

Module 1: Introduction to Climate Change in the Circumpolar World

1.1: Introduction to Climate Change and the Circumpolar World

1.1 Learning Objectives

- Define climate, climate change, and the circumpolar world
- Describe and appreciate the significance of climate change in the circumpolar world

1.1 Resources

Climate Atlas of Canada. Indigenous Knowledges and Climate Change.

<https://climateatlas.ca/indigenous-knowledges-and-climate-change>.

Dessler, A. E. 2021: Introduction to Modern Climate Change (3rd ed.). Cambridge: Cambridge University Press. ISBN: 9781108879125. – Chapter 1: An Introduction to the Climate Problem

SEARCH, O. Ahkinga, E. Alexander, M. D. Apassingok, B. Baker, M. Baker, M. Berman, M. Blair, E. Bloom, N. J. Burns, A. E. Copenhaver, E. Q. Cravalho, J. Donatuto, K. Dunton, S. V. Fletcher, E. Froehlich, J. C. George, C. Harris, M. Heavner, M. Hoffbeck, M. Holland, M. T. Jorgenson, B. P. Kelly, E. Kerttula, G. W. Kling, C. W. Koch, L. Landrum, S. Lange, M. K. Lukin, E. Marino, V. K. Metcalf, C. Nunn, R. Pincus, P. Pungowiyi, M. Robards, J. Q. Schaeffer, A. Shahbazi, A. Shultz, D. T. Turner, J. E. Walsh, F. Wiese, and G. Wong, Wilson Justin, 2022. Consequences of Rapid Environmental Arctic Change for People. Arctic Report Card 2022, M. L. Druckenmiller, R. L. Thoman, and T. A. Moon, Eds., <https://doi.org/10.25923/kgm2-9k50>.

Thoman, R. L., T. A. Moon, and M. L. Druckenmiller, Eds., 2023: Arctic Report Card 2023. <https://doi.org/10.25923/5vfa-k694>.

1.2: Climate Change Evidence Through Multiple Lenses

1.2 Learning Objectives

- Compare and contrast different knowledge frameworks and their contributions to understanding climate change (e.g., Traditional Knowledge, western scientific knowledge, two-eyed seeing approaches)
- Discuss and appreciate the value of incorporating multiple knowledge frameworks within climate change research

1.2 Resources

Canadian Climate Institute. The ‘two-eyed seeing’ of cross-cultural research camps. <https://climateinstitute.ca/publications/cross-cultural-research-camps/>

Climate Atlas of Canada. Indigenous Knowledges and Climate Change. <https://climateatlas.ca/indigenous-knowledges-and-climate-change>.

Glenn-Borade, R. T., B. Adams, R. Schaeffer, C. SimsKayotuk, G. Omnik, J. M. Leavitt, and D. D. W. Hauser. 2023. Nunaqqit Savaqatigivlugich: Working With Communities to Observe the Arctic. Arctic Report Card 2023, Thoman, R. L., T. A. Moon, and M. L. Druckenmiller, Eds., <https://doi.org/10.25923/2sx6-kx89>.

Reid, A. J., Eckert, L. E., Lane, J., Young, N., Hinch, S. G., Darimont, C. T., Cooke, S. J., Ban, N. C., & Marshall, A. 2021. “Two-Eyed Seeing”: An Indigenous framework to transform fisheries research and management. *Fish and Fisheries*, 22(2), 243–261. <https://doi.org/10.1111/faf.12516>.

Saami Council. 2023. Climate Change in Sápmi – an overview and a Path Forward. <https://www.saamicouncil.net/documentarchive/sami-climate-report>.

Stone, R. 2020. As the Arctic thaws, Indigenous Alaskans demand a voice in climate change research: National Science Foundation program struggles to bridge scientists and communities. *Science*. <https://doi.org/10.1126/science.abe7149>

Invite stories from a local elder

1.3: Climate Change, Western Scientific Knowledge

1.3 Learning Objectives

- Compare and contrast the features in the paleo- and present climate records
- Identify examples and describe how proxies are used in the long- and short-term climate reconstructions
- Describe the process of oxygen isotope fractionation under different climate conditions (including isotope compositions in the ocean, in ocean sediments, and in ice)
- List and describe the mechanisms of natural climate variation: solar variability, Milankovitch cycles, continental position and topography, atmospheric gases and aerosols
- Discuss additional mechanisms of current climate variation

1.3 Resources

Dessler, A. E. 2021: Introduction to Modern Climate Change (3rd ed.). Cambridge: Cambridge University Press. ISBN: 9781108879125. – Chapter 7: Why is the Climate Changing

Eyring, V., N.P. Gillett, K.M. Achuta Rao, R. Barimalala, M. Barreiro Parrillo, N. Bellouin, C. Cassou, P.J. Durack, Y. Kosaka, S. McGregor, S. Min, O. Morgenstern, and Y. Sun, 2021: Human Influence on the Climate System. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 423–552, doi:10.1017/9781009157896.005.

Gulev, S.K., P.W. Thorne, J. Ahn, F.J. Dentener, C.M. Domingues, S. Gerland, D. Gong, D.S. Kaufman, H.C. Nnamchi, J. Quaas, J.A. Rivera, S. Sathyendranath, S.L. Smith, B. Trewin, K. von Schuckmann, and R.S. Vose, 2021: Changing State of the Climate System. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 287–422, doi:10.1017/9781009157896.004.

Module 2: Understanding the Climate System

2.1: What is Climate?

2.1 Learning Objectives

- Differentiate between climate and weather
- Utilize the Köppen-Geiger climate classification to identify climate zones in the circumpolar regions
- Discuss the significance of climate to the circumpolar environment, ecosystems, and way of life

2.1 Resources

Beck, H., Zimmermann, N., McVicar, T. et al. 2018. Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Sci Data* 5, 180214. <https://doi.org/10.1038/sdata.2018.214>.

Dessler, A. E. 2021: *Introduction to Modern Climate Change* (3rd ed.). Cambridge: Cambridge University Press. ISBN: 9781108879125. – Chapter 1: An Introduction to the Climate Problem & Chapter 2: Is the Climate Changing

2.2: Essentials of Radiation on Earth

2.2 Learning Objectives

- Define energy, temperature, and power
- Describe electromagnetic radiation and identify which wavelengths of the electromagnetic spectrum apply to the global radiative forcing
- Apply Wien's displacement law to relate the wavelength of peak power emitted from a blackbody with a particular temperature
- Apply the Stefan-Boltzmann equation to characterize the relationship between temperature of a blackbody and the total power radiated
- Describe the components of the global energy balance in terms of the sources and pathways of shortwave and longwave radiation

2.2 Resources

Dessler, A. E. 2021: Introduction to Modern Climate Change (3rd ed.). Cambridge: Cambridge University Press. ISBN: 9781108879125. – Chapter 3: Radiation and Energy Balance & Chapter 4: A Simple Climate Model

Forster, P., T. Storelvmo, K. Armour, W. Collins, J.-L. Dufresne, D. Frame, D.J. Lunt, T. Mauritsen, M.D. Palmer, M. Watanabe, M. Wild, and H. Zhang, 2021: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 923–1054, doi: 10.1017/9781009157896.009.

2.3: The Global Energy Balance

2.3 Learning Objectives

- Characterize Earth's incoming solar radiation
- Evaluate the pathways of radiation through matter: reflection, absorption, transmission
- Determine the amount of energy emitted by an object based on the material's emissivity
- Apply Kirchoff's Law to describe that good absorbers are good emitters of energy
- Evaluate a simple layer model of the Earth's energy balance
- Describe the greenhouse effect in terms of Earth's energy balance
- Explain how the greenhouse effect makes the planet habitable and how it contributes to climate change

2.3 Resources

Dessler, A. E. 2021: Introduction to Modern Climate Change (3rd ed.). Cambridge: Cambridge University Press. ISBN: 9781108879125. Chapter 4: A Simple Climate Model

Forster, P., T. Storelvmo, K. Armour, W. Collins, J.-L. Dufresne, D. Frame, D.J. Lunt, T. Mauritsen, M.D. Palmer, M. Watanabe, M. Wild, and H. Zhang, 2021: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 923–1054, doi: 10.1017/9781009157896.009.

2.4: The Carbon Cycle and Greenhouse Gases

2.4 Learning Objectives

- Describe and sketch the carbon cycle
- Explain the greenhouse effect
- Provide examples and sources of the predominant greenhouse gases
- Identify the contributing factors to the atmospheric carbon dioxide concentrations represented by the Keeling Curve
- Compare and contrast the absorption spectrum of greenhouse gases
- Describe the atmospheric window and discuss the implications on the global energy budget

2.4 Resources

Canadell, J.G., P.M.S. Monteiro, M.H. Costa, L. Cotrim da Cunha, P.M. Cox, A.V. Eliseev, S. Henson, M. Ishii, S. Jaccard, C. Koven, A. Lohila, P.K. Patra, S. Piao, J. Rogelj, S. Syampungani, S. Zaehle, and K. Zickfeld, 2021: Global Carbon and other Biogeochemical Cycles and Feedbacks. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 673–816, doi:10.1017/9781009157896.007.

Dessler, A. E. 2021: *Introduction to Modern Climate Change* (3rd ed.). Cambridge: Cambridge University Press. ISBN: 9781108879125. Chapter 5: The Carbon Cycle & Chapter 7: Why is the Climate Changing

National Oceanic and Atmospheric Administration. The Atmospheric Window.
<https://www.noaa.gov/jetstream/satellites/absorb>

2.5: Climate Forcing and Feedbacks

2.5 Learning Objectives

- Discuss the impact of time lags in the climate system and the impact it has on equilibrium of the global energy budget and global temperatures
- Define radiative forcing and provide examples of positive and negative radiative forcings
- Define and apply climate sensitivity
- Define and identify positive and negative feedbacks
- Describe examples of fast (ice-albedo, water vapor, lapse rate, cloud) and slow (carbon-cycle, vegetation, chemical weathering) feedbacks

2.5 Resources

Dessler, A. E. 2021: Introduction to Modern Climate Change (3rd ed.). Cambridge: Cambridge University Press. ISBN: 9781108879125. Chapter 6: Forcing, Feedbacks, and Climate Sensitivity

Forster, P., T. Storelvmo, K. Armour, W. Collins, J.-L. Dufresne, D. Frame, D.J. Lunt, T. Mauritsen, M.D. Palmer, M. Watanabe, M. Wild, and H. Zhang, 2021: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 923–1054, doi: 10.1017/9781009157896.009.

Module 3: Climate Modelling

3.1: Climate Models

3.1 Learning Objectives

- Explain the motivation for climate modelling
- Describe the fundamentals of climate modelling, including grids, resolution, forcing parameters, spin-up, physics, parameterizations
- Describe the different emission scenarios: Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs)
- Discuss model variability and the role of model intercomparison projects
- Explain model limitations and uncertainty
- Discuss when a regional model may be preferred over a global model

3.1 Resources

Chen, D., M. Rojas, B.H. Samset, K. Cobb, A. Diongue Niang, P. Edwards, S. Emori, S.H. Faria, E. Hawkins, P. Hope, P. Huybrechts, M. Meinshausen, S.K. Mustafa, G.-K. Plattner, and A.-M. Tréguier, 2021: Framing, Context, and Methods. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 147–286, doi:10.1017/9781009157896.003.

Dessler, A. E. 2021: *Introduction to Modern Climate Change* (3rd ed.). Cambridge: Cambridge University Press. ISBN: 9781108879125. Chapter 8: Predictions of Future Climate Change

World Climate Research Programme. WCRP Coupled Model Intercomparison Project (CMIP). <https://www.wcrp-climate.org/wgcm-cmip>

3.2: Future Climate Projections

3.2 Learning Objectives

- Identify changes in future global temperature projections based on different emission scenarios
- Discuss the implications of global warming 1.5°C above pre-industrial levels
- Describe the impact that global increases in temperature will have in the circumpolar north

3.2 Resources

- Dessler, A. E. 2021: Introduction to Modern Climate Change (3rd ed.). Cambridge: Cambridge University Press. ISBN: 9781108879125. Chapter 8: Predictions of Future Climate Change & Chapter 9: Impacts of Climate Change
- Hoegh-Guldberg, O., D. Jacob, M. Taylor, M. Bindi, S. Brown, I. Camilloni, A. Diedhiou, R. Djalante, K.L. Ebi, F. Engelbrecht, J. Guiot, Y. Hijikata, S. Mehrotra, A. Payne, S.I. Seneviratne, A. Thomas, R. Warren, and G. Zhou, 2018: Impacts of 1.5°C Global Warming on Natural and Human Systems. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 175-312. <https://doi.org/10.1017/9781009157940.005>.
- Lee, J.-Y., J. Marotzke, G. Bala, L. Cao, S. Corti, J.P. Dunne, F. Engelbrecht, E. Fischer, J.C. Fyfe, C. Jones, A. Maycock, J. Mutemi, O. Ndiaye, S. Panickal, and T. Zhou, 2021: Future Global Climate: Scenario-Based Projections and Near-Term Information. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 553–672, doi:10.1017/9781009157896.006.
- Post, E., R. B. Alley, T. R. Christensen, et al. 2019. The polar regions in a 2°C warmer world. Science Advances Review. 5:eaaw9883.

Module 4: Environmental Responses to Climate Change

4.1: Climate Change and the Atmosphere

4.1 Learning Objectives

- Explain the impact of high and low clouds in the climate system
- Describe changes in temperature and precipitation in the circumpolar north
- Describe the predictions of changes to the type of precipitation within the circumpolar north
- Discuss the influence of climate change on extreme events (e.g., storms, flooding, droughts, fires) and the socio-economic impacts on northern communities

4.1 Resources

Ballinger, T. J., S. Bigalke, J. E. Walsh, B. Brettschneider, R. L. Thoman, U. S. Bhatt, E. Hanna, I. Hanssen-Bauer, S. -J. Kim, J. E. Overland, and M. Wang. 2023. Surface Air Temperature. Arctic Report Card 2023, Thoman, R. L., T. A. Moon, and M. L. Druckenmiller, Eds., <https://doi.org/10.25923/x3ta-6e63>.

Bitanja, R. 2018. The impact of Arctic warming on increased rainfall. Nature Scientific Reports 8:16001 DOI:10.1038/s41598-018-34450-3

Dessler, A. E. 2021: Introduction to Modern Climate Change (3rd ed.). Cambridge: Cambridge University Press. ISBN: 9781108879125. Chapter 9: Impacts of Climate Change

Lee, J.-Y., J. Marotzke, G. Bala, L. Cao, S. Corti, J.P. Dunne, F. Engelbrecht, E. Fischer, J.C. Fyfe, C. Jones, A. Maycock, J. Mutemi, O. Ndiaye, S. Panickal, and T. Zhou, 2021: Future Global Climate: Scenario-Based Projections and Near-Term Information. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 553–672, doi:10.1017/9781009157896.006.

Meredith, M., M. Sommerkorn, S. Cassotta, C. Derksen, A. Ekaykin, A. Hollowed, G. Kofinas, A. Mackintosh, J. Melbourne-Thomas, M.M.C. Muelbert, G. Ottersen, H. Pritchard, and E.A.G. Schuur, 2019: Polar Regions. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 203–320. <https://doi.org/10.1017/9781009157964.005>.

Walsh, J. E., S. Bigalke, S. A. McAfee, R. Lader, M. C. Serreze, and T. J. Ballinger. 2023. Precipitation. Arctic Report Card 2023, Thoman, R. L., T. A. Moon, and M. L. Druckenmiller, Eds., <https://doi.org/10.25923/hcm7-az41>.

4.2: Climate Change and the Oceans

4.2 Learning Objectives

- Explain the difference between heating on land and heating of the ocean
- Explain the significance of air-sea interactions within the climate system
- Discuss the impact of climate change on the ocean carbonate system and ocean acidification
- Identify and describe the contributing factors to sea level rise (e.g., thermal expansion and melting land ice)
- Discuss the socio-economic impacts of sea level rise on northern communities
- Describe the impacts of climate change on Arctic Ocean and North Atlantic circulation patterns and deep water formation

4.2 Resources

Dessler, A. E. 2021: Introduction to Modern Climate Change (3rd ed.). Cambridge: Cambridge University Press. ISBN: 9781108879125.
Chapter 9: Impacts of Climate Change

Lee, J.-Y., J. Marotzke, G. Bala, L. Cao, S. Corti, J.P. Dunne, F. Engelbrecht, E. Fischer, J.C. Fyfe, C. Jones, A. Maycock, J. Mutemi, O. Ndiaye, S. Panickal, and T. Zhou, 2021: Future Global Climate: Scenario-Based Projections and Near-Term Information. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 553–672, doi:10.1017/9781009157896.006.

Meredith, M., M. Sommerkorn, S. Cassotta, C. Derksen, A. Ekaykin, A. Hollowed, G. Kofinas, A. Mackintosh, J. Melbourne-Thomas, M.M.C. Muelbert, G. Ottersen, H. Pritchard, and E.A.G. Schuur, 2019: Polar Regions. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 203–320. <https://doi.org/10.1017/9781009157964.005>.

Timmermans, M. –L. and Z. Labe, 2023. Sea Surface Temperature. Arctic Report Card 2023, Thoman, R. L., T. A. Moon, and M. L. Druckenmiller, Eds., <https://doi.org/10.25923/e8jc-f342>.

4.3: Climate Change and the Cryosphere

4.2 Learning Objectives

- Compare and contrast sea ice extent in the Arctic and Antarctic Oceans
- Describe the changes in minimum Arctic sea ice extent over time
- Describe climate related changes to glaciers and ice sheets
- Determine how changes in the cryosphere can impact Earth's albedo
- Explain Arctic amplification
- Describe permafrost and its role in carbon storage and wetland ecosystems
- Discuss the influence of climate change to the cryosphere and the socio-economic impacts on northern communities

4.2 Resources

- Dessler, A. E. 2021: Introduction to Modern Climate Change (3rd ed.). Cambridge: Cambridge University Press. ISBN: 9781108879125. Chapter 8: Predictions of Future Climate Change & Chapter 9: Impacts of Climate Change
- Lee, J.-Y., J. Marotzke, G. Bala, L. Cao, S. Corti, J.P. Dunne, F. Engelbrecht, E. Fischer, J.C. Fyfe, C. Jones, A. Maycock, J. Mutemi, O. Ndiaye, S. Panickal, and T. Zhou, 2021: Future Global Climate: Scenario-Based Projections and Near-Term Information. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 553–672, doi:10.1017/9781009157896.006.
- Meredith, M., M. Sommerkorn, S. Cassotta, C. Derksen, A. Ekaykin, A. Hollowed, G. Kofinas, A. Mackintosh, J. Melbourne-Thomas, M.M.C. Muelbert, G. Ottersen, H. Pritchard, and E.A.G. Schuur, 2019: Polar Regions. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 203–320. <https://doi.org/10.1017/9781009157964.005>.
- Shugar, D. H., Clague, J. J., Best, J. L., Schoof, C., Willis, M. J., Copland, L., & Roe, G. H. 2017. River piracy and drainage basin reorganization led by climate-driven glacier retreat. *Nature Geoscience*, 10(5), 370–375. <https://doi.org/10.1038/ngeo2932>
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Module 5: Ecosystem Responses to Climate Change

5.1: Vegetation Responses to Climate Change

5.1 Learning Objectives

- Describe photosynthesis and the carbon storage potential and predicted changes within the Circumpolar Boreal forest and Arctic Regions
- Describe the impact of temperature and sea ice to marine algae in the Arctic Ocean
- Characterize features of wetlands and peatlands and how climate change is impacting them, including impacts on methane, carbon, and water cycles
- Summarize some examples of vegetation changes, such as Northern Coniferous Forest and Tundra biome boundary changes
- Describe shrubification of Arctic and sub-Arctic regions

5.1 Resources

- Brandt, J. P., Flannigan, M. D., Maynard, D. G., Thompson, I. D., & Volney, W. J. A. 2013. An introduction to Canada's boreal zone: Ecosystem processes, health, sustainability, and environmental issues. *Environmental Reviews*, 21(4), 207–226. <https://doi.org/10.1139/er-2013-0040>
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- Frost, G. V., M. J. Macander, U. S. Bhatt, L. T. Berner, J. W. Bjerke, H. E. Epstein, B. C. Forbes, M. J. Lara, R. Í. Magnússon, P. M. Montesano, G. K. Phoenix, S. P. Serbin, H. Tømmervik, C. Waigl, D. A. Walker, and D. Yang. 2023. Tundra Greenness. . *Arctic Report Card 2023*, Thoman, R. L., T. A. Moon, and M. L. Druckenmiller, Eds., <https://doi.org/10.25923/s86a-jn24>.
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- Post, E., R. B. Alley, T. R. Christensen, et al. 2019. The polar regions in a 2°C warmer world. *Science Advances Review*. 5:eaaw9883.
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5.2: Wildlife Responses to Climate Change

5.2 Learning Objectives

- Characterize thermal tolerance ranges using northern species as examples, such as pika, lemming
- Characterize range shifts and contractions in the circumpolar North
- Discuss changes to timing (phenology) and this can be mistimed or (asynchronous) between species
 - Describe changes to phenology in boreal Europe, compare to phenological shifts in North America and how this can cause population decline, or other changes
- Characterize and define refugia from climate change
- Describe adaptation through behavior and natural selection

5.2 Resources

- Schoen, E. R., K. G. Howard, J. M. Murphy, D. E. Schindler, P. A. H. Westley, and V. R. von Biela. 2023. Divergent Responses of Western Alaska Salmon to a Changing Climate. Arctic Report Card 2023, Thoman, R. L., T. A. Moon, and M. L. Druckenmiller, Eds., <https://doi.org/10.25923/f2hv-5581>.
- Sharma, S., Couturier, S., & Côté, S. D. 2009. Impacts of Climate Change on the Seasonal Distribution of Migratory Caribou. *Global Change Biology*, 15(10), 2549–2562. <https://doi.org/10.1111/j.1365-2486.2009.01945.x>
- Yandow, L. H., Chalfoun, A. D., & Doak, D. F. 2015. Climate Tolerances and Habitat Requirements Jointly Shape the Elevational Distribution of the American Pika (*Ochotona princeps*), with Implications for Climate Change Effects. *PLOS ONE*, 10(8), e0131082. <https://doi.org/10.1371/journal.pone.0131082>

5.3: Climate Change and Extinction

5.3 Learning Objectives

- Summarize global temperature changes and mass extinctions across geologic time
- Compare and contrast past extinctions events with current mass extinction and connections to global temperature
- Describe (generally) how climate change causes extinction
- Provide examples of timing (phenology) and community changes and habitat loss (ice - polar bear, ivory gull; tundra - caribou)
- Define what a keystone species is and provide examples of keystone species in local ecosystems
- Discuss whether restoration or re-introduction of keystone species could be possible
- Discuss the vulnerability of Arctic and sub-Arctic plants, lichen and moss of the Arctic and boreal regions to climate change (in particular to changes in moisture regimes)

5.3 Resources

- Brandt, J. P., Flannigan, M. D., Maynard, D. G., Thompson, I. D., & Volney, W. J. A. 2013. An introduction to Canada's boreal zone: Ecosystem processes, health, sustainability, and environmental issues. *Environmental Reviews*, 21(4), 207–226. <https://doi.org/10.1139/er-2013-0040>
- Cahill, A. E., M. E. Aiello-Lammens, M. C. Fisher-Reid, X. Hua, C. J. Karanewsky, H. Y. Ryu, G. C. Sbeglia, F. Spagnolo, J. B. Waldron, O. Warsi, and J. J. Wiens. 2013. How does climate change cause extinction? *Proceedings of the Royal Society B-Biological Sciences* 280:20121890.
- Mayhew, P. J., Jenkins, G. B., & Benton, T. G. 2008. A long-term association between global temperature and biodiversity, origination and extinction in the fossil record. *Proceedings of the Royal Society B-Biological Sciences*, 275(1630), 47–53. <https://doi.org/10.1098/rspb.2007.1302>

5.4: Climate Change and Interactions with Humans

5.4 Learning Objectives

- Describe ecosystem services and how they may be impacted by climate change
- Describe human climate migrants and risks of overexploitation
- Describe invasive species, how they are influenced by climate change and the impact they have on biodiversity
- Discuss issues of climate-related food security in northern communities

5.4 Resources

Bogdanova, E., Andronov, S., Soromotin, A., Detter, G., Sizov, O., Hossain, K., Raheem, D., & Lobanov, A. 2021. The impact of climate change on the food (In)security of the Siberian Indigenous peoples in the Arctic: Environmental and health risks. *Sustainability*, 13(5), 2561. <https://doi.org/10.3390/su13052561>

Cattaneo, C., Beine, M., Fröhlich, C.J., Kniveton, D., Martinez-Zarzoso, I., Mastrorillo, M., Millock, K., Piguet, E. and Schraven, B. 2019. Human migration in the era of climate change. *Review of Environmental Economics and Policy*.

Darimont, C.T., Cooke, R., Bourbonnais, M.L. et al. 2023. Humanity's diverse predatory niche and its ecological consequences. *Communications Biology*. 6, 609. <https://doi.org/10.1038/s42003-023-04940-w>

Mooney, H., Larigauderie, A., Cesario, M., Elmquist, T., Hoegh-Guldberg, O., Lavorel, S., Mace, G. M., Palmer, M., Scholes, R., & Yahara, T. 2009. Biodiversity, climate change, and ecosystem services. *Current Opinion in Environmental Sustainability*, 1(1), 46–54. <https://doi.org/10.1016/j.cosust.2009.07.006>

WWF. 2020. Living Planet Report 2020-Bending the curve of biodiversity loss. Almond, R.E.A., Grooten M. and Petersen, T. (Eds). WWF, Gland, Switzerland.

5.5: Modeling the Ecological Impacts of Climate Change on Species

5.5 Learning Objectives

- Provide an overview of modeling methods to predict change in abundance and distribution of organisms (e.g., species distribution modeling, sometimes called ecological niche modeling)
- Describe examples of mathematical methods and models (e.g., Boosted Regression Trees, MAXENT, Neural Network, Random Forests, log-linear modelling)
- Discuss the reliance on climate models and vegetation models to inform modelling procedures (including error and confidence levels)

5.5 Resources

Stralberg, D., Bayne, E. M., Cumming, S. G., Sólymos, P., Song, S. J., & Schmiegelow, F. K. A. 2015. Conservation of future boreal forest bird communities considering lags in vegetation response to climate change: A modified refugia approach. *Diversity and Distributions*, 21(9), 1112–1128. <https://doi.org/10.1111/ddi.12356>

Module 6: Looking Forward

6.1: Human Responses to Climate Change

6.1 Learning Objectives

- Define and provide examples of climate change mitigation and adaptation
- Define and provide examples of solar radiation management and carbon dioxide removal
- Describe different approaches to mitigation policy (e.g., market-based, informational/voluntary)

6.1 Resources

Dessler, A. E. 2021: Introduction to Modern Climate Change (3rd ed.).
Cambridge: Cambridge University Press. ISBN: 9781108879125. Chapter
11: Fundamentals of Climate Change Policy & Chapter 12: Mitigation
Policies

Dodson, J. C., Dérer, P., Cafaro, P., & Götmark, F. 2020. Population growth and
climate change: Addressing the overlooked threat multiplier. *Science of The
Total Environment*, 748, 141346.
<https://doi.org/10.1016/j.scitotenv.2020.141346>

6.2: Climate Leadership

6.2 Learning Objectives

- Describe different levels of governance and who makes climate change related decisions
- Describe the value of multiple perspectives when it comes to climate leadership
- Provide examples of Indigenous climate leadership within the circumpolar north

6.2 Resources

Climate Atlas of Canada. Indigenous Climate Action. <https://climateatlas.ca/video/indigenous-climate-action>.

Government of Yukon. 2020. Our Clean Future: A Yukon strategy for climate change, energy and a green economy.

Indigenous Climate Action. 2022. Indigenous-led Climate Policy.

Jodoin, S., A. Corrobow, and S. Snow. 2020. Realizing the right to be cold? Framing processes and outcomes associated with the Inuit petition on human rights and global warming. *Law and Society Review* 54(1):168-200.

Meredith, M., M. Sommerkorn, S. Cassotta, C. Derksen, A. Ekaykin, A. Hollowed, G. Kofinas, A. Mackintosh, J. Melbourne-Thomas, M.M.C. Muelbert, G. Ottersen, H. Pritchard, and E.A.G. Schuur, 2019: Polar Regions. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 203–320. <https://doi.org/10.1017/9781009157964.005>.

Saami Council. 2023. Climate Change in Sápmi – an overview and a Path Forward. <https://www.saamicouncil.net/documentarchive/sami-climate-report>.