 2011), a result supported by satellite data indicating a trend of 3.4 ± 0.4 mm/year (0.13 ± 0.02 inches/year) over 1993–2015 (update to Nerem et al. 2010). These results indicate an additional GMSL rise of about 7 cm (3 inches) since 1990 (Figure 12.2b, Figure 12.3a) and 18–21 cm (7–8 inches) since 1900. Satellite (altimetry and gravity) and in situ water column (Argo floats) measurements show that, since 2005, about one third of GMSL rise has been from steric changes (primarily thermal expansion) and about two thirds from the addition of mass to the ocean, which represents a growing land-ice contribution (compared to steric) and a departure from the relative contributions earlier in the 20th century (Church et al. 2013; Llovel et al. 2014; Leuliette 2015; Merrifield et al. 2015; Chambers et al. 2017; Leuliette and Nerem 2016) (Figure 12.3a).

In addition to land ice, the mass-addition contribution also includes net changes in global land-water storage. This term varied in sign over the course of the last century, with human-induced changes in land-water storage being negative (perhaps as much as about –0.6 mm/year [–0.02 inches/year]) during the period of heavy dam construction in the middle of the last century, and turning positive in the 1990s as groundwater withdrawal came to dominate (Wada et al. 2017). On decadal timescales, precipitation variability can dominate human-induced changes in land water storage; recent satellite-gravity estimates suggest that, over 2002–2014, a human-caused land-water contribution to GMSL of 0.4 mm/year (0.02 inches/year) was more than offset by –0.7 mm/year (–0.03 inches/year) due to natural variability (Reager et al. 2016).

FINAL DRAFT

Comparison of results from a variety of approaches supports the conclusion that a substantial fraction of GMSL rise since 1900 is attributable to human-caused climate change (Kopp et al. 2016; Slangen et al. 2016; Jevrejeva et al. 2009; Dangendorf et al. 2015; Becker et al. 2014; Marcos and Amores 2014; Slangen et al. 2014a; Marzeion et al. 2014; Marcos et al. 2017). For example, based on the long term historical relationship between temperature and rate of GMSL change, Kopp et al. (2016) found that GMSL rise would *extremely likely* have been less than 59% of observed in the absence of 20th century global warming, and that it is *very likely* that GMSL has been higher since 1960 than it would have been without 20th century global warming (Figure 12.3b). Similarly, using a variety of models for individual components, Slangen et al. (2016) found that about 80% of the GMSL rise they simulated for 1970–2005 and about half of that which they simulated for 1900–2005 was attributable to anthropogenic forcing.

Over timescales of a few decades, ocean–atmosphere dynamics drive significant variability in sea surface height, as can be observed by satellite (Figure 12.3c) and in tide gauge records that have been adjusted to account for background rates of rise due to long term factors like glacio-isostatic adjustments. For example, the U.S. Pacific Coast experienced a slower-than-global increase between about 1980 and 2011, while the western tropical Pacific experienced a faster-than-global increase in the 1990s and 2000s. This pattern was associated with changes in average winds linked to the Pacific Decadal Oscillation (PDO) (Bromirski et al. 2011; Zhang and Church 2012; Merrifield 2011) and appears to have reversed since about 2012 (Hamlington et al. 2016). Along the Atlantic coast, the U.S. Northeast has experienced a faster-than-global increase since the 1970s, while the U.S. Southeast has experienced a slower-than-global increase since the 1970s. This pattern appears to be tied to changes in the Gulf Stream (Yin and Goddard 2013; Ezer 2013; Kopp 2013; Kopp et al. 2015b), although whether these changes represent natural variability or a long term trend remains uncertain (Rahmstorf et al. 2015).

[INSERT FIGURE 12.3 HERE]

12.4.2 Ice Sheet Gravity and Altimetry and Visual Observations

Since NCA3, Antarctica and Greenland have continued to lose ice mass, with mounting evidence accumulating that mass loss is accelerating. Studies using repeat gravimetry (GRACE satellites), repeat altimetry, GPS monitoring, and mass balance calculations generally agree on accelerating mass loss in Antarctica (Shepherd et al. 2012; Scambos and Shuman 2016; Seo et al. 2015; Martín-Español et al. 2016). Together, these indicate a mass loss of roughly 100 Gt/year (gigatonnes/year) over the last decade (a contribution to GMSL of about 0.3 mm/year [0.01 inches/year]). Positive accumulation rate anomalies in East Antarctica, especially in Dronning Maud Land (Helm et al. 2014), have contributed to the trend of slight growth there (e.g., Seo et al. 2015; Martín-Español et al. 2016), but this is more than offset by mass loss elsewhere, especially in West Antarctica along the coast facing the Amundsen Sea (Sutterley et al. 2014; Mouginot et al. 2014), Totten Glacier in East Antarctica (Khazendar et al. 2013; Li et al. 2015), and along the Antarctic Peninsula (Seo et al. 2015; Wouters et al. 2015; Martín-Español et al.

FINAL DRAFT

2016). Floating ice shelves around Antarctica are losing mass at an accelerating rate (Paolo et al. 2015). Mass loss from floating ice shelves does not directly affect GMSL, but does allow faster flow of ice from the ice sheet into the ocean.

Estimates of mass loss in Greenland based on mass balance from input-output, repeat gravimetry, repeat altimetry, and aerial imagery as discussed in Chapter 11: Arctic Changes reveal a recent acceleration (Khan et al. 2014). Mass loss averaged approximately 75 Gt/year (about 0.2 mm/year [0.01 inches/year] GMSL rise) from 1900 to 1983, continuing at a similar rate of approximately 74 Gt/year through 2003 before accelerating to 186 Gt/year (0.5 mm/year [0.02 inches/year] GMSL rise) from 2003 to 2010 (Kjeldsen et al. 2015). Strong interannual variability does exist (see Ch. 11: Arctic Changes), such as during the exceptional melt year from April 2012 to April 2013, which resulted in mass loss of approximately 560 Gt (1.6 mm/year [0.06 inches/year]) (Tedesco et al. 2013). More recently (April 2014–April 2015), annual mass losses have resumed the accelerated rate of 186 Gt/year (Kjeldsen et al. 2015; Tedesco et al. 2016). Mass loss over the last century has reversed the long-term trend of slow thickening linked to the continuing evolution of the ice sheet from the end of the last ice age (MacGregor et al. 2016).

12.5 Projected Sea Level Rise

12.5.1 Scenarios of Global Mean Sea Level Rise

No single physical model is capable of accurately representing all of the major processes contributing to GMSL and regional/local RSL rise. Accordingly, the U.S. Interagency Sea Level Rise Task Force (Sweet et al. 2017; henceforth referred to as "Interagency") has revised the GMSL rise scenarios for the United States and now provides six scenarios that can be used for assessment and risk-framing purposes (Figure 12.4a; Table 12.1). The low scenario of 30 cm (about 1 foot) GMSL rise by 2100 is consistent with a continuation of the recent approximately 3 mm/year (0.12 inches/year) rate of rise through to 2100 (Table 12.2), while the five other scenarios span a range of GMSL rise between 50 and 250 cm (1.6 and 8.2 feet) in 2100, with corresponding rise rates between 5 mm/year (0.2 inches/year) to 44 mm/year (1.7 inches/year) towards the end of this century (Table 12.2). The highest scenario of 250 cm is consistent with several literature estimates of the maximum physically plausible level of 21st century sea level rise (e.g., Pfeffer et al. 2008, updated with Sriver et al. 2012 estimates of thermal expansion and Bamber and Aspinall 2013 estimates of Antarctic contribution, and incorporating land water storage, as discussed in Miller et al. 2013; Kopp et al. 2014). It is also consistent with the high end of recent projections of Antarctic ice sheet melt discussed below (DeConto and Pollard 2016). The Interagency GMSL scenario interpretations are shown in Table 12.3.

[INSERT FIGURE 12.4 HERE]

The Interagency scenario approach is similar to local RSL rise scenarios of Hall et al. (2016) used for all coastal U.S. Department of Defense installations worldwide. The Interagency

FINAL DRAFT

approach starts with a probabilistic projection framework to generate time series and regional projections consistent with each GMSL rise scenario for 2100 (Kopp et al. 2014). That framework combines probabilistic estimates of contributions to GMSL and regional RSL rise from ocean processes, cryospheric processes, geological processes, and anthropogenic land-water storage. Pooling the Kopp et al. (2014) projections across RCP2.6, 4.5, and 8.5, the probabilistic projections are filtered to identify pathways consistent with each of these 2100 levels with median (and 17th and 83rd percentiles) picked from each of the filtered subsets.

Table 12.1. The Interagency GMSL rise scenarios in meters (feet) relative to 2000. All values are 19-year averages of GMSL centered at the identified year. To convert from a 1991–2009 tidal datum to the 1983–2001 tidal datum, add 2.4 cm (0.9 inches).

Scenario	**2020**	**2030**	**2050**	**2100**
Low	0.06 (0.2)	0.09 (0.3)	0.16 (0.5)	0.30 (1.0)
Intermediate-Low	0.08 (0.3)	0.13 (0.4)	0.24 (0.8)	0.50 (1.6)
Intermediate	0.10 (0.3)	0.16 (0.5)	0.34 (1.1)	1.0 (3.3)
Intermediate-High	0.10 (0.3)	0.19 (0.6)	0.44 (1.4)	1.5 (4.9)
High	0.11 (0.4)	0.21 (0.7)	0.54 (1.8)	2.0 (6.6)
Extreme	0.11 (0.4)	0.24 (0.8)	0.63 (2.1)	2.5 (8.2)

Table 12.2. Rates of GMSL rise in the Interagency scenarios in mm/year (inches/year). All values represent 19-year average rates of change, centered at the identified year.

Scenario	**2020**	**2030**	**2050**	**2090**
Low	3 (0.1)	3 (0.1)	3 (0.1)	3 (0.1)

FINAL DRAFT

Intermediate-Low	5 (0.2)	5 (0.2)	5 (0.2)	5 (0.2)
Intermediate	6 (0.2)	7 (0.3)	10 (0.4)	15 (0.6)
Intermediate-High	7 (0.3)	10 (0.4)	15 (0.6)	24 (0.9)
High	8 (0.3)	13 (0.5)	20 (0.8)	35 (1.4)
Extreme	10 (0.4)	15 (0.6)	25 (1.0)	44 (1.7)

1

2 **Table 12.3.** Interpretations of the Interagency GMSL rise scenarios

Scenario	**Interpretation**
Low	Continuing current rate of GMSL rise, as calculated since 1993 Low end of *very likely* range under RCP2.6
Intermediate-Low	Modest increase in rate Middle of *likely* range under RCP2.6 Low end of *likely* range under RCP4.5 Low end of *very likely* range under RCP8.5
Intermediate	High end of *very likely* range under RCP4.5 High end of *likely* range under RCP8.5 Middle of *likely* range under RCP4.5 when accounting for possible ice cliff instabilities
Intermediate-High	Slightly above high end of *very likely* range

FINAL DRAFT

	under RCP8.5 Middle of *likely* range under RCP8.5 when accounting for possible ice cliff instabilities
High	High end of *very likely* range under RCP8.5 when accounting for possible ice cliff instabilities
Extreme	Consistent with estimates of physically possible "worst case"

12.5.2 Probabilities of Different Sea Level Rise Scenarios

Several studies have estimated the probabilities of different amounts of GMSL rise under different emissions pathways (e.g., Church et al. 2013; Kopp et al. 2014; Slangen et al. 2014b; Jevrejeva et al. 2014; Grinsted et al. 2015; Kopp et al. 2016; Mengel et al. 2016; Jackson and Jevrejeva 2016) using a variety of methods, including both statistical and physical models. Most of these studies are in general agreement that GMSL rise by 2100 is *very likely* to be between about 25–80 cm (0.8–2.6 feet) under RCP2.6, 35–95 cm (1.1–3.1 feet) under RCP4.5, and 50–130 cm (1.6–4.3 feet) under RCP8.5, although some projections extend the *very likely* range for RCP8.5 as high as 160–180 cm (5–6 feet) (Kopp et al. 2014, sensitivity study; Jevrejeva et al. 2014; Jackson and Jevrejeva 2016). Based on Kopp et al. (2014), the probability of exceeding the amount of GMSL in 2100 under the Interagency scenarios is shown in Table 12.4.

The Antarctic projections of Kopp et al. (2014), the GMSL projections of which underlie Table 12.4, are consistent with a statistical-physical model of the onset of marine ice sheet instability calibrated to observations of ongoing retreat in the Amundsen Embayment sector of West Antarctica (Ritz et al. 2015). Ritz et al. (2015)'s 95th percentile Antarctic contribution to GMSL of 30 cm by 2100 is comparable to Kopp et al. (2014)'s 95th percentile projection of 33 cm under RCP8.5. However, emerging science suggests that these projections may understate the probability of faster-than-expected ice sheet melt, particularly for high-end warming scenarios. While these probability estimates are consistent with the assumption that the relationship between global temperature and GMSL in the coming century will be similar to that observed over the last two millennia (Rahmstorf 2007; Kopp et al. 2016), emerging positive feedbacks (self-amplifying cycles) in the Antarctic Ice Sheet especially (Rignot et al. 2014; Joughin et al. 2014) may invalidate that assumption. Physical feedbacks that until recently were not incorporated into ice sheet models (Pollard et al. 2015) could add about 0–10 cm (0–0.3 feet), 20–50 cm (0.7–1.6 feet) and 60–110 cm (2.0–3.6 feet) to central estimates of current century sea

FINAL DRAFT

level rise under RCP2.6, RCP4.5 and RCP8.5, respectively (DeConto and Pollard 2016). In addition to marine ice sheet instability, examples of these interrelated processes include ice cliff instability and ice shelf hydrofracturing. Processes underway in Greenland may also be leading to accelerating high-end melt risk. Much of the research has focused on changes in surface albedo driven by the melt-associated unmasking and concentration of impurities in snow and ice (Tedesco et al. 2016). However, ice dynamics at the bottom of the ice sheet may be important as well, through interactions with surface runoff or a warming ocean. As an example of the latter, Jakobshavn Isbræ, Kangerdlugssuaq Glacier, and the Northeast Greenland ice stream may be vulnerable to marine ice sheet instability (Khan et al. 2014).

Table 12.4. Probability of exceeding the Interagency GMSL scenarios in 2100 per Kopp et al. (2014). New evidence regarding the Antarctic ice sheet, if sustained, may significantly increase the probability of the intermediate-high, high and extreme scenarios, particularly for RCP8.5, but these results have not yet been incorporated into a probabilistic analysis.

Scenario	**RCP2.6**	**RCP4.5**	**RCP8.5**
Low	94%	98%	100%
Intermediate-Low	49%	73%	96%
Intermediate	2%	3%	17%
Intermediate-High	0.4%	0.5%	1.3%
High	0.1%	0.1%	0.3%
Extreme	0.05%	0.05%	0.1%

12.5.3 Sea Level Rise after 2100

GMSL rise will not stop in 2100, and so it is useful to consider extensions of GMSL rise projections beyond this point. By 2200, the 0.3–2.5 meters (1.0–8.2 feet) range spanned by the six Interagency GMSL scenarios in year 2100 increases to about 0.4–9.7 meters (1.3–31.8 feet), as shown in Table 12.5. These six scenarios imply average rates of GMSL rise over the first half of the next century of 1.4 mm/year (0.06 inch/year), 4.6 mm/yr (0.2 inch/year), 16 mm/year (0.6 inch/year), 32 mm/year (1.3 inches/year), 46 mm/yr (1.8 inches/year) and 60 mm/year (2.4

FINAL DRAFT

inches/year), respectively. Excluding the possible effects of still emerging science regarding ice cliffs and ice shelves, it is very likely that by 2200 GMSL will have risen by 0.3–2.4 meters (1.0–7.9 feet) under RCP2.6, 0.4–2.7 meters (1.3–8.9 feet) under RCP4.5, and 1.0–3.7 meters (3.3–12 feet) under RCP8.5 (Kopp et al. 2014).

Under most projections, GMSL rise will also not stop in 2200. The concept of a "sea level rise commitment" refers to the long-term projected sea level rise were the planet's temperature to be stabilized at a given level (e.g., Levermann et al. 2013; Golledge et al. 2015). The paleo sea level record suggests that even 2°C (3.6°F) of global average warming above the preindustrial temperature may represent a commitment to several meters of rise. One modeling study suggesting a 2,000-year commitment of 2.3 m/°C (4.2 feet/°F) (Levermann et al. 2013) indicates that emissions through to 2100 would lock in a likely 2,000-year GMSL rise commitment of about 0.7–4.2 meters (2.3–14 feet) under RCP2.6, about 1.7–5.6 meters (5.6–19 feet) under RCP4.5, and about 4.3–9.9 meters (14–33 feet) under RCP8.5 (Strauss et al. 2015). However, as with the 21st century projections, emerging science regarding the sensitivity of the Antarctic Ice Sheet may increase the estimated sea level rise over the next millennium, especially for high emissions pathways (DeConto and Pollard 2016). Large-scale climate geoengineering might reduce these commitments (Irvine et al. 2009; Applegate and Keller 2015), but may not be able to avoid lock-in of significant change (Lenton 2011; Barrett et al. 2014; Markusson et al. 2014; Sillmann et al. 2015). Once changes are realized, they will be effectively irreversible for many millennia, even if humans artificially accelerate the removal of CO_2 from the atmosphere (DeConto and Pollard 2016).

The 2,000-year commitment understates the full sea level rise commitment, due to the long response time of the polar ice sheets. Paleo sea level records (Figure 12.2a) suggest that 1°C of warming may already represent a long-term commitment to more than 6 meters (20 feet) of GMSL rise (Dutton and Lambeck 2012; Kopp et al. 2009; Dutton et al. 2015). A 10,000-year modeling study (Clark et al. 2016) suggests that 2°C warming represents a 10,000-year commitment to about 25 meters (80 feet) of GMSL rise, driven primarily by a loss of about one-third of the Antarctic ice sheet and three-fifths of the Greenland ice sheet, while the 21st century RCP8.5 emissions represent a 10,000-year commitment to about 38 meters (125 feet) of GMSL rise, including a complete loss of the Greenland ice sheet over about 6,000 years.

Table 12.5. Post-2100 extensions of the Interagency GMSL rise scenarios in meters (feet)

Scenario	**2100**	**2120**	**2150**	**2200**
Low	0.30 (1.0)	0.34 (1.1)	0.37 (1.2)	0.39 (1.3)
Intermediate-Low	0.50 (1.6)	0.60 (2.0)	0.73 (2.4)	0.95 (3.1)

FINAL DRAFT

Intermediate	1.0 (3.3)	1.3 (4.3)	1.8 (5.9)	2.8 (9.2)
Intermediate-High	1.5 (4.9)	2.0 (6.6)	3.1 (10)	5.1 (17)
High	2.0 (6.6)	2.8 (9.2)	4.3 (14)	7.5 (25)
Extreme	2.5 (8.2)	3.6 (12)	5.5 (18)	9.7 (32)

12.5.4 Regional Projections of Sea Level Change

Because the different factors contributing to sea level change give rise to different spatial patterns, projecting future RSL change at specific locations requires not just an estimate of GMSL change but estimates of the different processes contributing to GMSL change—each of which has a different associated spatial pattern—as well as of the processes contributing exclusively to regional or local change. Based on the process-level projections of the Interagency GMSL scenarios, several key regional patterns are apparent in future U.S. RSL rise as shown for the Intermediate (1 meter [3.3 feet] GMSL rise by 2100 scenario) in Figure 12.4b.

(1) RSL rise due to Antarctic Ice Sheet melt is greater than GMSL rise along all U.S. coastlines due to static-equilibrium effects.

(2) RSL rise due to Greenland Ice Sheet melt is less than GMSL rise in the continental U.S. due to static-equilibrium effects. This effect is especially strong in the Northeast.

(3) RSL rise is additionally augmented in the Northeast by the effects of glacial isostatic adjustment.

(4) The Northeast is also exposed to rise due to changes in the Gulf Stream and reductions in the Atlantic meridional overturning circulation (AMOC). Were the AMOC to collapse entirely—an outcome viewed as unlikely in the 21st century—it could result in as much as approximately 0.5 meters (1.6 feet) of additional regional sea level rise (Gregory and Lowe 2000; Levermann et al. 2005; see Ch. 15: Potential Surprises for further discussion).

(5) The western Gulf of Mexico and parts of the U.S. Atlantic Coast south of New York are currently experiencing significant RSL rise caused by the withdrawal of groundwater (along the Atlantic Coast) and of both fossil fuels and groundwater (along the Gulf Coast). Continuation of these practices will further amplify RSL rise.

FINAL DRAFT

(6) The presence of glaciers in Alaska and their proximity to the Pacific Northwest reduces RSL rise in these regions, due to both the ongoing glacial isostatic adjustment to past glacier shrinkage and to the static-equilibrium effects of projected future losses.

(7) Because they are far from all glaciers and ice sheets, RSL rise in Hawai‘i and other Pacific islands due to any source of melting land ice is amplified by the static-equilibrium effects.

12.6 Extreme Water Levels

12.6.1 Observations

Coastal flooding during extreme high-water events has become deeper due to local RSL rise and more frequent from a fixed-elevation perspective (Menéndez and Woodworth 2010; Kemp and Horton 2013; Sweet et al. 2013; Hall et al. 2016). Trends in annual frequencies surpassing local emergency preparedness thresholds for minor tidal flooding (i.e., “nuisance” levels of about 30–60 cm [1–2 feet]) that begin to flood infrastructure and trigger coastal flood “advisories” by NOAA’s National Weather Service have increased 5- to 10-fold or more since the 1960s along the U.S. coastline (Sweet et al. 2014), as shown in Figure 12.5a. Locations experiencing such trend changes (based upon fits of flood days per year of Sweet and Park 2014) include Atlantic City and Sandy Hook, NJ; Philadelphia, PA; Baltimore and Annapolis, MD; Norfolk, VA; Wilmington, NC; Charleston, SC; Savannah, GA; Mayport and Key West, FL; Port Isabel, TX, La Jolla, CA; and Honolulu, HI. In fact, over the last several decades, minor tidal flood rates have been accelerating within several (more than 25) East and Gulf Coast cities with established elevation thresholds for minor (nuisance) flood impacts, fastest where elevation thresholds are lower, local RSL rise is higher, and extreme variability less (Ezer and Atkinson 2014; Sweet et al. 2014; Sweet and Park 2014).

Trends in extreme water levels (for example, monthly maxima) in excess of mean sea levels (for example, monthly means) exist, but are not commonplace (Menéndez and Woodworth 2010; Talke et al. 2014; Wahl and Chambers 2015; Reed et al. 2015; Marcos et al. 2017). More common are regional time dependencies in high-water probabilities, which can co-vary on an interannual basis with climatic and other patterns (Menéndez and Woodworth 2010; Grinsted et al. 2013; Marcos et al. 2015; Woodworth and Menéndez 2015; Wahl and Chambers 2016; Mawdsley and Haigh 2016; Sweet et al. 2016). These patterns are often associated with anomalous oceanic and atmospheric conditions (Feser et al. 2015; Colle et al. 2015). For instance, the probability of experiencing minor tidal flooding is compounded during El Niño periods along portions of the West and Mid-Atlantic Coasts (Sweet and Park 2014) from a combination of higher sea levels and enhanced synoptic forcing and storm surge frequency (Sweet and Zervas 2011; Thompson et al. 2013; Hamlington et al. 2015; Woodworth and Menéndez 2015).

FINAL DRAFT

12.6.2 Influence of Projected Sea Level Rise on Coastal Flood Frequencies

The extent and depth of minor-to-major coastal flooding during high-water events will continue to increase in the future as local RSL rises (Tebaldi et al. 2012; Horton et al. 2011; Woodruff et al. 2013; Kopp et al. 2014; Sweet and Park 2014; Buchanan et al. 2016; Hall et al. 2016; Dahl et al. 2017; Sweet et al. 2017). Relative to fixed elevations, the frequency of high-water events will increase the fastest where extreme variability is less and the rate of local RSL rise is higher (Hunter 2012; Tebaldi et al. 2012; Kopp et al. 2014; Sweet and Park 2014; Buchanan et al. 2016; Sweet et al. 2017). Under the RCP-based probabilistic RSL projections of Kopp et al. 2014, at tide gauge locations along the contiguous U.S. coastline, a median 8-fold increase (range of 1.1- to 430-fold increase) is expected by 2050 in the annual number of floods exceeding the elevation of the current 100-year flood event (measured with respect to a 1991–2009 baseline sea level) (Buchanan et al. 2016). Under the same forcing, the frequency of minor tidal flooding (with contemporary recurrence intervals generally <1 year [Sweet et al. 2014]) will increase even more so in the coming decades (Sweet and Park 2014; Moftakhari et al. 2015) and eventually occur on a daily basis (Figure 12.5b). With only about 0.35 m (<14 inches) of additional local RSL rise (with respect to the year 2000), annual frequencies of moderate level flooding—those locally with a 5-year recurrence interval (Figure 12.5c) and associated with a NOAA coastal flood warning of serious risk to life and property—will increase 25-fold at the majority of NOAA tide gauge locations along the U.S. coastline (outside of Alaska) by or about (±5 years) 2080, 2060, 2040, and 2030 under the Interagency Low, Intermediate-Low, Intermediate, and Intermediate-High GMSL scenarios, respectively (Sweet et al. 2017). Figure 12.5d, which shows the decade in which the frequency of such moderate level flooding will increase 25-fold under the Interagency Intermediate Scenario, highlights that the mid- and Southeast Atlantic, western Gulf of Mexico, California, and the Island States and Territories are most susceptible to rapid changes in potentially damaging flood frequencies.

[INSERT FIGURE 12.5 HERE]

12.6.3 Waves and Impacts

The combination of a storm surge at high tide with additional dynamic effects from waves (Stockdon et al. 2006; Sweet et al. 2015) creates the most damaging coastal hydraulic conditions (Moritz et al. 2015). Simply with higher-than-normal sea levels, wave action increases the likelihood for extensive coastal erosion (Barnard et al. 2011; Theuerkauf et al. 2014; Serafin and Ruggiero 2014) and low-island overwash (Hoeke et al. 2013). Wave runup is often the largest water level component during extreme events especially along island coastlines where storm surge is constrained by bathymetry (Tebaldi et al. 2012; Woodruff et al. 2013; Hall et al. 2016). On an interannual basis, wave impacts are correlated across the Pacific Ocean with phases of ENSO (Stopa and Cheung 2014; Barnard et al. 2015). Over the last half century, there has been an increasing trend in wave height and power within the North Pacific Ocean (Bromirski et al. 2013; Erikson et al. 2015) that is modulated by the PDO (Aucan et al. 2012; Bromirski et al.

FINAL DRAFT

2013). Resultant increases in wave run-up have been more of a factor than RSL rise in terms of impacts along the U.S. Northwest Pacific Coast over the last several decades (Ruggiero 2013). In the Northwest Atlantic Ocean, no long-term trends in wave power have been observed over the last half century (Bromirski and Cayan 2015), though hurricane activity drives interannual variability (Bromirski and Kossin 2008). In terms of future conditions this century, increases in mean and maximum seasonal wave heights are projected within parts of the northeast Pacific, northwest Atlantic, and Gulf of Mexico (Graham et al. 2013; Wang et al. 2014; Erikson et al. 2015; Shope et al. 2016).

12.6.4 Sea Level Rise, Changing Storm Characteristics, and Their Interdependencies

Future probabilities of extreme coastal floods will depend upon the amount of local RSL rise, changes in coastal storm characteristics, and their interdependencies. For instance, there have been more storms producing concurrent locally extreme storm surge and rainfall (not captured in tide gauge data) along the U.S. East and Gulf Coasts over the last 65 years, with flooding further compounded by local RSL rise (Wahl et al. 2015). Hemispheric-scale extratropical cyclones may experience a northward shift this century, with some studies projecting an overall decrease in storm number (Colle et al. 2015 and references therein). The research is mixed about strong extratropical storms; studies find potential increases in frequency and intensity in some regions, like within the Northeast (Colle et al. 2013), whereas others project decreases in strong extratropical storms in some regions (e.g., Zappa et al. 2013).

For tropical cyclones, model projections for the North Atlantic mostly agree that intensities and precipitation rates will increase this century (see Ch. 9: Extreme Storms), although some model evidence suggests that track changes could dampen the effect in the U.S. Mid-Atlantic and Northeast (Hall and Yonekura 2013). Assuming other storm characteristics do not change, sea level rise will increase the frequency and extent of extreme flooding associated with coastal storms, such as hurricanes and nor'easters. A projected increase in the intensity of hurricanes in the North Atlantic could increase the probability of extreme flooding along most of the U.S. Atlantic and Gulf Coast States beyond what would be projected based solely on RSL rise (Grinsted et al. 2013; Lin et al. 2012; Little et al. 2015; Lin et al. 2016). In addition, RSL increases are projected to cause a nonlinear increase in storm surge heights in shallow bathymetry environments (Smith et al. 2010; Atkinson et al. 2013; Bilskie et al. 2014; Passeri et al. 2015; Bilskie et al. 2016) and extend wave propagation and impacts landward (Smith et al. 2010; Atkinson et al. 2013). However, there is low confidence in the magnitude of the increase in intensity and the associated flood risk amplification, and it could be offset or amplified by other factors, such as changes in storm frequency or tracks (e.g., Knutson et al. 2013, 2015)

FINAL DRAFT

TRACEABLE ACCOUNTS

Key Finding 1

Global mean sea level (GMSL) has risen by about 7–8 inches (about 16–21 cm) since 1900, with about 3 of those inches (about 7 cm) occurring since 1993 (*very high confidence*). Human-caused climate change has made a substantial contribution to GMSL rise since 1900 (*high confidence*), contributing to a rate of rise that is greater than during any preceding century in at least 2,800 years (*medium confidence*).

Description of evidence base

Multiple researchers, using different statistical approaches, have integrated tide gauge records to estimate GMSL rise since the late nineteenth century (e.g., Church and White 2006, 2011; Hay et al. 2015; Jevrejeva et al. 2009). The most recent published rate estimates are 1.2 ± 0.2 (Hay et al. 2015) or 1.5 ± 0.2 (Church and White 2011) mm/year over 1901–1990. Thus, these results indicate about 11–14 cm (4–5 inches) of GMSL rise from 1901 to 1990. Tide gauge analyses indicate that GMSL rose at a considerably faster rate of about 3 mm/year (0.12 inches/year) since 1993 (Hay et al. 2015; Church and White 2011), a result supported by satellite data indicating a trend of 3.4 ± 0.4 mm/year (0.13 inches/year) over 1993–2015 (update to Nerem et al. 2010) (Figure 12.3a). These results indicate an additional GMSL rise of about 7 cm (3 inches) rise since 1990. Thus, total GMSL rise since 1900 is about 18–21 cm (7–8 inches).

The finding regarding the historical context of the 20th century change is based upon Kopp et al. (2016), who conducted a meta-analysis of geological RSL reconstructions spanning the last 3,000 years from 24 locations around the world as well as tide gauge data from 66 sites and the tide gauge based GMSL reconstruction of Hay et al. (2015). By constructing a spatio-temporal statistical model of these data sets, they identified the common global sea level signal over the last three millennia and its uncertainties. They found a 95% probability that the average rate of GMSL change over 1900–2000 was greater than during any preceding century in at least 2,800 years.

The finding regarding the substantial human contribution is based upon several lines of evidence. Kopp et al. (2016), based on the long term historical relationship between temperature and the rate of sea level change, found that it is *extremely likely* that GMSL rise would have been <59% of observed in the absence of 20th century global warming, and that it is *very likely* that GMSL has been higher since 1960 than it would have been without 20th century global warming. Using a variety of models for individual components, Slangen et al. (2016) found that 69% ± 31% out of the 87% ± 20% of GMSL rise over 1970–2005 that their models simulated was attributable to anthropogenic forcing, and that 37% ± 38% out of 74% ± 22% simulated was attributable over 1900–2005. Jevrejeva et al. (2009), using the relationship between forcing and GMSL over 1850 and 2001 and CMIP3 models, found that ~75% of GMSL rise in the 20th century is attributable to anthropogenic forcing. Marcos and Amores (2014), using CMIP5 models, found that ~87% of

FINAL DRAFT

ocean heat uptake since 1970 in the top 700 m of the ocean has been due to anthropogenic forcing. Slangen et al. (2014a), using CMIP5, found that anthropogenic forcing was required to explain observed thermosteric SLR over 1957–2005. Marzeion et al. (2014) found that 25% ± 35% of glacial loss over 1851–2010, and 69% ± 24% over 1991–2010, was attributable to anthropogenic forcing. Dangendorf et al (2015), based on time series analysis, found that >45% of observed GMSL trend since 1900 cannot (with 99% probability) be explained by multi-decadal natural variability. Becker et al. (2014), based on time series analysis, found a 99% probability that at least 1.0 or 1.3 mm/year of GMSL rise over 1880–2010 is anthropogenic.

Major uncertainties

Uncertainties in reconstructed GMSL change relate to the sparsity of tide gauge records, particularly before the middle of the twentieth century, and to different statistical approaches for estimating GMSL change from these sparse records. Uncertainties in reconstructed GMSL change before the twentieth century also relate to the sparsity of geological proxies for sea level change, the interpretation of these proxies, and the dating of these proxies. Uncertainty in attribution relates to the reconstruction of past changes and the magnitude of unforced variability.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Confidence is *very high* in the rate of GMSL rise since 1900, based on multiple different approaches to estimating GMSL rise from tide gauges and satellite altimetry. Confidence is *high* in the substantial human contribution to GMSL rise since 1900, based on both statistical and physical modeling evidence. It is *medium* that the magnitude of the observed rise since 1900 is unprecedented in the context of the previous 2,700 years, based on meta-analysis of geological proxy records.

Summary sentence or paragraph that integrates the above information

This key finding is based upon multiple analyses of tide gauge and satellite altimetry records, on a meta-analysis of multiple geological proxies for pre-instrumental sea level change, and on both statistical and physical analyses of the human contribution to GMSL rise since 1900.

Key Finding 2

Relative to the year 2000, GMSL is *very likely* to rise by 0.3–0.6 feet (9–18 cm) by 2030, 0.5–1.2 feet (15–38 cm) by 2050, and 1 to 4 feet (30–130 cm) by 2100 (*very high confidence in lower bounds; medium confidence in upper bounds for 2030 and 2050; low confidence in upper bounds for 2100*). Future emissions pathways have little effect on projected GMSL rise in the first half of the century, but significantly affect projections for the second half of the century (*high*

FINAL DRAFT

confidence). Emerging science regarding Antarctic ice sheet stability suggests that, for high emission scenarios, a GMSL rise exceeding 8 feet (2.4 m) by 2100 is physically possible, although the probability of such an extreme outcome cannot currently be assessed. Regardless of emissions pathway, it is *extremely likely* that GMSL rise will continue beyond 2100 (*high confidence*).

Description of evidence base

The lower bound of the *very likely* range is based on a continuation of the observed approximately 3 mm/year rate of GMSL rise. The upper end of the *very likely* range is based upon estimates for RCP8.5 from three studies producing fully probabilistic projections across multiple RCPs. Kopp et al. (2014) fused multiple sources of information accounting for the different individual process contributing to GMSL rise. Kopp et al. (2016) constructed a semi-empirical sea level model calibrated to the Common Era sea level reconstruction. Mengel et al. (2016) constructed a set of semi-empirical models of the different contributing processes. All three studies show negligible RCP dependence in the first half of this century, becoming more prominent in the second half of the century. A sensitivity study by Kopp et al. (2014), as well as studies by Jevrejeva et al. (2014) and by Jackson and Jevrejeva (2016), used frameworks similar to Kopp et al. (2016) but incorporated directly an expert elicitation study on ice sheet stability (Bamber and Aspinall 2013). (This study was incorporated in Kopp et al. [2014]'s main results with adjustments for consistency with Church et al. 2013). These studies extend the *very likely* range for RCP8.5 as high as 160–180 cm (5–6 feet) (Kopp et al. 2014, sensitivity study; Jevrejeva et al. 2014; Jackson and Jevrejeva 2016).

To estimate the effect of incorporating the DeConto and Pollard (2016) projections of Antarctic ice sheet melt, we note that Kopp et al. (2014)'s median projection of Antarctic melt in 2100 is 4 cm (1.6 inches) (RCP2.6), 5 cm (2 inches) (RCP4.5), or 6 cm (2.4 inches) (RCP8.5). By contrast, DeConto and Pollard (2016)'s ensemble mean projections are (varying the assumptions for the size of Pliocene mass loss and the bias correction in the Amundsen Sea) 2–14 cm (0.1–0.5 foot) for RCP2.6, 26–58 cm (0.9–1.9 feet) for RCP4.5, and 64–114 cm (2.1–3.7 ft) for RCP8.5. Thus, we conclude that DeConto and Pollard (2016)'s projection would lead to a –10 cm (–0.1–0.3 ft) increase in median RCP2.6 projections, a 21–53 cm (0.7–1.7 feet) increase in median RCP4.5 projections, and a 58–108 cm (1.9–3.5 feet) increase in median RCP8.5 projections.

Very likely ranges, 2030 relative to 2000 in cm (feet)

	Kopp et al. (2014)	Kopp et al. (2016)	Mengel et al. (2016)
RCP8.5	11–18 (0.4–0.6)	8–15 (0.3–0.5)	7–12 (0.2–0.4)

FINAL DRAFT

RCP4.5	10–18 (0.3–0.6)	8–15 (0.3–0.5)	7–12 (0.2–0.4)
RCP2.6	10–18 (0.3–0.6)	8–15 (0.3–0.5)	7–12 (0.2–0.4)

Very likely ranges, 2050 relative to 2000 in cm (feet)

	Kopp et al. (2014)	Kopp et al. (2016)	Mengel et al. (2016)
RCP8.5	21–38 (0.7–1.2)	16–34 (0.5–1.1)	15–28 (0.5–0.9)
RCP4.5	18–35 (0.6–1.1)	15–31 (0.5–1.0)	14–25 (0.5–0.8)
RCP2.6	18–33 (0.6–1.1)	14–29 (0.5–1.0)	13–23 (0.4–0.8)

Very likely ranges, 2100 relative to 2000 in cm (feet)

	Kopp et al. (2014)	Kopp et al. (2016)	Mengel et al. (2016)
RCP8.5	55–121 (1.8–4.0)	52–131 (1.7–4.3)	57–131 (1.9–4.3)
RCP4.5	36–93 (1.2–3.1)	33–85 (1.1–2.8)	37–77 (1.2–2.5)
RCP2.6	29–82 (1.0–2.7)	24–61 (0.8–2.0)	28–56 (0.9–1.8)

Major uncertainties

Since NCA3, multiple different approaches have been used to generate probabilistic projections of GMSL rise, conditional upon the RCPs. These approaches are in general agreement. However, emerging results indicate that marine-based sectors of the Antarctic Ice Sheet are more unstable than previous modeling indicated. The rate of ice sheet mass changes remains challenging to project.

FINAL DRAFT

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is *very high* confidence that future GMSL rise over the next several decades will be at least as fast as a continuation of the historical trend over the last quarter century would indicate. There is *medium* confidence in the upper end of very likely ranges for 2030 and 2050. Due to possibly large ice sheet contributions, there is *low* confidence in the upper end of very likely ranges for 2100. Based on multiple projection methods, there is *high confidence* that differences between emission scenarios are small before 2050 but significant beyond 2050.

Summary sentence or paragraph that integrates the above information

This key finding is based upon multiple methods for estimating the probability of future sea level change and on new modeling results regarding the stability of marine based ice in Antarctica.

Key Finding 3

Relative sea level (RSL) rise in this century will vary along U.S. coastlines due, in part, to changes in Earth's gravitational field and rotation from melting of land ice, changes in ocean circulation, and vertical land motion (*very high confidence*). For almost all future GMSL rise scenarios, RSL rise is *likely* to be greater than the global average in the U.S. Northeast and the western Gulf of Mexico. In intermediate and low GMSL rise scenarios, RSL rise is *likely* to be less than the global average in much of the Pacific Northwest and Alaska. For high GMSL rise scenarios, RSL rise is *likely* to be higher than the global average along all U.S. coastlines outside Alaska. Almost all U.S. coastlines experience more than global-mean sea-level rise in response to Antarctic ice loss, and thus would be particularly affected under extreme GMSL rise scenarios involving substantial Antarctic mass loss (*high confidence*).

Description of evidence base

The processes that cause geographic variability in RSL change are reviewed by Kopp et al. (2015a). Long tide gauge data sets show the RSL rise caused by vertical land motion due to glacio-isostatic adjustment and fluid withdrawal along many U.S. coastlines (PSMSL 2016; Holgate et al. 2013). These observations are corroborated by glacio-isostatic adjustment models, by GPS observations, and by geological data (e.g., Engelhart and Horton 2012). The physics of the gravitational, rotational and flexural "static-equilibrium fingerprint" response of sea level to redistribution of mass from land ice to the oceans is well established (Farrell and Clark 1976; Mitrovica et al. 2011). GCM studies indicate the potential for a Gulf Stream contribution to sea level rise in the U.S. Northeast (Yin et al. 2009; Yin and Goddard 2013). Kopp et al. (2014) and Slangen et al. (2014a) accounted for land motion (only glacial isostatic adjustment for Slangen et al.), fingerprint, and ocean dynamic responses. Comparing projections of local RSL change and

FINAL DRAFT

GMSL change in these studies indicate that local rise is likely to be greater than the global average along the U.S. Atlantic and Gulf Coasts and less than the global average in most of the Pacific Northwest. Sea level rise projections in this report are developed by an Interagency Sea Level Rise Task Force (Sweet et al. 2017).

Major uncertainties

Since NCA3, multiple authors have produced global or regional studies synthesizing the major process that causes global and local sea level change to diverge. The largest sources of uncertainty in the geographic variability of sea level change are ocean dynamic sea level change and, for those regions where sea level fingerprints for Greenland and Antarctica differ from the global mean in different directions, the relative contributions of these two sources to projected sea level change.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Because of the enumerated physical processes, there is *very high* confidence that RSL change will vary across U.S. coastlines. There is *high* confidence in the likely differences of RSL change from GMSL change under different levels of GMSL change, based on projections incorporating the different relevant processes.

Summary sentence or paragraph that integrates the above information

The part of the key finding regarding the existence of geographic variability is based upon a broader observational, modeling, and theoretical literature. The specific differences are based upon the scenarios described by the Interagency Sea Level Rise Task Force (Sweet et al. 2017)

Key Finding 4

As sea levels have risen, the number of tidal floods each year that cause minor impacts (also called “nuisance floods”) have increased 5- to 10-fold since the 1960s in several U.S. coastal cities (*very high confidence*). Rates of increase are accelerating in over 25 Atlantic and Gulf Coast cities (*very high confidence*). Tidal flooding will continue increasing in depth, frequency, and extent this century (*very high confidence*).

Description of evidence base

Sweet et al. (2014) examined 45 NOAA tide gauge locations with hourly data since 1980 and Sweet and Park (2014) examined a subset of these (27 locations) with hourly data prior to 1950, all with a National Weather Service elevation threshold established for minor “nuisance” flood impacts. Using linear or quadratic fits of annual number of days exceeding the minor thresholds,

FINAL DRAFT

Sweet and Park (2014) find increases in trend-derived values between 1960 and 2010 greater than 10-fold at 8 locations, greater than 5-fold at 6 locations, and greater than 3-fold at 7 locations. Sweet et al. (2014), Sweet and Park (2014), and Ezer and Atkinson (2014) find that annual minor tidal flood frequencies since 1980 are accelerating along locations on the East and Gulf Coasts (>25 locations, Sweet et al. 2014) due to continued exceedance of a typical high-water distribution above elevation thresholds for minor impacts.

Historical changes over the last 60 years in flood probabilities have occurred most rapidly where RSL rates were highest and where tide ranges and extreme variability is less (Sweet and Park 2014). In terms of future rates of changes in extreme event probabilities relative to fixed elevations, Hunter (2012), Tebaldi et al. (2012), Kopp et al. (2014), Sweet and Park (2014) and Sweet et al. (2017) all find that locations with less extreme variability and higher RSL rise rates are most prone.

Major uncertainties

Minor flooding probabilities have been only assessed where a tide gauge is present with >30 years of data and where a NOAA National Weather Service elevation threshold for impacts has been established. There are likely many other locations experiencing similar flooding patterns, but an expanded assessment is not possible at this time.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is *very high* confidence that exceedance probabilities of high tide flooding at dozens of local-specific elevation thresholds have significantly increased over the last half century, often in an accelerated fashion, and that exceedance probabilities will continue to increase this century.

Summary sentence or paragraph that integrates the above information

This key finding is based upon several studies finding historic and projecting future changes in high-water probabilities for local-specific elevation thresholds for flooding.

Key Finding 5

Assuming storm characteristics do not change, sea level rise will increase the frequency and extent of extreme flooding associated with coastal storms, such as hurricanes and nor'easters (*very high confidence*). A projected increase in the intensity of hurricanes in the North Atlantic could increase the probability of extreme flooding along most of the U.S. Atlantic and Gulf Coast states beyond what would be projected based solely on RSL rise. However, there is *low confidence* in the magnitude of the increase in intensity and the associated flood risk

FINAL DRAFT

amplification, and these effects could be offset or amplified by other factors, such as changes in storm frequency or tracks.

Description of evidence base

The frequency, extent, and depth of extreme event-driven (for example, 5 to 100 year event probabilities) coastal flooding relative to existing infrastructure will continue to increase in the future as local RSL rises (Tebaldi et al. 2012; Horton et al. 2011; Woodruff et al. 2013; Sweet et al. 2013; Kopp et al. 2014; Buchanan et al. 2016; Hall et al. 2016; Sweet et al. 2017). Extreme flood probabilities will increase regardless of change in storm characteristics, which may exacerbate such changes. Model-based projections of tropical storms and related major storm surges within the North Atlantic mostly agree that intensities and frequencies of the most intense storms will increase this century (Grinsted et al. 2013; Lin et al. 2012; Little et al. 2015; Knutson et al. 2013; Lin et al. 2016). However, the projection of increased hurricane intensity is more robust across models than the projection of increased frequency of the most intense storms, since a number of models project a decrease in the overall number of tropical storms and hurricanes in the North Atlantic, although high-resolution models generally project increased mean hurricane intensity (e.g., Knutson et al. 2013). In addition, there is model evidence for a change in tropical cyclone tracks in warm years that minimizes the increase in landfalling hurricanes in the U.S. Mid-Atlantic or Northeast (Hall and Yonekura 2013).

Major uncertainties

Uncertainties remain large with respect to the precise change in future risk of a major coastal impact at a specific location from changes in the most intense tropical cyclone characteristics and tracks beyond changes imposed from local sea level rise.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is *low confidence* that the flood risk at specific locations will be amplified from a major tropical storm this century.

Summary sentence or paragraph that integrates the above information

This key finding is based upon several modeling studies of future hurricane characteristics and associated increases in major storm surge risk amplification.

FINAL DRAFT

FIGURES

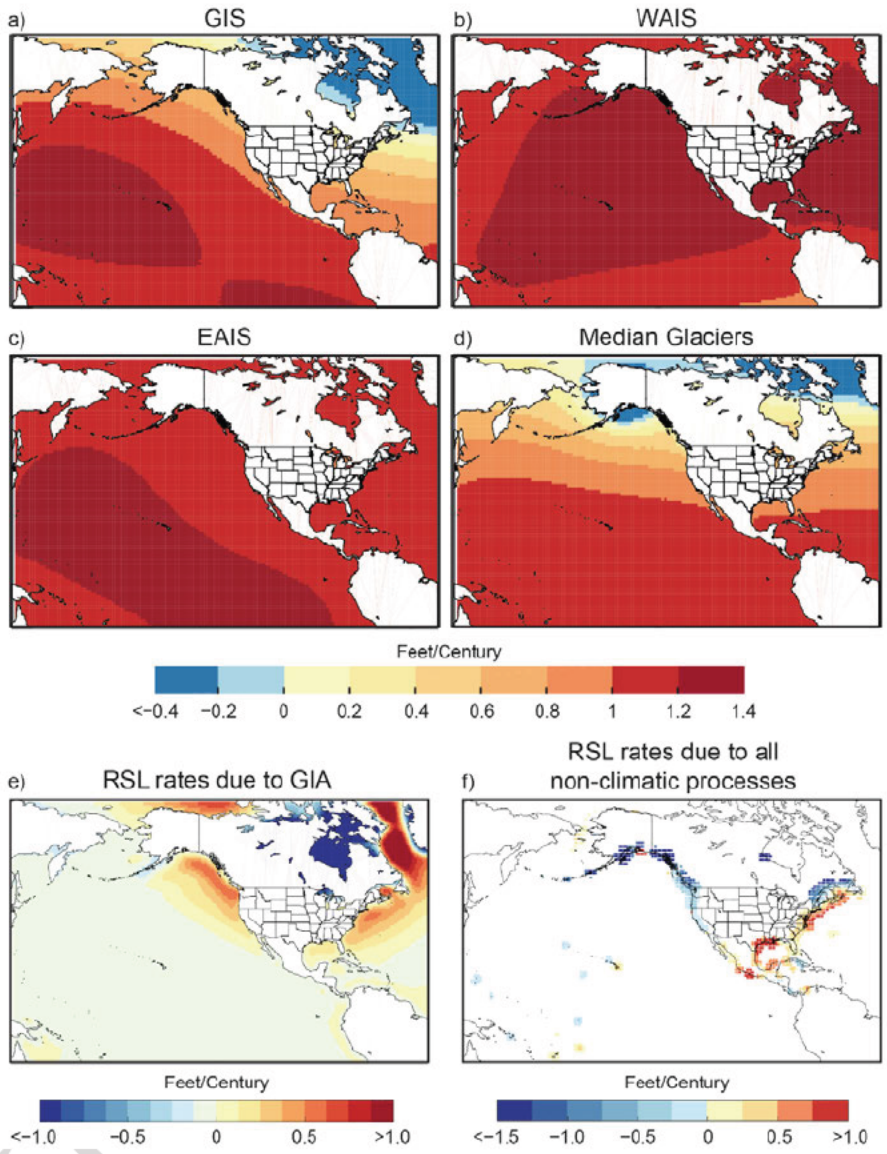

Figure 12.1: (a–d) Static-equilibrium fingerprints of the relative sea level (RSL) effect of land ice melt, in units of feet of RSL change per feet of global mean sea level (GMSL) change, for mass loss from (a) Greenland, (b) West Antarctica, (c) East Antarctica, and (d) the median projected combination of melting glaciers, after Kopp et al. (2014, 2015a). (e) Model projections of the rate of RSL rise due to glacial-isostatic adjustment (units of feet/century), after Kopp et al. (2015a). (f) Tide gauge-based estimates of the non-climatic, long term contribution to RSL rise, including the effects of glacial isostatic adjustment, tectonics, and sediment compaction (units of feet/century) (Kopp et al. 2014). [Figure source: (a)–(d) Kopp et al. 2015a, (e) adapted from Kopp et al. 2015a; (f) adapted from Sweet et al. 2017].

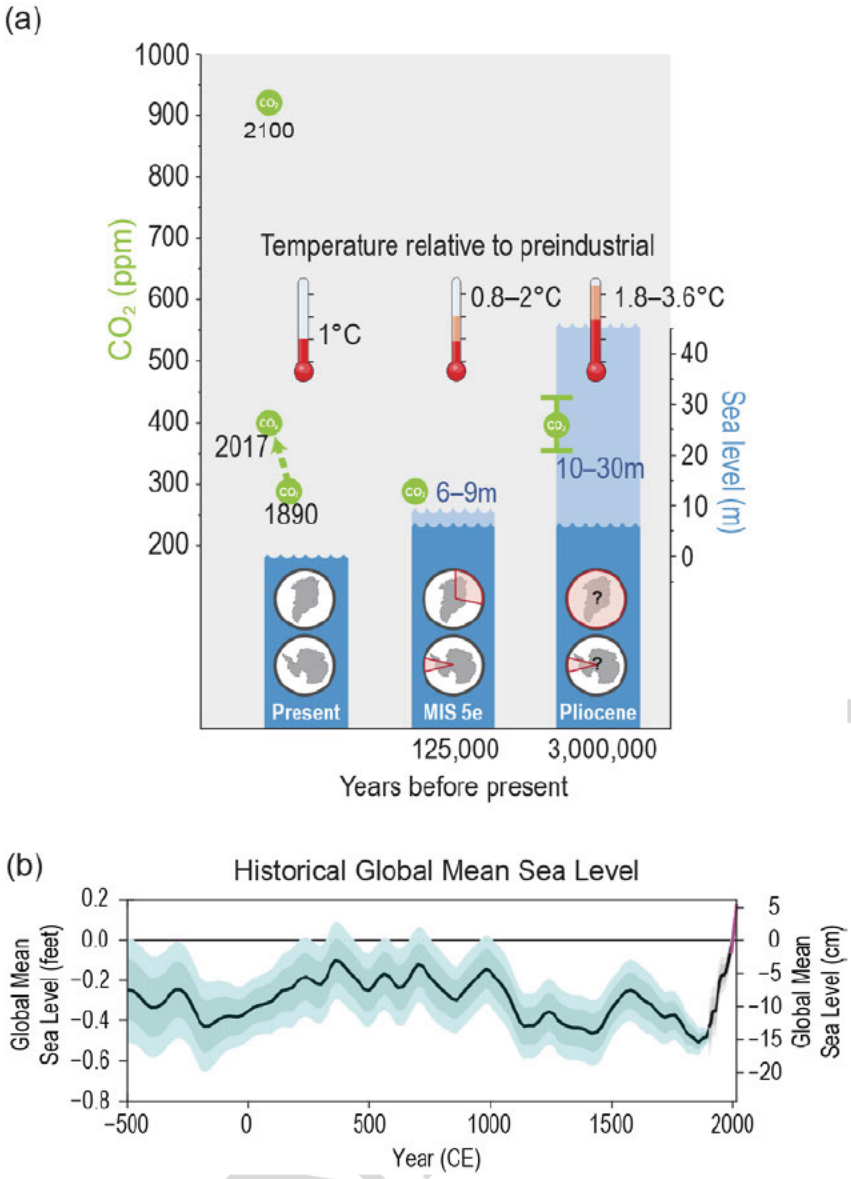

Figure 12.2: (a) The relationship between peak global mean temperature, maximum global mean sea level (GMSL), and source(s) of meltwater over three periods in the past with global mean temperature comparable to or warmer than present. Light blue shading indicates uncertainty of GMSL maximum. Red pie charts over Greenland and Antarctica denote fraction, not location, of ice retreat. (b) GMSL rise from –500 to 1900 CE, from Kopp et al. 2016's geological and tide gauge-based reconstruction (blue), from 1900 to 2010 from Hay et al. 2015's tide gauge-based reconstruction (black), and from 1992 to 2015 from the satellite-based reconstruction updated from Nerem et al. 2010 (magenta). [Figure source: (a) adapted from Dutton et al. 2015 and (b) Sweet et al. 2017].

DRAFT

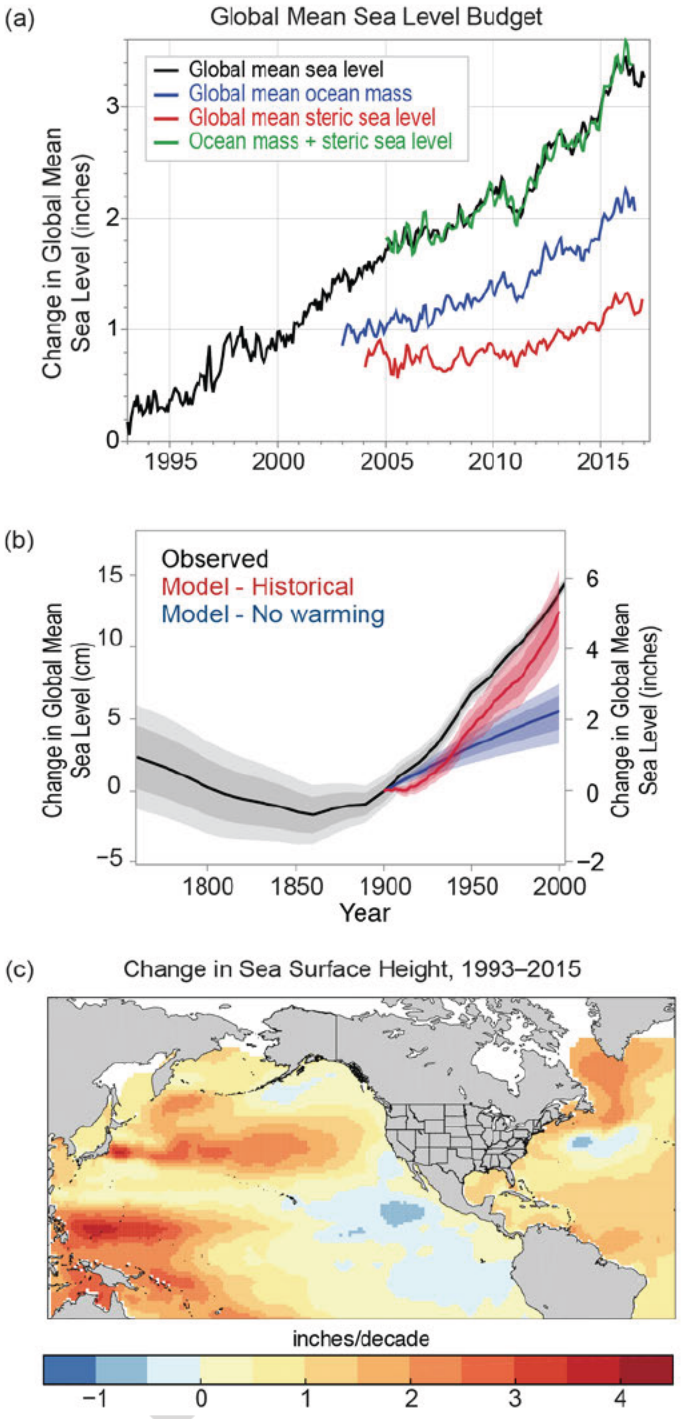

Figure 12.3: (a) Contributions of ocean mass changes from land ice and land water storage (measured by satellite gravimetry) and ocean volume changes (or steric, primarily from thermal expansion measured by in situ ocean profilers) and their comparison to global mean sea level (GMSL) change (measured by satellite altimetry) since 1993. (b) An estimate of modeled GMSL rise in the absence of 20th century warming (blue) and from the same model with observed warming (red), compared to observed GMSL change (black). Heavy/light shading indicates the

DRAFT

17th–83rd and 5th–95th percentiles. (c) Rates of change from 1993 to 2015 in sea surface height from satellite altimetry data; updated from Kopp et al. 2015a using data updated from Church and White 2011. [Figure source: (a) adapted and updated from Leuliette and Nerem 2016, (b) adapted from Kopp et al. (2016) and (c) adapted and updated from Kopp et al. 2015a].

FINAL DRAFT

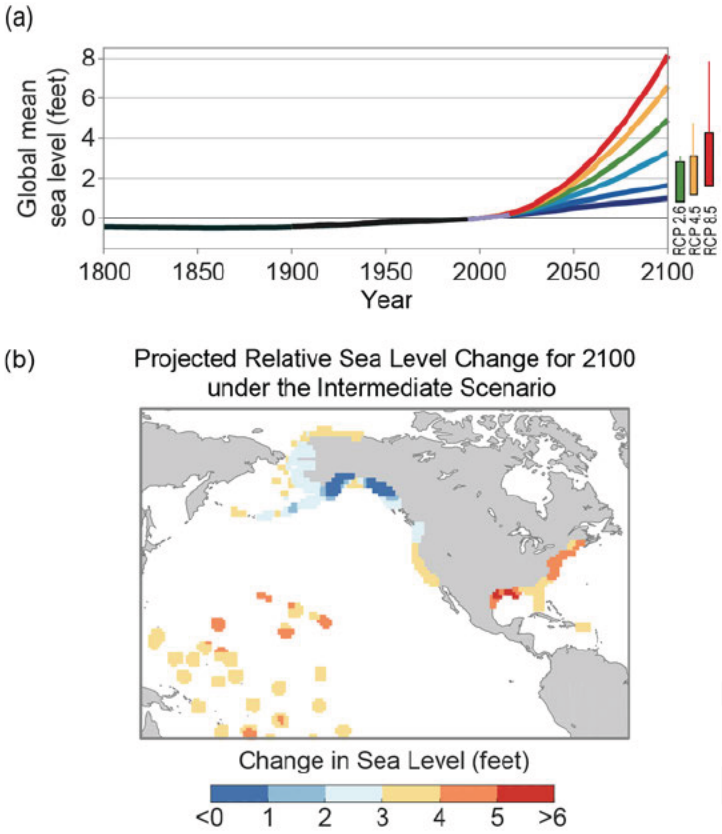

Figure 12.4: (a) Global mean sea level (GMSL) rise from 1800 to 2100, based on Figure 12.2b from 1800 to 2015, the six Interagency (Sweet et al. 2017) GMSL scenarios (navy blue, royal blue, cyan, green, orange and red curves), the *very likely* ranges in 2100 for different RCPs from this chapter (colored boxes), and lines augmenting the *very likely* ranges by the difference between the median Antarctic contribution of Kopp et al. 2014 and the various median Antarctic projections of DeConto and Pollard (2016). (b) Relative sea level (RSL) rise (feet) in 2100 projected for the Interagency Intermediate Scenario (1-meter [3.3 feet] GMSL rise by 2100) (Figure source: Sweet et al. 2017).

FINAL DRAFT

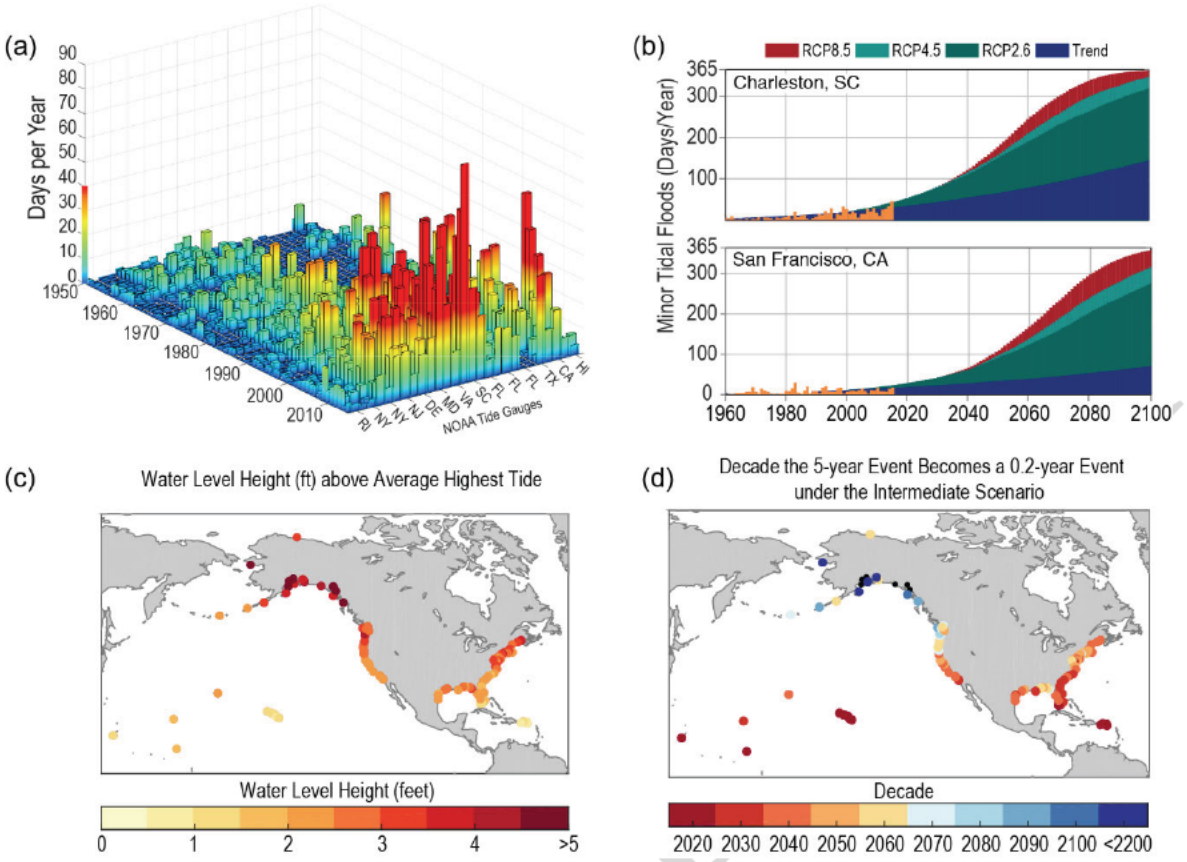

Figure 12.5: (a) Tidal floods (days per year) exceeding NOAA thresholds for minor impacts at 28 NOAA tide gauges through 2015 showing (b) historical exceedances (orange) for two of the locations—Charleston, SC and San Francisco, CA—and future projections through 2100 based upon the continuation of the historical trend (blue) and under median RCP2.6, 4.5 and 8.5 conditions. (c) Water level heights above average highest tide associated with a local 5-year recurrence probability and (d) the future decade when the 5-year event becomes a 0.2-year (5 or more times a year) event under the Interagency Intermediate scenario; black dots imply that a 5-year to 0.2-year frequency change does not unfold by 2200 under the Intermediate scenario. [Figure source: (a) adapted from Sweet and Marra 2016, (b) adapted from Sweet and Park 2014, (c) and (d) Sweet et al. 2017]

FINAL

REFERENCES

Applegate, P.J. and K. Keller, 2015: How effective is albedo modification (solar radiation management geoengineering) in preventing sea-level rise from the Greenland Ice Sheet? *Environmental Research Letters,* **10,** 084018. http://dx.doi.org/10.1088/1748-9326/10/8/084018

Atkinson, J., J.M. Smith, and C. Bender, 2013: Sea-level rise effects on storm surge and nearshore waves on the Texas coast: Influence of landscape and storm characteristics. *Journal of Waterway, Port, Coastal, and Ocean Engineering,* **139,** 98-117. http://dx.doi.org/10.1061/(ASCE)WW.1943-5460.0000187

Aucan, J., R. Hoeke, and M.A. Merrifield, 2012: Wave-driven sea level anomalies at the Midway tide gauge as an index of North Pacific storminess over the past 60 years. *Geophysical Research Letters,* **39,** L17603. http://dx.doi.org/10.1029/2012GL052993

Bamber, J.L. and W.P. Aspinall, 2013: An expert judgement assessment of future sea level rise from the ice sheets. *Nature Climate Change,* **3,** 424-427. http://dx.doi.org/10.1038/nclimate1778

Barnard, P.L., J. Allan, J.E. Hansen, G.M. Kaminsky, P. Ruggiero, and A. Doria, 2011: The impact of the 2009–10 El Niño Modoki on U.S. West Coast beaches. *Geophysical Research Letters,* **38,** L13604. http://dx.doi.org/10.1029/2011GL047707

Barnard, P.L., A.D. Short, M.D. Harley, K.D. Splinter, S. Vitousek, I.L. Turner, J. Allan, M. Banno, K.R. Bryan, A. Doria, J.E. Hansen, S. Kato, Y. Kuriyama, E. Randall-Goodwin, P. Ruggiero, I.J. Walker, and D.K. Heathfield, 2015: Coastal vulnerability across the Pacific dominated by El Niño/Southern Oscillation. *Nature Geoscience,* **8,** 801-807. http://dx.doi.org/10.1038/ngeo2539

Barrett, S., T.M. Lenton, A. Millner, A. Tavoni, S. Carpenter, J.M. Anderies, F.S. Chapin, III, A.-S. Crepin, G. Daily, P. Ehrlich, C. Folke, V. Galaz, T. Hughes, N. Kautsky, E.F. Lambin, R. Naylor, K. Nyborg, S. Polasky, M. Scheffer, J. Wilen, A. Xepapadeas, and A. de Zeeuw, 2014: Climate engineering reconsidered. *Nature Climate Change,* **4,** 527-529. http://dx.doi.org/10.1038/nclimate2278

Becker, M., M. Karpytchev, and S. Lennartz-Sassinek, 2014: Long-term sea level trends: Natural or anthropogenic? *Geophysical Research Letters,* **41,** 5571-5580. http://dx.doi.org/10.1002/2014GL061027

Bilskie, M.V., S.C. Hagen, S.C. Medeiros, and D.L. Passeri, 2014: Dynamics of sea level rise and coastal flooding on a changing landscape. *Geophysical Research Letters,* **41,** 927-934. http://dx.doi.org/10.1002/2013GL058759

FINAL DRAFT

Bilskie, M.V., S.C. Hagen, K. Alizad, S.C. Medeiros, D.L. Passeri, H.F. Needham, and A. Cox, 2016: Dynamic simulation and numerical analysis of hurricane storm surge under sea level rise with geomorphologic changes along the northern Gulf of Mexico. *Earth's Future,* **4,** 177-193. http://dx.doi.org/10.1002/2015EF000347

Boon, J.D., 2012: Evidence of sea level acceleration at U.S. and Canadian tide stations, Atlantic Coast, North America. *Journal of Coastal Research***,** 1437-1445. http://dx.doi.org/10.2112/JCOASTRES-D-12-00102.1

Bromirski, P.D. and D.R. Cayan, 2015: Wave power variability and trends across the North Atlantic influenced by decadal climate patterns. *Journal of Geophysical Research: Oceans,* **120,** 3419-3443. http://dx.doi.org/10.1002/2014JC010440

Bromirski, P.D. and J.P. Kossin, 2008: Increasing hurricane wave power along the U.S. Atlantic and Gulf coasts. *Journal of Geophysical Research,* **113,** C07012. http://dx.doi.org/10.1029/2007JC004706

Bromirski, P.D., A.J. Miller, R.E. Flick, and G. Auad, 2011: Dynamical suppression of sea level rise along the Pacific coast of North America: Indications for imminent acceleration. *Journal of Geophysical Research,* **116,** C07005. http://dx.doi.org/10.1029/2010JC006759

Bromirski, P.D., D.R. Cayan, J. Helly, and P. Wittmann, 2013: Wave power variability and trends across the North Pacific. *Journal of Geophysical Research: Oceans,* **118,** 6329-6348. http://dx.doi.org/10.1002/2013JC009189

Buchanan, M.K., R.E. Kopp, M. Oppenheimer, and C. Tebaldi, 2016: Allowances for evolving coastal flood risk under uncertain local sea-level rise. *Climatic Change,* **137,** 347-362. http://dx.doi.org/10.1007/s10584-016-1664-7

Carlson, A.E., A.N. LeGrande, D.W. Oppo, R.E. Came, G.A. Schmidt, F.S. Anslow, J.M. Licciardi, and E.A. Obbink, 2008: Rapid early Holocene deglaciation of the Laurentide ice sheet. *Nature Geoscience,* **1,** 620-624. http://dx.doi.org/10.1038/ngeo285

Chambers, D.P., A. Cazenave, N. Champollion, H. Dieng, W. Llovel, R. Forsberg, K. von Schuckmann, and Y. Wada, 2017: Evaluation of the global mean sea level budget between 1993 and 2014. *Surveys in Geophysics,* **38,** 309–327. http://dx.doi.org/10.1007/s10712-016-9381-3

Church, J.A. and N.J. White, 2006: A 20th century acceleration in global sea-level rise. *Geophysical Research Letters,* **33,** L01602. http://dx.doi.org/10.1029/2005GL024826

Church, J.A. and N.J. White, 2011: Sea-level rise from the late 19th to the early 21st century. *Surveys in Geophysics,* **32,** 585-602. http://dx.doi.org/10.1007/s10712-011-9119-1

FINAL DRAFT

Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer, and A.S. Unnikrishnan, 2013: Sea level change. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1137–1216. http://www.climatechange2013.org/report/full-report/

Clark, P.U., A.S. Dyke, J.D. Shakun, A.E. Carlson, J. Clark, B. Wohlfarth, J.X. Mitrovica, S.W. Hostetler, and A.M. McCabe, 2009: The last glacial maximum. *Science,* **325,** 710-714. http://dx.doi.org/10.1126/science.1172873

Clark, P.U., J.D. Shakun, S.A. Marcott, A.C. Mix, M. Eby, S. Kulp, A. Levermann, G.A. Milne, P.L. Pfister, B.D. Santer, D.P. Schrag, S. Solomon, T.F. Stocker, B.H. Strauss, A.J. Weaver, R. Winkelmann, D. Archer, E. Bard, A. Goldner, K. Lambeck, R.T. Pierrehumbert, and G.-K. Plattner, 2016: Consequences of twenty-first-century policy for multi-millennial climate and sea-level change. *Nature Climate Change*, **6,** 360-369. http://dx.doi.org/10.1038/nclimate2923

Colle, B.A., Z. Zhang, K.A. Lombardo, E. Chang, P. Liu, and M. Zhang, 2013: Historical evaluation and future prediction of eastern North American and western Atlantic extratropical cyclones in the CMIP5 models during the cool season. *Journal of Climate,* **26,** 6882-6903. http://dx.doi.org/10.1175/JCLI-D-12-00498.1

Colle, B.A., J.F. Booth, and E.K.M. Chang, 2015: A review of historical and future changes of extratropical cyclones and associated impacts along the US East Coast. *Current Climate Change Reports,* **1,** 125-143. http://dx.doi.org/10.1007/s40641-015-0013-7

Dahl, K.A., M.F. Fitzpatrick, and E. Spanger-Siegfried, 2017: Sea level rise drives increased tidal flooding frequency at tide gauges along the U.S. East and Gulf Coasts: Projections for 2030 and 2045. *PLOS ONE,* **12,** e0170949. http://dx.doi.org/10.1371/journal.pone.0170949

Dangendorf, S., M. Marcos, A. Müller, E. Zorita, R. Riva, K. Berk, and J. Jensen, 2015: Detecting anthropogenic footprints in sea level rise. *Nature Communications,* **6,** 7849. http://dx.doi.org/10.1038/ncomms8849

DeConto, R.M. and D. Pollard, 2016: Contribution of Antarctica to past and future sea-level rise. *Nature,* **531,** 591-597. http://dx.doi.org/10.1038/nature17145

Deschamps, P., N. Durand, E. Bard, B. Hamelin, G. Camoin, A.L. Thomas, G.M. Henderson, J.i. Okuno, and Y. Yokoyama, 2012: Ice-sheet collapse and sea-level rise at the Bolling warming 14,600[thinsp]years ago. *Nature,* **483,** 559-564. http://dx.doi.org/10.1038/nature10902

FINAL DRAFT

Dutton, A., A.E. Carlson, A.J. Long, G.A. Milne, P.U. Clark, R. DeConto, B.P. Horton, S. Rahmstorf, and M.E. Raymo, 2015: Sea-level rise due to polar ice-sheet mass loss during past warm periods. *Science,* **349**. http://dx.doi.org/10.1126/science.aaa4019

Dutton, A. and K. Lambeck, 2012: Ice volume and sea level during the Last Interglacial. *Science,* **337,** 216-219. http://dx.doi.org/10.1126/science.1205749

Engelhart, S.E. and B.P. Horton, 2012: Holocene sea level database for the Atlantic coast of the United States. *Quaternary Science Reviews,* **54,** 12-25. http://dx.doi.org/10.1016/j.quascirev.2011.09.013

Erikson, L.H., C.A. Hegermiller, P.L. Barnard, P. Ruggiero, and M. van Ormondt, 2015: Projected wave conditions in the Eastern North Pacific under the influence of two CMIP5 climate scenarios. *Ocean Modelling,* **96 (12), Part 1,** 171-185. http://dx.doi.org/10.1016/j.ocemod.2015.07.004

Ezer, T., 2013: Sea level rise, spatially uneven and temporally unsteady: Why the U.S. East Coast, the global tide gauge record, and the global altimeter data show different trends. *Geophysical Research Letters,* **40,** 5439-5444. http://dx.doi.org/10.1002/2013GL057952

Ezer, T. and L.P. Atkinson, 2014: Accelerated flooding along the U.S. East Coast: On the impact of sea-level rise, tides, storms, the Gulf Stream, and the North Atlantic Oscillations. *Earth's Future,* **2,** 362-382. http://dx.doi.org/10.1002/2014EF000252

Farrell, W.E. and J.A. Clark, 1976: On postglacial sea level. *Geophysical Journal International,* **46,** 647-667. http://dx.doi.org/10.1111/j.1365-246X.1976.tb01252.x

Feser, F., M. Barcikowska, O. Krueger, F. Schenk, R. Weisse, and L. Xia, 2015: Storminess over the North Atlantic and northwestern Europe—A review. *Quarterly Journal of the Royal Meteorological Society,* **141,** 350-382. http://dx.doi.org/10.1002/qj.2364

Galloway, D., D.R. Jones, and S.E. Ingebritsen, 1999: Land Subsidence in the United States. USGS Circular 1182. U.S. Geological Survey, Reston, VA. 6 pp. https://pubs.usgs.gov/circ/circ1182/

Goddard, P.B., J. Yin, S.M. Griffies, and S. Zhang, 2015: An extreme event of sea-level rise along the Northeast coast of North America in 2009–2010. *Nature Communications,* **6,** 6346. http://dx.doi.org/10.1038/ncomms7346

Golledge, N.R., D.E. Kowalewski, T.R. Naish, R.H. Levy, C.J. Fogwill, and E.G.W. Gasson, 2015: The multi-millennial Antarctic commitment to future sea-level rise. *Nature,* **526,** 421-425. http://dx.doi.org/10.1038/nature15706

FINAL DRAFT

Graham, N.E., D.R. Cayan, P.D. Bromirski, and R.E. Flick, 2013: Multi-model projections of twenty-first century North Pacific winter wave climate under the IPCC A2 scenario. *Climate Dynamics,* **40,** 1335-1360. http://dx.doi.org/10.1007/s00382-012-1435-8

Gregory, J. M., and J. A. Lowe, 2000: Predictions of global and regional sea-level rise using AOGCMs with and without flux adjustment. *Geophysical Research Letters*, **27** (19), 3069-3072, doi:10.1029/1999GL011228.

Grinsted, A., J.C. Moore, and S. Jevrejeva, 2013: Projected Atlantic hurricane surge threat from rising temperatures. *Proceedings of the National Academy of Sciences,* **110,** 5369-5373. http://dx.doi.org/10.1073/pnas.1209980110

Grinsted, A., S. Jevrejeva, R.E.M. Riva, and D. Dahl-Jensen, 2015: Sea level rise projections for northern Europe under RCP8.5. *Climate Research,* **64,** 15-23. http://dx.doi.org/10.3354/cr01309

Hall, J.A., S. Gill, J. Obeysekera, W. Sweet, K. Knuuti, and J. Marburger, 2016: Regional Sea Level Scenarios for Coastal Risk Management: Managing the Uncertainty of Future Sea Level Change and Extreme Water Levels for Department of Defense Coastal Sites Worldwide. U.S. Department of Defense, Strategic Environmental Research and Development Program, Alexandria VA. 224 pp. https://www.usfsp.edu/icar/files/2015/08/CARSWG-SLR-FINAL-April-2016.pdf

Hall, T. and E. Yonekura, 2013: North American tropical cyclone landfall and SST: A statistical model study. *Journal of Climate,* **26,** 8422-8439. http://dx.doi.org/10.1175/jcli-d-12-00756.1

Hamlington, B.D., R.R. Leben, K.Y. Kim, R.S. Nerem, L.P. Atkinson, and P.R. Thompson, 2015: The effect of the El Niño–Southern Oscillation on U.S. regional and coastal sea level. *Journal of Geophysical Research: Oceans,* **120,** 3970-3986. http://dx.doi.org/10.1002/2014JC010602

Hamlington, B.D., S.H. Cheon, P.R. Thompson, M.A. Merrifield, R.S. Nerem, R.R. Leben, and K.Y. Kim, 2016: An ongoing shift in Pacific Ocean sea level. *Journal of Geophysical Research: Oceans,* **121,** 5084-5097. http://dx.doi.org/10.1002/2016JC011815

Hay, C.C., E. Morrow, R.E. Kopp, and J.X. Mitrovica, 2015: Probabilistic reanalysis of twentieth-century sea-level rise. *Nature,* **517,** 481-484. http://dx.doi.org/10.1038/nature14093

Haywood, A.M., D.J. Hill, A.M. Dolan, B.L. Otto-Bliesner, F. Bragg, W.L. Chan, M.A. Chandler, C. Contoux, H.J. Dowsett, A. Jost, Y. Kamae, G. Lohmann, D.J. Lunt, A. Abe-Ouchi, S.J. Pickering, G. Ramstein, N.A. Rosenbloom, U. Salzmann, L. Sohl, C. Stepanek, H. Ueda, Q. Yan, and Z. Zhang, 2013: Large-scale features of Pliocene climate: Results from the Pliocene Model Intercomparison Project. *Climate of the Past*, **9,** 191-209. http://dx.doi.org/10.5194/cp-9-191-2013

FINAL DRAFT

Helm, V., A. Humbert, and H. Miller, 2014: Elevation and elevation change of Greenland and Antarctica derived from CryoSat-2. *The Cryosphere,* **8,** 1539-1559. http://dx.doi.org/10.5194/tc-8-1539-2014

Hoeke, R.K., K.L. McInnes, J.C. Kruger, R.J. McNaught, J.R. Hunter, and S.G. Smithers, 2013: Widespread inundation of Pacific islands triggered by distant-source wind-waves. *Global and Planetary Change,* **108,** 128-138. http://dx.doi.org/10.1016/j.gloplacha.2013.06.006

Hoffman, J.S., P.U. Clark, A.C. Parnell, and F. He, 2017: Regional and global sea-surface temperatures during the last interglaciation. *Science,* **355,** 276-279. http://dx.doi.org/10.1126/science.aai8464

Holgate, S.J., A. Matthews, P.L. Woodworth, L.J. Rickards, M.E. Tamisiea, E. Bradshaw, P.R. Foden, K.M. Gordon, S. Jevrejeva, and J. Pugh, 2013: New data systems and products at the Permanent Service for Mean Sea Level. *Journal of Coastal Research*, **29,** 493-504. http://dx.doi.org/10.2112/JCOASTRES-D-12-00175.1

Horton, R.M., V. Gornitz, D.A. Bader, A.C. Ruane, R. Goldberg, and C. Rosenzweig, 2011: Climate hazard assessment for stakeholder adaptation planning in New York City. *Journal of Applied Meteorology and Climatology,* **50,** 2247-2266. http://dx.doi.org/10.1175/2011JAMC2521.1

Hunter, J., 2012: A simple technique for estimating an allowance for uncertain sea-level rise. *Climatic Change,* **113,** 239-252. http://dx.doi.org/10.1007/s10584-011-0332-1

Irvine, P.J., D.J. Lunt, E.J. Stone, and A. Ridgwell, 2009: The fate of the Greenland Ice Sheet in a geoengineered, high CO 2 world. *Environmental Research Letters,* **4,** 045109. http://dx.doi.org/10.1088/1748-9326/4/4/045109

Jackson, L.P. and S. Jevrejeva, 2016: A probabilistic approach to 21st century regional sea-level projections using RCP and High-end scenarios. *Global and Planetary Change,* **146,** 179-189. http://dx.doi.org/10.1016/j.gloplacha.2016.10.006

Jevrejeva, S., A. Grinsted, and J.C. Moore, 2009: Anthropogenic forcing dominates sea level rise since 1850. *Geophysical Research Letters,* **36,** L20706. http://dx.doi.org/10.1029/2009GL040216

Jevrejeva, S., A. Grinsted, and J.C. Moore, 2014: Upper limit for sea level projections by 2100. *Environmental Research Letters,* **9,** 104008. http://dx.doi.org/10.1088/1748-9326/9/10/104008

Joughin, I., B.E. Smith, and B. Medley, 2014: Marine ice sheet collapse potentially under way for the Thwaites Glacier Basin, West Antarctica. *Science,* **344,** 735-738. http://dx.doi.org/10.1126/science.1249055

FINAL DRAFT

Kemp, A.C. and B.P. Horton, 2013: Contribution of relative sea-level rise to historical hurricane flooding in New York City. *Journal of Quaternary Science,* **28,** 537-541. http://dx.doi.org/10.1002/jqs.2653

Kemp, A.C., B.P. Horton, J.P. Donnelly, M.E. Mann, M. Vermeer, and S. Rahmstorf, 2011: Climate related sea-level variations over the past two millennia. *Proceedings of the National Academy of Sciences,* **108,** 11017-11022. http://dx.doi.org/10.1073/pnas.1015619108

Khan, S.A., K.H. Kjaer, M. Bevis, J.L. Bamber, J. Wahr, K.K. Kjeldsen, A.A. Bjork, N.J. Korsgaard, L.A. Stearns, M.R. van den Broeke, L. Liu, N.K. Larsen, and I.S. Muresan, 2014: Sustained mass loss of the northeast Greenland ice sheet triggered by regional warming. *Nature Climate Change,* **4,** 292-299. http://dx.doi.org/10.1038/nclimate2161

Khazendar, A., M.P. Schodlok, I. Fenty, S.R.M. Ligtenberg, E. Rignot, and M.R. van den Broeke, 2013: Observed thinning of Totten Glacier is linked to coastal polynya variability. *Nature Communications,* **4,** 2857. http://dx.doi.org/10.1038/ncomms3857

Kjeldsen, K.K., N.J. Korsgaard, A.A. Bjørk, S.A. Khan, J.E. Box, S. Funder, N.K. Larsen, J.L. Bamber, W. Colgan, M. van den Broeke, M.-L. Siggaard-Andersen, C. Nuth, A. Schomacker, C.S. Andresen, E. Willerslev, and K.H. Kjær, 2015: Spatial and temporal distribution of mass loss from the Greenland Ice Sheet since AD 1900. *Nature,* **528,** 396-400. http://dx.doi.org/10.1038/nature16183

Knutson, T.R., J.J. Sirutis, M. Zhao, R.E. Tuleya, M. Bender, G.A. Vecchi, G. Villarini, and D. Chavas, 2015: Global projections of intense tropical cyclone activity for the late twenty-first century from dynamical downscaling of CMIP5/RCP4.5 scenarios. *Journal of Climate,* **28,** 7203-7224. http://dx.doi.org/10.1175/JCLI-D-15-0129.1

Knutson, T.R., J.J. Sirutis, G.A. Vecchi, S. Garner, M. Zhao, H.-S. Kim, M. Bender, R.E. Tuleya, I.M. Held, and G. Villarini, 2013: Dynamical downscaling projections of twenty-first-century Atlantic hurricane activity: CMIP3 and CMIP5 model-based scenarios. *Journal of Climate,* **27,** 6591-6617. http://dx.doi.org/10.1175/jcli-d-12-00539.1

Kopp, R.E., 2013: Does the mid-Atlantic United States sea level acceleration hot spot reflect ocean dynamic variability? *Geophysical Research Letters,* **40,** 3981-3985. http://dx.doi.org/10.1002/grl.50781

Kopp, R.E., F.J. Simons, J.X. Mitrovica, A.C. Maloof, and M. Oppenheimer, 2009: Probabilistic assessment of sea level during the last interglacial stage. *Nature,* **462,** 863-867. http://dx.doi.org/10.1038/nature08686

Kopp, R.E., R.M. Horton, C.M. Little, J.X. Mitrovica, M. Oppenheimer, D.J. Rasmussen, B.H. Strauss, and C. Tebaldi, 2014: Probabilistic 21st and 22nd century sea-level projections at a

FINAL DRAFT

global network of tide-gauge sites. *Earth's Future,* **2,** 383-406. http://dx.doi.org/10.1002/2014EF000239

Kopp, R.E., C.C. Hay, C.M. Little, and J.X. Mitrovica, 2015: Geographic variability of sea-level change. *Current Climate Change Reports,* **1,** 192-204. http://dx.doi.org/10.7282/T37W6F4P

Kopp, R.E., B.P. Horton, A.C. Kemp, and C. Tebaldi, 2015: Past and future sea-level rise along the coast of North Carolina, USA. *Climatic Change,* **132,** 693-707. http://dx.doi.org/10.1007/s10584-015-1451-x

Kopp, R.E., A.C. Kemp, K. Bittermann, B.P. Horton, J.P. Donnelly, W.R. Gehrels, C.C. Hay, J.X. Mitrovica, E.D. Morrow, and S. Rahmstorf, 2016: Temperature-driven global sea-level variability in the Common Era. *Proceedings of the National Academy of Sciences,* **113,** E1434-E1441. http://dx.doi.org/10.1073/pnas.1517056113

Lambeck, K., H. Rouby, A. Purcell, Y. Sun, and M. Sambridge, 2014: Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. *Proceedings of the National Academy of Sciences,* **111,** 15296-15303. http://dx.doi.org/10.1073/pnas.1411762111

Lenton, T.M., 2011: Early warning of climate tipping points. *Nature Climate Change,* **1,** 201-209. http://dx.doi.org/10.1038/nclimate1143

Lentz, E.E., E.R. Thieler, N.G. Plant, S.R. Stippa, R.M. Horton, and D.B. Gesch, 2016: Evaluation of dynamic coastal response to sea-level rise modifies inundation likelihood. *Nature Climate Change,* **6,** 696-700. http://dx.doi.org/10.1038/nclimate2957

Leuliette, E.W., 2015: The balancing of the sea-level budget. *Current Climate Change Reports,* **1,** 185-191. http://dx.doi.org/10.1007/s40641-015-0012-8

Leuliette, E.W. and R.S. Nerem, 2016: Contributions of Greenland and Antarctica to global and regional sea level change. *Oceanography,* **29,** 154-159. http://dx.doi.org/10.5670/oceanog.2016.107

Levermann, A., A. Griesel, M. Hofmann, M. Montoya, and S. Rahmstorf, 2005: Dynamic sea level changes following changes in the thermohaline circulation. *Climate Dynamics*, **24** (4), 347-354, doi:10.1007/s00382-004-0505-y.

Levermann, A., P.U. Clark, B. Marzeion, G.A. Milne, D. Pollard, V. Radic, and A. Robinson, 2013: The multimillennial sea-level commitment of global warming. *Proceedings of the National Academy of Sciences,* **110,** 13745-13750. http://dx.doi.org/10.1073/pnas.1219414110

FINAL DRAFT

Li, X., E. Rignot, M. Morlighem, J. Mouginot, and B. Scheuchl, 2015: Grounding line retreat of Totten Glacier, East Antarctica, 1996 to 2013. *Geophysical Research Letters,* **42,** 8049-8056. http://dx.doi.org/10.1002/2015GL065701

Lin, N., K. Emanuel, M. Oppenheimer, and E. Vanmarcke, 2012: Physically based assessment of hurricane surge threat under climate change. *Nature Climate Change,* **2,** 462-467. http://dx.doi.org/10.1038/nclimate1389

Lin, N., R.E. Kopp, B.P. Horton, and J.P. Donnelly, 2016: Hurricane Sandy's flood frequency increasing from year 1800 to 2100. *Proceedings of the National Academy of Sciences,* **113,** 12071-12075. http://dx.doi.org/10.1073/pnas.1604386113

Little, C.M., R.M. Horton, R.E. Kopp, M. Oppenheimer, and S. Yip, 2015: Uncertainty in twenty-first-century CMIP5 sea level projections. *Journal of Climate,* **28,** 838-852. http://dx.doi.org/10.1175/JCLI-D-14-00453.1

Llovel, W., J.K. Willis, F.W. Landerer, and I. Fukumori, 2014: Deep-ocean contribution to sea level and energy budget not detectable over the past decade. *Nature Climate Change,* **4,** 1031-1035. http://dx.doi.org/10.1038/nclimate2387

MacGregor, J.A., W.T. Colgan, M.A. Fahnestock, M. Morlighem, G.A. Catania, J.D. Paden, and S.P. Gogineni, 2016: Holocene deceleration of the Greenland Ice Sheet. *Science,* **351,** 590-593. http://dx.doi.org/10.1126/science.aab1702

Marcos, M. and A. Amores, 2014: Quantifying anthropogenic and natural contributions to thermosteric sea level rise. *Geophysical Research Letters,* **41,** 2502-2507. http://dx.doi.org/10.1002/2014GL059766

Marcos, M., F.M. Calafat, Á. Berihuete, and S. Dangendorf, 2015: Long-term variations in global sea level extremes. *Journal of Geophysical Research: Oceans,* **120,** 8115-8134. http://dx.doi.org/10.1002/2015JC011173

Marcos, M., B. Marzeion, S. Dangendorf, A.B.A. Slangen, H. Palanisamy, and L. Fenoglio-Marc, 2017: Internal variability versus anthropogenic forcing on sea level and its components. *Surveys in Geophysics,* **38,** 329–348. http://dx.doi.org/10.1007/s10712-016-9373-3

Markusson, N., F. Ginn, N. Singh Ghaleigh, and V. Scott, 2014: 'In case of emergency press here': Framing geoengineering as a response to dangerous climate change. *Wiley Interdisciplinary Reviews: Climate Change,* **5,** 281-290. http://dx.doi.org/10.1002/wcc.263

Martín-Español, A., A. Zammit-Mangion, P.J. Clarke, T. Flament, V. Helm, M.A. King, S.B. Luthcke, E. Petrie, F. Rémy, N. Schön, B. Wouters, and J.L. Bamber, 2016: Spatial and temporal Antarctic Ice Sheet mass trends, glacio-isostatic adjustment, and surface processes

FINAL DRAFT

from a joint inversion of satellite altimeter, gravity, and GPS data. *Journal of Geophysical Research: Earth Surface,* **121,** 182-200. http://dx.doi.org/10.1002/2015JF003550

Marzeion, B., J.G. Cogley, K. Richter, and D. Parkes, 2014: Attribution of global glacier mass loss to anthropogenic and natural causes. *Science,* **345,** 919-921. http://dx.doi.org/10.1126/science.1254702

Mawdsley, R.J. and I.D. Haigh, 2016: Spatial and temporal variability and long-term trends in skew surges globally. *Frontiers in Marine Science,* **3**. http://dx.doi.org/10.3389/fmars.2016.00029

Menéndez, M. and P.L. Woodworth, 2010: Changes in extreme high water levels based on a quasi-global tide-gauge data set. *Journal of Geophysical Research,* **115,** C10011. http://dx.doi.org/10.1029/2009JC005997

Mengel, M., A. Levermann, K. Frieler, A. Robinson, B. Marzeion, and R. Winkelmann, 2016: Future sea level rise constrained by observations and long-term commitment. *Proceedings of the National Academy of Sciences,* **113,** 2597-2602. http://dx.doi.org/10.1073/pnas.1500515113

Merrifield, M.A., 2011: A shift in western tropical Pacific sea level trends during the 1990s. *Journal of Climate,* **24,** 4126-4138. http://dx.doi.org/10.1175/2011JCLI3932.1

Merrifield, M.A., P. Thompson, E. Leuliette, G.T. Mitchum, D.P. Chambers, S. Jevrejeva, R.S. Nerem, M. Menéndez, W. Sweet, B. Hamlington, and J.J. Marra, 2015: [Global Oceans] Sea level variability and change [in "State of the Climate in 2014"]. *Bulletin of the American Meteorological Society,* **96 (12),** S82-S85. http://dx.doi.org/10.1175/2015BAMSStateoftheClimate.1

Miller, K.G., M.A. Kominz, J.V. Browning, J.D. Wright, G.S. Mountain, M.E. Katz, P.J. Sugarman, B.S. Cramer, N. Christie-Blick, and S.F. Pekar, 2005: The Phanerozoic record of global sea-level change. *Science,* **310,** 1293-1298. http://dx.doi.org/10.1126/science.1116412

Miller, K.G., J.D. Wright, J.V. Browning, A. Kulpecz, M. Kominz, T.R. Naish, B.S. Cramer, Y. Rosenthal, W.R. Peltier, and S. Sosdian, 2012: High tide of the warm Pliocene: Implications of global sea level for Antarctic deglaciation. *Geology,* **40,** 407-410. http://dx.doi.org/10.1130/g32869.1

Miller, K.G., R.E. Kopp, B.P. Horton, J.V. Browning, and A.C. Kemp, 2013: A geological perspective on sea-level rise and its impacts along the U.S. mid-Atlantic coast. *Earth's Future,* **1,** 3-18. http://dx.doi.org/10.1002/2013EF000135

FINAL DRAFT

Mitrovica, J.X., N. Gomez, E. Morrow, C. Hay, K. Latychev, and M.E. Tamisiea, 2011: On the robustness of predictions of sea level fingerprints. *Geophysical Journal International,* **187,** 729-742. http://dx.doi.org/10.1111/j.1365-246X.2011.05090.x

Moftakhari, H.R., A. AghaKouchak, B.F. Sanders, D.L. Feldman, W. Sweet, R.A. Matthew, and A. Luke, 2015: Increased nuisance flooding along the coasts of the United States due to sea level rise: Past and future. *Geophysical Research Letters,* **42,** 9846-9852. http://dx.doi.org/10.1002/2015GL066072

Moritz, H., K. White, B. Gouldby, W. Sweet, P. Ruggiero, M. Gravens, P. O'Brien, H. Moritz, T. Wahl, N.C. Nadal-Caraballo, and W. Veatch, 2015: USACE adaptation approach for future coastal climate conditions. *Proceedings of the Institution of Civil Engineers - Maritime Engineering,* **168,** 111-117. http://dx.doi.org/10.1680/jmaen.15.00015

Mouginot, J., E. Rignot, and B. Scheuchl, 2014: Sustained increase in ice discharge from the Amundsen Sea Embayment, West Antarctica, from 1973 to 2013. *Geophysical Research Letters,* **41,** 1576-1584. http://dx.doi.org/10.1002/2013GL059069

Nerem, R.S., D.P. Chambers, C. Choe, and G.T. Mitchum, 2010: Estimating mean sea level change from the TOPEX and Jason altimeter missions. *Marine Geodesy,* **33,** 435-446. http://dx.doi.org/10.1080/01490419.2010.491031

Paolo, F.S., H.A. Fricker, and L. Padman, 2015: Volume loss from Antarctic ice shelves is accelerating. *Science,* **348,** 327-331. http://dx.doi.org/10.1126/science.aaa0940

Passeri, D.L., S.C. Hagen, S.C. Medeiros, M.V. Bilskie, K. Alizad, and D. Wang, 2015: The dynamic effects of sea level rise on low-gradient coastal landscapes: A review. *Earth's Future,* **3,** 159-181. http://dx.doi.org/10.1002/2015EF000298

Pfeffer, W.T., J.T. Harper, and S. O'Neel, 2008: Kinematic constraints on glacier contributions to 21st-century sea-level rise. *Science,* **321,** 1340-1343. http://dx.doi.org/10.1126/science.1159099

Pollard, D., R.M. DeConto, and R.B. Alley, 2015: Potential Antarctic Ice Sheet retreat driven by hydrofracturing and ice cliff failure. *Earth and Planetary Science Letters,* **412,** 112-121. http://dx.doi.org/10.1016/j.epsl.2014.12.035

PSMSL, 2016: Obtaining tide guage data. Permanent Service for Mean Sea Level. http://www.psmsl.org/data/obtaining/

Rahmstorf, S., 2007: A semi-empirical approach to projecting future sea-level rise. *Science,* **315,** 368-370. http://dx.doi.org/10.1126/science.1135456

FINAL DRAFT

Rahmstorf, S., J.E. Box, G. Feulner, M.E. Mann, A. Robinson, S. Rutherford, and E.J. Schaffernicht, 2015: Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. *Nature Climate Change,* **5,** 475-480. http://dx.doi.org/10.1038/nclimate2554

Reager, J.T., A.S. Gardner, J.S. Famiglietti, D.N. Wiese, A. Eicker, and M.-H. Lo, 2016: A decade of sea level rise slowed by climate-driven hydrology. *Science,* **351,** 699-703. http://dx.doi.org/10.1126/science.aad8386

Reed, A.J., M.E. Mann, K.A. Emanuel, N. Lin, B.P. Horton, A.C. Kemp, and J.P. Donnelly, 2015: Increased threat of tropical cyclones and coastal flooding to New York City during the anthropogenic era. *Proceedings of the National Academy of Sciences,* **112,** 12610-12615. http://dx.doi.org/10.1073/pnas.1513127112

Rietbroek, R., S.-E. Brunnabend, J. Kusche, J. Schröter, and C. Dahle, 2016: Revisiting the contemporary sea-level budget on global and regional scales. *Proceedings of the National Academy of Sciences,* **113,** 1504-1509. http://dx.doi.org/10.1073/pnas.1519132113

Rignot, E., J. Mouginot, M. Morlighem, H. Seroussi, and B. Scheuchl, 2014: Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler Glaciers, West Antarctica, from 1992 to 2011. *Geophysical Research Letters,* **41,** 3502-3509. http://dx.doi.org/10.1002/2014GL060140

Ritz, C., T.L. Edwards, G. Durand, A.J. Payne, V. Peyaud, and R.C.A. Hindmarsh, 2015: Potential sea-level rise from Antarctic ice-sheet instability constrained by observations. *Nature,* **528,** 115-118. http://dx.doi.org/10.1038/nature16147

Ruggiero, P., 2013: Is the intensifying wave climate of the U.S. Pacific Northwest increasing flooding and erosion risk faster than sea-level rise? *Journal of Waterway, Port, Coastal, and Ocean Engineering,* **139,** 88-97. http://dx.doi.org/10.1061/(ASCE)WW.1943-5460.0000172

Sallenger, A.H., K.S. Doran, and P.A. Howd, 2012: Hotspot of accelerated sea-level rise on the Atlantic coast of North America. *Nature Climate Change,* **2,** 884-888. http://dx.doi.org/10.1038/nclimate1597

Scambos, T. and C. Shuman, 2016: Comment on 'Mass gains of the Antarctic ice sheet exceed losses' by H. J. Zwally and others. *Journal of Glaciology,* **62,** 599-603. http://dx.doi.org/10.1017/jog.2016.59

Seo, K.-W., C.R. Wilson, T. Scambos, B.-M. Kim, D.E. Waliser, B. Tian, B.-H. Kim, and J. Eom, 2015: Surface mass balance contributions to acceleration of Antarctic ice mass loss during 2003–2013. *Journal of Geophysical Research: Solid Earth,* **120,** 3617-3627. http://dx.doi.org/10.1002/2014JB011755

FINAL DRAFT

Serafin, K.A. and P. Ruggiero, 2014: Simulating extreme total water levels using a time-dependent, extreme value approach. *Journal of Geophysical Research: Oceans,* **119,** 6305-6329. http://dx.doi.org/10.1002/2014JC010093

Shennan, I., A.J. Long, and B.P. Horton, eds., 2015: *Handbook of Sea-Level Research*. John Wiley & Sons, Ltd, 581 pp. http://dx.doi.org/10.1002/9781118452547

Shepherd, A., E.R. Ivins, A. Geruo, V.R. Barletta, M.J. Bentley, S. Bettadpur, K.H. Briggs, D.H. Bromwich, R. Forsberg, N. Galin, M. Horwath, S. Jacobs, I. Joughin, M.A. King, J.T.M. Lenaerts, J. Li, S.R.M. Ligtenberg, A. Luckman, S.B. Luthcke, M. McMillan, R. Meister, G. Milne, J. Mouginot, A. Muir, J.P. Nicolas, J. Paden, A.J. Payne, H. Pritchard, E. Rignot, H. Rott, L. Sandberg Sørensen, T.A. Scambos, B. Scheuchl, E.J.O. Schrama, B. Smith, A.V. Sundal, J.H. van Angelen, W.J. van de Berg, M.R. van den Broeke, D.G. Vaughan, I. Velicogna, J. Wahr, P.L. Whitehouse, D.J. Wingham, D. Yi, D. Young, and H.J. Zwally, 2012: A reconciled estimate of ice-sheet mass balance. *Science,* **338,** 1183-1189. http://dx.doi.org/10.1126/science.1228102

Shope, J.B., C.D. Storlazzi, L.H. Erikson, and C.A. Hegermiller, 2016: Changes to extreme wave climates of islands within the western tropical Pacific throughout the 21st century under RCP 4.5 and RCP 8.5, with implications for island vulnerability and sustainability. *Global and Planetary Change,* **141,** 25-38. http://dx.doi.org/10.1016/j.gloplacha.2016.03.009

Sillmann, J., T.M. Lenton, A. Levermann, K. Ott, M. Hulme, F. Benduhn, and J.B. Horton, 2015: Climate emergencies do not justify engineering the climate. *Nature Climate Change,* **5,** 290-292. http://dx.doi.org/10.1038/nclimate2539

Slangen, A.B.A., M. Carson, C.A. Katsman, R.S.W. van de Wal, A. Köhl, L.L.A. Vermeersen, and D. Stammer, 2014: Projecting twenty-first century regional sea-level changes. *Climatic Change,* **124,** 317-332. http://dx.doi.org/10.1007/s10584-014-1080-9

Slangen, A.B.A., J.A. Church, X. Zhang, and D. Monselesan, 2014: Detection and attribution of global mean thermosteric sea level change. *Geophysical Research Letters,* **41,** 5951-5959. http://dx.doi.org/10.1002/2014GL061356

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

Smith, J.M., M.A. Cialone, T.V. Wamsley, and T.O. McAlpin, 2010: Potential impact of sea level rise on coastal surges in southeast Louisiana. *Ocean Engineering,* **37,** 37-47. http://dx.doi.org/10.1016/j.oceaneng.2009.07.008

FINAL DRAFT

Sriver, R.L., N.M. Urban, R. Olson, and K. Keller, 2012: Toward a physically plausible upper bound of sea-level rise projections. *Climatic Change,* **115,** 893-902. http://dx.doi.org/10.1007/s10584-012-0610-6

Stockdon, H.F., R.A. Holman, P.A. Howd, and A.H. Sallenger, Jr., 2006: Empirical parameterization of setup, swash, and runup. *Coastal Engineering,* **53,** 573-588. http://dx.doi.org/10.1016/j.coastaleng.2005.12.005

Stopa, J.E. and K.F. Cheung, 2014: Periodicity and patterns of ocean wind and wave climate. *Journal of Geophysical Research: Oceans,* **119,** 5563-5584. http://dx.doi.org/10.1002/2013JC009729

Strauss, B.H., S. Kulp, and A. Levermann, 2015: Carbon choices determine US cities committed to futures below sea level. *Proceedings of the National Academy of Sciences,* **112,** 13508-13513. http://dx.doi.org/10.1073/pnas.1511186112

Sutterley, T.C., I. Velicogna, E. Rignot, J. Mouginot, T. Flament, M.R. van den Broeke, J.M. van Wessem, and C.H. Reijmer, 2014: Mass loss of the Amundsen Sea embayment of West Antarctica from four independent techniques. *Geophysical Research Letters,* **41,** 8421-8428. http://dx.doi.org/10.1002/2014GL061940

Sweet, W.V. and J.J. Marra, 2016: State of U.S. Nuisance Tidal Flooding. Supplement to State of the Climate: National Overview for May 2016. National Oceanic and Atmospheric Administration, National Centers for Environmental Information, 5 pp. http://www.ncdc.noaa.gov/monitoring-content/sotc/national/2016/may/sweet-marra-nuisance-flooding-2015.pdf

Sweet, W.V. and J. Park, 2014: From the extreme to the mean: Acceleration and tipping points of coastal inundation from sea level rise. *Earth's Future,* **2,** 579-600. http://dx.doi.org/10.1002/2014EF000272

Sweet, W.V. and C. Zervas, 2011: Cool-season sea level anomalies and storm surges along the U.S. East Coast: Climatology and comparison with the 2009/10 El Niño. *Monthly Weather Review,* **139,** 2290-2299. http://dx.doi.org/10.1175/MWR-D-10-05043.1

Sweet, W.V., C. Zervas, S. Gill, and J. Park, 2013: Hurricane Sandy inundation probabilities of today and tomorrow [in "Explaining Extreme Events of 2012 from a Climate Perspective"]. *Bulletin of the American Meteorological Society,* **94 (9),** S17-S20. http://dx.doi.org/10.1175/BAMS-D-13-00085.1

Sweet, W., J. Park, J. Marra, C. Zervas, and S. Gill, 2014: Sea Level Rise and Nuisance Flood Frequency Changes around the United States. NOAA Technical Report NOS CO-OPS 073. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD. 58 pp.

FINAL DRAFT